Introduction to Nuclear Fusion as An Energy Source

Po-Yu Chang

Institute of Space and Plasma Sciences, National Cheng Kung University

Lecture 13

2026 spring semester

Tuesday 9:00-12:00

Materials:

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

Online courses:

https://reurl.cc/GaLmxA (Google meet)

2026/6/4 updated

Note!

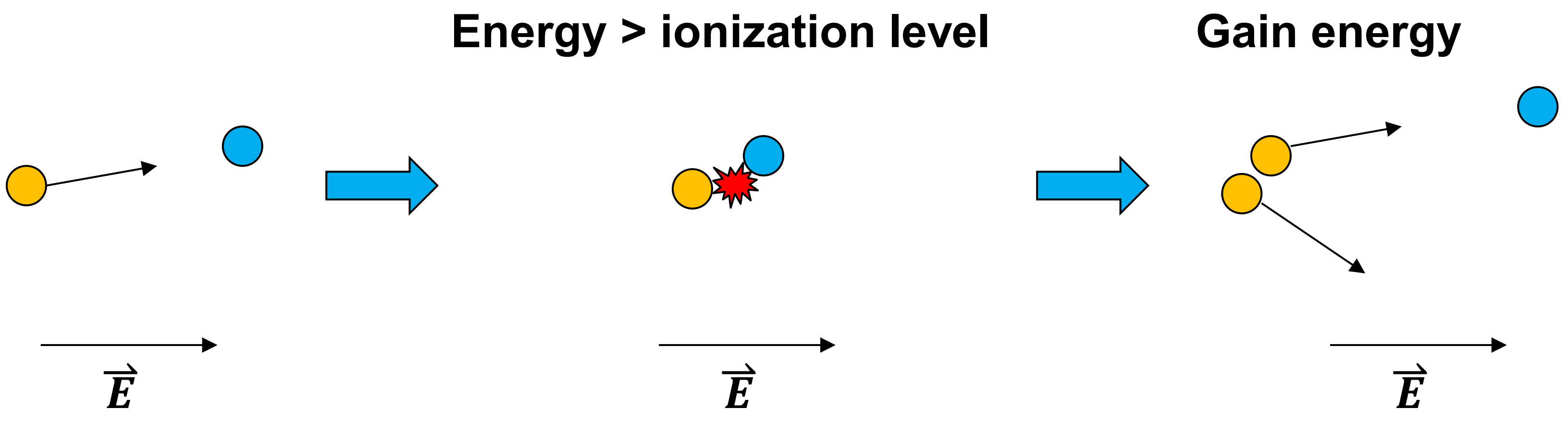
- **Final exam:**
  - **6/18 (Closed book, no cheating sheet is allowed.).**
  - **The final exam covers the entire semester's content.**

Course Outline

- **Magnetic confinement fusion (MCF)**
  - **Gyro motion, MHD**
  - **1D equilibrium (z pinch, theta pinch)**
  - **Drift: ExB drift, grad B drift, and curvature B drift**
  - **Tokamak, Stellarator (toroidal field, poloidal field)**
  - **Magnetic flux surface**
  - **2D axisymmetric equilibrium of a torus plasma: Grad-Shafranov equation.**
  - **Stability (Kink instability, sausage instability, Safety factor Q)**
  - **Central-solenoid (CS) start-up (discharge) and current drive**
  - **CS-free current drive: electron cyclotron current drive, bootstrap current.**
  - **Auxiliary Heating: ECRH, Ohmic heating, Neutral beam injection.**

Collisions play an important role in ionization process

- **At the microscopic level, breakdown requires the presence of <u>sufficiently energy charge particles</u> that have acquired enough energy from the applied electric field between <u>two energy-dissipating collisions to ionize the material</u> and to <u>create more charge particles</u>.**



In most cases, <u>electrons</u> dominate the breakdown process since its mobility is much larger than that of ions

$$E_{\mathrm{k}} = \frac{1}{2} m v^2 \qquad v = \sqrt{\frac{2E_{\mathrm{k}}}{m}} \qquad E_{\mathrm{k}} \sim kT$$

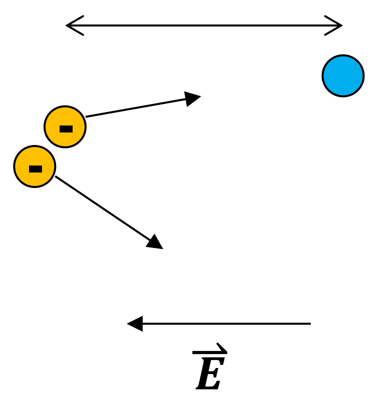
Collision time: $t = \frac{s}{\sqrt{\frac{2E_{\mathrm{k}}}{m}}} \sim \frac{n^{-1/3}}{\sqrt{T}} \sqrt{m}$ $\qquad n = \frac{\#/}{V} \sim \frac{\#//}{S^3} \qquad s \sim n^{-1/3}$

$$\frac{m_{\mathrm{i}}}{m_{\mathrm{e}}} \sim 2000 \times \text{Atomic mass} \qquad \frac{t_{\mathrm{i}}}{t_{\mathrm{e}}} \sim 45 \times \sqrt{A}$$

Mean free path is important in ionization process

- For an electron to acquire enough energy between collisions, its <u>mean free path</u> in the material must be sufficiently long.

Mean free path, λ



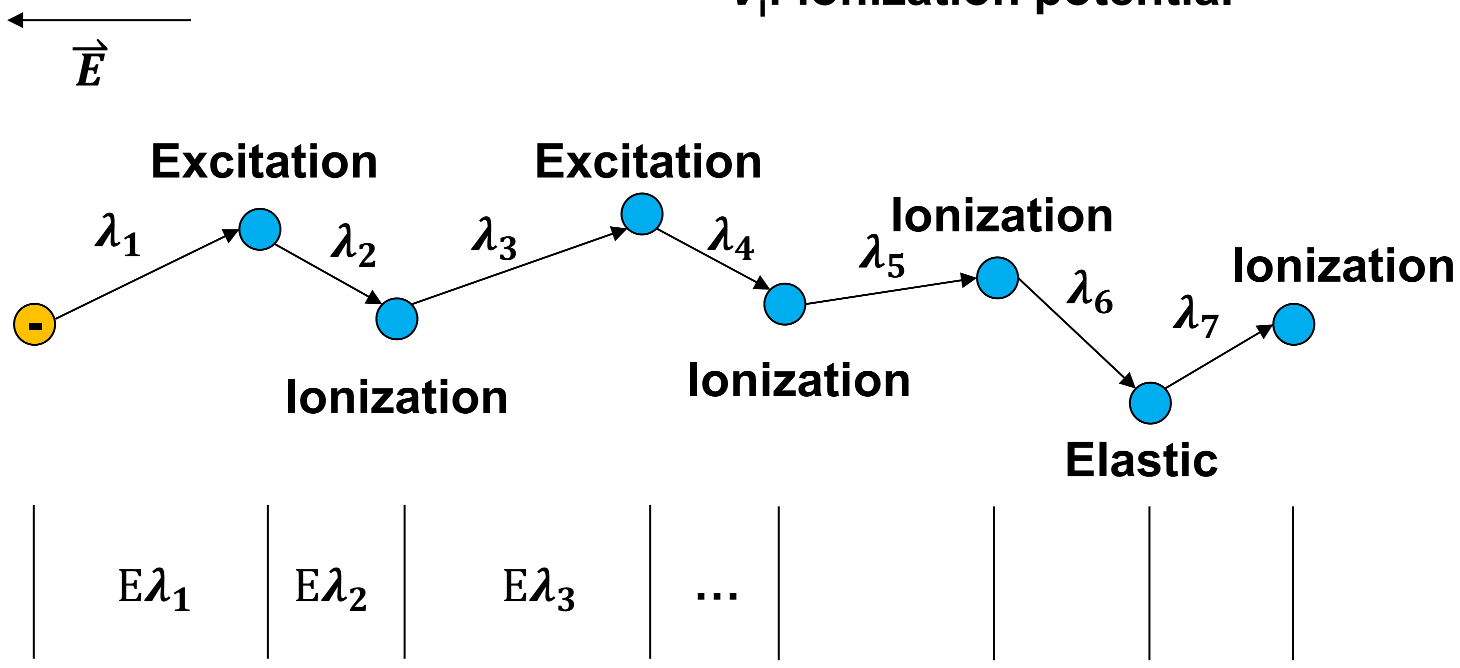
$$E_k = e \times E \times \lambda = \mathrm{eV}$$

Electron impact ionization is the most important process in a breakdown of gases

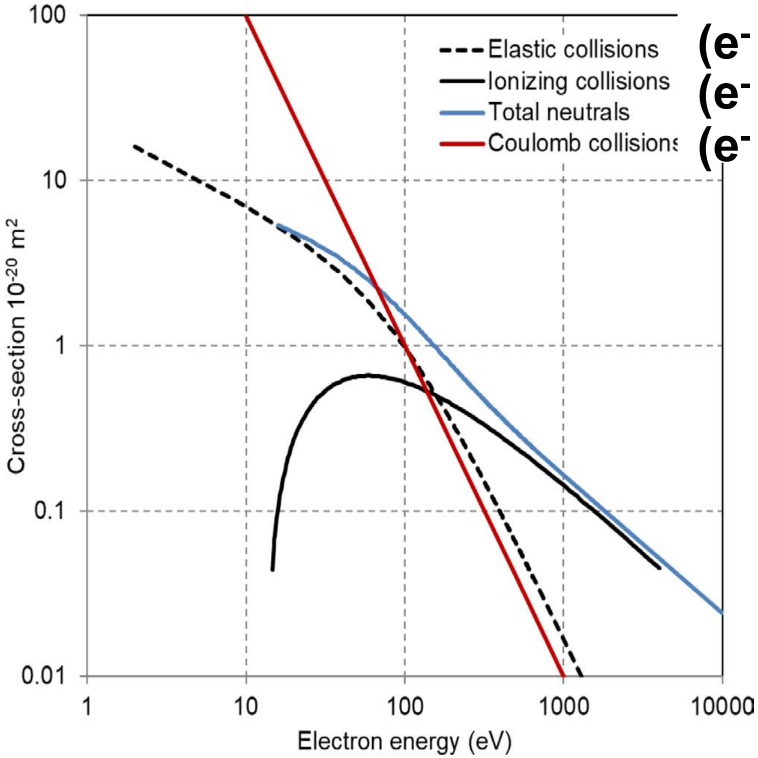
- **Electron impact ionization: $A + e^- \rightarrow A^+ + e^- + e^-$**
  - **The most important process in the breakdown of gases but is not sufficient alone to result in the breakdown.**

$$eE\lambda_{e,i} \geq eV_i$$

V_i: ionization potential



Collision cross-sections of elastic, ionizing collisions between e^- and H_2 and coulomb collisions



(e^- vs H_2)

($e^- + H_2 \rightarrow 2e^- + H^+ + H$)

(e^- vs H^+)

$$\sigma_{\mathrm{elastic,m^2}} = \frac{1.75 \times 10^{-16}}{\left(W_{\mathrm{e,eV}}{}^{1.5} + 750\right)\sqrt{W_{\mathrm{e,eV}}}}$$

$$\sigma_{\mathrm{ionizing,m^2}} \sim 3 \times 10^{-20}\left(ln\epsilon - 0.69 + \frac{0.66}{\epsilon}\right)\epsilon^{-1}$$

$$\epsilon = \frac{W_{\mathrm{e}}}{E_{\mathrm{ion}}} \quad E_{\mathrm{ion}} \sim 15\ \mathrm{eV\ for\ H_2}$$

$$\sigma_{\mathrm{coulomb}} = \frac{e^4}{4\pi\epsilon_{\mathrm{o}}{}^2 m_{\mathrm{e}}{}^2 v_{\mathrm{e}}{}^2}\ln\Lambda$$

$$= \frac{e^4}{16\pi\epsilon_{\mathrm{o}}{}^2 W_{\mathrm{e}}{}^2}\ln\Lambda \sim 10^{-16} W_{\mathrm{e}}{}^{-2}$$

$$\mathrm{for}\ \ln\Lambda \sim 13 - 15$$

$$\nu = n v_E \sigma$$

$$\lambda = \frac{1}{n\sigma}$$

P. C. de Vries and Y. Gribov, Nucl. Fusion, **59**, 096043 (2019)

Townsend avalanche process for Tokamak breakdown

- **The first Townsend coefficient α: the number of ionizing collisions made on the average by an electron as it travels 1 m along the electric field:**

$$\alpha \sim \frac{1}{\lambda_i} = \frac{\nu_{ei}}{\bar{v}_e} = \frac{n_0 \langle \sigma v_e \rangle_{ne}}{\bar{v}_e} = \frac{p}{T} \frac{\langle \sigma v \rangle_{ne}}{\bar{v}_e} \equiv Ap \qquad A \equiv \frac{1}{T} \frac{\langle \sigma v \rangle_{ne}}{\bar{v}_e}$$

- **Number of primary electrons with energy higher than the ionization potential:**

$$dn_e = -n_e \frac{dx_i}{\lambda_i} \quad \Rightarrow \quad \frac{n_e(x_i)}{n_{e0}} = \exp\left(-\frac{x_i}{\lambda_i}\right)$$

$$\alpha \equiv \frac{\#/\text{ ionization collisions}}{\text{per electron}} \times (\#/\text{electron with E} > \text{ionization potential})$$

$$= \frac{1}{\lambda_i} \frac{n_e(x_i)}{n_{e0}} = \frac{1}{\lambda_i} \exp\left(-\frac{x_i}{\lambda_i}\right)$$

$$\alpha = Ap \exp(-Apx_i)$$

A = 3.83 $m^{-1}Pa^{-1}$ = 1060 $m^{-1}Torr^{-1}$

B = 96.6 $Vm^{-1}Pa^{-1}$ = 35000 $m^{-1}Torr^{-1}$

$$\alpha = Ap\exp\left(-\frac{AV^*}{E/p}\right) \equiv Ap\exp\left(-\frac{B}{E/p}\right) \qquad x_i \approx \frac{V^*}{E} \text{ where } V^* > V_i$$

- **The parameters *A* and *B* must be experimentally determined.**

Paschen-like curve for minimum breakdown voltage

$\alpha \sim \frac{1}{\lambda_i} = Ap \quad \alpha = Ap\exp\left(-\frac{B}{E/p}\right)$

A **= 3.83 m^{-1}Pa^{-1} = 1060 m^{-1}Torr^{-1}**

B **= 96.6 Vm^{-1}Pa^{-1} = 35000 m^{-1}Torr^{-1}**

- **For *p*=1 mPa,** $\lambda_i \sim 262\ \mathrm{m}$ **, for ITER,** $2\pi r_o \sim 38\ \mathrm{m}$ $\quad \frac{\lambda_i}{2\pi r_o} \sim 7$

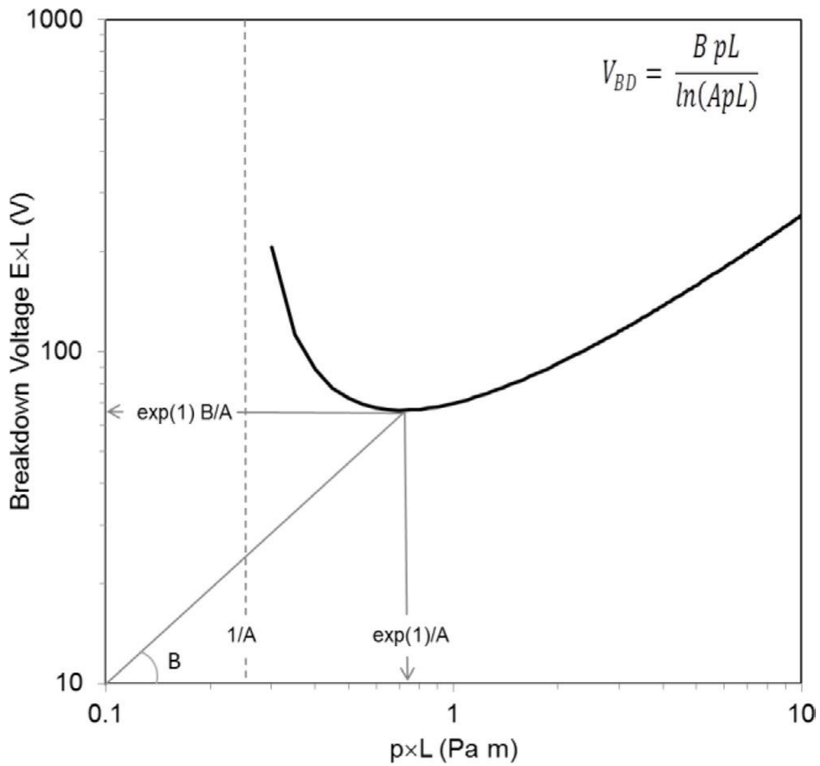
- **For breakdown to happen:**

$$\alpha L > 1 \quad \alpha L = ApL\exp\left(-\frac{BpL}{V_{BD}}\right) > 1$$

$$\exp\left(-\frac{BpL}{V_{BD}}\right) > \frac{1}{ApL}$$

$$-\frac{BpL}{V_{BD}} > -\ln(ApL)$$

$$V_{BD} > \frac{BpL}{\ln(ApL)} \quad E_{BD} > \frac{Bp}{\ln(ApL)}$$



P. C. de Vries and Y. Gribov, Nucl. Fusion, **59**, 096043 (2019)

Perpendicular stray-field (B_z) needs to be as small as possible

- For *p*=1 mPa, $\lambda_\mathrm{i} \sim 262\ \mathrm{m}$, for ITER, $2\pi r_\mathrm{o} \sim 38\ \mathrm{m}$ $\frac{\lambda_\mathrm{i}}{2\pi r_\mathrm{o}} \sim 7$

$\frac{B_z}{B_T} \sim 10^{-3}$ $\lambda_i \times \frac{B_z}{B_T} = 0.26\ \mathrm{m}$

- For ITER,

$$E \sim E_\mathrm{loop} = 0.3\ \mathrm{V/m}$$

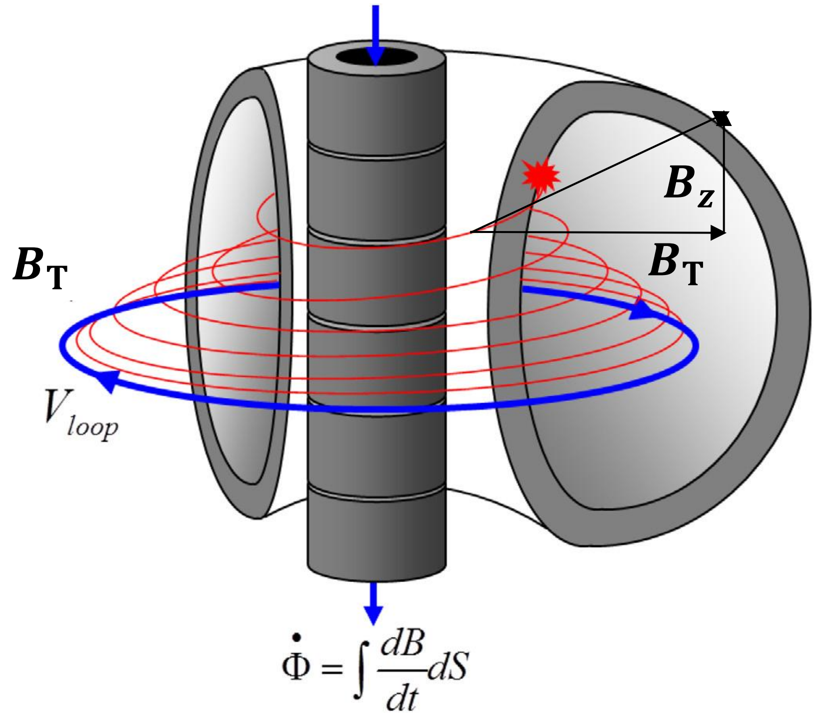
$$p = 1\ \mathrm{mPa} \qquad L_\mathrm{BD} = 357\ \mathrm{m}$$

- Required loop field:

$$E_\mathrm{BD} > \frac{Bp}{\ln(ApL)}$$

$$E_\mathrm{BD} > \frac{1.25 \times 10^4 P_\mathrm{Torr}}{\ln(510 P L_\mathrm{c})}$$

$$L_\mathrm{c} = 0.25 a_\mathrm{eff} \left(\frac{B_z}{B_T}\right)$$



- **W/ preionization**: $E_\mathrm{T} \frac{B_\mathrm{T}}{B_z} \geq 100\ \mathrm{V/m}$
- **Purely Ohmic discharges**: $E_\mathrm{T} \frac{B_\mathrm{T}}{B_z} \geq 1000\ \mathrm{V/m}$

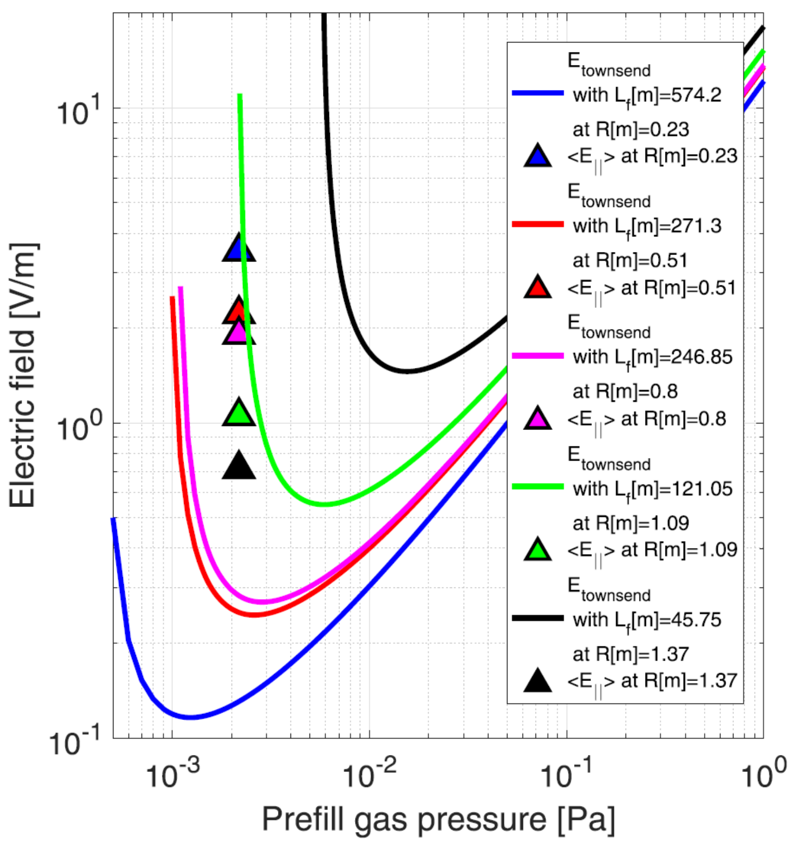
P. C. de Vries and Y. Gribov, Nucl. Fusion, **59**, 096043 (2019)
S. J. Doyle et al, Fusion Eng. Des. **171**, 112706 (2021)

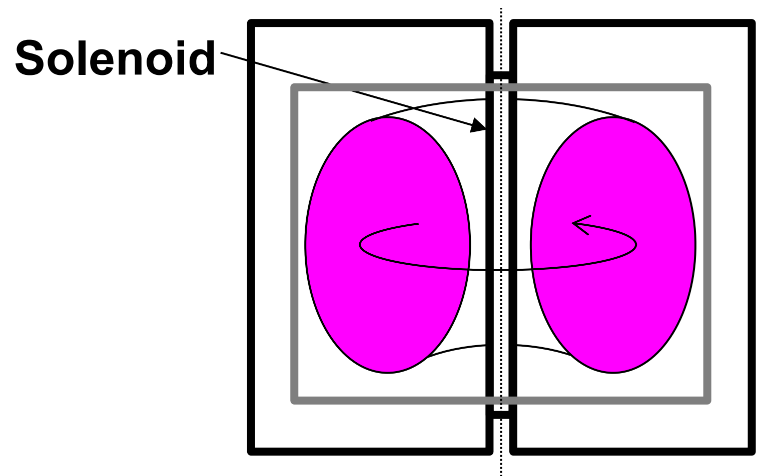
Examples or required loop electric fields

$$E_{\mathrm{BD}} > \frac{1.25 \times 10^{4} P_{\mathrm{Torr}}}{\ln(510 P L_{\mathrm{c}})}$$

$$L_{\mathrm{c}} = 0.25 a_{\mathrm{eff}} \left(\frac{B_z}{B_T}\right)$$

- **W/ preionization:** $E_{\mathrm{T}} \frac{B_{\mathrm{T}}}{B_{\mathrm{z}}} \geq 100\,\mathrm{V/m}$
- **Purely Ohmic discharges:** $E_{\mathrm{T}} \frac{B_{\mathrm{T}}}{B_{\mathrm{z}}} \geq 1000\,\mathrm{V/m}$





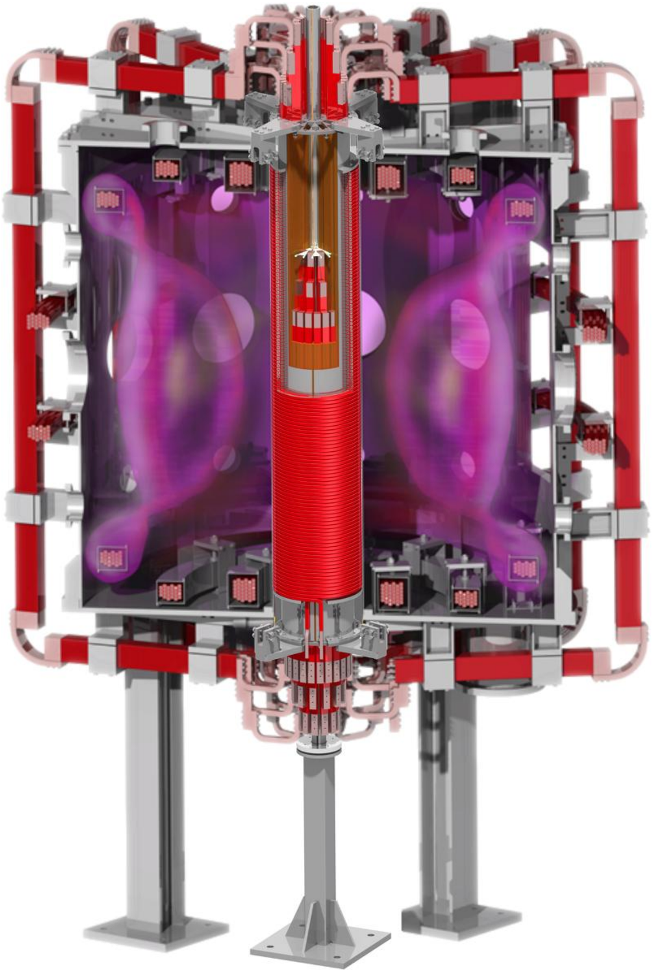
$$V_{\phi} = -\frac{\partial \phi}{\partial t} \equiv M \frac{\partial I_{CS}}{\partial t}$$

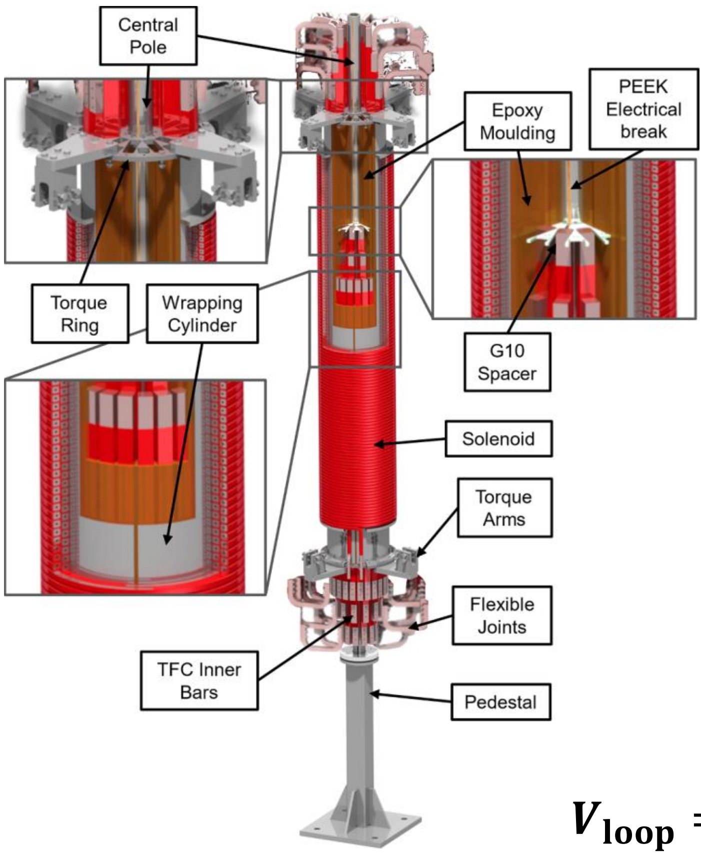
$$E_{\phi} = -\frac{1}{2\pi r} \frac{\partial \phi}{\partial t}$$

H.-T. Kim, etc., Nucl. Fusion **62**, 126012 (2022)
S. J. Doyle et al, Fusion Eng. Des. **171**, 112706 (2021)

Central solenoid can be used to provide the required loop voltage for breakdown

- **SMART:**

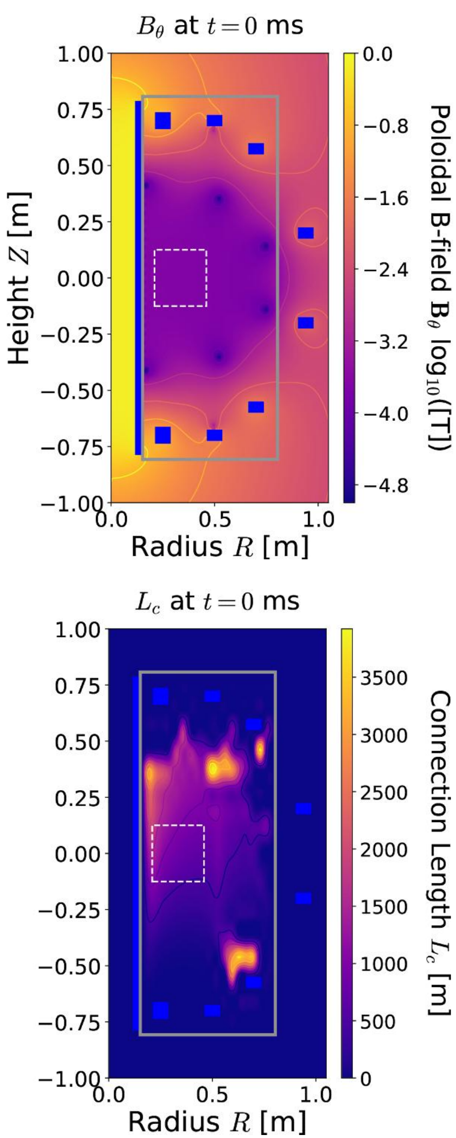




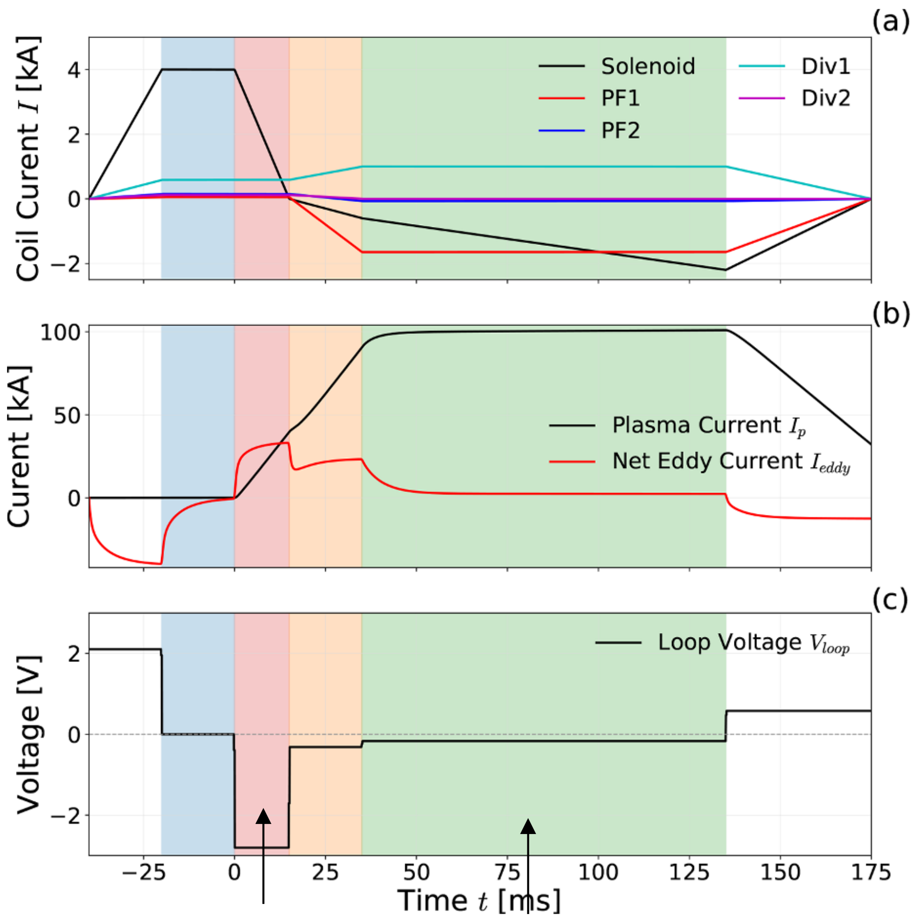
$$V_{\mathrm{loop}} = \frac{A_{\mathrm{sol}}\mu N_{\mathrm{sol}}}{L_{\mathrm{sol}}}\frac{dI_{\mathrm{sol}}}{dt}$$

J. Segado-Fernandez et al, Fusion Eng. Des. **193**, 113832 (2023)

Poloidal coils are used to reduce the stray field during breakdown



- **Currents of SMART**

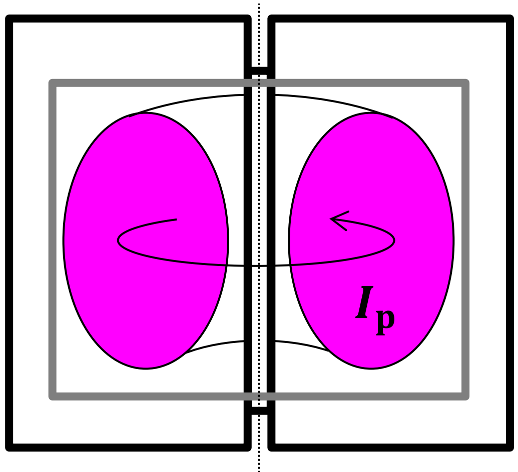


Breakdown

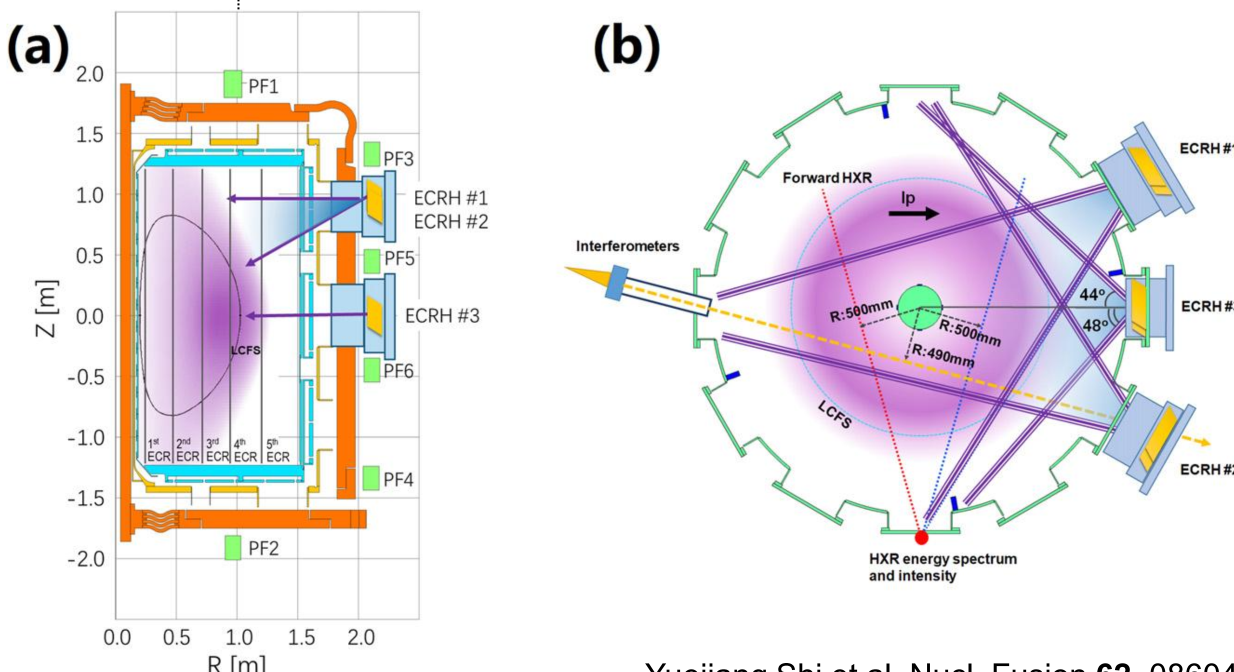
Plasma current is driven

S. J. Doyle, etc., Fusion Eng. Des. **171**, 112706 (2021)

Momentum exchange may be needed to drive plasma current



$$\vec{j}_{\mathrm{p}} = \Sigma q n \vec{v} = -e n_{\mathrm{e}} \vec{v}_{\mathrm{e}} + e n_{\mathrm{i}} \vec{v}_{\mathrm{i}}$$



Yuejiang Shi et al, Nucl. Fusion **62**, 086047 (2022)

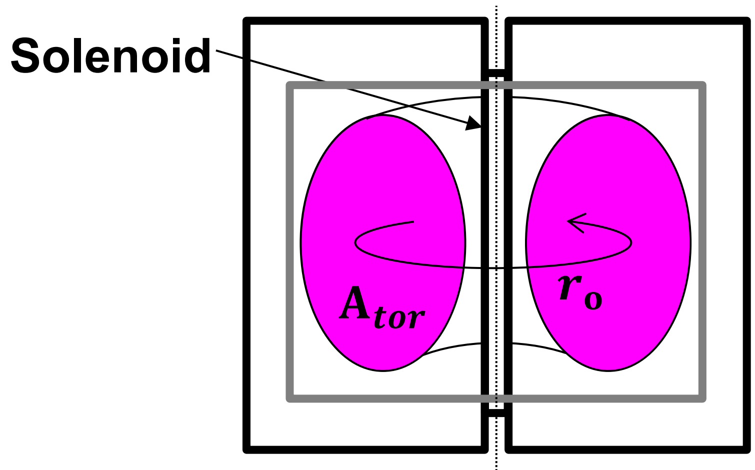
Solenoid can be used to drive the plasma current

$$L_{\mathrm{tor}}\frac{dI}{dt}+IR=V_{\mathrm{loop}}=M\frac{dI_{\mathrm{sol}}}{dt}$$

$$L_{\mathrm{tor}}=\mu_{\mathrm{o}}r_{\mathrm{o}}\left[\ln\left(\frac{8r_{\mathrm{o}}}{a}\right)-1.5\right]$$

$$R_{\mathrm{spitzer}}=\eta_{\mathrm{spiter}}\frac{2\pi r_{\mathrm{o}}}{A_{\mathrm{tor}}}$$

$$\eta_{\mathrm{spiter}}=5.2\times10^{-3}Z\ln\Lambda\,T_{e,(\mathrm{eV})}^{-3/2}$$



Current is initially driven at the surface and then diffuses into the plasma

- **Simplified Ohm's law:** $\vec{E} + \vec{v} \times \vec{B} = \eta\, \vec{j}$

- **Assuming a stationary plasma:** $\nabla \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t} = \nabla \times \left(\eta\, \vec{j}\right)$

- **Assuming a constant *η*:**

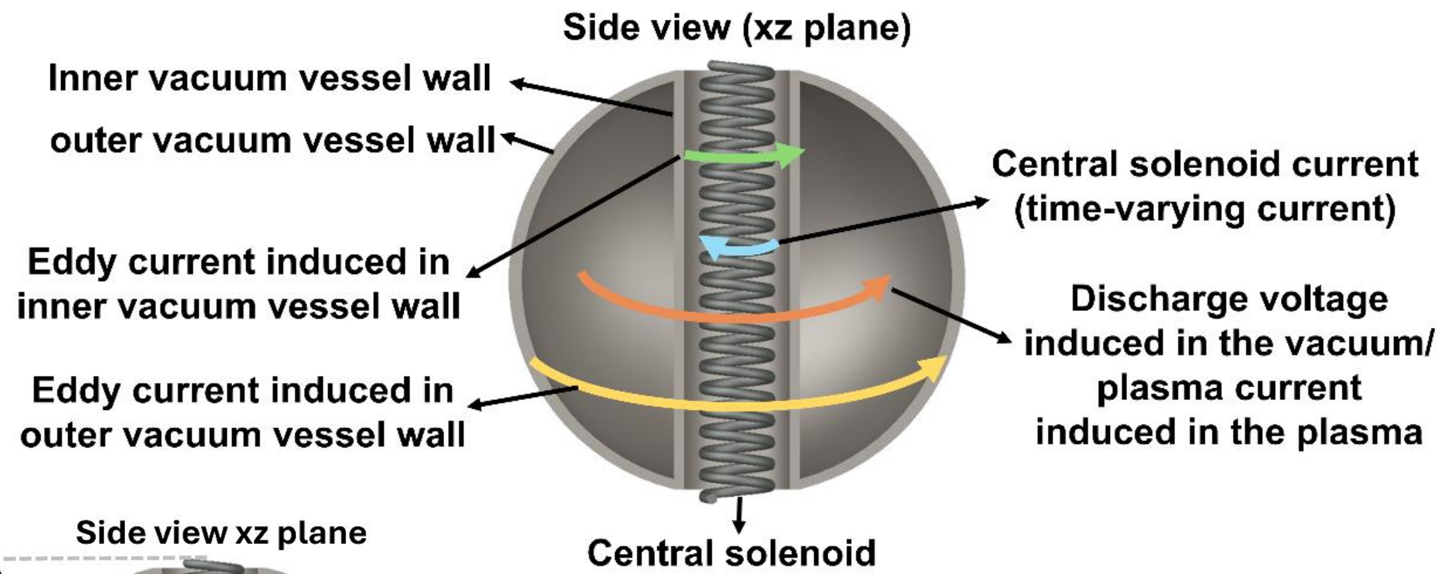
$$-\frac{\partial}{\partial t}\nabla \times \vec{B} = \eta \nabla \times \nabla \times \vec{j}$$
$$= \eta\left(\nabla\left(\nabla \cdot \vec{j}\right) - \nabla^2 \vec{j}\right)$$
$$\frac{\partial \vec{j}}{\partial t} = \frac{\eta}{\mu_o}\nabla^2 \vec{j}$$

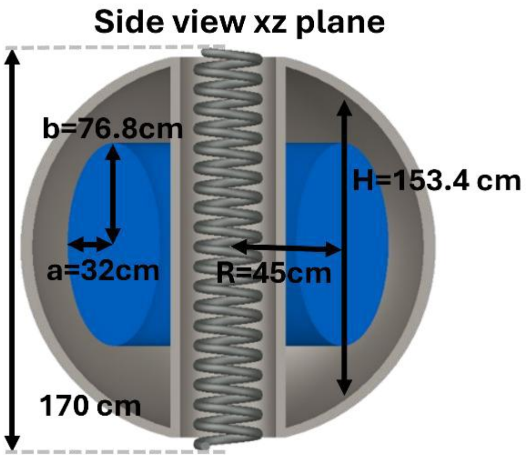
- **Assuming non-constant *η*:**

$$\frac{\partial \vec{j}}{\partial t} = \frac{1}{\mu_o}\nabla^2\left(\eta\, \vec{j}\right) - \nabla\left[\nabla \cdot \left(\mu\, \vec{j}\right)\right] \qquad \frac{\partial j_T}{\partial t} = \frac{1}{\mu_o}\nabla^2(\eta j_T)$$

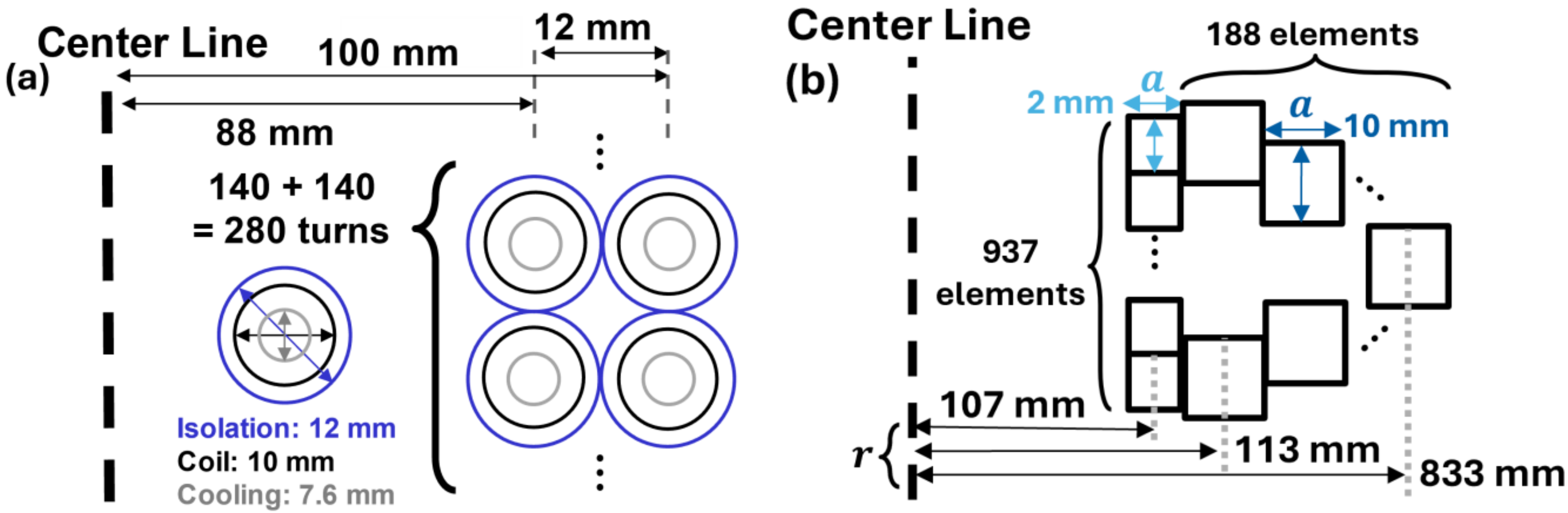
- **Since *η α* $T^{-3/2}$, resistance drops with higher temperature. The typical limited temperature is ~3 keV.**

Eddy current needed to be considered





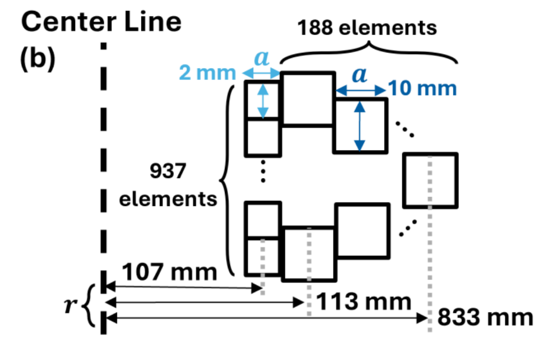
Chamber is broken into ring elements carrying eddy currents



The eddy current in each chamber element is solved numerically

$$\overleftrightarrow{M}\frac{d\vec{I}}{dt} + \overleftrightarrow{R}_{\Omega}\vec{I} = \vec{V} \qquad \overleftrightarrow{M}\frac{\vec{I'} - \vec{I}}{\Delta t} + \overleftrightarrow{R}_{\Omega}\vec{I} = \vec{V}$$

$$\vec{I'} = \left(\overleftrightarrow{1} - \Delta t\,\overleftrightarrow{M}^{-1}\overleftrightarrow{R}_{\Omega}\right)\vec{I} + \Delta t\,\overleftrightarrow{M}^{-1}\vec{V}$$

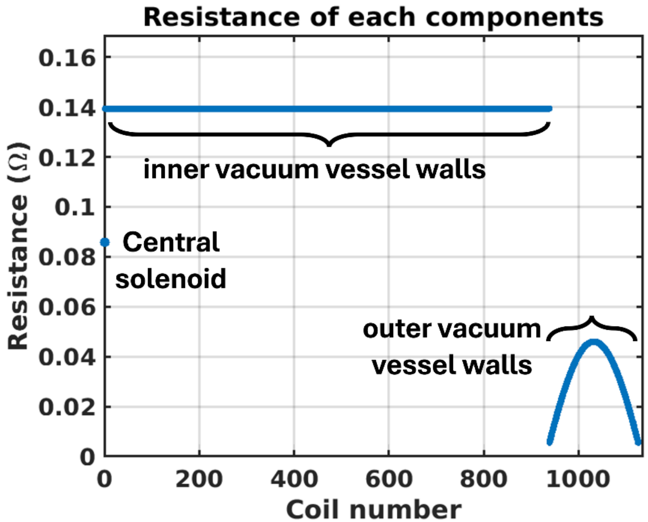


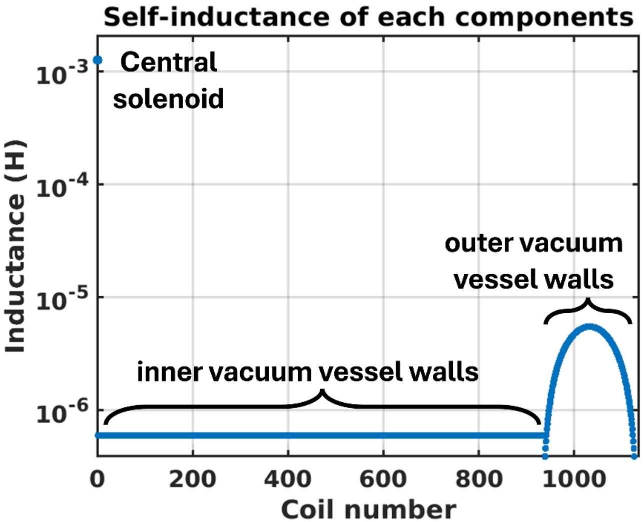
$$\vec{V} = \overleftrightarrow{M}\frac{d\vec{I}}{dt} + \overleftrightarrow{R}\vec{I}$$

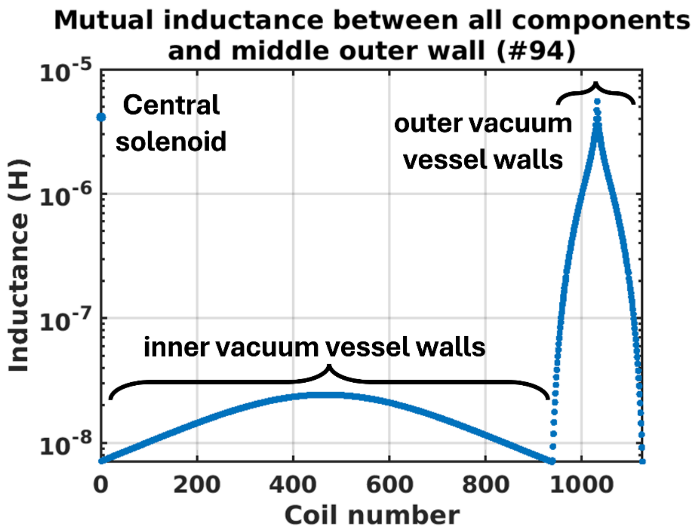
$$\Rightarrow \begin{bmatrix} V_{c1} \\ V_{c2} \\ \vdots \\ V_{v1} \\ V_{v2} \\ \vdots \\ V_{p} \end{bmatrix} = \begin{bmatrix} L_{c1} & M_{c1,c2} & M_{c1,c3} & \cdots & M_{c1,v1} & M_{c1,v2} & M_{c1,v3} & \cdots & M_{c1,p} \\ M_{c2,c1} & L_{c2} & M_{c2,c3} & \cdots & M_{c2,v1} & M_{c2,v2} & M_{c2,v3} & \cdots & M_{c2,p} \\ M_{c3,c1} & M_{c3,c2} & L_{c3} & \cdots & M_{c3,v1} & M_{c3,v2} & M_{c3,v3} & \cdots & M_{c3,p} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ M_{v1,c1} & M_{v1,c2} & M_{v1,c3} & \cdots & L_{v1} & M_{v1,v2} & M_{v1,v3} & \cdots & M_{v1,p} \\ M_{v2,c1} & M_{v2,c2} & M_{v2,c3} & \cdots & M_{v2,v1} & L_{v2} & M_{v2,v3} & \cdots & M_{v2,p} \\ M_{v3,c1} & M_{v3,c2} & M_{v3,c3} & \cdots & M_{v3,v1} & M_{v3,v2} & L_{v3} & \cdots & M_{v3,p} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ M_{p,c1} & M_{p,c2} & M_{p,c3} & \cdots & M_{p,v1} & M_{p,v2} & M_{p,v3} & \cdots & L_{p} \end{bmatrix} \begin{bmatrix} I'_{c1} \\ I'_{c2} \\ \vdots \\ I'_{v1} \\ I'_{v2} \\ \vdots \\ I'_{p} \end{bmatrix}$$

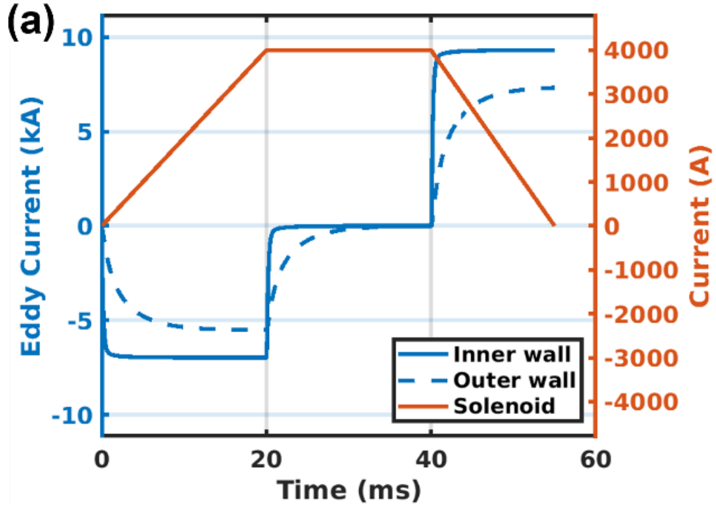
$$+ \begin{bmatrix} R_{c1} & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & R_{c2} & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & R_{v1} & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & R_{v2} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \cdots & R_{p} \end{bmatrix} \begin{bmatrix} I_{c1} \\ I_{c2} \\ \vdots \\ I_{v1} \\ I_{v2} \\ \vdots \\ I_{p} \end{bmatrix}. \qquad (2)$$

Eddy current on the chamber wall is induced when the current of the solenoid changes with time

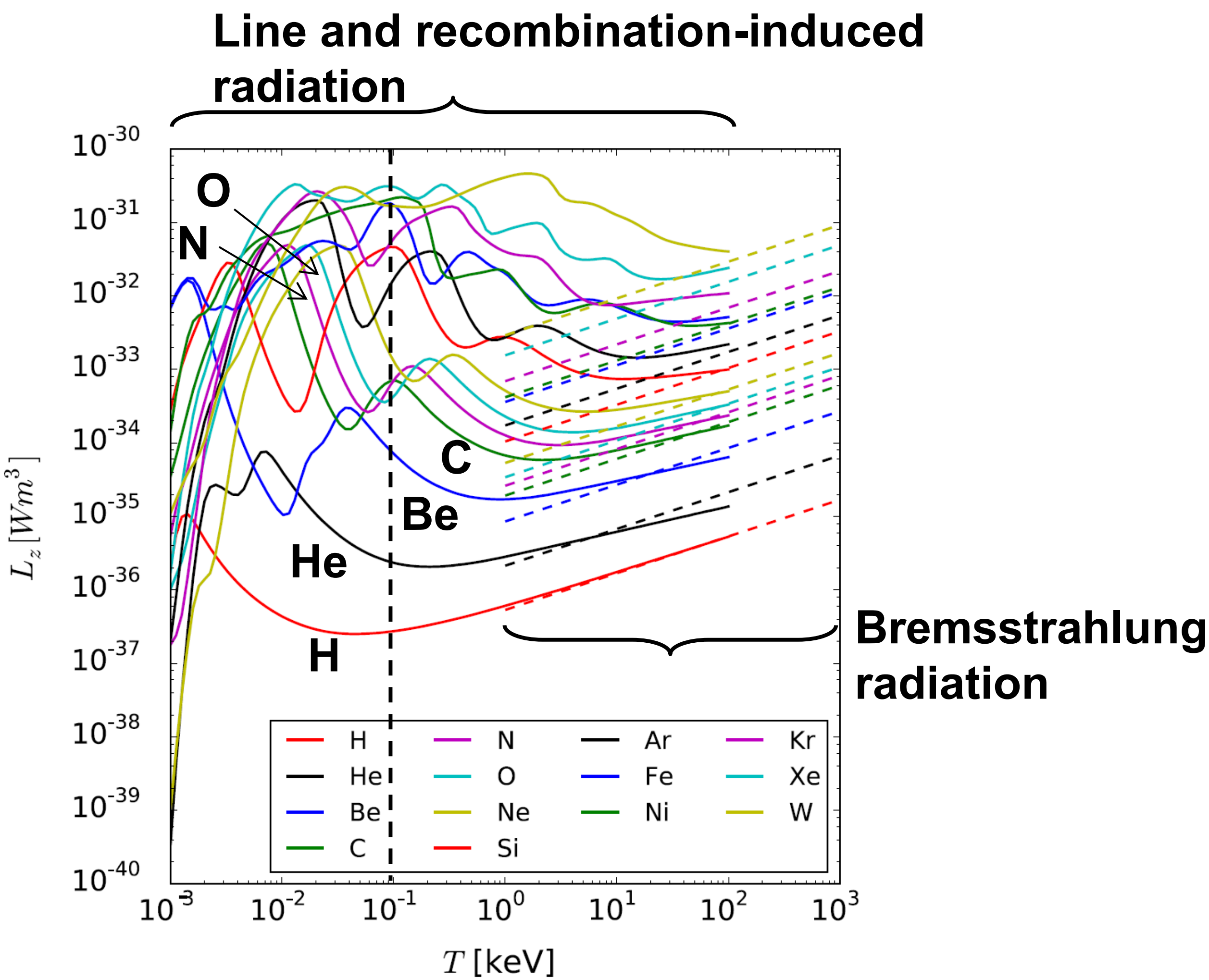






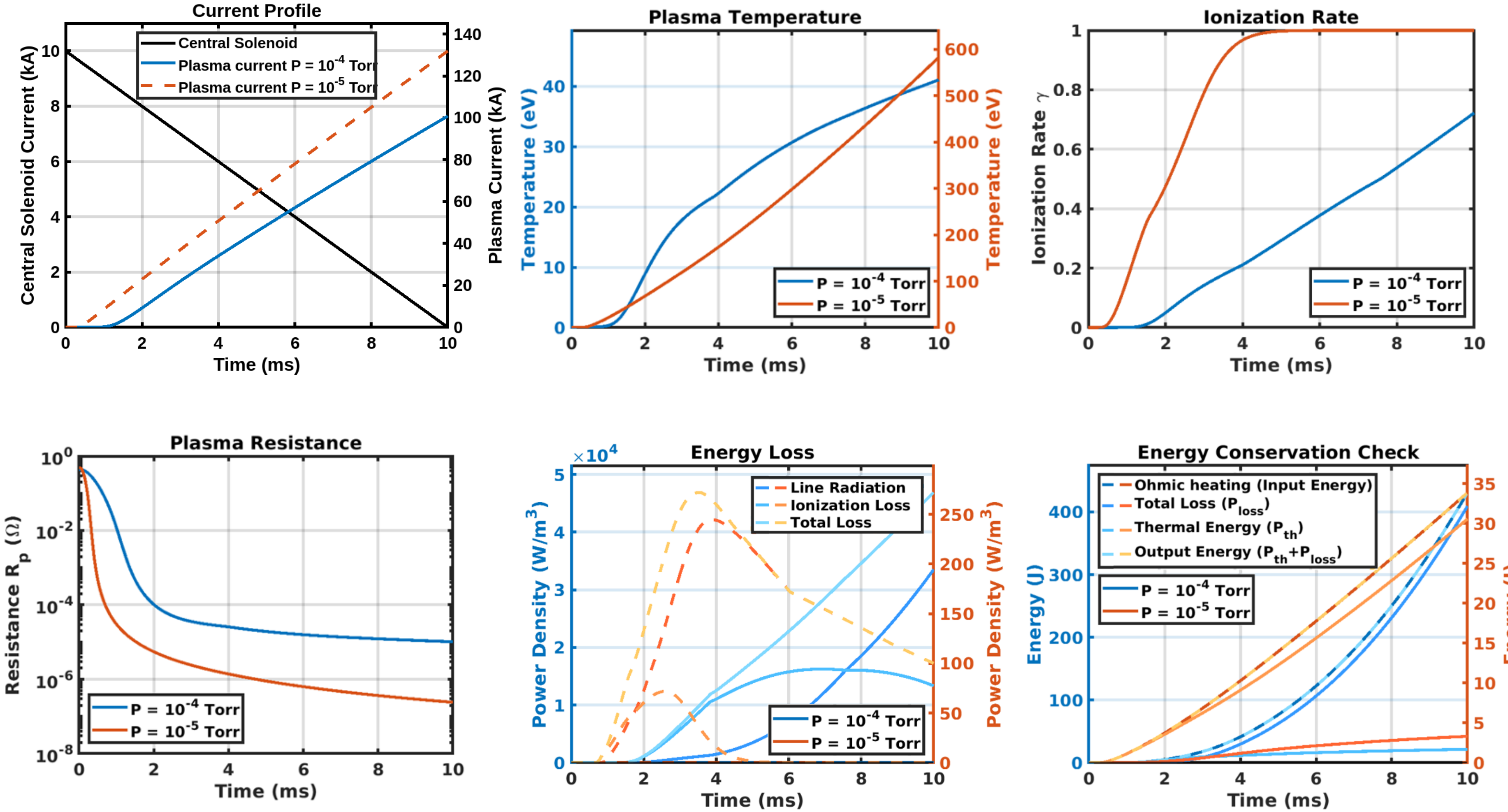


Temperature of 100 eV is the threshold of radiation barrier by impurities

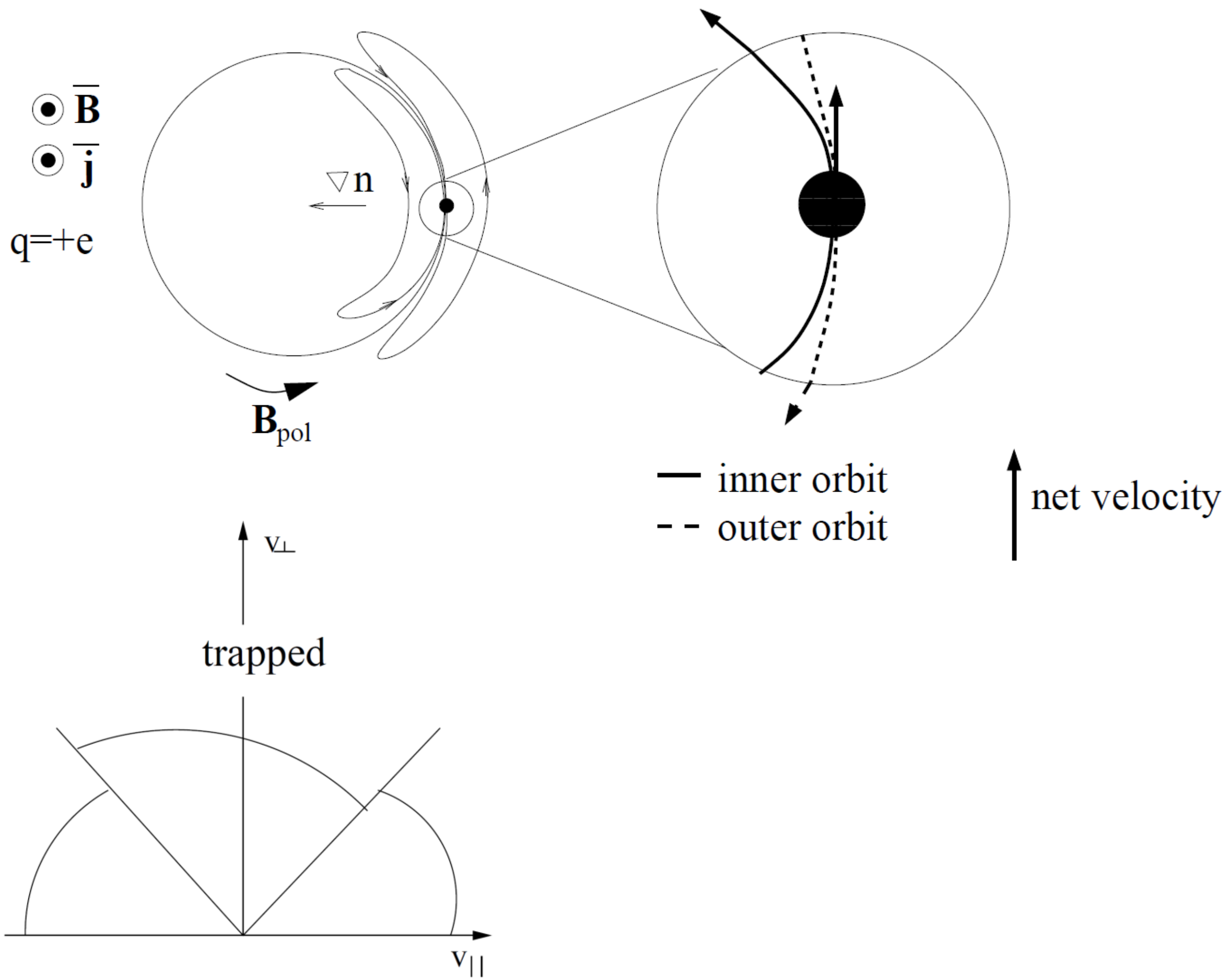


H. Lux, etc., Fusion Eng. Des. **42**, 101 (2015)

Plasma temperature can be estimated using the simple circuit model



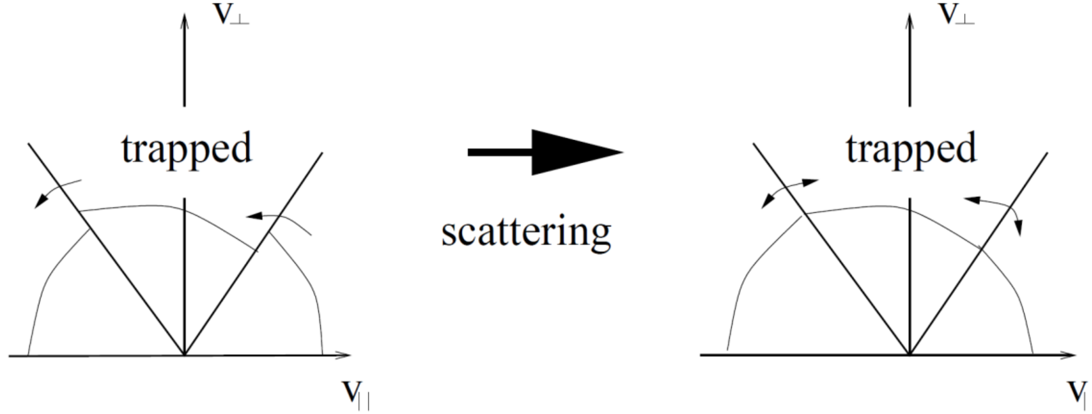
A banana current is generated when there is a pressure gradient in the plasma

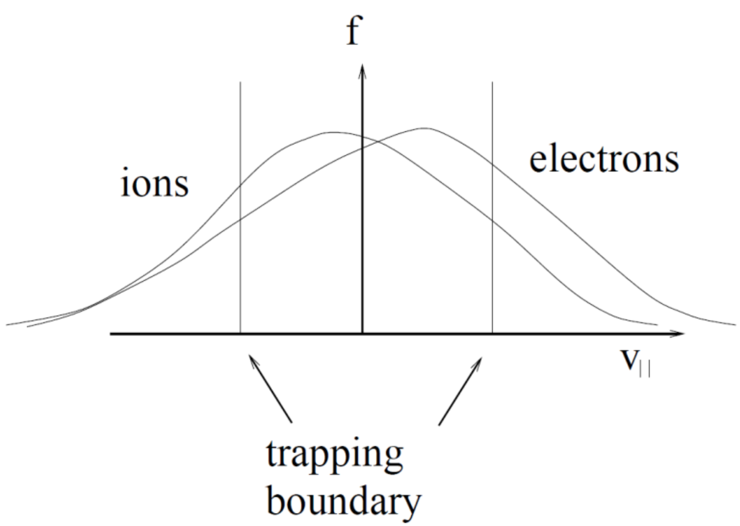


Samuli Saarelma, Helsinki University of Technology, PhD Thesis 2015

Bootstrap current is generated when passing particles are scattered by the trapped particles

- **Scattering smooths the velocity distribution and shifts it in the parallel direction, i.e., a current is generated. It is called the bootstrap current.**





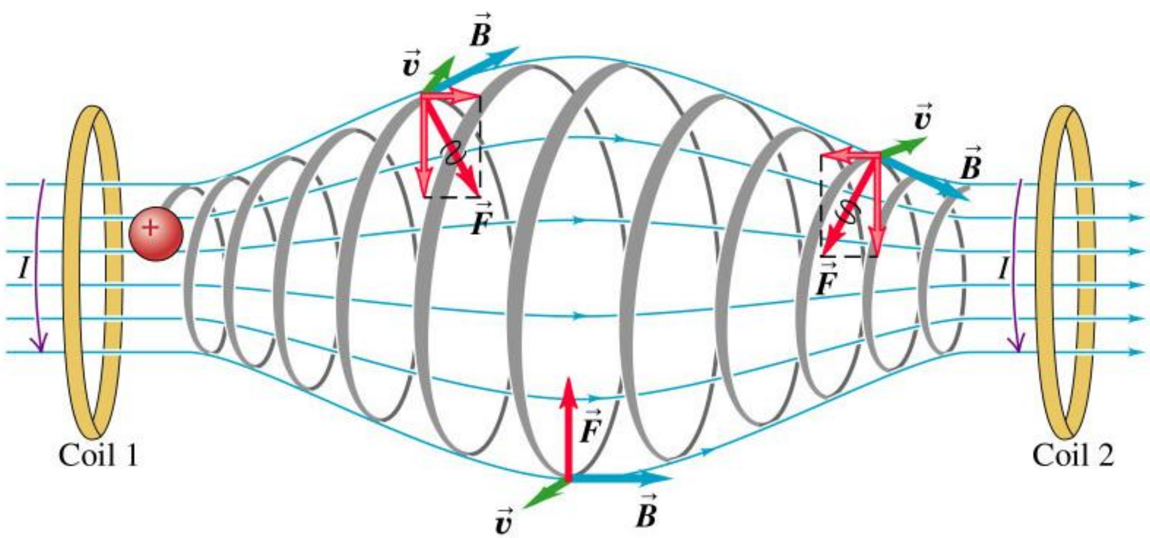
$$j = -enu_{||e} + enu_{||i} = 4\epsilon^{3/2}\frac{1}{B_p}T\frac{dn}{dr}$$

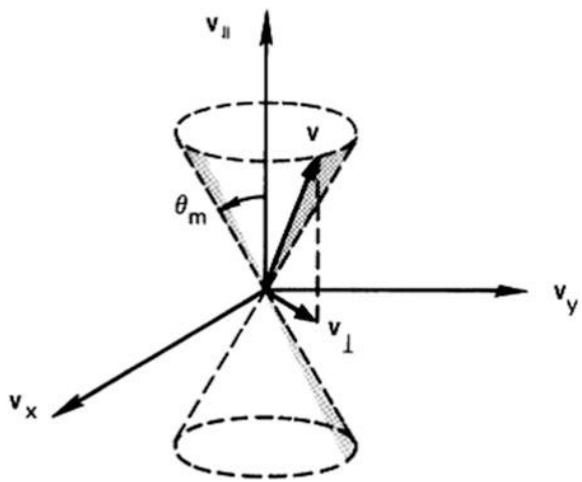
- **The bootstrap current is vital for steady-state operation.**

Samuli Saarelma, Helsinki University of Technology, PhD Thesis 2015

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.





$$v'_{\perp}{}^2 = v_{\perp o}{}^2 + v_{||o}{}^2 \equiv v_o{}^2$$

$$\frac{1}{2}mv^2 = \frac{1}{2}mv_{||}{}^2 + \frac{1}{2}mv_{\perp}{}^2 \qquad \text{Invarient: } \mu \equiv \frac{1}{2}\frac{mv_{\perp}{}^2}{B}$$

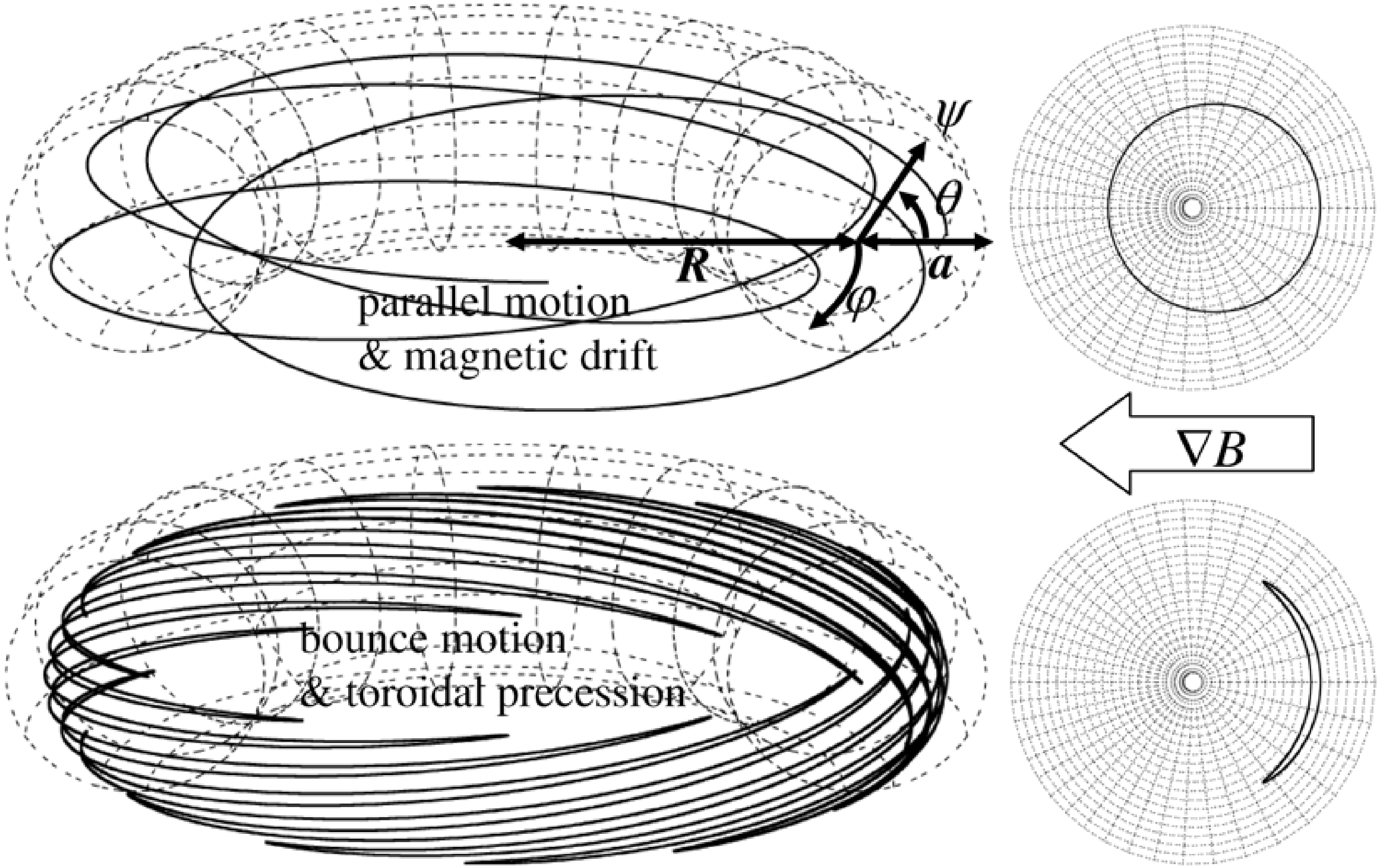
$$\frac{B_o}{B'} = \frac{v_{\perp o}{}^2}{v'_{\perp}{}^2} = \frac{v_{\perp o}{}^2}{v_o{}^2} \equiv sin^2\theta$$

$$\frac{B_o}{B_m} \equiv \frac{1}{R_m} = sin^2\theta_m$$

- 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

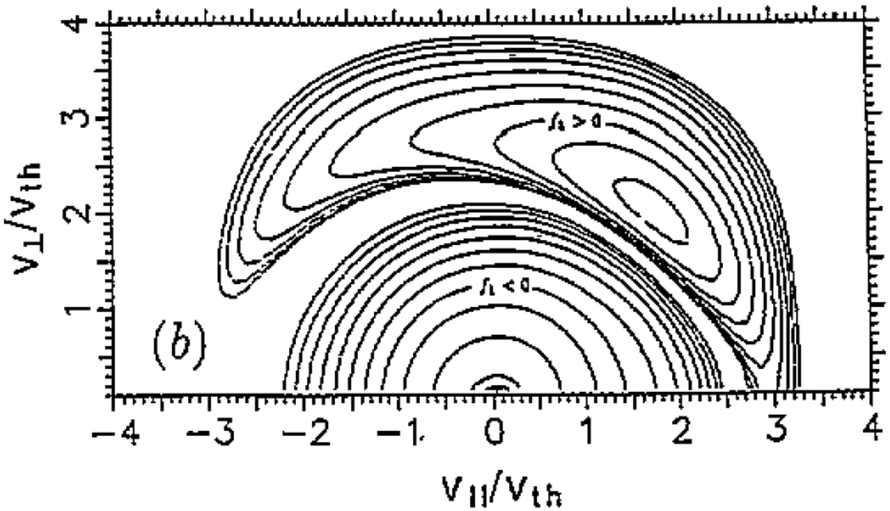
The trajectories of charged particles follow the toroidal field lines



X. Garbet et al, Nucl. Fusion **50**, 043002 (2010)

The collisional re-distribution of the ECRH-driven anisotropy in $E_\perp$ causes some parallel momentum to flow from e^- to ions

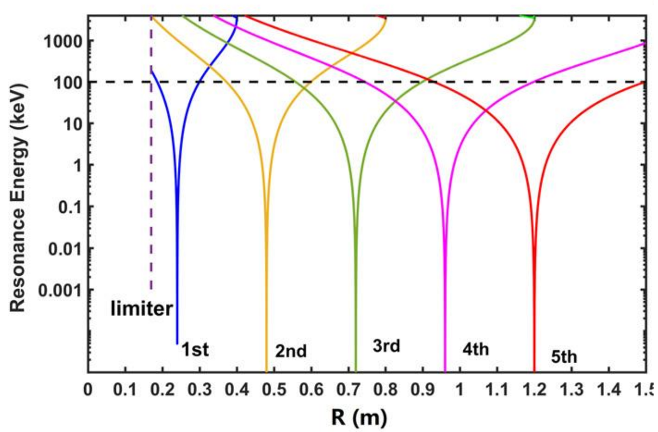
- **Coulomb collisions are more efficient at lower energies.**

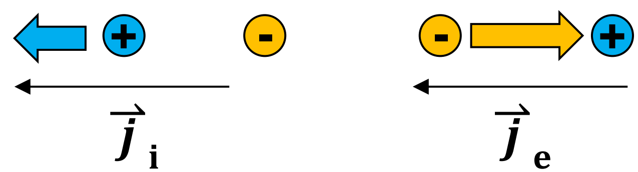


Velocity: $v_2 > v_1$

Collisions: $\nu_2 < \nu_1$

- **Electron cyclotron current drive:**





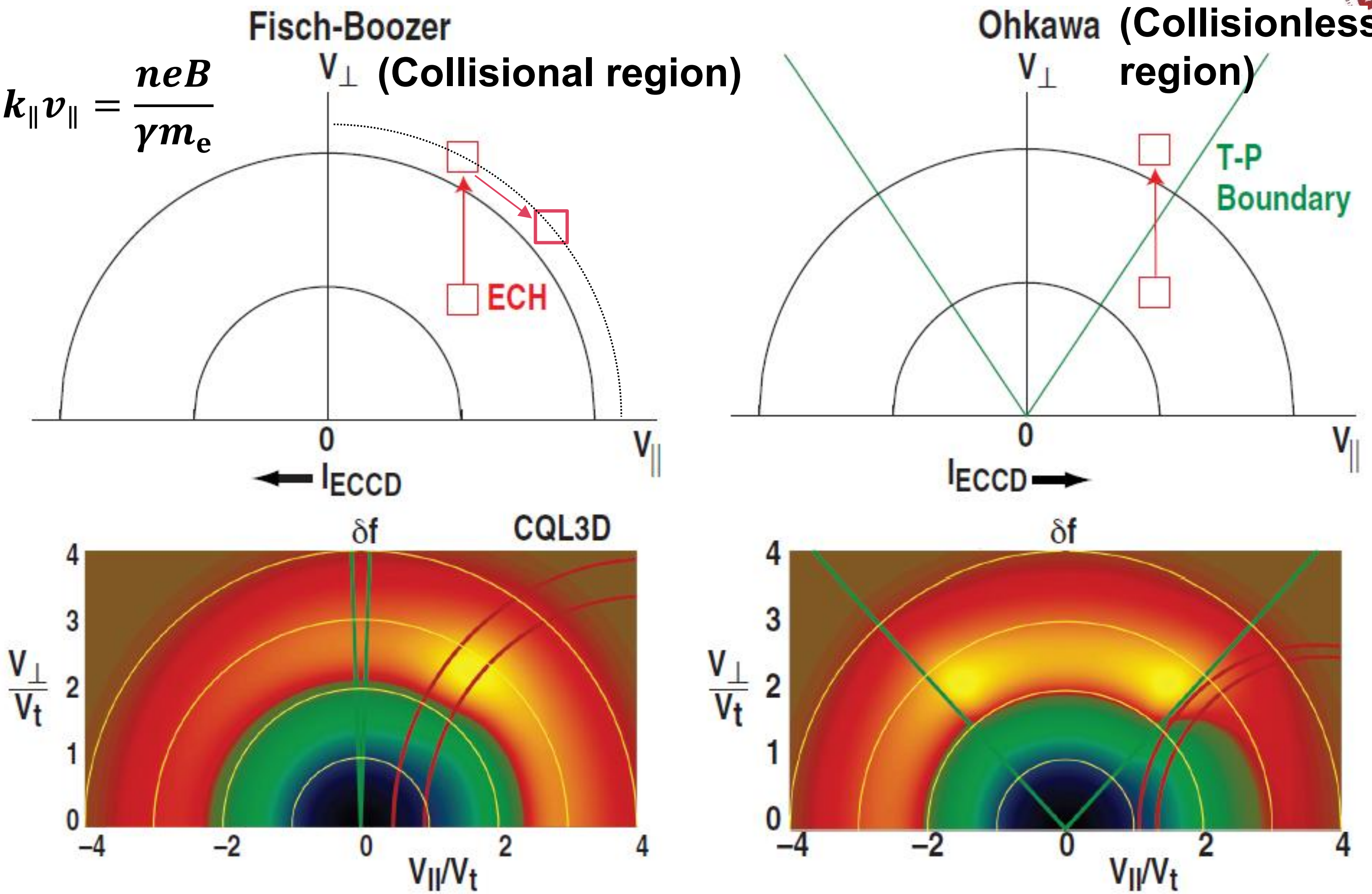
$$\vec{j}_p = -en_e\,\vec{v}_e + en_i\,\vec{v}_i$$

$$\vec{P} = n_e m_e\,\vec{v}_e + n_i m_i\,\vec{v}_i \approx 0$$

V. Erckmann and U. Gasparion, Plasma Phys. Control. Fusion **36**, 1869 (1994)
Yuejiang Shi et al, Nucl. Fusion **62**, 086047 (2022)

Passing electrons can be trapped if the $v_\perp$ is increased by heating

$$\omega - k_\parallel v_\parallel = \frac{neB}{\gamma m_e}$$



Lecture note “Physics and Applications of Electron Cyclotron Heating and Current Drive” by R. Prater from GA at 6th ITER International School 2012, Institute for Plasma Research, Gandhinagar Ahmedabad, India, December 2-6, 2012

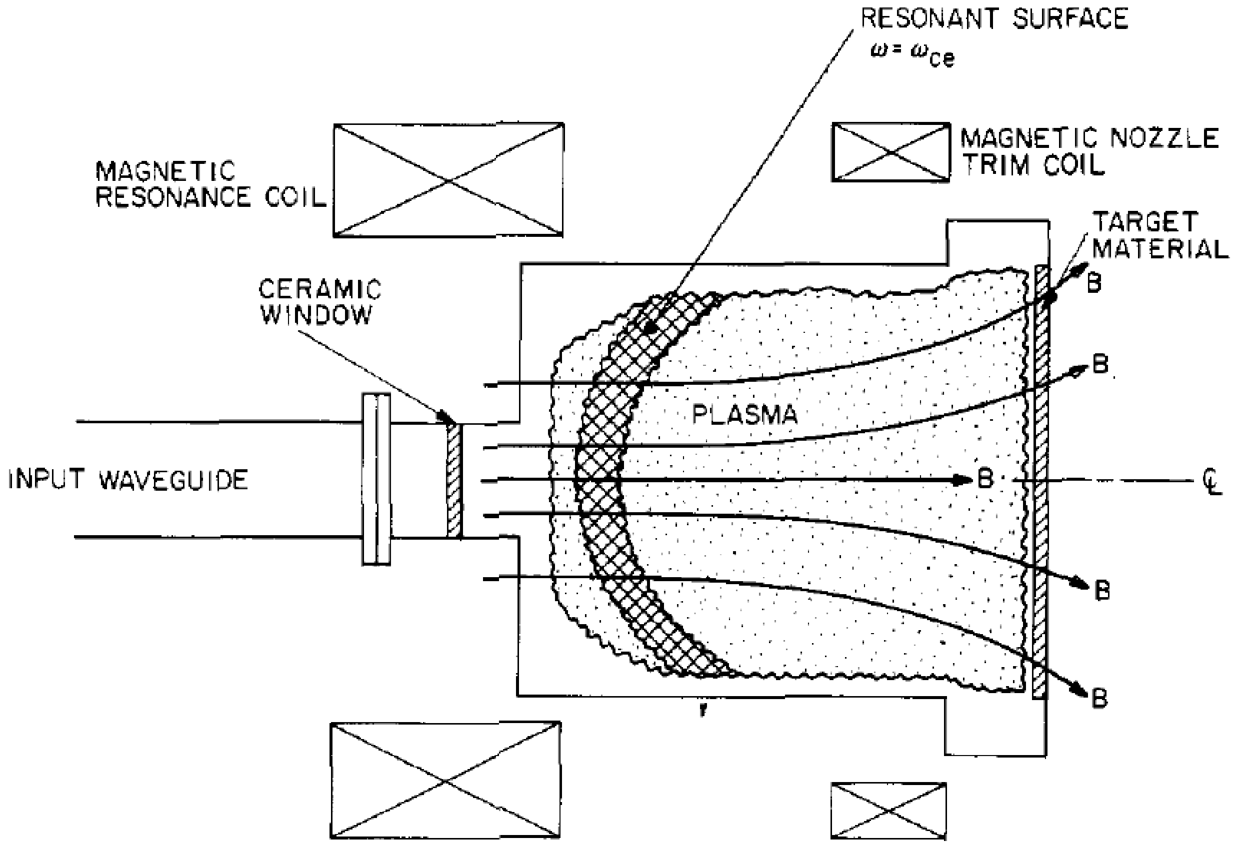
Comparison of Fisch-Boozer Mechanism and Ohkawa Mechanism

Aspect	Fisch–Boozer Mechanism[1]	Ohkawa Mechanism[2]
Physical Process	Asymmetric heating of passing electrons with subsequent collisional momentum transfer	Selective de-trapping of barely trapped electrons into passing orbits (collisionless mechanism)
Requires collisions?	Yes (collisional mechanism)	No (collisionless pitch-angle scattering)
Key Particle Population	Passing electrons	Trapped (or barely trapped) electrons
Wave absorption location	Depends on Doppler-shifted resonance; typically near magnetic axis or mid-radius	Usually near edge where barely trapped particles are abundant

1 N. J. Fisch and A. H. Boozer, Phys. Rev. Lett. 45, 720 (1980).
2 T. Ohkawa, “Steady state operation of tokamaks by rf heating,” General Atomics Report No. GA-A13847 (1976).

Strong absorption occurs when the frequency matches the electron cyclotron frequency

- **Electron cyclotron resonance (ECR) plasma reactor**



Electron cyclotron frequency depends on magnetic field only

$$m_e \frac{d\vec{v}}{dt} = -\frac{e}{c}\,\vec{v} \times \vec{B}$$

- Assuming $\vec{B} = B\hat{z}$ and the electron oscillates in x-y plane

$$m_e \dot{v}_x = -\frac{e}{c} B v_y \qquad m_e \dot{v}_z = 0$$

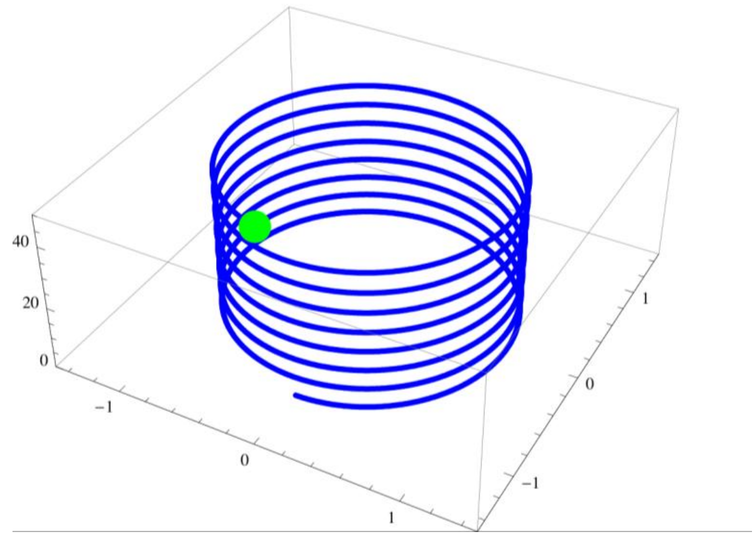
$$m_e \dot{v}_y = \frac{e}{c} B v_x$$

$$\ddot{v}_x = -\frac{eB}{m_e c}\dot{v}_y = -\left(\frac{eB}{m_e c}\right)^2 v_x$$

$$\ddot{v}_y = -\frac{eB}{m_e c}\dot{v}_x = -\left(\frac{eB}{m_e c}\right)^2 v_y$$

- Therefore

$$\omega_{ce} = \frac{eB}{m_e c}$$



Electrons keep getting accelerated when a electric field rotates in electron's gyrofrequency

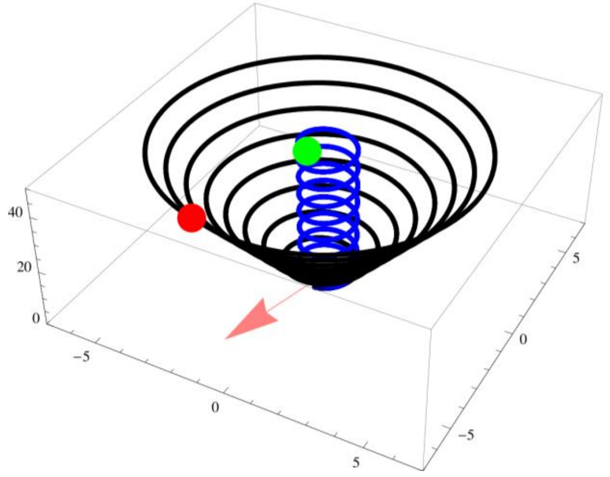
$$m_e \frac{d\vec{v}}{dt} = -\frac{e}{c}\,\vec{v}\times\vec{B} - e\,\vec{E} \qquad \vec{B} = B_0\hat{z} \qquad \vec{E} = E_0[\hat{x}\cos(\omega t) + \hat{y}\sin(\omega t)]$$

$$m_e\dot{v}_x = -\frac{e}{c}Bv_y + E_0\cos(\omega t) \qquad m_e\dot{v}_y = \frac{e}{c}Bv_x + E_0\sin(\omega t) \qquad m_e\dot{v}_z = 0$$

$$\ddot{v}_x = -\frac{eB}{m_e c}\dot{v}_y - \frac{E_0}{m_e}\omega\sin(\omega t) = -\omega_{ce}{}^2 v_x - \frac{E_0}{m_e}(\omega_{ce}+\omega)\sin(\omega t)$$

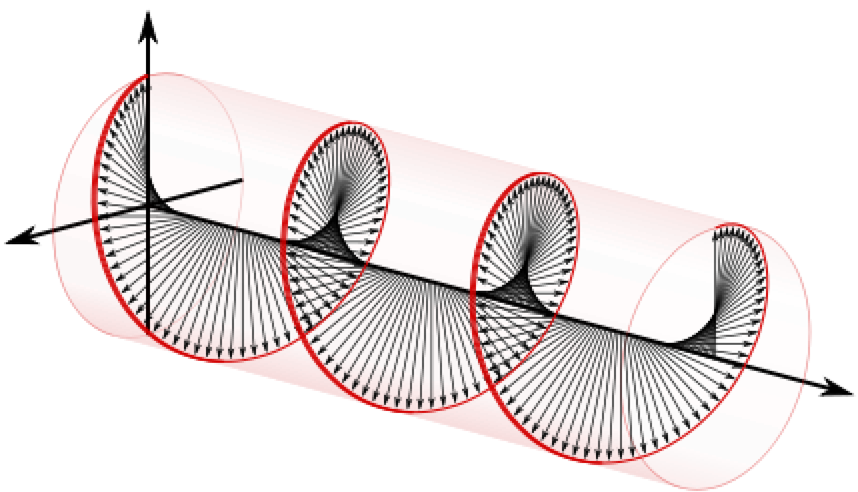
$$\ddot{v}_y = -\frac{eB}{m_e c}\dot{v}_x + \frac{E_0}{m_e}\omega\cos(\omega t) = -\omega_{ce}{}^2 v_y + \frac{E_0}{m_e}(\omega_{ce}+\omega)\cos(\omega t)$$

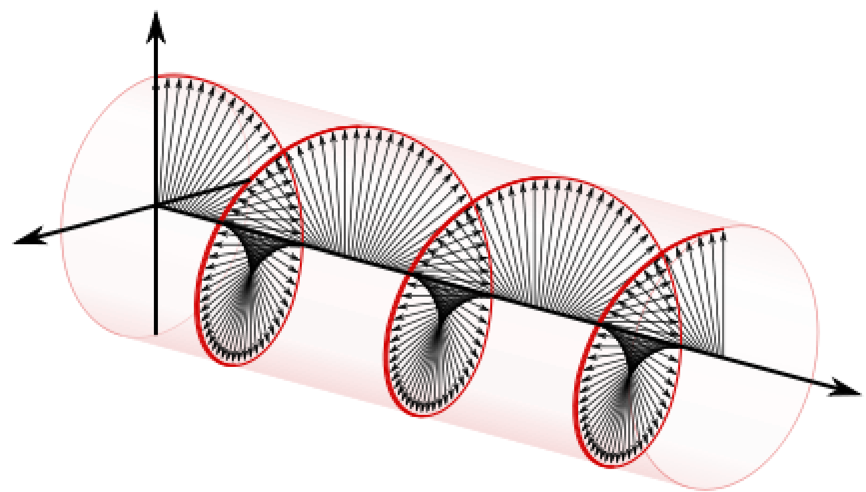
$$\omega_{ce} = \frac{eB}{m_e c}$$



Electric field in a circular polarized electromagnetic wave keeps rotating as the wave propagates

- **Right-handed polarization**
- **Left-handed polarization**





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

Only right-handed polarization can resonance with electron's gyromotion

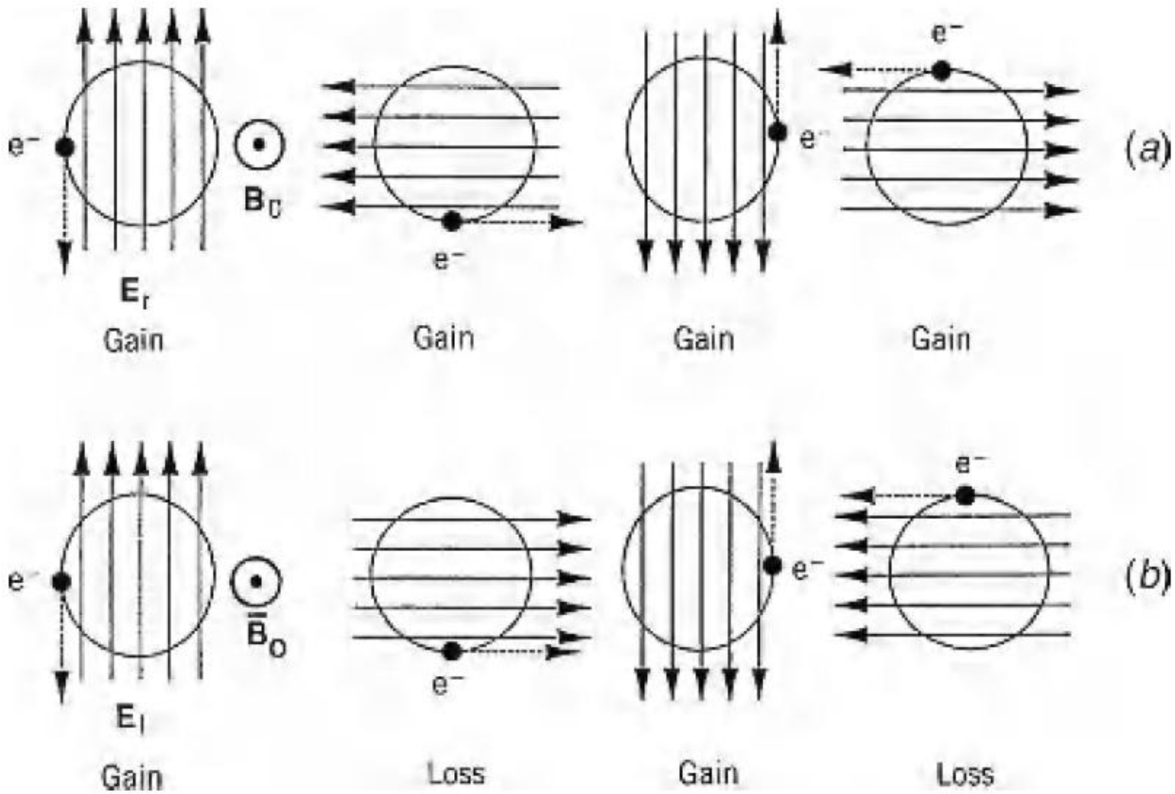
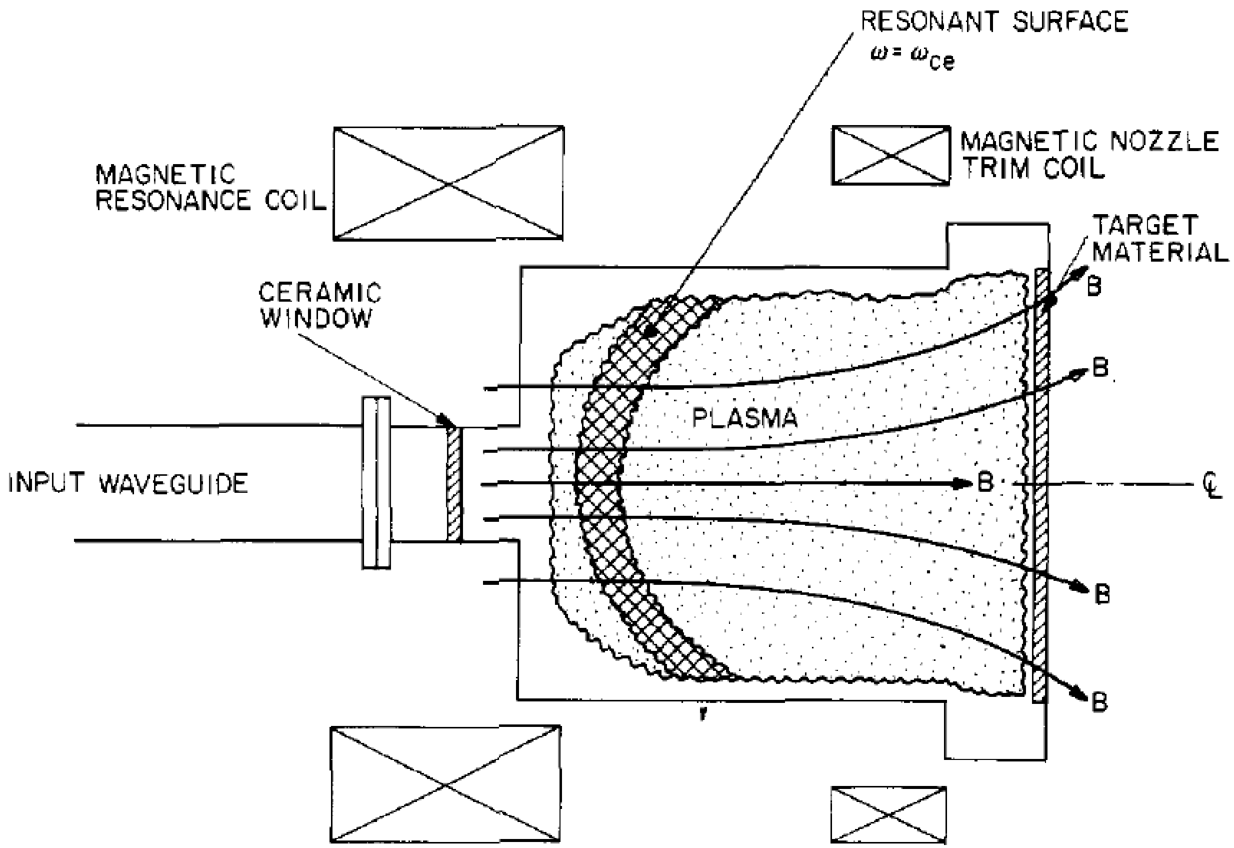


FIGURE 13.5. Basic principle of ECR heating: (*a*) continuous energy gain for right-hand polarization; (*b*) oscillating energy for left-hand polarization (after Lieberman and Gottscho, 1994).

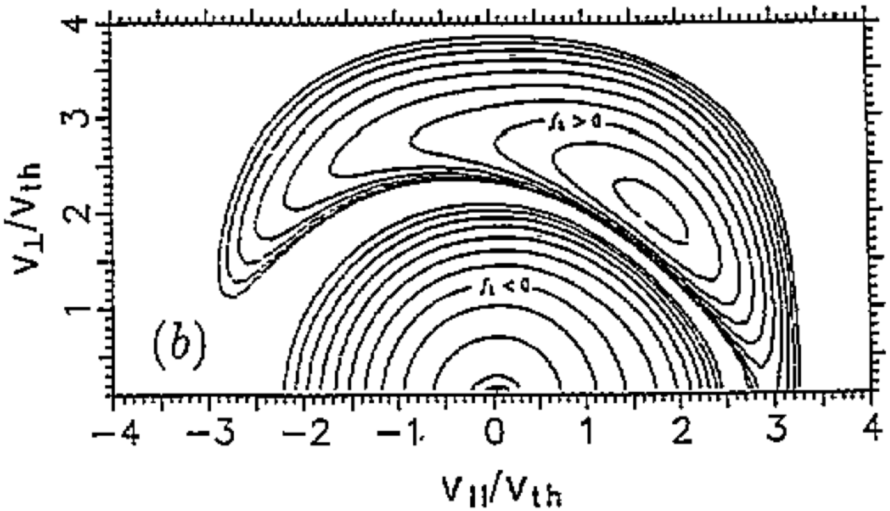
Strong absorption occurs when the frequency matches the electron cyclotron frequency

- **Electron cyclotron resonance (ECR) plasma reactor**



The collisional re-distribution of the ECRH-driven anisotropy in $E_{\perp}$ causes some parallel momentum to flow from e^{-} to ions

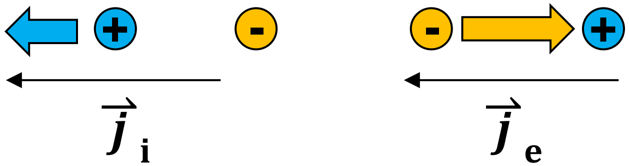
- **Coulomb collisions are more efficient at lower energies.**



Velocity: $v_2 > v_1$

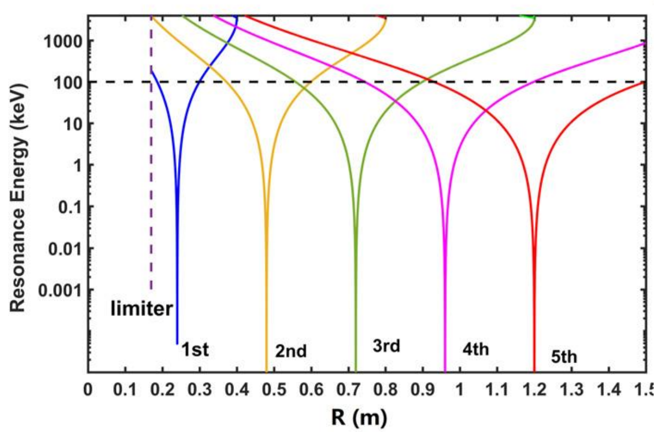
Collisions: $\nu_2 < \nu_1$

- **Electron cyclotron current drive:**



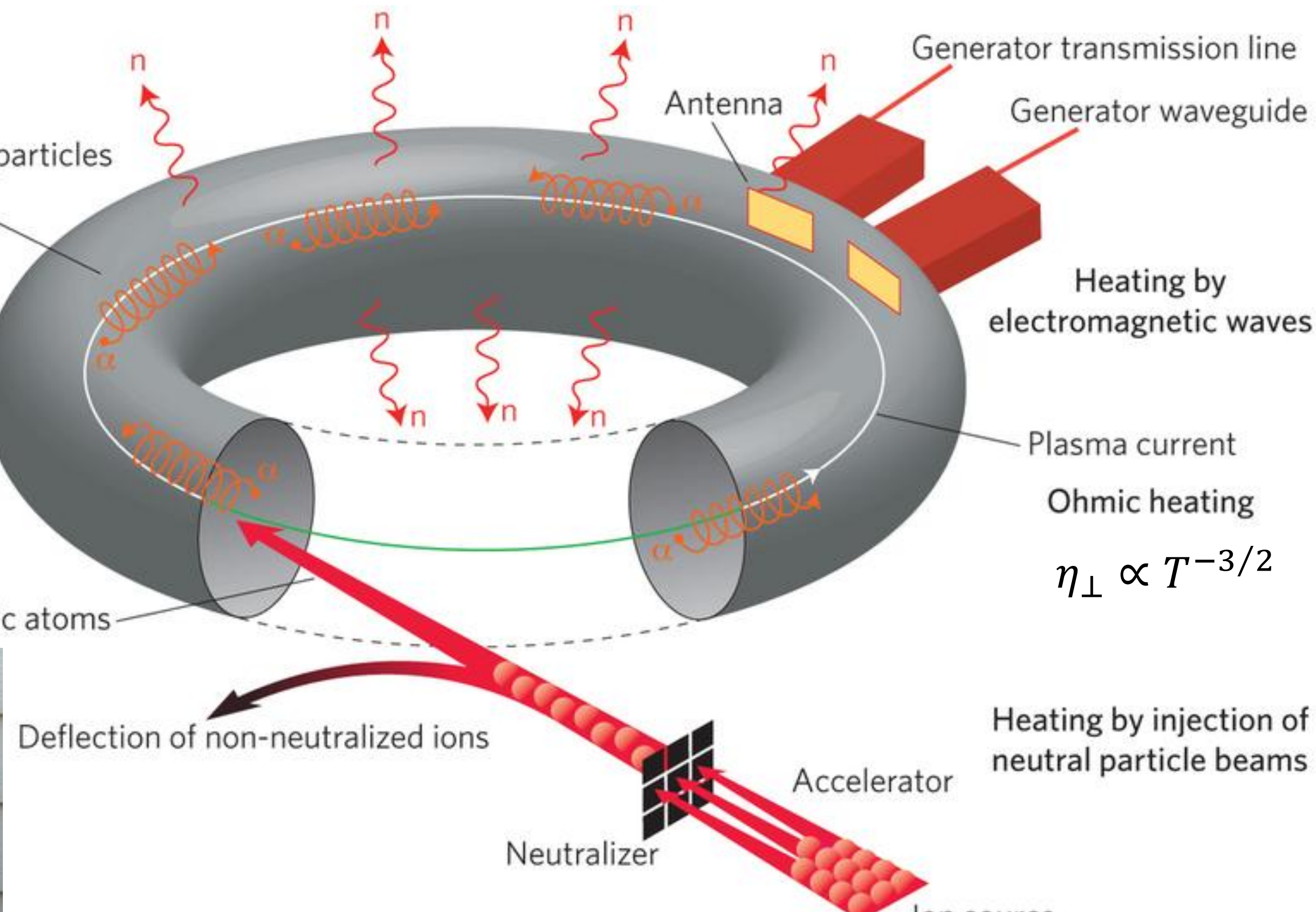
$$\vec{j}_{\mathrm{p}} = -en_{\mathrm{e}}\,\vec{v}_{\mathrm{e}} + en_{\mathrm{i}}\,\vec{v}_{\mathrm{i}}$$

$$\vec{P} = n_{\mathrm{e}}m_{\mathrm{e}}\,\vec{v}_{\mathrm{e}} + n_{\mathrm{i}}m_{\mathrm{i}}\,\vec{v}_{\mathrm{i}} \approx 0$$



V. Erckmann and U. Gasparion, Plasma Phys. Control. Fusion **36**, 1869 (1994)
Yuejiang Shi et al, Nucl. Fusion **62**, 086047 (2022)

Neutral beam injector is one of the main heat mechanisms in MCF



$$\eta_{\perp} \propto T^{-3/2}$$

D. Mazon, etc., NATURE PHYSICS, 12, 14, 2016
https://zh.wikihow.com/%E5%9C%A8%E6%89%8B%E6%8C%87%E4%B8%8A%E8%BD%AC%E7%AF%AE%E7%90%83

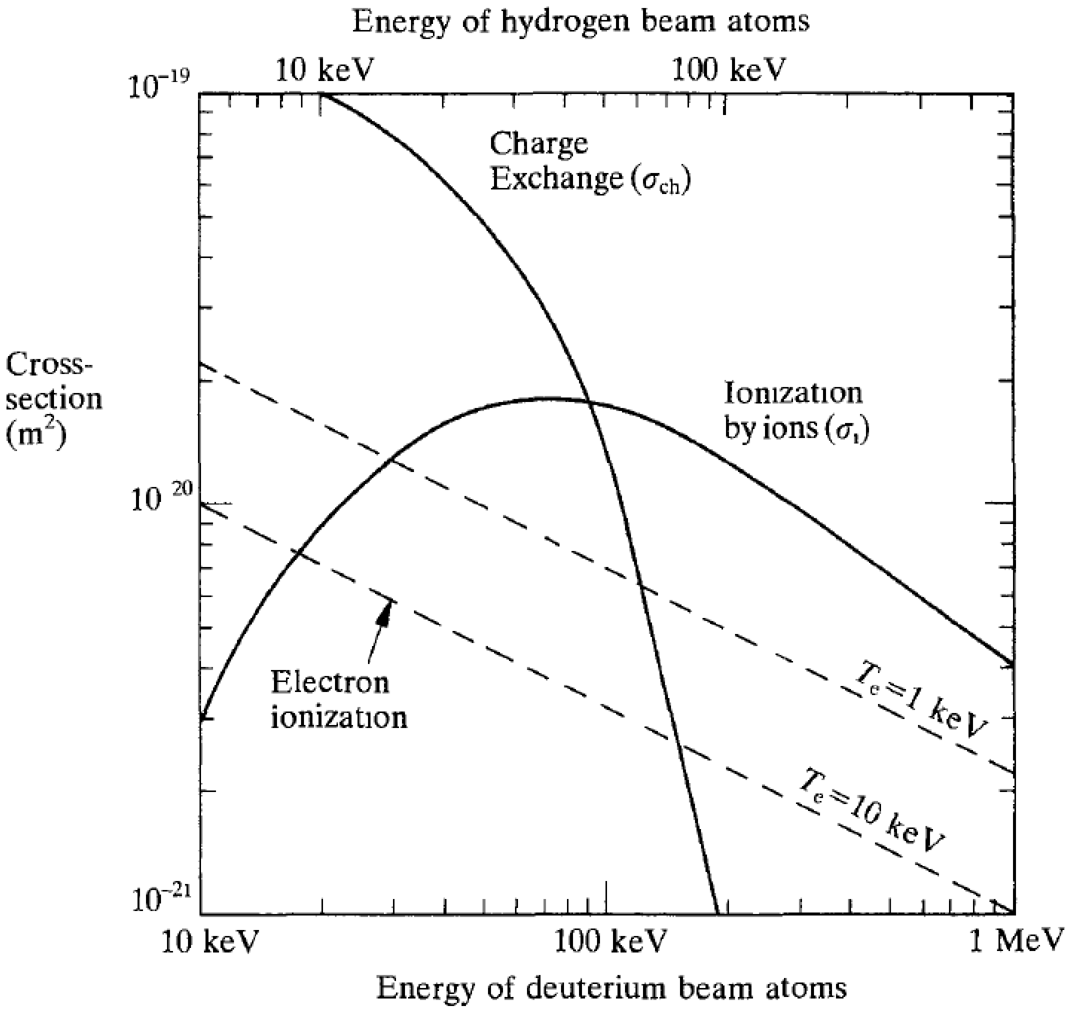
Varies way of heating a MCF device

System		Frequency/ energy	Maximum power coupled to plasma	Overall system efficiency	Development/ demonstration required	Remarks
ECRF	Demonstrated in tokamaks	28–157 GHz	2.8 MW, 0.2 s	30–40%	Power sources and windows, off-axis CD	Provides off-axis CD
	ITER needs	150–170 GHz	50 MW, S S			
ICRF	Demonstrated in tokamaks	25–120 MHz	22 MW, 3 s (L-mode); 16.5 MW, 3 s (H-mode)	50–60%	ELM tolerant system	Provides ion heating and smaller ELMs
	ITER needs	40–75 MHz	50 MW, S S			
LHRF	Demonstrated in tokamaks	1.3–8 GHz	2.5 MW, 120 s; 10 MW, 0.5 s	45–55%	Launcher, coupling to H-mode	Provides off-axis CD
	ITER needs	5 GHz	50 MW, S S			
NBI +ve ion	Demonstrated in tokamaks	80–140 keV	40 MW, 2 s; 20 MW, 8 s	35–45%	None	Not applicable
	ITER needs	None	None			
NBI −ve ion	Demonstrated in tokamaks	0.35 MeV	5.2 MW, D^-, 0.8 s (from 2 sources)			
	ITER needs	1 MeV	50 MW, S S	∼37%	System, tests on tokamak, plasma CD	provides rotation

'S S' indicates steady state

Nuclear Fusion, 39, 2495, 1999

Neutral atoms are ionized by collisions in the plasma



- **Charge exchange:**

  $H_b + H_p^+ \rightarrow H_b^+ + H_p$

- **Ionization by ions**

  $H_b + H_p^+ \rightarrow H_b^+ + H_p^+ + e^-$

- **Ionization by electrons**

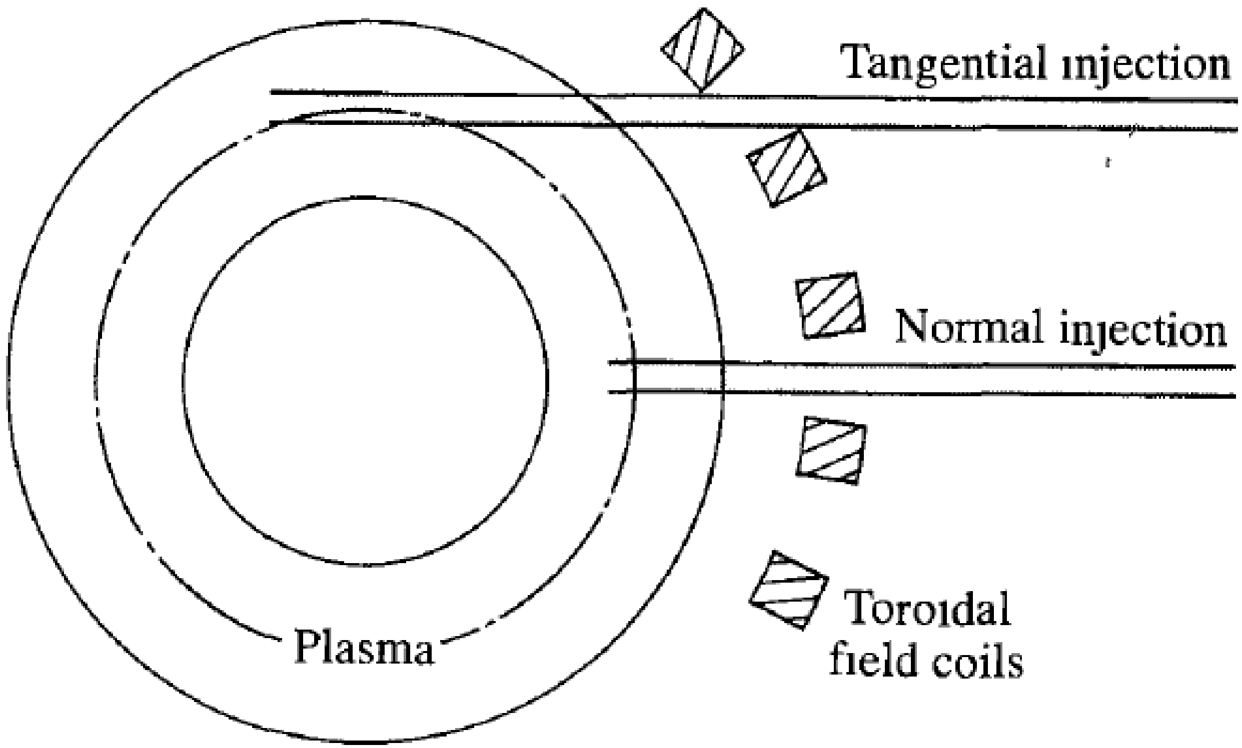
  $H_b + e^- \rightarrow H_b^+ + 2e^-$

b: beam
p: plasma

John Wesson, Tokamaks 3rd edition

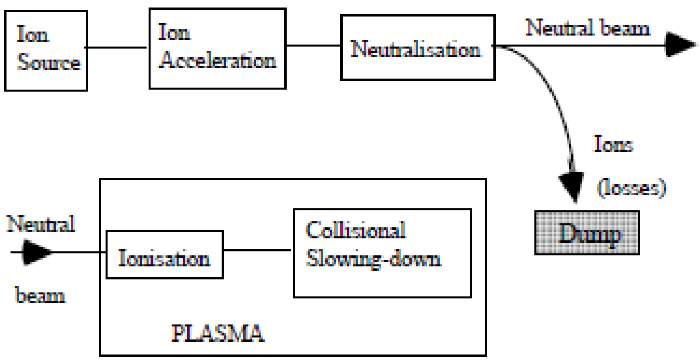
Neutral beam absorption length increases with tangential injection

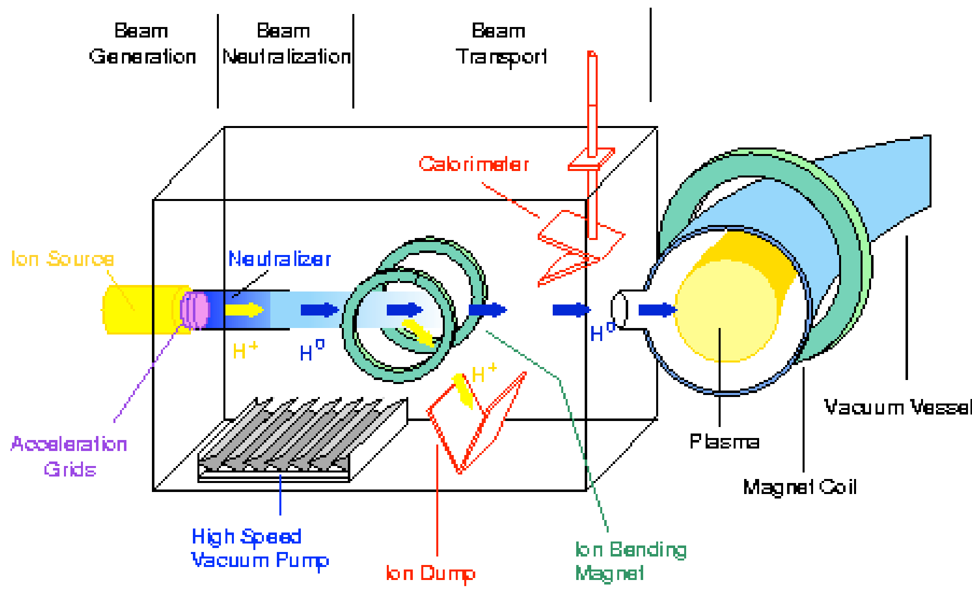
- **It is more difficult to access through the toroidal field coils with tangential injection.**



John Wesson, Tokamaks 3rd edition

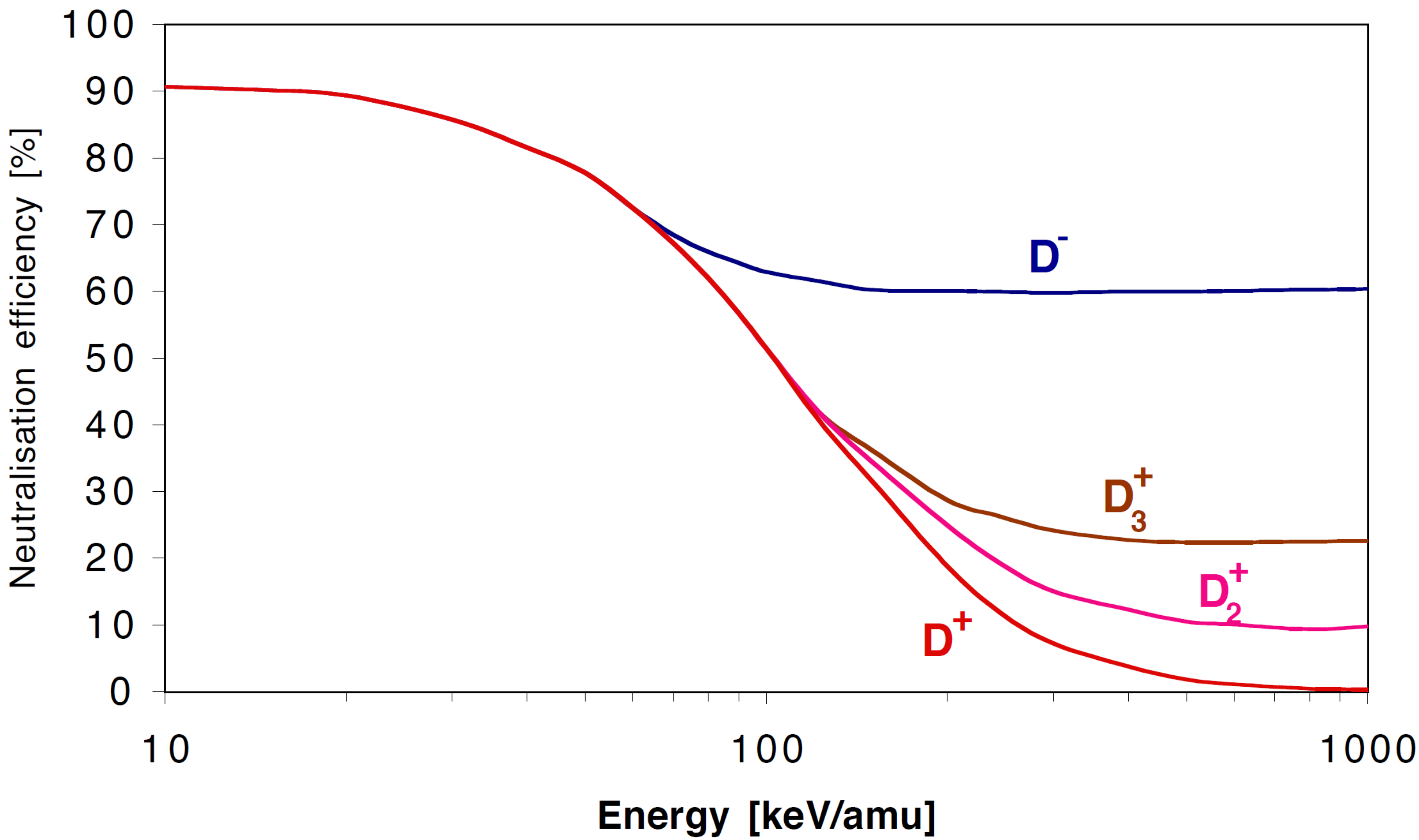
Neutral particles heat the plasma via coulomb collisions





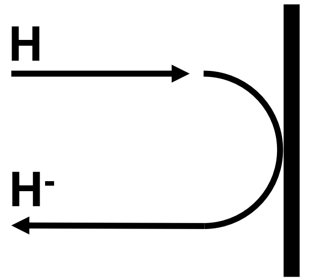
1. create energetic (fast) neutral ions
2. ionize the neutral particles
3. heat the plasma (electrons and ions) via Coulomb collisions

Negative ion source is preferred due to higher neutralization efficiency



There are two ways to make negative ions – surface and volume production

- **Surface production, depends on :**
  - **Work function Φ**
  - **Electron affinity level, 0.75 eV for H^-**
  - **Perpendicular velocity**
  - **Work function can be reduced by covering the metal surface with cesium**



$$H + e^- \longrightarrow H^-$$

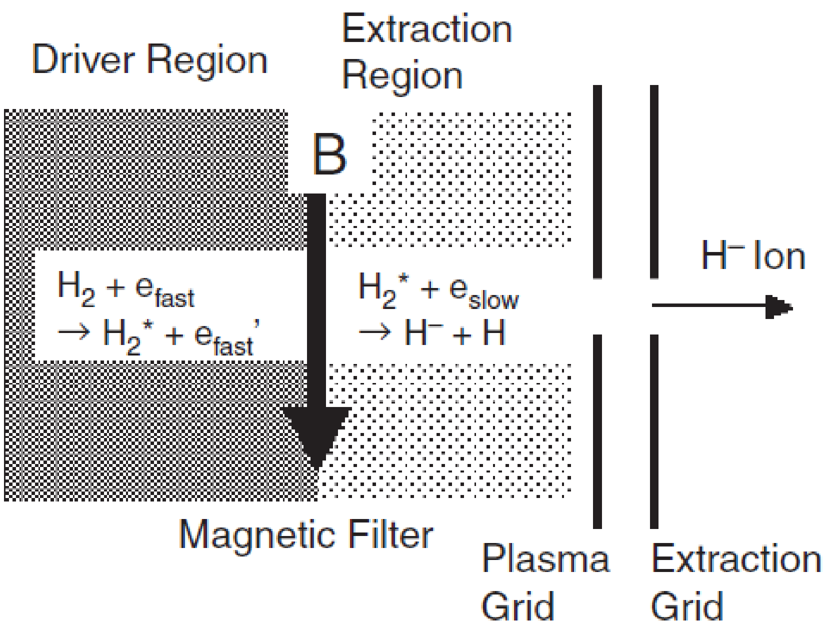
$$H^+ + 2e^- \longrightarrow H^-$$

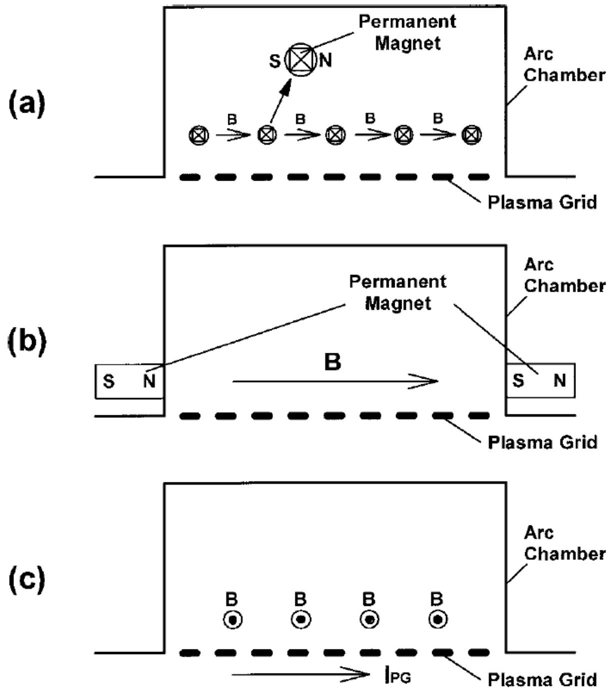
- **Volume production:**

$$H_2 + e_{fast}(>20\ \text{eV}) \rightarrow H_2^*(\text{excited state}) + e_{fast},$$

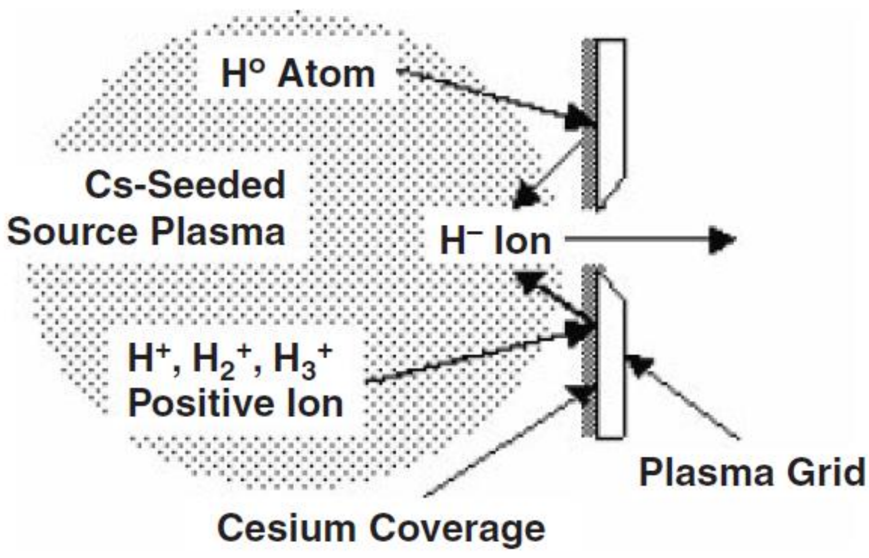
$$H_2^*(\text{excited state}) + e_{slow}(\approx 1\ \text{eV}) \rightarrow H^- + H.$$

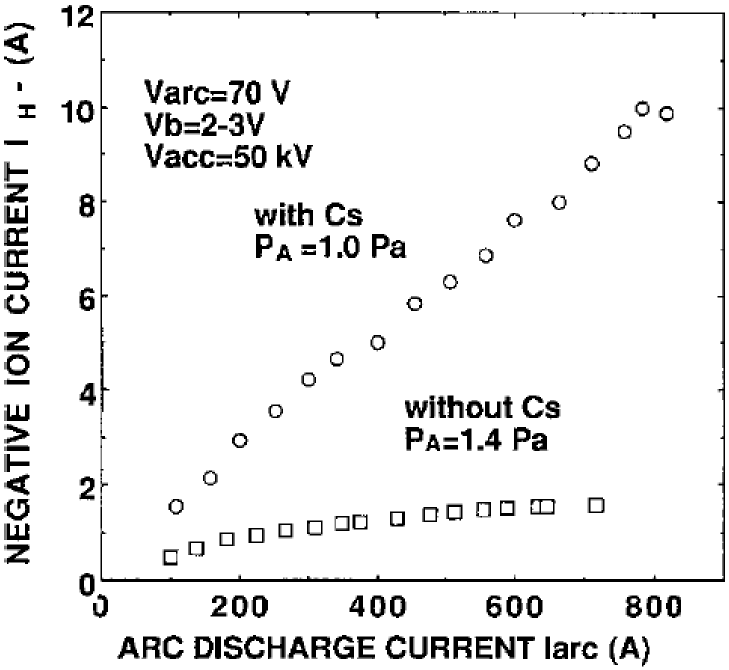
Two-chamber method of negative ions in volume production with a magnetic filter



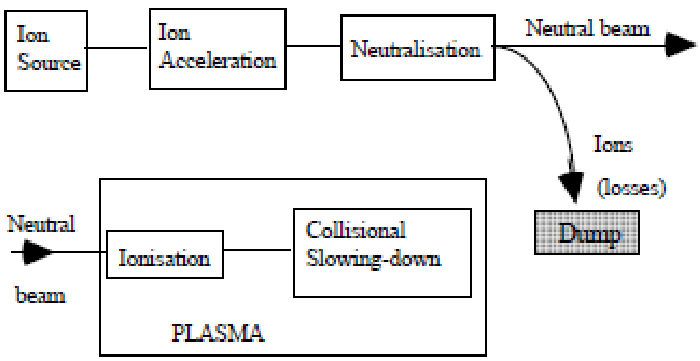


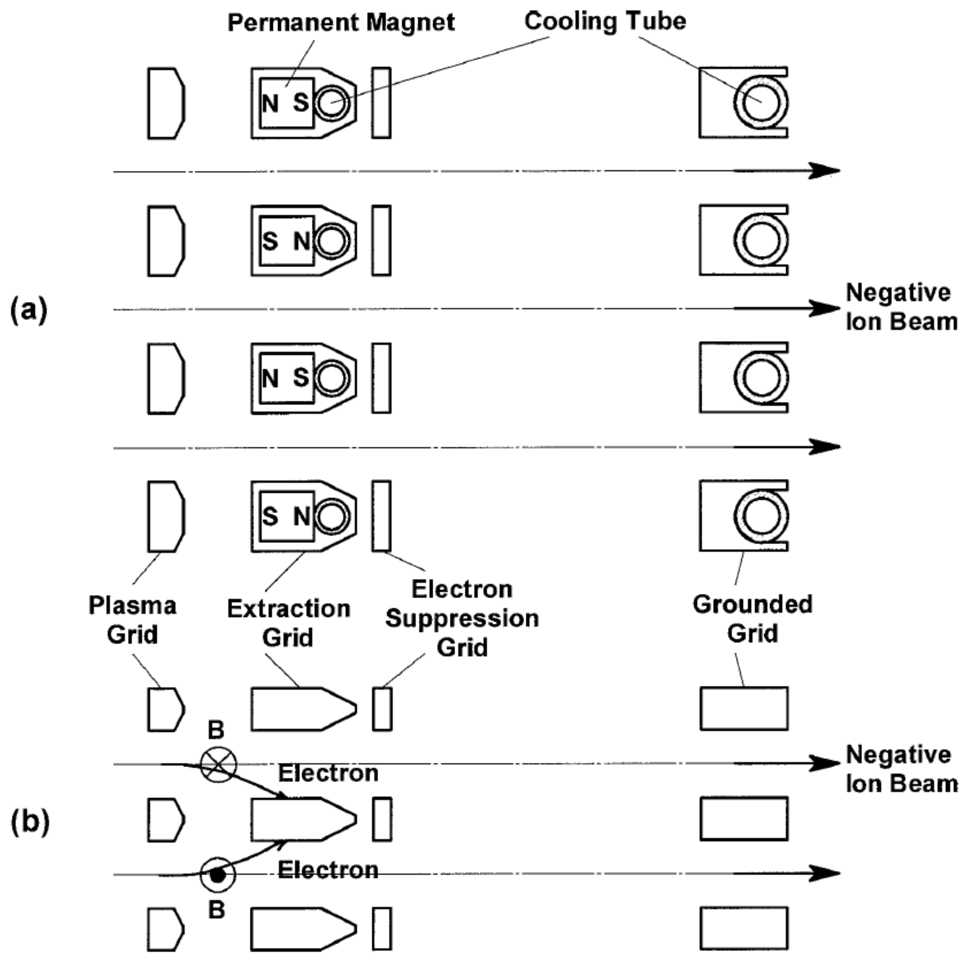
Adding cesium increases negative ion current





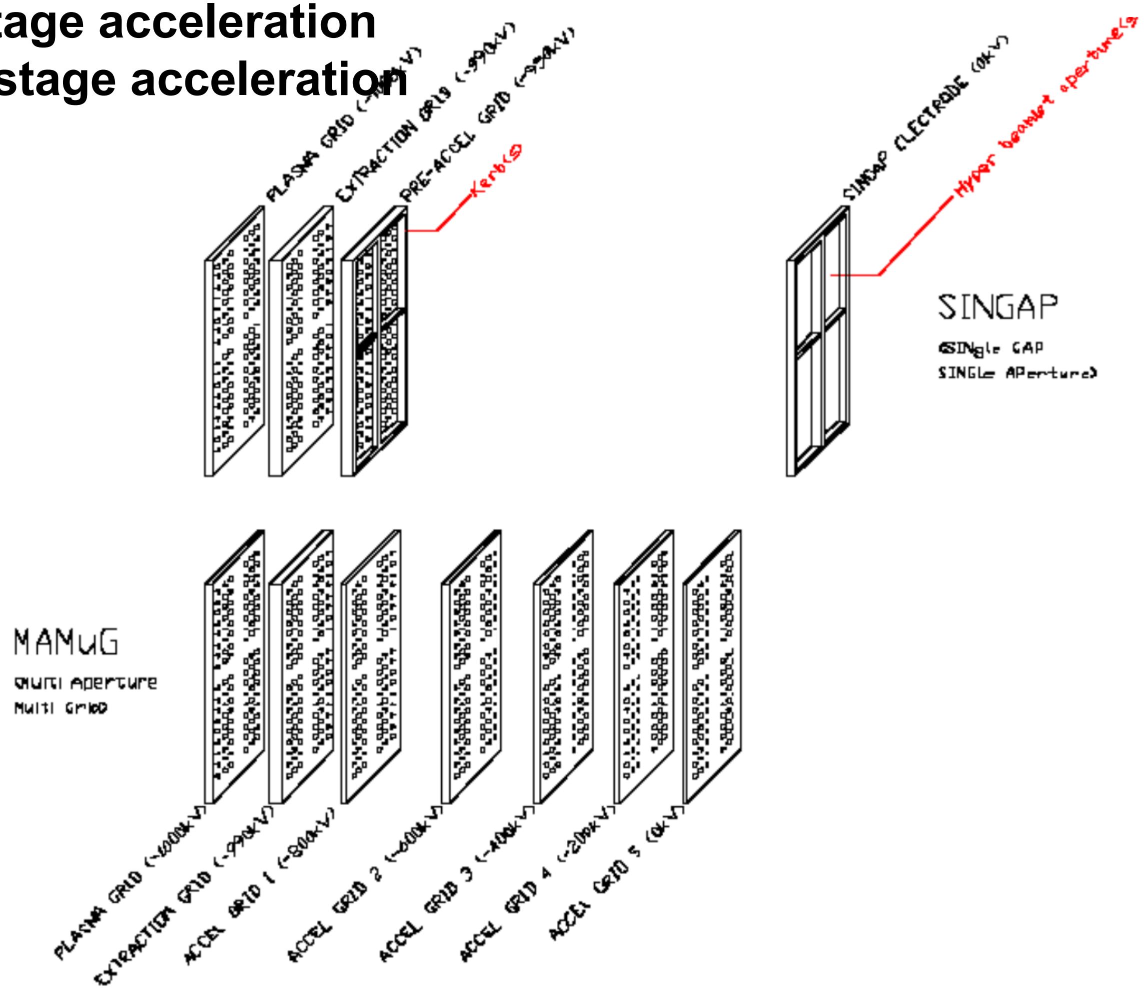
Electrons need to be filtered out since they are extracted together with negative ions





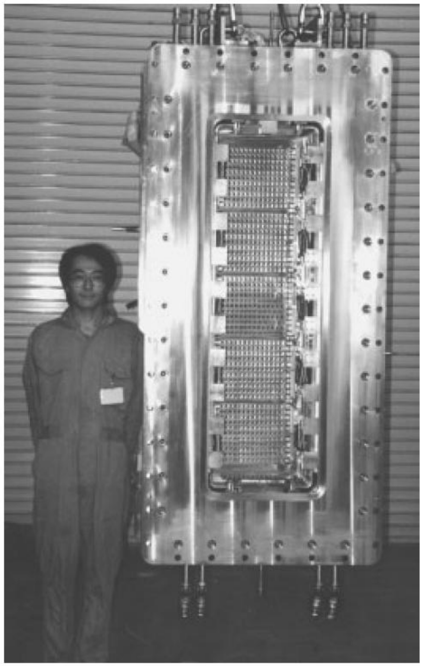
Acceleration

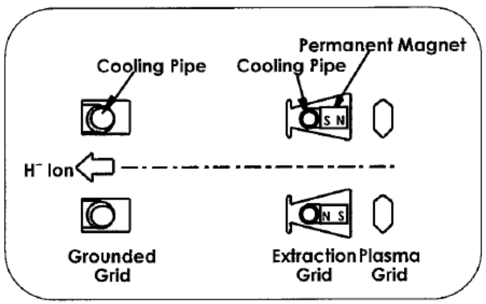
- **Multi-stage acceleration**
- **Single-stage acceleration**



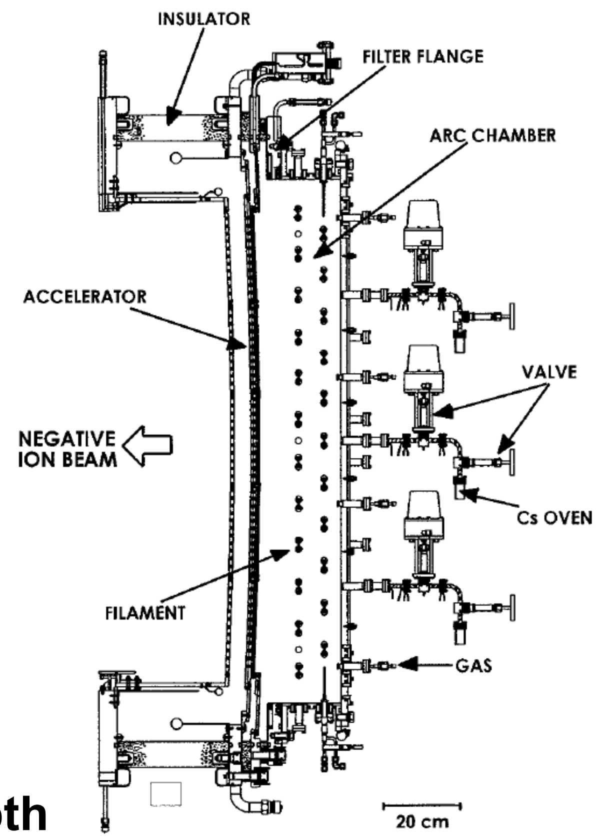
The ITER neutral beam system: status of the project and review of the main technological issues, presented by V. Antoni

NBI system of the LHD fusion machine





Negative Ion Accelerator

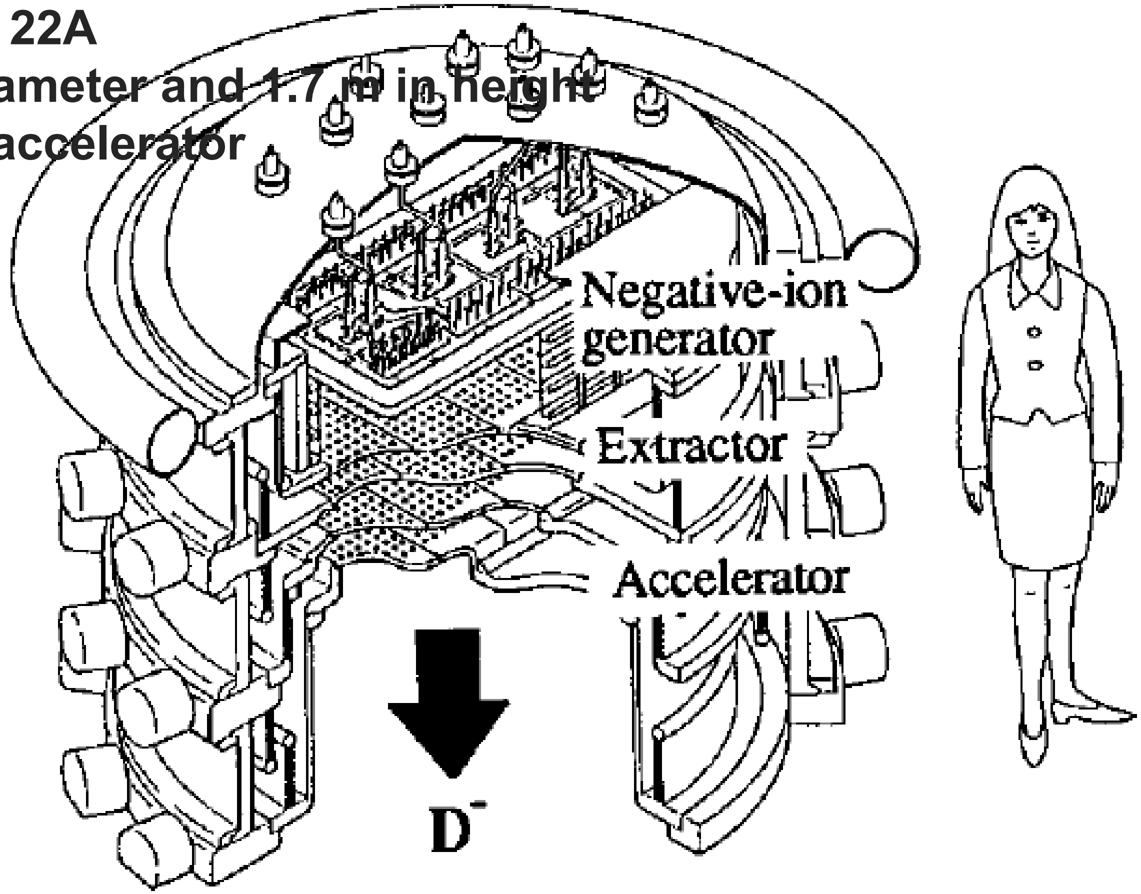


- **180 keV and 30 A**
- **Arc chamber: 35 cm x 145 cm, 21cm in depth**
- **Single stage accelerator**

Y. Takeiri, etc., Nucl. Fusion, 46, S199, 2006

JT60U NBI system

- JT-60 (Japan-Torus) is a tokamak in Japan.
- 550 keV, 22A
- 2m in diameter and 1.7 m in height
- 3-stage accelerator



Neutralization

- Gas neutralization
  - Collisions between fast negative ions and atoms

$$H^- + H_2 \longrightarrow H + H_2 + e^-$$

  - Fast ions can lose another electron after neutralized

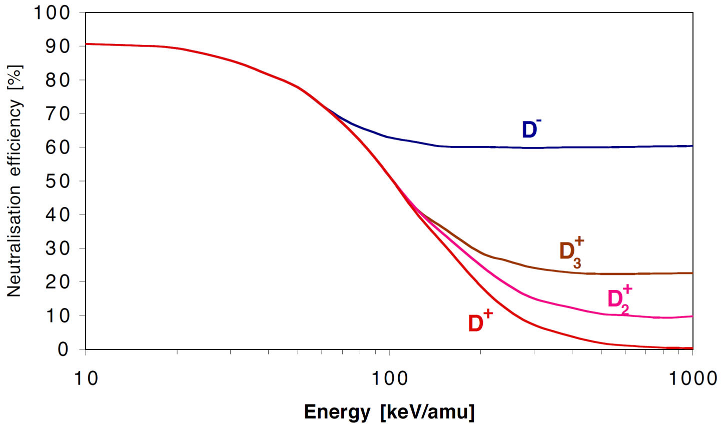
$$H + H_2 \longrightarrow H^+ + H_2 + e^-$$

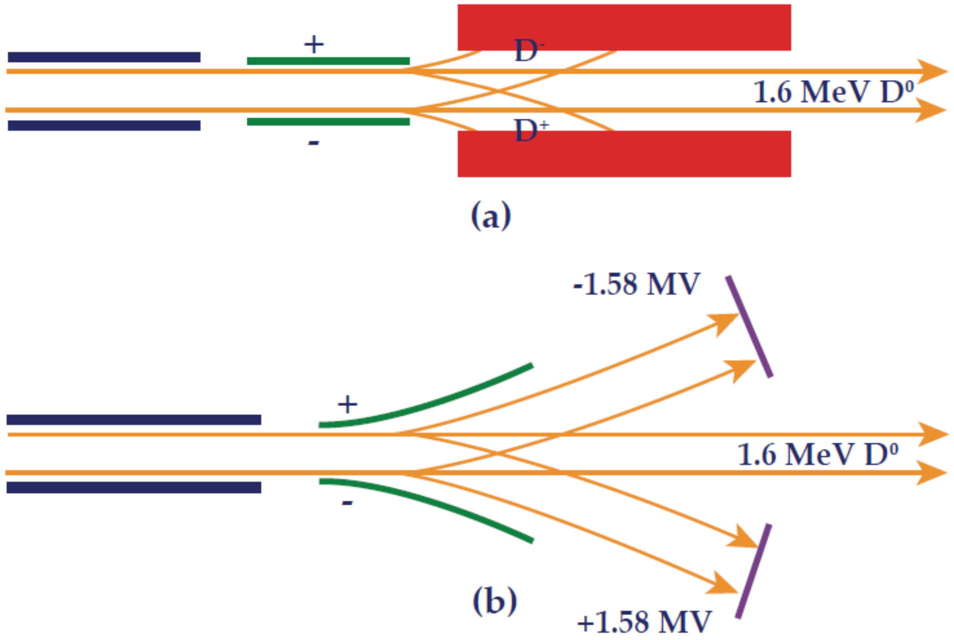
- Plasma neutralization
  - Collisions with charged particles in plasma

$$H^- + X(e, \mathrm{Ar}, H^+, {H_2}^+) \longrightarrow H + X + e^-$$

  - The efficiencies reach up to 85% for fully ionized hydrogen plasma

Beam dump

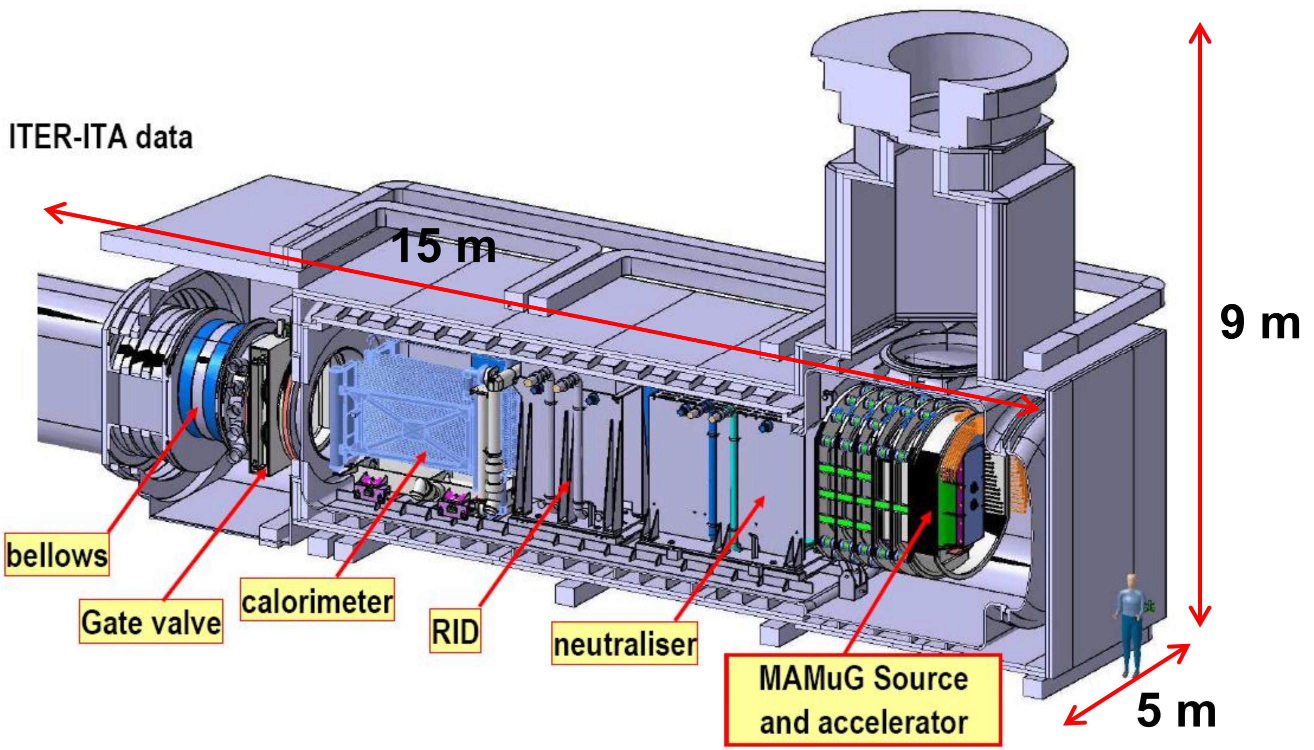




R. W. Moir, Fusion Technology, 25, 129, 1994

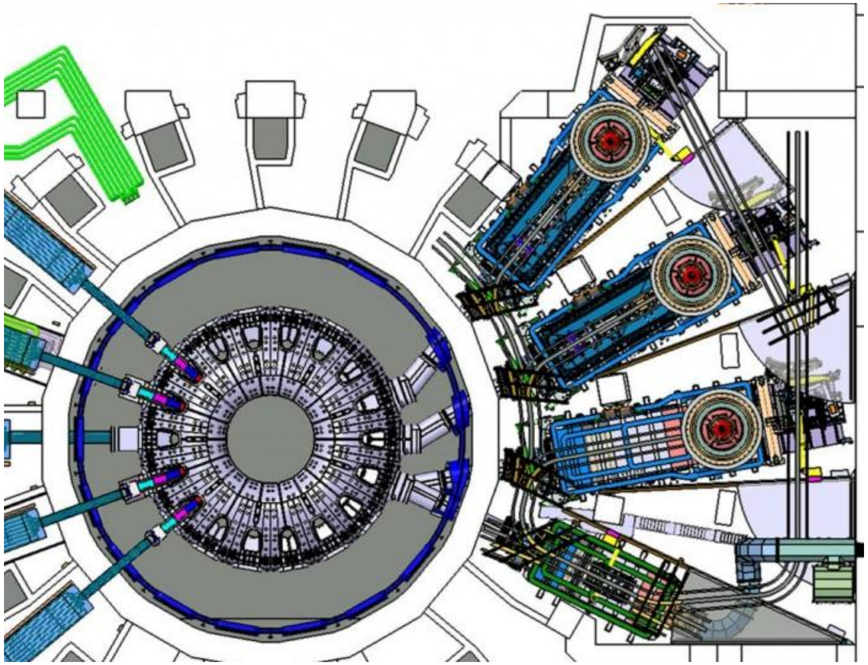
NBI for ITER

- beam components (Ion Source, Accelerator, Neutralizer, Residual Ion Dump and Calorimeter)
- other components (cryo-pump, vessels, fast shutter, duct, magnetic shielding, and residual magnetic field compensating coils)



The ITER neutral beam system: status of the project and review of the main technological issues, presented by V. Antoni

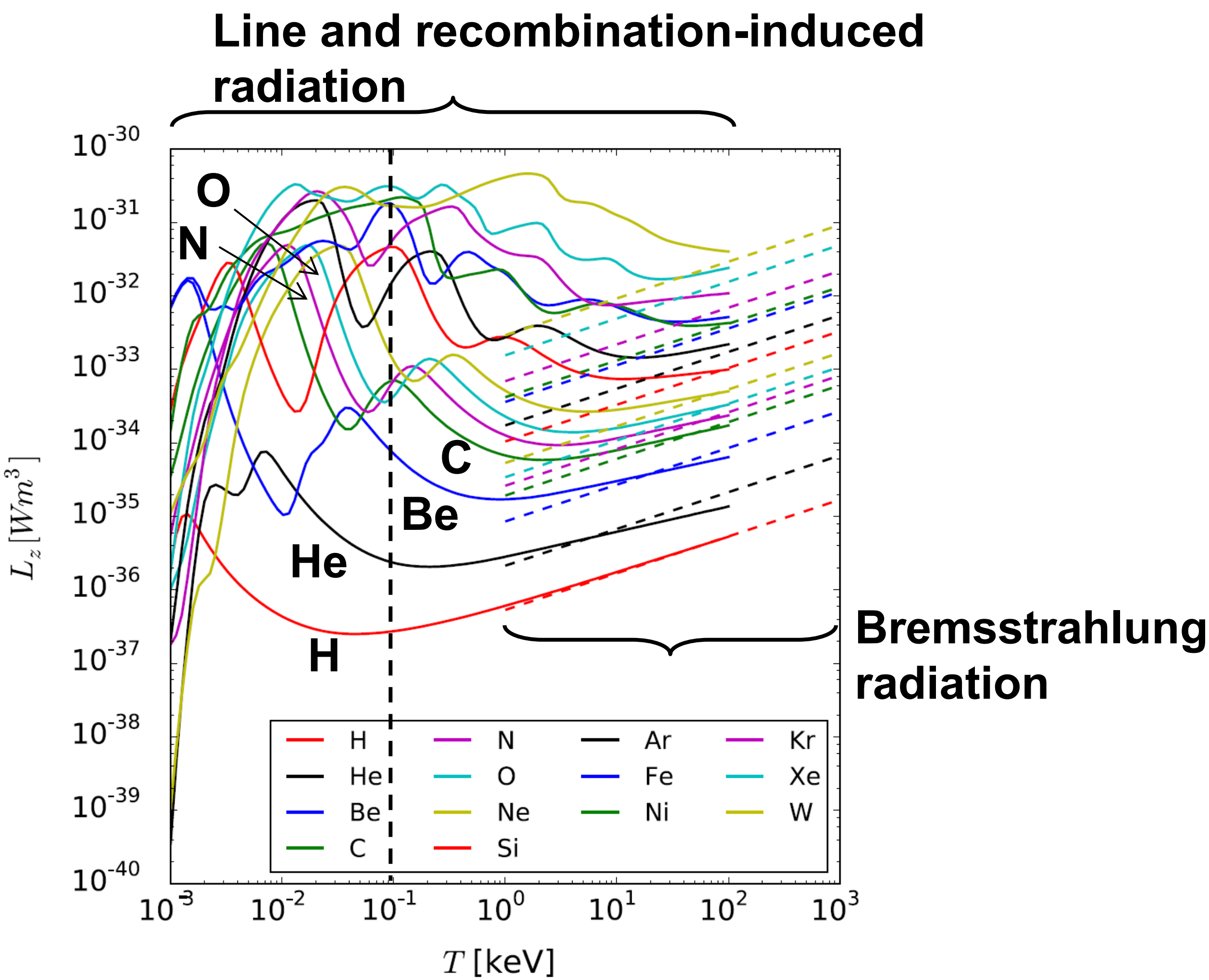
Neutral beam penetration



- Parallel direction
  - Longest path through the densest part of the plasma
  - Harder to be built
- Perpendicular direction
  - Path is short
  - Larger perpendicular energies leads to larger losses
  - Easier to be built

https://www.iter.org

Temperature of 100 eV is the threshold of radiation barrier by impurities



H. Lux, etc., Fusion Eng. Des. **42**, 101 (2015)

Reference for MCF

- Jeffrey P. Freidberg, Ideal Magnetohydrodynamics
- John Wesson, Tokamaks
- Tokamak Physics by 陳騮 院士

Course Outline

- **Inertial confinement fusion (ICF)**
  - **Plasma frequency and critical density**
  - **Direct- and indirect- drive**
  - **Laser generated pressure (Inverse bremsstrahlung and Ablation pressure)**
  - **Burning fraction, why compressing a capsule?**
  - **Implosion dynamics**
  - **Shock (Compression with different adiabat)**
  - **Laser pulse shape**
  - **Rocket model, shell velocity**
  - **Laser-plasma interaction (Stimulated Raman Scattering, SRS; Stimulated Brillouin Scattering, SBS; Two-plasmon decay)**
  - **Instabilities (Rayleigh-taylor instability, Kelvin-Helmholtz instability, Richtmeyer-Meshkov instability)**

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

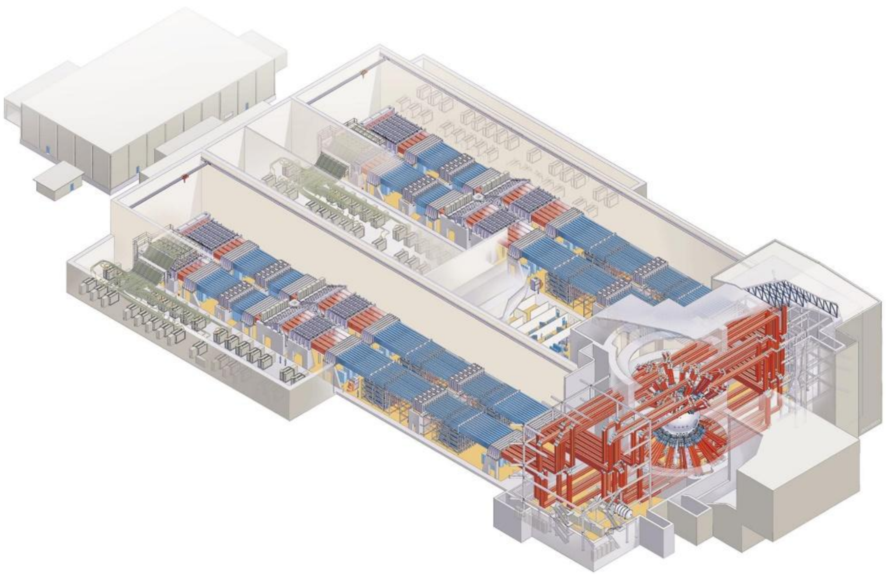
S_k: heat conduction lost

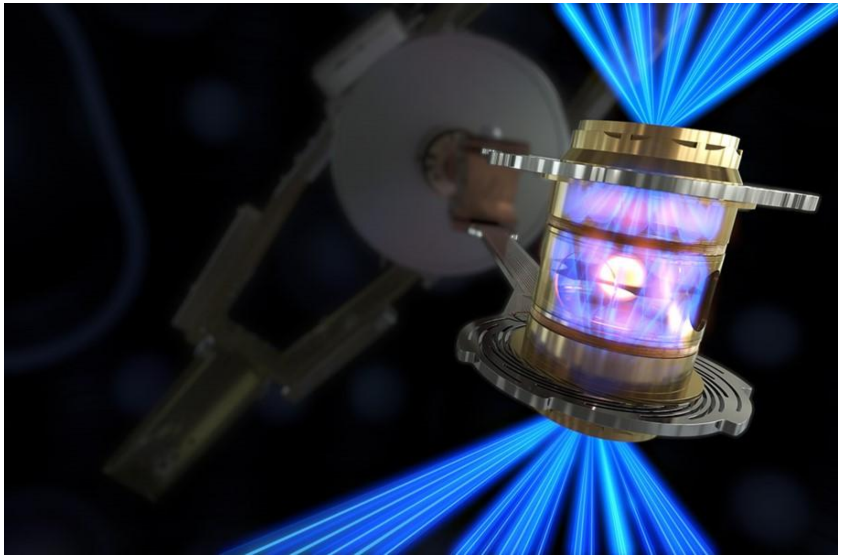
Ignition condition: $P\tau$ > 10 atm-s = 10 Gbar - ns

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

Significant breakthrough was achieved in ICF recently

- Inertial confinement fusion (ICF)



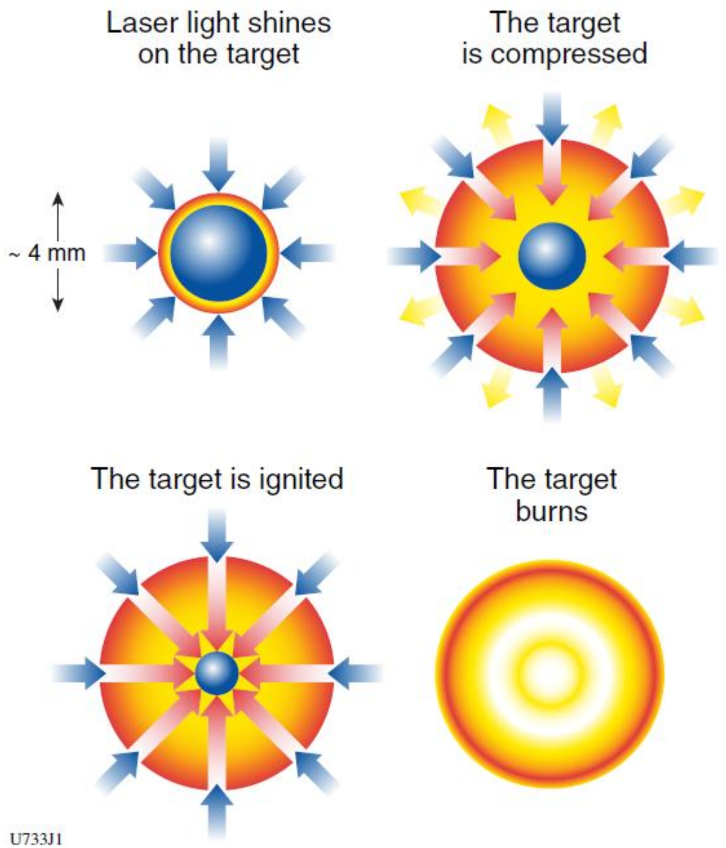


- National Ignition Facility (NIF) demonstrated a gain grater than 1 for the first time on 2022/12/5. The yield of 3.15 MJ from the 2.05-MJ input laser energy, i.e., Q=1.5.

https://zh.wikipedia.org/wiki/國家點火設施
https://www.science.org/content/article/historic-explosion-long-sought-fusion-breakthrough

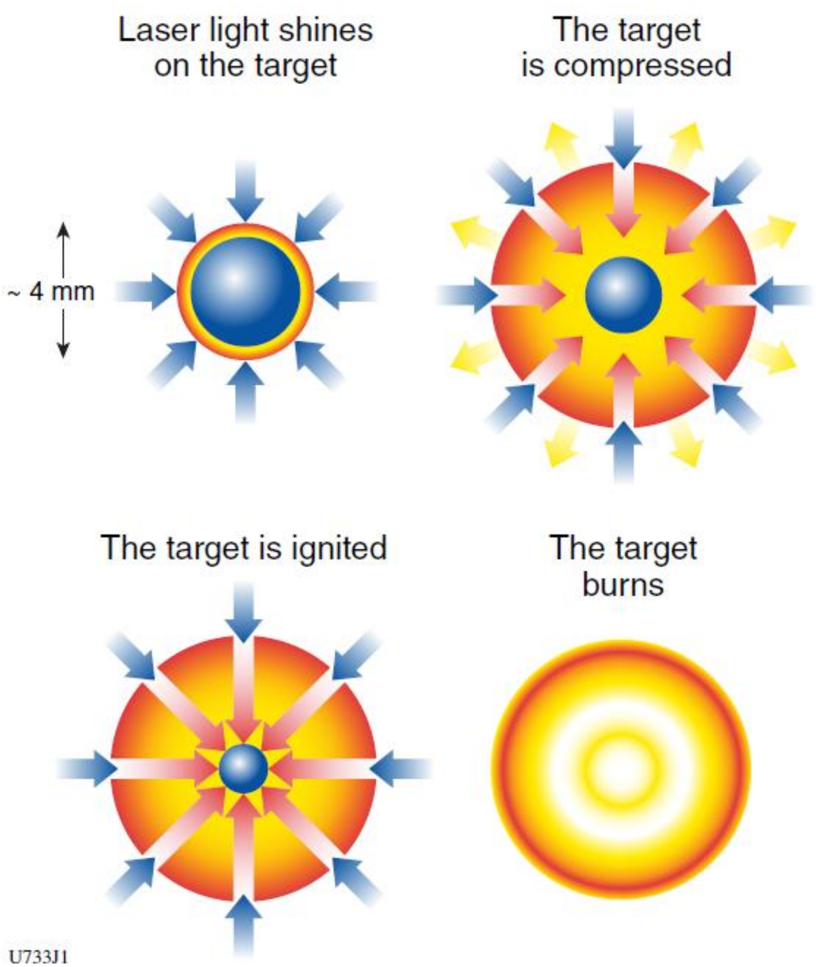
Don’t confine it!

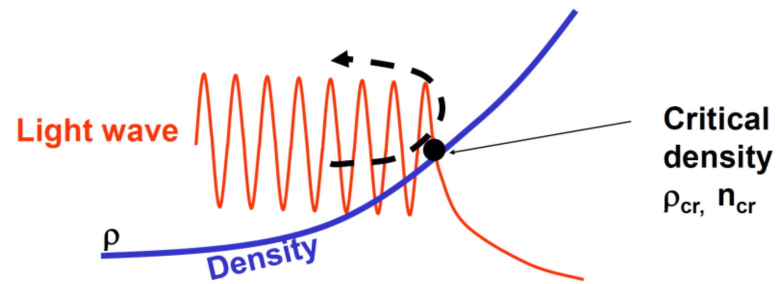
- **Solution 2: Inertial confinement fusion (ICF). Or you can say it is confined by its own inertia: P~Gigabar, τ~nsec, T~10 keV (10^8 ^{0}C)**

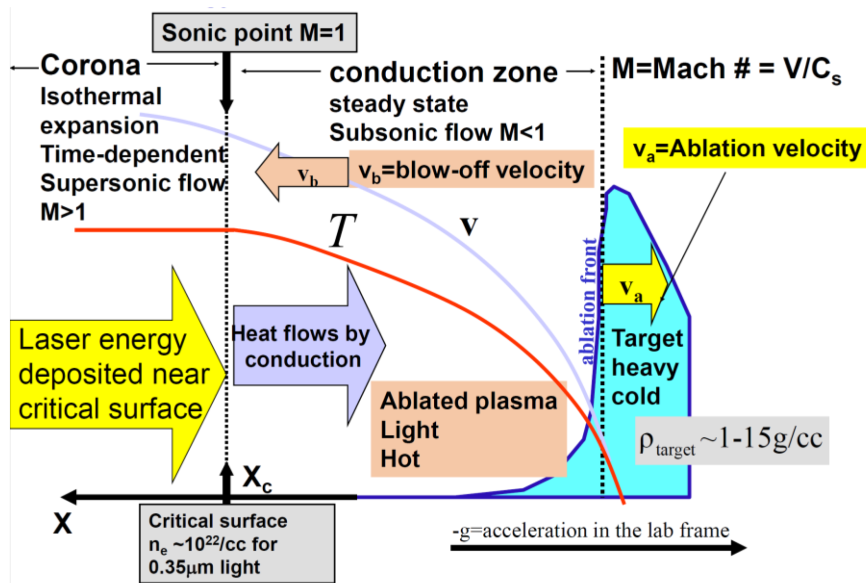


Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

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

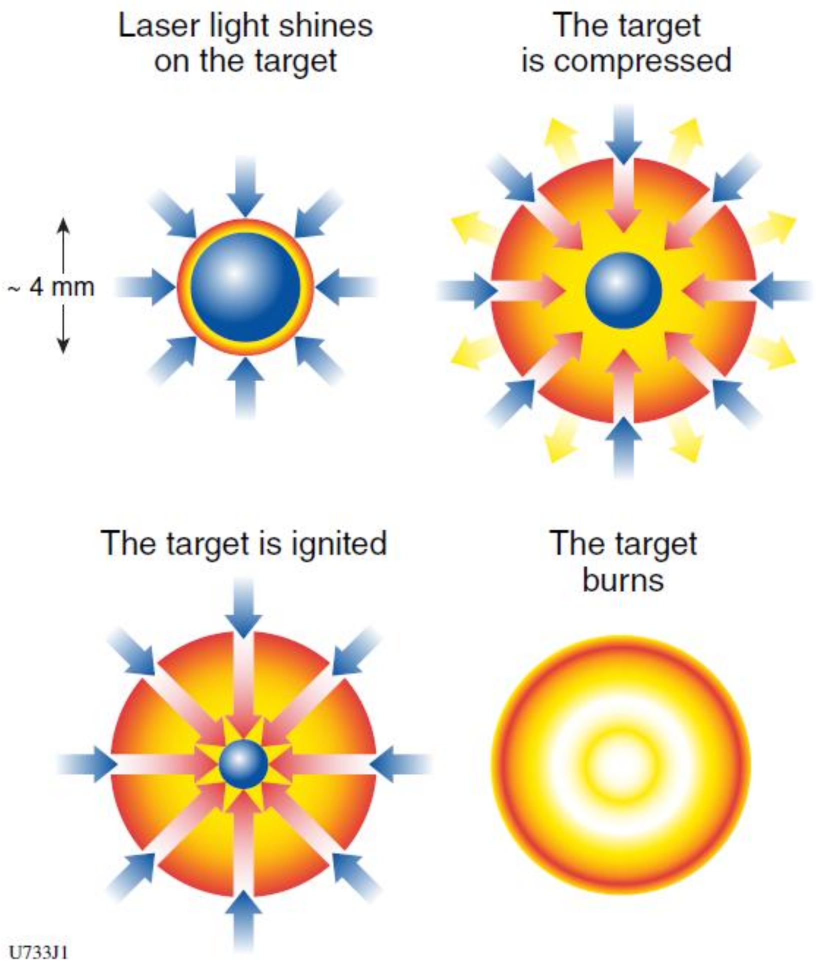




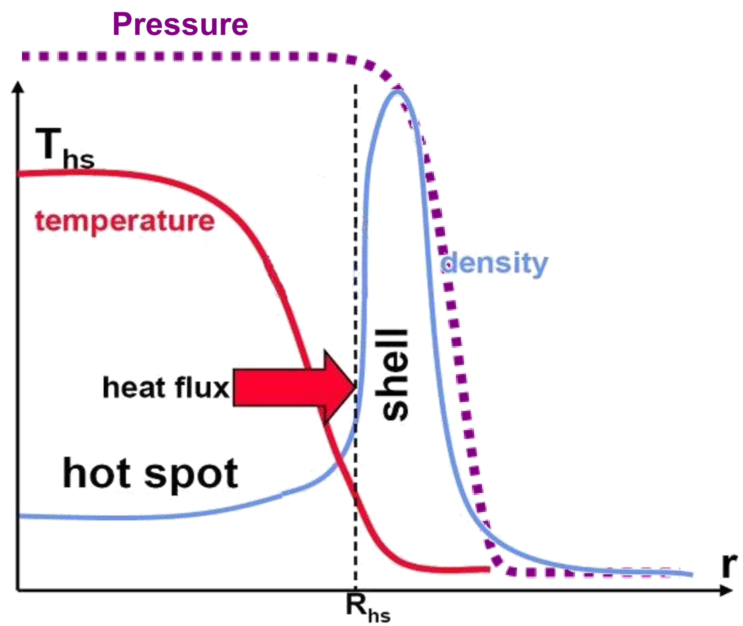


Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester
R. Betti, HEDSA HEDP Summer School, 2015

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



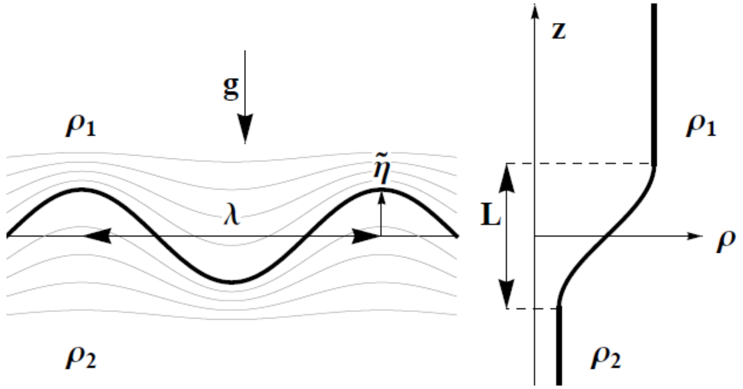
Spatial profile at stagnation



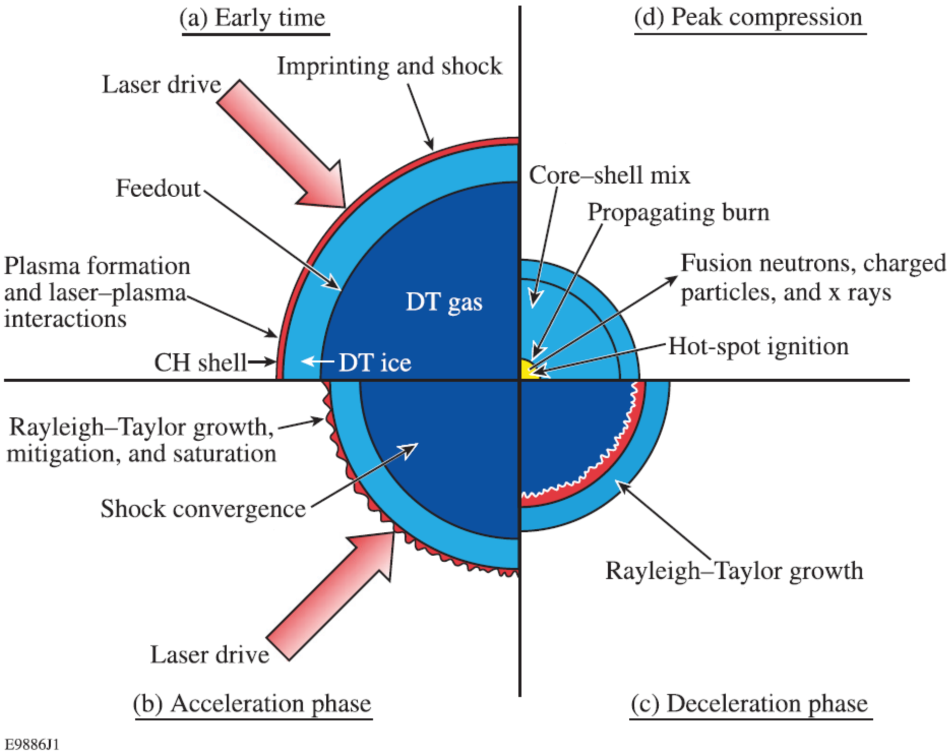
Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

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

- **Rayleigh-Taylor instability**

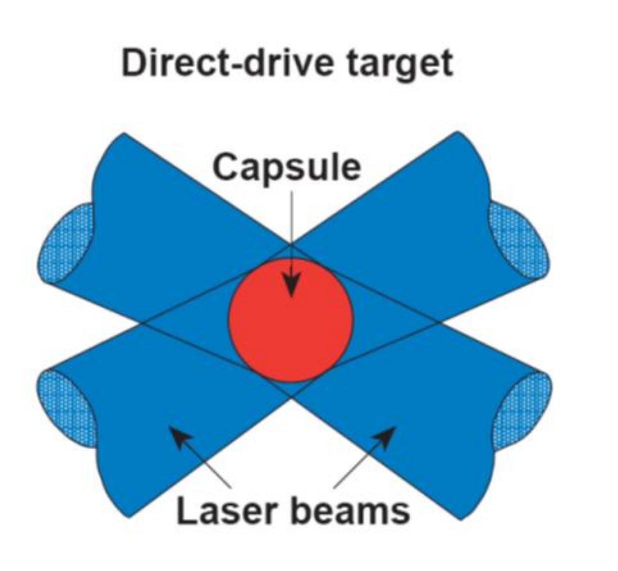


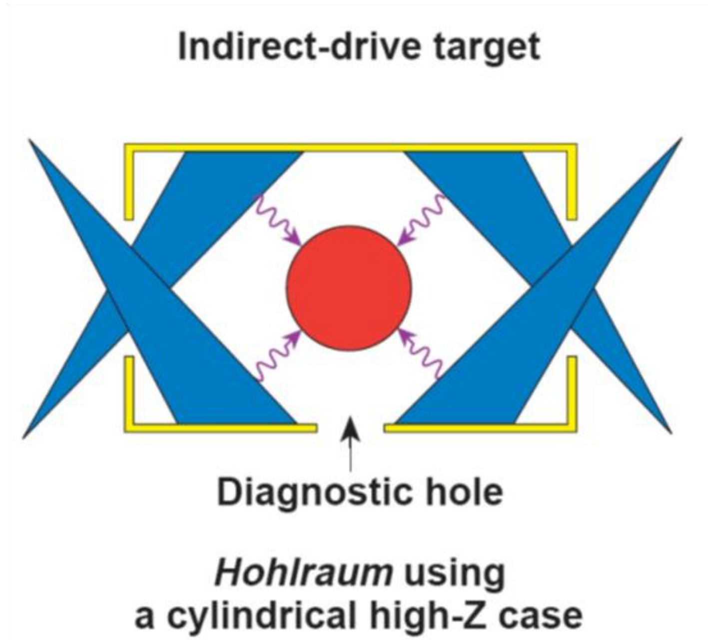
- **Stages of a target implosion**



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

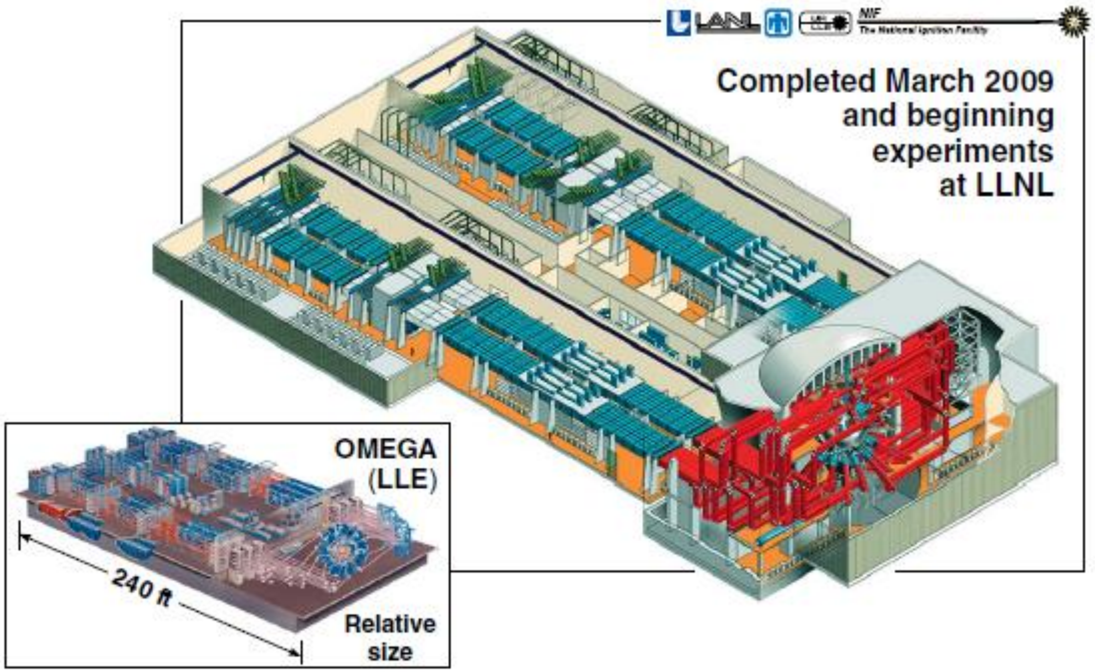
A spherical capsule can be imploded through directly or indirectly laser illumination





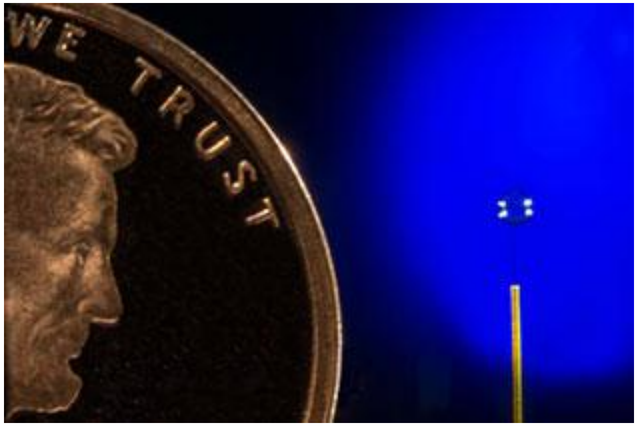
*R. Betti, HEDSA HEDP Summer School, 2015

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

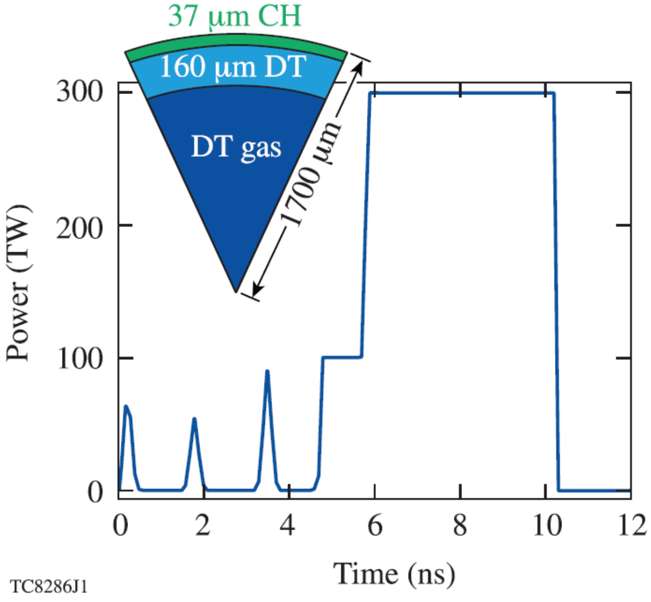


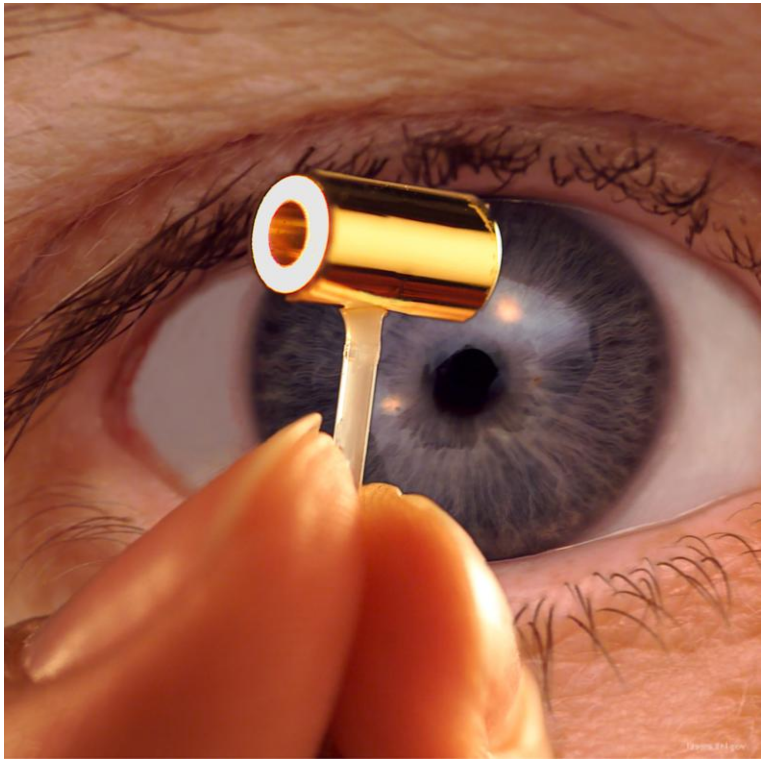
OMEGA experiments are integral to an ignition demonstration on the NIF.

Targets used in ICF



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



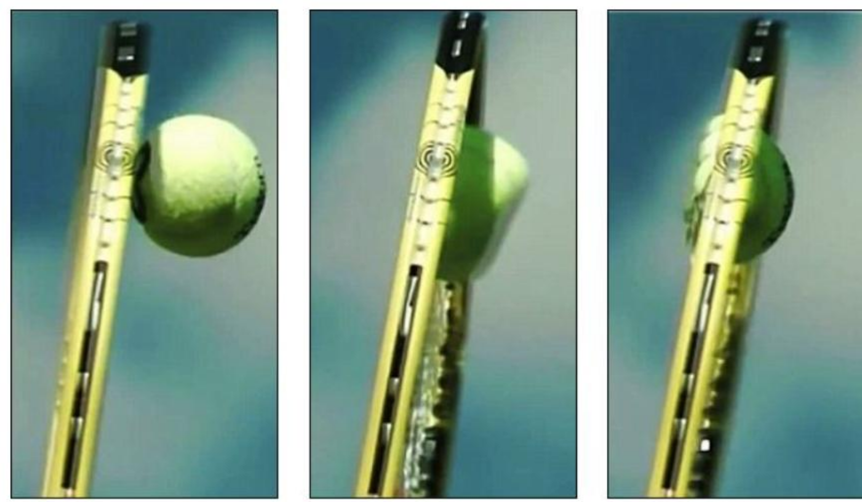


http://www.lle.rochester.ed
https://en.wikipedia.org/wiki/Inertial_confinement_fusion
R. S. Craxton, etc., *Phys. Plasmas* **22**, 110501 (2015)

Softer material can be compressed to higher density

- **Compression of a baseball**

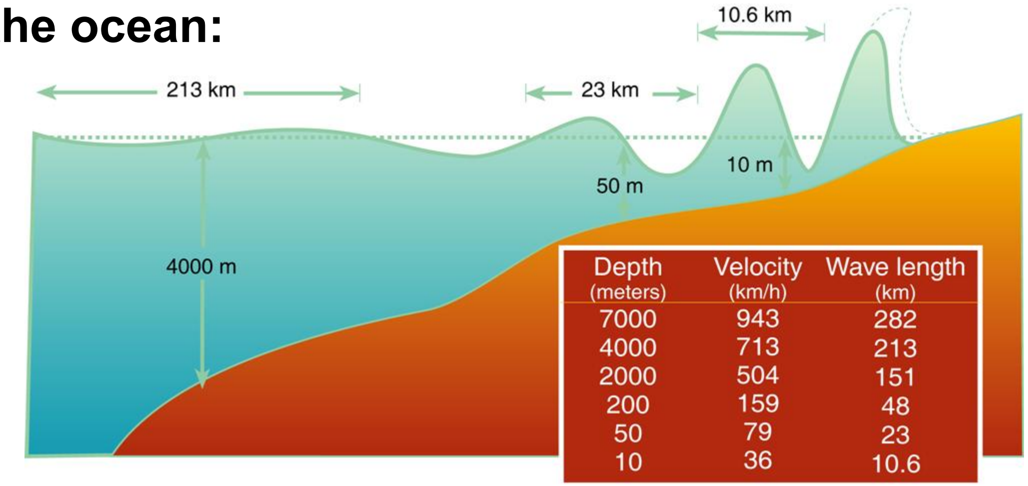
- **Compression of a tennis ball**



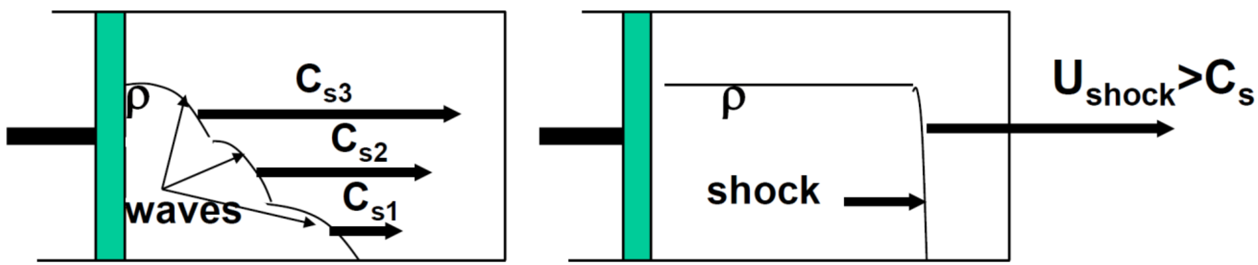
https://www.youtube.com/watch?v=uxlIdMoAwbY
https://newsghana.com.gh/wimbledon-slow-motion-video-of-how-a-tennis-ball-turns-to-goo-after-serve/

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

- **Wave in the ocean:**



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



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

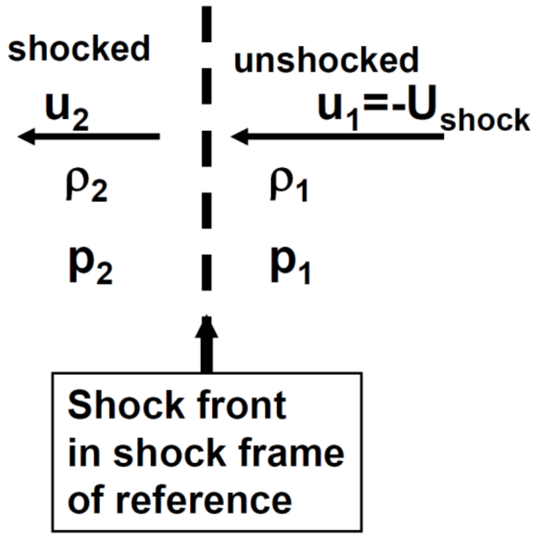
http://neamtic.ioc-unesco.org/tsunami-info/the-cause-of-tsunamis
*R. Betti, HEDSA HEDP Summer School, 2015

Rankine-Hugoniot conditions are obtained using conservation of mass, momentum and energy across the shock front

$$\rho_1 u_1 = \rho_2 u_2$$

$$p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2$$

$$u_1 \left(\varepsilon_1 + p_1\right) = u_2 \left(\varepsilon_2 + p_2\right)$$



- **Ideal gas/plasma:**

$$\varepsilon = \frac{3}{2}p + \rho\frac{u^2}{2}$$

- **With assigned ρ_1, p_1, and p_2, ρ_2, u_2, and u_1=-U_{shock} can be obtained using Rankine-Hugoniont conditions**

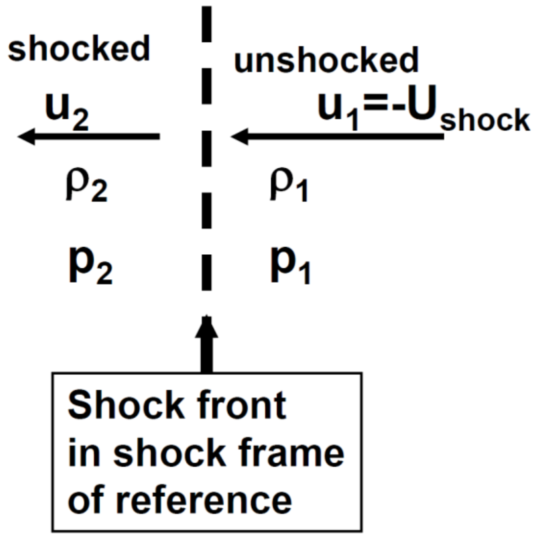
For a strong shock where $p_2 >> p_1$, the R-H conditions are simplified

$$\frac{\rho_2}{\rho_1} \approx 4$$

$$U_{\text{shock}} = -u_1 \approx \sqrt{\frac{4p_2}{3\rho_1}}$$

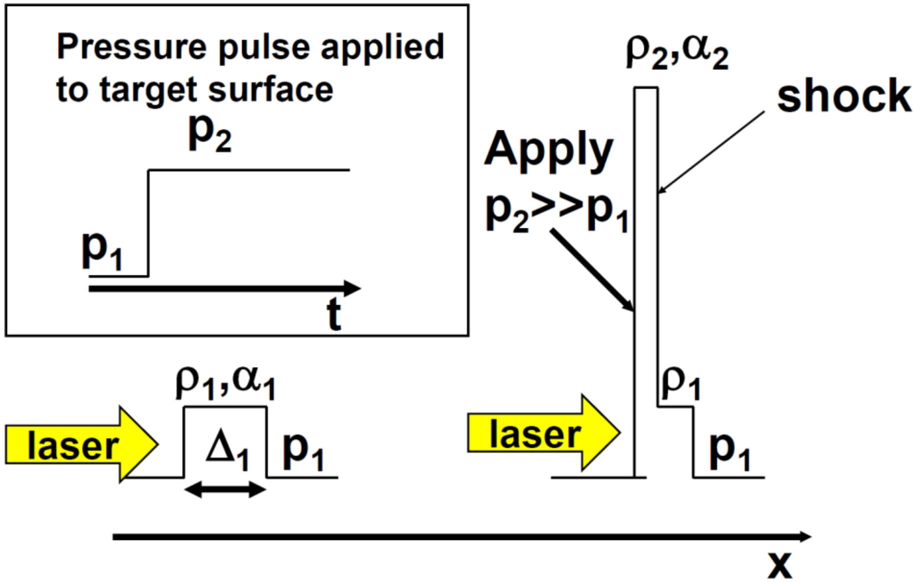
$$u_2 \approx \sqrt{\frac{p_2}{12\rho_1}}$$

$$\frac{\alpha_2}{\alpha_1} = \frac{p_2/\rho_2^{5/3}}{p_1/\rho_1^{5/3}} \approx \frac{1}{4^{5/4}}\frac{p_2}{p_1} >> 1$$



- **The adiabat increases through the shock.**

In an ideal gas/plasma, the adiabat α only raises when a shock is present



- **Post-shock density**

$$\rho_2 \approx 4\rho_1$$

- **Adiabat set by the shock for DT:**

$$\alpha_2 \approx \frac{p_{2,\mathrm{Mbar}}}{2.2\left(4\rho_{1,\mathrm{g/cc}}\right)^{5/3}}$$

- **Time required for the shock to reach the rear target surface (shock break-out time, t_{sb})**

$$t_{\mathrm{sb}} = \frac{\Delta_1}{u_{\mathrm{shock}}} = \Delta_1\sqrt{\frac{3\rho_1}{4p_2}} \propto \sqrt{\frac{1}{\alpha_2\rho_1^{2/3}}}$$

$$U_{\mathrm{shock}} = -u_1 \approx \sqrt{\frac{4p_2}{3\rho_1}}$$

Higher laser intensity leads to higher adiabat

- **For a cryogenic solid DT target at 18 k:**

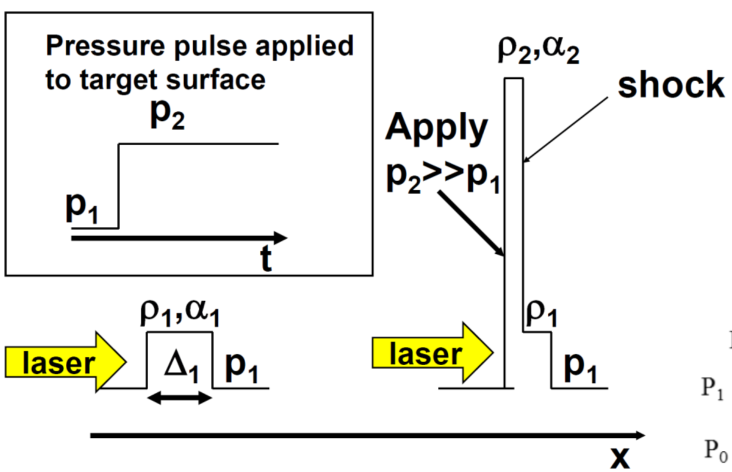
$$\rho_1 = 0.25 \text{ g/cc} \qquad \alpha = \frac{p_{\text{Mbar}}}{2.2} \qquad p \approx 83 \left(\frac{I_{15}}{\lambda_{\mu\text{m}}/0.35} \right)^{2/3}$$

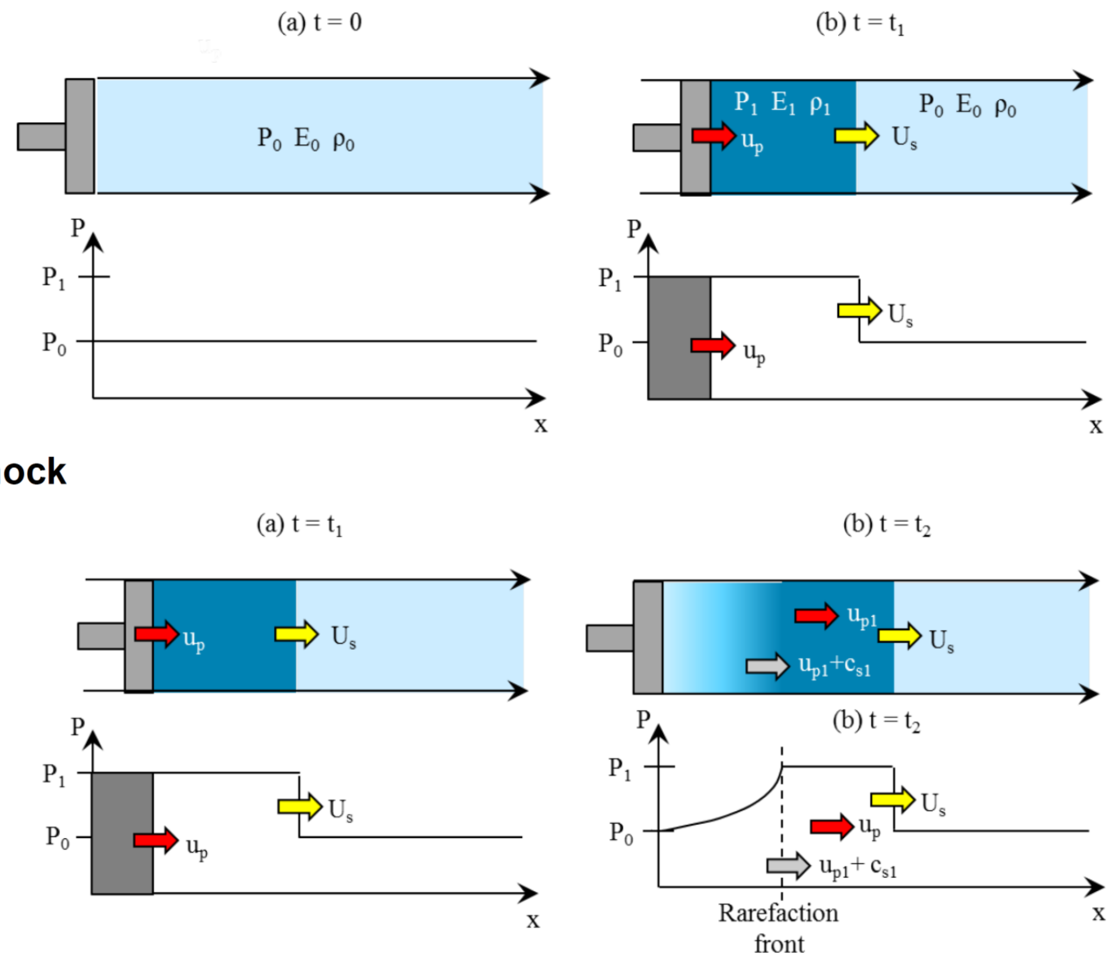
$$I \approx 4.3 \times 10^{12} \text{ w/cm}^2 \quad \Rightarrow \quad p = 2.2 \text{ Mbar} \quad \Rightarrow \quad \alpha = 1$$

$$I \approx 1.2 \times 10^{13} \text{ w/cm}^2 \quad \Rightarrow \quad p = 4.4 \text{ Mbar} \quad \Rightarrow \quad \alpha = 2$$

$$I \approx 2.2 \times 10^{13} \text{ w/cm}^2 \quad \Rightarrow \quad p = 6.6 \text{ Mbar} \quad \Rightarrow \quad \alpha = 3$$

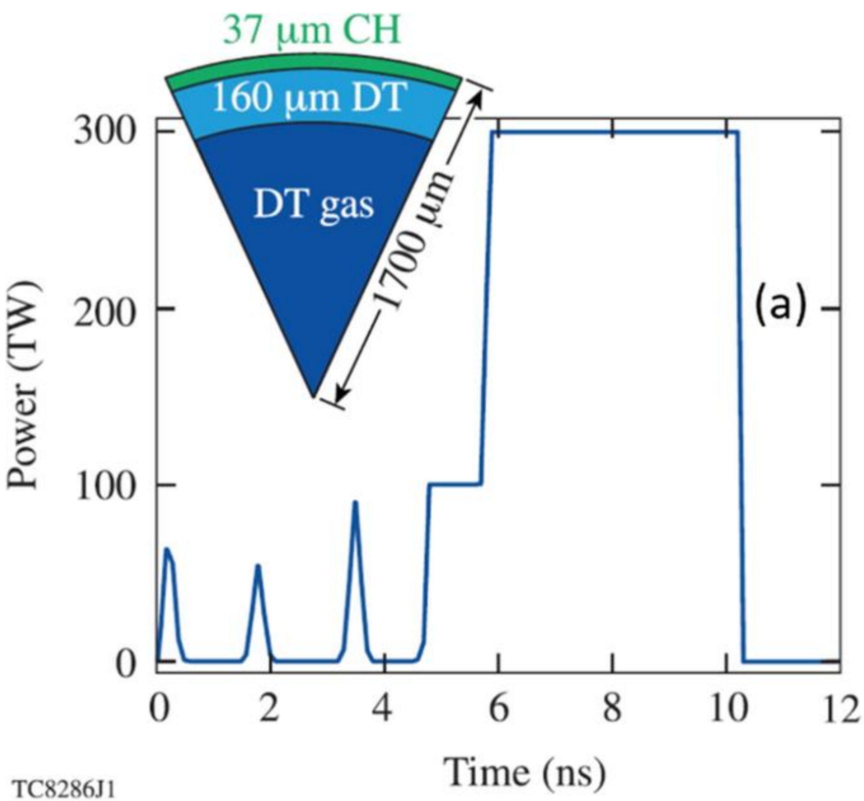
A shock or a rarefaction wave may be formed depending on the driving force from the piston

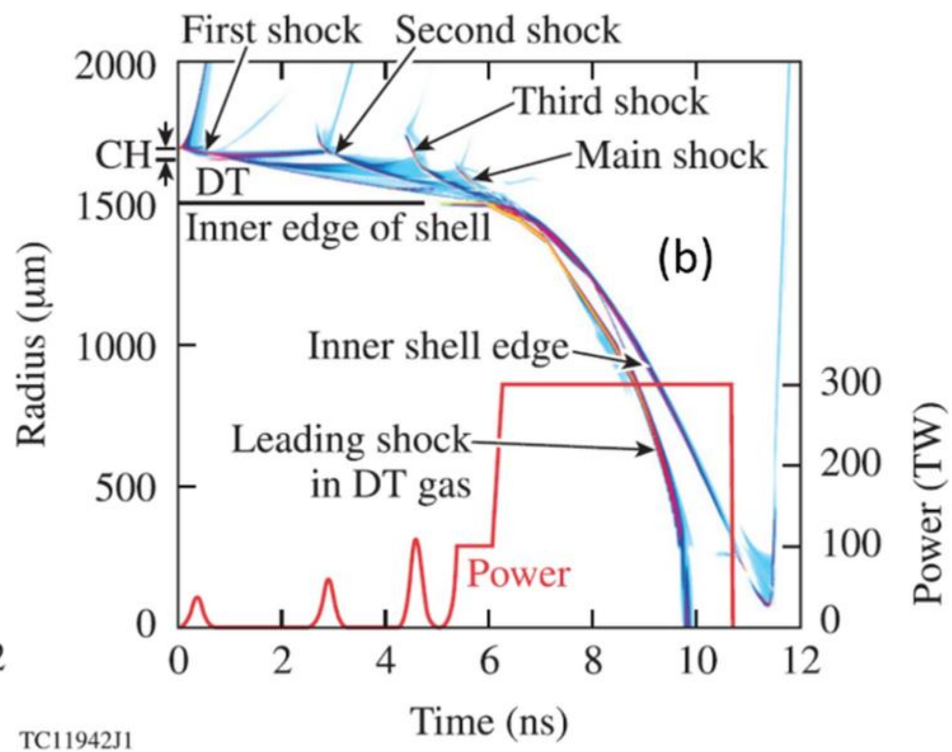




Michelle Colleen Gregor, PhD Thesis, U of Rochester, 2017

Multiple shock can be generated with multiple pickets

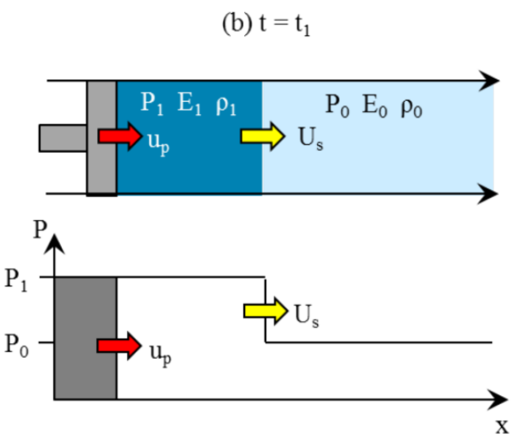


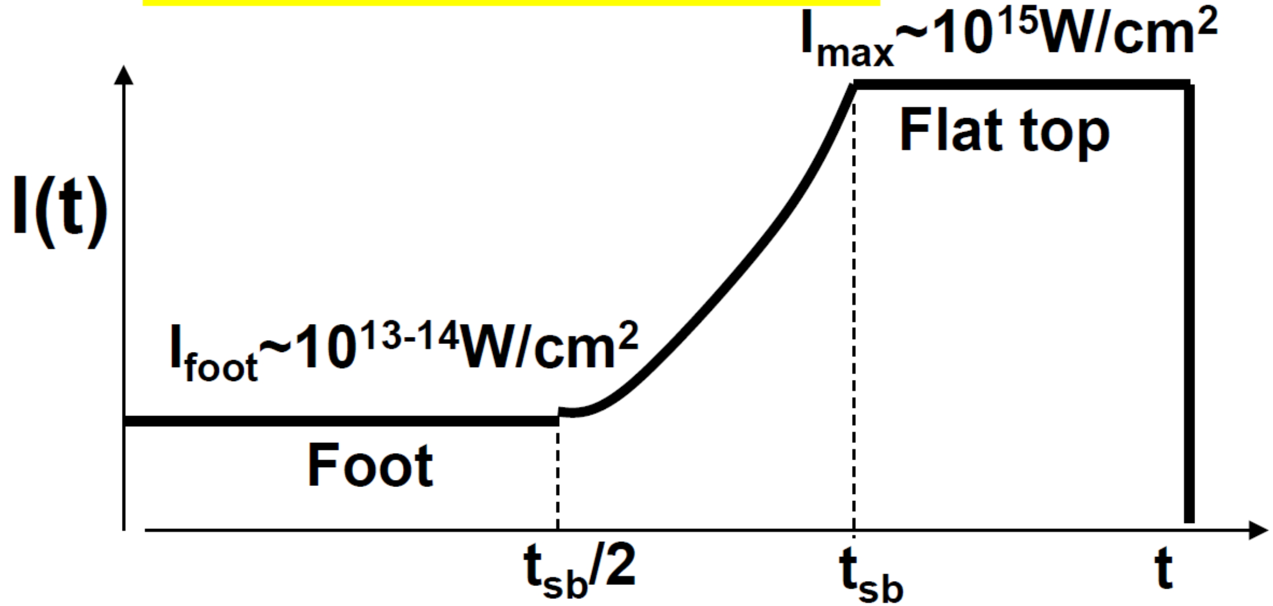


T. Ditmire, etc., J. Fusion Energy **42**, 27 (2023)
R. S. Craxton, etc., Phys. Plasmas 22, 110501 (2015)

The pressure must be "slowly" increased after the first shock to avoid raising the adiabat

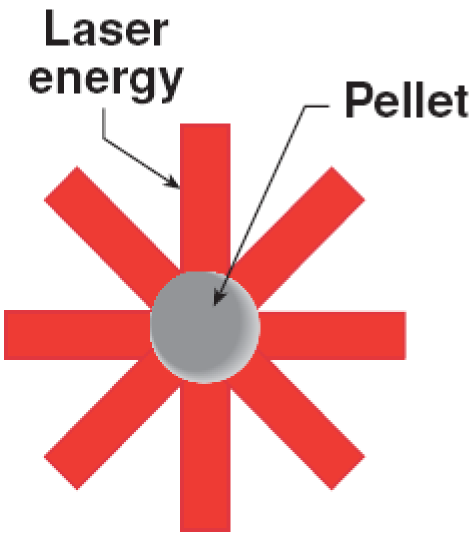
Laser pulse shape

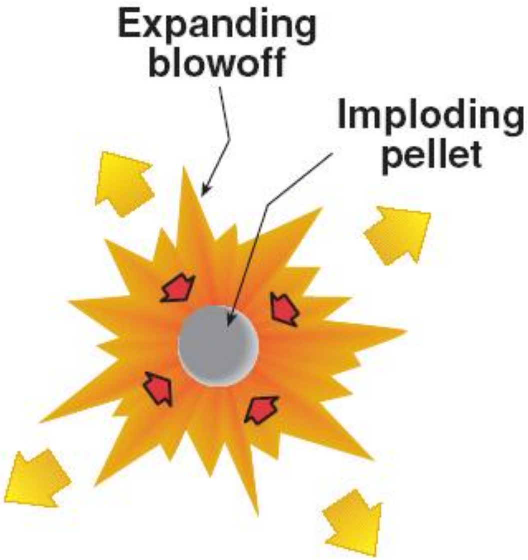




- After the foot of the laser pulse, the laser intensity must be raised starting at about $0.5t_{sb}$ and reach its peak at about t_{sb}
- Reaching I_{max} at t_{sb} prevents a rarefaction/decompression wave to propagate back from the rear target surface and decompress the target.

Most of the absorbed laser energy goes into the kinetic and thermal energy of the expanding blow-off plasma





- **The rocket model:**

Shell Newton's law

$$M\frac{du}{dt} = -4\pi R^2 p_{\mathrm{a}}$$

Shell mass decreases due to ablation

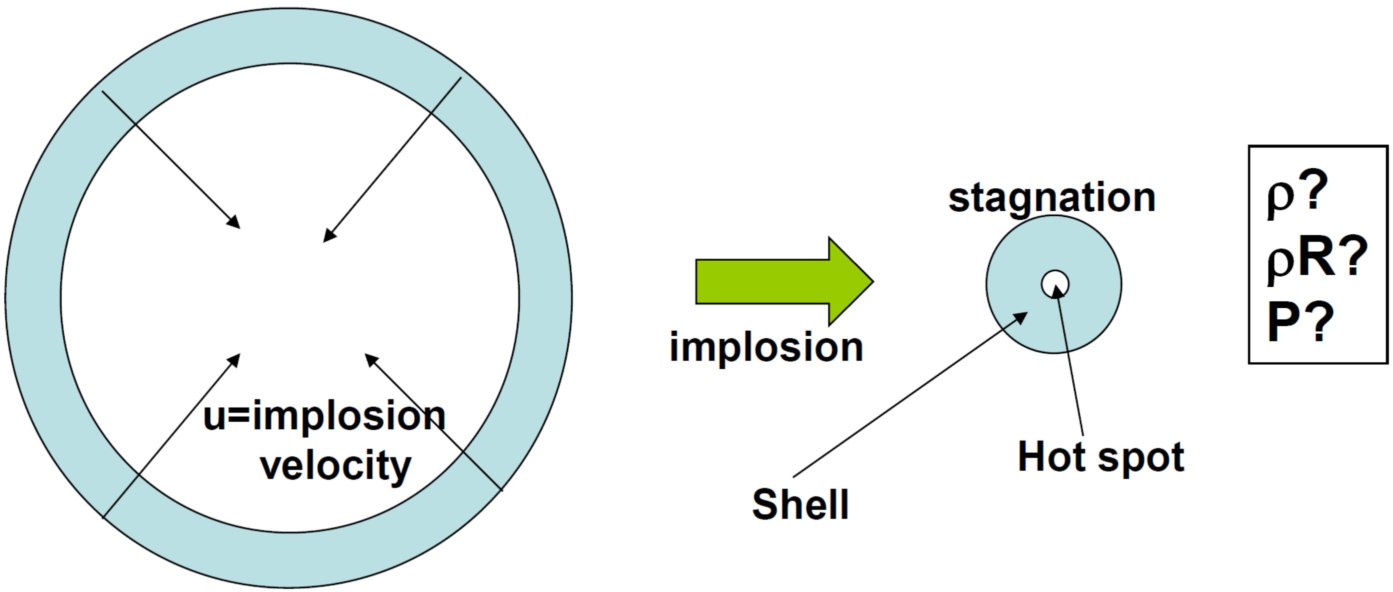
$$\frac{dM}{dt} = -4\pi R^2 \dot{m}_{\mathrm{a}}$$

p_a =ablation rate x exhaust velocity

$$p_{\mathrm{a}} = \dot{m}_{\mathrm{a}} u_{\mathrm{exhaust}}$$

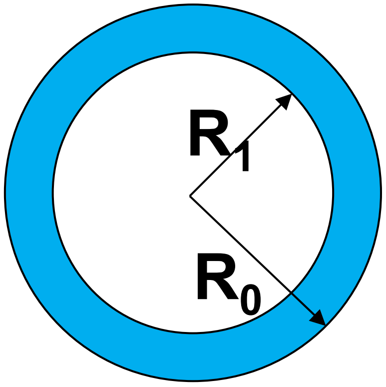
One dimensional implosion hydrodynamics

- **What are the stagnation values of the relevant hydrodynamic properties?**

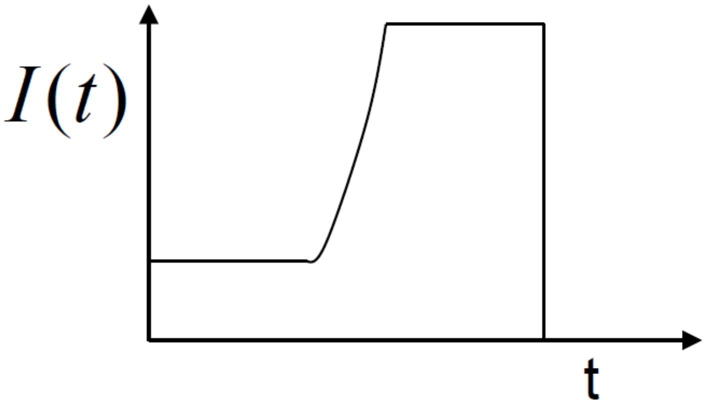


What variables can be controlled?

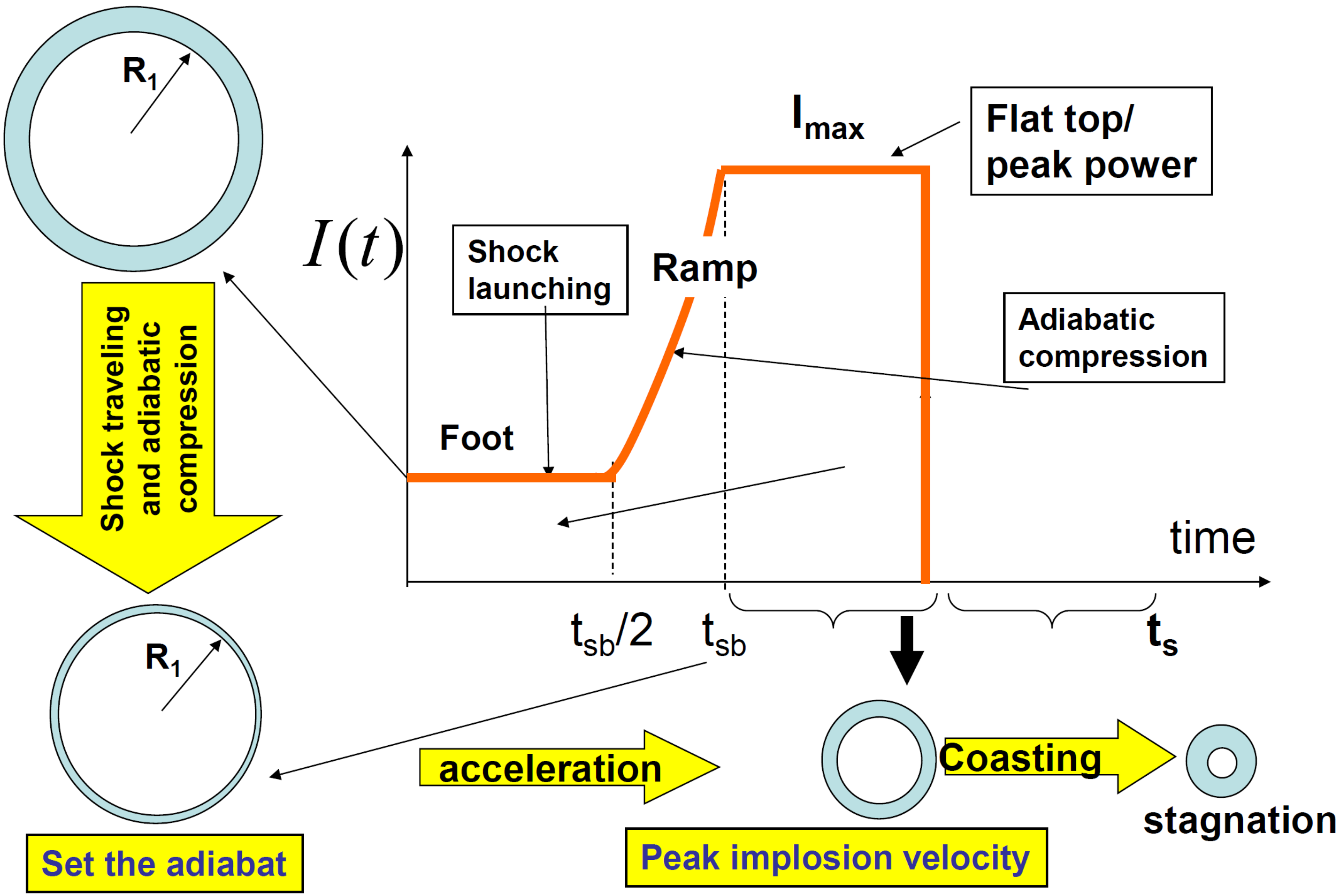
- Shell outer radius R_0 at time t=0
- Shell inner radius R_1 at time t=0
- The total laser energy on target
- Adiabat α through shocks
- Applied pressure p(t) through the pulse shape I(t)



$$\alpha \sim \frac{p}{\rho^{5/3}} \qquad p \sim I^{2/3}$$

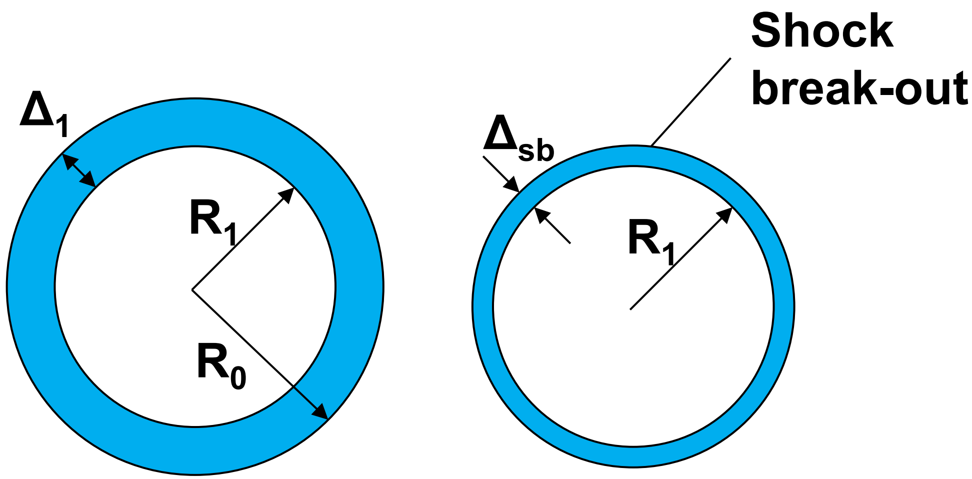


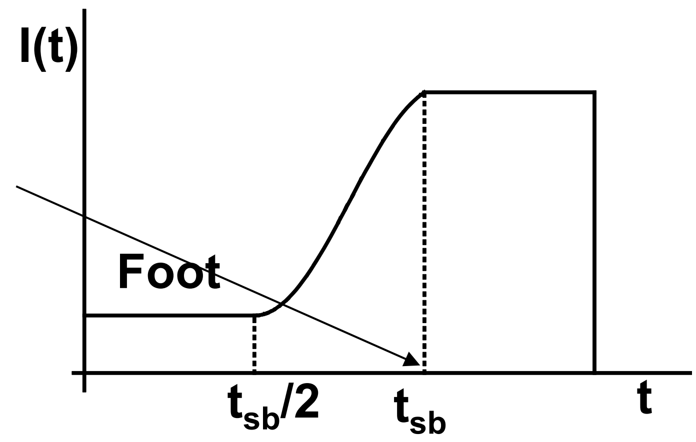
There are three stages in the laser pulse: foot, ramp, and flat top



The adiabat is set by the shock launched by the foot of the laser pulse

$\rho_1 = \text{initial density}$





$$\alpha \sim \frac{p}{\rho^{5/3}} \sim \frac{p_{\text{foot}}}{(4\rho_1)^{5/3}}$$

$$\rho_{\text{sb}} \sim \left(\frac{p_{\max}}{\alpha}\right)^{5/3} \doteq 4\rho_1 \left(\frac{p_{\max}}{p_{\text{foot}}}\right)^{5/3}$$

$$m_{\text{sb}} \sim 4\pi {R_1}^2 \Delta_1 \rho_1 = 4\pi {R_1}^2 \Delta_{\text{sb}} \rho_{\text{sb}}$$

$$\Delta_1 \rho_1 = \Delta_{\text{sb}} \rho_{\text{sb}}$$

$$\Delta_{\text{sb}} = \Delta_1 \frac{\rho_1}{\rho_{\text{sb}}} \sim \Delta_1 \frac{\rho_1}{4\rho_1 \left(\frac{p_{\max}}{p_{\text{foot}}}\right)^{3/5}} = \frac{\Delta_1}{4} \left(\frac{p_{\text{foot}}}{p_{\max}}\right)^{3/5}$$

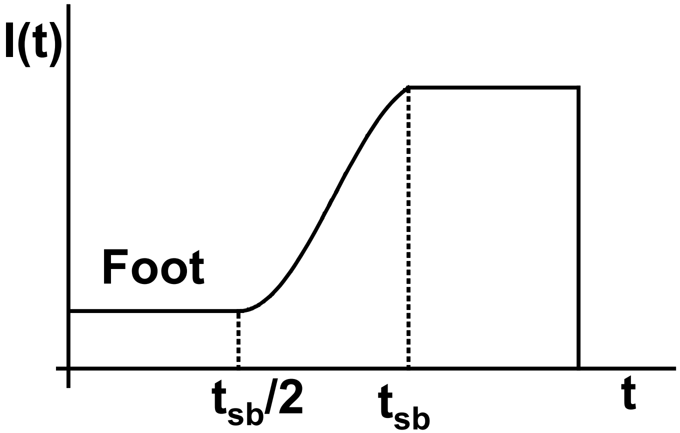
The final implosion velocity can be found using IFAR

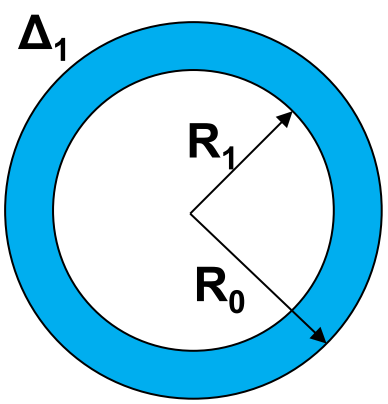
$$u_{\max}{}^2 \sim IFAR \times \alpha^{3/5} I^{4/15}$$

$$IFAR = 4A_1\left(\frac{I_{\max}}{I_{\text{foot}}}\right)^{2/5}$$

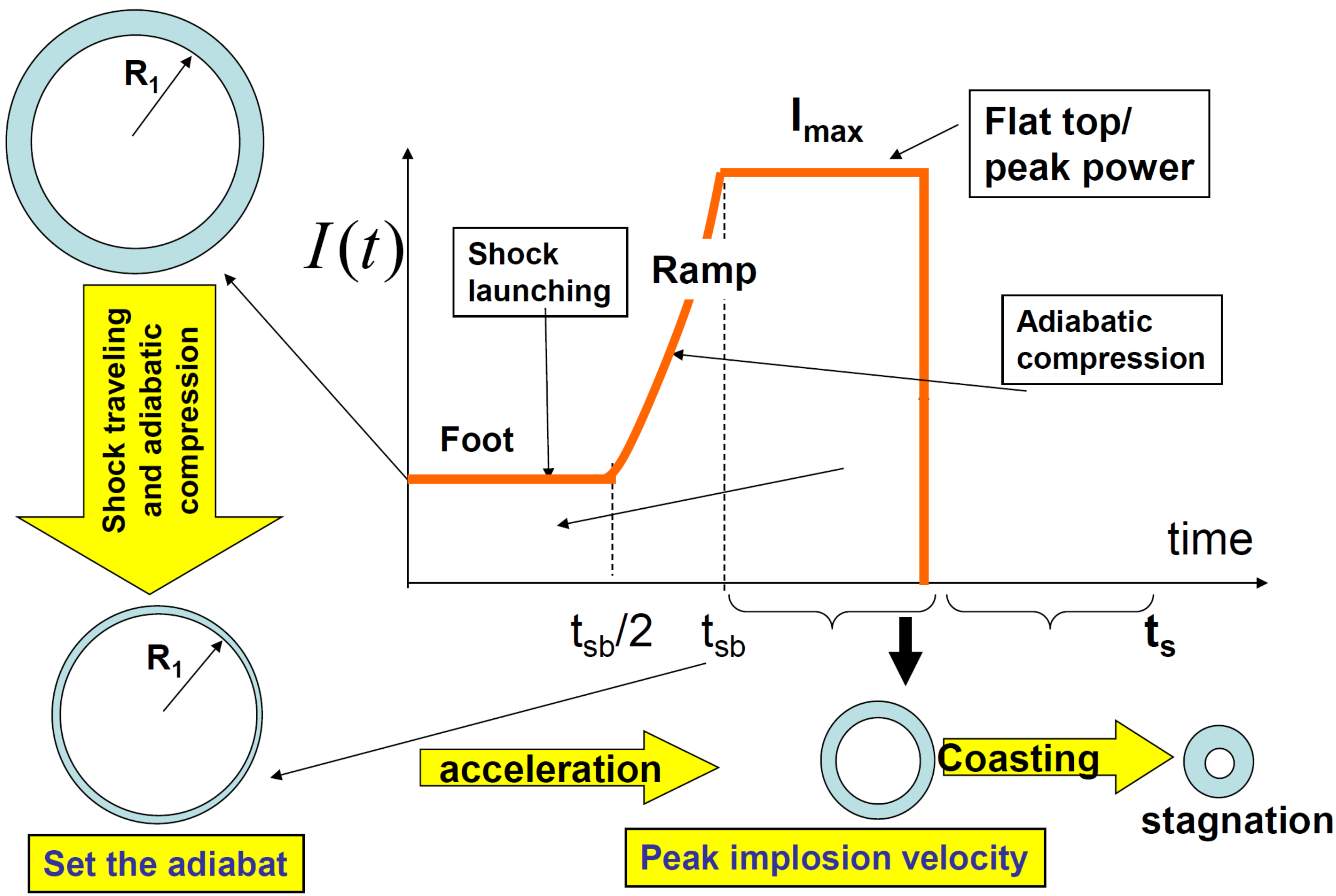
$$A_1 = \frac{R_1}{\Delta_1}$$

$$u_{\max,\text{cm}/s} \approx 10^7\sqrt{0.7A_1\alpha^{3/5}I_{15,\max}{}^{4/15}\left(\frac{I_{\max}}{I_{\text{foot}}}\right)^{2/5}}$$

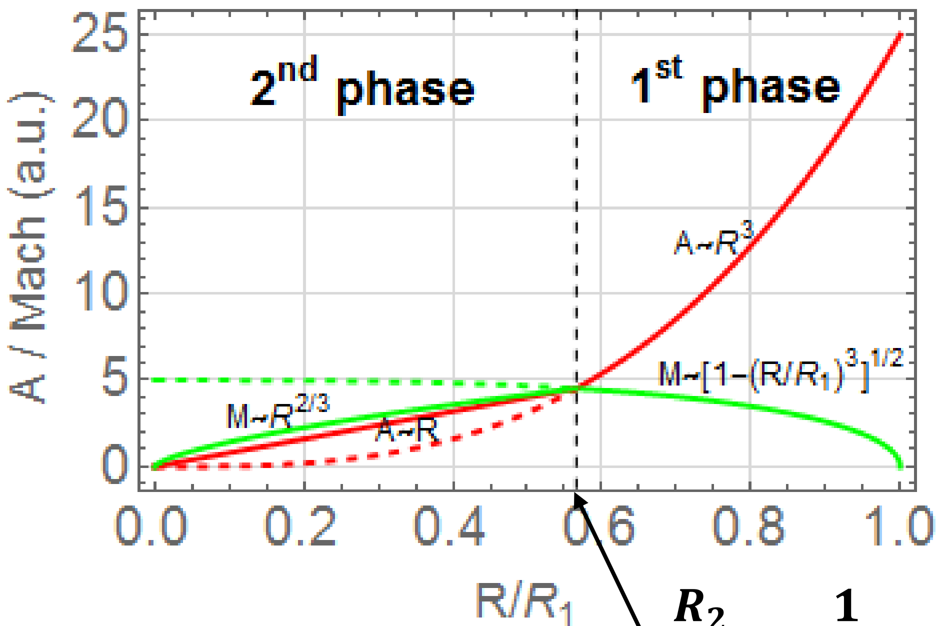




There are three stages in the laser pulse: foot, ramp, and flat top



Summary of phase 2 (coasting phase)



$$\frac{R_2}{R_1} \sim \frac{1}{{A_{\mathrm{sb}}}^{1/6}}$$

$$1 < A < \sqrt{A_{\mathrm{sb}}} \qquad A < \mathrm{Mach}$$

$$\frac{1}{\sqrt{A_{\mathrm{sb}}}} \sim \frac{1}{A_2} < \frac{R}{R_2} < 1$$

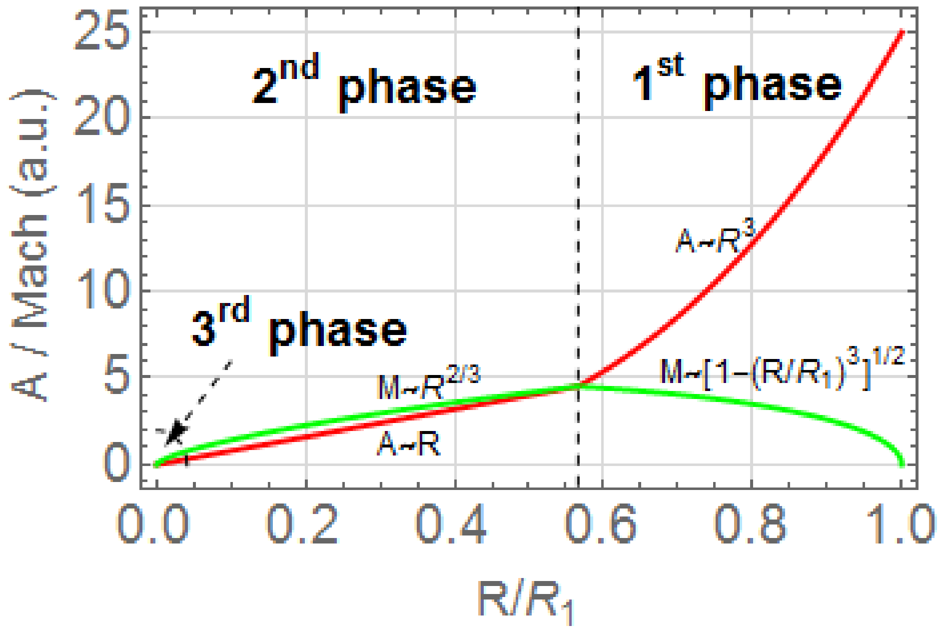
$$A = A_2\left(\frac{R}{R_2}\right) \sim \sqrt{A_{\mathrm{sb}}}\left(\frac{R}{R_2}\right)$$

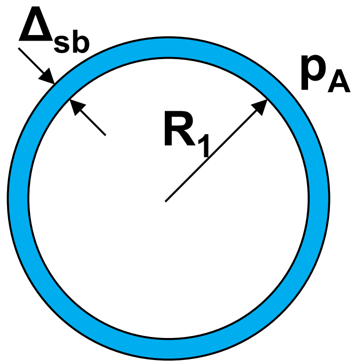
$$Mach \sim \mathrm{Mach}_2\left(\frac{R}{R_2}\right)^{2/3} \sim \sqrt{A_{\mathrm{sb}}}\left(\frac{R}{R_2}\right)^{2/3}$$

$$Mach_2 = \mathrm{Mach}_{\mathrm{max}} \simeq A_2 = \sqrt{A_{\mathrm{sb}}}$$

$$\Delta \simeq \mathrm{constant} = \Delta_2 \sim \frac{R_1}{{A_{\mathrm{sb}}}^{2/3}} \qquad \bar{\rho} \simeq \rho_2\left(\frac{R_2}{R}\right)^2 \sim \rho_{\mathrm{sb}}\left(\frac{R_2}{R}\right)^2$$

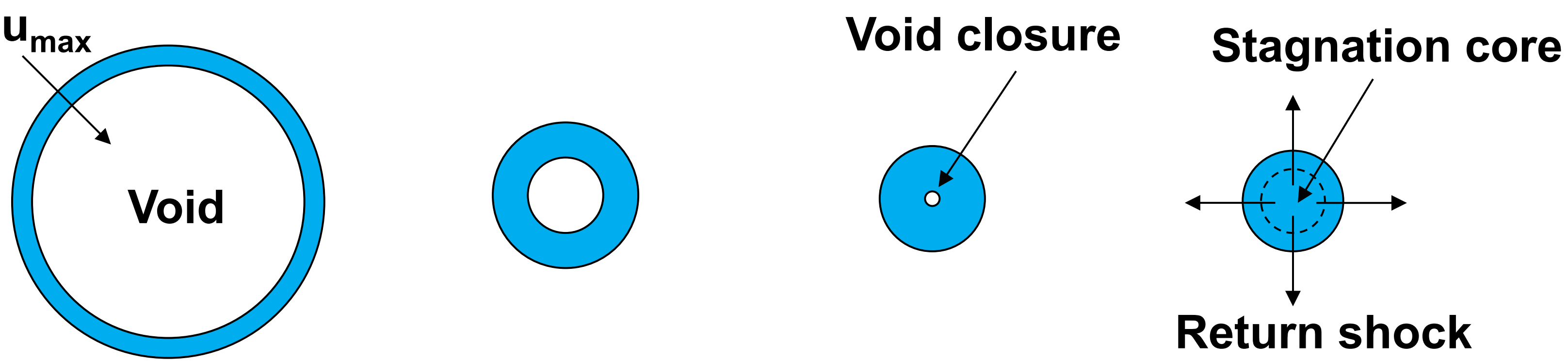
How about the 3rd phase where A~1 ?





- 1st phase: acceleration
- 2nd phase: coasting
- 3rd phase: stagnation

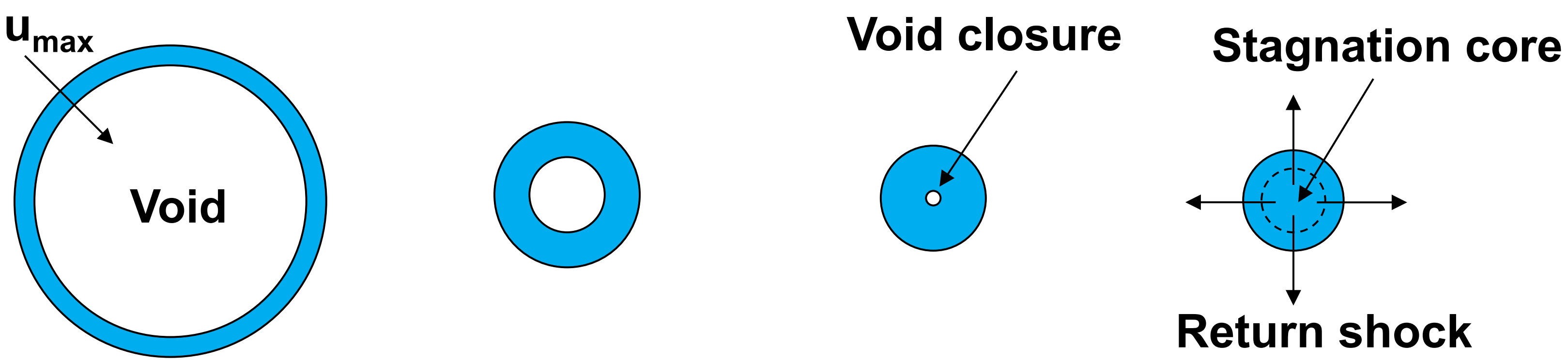
The thin shell model breaks down when A~1

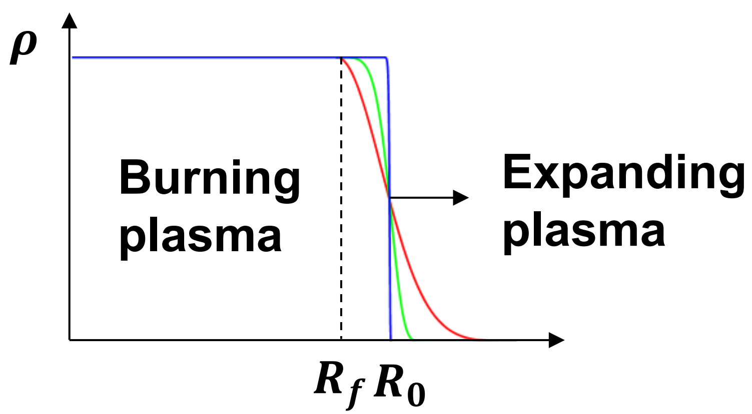


- **When *A*~1 => *Δ*~*R*, the “void” inside the shell closes and a “return shock” propagating outward is generated due to the collision of the shell with itself**
- **The density is compressed by a factor no more than 4 even if the strong shock is generated**

$\rho_{st} \sim \rho_3$ **where** ρ_3 **is the density right before the void closure**

Calculation of the burn-up fraction





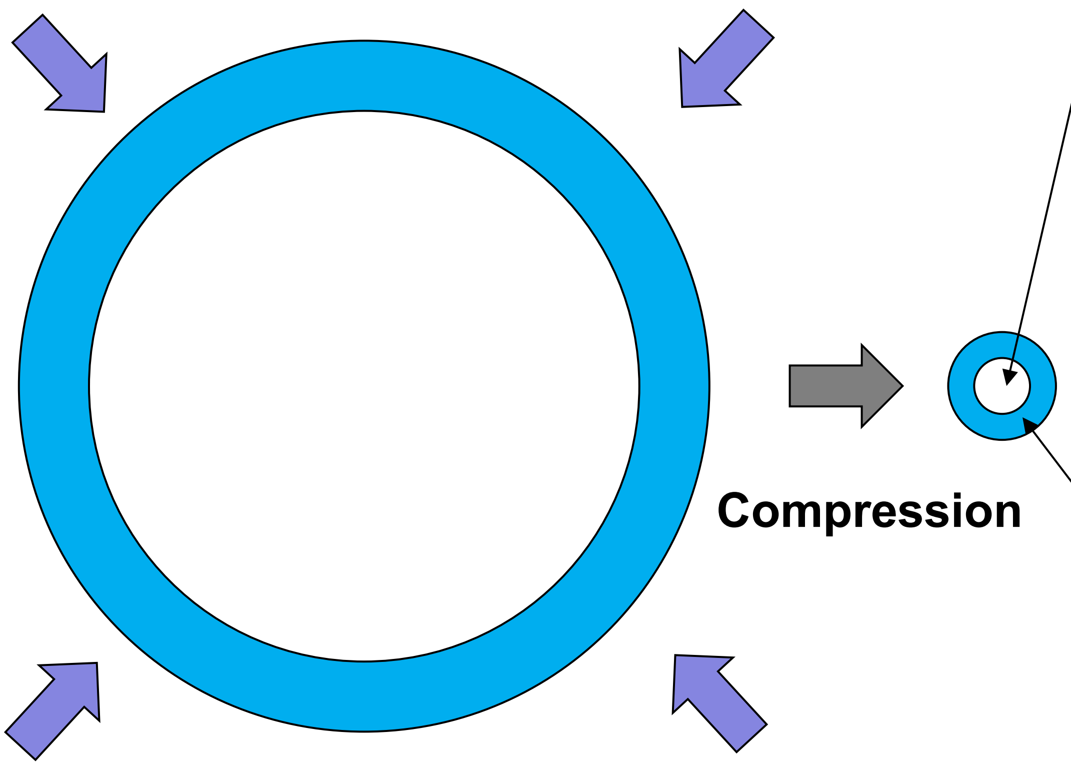
$$R_f = R_0 - C_s t$$

$$\frac{\partial n_i}{\partial t} = -\nabla \cdot (n_i v) - \frac{{n_i}^2}{4} < \sigma v > \times 2$$

Summary

- **Possible fuel assembly for 1MJ ICF driver**

$E_{\text{laser}} = 1\text{MJ} \quad \eta_h \approx 1\%$



$\rho_{\text{DT}} = 0.25\, g/\text{cm}^3 \quad R_{\text{init}} \simeq 2.6\text{mm}$

Hot spot

$M_h \approx 20\mu\text{g} \quad (\rho R)_h \approx 0.3\, g/\text{cm}^2$

$\rho_h \approx 70\, g/\text{cm}^3 \quad R_h \approx 40\mu\text{m}$

$\frac{M_h}{M_0} \sim 0.01$

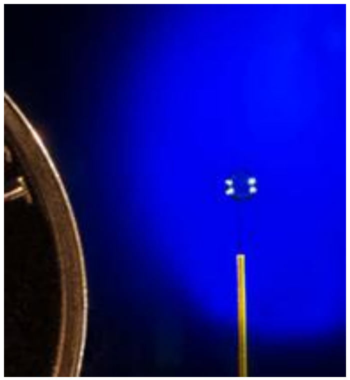
Dense fuel

$M_0 \approx 2\text{mg} \quad (\rho R) \approx 3\, g/\text{cm}^2$

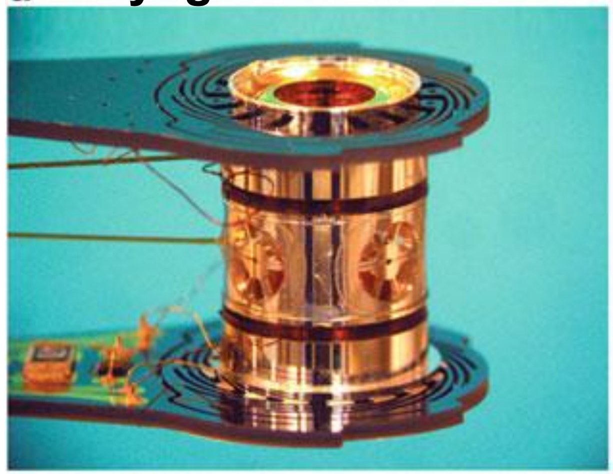
$\rho \approx 250\, g/\text{cm}^3 \quad R \approx 120\mu\text{m}$

Convergence ratio ~20

Targets used in ICF



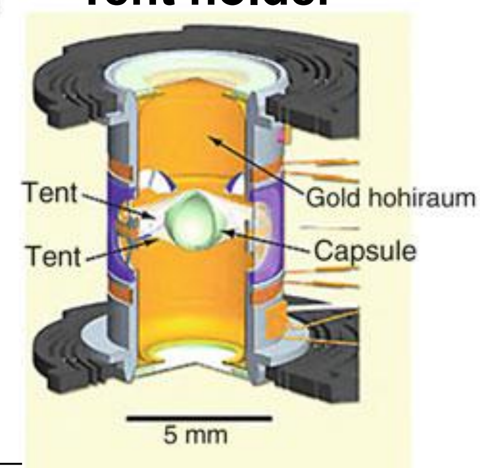
Cryogenic hohlraum



Cryogenic shroud

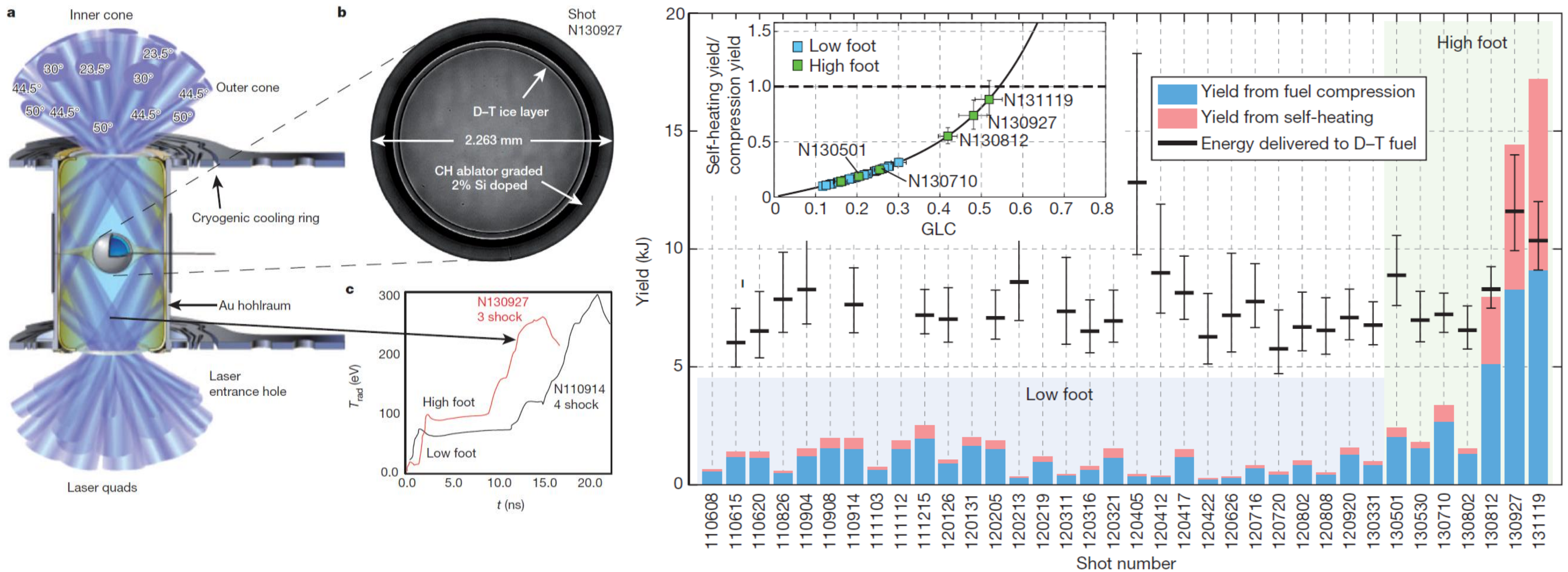
Rugby hohlraum

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
https://www.llnl.gov/news/nif-shot-lights-way-new-fusion-ignition-phase

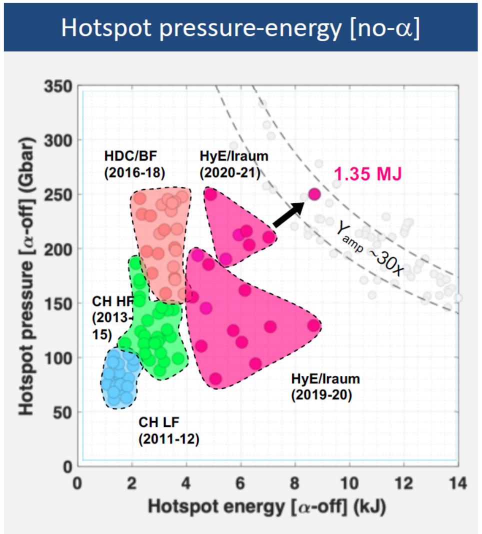
Nature letter “Fuel gain exceeding unity in an inertially confined fusion implosion”

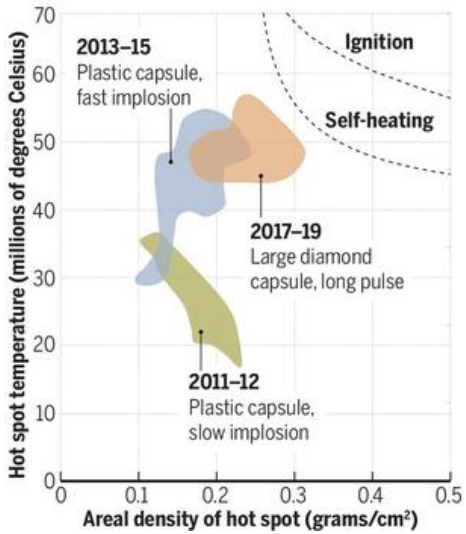


- **Fuel gain exceeding unity was demonstrated for the first time.**

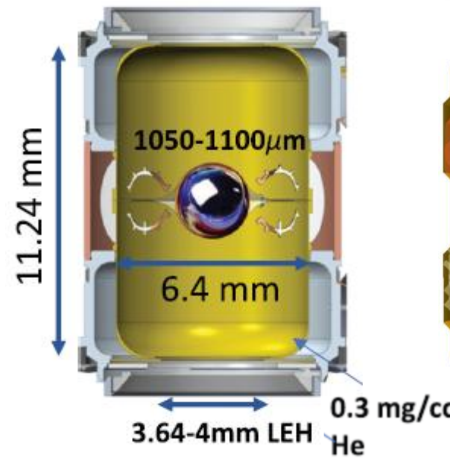
Nature 506, p343, 2014

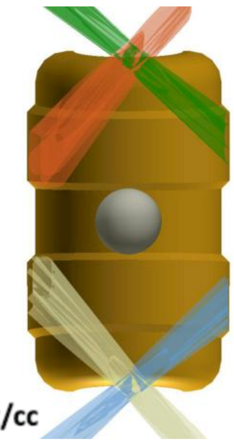
The hot spot has entered the burning plasma regime

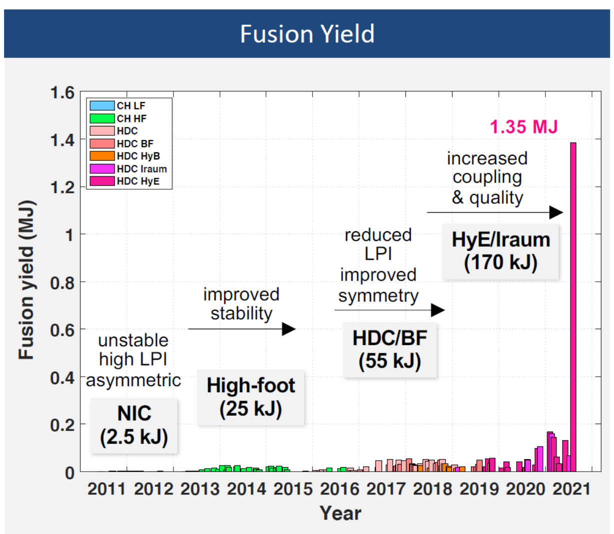




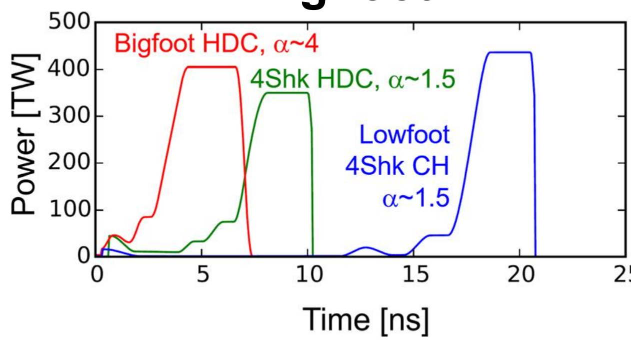
- **Hybrid-E**
- **I-raum**

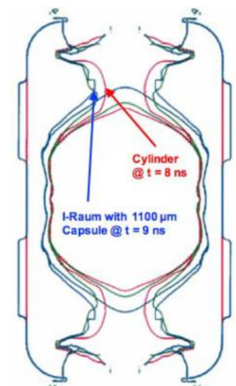






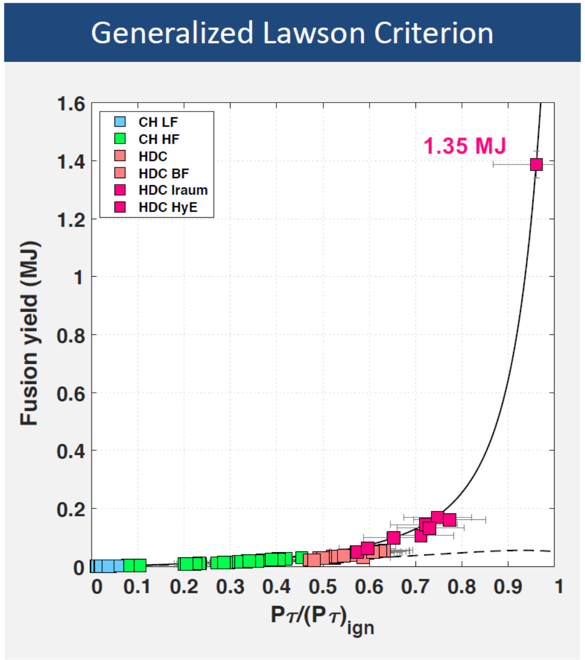
- **Big foot**

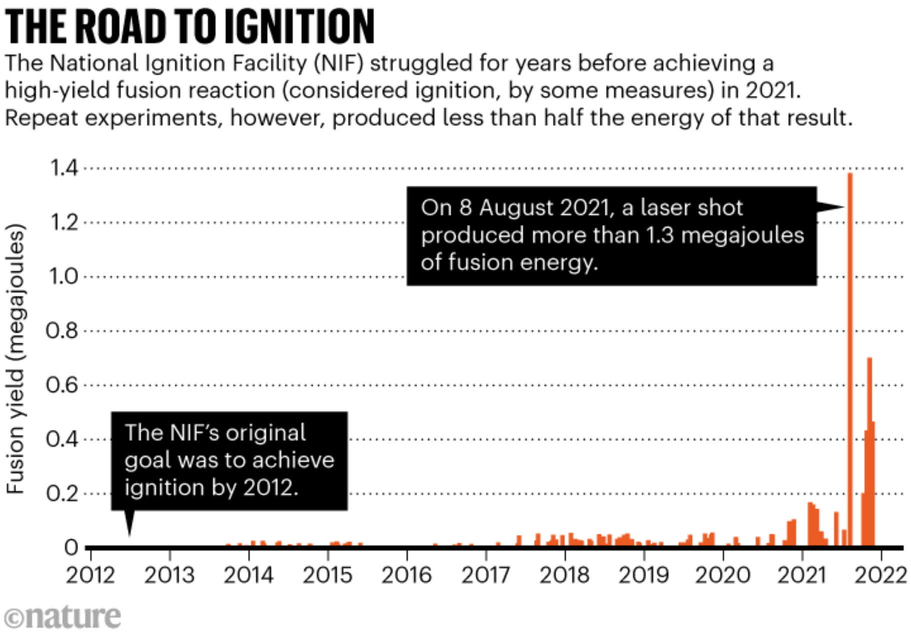




T. Ma, ARPA-E workshop, April 26, 2022
Science 370, p1019, 2020
D. T. Casey, etc., Phys. Plasmas, 25, 056308 (2018)
A. L. Kritcher, etc., Phys. Plasmas, 28, 072706 (2021)
H. F. Robey, etc., Phys. Plasmas, 25, 012711 (2018)

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)

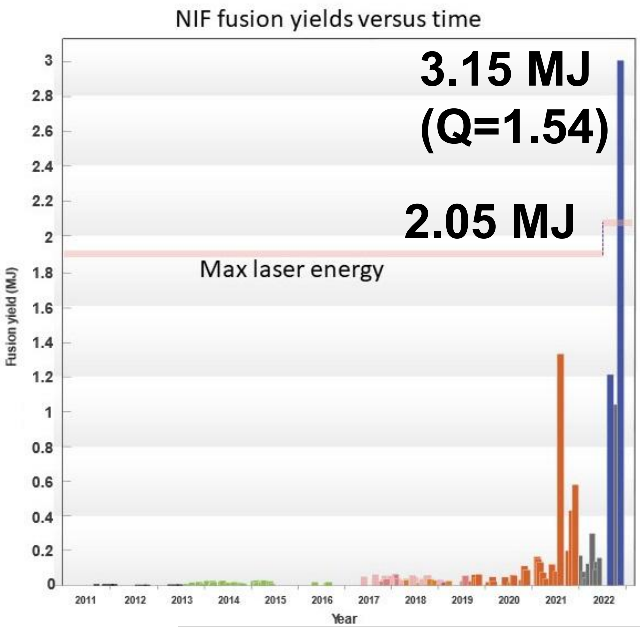


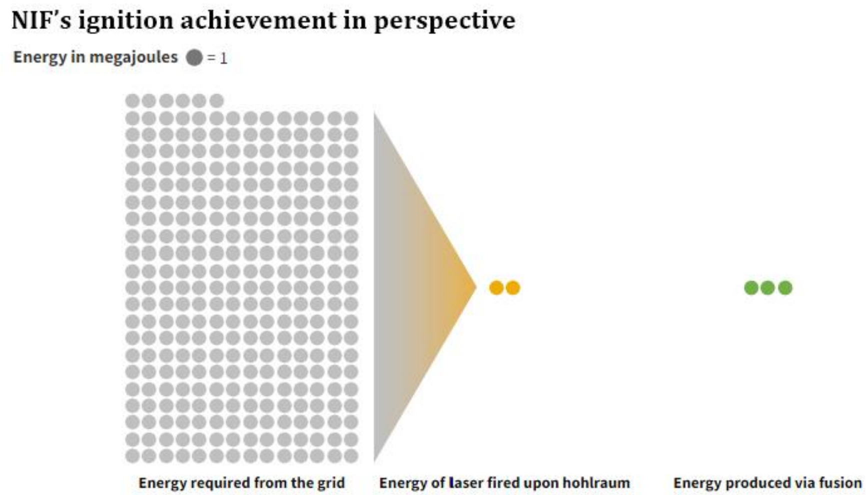


- **National Ignition Facility (NIF) achieved a yield of more than 1.3 MJ (Q~0.7). This advancement puts researchers at the threshold of fusion ignition.**
- **Laser-fusion facility heads back to the drawing board.**

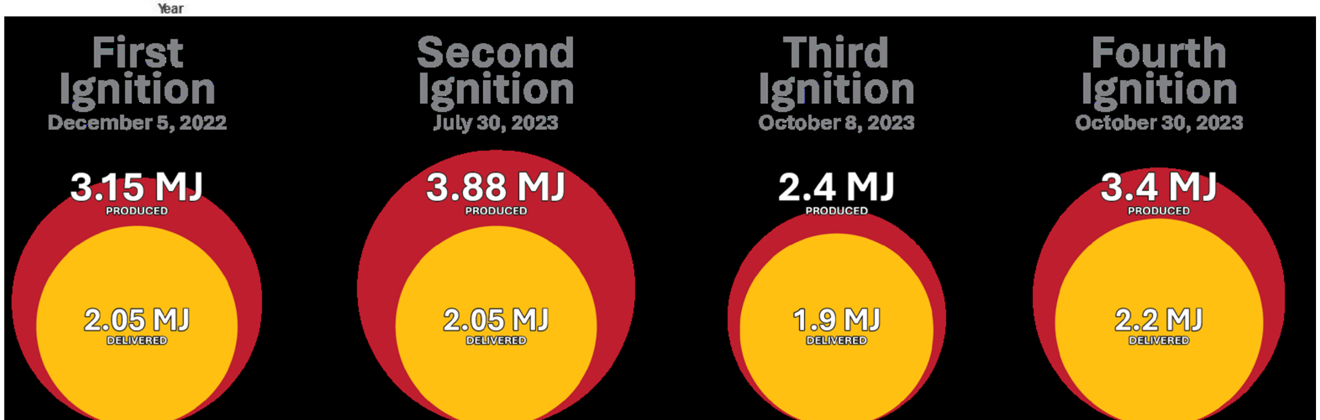
T. Ma, ARPA-E workshop, April 26, 2022
J. Tollefson, Nature (News) 608, 20 (2022)

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



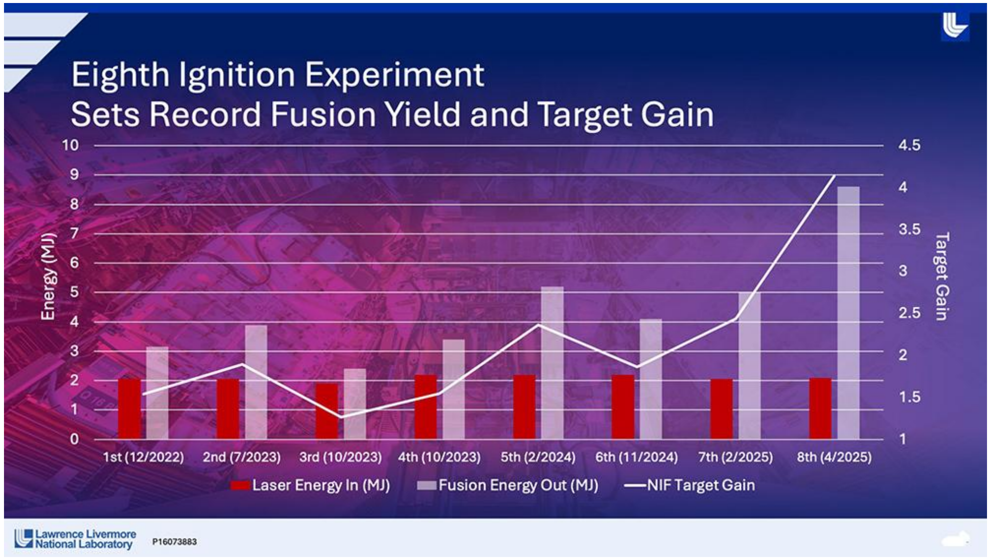


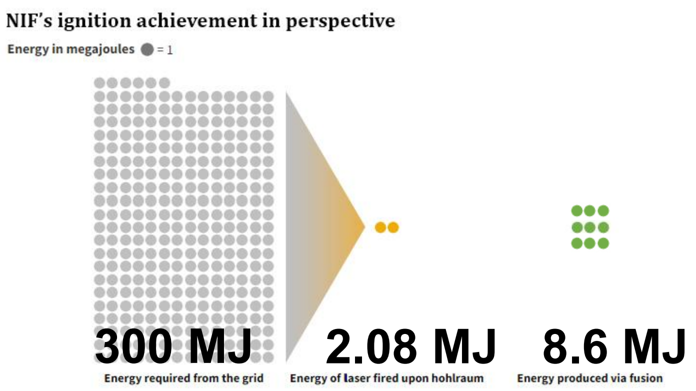
300 MJ 2.05 MJ 3.15 MJ



https://physicstoday.scitation.org/do/10.1063/PT.6.2.20221213a/full/
The age of ignition: anniversary edition, LLNL-BR-857901

A gain over 4 has been achieved





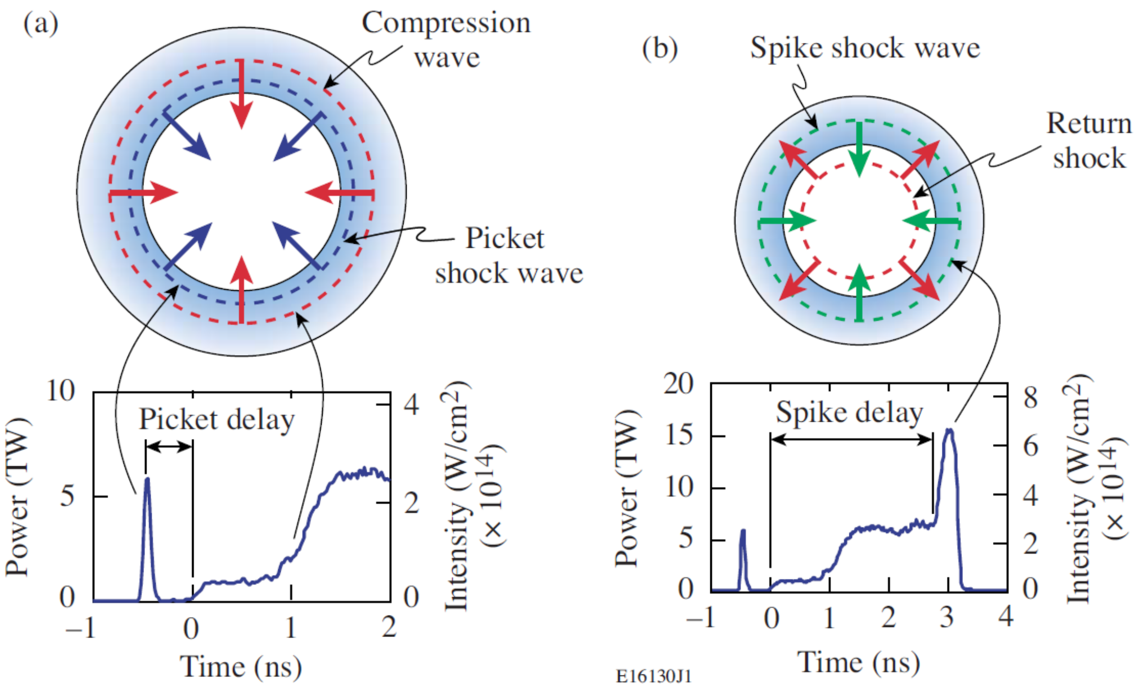
- **In recent attempts, the team at NIF increased the yield of the experiment, first to 5.2 megajoules and then again to 8.6 megajoules, according to a source with knowledge of the experiment.**

https://physicstoday.scitation.org/do/10.1063/PT.6.2.20221213a/full/
https://lasers.llnl.gov/science/achieving-fusion-ignition

Skip

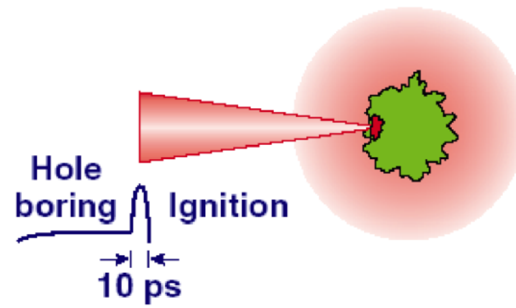
External “spark” can be used for ignition

- **Shock ignition**

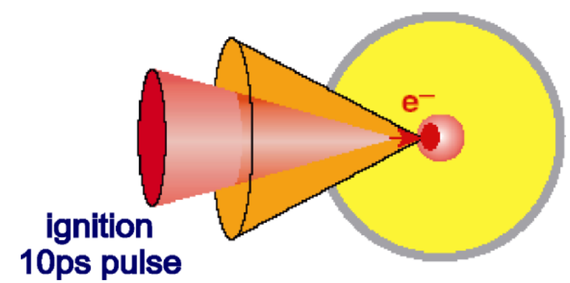


- **Fast ignition**

a) channeling FI concept



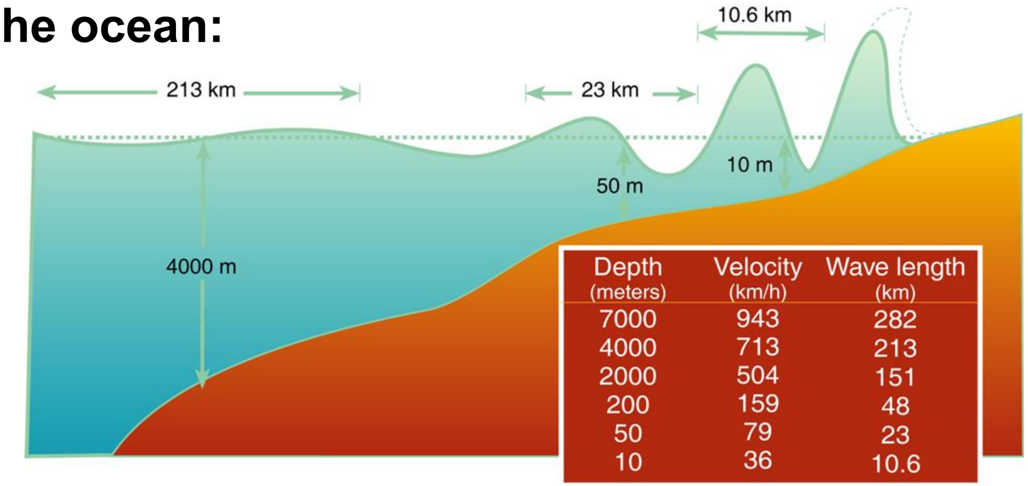
b) cone-in-shell FI concept



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

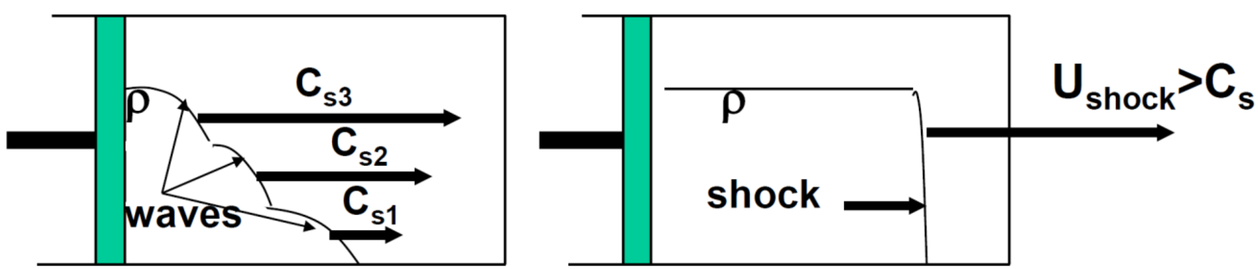
A shock is formed due to the increasing sound speed of a compressed gas/plasma

- **Wave in the ocean:**



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

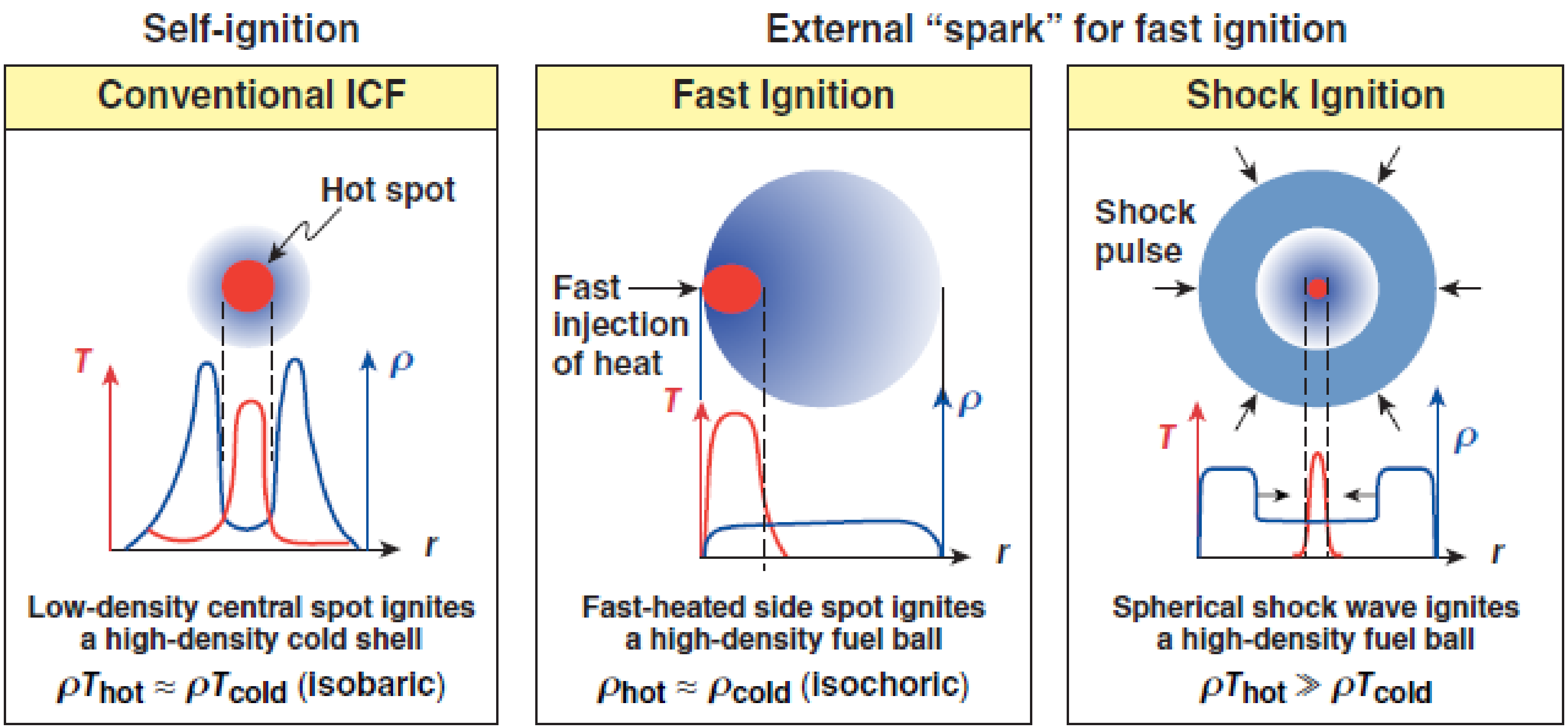
- **Acoustic/compression wave driven by a piston:**



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

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

Ignition can happen by itself or being triggered externally

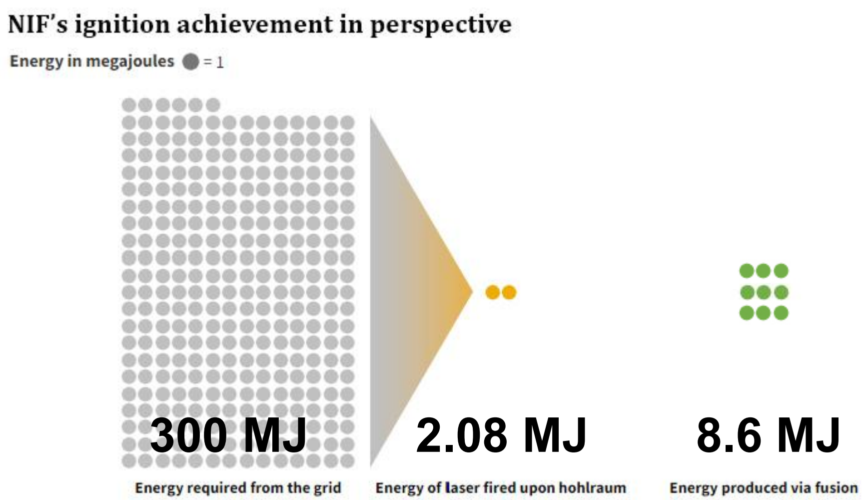


P. B. Radha, Fusion Energy Conference,2018

Reference for ICF

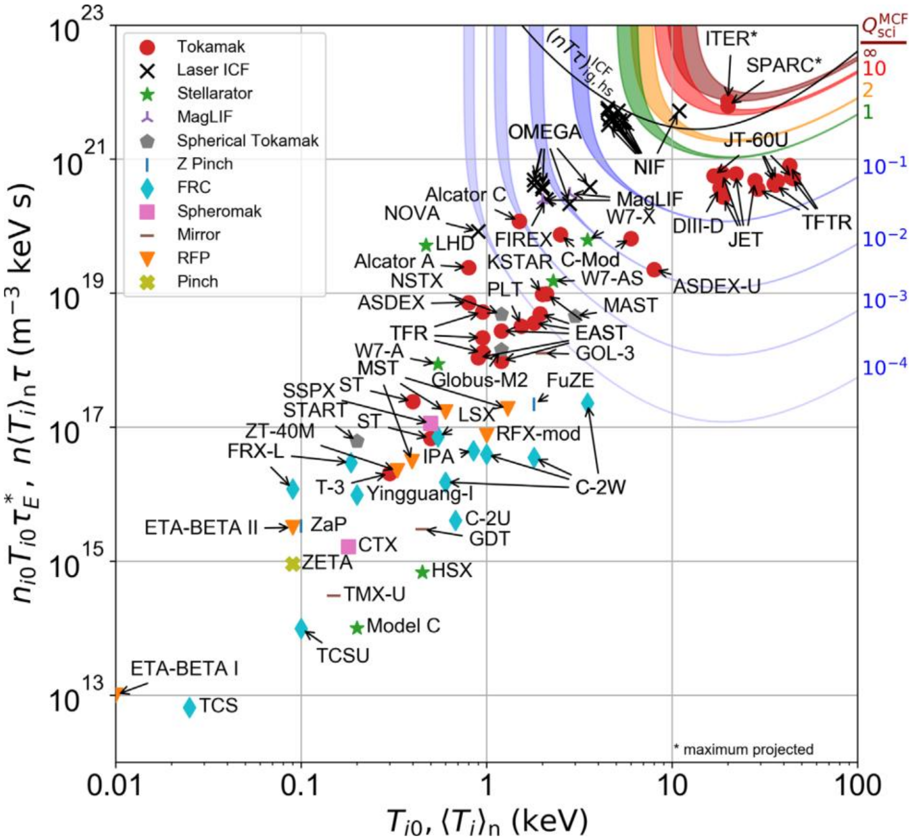
- Riccardo Betti, University of Rochester, HEDSA HEDP summer school, San Diego, CA, August 16-21, 2015
- ICF lectures for course PHY558/ME533
- The physics of inertial fusion, by S. Atzeni, J. Meyer-Ter-Vehn

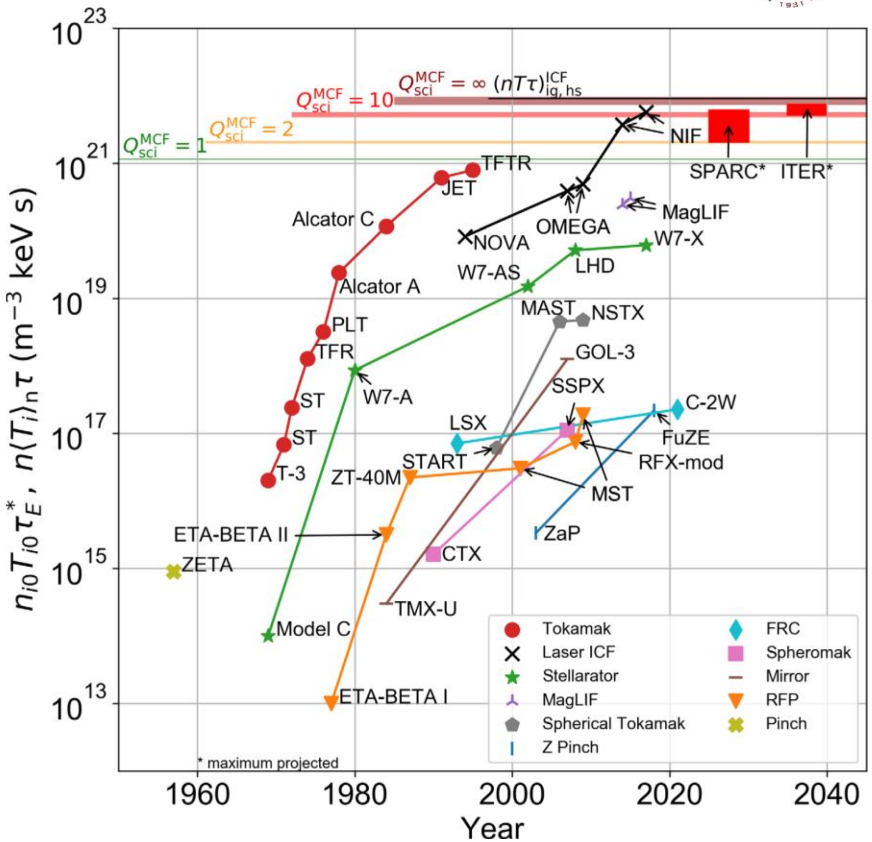
“Ignition” (target gain larger than one) was achieved in National Ignition Facility (NIF) on 2022/12/5



https://physicstoday.scitation.org/do/10.1063/PT.6.2.20221213a/full/
https://lasers.llnl.gov/science/achieving-fusion-ignition

We are closed to ignition!



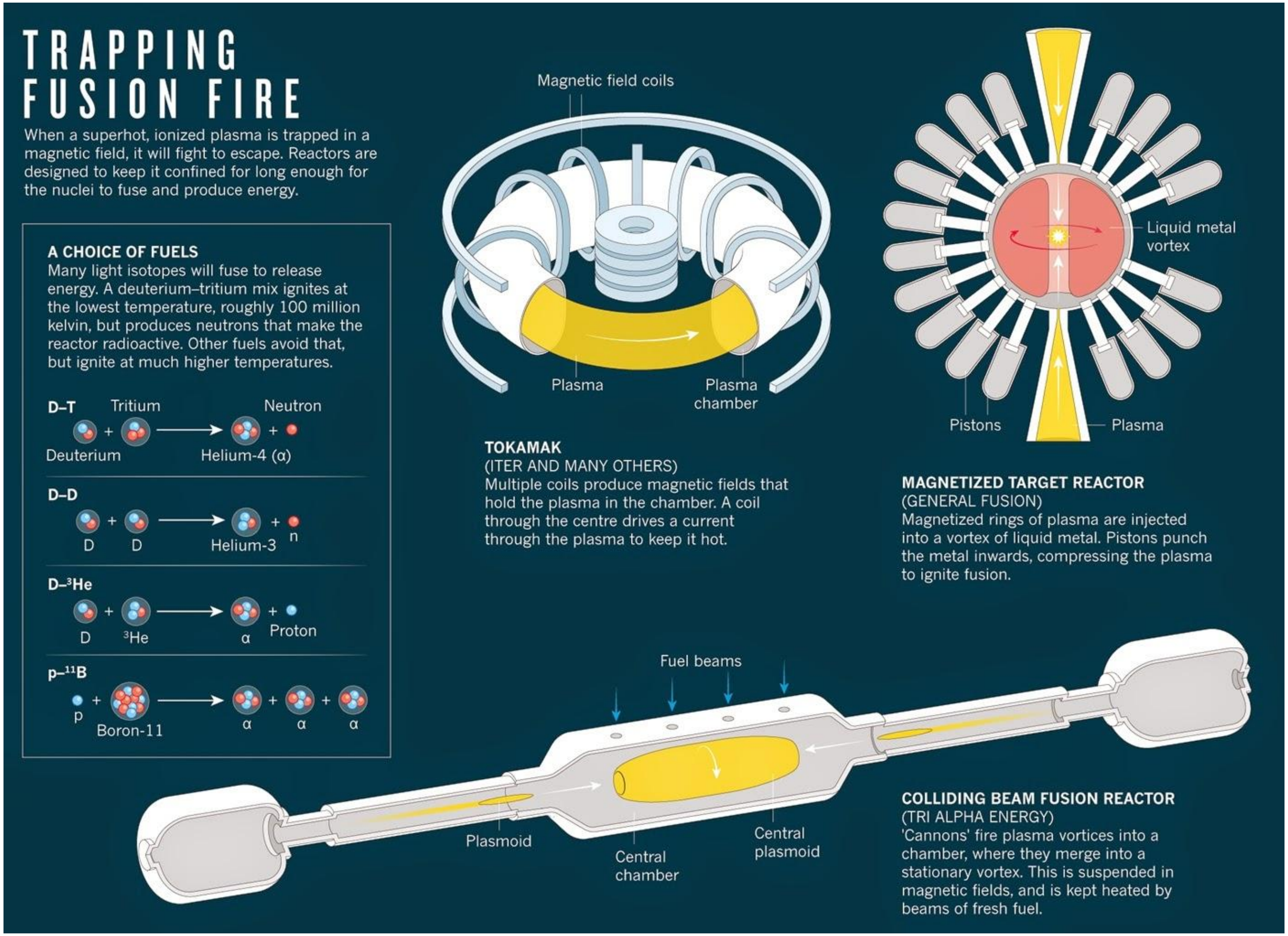


- **Lawson criteria (Ignition condition): Pτ > 10 atm-s = 10 Gbar - ns**

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

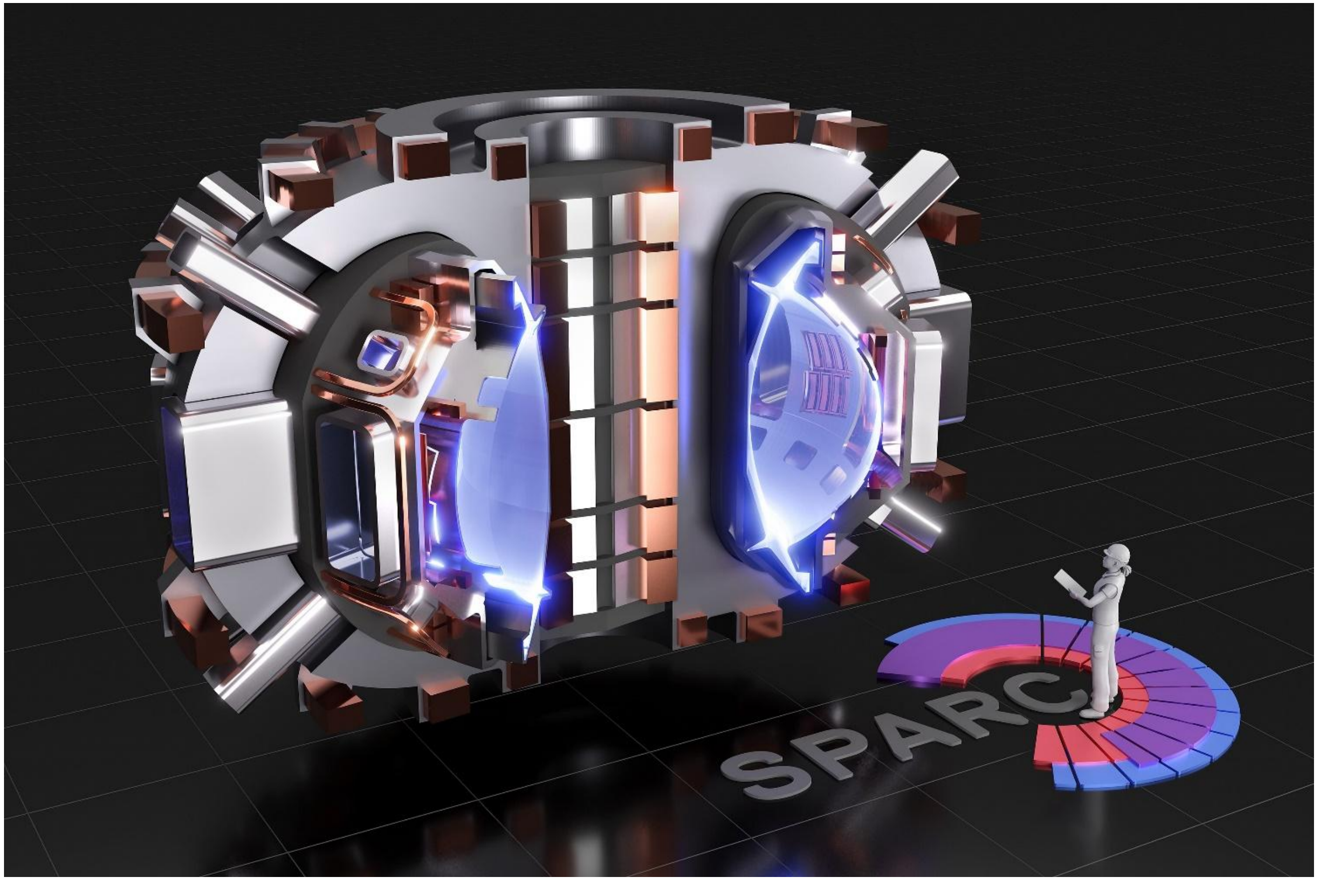
Samuel E. Wurzel and Scott C. Hsu, Phys. Plasmas, **29**, 062103 (2022)

There are alternative



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

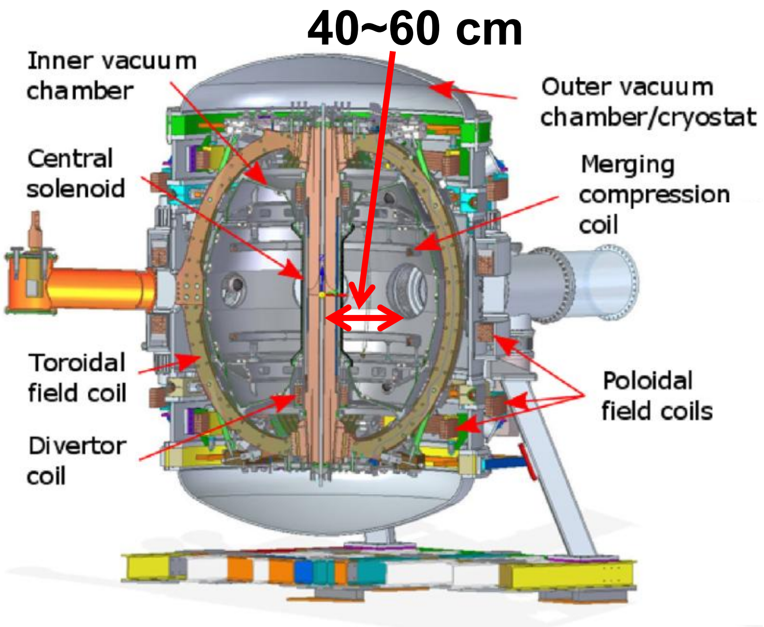
Commonwealth Fusion Systems, a MIT spin-out company, is building a high-magnetic field tokamak



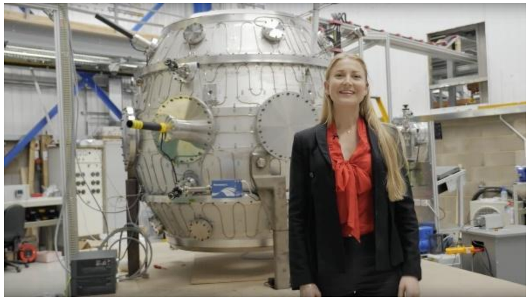
- Fusion power ∝ B^4.
- The fusion gain Q > 2 is expected for SPARC tokamak.

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

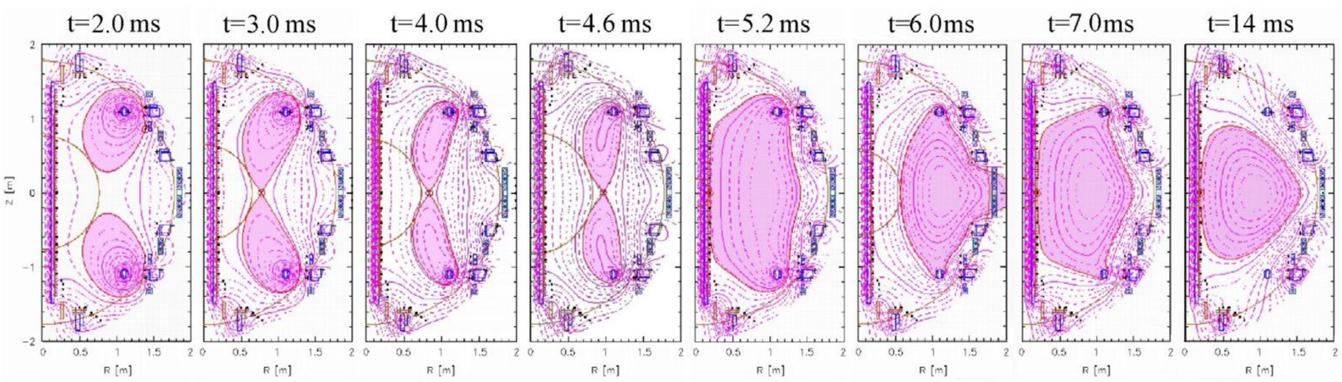
Merging compression is used to heat the tokamak at the start-up process in ST40 Tokamak at Tokamak Energy Ltd



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

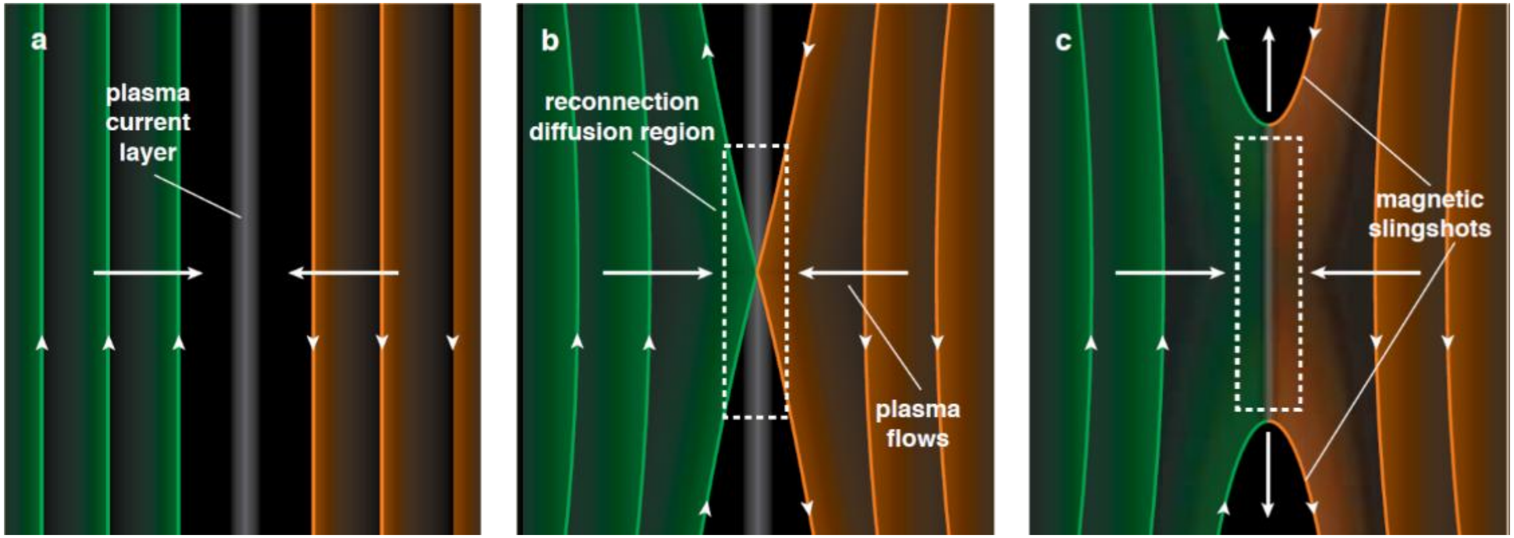


- **Merging compression**



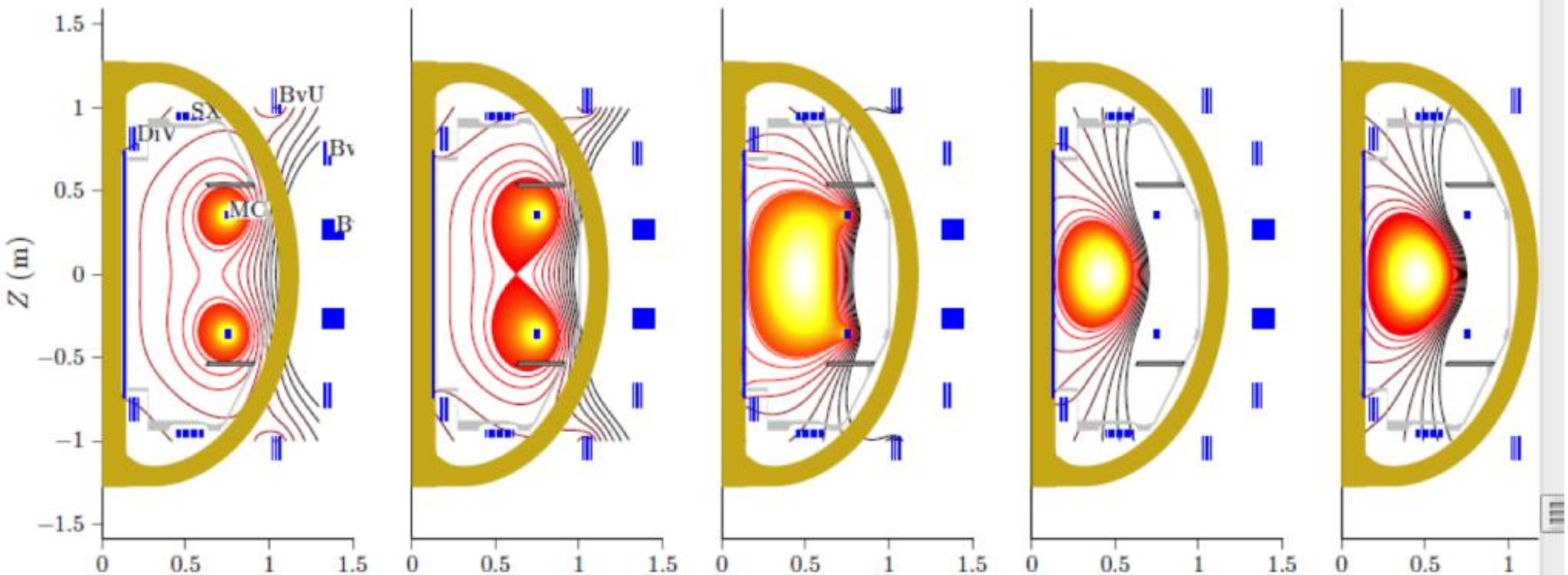
M. Gryaznevich, etc., Fusion Eng. Design, **123**,177 (2017)
https://www.tokamakenergy.co.uk/
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

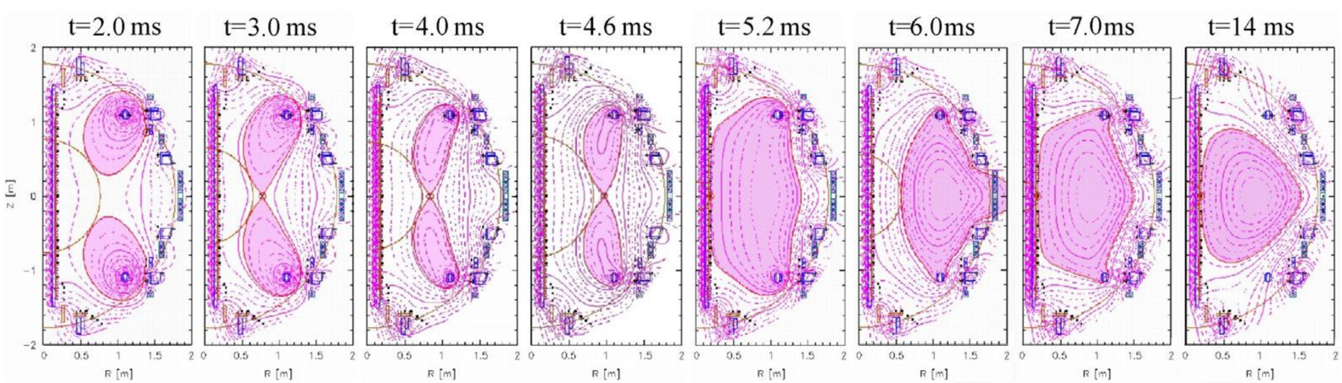
Reconnection



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

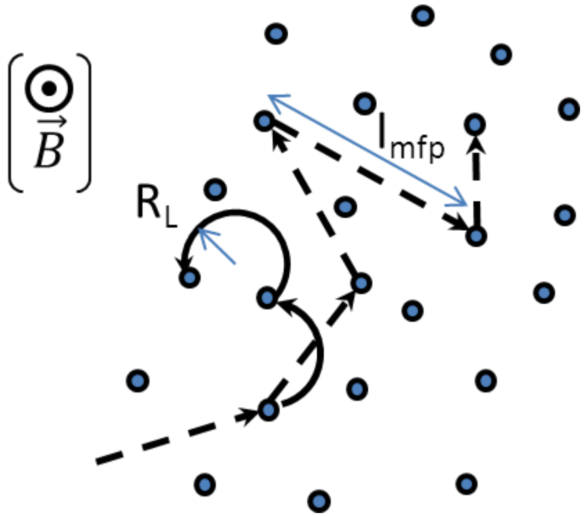
Merging compression is used to heat the plasma





http://www.100milliondegrees.com/merging-compression/
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

A strong magnetic field reduces the heat flux



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

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

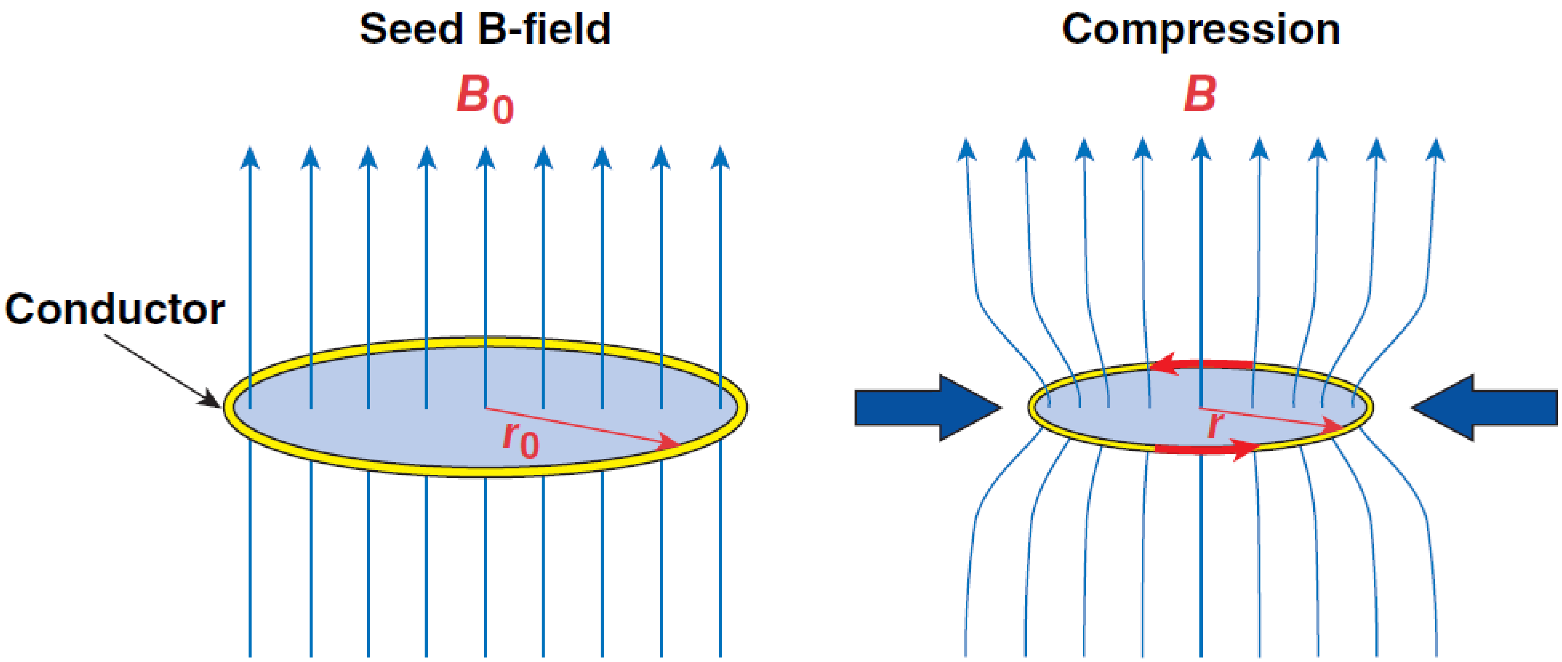
$$\kappa_{\perp} = \frac{\kappa_{||}}{\chi^2}$$ **for large Hall parameter** $\chi \propto \frac{l_{mfp}}{R_L} >> 1$

- **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.

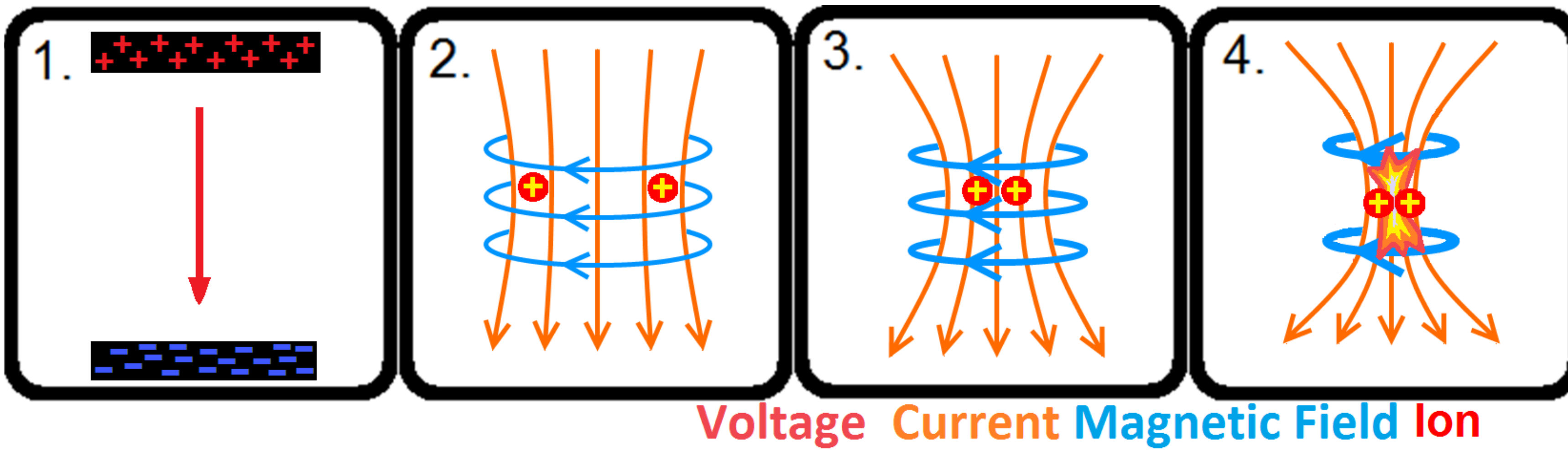
Principle of frozen magnetic flux in a good conductor is used to compress fields



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

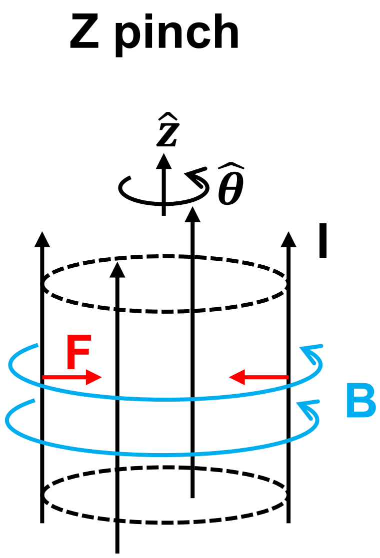
M. Hohenberger, P.-Y. Chang, *et al.*, Phys. Plasmas 19, 056306 (2012).

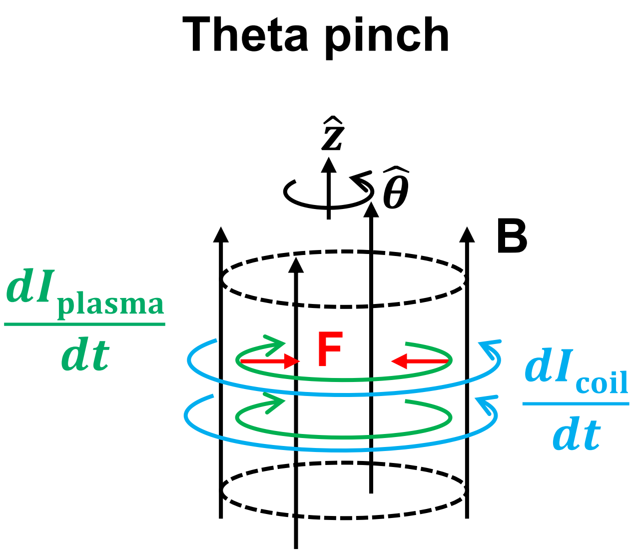
Plasma can be pinched by parallel propagating plasmas



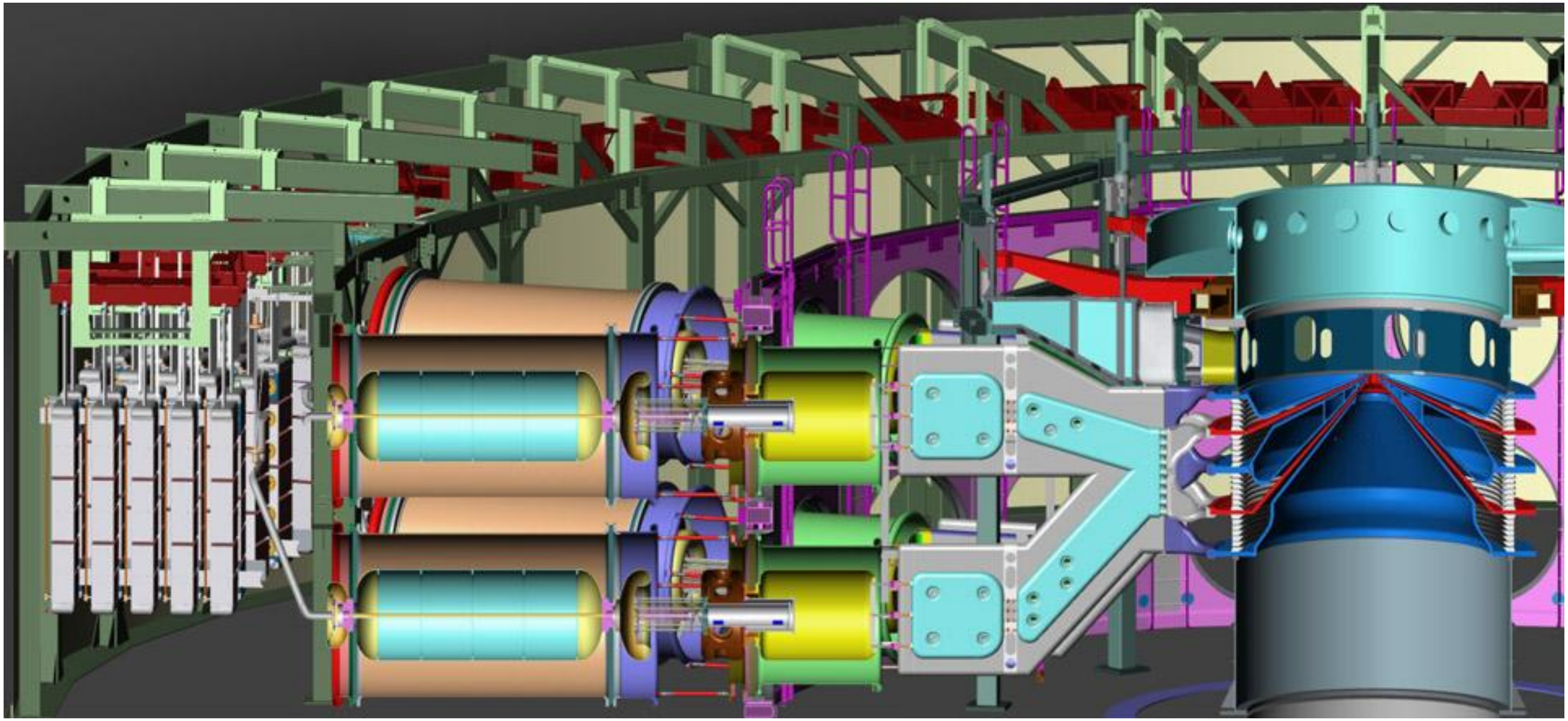
https://en.wikipedia.org/wiki/Pinch_(plasma_physics)

Plasma can be heated via pinches



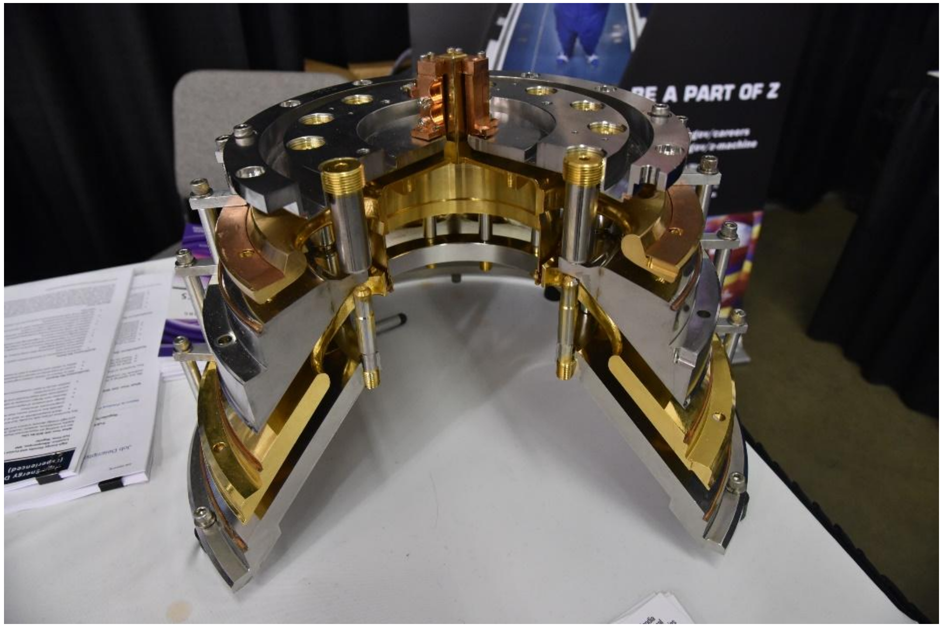


Sandia's Z machine is the world's most powerful and efficient laboratory radiation source

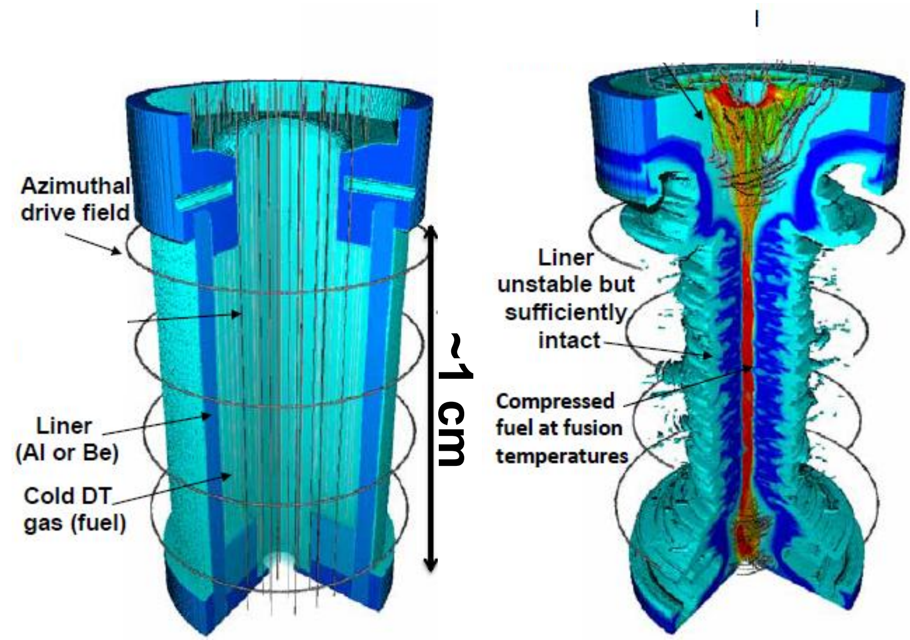


- Stored energy: 20 MJ
- Marx charge voltage: 85 kV
- Peak electrical power: 85 TW
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray emissions: 350 TW
- Peak X-ray output: 2.7 MJ

Z machine



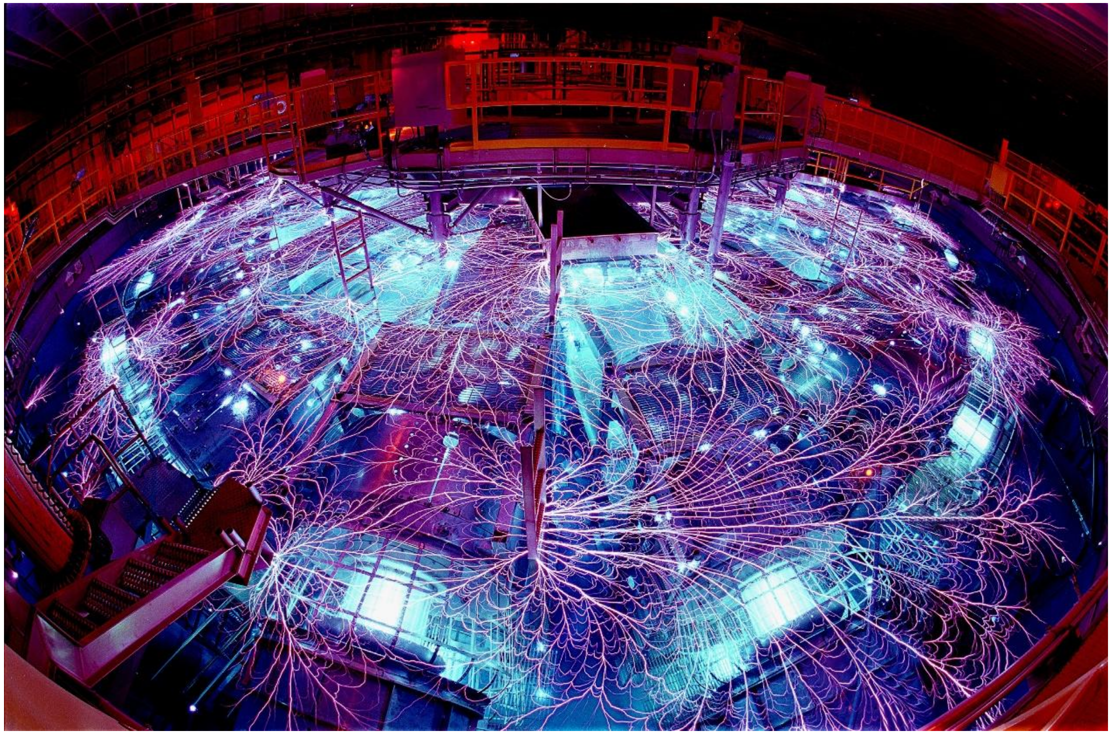
Z machine



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

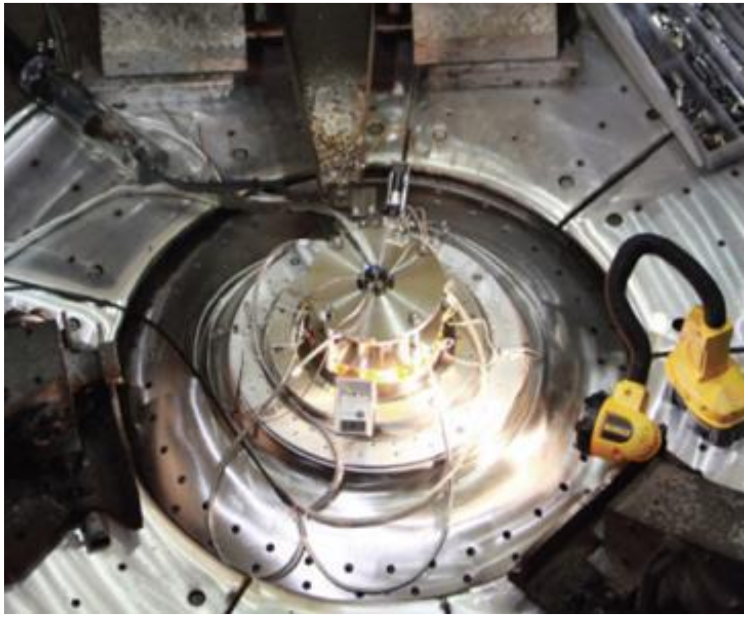
- **Peak current: 26 MA**
- **Rise time: 100 ns**
- **Peak X-ray output: 2.7 MJ**

Z machine discharge



Before and after shots

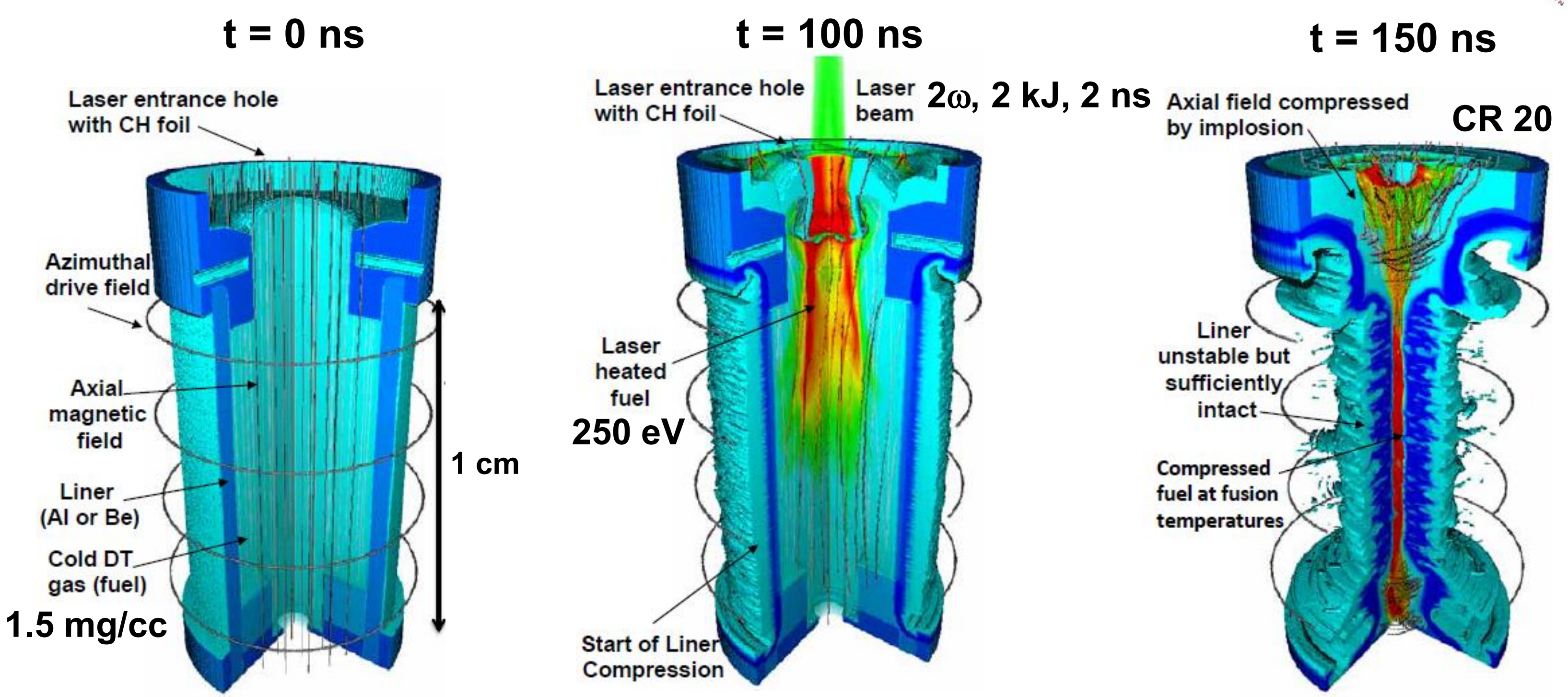
- **Before shots**



- **After shots**

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

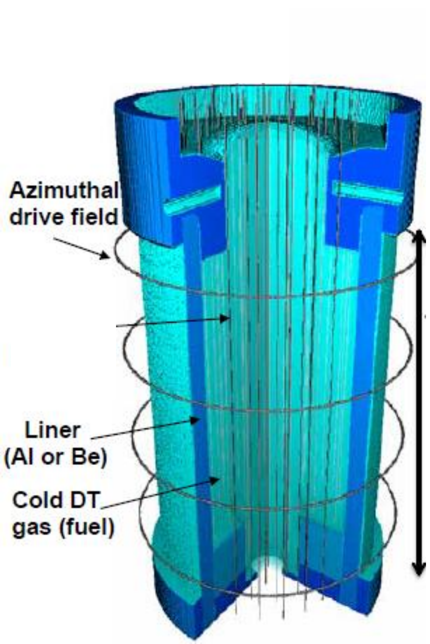
Promising results were shown in MagLIF concept conducted at the Sandia National Laboratories

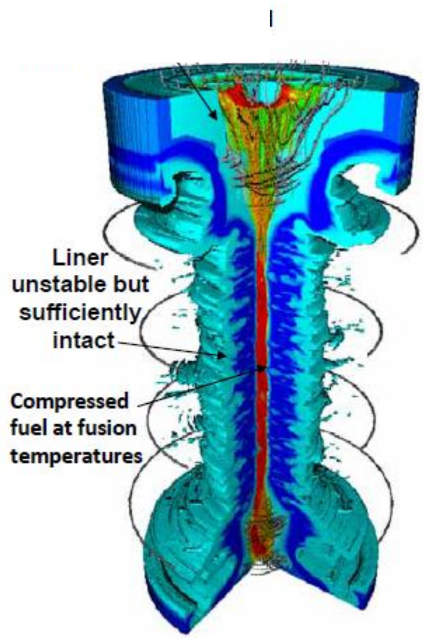


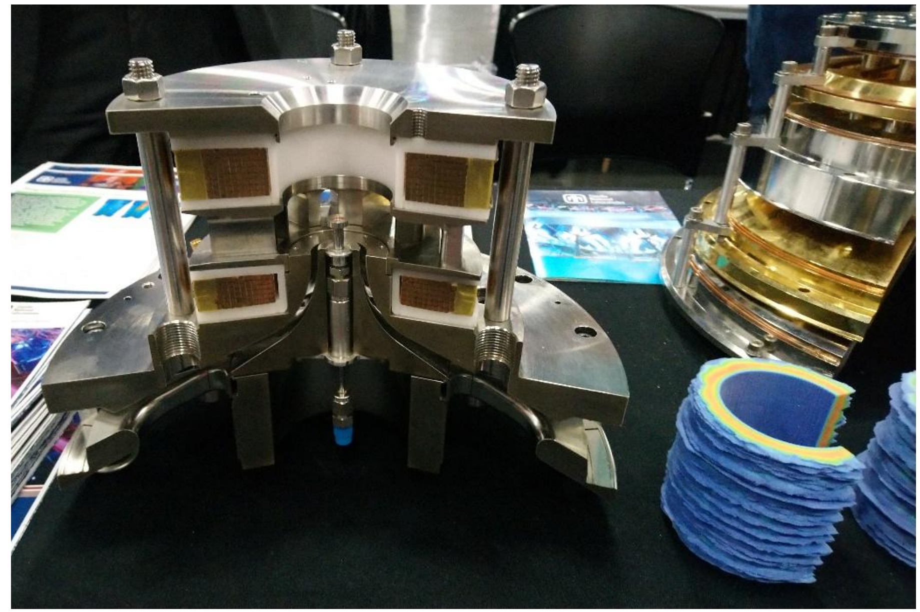
The stagnation plasma reached fusion-relevant temperatures with a 70 km/s implosion velocity

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

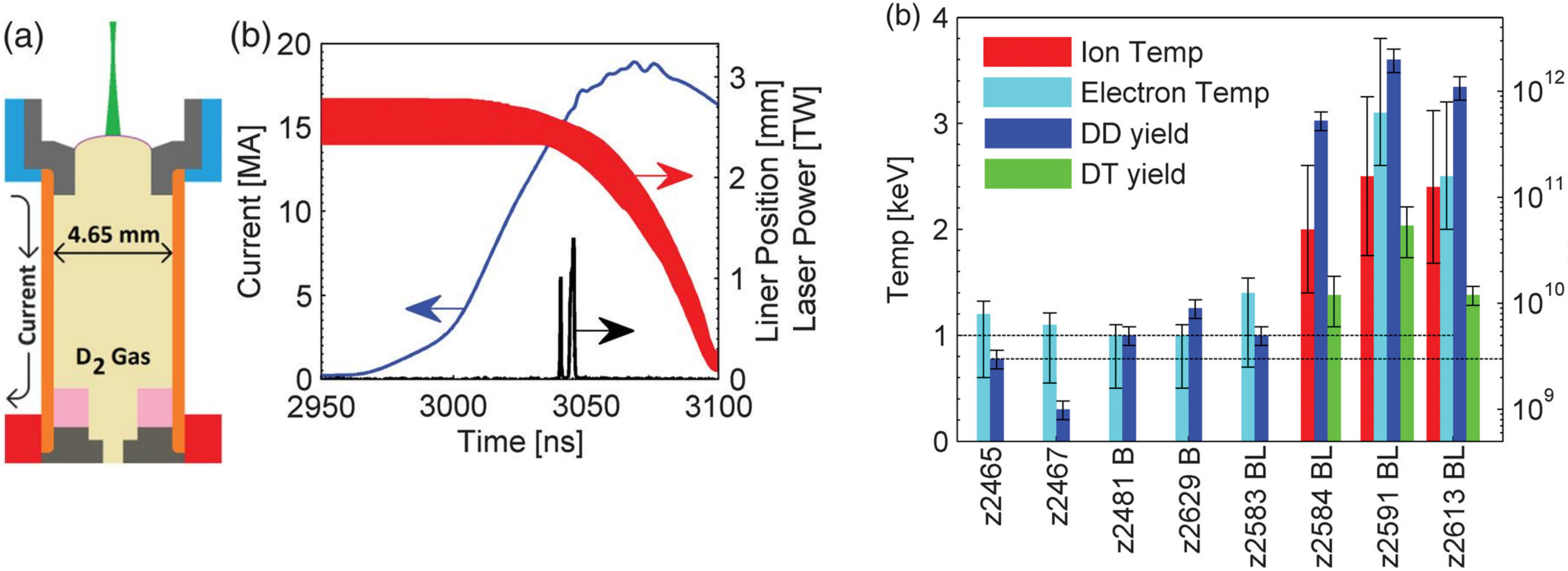
MagLIF target







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

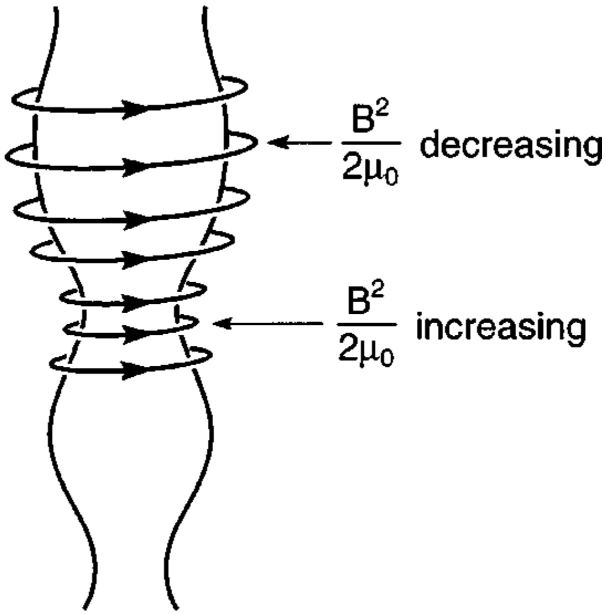


M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)

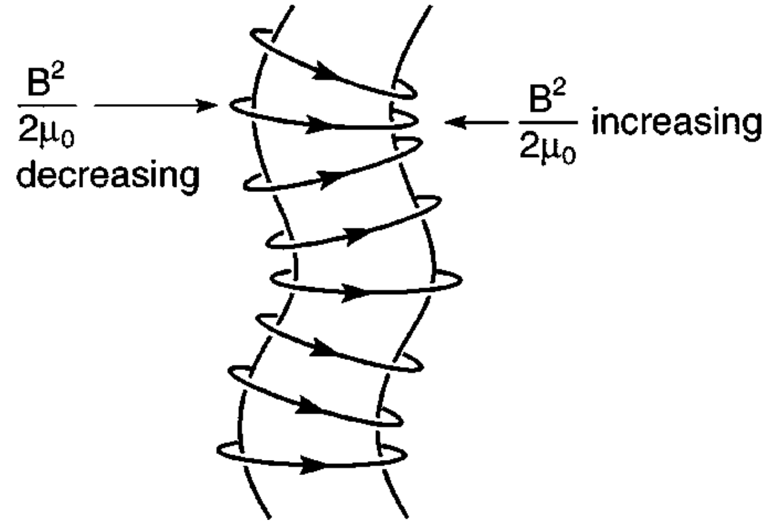
Sheared flow stabilizes MHD instabilities

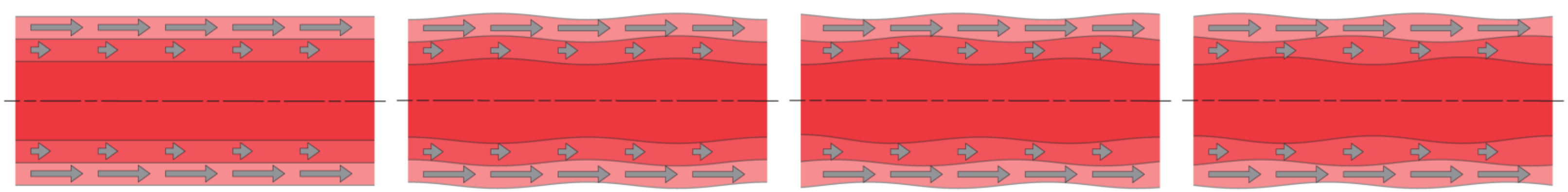
m = 0 (sausage)

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



m = 1 (kink)

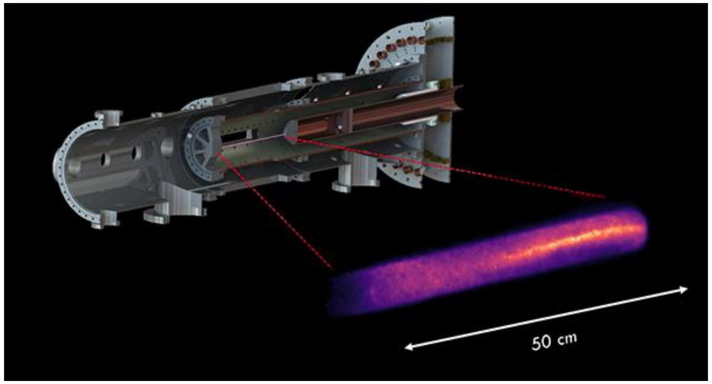


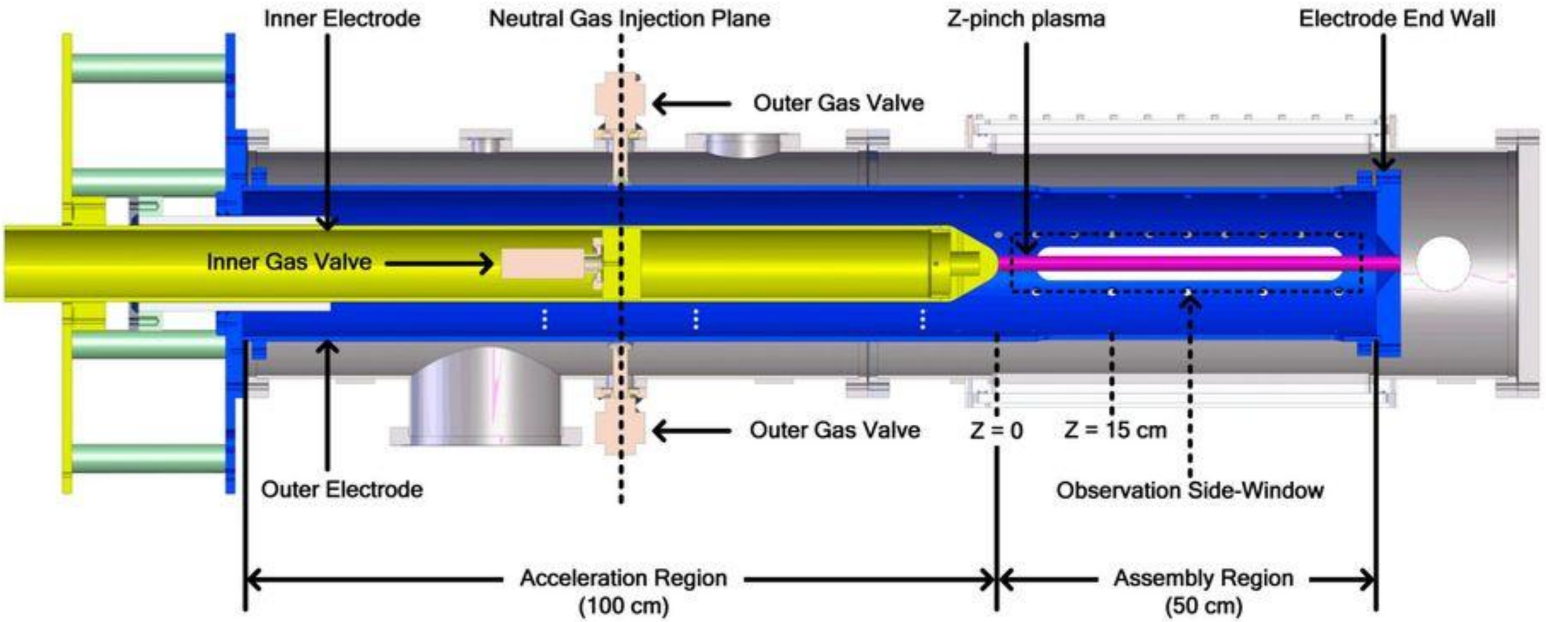


$$\frac{dV_Z}{dr} \neq 0$$

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

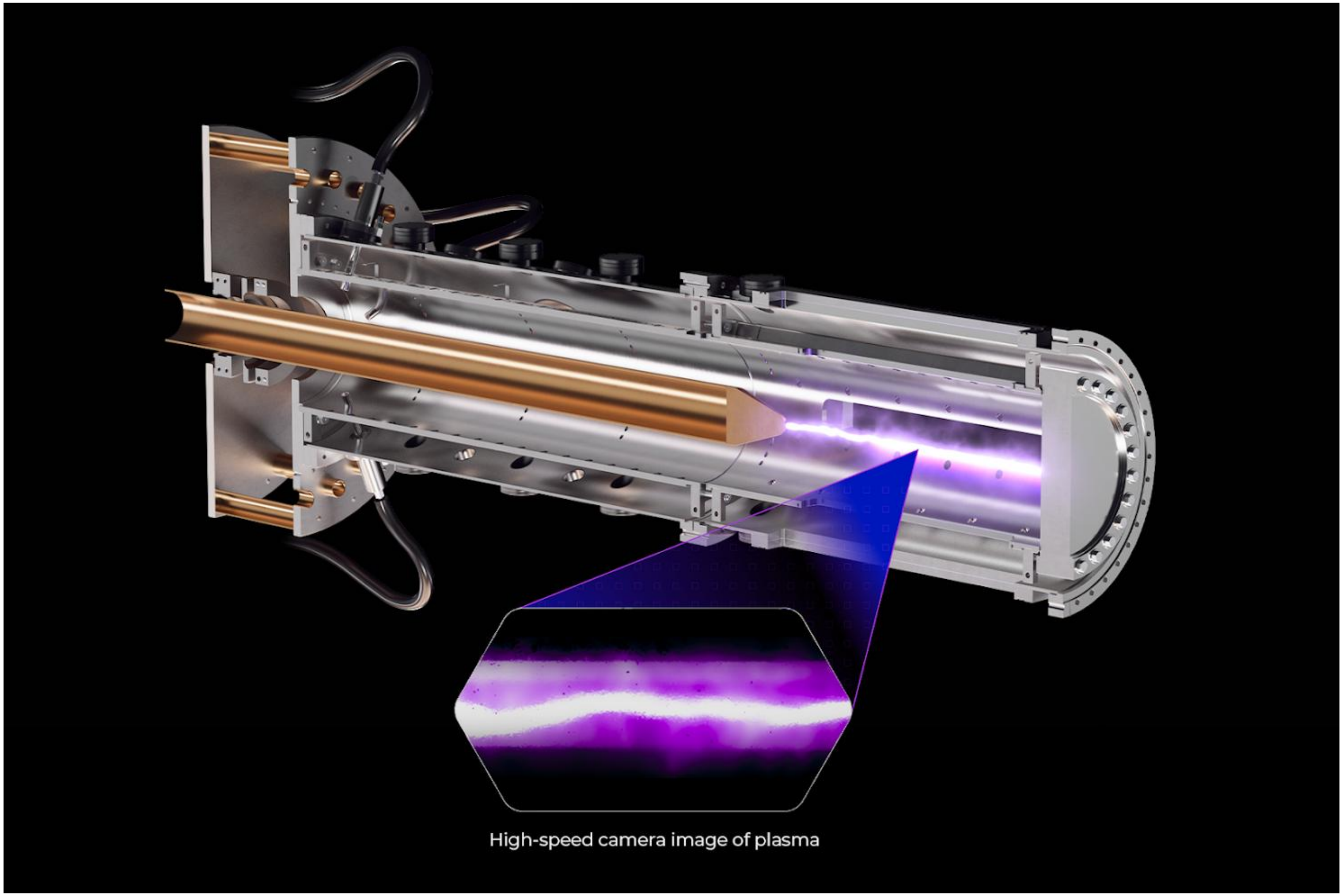
A z-pinch plasma can be stabilized by sheared flows





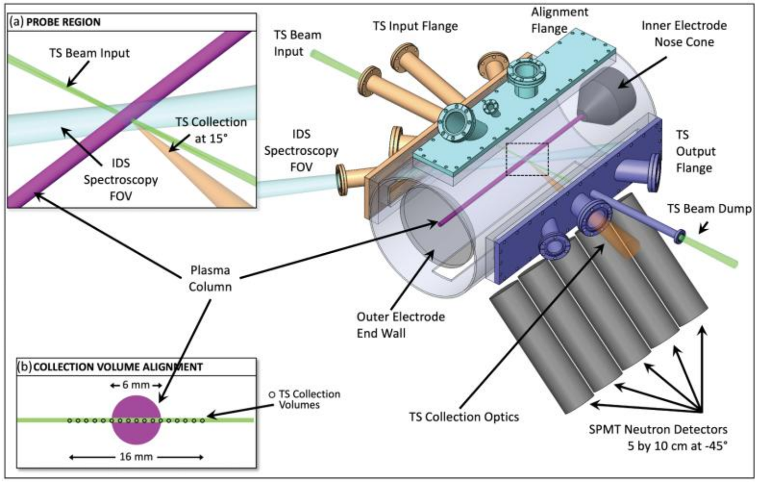
https://www.zapenergyinc.com/about

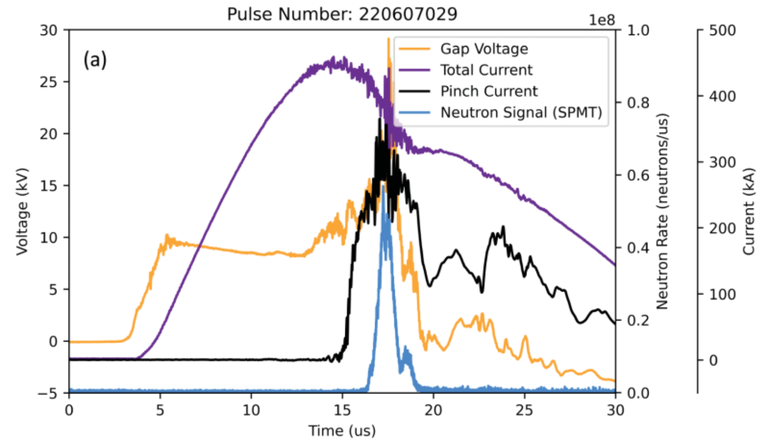
A. D. Stepanov, etc., Phys. Plasmas 27, 112503 (2020)

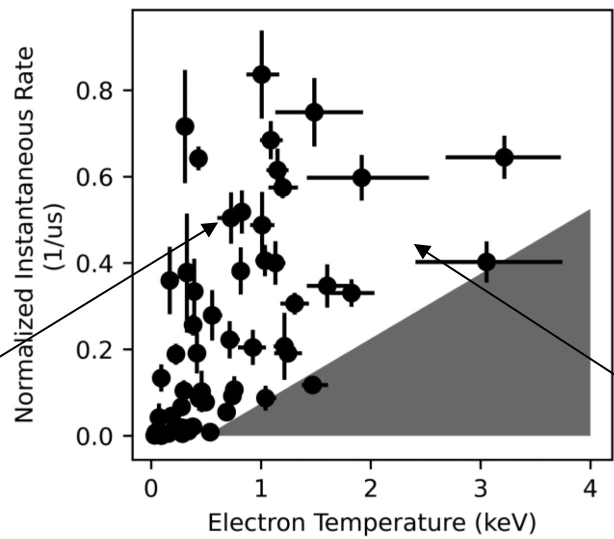


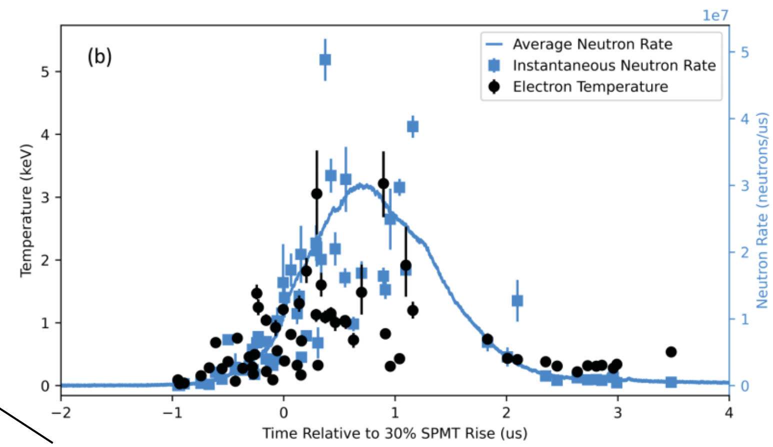
https://www.powerelectronicsnews.com/zap-energys-vision-for-fusion-power/

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







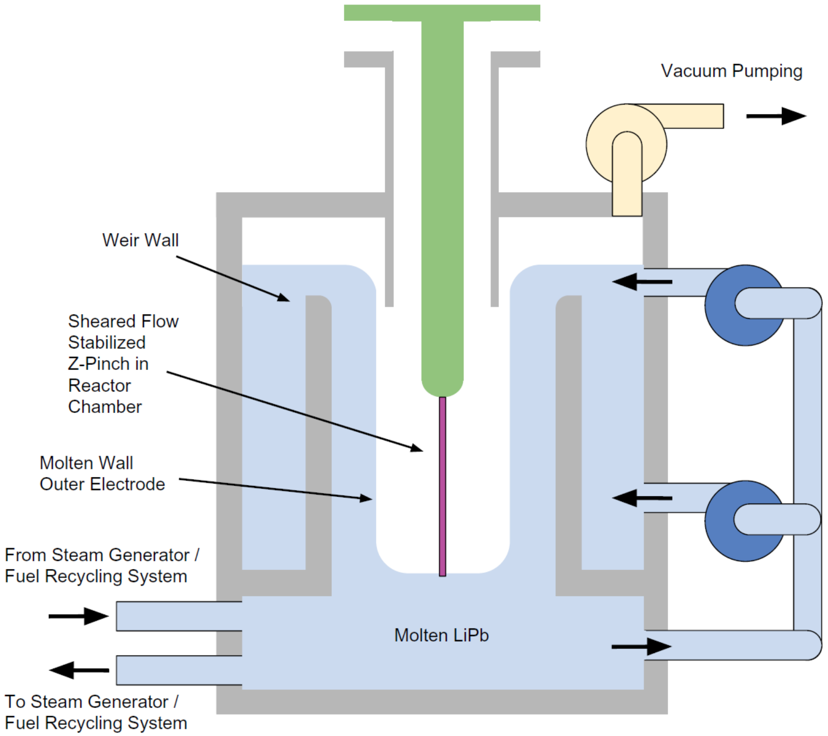


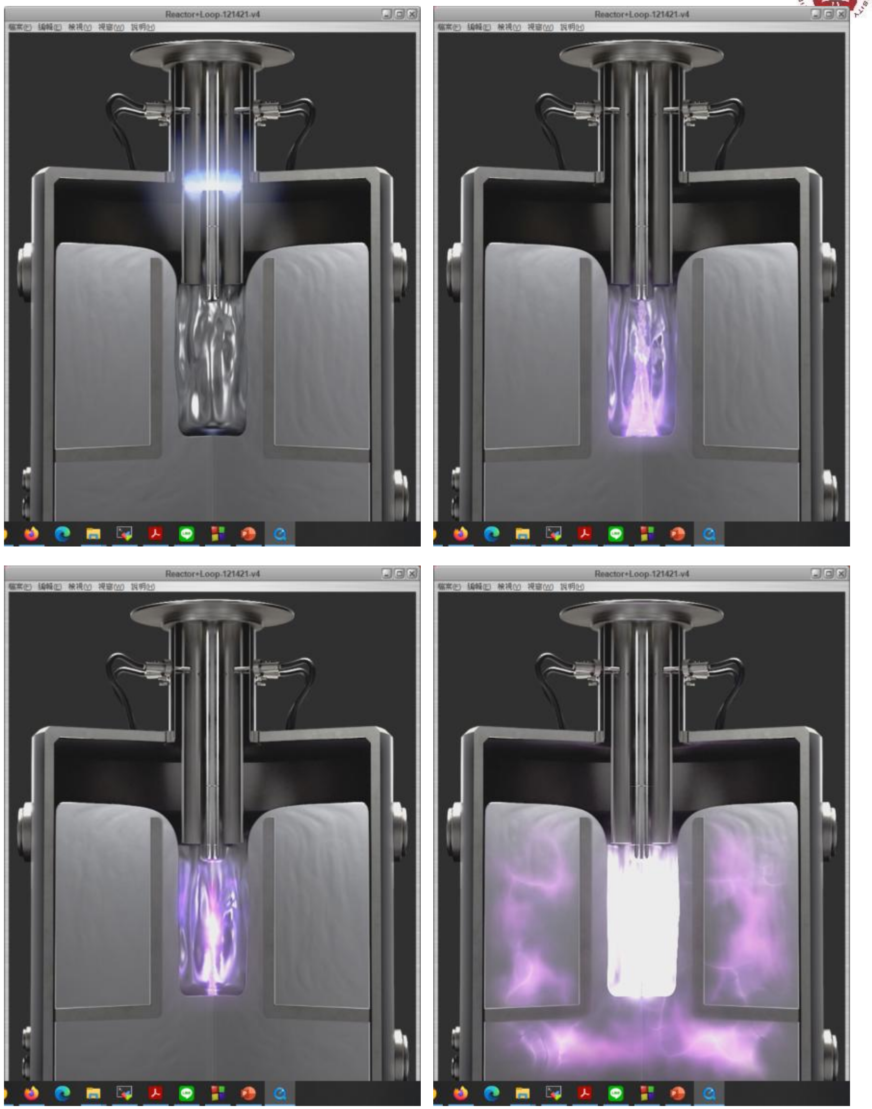
- **Thomson scattering measurement missed the high temperature region.**

- **High temperature coincide with high rate.**

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

Fusion reactor concept by ZAP energy

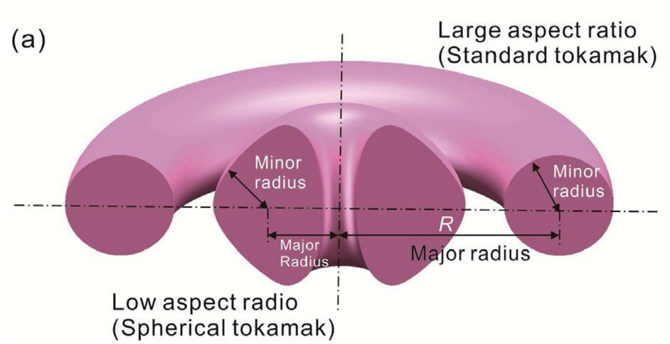




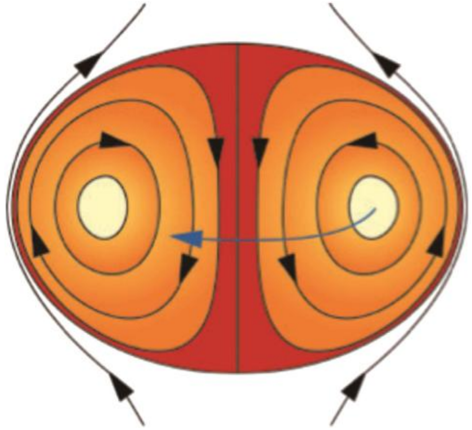
https://www.zapenergyinc.com/about
E. G. Forbes, etc., Fusion Sci. Tech. 75, 599 (2019)

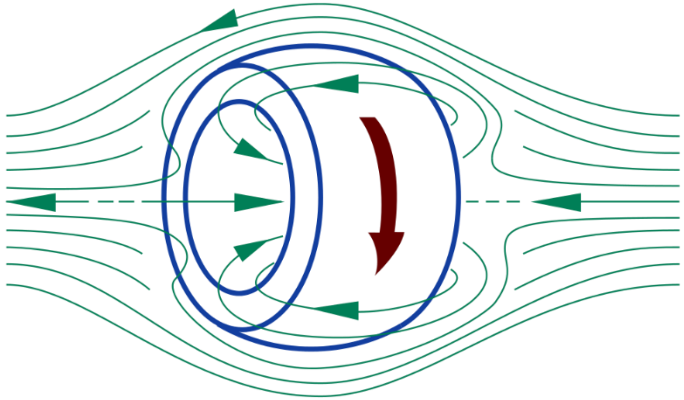
Spherical torus (ST) and compact torus (CT)

- **Spherical torus (ST)**



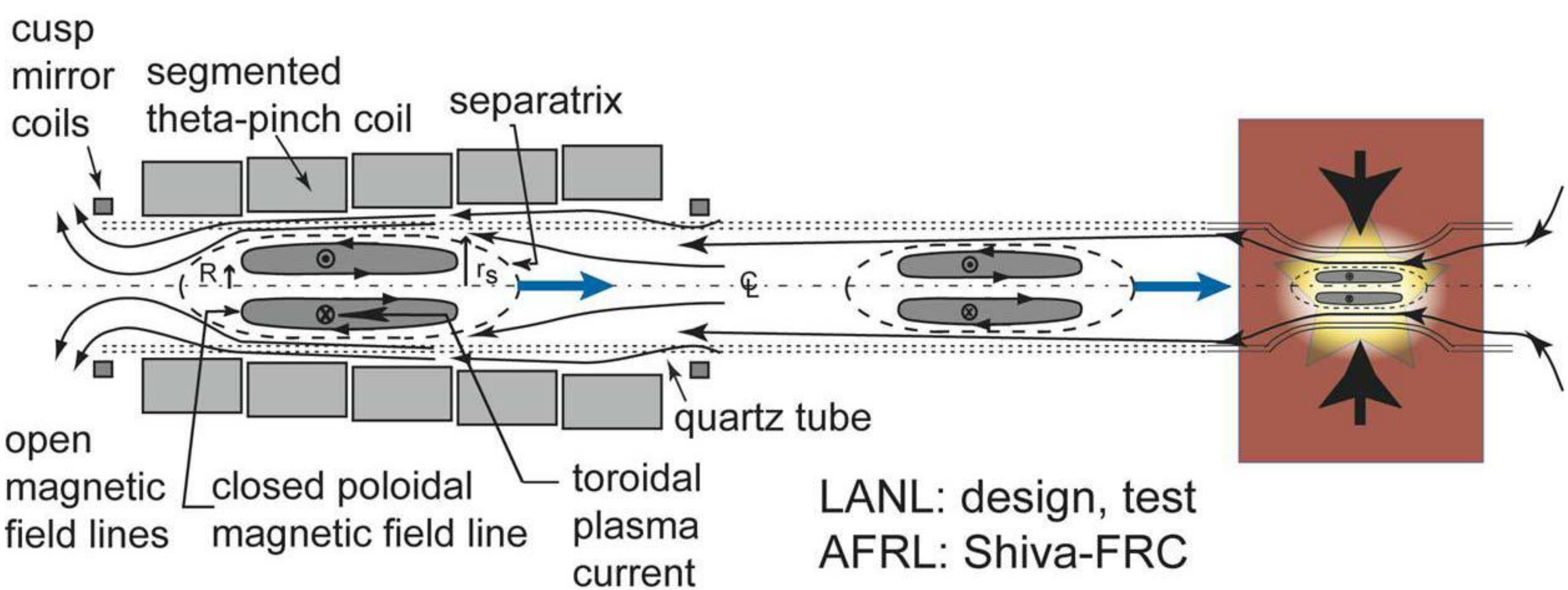
- **Compact torus (CT)**
  - **Spheromak**
  - **Field reversed configuration (FRC)**



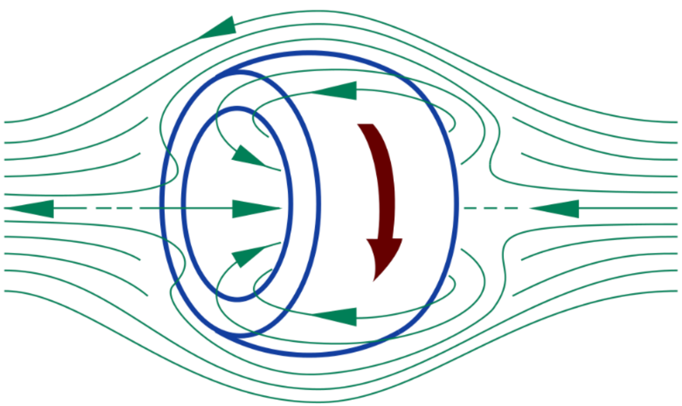


Zhe Gao, Matter Radiat. Extremes **1**, 153 (2016)
https://en.wikipedia.org/wiki/Field-reversed_configuration

Field reverse configuration is used in Tri-alpha energy

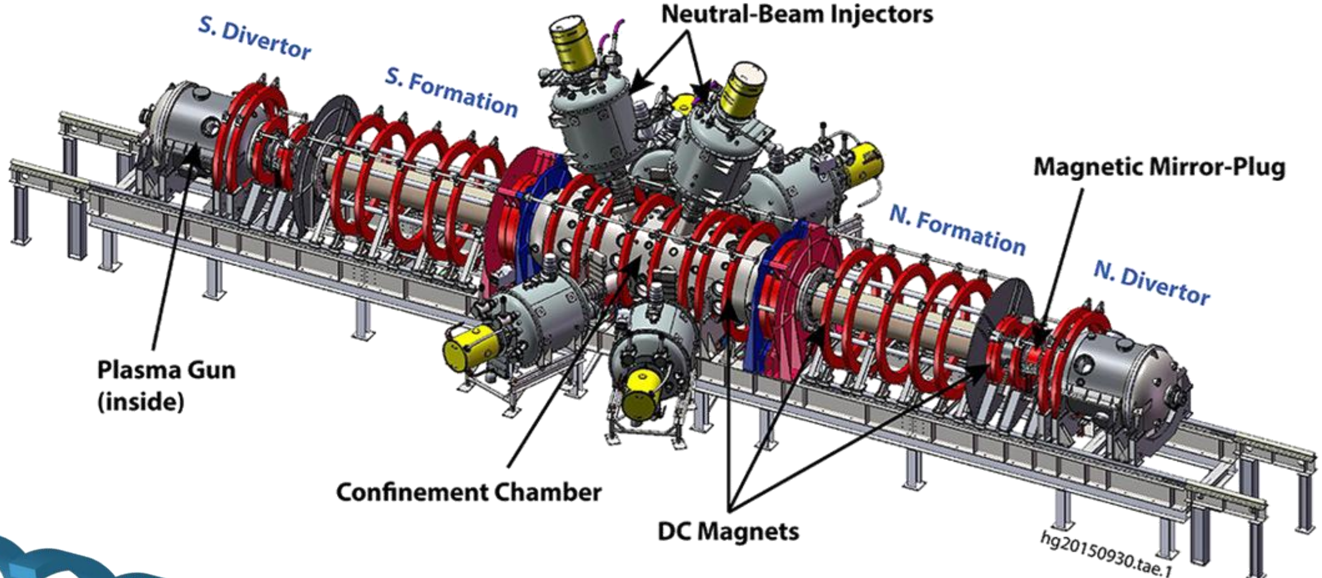


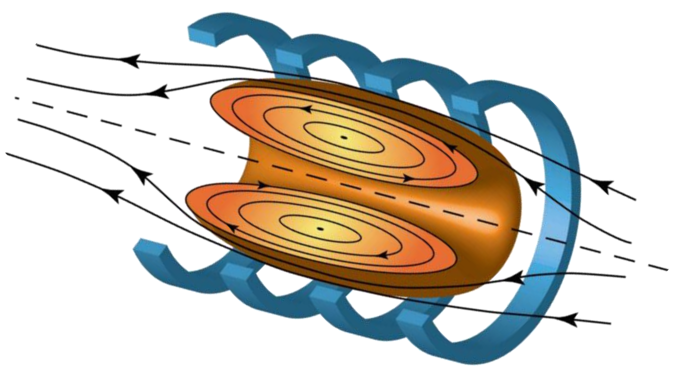
LANL: design, test
AFRL: Shiva-FRC



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

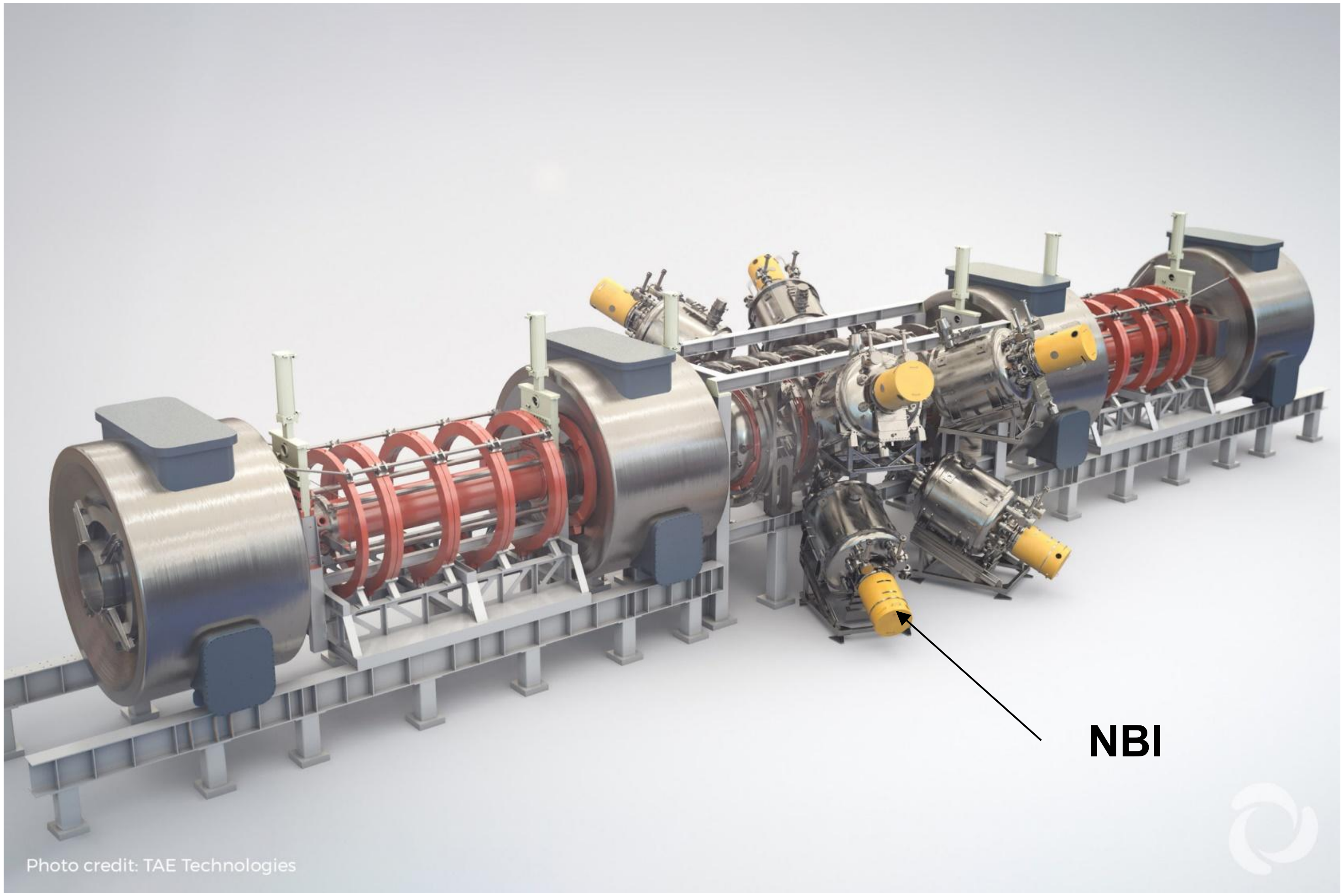
Field reverse configuration is used in Tri-alpha energy





http://trialphaenergy.com/
Zhe Gao, Matter Radiat. Extremes **1**, 153 (2016)

NBI for Tri-Alpha Energy Technologies

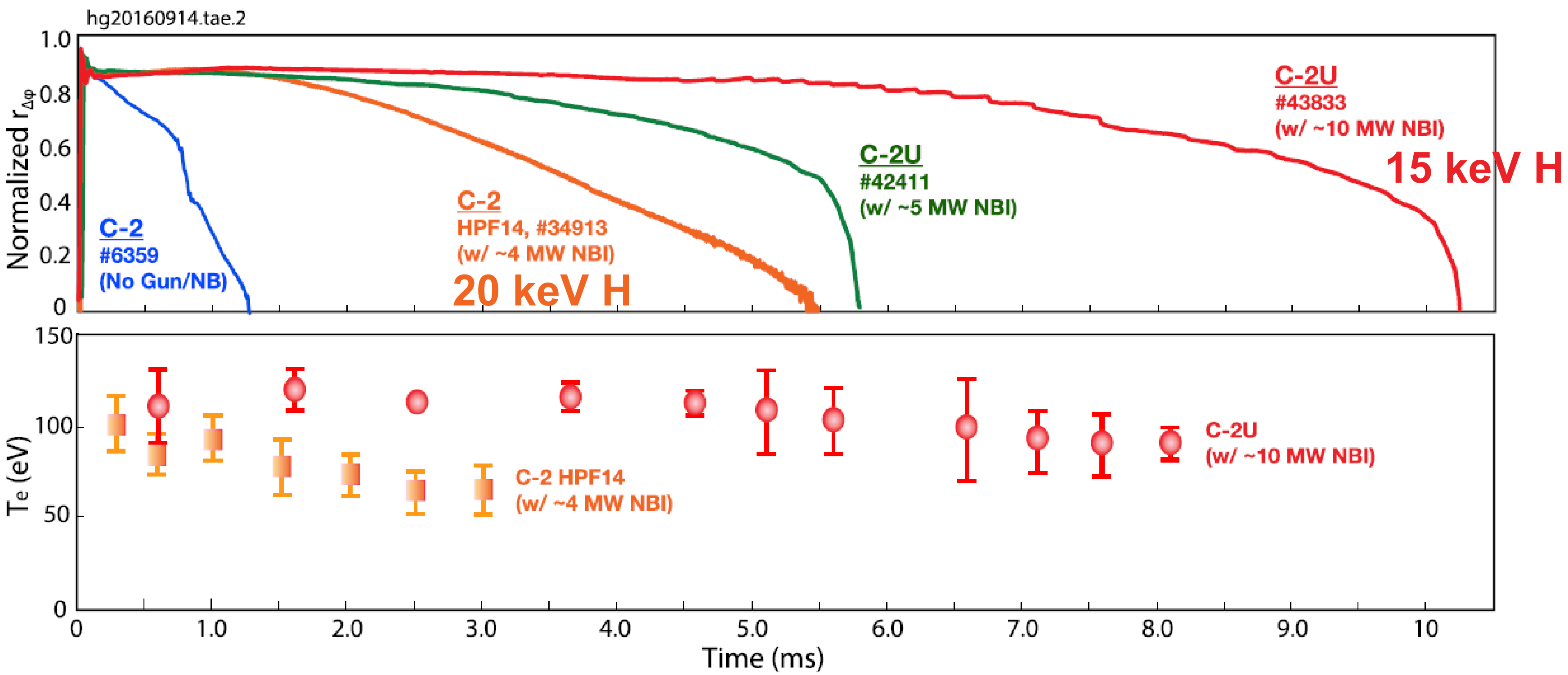


https://tae.com/media/

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

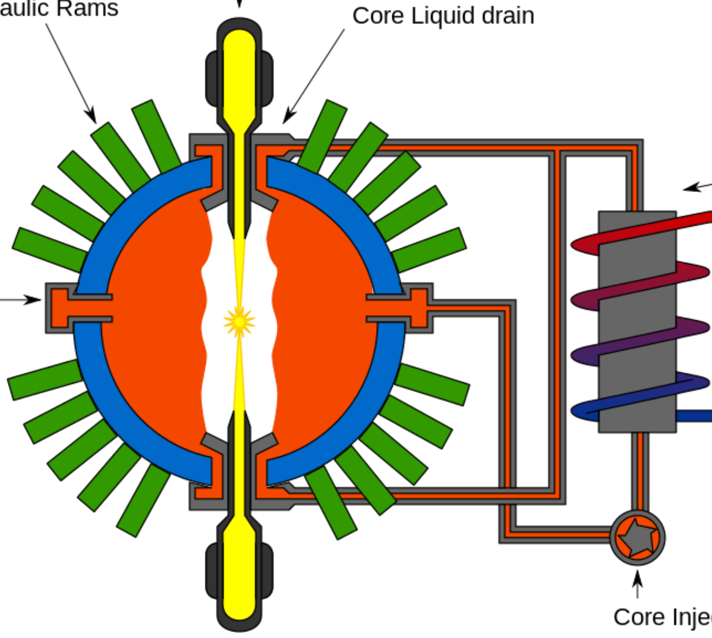
https://tae.com/media/
https://zh.wikihow.com/%E5%9C%A8%E6%89%8B%E6%8C%87%E4%B8%8A%E8%BD%AC%E7%AF%AE%E7%90%83

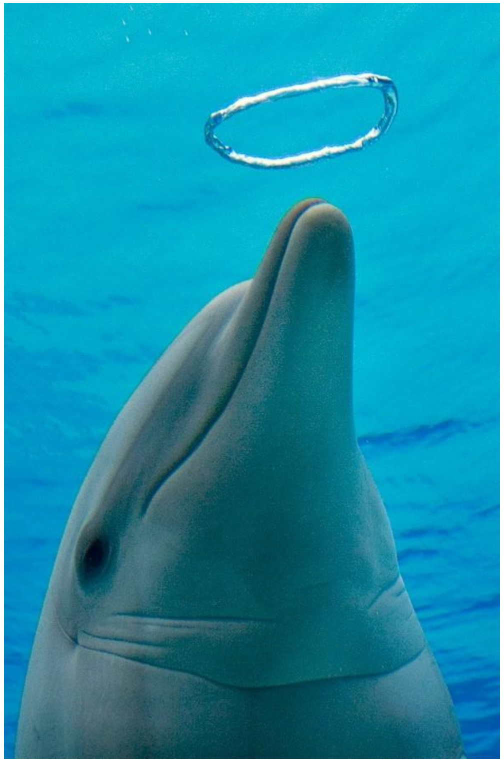
FRC sustain longer with neutral beam injection



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

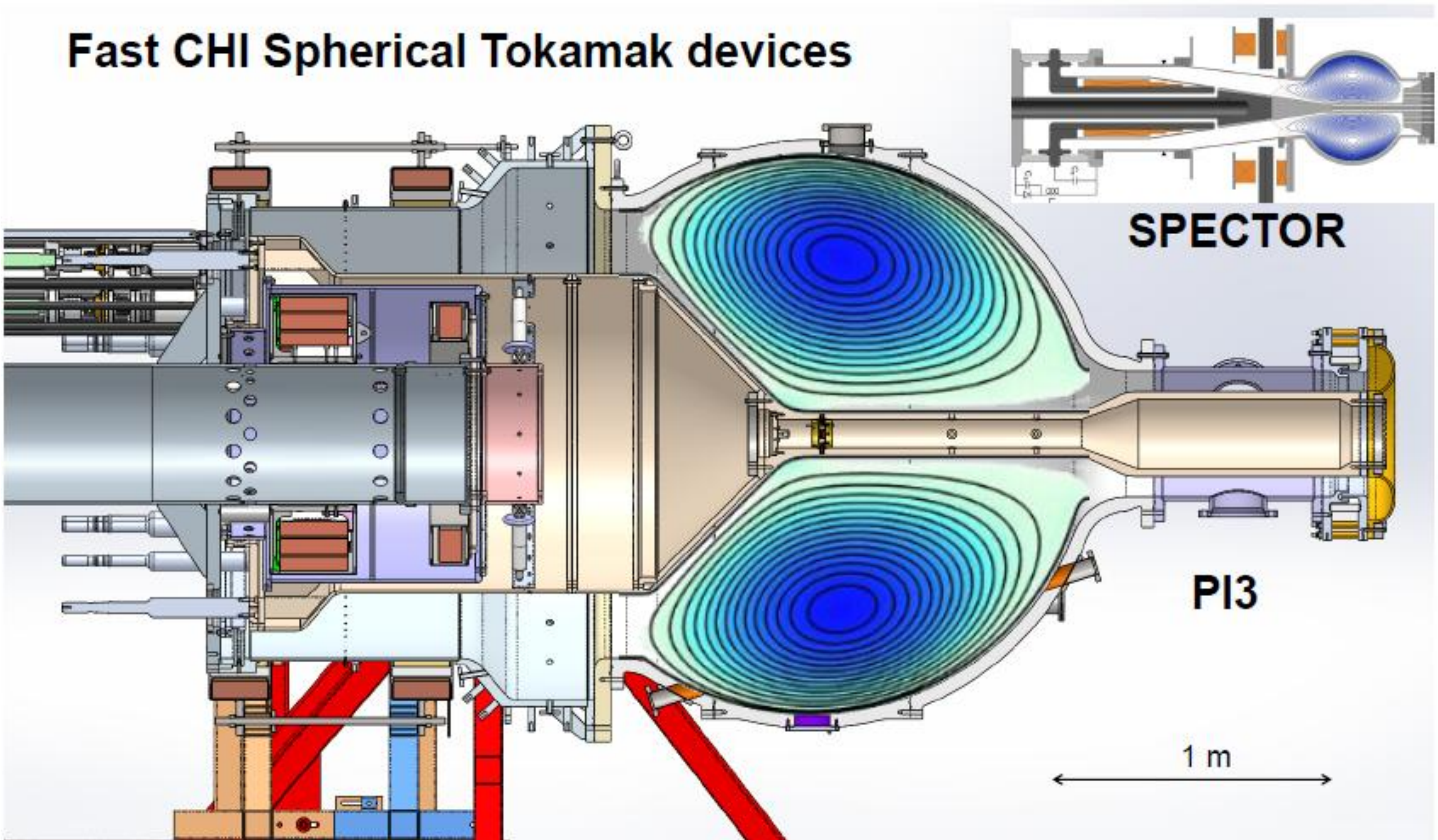
General fusion is a design ready to be migrated to a power plant





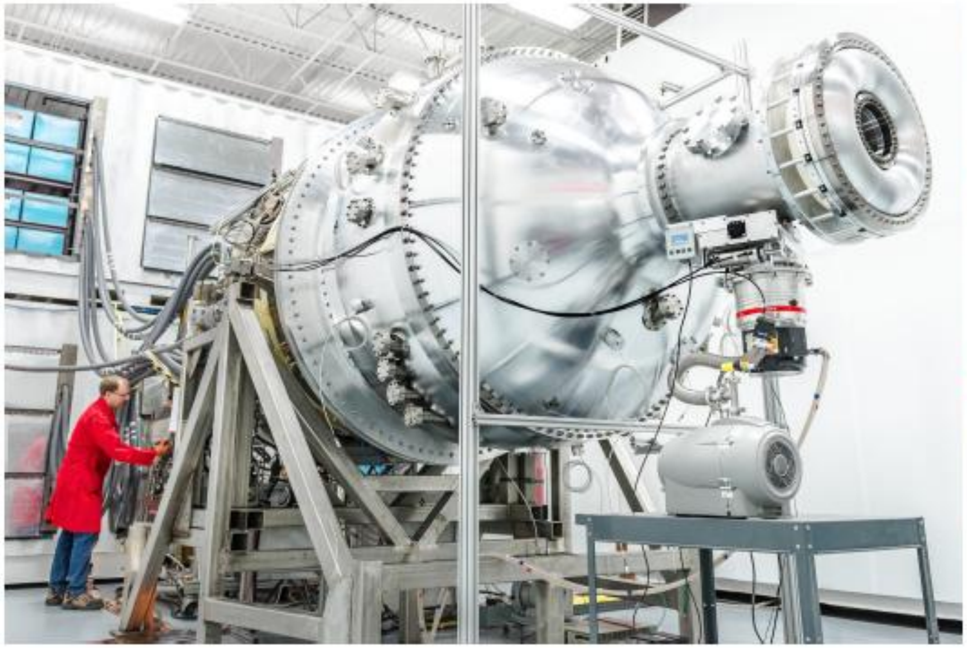
https://en.wikipedia.org/wiki/General_Fusion

A spherical tokamak is first generated



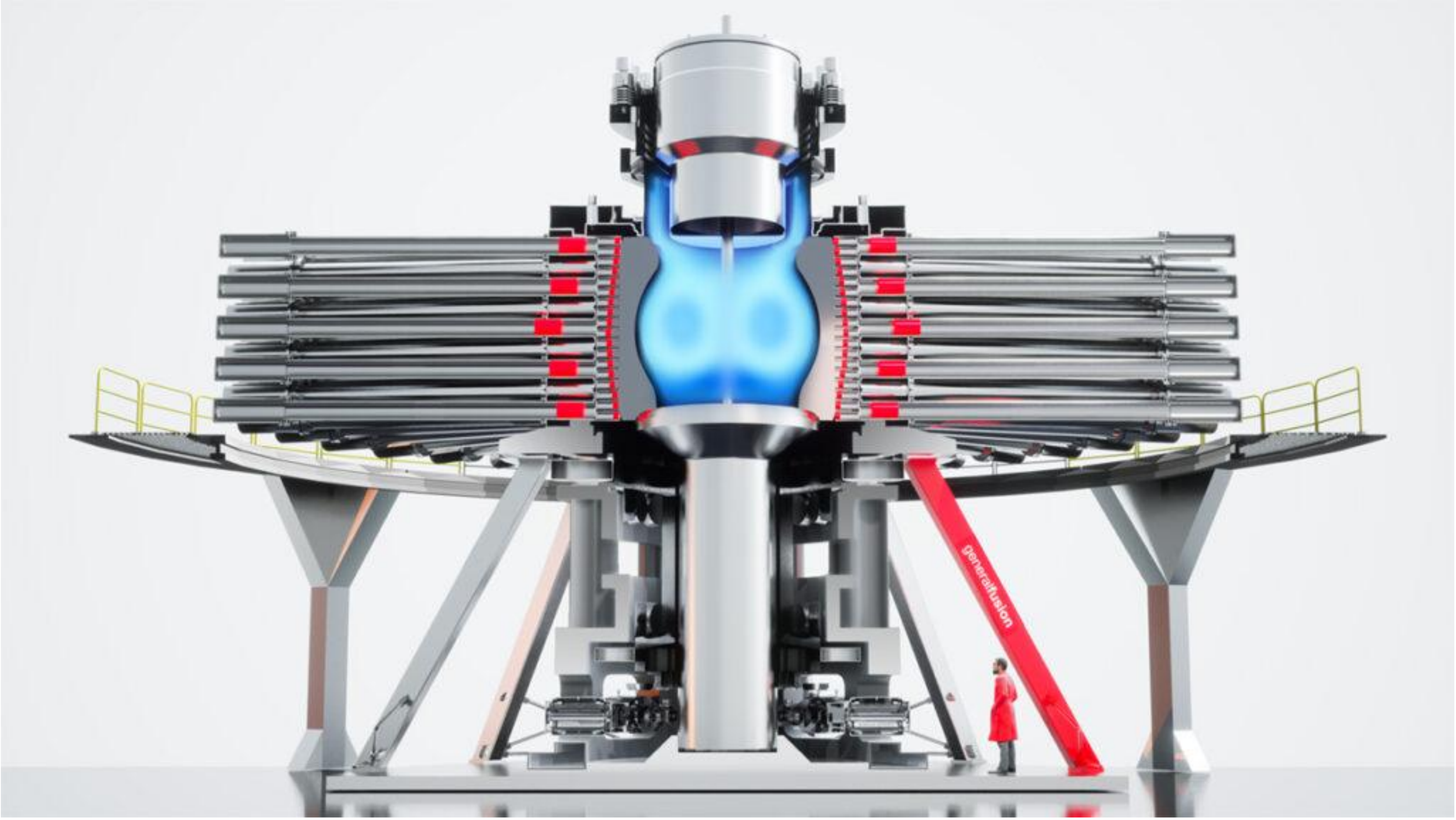
K. EPP, etc., 60th APS-DPP, CP11.00192

Plasma injector for the spherical tokamak

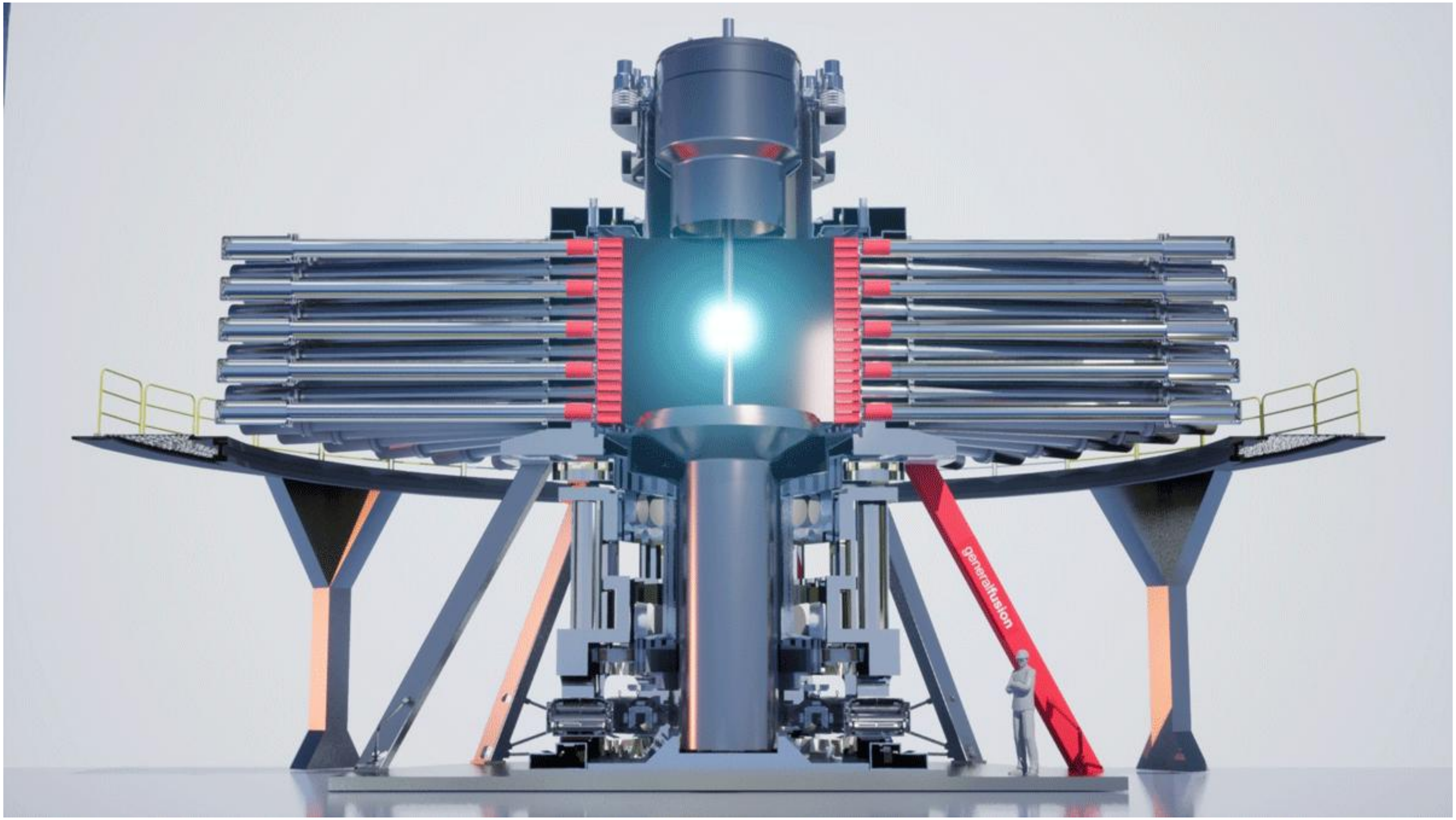


K. EPP, etc., 60th APS-DPP, CP11.00192

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

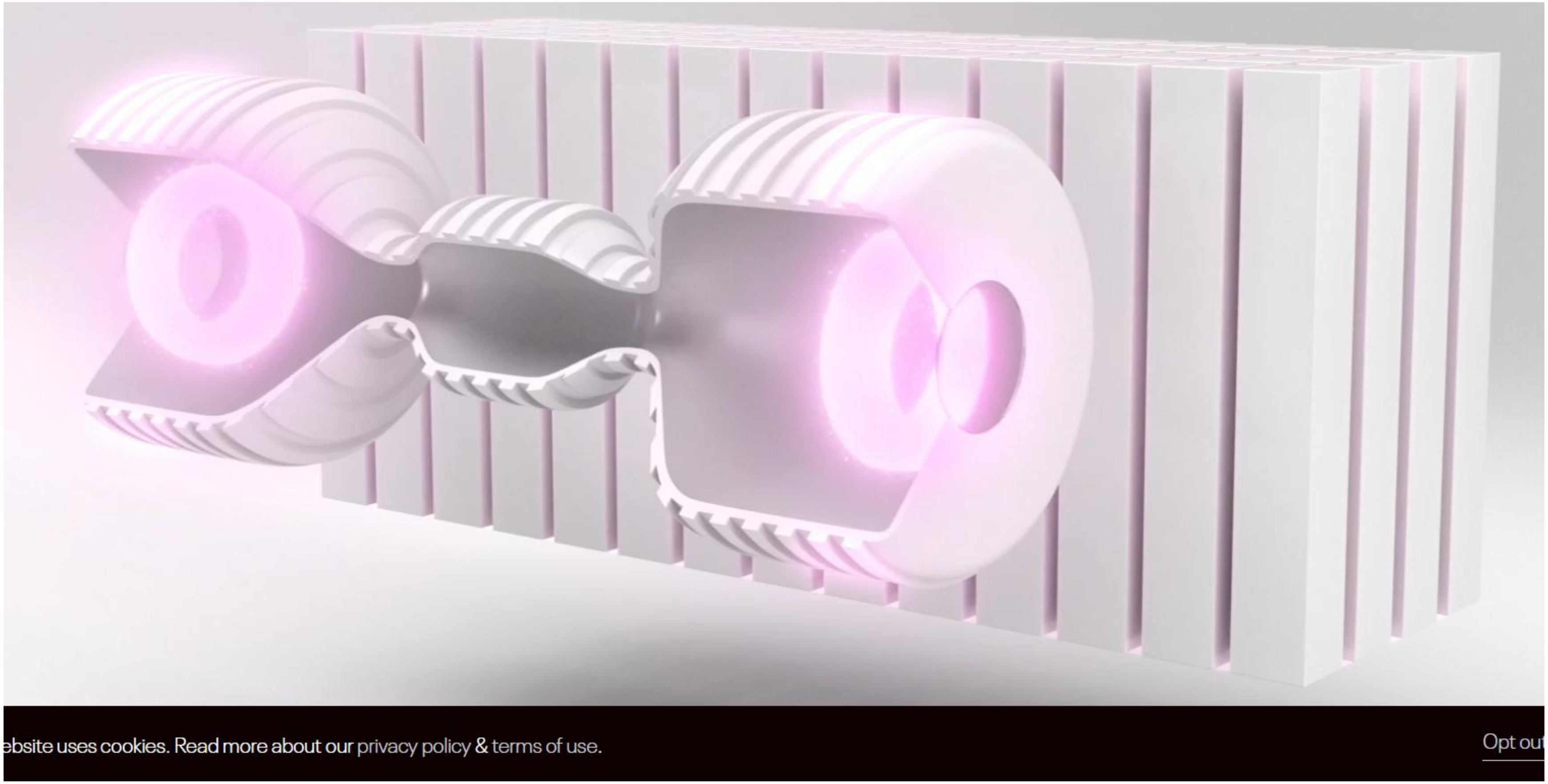
An artist's impression of what the new demonstration plant might look like

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

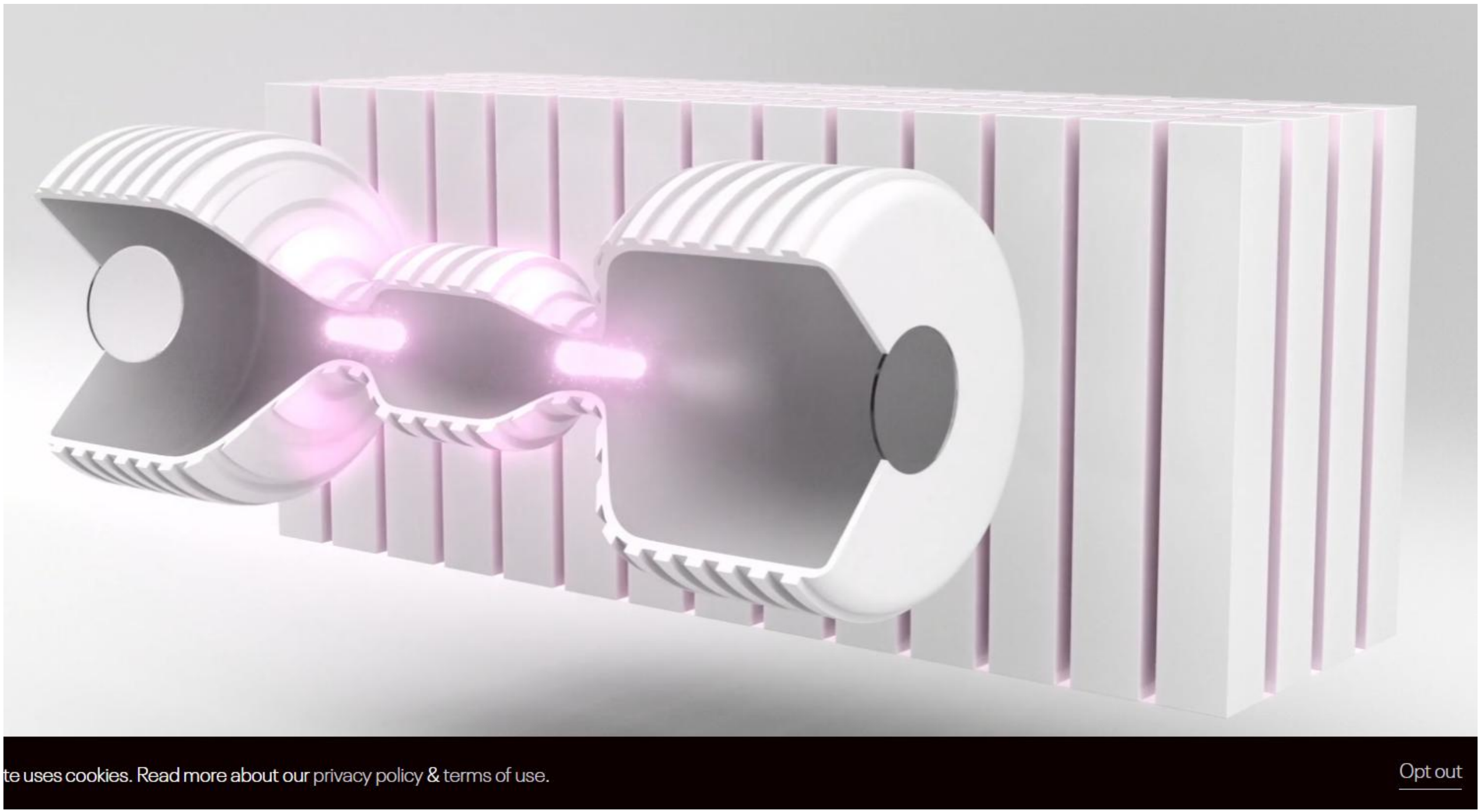
https://www.bbc.com/news/science-environment-57512229

Helion energy is compressing the two merging FRCs



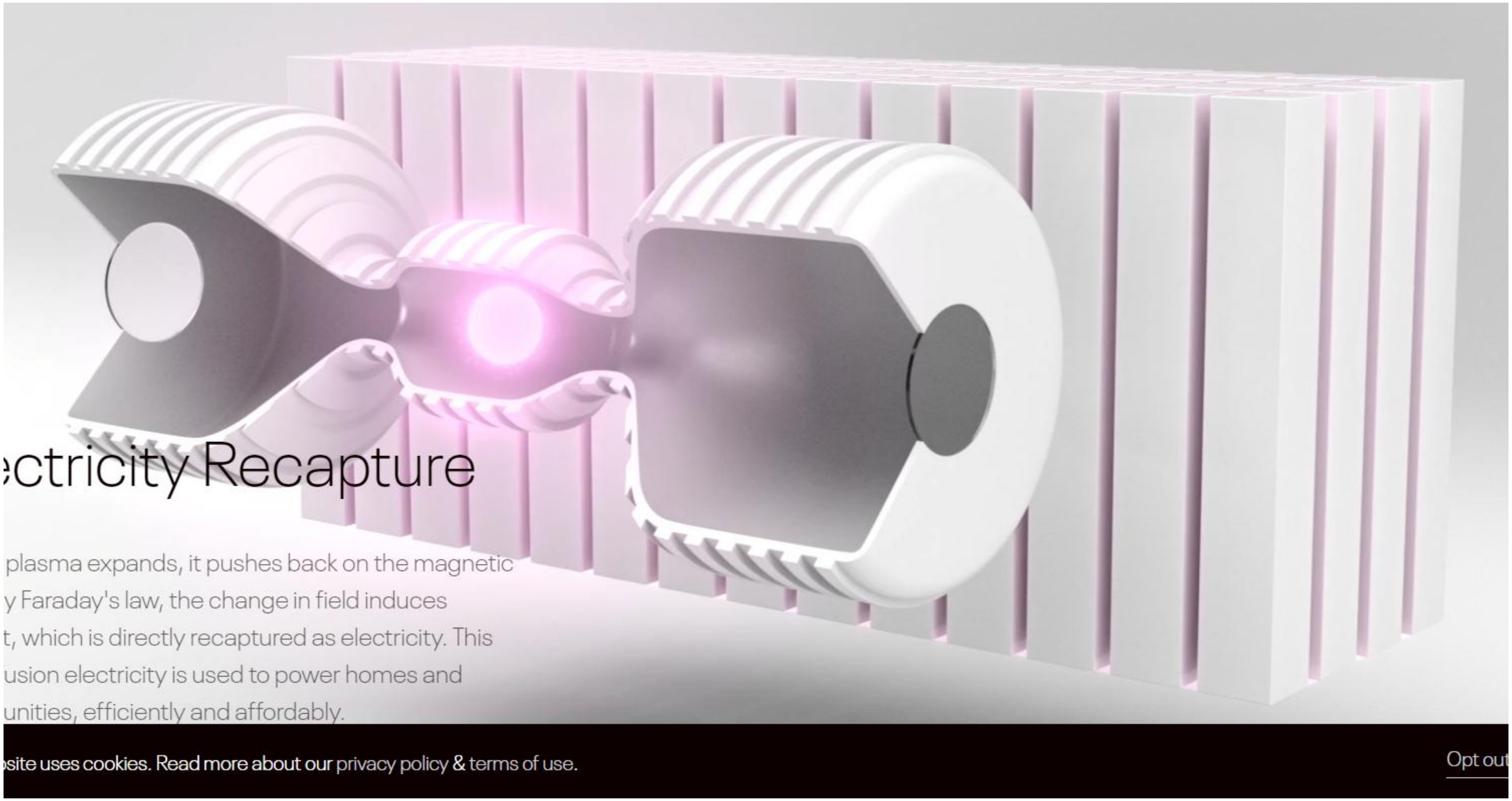
https://www.helionenergy.com/

Two FRCs are accelerated toward each other



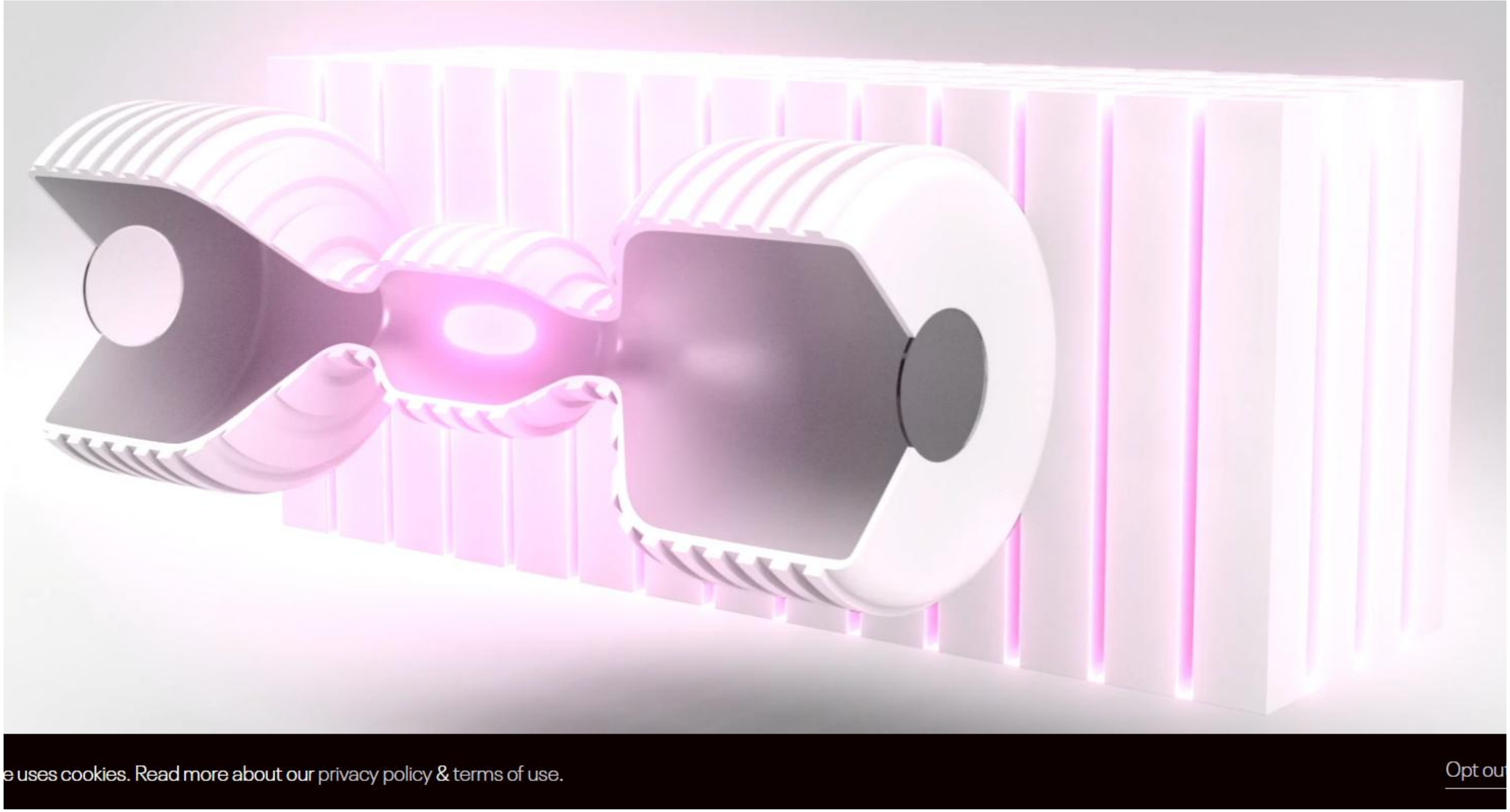
https://www.helionenergy.com/

Two FRCs merge with each other



https://www.helionenergy.com/

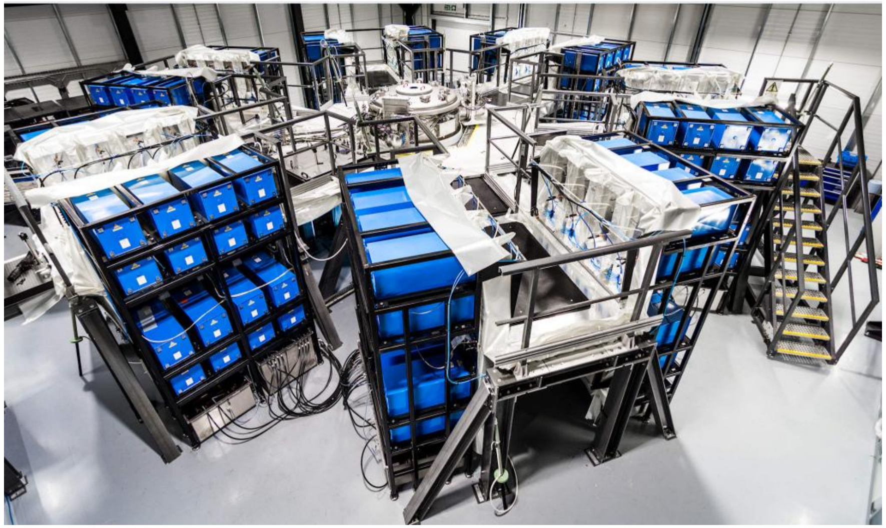
The merged FRC is compressed electrically to high temperature



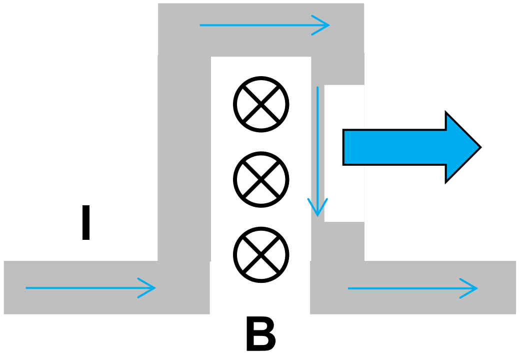
- **Similar concept will be studied in our laboratory.**

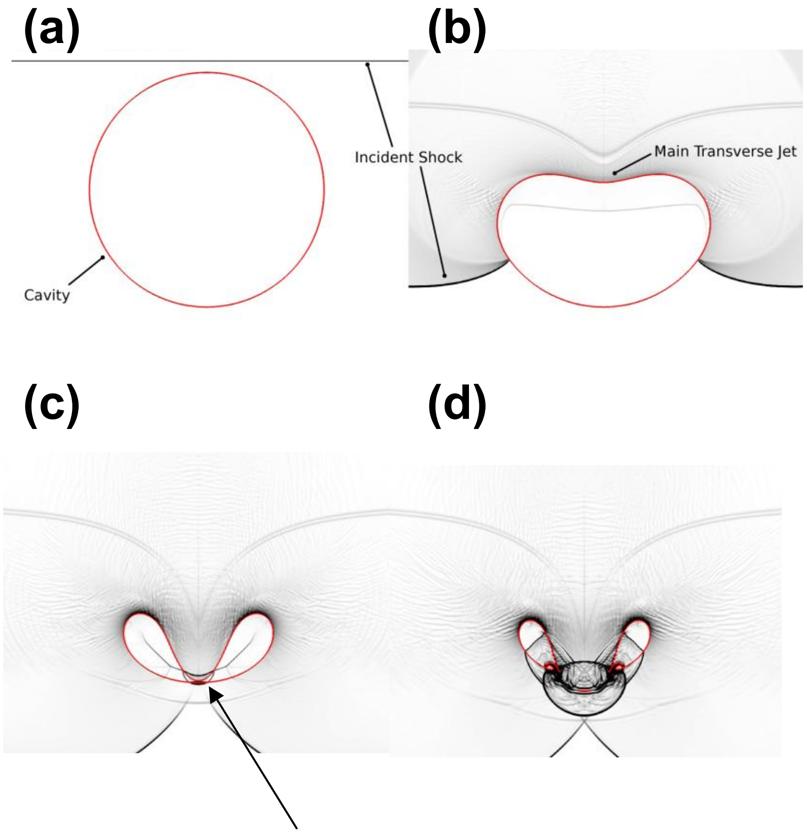
https://www.helionenergy.com/

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.**

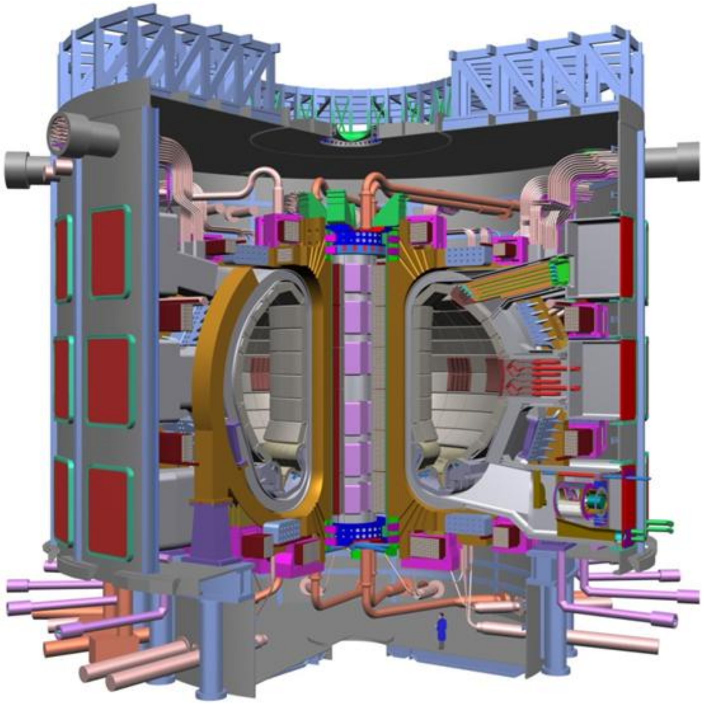
https://firstlightfusion.com/
B. Tully and N. Hawker, Phys. Rev. **E93**, 053105 (2016)

A gas gun is used to eject the projectile

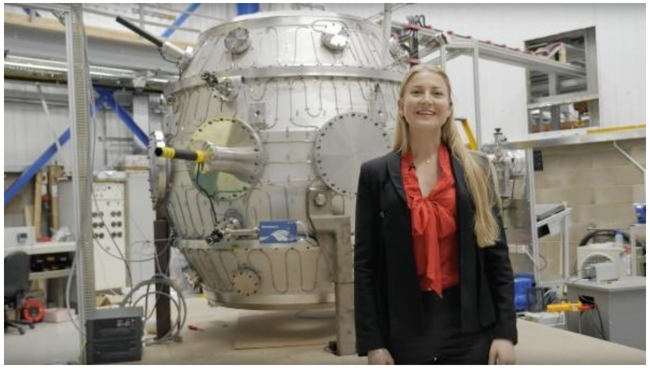
https://www.youtube.com/watch?v=JN7IyxC11n0
https://www.youtube.com/watch?v=aW4eufacf-8

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

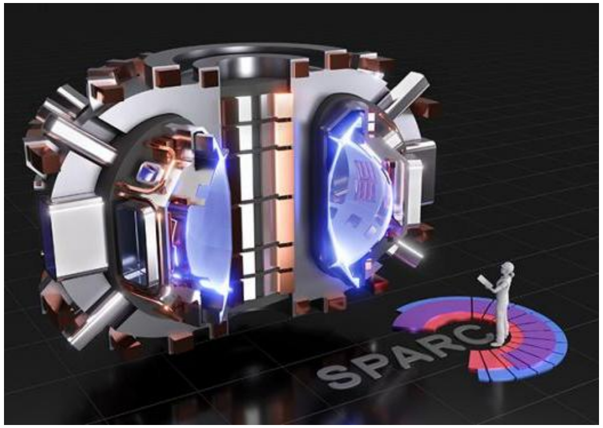
- **ITER – 2025 First Plasma**
  2035 D-T Exps
  2050 DEMO



- **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

FUSION INDUSTRY ASSOCIATION

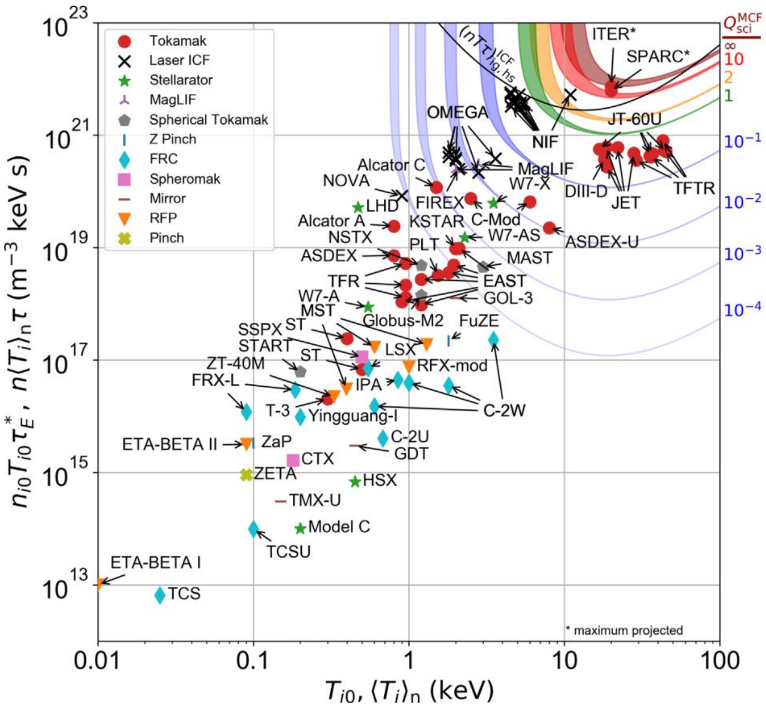
generalfusion
Commonwealth Fusion Systems
tae
ZAP ENERGY
TYPE ONE ENERGY
HELION
OPENSTAR TECHNOLOGIES LTD
REALTA FUSION
THEA ENERGY
Tokamak Energy
XCIMER ENERGY CORPORATION
acceleron
ANUBAL FUSION
BLUE LASER FUSION
ELECTRIC FUSION SYSTEMS
Helical Fusion
HelicitySpace
HORNE TECHNOLOGIES
PRANOS FUSION ENERGY
RENAISSANCE FUSION
SHINE
STELLAREX
TERRA FUSION

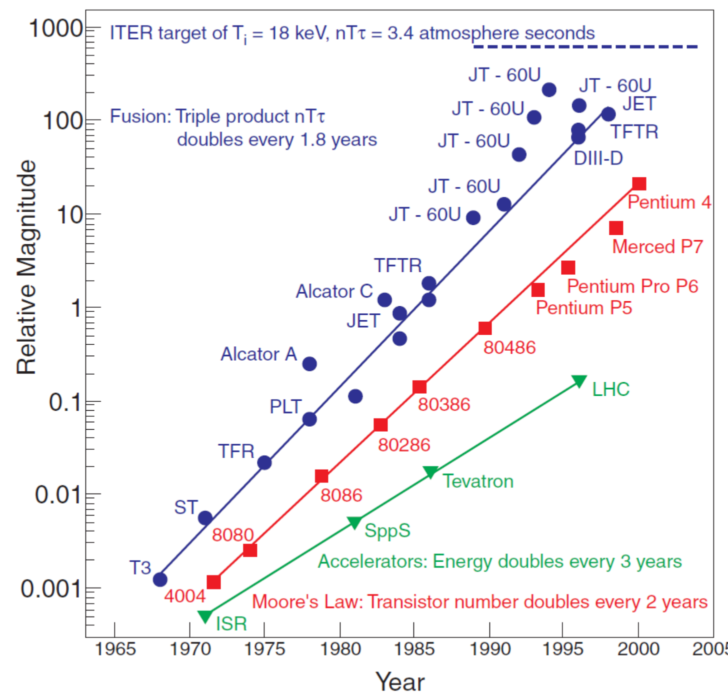
AVALANCHE
Proxima Fusion
PACIFIC FUSION
EX-Fusion
first light
FOCUSED
fuse
GAUSS FUSION
HB11 ENERGY
KYOTO FUSIONEERING
MarvelFusion
LaserFusionX
LONGVIEW FUSION
LPP FUSION
MARITIME FUSION
MIFTI
nearstar FUSION
NOVATRON
nT-tao Compact Fusion Power

MCF
MTF
ICF

https://www.fusionindustryassociation.org/members

We are closed to ignition!

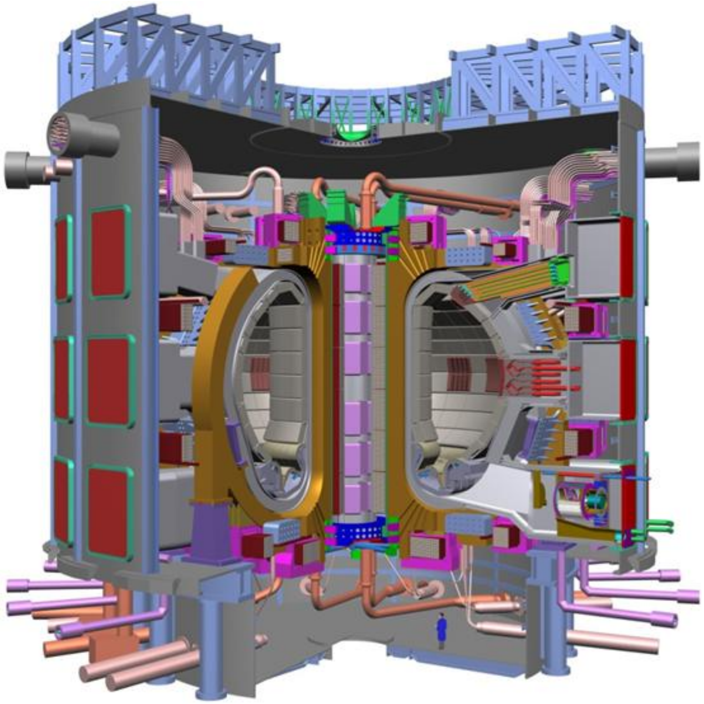




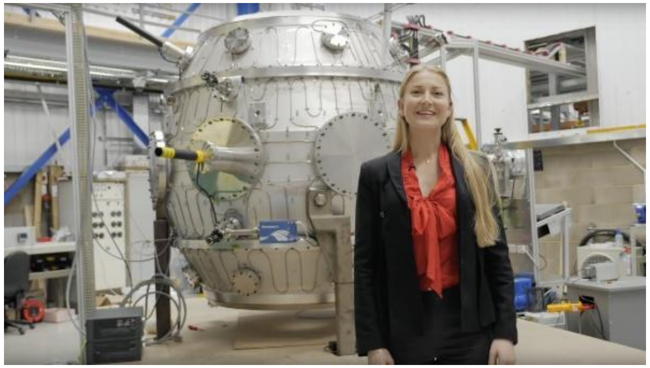
Samuel E. Wurzel and Scott C. Hsu, Phys. Plasmas, **29**, 062103 (2022)
R. Betti, etc., Phys. Plasmas, **17**, 058102 (2010)

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

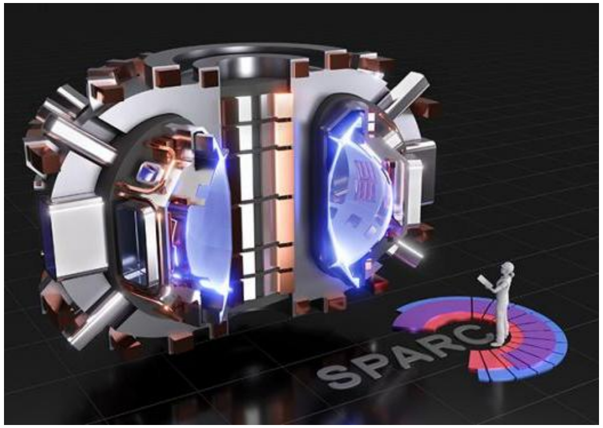
- **ITER – 2025 First Plasma**
  2035 D-T Exps
  2050 DEMO



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

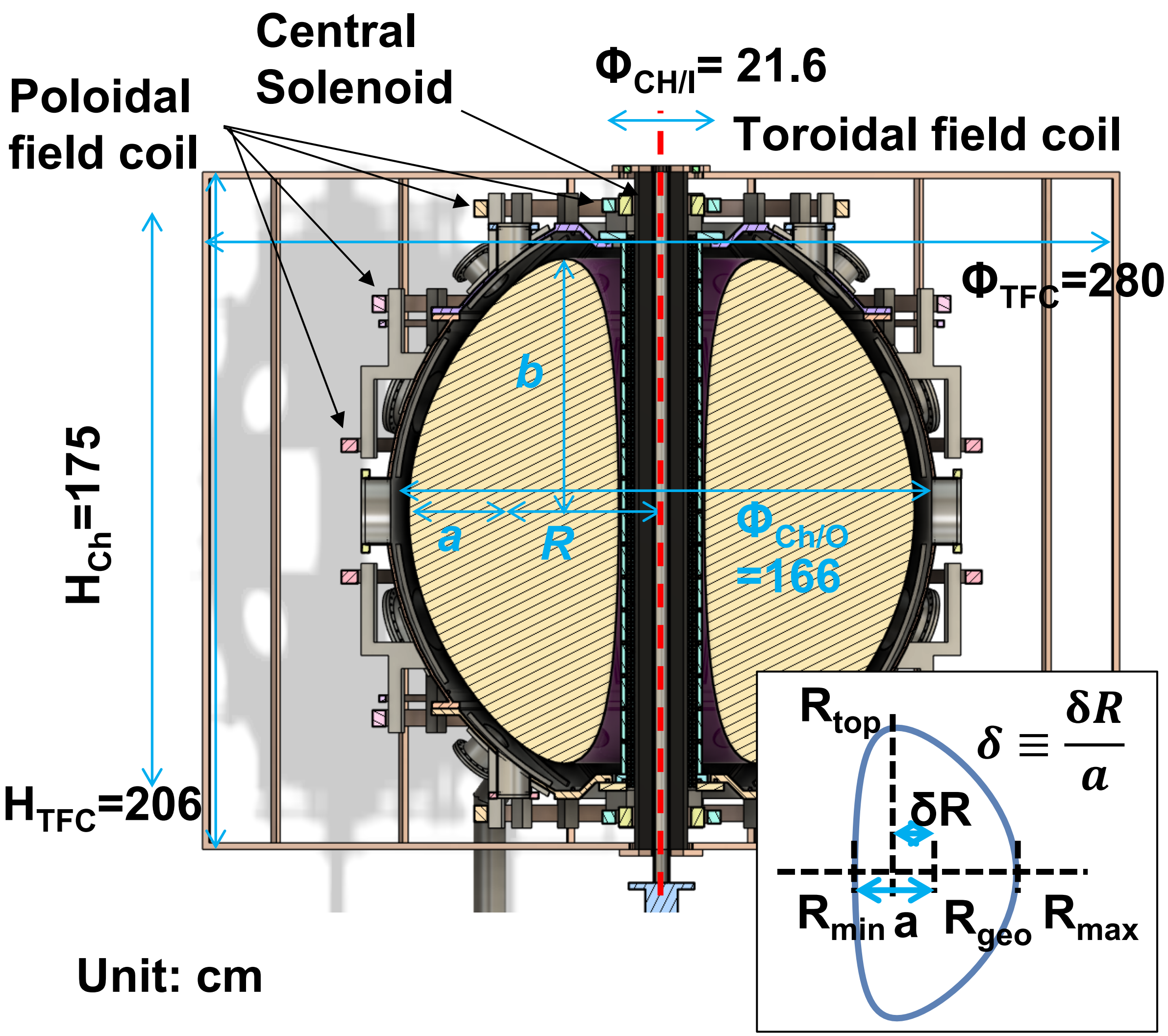


- **Commonwealth Fusion Systems, USA – 2025 Gain**



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

Formosa Integrated Research Spherical Tokamak (FIRST)



Unit: cm

- $R/a/b$=45/32/76.8 cm
- Aspect ratio = R/a = 1.5
- $k = b/a$ = 2.4
- δ = 0.5
- B_T = 0.1 ~ 0.5 T
- $T \geq$ 100 eV
- $I_p \geq$ 100 kA
- Gas: H_2
- Ohmic heating
- Duration: 100 ms
- TFC x16; PFC x12; CS
- FIRST is targeted for
  - Low aspect ratio
  - High beta
  - High bootstrap current

- **First plasma: 2026.**

- FIRST is still under detailed designed. Figure here may NOT the final design.

Teams

- 馬維揚團隊 @ 國家原子能科技研究院
  - Site
- 張博宇團隊 @ 成功大學 太空與電漿科學研究所
  - System design and development/diagnostics
- 向克強團隊 @ 成功大學 前瞻電漿中心
  - Theoretical design
- 河森榮一郎團隊 @ 成功大學 太空與電漿科學研究所
  - Diagnostics
- 柳克強團隊 @ 清華大學 工程與系統科學系
  - Diagnostics
- 蔡宗哲團隊 @ 國家高速網路與計算中心
  - Simulation
- 張存續團隊 @ 清華大學 物理系
  - RF startup

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