Application of Plasma Phenomena

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Institute of Space and Plasma Sciences, National Cheng Kung University

Lecture 11

2024 spring semester

Tuesday 9:10-12:00

Materials:

https://capst.ncku.edu.tw/PGS/index.php/teaching/

Online courses:

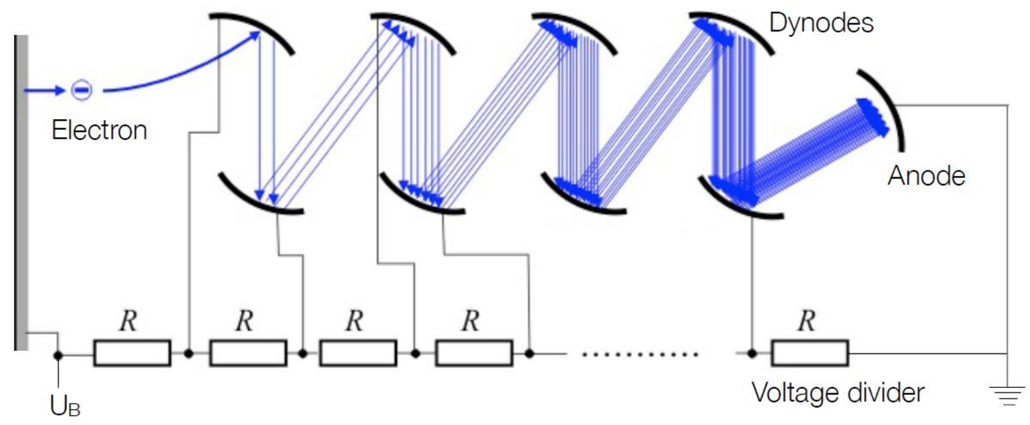
https://nckucc.webex.com/nckucc/j.php?MTID=m4082f23c59af0571015416f6e58dd803

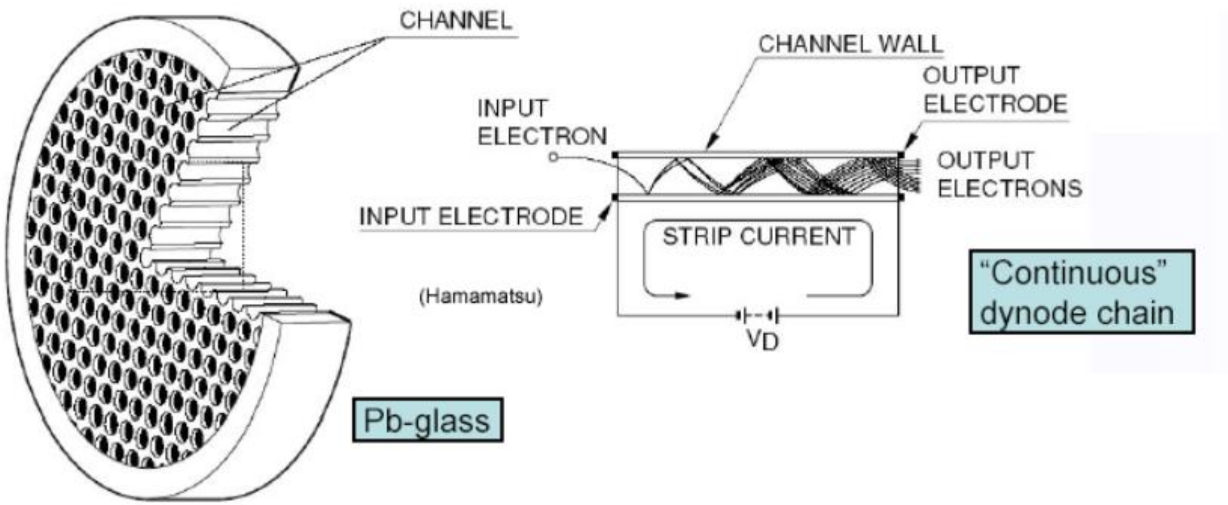
2024/5/21 updated

Note!

- **Quiz in class on 5/28!**

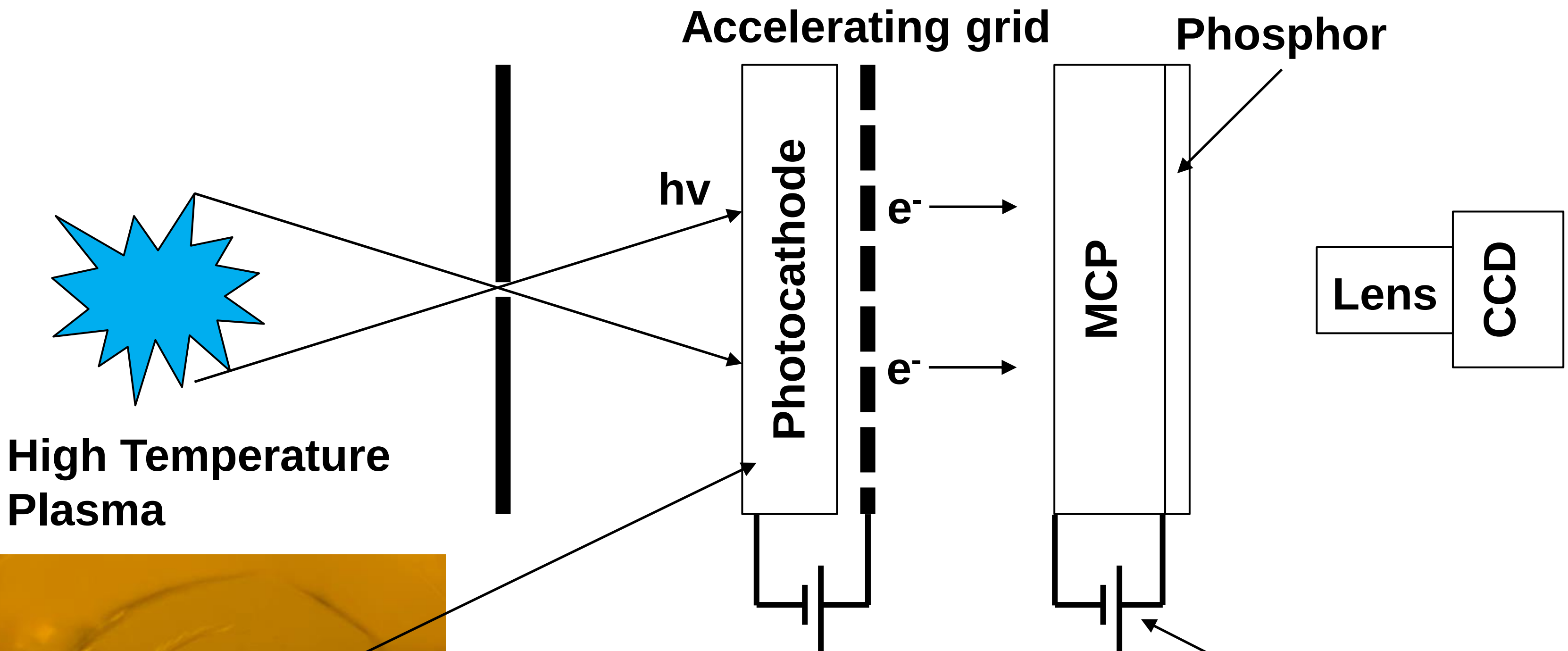
The number of electrons can be increased through photomultipliers or microchannel plate (MCP)

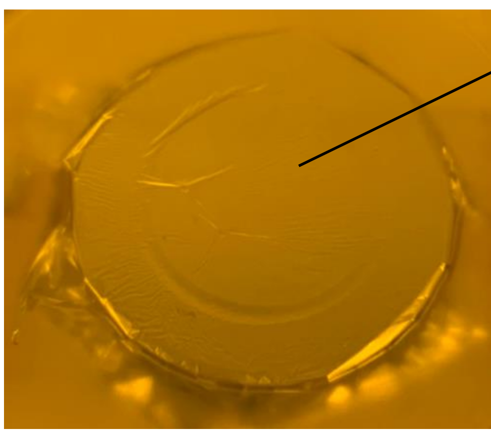


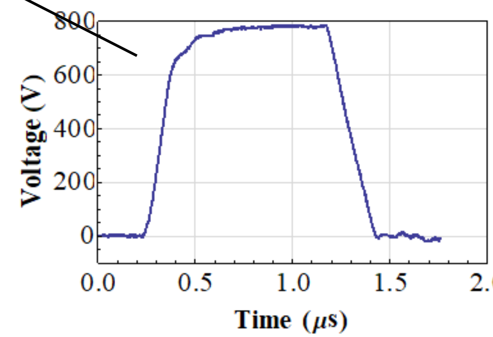


http://www.kip.uni-heidelberg.de/~coulon/Lectures/DetectorsSoSe10/

X-rays are imaged using photocathode, MCP, phosphor, and CCD





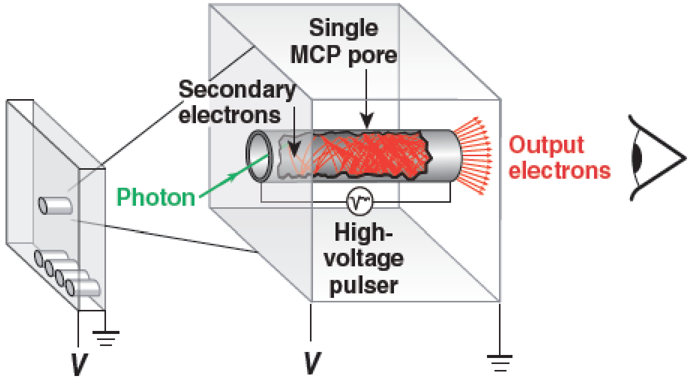


- CsI is used right now.
- Prof. Chou @ Photonics, NCKU is developing 50nm Au foil for us.

- Images can be gated using fast high voltage pulses.

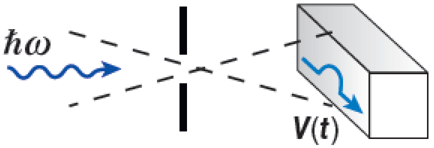
A framing camera provides a series of time-gated 2-D images, similar to a movie camera

- The building block of a framing camera is a gated microchannel-plate (MCP) detector
- An MCP is a plate covered with small holes, each acts as a photomultiplier



Multiple electrons are produced each time an electron or photon hits the wall

- A voltage pulse is sent down the plate, gating the detector

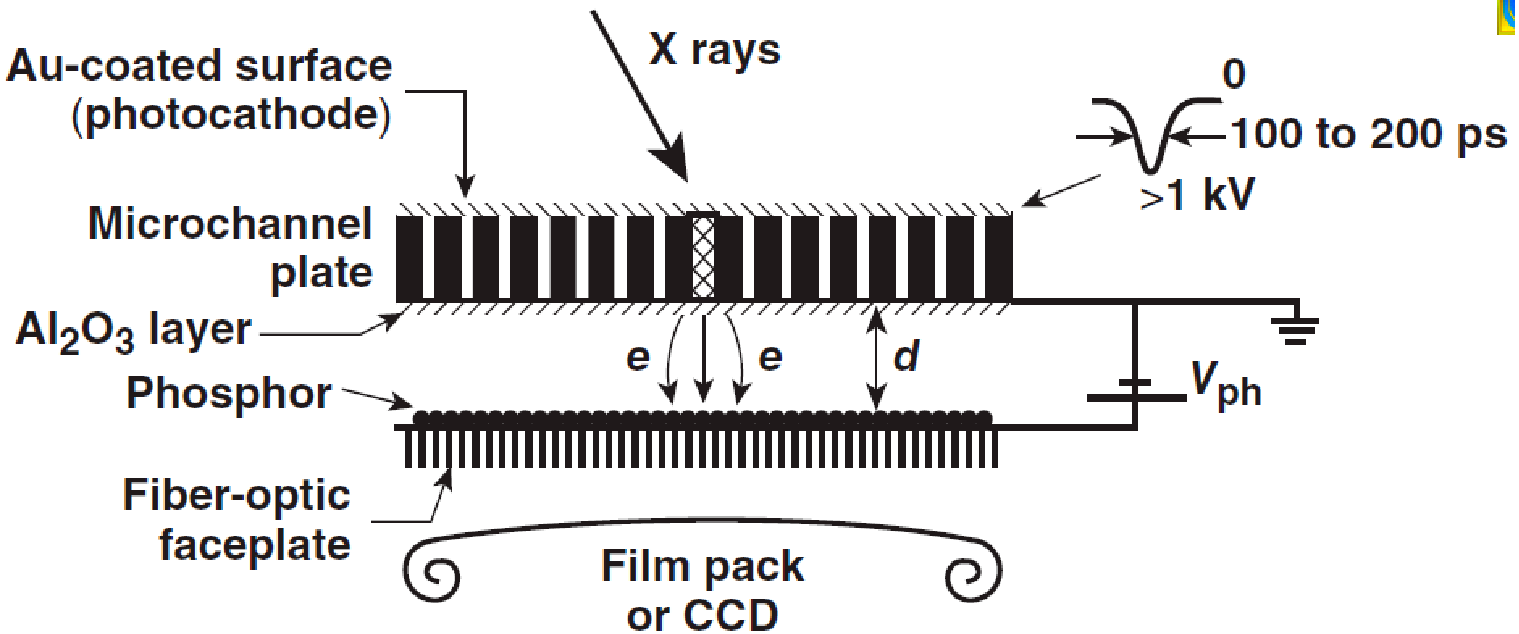


The detector is only on when the voltage pulse is present

E13986b

http://hedpschool.lle.rochester.edu/1000_proc2013.php

A framing camera detector consists of a microchannel plate (MCP) in front of a phosphor screen



- Electrons are multiplied through MCP by voltage V_c
- Images are recorded on film behind phosphor
- Insulating Al_2O_3 layer allows for V_{ph} to be increased, thereby improving the spatial resolution of phosphor

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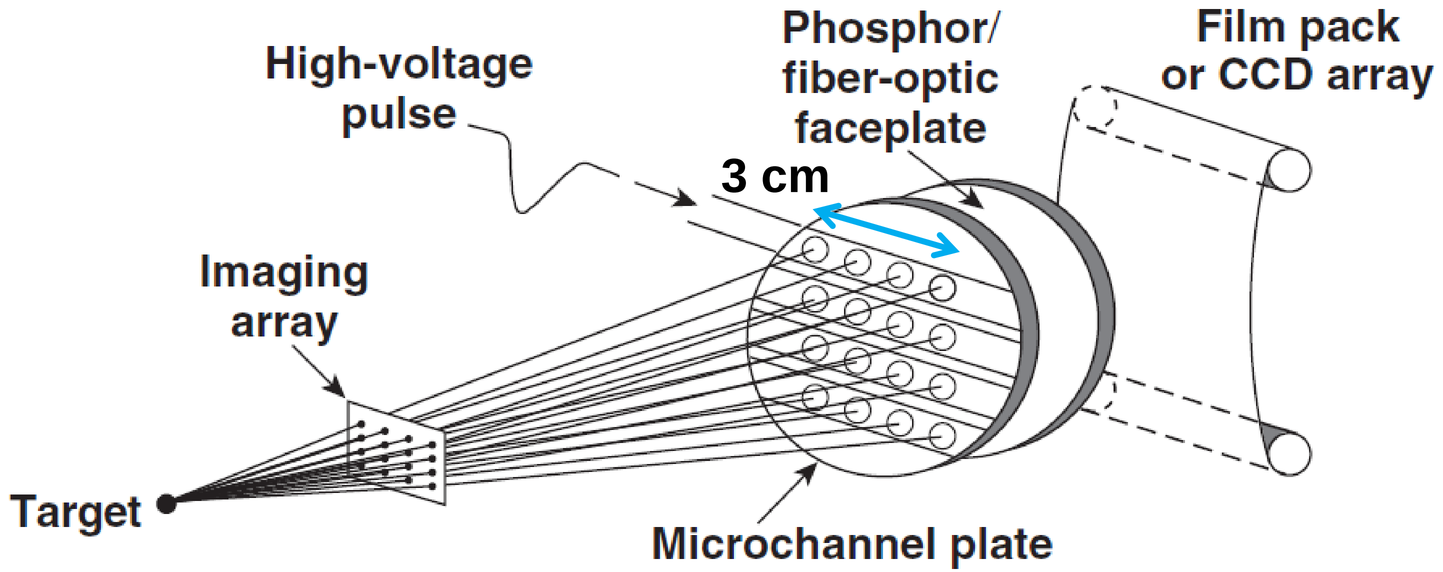
http://hedpschool.lle.rochester.edu/1000_proc2013.php

Framing camera

Two-dimensional time-resolved images are recorded using x-ray framing cameras



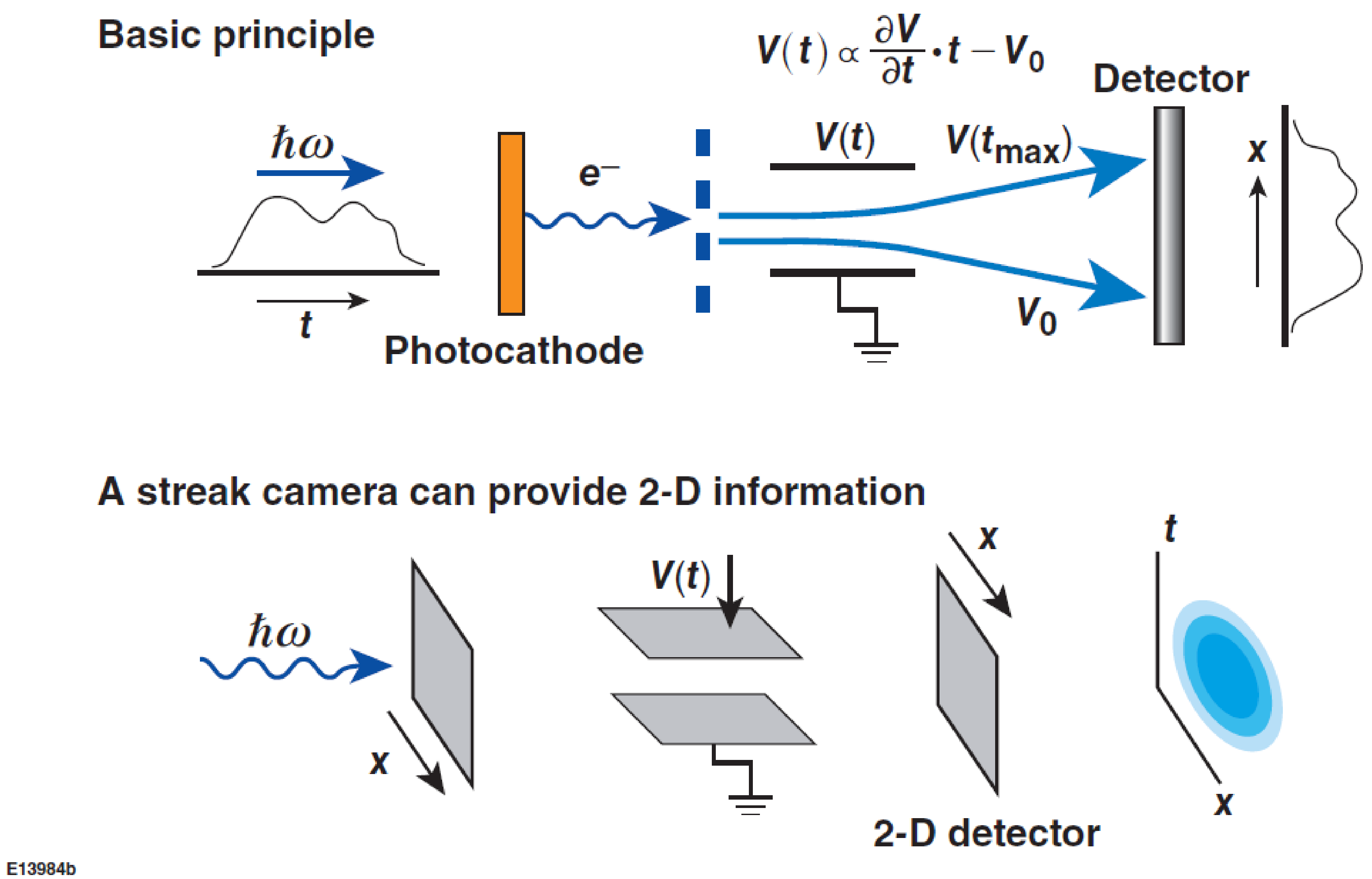
- Temporal resolution = 35 to 40 ps
- Imaging array: Pinholes: 10- to 12-μm resolution, 1 to 4 keV
- Space-resolved x-ray spectra can be obtained by using Bragg crystals and imaging slits

E7105b

Ex: $$\Delta t = \frac{3\ \mathrm{cm}/3}{3 \times 10^{10}\ \mathrm{cm/s}} = 33\ \mathrm{ps}$$

http://hedpschool.lle.rochester.edu/1000_proc2013.php

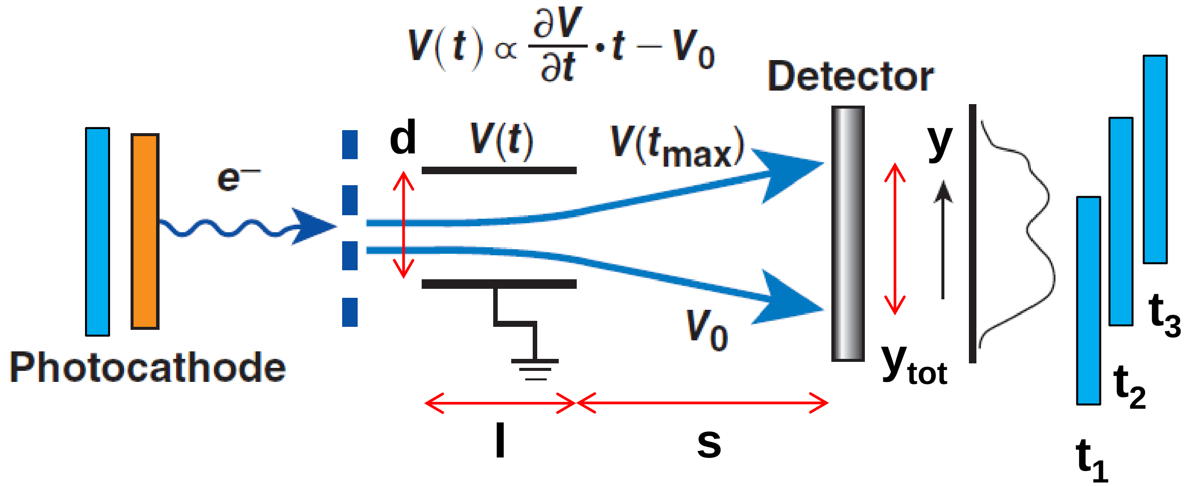
A streak camera provides temporal resolution of 1-D data



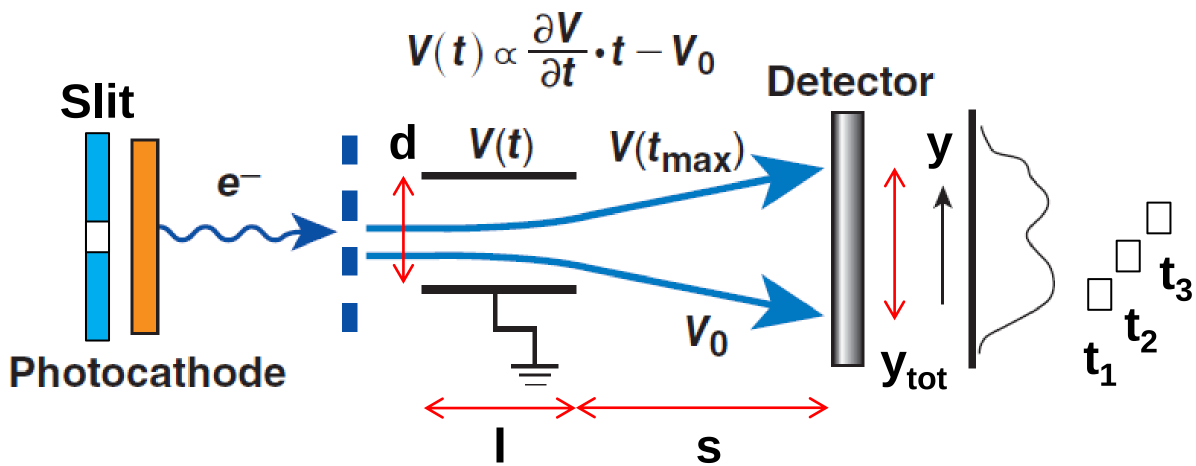
http://hedpschool.lle.rochester.edu/1000_proc2013.php

A slit is to prevent spatial information at different times interfering with each other

Imaging system
- Visible light: regular lens
- X rays: pinhole

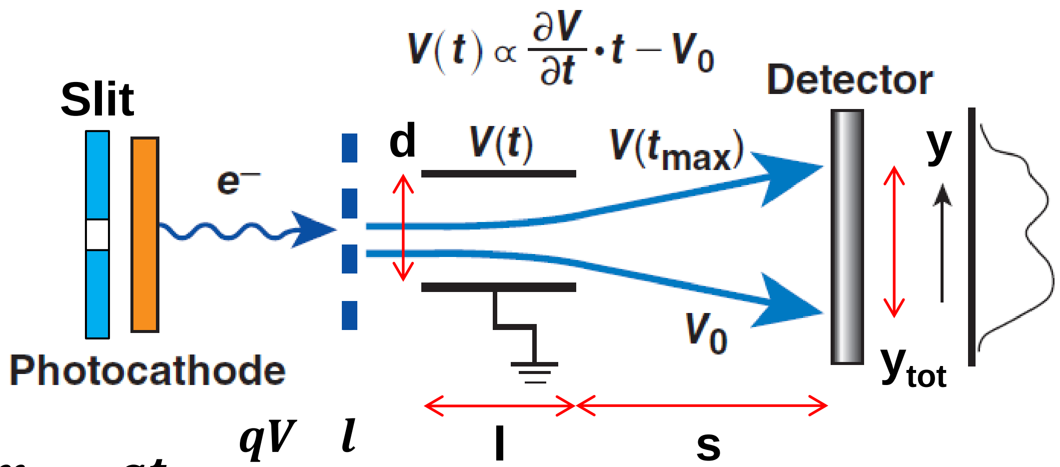


Imaging system
- Visible light: regular lens
- X rays: pinhole



A temporal resolution higher than 15 ps is expected

Imaging system
- **Visible light: regular lens**
- **X rays: pinhole**



$$a = \frac{F}{m} = \frac{qE}{m} = \frac{qV}{md} \qquad v_{\perp} = at = \frac{qV}{md}\frac{l}{v_{||}}$$

$$y = s\,\mathrm{Tan}\theta = s\frac{V_{\perp}}{V_{||}} = \frac{1}{2E_k}\frac{l}{d}sqV = \frac{1}{2E_k}\frac{l}{d}sq(V_0 + V't)$$

- **Let d=10 mm, l=20 mm, s=50 mm, E_k=1 keV, V=-200 ~ 200 V**

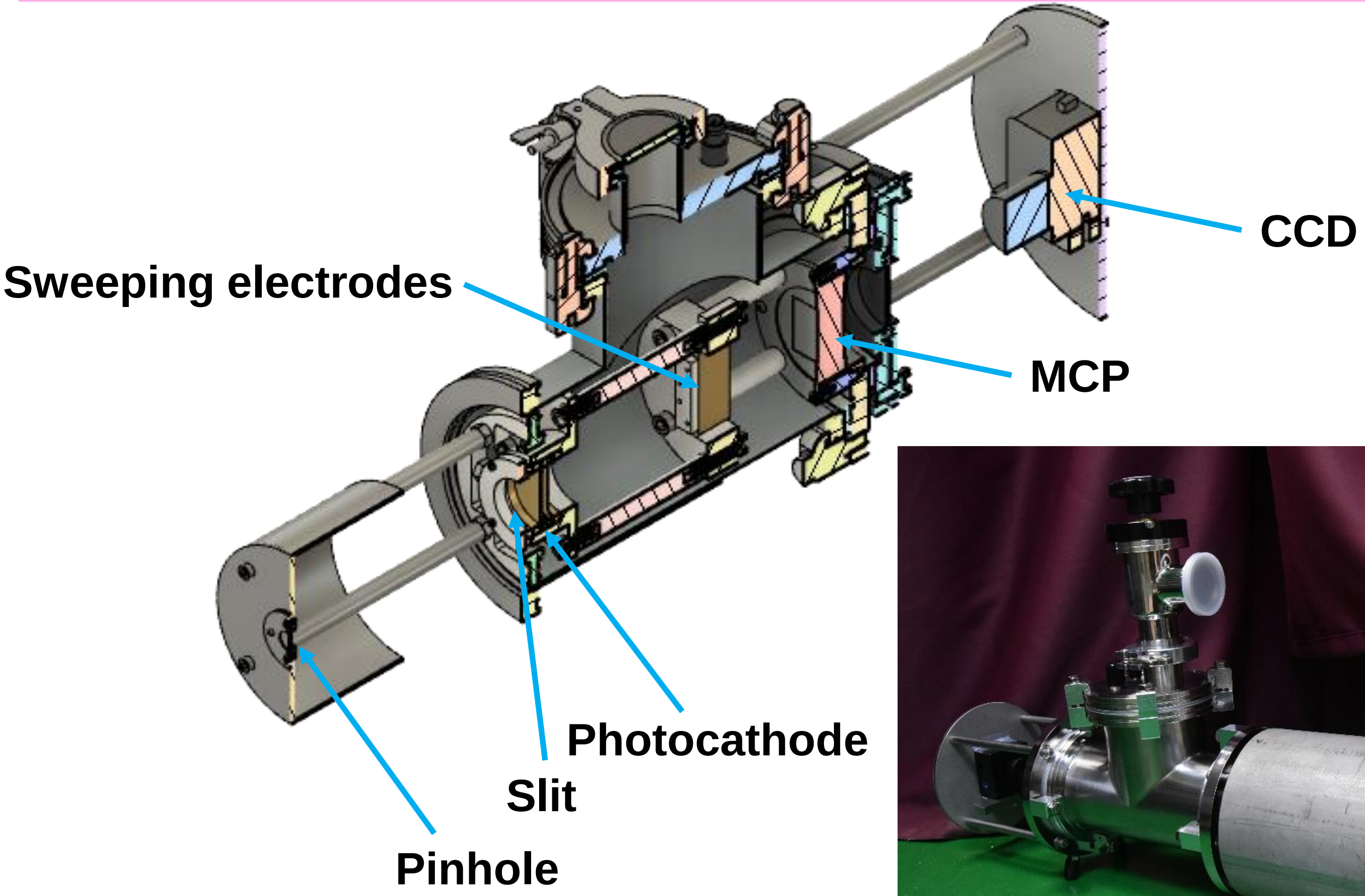
$$V' \equiv \frac{V_{\text{tot}}}{t_{\text{tot}}} = 0.06\,\text{kV/ns} \qquad y_{\text{tot}} = 15\text{mm} \qquad y_{\text{tot}} = 15\text{mm}$$

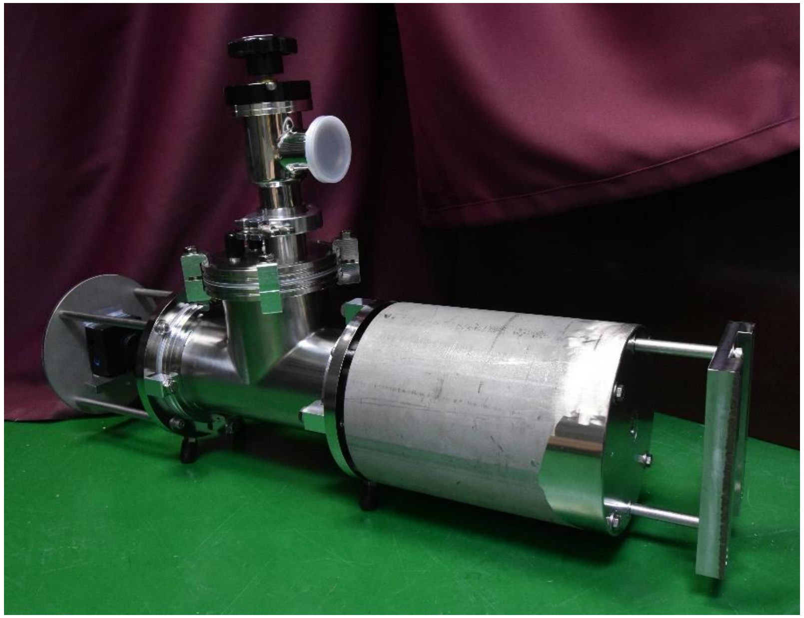
- **Temporal resolution:**

$$\delta t = \delta y \frac{2E_k d}{lsqV'} = 15\text{ ps} \quad \text{for} \quad \delta y = 45\mu\text{m}$$

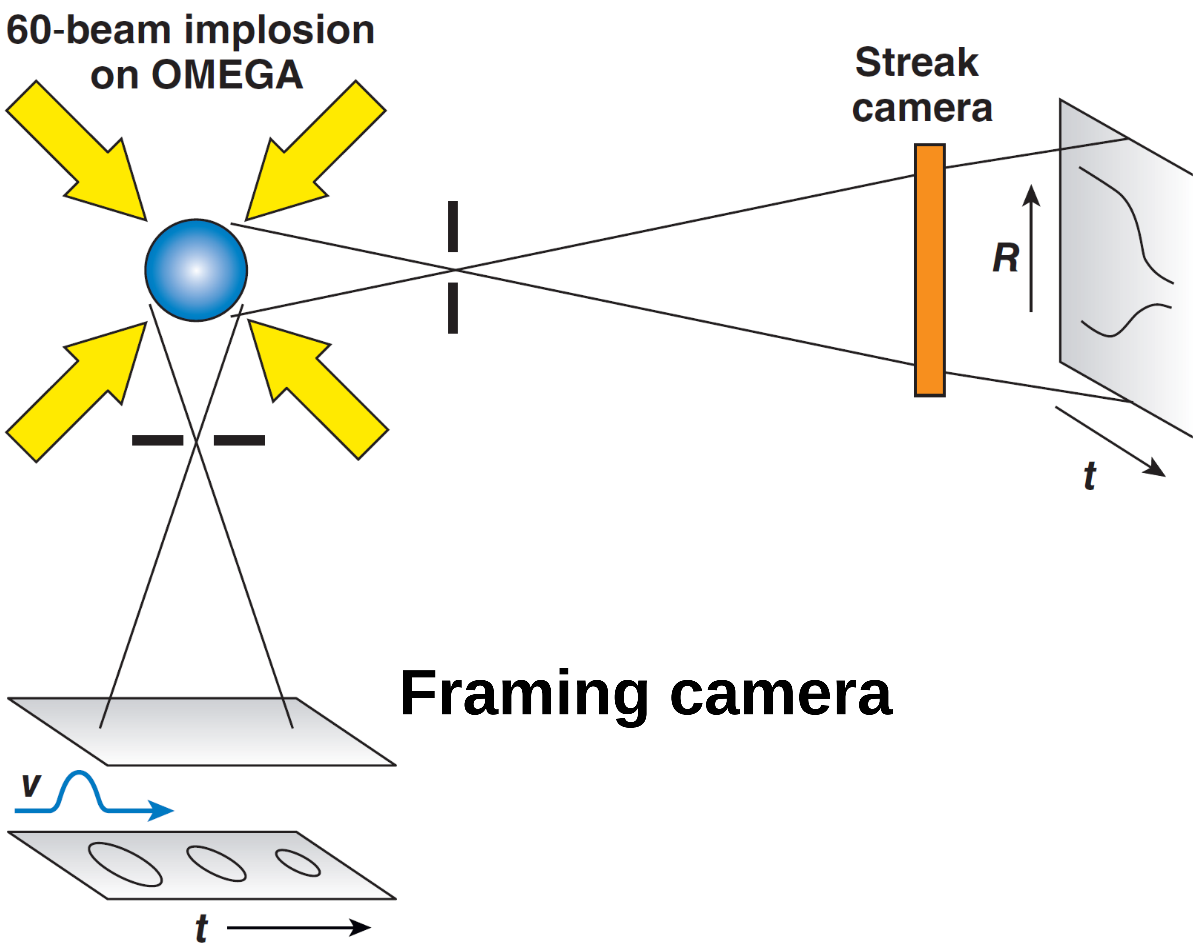
- **δt will be adjusted by changing E_k.**

A streak camera with temporal resolution of 15 ps has been developed

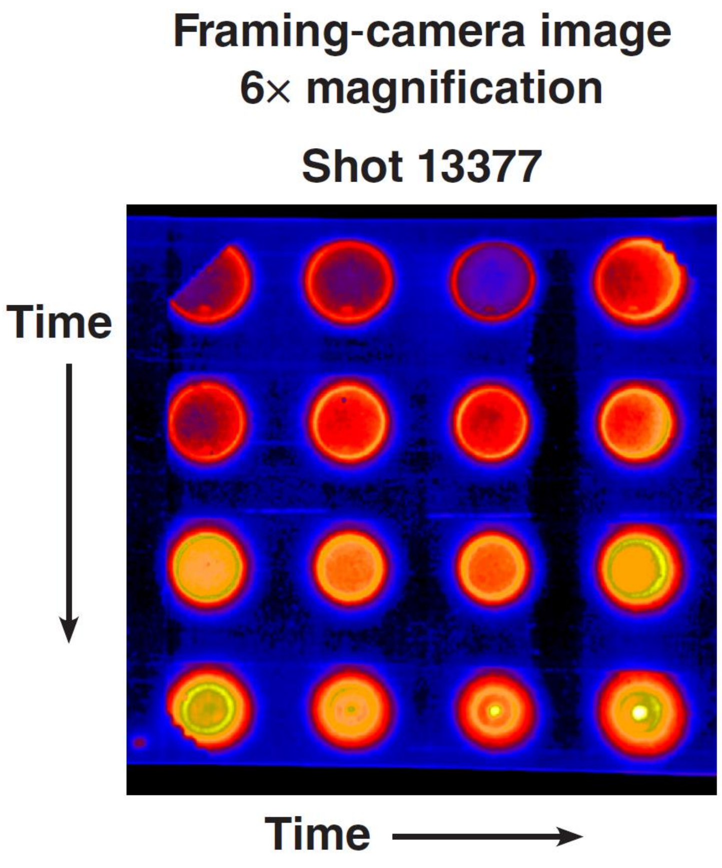


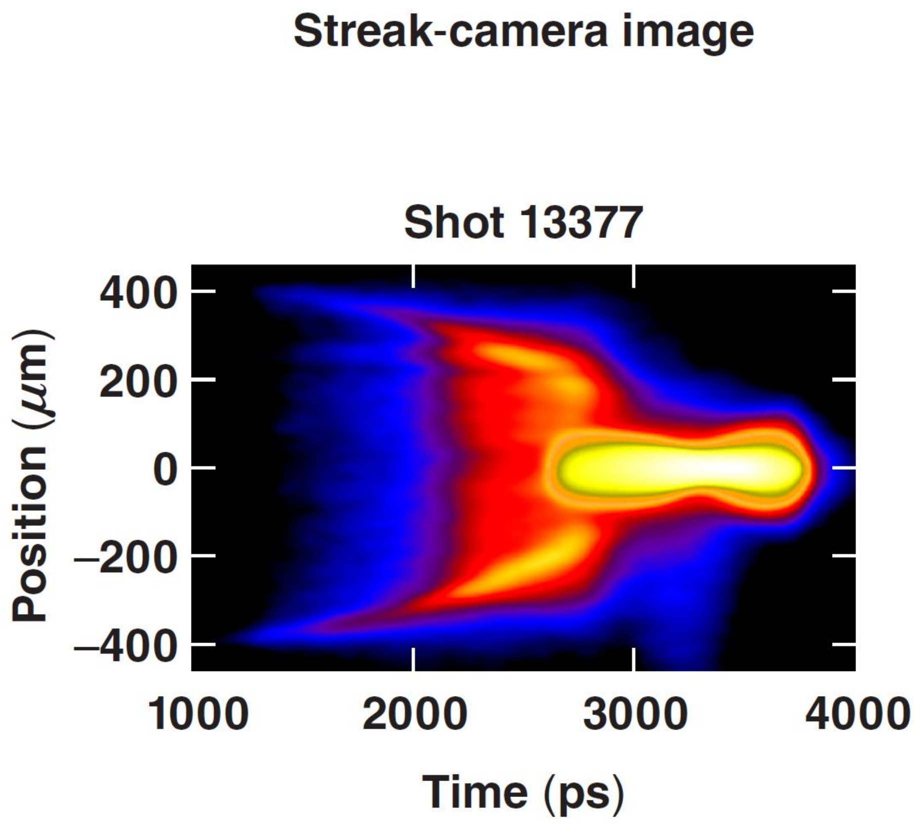


Shell trajectories can be measured using framing camera or streak camera

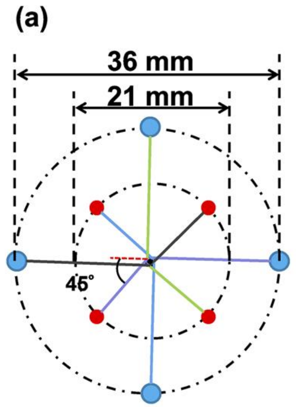


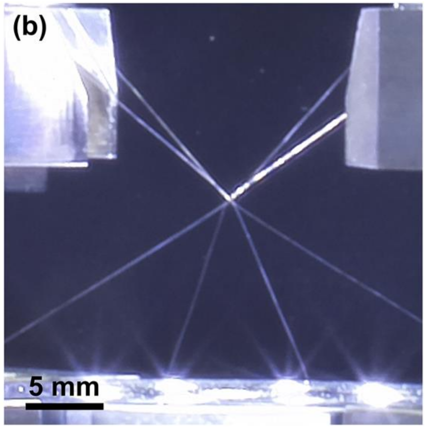
Comparison of images from framing camera versus streak camera

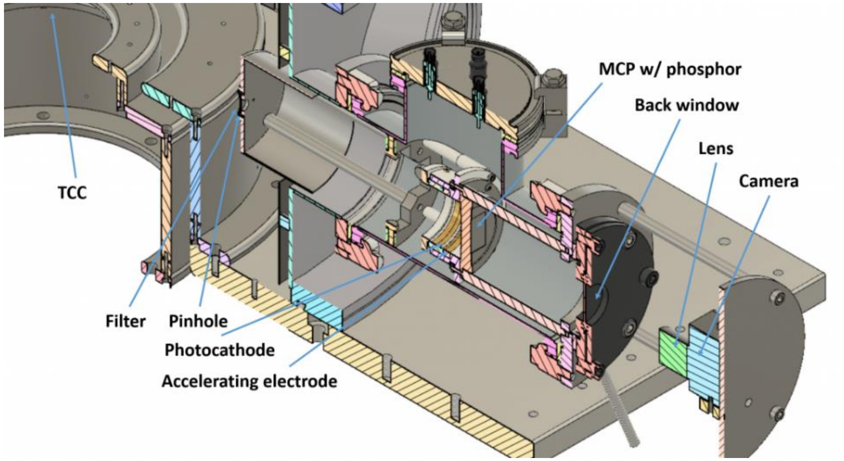


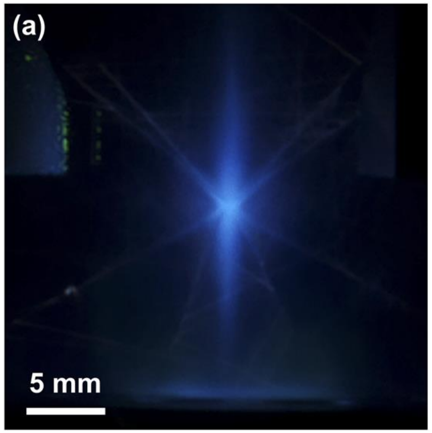


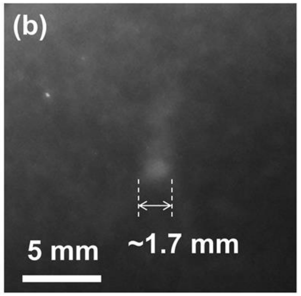
We demonstrated using x-ray pinhole camera to capture the radiation from an imploded x pinch





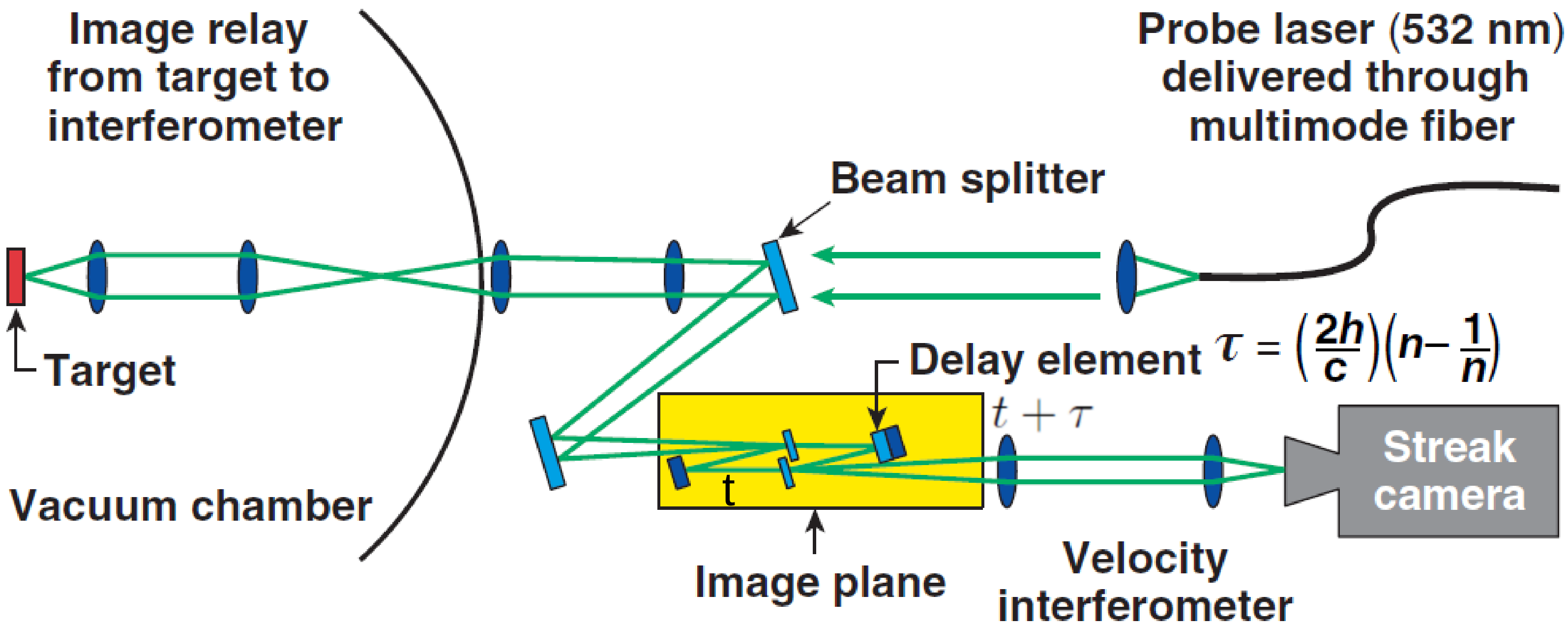


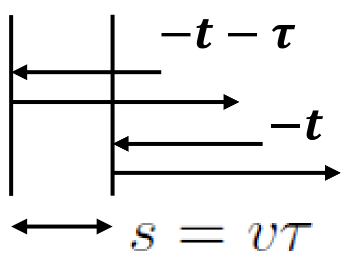




P.-Y. Chang *et al.*, Rev. Sci. Instrum **93**, 043505 (2022)

Shock velocities are measured using time-resolved Velocity Interferometer System for Any Reflector (VISAR)

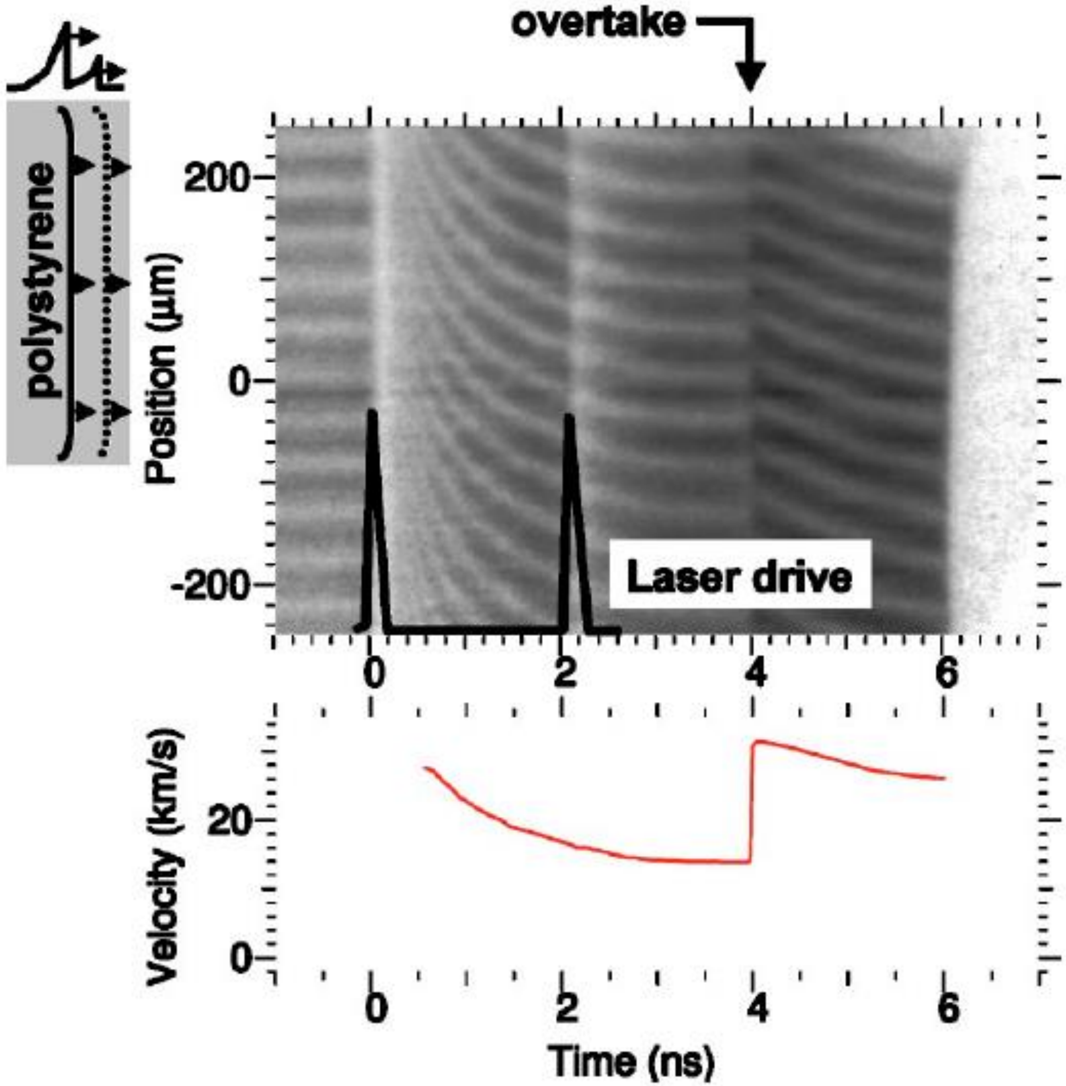


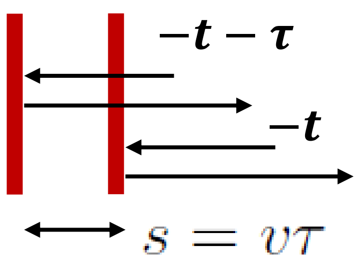


$$\Delta\phi = \frac{v\tau}{\lambda} \propto v$$

http://hedpschool.lle.rochester.edu/1000_proc2013.php

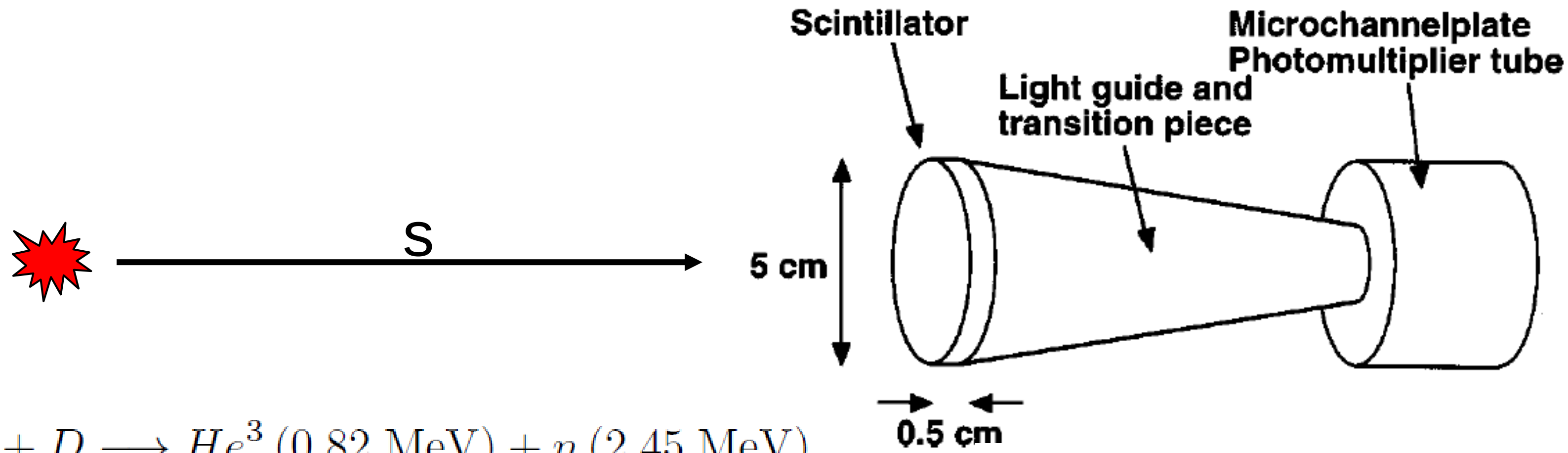
Shock velocities are measured using time-resolved Velocity Interferometer System for Any Reflector (VISAR)





P. M. Celliers *et al.*, Rev. Sci. Insytum. **75**, 4916 (2004)

Neutron average temperature is obtained using Neutron Time of Flight (NToF)

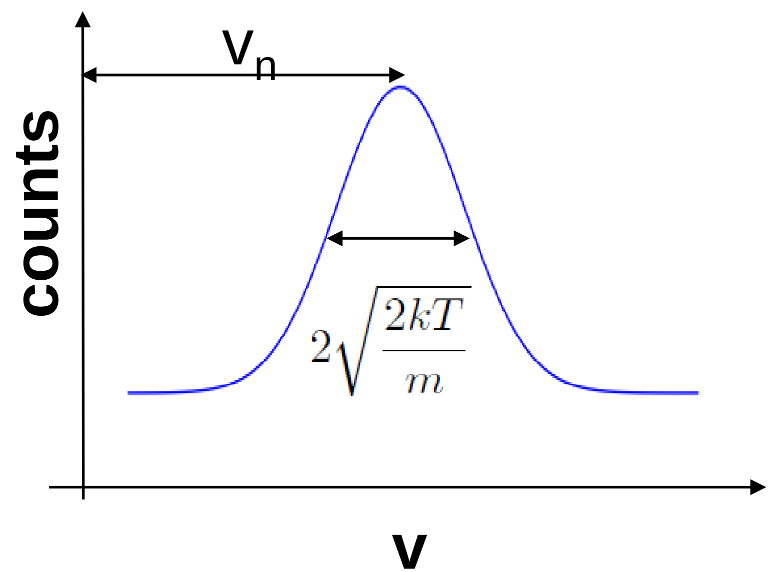


$$D + D \longrightarrow He^3\,(0.82\ \mathrm{MeV}) + n\,(2.45\ \mathrm{MeV})$$

$$D + T \longrightarrow He^4\,(3.5\ \mathrm{MeV}) + n\,(14.1\ \mathrm{MeV})$$

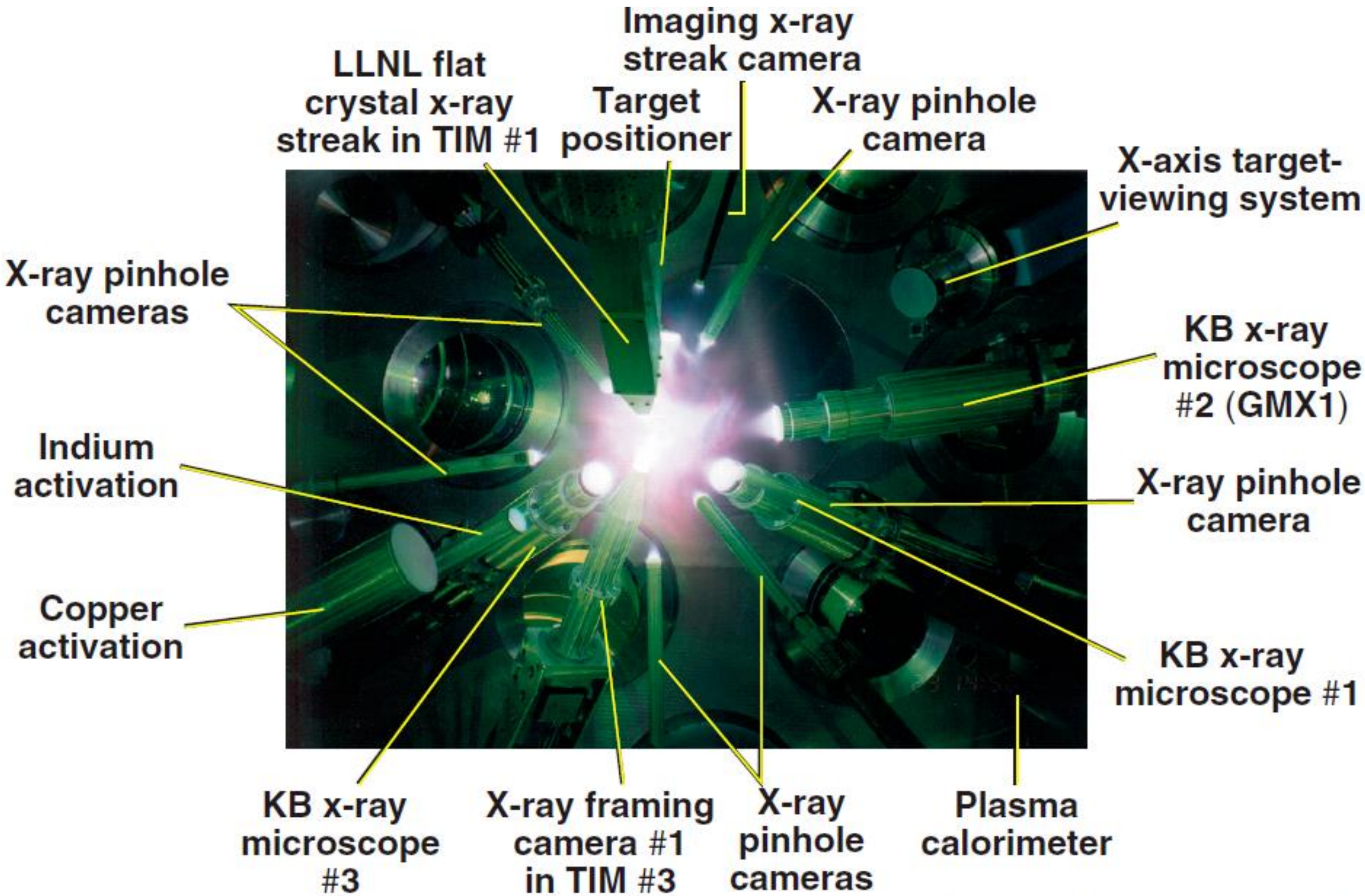
$$s = vt \qquad v = \frac{s}{t}$$

$$f(v) = \sqrt{\left(\frac{m}{2\pi kT}\right)} \exp\left(-\frac{mv^2}{2kT}\right)$$



T. J. Murphy *et al.*, Rev. Sci. Instrum. **72**, 773 (2001)

The OMEGA Facility is carrying out ICF experiments using a full suite of target diagnostics

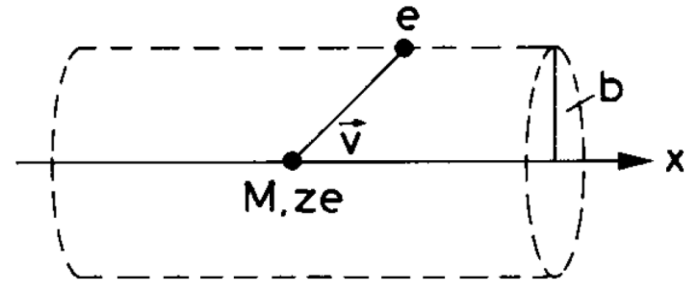


E8012b

Photo taken from port H11B

Energetic charged particles losses most of its energy right before it stops

Momentum transfer:

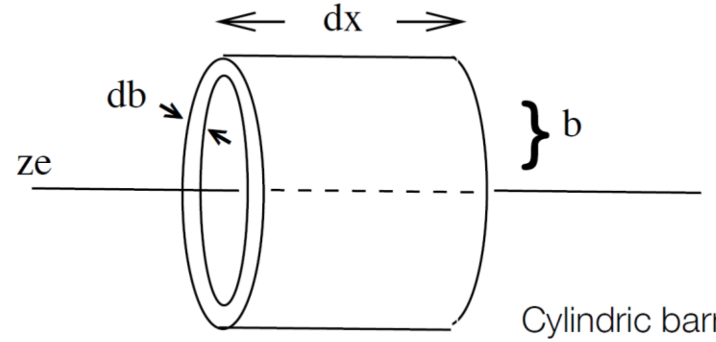


$$\Delta p_\perp = \int F_\perp dt = \int F_\perp \frac{dt}{dx} dx = \int F_\perp \frac{dx}{v}$$

$$= \int_{-\infty}^{\infty} \frac{ze^2}{(x^2+b^2)} \cdot \frac{b}{\sqrt{x^2+b^2}} \cdot \frac{1}{v}\, dx = \frac{ze^2 b}{v}\left[\frac{x}{b^2\sqrt{x^2+b^2}}\right]_{-\infty}^{\infty} = \frac{2ze^2}{bv}$$

$\Delta p_{||}$: averages to zero

$$\Delta E(b) = \frac{\Delta p^2}{2m_e} \qquad N_e = n \cdot (2\pi b) \cdot db\, dx$$



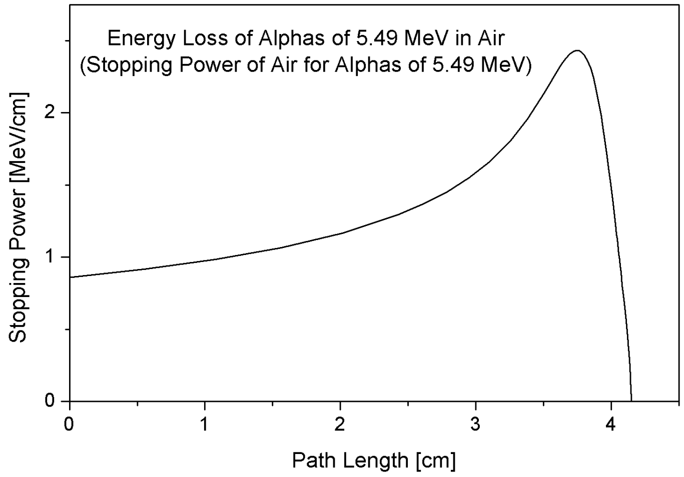
Cylindric barrel with N_e electrons

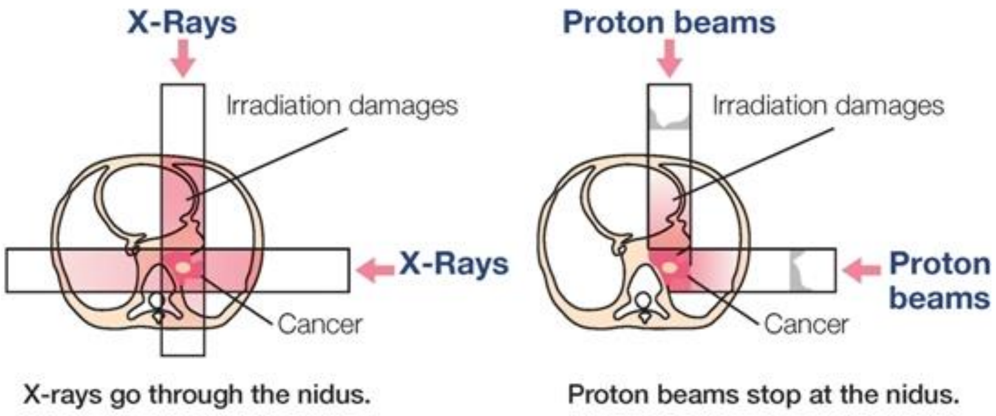
$$-dE(b) = \frac{\Delta p^2}{2m_e} \cdot 2\pi n b\, db\, dx$$

$$-\frac{dE}{dx} = \frac{4\pi\, n\, z^2 e^4}{m_e v^2} \cdot \int_{b_{\min}}^{b_{\max}} \frac{db}{b} = \frac{4\pi\, n\, z^2 e^4}{m_e v^2} \ln \frac{b_{\max}}{b_{\min}}$$

http://www.kip.uni-heidelberg.de/~coulon/Lectures/DetectorsSoSe10/

Proton therapy takes the advantage of using Bragg peak



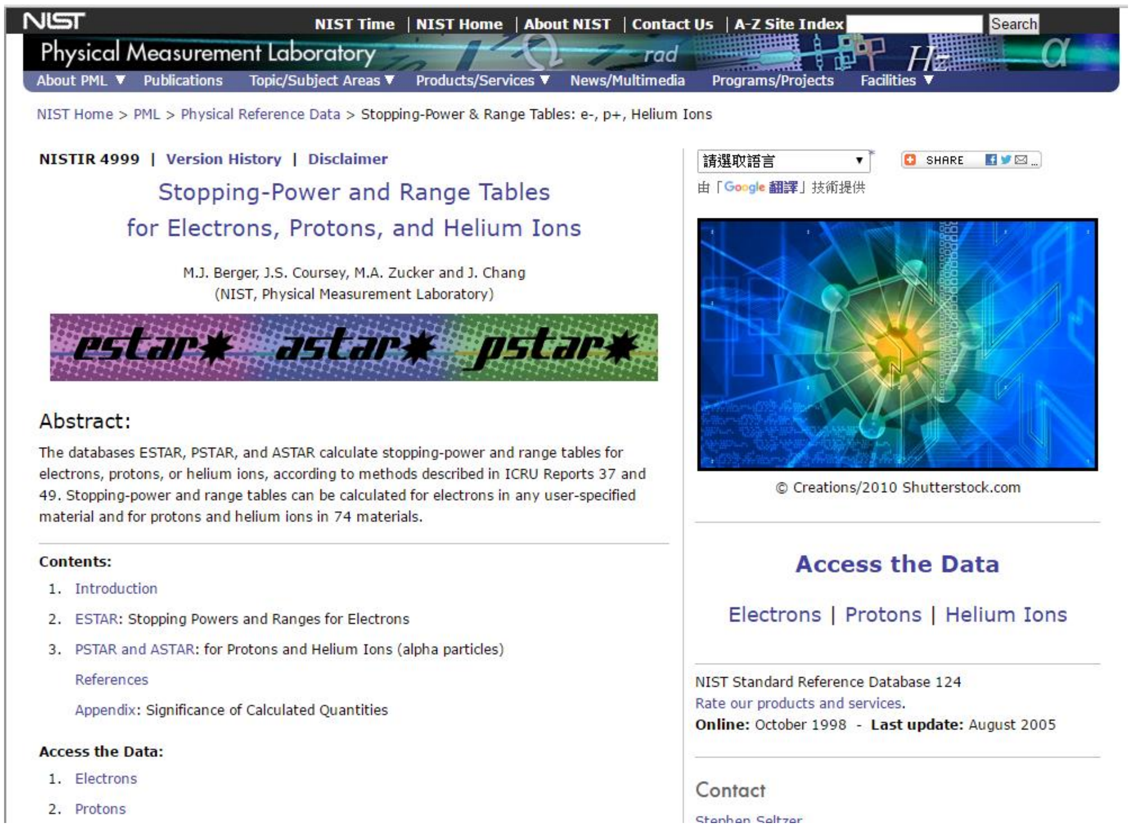


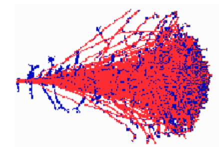
http://www.shi.co.jp/quantum/eng/product/proton/proton.html

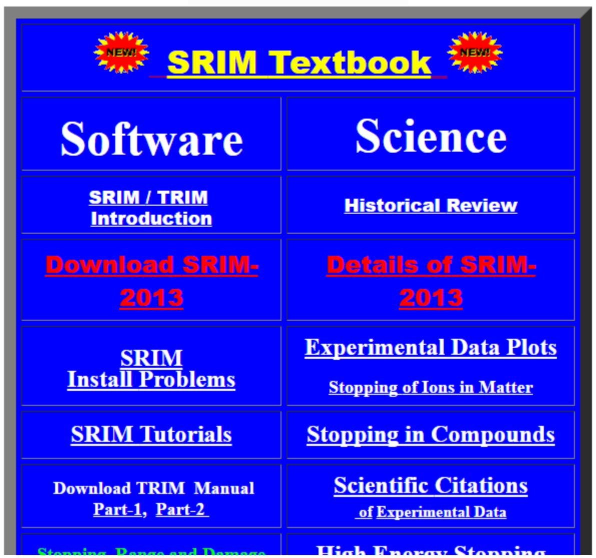
There are two suggested website for getting the information of proton stopping power in different materials

http://www.nist.gov/pml/data/star/

http://www.srim.org/







The thickness of a filter can be decided from the range data from NIST website

COPPER

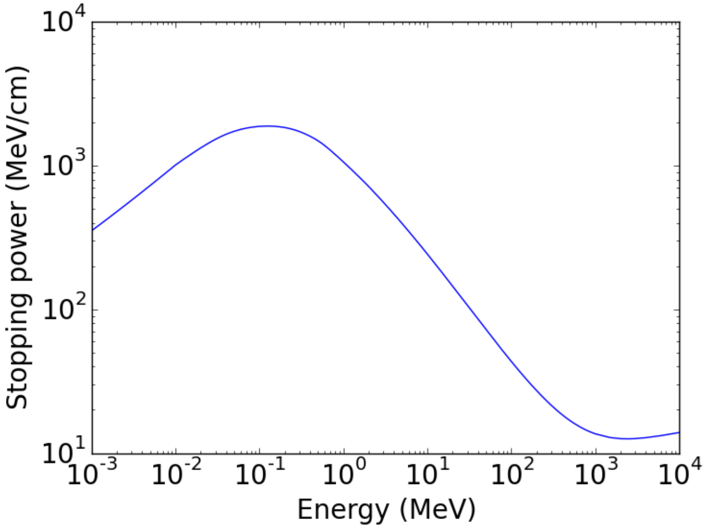
To download data in spreadsheet (array) form, choose a delimiter and use the checkboxes in the table heading. After downloading, save the output by using your browser's Save As feature.

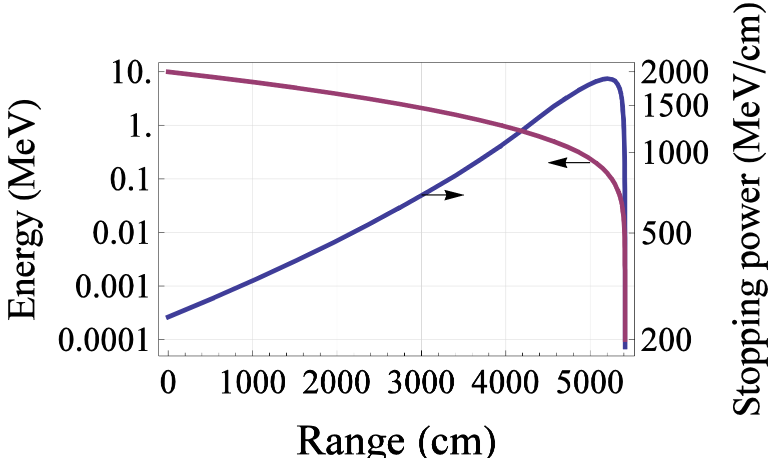
Delimiter:
- space
- | (vertical bar)
- tab (some browsers may use spaces instead)
- newline

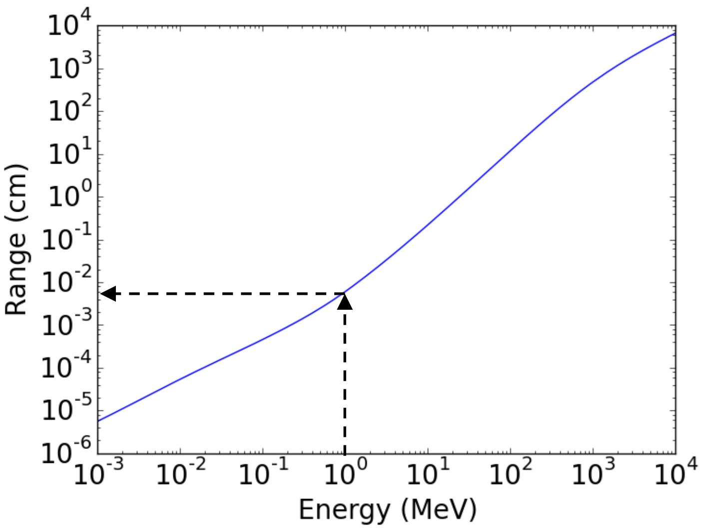
Download data | Reset

$\frac{dE}{\rho dx}$ ρx

(required) Kinetic Energy (MeV)	Stopping Power (MeV cm²/g)			Range		
	Electronic	Nuclear	Total	CSDA (g/cm²)	Projected (g/cm²)	Detour Factor Projected / CSDA
1.000E-03	3.490E+01	4.408E+00	3.931E+01	4.116E-05	5.620E-06	0.1365
1.500E-03	4.274E+01	4.231E+00	4.697E+01	5.267E-05	8.301E-06	0.1576
2.000E-03	4.935E+01	4.049E+00	5.340E+01	6.263E-05	1.101E-05	0.1759
2.500E-03	5.518E+01	3.876E+00	5.906E+01	7.152E-05	1.374E-05	0.1921
3.000E-03	6.045E+01	3.718E+00	6.416E+01	7.964E-05	1.647E-05	0.2068
4.000E-03	6.980E+01	3.440E+00	7.324E+01	9.419E-05	2.194E-05	0.2329
5.000E-03	7.804E+01	3.207E+00	8.124E+01	1.071E-04	2.739E-05	0.2556
6.000E-03	8.548E+01	3.010E+00	8.849E+01	1.189E-04	3.280E-05	0.2758
7.000E-03	9.233E+01	2.840E+00	9.517E+01	1.298E-04	3.817E-05	0.2940
8.000E-03	9.871E+01	2.692E+00	1.014E+02	1.400E-04	4.347E-05	0.3106
9.000E-03	1.047E+02	2.561E+00	1.073E+02	1.496E-04	4.872E-05	0.3258
1.000E-02	1.104E+02	2.445E+00	1.128E+02	1.587E-04	5.391E-05	0.3398

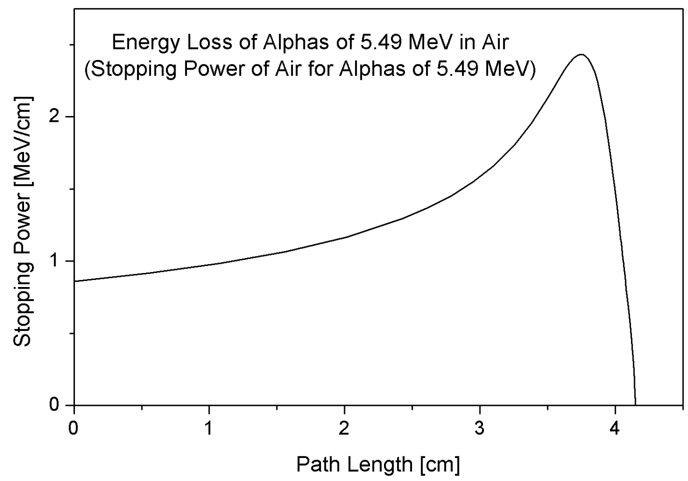


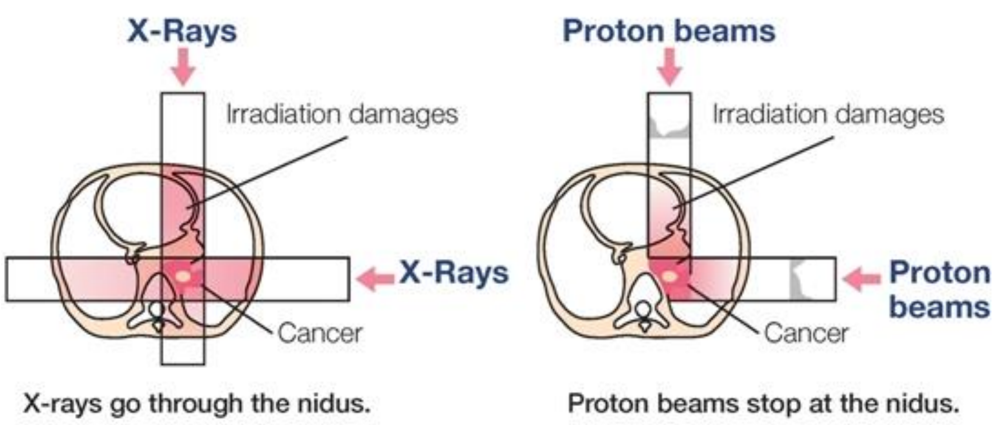




$$\frac{dE}{dx} = f(E) \Rightarrow x = \int_{E_i}^{E_f} \frac{dE}{f(E)}$$

Proton therapy takes the advantage of using Bragg peak





http://www.shi.co.jp/quantum/eng/product/proton/proton.html

Saha equation gives the relative proportions of atoms of a certain species that are in two different states of ionization in thermal equilibrium

$$\frac{n_{r+1} n_e}{n_r} = \frac{G_{r+1} g_e}{G_r} \frac{(2\pi m_e KT)^{3/2}}{h^3} \exp\left(-\frac{\chi_r}{KT}\right)$$

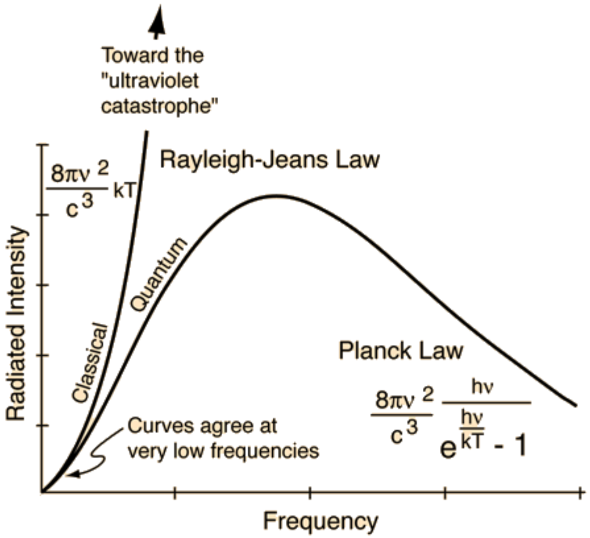
- n_{r+1}, n_r: Density of atoms in ionization state r+1, r (m^{-3})
- n_e: Density of electrons (m^{-3})
- G_{r+1}, G_r: Partition function of ionization state r+1, r
- g_e=2: Statistical weight of the electron
- m_e: Mass of the electron
- χ_r: Ionization potential of ground level of state r to reach to the ground level of state r+1
- T: Temperature
- h: Planck's constant
- K: Boltzmann constant

Supplement to Ch. 6 of Astrophysics Processes by Hale Bradt (http://homepages.spa.umn.edu/~kd/Ast4001-2015/NOTES/n052-saha-bradt.pdf)

Some backgrounds of quantum mechanics

- **Planck blackbody function:**

$$u(\nu, T) = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{\mathrm{h\nu/KT}} - 1}\left(W/m^3\,\mathrm{Hz}\right)$$



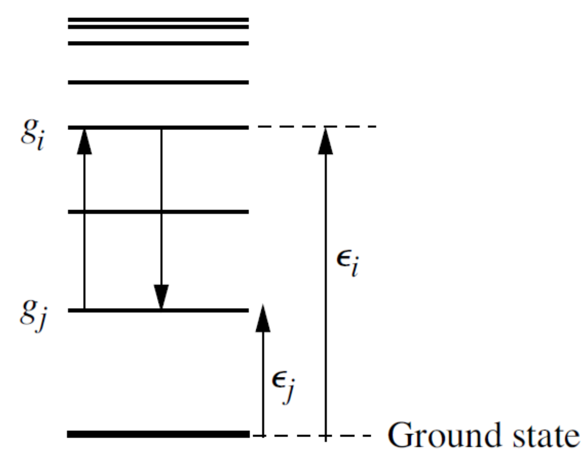
- **Boltzmann formula:**
  - g_i, g_j: statistical weight

$$\frac{n_i}{n_j} = \frac{g_i e^{-\epsilon_i/\mathrm{KT}}}{g_j e^{-\epsilon_j/\mathrm{KT}}} = \frac{g_i}{g_j} e^{-h\nu_{\mathrm{ij}}/\mathrm{KT}} \qquad \frac{g_i}{g_j} = \frac{2J_i + 1}{2J_j + 1}$$

(J: angular momenta quantum number)

  - Number in the i[th] state to the total atom:

$$\frac{n_i}{n} = \frac{n_i}{\Sigma n_j} \equiv \frac{g_i e^{-\epsilon_i/\mathrm{KT}}}{G} \qquad G \equiv \Sigma g_j e^{-\epsilon_j/\mathrm{KT}}$$



G: partition function of statistical weight for the atom, taking into account all its excited states.

http://hyperphysics.phy-astr.gsu.edu/hbase/mod6.html

Einstein coefficient

- **Probability of electron energy transition:**
  - **Excitation (↑):** $P_{\text{ji}} = B_{\text{ji}} u(\nu, T)$
  - **De-excitation (↓):** $P_{\text{ij}} = A_{\text{ij}} + B_{\text{ij}} u(\nu, T)$
- **In thermal equilibrium:**

$$n_i\left(A_{\text{ij}} + B_{\text{ij}} u\right) = n_j B_{\text{ji}} u$$

$$\frac{g_i}{g_j} e^{-x}\left(A_{\text{ij}} + B_{\text{ij}} u\right) = B_{\text{ji}} u \qquad x \equiv \frac{\text{h}\nu}{\text{KT}}$$

$$u = a(e^x - 1)^{-1} \qquad a \equiv \frac{8\pi \text{h}\nu^3}{c^3}$$

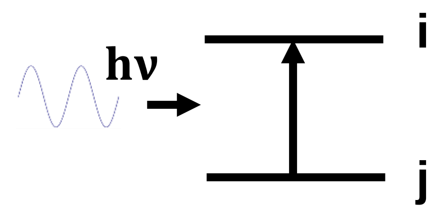
$$a\left(e^x B_{\text{ji}} - \frac{g_i}{g_j} B_{\text{ij}}\right) = (e^x - 1)\frac{g_i}{g_j} A_{\text{ij}}$$

- **The Einstein coefficients are independent of T or ν.**

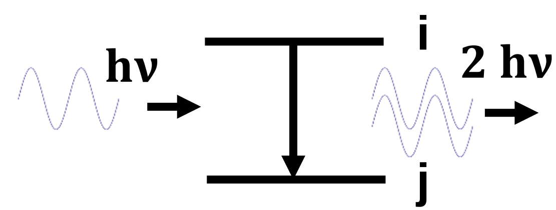
$$x \to 0, e^x \to 1 \qquad x \to \infty, e^x \to \infty$$

$$\frac{B_{\text{ij}}}{B_{\text{ji}}} = \frac{g_j}{g_i} \qquad aB_{\text{ji}} = \frac{g_i}{g_j} A_{\text{ij}} \qquad \frac{A_{\text{ij}}}{B_{\text{ij}}} = \frac{8\pi h\nu^3}{c^3}$$

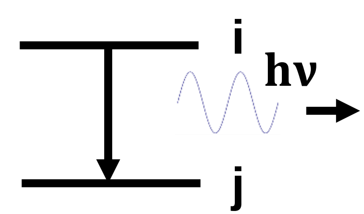
- **Photoexcitation:**



- **Induced radiation:**



- **Spontaneous radiation:**



Saha equation is derived using the transition between different ionization states

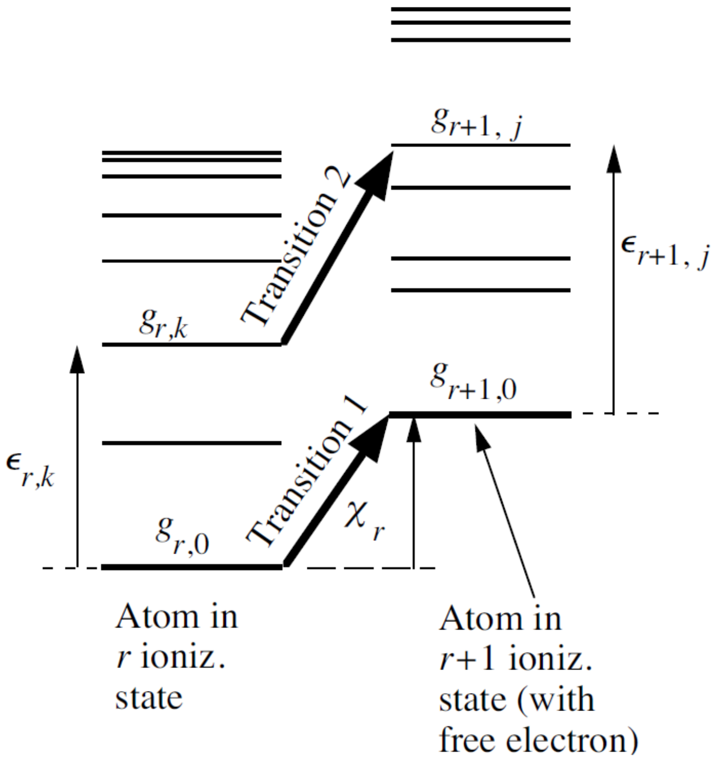
- **Required photon energy for transition 1 from the ground state of r ionization state to the ground state of r+1 ionization state:**

$$\mathbf{h\nu} = \chi_r + \frac{p^2}{2m}$$

Energy of the free electron

- **Required photon energy for transition 2 from the energy level k of r ionization state to the energy level j of r+1 ionization state:**

$$\mathbf{h\nu} = \chi_r + \epsilon_{r+1,j} - \epsilon_{r,k} + \frac{p^2}{2m}$$



Saha equation is derived using the transition between different ionization states

- **Photoionization:**

$$R_{\text{pi}} = n_{r,k} u(\nu) B_{r,k\to r+1,j}$$

- **Induced radiation:**

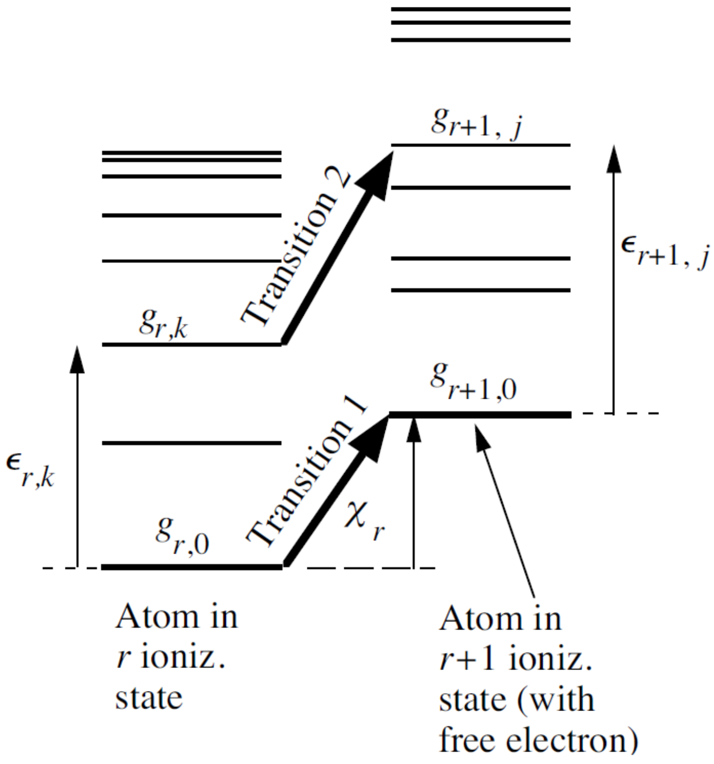
$$R_{\text{ir}} = n_{r+1,j} n_{e,p}(p) u(\nu) B_{r+1,j\to r,k}$$

- **Spontaneous emission:**

$$R_{\text{sr}} = n_{r+1,j} n_{e,p}(p) A_{r+1,j\to r,k}$$

- **In thermal equilibrium:**

$$n_{r+1,j} n_{e,p} A_{r+1,j\to r,k} + n_{r+1,j} n_{e,p} u B_{r+1,j\to r,k} = n_{r,k} u B_{r,k\to r+1,j}$$



- **Einstein coefficients:**

$$\frac{B_{r,k\to r+1,j}}{B_{r+1,j\to r,k}} = \frac{g_{r+1,j}}{g_{r,k}} \frac{g_e 4\pi p^2}{h^3} \qquad \frac{A_{r+1,j\to r,k}}{B_{r+1,j\to r,k}} = \frac{8\pi h \nu^3}{c^3}$$

Saha equation - continued

$$n_{r+1,j}n_{e,p}A_{r+1,j\to r,k} + n_{r+1,j}n_{e,p}uB_{r+1,j\to r,k} = n_{r,k}uB_{r,k\to r+1,j}$$

$$n_{r+1,j}n_{e,p}\frac{A_{r+1,j\to r,k}}{B_{r+1,j\to r,k}} + n_{r+1,j}n_{e,p}u = n_{r,k}u\frac{B_{r,k\to r+1,j}}{B_{r+1,j\to r,k}}$$

$$\frac{n_{r+1,j}n_{e,p}}{n_{r,k}} = \left(\frac{A_{r+1,j\to r,k}}{uB_{r+1,j\to r,k}} + 1\right)^{-1}\frac{B_{r,k\to r+1,j}}{B_{r+1,j\to r,k}}$$

$$\frac{B_{r,k\to r+1,j}}{B_{r+1,j\to r,k}} = \frac{g_{r+1,j}}{g_{r,k}}\frac{g_e 4\pi p^2}{h^3}$$

$$n_{e,p}(p) = \frac{n_e 4\pi p^2}{(2\pi\mathrm{mKT})^{3/2}}\exp\left(-\frac{p^2}{2\mathrm{mKT}}\right)$$

$$\frac{A_{r+1,j\to r,k}}{B_{r+1,j\to r,k}} = \frac{8\pi h\nu^3}{c^3}$$

$$\frac{n_{r+1,j}n_e}{n_{r,k}} = \frac{(2\pi\mathrm{mKT})^{3/2}}{4\pi p^2}\exp\left(\frac{p^2}{2\mathrm{mKT}}\right)\left[\frac{c^3}{8\pi h\nu^3}\left(e^{\mathrm{h}\nu/\mathrm{KT}} - 1\right)\frac{8\pi h\nu^3}{c^3} + 1\right]^{-1}\frac{g_{r+1,j}}{g_{r,k}}\frac{g_e 4\pi p^2}{h^3}$$

$$\frac{n_{r+1,j}n_e}{n_{r,k}} = \frac{(2\pi\mathrm{mKT})^{3/2}}{h^3}\frac{g_{r+1,j}g_e}{g_{r,k}}\exp\left[\frac{1}{\mathrm{KT}}\left(\frac{p^2}{2m} - \mathrm{h}\nu\right)\right]$$

Saha equation - continued

$$\frac{n_{r+1,j}n_e}{n_{r,k}} = \frac{(2\pi \mathrm{mKT})^{3/2}}{h^3}\frac{g_{r+1,j}g_e}{g_{r,k}}\exp\left[\frac{1}{\mathrm{KT}}\left(\frac{p^2}{2m} - \mathrm{h\nu}\right)\right]$$

$$\frac{n_{r+1,j}n_e}{n_{r,k}} = \frac{(2\pi \mathrm{mKT})^{3/2}}{h^3}\frac{g_{r+1,j}g_e}{g_{r,k}}\exp\left[\frac{1}{\mathrm{KT}}\left(\frac{p^2}{2m} - \chi_r - \epsilon_{r+1,j} + \epsilon_{r,k} - \frac{p^2}{2m}\right)\right]$$

$$\frac{n_{r+1,j}n_e}{n_{r,k}} = \frac{(2\pi \mathrm{mKT})^{3/2}}{h^3}\frac{g_{r+1,j}\exp\left(\frac{\epsilon_{r+1,j}}{\mathrm{KT}}\right)g_e}{g_{r,k}\exp\left(\frac{\epsilon_{r,k}}{\mathrm{KT}}\right)}\exp\left(-\frac{\chi_r}{\mathrm{KT}}\right)$$

$$\frac{n_{r,k}}{n_r} = \frac{g_{r,k}e^{-\epsilon_{r,k}/\mathrm{KT}}}{G_r} \qquad G_r = \Sigma g_{r,k}e^{-\epsilon_{r,k}/\mathrm{KT}}$$

$$\frac{n_{r+1,j}}{n_{r+1}} = \frac{g_{r+1,j}e^{-\epsilon_{r+1,j}/\mathrm{KT}}}{G_{r+1}} \qquad G_{r+1} = \Sigma g_{r+1,j}e^{-\epsilon_{r+1,j}/\mathrm{KT}}$$

$$\frac{n_{r+1}n_e}{n_r} = \frac{G_{r+1}g_e}{G_r}\frac{(2\pi m_e KT)^{3/2}}{h^3}\exp\left(-\frac{\chi_r}{KT}\right)$$

Saha equation – example: hydrogen plasma of the sun

- **Photosphere of the sun – hydrogen atoms in an optically thick gas in thermal equilibrium at temperature T=6400 K.**
  - **Neutral hydrogen (r state / ground state)**

$$G_r = \Sigma g_{r,k} = g_{r,0} + g_{r,1}\exp\left(-\frac{\epsilon_{r,1}}{KT}\right) + \cdots = 2 + 8\exp\left(-\frac{10.2\text{eV}}{0.56\text{eV}}\right) + \cdots$$

$$= 2 + 9.8 \times 10^{-8} + \cdots \approx 2$$

  - **Ionized state (r+1 state)**

$$G_{r+1} = \Sigma g_{r+1,j} = g_{r+1,0} + g_{r+1,1}\exp\left(-\frac{\epsilon_{r+1,1}}{KT}\right) + \cdots \approx 1$$

  - **Other information:** $g_e = 2$ $\chi_r = 13.6\text{eV}$; $\text{kT} = 0.56\text{eV}$ $n_{r+1} = n_e$

$$\frac{{n_{r+1}}^2}{n_r} = 2.41 \times 10^{21}\,\frac{1 \times 2}{2}(6400)^{3/2}\exp\left(-\frac{13.6}{0.56}\right) = 3.5 \times 10^{16} m^{-3}$$

It is mostly neutral in the photosphere of the sun

- **Assuming 50 % ionization:**

$$n_{r+1} = n_r = 3.5 \times 10^{16} m^{-3} \qquad n = n_{r+1} + n_r = 7 \times 10^{16} m^{-3}$$

- **In the photosphere of the sun:**

$$\rho \sim 3 \times 10^{-4}\,\mathrm{kg}/m^3 \rightarrow n = 2 \times 10^{23} m^{-3} \gg 7 \times 10^{16} m^{-3}$$

- **At higher densities n at the same temperature, there should be more collisions leading to higher recombination rate and thus the plasma is less than 50 % ionization.**

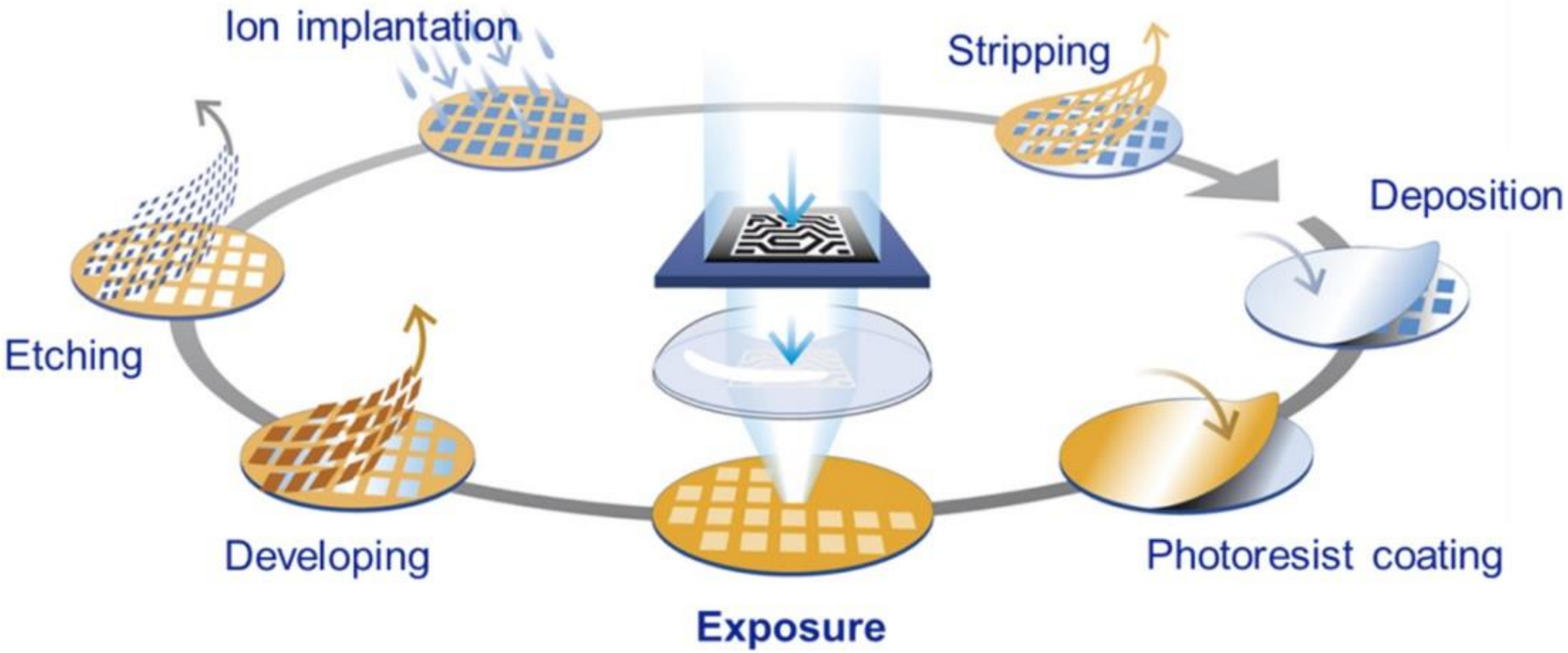
$\Rightarrow$ **Less than 50 % ionization**

- **Use the total number density to estimate the ionization percentage:**

$$n_{r+1} + n_r = 2 \times 10^{23}$$

$$\frac{n_{r+1}}{n_r} = 4 \times 10^{-4} @ 6400K$$

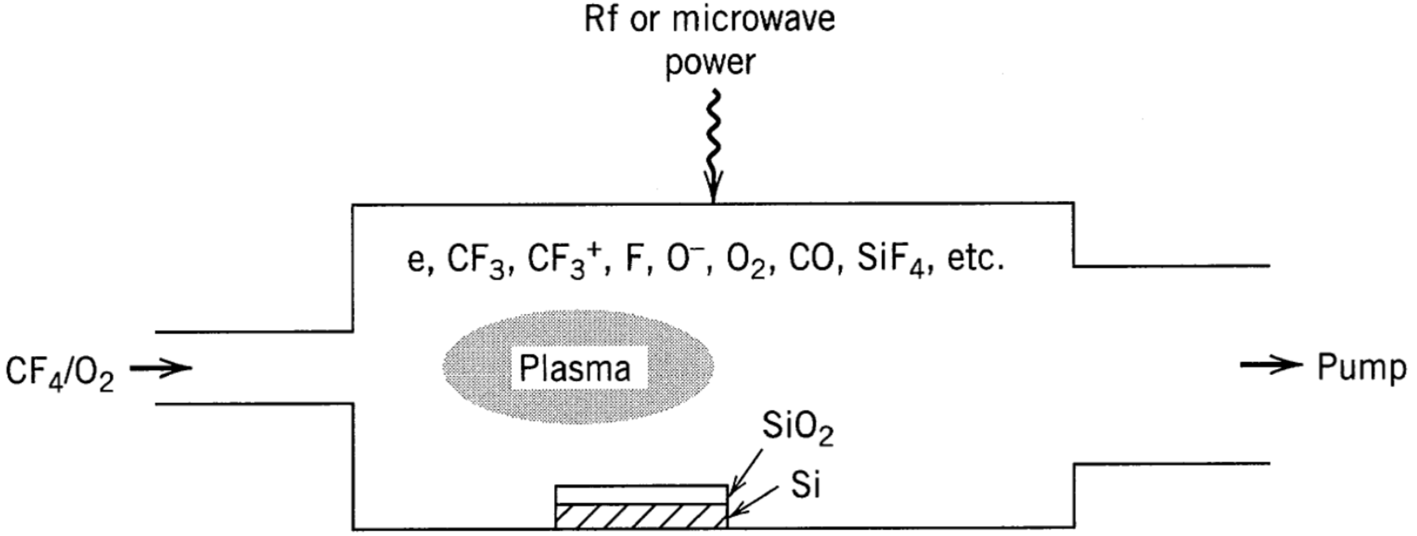
A semiconductor device is fabricated by many repetitive production process



Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

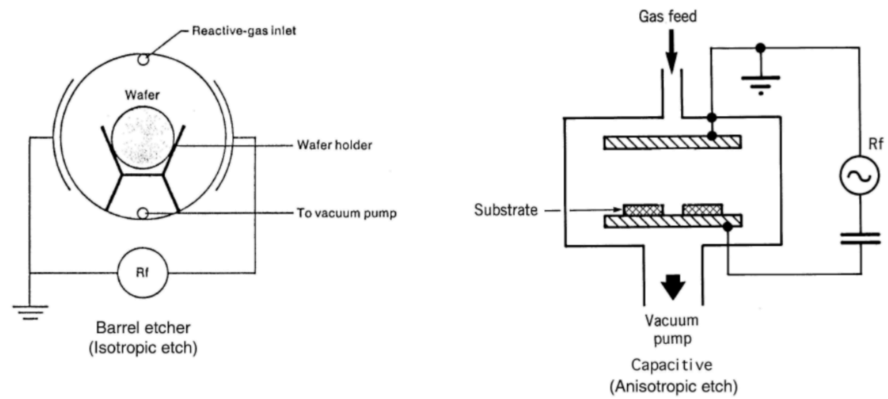
Reference for material processing

- Principles of plasma discharges and materials processing, 2nd edition, by Michael A. Lieberman and Allan J. Lichtenberg
- http://www.eecs.berkeley.edu/~lieber/
- Materials science of thin films, 2nd edition, by Milton Ohring
- Plasma etching, by Dennis M. Manos and Daniel L. Flamm
- Industrial plasma engineering, volume 1, by J. Reece Roth

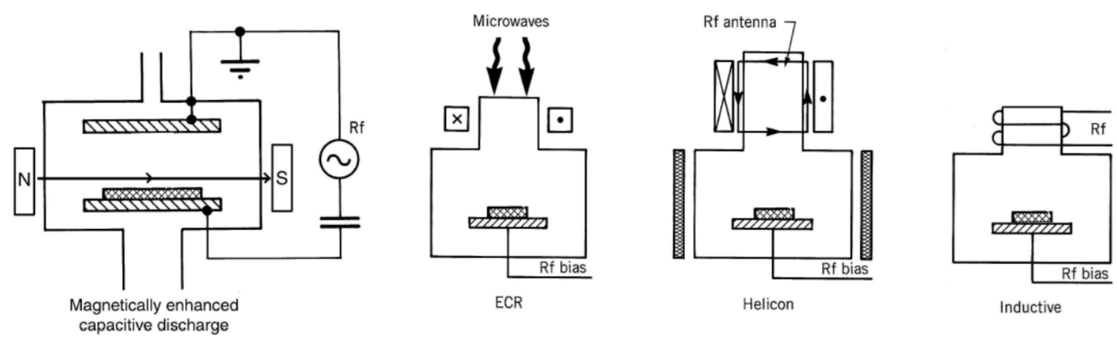


Evolution of etching discharges

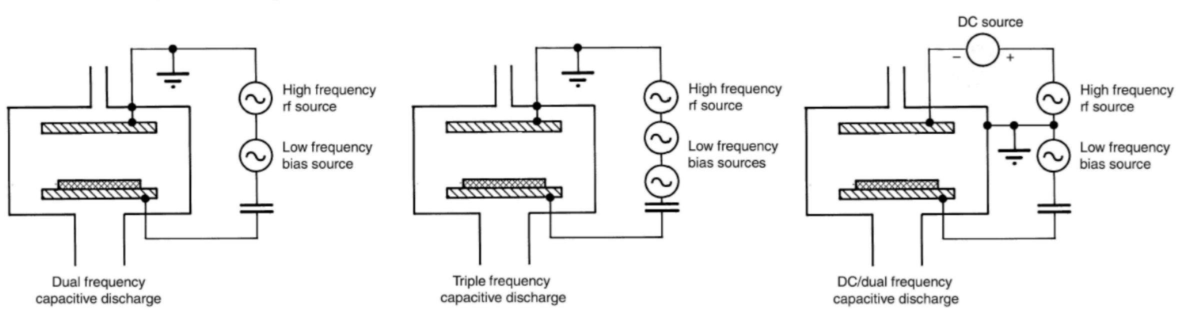
1st generation
(1 source, multi-wafer, low density)



2nd generation
(2 sources, single-wafer, high density)

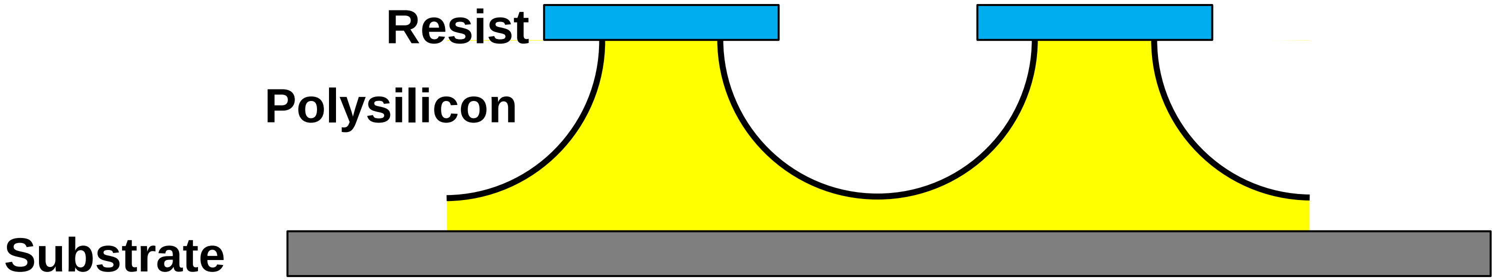


3rd generation
(multi-sources, single-wafer, moderate density)

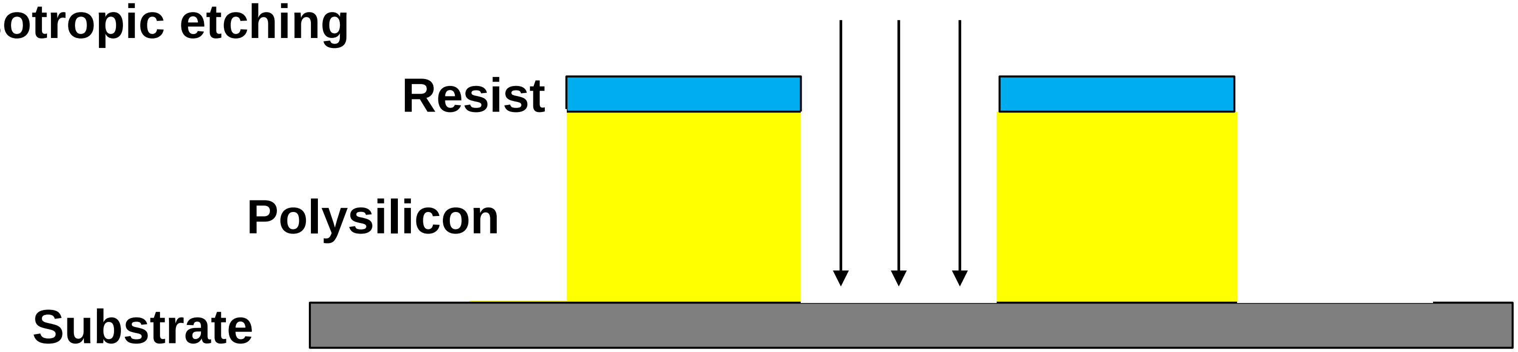


There are two types of etching: isotropic vs anistropic

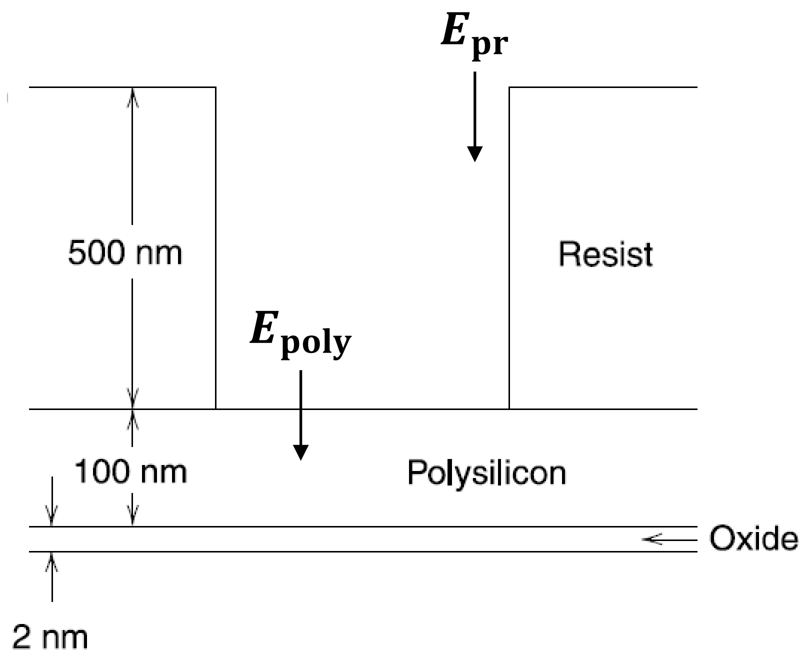
- Isotropic etching



- Anisotropic etching



Plasma etch requirements – etch rate



- **Etch time needs to be within a few minutes:**

$$E_{pr} \geq 250\,\mathrm{nm/min}$$

$$E_{poly} \geq 50\,\mathrm{nm/min}$$

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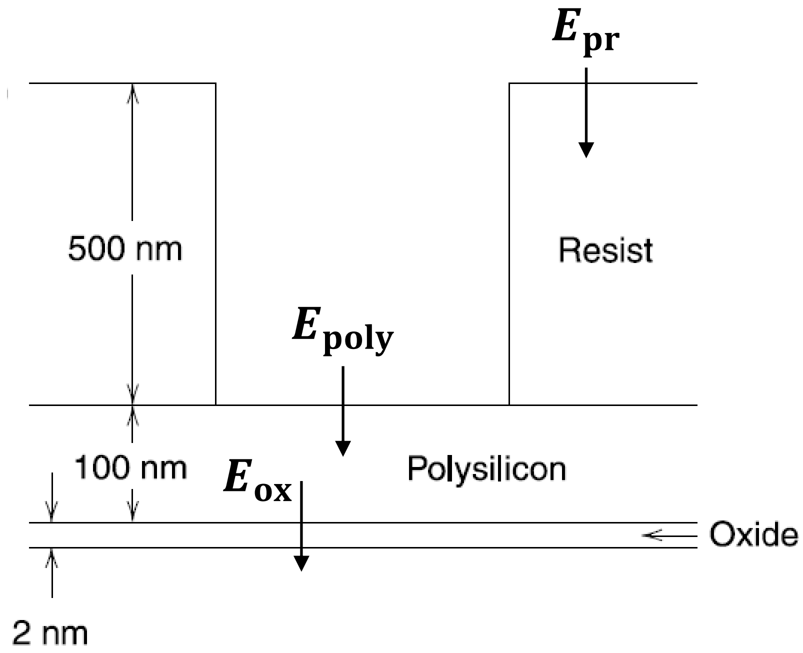
Plasma etch requirements - selectivity



- **Selectivity between polysilicon and resist:**

$$s = \frac{E_{poly} \triangle t}{E_{pr} \triangle t} >> \frac{100\text{nm}}{500\text{nm}} = 0.2$$

- **Assuming 20% non-uniformity on the wafer:**

$$s = \frac{E_{poly} \triangle t}{E_{ox} \triangle t} >> \frac{20\% \times 100\text{nm}}{2\text{nm}} = 10$$

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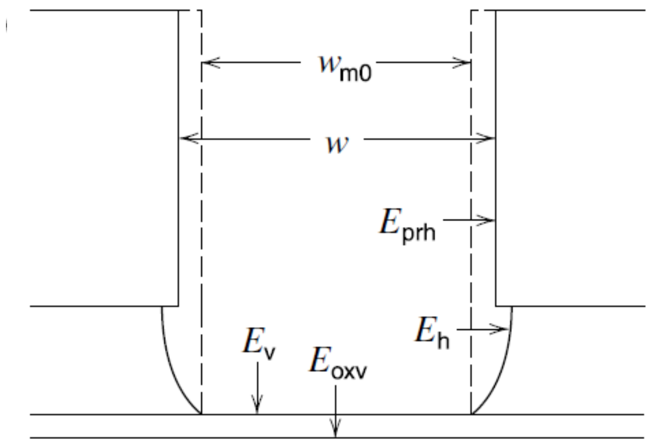
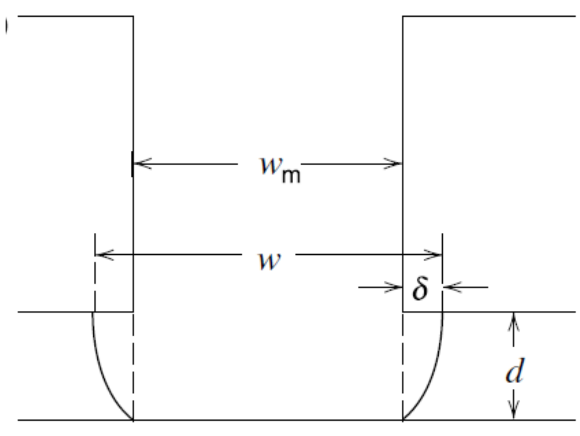
Plasma etch requirements – Anisotropy





- **Anisotropy**

$$a_h = \frac{E_v}{E_h} = \frac{d}{\delta}$$

$$w = w_m + 2\delta$$

$$a_h \geq \frac{2d}{w - w_m}$$

- **The smallest feature size where w_m=0:**

$$w \approx \frac{2d}{a_h}$$

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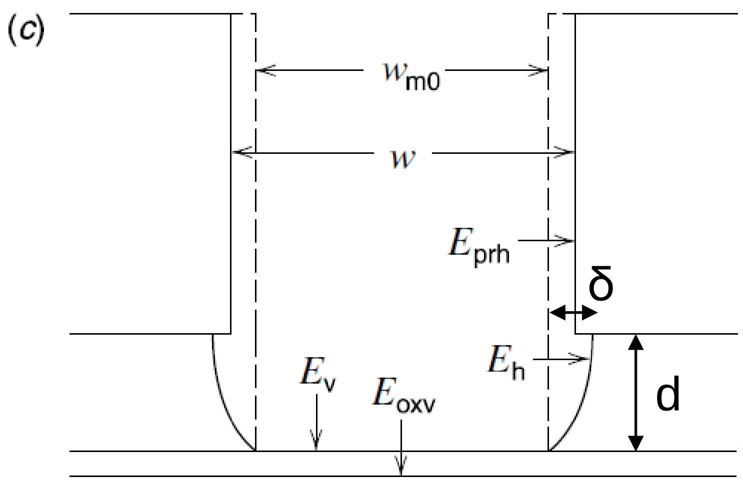
Plasma etch requirements – Anisotropy including etching on photoresist

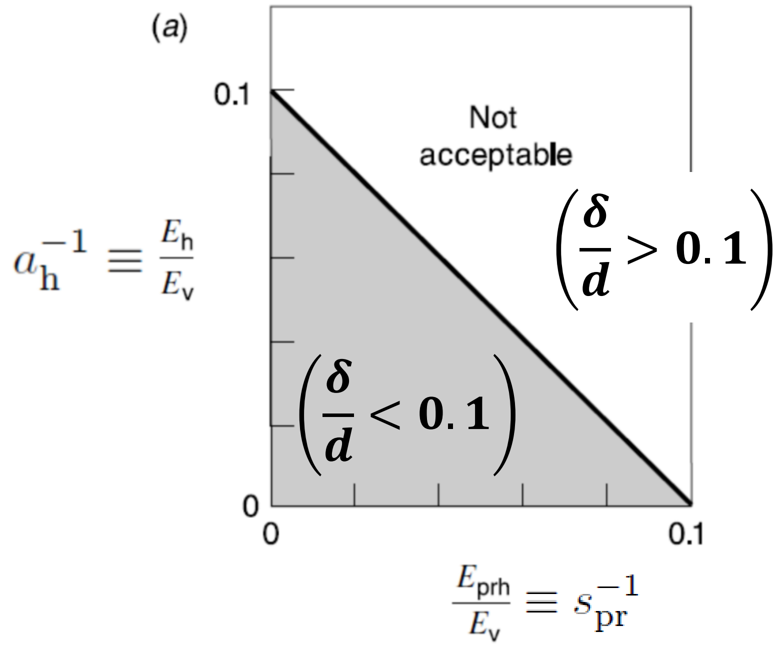


$$\delta \approx (E_h + E_{prh})\, t$$

$$t = \frac{d}{E_v}$$

$$\delta \approx d\frac{E_h + E_{prh}}{E_v}$$

$$\frac{E_h + E_{prh}}{E_v} \approx \frac{\delta}{d}$$



$$\frac{E_h}{E_V} + \frac{E_{prh}}{E_V} = a_h{}^{-1} + s_{pr}{}^{-1} \approx \frac{\delta}{d} \equiv 0.1$$

- The contribution of the horizontal etching is from both E_h and E_{prh}.

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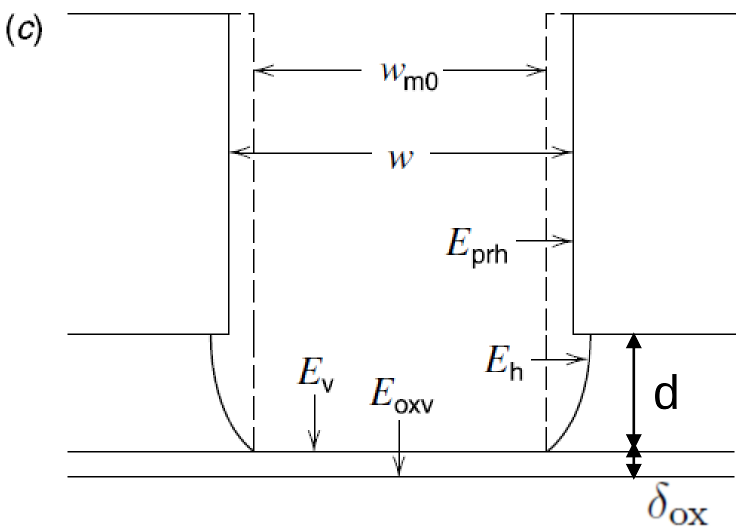
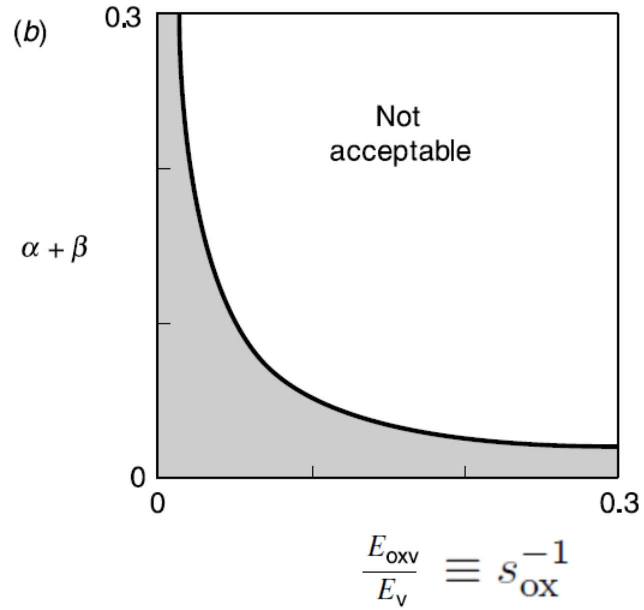
Plasma etch requirements – Uniformity on selectivity and anisotropy





$$d \rightarrow d(1 \pm \alpha) \qquad E_v \rightarrow E_v(1 \pm \beta)$$

where α, β are variations.

$$t_{max} = \frac{d(1+\alpha)}{E_v(1-\beta)} \approx \frac{d}{E_v}(1+\alpha+\beta)$$

$$t_{min} = \frac{d(1-\alpha)}{E_v(1+\beta)} \approx \frac{d}{E_v}(1-\alpha-\beta)$$

$$\delta_{ox} = (t_{max} - t_{min})E_{oxv} = \frac{d}{E_v} 2(\alpha+\beta)E_{oxv}$$

$$2(\alpha+\beta)\frac{E_{oxv}}{E_v} = \frac{\delta_{ox}}{d}$$

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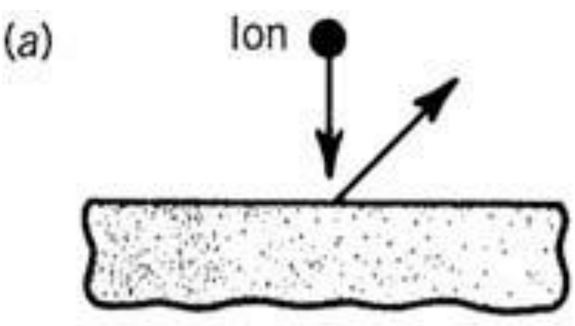
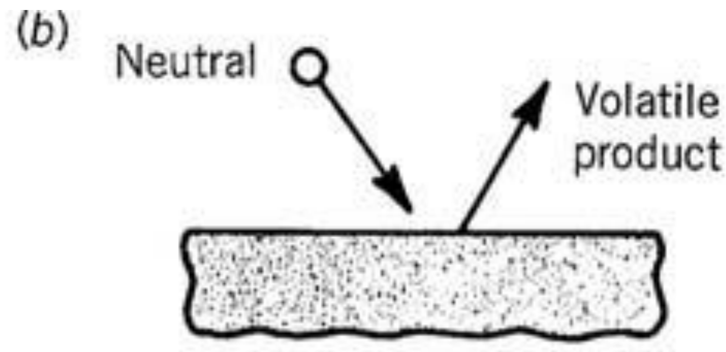
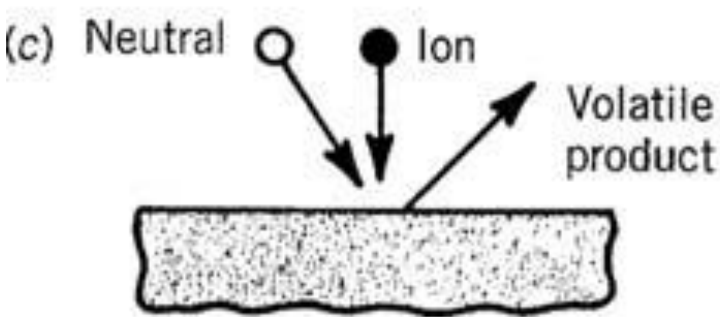
There are four major plasma etching mechanisms

- **Sputtering**

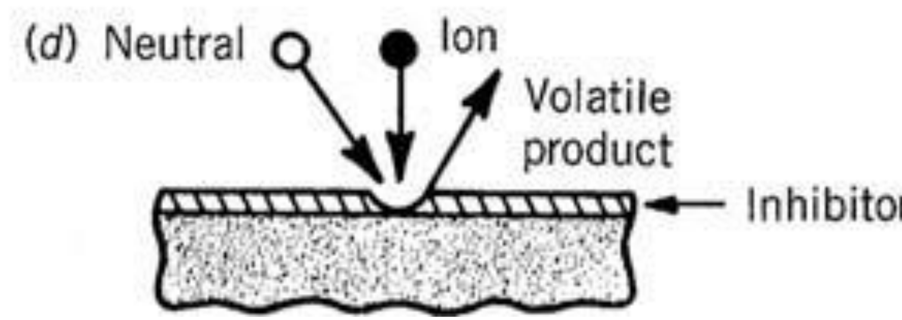


- **Pure chemical etching**





- **Ion energy-driven etching**



- **Ion-enhanced inhibitor etching**

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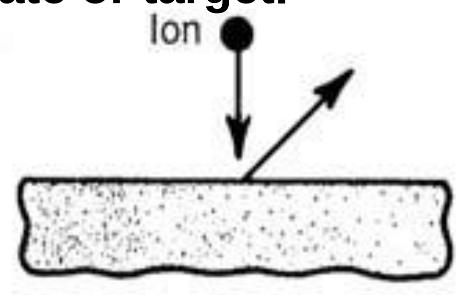
Sputtering is an unselective but anisotropic process

- Unselective process.
- Anisotropic process, strongly sensitive to the angle of incidence of the ion.
- Sputtering rates of different materials are roughly the same.
- Sputtering rates are generally low because the yield is typically of order one atom per incident ion.
- Sputtering is the only one of the four etch processes that can remove nonvolatile products from a surface.
- The process is generally under low pressure since the mean free path of the sputtered atoms must be large enough to prevent redeposition on the substrate or target.



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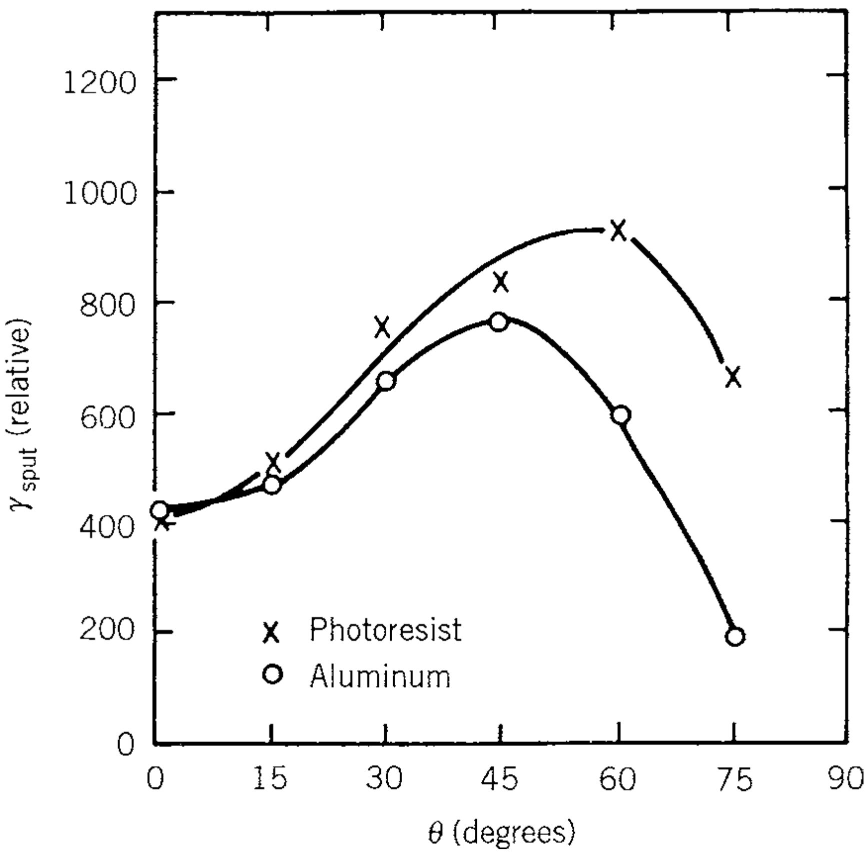
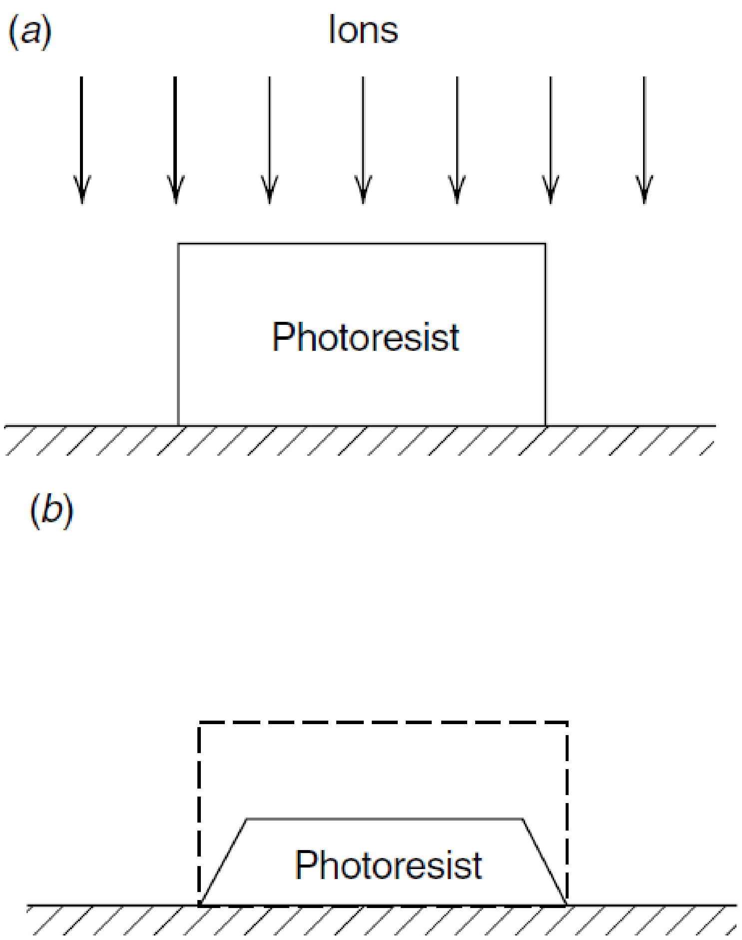
Topographical patterns might not be faithfully transferred during sputter etching





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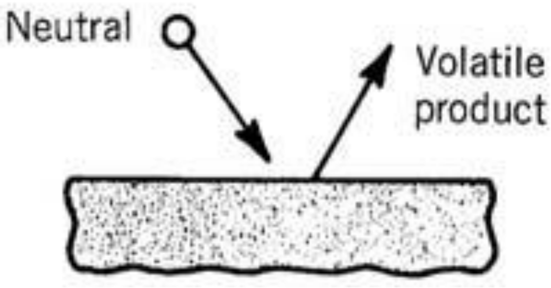
Pure chemical etching

Atoms or molecules chemically react with the surface to form gas-phase products

- **Highly chemically selective, e.g.,**

$$\mathrm{Si(s) + 4F \longrightarrow SiF_4(g)}$$

$$\mathrm{photoresist + O(g) \longrightarrow CO_2(g) + H_2O(g)}$$



- **Almost invariably isotropic.**
- **Etch products must be volatile.**
- **The etch rate can be quite large.**
- **Etch rate are generally not limited by the rate of arrival of etchant atoms, but by one of a complex set of reactions at the surface leading to formation of etch products.**

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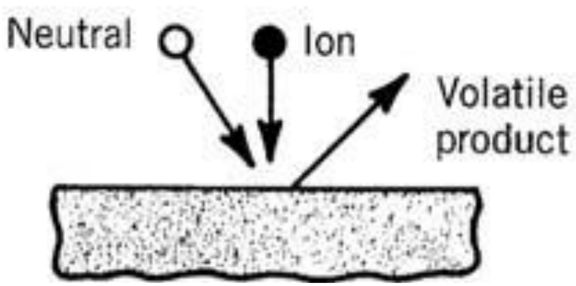
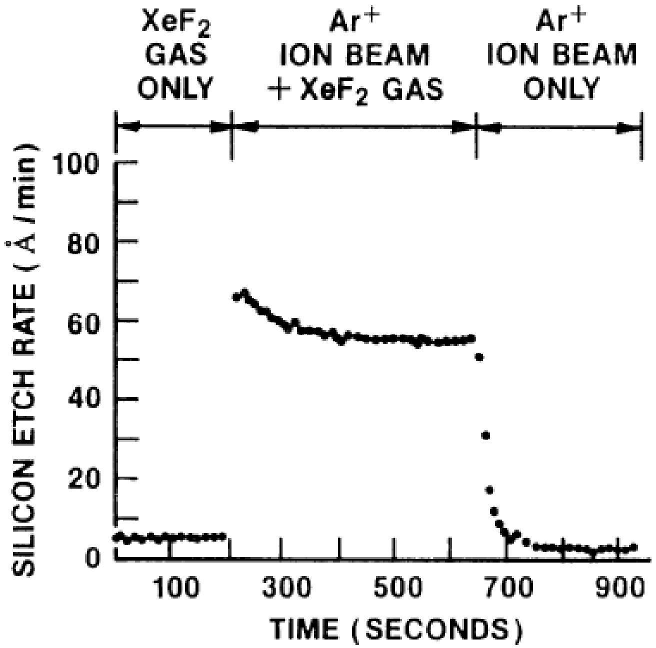
Ion-enhanced energy-driven etching

The discharge supplies both etchants and energetic ions to the surface





- **Low chemical etch rate of silicon substrate in XeF2 etchant gas.**
- **Tenfold increase in etch rate with XeF_2 + 500 V argon ions, simulating ion-enhanced plasma etching.**
- **Very low "etch rate" due to the physical sputtering of silicon by ion bombardment alone.**

Plasma etching, by Daniel L. Flamm and G. Kenneth Herb

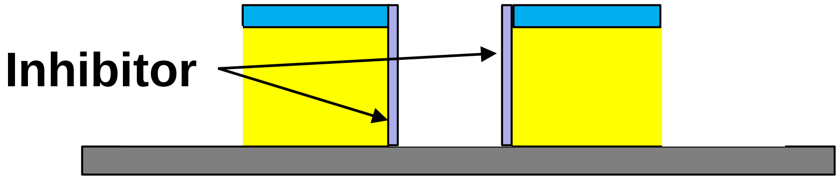
Ion-enhanced energy-driven etching has the characteristic of both sputtering and pure chemical etching

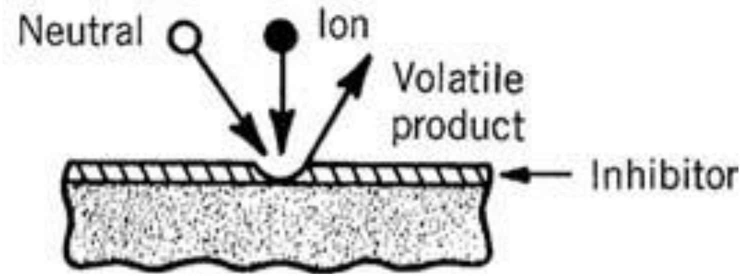
- **Chemical in nature but with a reaction rate determined by the energetic ion bombardment.**
- **Product must be volatile.**
- **Highly anisotropic.**

Ion-enhanced inhibitor etching

An inhibitor species is used

- Inhibitor precursor molecules that absorb or deposit on the substrate form a protective layer or polymer film.
- Etchant is chosen to produce a high chemical etch rate of the substrate in the absence of either ion bombardment or the inhibitor.
- Ion bombardment flux prevents the inhibitor layer from forming or clears it as it forms.
- Where the ion flux does not fall, the inhibitor protects the surface (side wall) from the etchant.
- May not be as selective as pure chemical etching.
- A volatile etch product must be formed.
- Contamination of the substrate and final removal of the protective inhibitor film are other issues.





Comparison of different processes

	Sputtering etching	Pure chemical etching	Ion energy-driven etching	Ion-enhanced Inhibitor etching
Selectivity	X	O	O	O
Anisotropic	O	X	O	O
Volatile product	X	O	O	O

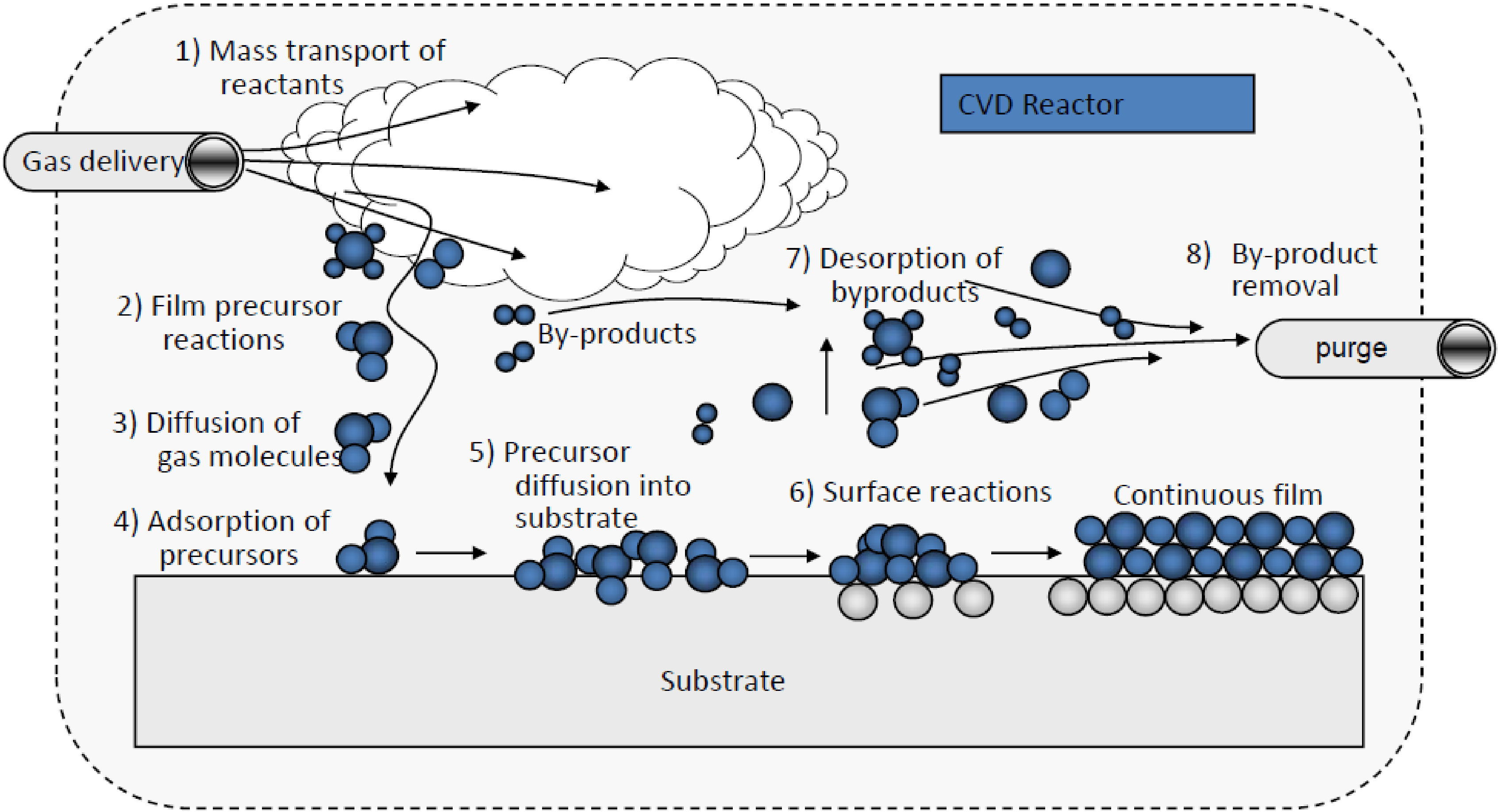
TABLE 15.1. Etch Chemistries Based on Product Volatility

Material	Etchant Atoms
Si, Ge	F, Cl, Br
SiO_2	F, F + C
Si_3N_4, silicides	F
Al	Cl, Br
Cu	Cl ($T > 210°C$)
C, organics	O
W, Ta, Ti, Mo, Nb	F, Cl
Au	Cl
Cr	Cl, Cl + O
GaAs	Cl, Br
InP	Cl, C + H

Deposition and implementation

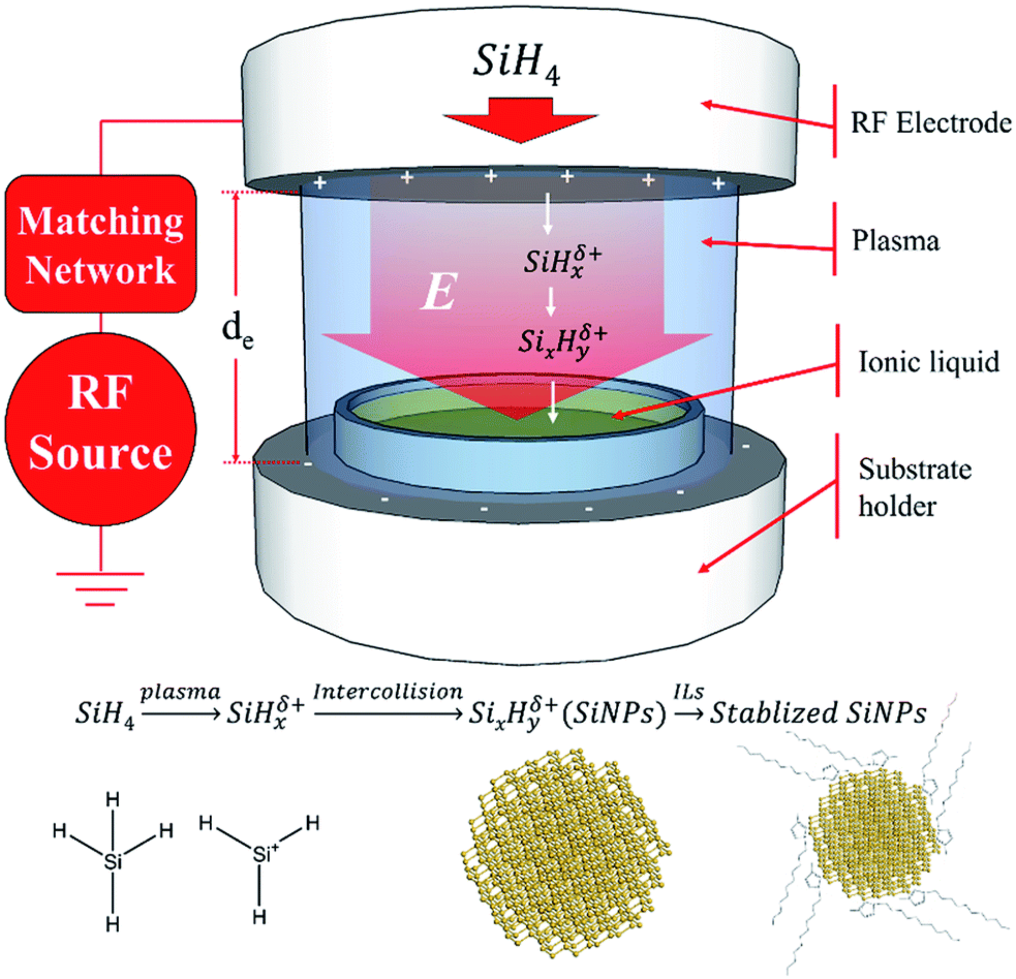
- Plasma-assisted deposition, implantation, and surface modification are important material processes for producing films on surfaces and modifying their properties
- Example processes:
  - Plasma-enhanced chemical vapor deposition (PECVD)
  - Sputter deposition / physical vapor deposition (PVD)
  - Plasma-immersion ion implantation (PIII)

Chemical Vapor Deposition (CVD)



http://www.ece.uah.edu/courses/material/EE410-Wms/

Plasma-enhanced chemical vapor deposition (PECVD)



Films can be deposited in low temperatures using plasma deposition

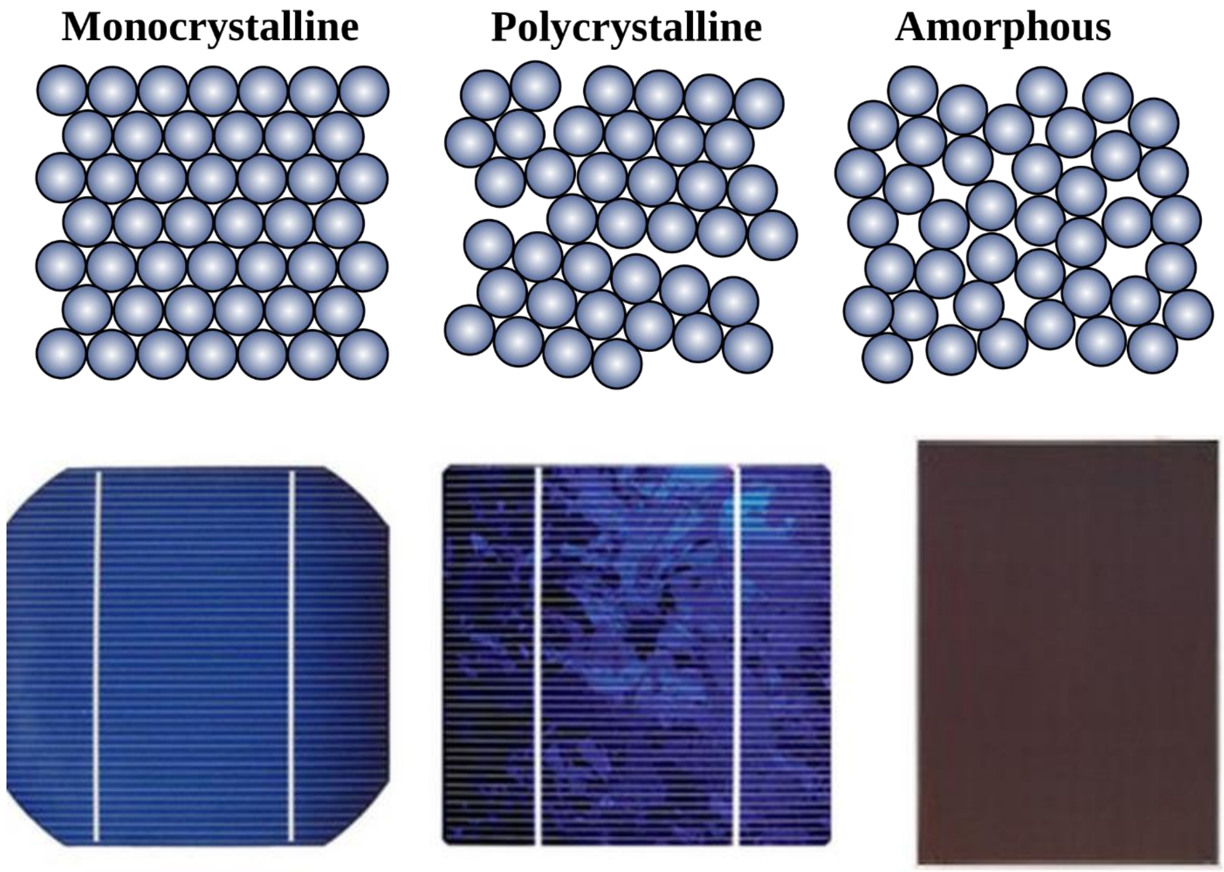
- **Device structures are sensitive to temperature, high-temperature deposition processes cannot be used in many cases.**
- **High-temperature films can be deposited at low temperatures.**
- **Unique films not found in nature can be deposited, e.g., diamond.**

Working temperature is determined by the desired film properties

- **CVD – consists of a thermally activated set of gas-phase and surface reactions that produce a solid product at a surface.**
- **PECVD – gas-phase and the surface reactions are controlled or modified by the plasma properties.**
- **Te~2-5 eV in PECVD is much greater than the substrate temperature, the temperature in PECVD is much less that CVD.**
- **Deposition rates are usually not very sensitive to the substrate temperature T.**
- **Film properties such as composition, stress, and morphology, are functions of T.**
- **Low-temperature PECVD films are amorphous, not crystalline, which can more easily be achieved with chemical vapor deposition (CVD).**

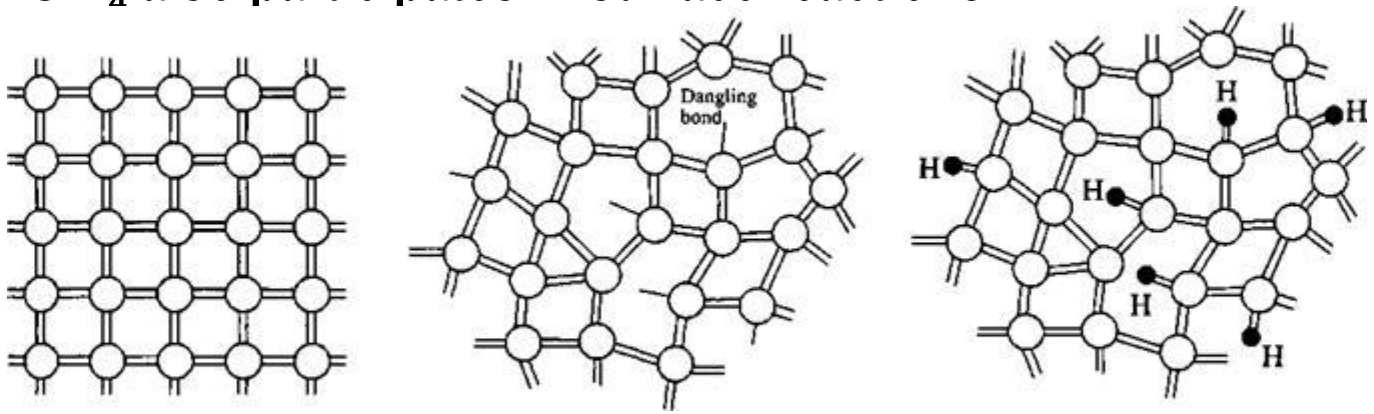
Example of using PECVD – amorphous silicon

- **Amorphous silicon thin films are used in solar cells**



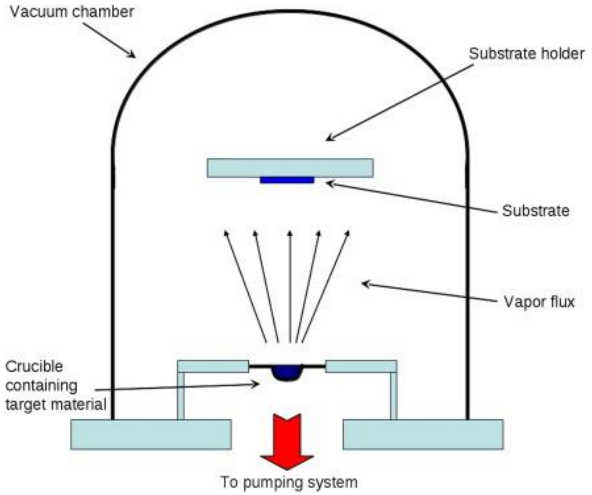
Example of using PECVD – amorphous silicon

- H is required so that SiH_4 is used
  - For the material to be semiconducting.
  - Terminate the dangling bonds.
  - The dangling bonds are created by ion bombardment (SiH_3^+) which also removes hydrogen from the surface.
  - SiH_3 and SiH_2 radicals are important precursors for film growth while SiH_4 also participates in surface reactions.

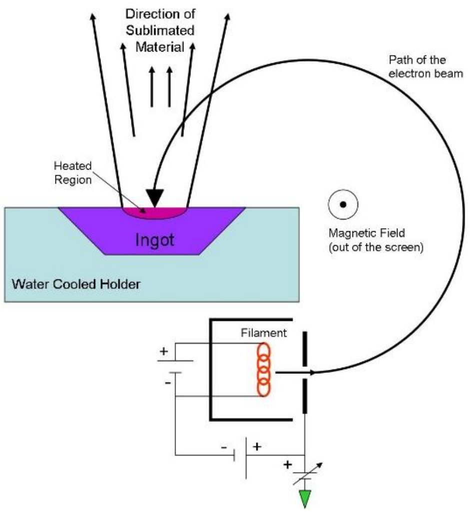


Physical vapor deposition can be achieved by heating the deposited material

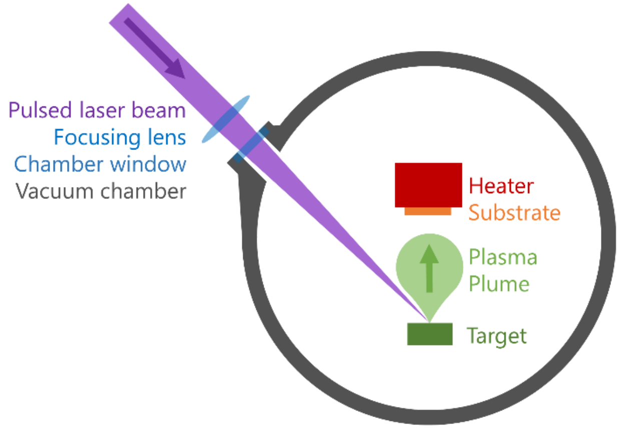
- **Thermal evaporator**



- **Electron-beam evaporator**



- **Pulsed-laser deposition**



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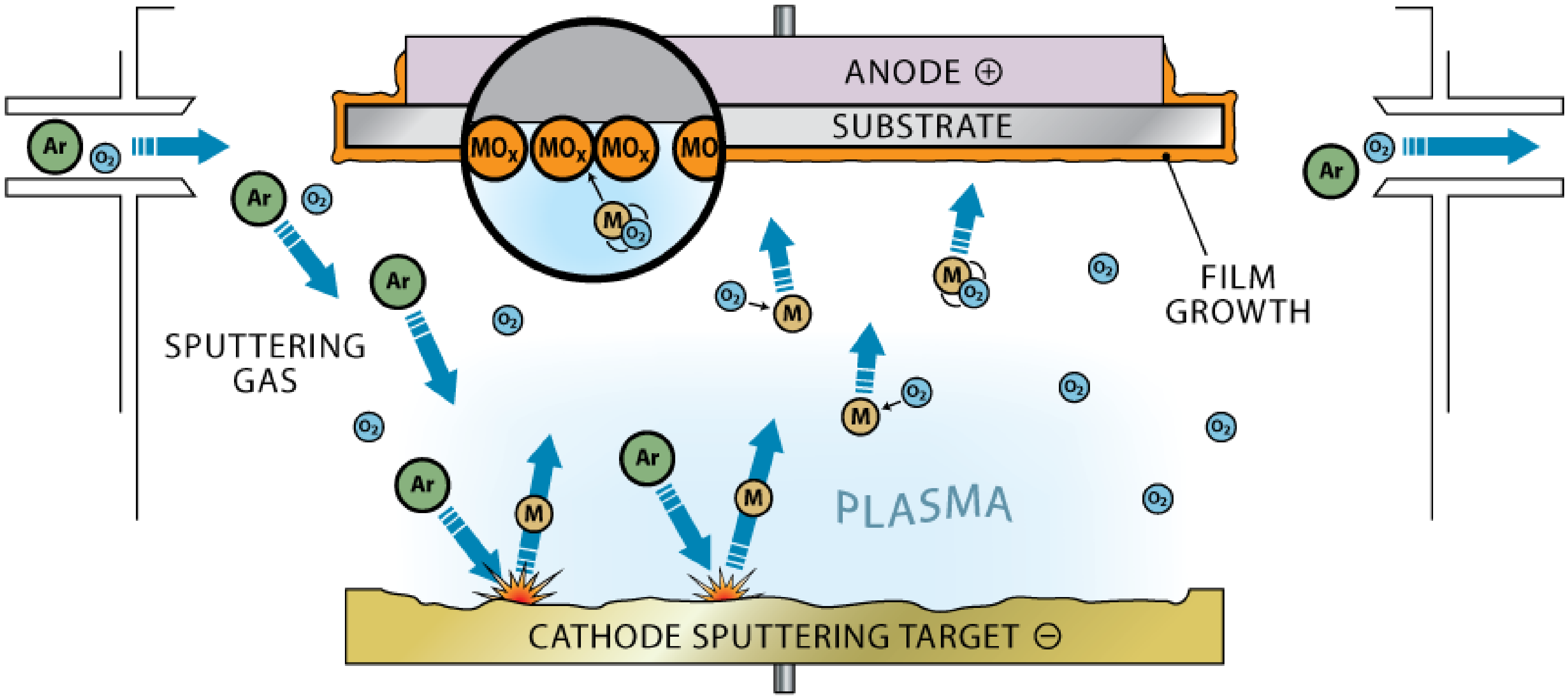
https://en.wikipedia.org/wiki/Pulsed_laser_deposition
Engineered biomimicry by A. Lakhtakia and R. J. Martin-Palma
https://en.wikipedia.org/wiki/Electron-beam_physical_vapor_deposition

Sputtering deposition

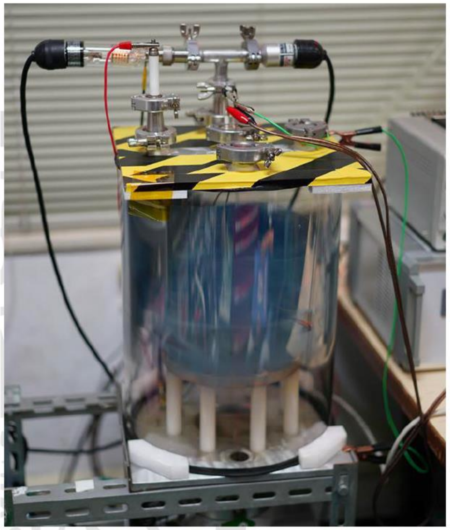


http://lnf-wiki.eecs.umich.edu/wiki/Sputter_deposition

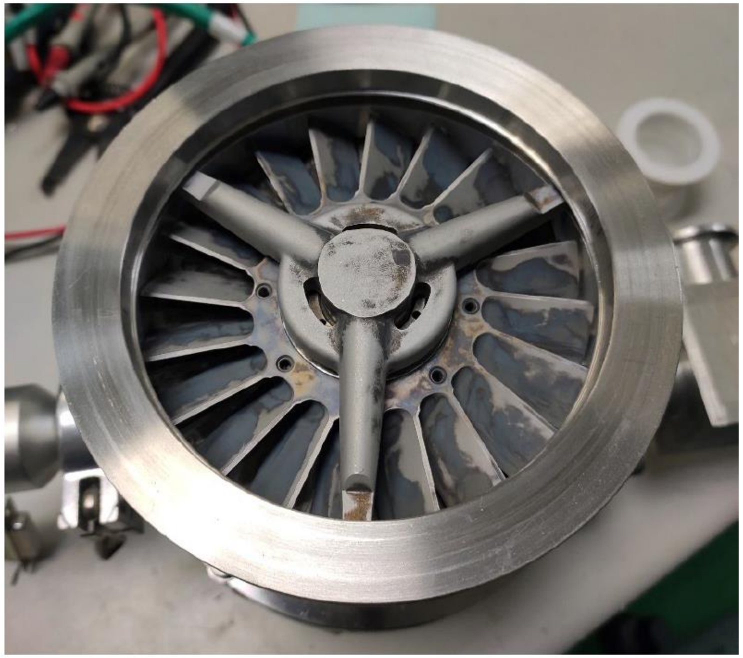
The chamber becomes very dirty after the deposition process

- **Before**

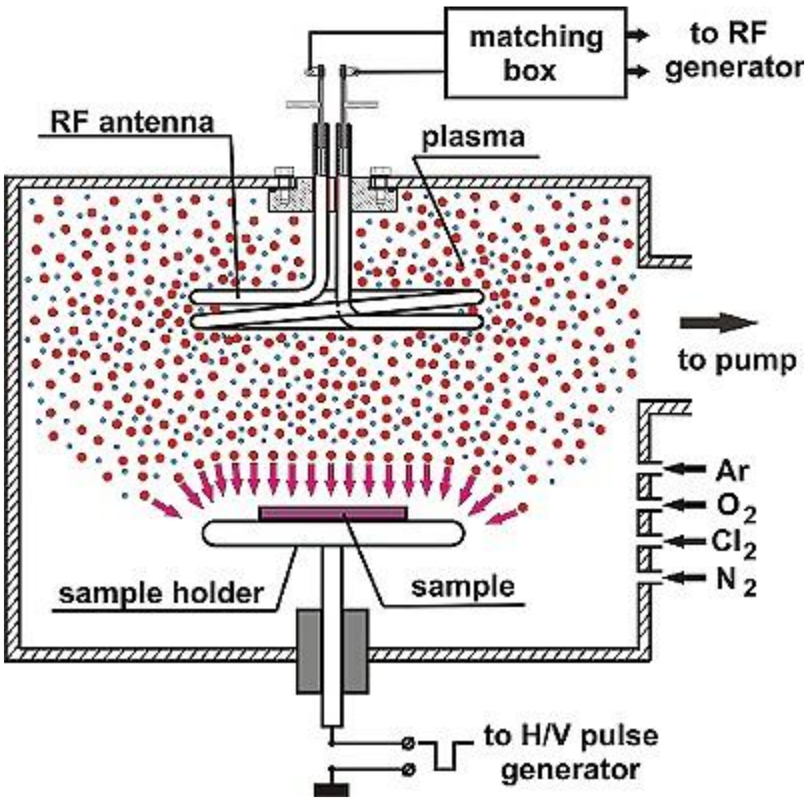
- **After**

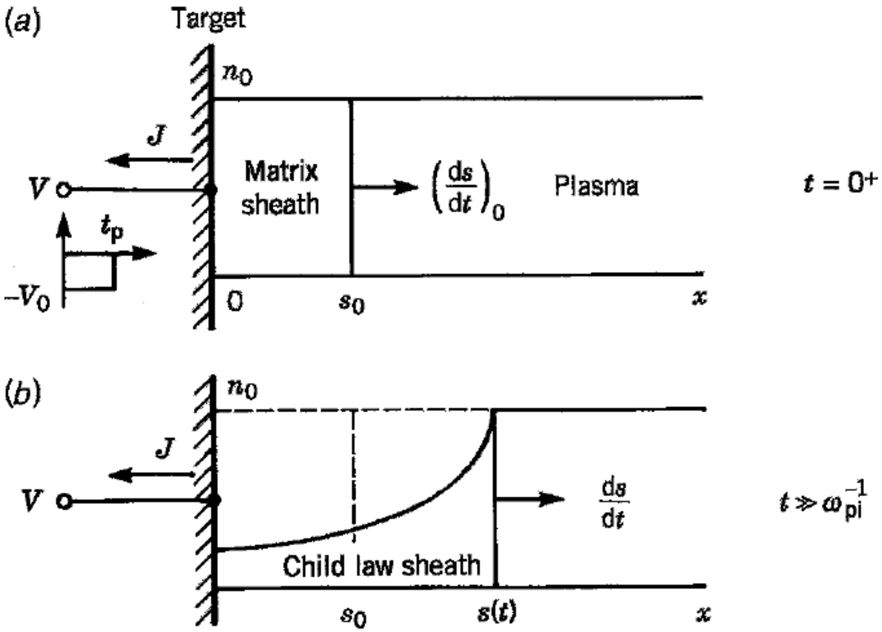


- **The turbomolecular pump is also very dirty after the process.**



Plasma-immersion ion implantation (PIII)

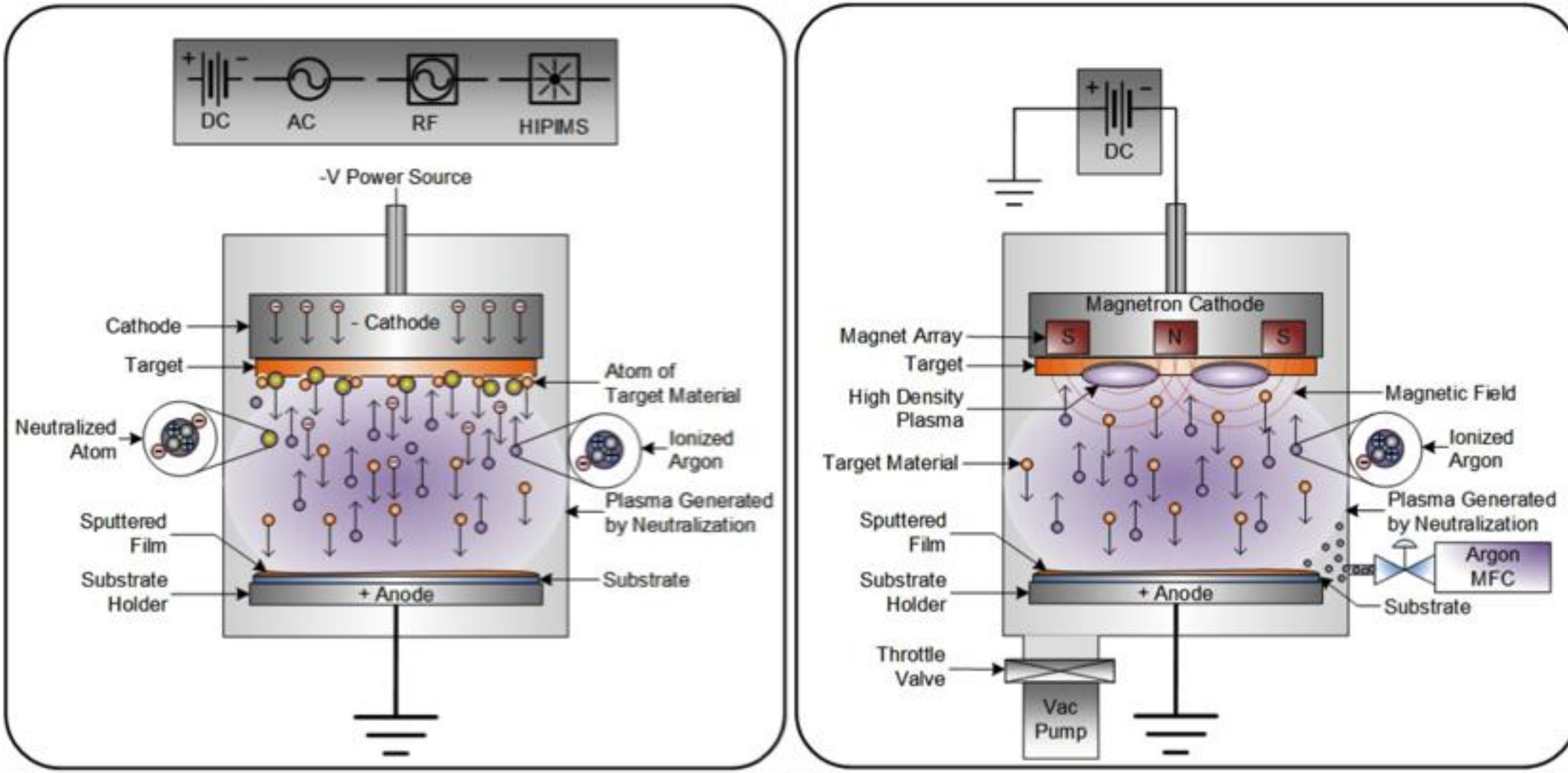




- **Silicon doping – ions such as B, P, As are implanted**
- **Surface hardening of metals – N, C are implanted**

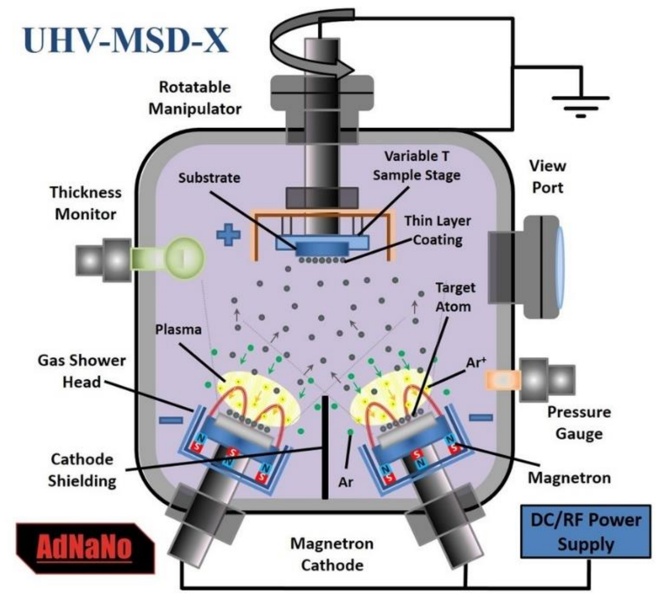
https://www.hzdr.de/db/Cms?pOid=10890&pNid=306

Magnetron sputtering provides higher deposition rates than conventional sputtering



http://www.semicore.com/what-is-sputtering

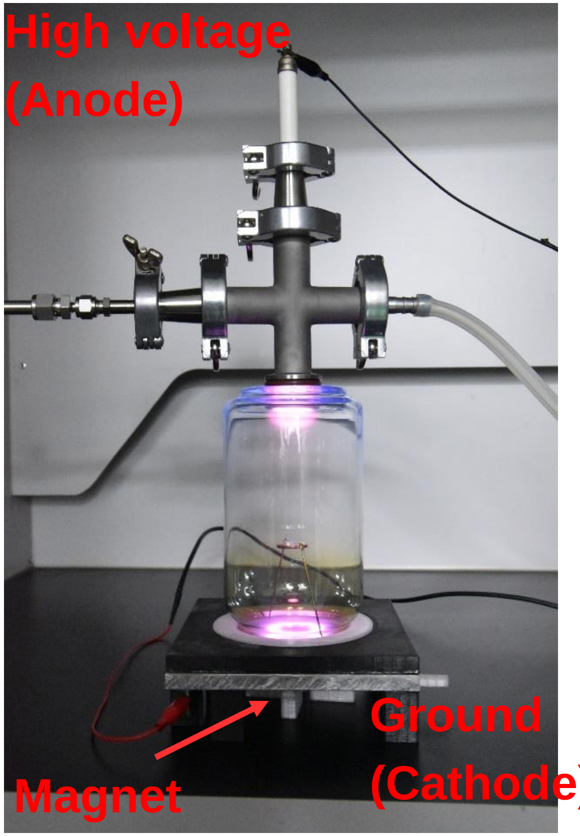
Examples of magnetron sputtering deposition

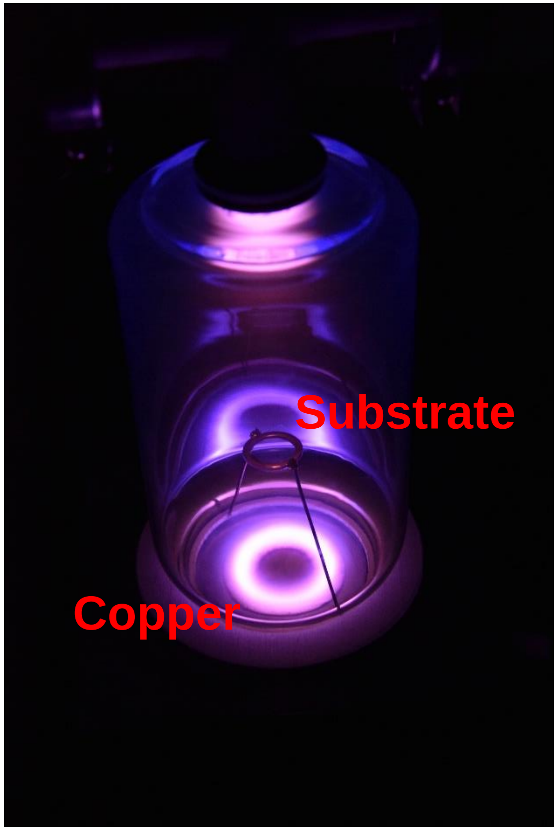


https://angstromengineering.com/tech/magnetron-sputtering/pulsed-dc/
https://dynavac.com/wp-content/uploads/2017/09/Confocal-Sputtering-2.jpg
https://www.adnano-tek.com/magnetron-sputtering-deposition-msd.html

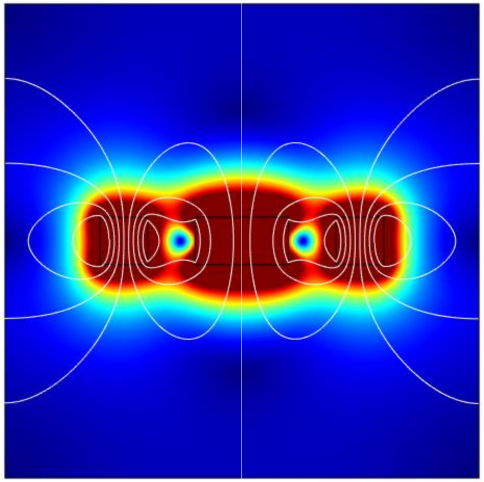
Demonstration experiments – magnetron sputtering

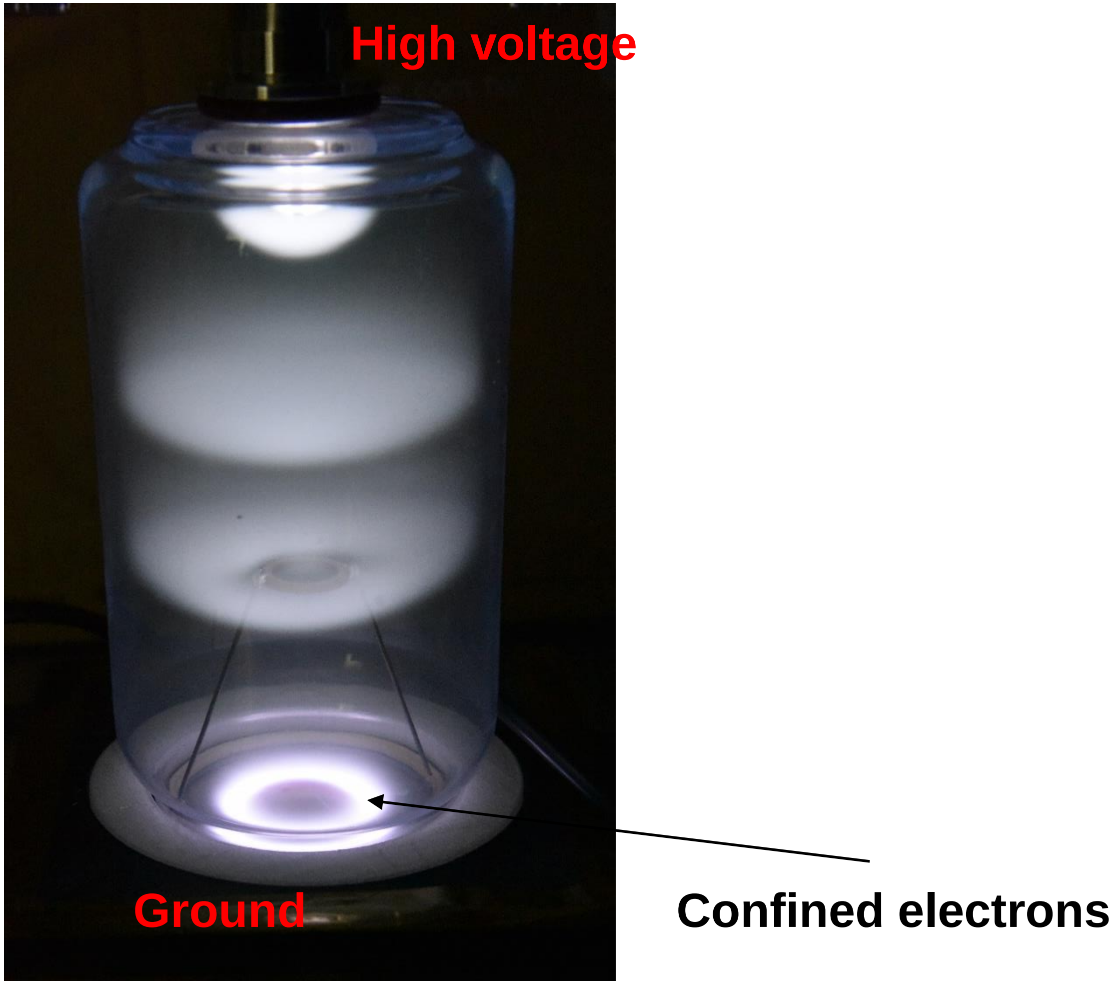
- System
- Without magnet
- With magnet



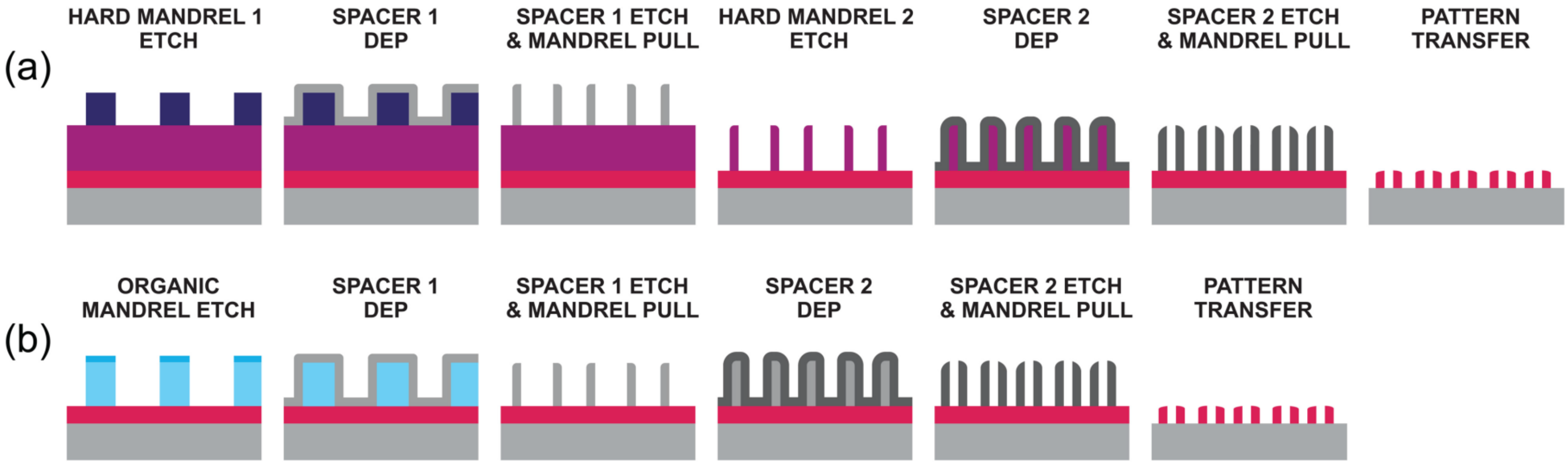


A bright ring occurs when the magnet is inserted into the system





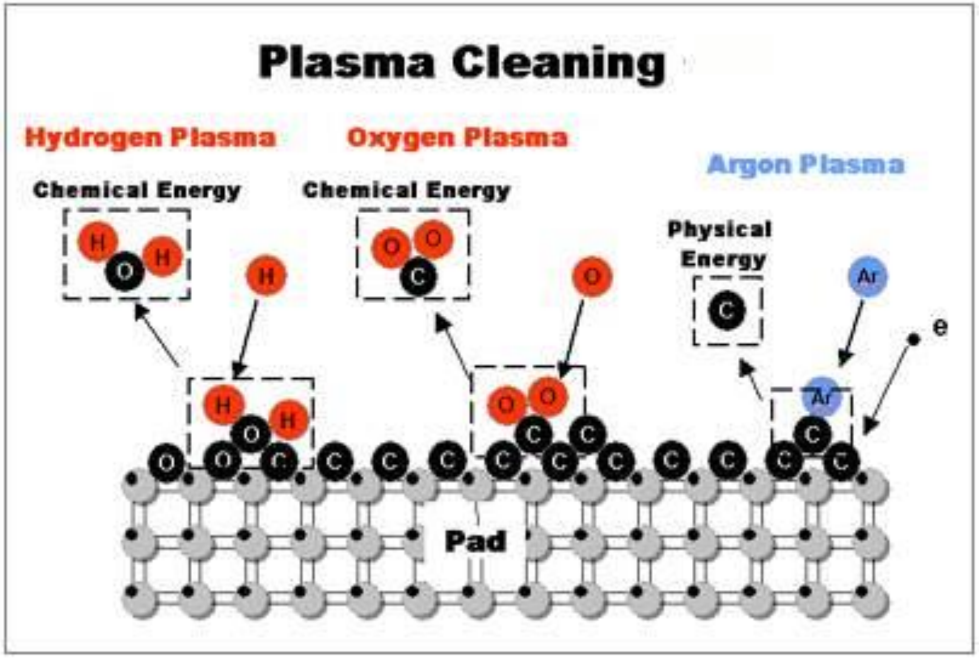
self-aligned quadruple patterning



H. C. M. Knoops *et al.*, J. Vac. Sci. Technol. **A 37**, 030902 (2019)

Plasma can be used for cleaning surface

- Cleaning mechanisms:
  - Chemical reactions by free radicals
  - Physical sputtering by high energy ions



湌鼎奈米科技股份有限公司
https://www.ecplaza.net/products/plasma-cleaning_111807

Free radicals are generated and used in chemical reactions

$$e^{-} + H_2 \rightarrow 2H \bullet \qquad e^{-} + O_2 \rightarrow 2O \bullet \qquad \mathrm{O} \bullet + O_2 \rightarrow O_3$$

- **Highly reactive free radicals generated in plasma may react with the hydrocarbon contaminants of surface oxide.**
- **Both H• and O• can react with grease or oil on surface to form volatile hydrocarbons.**

$$\mathrm{H} \bullet_{(g)} + C_n H_{2n+2(s)} \rightarrow \mathrm{CH}_{4(s)}$$

$$\mathrm{O} \bullet_{(g)} + C_n H_{2n+2(s)} \rightarrow \mathrm{CO}_{(s)} + \mathrm{CH}_x O_{y(g)} + H_2 O_{(g)}$$

- **O• is more reactive than H•. But O• may also react with surface metal to form oxide, deteriorating the material properties. Nevertheless, H• can make metal oxide back to metal.**

$$\mathrm{O} \bullet + \mathrm{Me} \rightarrow \mathrm{MeO}$$

$$\mathrm{H} \bullet + \mathrm{MeO} \rightarrow \mathrm{Me} + H_2 O$$

The effect of chemical reactions is increased as the pressure increases

- **Advantages:**
  - **Stable gas products are formed.**
  - **No redeposition problem.**
  - **High etching selectivity.**

- **Disadvantages:**
  - **Higher concentration of H_2 or O_2 is required to ensure an appropriate etching rate.**
  - **H_2 safety or O_2 strong oxidation ability needs to be monitored.**

High energy ions are used in physical sputtering cleaning

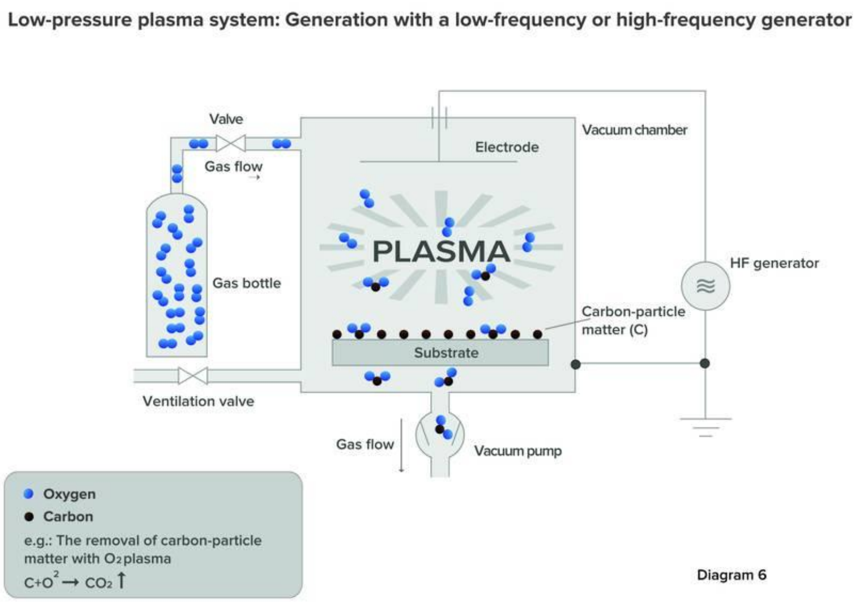
- Ions generated in plasma can be accelerated toward the substrate to physically bombard away the atoms of contaminants.
- The physical sputtering rate increases as the following quantities increase:
  - Plasma density;
  - Accelerating voltage;
  - Mass of bombardment atoms.
- The physical sputtering is also enhanced by lowering the pressure.
- High cathode bias is used.
- Ar^+ has strong sputtering effect.

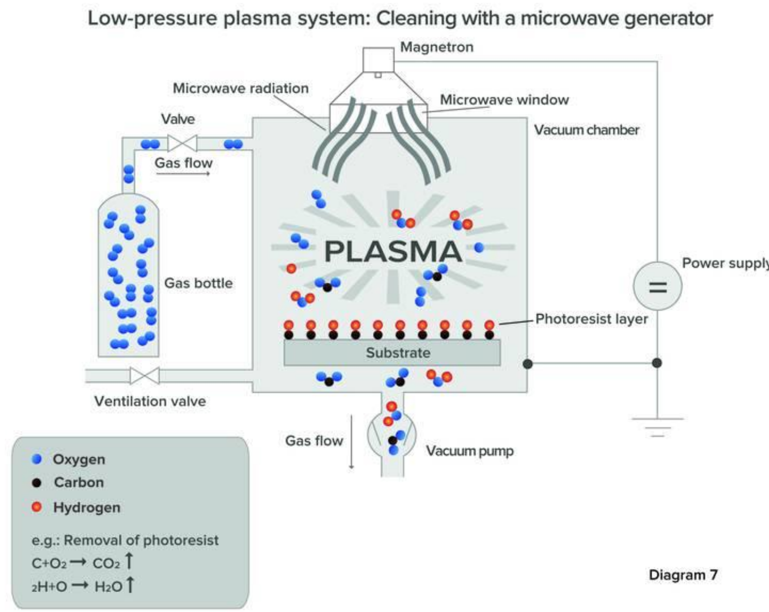
The physical sputtering rate increases with higher cathode bias and Ar concentration and lower pressure

- **Advantages:**
  - **Highly efficient cleaning effect can be achieved.**
  - **Gas consumption rate can be very low.**

- **Disadvantages:**
  - **Etching problems – non-selective etching by physical sputtering.**
  - **Redeposition problems: the products sputtered out may be highly unstable and tend to deposit again downstream.**

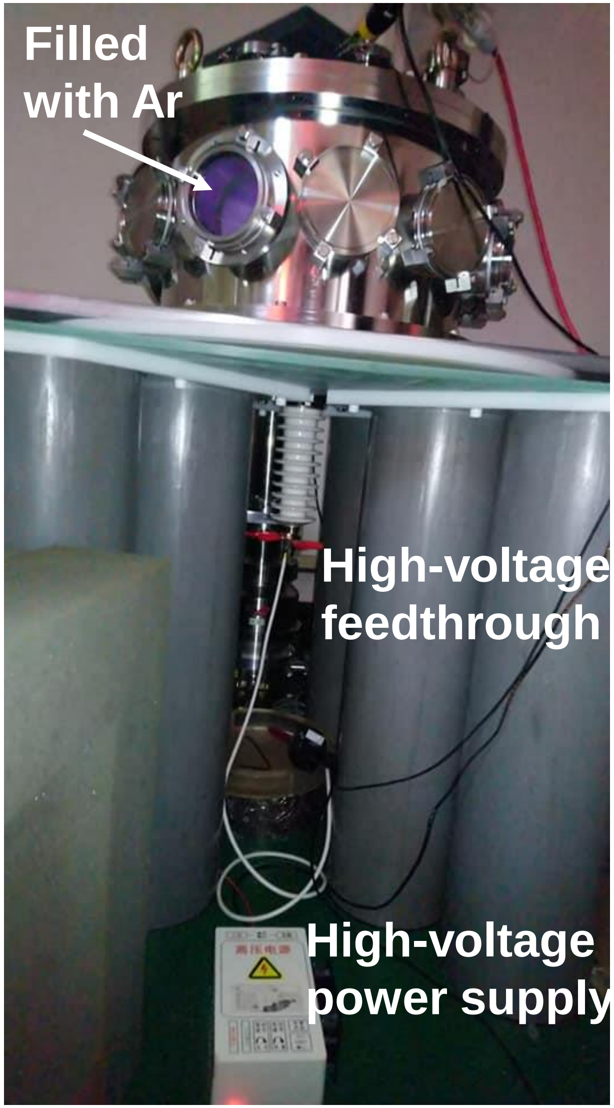
Plasma cleaning examples



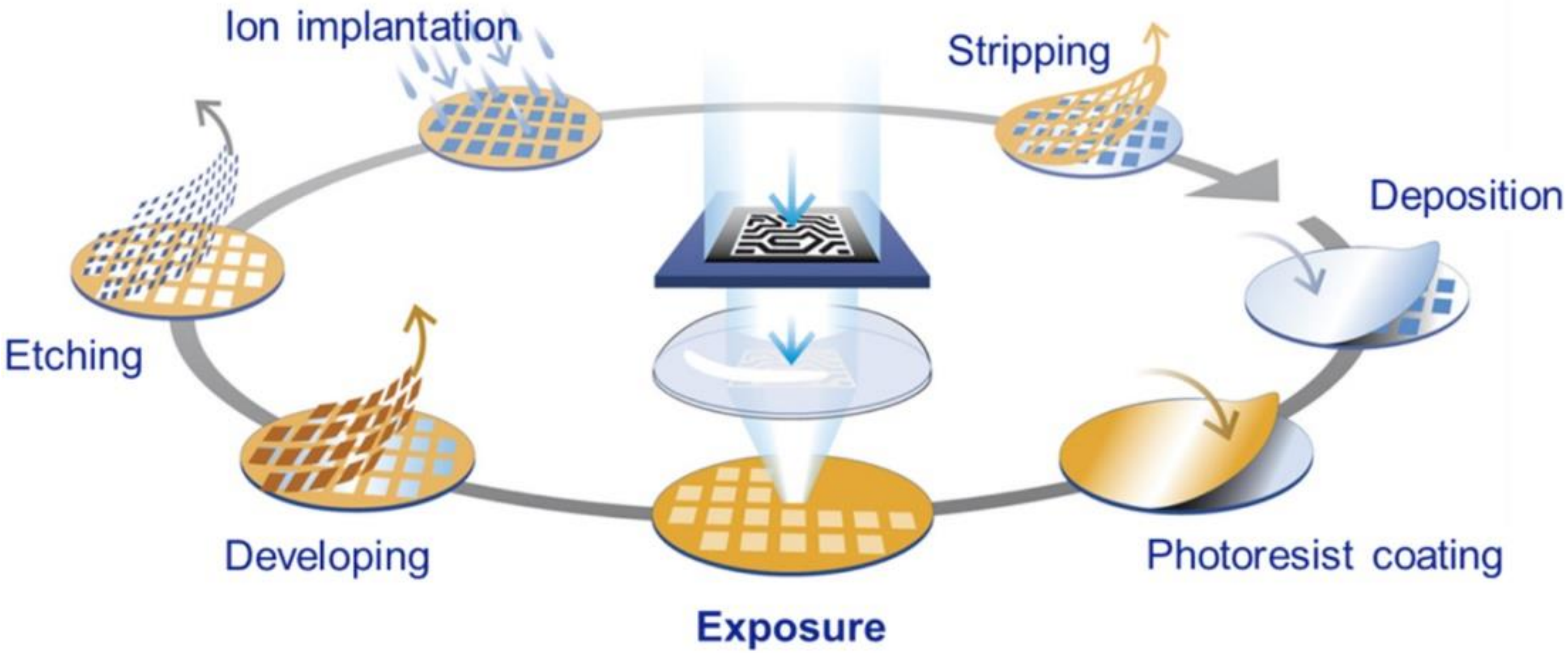


https://www.plasma.com/en/plasmatechnik/low-pressure-plasma/cleaning/

Plasma cleaning needs to work in the regime of abnormal glow discharge



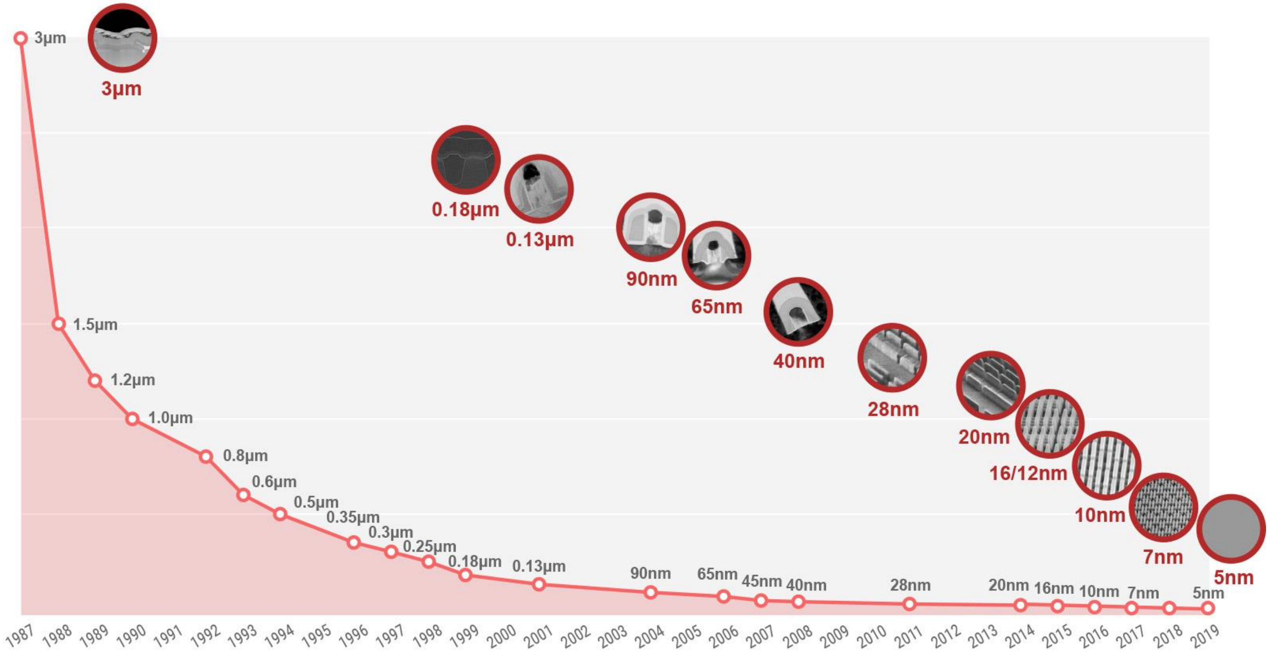
A semiconductor device is fabricated by many repetitive production process



Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

Ultraviolet lithography (EUVL) is one of the key technologies in semiconductor manufacturing nowadays

- **The process technology of Taiwan Semiconductor Manufacturing Company Limited (TSMC):**

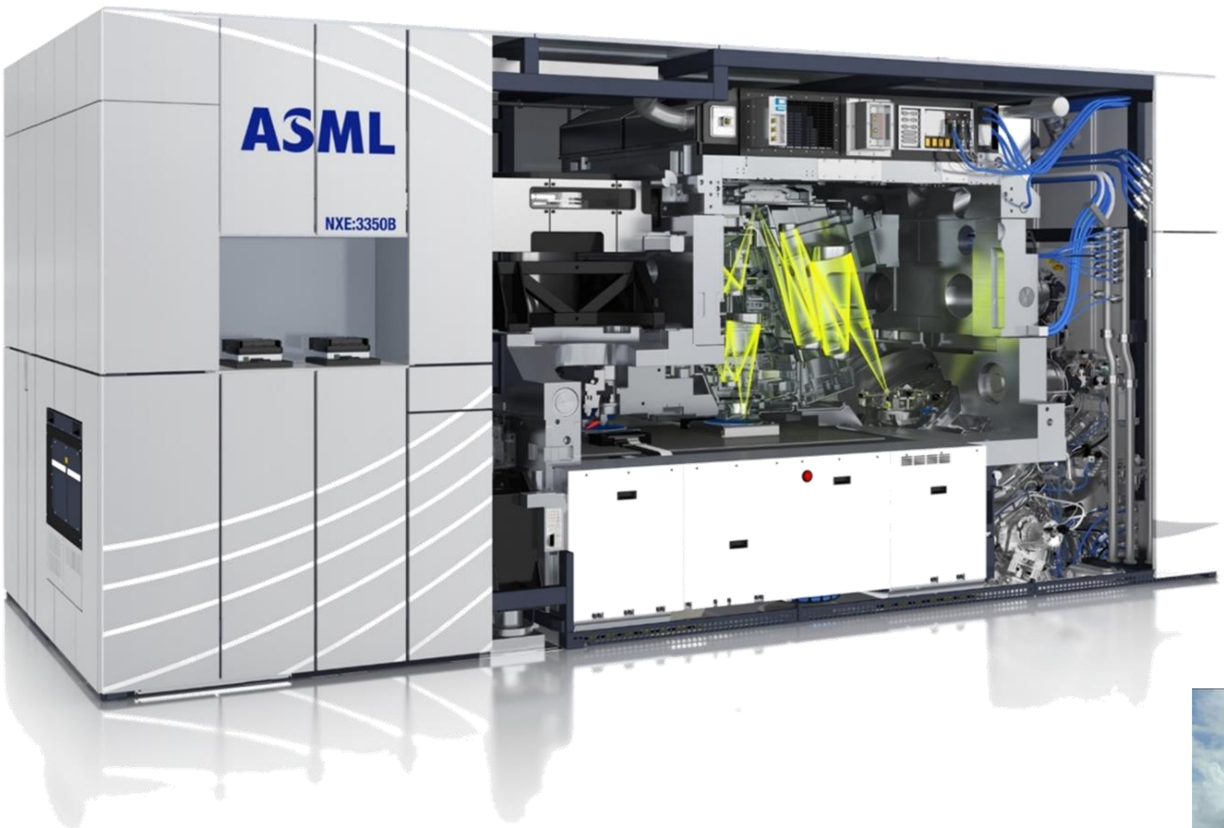


- **Optical diffraction needs to be taken into account.**
- **Shorter wavelength is preferred.**

- **Light source with a center wavelength of 13.5 nm is used.**

https://www.tsmc.com/chinese/dedicatedFoundry/technology/logic.htm

EUV lithography becomes important for semiconductor industry

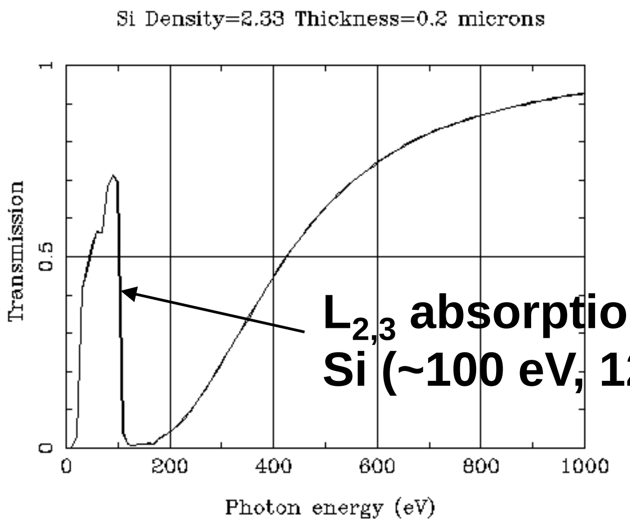


- **0.15 billion USD for each EUV light source.**

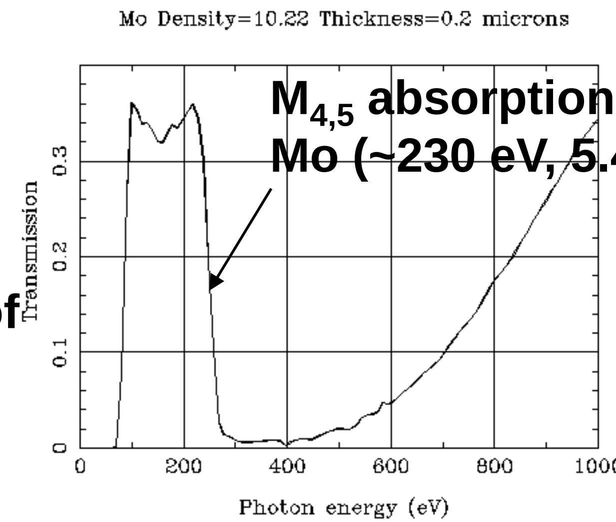
https://www.youtube.com/watch?v=NHSR6AHNiDs

http://finance.technews.tw/2019/01/25/euv-asml-2018/

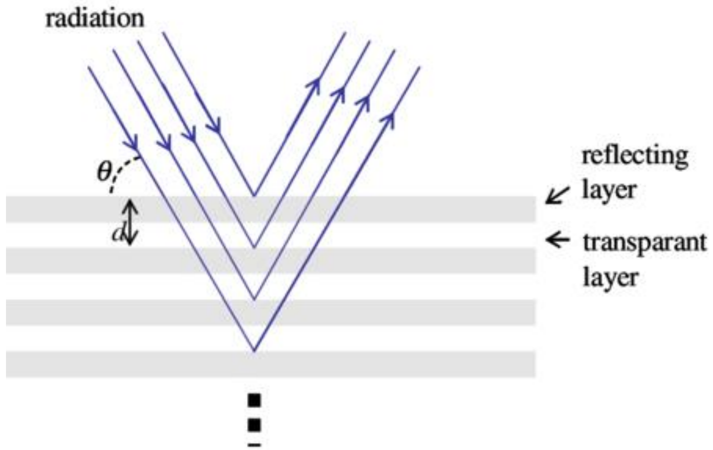
EUV light can only be reflected using multilayer mirrors

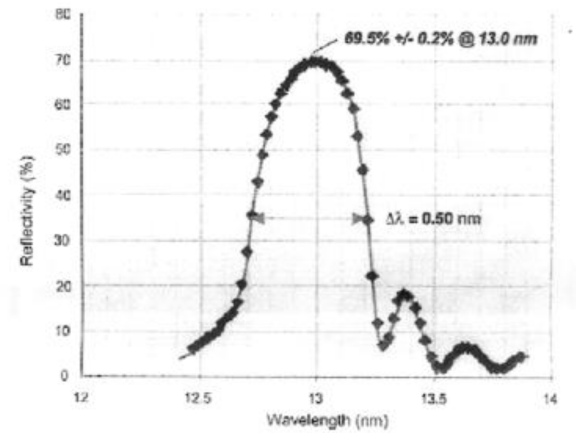


$L_{2,3}$ absorption edge of Si (~100 eV, 12.4 nm)



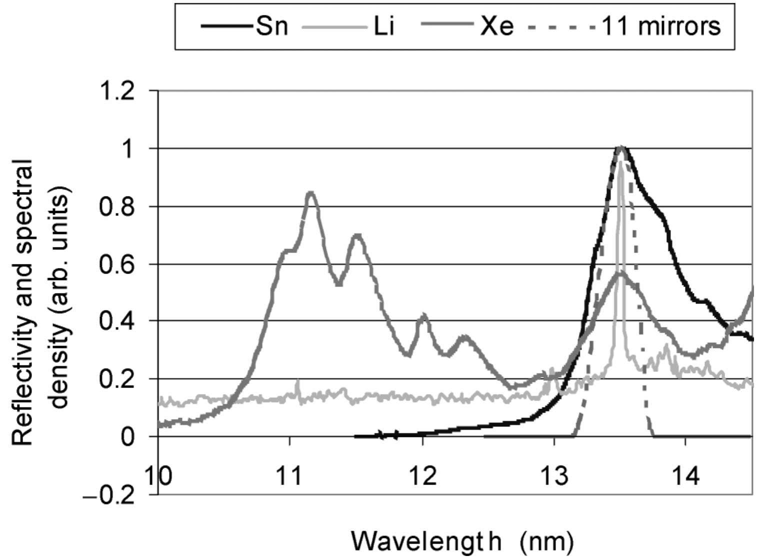
$M_{4,5}$ absorption edge of Mo (~230 eV, 5.4 nm)





https://henke.lbl.gov/optical_constants/
Mo/Si multilayer coating technology for EUVL, coating uniformity and time stability; E. Louis et al.; SPIE 4146-06, Soft X-ray and EUV Imaging Systems, San Diego, 2000.

13.5-nm EUV light is picked for EUV lithography

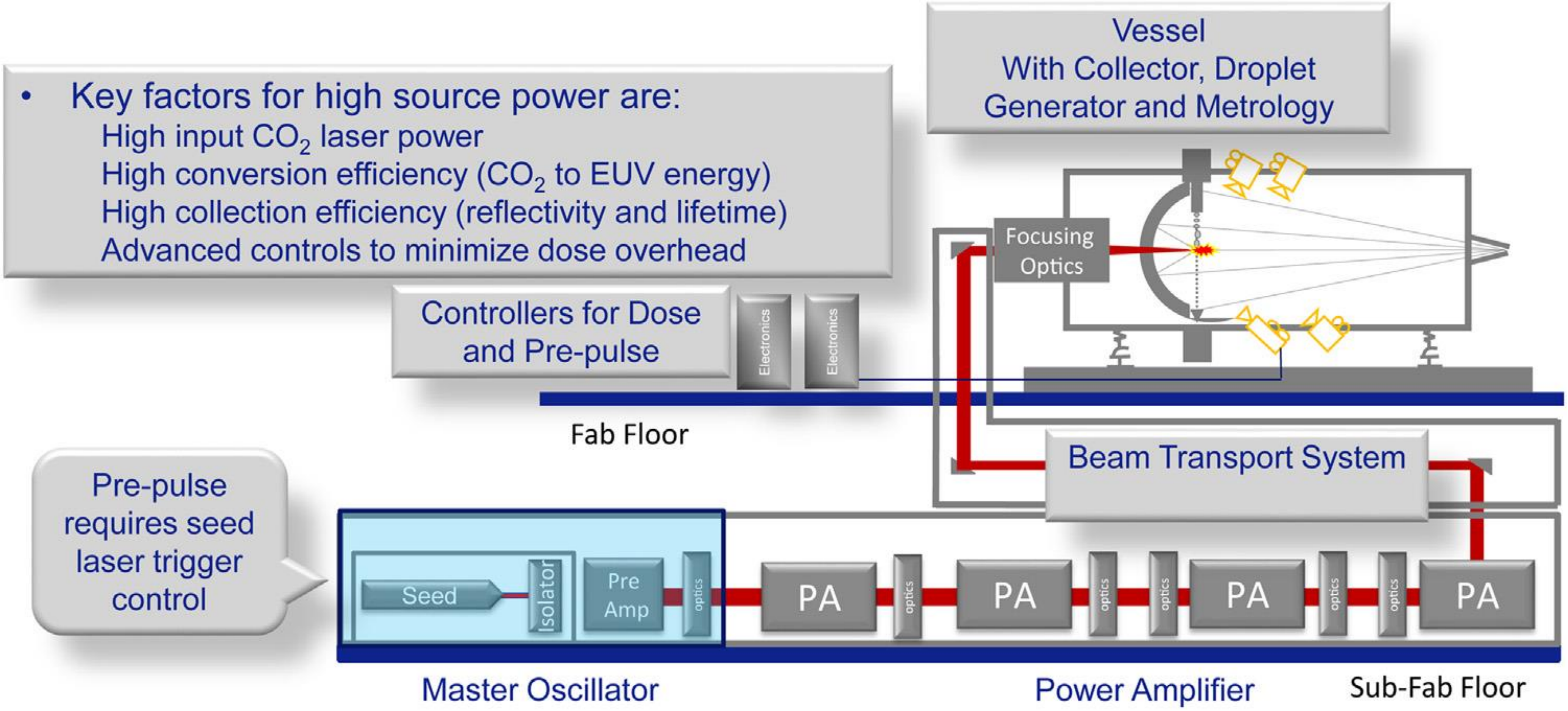


- $\lambda = 13.5\ \mathrm{nm} \pm 1\%$ **is required.**
- **At T=35-40 eV (~450,000 K), in-band emission occurs.**
- **Xenon:**
  - ***4p*^{6}4*d*^{8} → *4p*^{6}4*d*^{7}5*p***
    from single ion stage Xe^{10+}
  - **UTA @ 11 nm**
- **Tin:**
  - ***4p*^{6}4*d*^{N} → *4p*^{5}4*d*$^{N+1}$ + *4p*^{6}4*d*$^{N-1}$4*f***
    ($1 \le N \le 6$) in ions ranging from Sn^{8+} to Sn^{12+}
  - **UTA @ 13.5 nm**
- UTA: unresolved transition array

V. Bakshi, EUV sources for lithography
R. S. Abhari, etc., J. Micro/Nanolithography, MEMS, and MOEMS, 11, 021114 (2012)

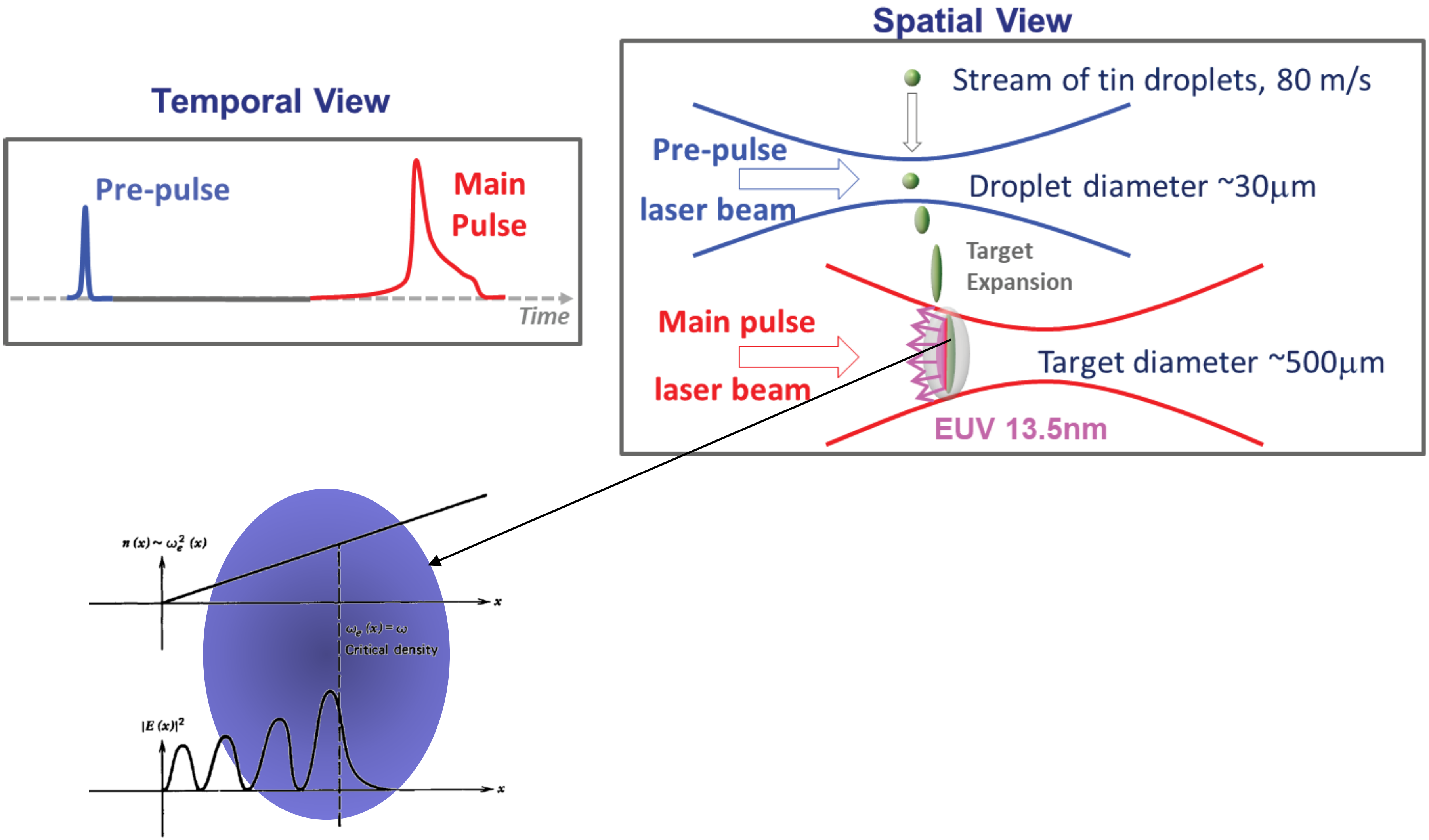
EUV light is generated from laser-produced plasma (LPP)

- Key factors for high source power are:
  - High input CO_2 laser power
  - High conversion efficiency (CO_2 to EUV energy)
  - High collection efficiency (reflectivity and lifetime)
  - Advanced controls to minimize dose overhead



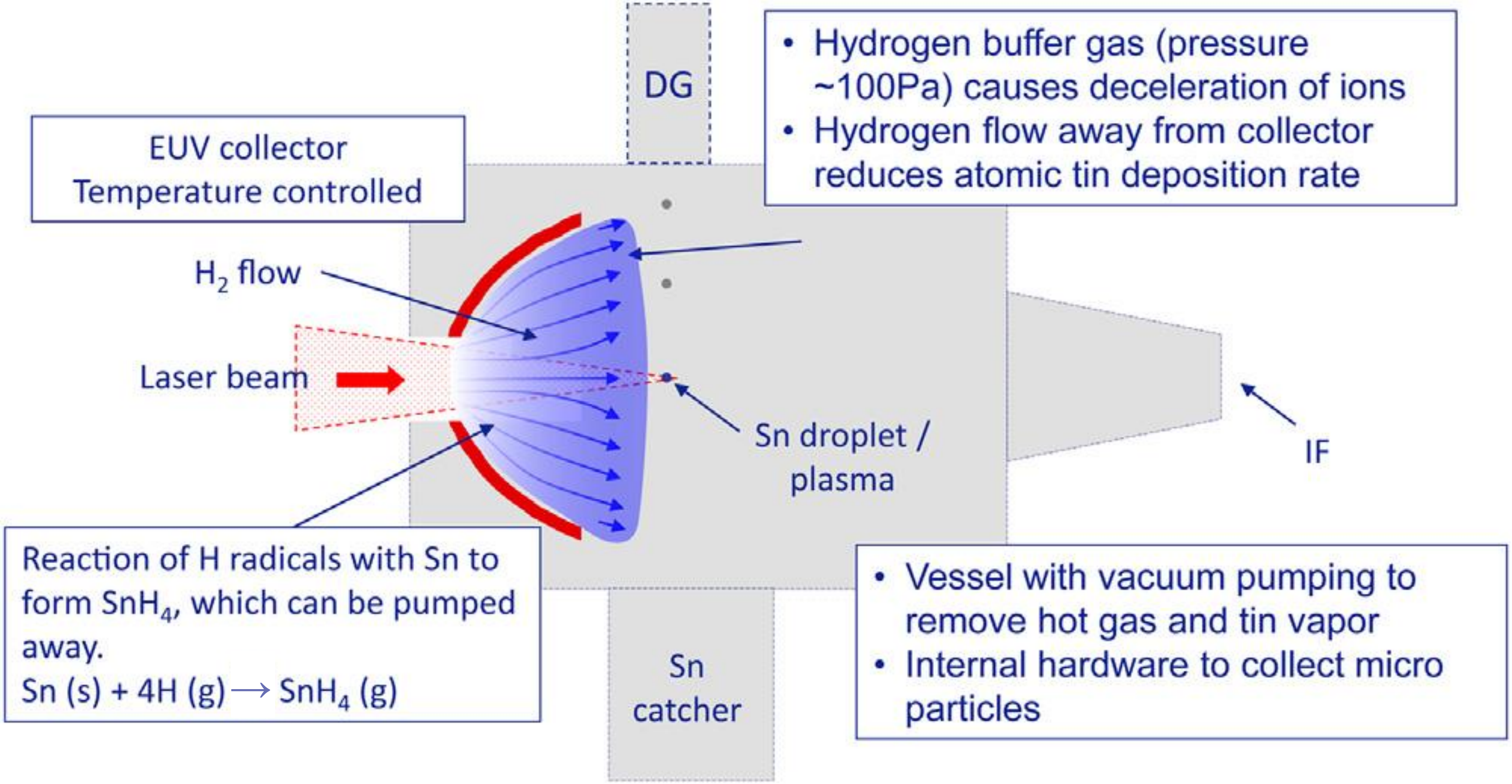
D.-K. Yang, etc., *Chip*, **1**, 100019 (2022)

Two laser pulses are used to heat the plasma



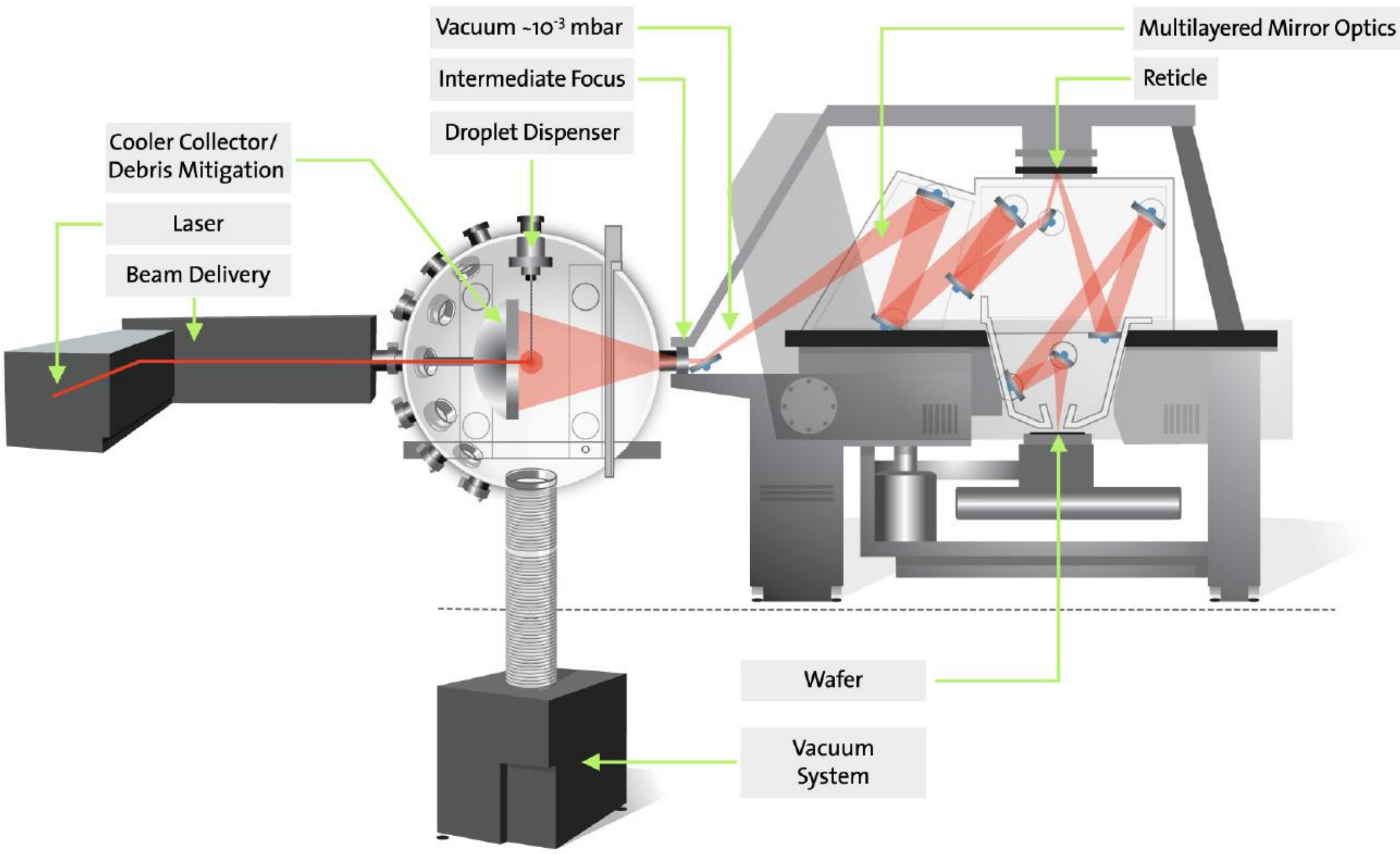
I. Fomenkov, etc., *Synch. Rad. News*, **32**, 3 (2019)

Hydrogen buffer gas with a pressure of ~100 Pa is used to protect the collector mirror



D.-K. Yang, etc., *Chip*, **1**, 100019 (2022)

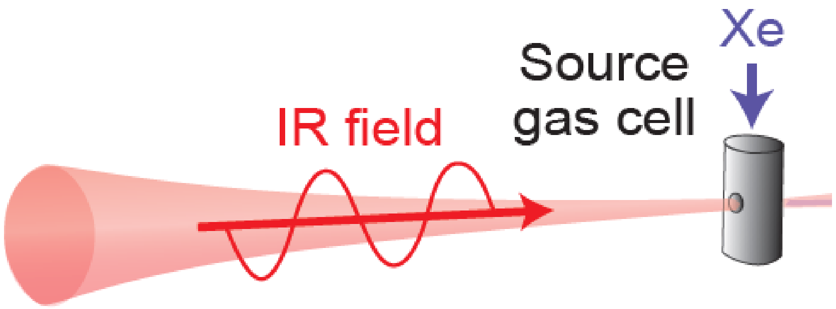
Laser-produced plasma (LPP) is used in the EUV lithography

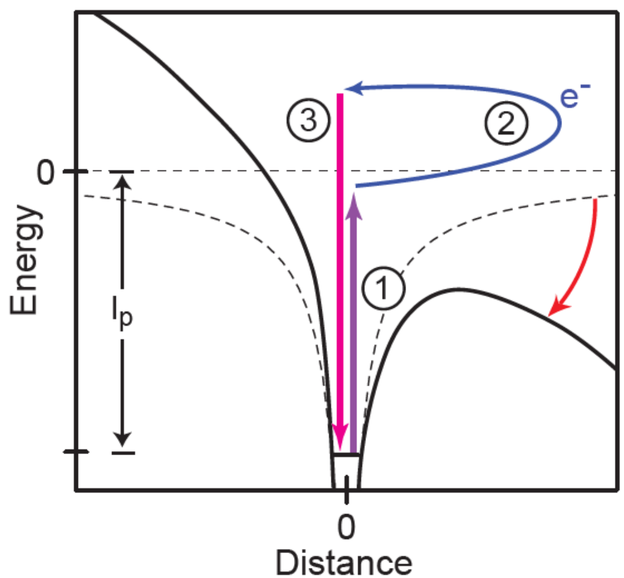


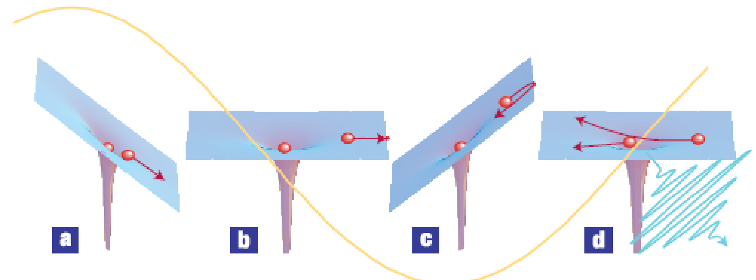
R. S. Abhari, etc., J. Micro/Nanolithography, MEMS, and MOEMS, 11, 021114 (2012)

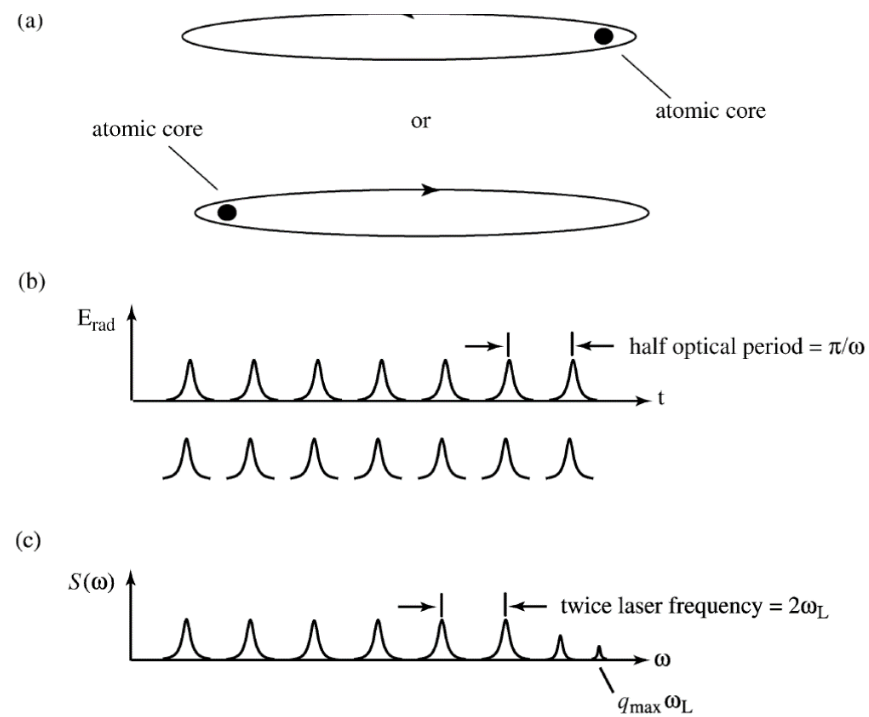
High harmonic generation from high-power laser

- **For I < 10^{18} w/cm^2**



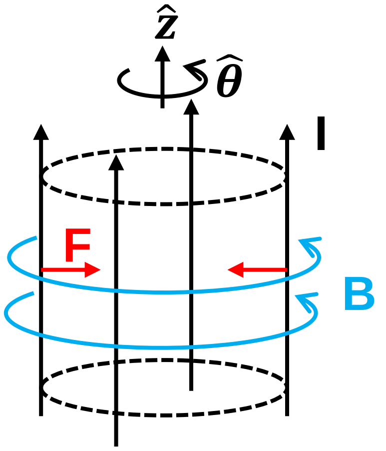






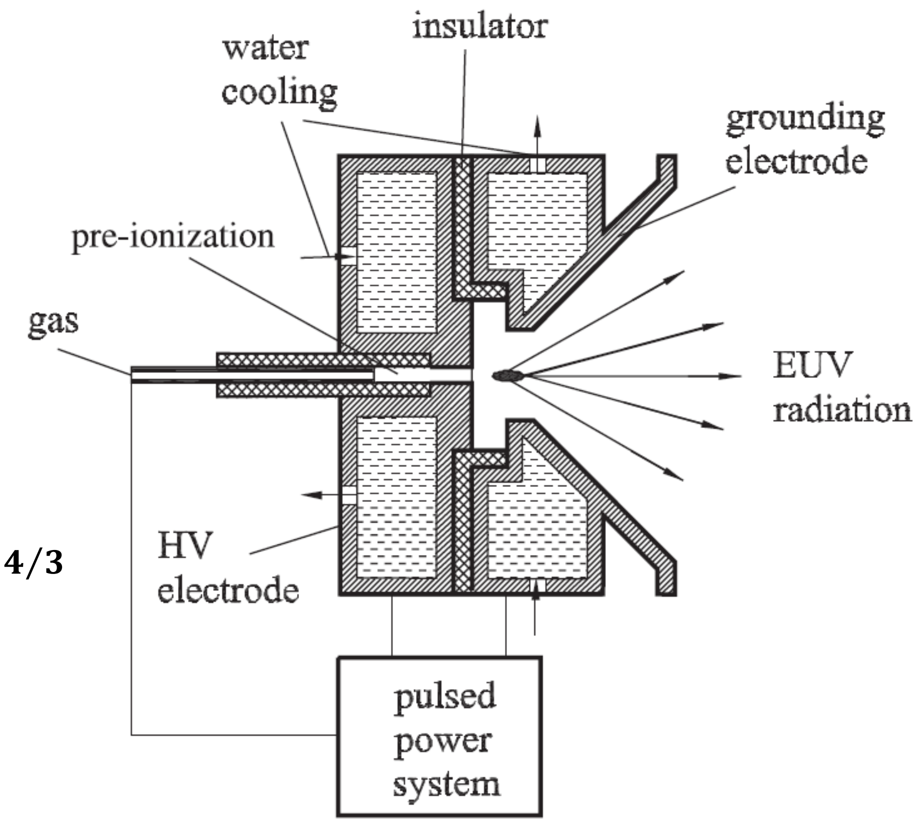
- M. Krüger, etc., Appl. Sci. 9, 378 (2019)
- Nonlinear Optics 3rd edition , by Robert W. Boyd
- P. B. Corkum and F. Krausz, Nature Phys., 3, 381 (2007)

EUV light can be generated using discharged-produced plasma



- **Adiabatic compression:**

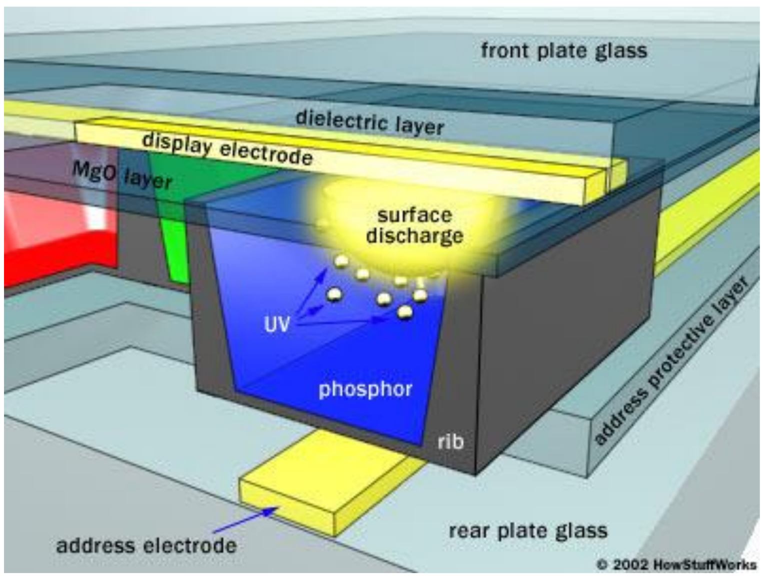
$$TV^{\gamma-1} = \text{const} \quad T_f = T_o\left(\frac{r_o}{r_f}\right)^{4/3}$$



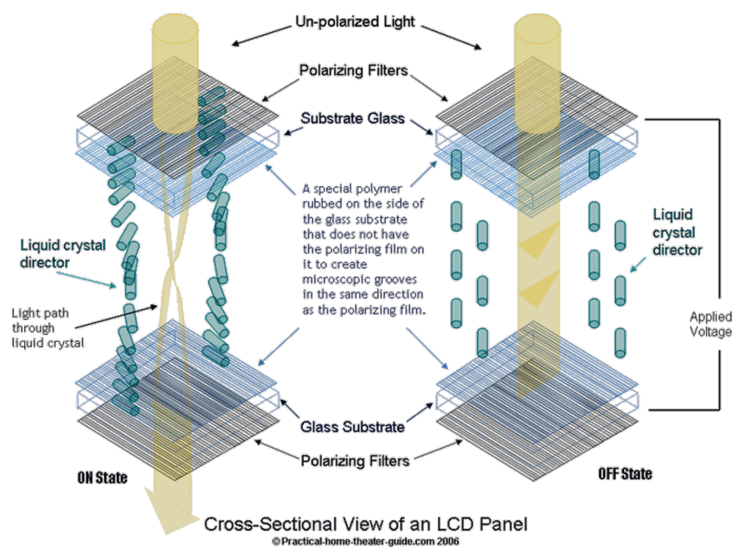
- JPDAP_37_p3254_2004_EUV sources using Xe and Sn discharge plasmas

Light source and display systems

Plasma display panel (PDP)



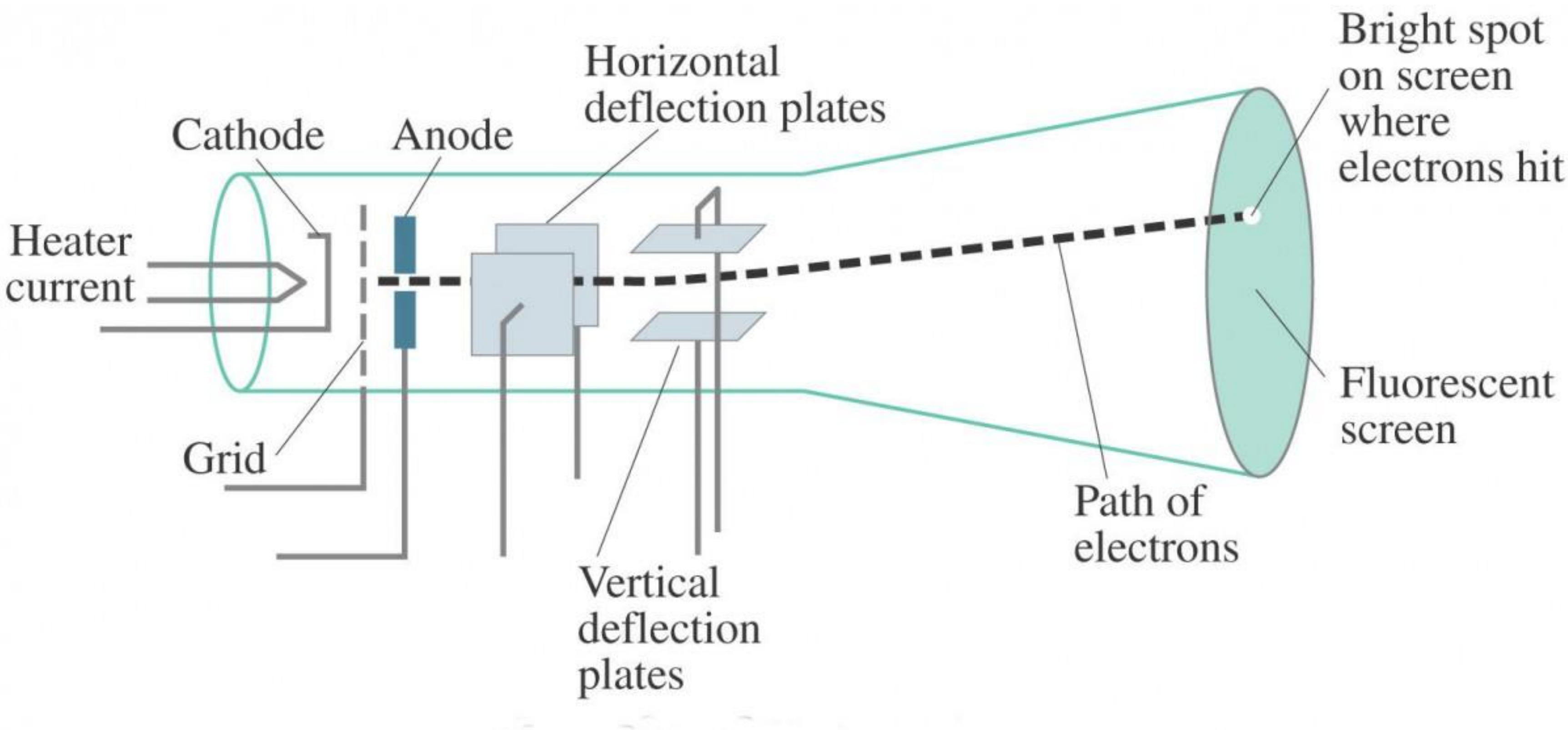
Liquid crystal display (LCD)



Outlines

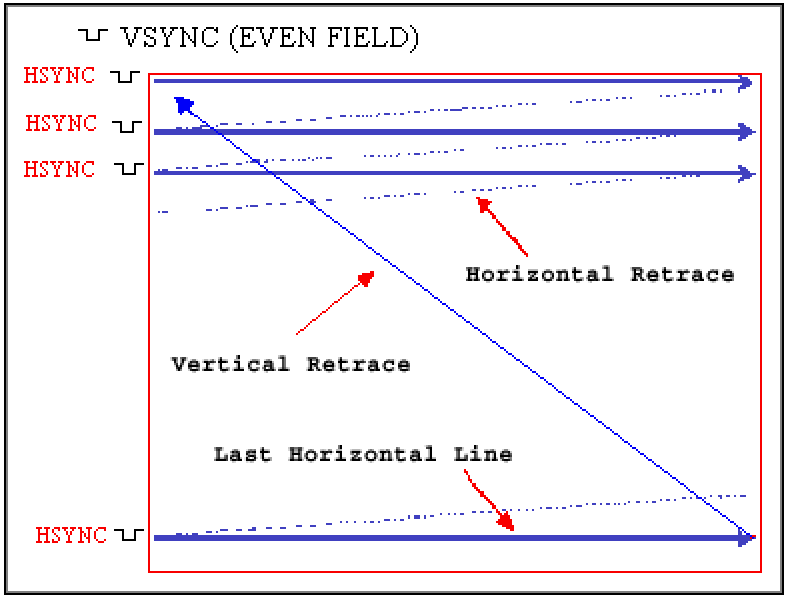
- Cathode Ray Tube
- Color space (CIE 1931 color spaces)
- History of plasma display panel (PDP)
- Design of PDP
- Liquid crystal display (LCD)
- LCD vs PDP

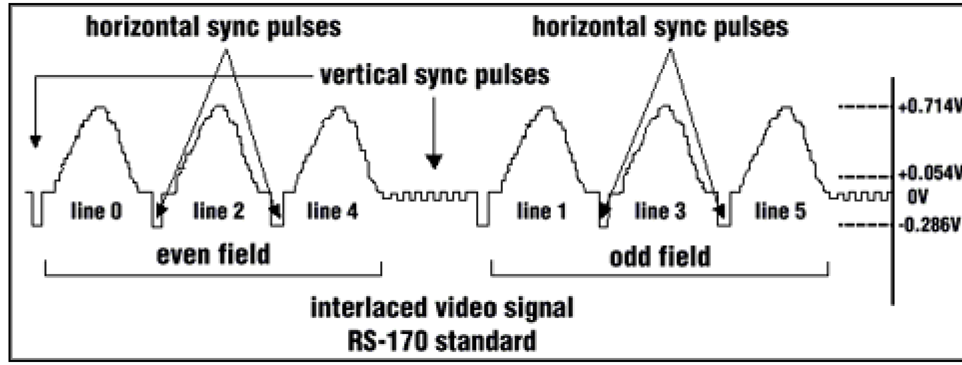
Cathode Ray Tube uses electron beams to light the fluorescent screen

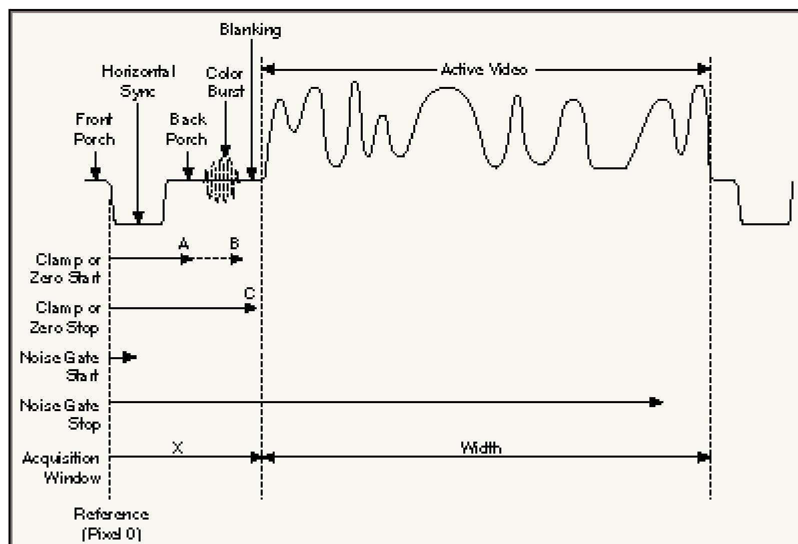


http://www.sciencefacts.net/cathode-ray-tube-crt.html

The image is shown by scanning through the whole screen with the single electron beam

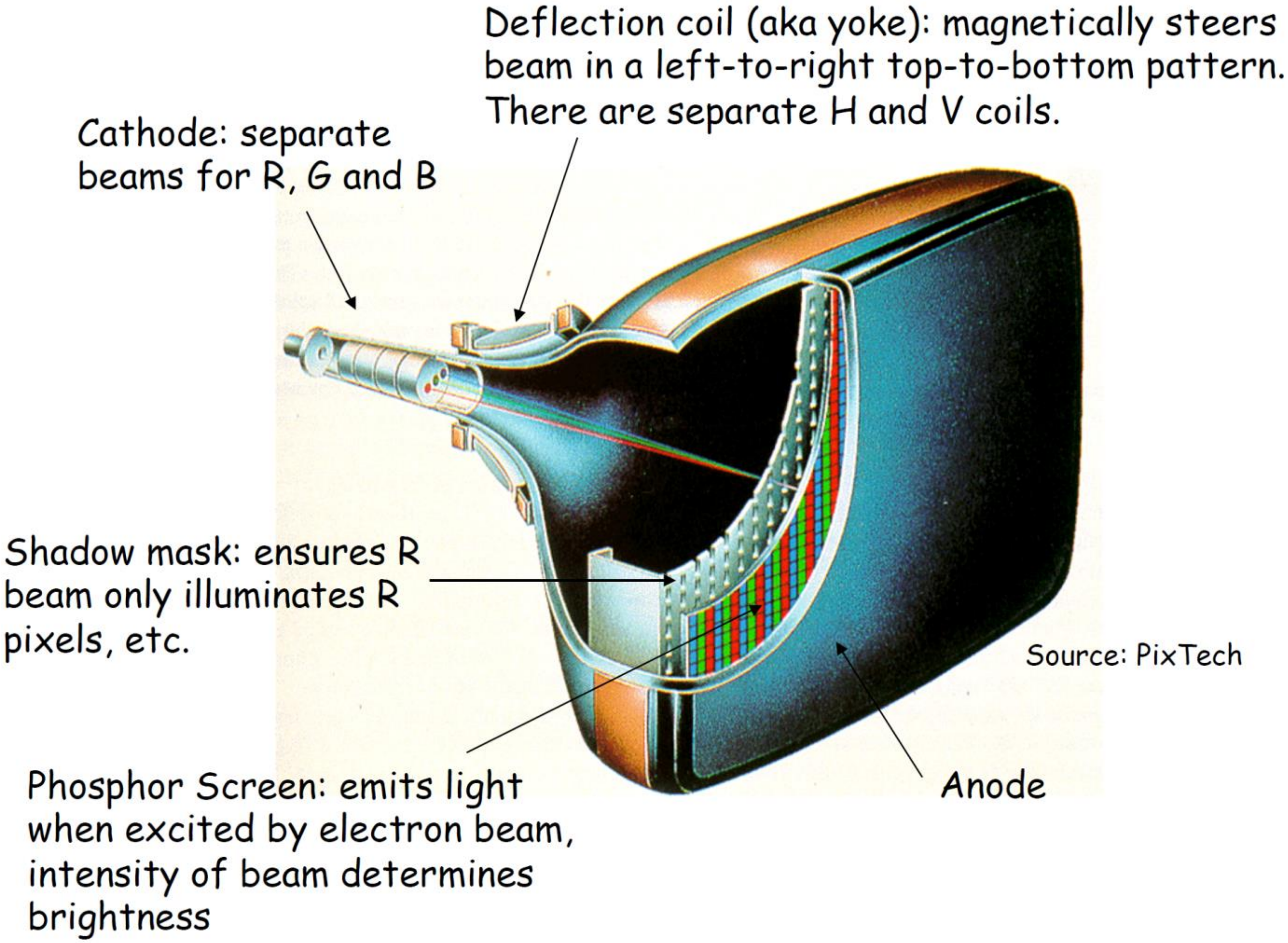






http://www.ni.com/white-paper/3020/en/#toc2

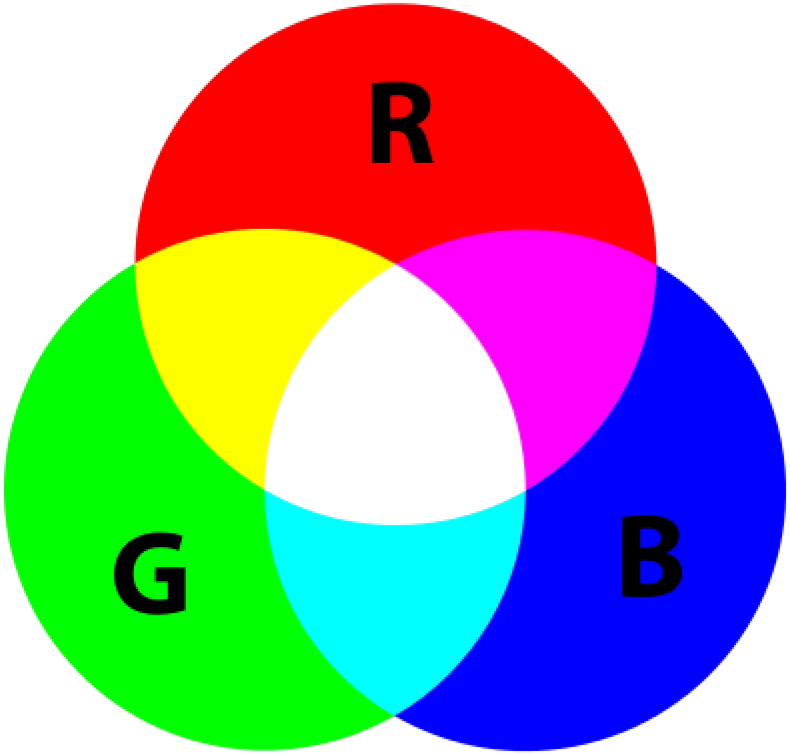
Color image is formed by using three electron beams scanning through three different color channels



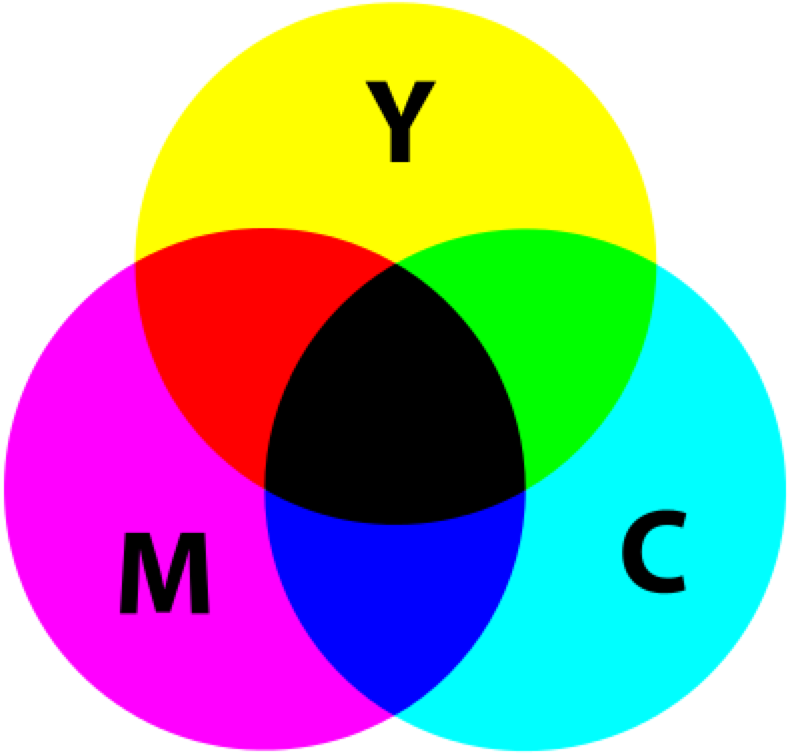
http://web.mit.edu/6.111/www/f2008/handouts/L12.pdf

Color can be created using three primary colors

Additive primaries

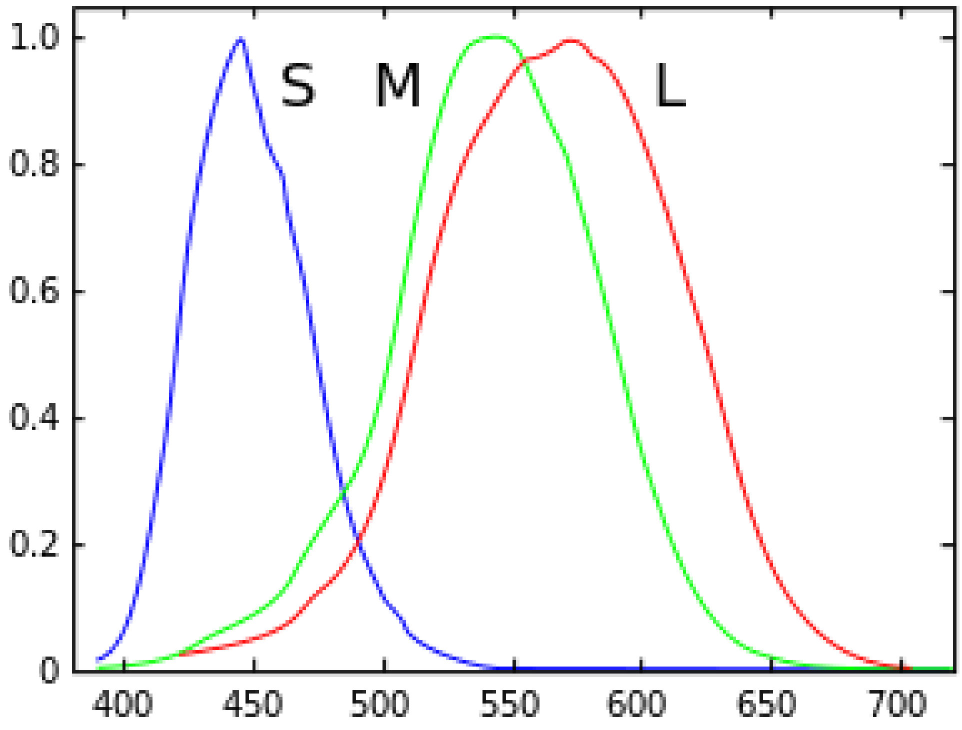


Subtractive primaries

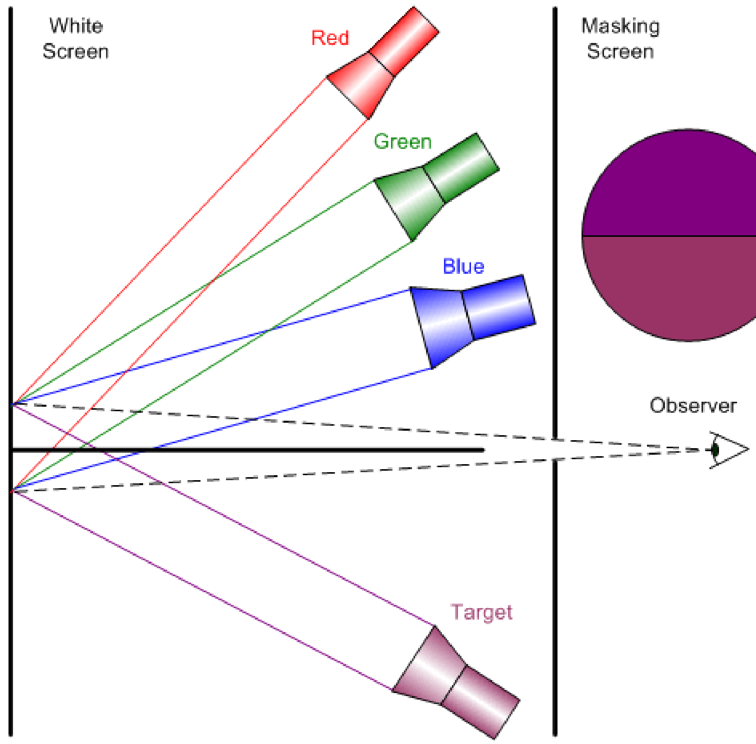


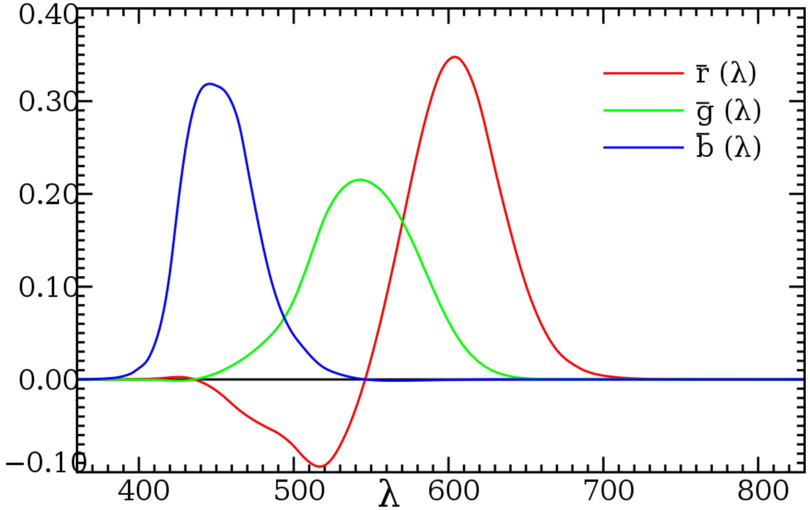
https://en.wikipedia.org/wiki/Primary_color

Human retina has three kinds of “cones” that have different spectral response



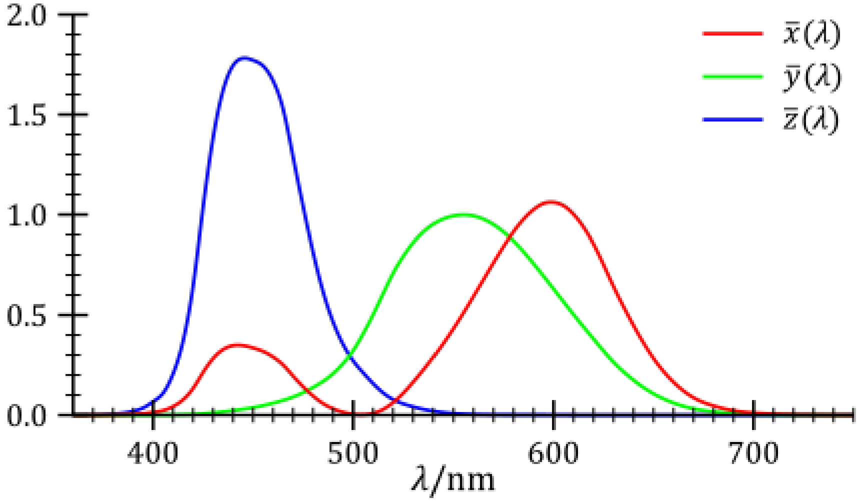
Spectral response of retina “cones” are tested using light sources with single wavelength

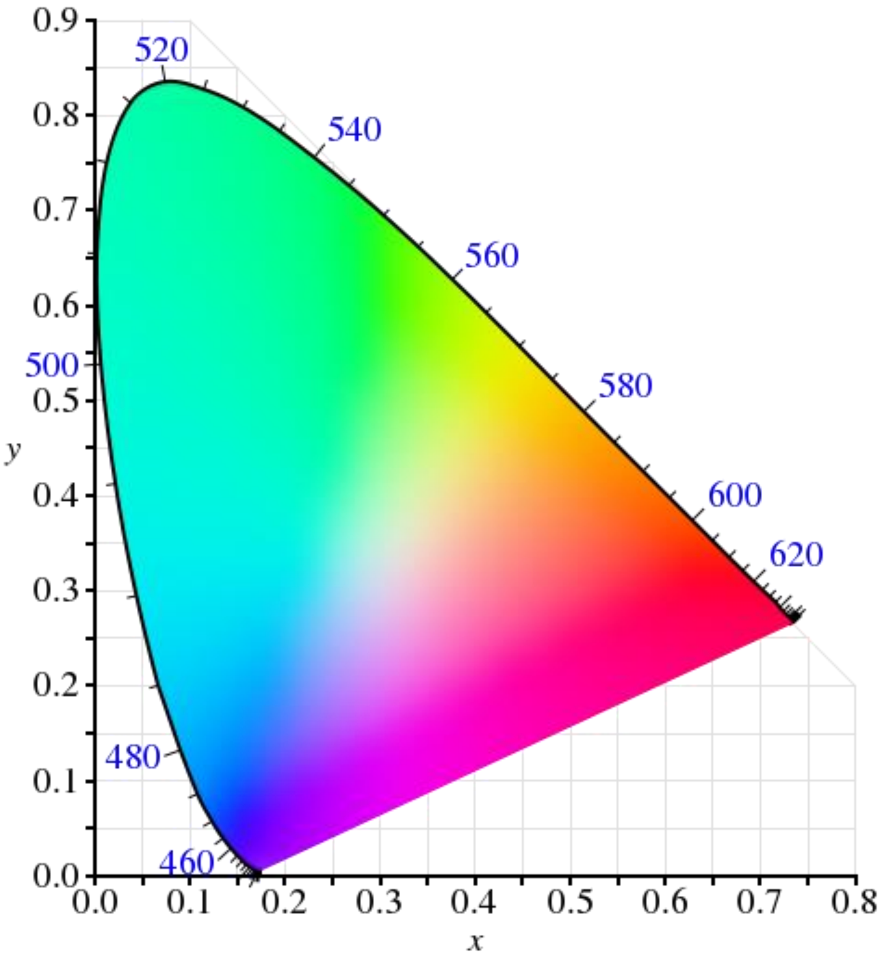




http://betterphotographytutorials.com/2011/08/01/light-and-colors-%E2%80%93-part-3/
https://en.wikipedia.org/wiki/CIE_1931_color_space

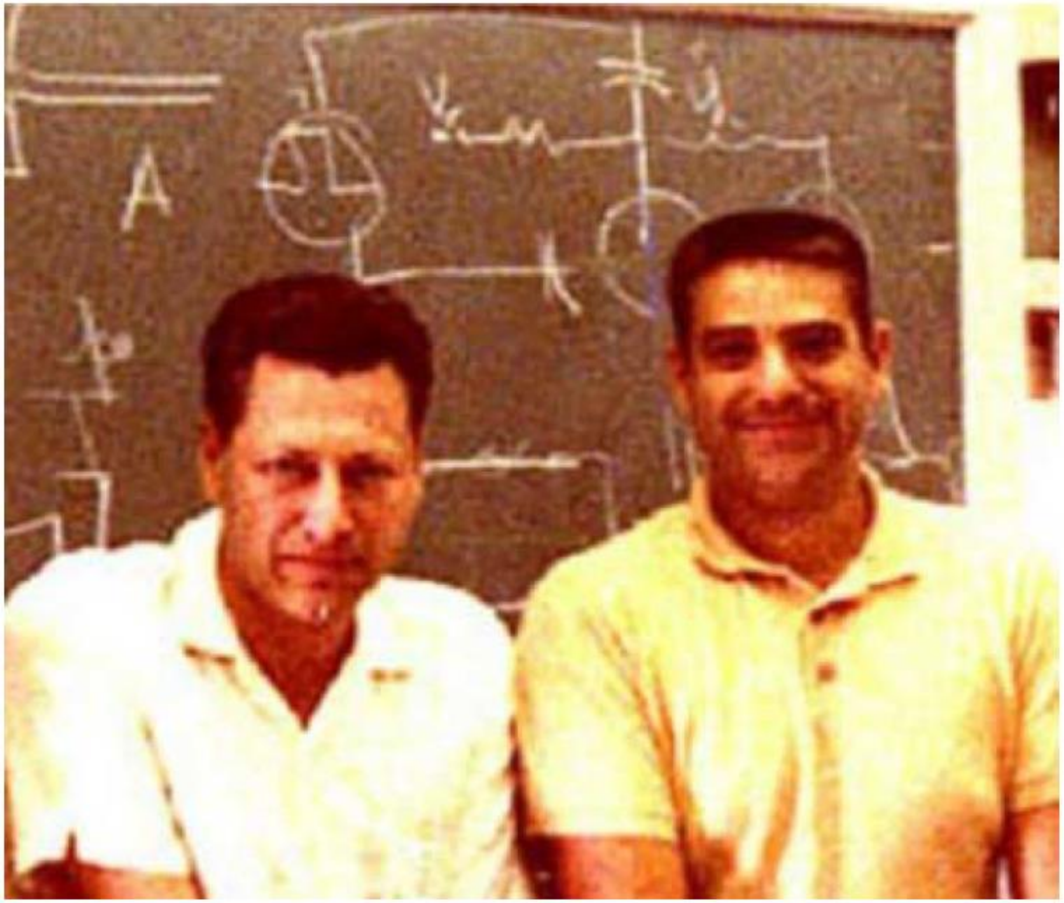
The CIE 1931 color space chromaticity diagram is the standard color space





https://en.wikipedia.org/wiki/CIE_1931_color_space

Plasma display panel was invented at the University of Illinois in 1967



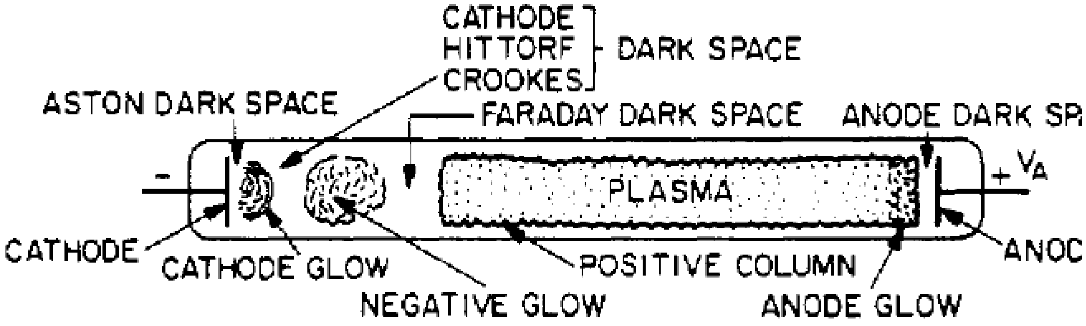
Prof. H. Gene Slottow **Prof. Donald L. Bitzer**

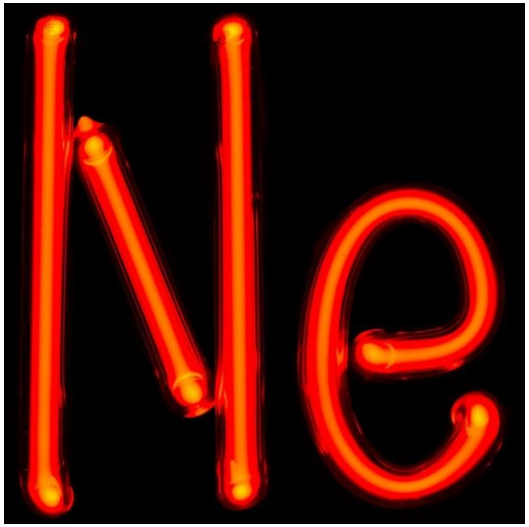
L. F. Weber, IEEE Trans. Plas. Scien., *34*, 268, 2006

PDP was invented due to a need for Programmed Logic for Automatic Teaching Operations (PLATO) in 1960s

https://topwallpapers.pw/computer/keyboards-computers-history-teletype-typewriters-desktop-hd-wallpaper-1035981/
https://en.wikipedia.org/wiki/Punched_tape
https://en.wikipedia.org/wiki/PLATO_(computer_system)

The positive column in a glow discharge is used to excite phosphors in color PDP

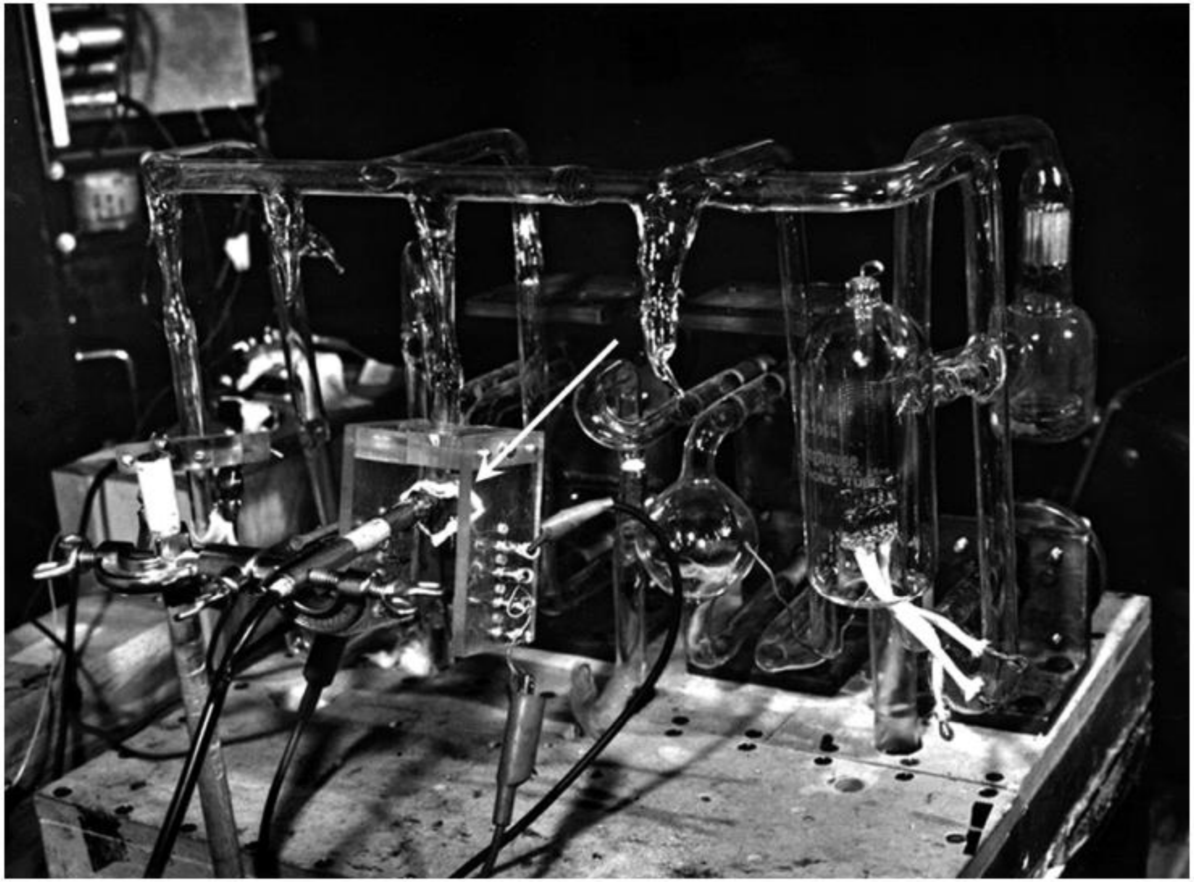




- **Majority of monochrome PDPs use the negative glow as the light source**
- **The positive column is used to excite phosphors in fluorescent lamps and in color PDPs**

Industrial plasma engineering, volume 1, by J. Reece Roth
https://en.wikipedia.org/wiki/Neon_lighting

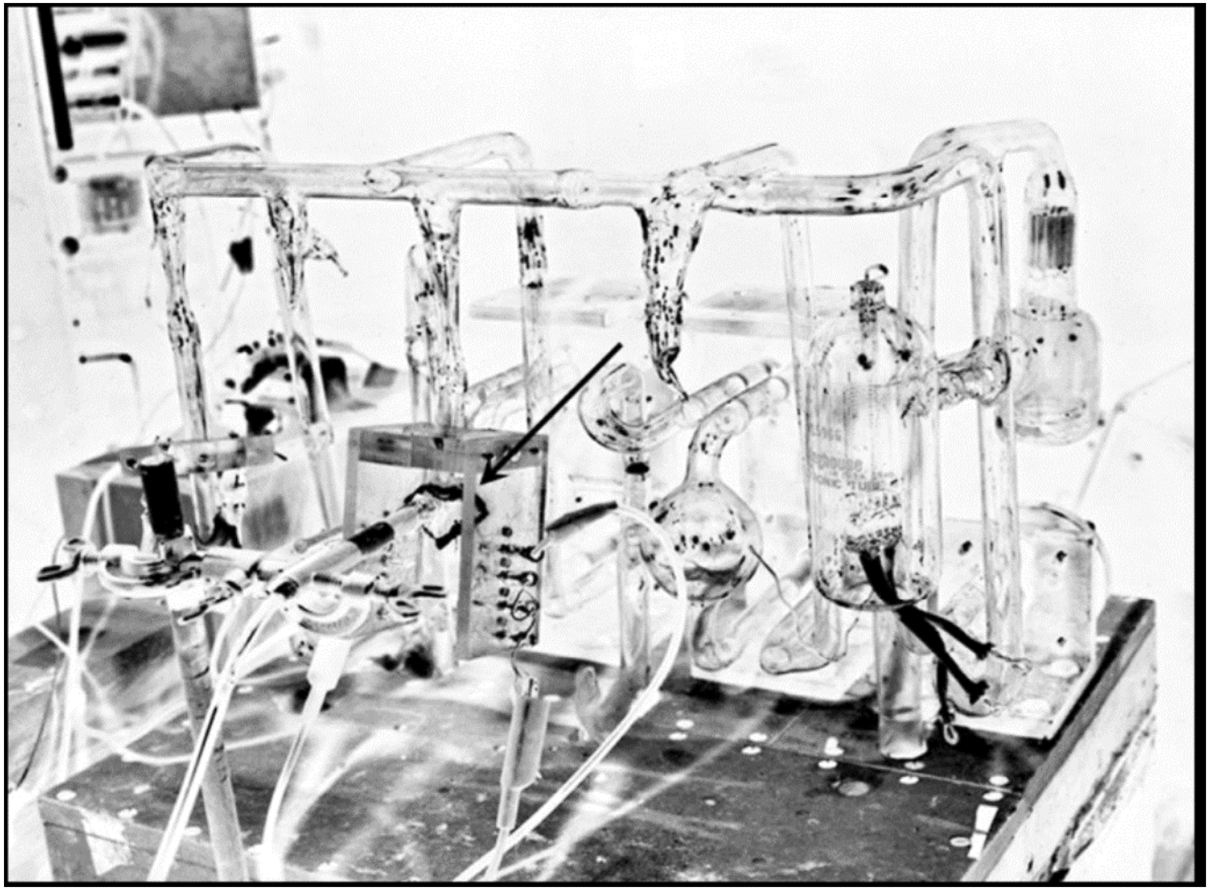
Early plasma panel (PD) attached to the glass vacuum system used for the first plasma displays at UI



- **It had the same alternating sustain voltage, neon, gas, and dielectric glass insulated electrodes that are used for plasma TVs today.**

L. F. Weber, IEEE Trans. Plas. Scien., *34*, 268, 2006

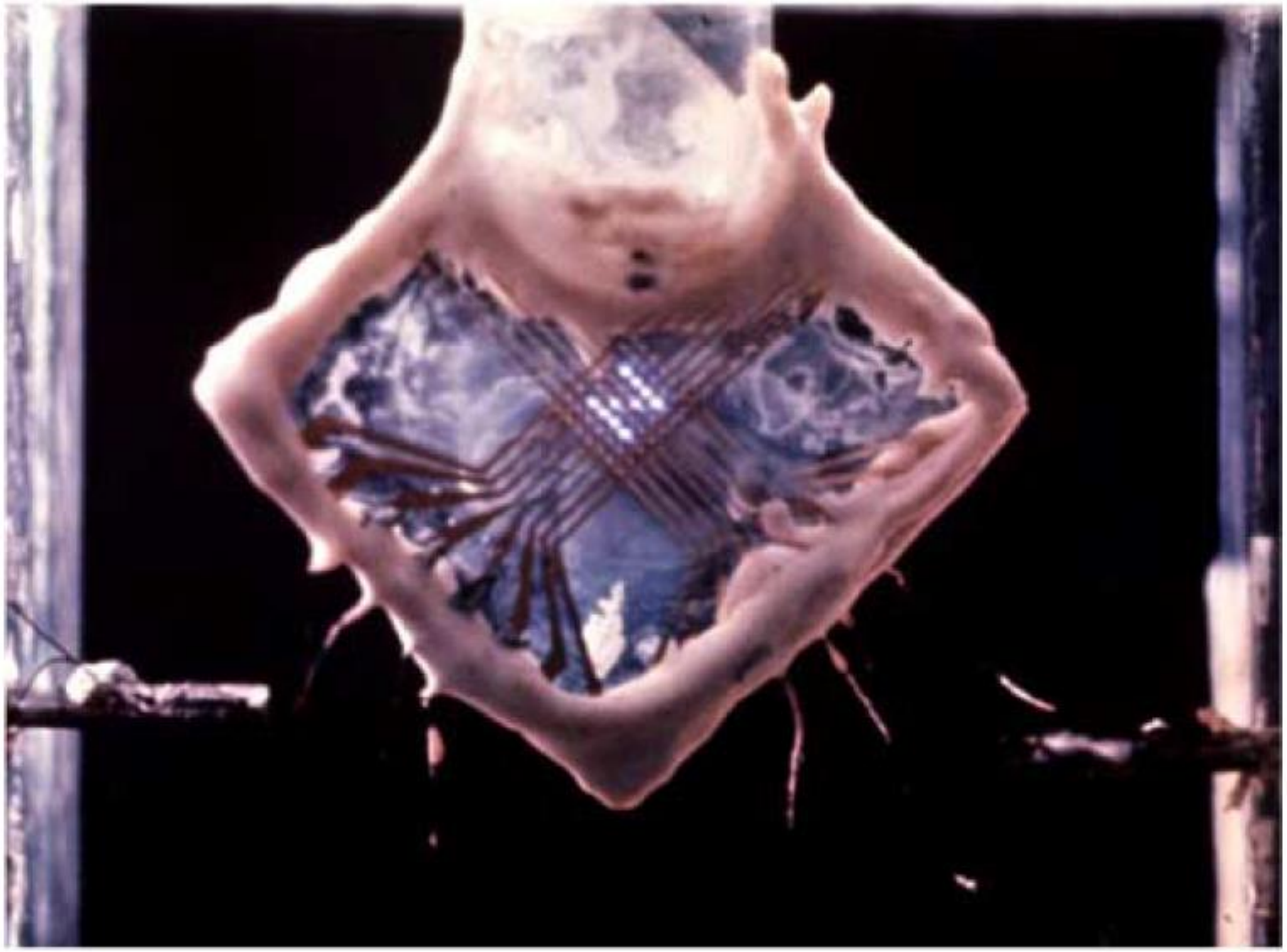
Early plasma panel (PD) attached to the glass vacuum system used for the first plasma displays at UI



- **It had the same alternating sustain voltage, neon, gas, and dielectric glass insulated electrodes that are used for plasma TVs today.**

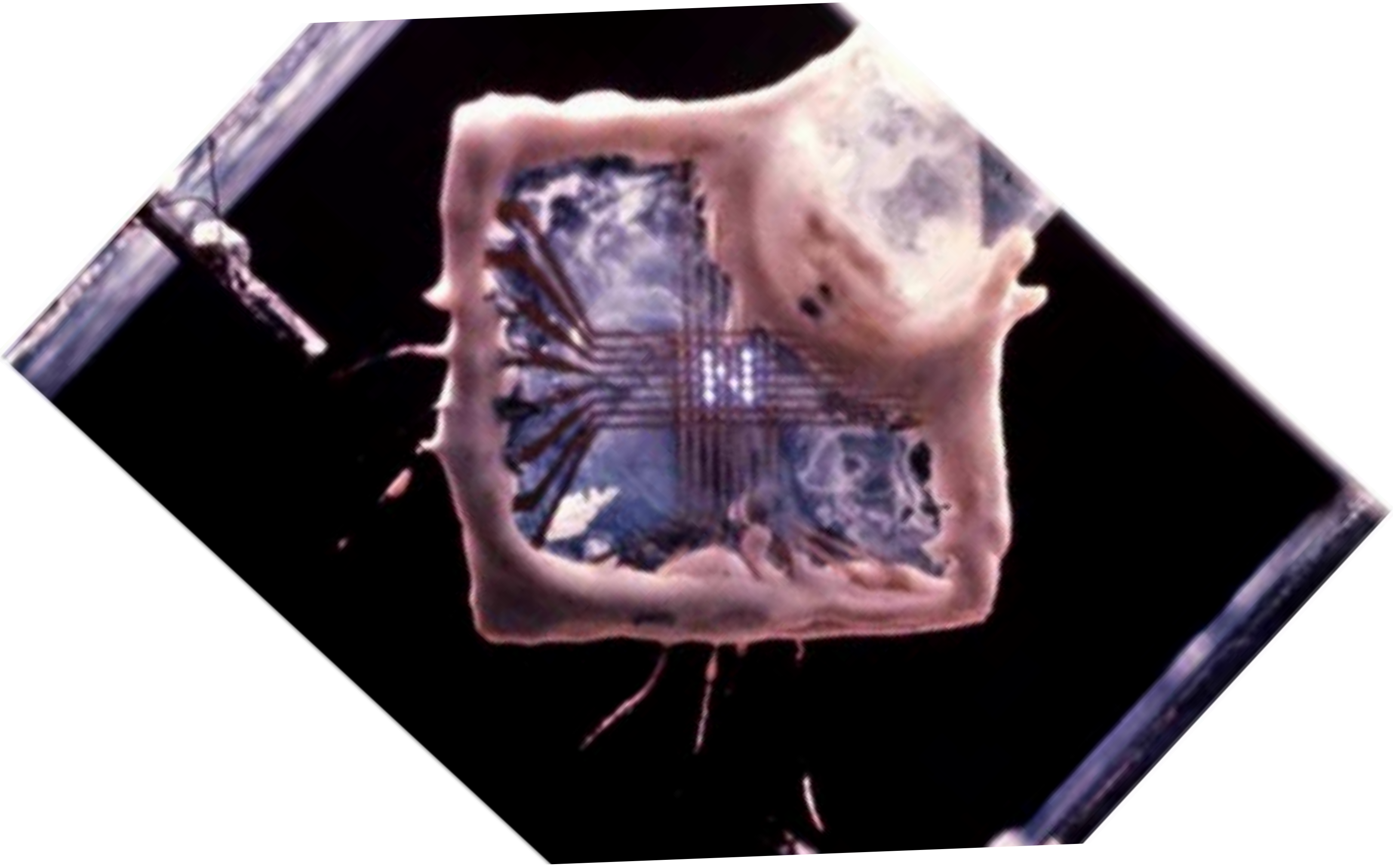
L. F. Weber, IEEE Trans. Plas. Scien., *34*, 268, 2006

Early 4x4 pixel panel has achieved matrix addressability for the first time



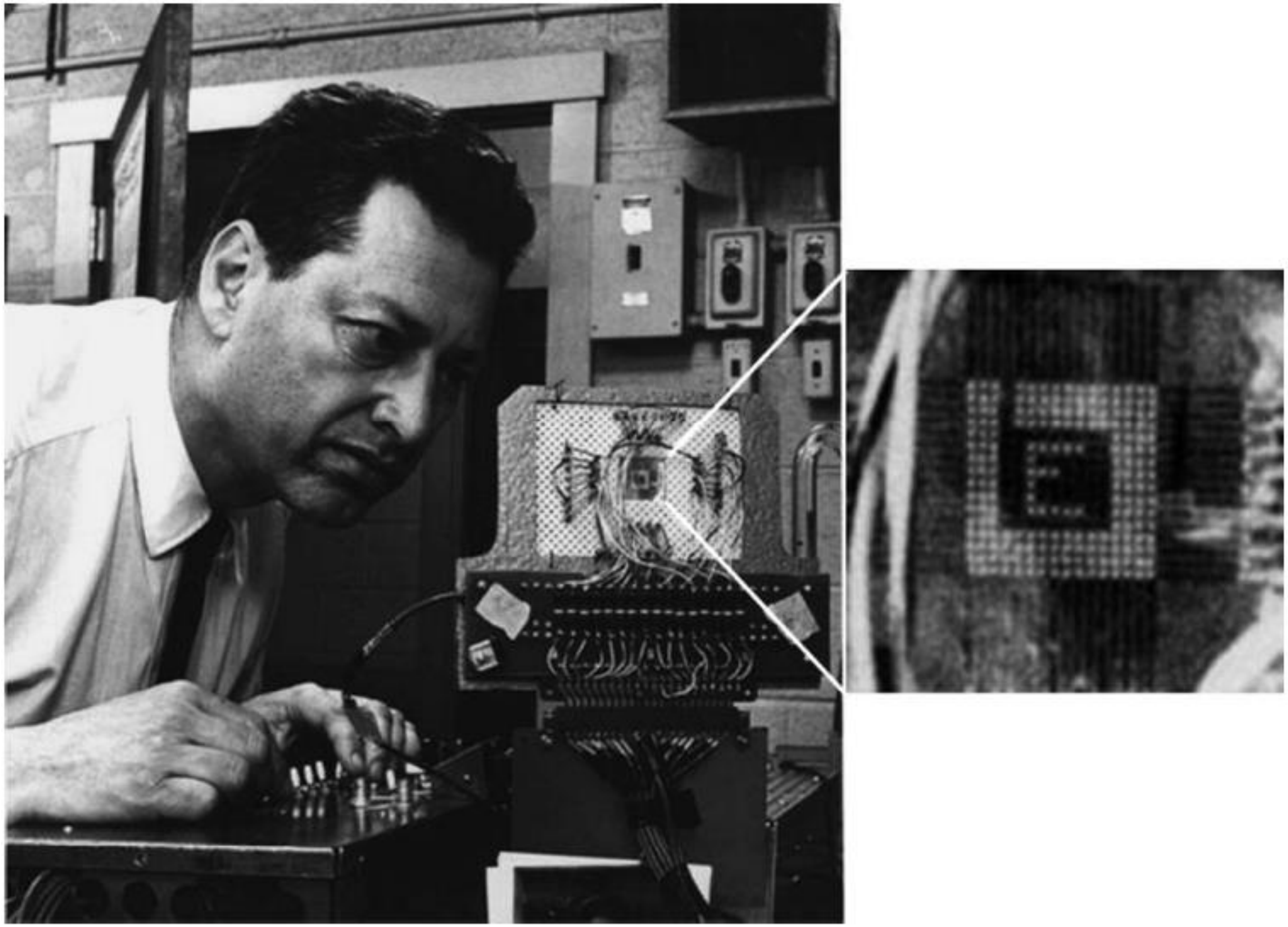
L. F. Weber, IEEE Trans. Plas. Scien., *34*, 268, 2006

Early 4x4 pixel panel has achieved matrix addressability for the first time



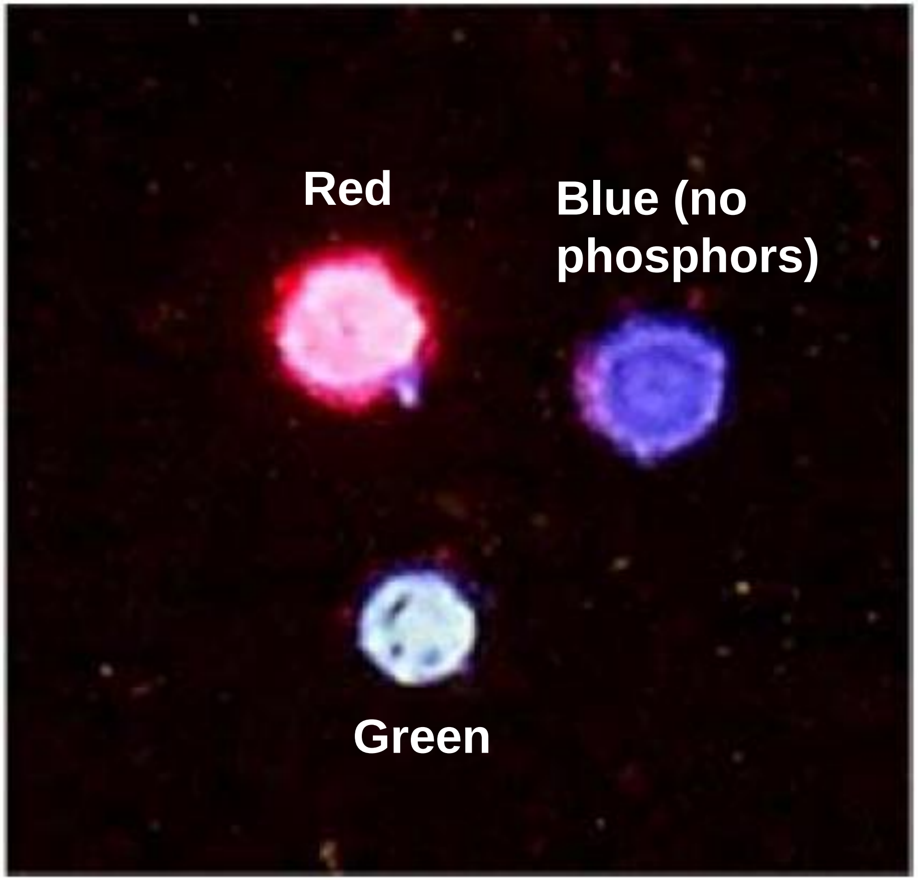
L. F. Weber, IEEE Trans. Plas. Scien., *34*, 268, 2006

A 16x16 pixel PD, developed in 1967, needed to be addressed manually



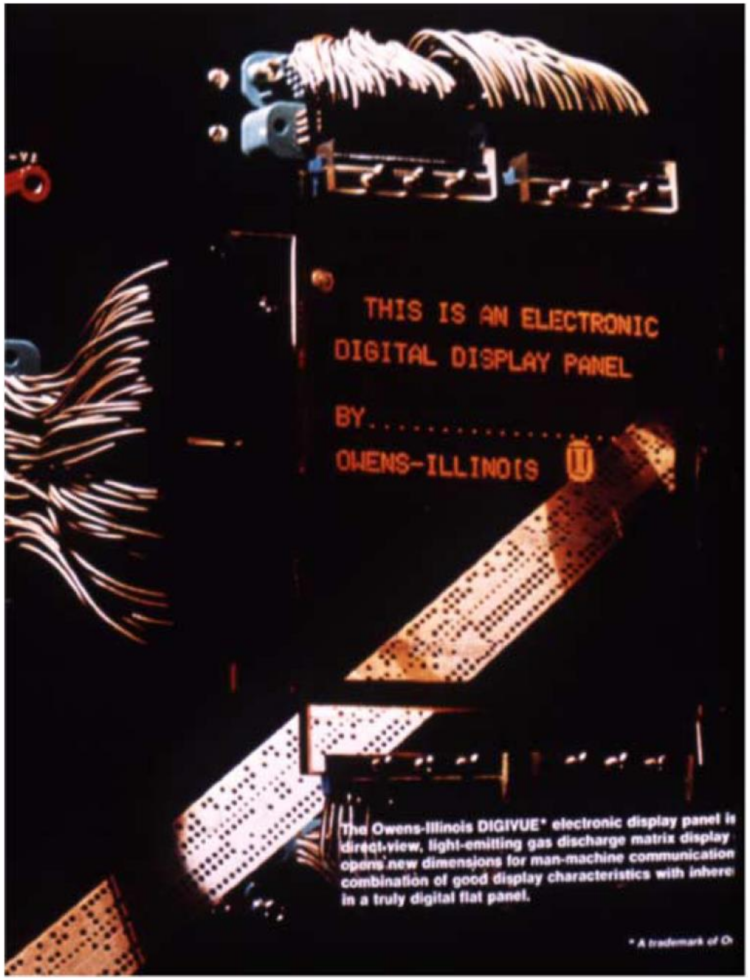
L. F. Weber, IEEE Trans. Plas. Scien., *34*, 268, 2006

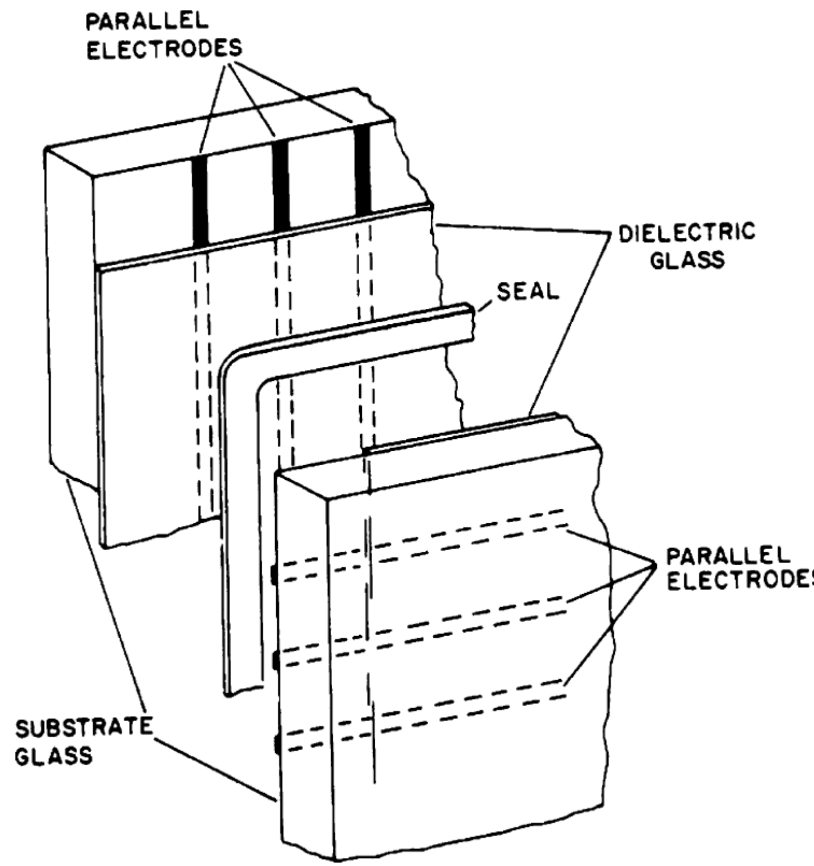
First color PD was three cell prototype with red and green color phosphors excited by a xenon gas discharge



L. F. Weber, IEEE Trans. Plas. Scien., *34*, 268, 2006

Open-cell structure developed in 1968



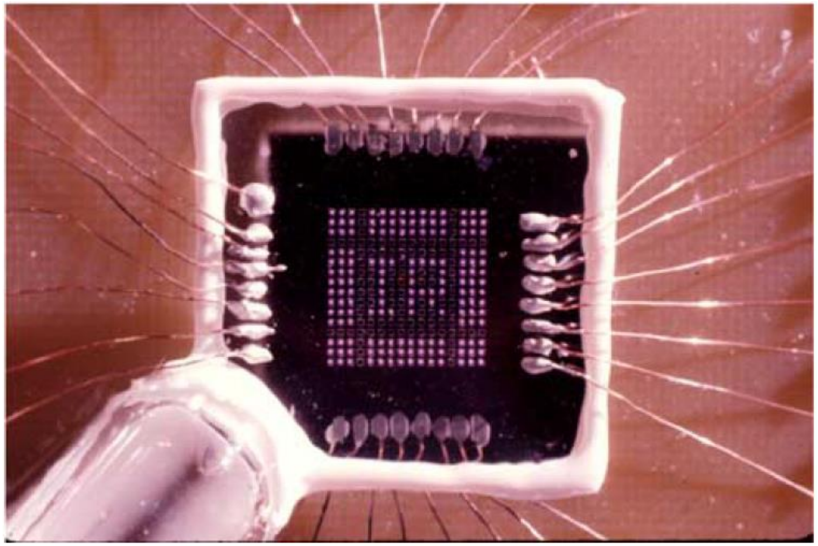


- **It could be baked under vacuum at 350 ºC to drive out contaminants.**

L. F. Weber, IEEE Trans. Plas. Scien., *34*, 268, 2006

More progress

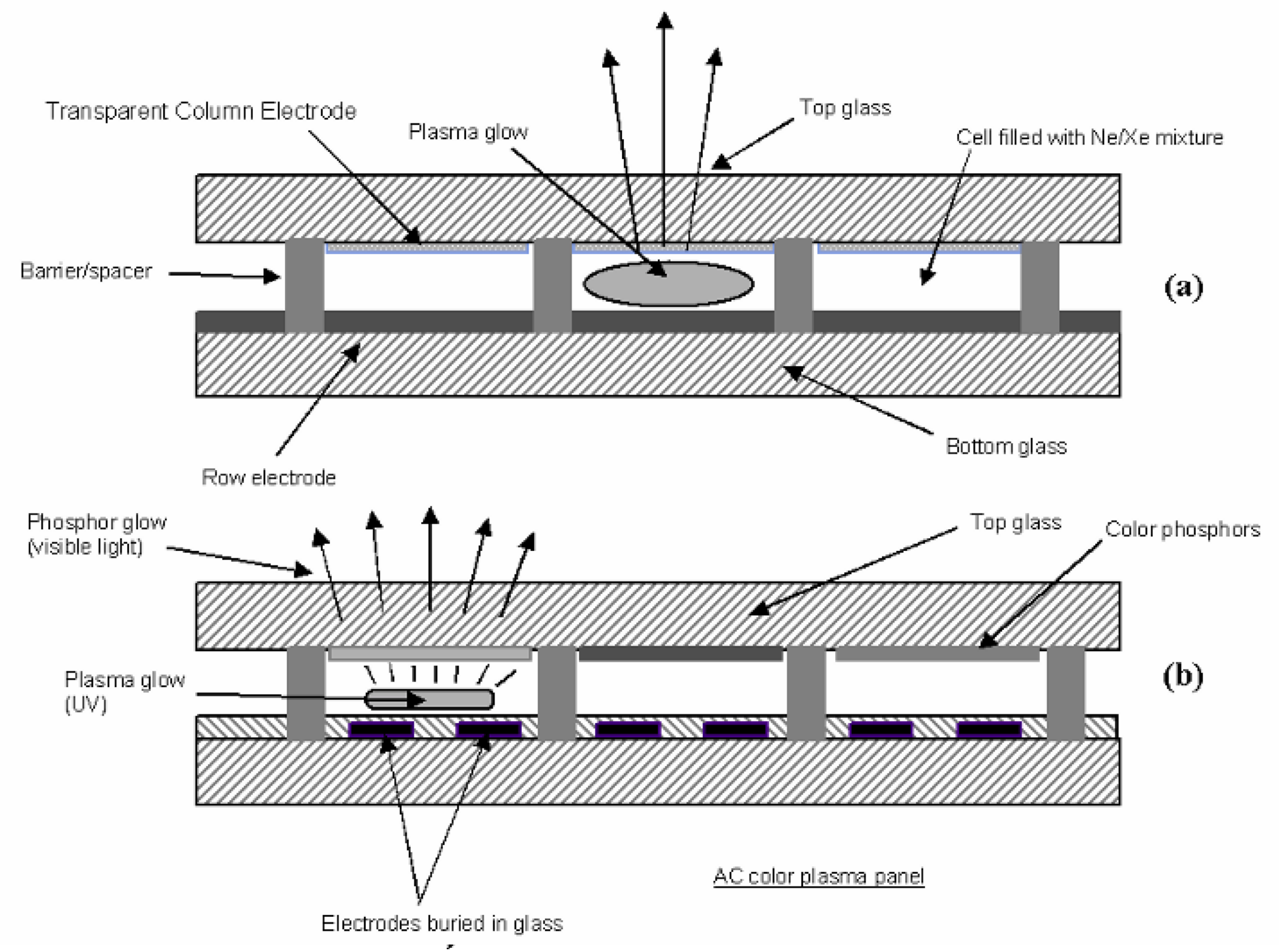
1968, University of Illinois
16x16 pixels



1971, Owens-Illinois
512x512 pixels

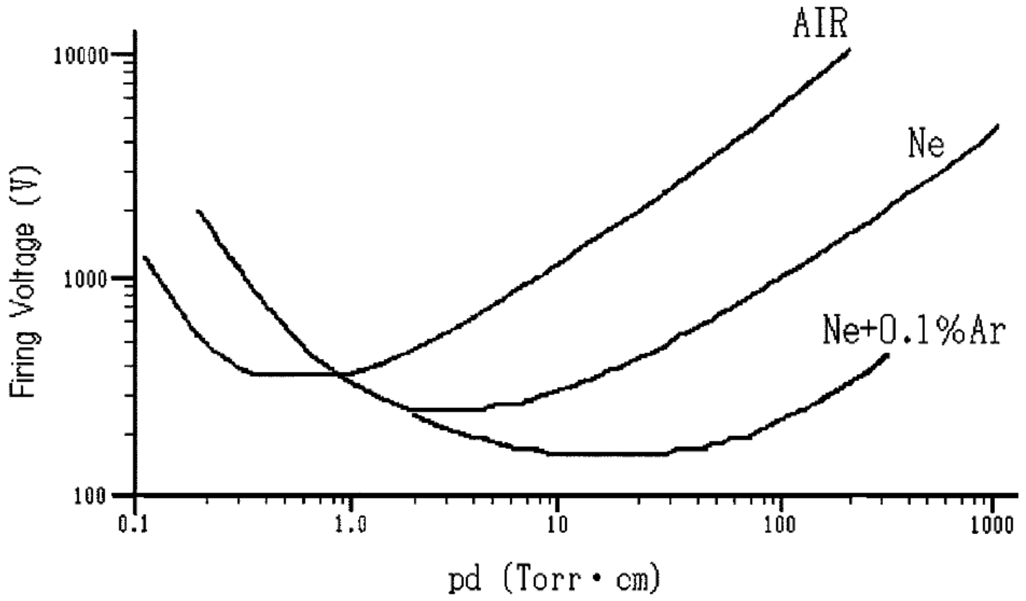
L. F. Weber, IEEE Trans. Plas. Scien., *34*, 268, 2006

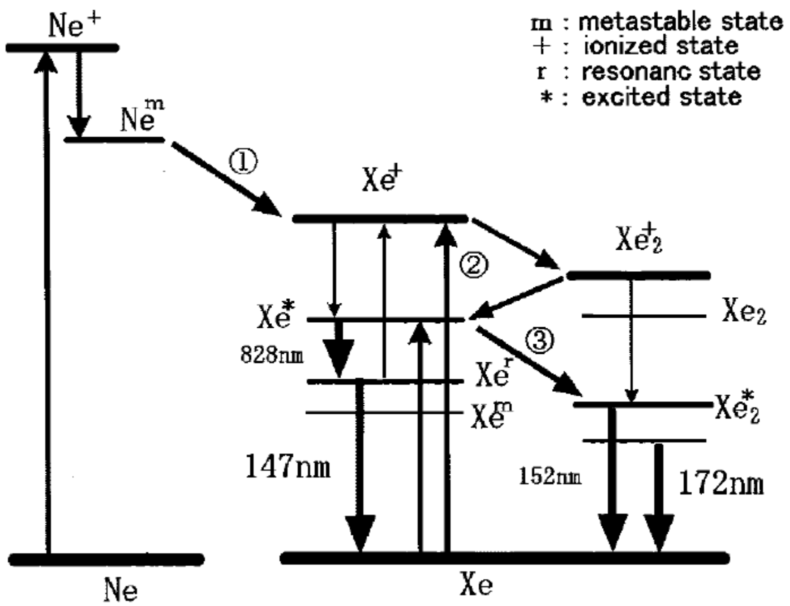
Color PDPs had short display lifetime due to the degradation of color phosphors caused by ion sputtering



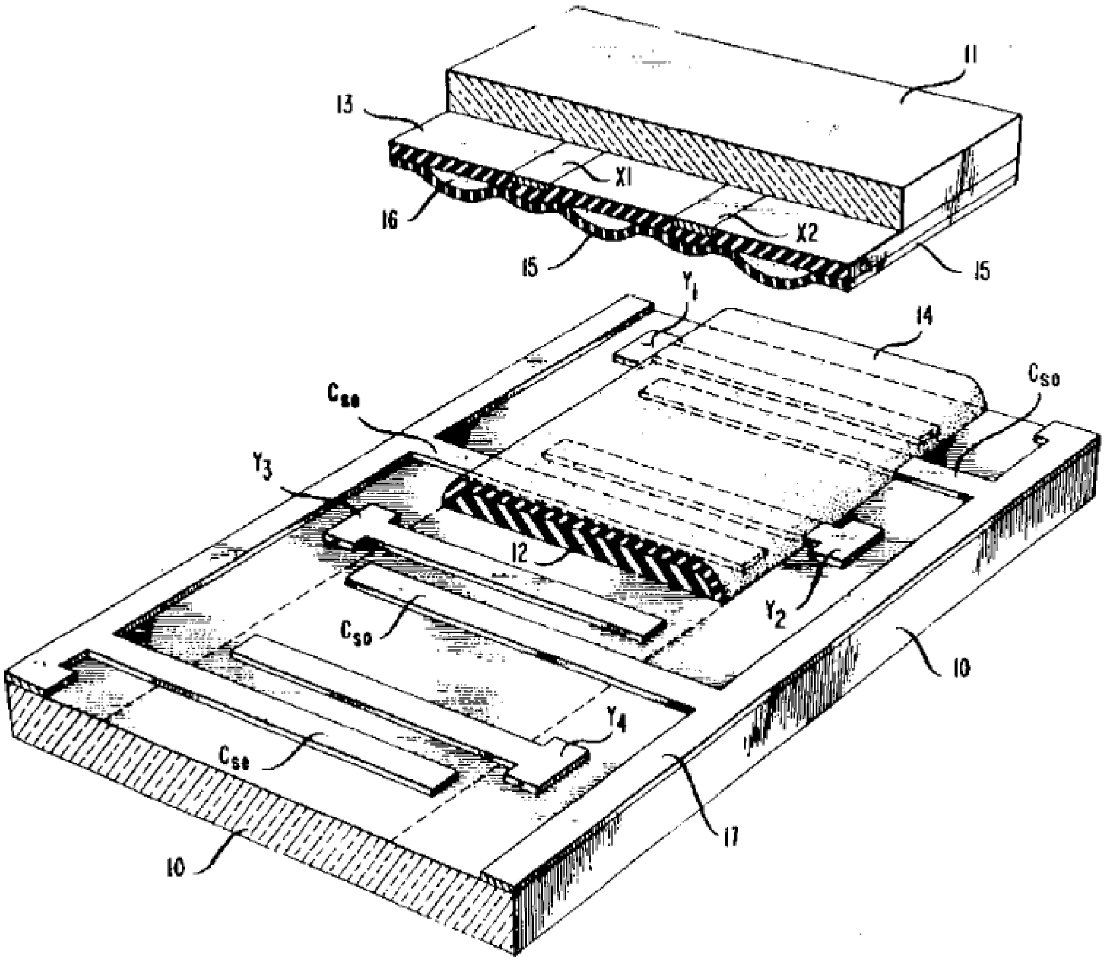
http://what-when-how.com/display-interfaces/display-technologies-and-applications-display-interfaces-part-3/

A lower breakdown voltages can be obtained with very small amounts of added gas



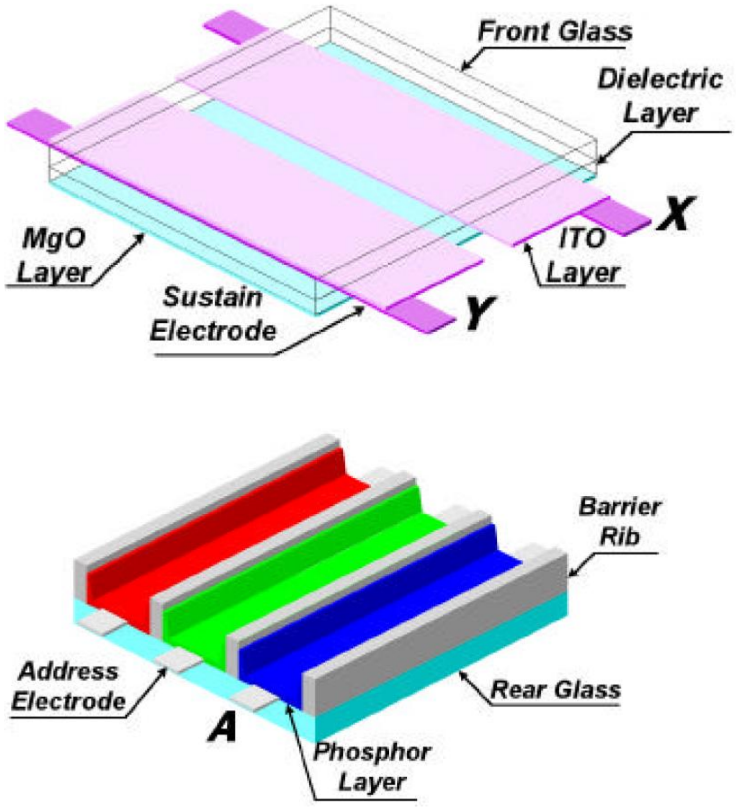


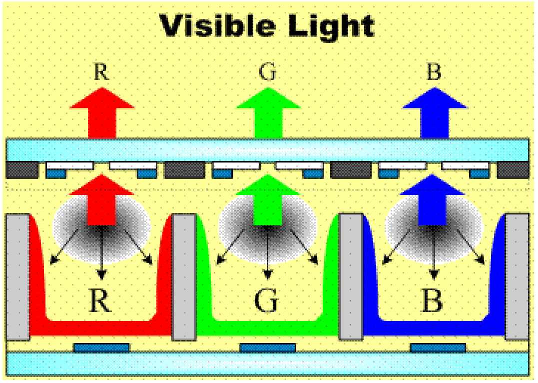
AT&T three-electrode patent



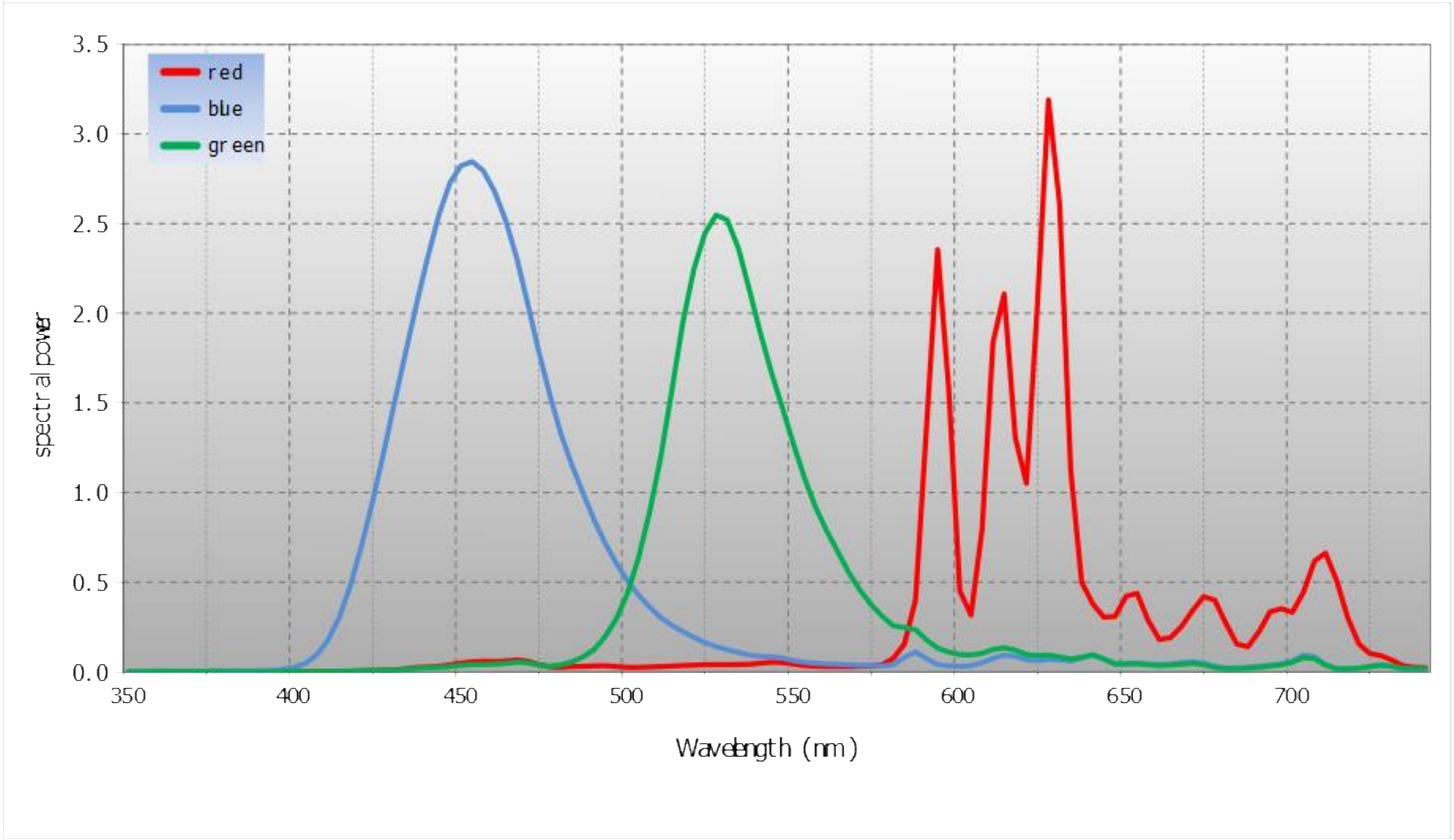
L. F. Weber, IEEE Trans. Plas. Scien., *34*, 268, 2006

Reflective phosphor geometry is used in most of today's plasma TVs

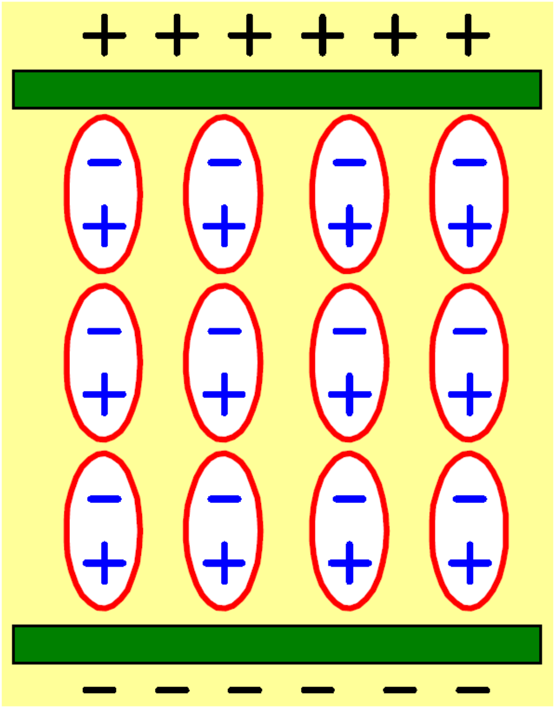


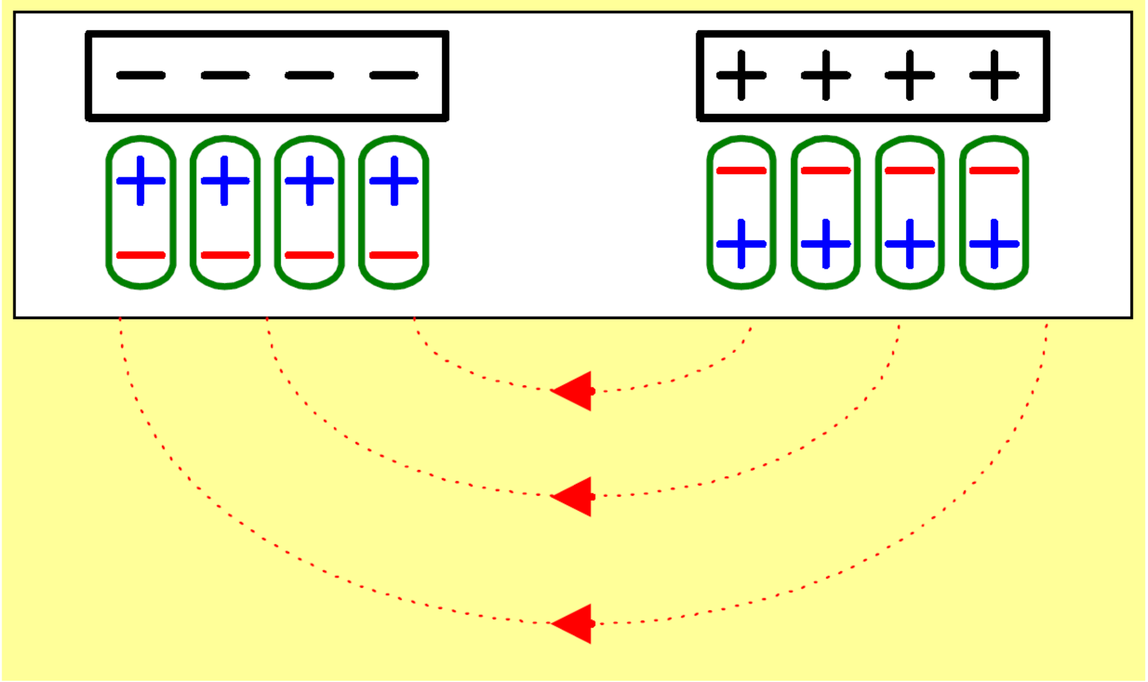


Spectrum of the different phosphors

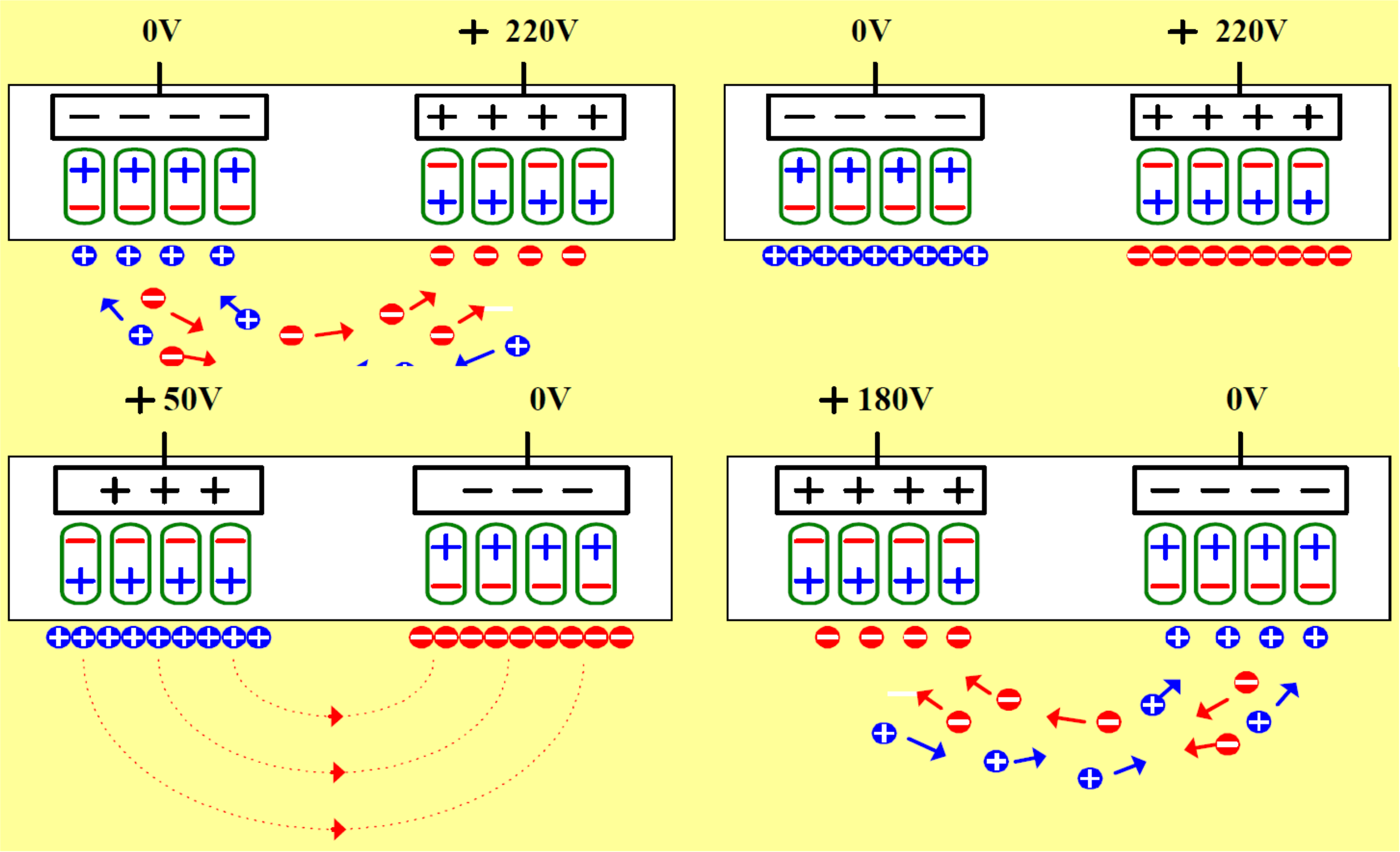


The foundation of AC discharge





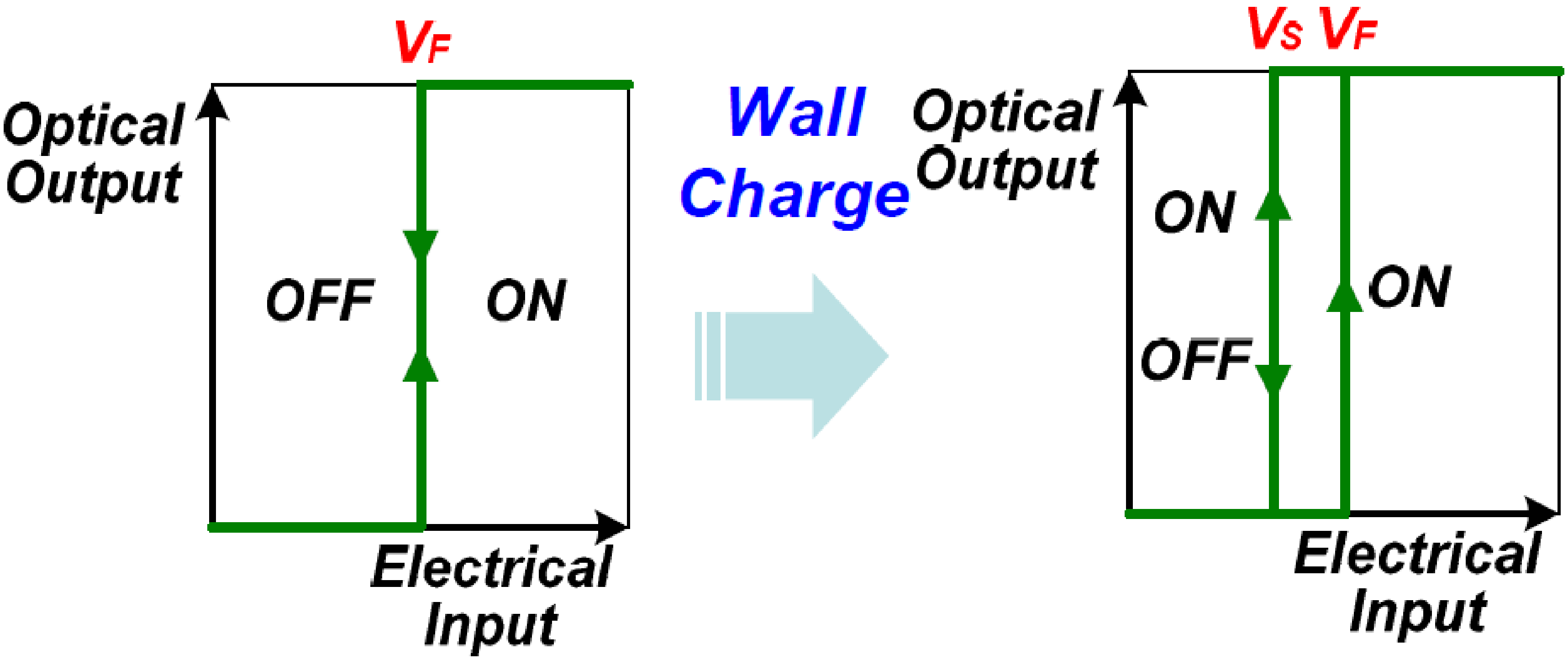
The plasma can be sustained using ac discharged



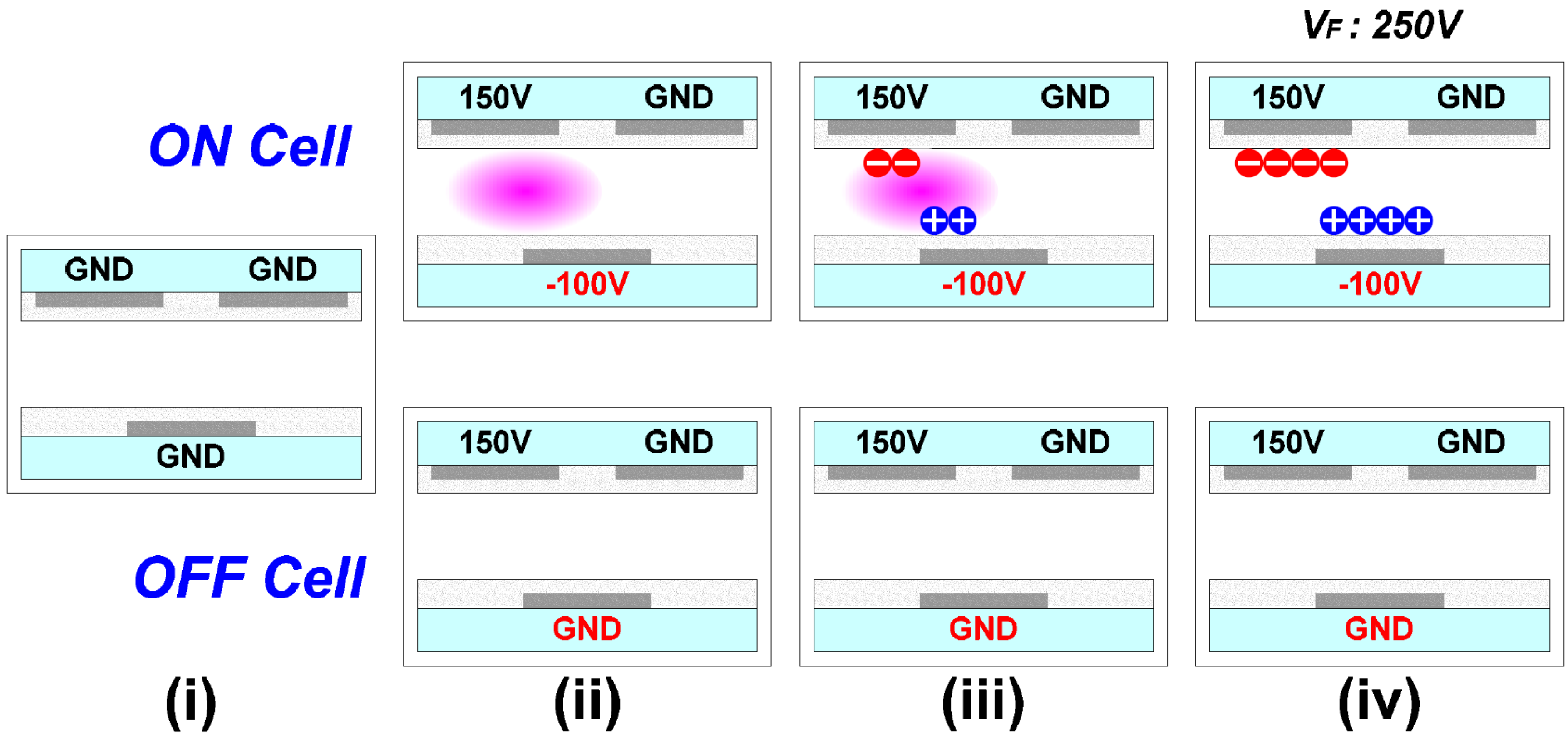
- **Wall discharge reduced the required discharge voltage**

Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

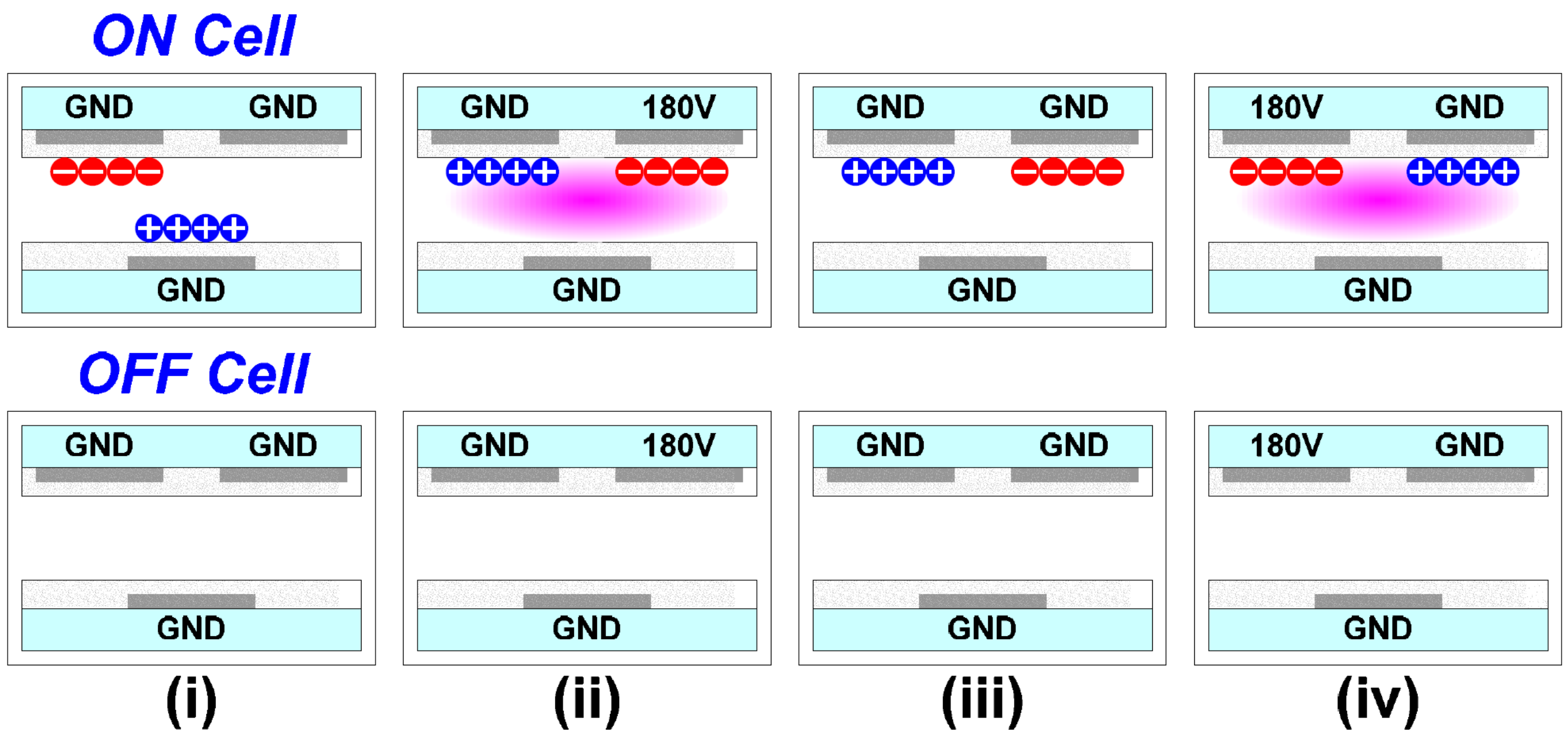
Wall discharge reduced the required discharge voltage



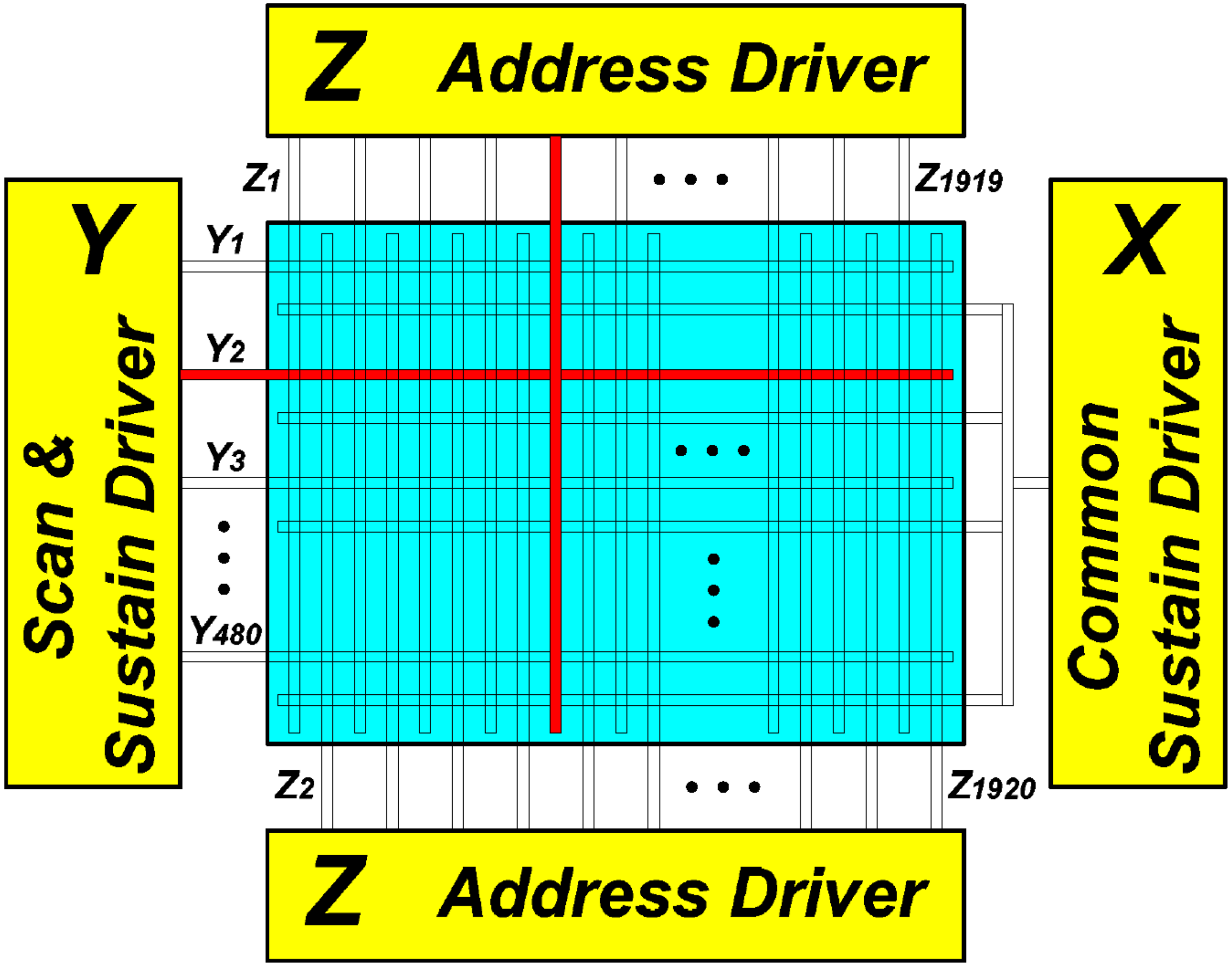
ON/OFF State Selection



Sustain discharge



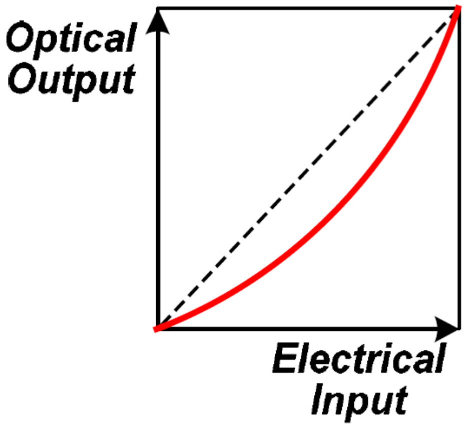
Address and sustain electrodes are connected to different drivers



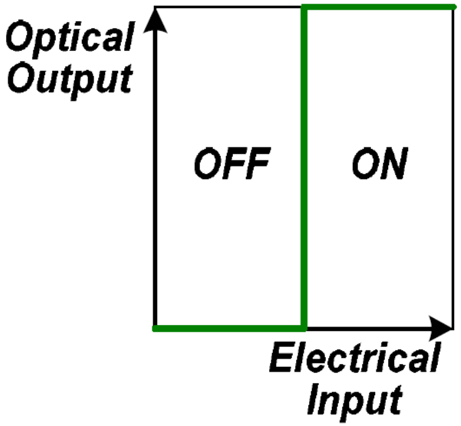
Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

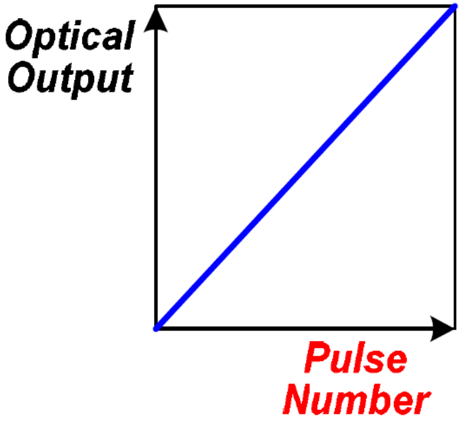
PDP pixel can only be either ON or OFF

- Cathode Ray Tube :



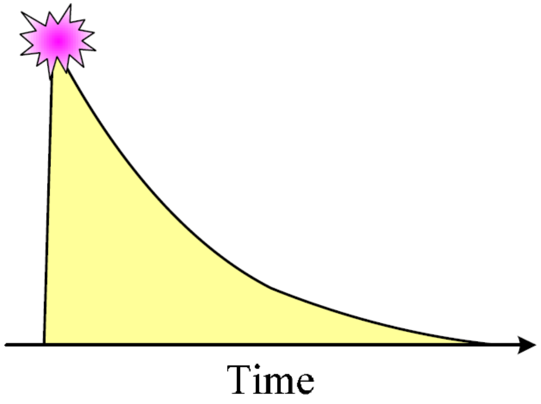
- Plasma Display Panel :



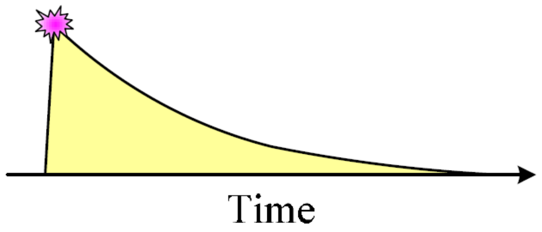


PDP luminance is controlled by using number of light pulses

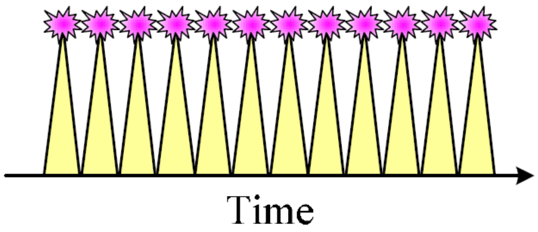
- CRT : Control the Luminance using Electron Beam Intensity



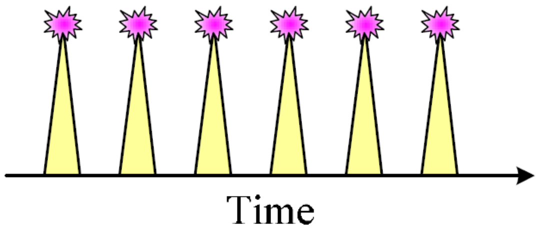
Luminance Ratio
2 : 1



- PDP : Control the Luminance using Number of Light Pulses

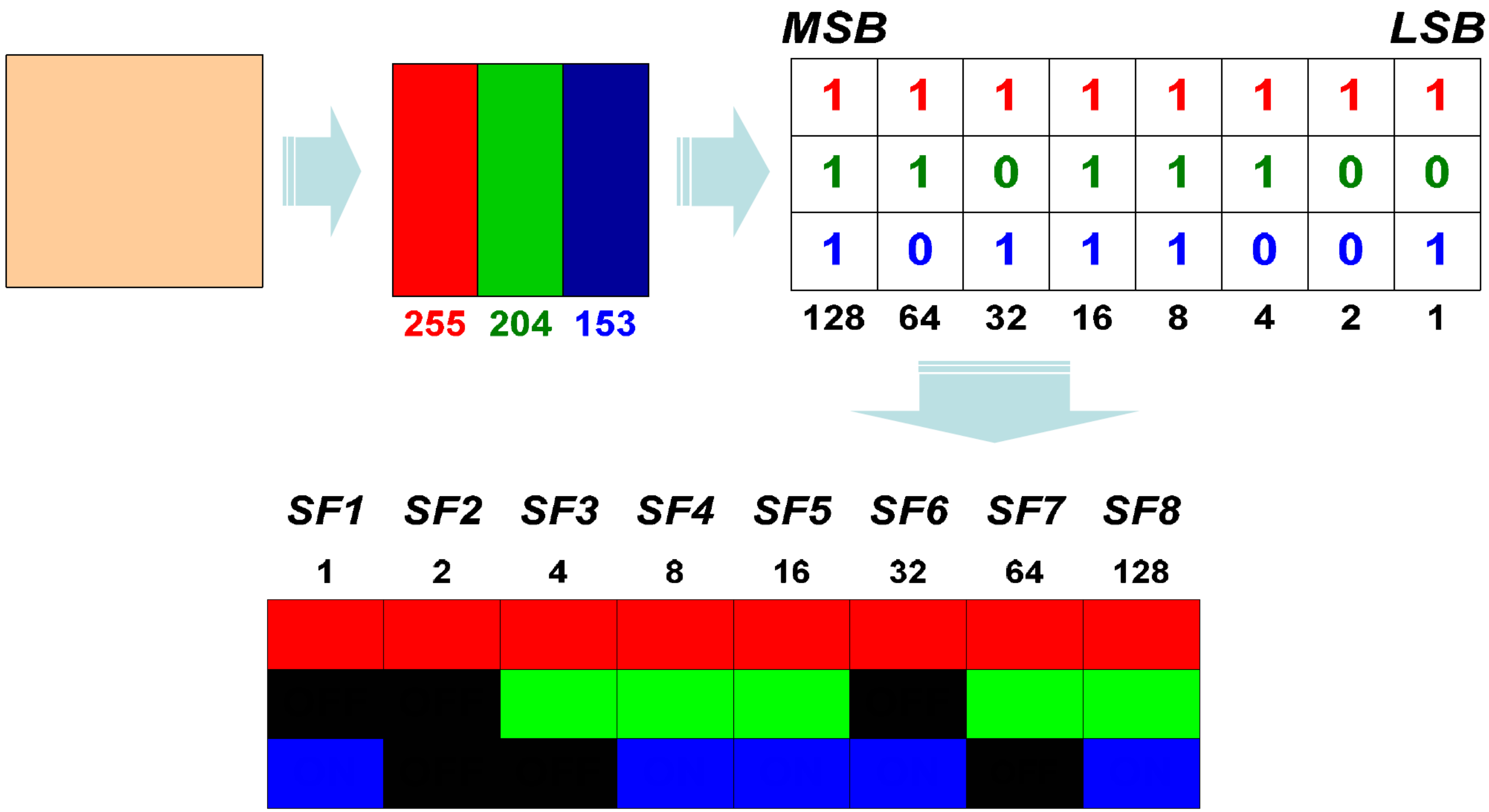


Luminance Ratio
2 : 1

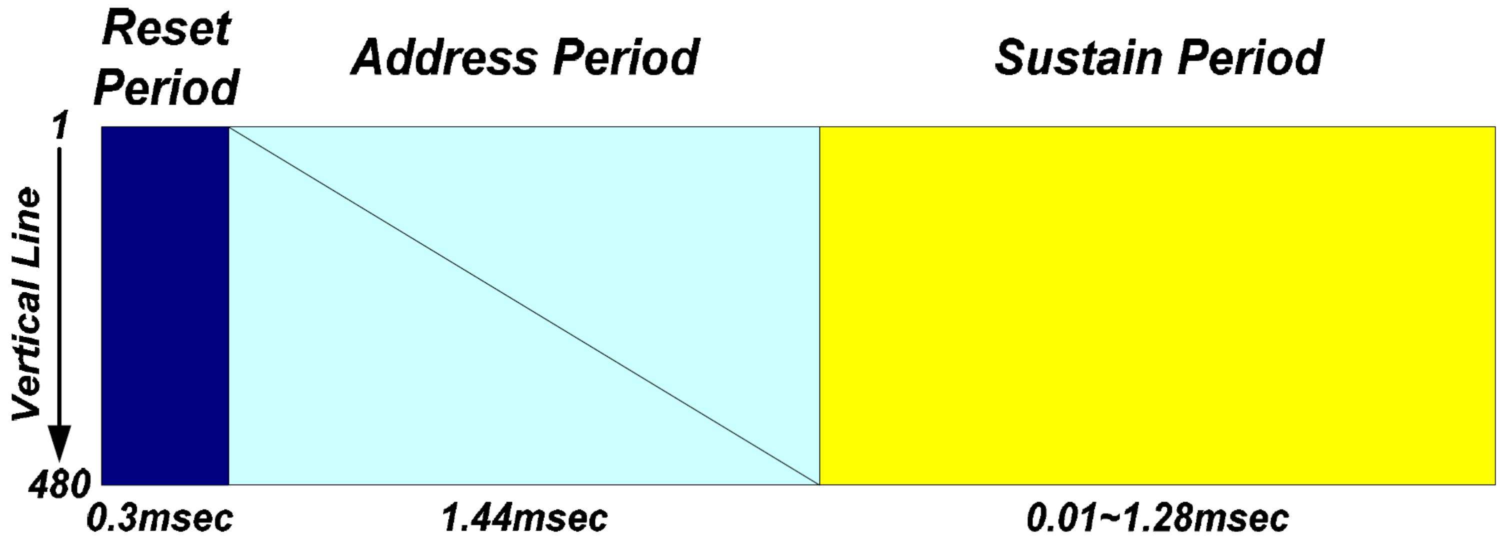


Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

A single field is divided into 8 subfield



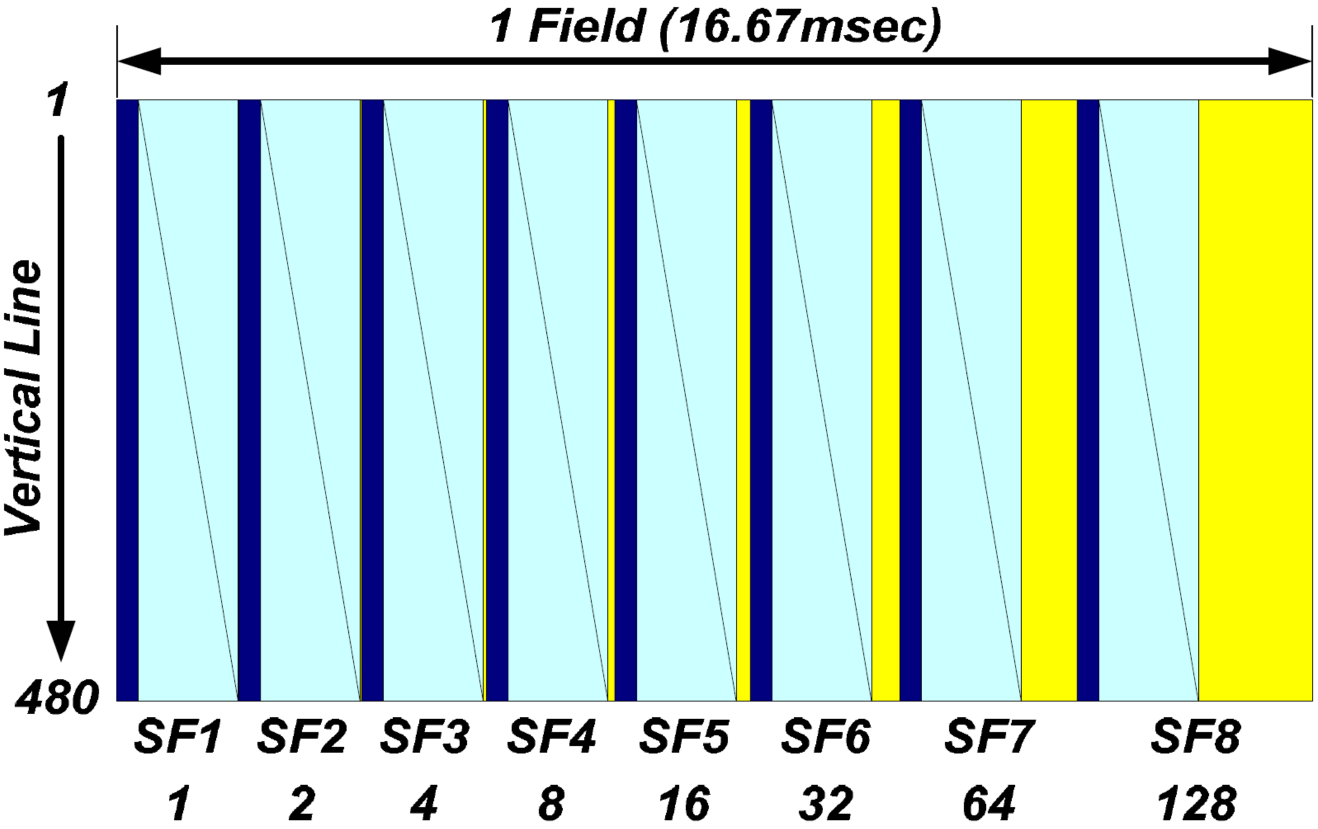
Composition of each subfield



Spec : VGA (640*480)
8 Subfield
0.03msec Address Pulse
100KHz Sustain Freq.

Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

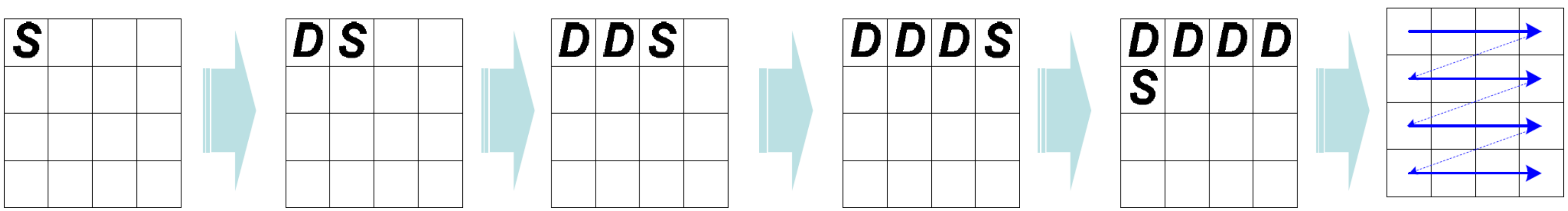
8 subfield in one TV-Field (ADS)



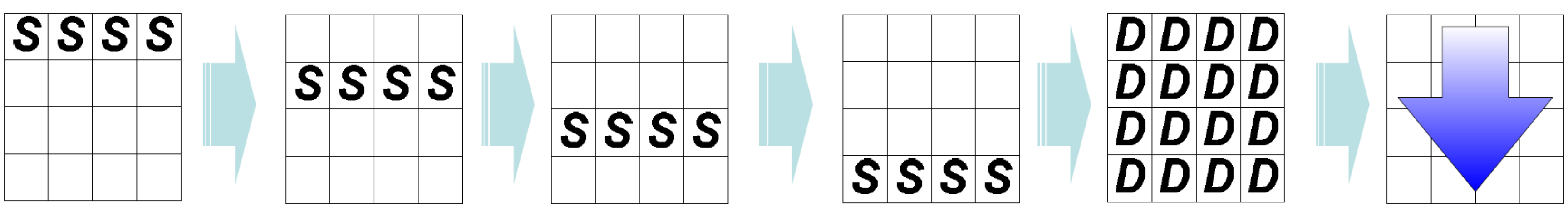
Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

PDP uses line-by-line scanning

- Cathode Ray Tube : Cell-by-Cell Scanning



- PDP : Line-by-Line Scanning

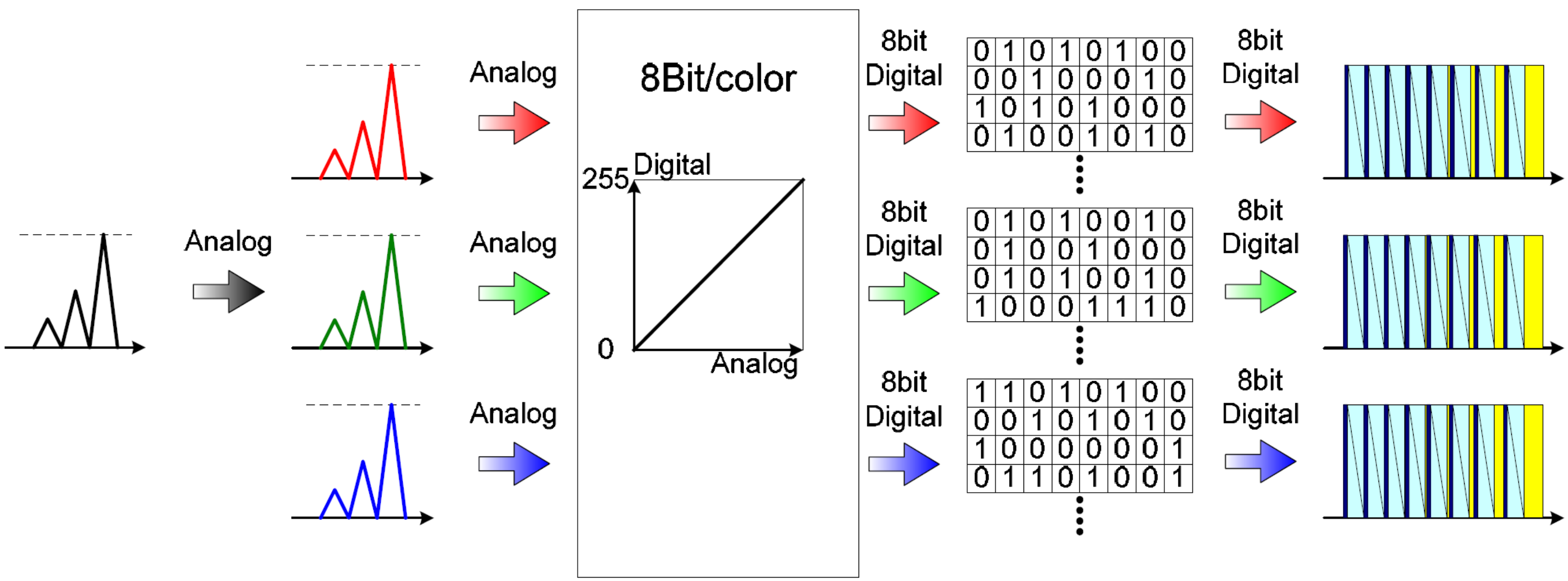


Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

Video signal processing

- Analog Video Signal ⇨ Digital Pulse Signal

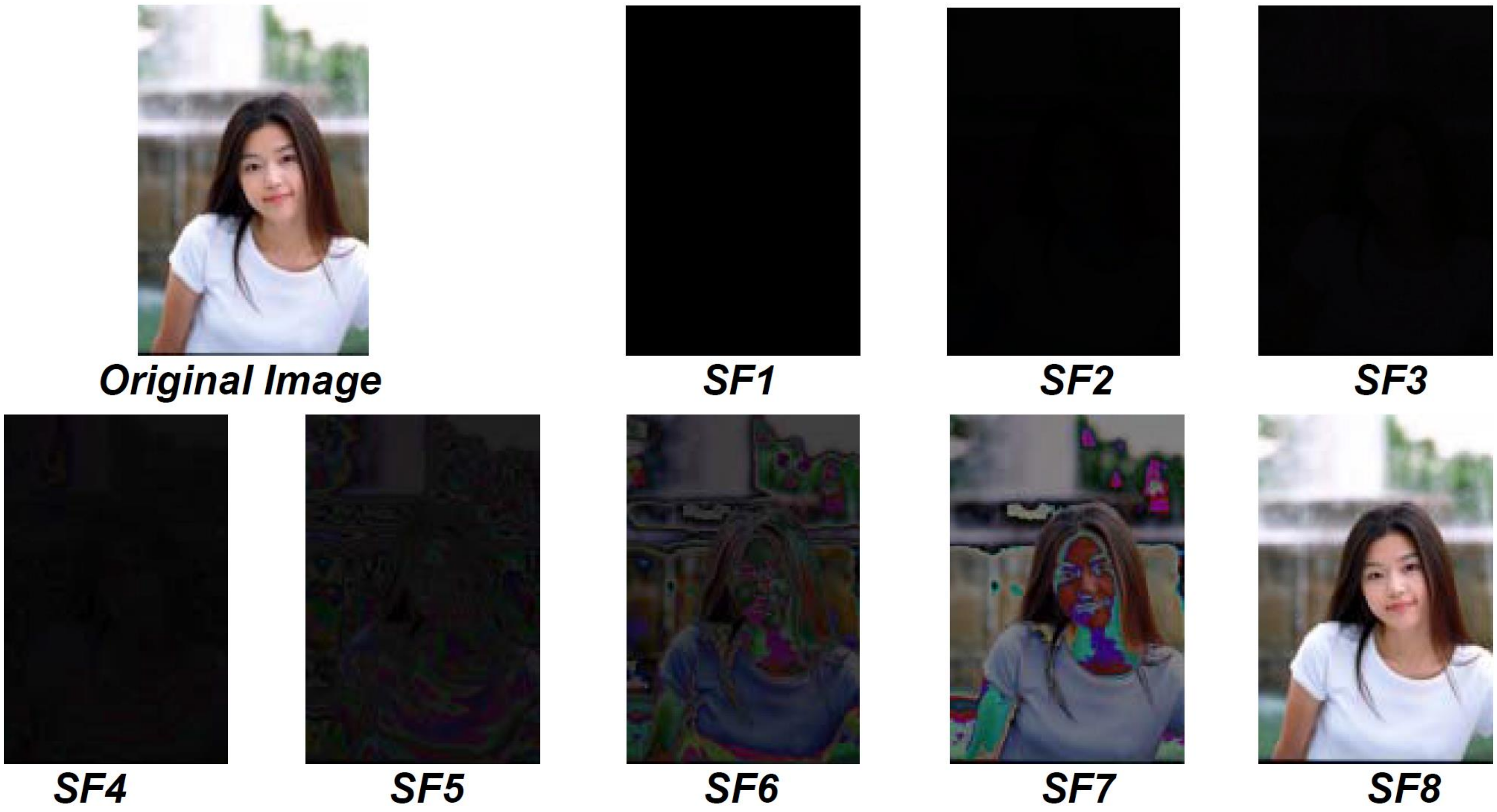
Input Analog Video Signal	Color Seperation	A/D Converter	8Bit Binary Code	Subfield Method



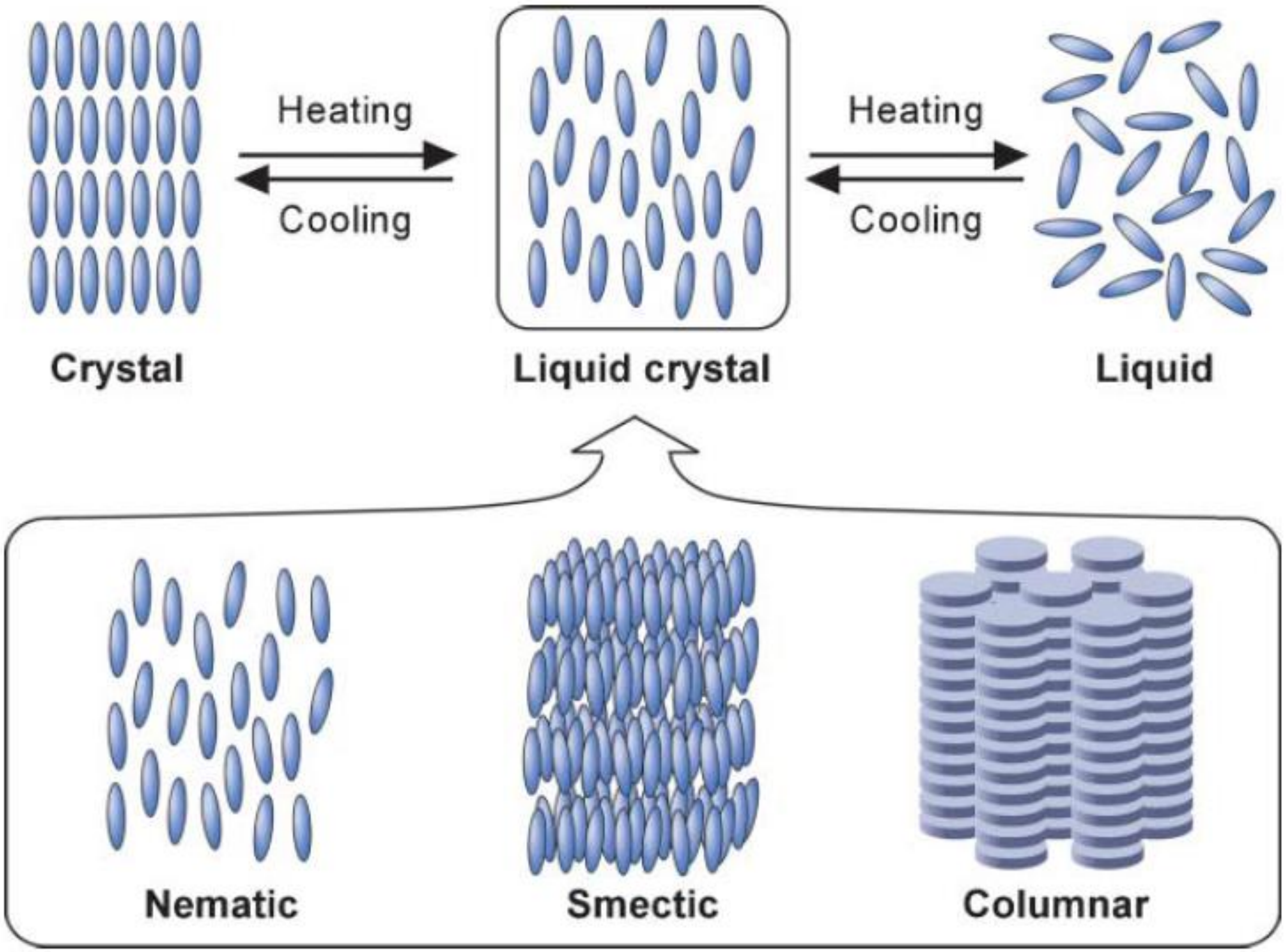
Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

Addressing period

Displaying period

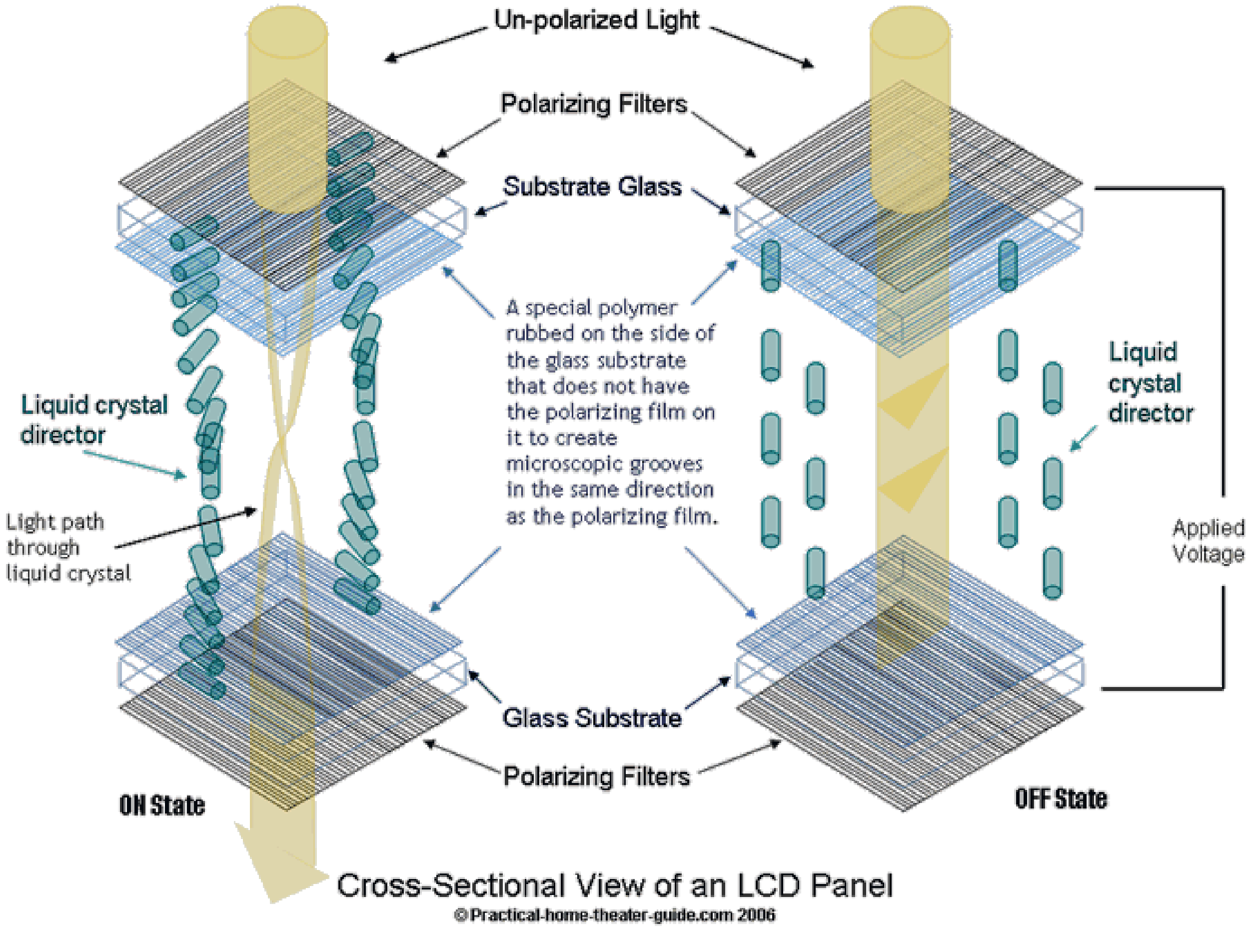


Liquid crystal are a special state of matter between liquid and crystal



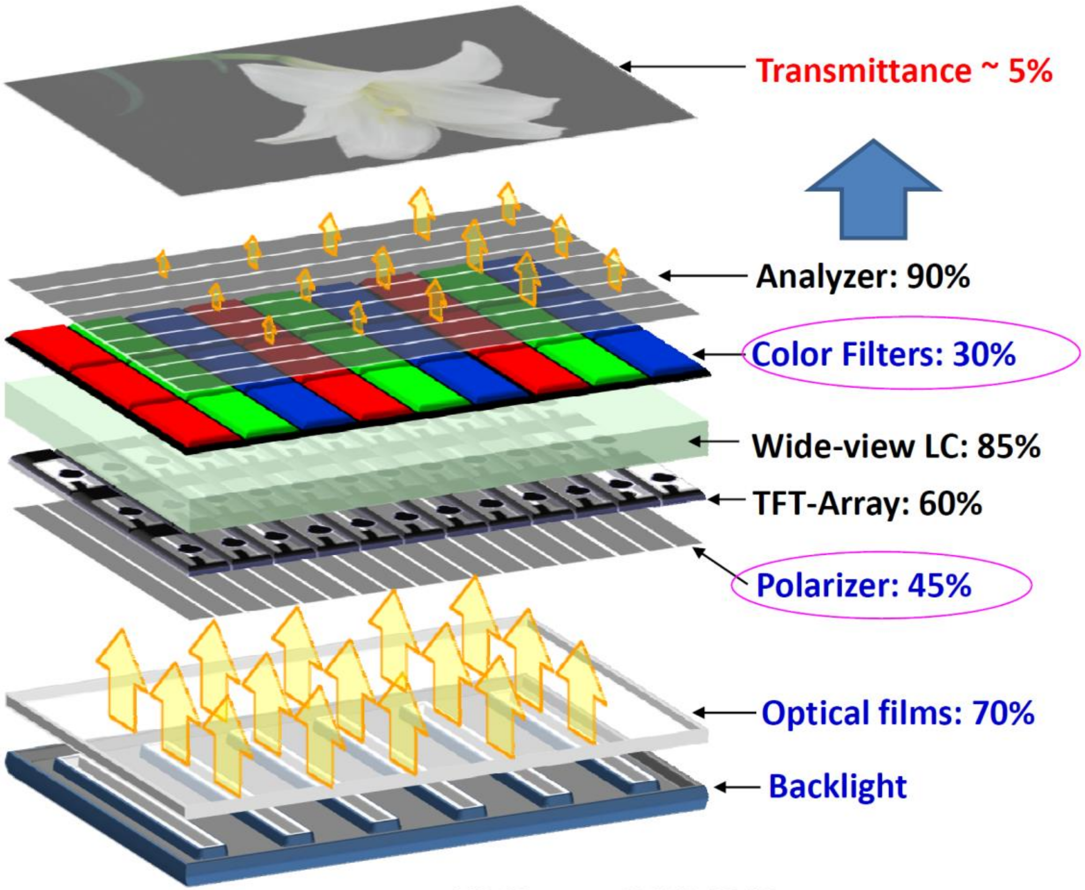
T. Kato, *et. al.*, Chem. Soc. Rev., *36*, 1845, 2007

Linear polarization of a light can be rotated by miss aligned liquid crystal



http://www.practical-home-theater-guide.com/lcd-display.html

Structure of Liquid crystal display (LCD)

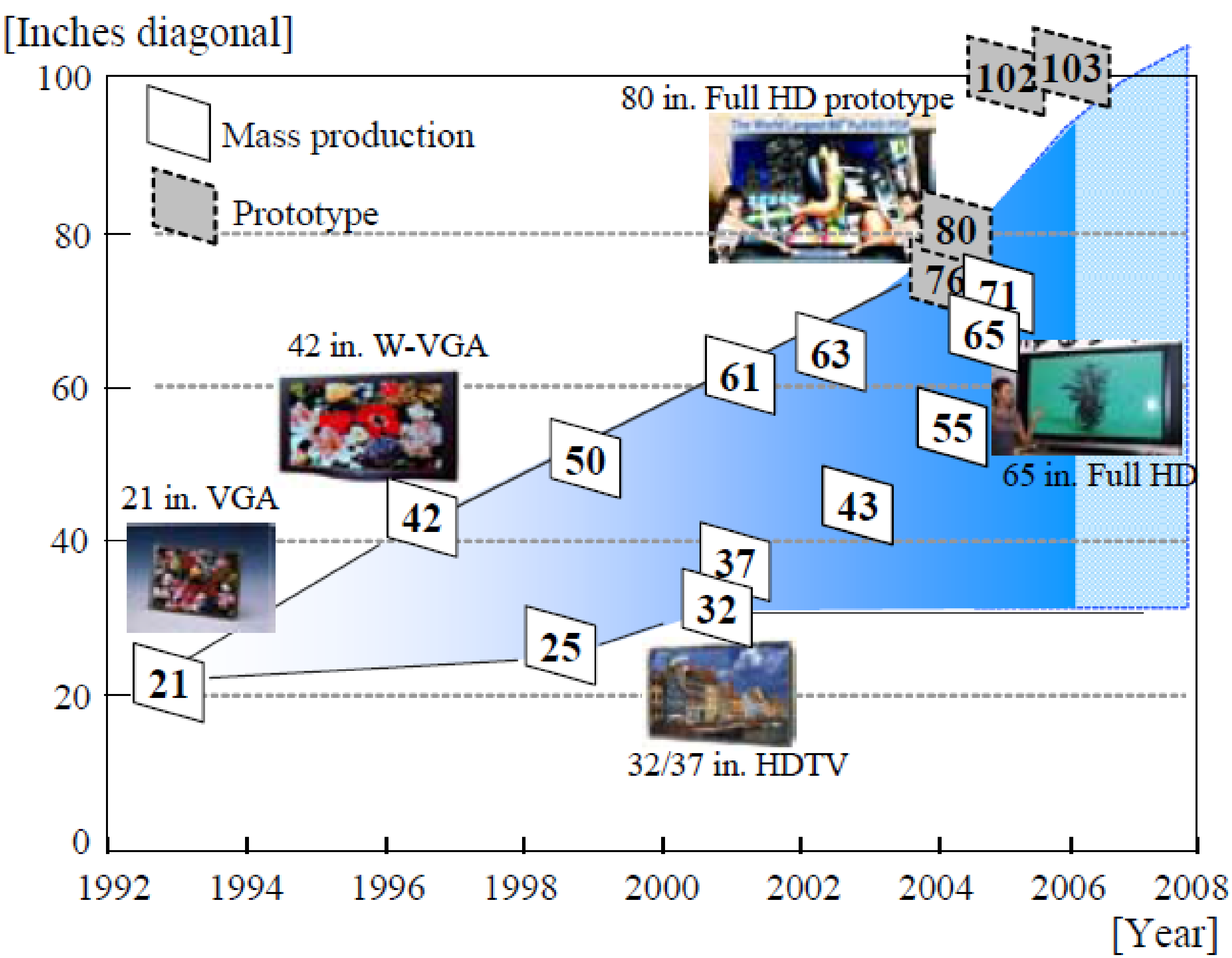


YB Huang, IDRC 2008

Notes from ST Wu, UCF

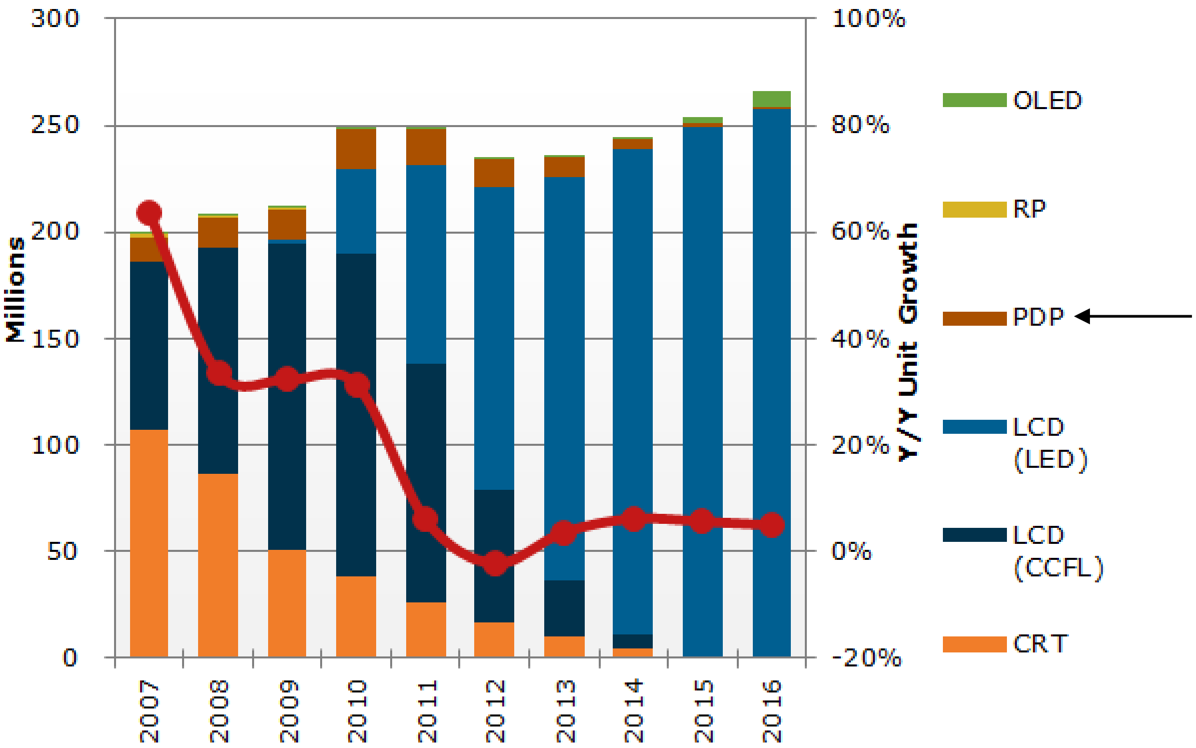
http://www6.cityu.edu.hk/cityu25/events/engineering/pdf/proftang.pdf

Optimistic projection of PDP market



Reality

TV Shipment Growth by Technology



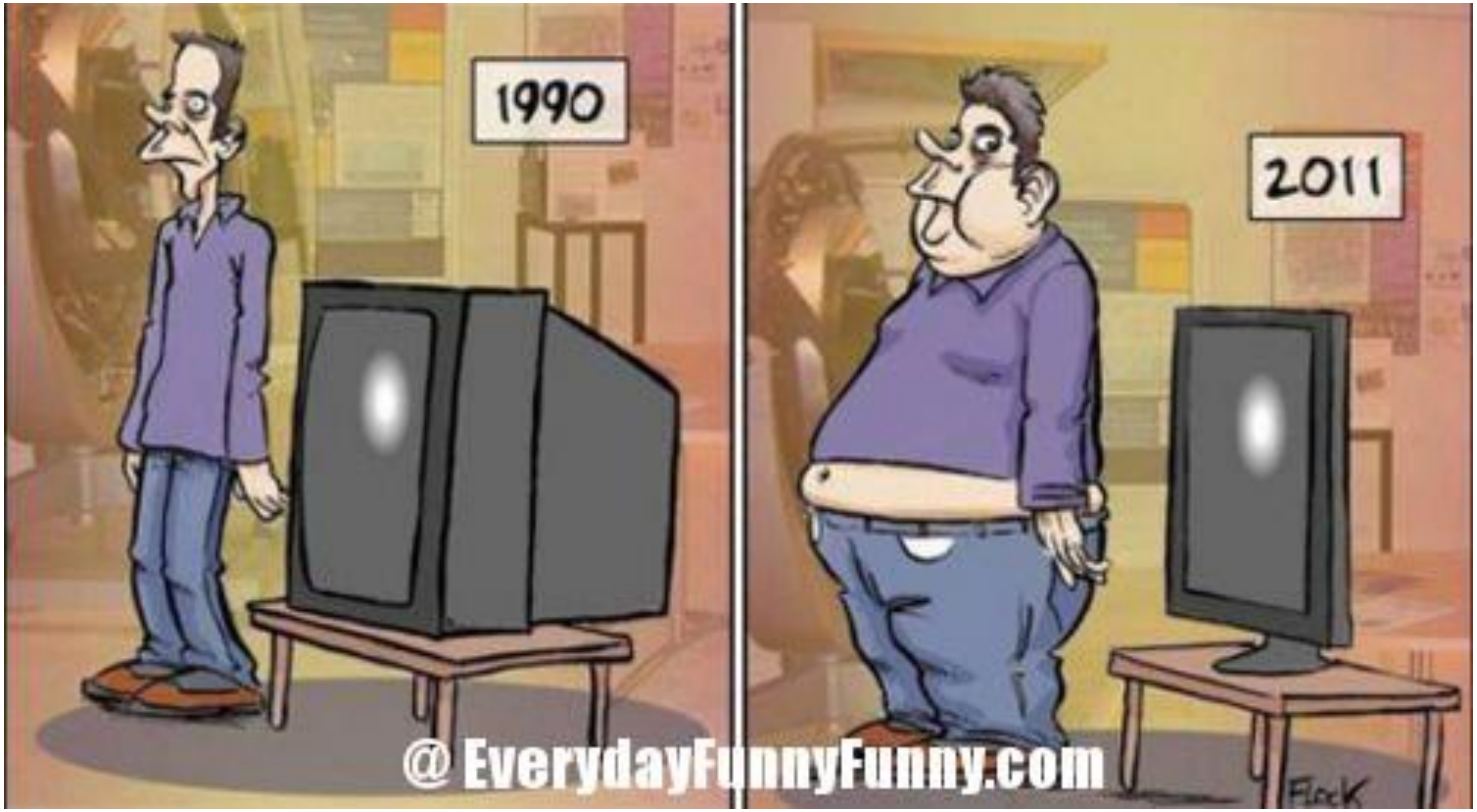
http://www.digitaltvnews.net/?p=22108

Too many reasons that PDP died!

- **Bright showroom conditions put plasmas at a distinct disadvantage versus LED-lit LCDs**
- **Aesthetics may have played a role in hastening plasma's demise**
- **UHD/4K caught on quickly**
- **Screen-size limitations also played a part in plasmas plight**
- **You can't bend a plasma**
- **Plasmas were harder to deal with than LCDs**
- **While OLED is still in the early stages of development, there's no question it offers greater potential than plasma**
- **Energy efficiency may have played a part in putting plasma out to pasture**
- **Plasma was the original flat-panel technology, People just thought of it as old technology.**
- **Projectors improved in quality and prices dropped**

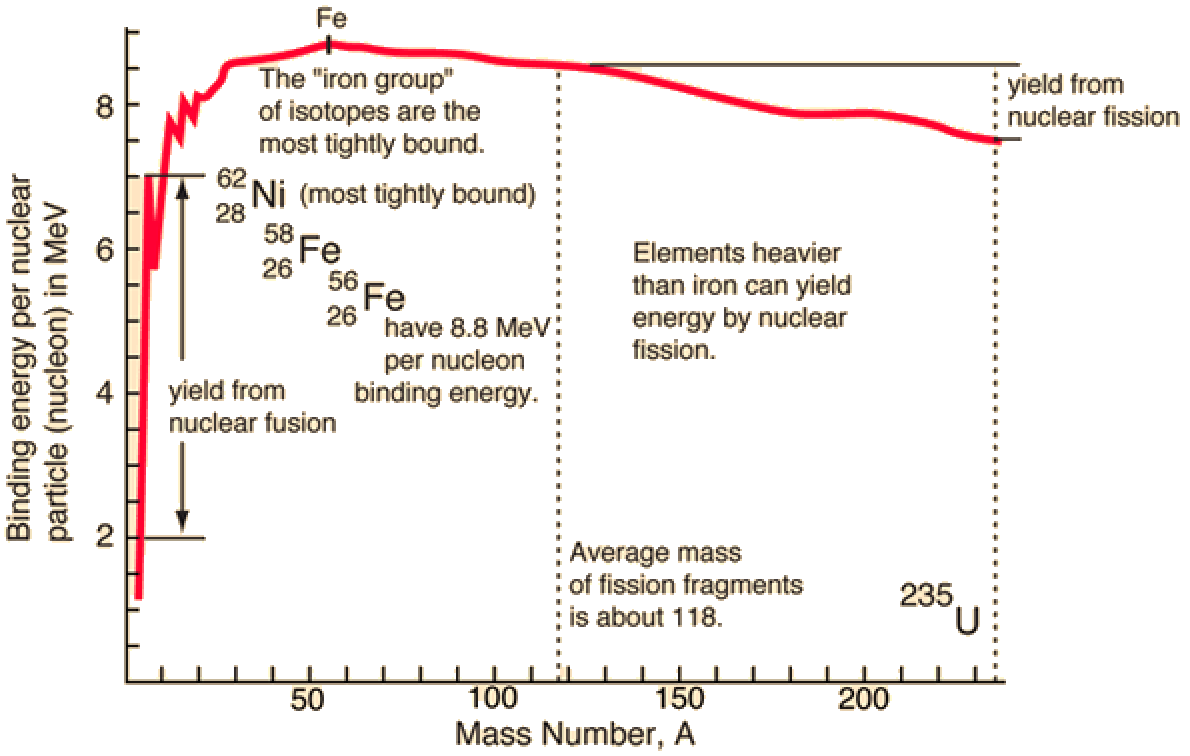
http://www.avsforum.com/forum/40-oled-technology-flat-panels-general/2080650-10-reasons-plasma-died.html

Let's stand up and do exercise!!



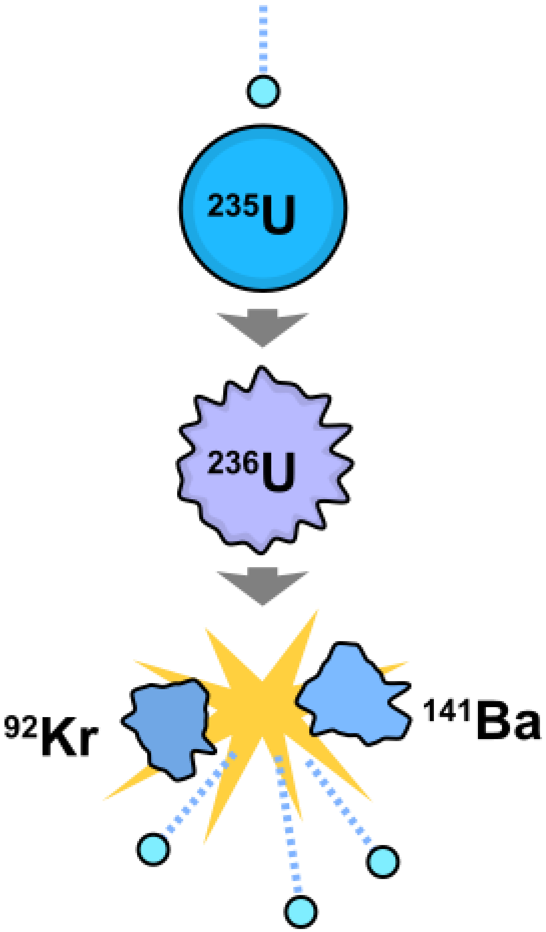
The hydrogen bomb

The “iron group” of isotopes are the most tightly bound



http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html

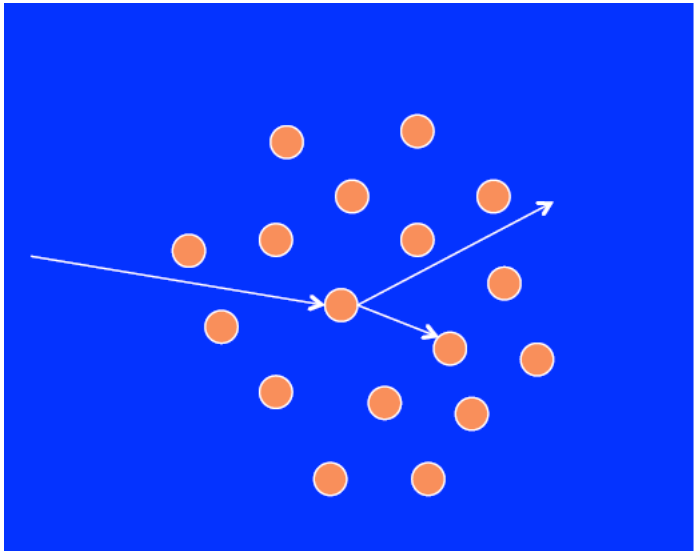
Chain reaction can happen in U^{235} fission reaction



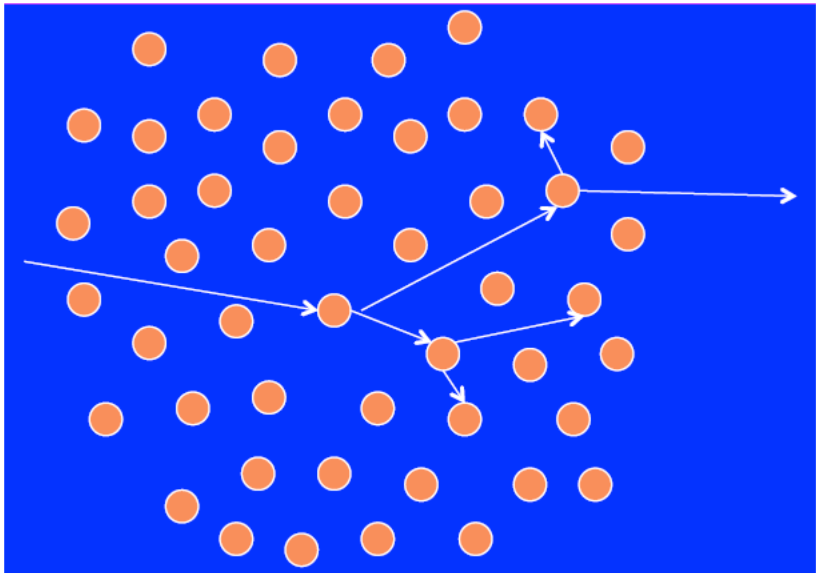
- ~ 200 million electron volts (MeV)/fission, ~million times more than chemical reactions
- Energy for bombs, or for civilian power can generate huge amounts of energy (and toxicity) in a small space with a modest amount of material
- Source of safety, security issues for nuclear power

https://en.wikipedia.org/wiki/Uranium-235
Talk given by Matthew Bunn, IGA-232: Controlling the World's Most Dangerous Weapons, Harvard Kennedy School, 2013

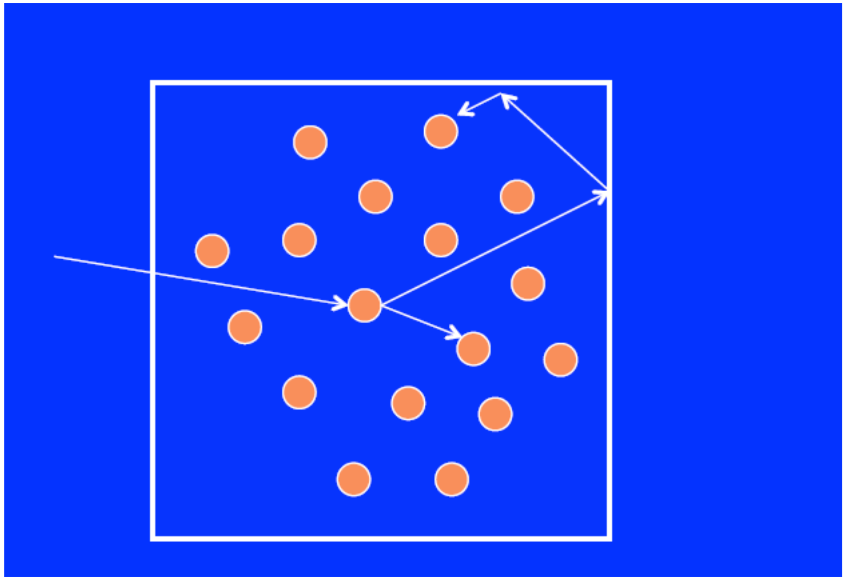
The neutrons are leaking out and stopping the chain reaction in a sub-critical mass



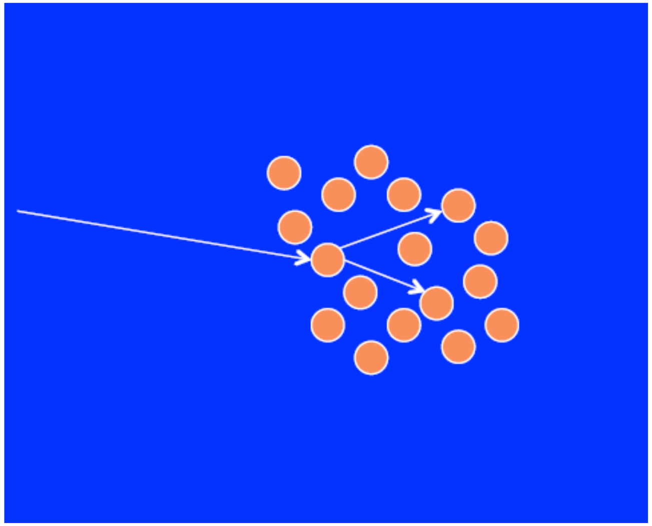
Solution 1: add more material



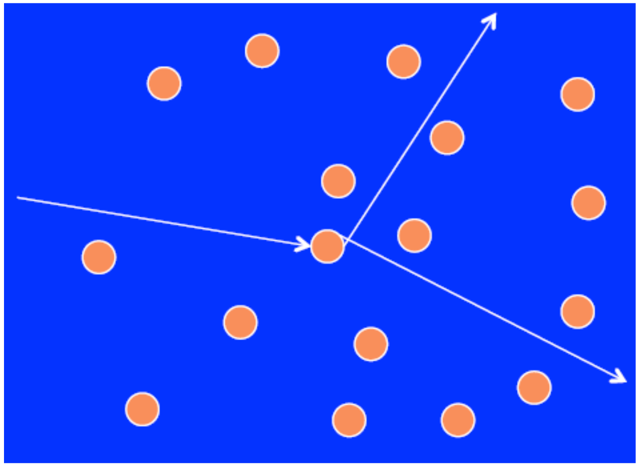
Solution2: reflect the neutron back in



Solution 3: increase the density



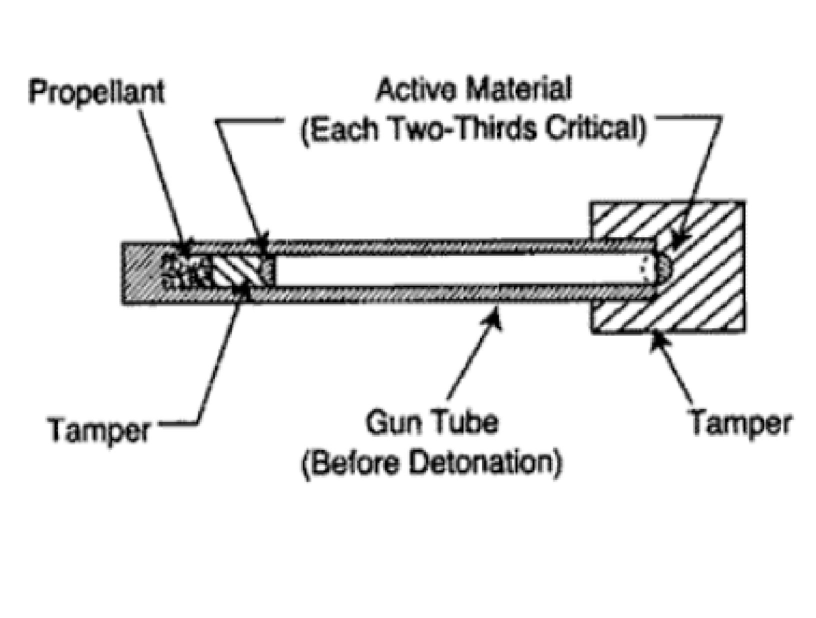
How to get the material together before it blows apart?



- **There are always neutrons around**
- **Once chain reaction starts, material will heat up, expand, stop reaction**
- **How to get enough material together fast enough?**

Gun-type bomb

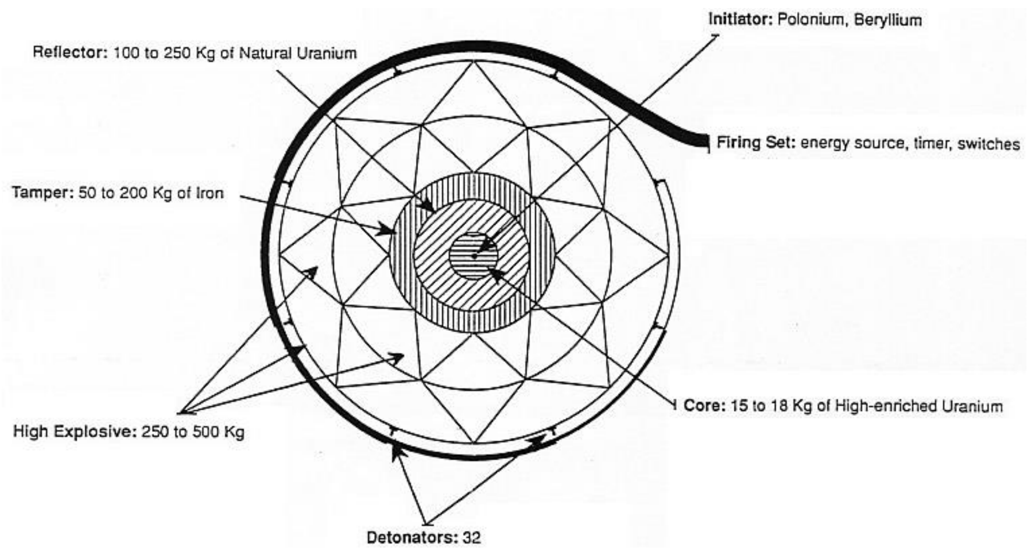
- **Simple, reliable – can be built without testing**
- **Highly inefficient – require lots of nuclear material (50-60 kg of 90% enriched HEU)**
- **Can only get high yield with HEU, not plutonium**
- **Hiroshima bomb: cannon that fired HEU projectile into HEU target**



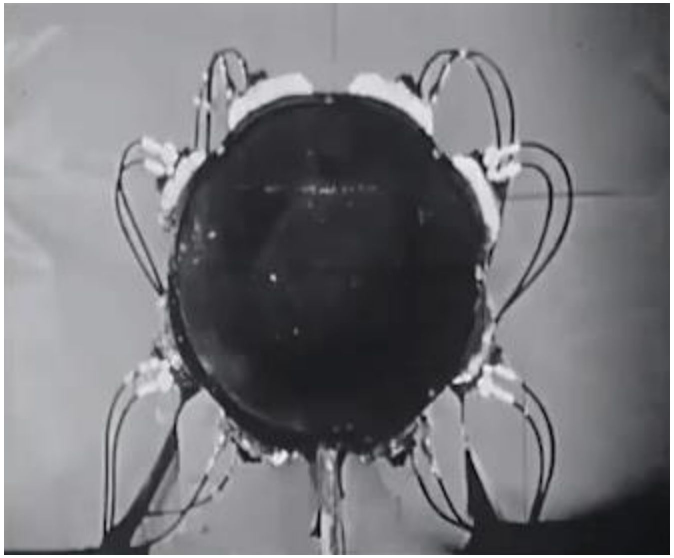
Source: NATO

Implosion design

- A schematic diagram of an implosion bomb



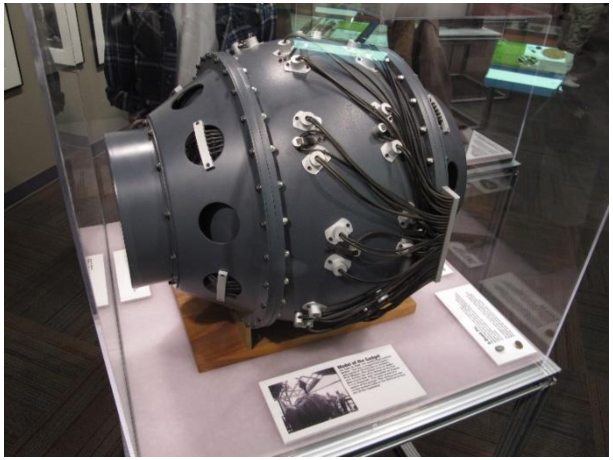
- Small-scale slow-motion cross-section of a shaped charge implosion design



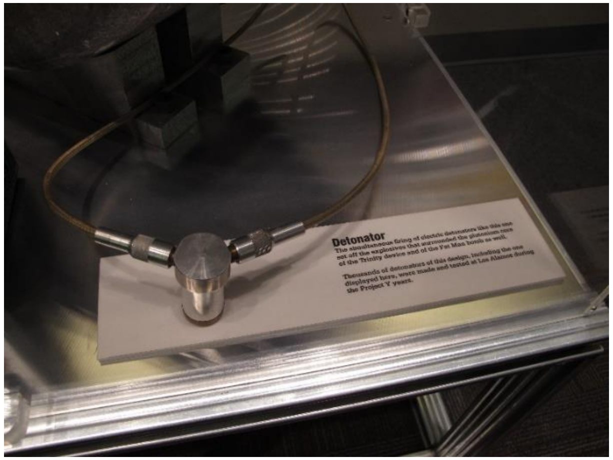
https://www.wisconsinproject.org/nuclear-weapons/
https://en.wikipedia.org/wiki/Trinity_%28nuclear_test%29

The 1st nuclear bomb: Trinity (Bradbury Science Museum)

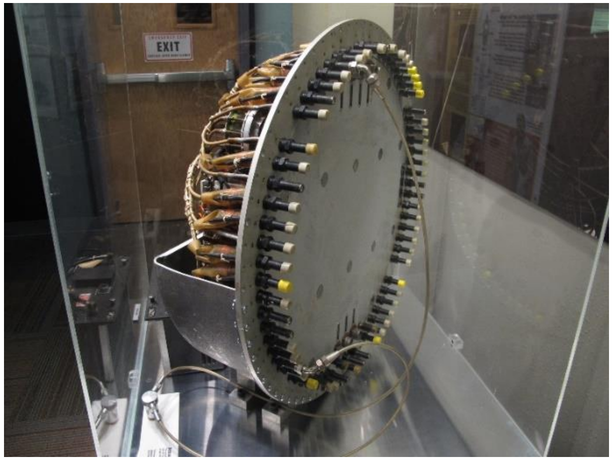
- **Model of the Trinity Gadget**



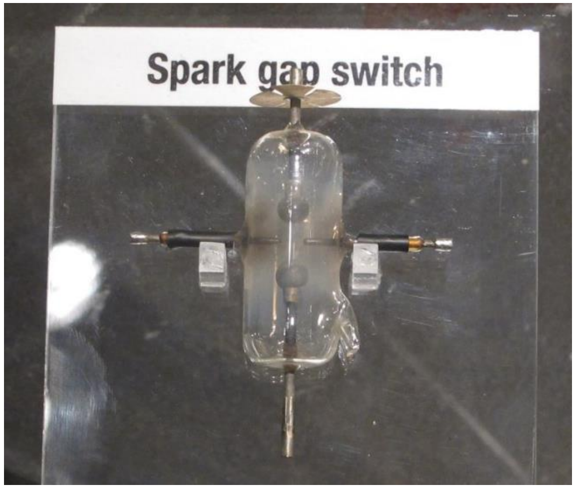
- **Project Y Atomic Bomb Detonator System**



- **Project Y Atomic Bomb Detonator System**

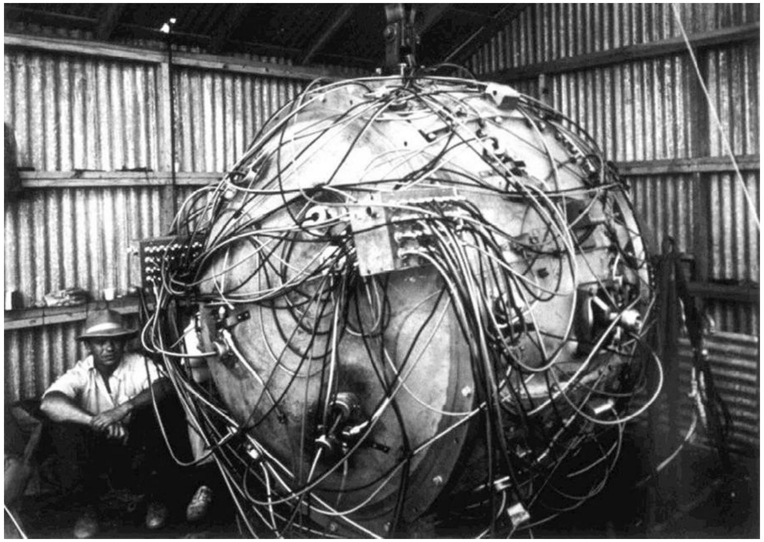


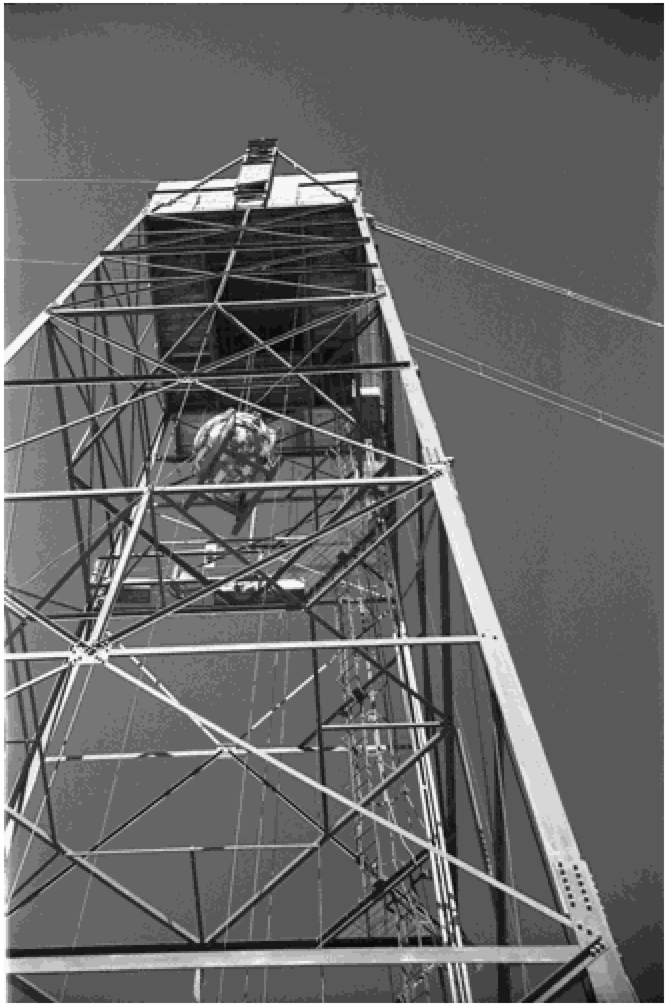
- **Project Y Atomic Bomb Detonator System Spark Gap Switch**



https://www.flickr.com/photos/rocbolt/with/8061684482

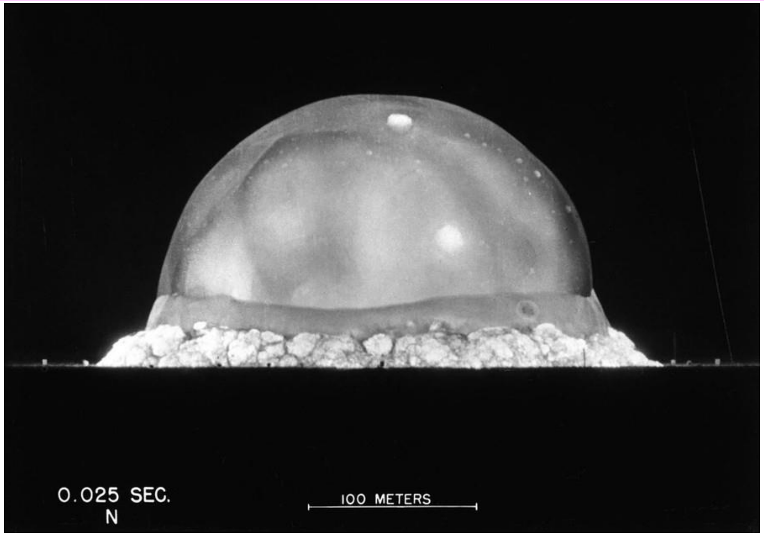
The 1st nuclear bomb: Trinity

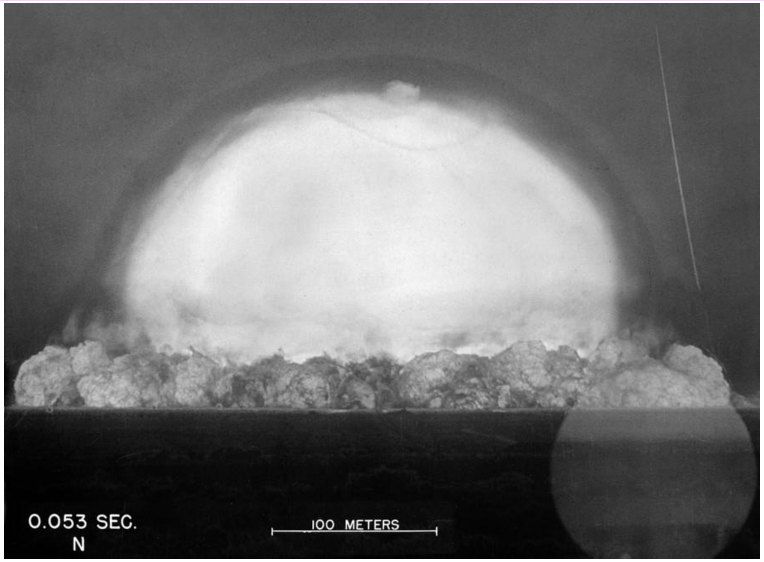




https://www.theatlantic.com/photo/2015/07/70-years-since-trinity-when-we-tested-nuclear-bombs/398735/
https://saddlebagnotes.com/arts-and-leisure/tucson-seismographs-detected-first-nuclear-test-at-trinity-n-m/article_b01c5b20-f6fb-11eb-a221-6327df2feaeb.html

Trinity explosion on July 16, 1945





https://www.theatlantic.com/photo/2015/07/70-years-since-trinity-when-we-tested-nuclear-bombs/398735/
https://en.wikipedia.org/wiki/Trinity_%28nuclear_test%29

Hiroshima Bomb – “Little Boy”

Gun Type – Easiest to design and build (Hiroshima bomb was never tested)

About 13 kiloton explosive yield

Talk given by Dr. Charles D. Ferguson, President, Federation of American Scientists, Department of Physics, Colloquium, American University, 2012

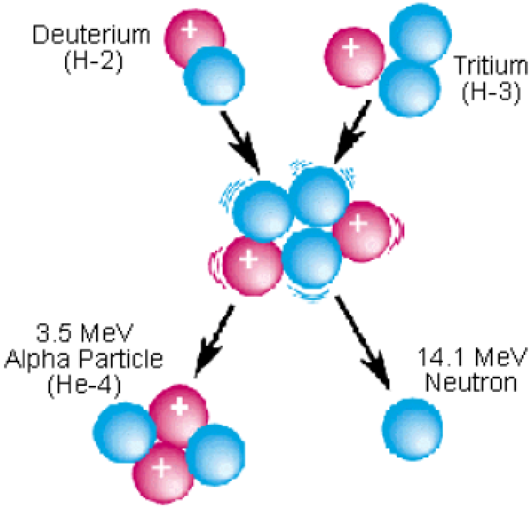
Atomic bomb is very destructive

Hiroshima: August 6, 1945

Nagasaki: August 9, 1945

Talk given by Dr. Charles D. Ferguson, President, Federation of American Scientists, Department of Physics, Colloquium, American University, 2012

The fusion process



Deuterium-Tritium Fusion Reaction

$^2H + ^3H \Rightarrow {}^4He + n + Q \equiv 17.6$ MeV

Energy release Q=17.6 MeV

In comparison

$^2H + ^2H \Rightarrow {}^1H + ^3H + Q \equiv 4.0$ MeV

$^2H + ^2H \Rightarrow {}^3He + n + Q \equiv 3.2$ MeV

$^3H + ^3H \Rightarrow {}^4He + 2n + Q \equiv 11.3$ MeV

$^{235}U + n \Rightarrow X_A + X_B + 3n + Q \approx 200$ MeV

Fusionable Material, deuterium ^2H (D) and tritium ^3H (t):

Deuterium: natural occurrence (heavy water) (0.015%).

Tritium: natural occurrence in atmosphere through cosmic ray bombardment; radioactive with $T_{1/2}$=12.3 y.

https://isnap.nd.edu/Lectures/phys20061/pdf/10.pdf

“Advantages” of hydrogen bomb

Fusion of $^2H + ^3H$: $$\frac{Q}{A} = \frac{17.6\ MeV}{(3+2)\ amu} = 3.5\ \frac{MeV}{amu}$$

Fission of ^{235}U: $$\frac{Q}{A} = \frac{200\ MeV}{236\ amu} = 0.85\ \frac{MeV}{amu}$$

Fusion is 4 times more powerful than fission and generates 24 times more neutrons!

Neutron production:

$$^2H + ^3H: \quad \frac{n}{A} = \frac{1}{5} = 0.2$$

$$^{235}U + n: \quad \frac{n}{A} = \frac{2}{236} = 0.0085$$

https://isnap.nd.edu/Lectures/phys20061/pdf/10.pdf

Hydrogen bomb uses a fission bomb to initiate the fusion reaction

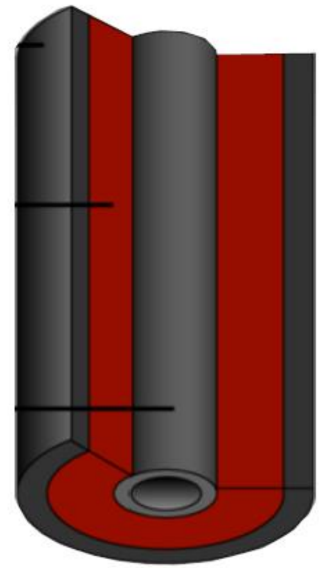
Primary Fission Device

Core: ^{239}Pu, ^{235}U, plus ^{2}H+^{3}H booster

Shell: ^{238}U tamper

High explosive lenses

Fuel



Secondary Fusion Device

Radiation channel

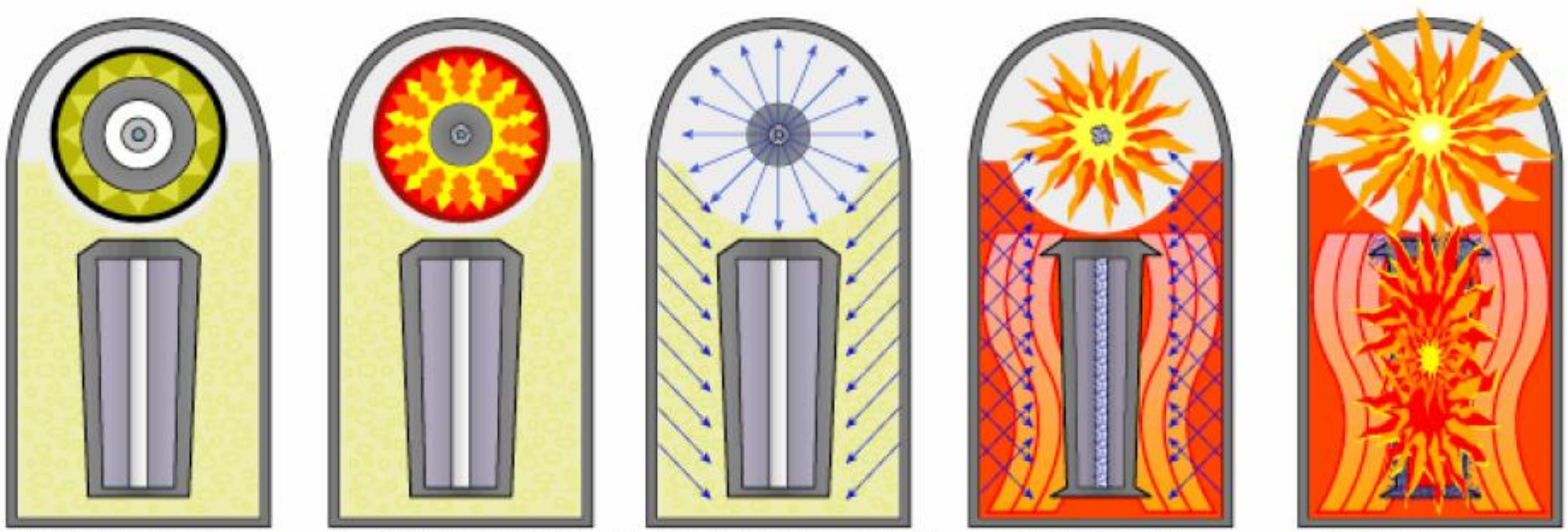
^{239}Pu sparkplug

^{6}Li, ^{2}H, ^{3}H fusion cell

^{238}U tamper

https://isnap.nd.edu/Lectures/phys20061/pdf/10.pdf

Event sequence



1. Warhead before firing; primary (fission bomb) at top, secondary (fusion fuel) at bottom, all suspended in polystyrene foam.

2. HE fires in primary, compressing plutonium core into supercriticality and beginning a fission reaction.

3. Fissioning primary emits X-rays which reflect along the inside of the casing, irradiating the polystyrene foam.

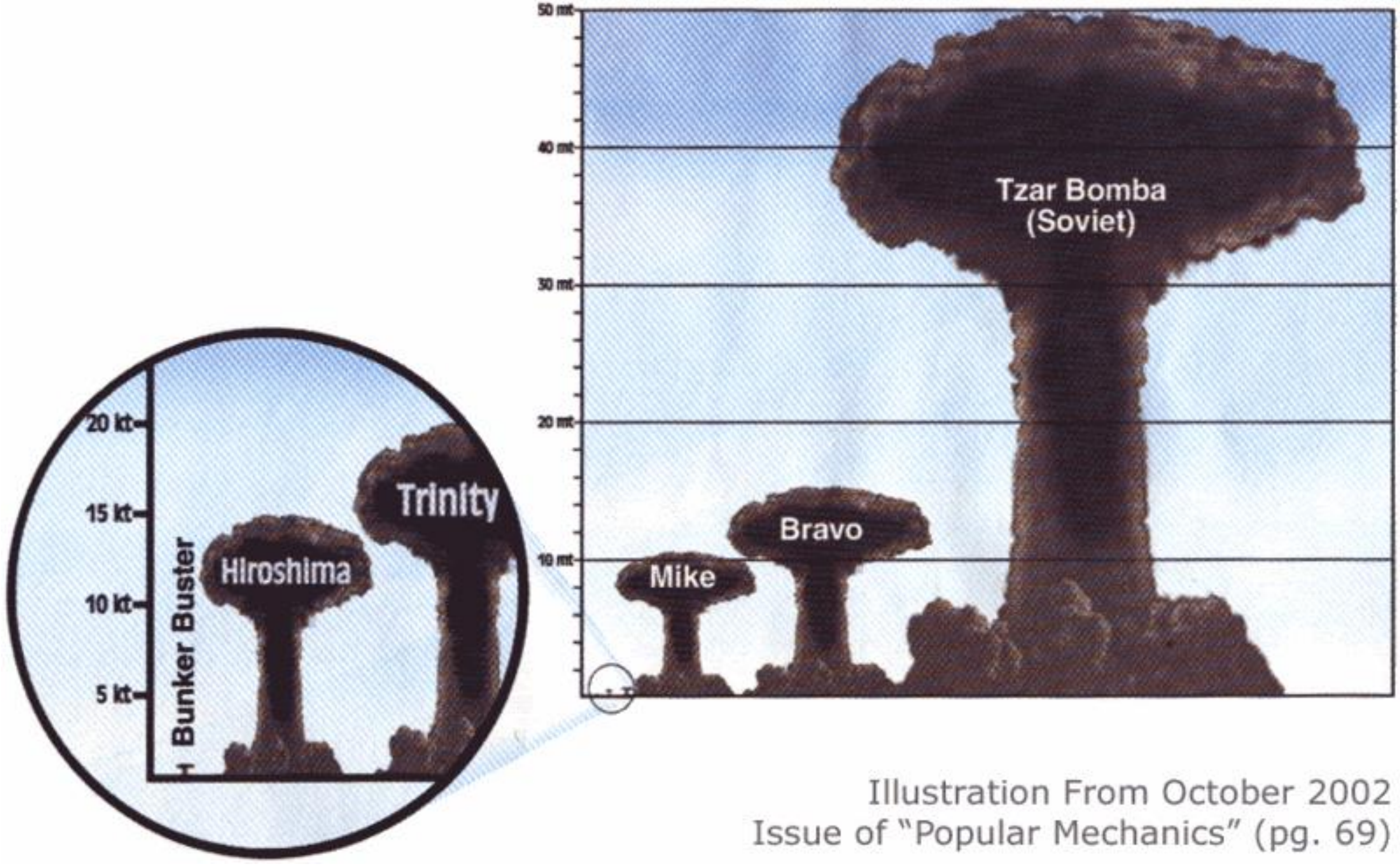
4. Polystyrene foam becomes plasma, compressing secondary, and plutonium sparkplug begins to fission.

5. Compressed and heated, lithium-6 deuteride fuel begins fusion reaction, neutron flux causes tamper to fission. A fireball is starting to form...

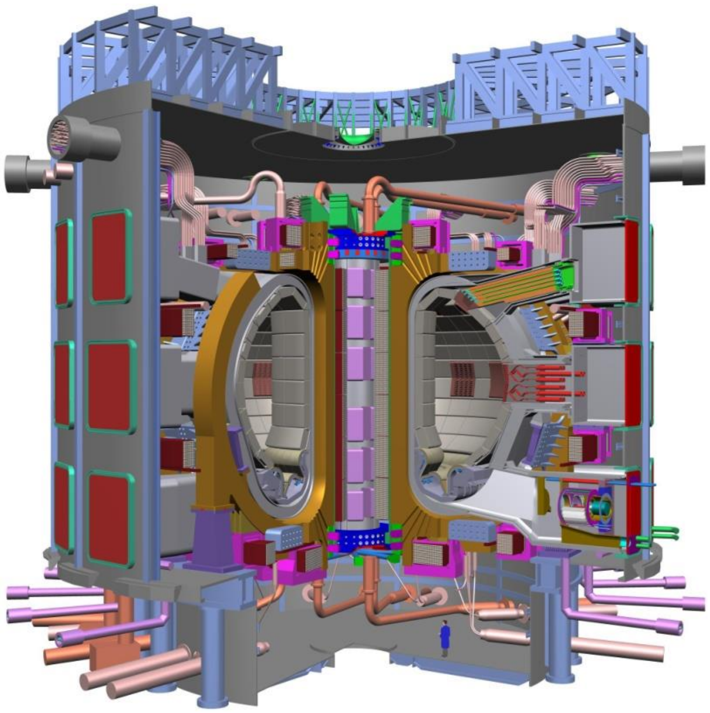
Additional pressure from recoil of exploding shell (ablation)!

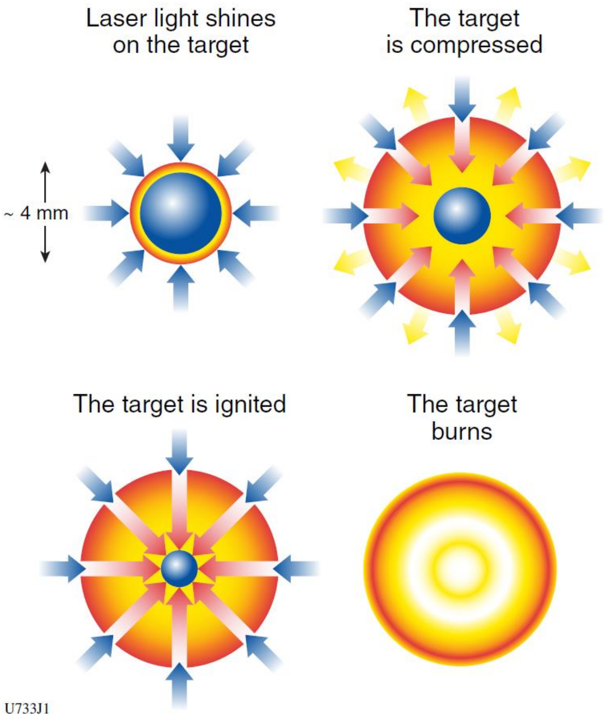
https://isnap.nd.edu/Lectures/phys20061/pdf/10.pdf

You don't want to build a hydrogen bomb!



To Fuse, or Not to Fuse...





Outline

- Introduction to nuclear fusion
- Magnetic confinement fusion (MCF)
  - Tokamak
  - Stellarator
- Inertial confinement fusion (ICF)
  - Indirection drive ICF
  - Direct drive ICF
- Innovation idea – MCF + ICF
- Pulsed-power system at NCKU

Outline

- **Introduction to nuclear fusion**
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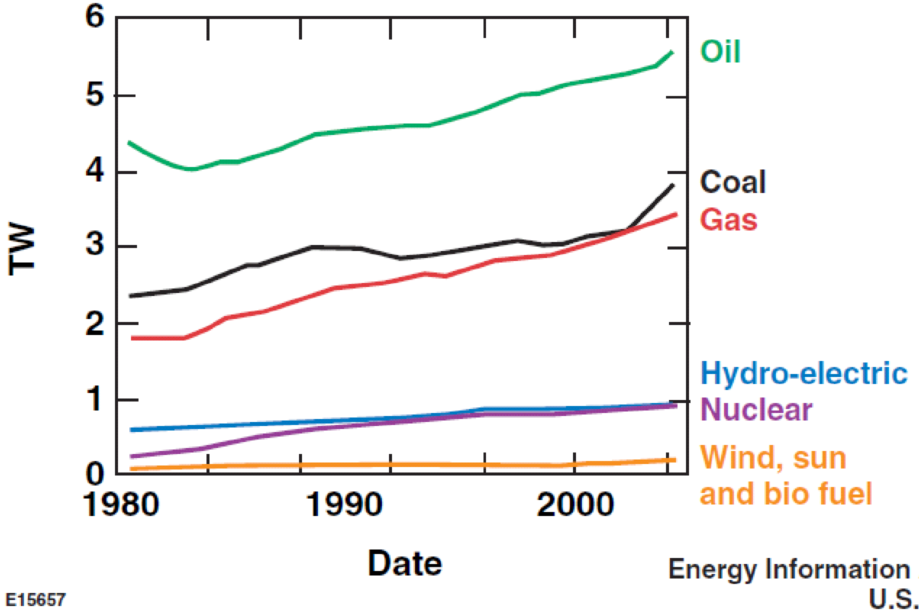
World energy consumption is dominated by the use of dwindling fossil fuels

Fossil fuel	Estimated reserve	(2005 consumption rate) Years remaining
Oil	1,277,702 million barrels	32 years
Natural gas	~6,500,000 billion cubic ft	72 years
Coal	1,081,279 million tons	252 years

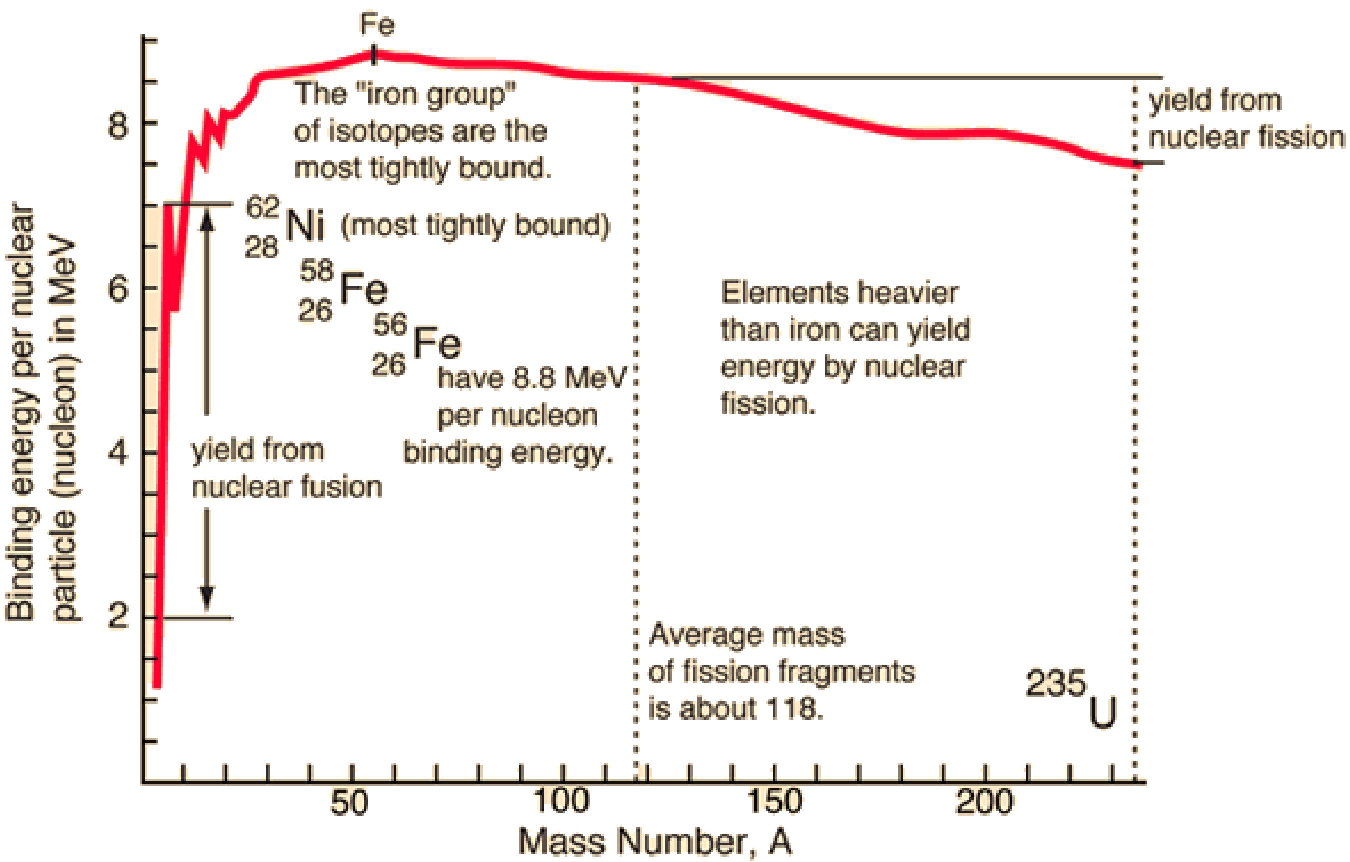


While predictions about the exact number of remaining years vary, fossil fuels will run out.

Energy Information Administration (EIA) 2006 Annual Report, U.S. Department of Energy, Washington, D.C.

*from Laboratory for Laser Energetics, University of Rochester, Rochester, NY

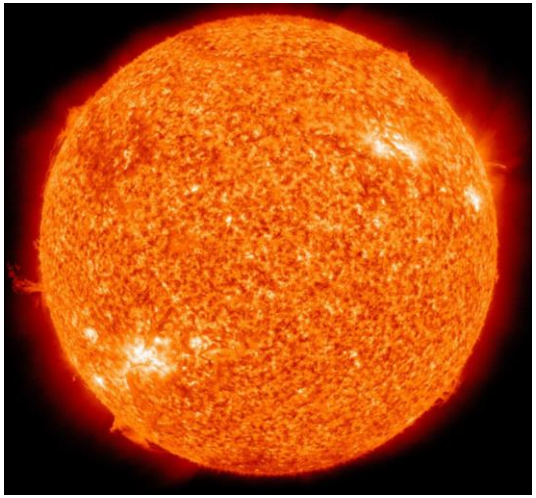
The "iron group" of isotopes are the most tightly bound

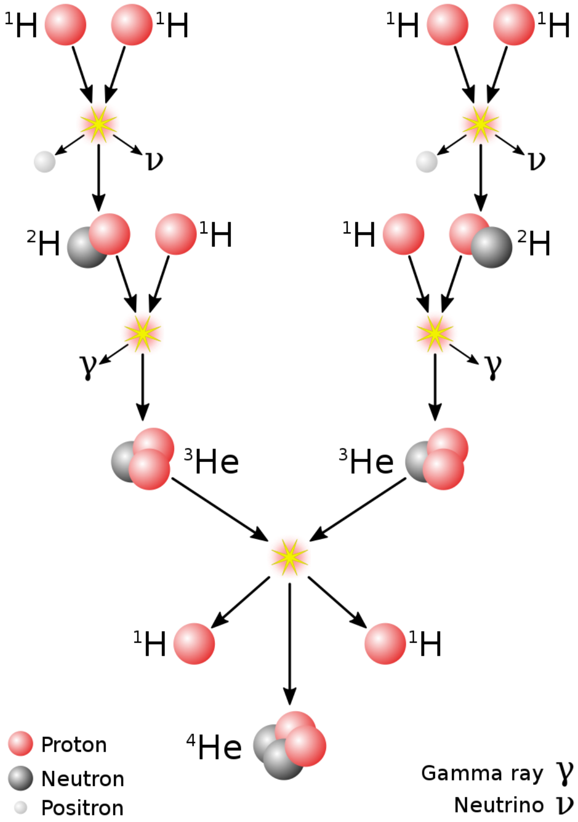


http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html

Fusion in the sun provides the energy

- **Proton-proton chain in sun or smaller**

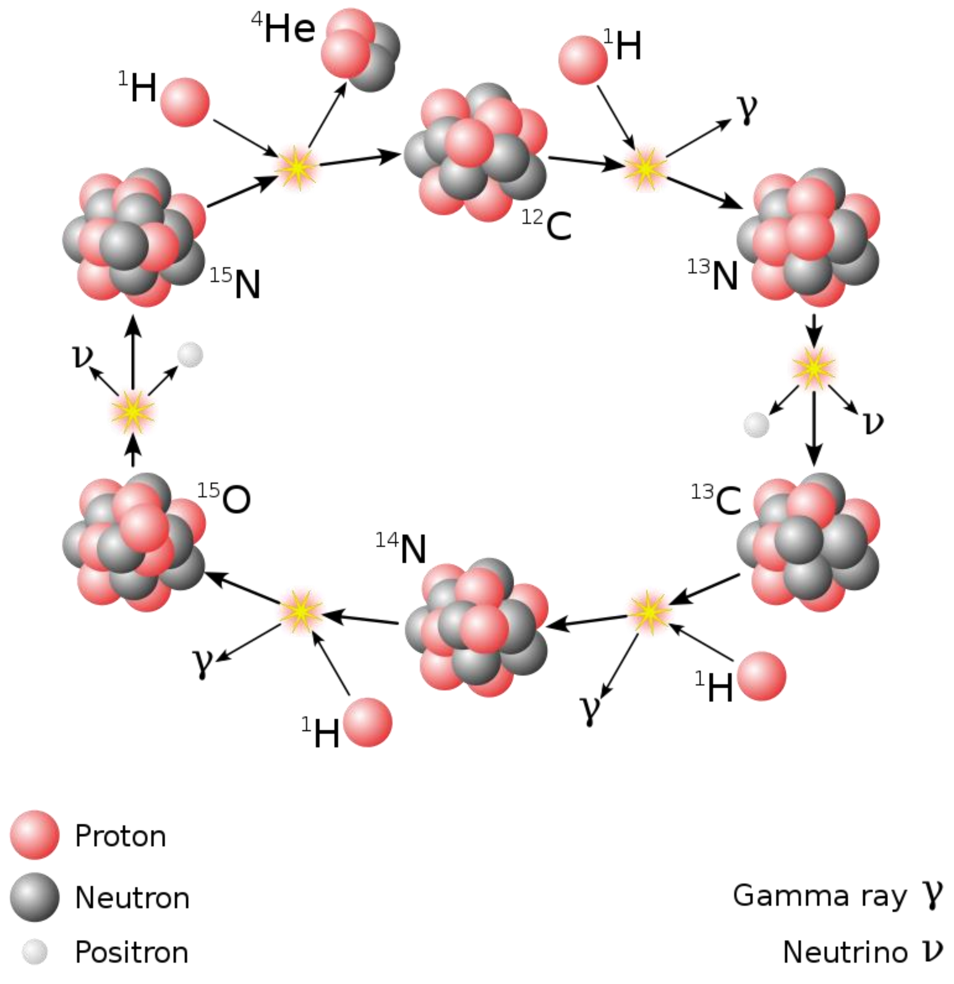




- **Particles are confined by the gravity.**

https://en.wikipedia.org/wiki/Sun
https://en.wikipedia.org/wiki/Nuclear_fusion

In heavy sun, the fusion reaction is the CNO cycle



https://en.wikipedia.org/wiki/Nuclear_fusion

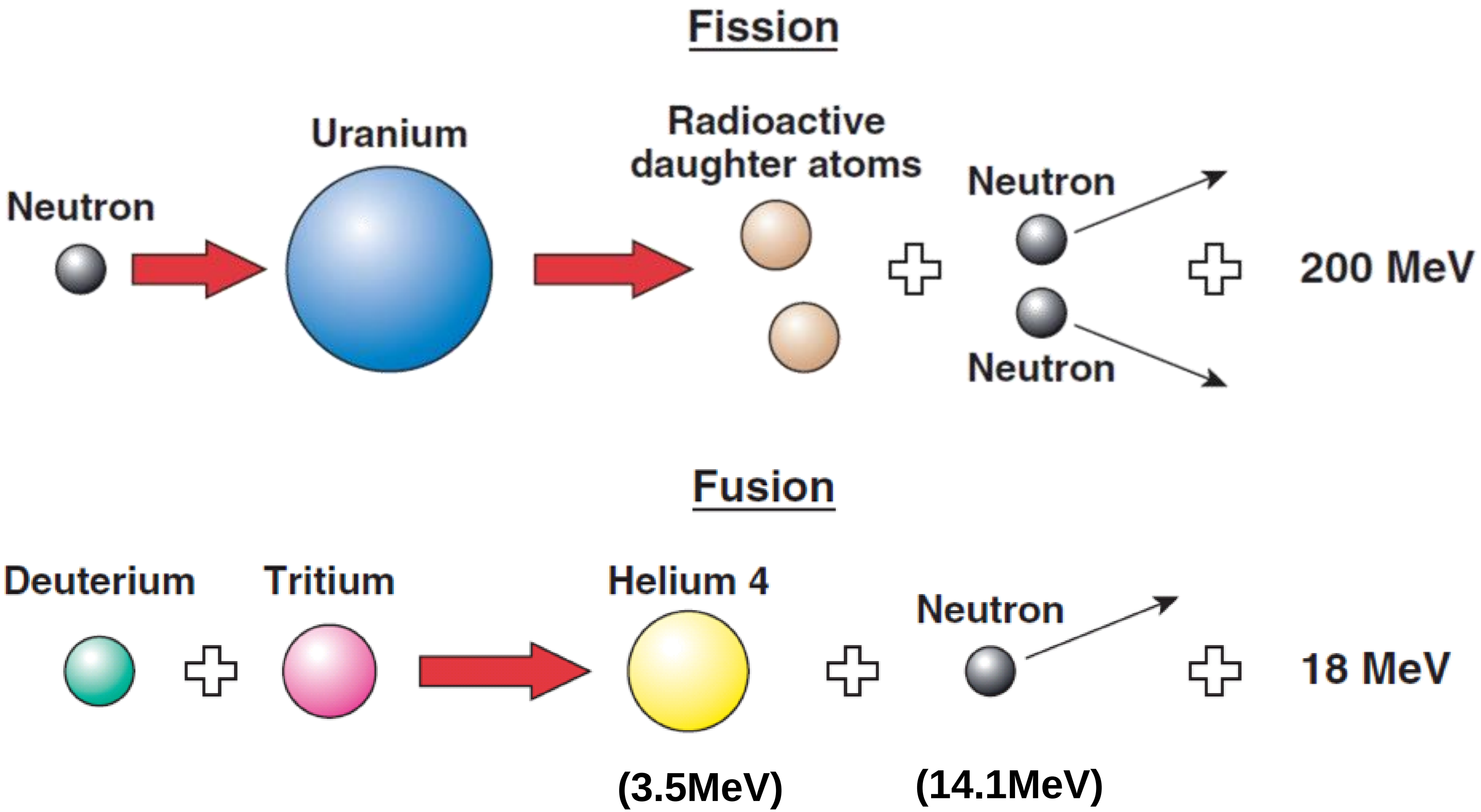
The cross section of proton-proton chain is much smaller than D T fusion

Reaction	$\sigma_{10\ keV}$ (barn)	$\sigma_{100\ keV}$ (barn)	σ_{max} (barn)	ε_{max} (keV)
$D+T \rightarrow \alpha+n$	2.72×10^{-2}	3.43	5.0	64
$D+T \rightarrow T+p$	2.81×10^{-4}	3.3×10^{-2}	0.06	1250
$D+T \rightarrow {}^{3}He+n$	2.78×10^{-4}	3.7×10^{-2}	0.11	1750
$T+T \rightarrow \alpha+2n$	7.90×10^{-4}	3.4×10^{-2}	0.16	1000
$D+{}^{3}He \rightarrow \alpha+p$	2.2×10^{-7}	0.1	0.9	250
$p+{}^{6}Li \rightarrow \alpha+{}^{3}He$	6×10^{-10}	7×10^{-3}	0.22	1500
$p+{}^{11}B \rightarrow 3\alpha$	(4.6×10^{-17})	3×10^{-4}	1.2	550
$p+p \rightarrow D+e^{+}+v$	(3.6×10^{-26})	(4.4×10^{-25})		
$p+{}^{12}C \rightarrow {}^{13}N+\gamma$	(1.9×10^{-26})	2.0×10^{-10}	1.0x10.4	400
${}^{12}C+{}^{12}C$ (all branches)		(5.0×10^{-103})		

- **"( )" are theoretical values while others are measured values.**

The Physics of Inertial Fusion, by Stefano Atzeni and Jürgen Meyer-Ter-Vehn

Nuclear fusion and fission release energy through energetic neutrons



Nuclear fusion provides more energy per atomic mass unit (amu) than nuclear fission

Fusion of $^2H + ^3H$: $$\frac{Q}{A} = \frac{17.6\ MeV}{(3+2)\ amu} = 3.5\ \frac{MeV}{amu}$$

Fission of ^{235}U: $$\frac{Q}{A} = \frac{200\ MeV}{236\ amu} = 0.85\ \frac{MeV}{amu}$$

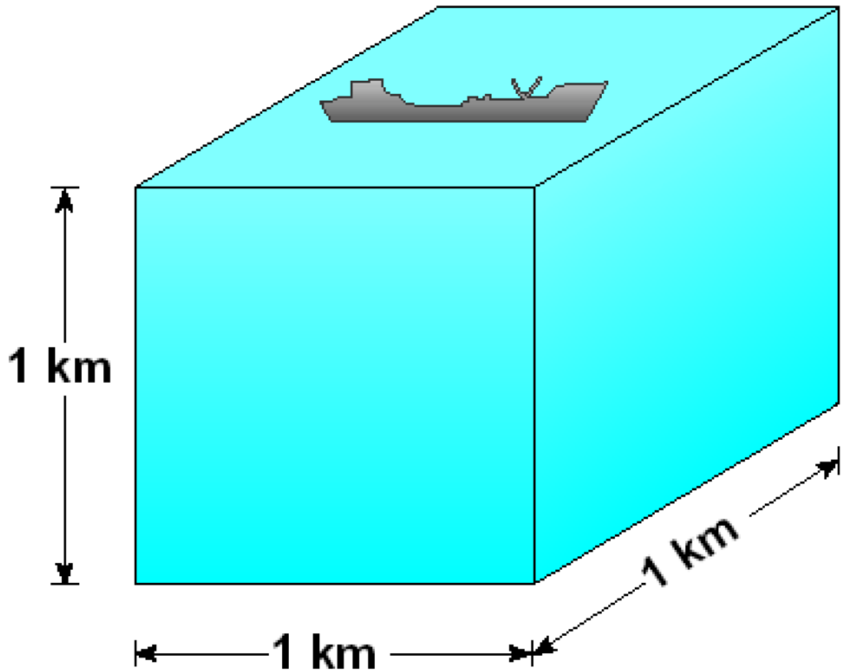
	Half-life (years)
U235	7.04×10^8
U238	4.47×10^9
…	
Tritium	12.3

What could you do with 1 kg DT?

- 1 kg DT -> 340 Tera joules
  - You can drive your car for ~40,000 km (back and forth between Keelung and Kaoshiung for 50 times).
  - You can keep your furnace running for 8 years.
  - You can blow things up! 1 TJ = 250 tons of TNT.

*R. Betti, HEDSA HEDP Summer School, 2015

Enormous fusion fuel can be produced from sea water

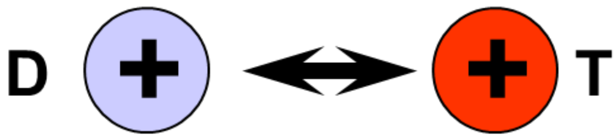


= Total energy of world oil reserve

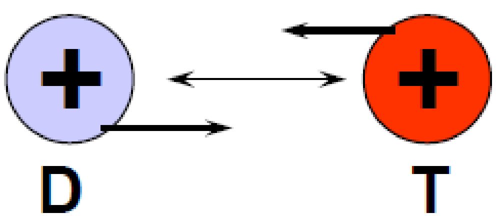
*R. Betti, HEDSA HEDP Summer School, 2015

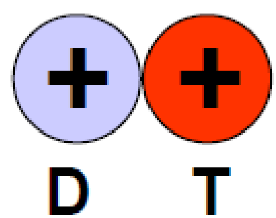
A “hot plasma” at 100M ⁰C is needed

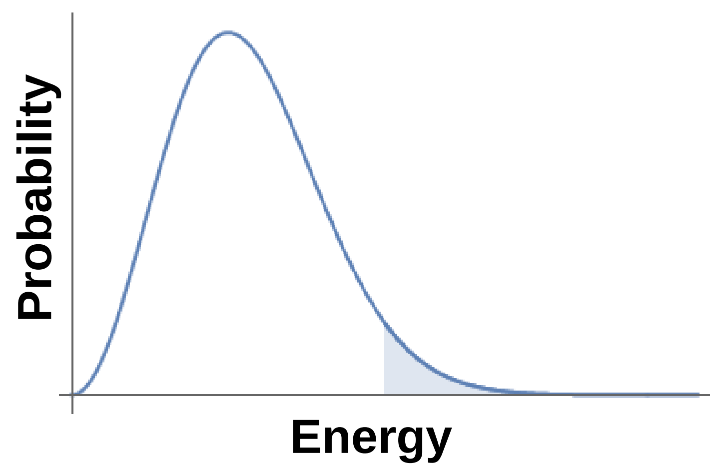
- **Probability for fusion reactions to occur is low at low temperatures due to the coulomb repulsion force.**



- **If the ions are sufficiently hot, i.e., large random velocity, they can collide by overcoming coulomb repulsion**





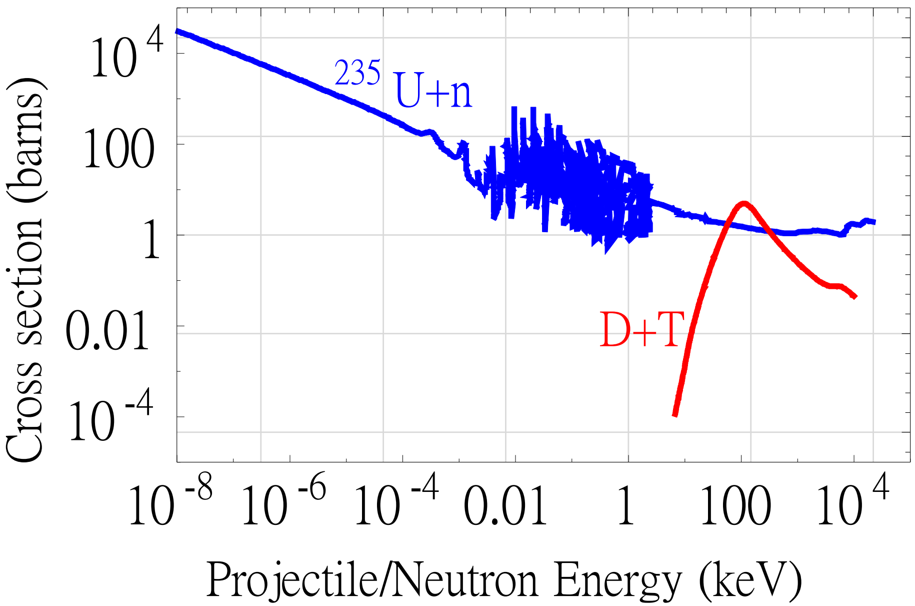


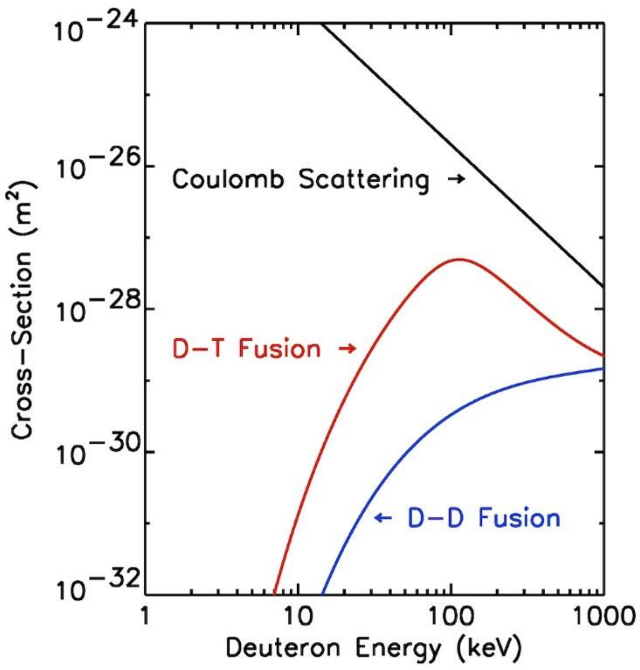
*R. Betti, HEDSA HEDP Summer School, 2015

Fusion is much harder than fission, a "hot plasma" at 100M ⁰C is needed

- **Fission:** $n +^{235}_{92} U \rightarrow^{236}_{92} U \rightarrow^{144}_{56} Ba +^{89}_{36} Kr + 3n + 177\ \mathrm{MeV}$
- **Fusion:** $D + T \rightarrow He^4\,(3.5\ \mathrm{MeV}) + n\,(14.1\ \mathrm{MeV})$

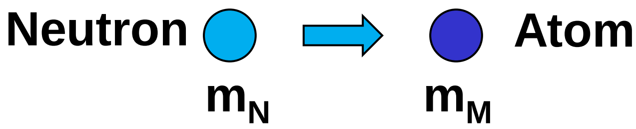
D ⊕ ⟷ ⊕ T





https://www6.lehigh.edu/~eus204/lab/PCL_fusion.php#x1-10096

Fast neutrons are slowed down due to the collisions

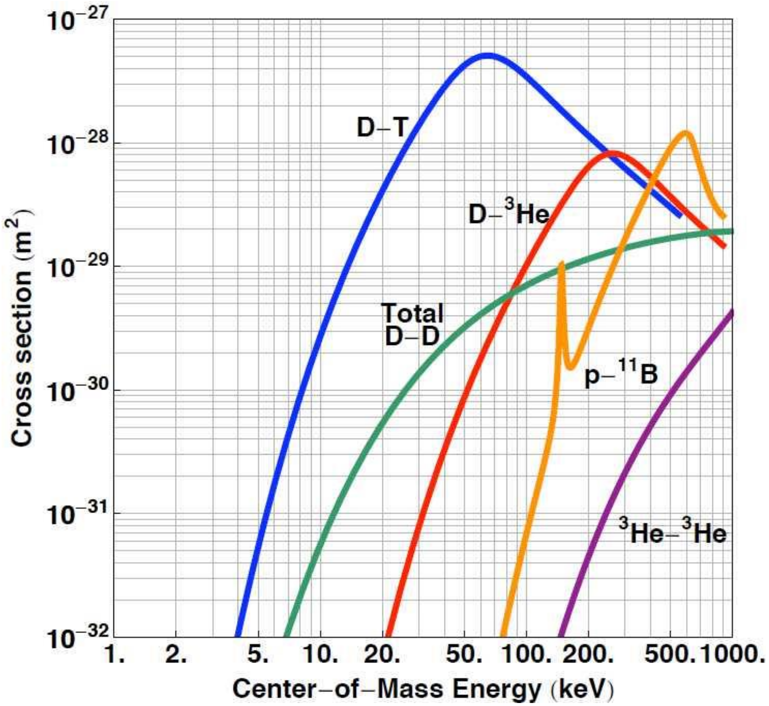


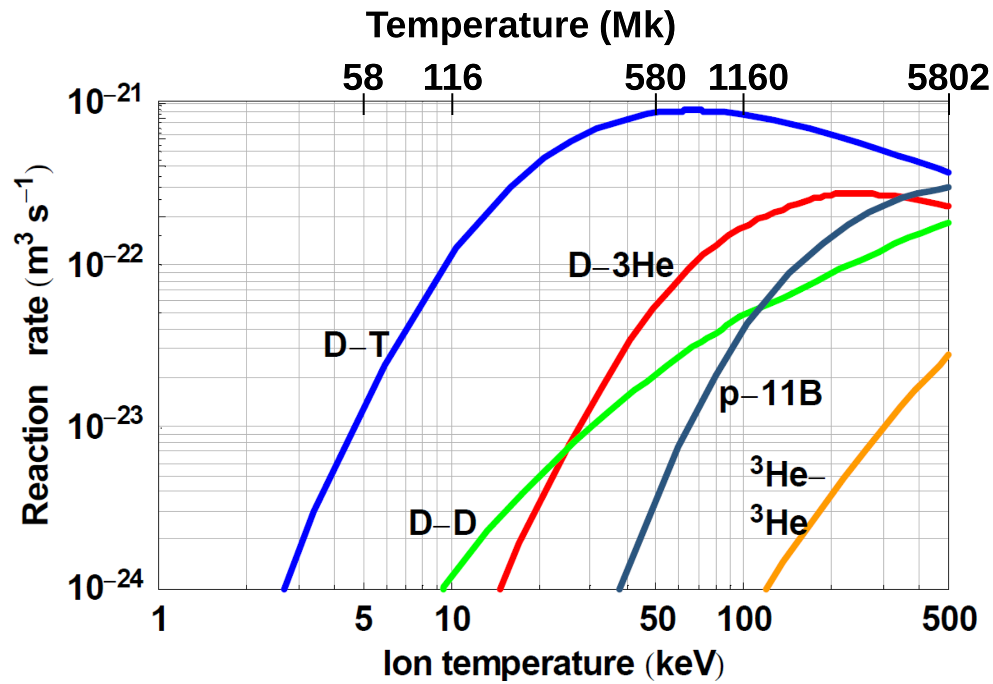
- **A moderator is used to slow down fast neutrons but not to absorb neutrons.**
- **For m_M~m_N, the energy decrement is higher. Therefore, H slows down neutron most efficiently.**
- **However, H + n → D, i.e., H absorbs neutrons.**
- **The best option is the D in the heavy water (D_2O).**

	Energy decrement	Neutron scattering cross section (σs) (Barns)	Neutron absorption cross section (σs) (Barns)
H	1	49 (H_2O)	0.66 (H_2O)
D	0.7261	10.6 (D_2O)	0.0013 (D_2O)
C	0.1589	4.7 (Graphite)	0.0035 (Graphite)

https://en.wikipedia.org/wiki/Neutron_moderator#cite_note-Weston-4
https://energyeducation.ca/encyclopedia/Neutron_moderator#cite_note-3

Fusion doesn’t come easy





$D + D \rightarrow T + p$

$\rightarrow He^3 + n$

$D + T \rightarrow He^4 + n$

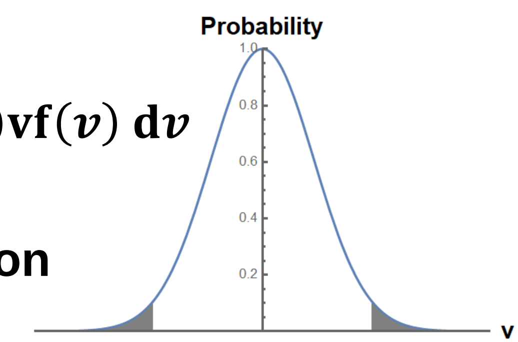
$D + He^3 \rightarrow He^4 + p$

$p + B^{11} \rightarrow 3He^4$

- **Reaction rate:**

$$<\sigma v>= \int \sigma(v) v f(v)\, dv$$

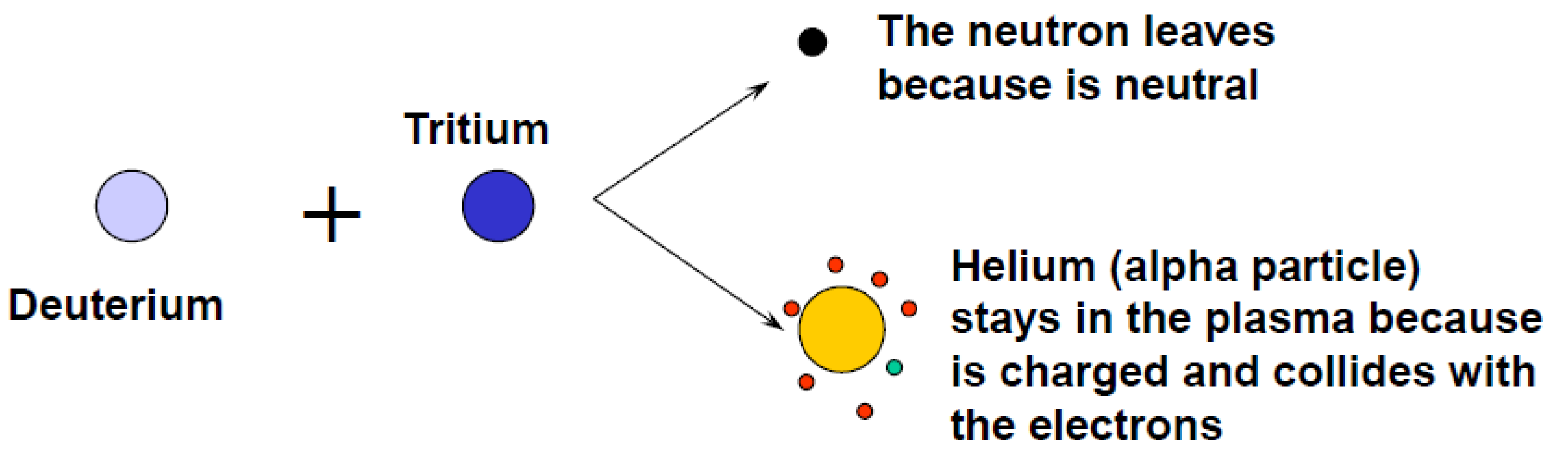
Cross section



https://i.stack.imgur.com/wXQD5.jpg
Santarius, J. F., “Fusion Space Propulsion – A Shorter Time Frame Than You Think”, JANNAF, Monterey, 5-8 December 2005.

It takes a lot of energy or power to keep the plasma at 100M ⁰C

- **Let the plasma do it itself!**



- **The α-particles heat the plasma.**

*R. Betti, HEDSA HEDP Summer School, 2015

Under what conditions the plasma keeps itself hot?

- **Steady state 0-D power balance:**

$S_\alpha + S_h = S_B + S_k$

S_α: α particle heating

S_h: external heating

S_B: Bremsstrahlung radiation

S_k: heat conduction lost

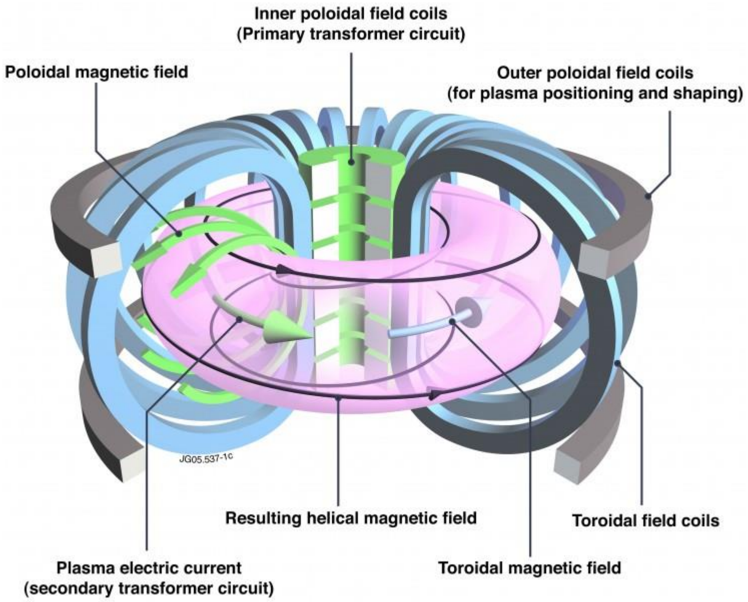
Ignition condition: Pτ > 10 atm-s = 10 Gbar - ns

- **P: pressure, or called energy density**
- **τ is confinement time**

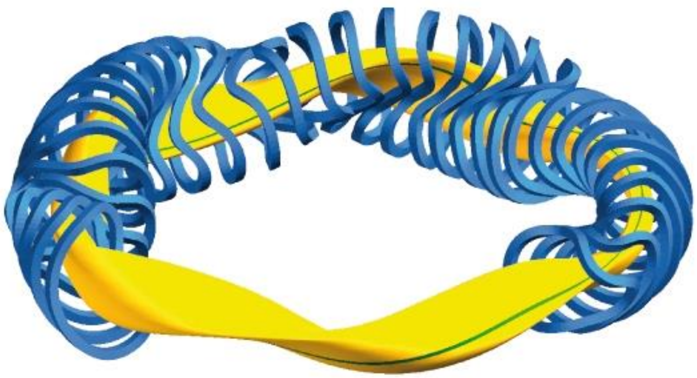
The plasma is too hot to be contained

- **Solution 1: Magnetic confinement fusion (MCF), use a magnetic field to contain it. P~atm, τ~sec, T~10 keV (10^8 ⁰C)**

Tokamak



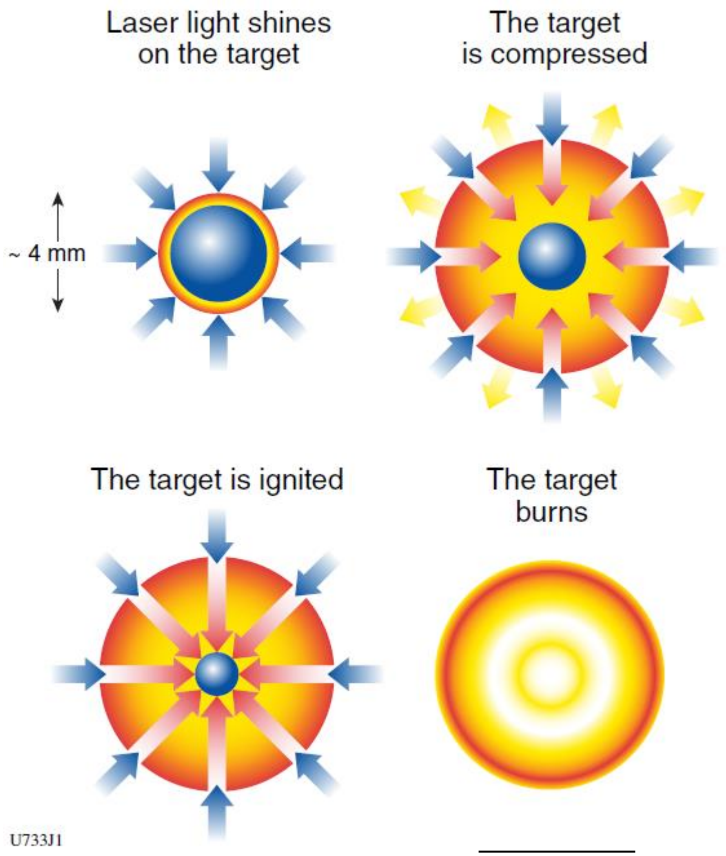
Stellarator



https://www.euro-fusion.org/2011/09/tokamak-principle-2/
https://en.wikipedia.org/wiki/Stellarator

Don't confine it!

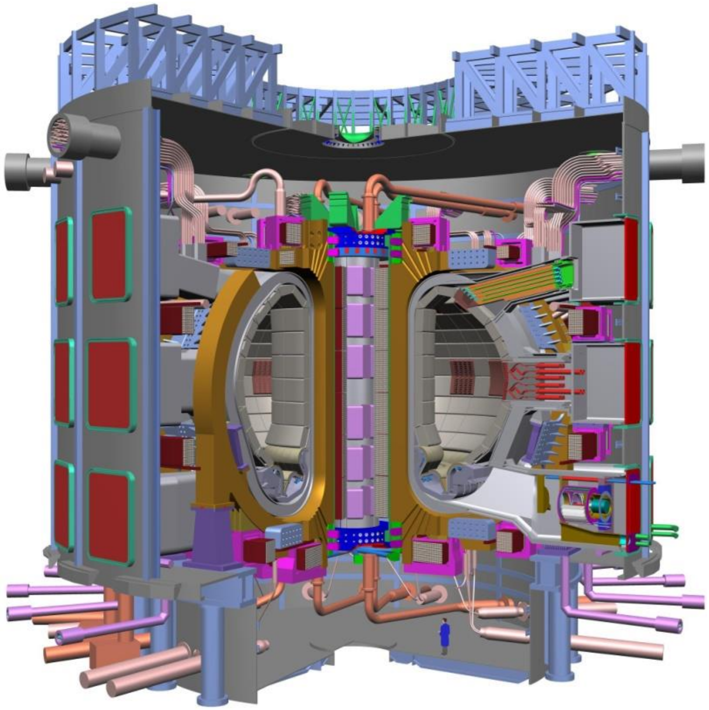
- **Solution 2: Inertial confinement fusion (ICF). Or you can say it is confined by its own inertia: P~Gigabar, τ~nsec, T~10 keV (10^8 ⁰C)**



Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

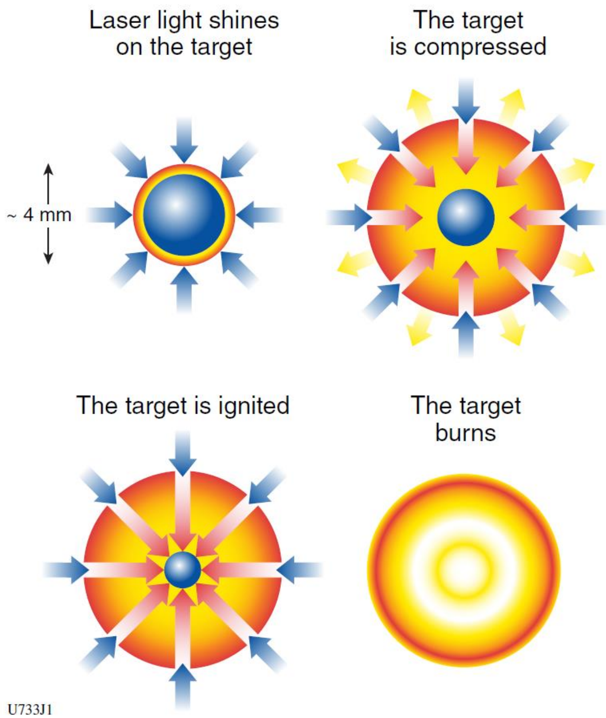
To control? Or not to control?

- **Magnetic confinement fusion (MCF)**



  - **Plasma is confined by toroidal magnetic field.**

- **Inertial confinement fusion (ICF)**



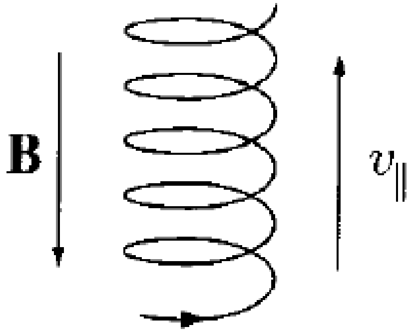
  - **A DT ice capsule filled with DT gas is imploded by laser.**

Laboratory for Laser Energetics, University of Rochester is a pioneer in laser fusion

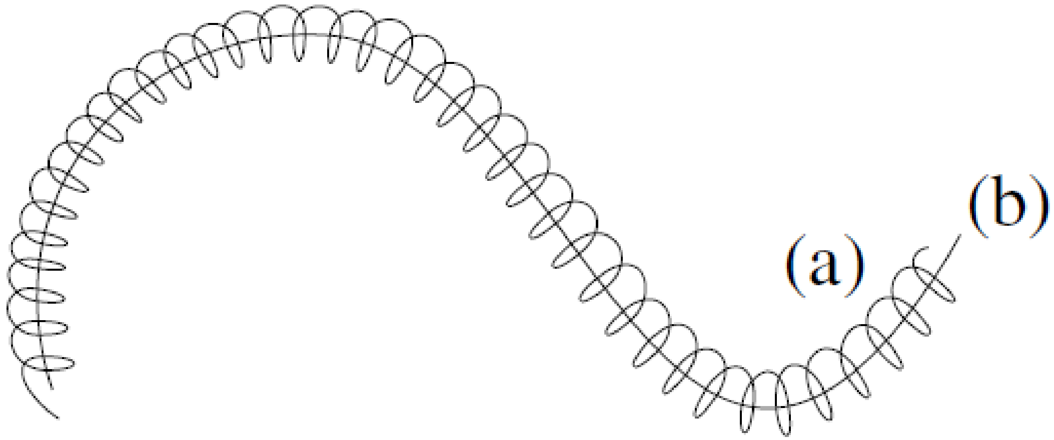
Outline

- Introduction to nuclear fusion
- **Magnetic confinement fusion (MCF)**
  - **Tokamak**
  - **Stellarator**
- Inertial confinement fusion (ICF)
  - Indirection drive ICF
  - Direct drive ICF
- Innovation idea – MCF + ICF
- Pulsed-power system at NCKU

Charged particles gyro around the magnetic fields

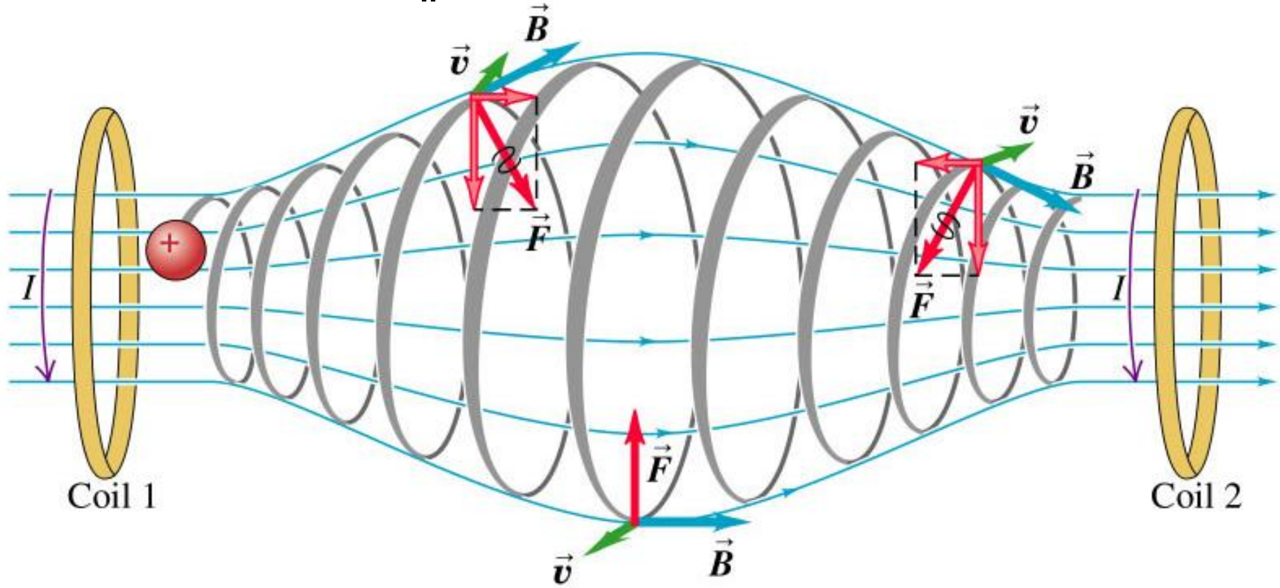


$$r_L = \frac{mv_\perp}{|q|B}$$



Charged particles can be partially confined by a magnetic mirror machine

- **Charged particles with small $v_{||}$ eventually stop and are reflected while those with large $v_{||}$ escape.**



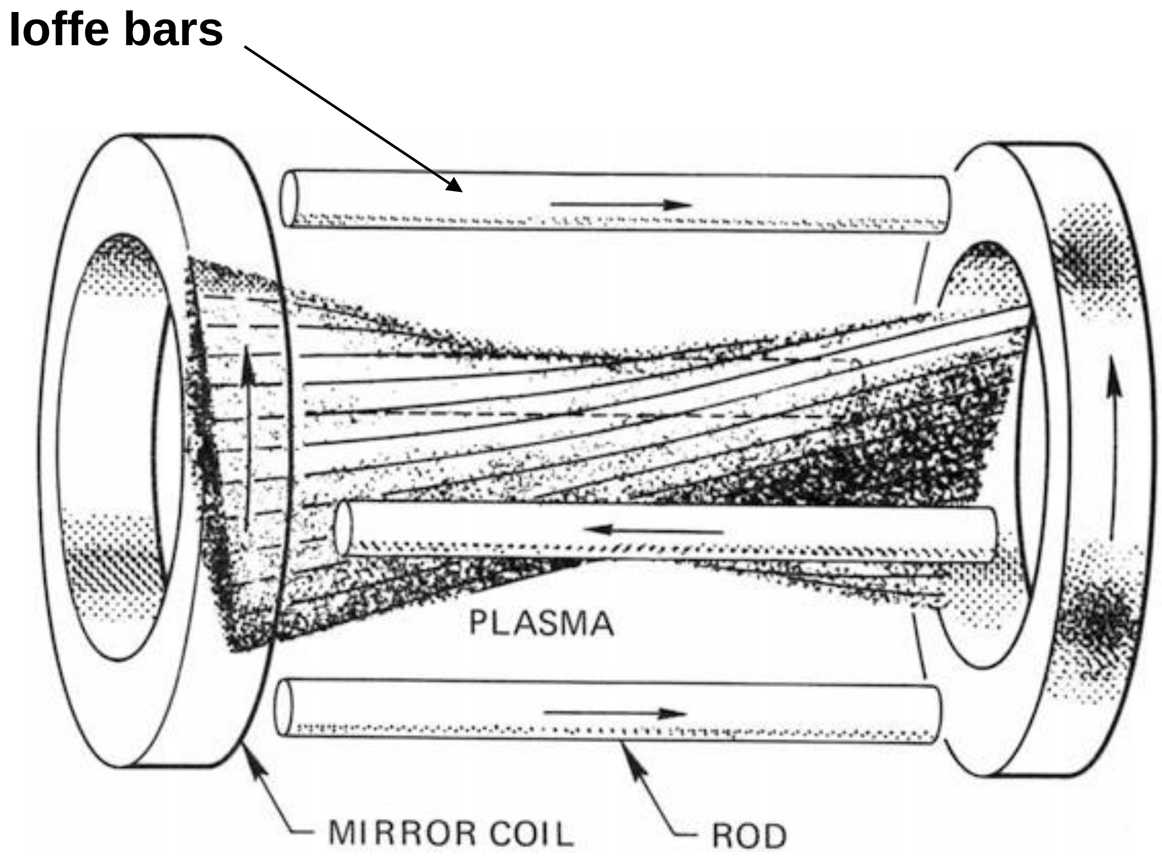
$$\frac{1}{2}mv^2 = \frac{1}{2}mv_{||}{}^2 + \frac{1}{2}mv_{\perp}{}^2$$

- **Large $v_{||}$ may occur from collisions between particles.**

- **Those confined charged particle are eventually lost due to collisions.**

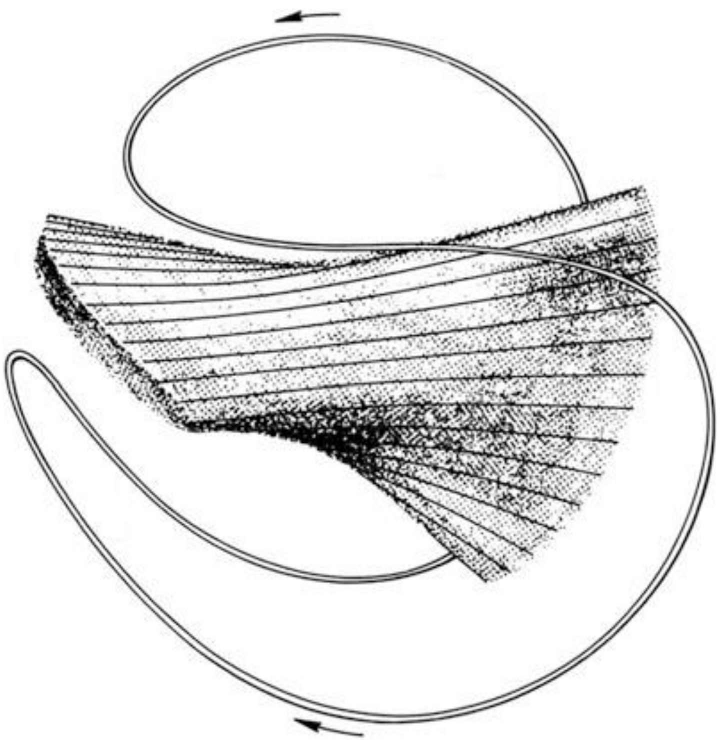
https://i.stack.imgur.com/GlzGZ.jpg

"Ioffe bars" are added to stabilize the Rayleigh-Taylor instabilities at the center of the mirror machine



A “baseball coil” is obtained if one links the coils and the bars into a single conductor

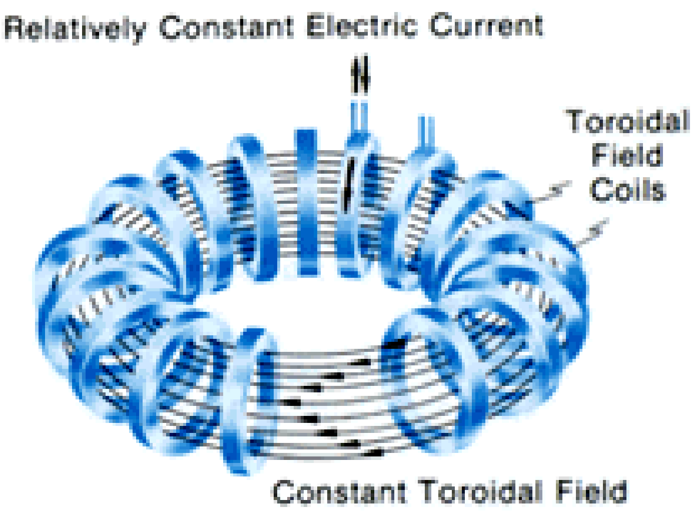
- **Baseball coil**

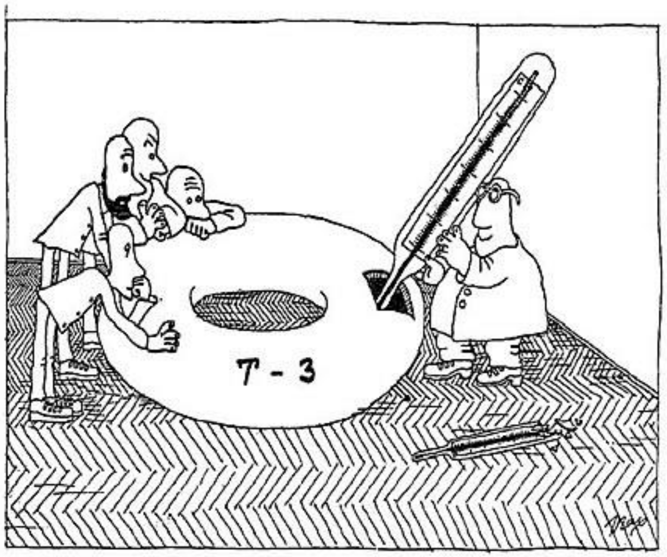


- **MFTF-B mirror machine**

Plasma can be confined in a doughnut-shaped chamber with toroidal magnetic field

- **Tokamak - "toroidal chamber with magnetic coils" (тороидальная камера с магнитными катушками)**

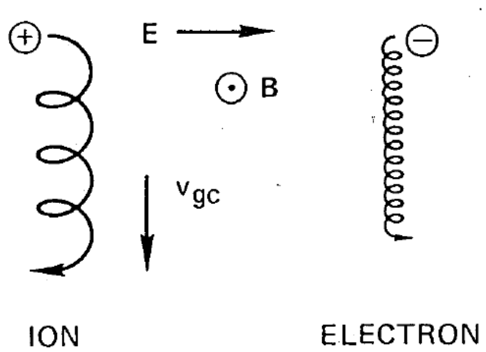




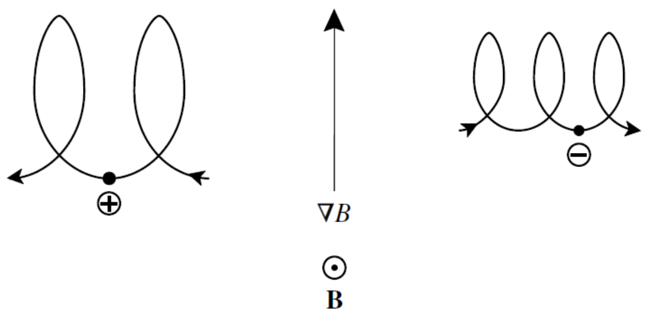
https://www.iter.org/mach/tokamak
https://en.wikipedia.org/wiki/Tokamak#cite_ref-4
Drawing from the talk “Evolution of the Tokamak” given in 1988 by B.B. Kadomtsev at Culham.

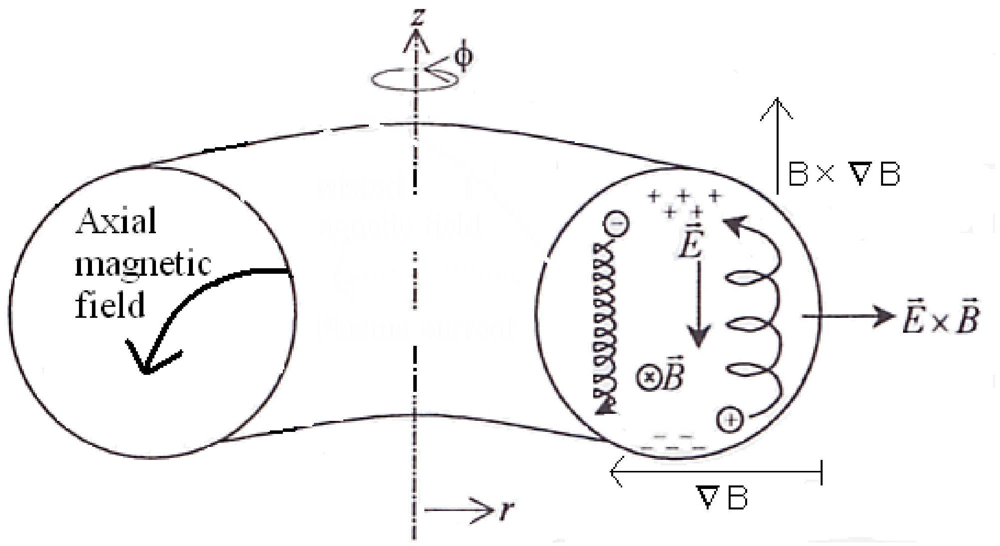
Charged particles drift across field lines

- **ExB drift**



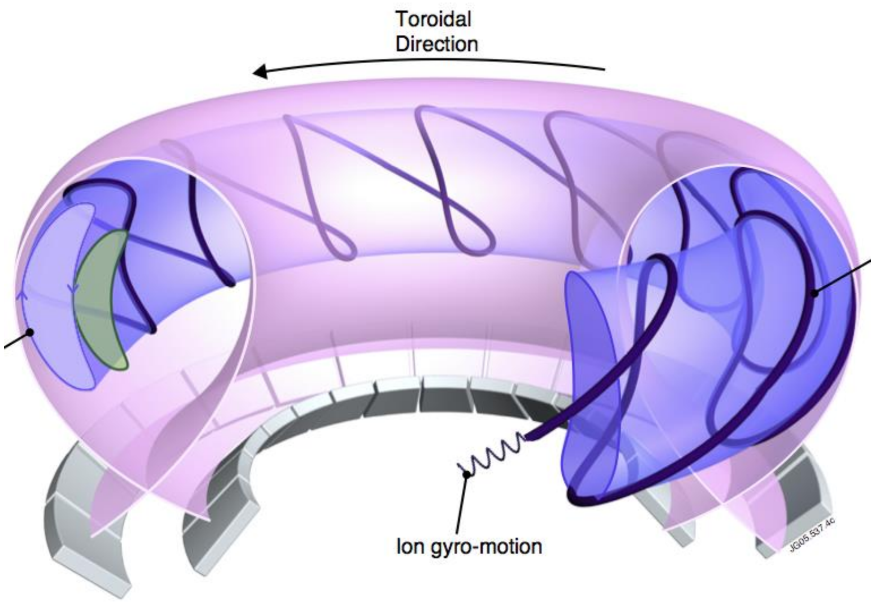
- **Grad-B drift**

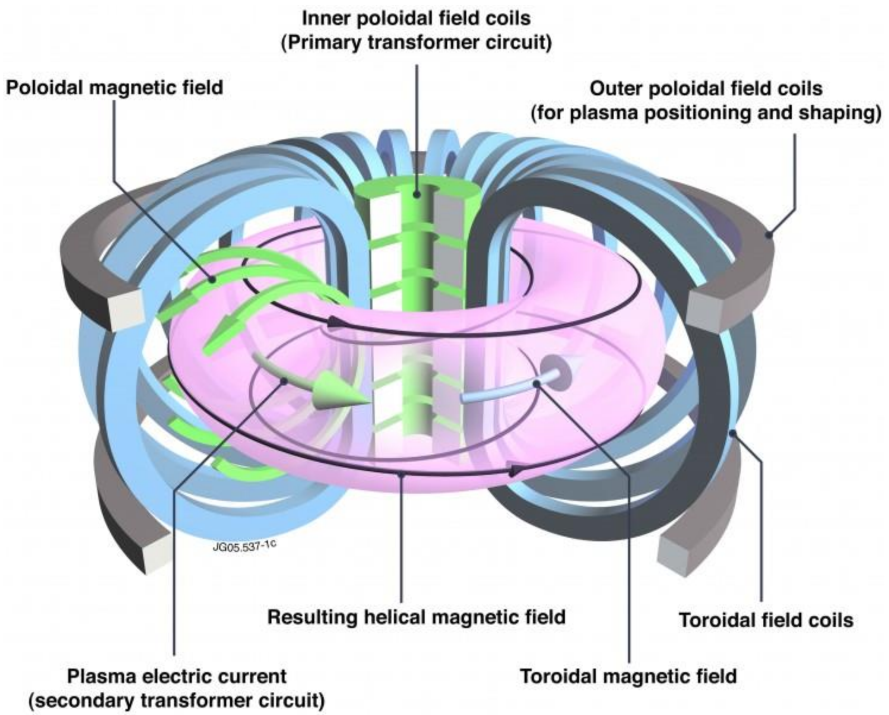




http://www.geocities.jp/tomoyahirata417/fusion/gennkou.htm

A poloidal magnetic field is required to reduce the drift across field lines

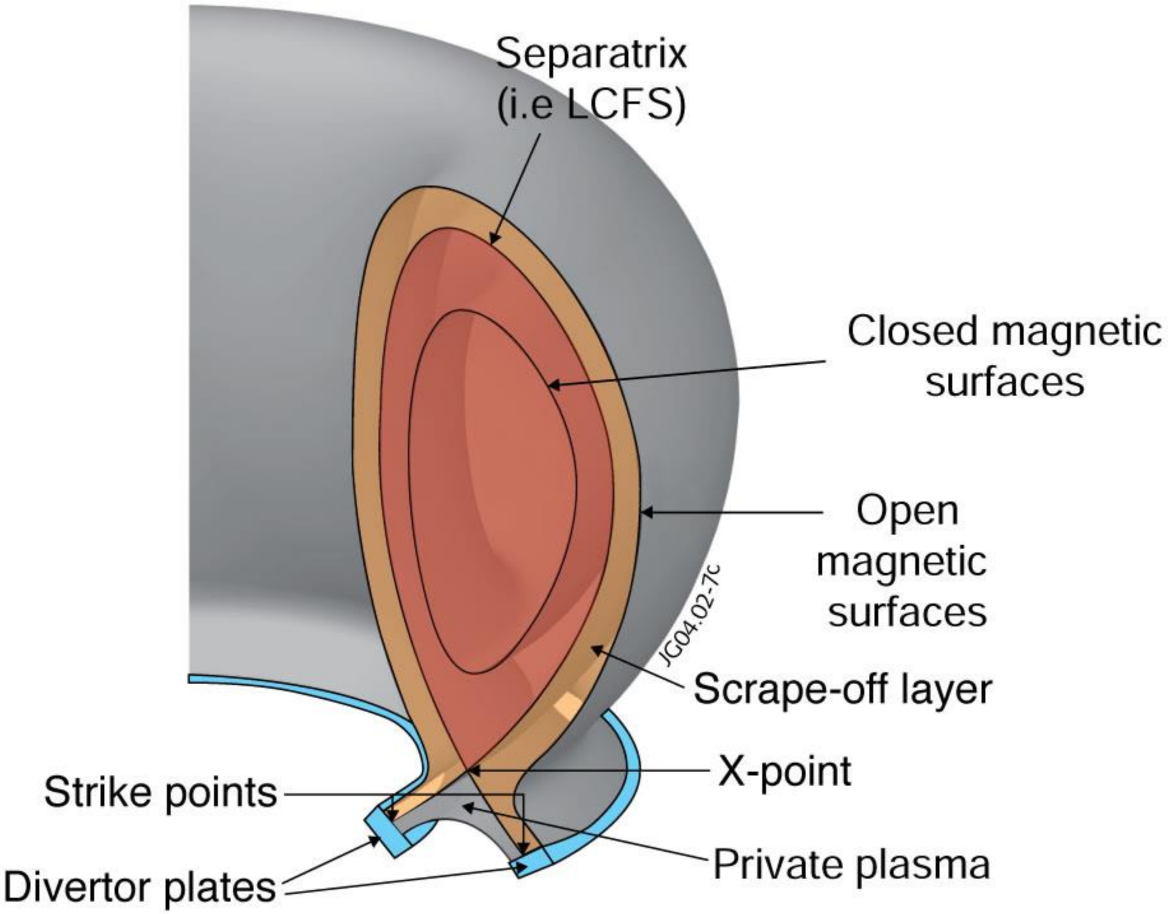




https://www.davidpace.com/keeping-fusion-plasmas-hot/
https://www.euro-fusion.org/2011/09/tokamak-principle-2/

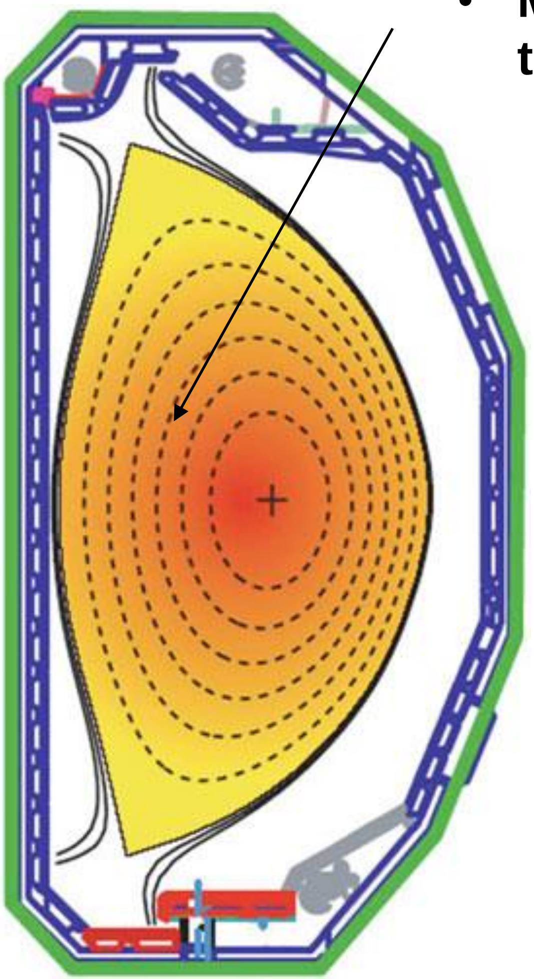
A poloidal magnetic field is required to reduce the drift across field lines

A divertor is needed to remove impurities and the power that escapes from the plasma



https://www.euro-fusion.org/newsletter/divertor-concepts/

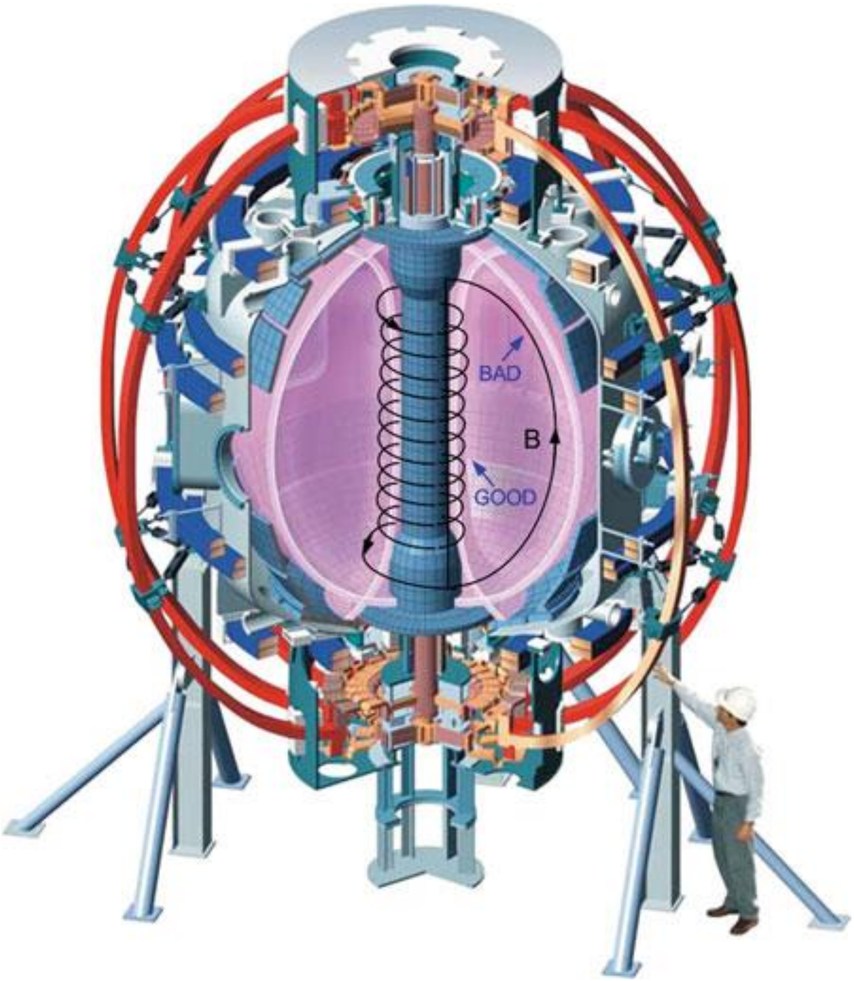
D-shaped tokamak with diverter is more preferred nowadays



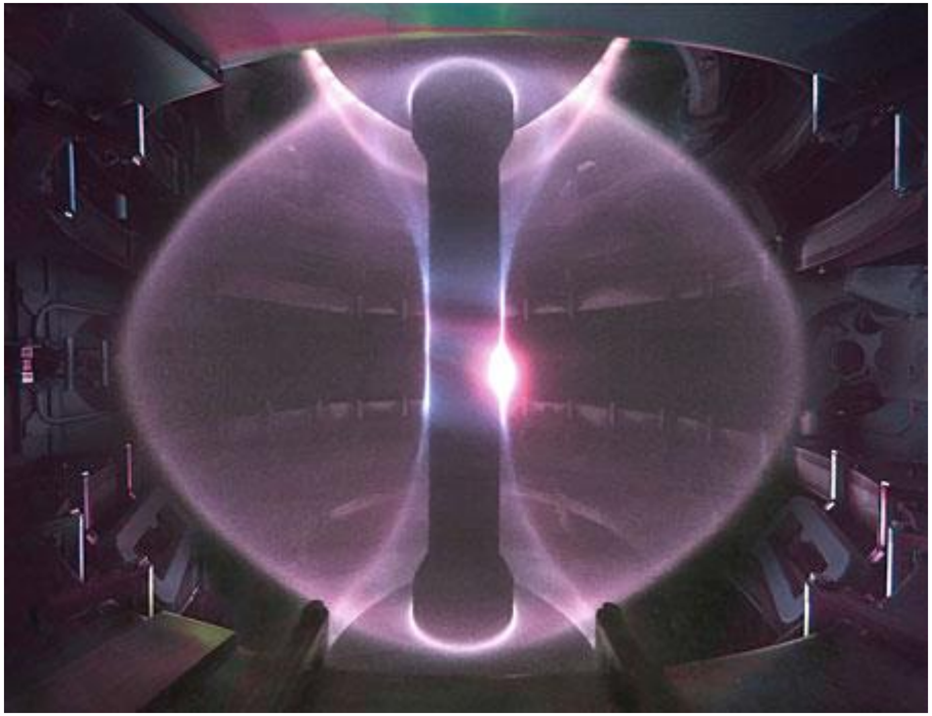
- **Make the plasma closer to the major axis**

Spherical tokamak is formed when the aspect ratio of a tokamak is reduced to the order of unity

- **NSTX @ Princeton**

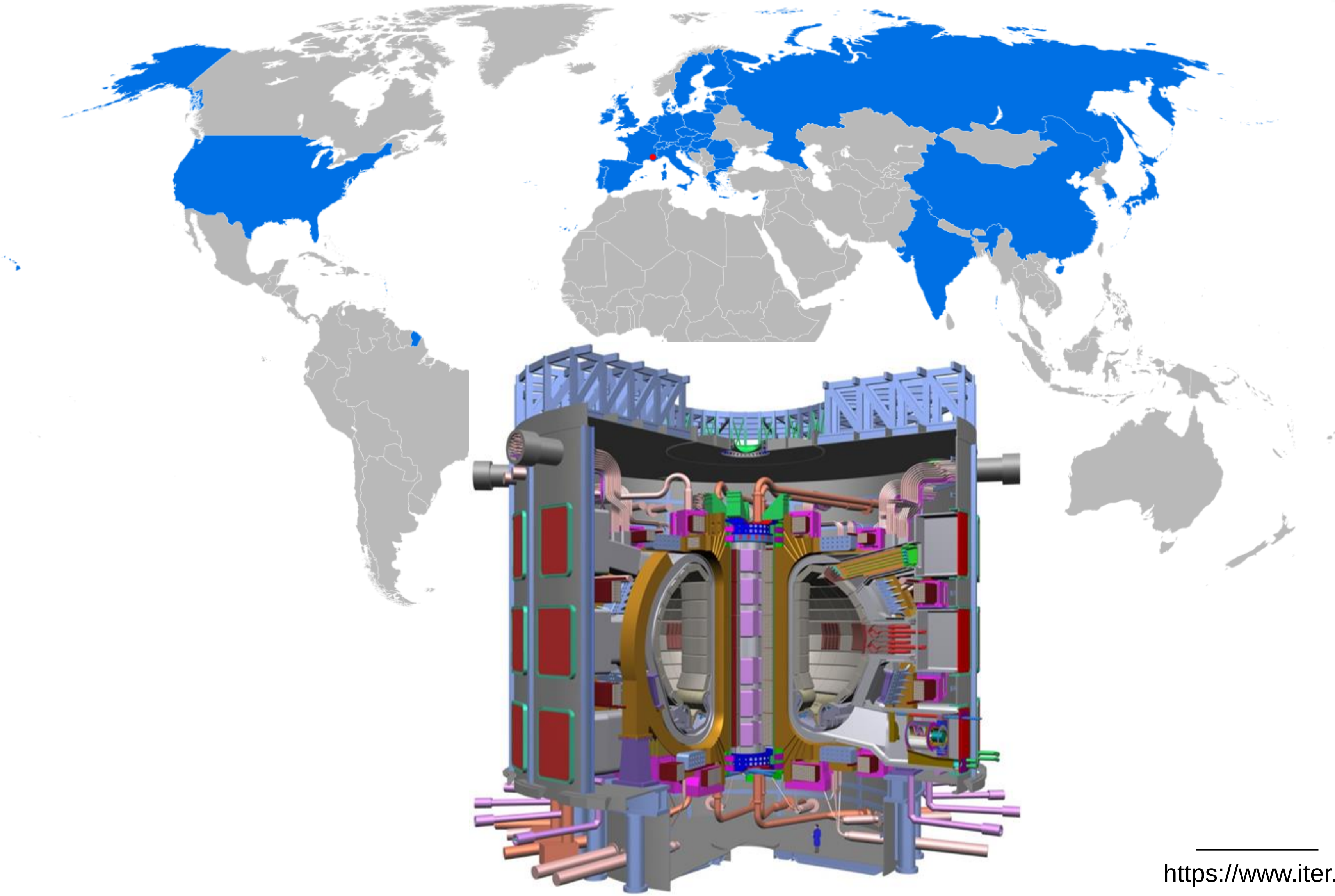


- **MegaAmpere Spherical Tokamak (MAST) @ Culham center for fusion energy, UK**



Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

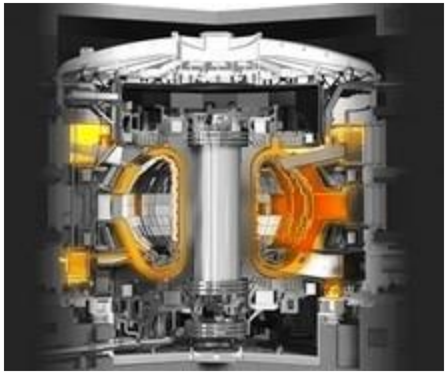
ITER ("The Way" in Latin) is one of the most ambitious energy projects in the world today



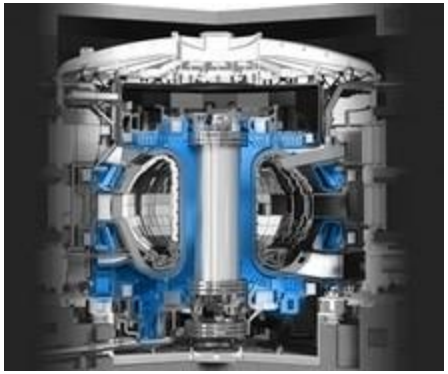
https://www.iter.org

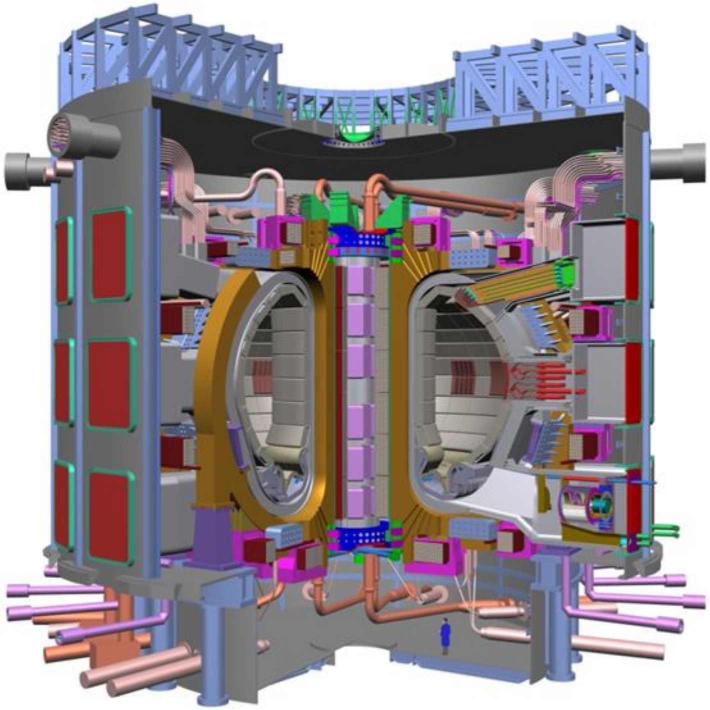
ITER ("The Way" in Latin) is one of the most ambitious energy projects in the world today

- **Vacuum vessel**

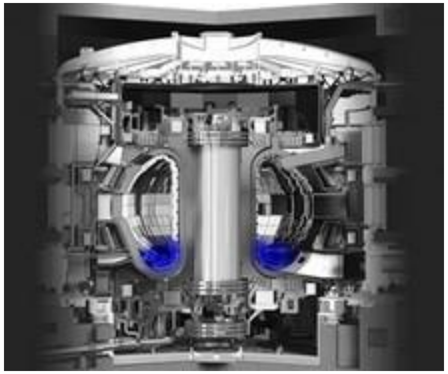


- **Magnets**

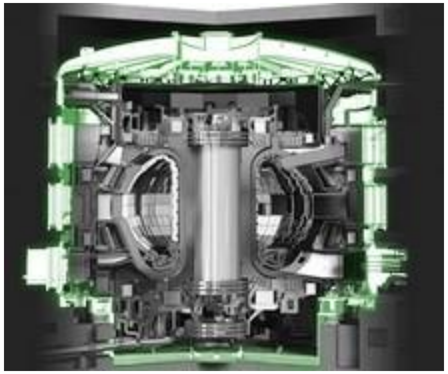




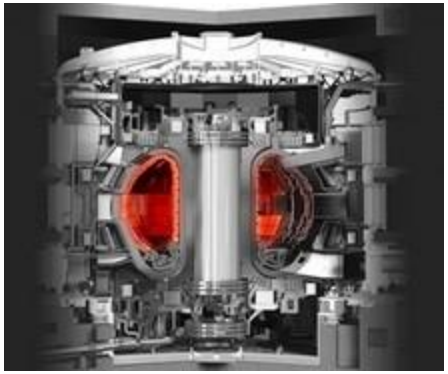
- **Divertor**



- **Cryostat**



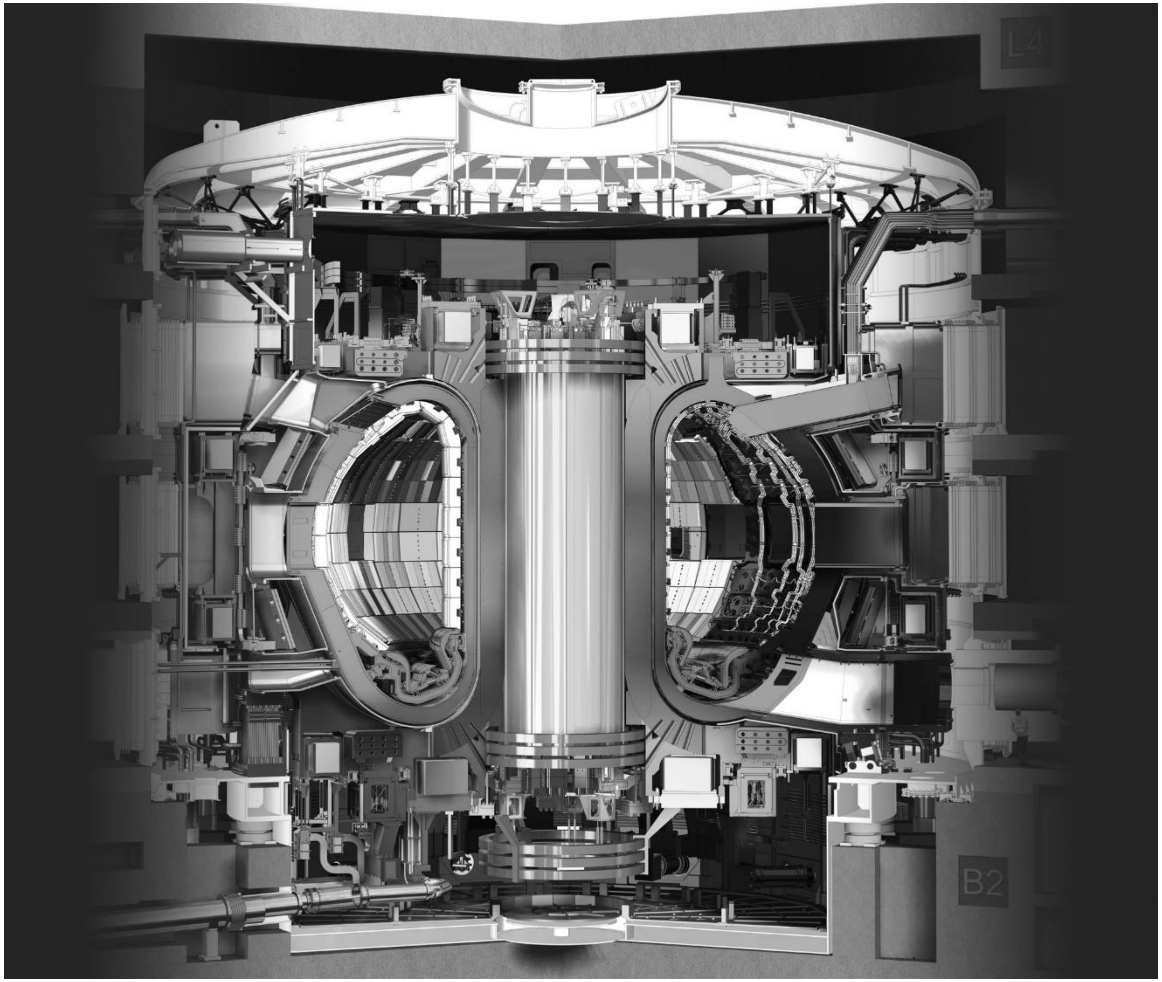
- **Blanket**



https://www.iter.org/

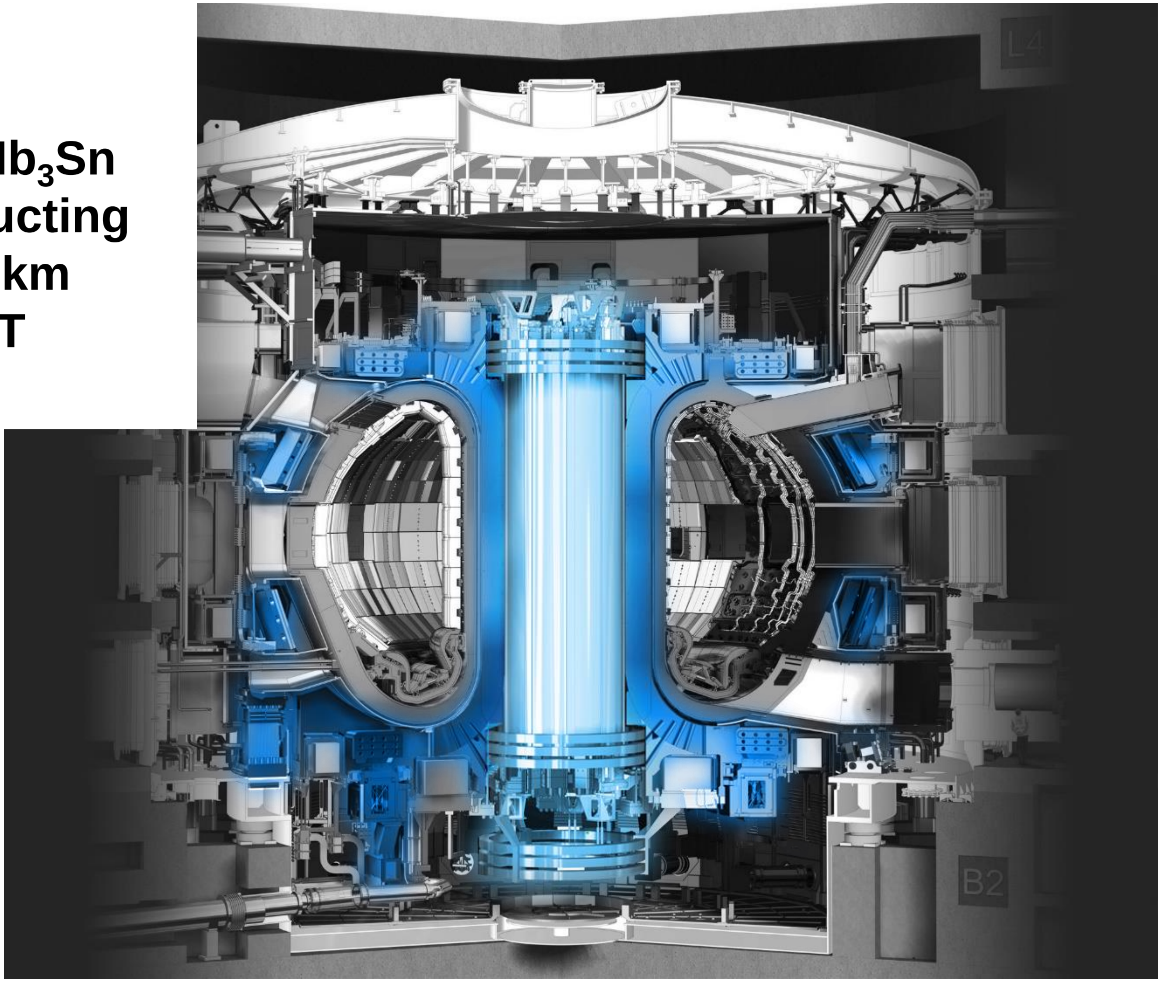
ITER

- T=150M ^{0}C
- P=500 MW



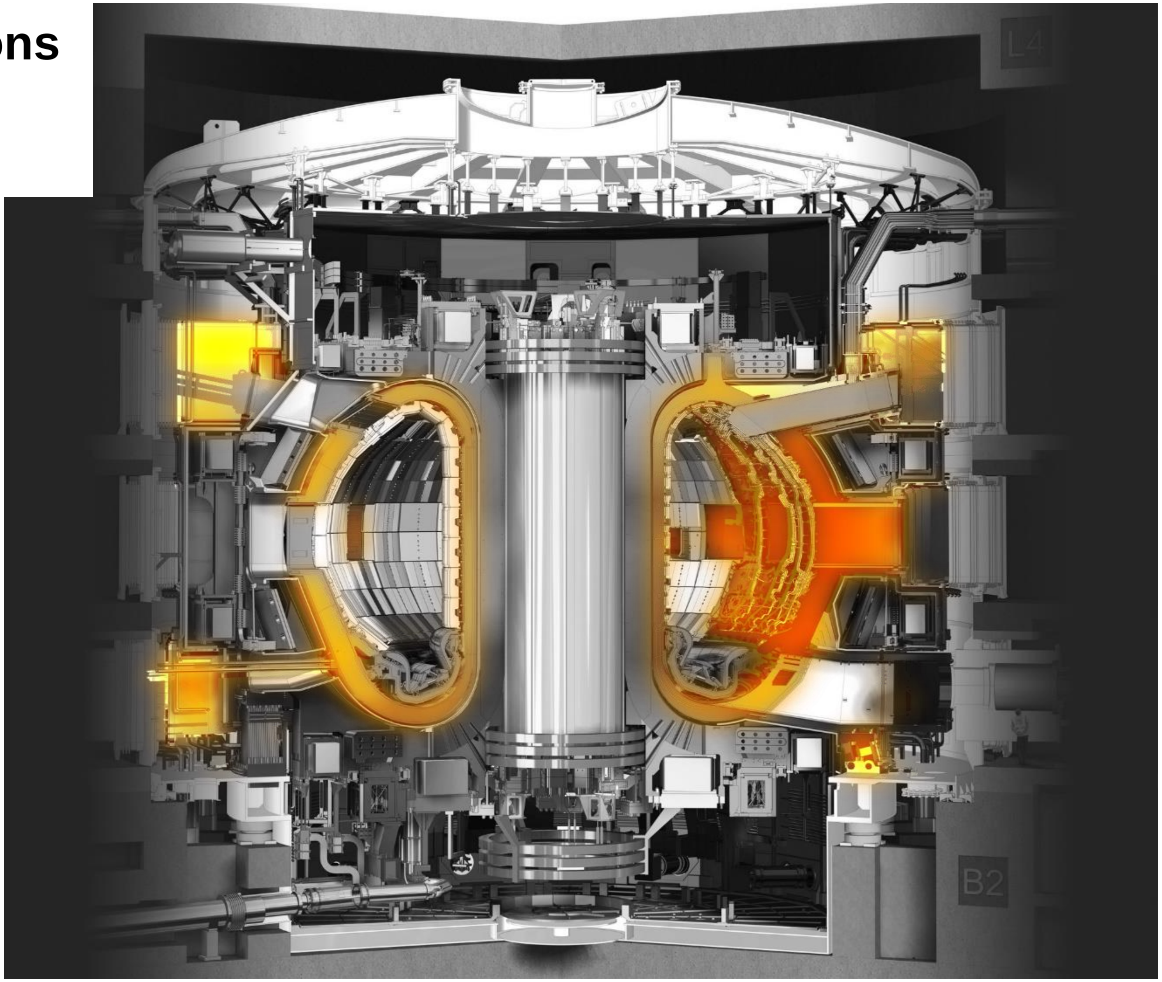
ITER – Magnets

- E_B=51 GJ
- T_B=4 K
- Length of Nb_3Sn superconducting strand: 10^5 km
- $B_{T,max}$=11.8 T
- $B_{P,max}$=6 T



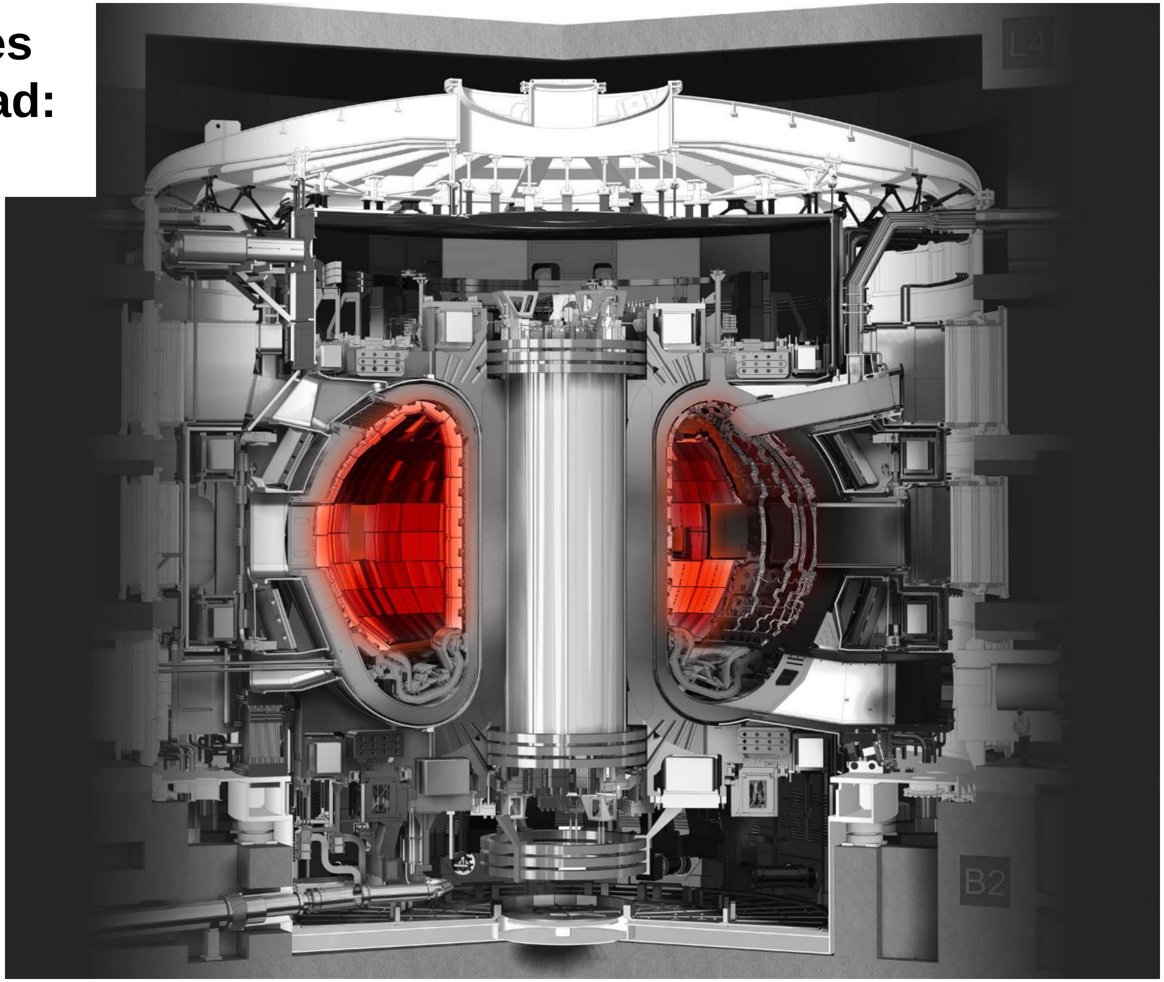
ITER – Vacuum vessel

- **W = 8000 tons**
- **V = 840 m³**
- **R = 6 m**



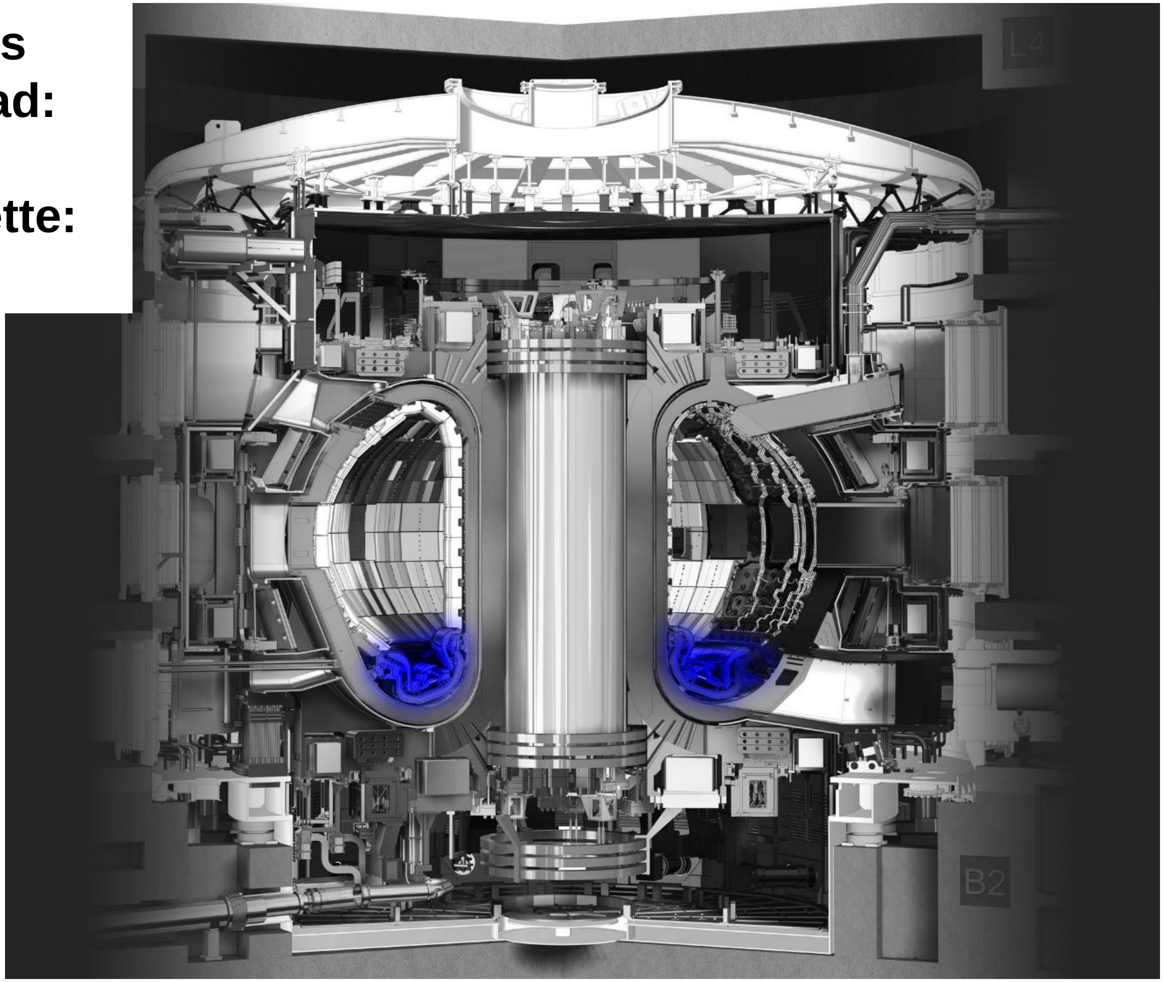
ITER – Blanket

- **440 modules**
- **Thermal load: 736 MW**



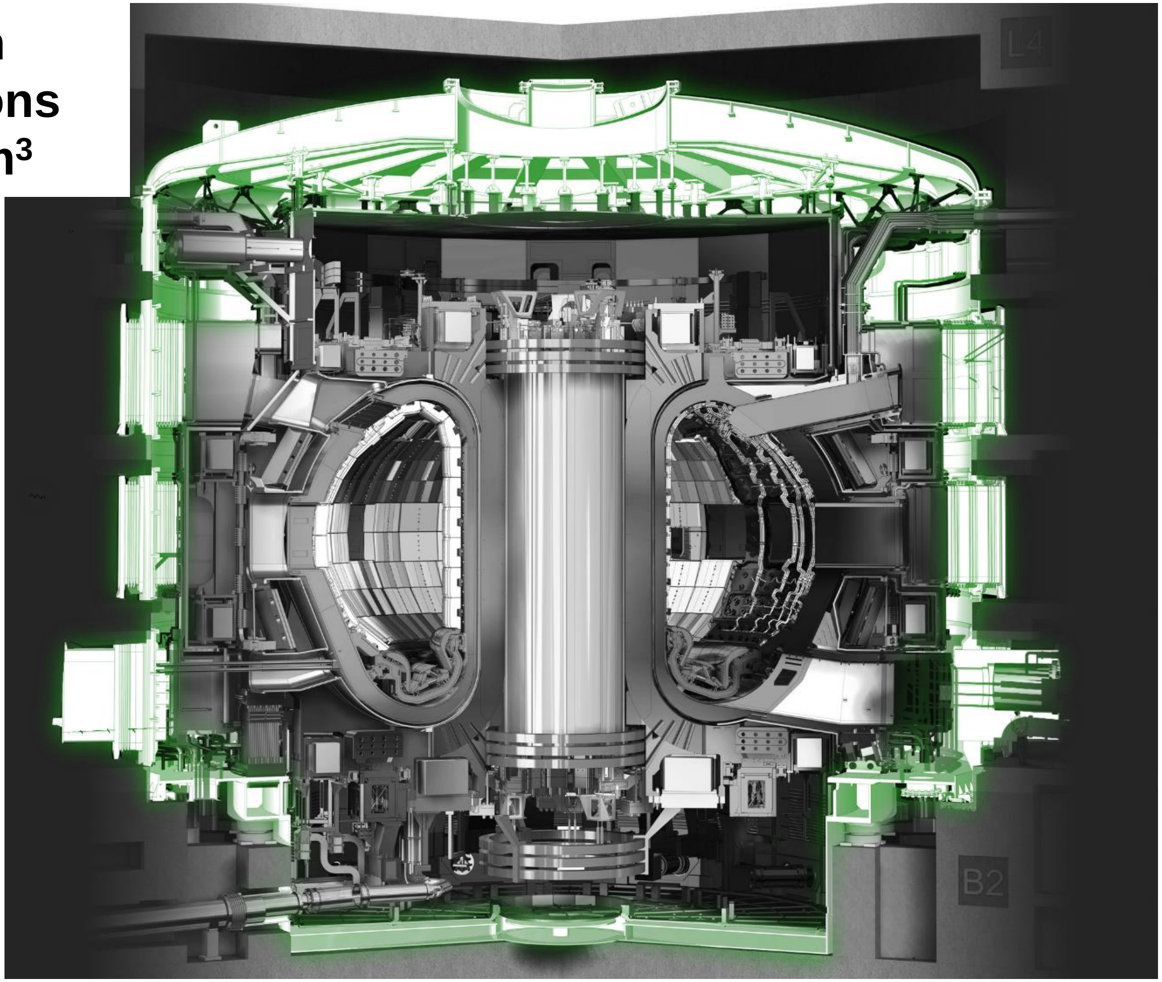
ITER – Divertor

- **54 cassettes**
- **Thermal load: 20 MW/m^2**
- **Each cassette: 10 tons**



ITER – Crystat

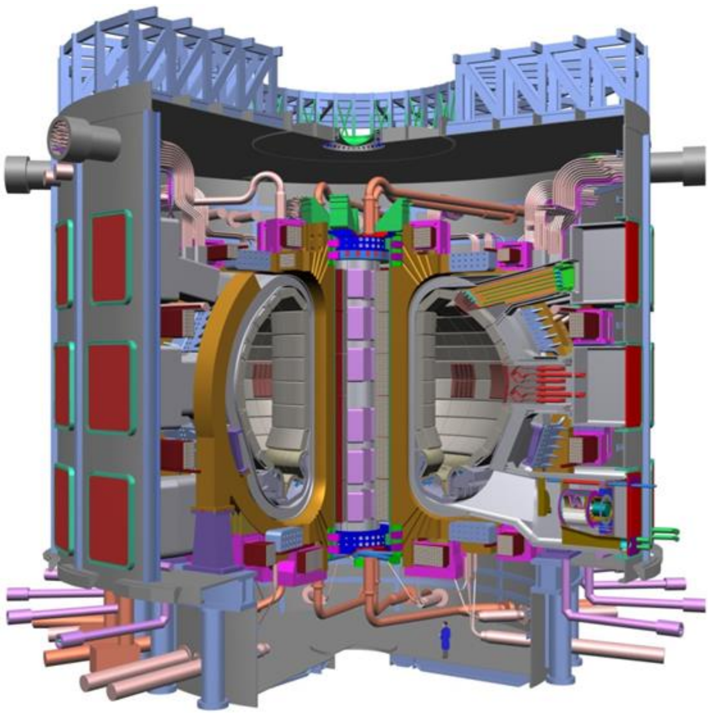
- $P = 10^{-6}$ atm
- W = 3800 tons
- $V = 16000\ m^3$



Supporting systems

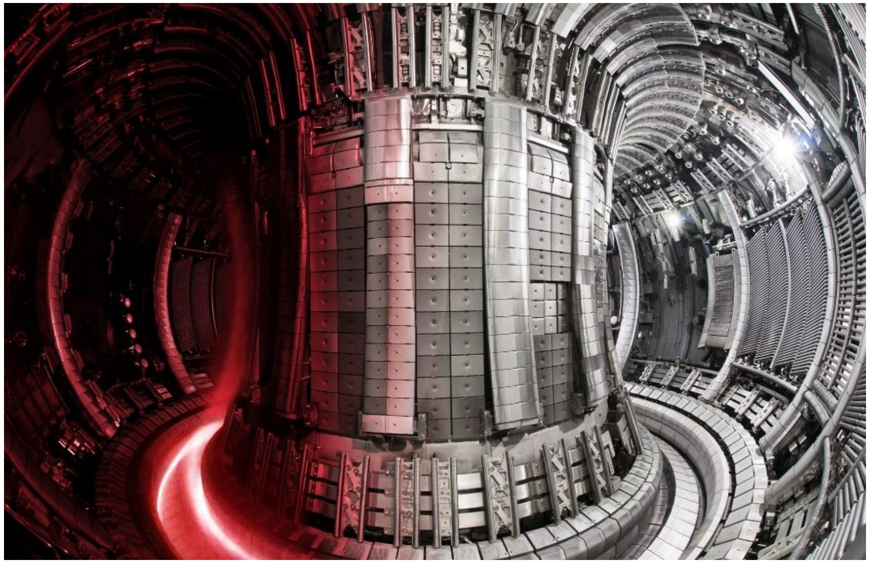
- Tritium breeding
- Control, Data access and Communication (CODAC)
- Cooling water
- Cryogenics
- Diagnostics
- Fuel cycle
- Hot cell - a secure environment for processing, repair or testing, etc., of components that have become activated by neutrons.
- Power supply
- Remote handling
- Heating and current drive
- Vacuum system

There is a long way to go, but we are on the right path…



- **Dec 2025 First Plasma**
- **2035 Deuterium-Tritium Operation begins**

Joint European Torus (JET) facility has a record-breaking 59 megajoules of sustained fusion energy

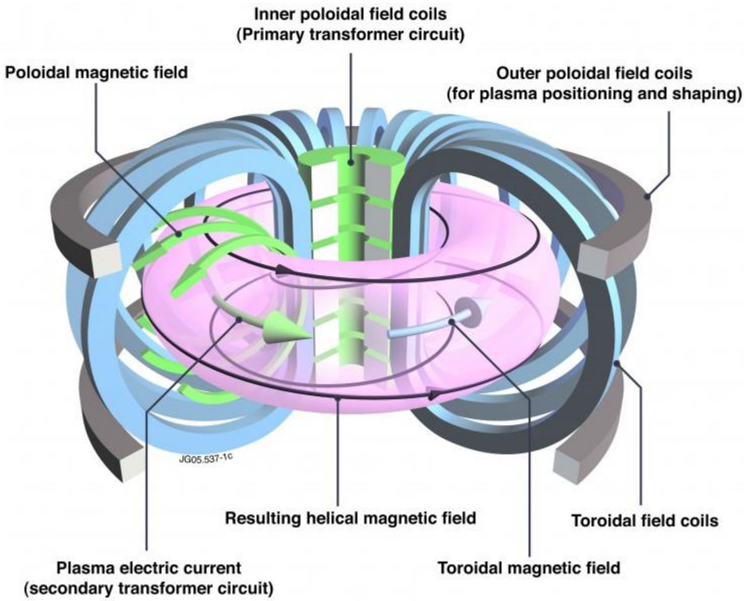


- **Record-breaking 59 megajoules of sustained fusion energy in Joint European Torus (JET) facility in Oxford demonstrates powerplant potential and strengthens case for ITER.**

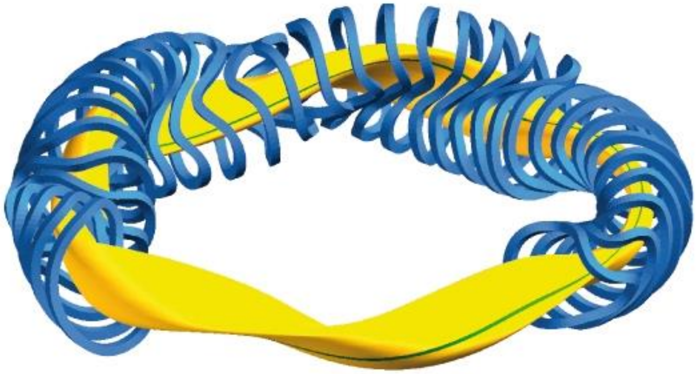
https://ccfe.ukaea.uk/resources/#gallery

Stellarator uses twisted coil to generate poloidal magnetic field

Tokamak

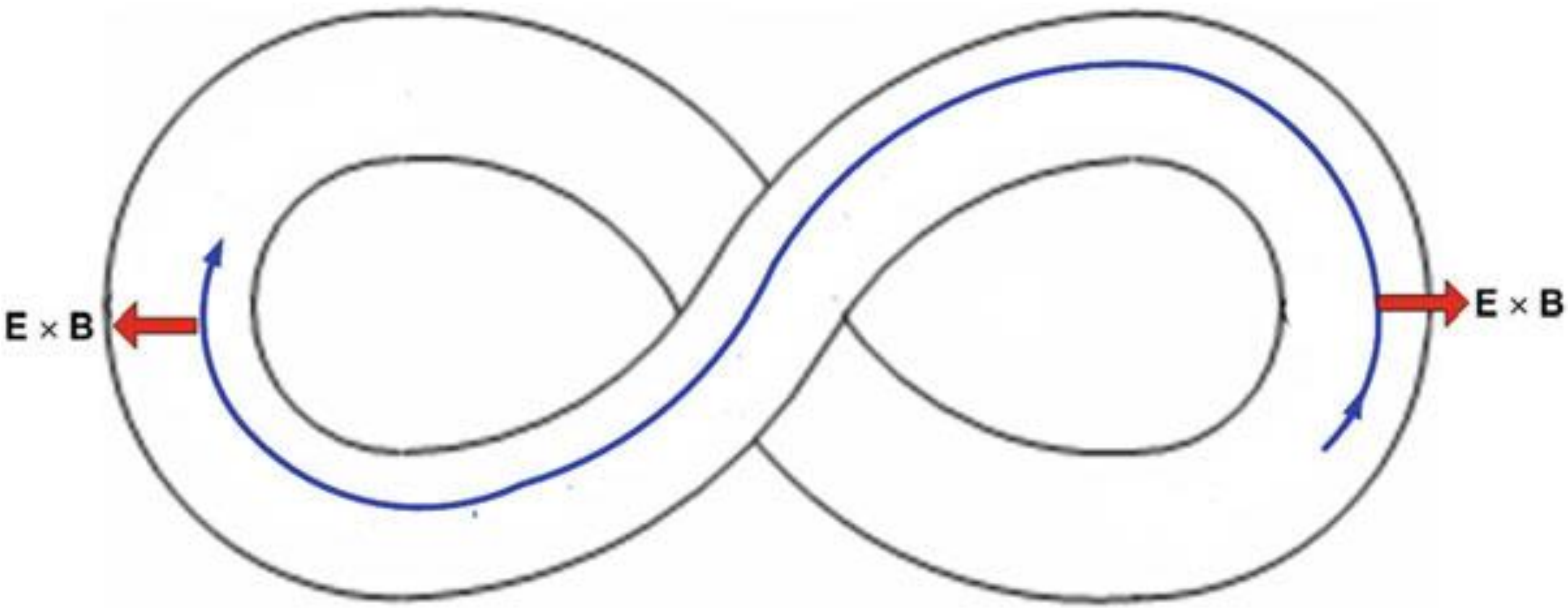


Stellarator



https://www.euro-fusion.org/2011/09/tokamak-principle-2/
https://en.wikipedia.org/wiki/Stellarator

A figure-8 stellarator solved the drift issues



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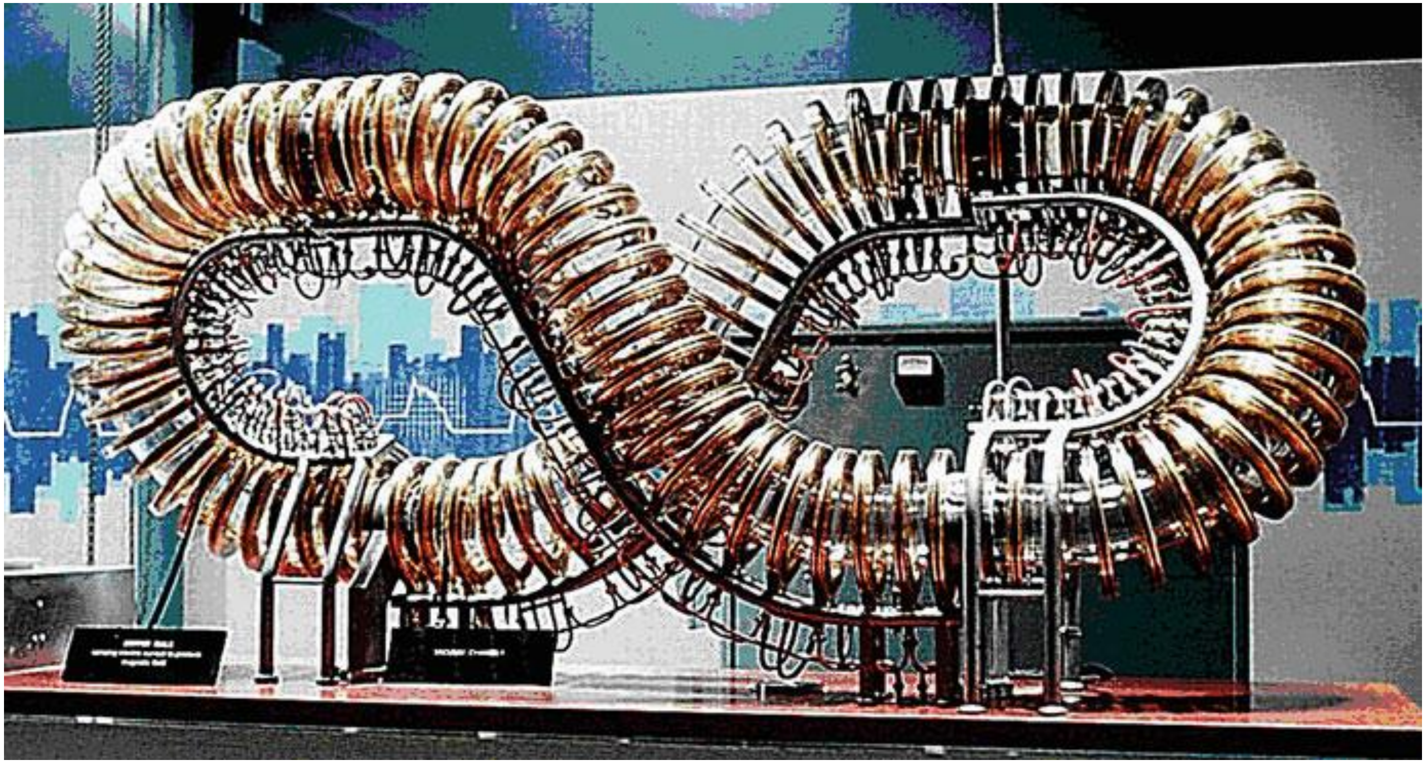
A figure-8 stellarator solved the drift issues

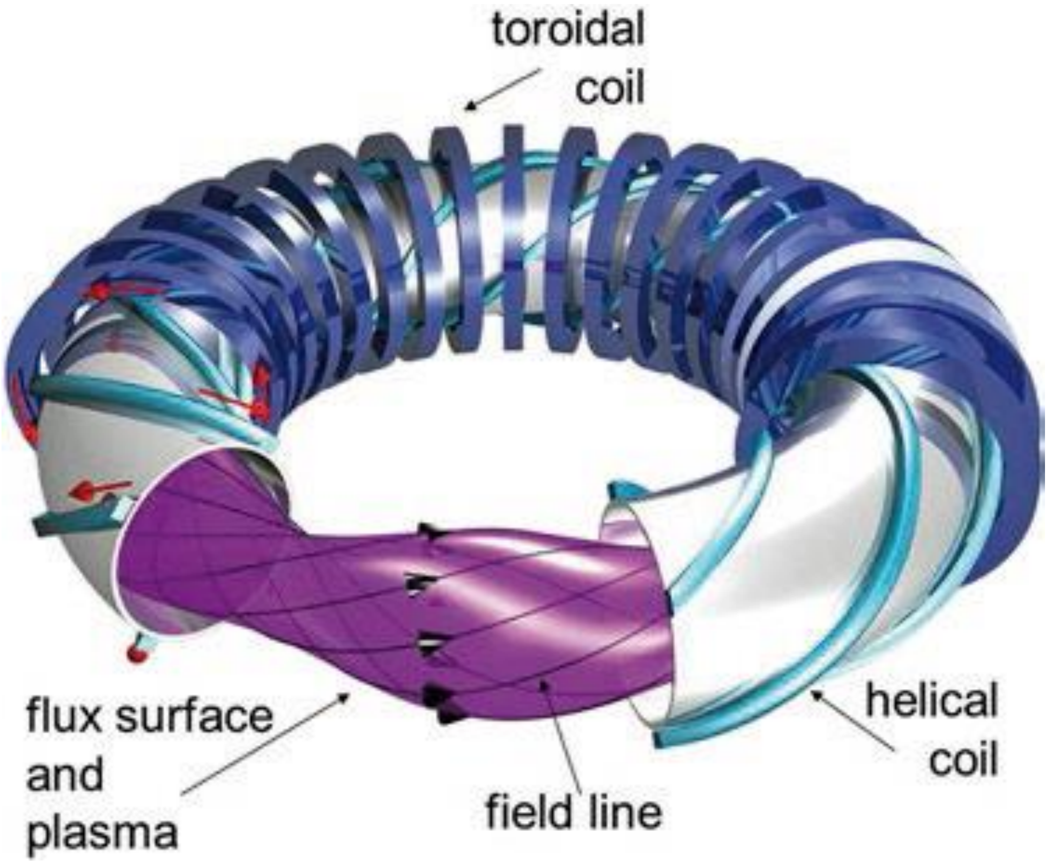
Lyman Spitzer, Jr. came out the idea during a long ride on a ski lift at Garmisch-Partenkirchen

https://www.snowtrex.de/magazin/skigebiete/garmisch-classic-zugspitze/

Exhibit model of a figure-8 stellarator for the Atoms for Peace conference in Geneva in 1958

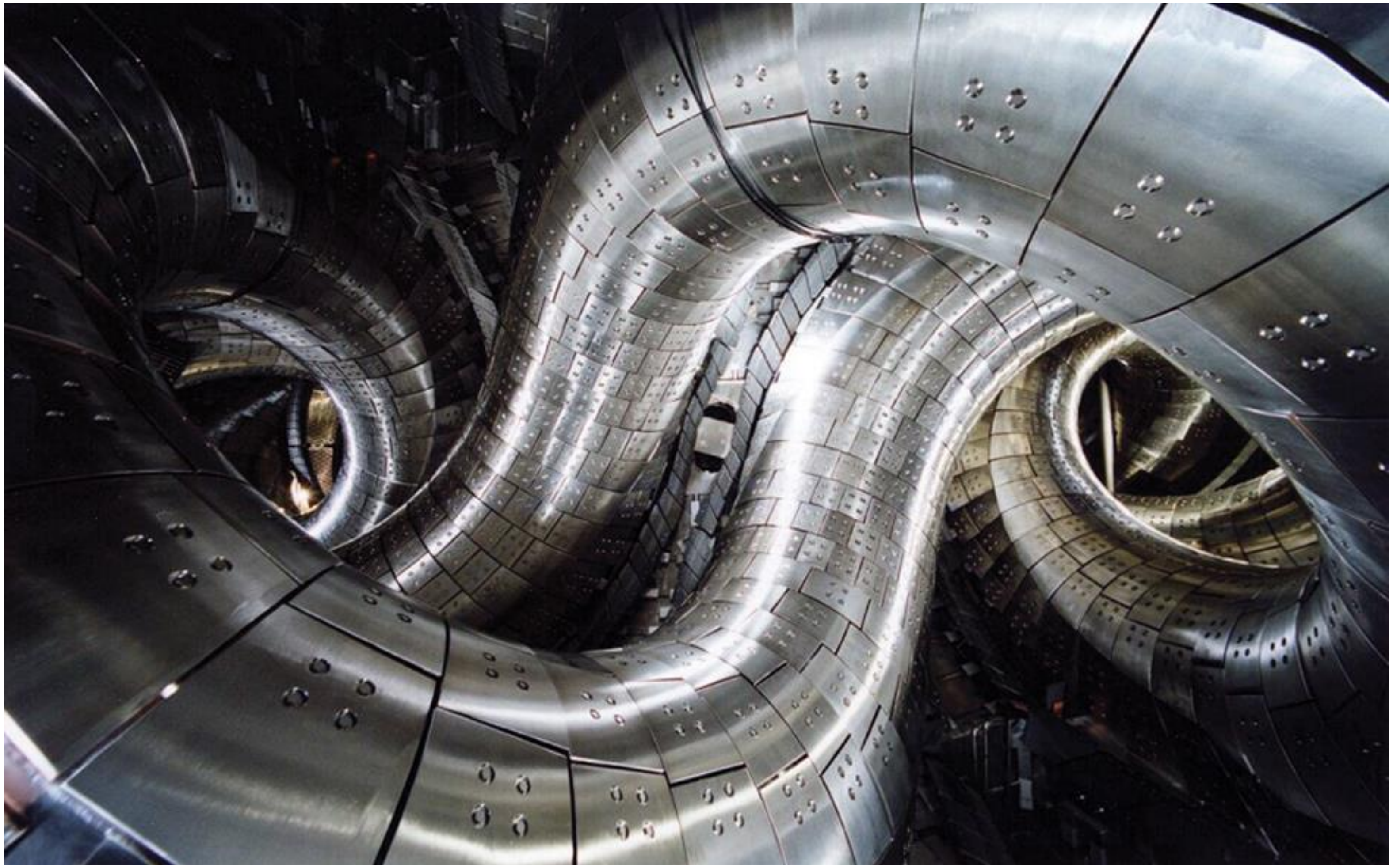


Twisted magnetic field lines can be provided by toroidal coils with helical coils



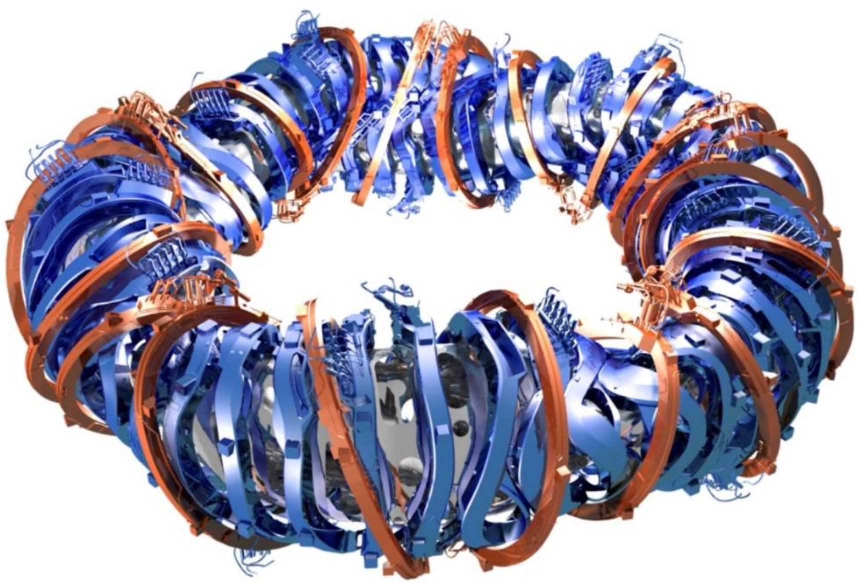
Wagner, F., Fusion energy. MRS Energy & Sustainability, 5, E8 (2018)

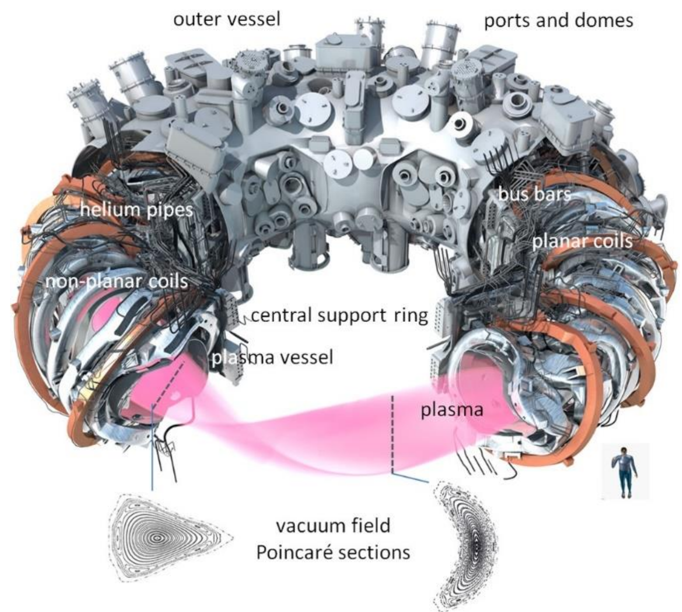
LHD stellarator in Japan



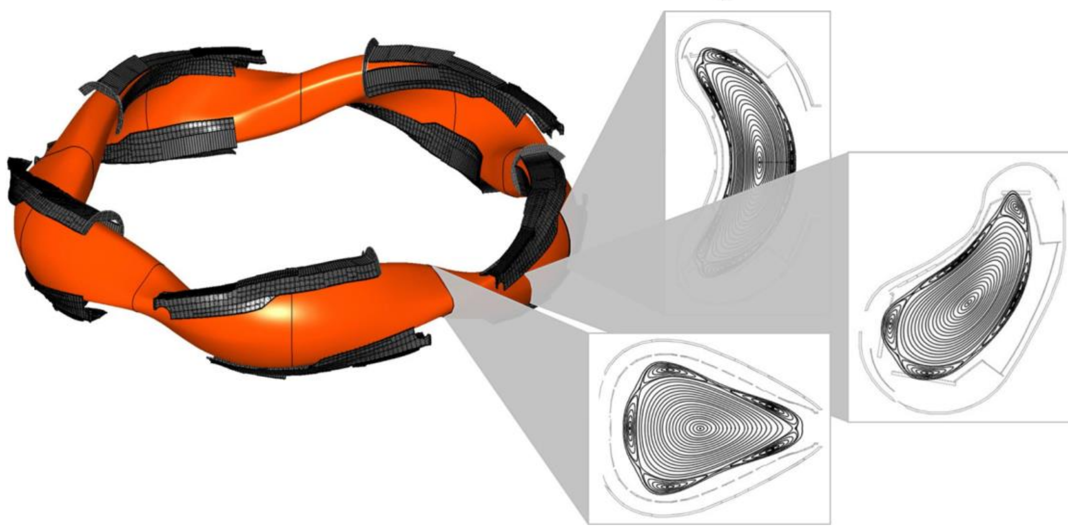
https://en.wikipedia.org/wiki/Large_Helical_Device

Wendelstein 7-X is a stellarator built by Max Planck Institute for Plasma Physics (IPP)

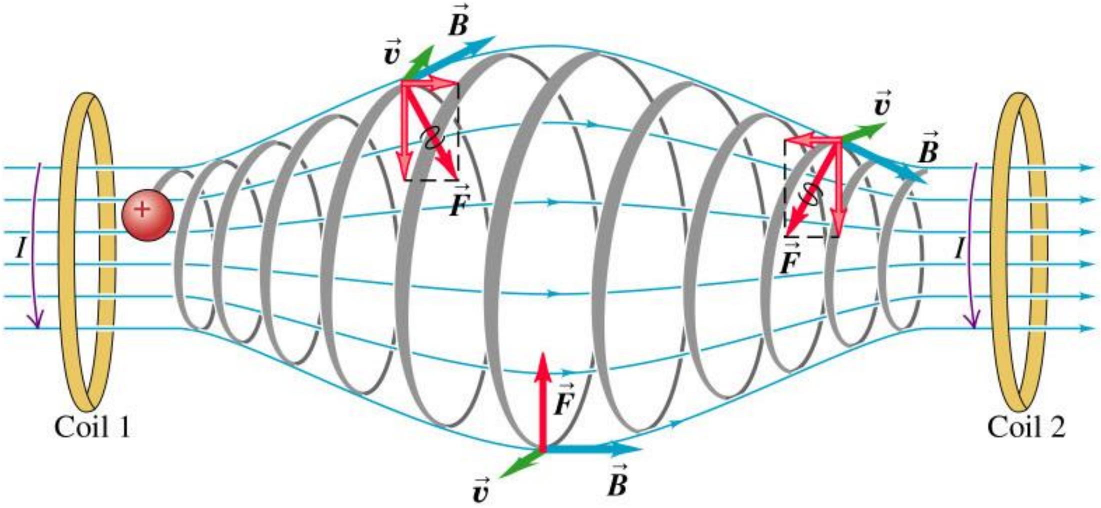


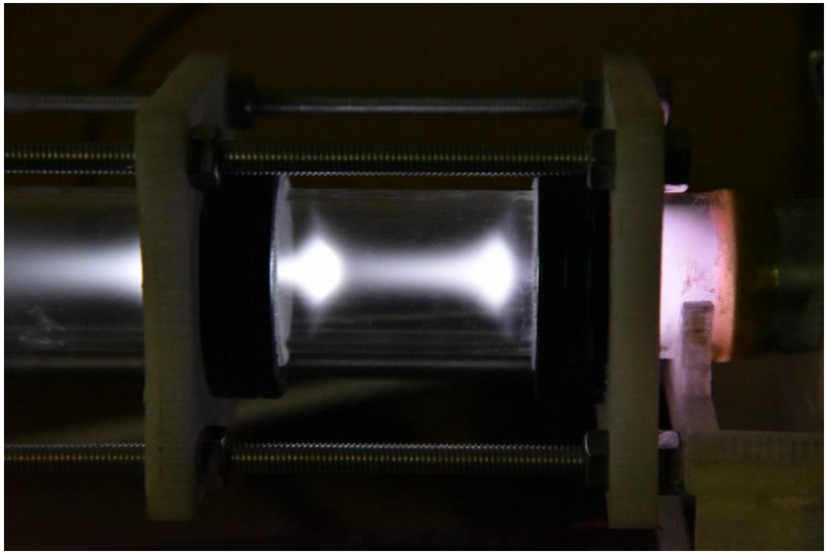


- **Wemdelstein 7-x is now installing new diverters.**



Demonstration of a magnetic mirror machine

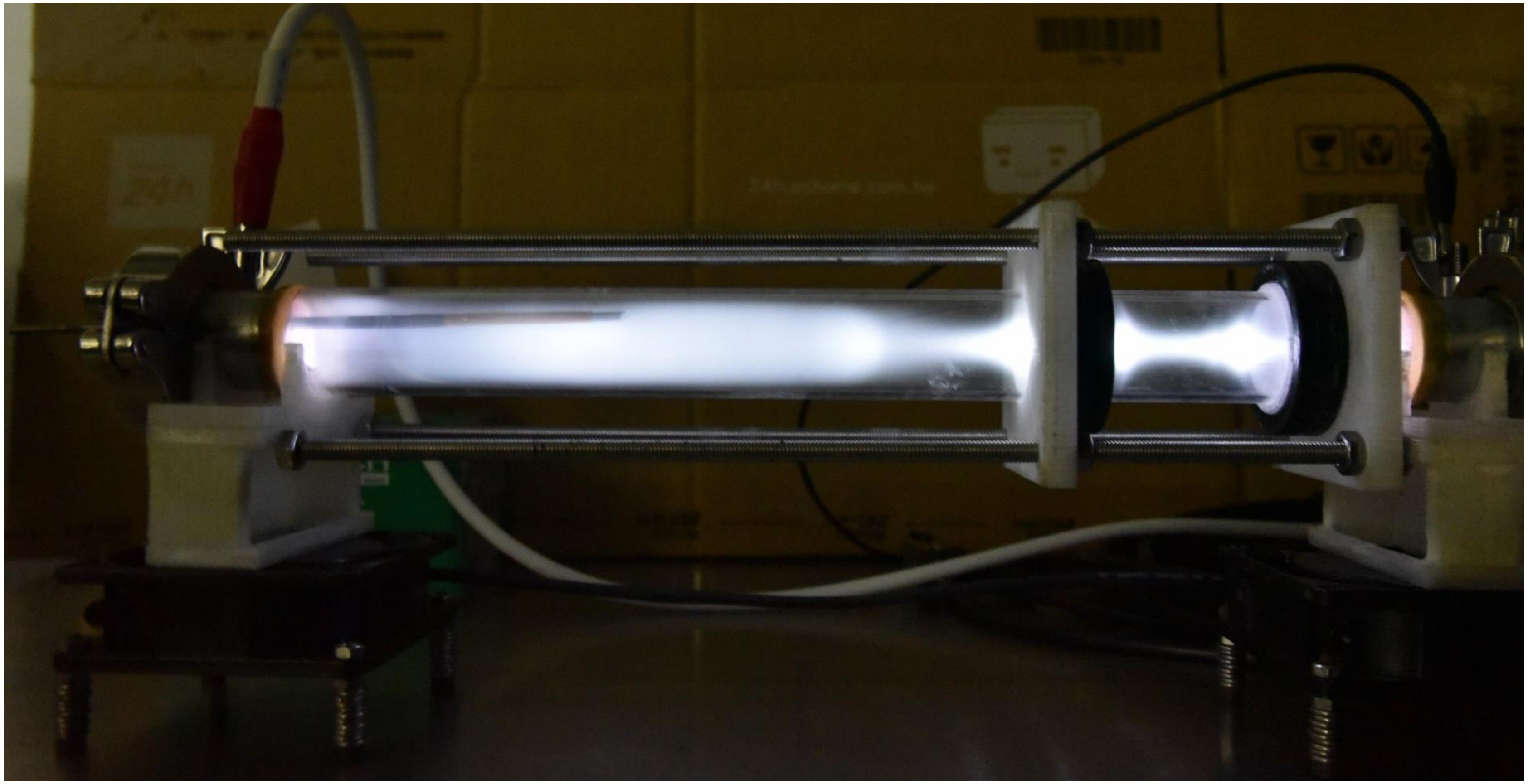




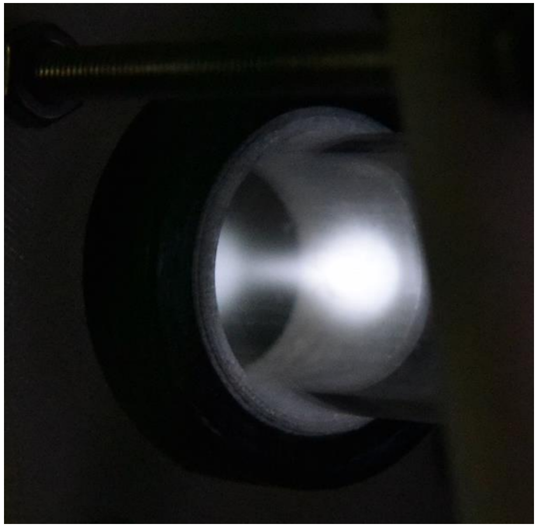
Show video.

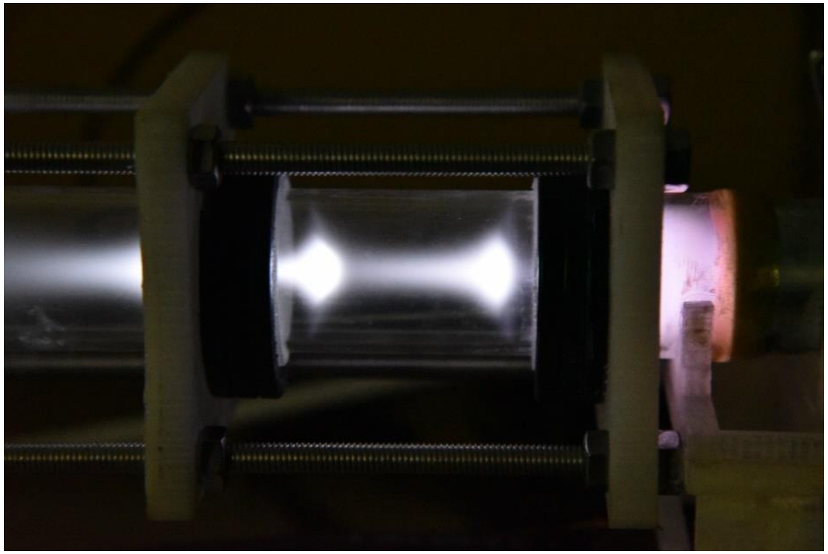
https://i.stack.imgur.com/GlzGZ.jpg

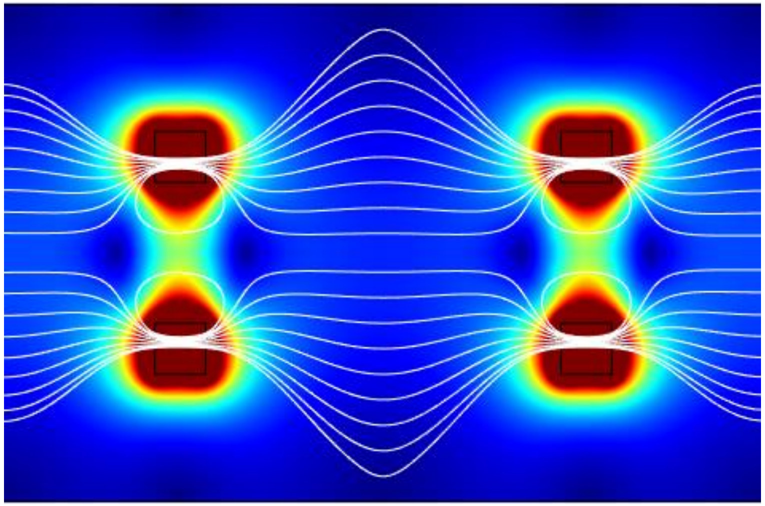
Plasma is partially confined by the magnetic field



Many mirror points are provided by a pair of ring-type magnets







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  - **Direct drive ICF**
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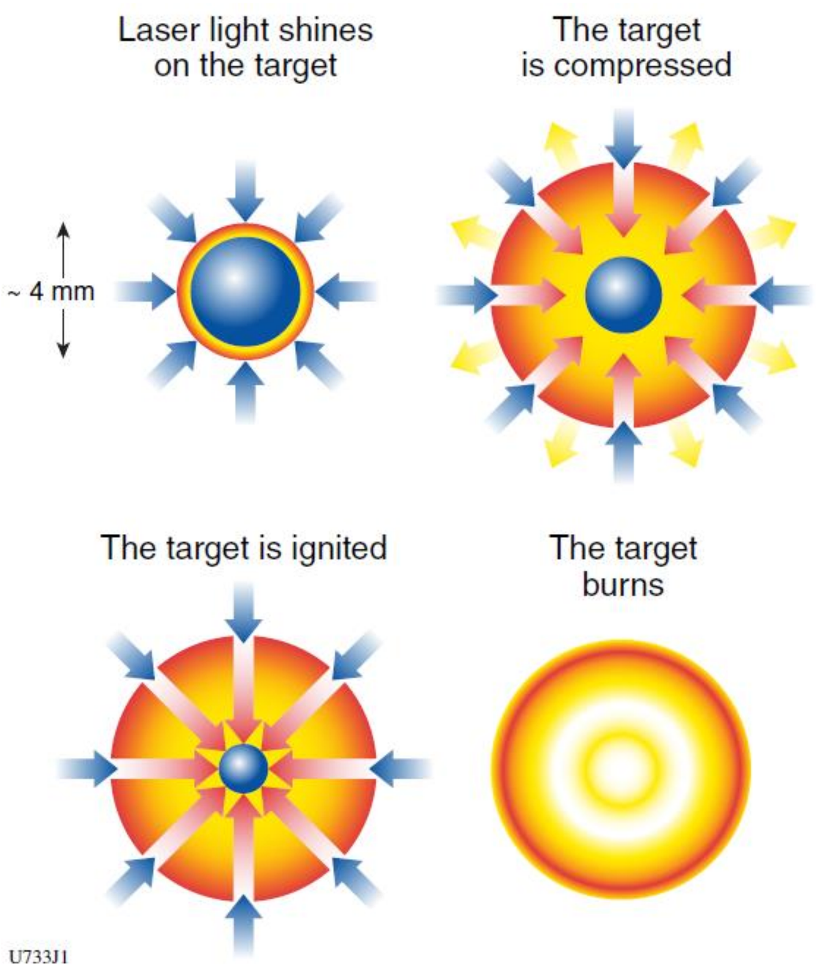
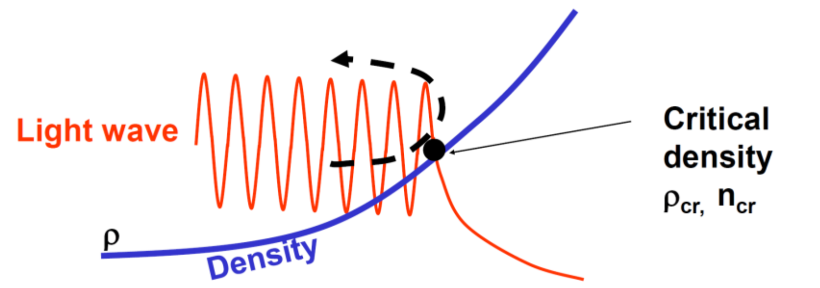
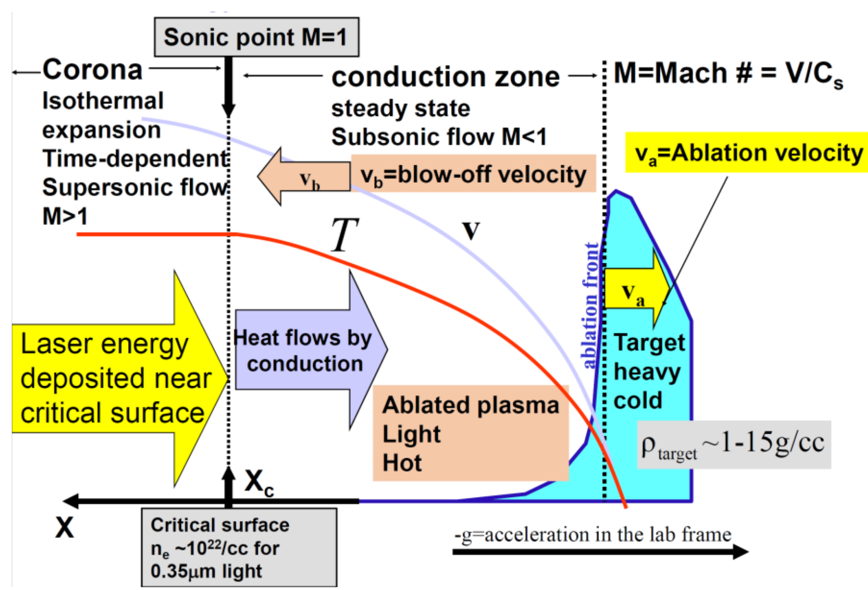
- Pulsed-power system at NCKU

Compression happens when outer layer of the target is heated by laser and ablated outward

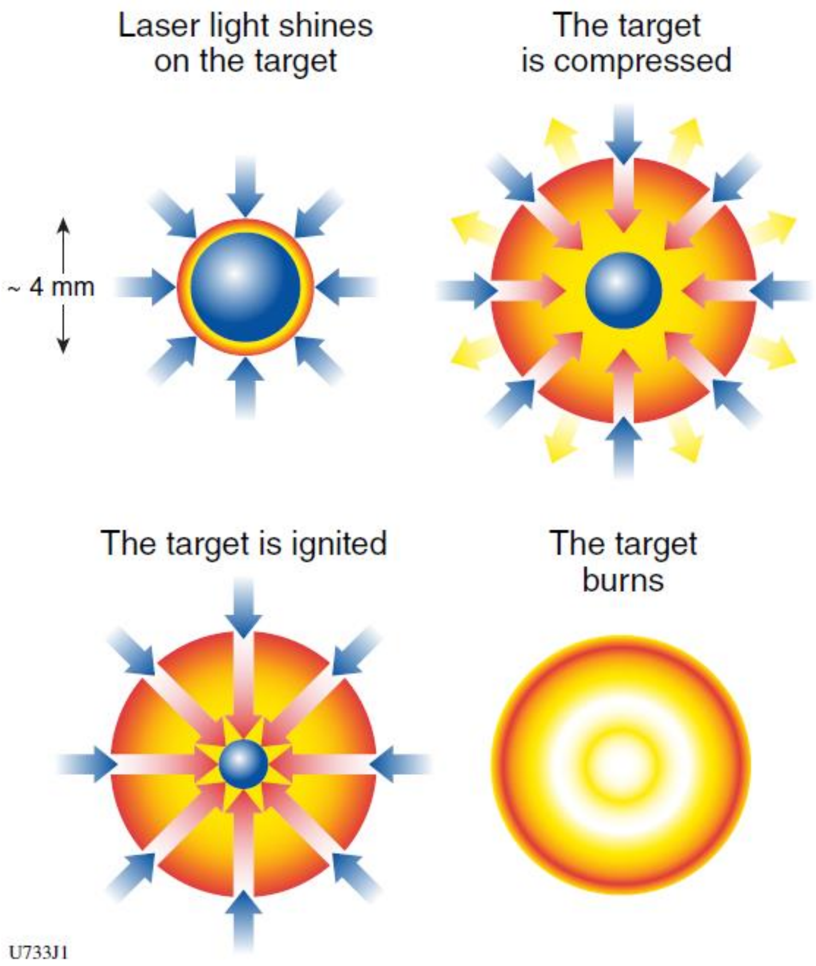




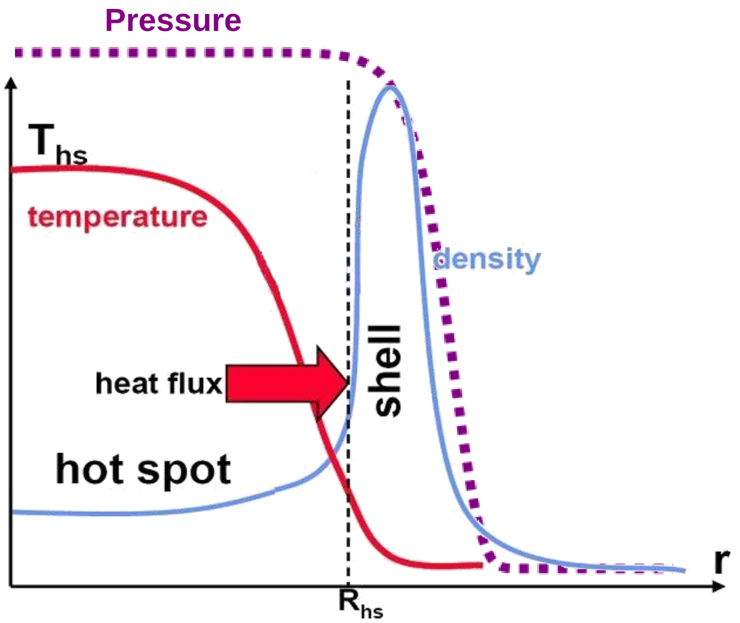


Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester
R. Betti, HEDSA HEDP Summer School, 2015

Plasma is confined by its own inertia in inertial confinement fusion (ICF)



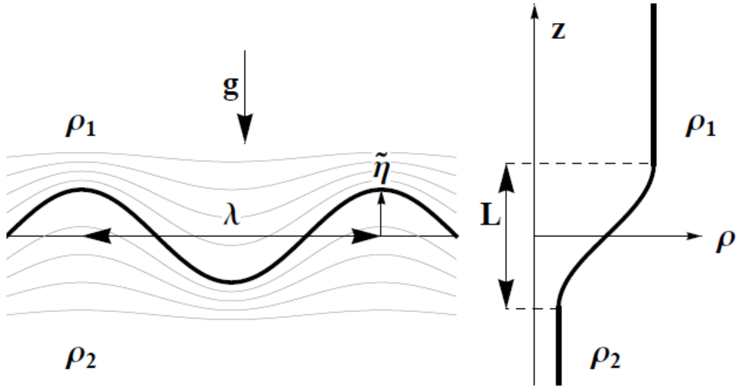
Spatial profile at stagnation



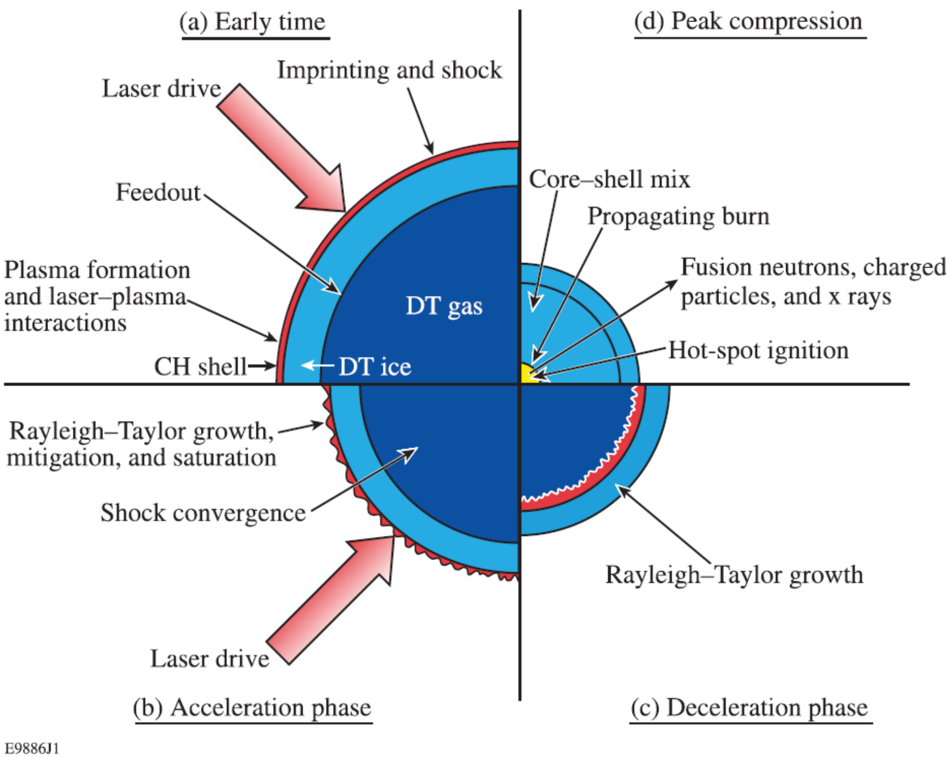
Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

A ball can not be compressed uniformly by being squeezed between several fingers

- **Rayleigh-Taylor instability**

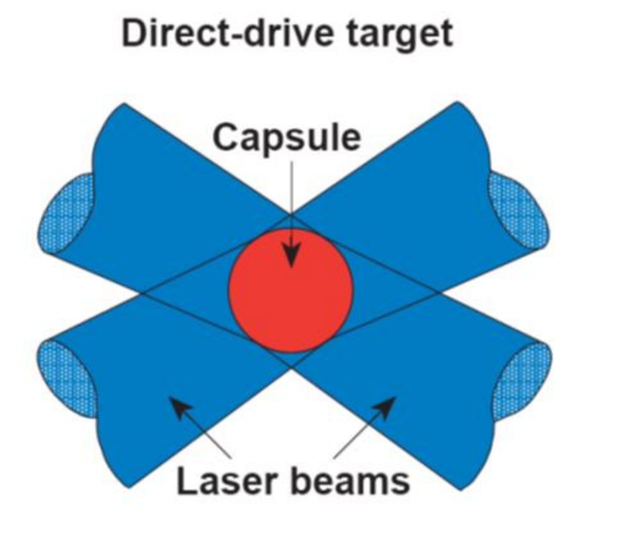


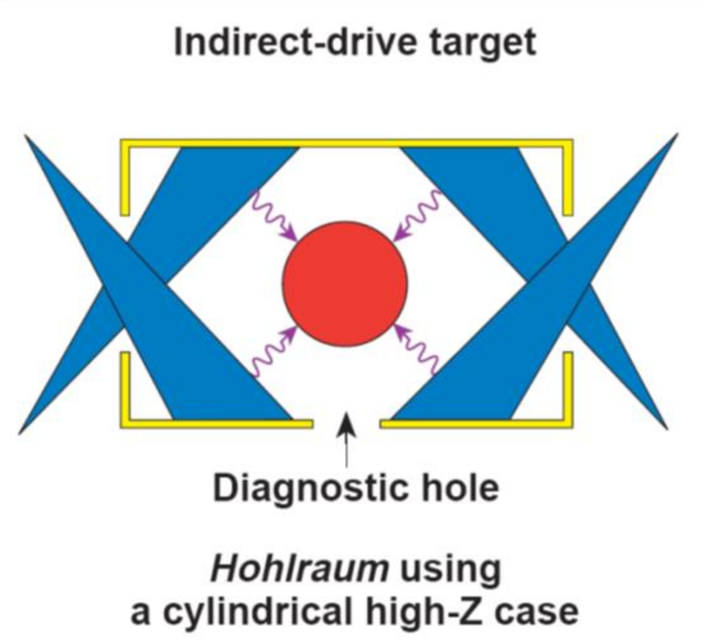
- **Stages of a target implosion**



P.-Y. Chang, PhD Thesis, U of Rochester (2013)
R. S. Craxton, etc., *Phys. Plasmas* **22**, 110501 (2015)

A spherical capsule can be imploded through directly or indirectly laser illumination





*R. Betti, HEDSA HEDP Summer School, 2015

Rochester is known as “The World's Image Center”

There are many famous optical companies at Rochester

Kodak

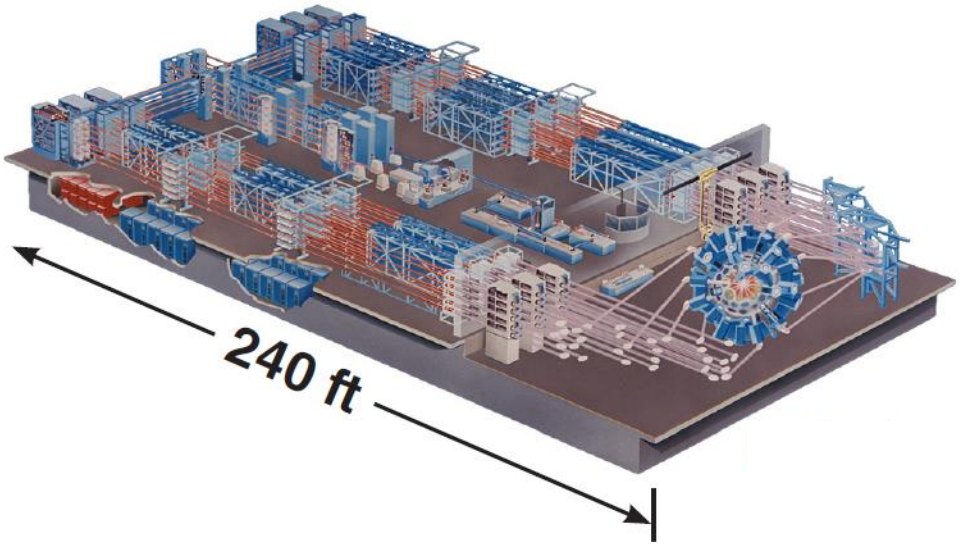
xerox ®

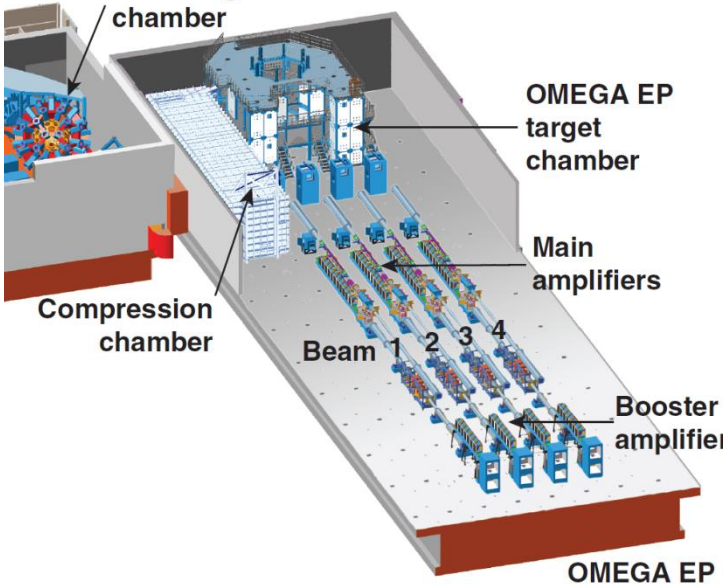
Eastman school of music

BAUSCH + LOMB

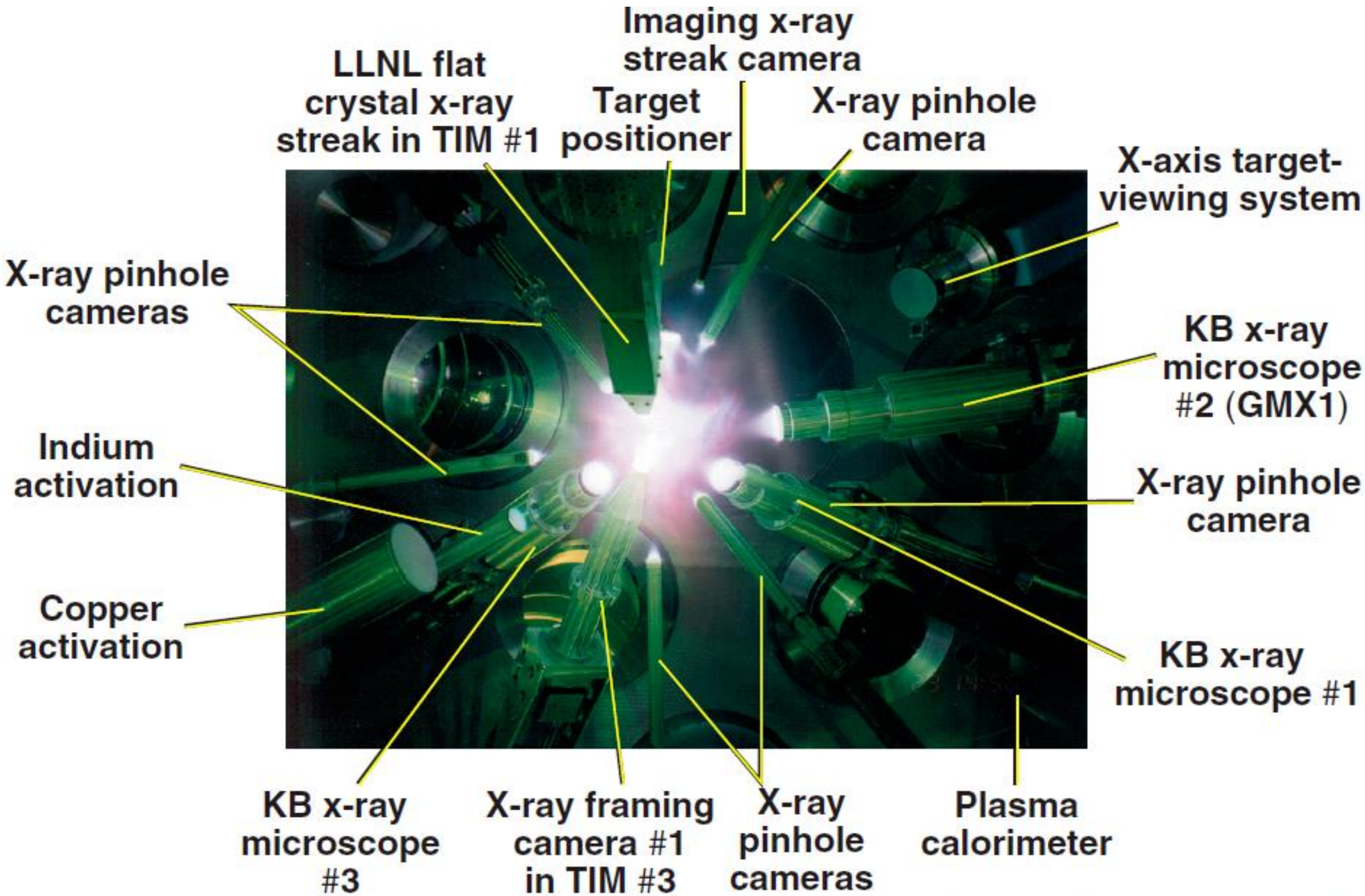
Laboratory for Laser Energetics, University of Rochester is a pioneer in laser fusion

- **OMEGA Laser System**
  - **60 beams**
  - **>30 kJ UV on target**
  - **1%~2% irradiation nonuniformity**
  - **Flexible pulse shaping**
- **OMEGA EP Laser System**
  - **4 beams; 6.5 kJ UV (10ns)**
  - **Two beams can be high-energy petawatt**
    - **2.6 kJ IR in 10 ps**
    - **Can propagate to the OMEGA or OMEGA EP target chamber**





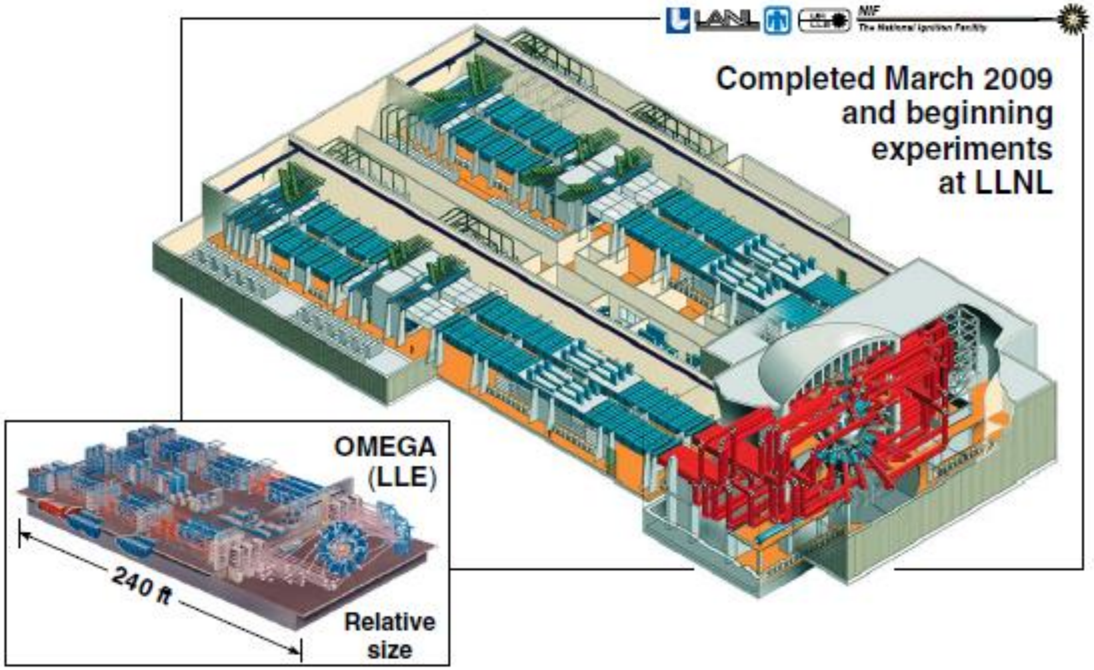
The OMEGA Facility is carrying out ICF experiments using a full suite of target diagnostics



E8012b

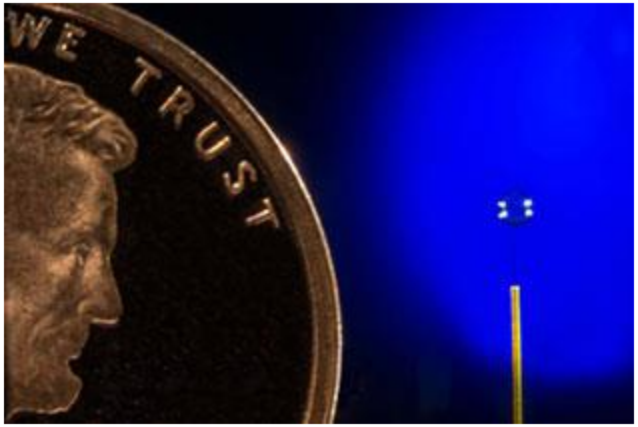
Photo taken from port H11B

The 1.8-MJ National Ignition Facility (NIF) will demonstrate ICF ignition and modest energy gain

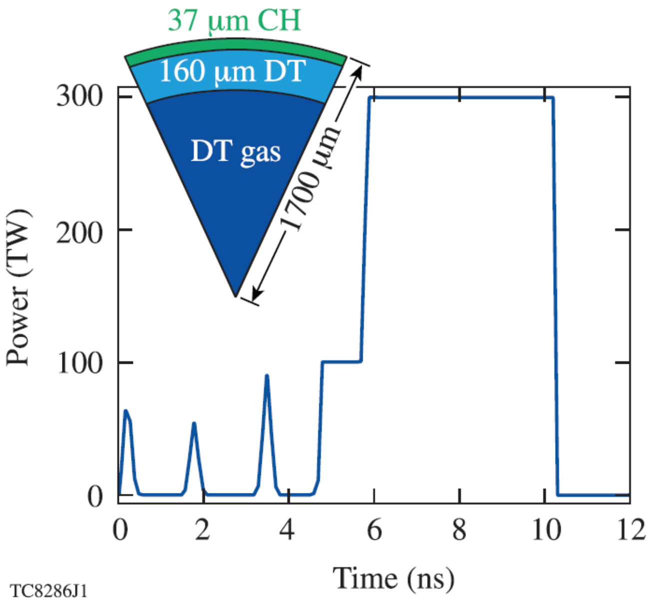


OMEGA experiments are integral to an ignition demonstration on the NIF.

Targets used in ICF



- **Triple-point temperature : 19.79 K**



http://www.lle.rochester.ed
https://en.wikipedia.org/wiki/Inertial_confinement_fusion
R. S. Craxton, etc., *Phys. Plasmas* **22**, 110501 (2015)

Softer material can be compressed to higher density

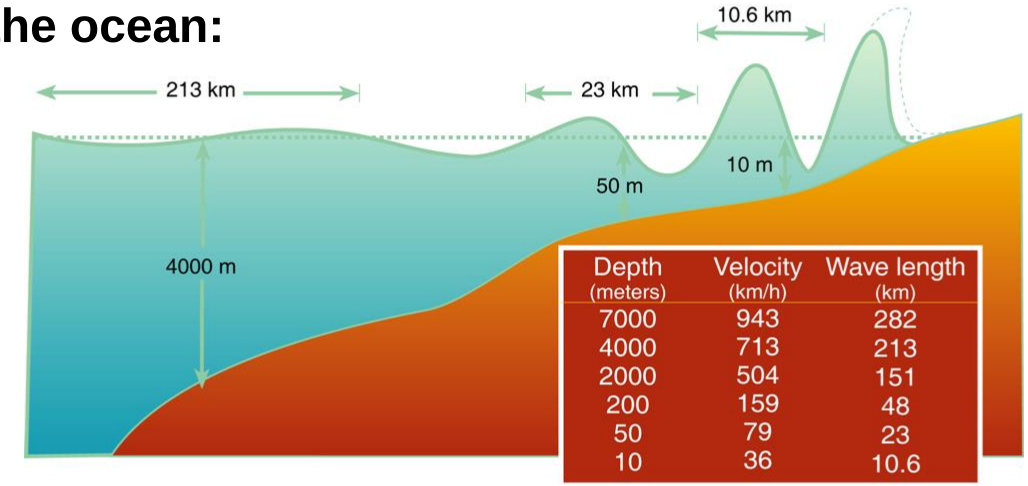
- **Compression of a baseball**

- **Compression of a tennis ball**

https://www.youtube.com/watch?v=uxlIdMoAwbY
https://newsghana.com.gh/wimbledon-slow-motion-video-of-how-a-tennis-ball-turns-to-goo-after-serve/

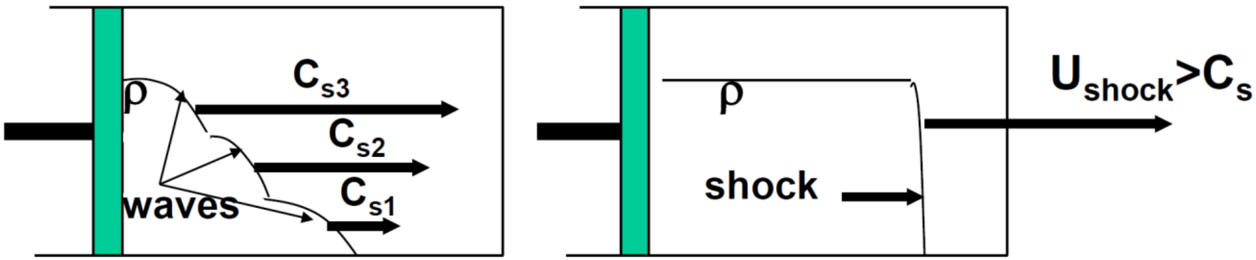
A shock is formed due to the increasing sound speed of a compressed gas/plasma

- **Wave in the ocean:**



Depth (meters)	Velocity (km/h)	Wave length (km)
7000	943	282
4000	713	213
2000	504	151
200	159	48
50	79	23
10	36	10.6

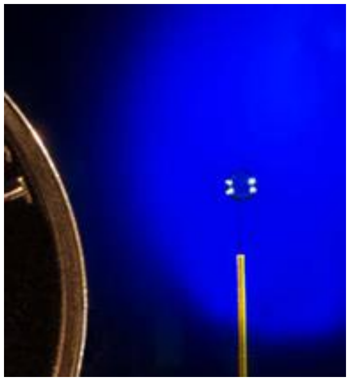
- **Acoustic/compression wave driven by a piston:**



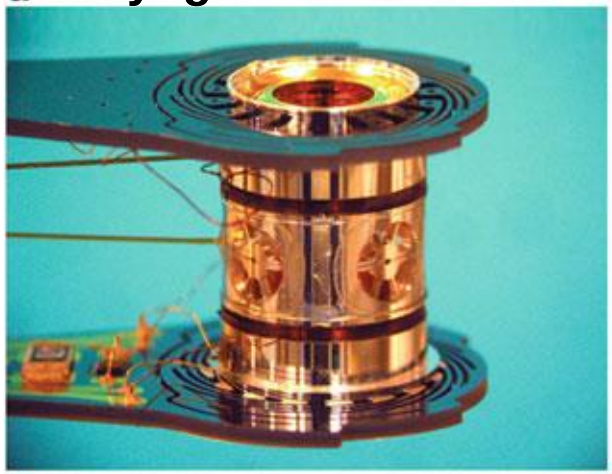
$$C_s \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha\rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\rho^{1/3}$$

http://neamtic.ioc-unesco.org/tsunami-info/the-cause-of-tsunamis
*R. Betti, HEDSA HEDP Summer School, 2015

Targets used in ICF

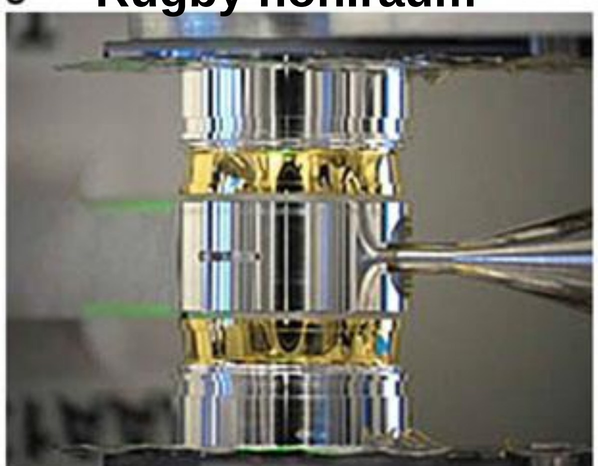


a Cryogenic hohlraum

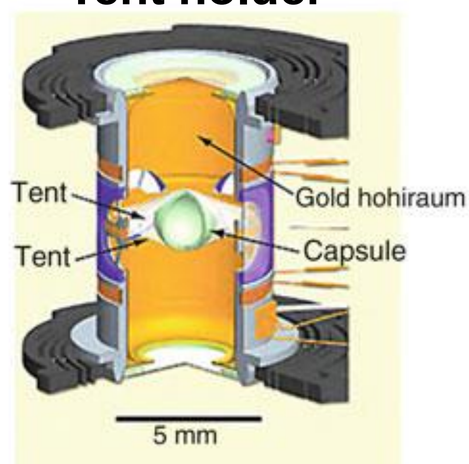


b

c Rugby hohlraum

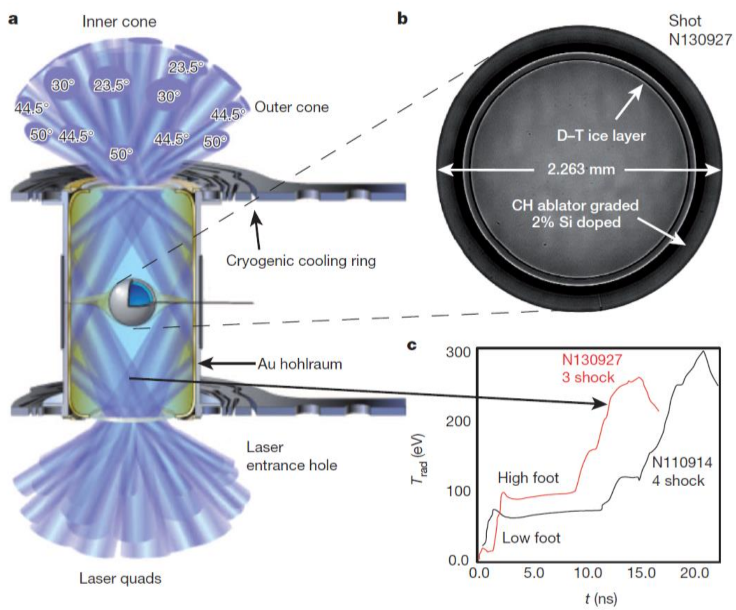


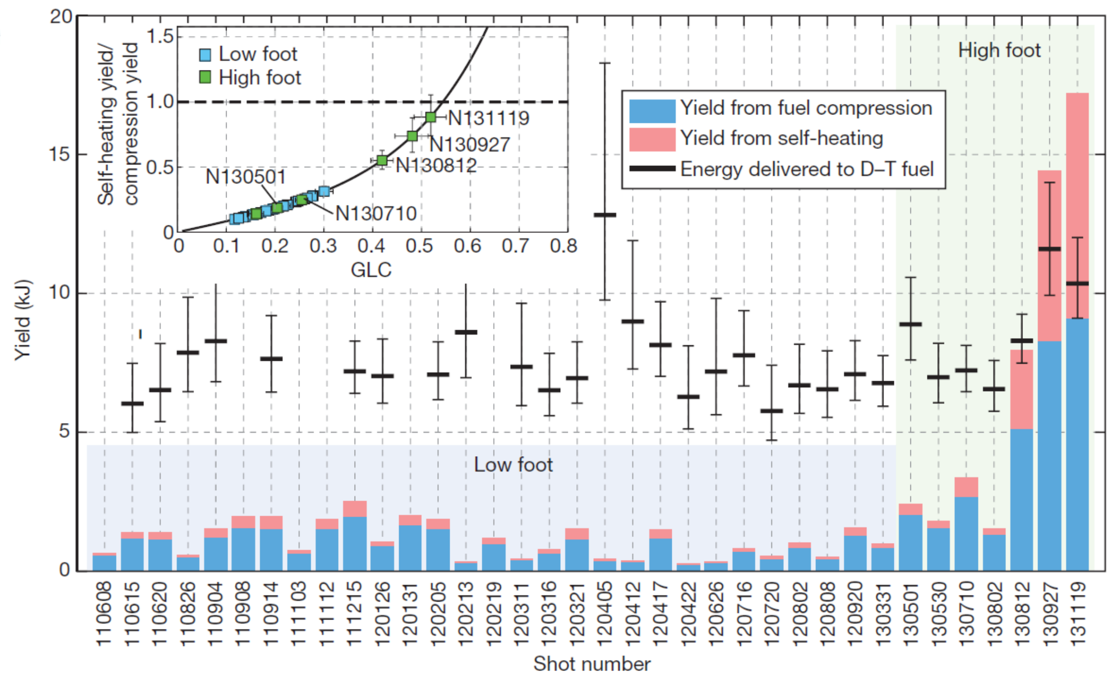
d Tent holder



https://www.lle.rochester.edu/index.php/2014/11/10/next-generation-cryo-target/
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

Nature letter “Fuel gain exceeding unity in an inertially confined fusion implosion”

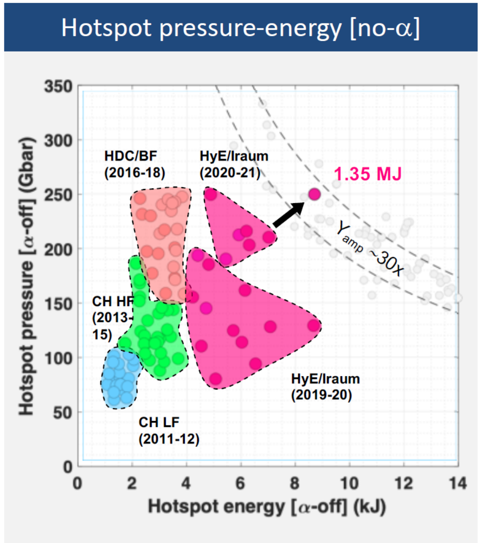


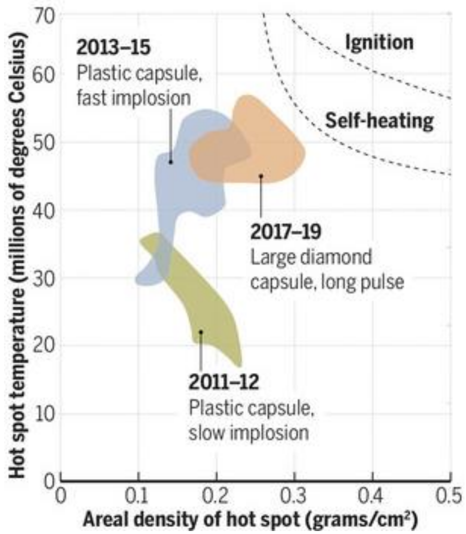


- **Fuel gain exceeding unity was demonstrated for the first time.**

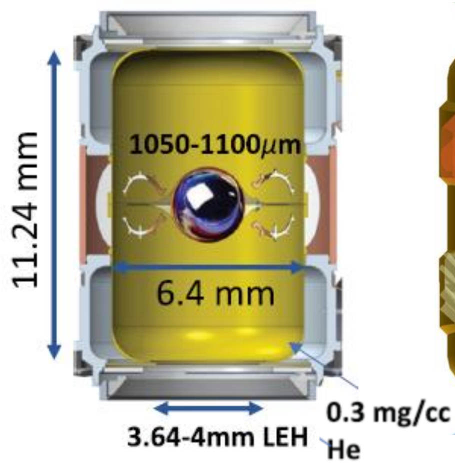
Nature 506, p343, 2014

The hot spot has entered the burning plasma regime

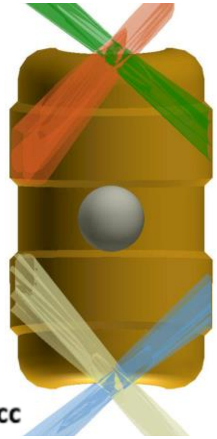


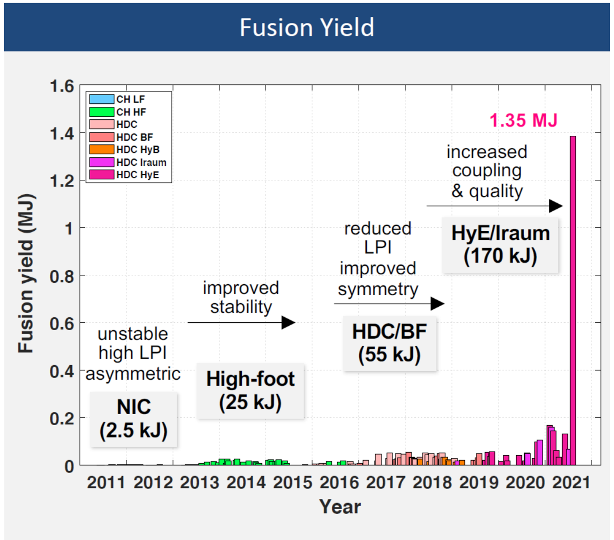


- **Hybrid-E**

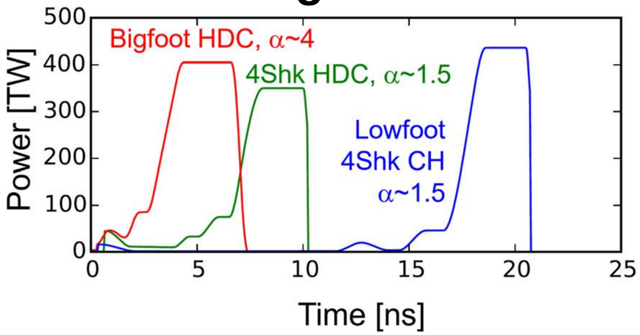


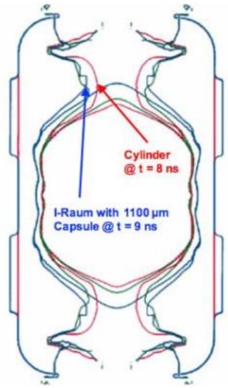
- **I-raum**





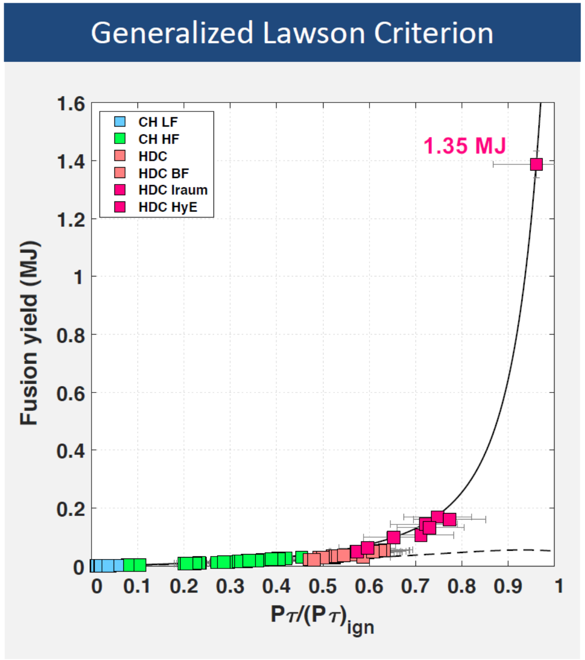
- **Big foot**

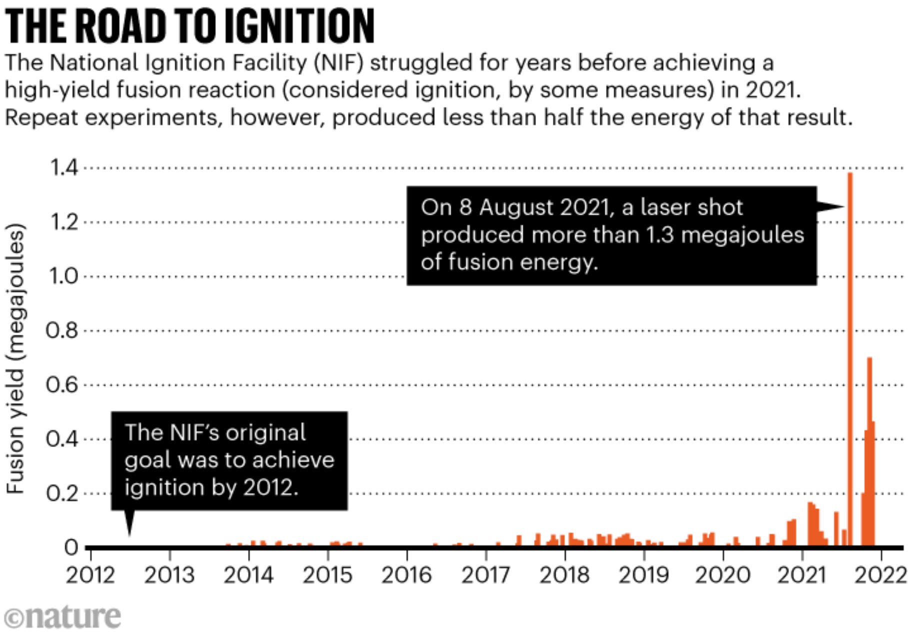




T. Ma, ARPA-E workshop, April 26, 2022
Science 370, p1019, 2020
D. T. Casey, etc., Phys. Plasmas, 25, 056308 (2018)
A. L. Kritcher, etc., Phys. Plasmas, 28, 072706 (2021)
H. F. Robey, etc., Phys. Plasmas, 25, 012711 (2018)

National Ignition Facility (NIF) achieved a yield of more than 1.3 MJ from ~1.9 MJ of laser energy in 2021 (Q~0.7)

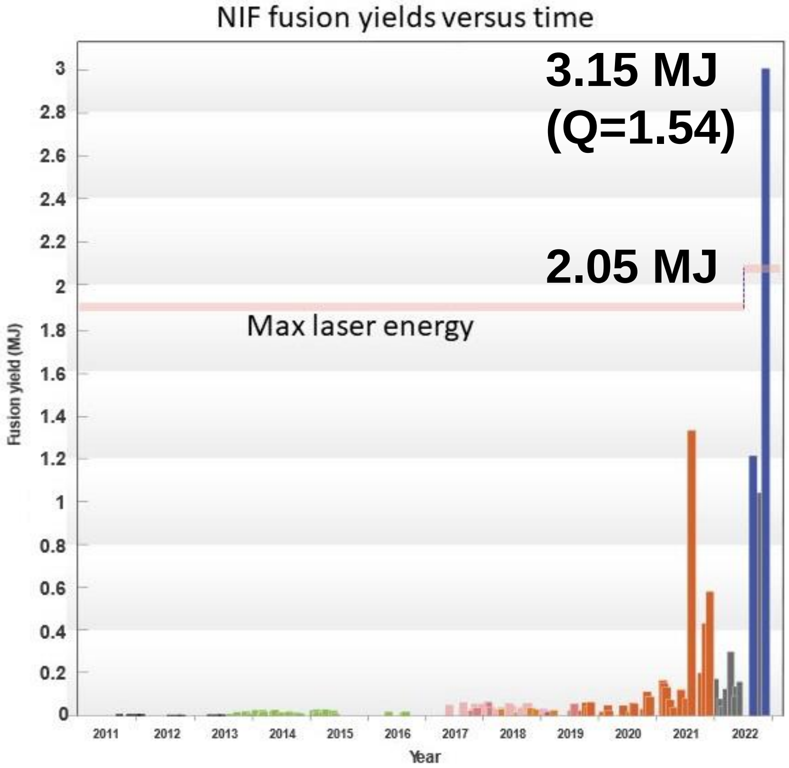


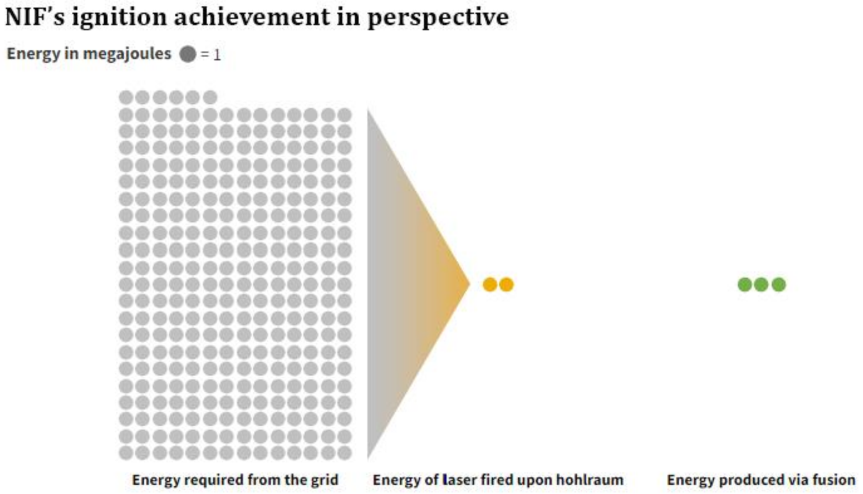


- **National Ignition Facility (NIF) achieved a yield of more than 1.3 MJ (Q~0.7). This advancement puts researchers at the threshold of fusion ignition.**
- **Laser-fusion facility heads back to the drawing board.**

T. Ma, ARPA-E workshop, April 26, 2022
J. Tollefson, Nature (News) 608, 20 (2022)

"Ignition" (target yield larger than one) was achieved in NIF on 2022/12/5



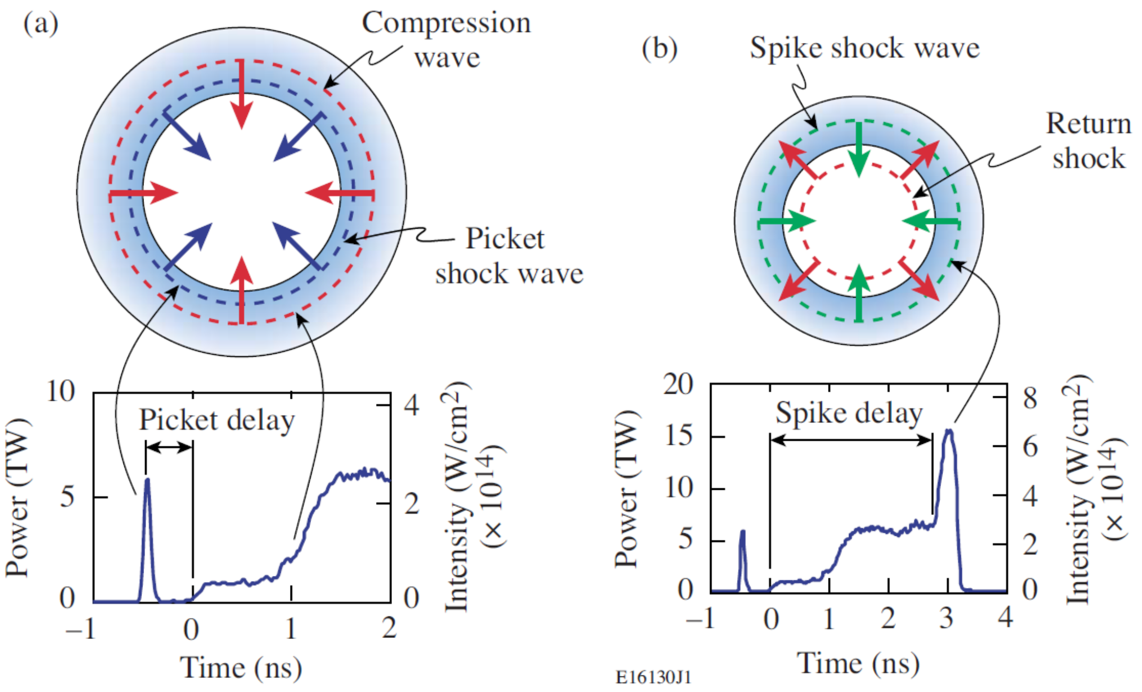


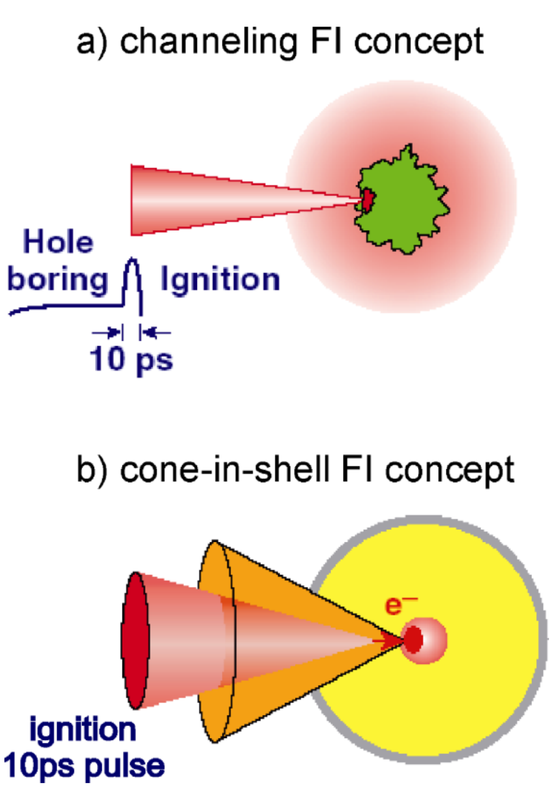
300 MJ 2.05 MJ 3.15 MJ

https://physicstoday.scitation.org/do/10.1063/PT.6.2.20221213a/full/

External "spark" can be used for ignition

- **Shock ignition**
- **Fast ignition**

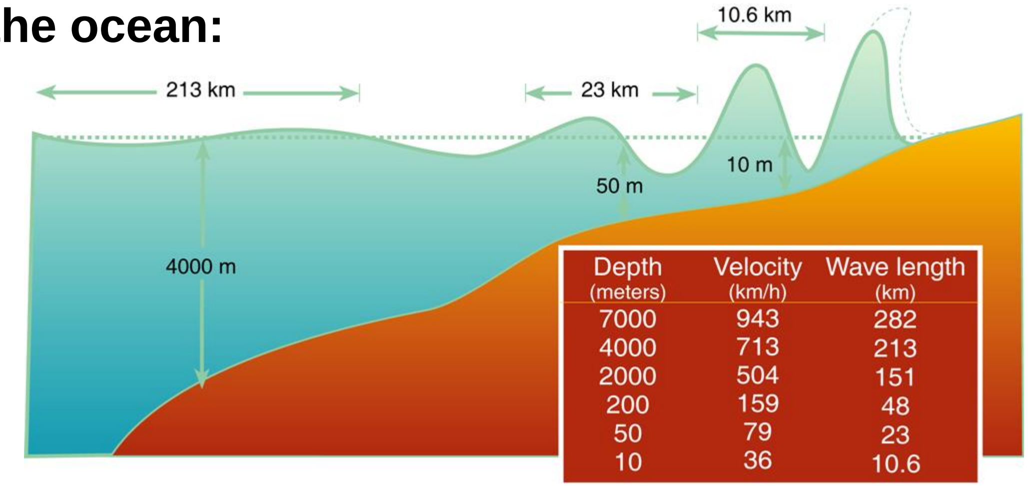




J. Badziak, Bull.Polish Acad. Sci. Tech. Sci.Phys. Plasmas 15, 056306 (2008)

A shock is formed due to the increasing sound speed of a compressed gas/plasma

- **Wave in the ocean:**



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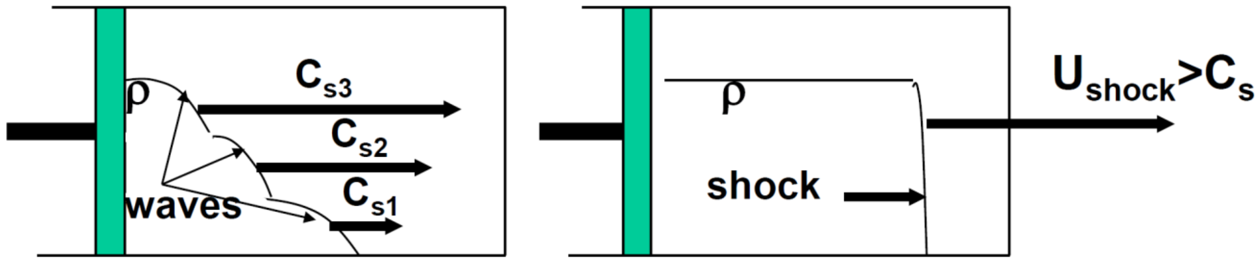
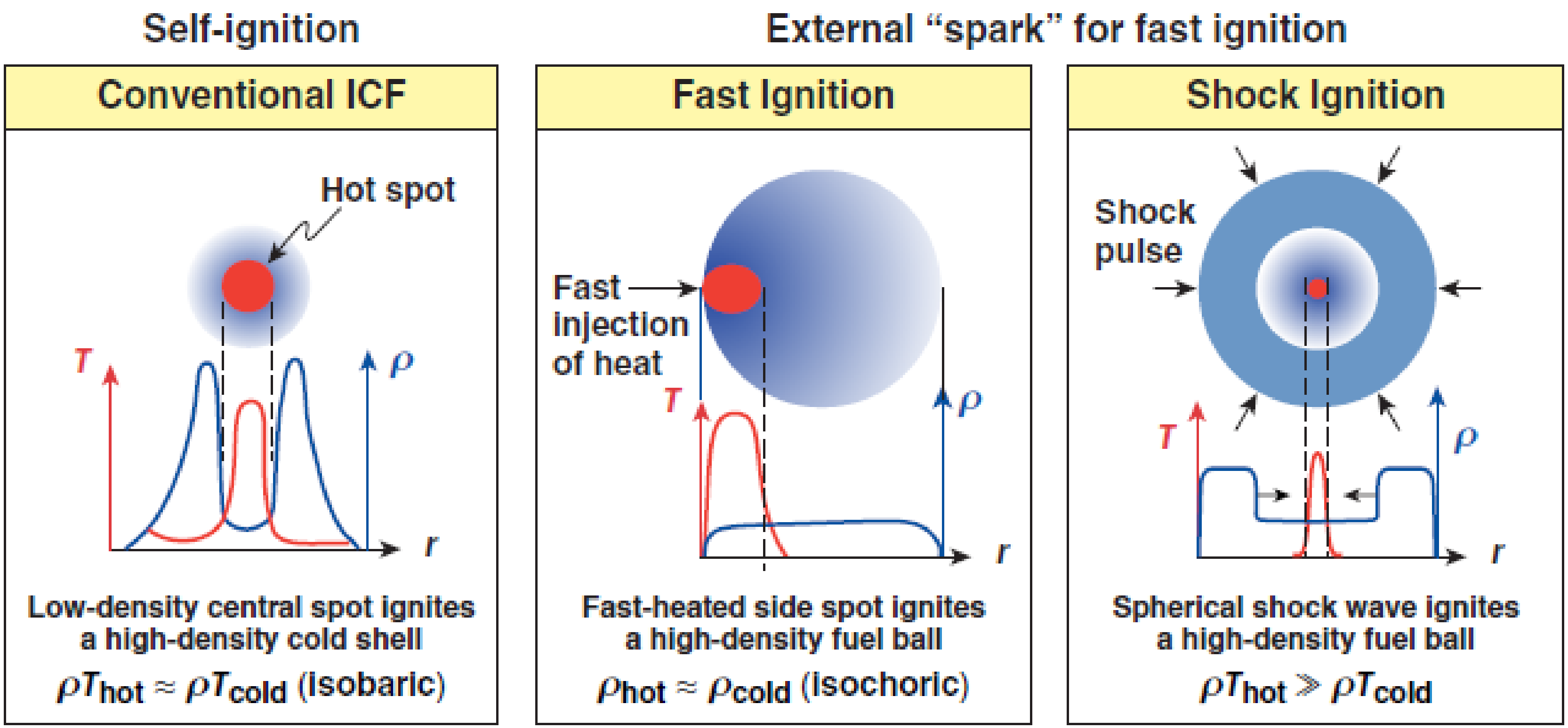


$$C_s \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha \rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\rho^{1/3}$$

http://neamtic.ioc-unesco.org/tsunami-info/the-cause-of-tsunamis
*R. Betti, HEDSA HEDP Summer School, 2015

Ignition can happen by itself or being triggered externally

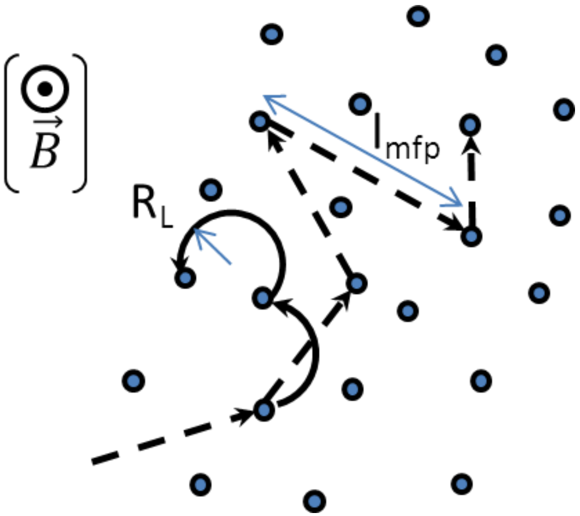


P. B. Radha, Fusion Energy Conference,2018

Outline

- Introduction to nuclear fusion
- Magnetic confinement fusion (MCF)
  - Tokamak
  - Stellarator
- Inertial confinement fusion (ICF)
  - Indirection drive ICF
  - Direct drive ICF
- **Innovation idea – MCF + ICF**
- Pulsed-power system at NCKU

A strong magnetic field reduces the heat flux



$$q_T = -\kappa_{||}\nabla_{||}T - \kappa_{\perp}\nabla_{\perp}T$$

$$\kappa_{||} = \kappa_0 T^{5/2}$$

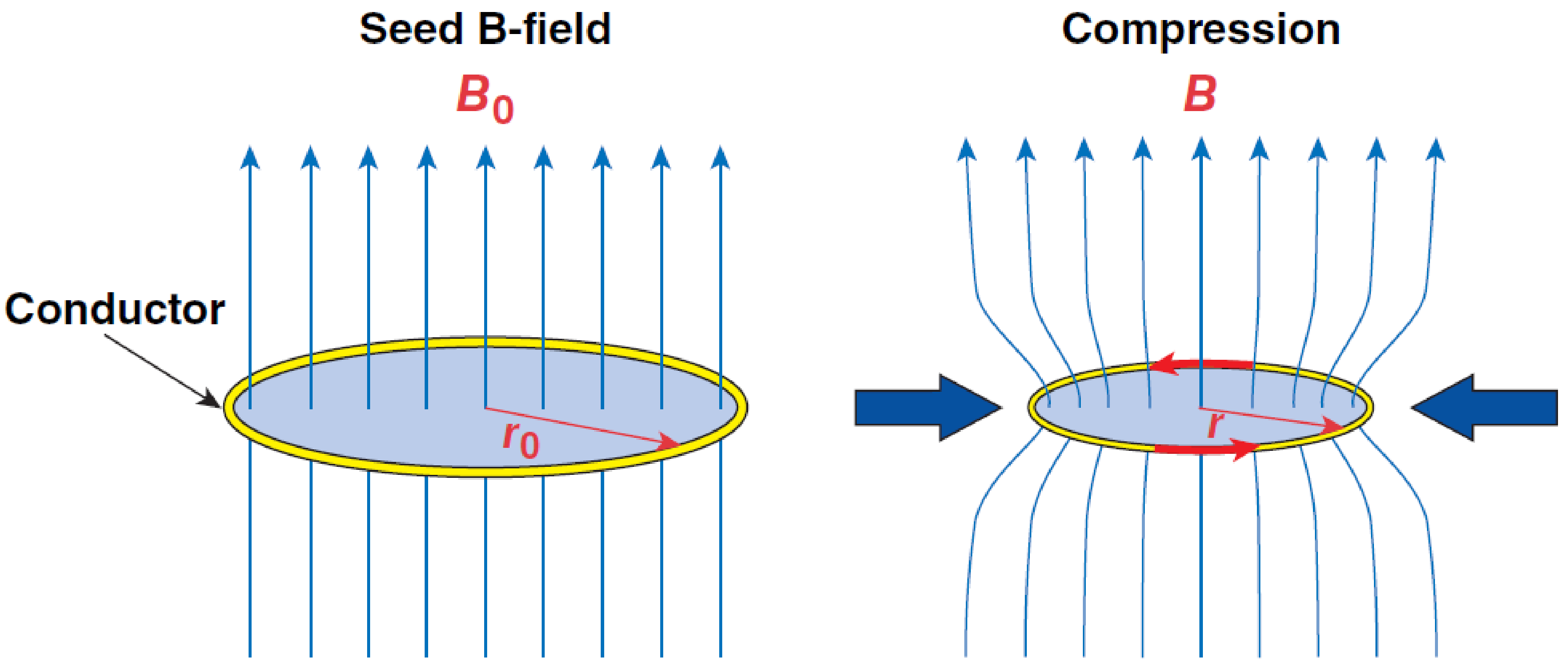
$$\kappa_{\perp} = \frac{\kappa_{||}}{\chi^2} \quad \text{for large Hall parameter } \chi \propto \frac{l_{mfp}}{R_L} >> 1$$

- **Typical hot spot conditions:**
  R_{hs} ~ 40 μm, ρ ~ 20 g/cm^3, T ~ 5 keV:

  $B > 10$ **MG is needed for** $\chi > 1$

Magnetic-flux compression can be used to provide the needed magnetic field.

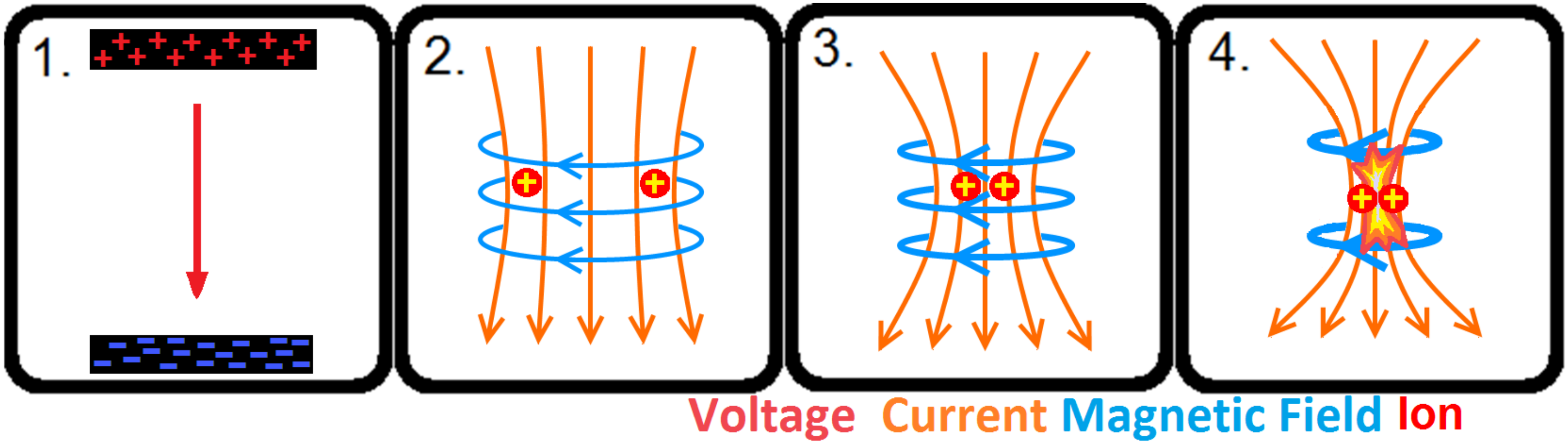
Principle of frozen magnetic flux in a good conductor is used to compress fields



$$\Phi = \pi r_0^2 B_0 = \pi r^2 B$$

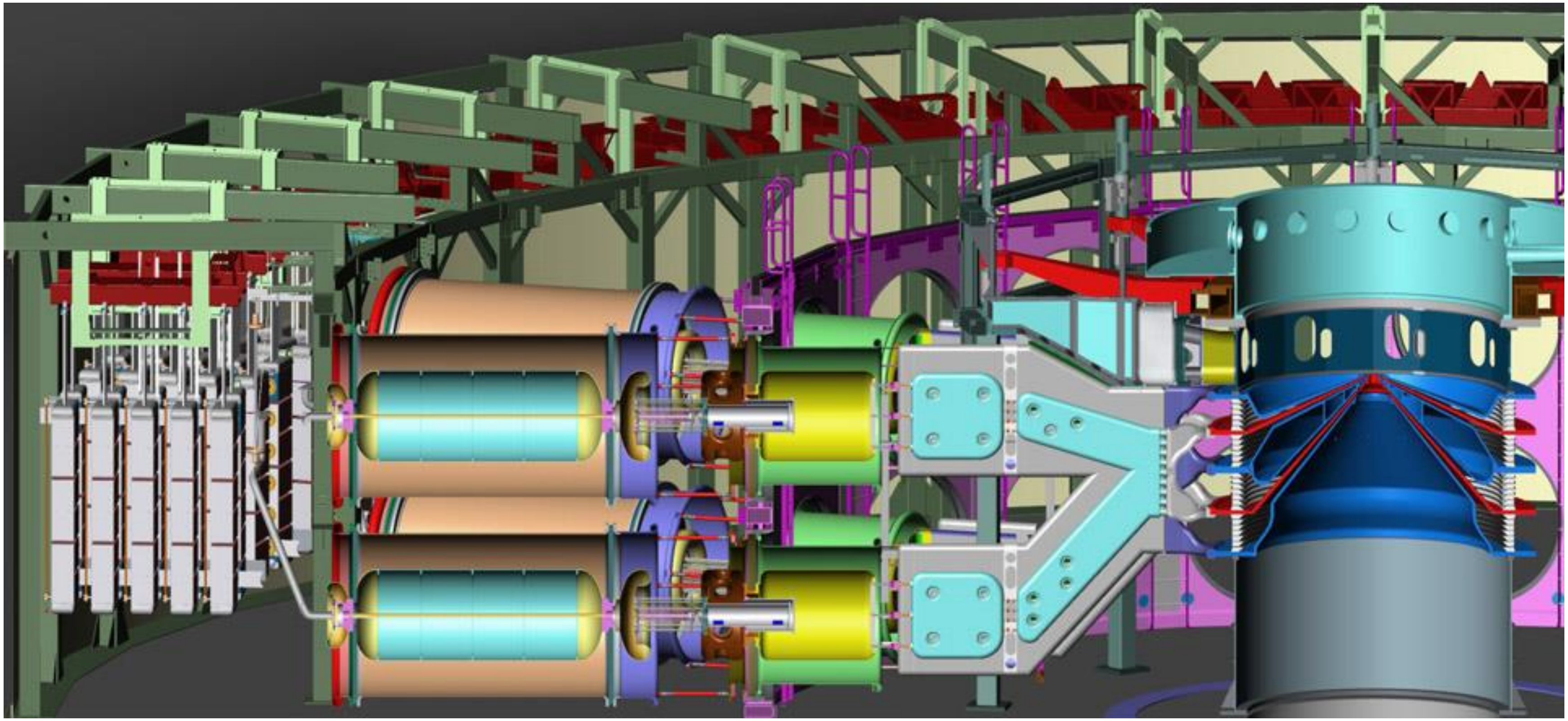
M. Hohenberger, P.-Y. Chang, *et al*., Phys. Plasmas 19, 056306 (2012).

Plasma can be pinched by parallel propagating plasmas



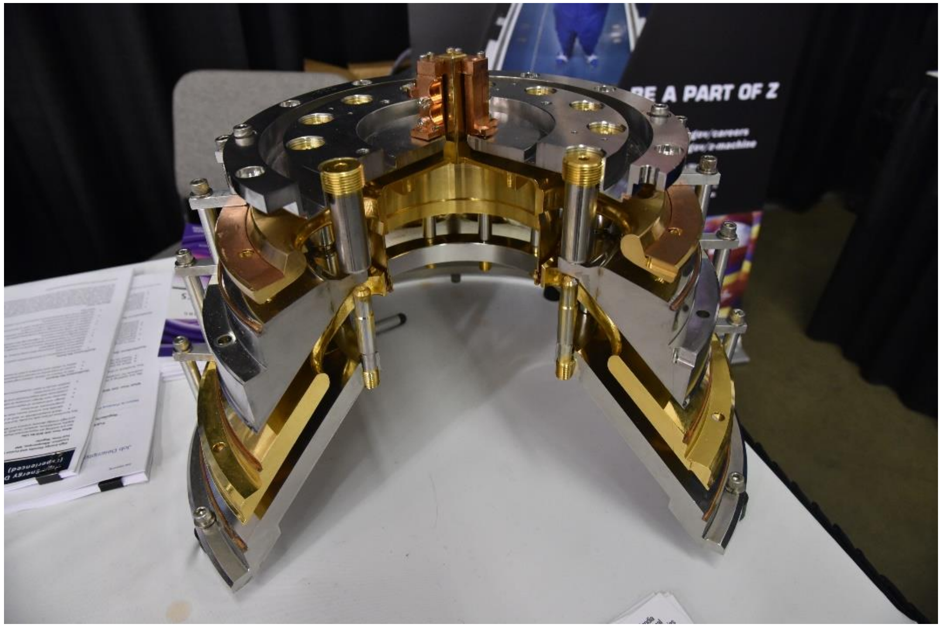
https://en.wikipedia.org/wiki/Pinch_(plasma_physics)

Sandia's Z machine is the world's most powerful and efficient laboratory radiation source

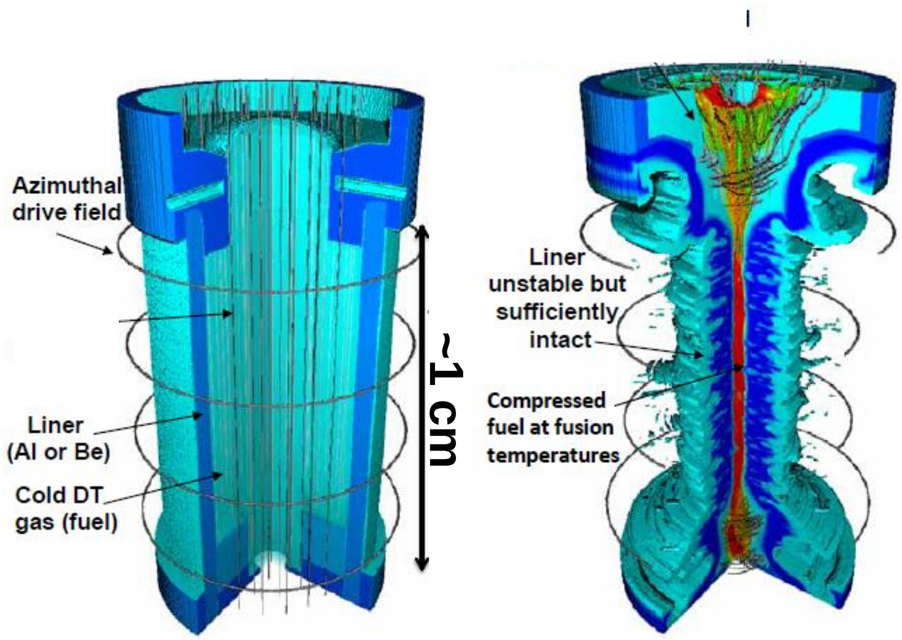


- Stored energy: 20 MJ
- Marx charge voltage: 85 kV
- Peak electrical power: 85 TW
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray emissions: 350 TW
- Peak X-ray output: 2.7 MJ

Z machine



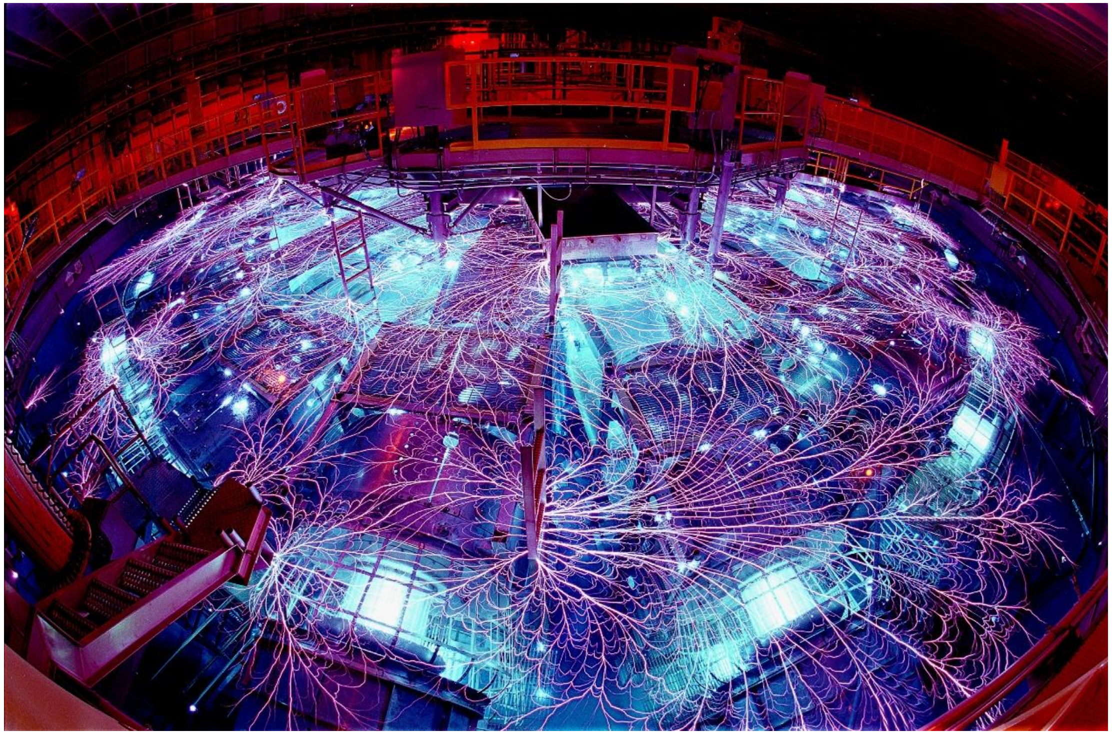
Z machine



- **Stored energy: 20 MJ**
- **Peak electrical power: 85 TW**

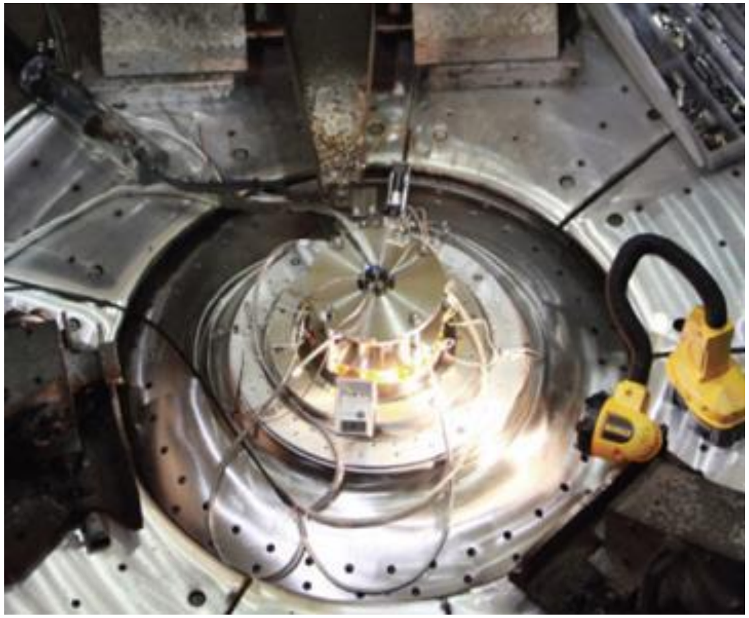
- **Peak current: 26 MA**
- **Rise time: 100 ns**
- **Peak X-ray output: 2.7 MJ**

Z machine discharge



Before and after shots

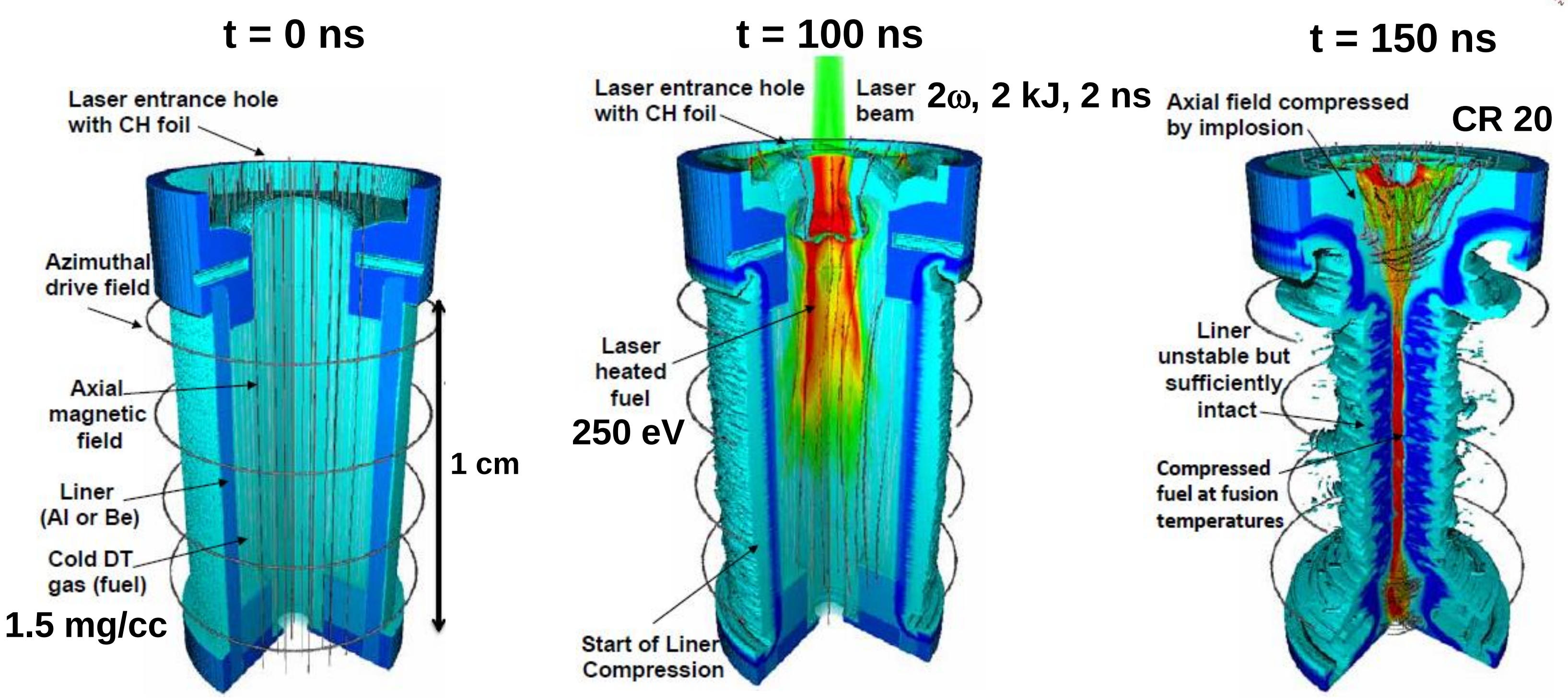
- **Before shots**



- **After shots**

SAND2017-0900PE_The sandia z machine - an overview of the world's most powerful pulsed power facility.pdf

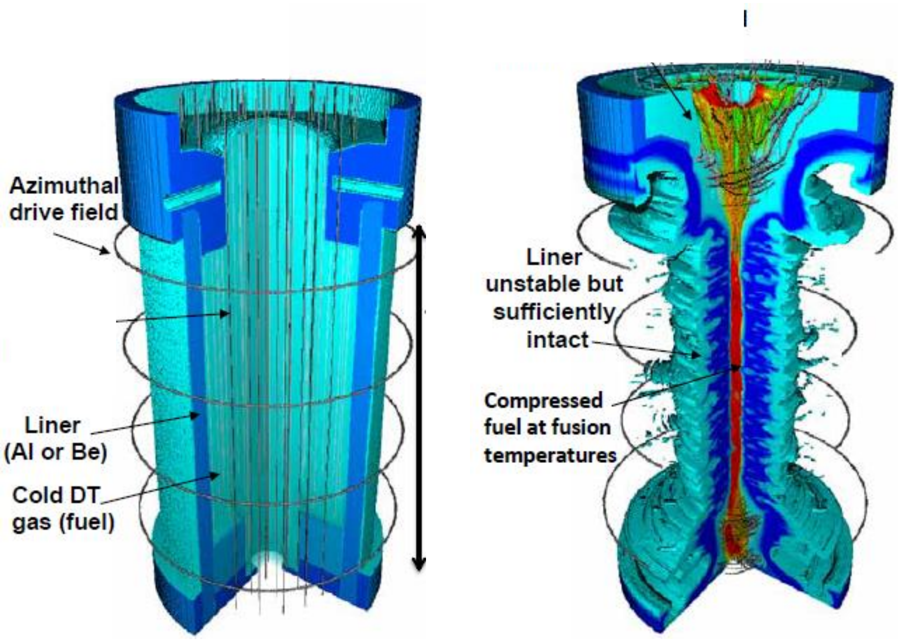
Promising results were shown in MagLIF concept conducted at the Sandia National Laboratories

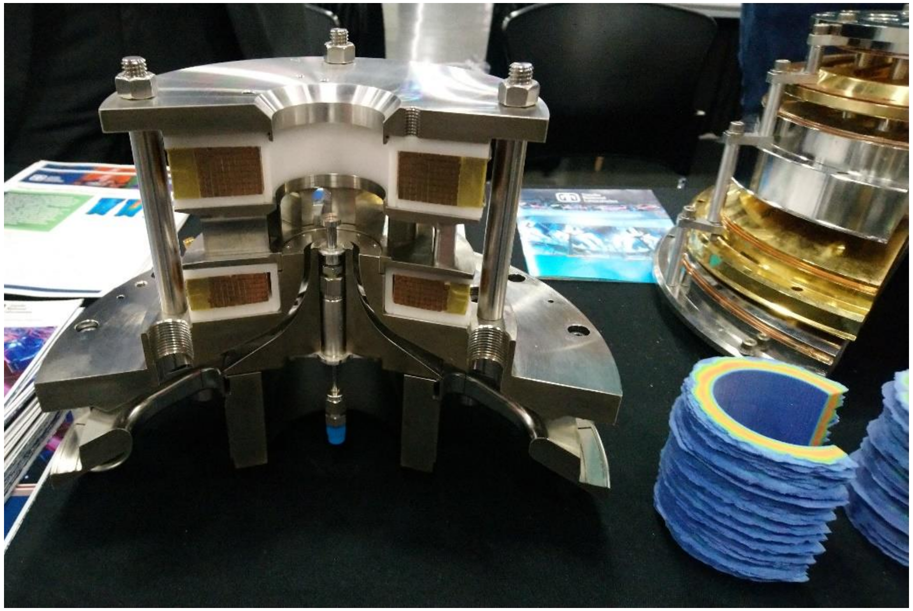


The stagnation plasma reached fusion-relevant temperatures with a 70 km/s implosion velocity

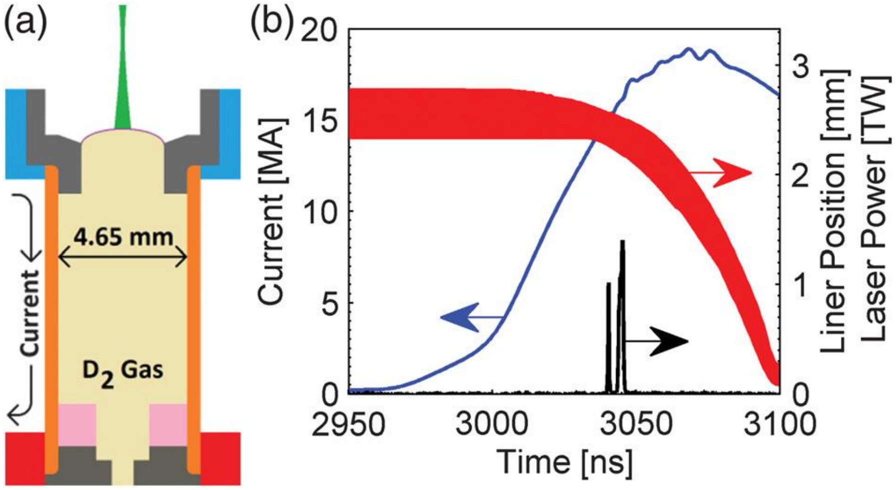
S. A. Slutz *et al* Phys. Plasmas 17 056303 (2010)
M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)

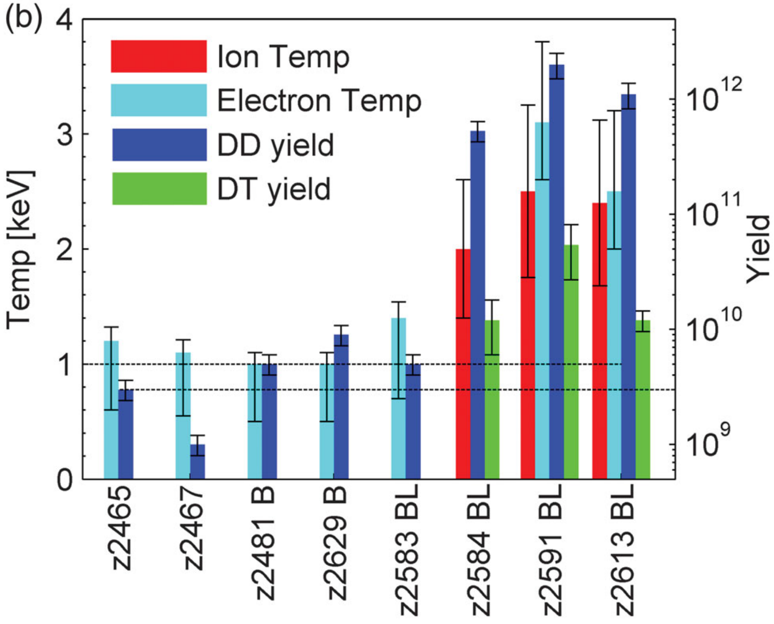
MagLIF target





Neutron yield increased by 100x with preheat and external magnetic field.



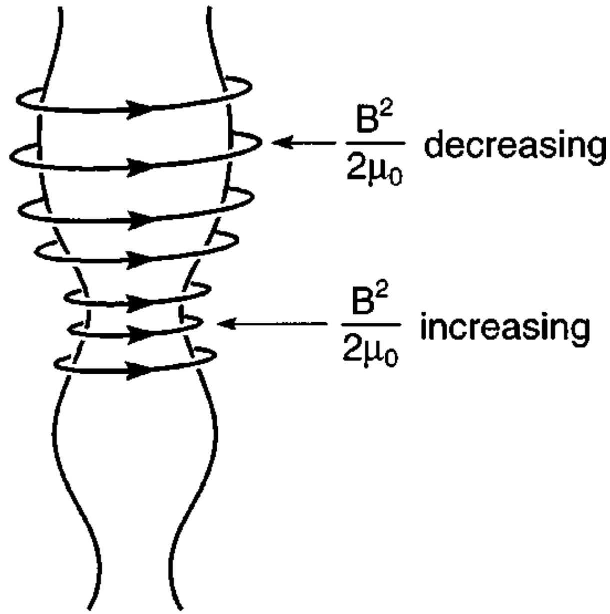


M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)

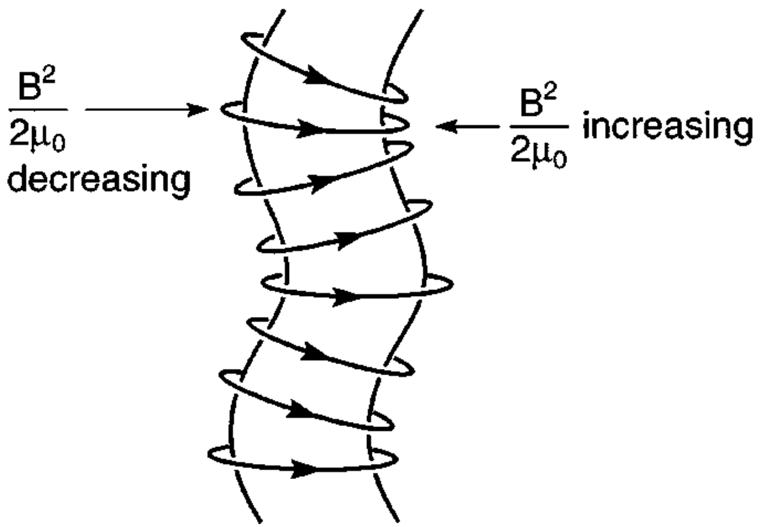
Sheared flow stabilizes MHD instabilities

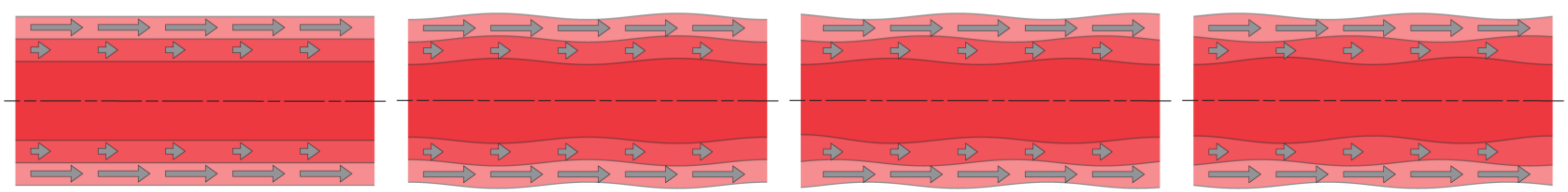
m = 0 (sausage)

Perturbation $\propto e^{(im\theta + ikz + \gamma t)}$



m = 1 (kink)

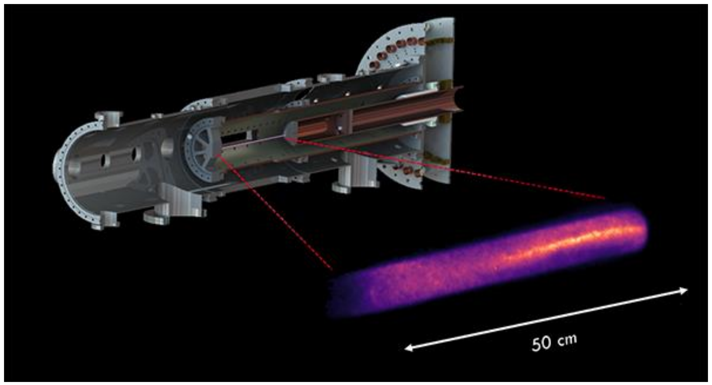




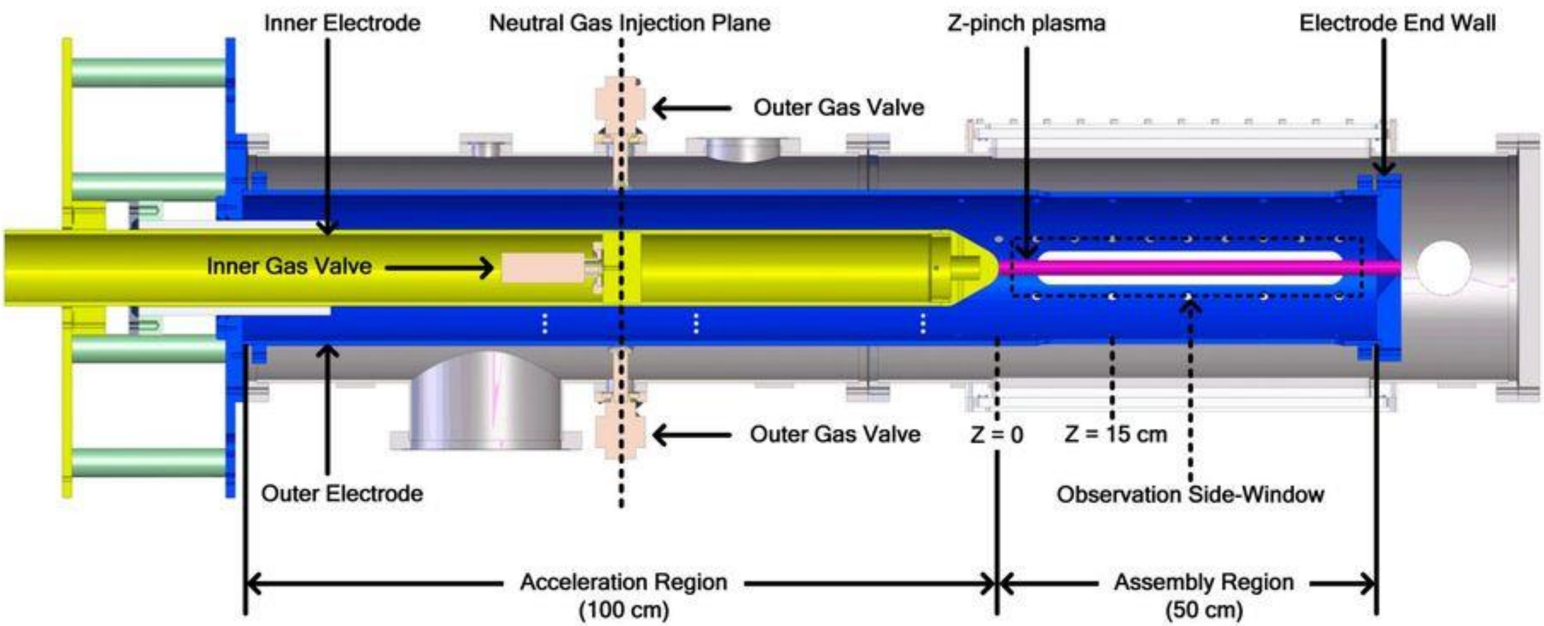
$$\frac{dV_Z}{dr} \neq 0$$

M. G. Haines, etc., Phys. Plasmas 7, 1672 (2000)
U. Shumlak, etc., Physical Rev. Lett. 75, 3285 (1995)
U. Shumlak, etc., ALPHA Annual Review Meeting 2017

A z-pinch plasma can be stabilized by sheared flows

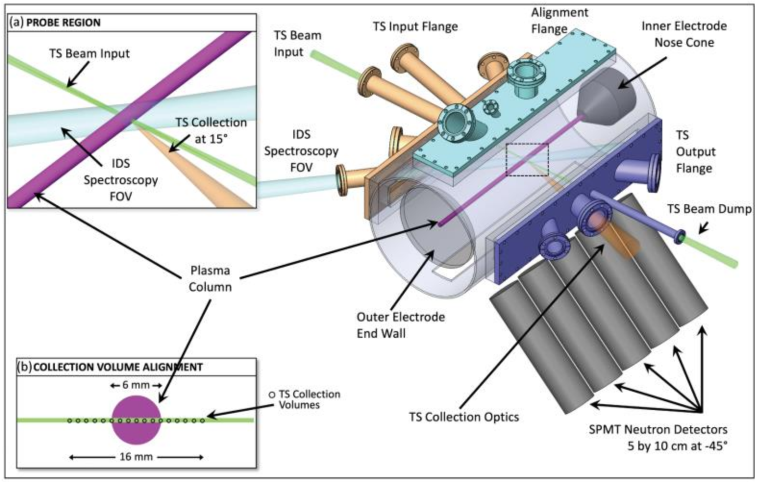


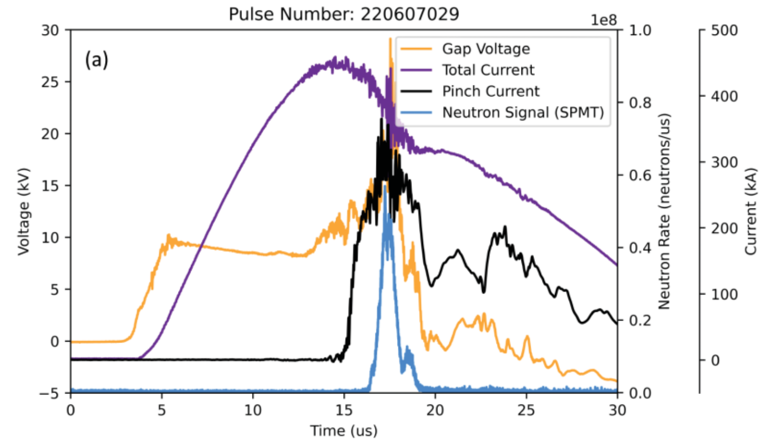
ZAP ENERGY™

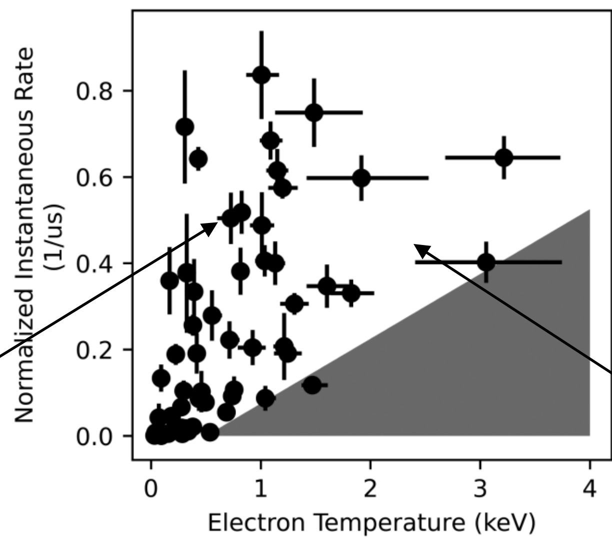


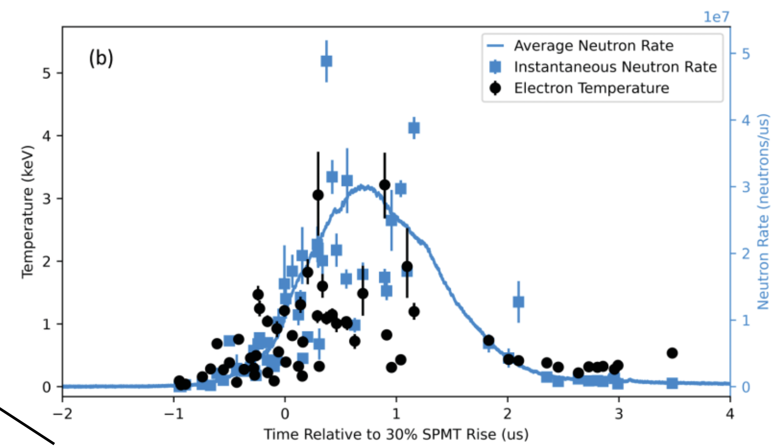
https://www.zapenergyinc.com/about
A. D. Stepanov, etc., Phys. Plasmas 27, 112503 (2020)

Elevated electron temperature coincident with observed fusion reactions in a sheared-flow-stabilized z pinch





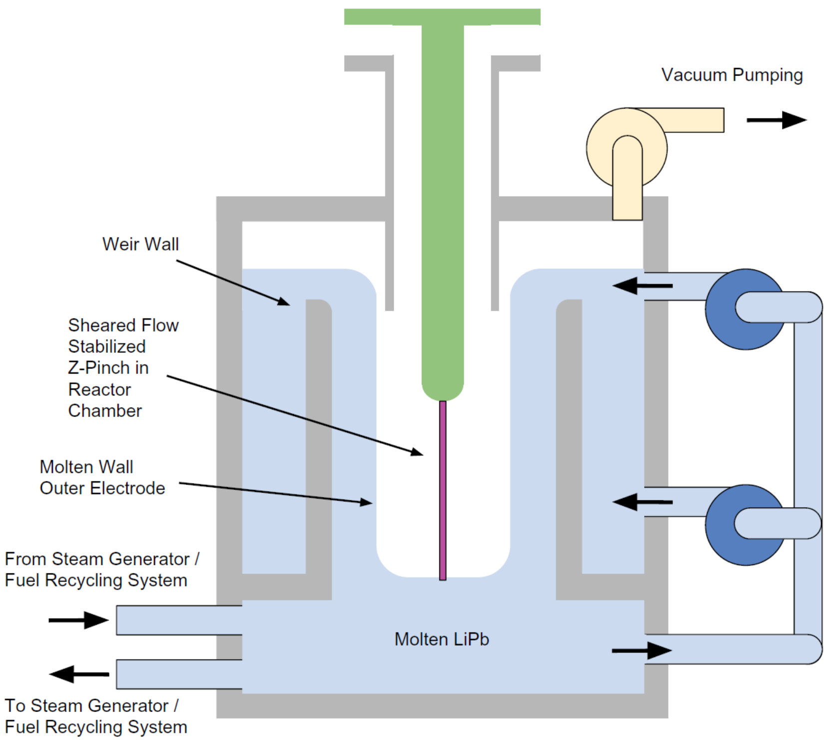


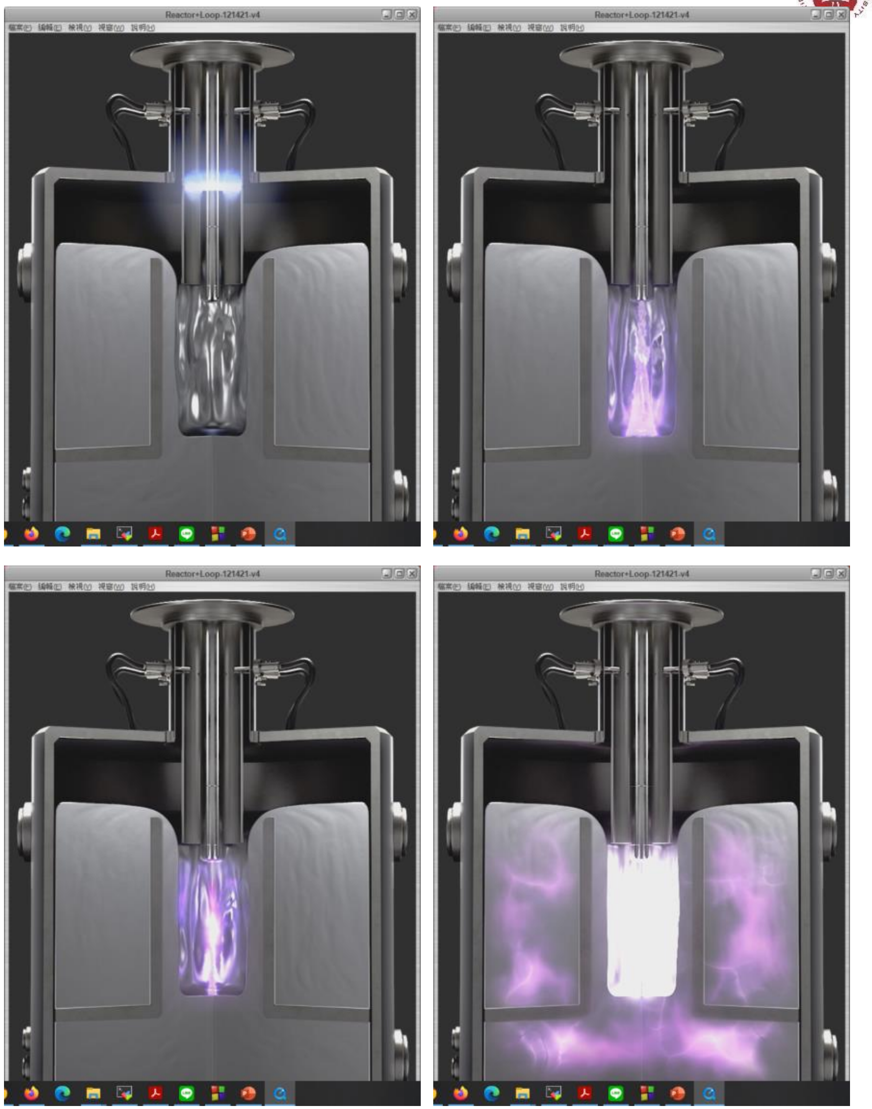


- **Thomson scattering measurement missed the high temperature region.**
- **High temperature coincide with high rate.**

B. Levitt, etc., Phys. Rev. Lett. **132**, 155101 (2024)

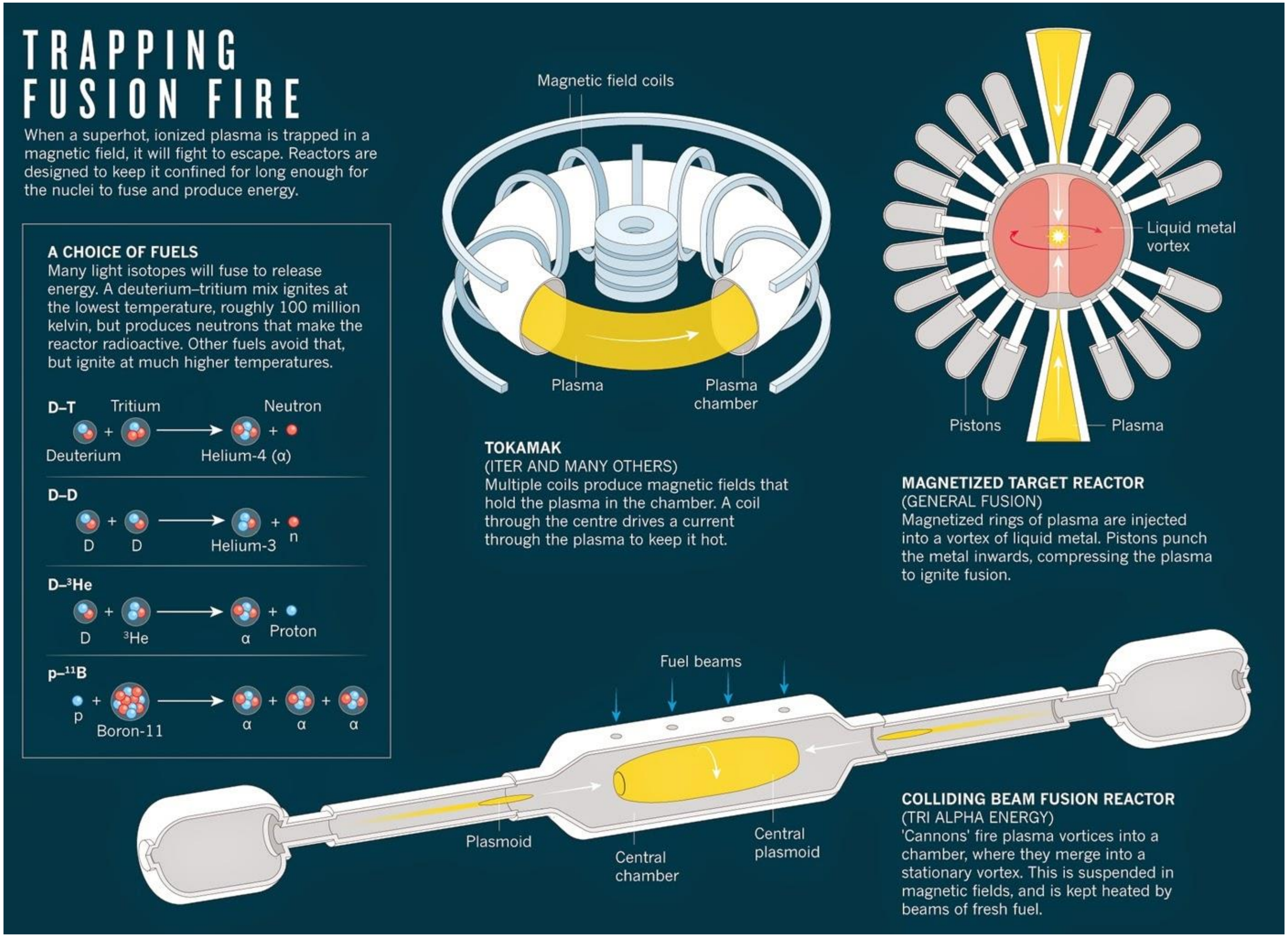
Fusion reactor concept by ZAP energy





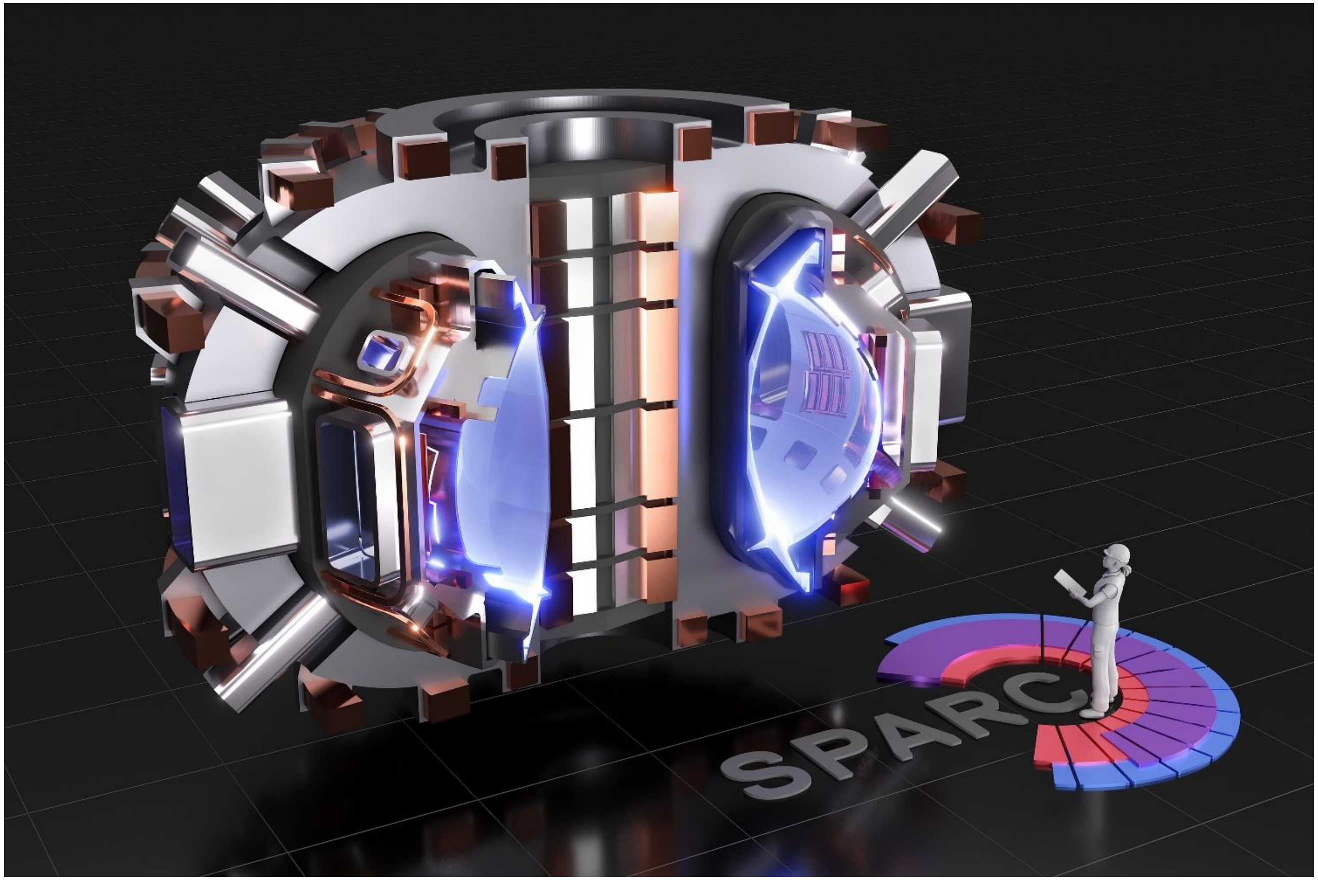
https://www.zapenergyinc.com/about
E. G. Forbes, etc., Fusion Sci. Tech. 75, 599 (2019)

There are alternative



http://www.nextbigfuture.com/2016/05/nuclear-fusion-comany-tri-alpha-energy.html

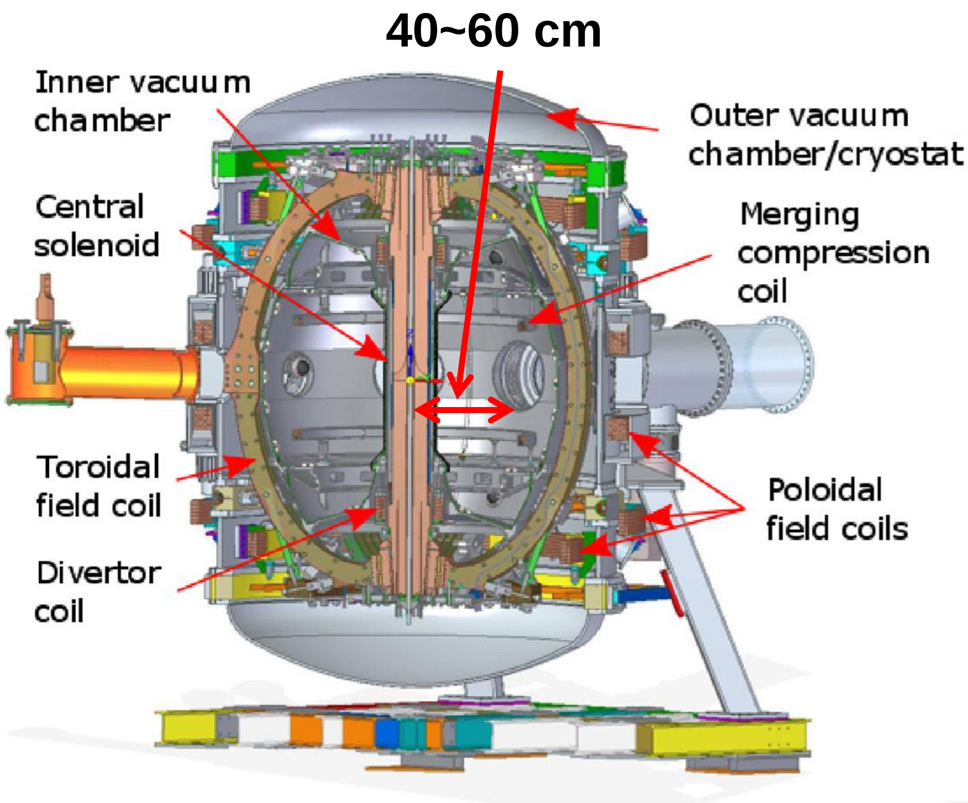
Commonwealth Fusion Systems, a MIT spin-out company, is building a high-magnetic field tokamak



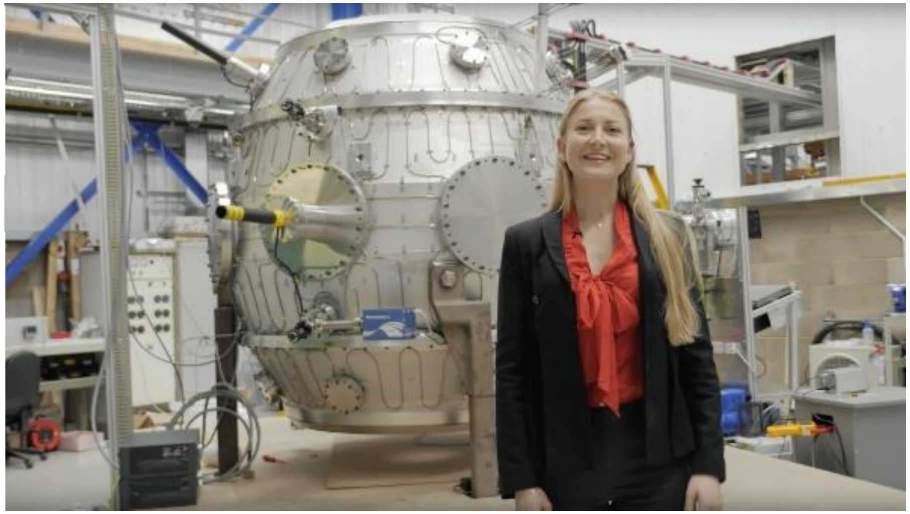
- **Fusion power ∝ B^4.**
- **The fusion gain Q > 2 is expected for SPARC tokamak.**

https://en.wikipedia.org/wiki/SPARC_(tokamak)

Merging compression is used to heat the tokamak at the start-up process in ST40 Tokamak at Tokamak Energy Ltd

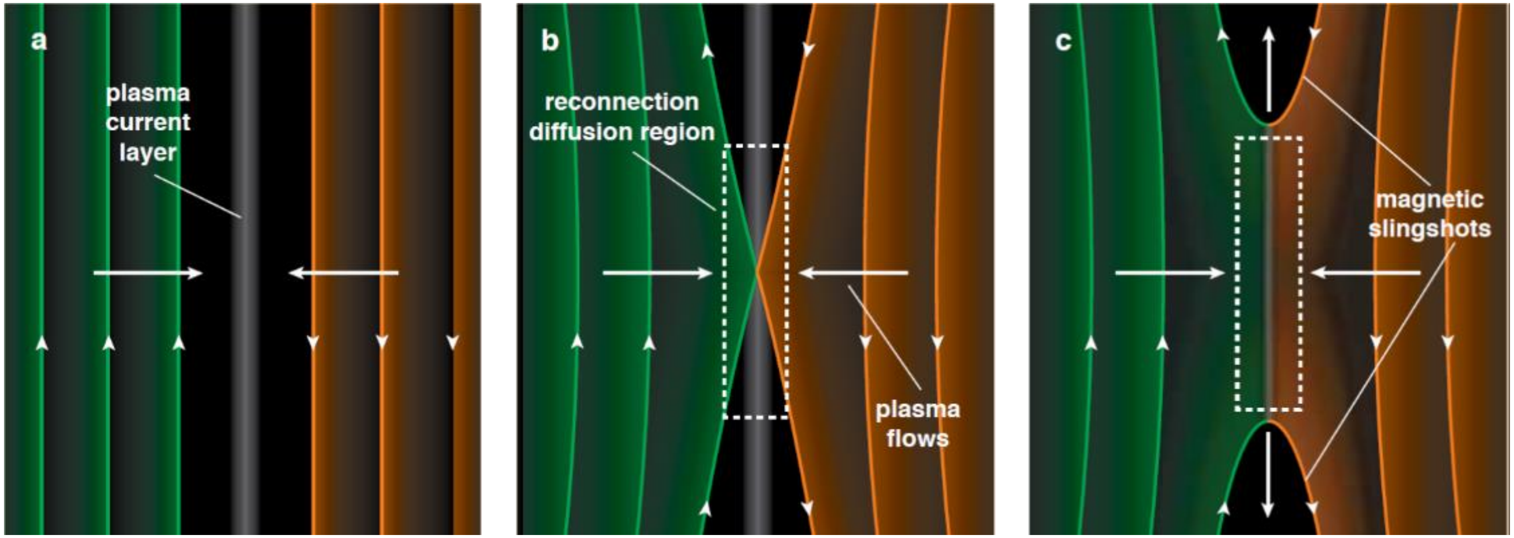


- **High temperature superconductors are used.**
- **B_T ~ 3 T**



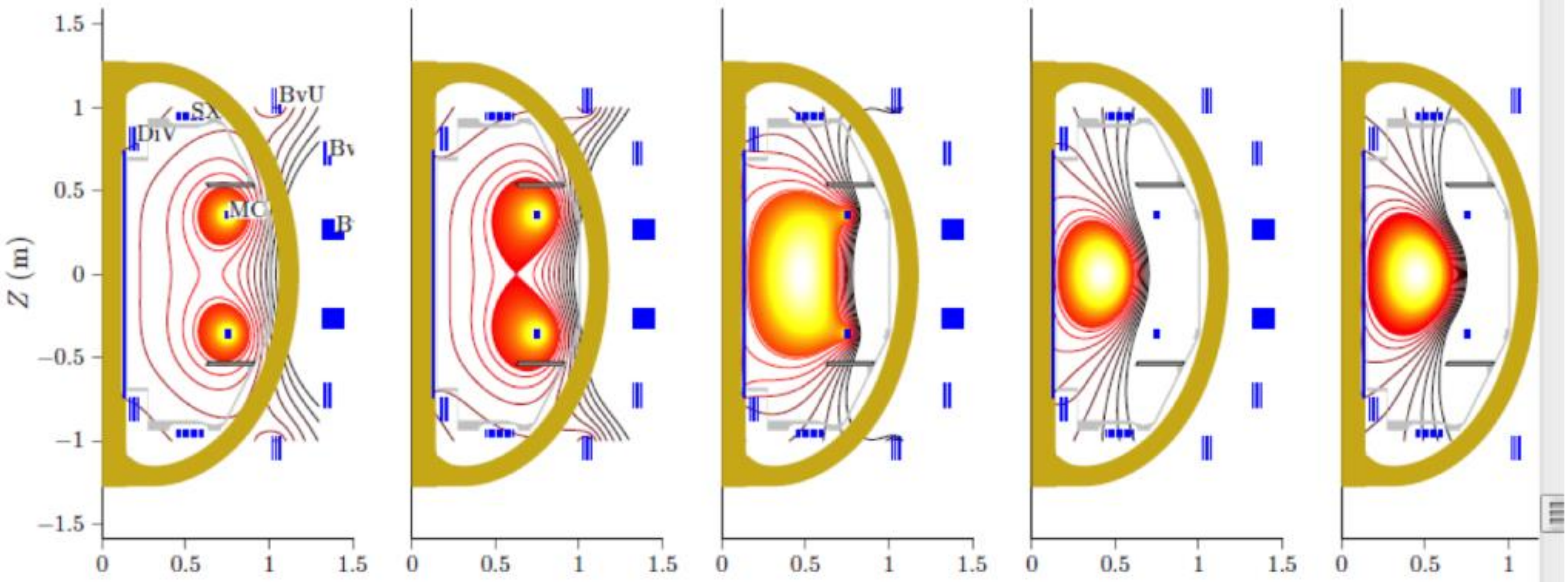
M. Gryaznevich, etc., Fusion Eng. Design, **123**,177 (2017)
https://www.tokamakenergy.co.uk/
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

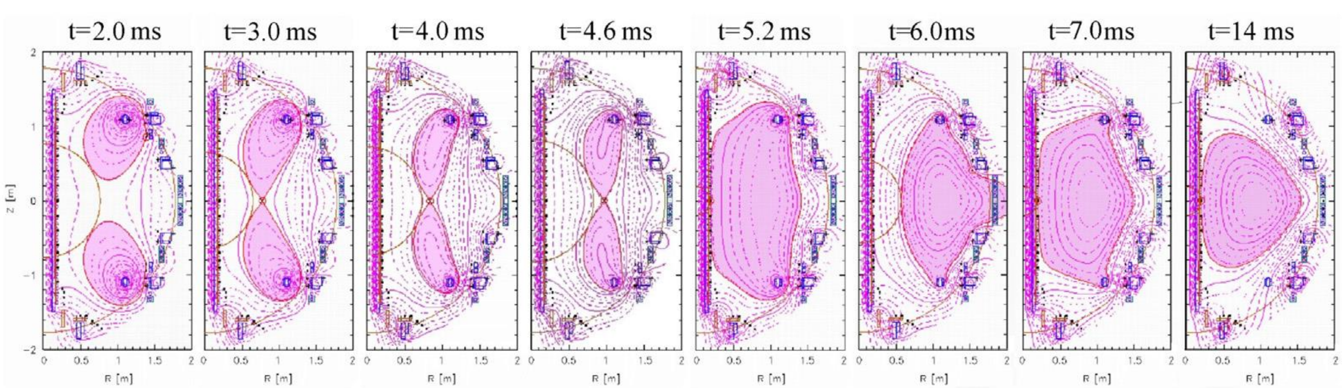
Reconnection



https://www.youtube.com/watch?v=7sS3Lpzh0Zw

Merging compression is used to heat the plasma



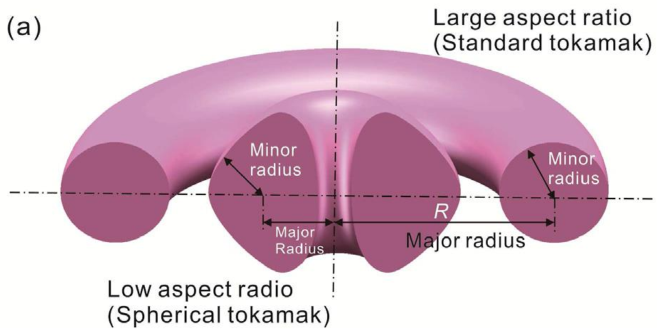


http://www.100milliondegrees.com/merging-compression/

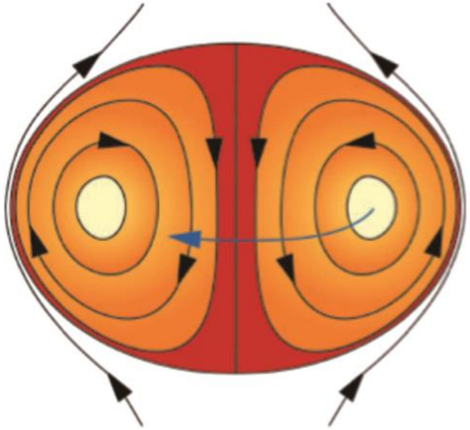
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

Spherical torus (ST) and compact torus (CT)

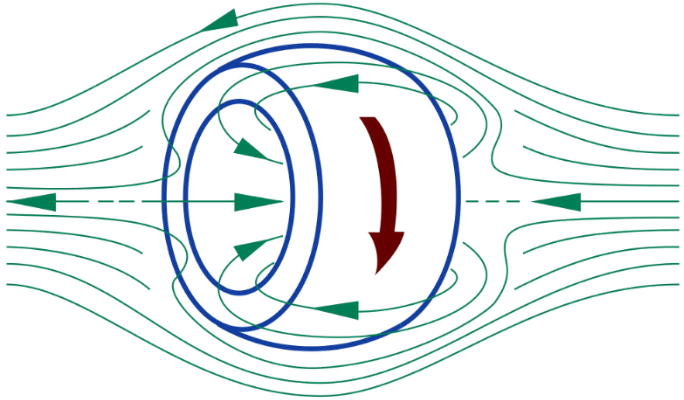
- Spherical torus (ST)



- Compact torus (CT)
  - Spheromak

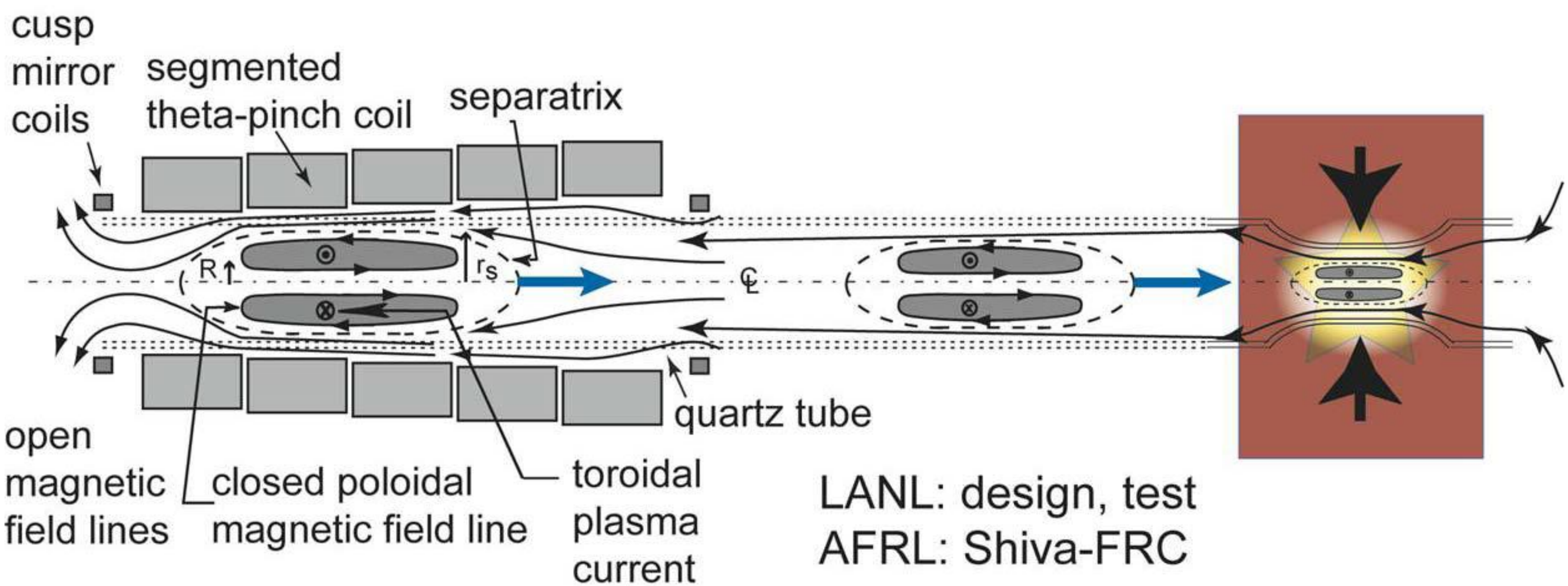


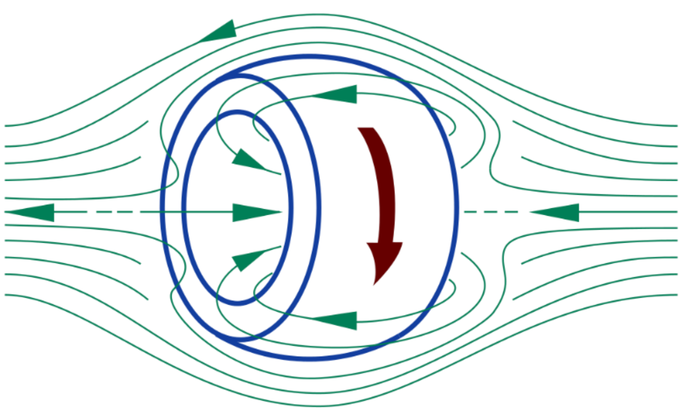
  - Field reversed configuration (FRC)



Zhe Gao, Matter Radiat. Extremes **1**, 153 (2016)
https://en.wikipedia.org/wiki/Field-reversed_configuration

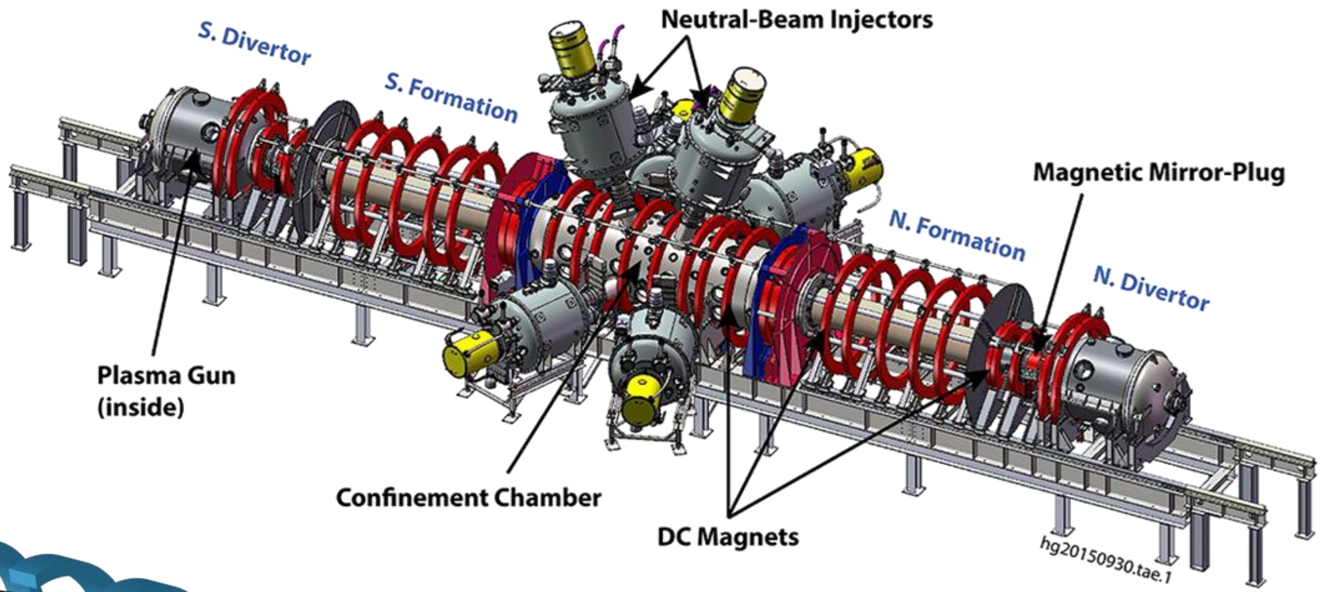
Field reverse configuration is used in Tri-alpha energy

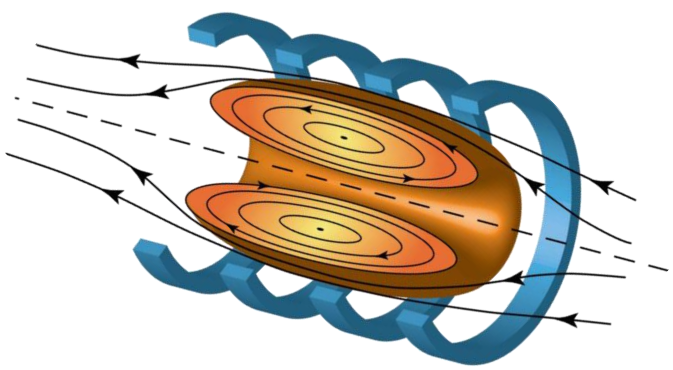




*Magneto-Inertial Fusion& Magnetized HED Physics by Bruno S. Bauer, UNR & Magneto-Inertial Fusion Community
**https://en.wikipedia.org/wiki/Field-reversed_configuration

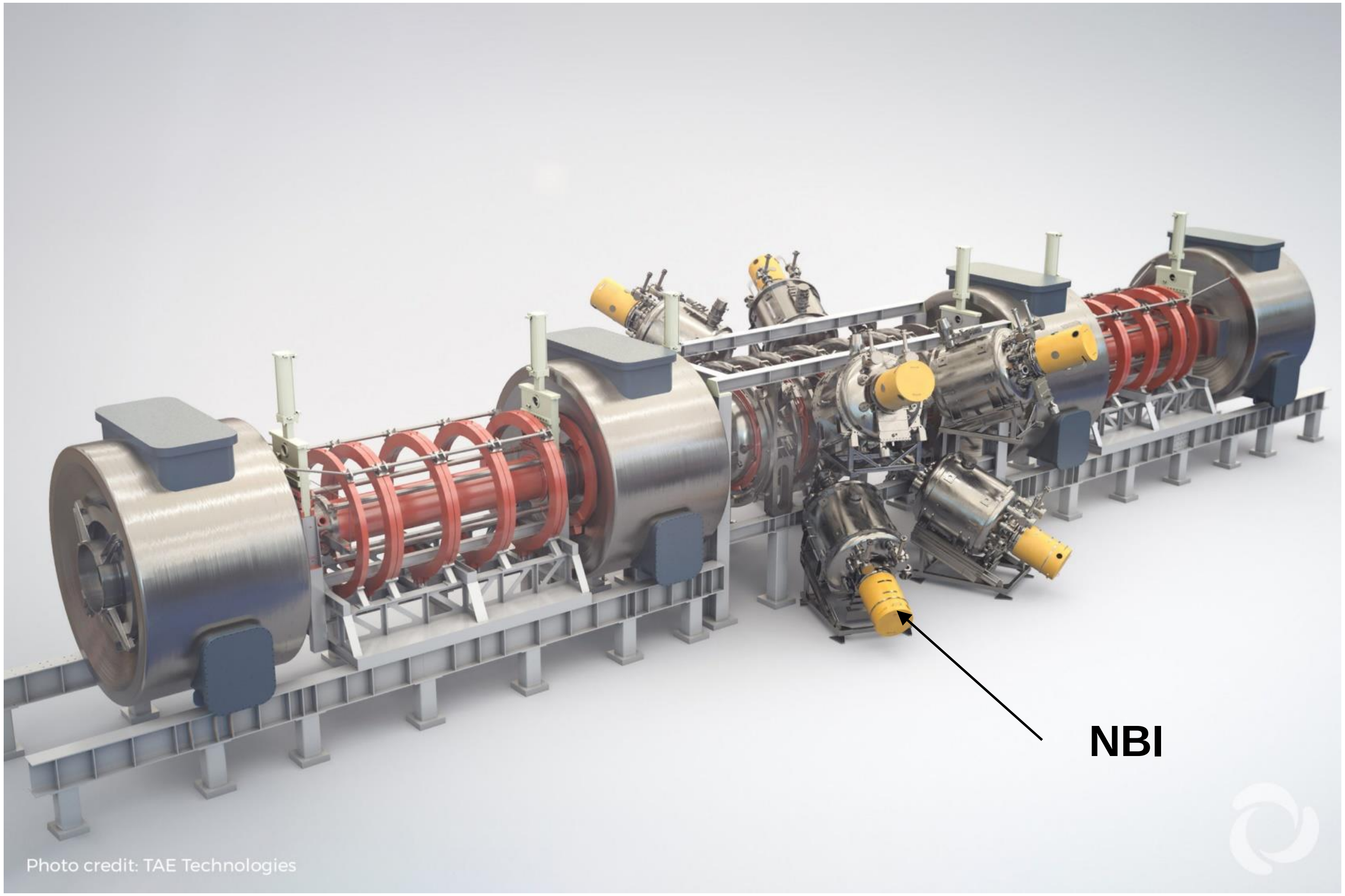
Field reverse configuration is used in Tri-alpha energy





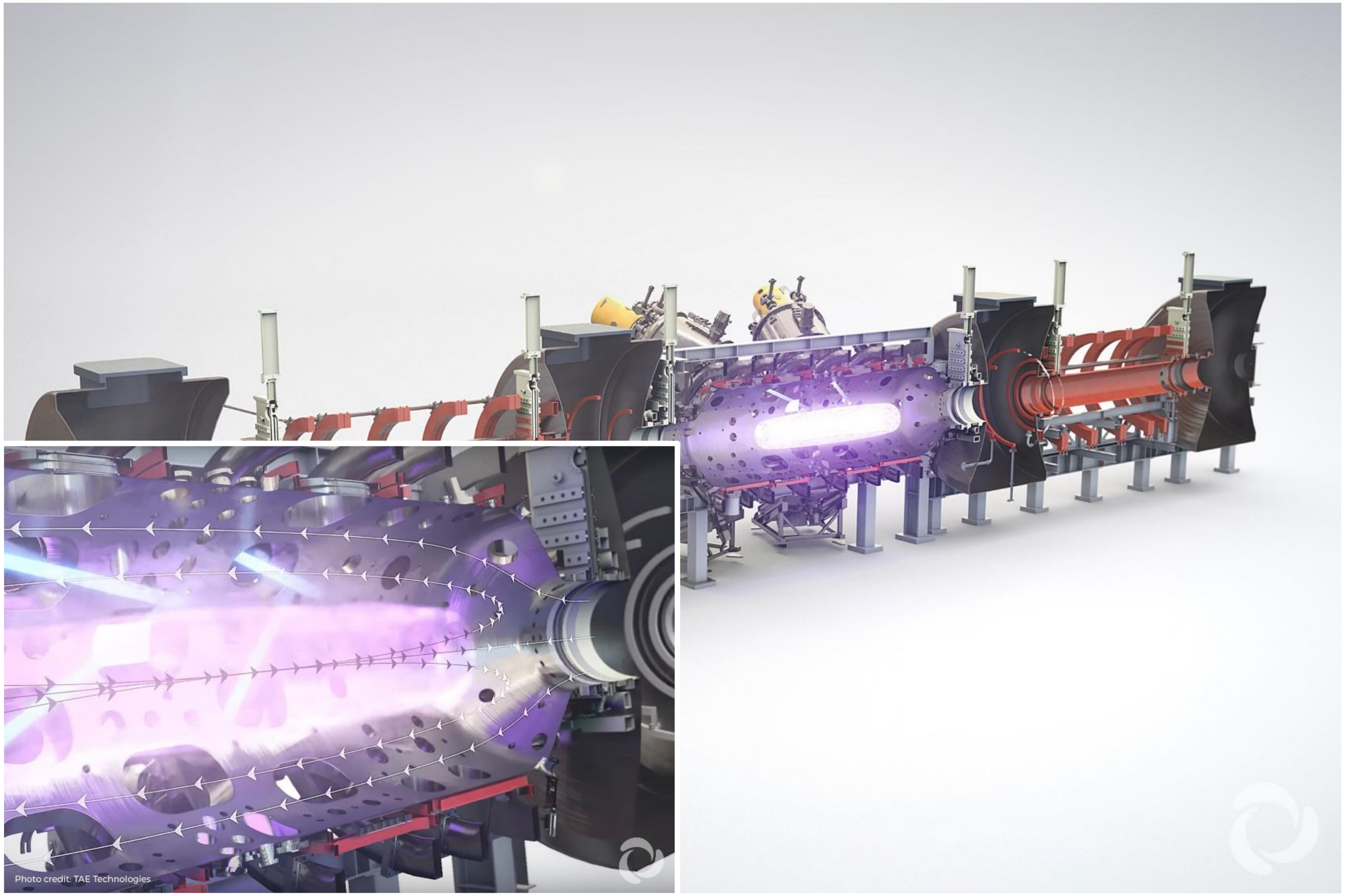
http://trialphaenergy.com/

NBI for Tri-Alpha Energy Technologies



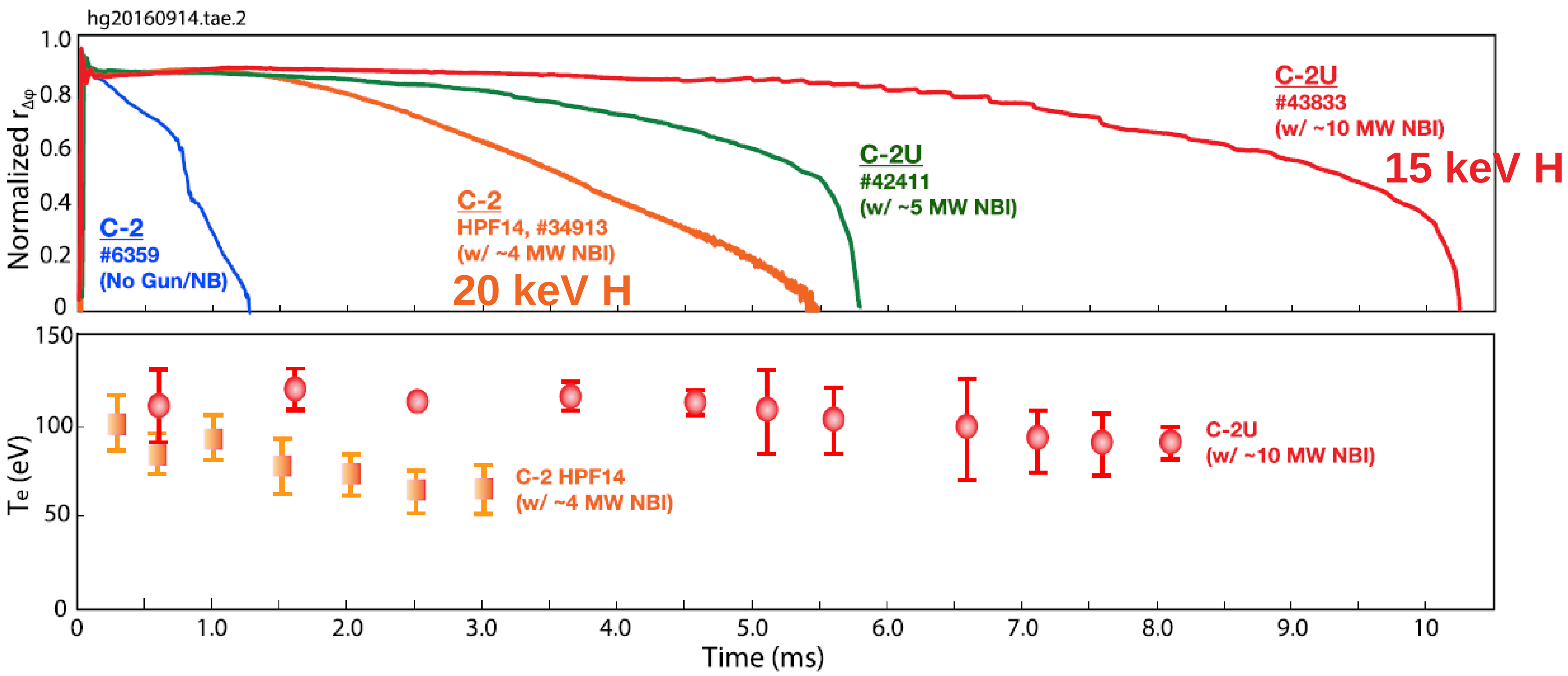
https://tae.com/media/

Neutral beams are injected in to the chamber for spinning the FRC



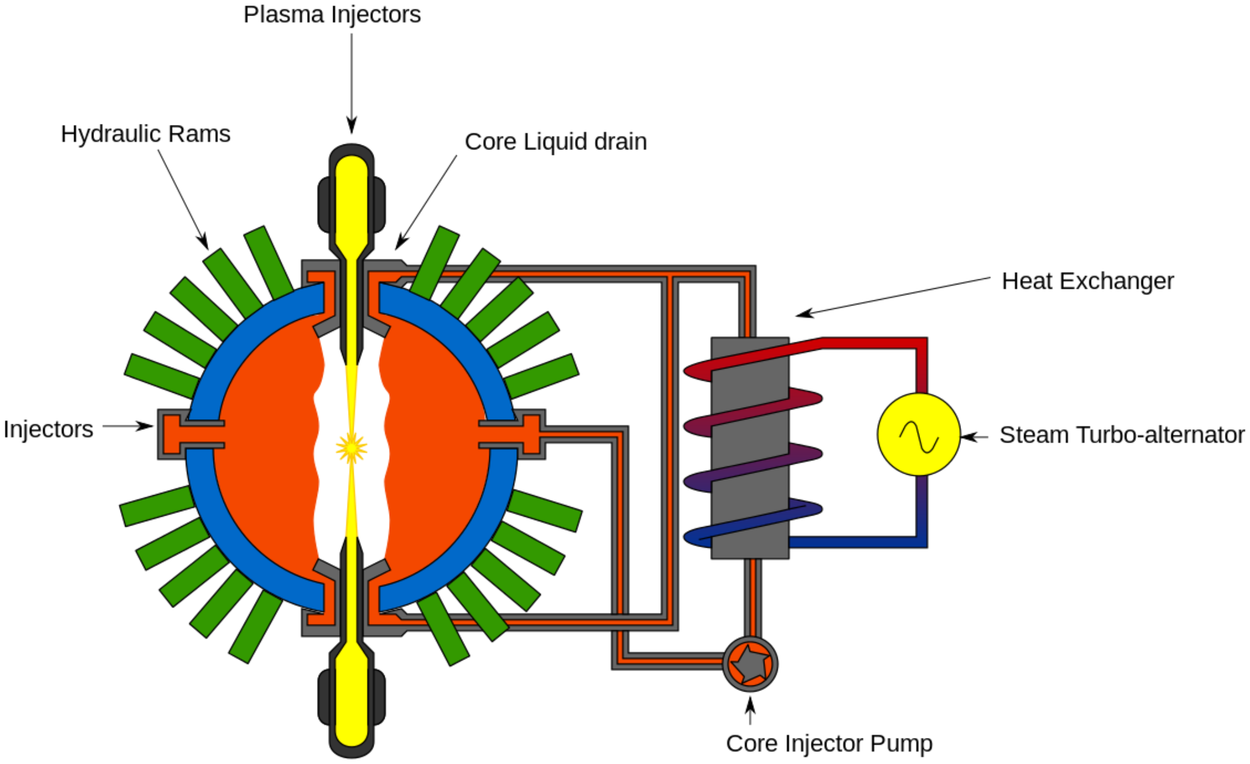
https://tae.com/media/

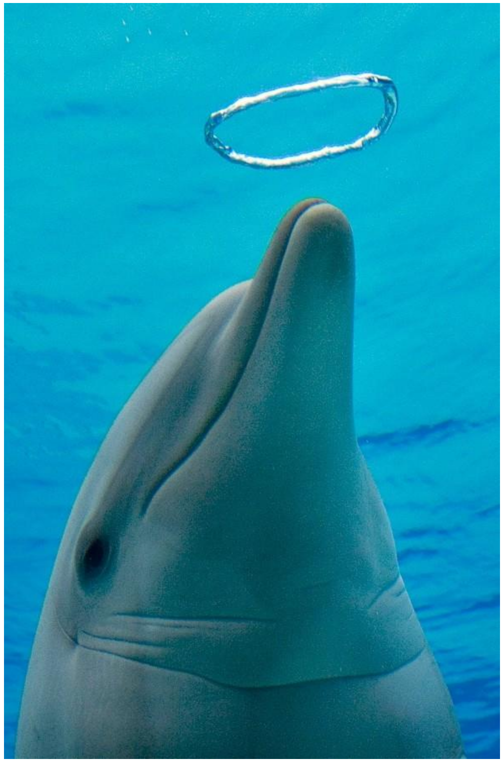
FRC sustain longer with neutral beam injection



H. Gota, *etc.*, Nucl. Fusion **57** (2017) 116021

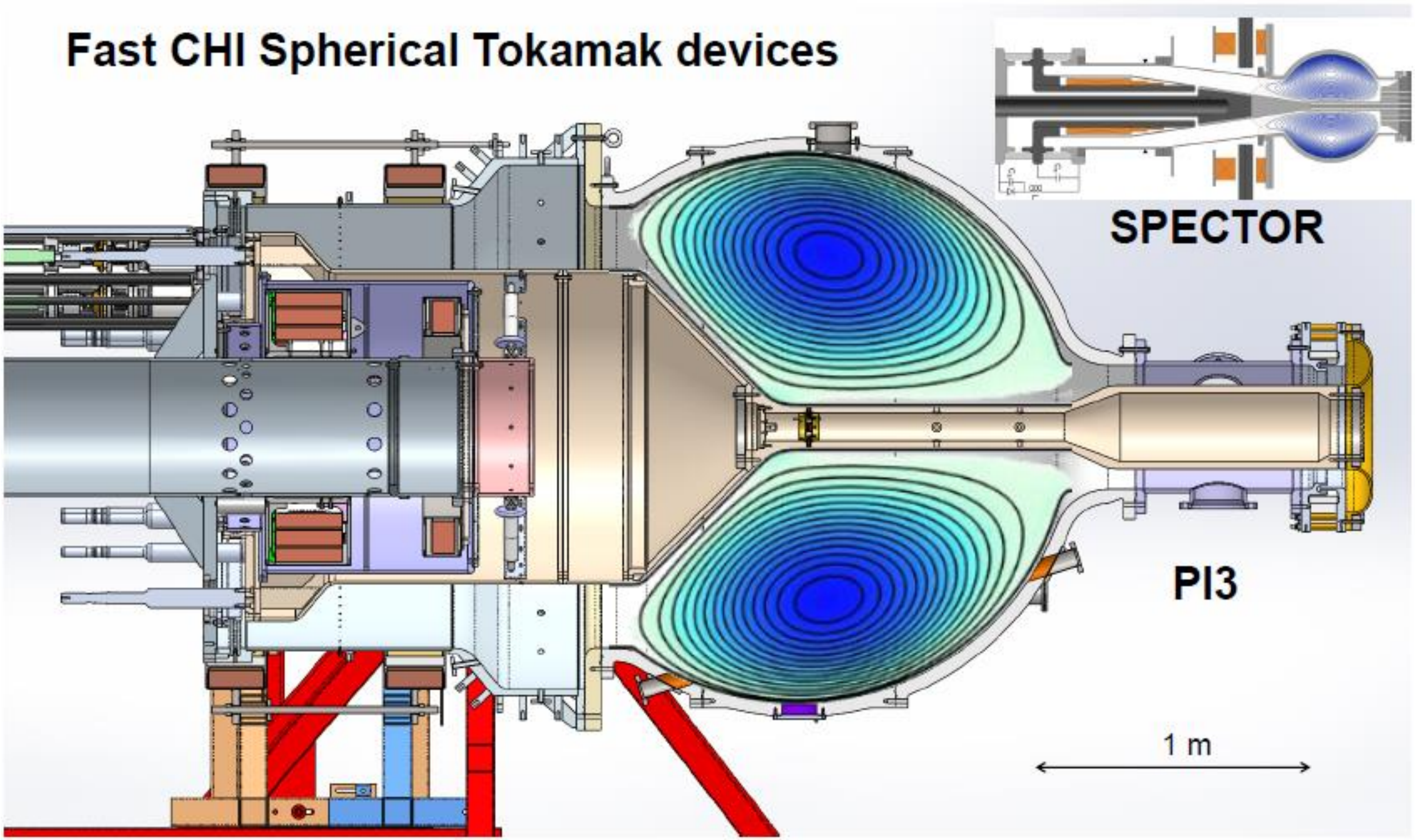
General fusion is a design ready to be migrated to a power plant





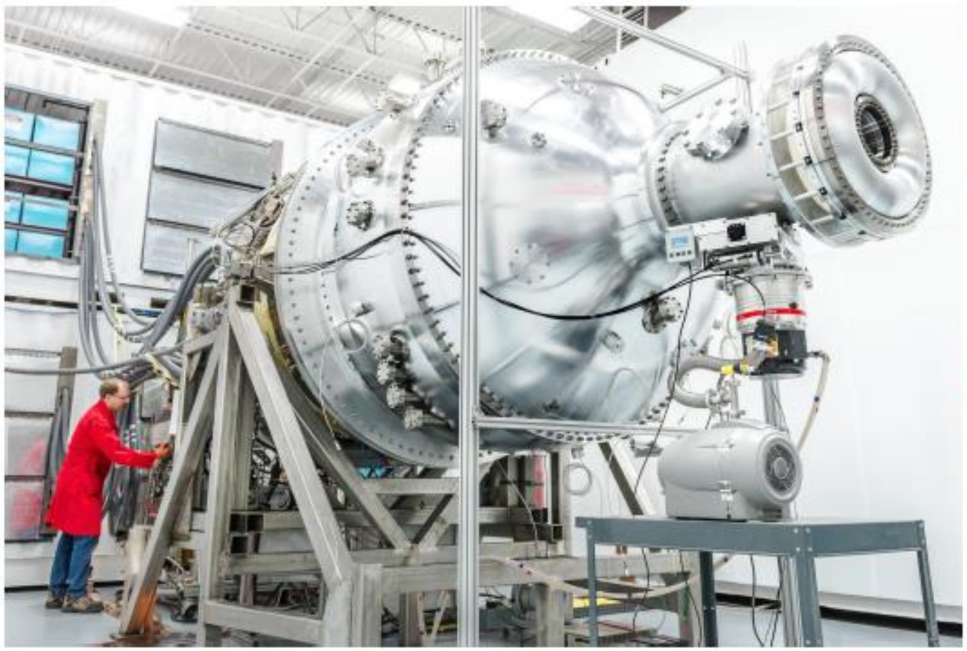
https://en.wikipedia.org/wiki/General_Fusion

A spherical tokamak is first generated



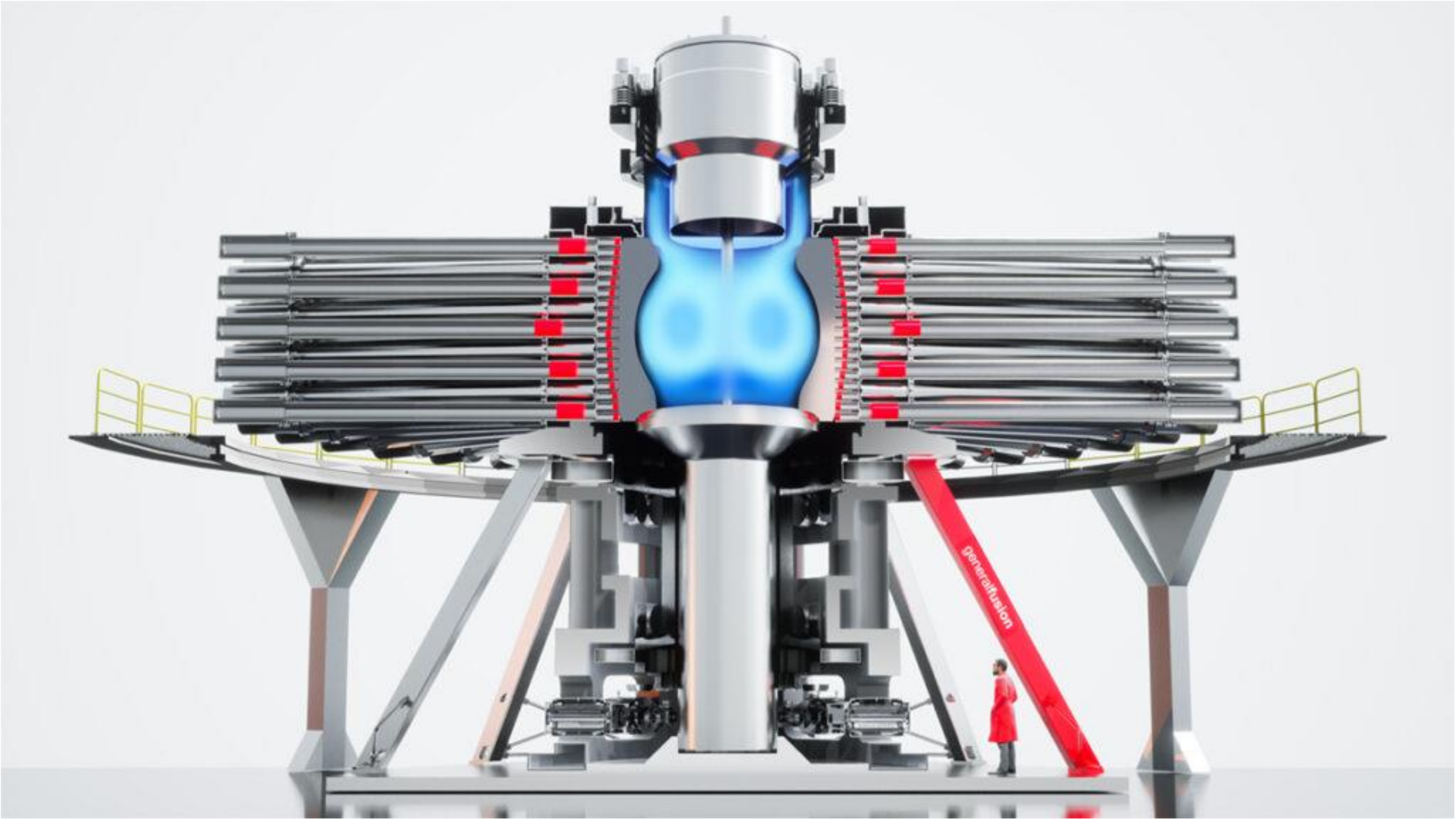
K. EPP, etc., 60th APS-DPP, CP11.00192

Plasma injector for the spherical tokamak

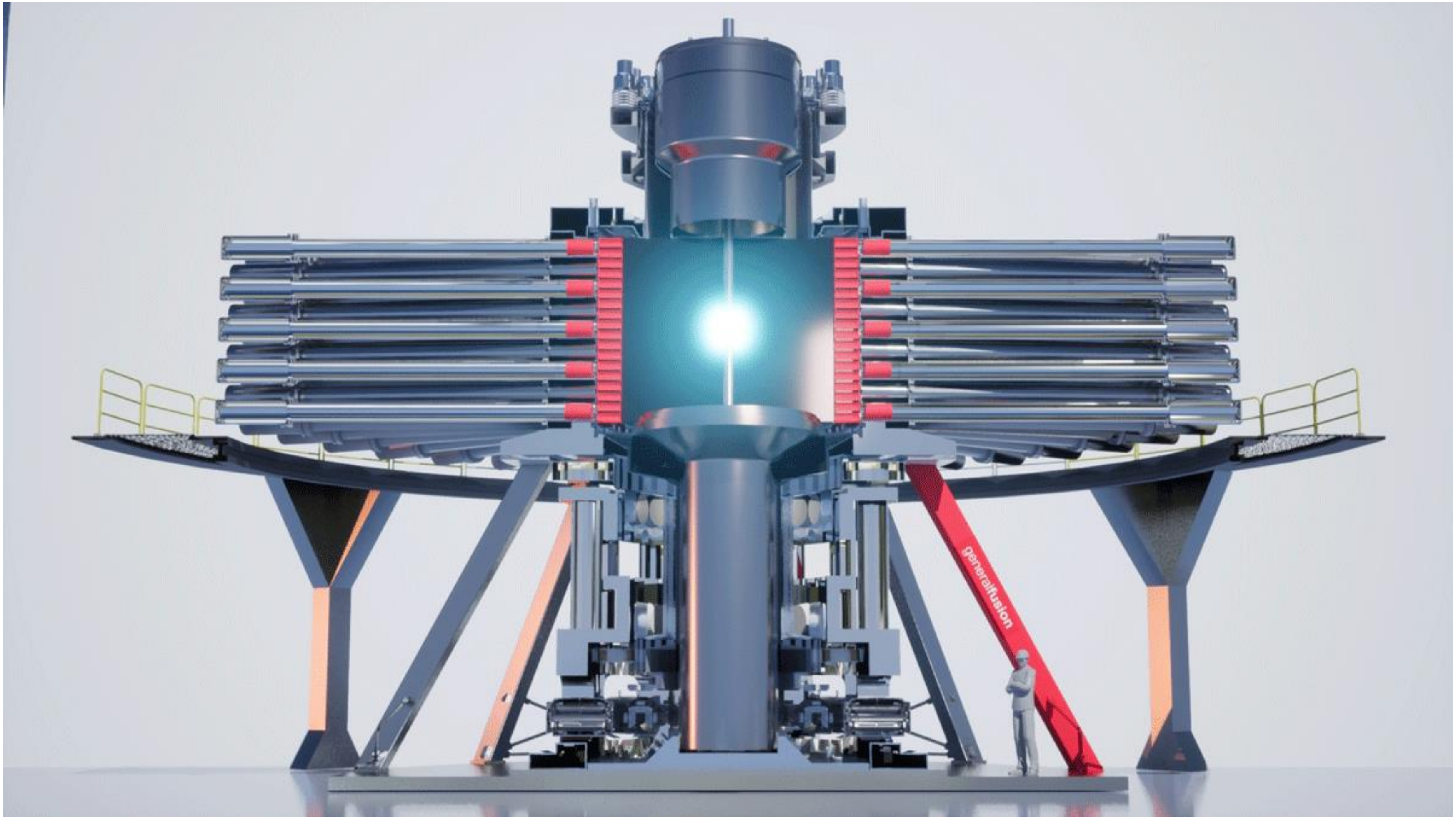


K. EPP, etc., 60th APS-DPP, CP11.00192

A spherical tokamak is generated in a liquid metal vortex



The spherical tokamak is compressed by the pressure provided by the sournding hydraulic pistons



BBC: General Fusion to build its Fusion Demonstration Plant in the UK, at the UKAEA Culham Campus

Nuclear energy: Fusion plant backed by Jeff Bezos to be built in UK

By Matt McGrath
Environment correspondent

17 June

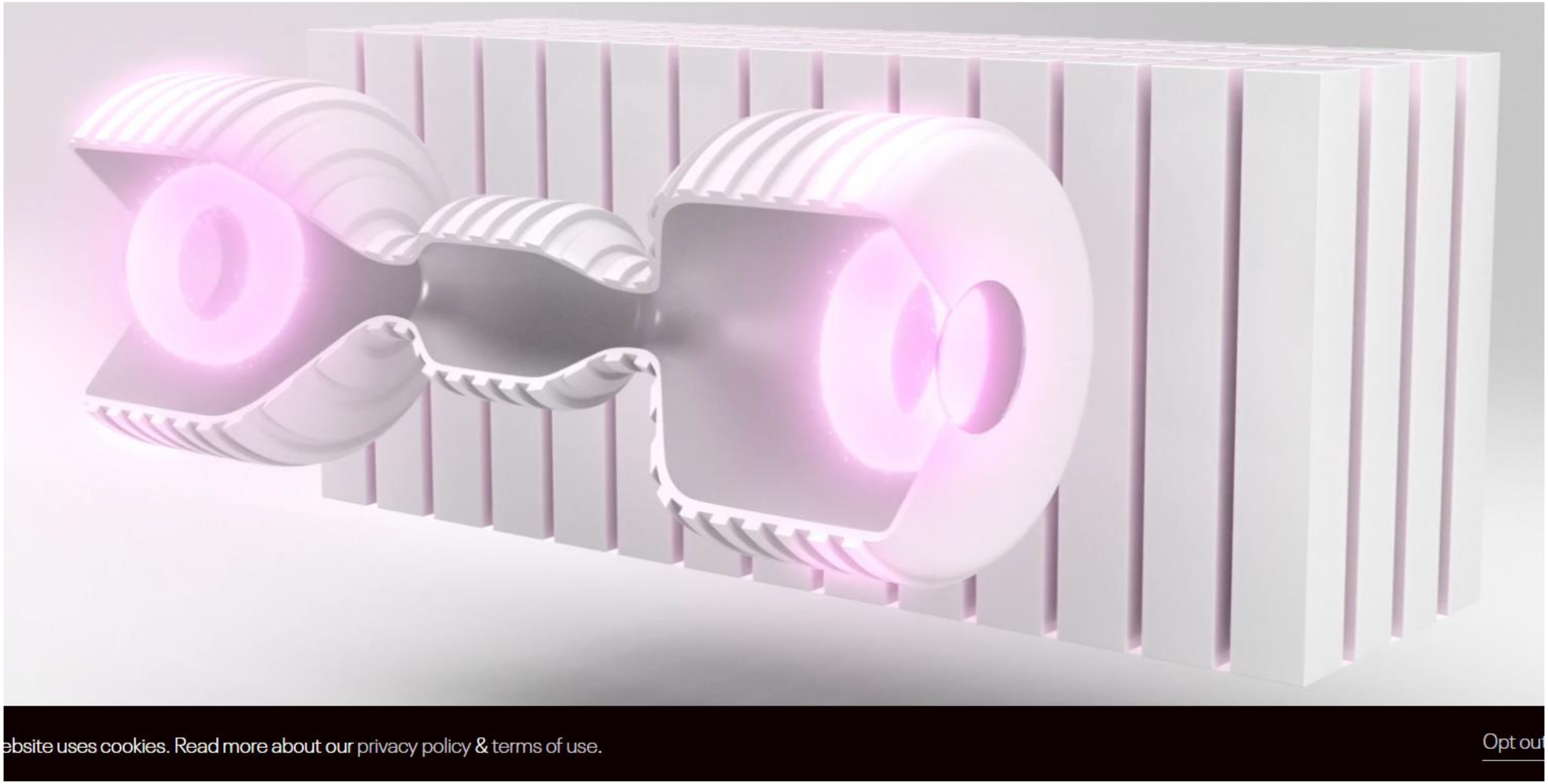
An artist's impression of what the new demonstration plant might look like

A company backed by Amazon's Jeff Bezos is set to build a large-scale nuclear fusion demonstration plant in Oxfordshire.

Canada's **General Fusion** is one of the leading private firms aiming to turn the

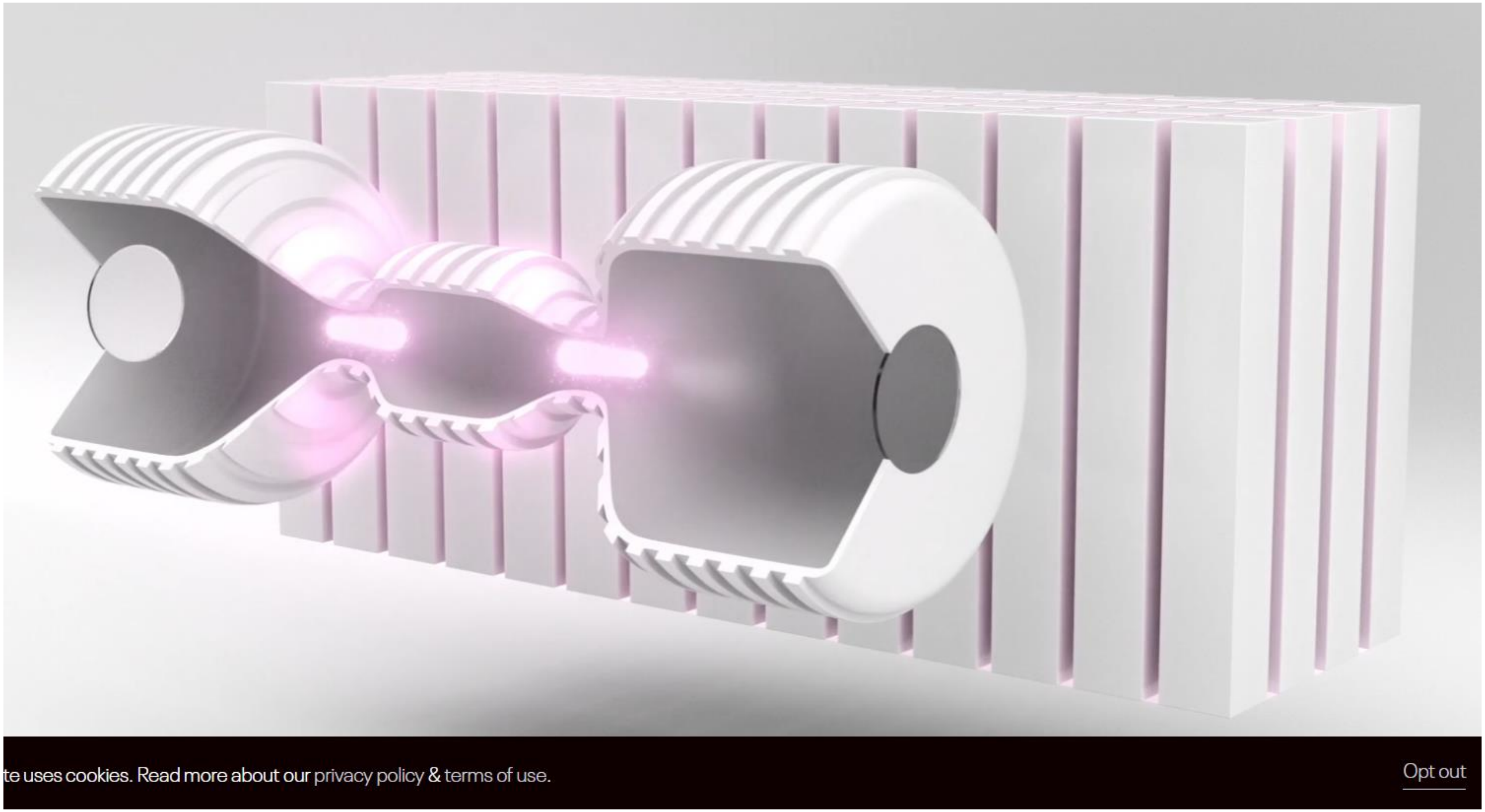
https://www.bbc.com/news/science-environment-57512229

Helion energy is compressing the two merging FRCs



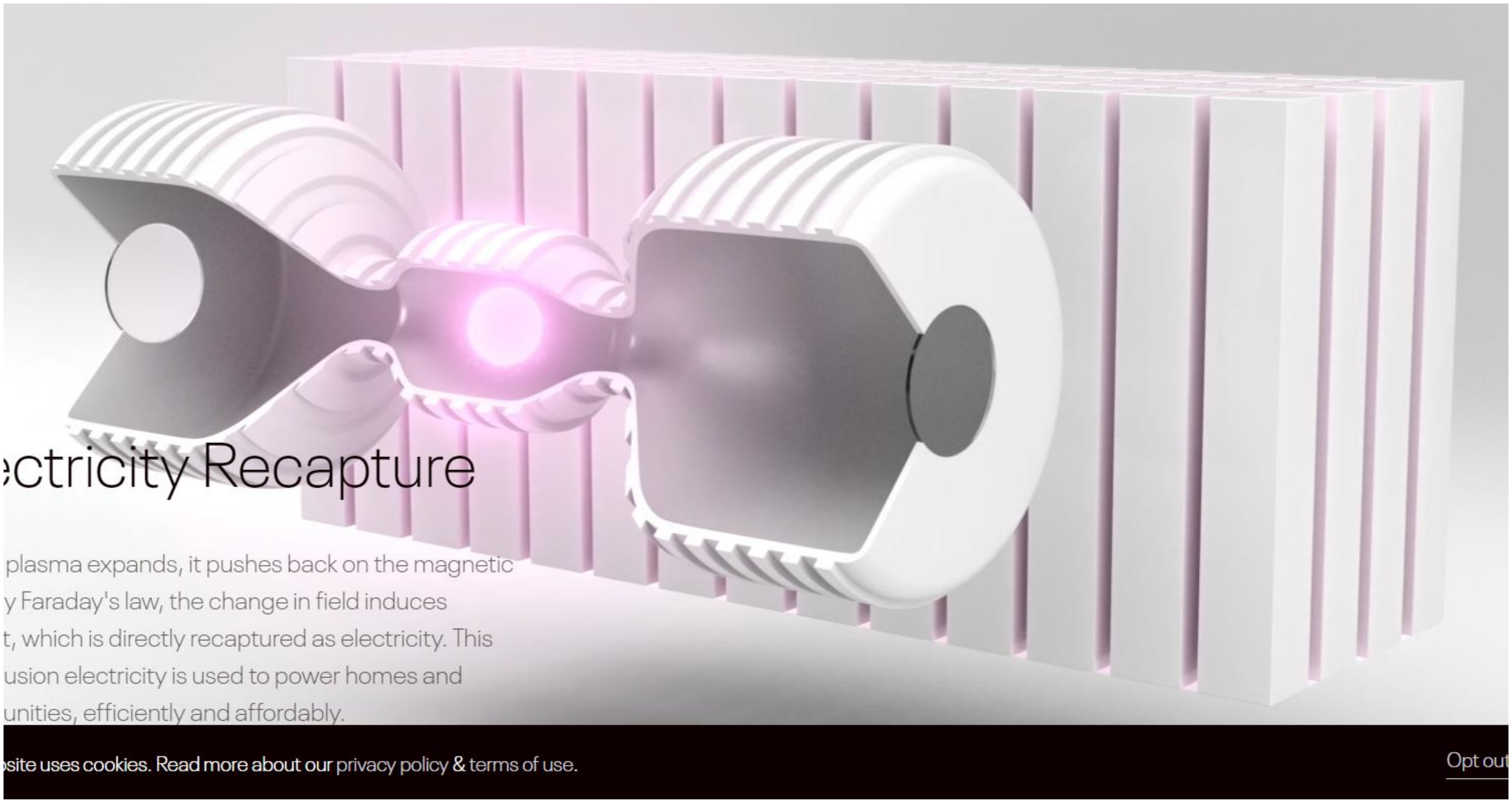
https://www.helionenergy.com/

Two FRCs are accelerated toward each other



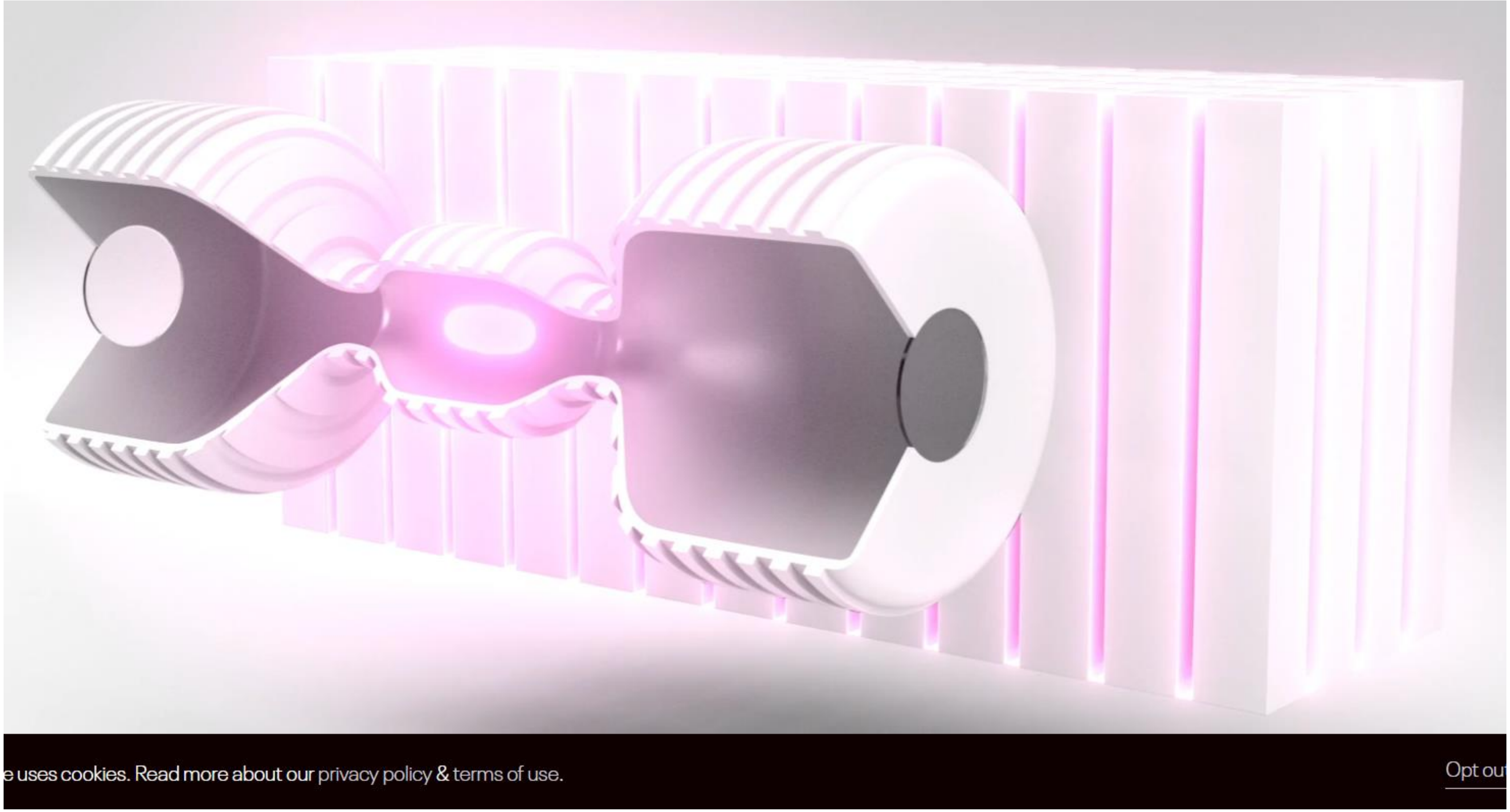
https://www.helionenergy.com/

Two FRCs merge with each other



https://www.helionenergy.com/

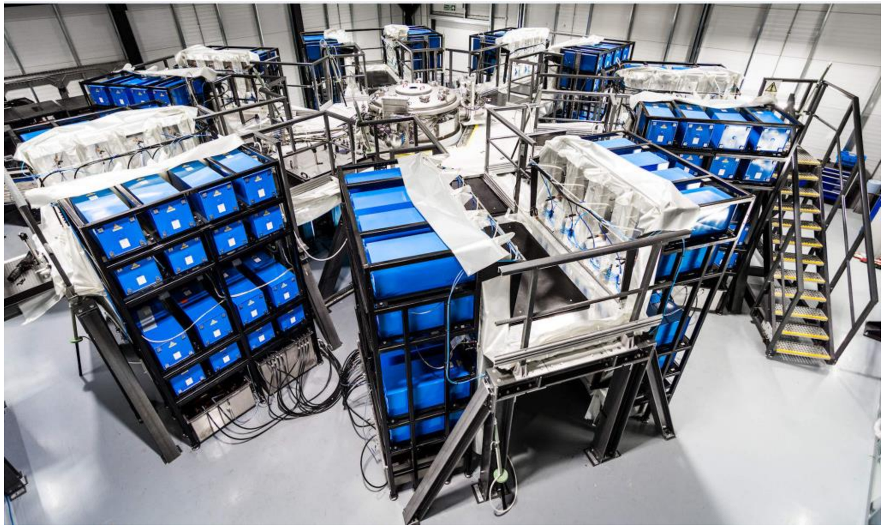
The merged FRC is compressed electrically to high temperature



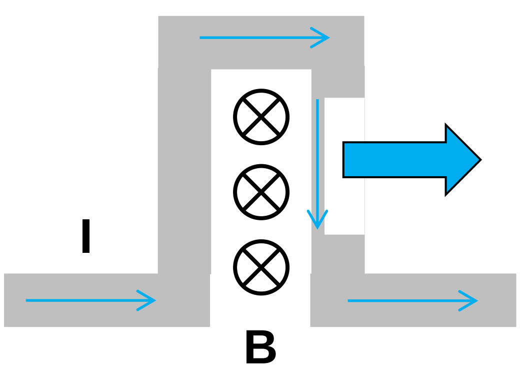
- **Similar concept will be studied in our laboratory.**

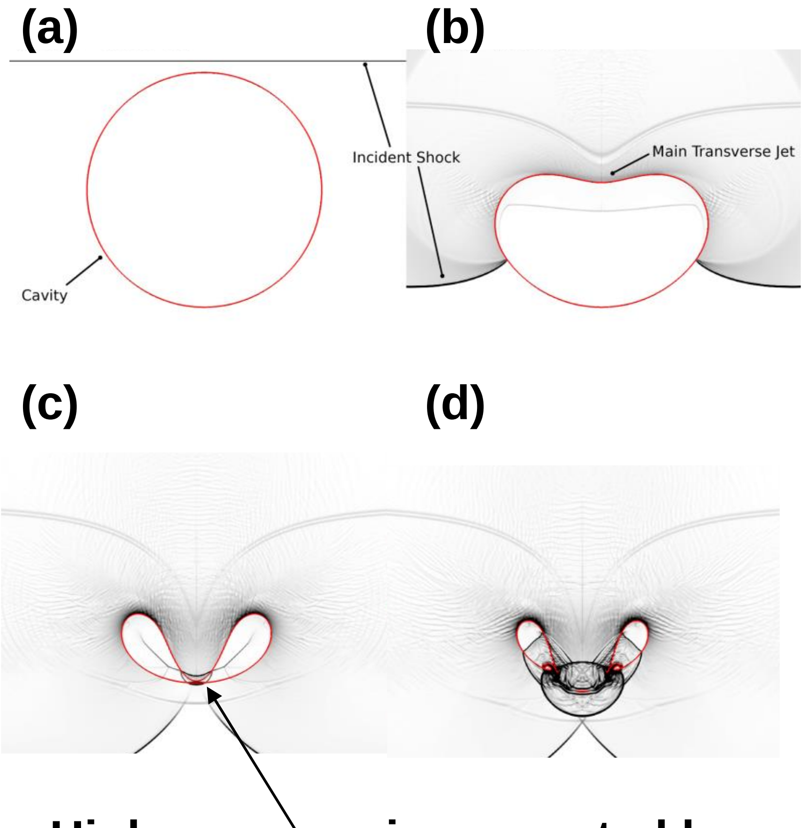
https://www.helionenergy.com/

Projectile Fusion is being established at First Light Fusion Ltd, UK



- Stored energy: 2.5 MJ @ 200 kV (C_{tot}=125 uF)
- I_{peak}=14 MA w/ T_{rise}~2us.





- High pressure is generated by the colliding shock.

https://www.youtube.com/watch?v=aTMPigL7FB8

https://firstlightfusion.com/

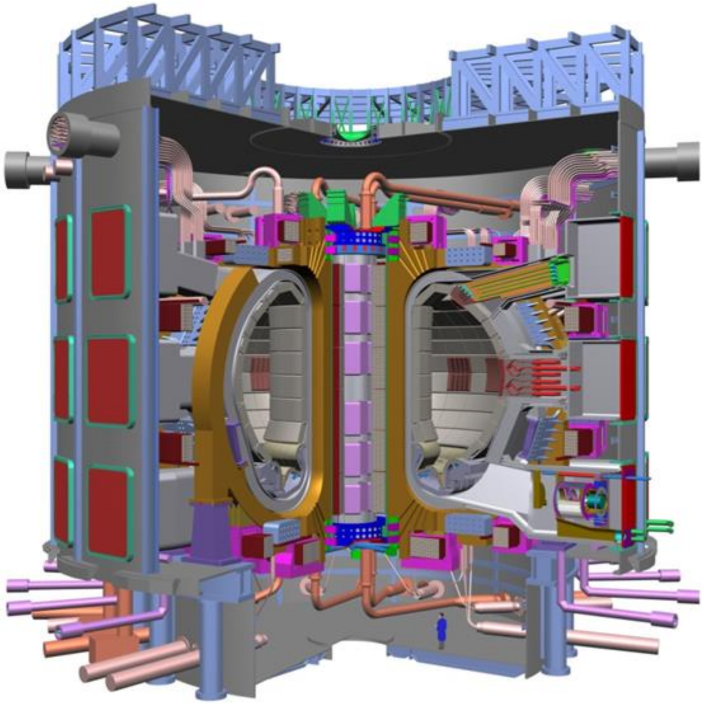
B. Tully and N. Hawker, Phys. Rev. **E93**, 053105 (2016)

A gas gun is used to eject the projectile

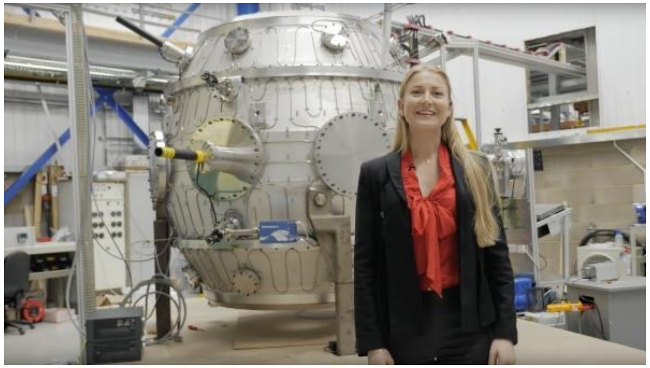
https://www.youtube.com/watch?v=JN7lyxC11n0
https://www.youtube.com/watch?v=aW4eufacf-8

Many groups aim to achieve ignition in the MCF regime in the near future

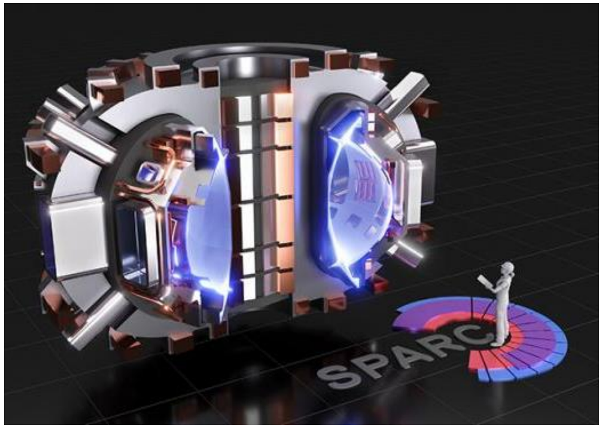
- **ITER – 2025 First Plasma**
  2035 D-T Exps
  2050 DEMO



- **Tokamak energy, UK**
  - **2025 Gain**
  - **2030 to power grid**



- **Commonwealth Fusion Systems, USA – 2025 Gain**



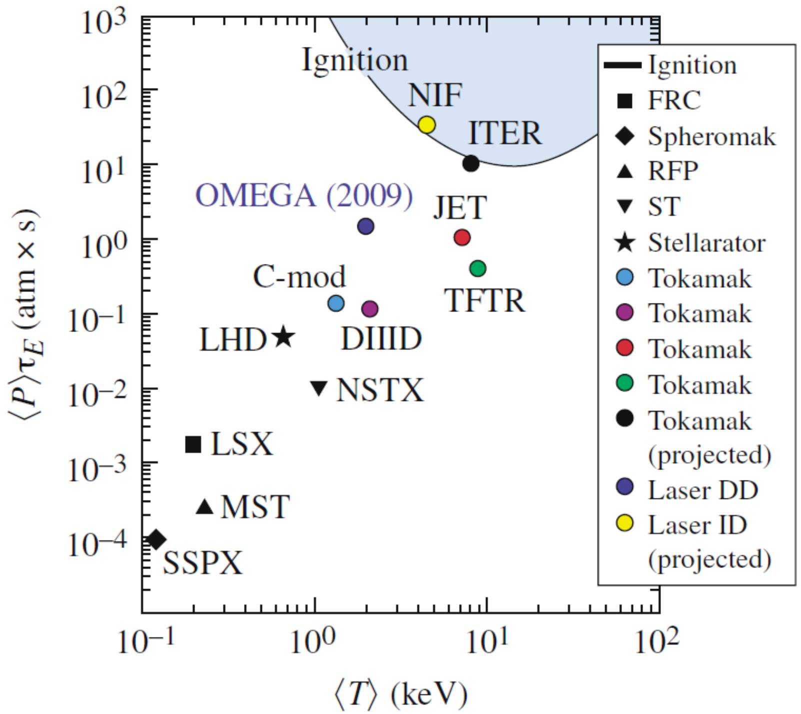
https://www.iter.org
https://www.tokamakenergy.co.uk/
https://www.psfc.mit.edu/sparc

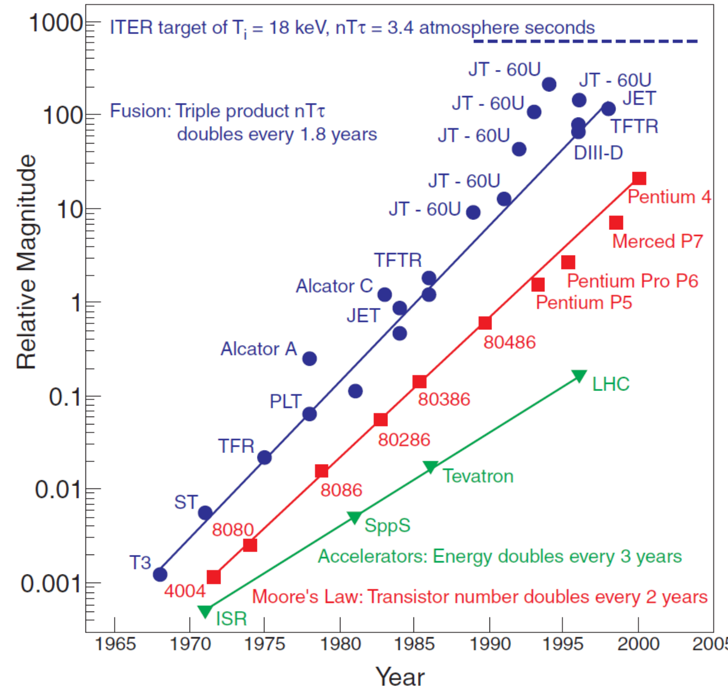
Fusion is blooming!

⋮

https://www.fusionindustryassociation.org/members

We are closed to ignition!





- **Other private companies:**

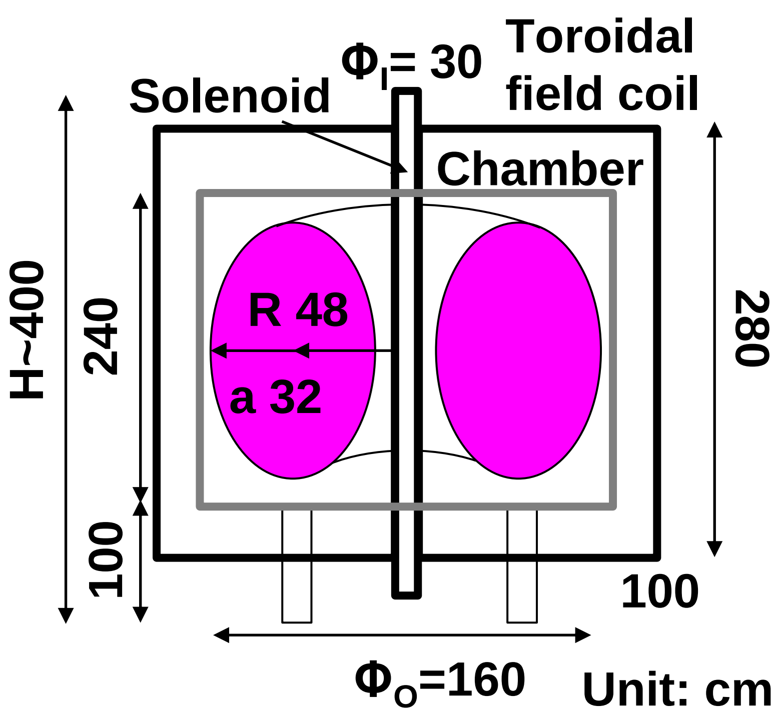
Tokamak **MTF** **ICF**

A. J. Webster, Phys. Educ. **38**, 135 (2003)
R. Betti, etc., Phys. Plasmas, **17**, 058102 (2010)

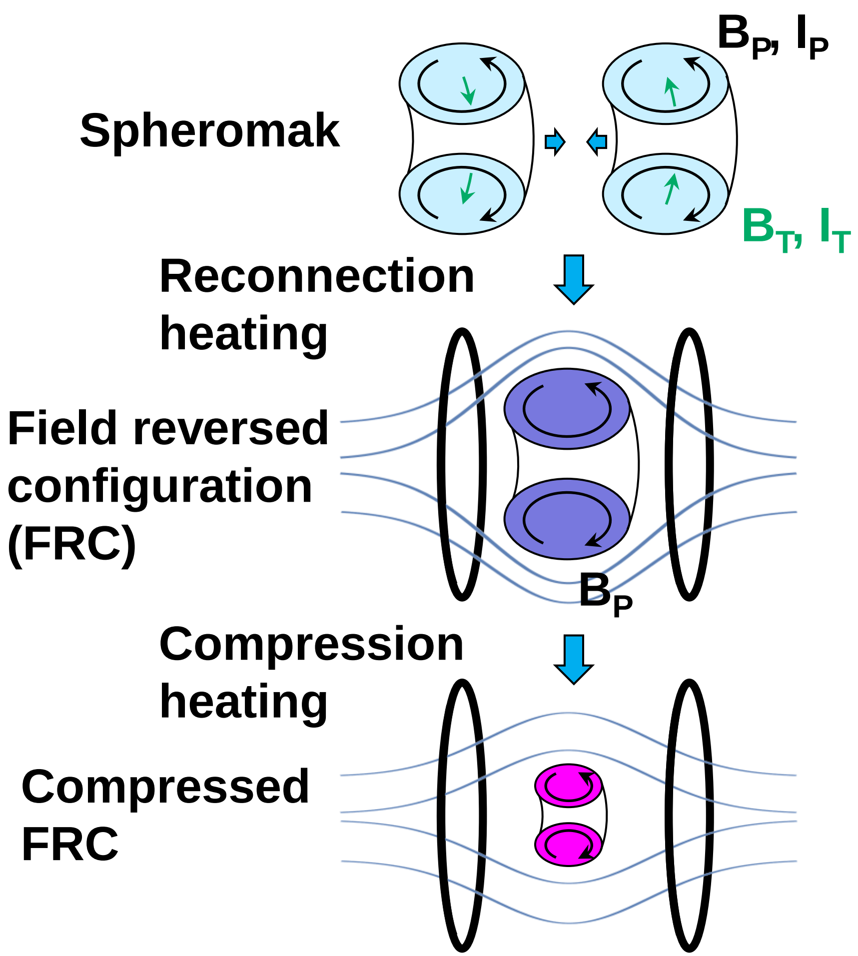
Fusion projects in Inst. Space and Plasma Sciences , National Cheng Kung University

- 國科會計畫 - 磁約束高溫電漿研究

Formosa Integrated Research Spherical Tokamak (FIRST)

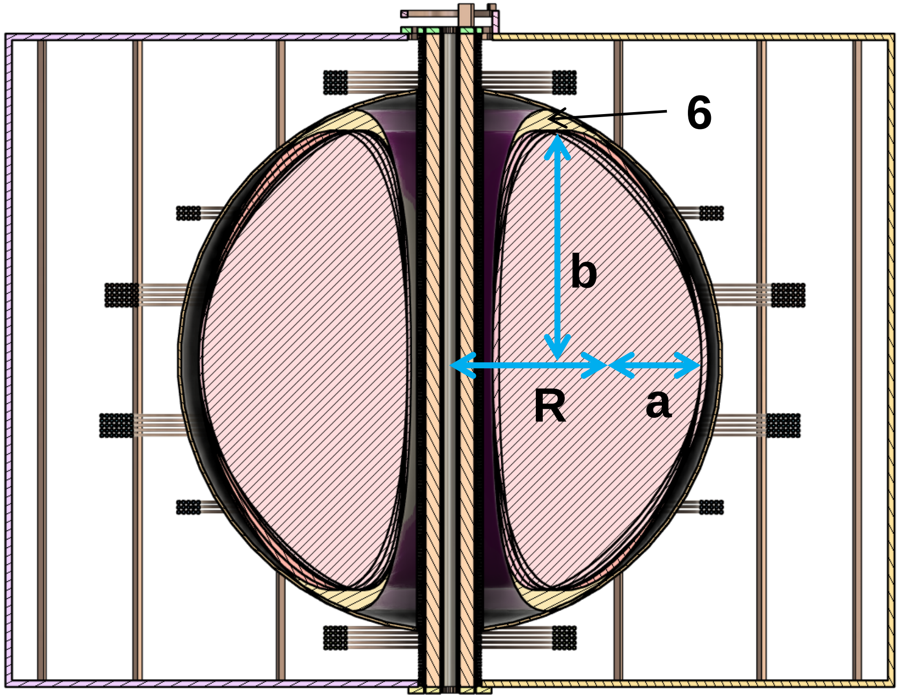


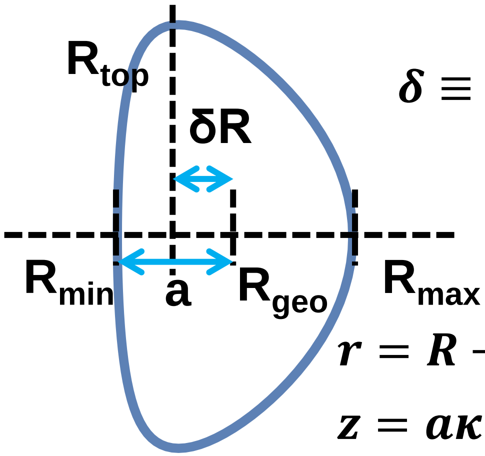
- Magneto-inertial fusion (MIF)



- We welcome anyone interested in fusion research to join our team!

A new design using a spherical chamber can tolerate several potential shapes and sides calculated by the theory group





$$\delta \equiv \frac{\delta R}{a}$$

$$r = R + a\mathrm{Cos}(\theta + \delta \mathrm{Sin}(\theta))$$

$$z = a\kappa \mathrm{Sin}(\theta)$$

- **Parameters:**
  - **Elongation κ=b/a**
  - **Triangularity δ**
  - **T~100 eV**
  - **B_T~0.5 T**
  - **I_p~100 kA**

		R (cm)	a (cm)	R/a	κ	δ
✓	1	45	32	1.41	2.2	0.5
✓	2	45	32	1.41	2.2	0.3
✓	3	45	32	1.41	2.2	0.4
✓	4	45	32	1.41	2.2	0.6
✓	5	47	32	1.47	2.2	0.5

- **We welcome anyone interested in fusion research to join us!**