

Introduction to Nuclear Fusion as An Energy Source



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Lecture 14

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)



Note!



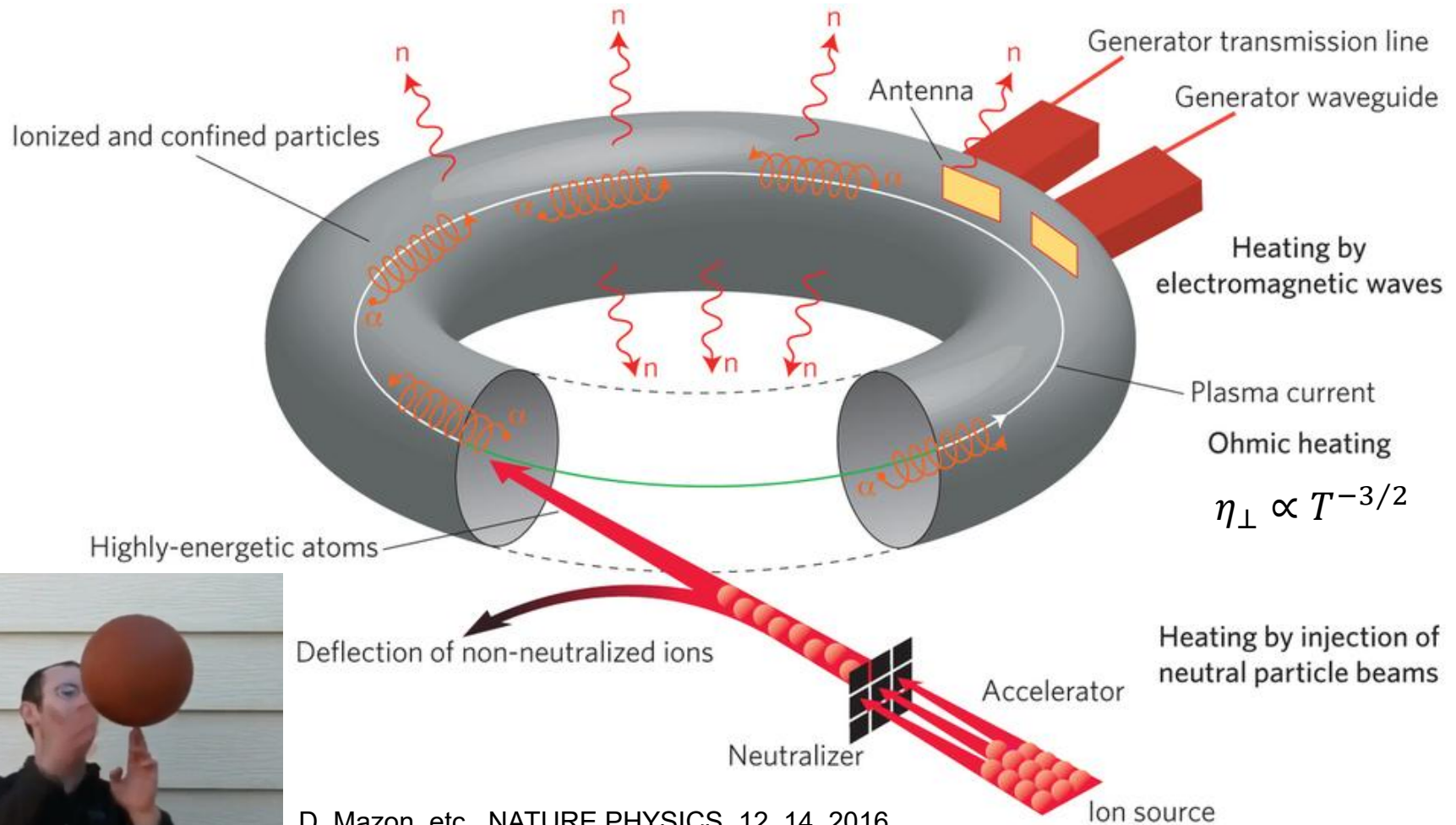
- **Final exam:**
 - **6/18 (Closed book, no cheating sheet is allowed.).**
 - **The final exam covers the entire semester's content.**

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.

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



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>



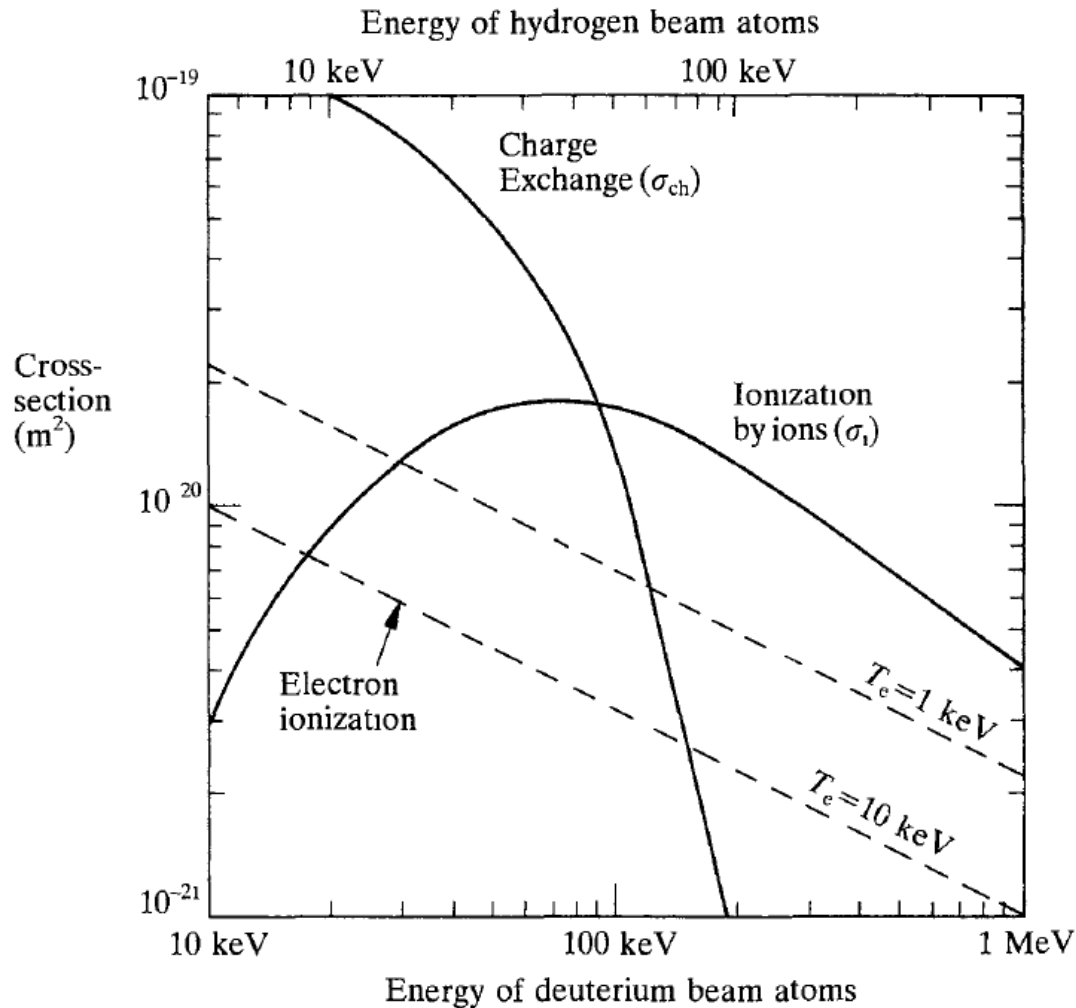
Varies way of heating a MCF device



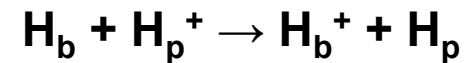
	System	Frequency/ energy	Maximum power coupled to plasma	Overall system efficiency	Development/ demonstration required	Remarks
ECRF	Demonstrated in tokamaks	28–157 GHz	2.8 MW, 0.2 s	30–40%	Power sources and windows, off-axis CD	Provides off-axis CD
	ITER needs	150–170 GHz	50 MW, SS			
ICRF	Demonstrated 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, SS			
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, SS			
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			
	–ve ion Demonstrated in tokamaks	0.35 MeV	5.2 MW, D ⁺ , 0.8 s (from 2 sources)	~37%	System, tests on tokamak, plasma CD	provides rotation
	ITER needs	1 MeV	50 MW, SS			

‘SS’ indicates steady state

Neutral atoms are ionized by collisions in the plasma



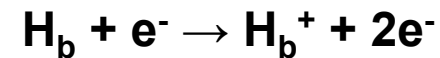
- Charge exchange:



- Ionization by ions



- Ionization by electrons

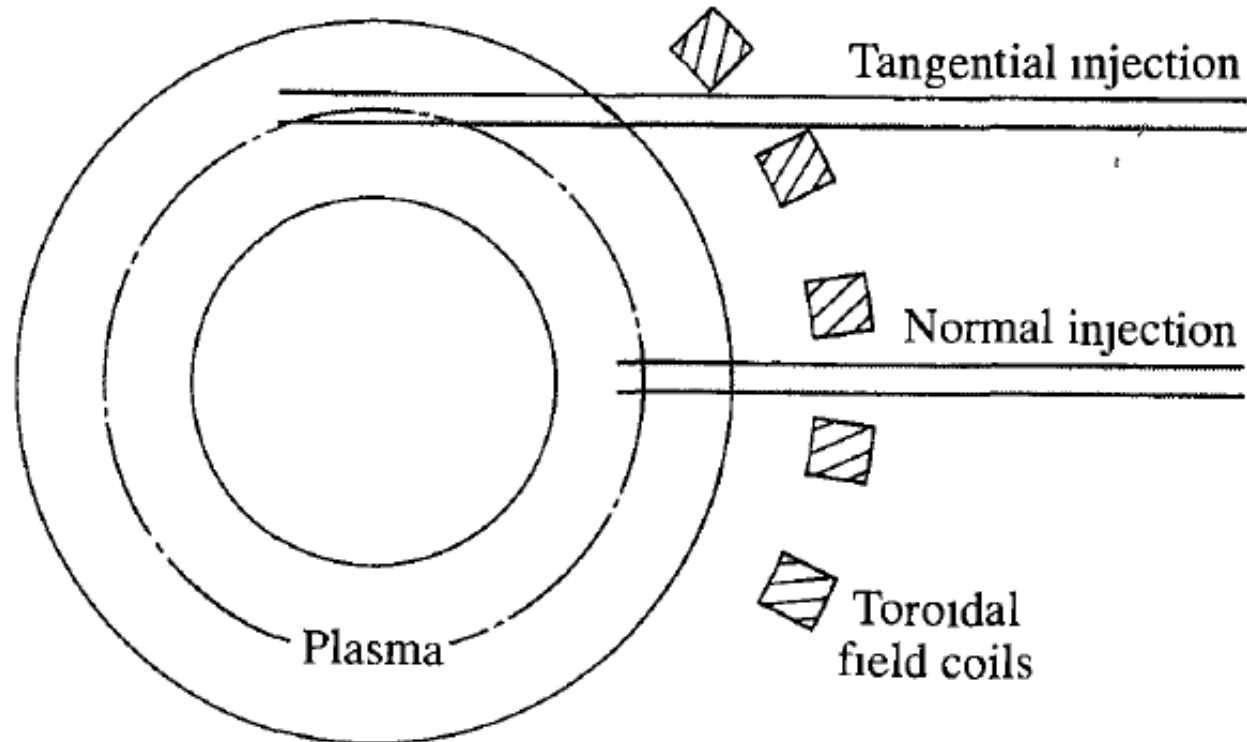


b: beam
p: plasma

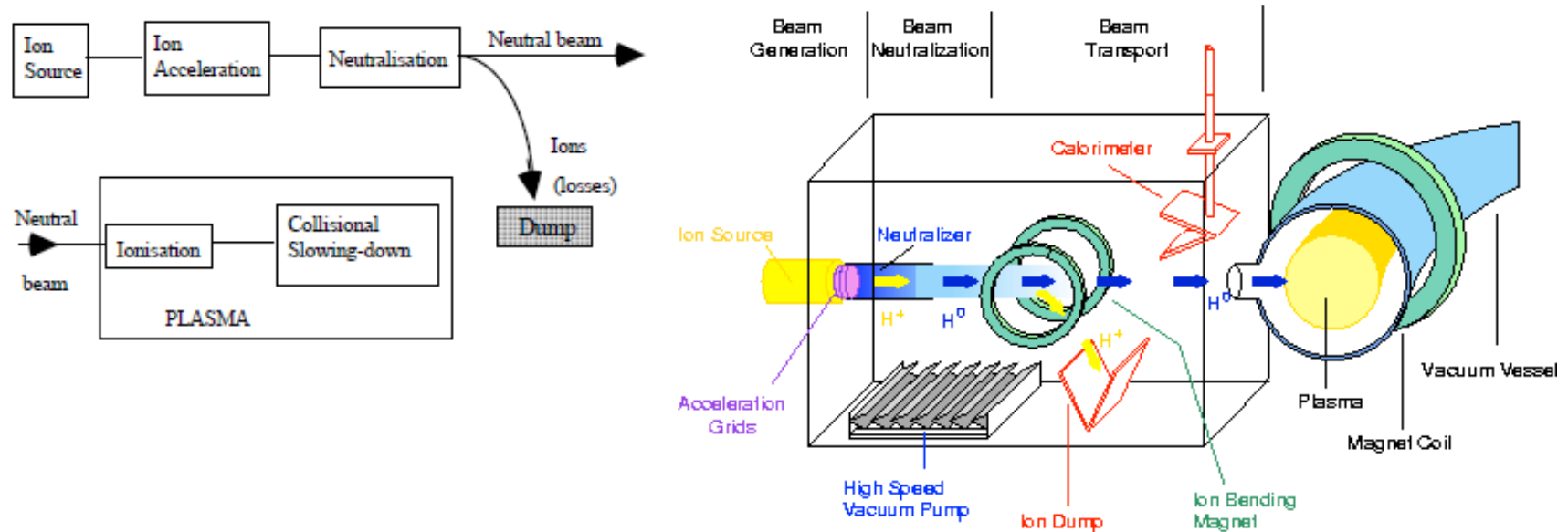
Neutral beam absorption length increases with tangential injection



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

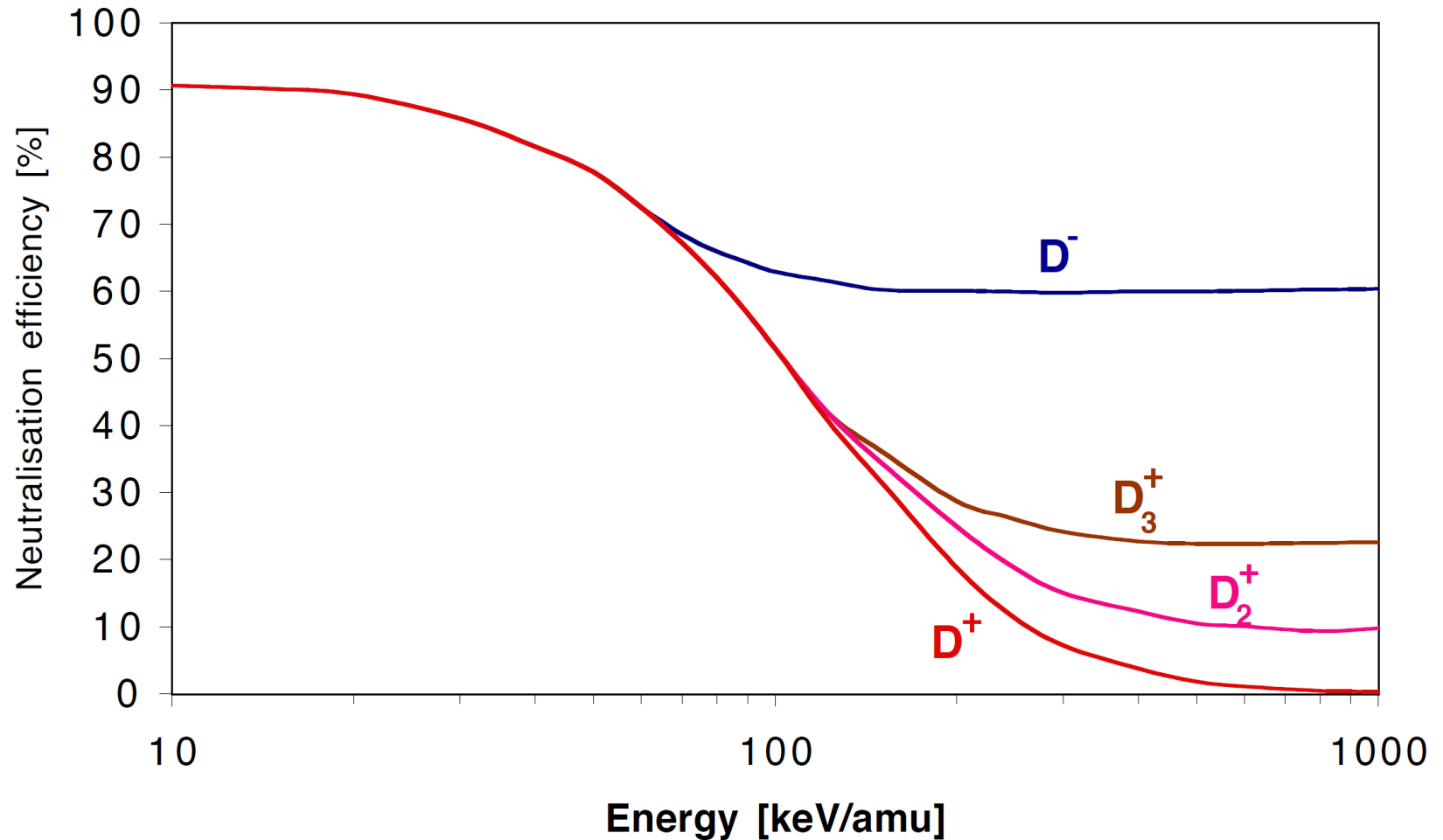


Neutral particles heat the plasma via coulomb collisions



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

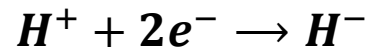
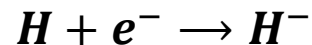
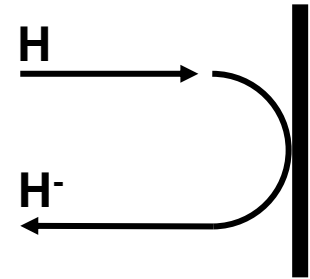


There are two ways to make negative ions – surface and volume production

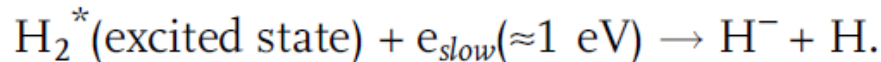
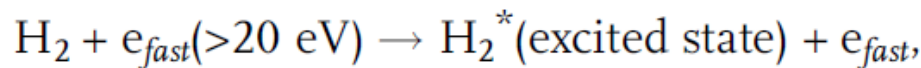


- **Surface production, depends on :**

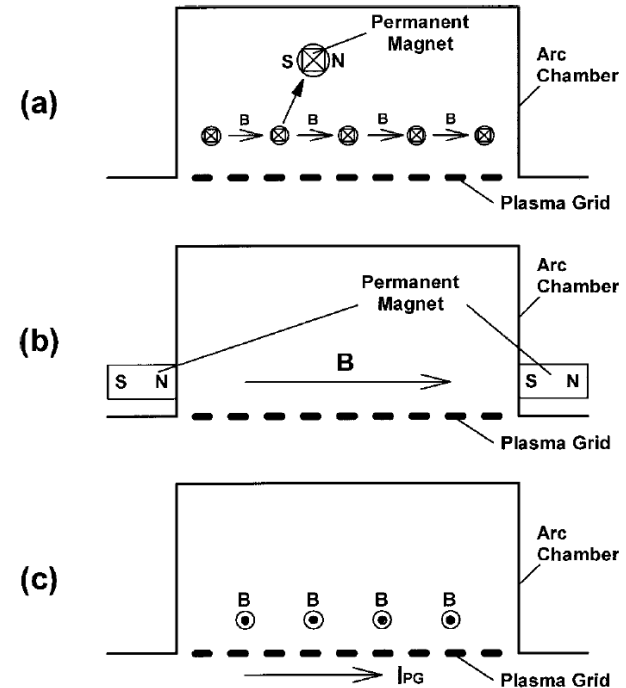
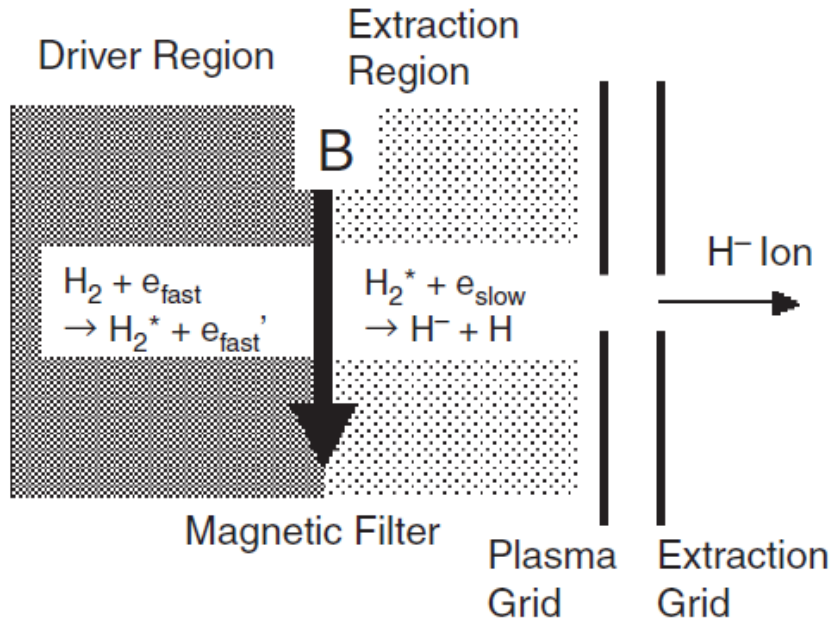
- **Work function Φ**
- **Electron affinity level, 0.75 eV for H^-**
- **Perpendicular velocity**
- **Work function can be reduced by covering the metal surface with cesium**



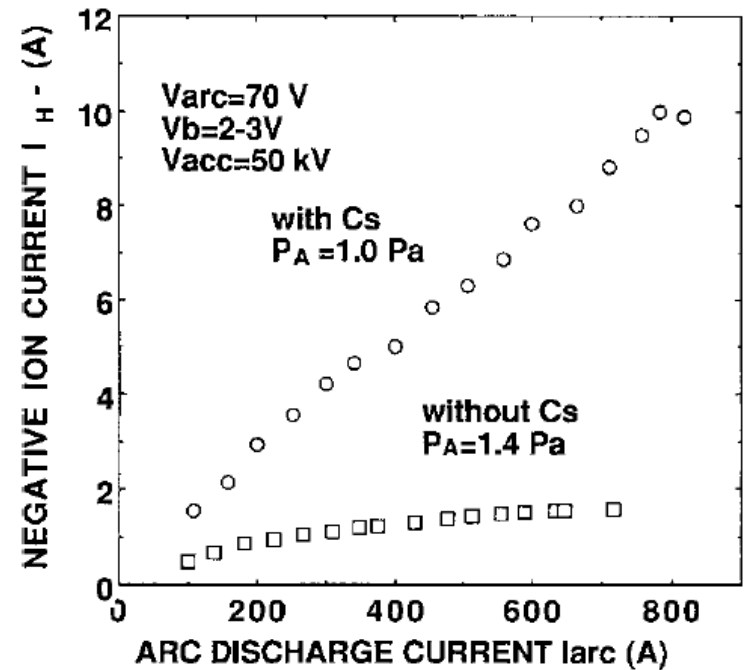
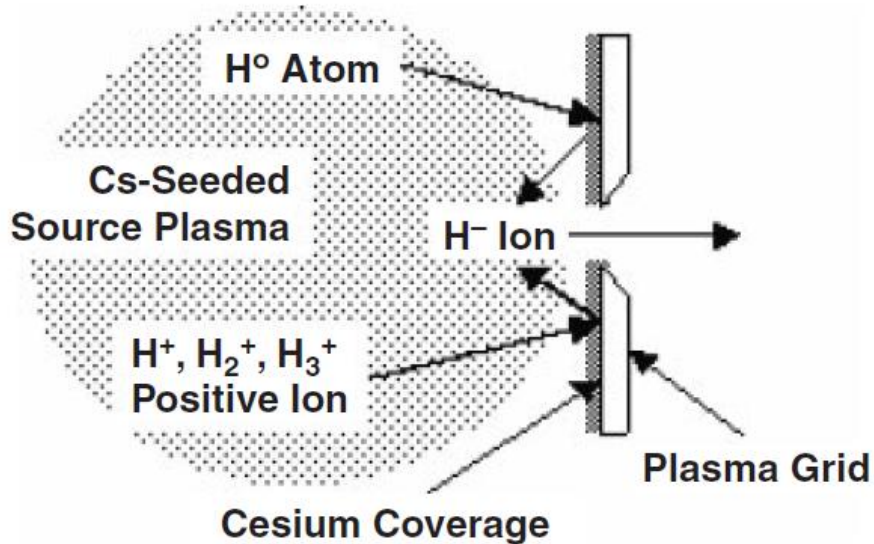
- **Volume production:**



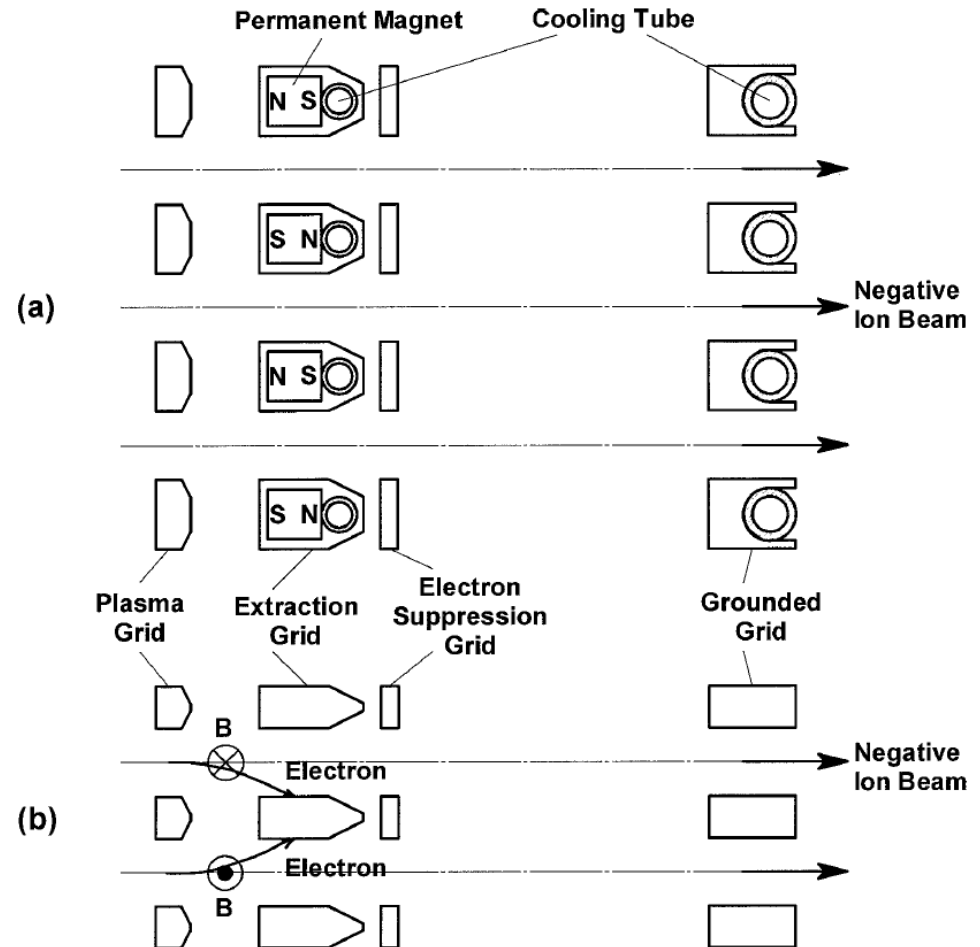
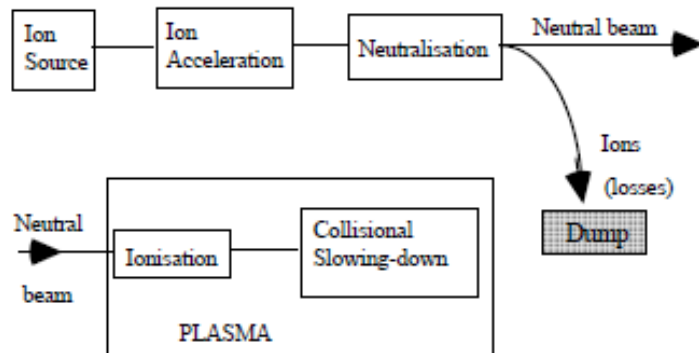
Two-chamber method of negative ions in volume production with a magnetic filter



Adding cesium increases negative ion current



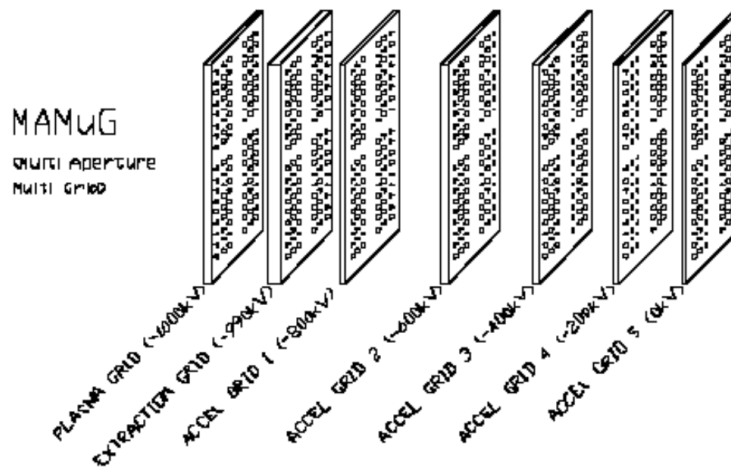
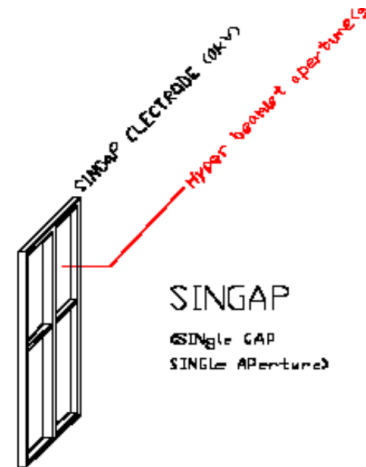
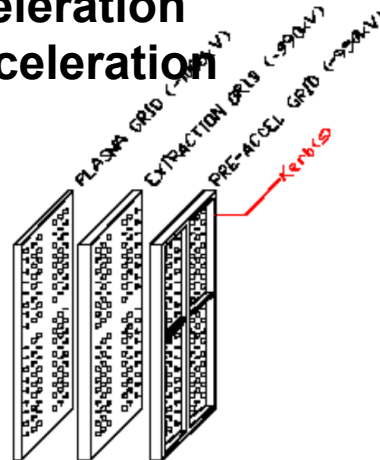
Electrons need to be filtered out since they are extracted together with negative ions



Acceleration

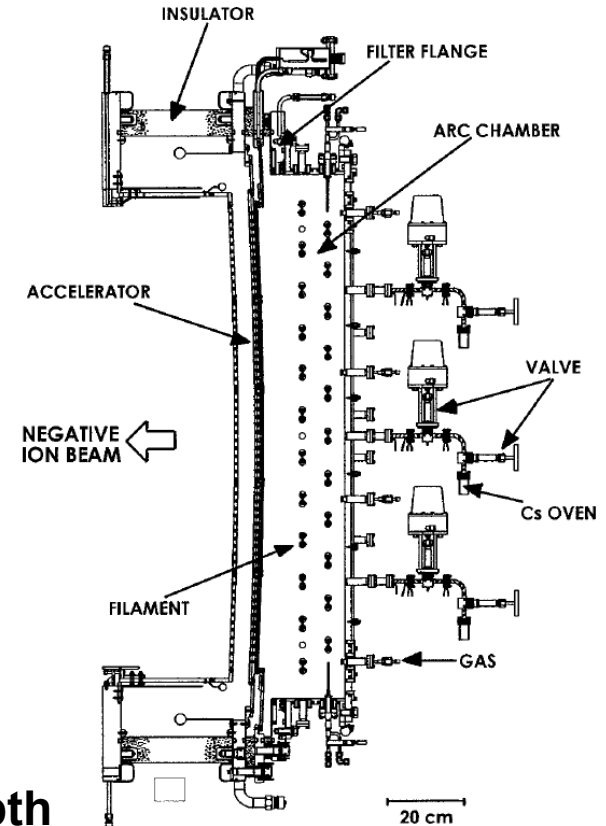
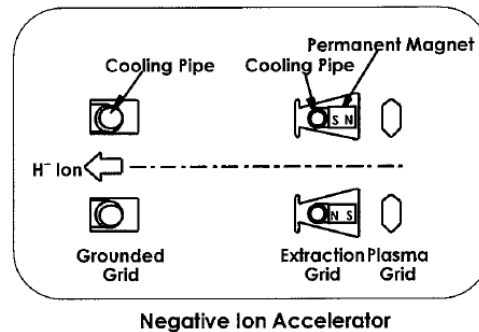
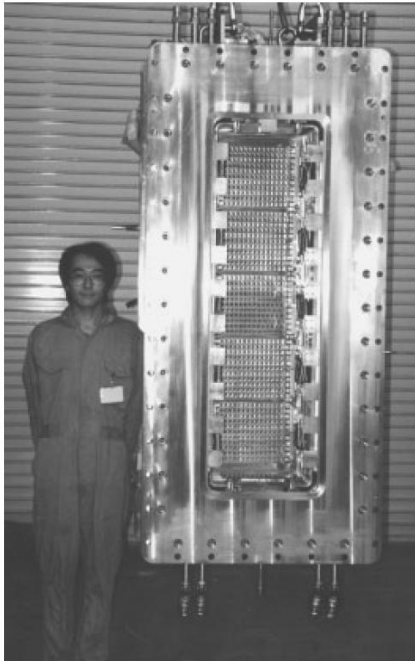


- Multi-stage acceleration
- Single-stage acceleration



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

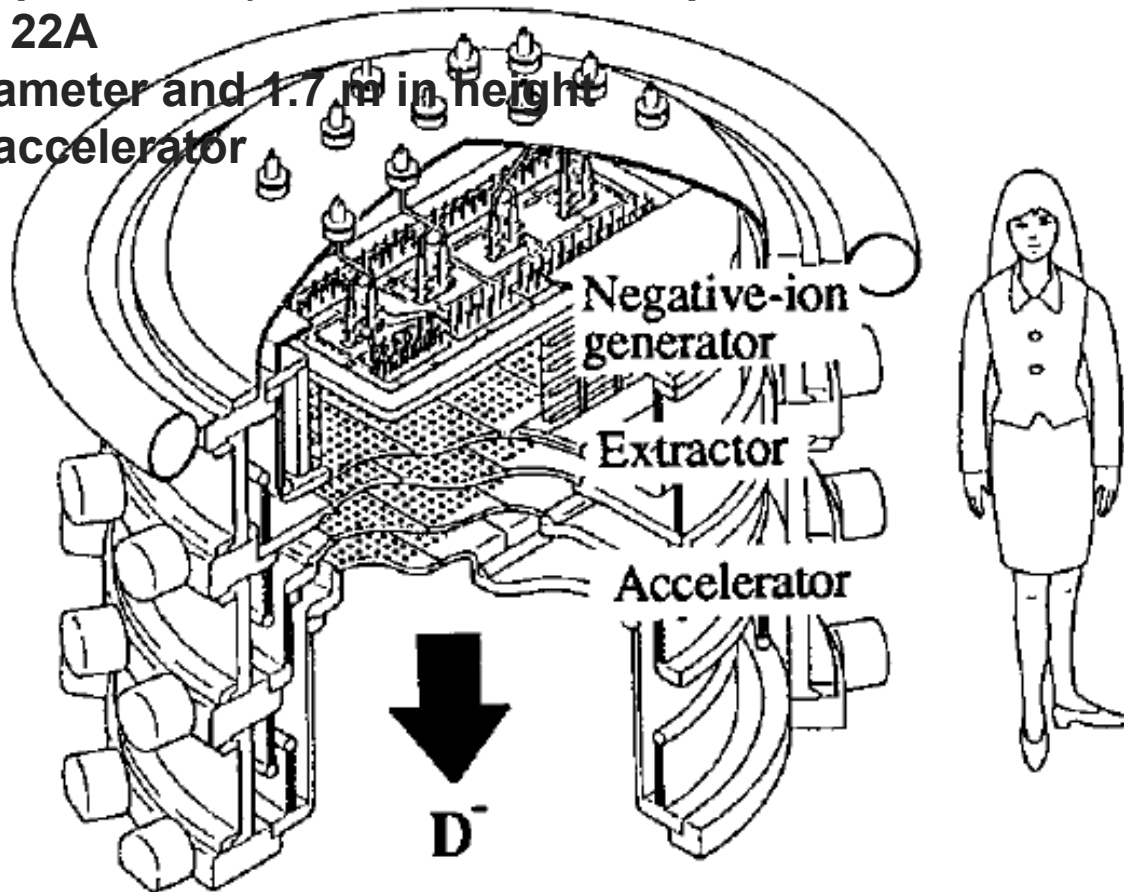


- 180 keV and 30 A
- Arc chamber: 35 cm x 145 cm, 21cm in depth
- Single stage accelerator

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

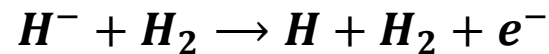


Neutralization



- **Gas neutralization**

- **Collisions between fast negative ions and atoms**

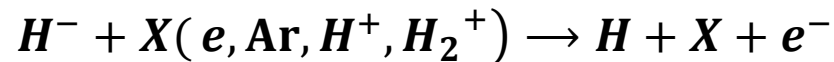


- **Fast ions can lose another electron after neutralized**



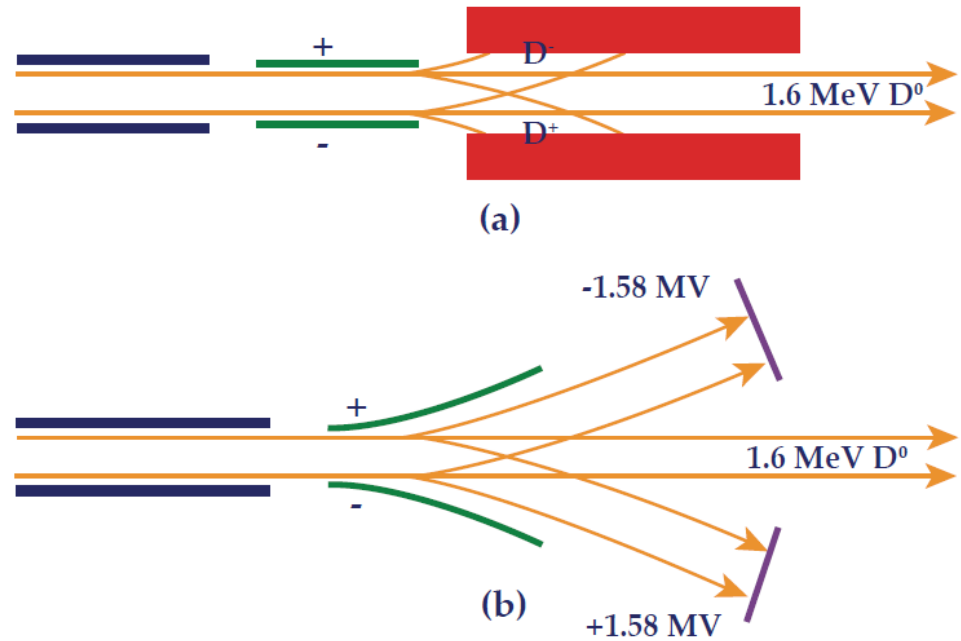
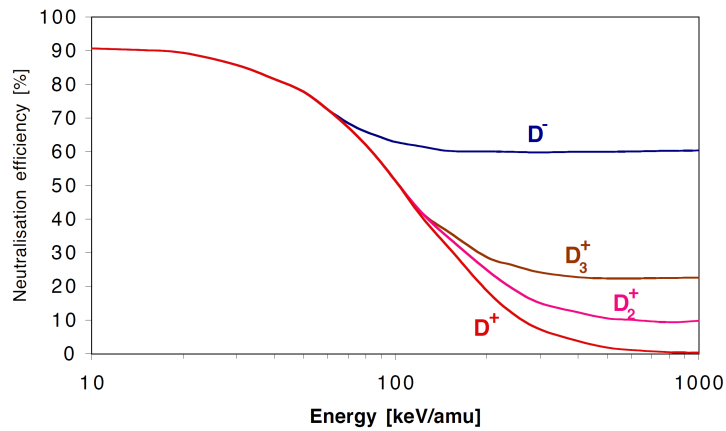
- **Plasma neutralization**

- **Collisions with charged particles in plasma**



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

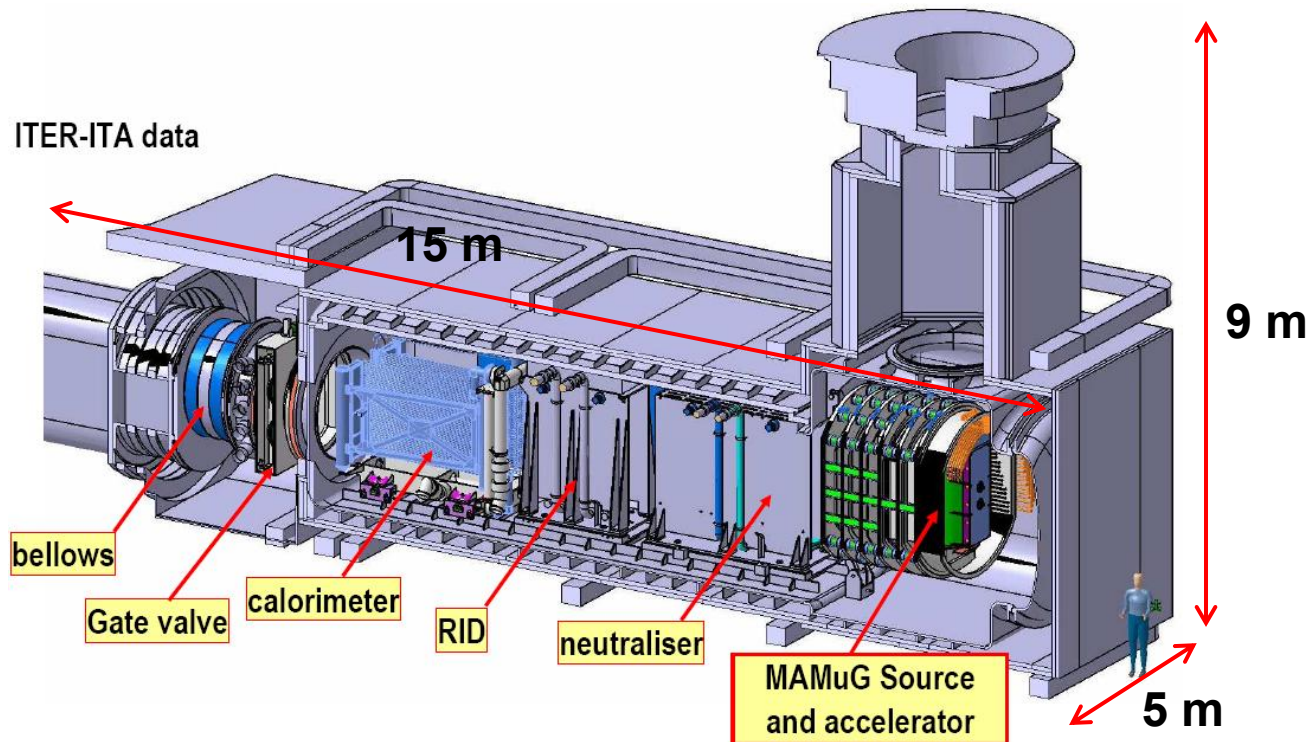
Beam dump



NBI for ITER

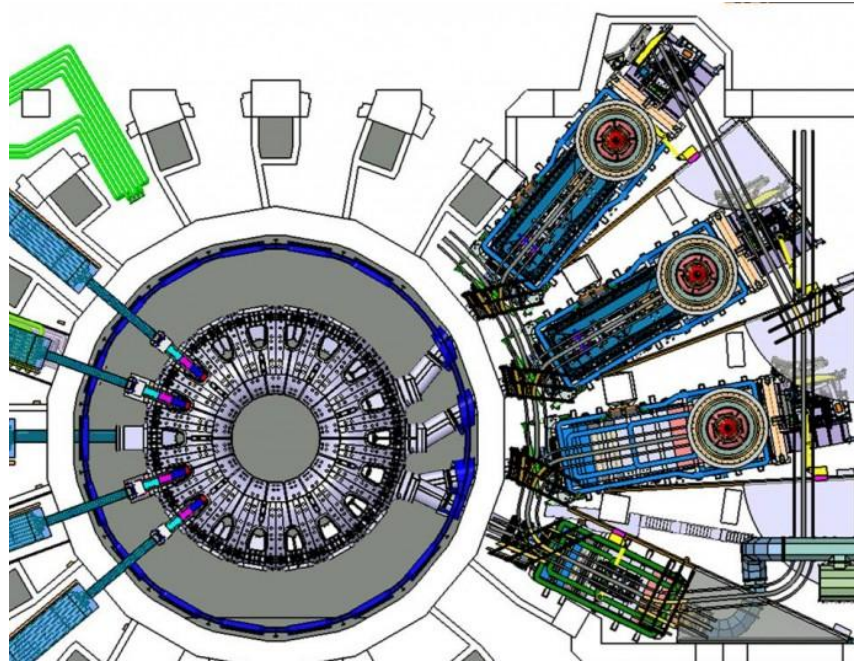


- beam components (Ion Source, Accelerator, Neutralizer, Residual Ion Dump and Calorimeter)
- other components (cryo-pump, vessels, fast shutter, duct, magnetic shielding, and residual magnetic field compensating coils)



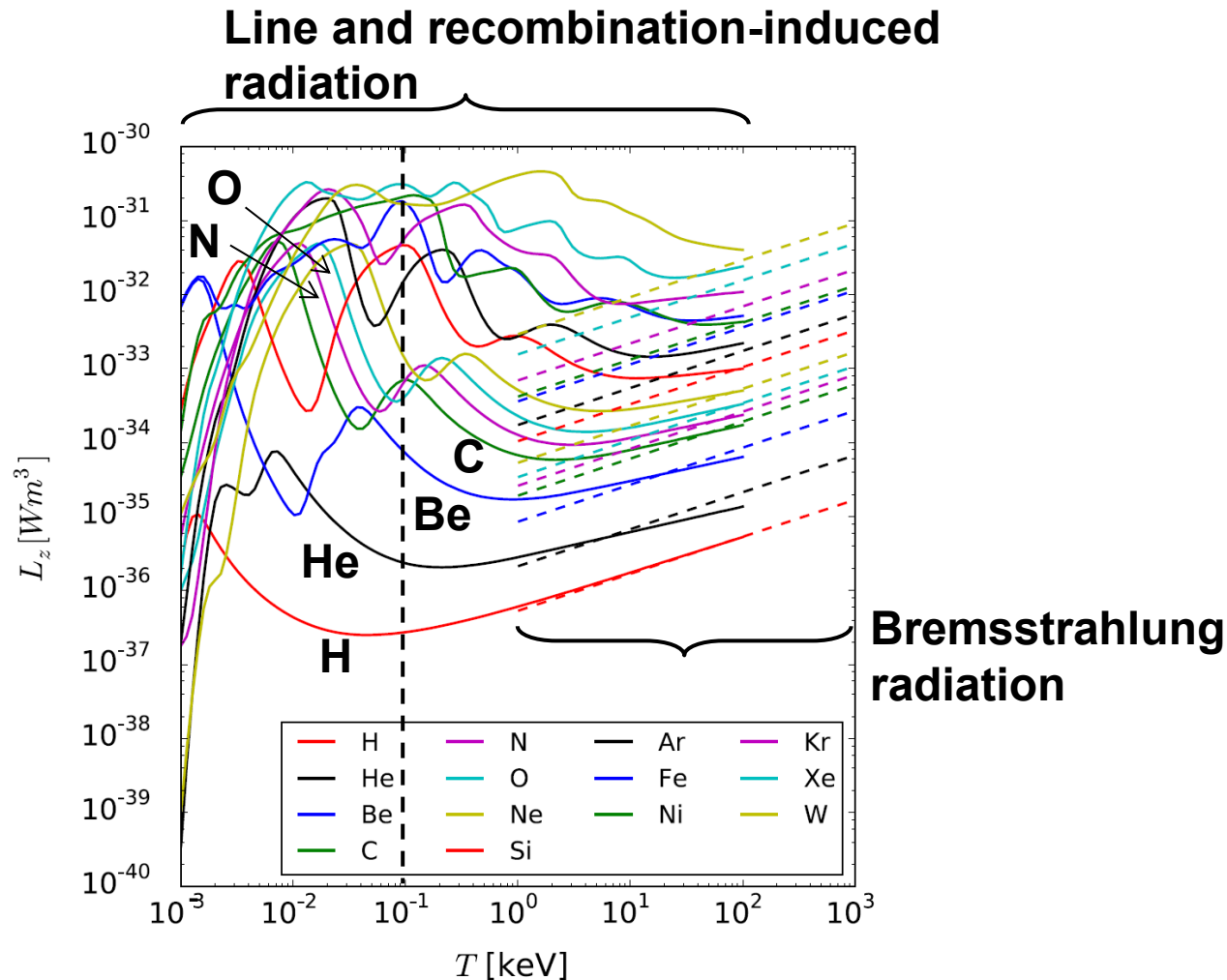
The ITER neutral beam system: status of the project and review of the main technological issues, presented by V. Antoni

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

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



Reference for MCF



- **Jeffrey P. Freidberg, Ideal Magnetohydrodynamics**
- **John Wesson, Tokamaks**
- **Tokamak Physics by 陳騷 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

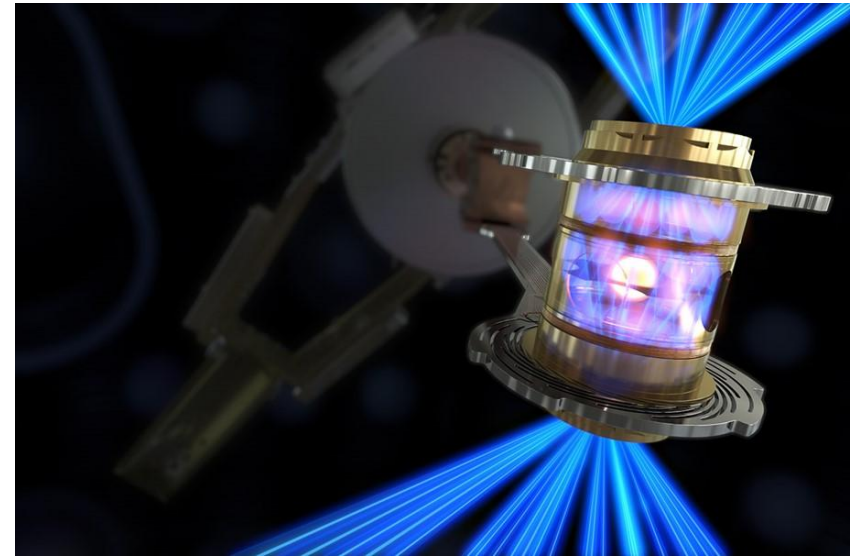
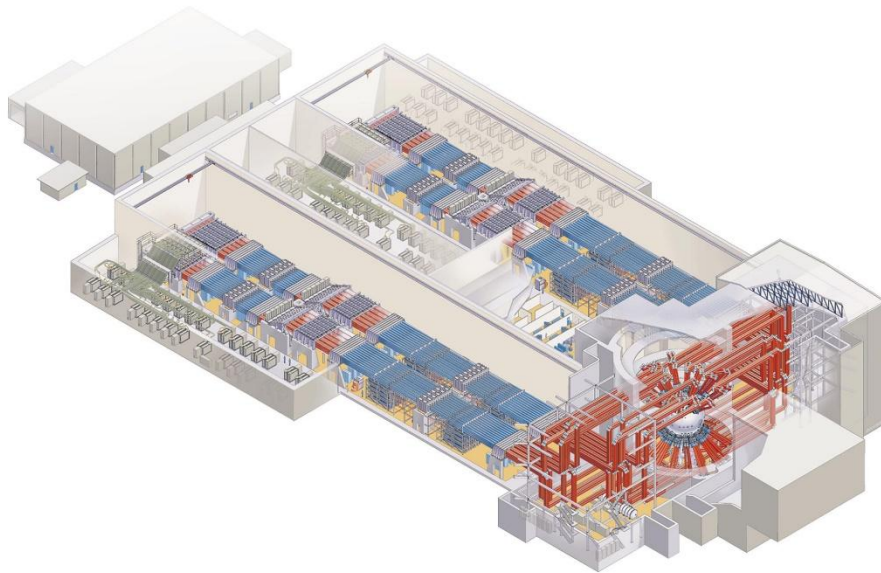
Ignition condition: $P\tau > 10 \text{ atm-s} = 10 \text{ Gbar - ns}$

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

Significant breakthrough was achieved in ICF recently



- Inertial confinement fusion (ICF)

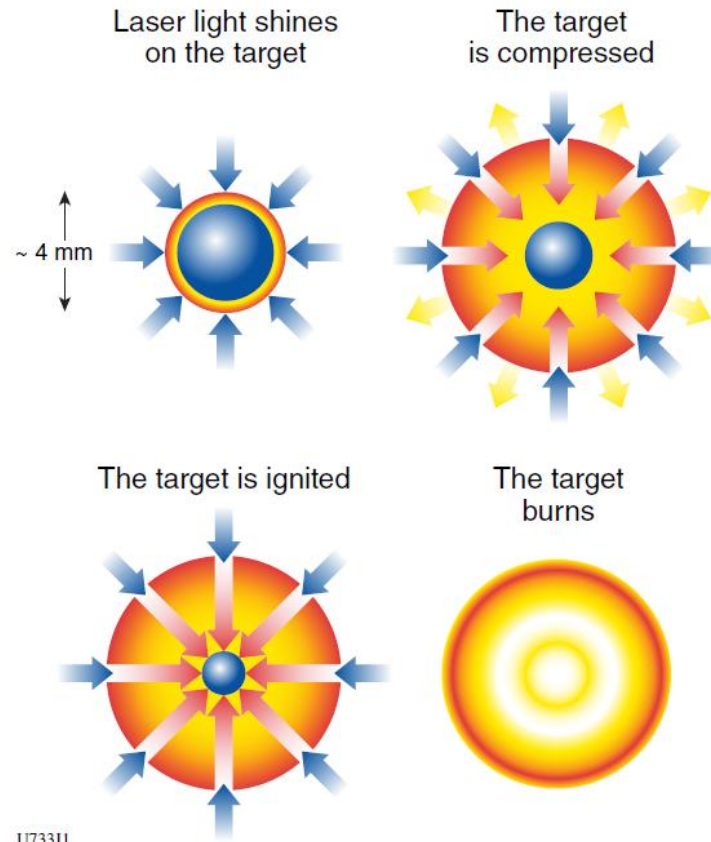


- **National Ignition Facility (NIF) demonstrated a gain greater than 1 for the first time on 2022/12/5. The yield of 3.15 MJ from the 2.05-MJ input laser energy, i.e., $Q=1.5$.**

Don't confine it!

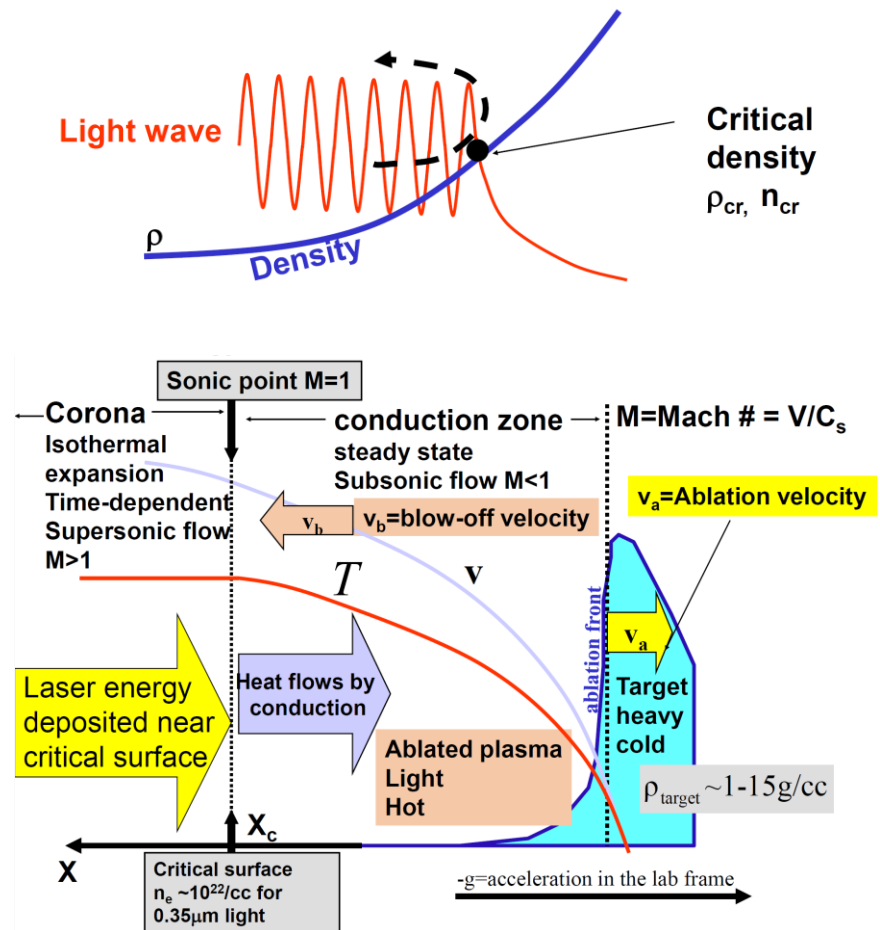
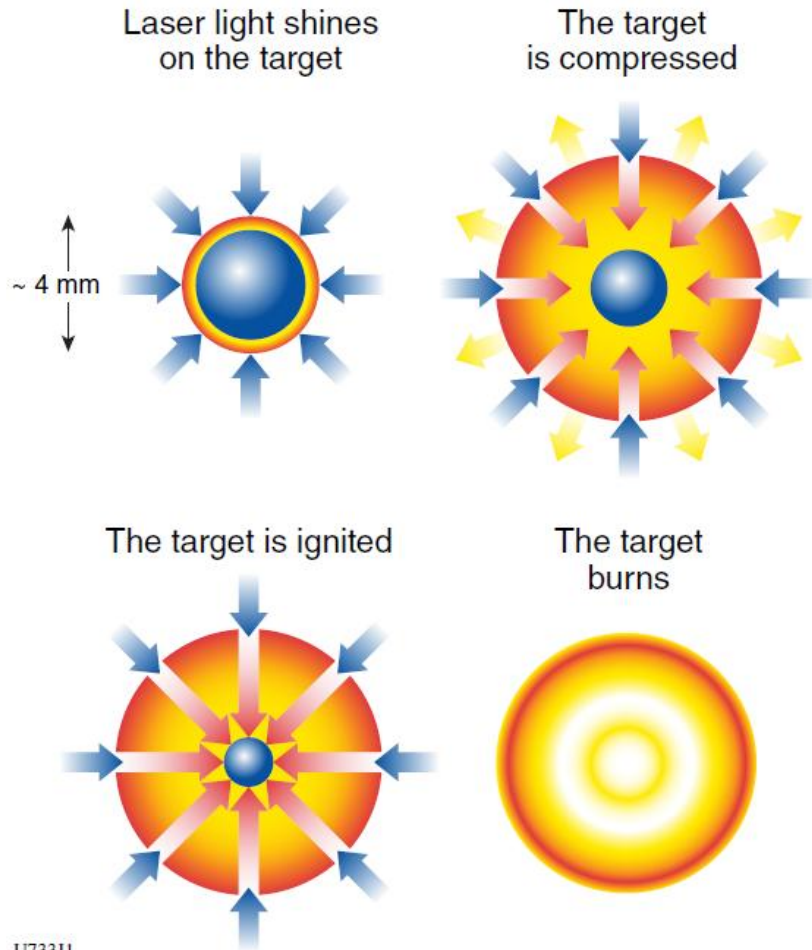


- **Solution 2: Inertial confinement fusion (ICF). Or you can say it is confined by its own inertia: $P \sim \text{Gigabar}$, $\tau \sim \text{nsec}$, $T \sim 10 \text{ keV}$ ($10^8 \text{ }^\circ\text{C}$)**

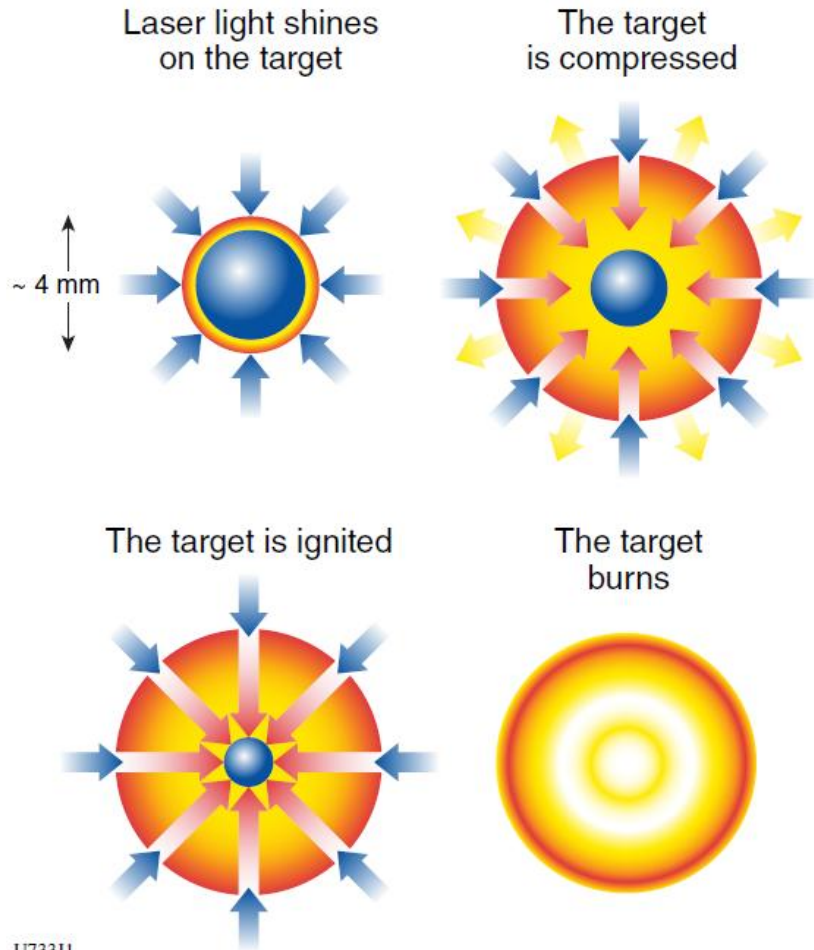


U733J1

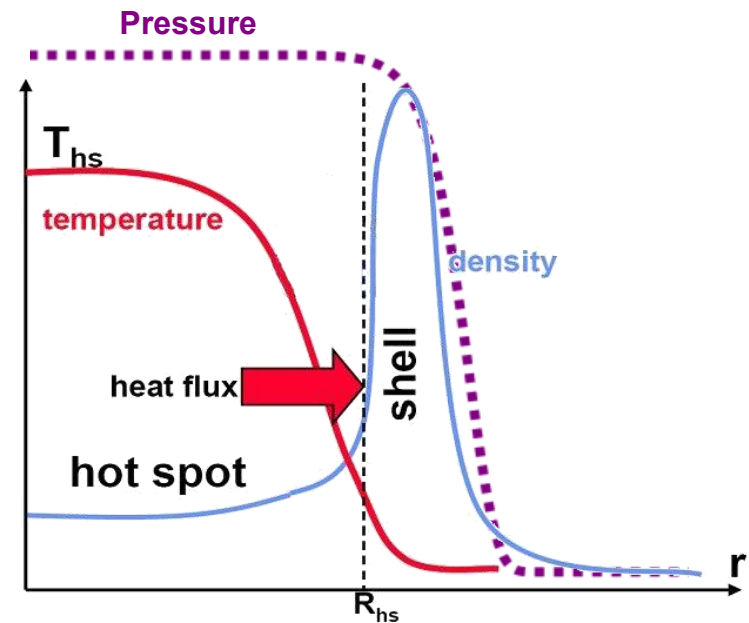
Compression happens when outer layer of the target is heated by laser and ablated outward



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



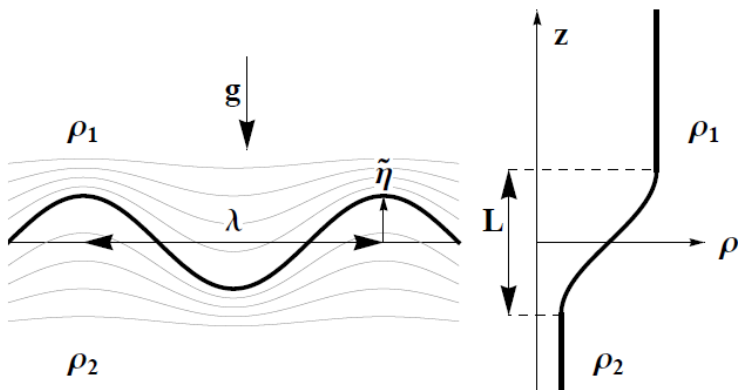
Spatial profile at stagnation



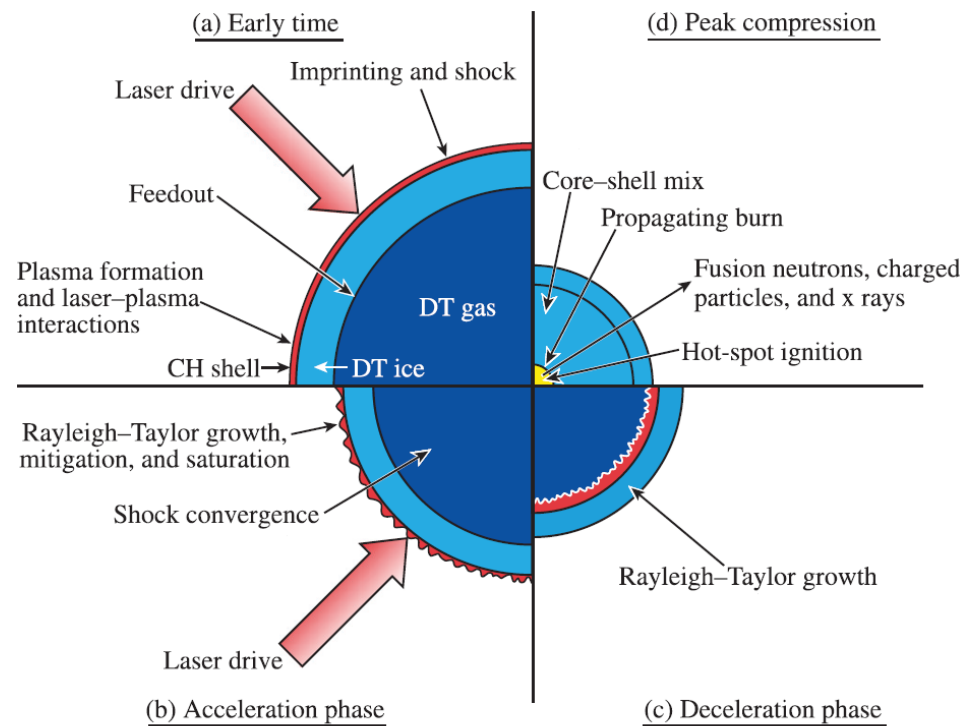
A ball can not be compressed uniformly by being squeezed between several fingers



• Rayleigh-Taylor instability



• Stages of a target implosion

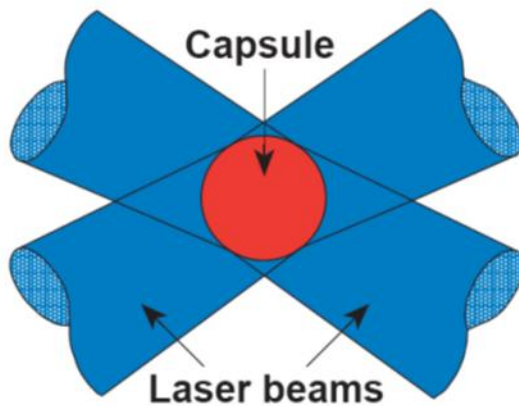


P.-Y. Chang, PhD Thesis, U of Rochester (2013)
R. S. Craxton, etc., *Phys. Plasmas* **22**, 110501 (2015)

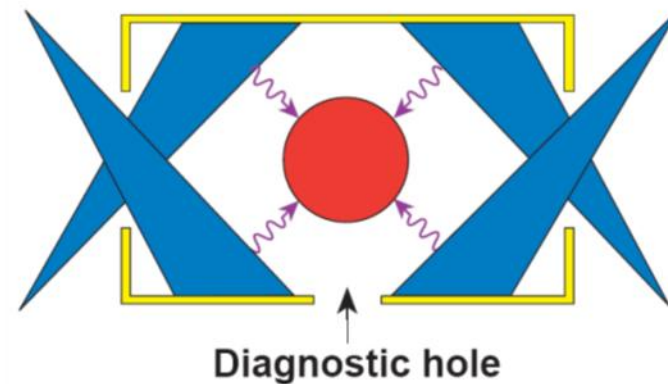
A spherical capsule can be imploded through directly or indirectly laser illumination



Direct-drive target

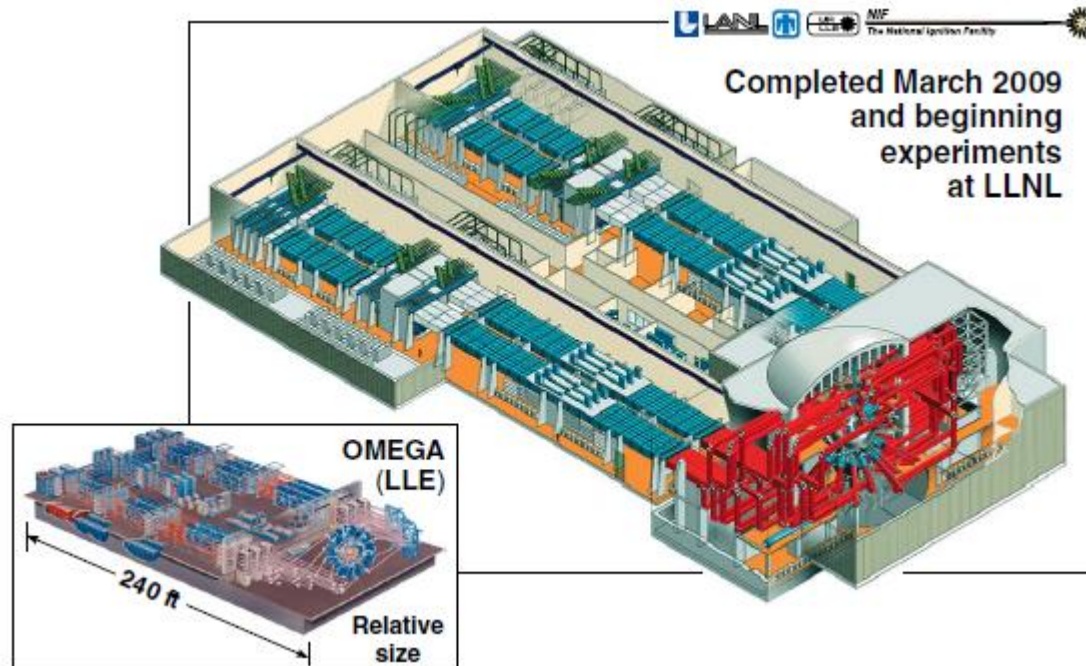


Indirect-drive target



Hohlraum using
a cylindrical high-Z case

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

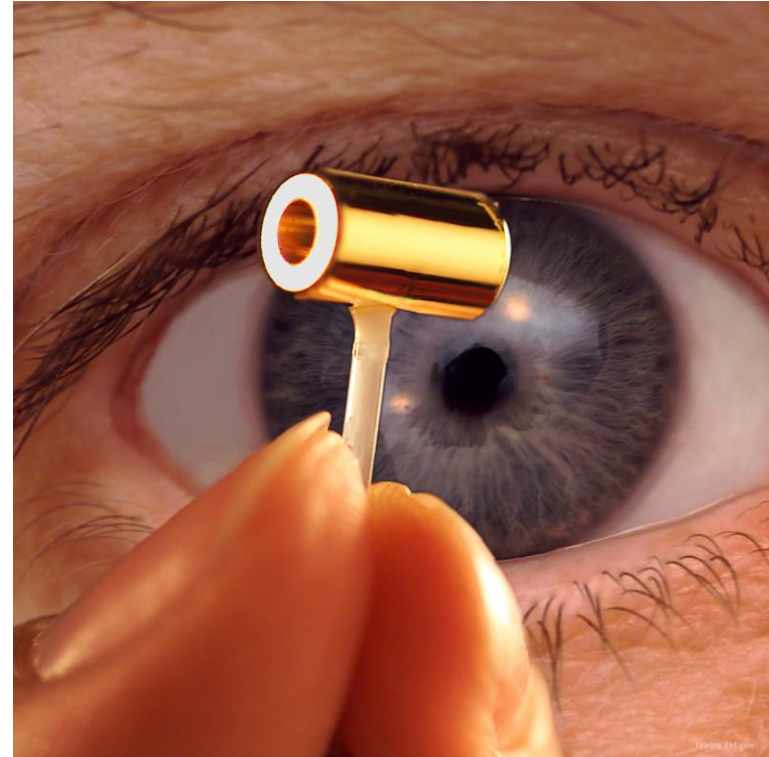
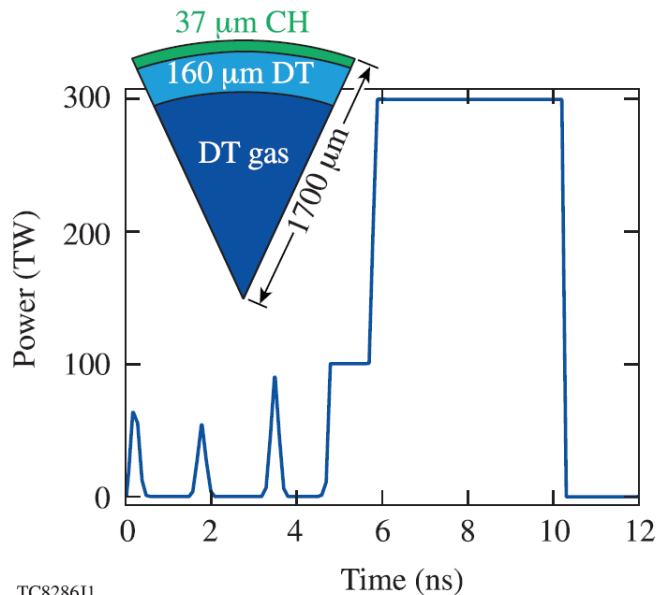


OMEGA experiments are integral to an ignition demonstration on the NIF.

Targets used in ICF



- Triple-point temperature : 19.79 K



<http://www.lle.rochester.edu>
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



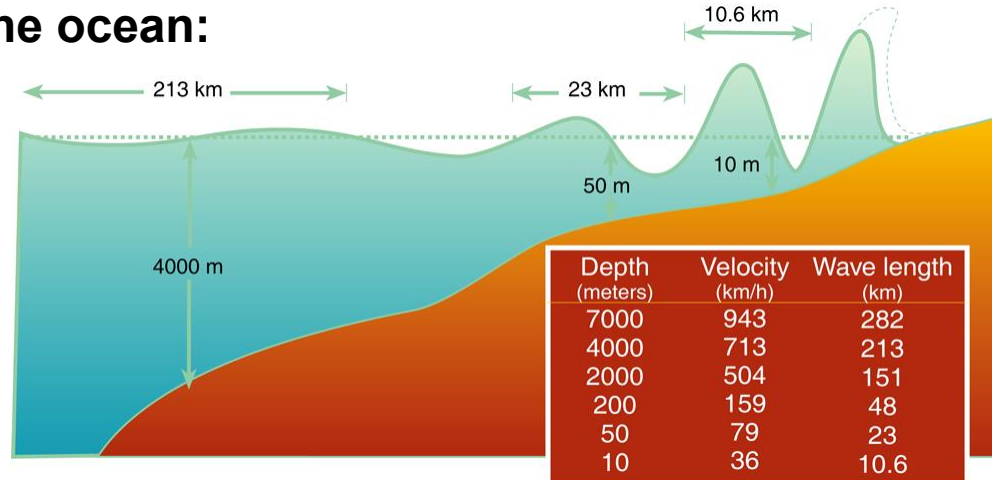
<https://www.youtube.com/watch?v=uxlldMoAwbY>

<https://newsghana.com.gh/wimbledon-slow-motion-video-of-how-a-tennis-ball-turns-to-goo-after-serve/>

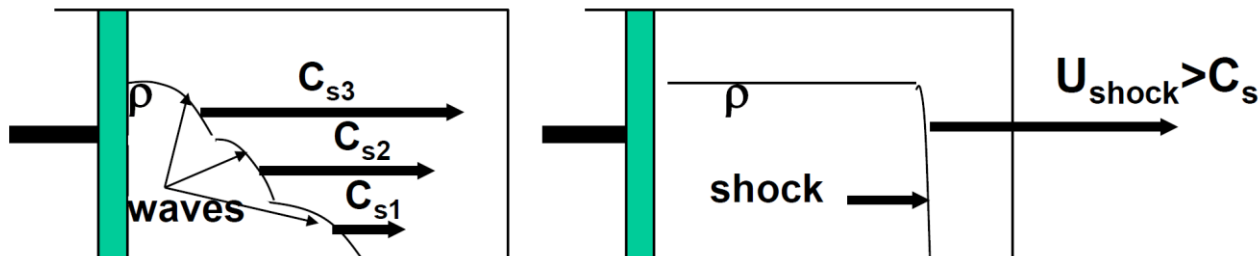
A shock is formed due to the increasing sound speed of a compressed gas/plasma



- Wave in the ocean:



- Acoustic/compression wave driven by a piston:



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

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



$$\rho_1 u_1 = \rho_2 u_2$$

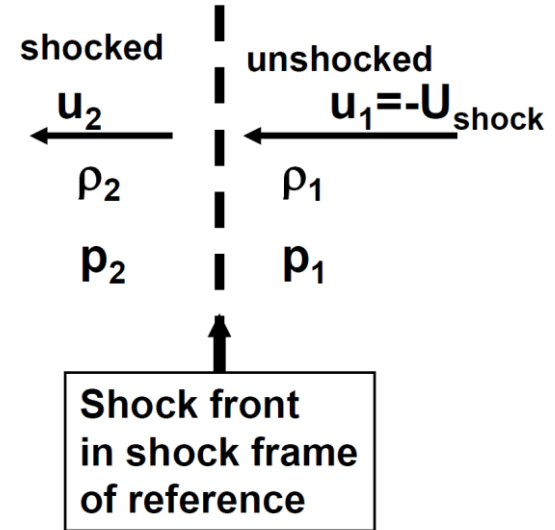
$$p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2$$

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

- **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 $u_1 = -U_{\text{shock}}$ can be obtained using Rankine-Hugoniot conditions



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

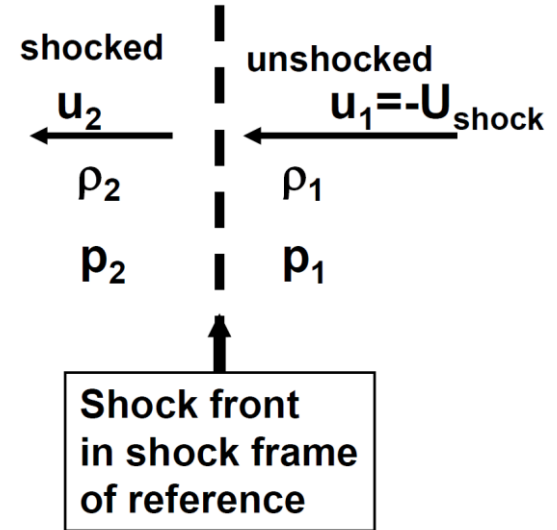


$$\frac{\rho_2}{\rho_1} \approx 4$$

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

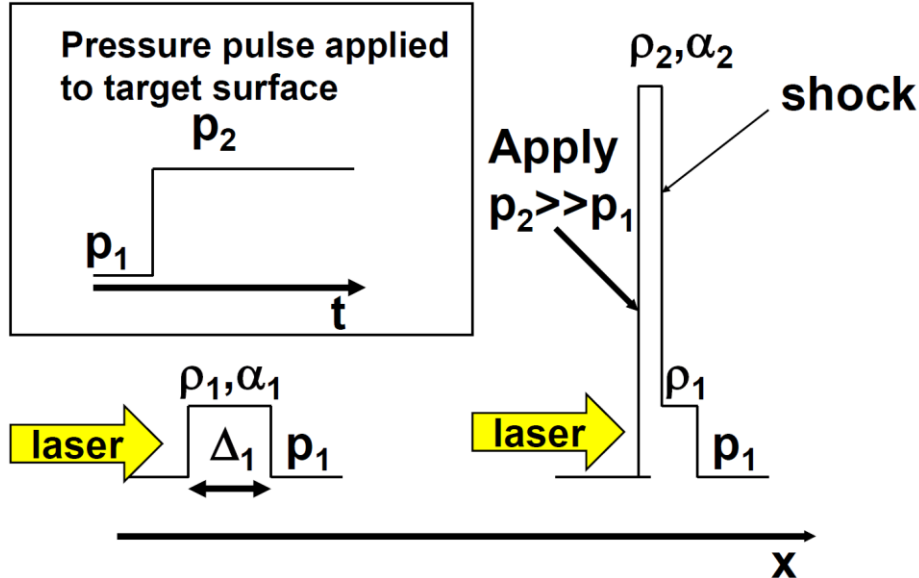
$$u_2 \approx \sqrt{\frac{p_2}{12\rho_1}}$$

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



- 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:**

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

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

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

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

Higher laser intensity leads to higher adiabat



- For a cryogenic solid DT target at 18 k:

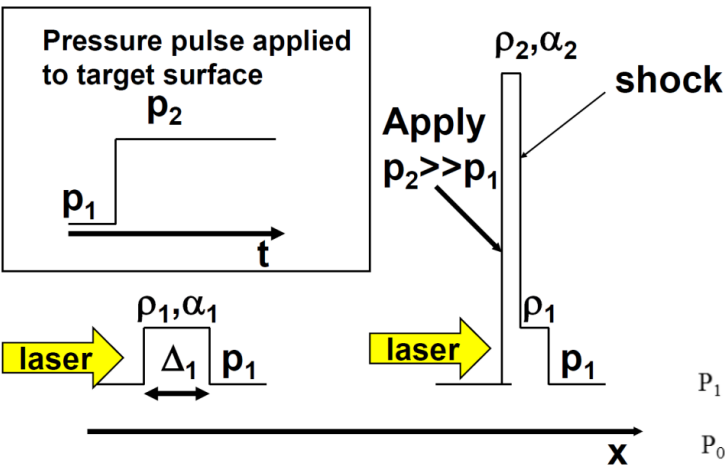
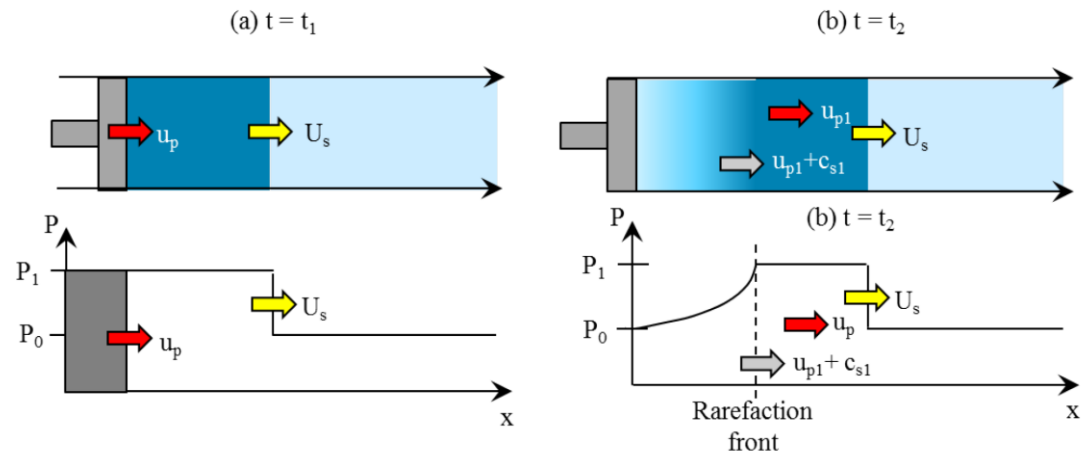
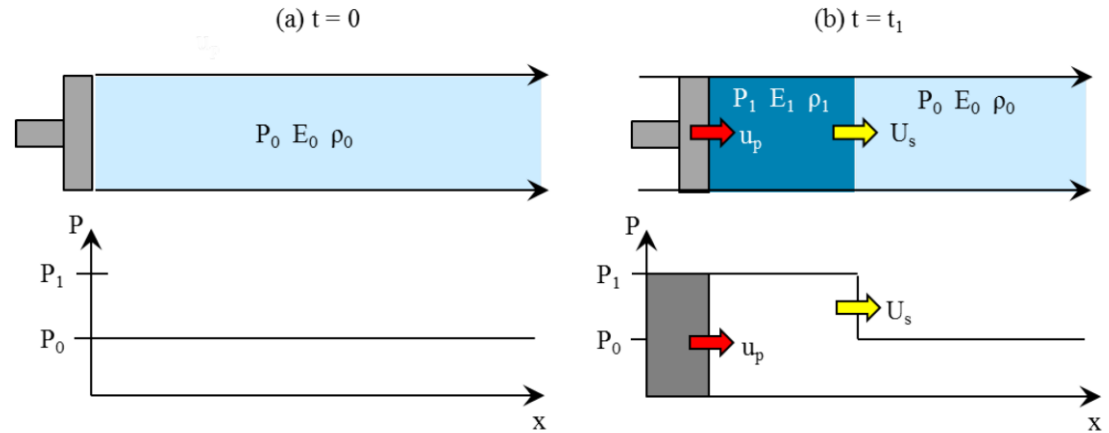
$$\rho_1 = 0.25 \text{ g/cc} \quad \alpha = \frac{p_{\text{Mbar}}}{2.2} \quad p \approx 83 \left(\frac{I_{15}}{\lambda_{\mu\text{m}}/0.35} \right)^{2/3}$$

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

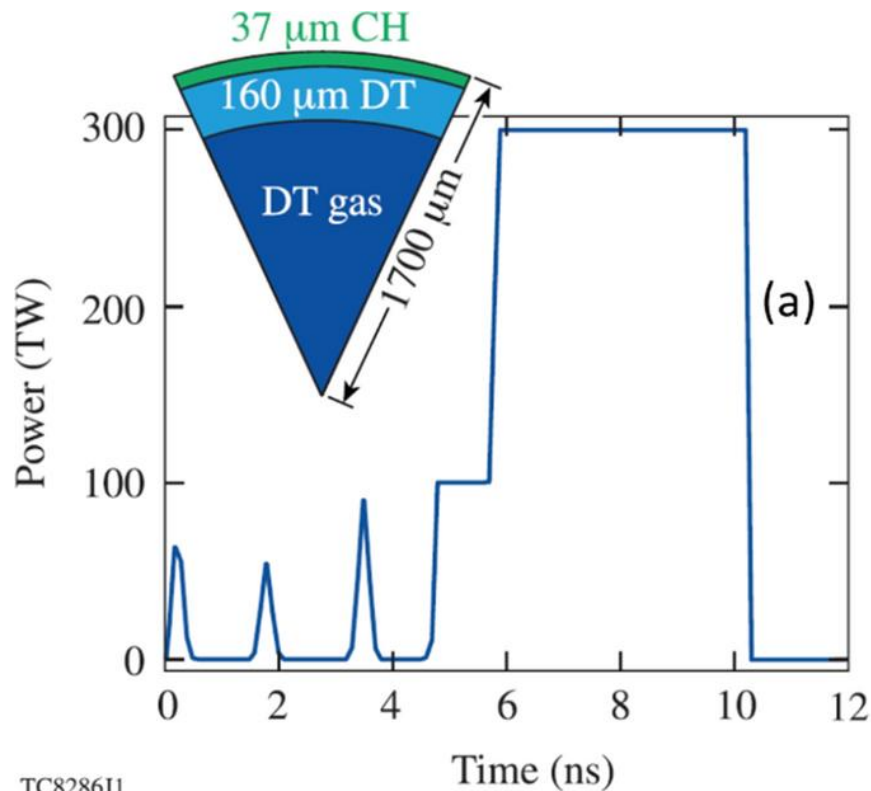
$$I \approx 1.2 \times 10^{13} \text{ W/cm}^2 \Rightarrow p = 4.4 \text{ Mbar} \Rightarrow \alpha = 2$$

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

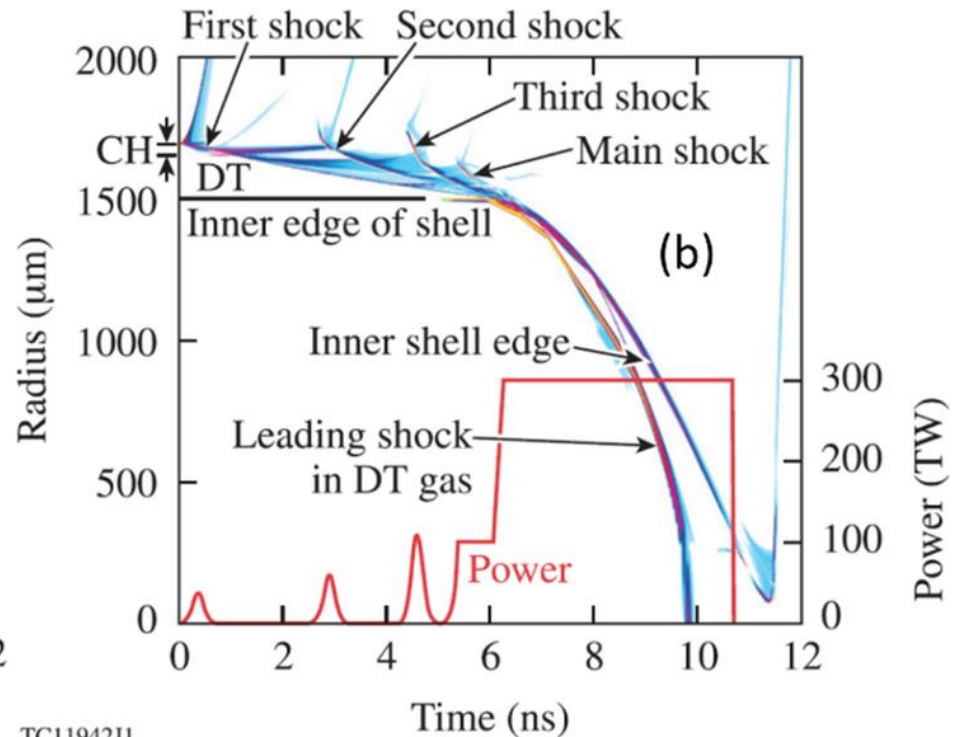
A shock or a rarefaction wave may be formed depending on the driving force from the piston



Multiple shock can be generated with multiple pickets



TC8286J1

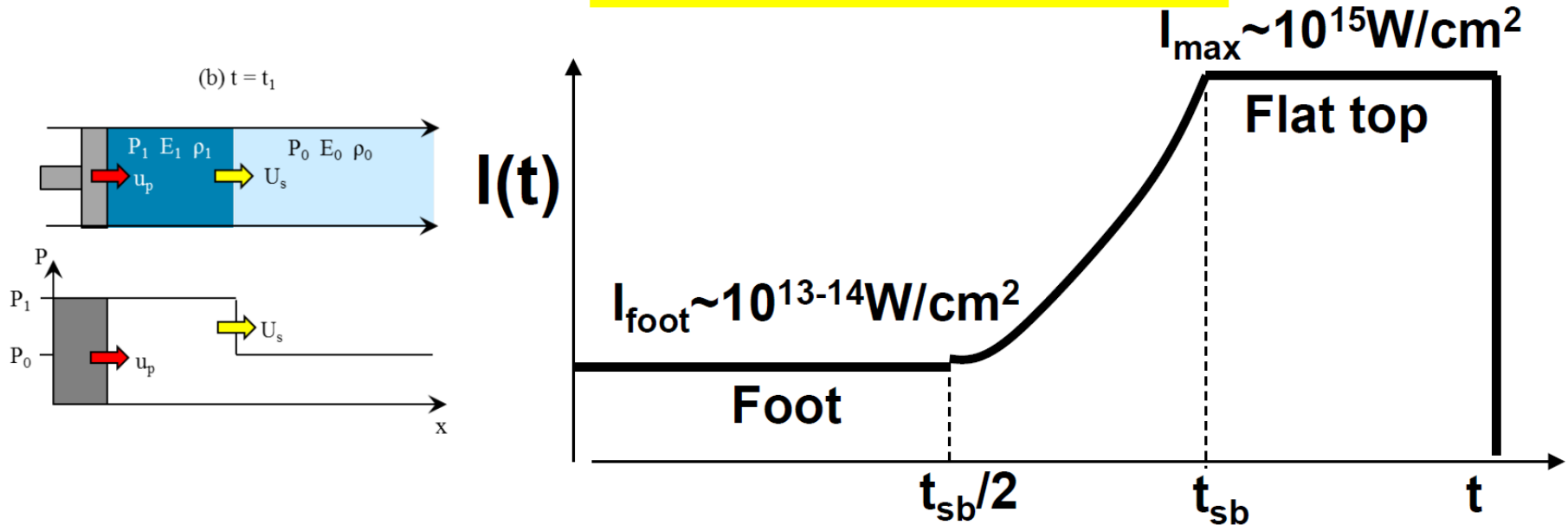


TC11942J1

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

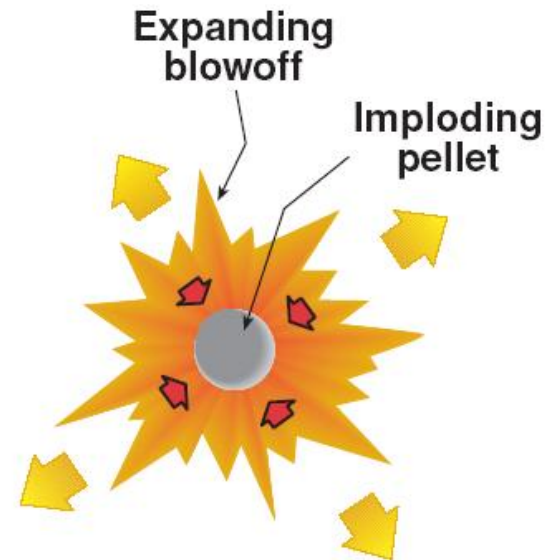
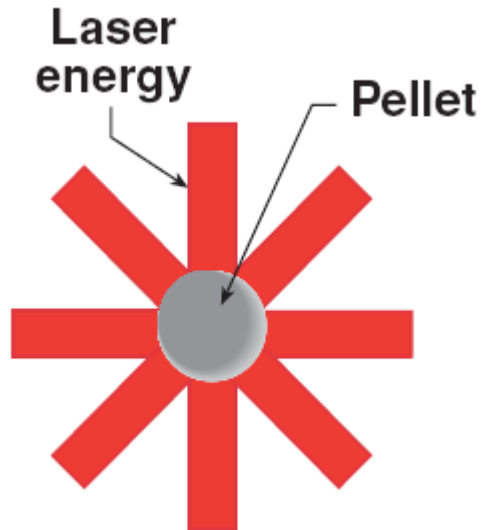


Laser pulse shape



- After the foot of the laser pulse, the laser intensity must be raised starting at about $0.5t_{\text{sb}}$ 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

$$M \frac{du}{dt} = -4\pi R^2 p_a$$

Shell mass decreases due to ablation

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

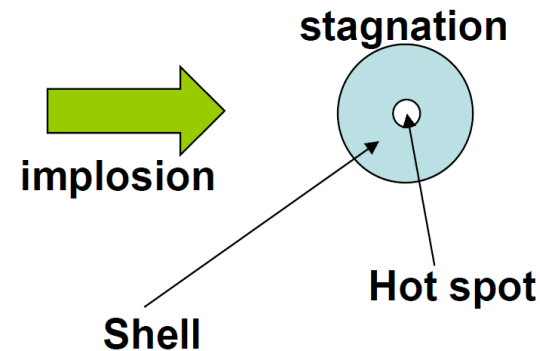
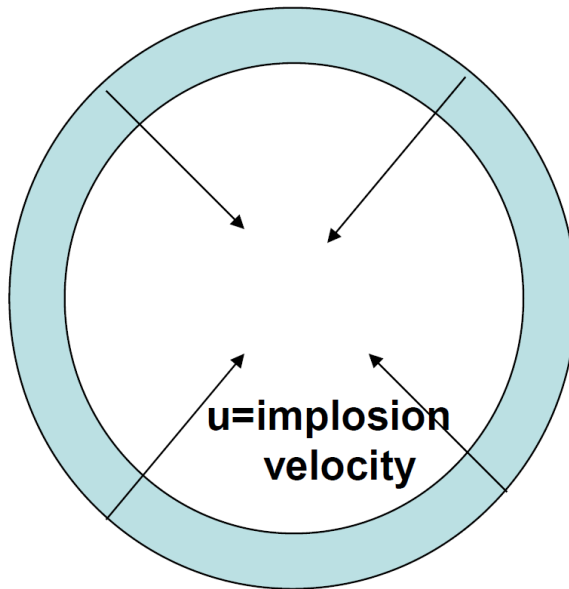
p_a = ablation rate x exhaust velocity

$$p_a = \dot{m}_a u_{\text{exhaust}}$$

One dimensional implosion hydrodynamics



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

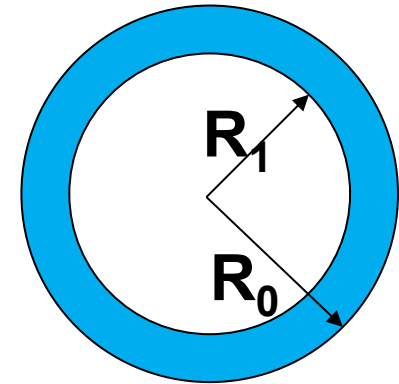


$\rho?$
 $\rho R?$
 $P?$

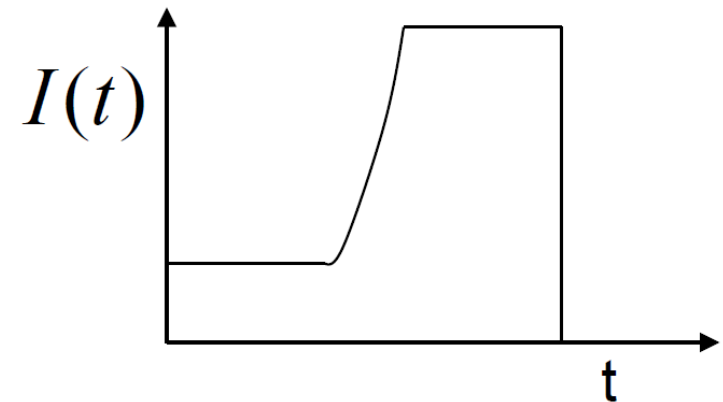
What variables can be controlled?



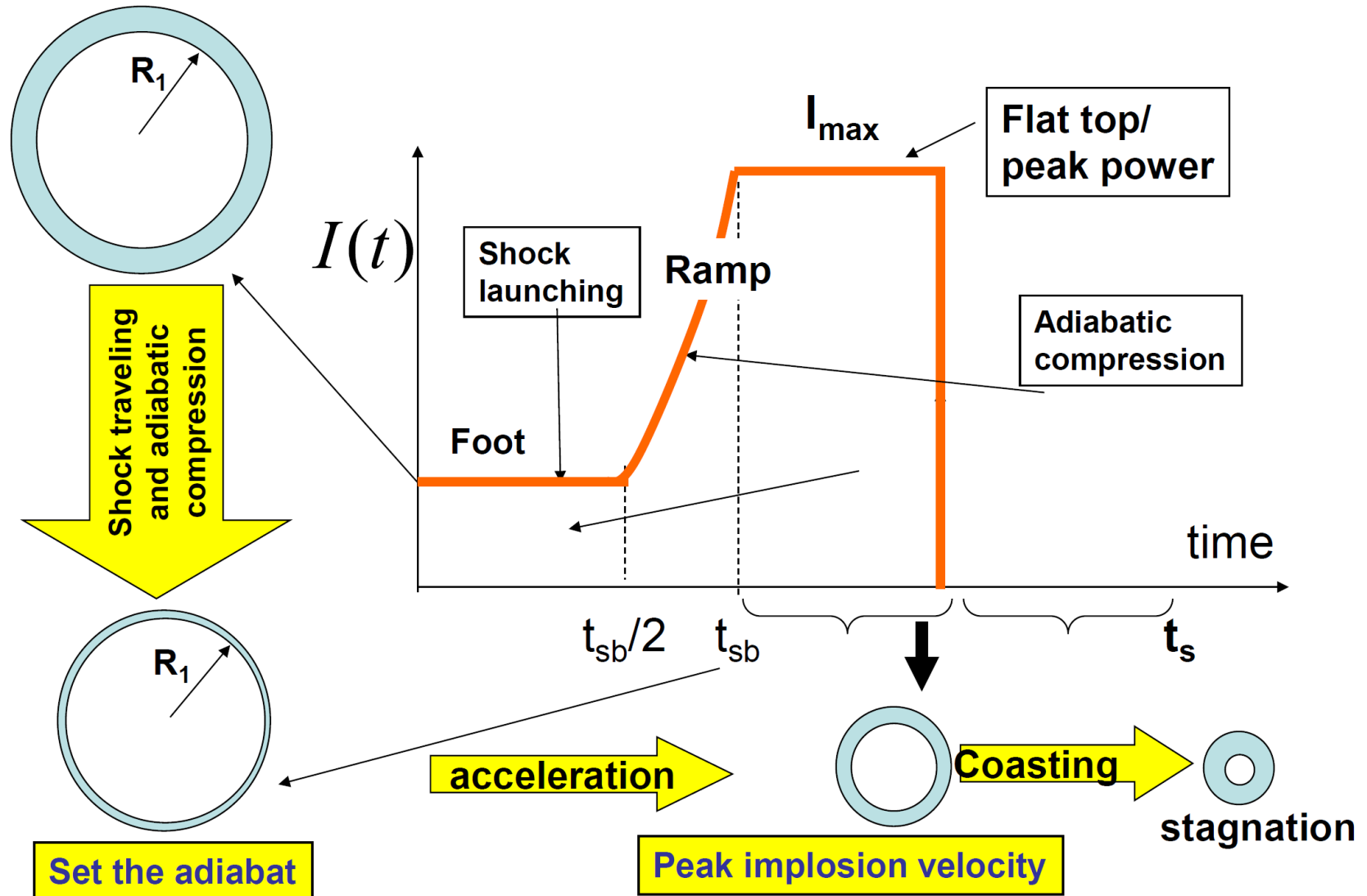
- Shell outer radius R_0 at time $t=0$
- Shell inner radius R_1 at time $t=0$
- The total laser energy on target
- Adiabatic α through shocks
- Applied pressure $p(t)$ through the pulse shape $I(t)$



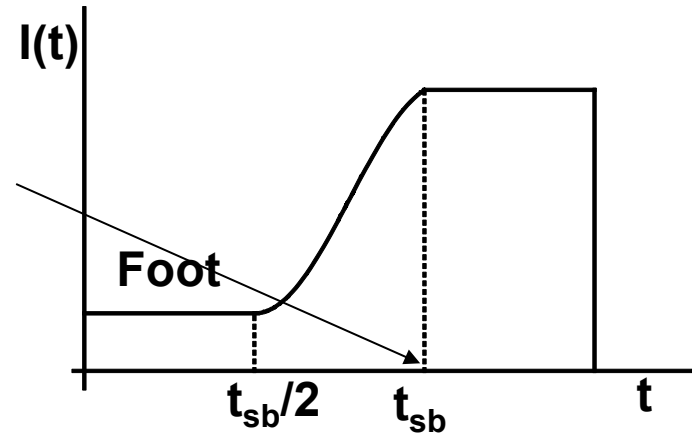
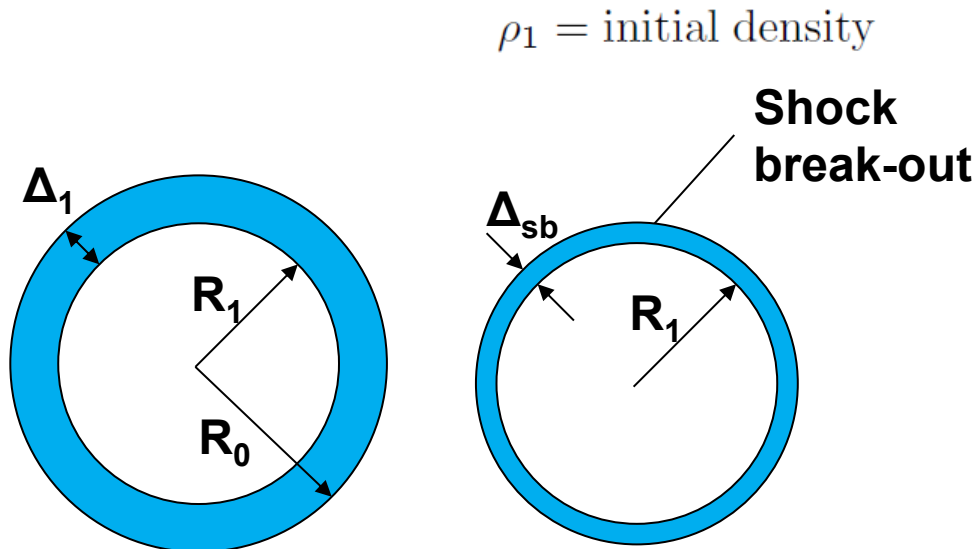
$$\alpha \sim \frac{p}{\rho^{5/3}} \quad p \sim I^{2/3}$$



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



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

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

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

The final implosion velocity can be found using IFAR

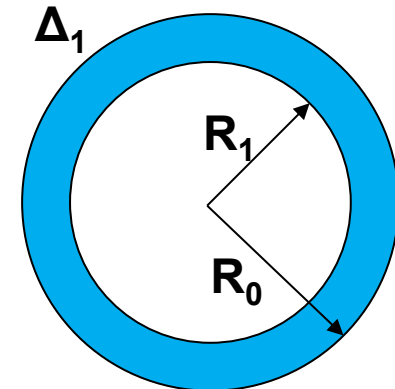
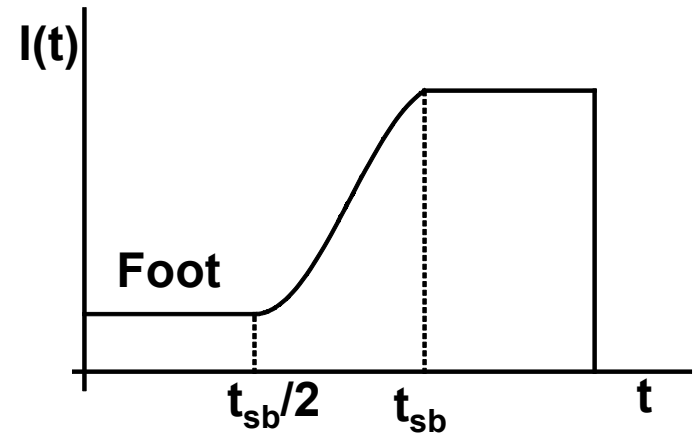


$$u_{\max}^2 \sim IFAR \times \alpha^{3/5} I^{4/15}$$

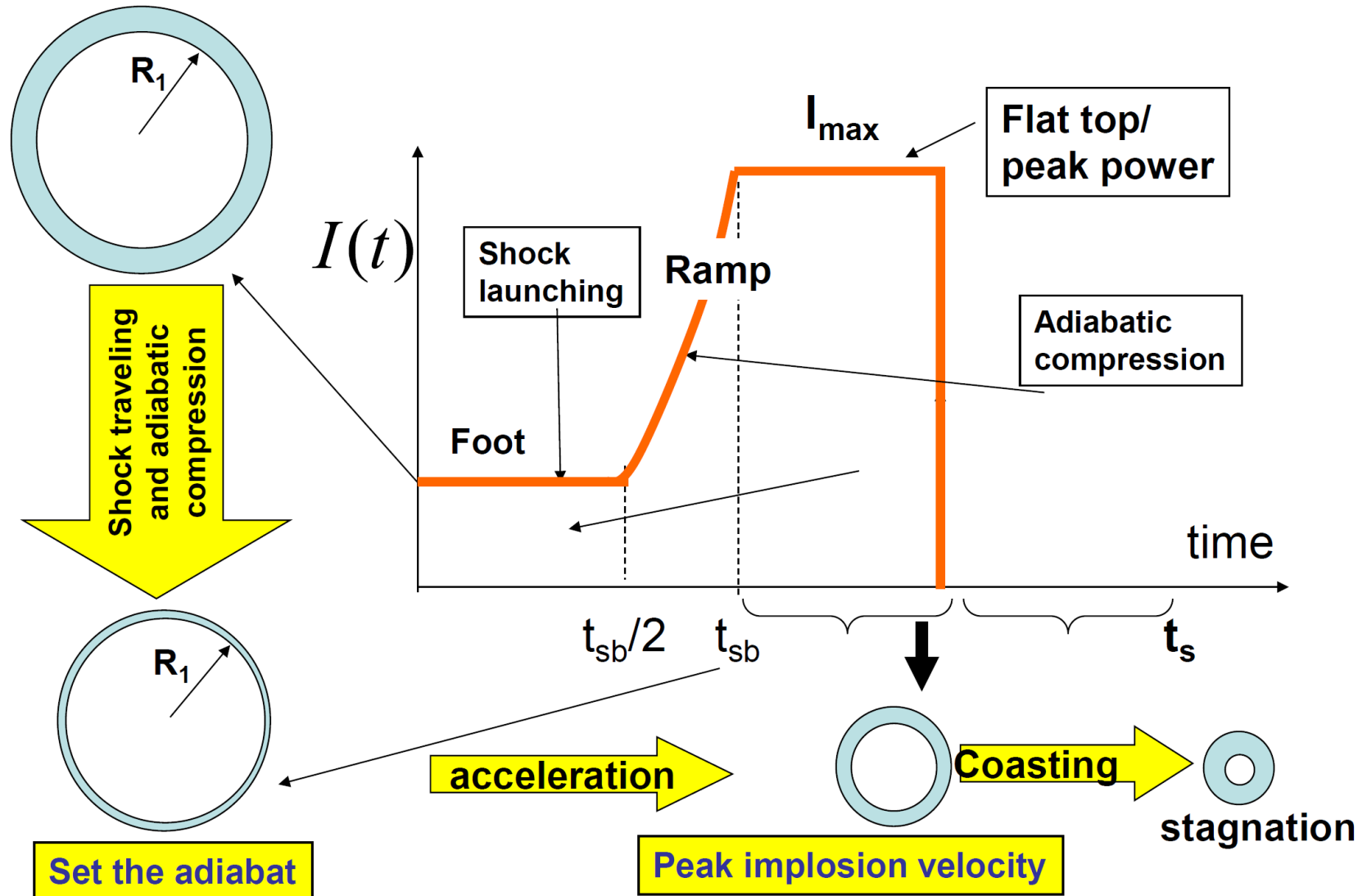
$$IFAR = 4A_1 \left(\frac{I_{\max}}{I_{\text{foot}}} \right)^{2/5}$$

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

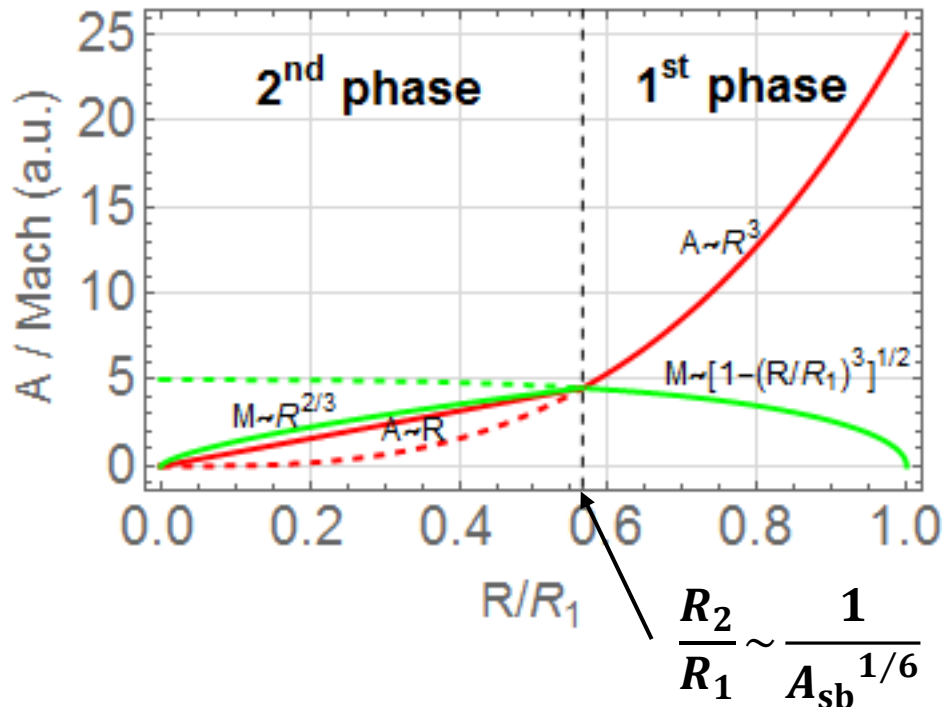
$$u_{\max, \text{cm/s}} \approx 10^7 \sqrt{0.7 A_1 \alpha^{3/5} I_{15, \max}^{4/15} \left(\frac{I_{\max}}{I_{\text{foot}}} \right)^{2/5}}$$



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



Summary of phase 2 (coasting phase)



$$1 < A < \sqrt{A_{\text{sb}}} \quad A < \text{Mach}$$

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

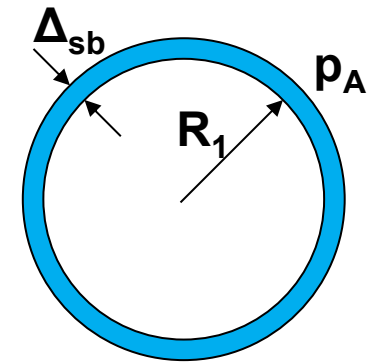
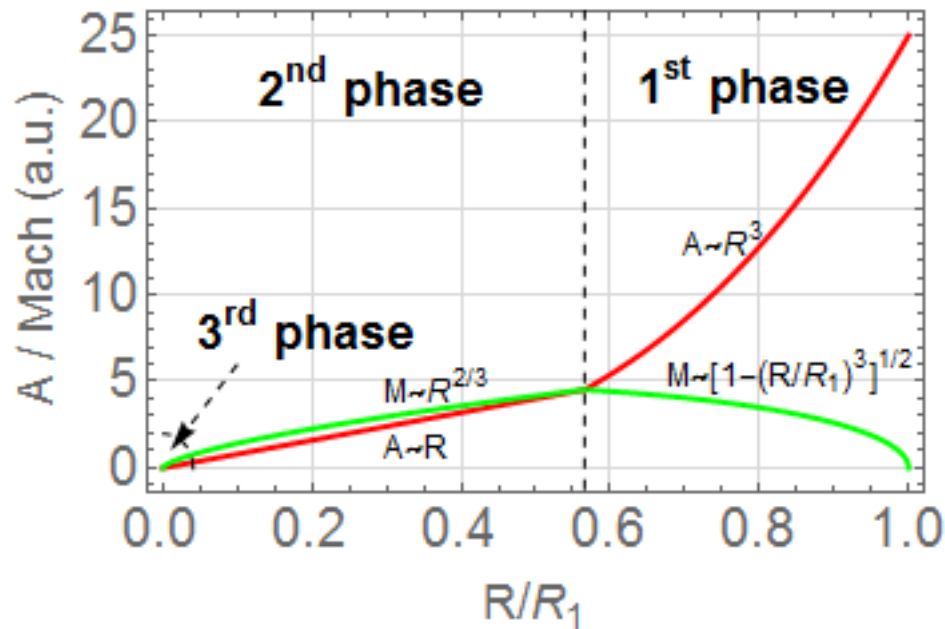
$$A = A_2 \left(\frac{R}{R_2} \right) \sim \sqrt{A_{\text{sb}}} \left(\frac{R}{R_2} \right)$$

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

$$\text{Mach}_2 = \text{Mach}_{\text{max}} \simeq A_2 = \sqrt{A_{\text{sb}}}$$

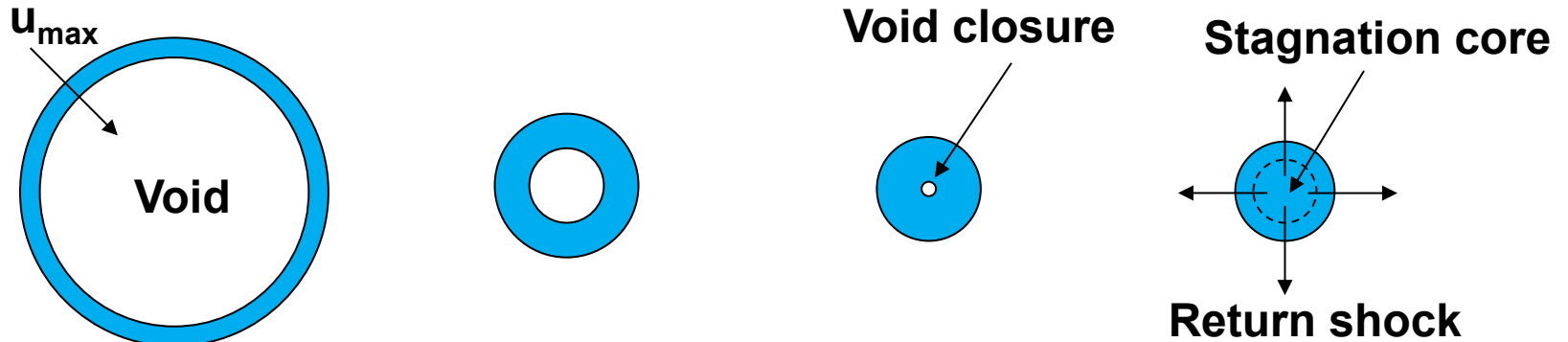
$$\Delta \simeq \text{constant} = \Delta_2 \sim \frac{R_1}{A_{\text{sb}}^{2/3}} \quad \bar{\rho} \simeq \rho_2 \left(\frac{R_2}{R} \right)^2 \sim \rho_{\text{sb}} \left(\frac{R_2}{R} \right)^2$$

How about the 3rd phase where $A \sim 1$?



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

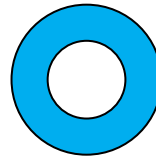
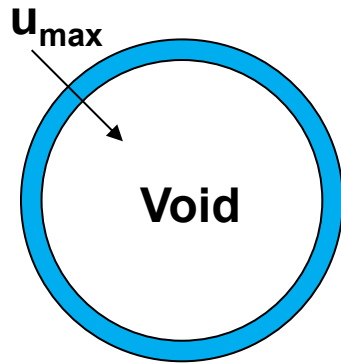
The thin shell model breaks down when $A \sim 1$



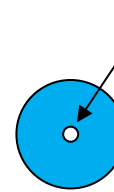
- When $A \sim 1 \Rightarrow \Delta \sim R$, the “void” inside the shell closes and a “return shock” propagating outward is generated due to the collision of the shell with itself
- The density is compressed by a factor no more than 4 even if the strong shock is generated

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

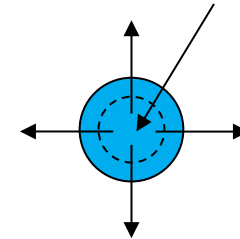
Calculation of the burn-up fraction



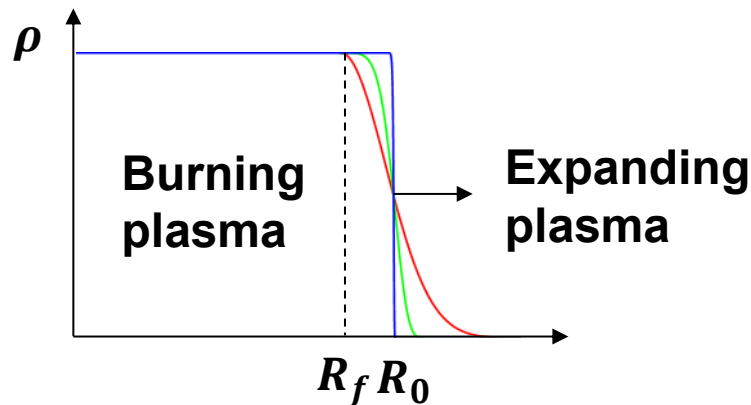
Void closure



Stagnation core



Return shock



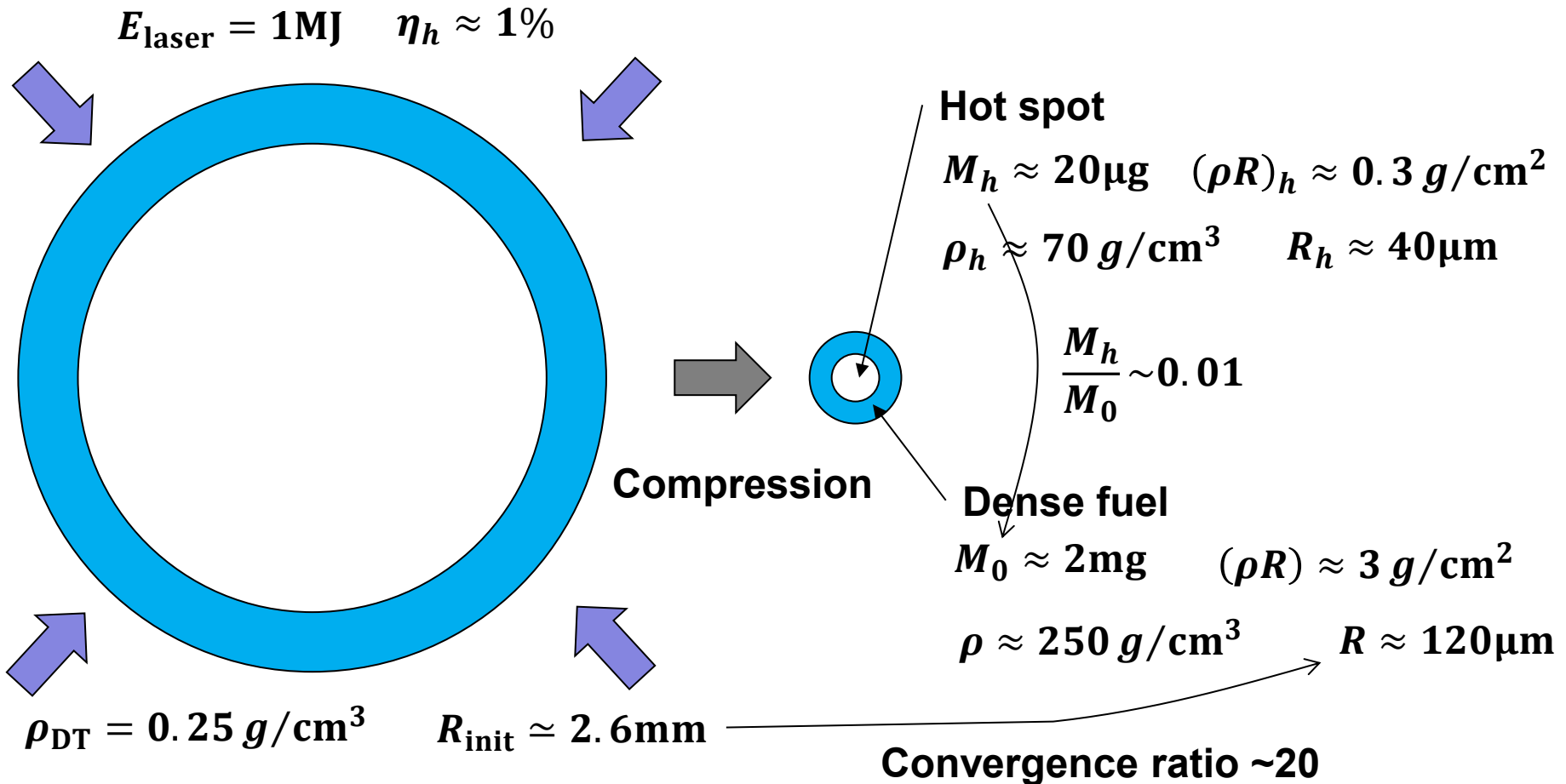
$$R_f = R_0 - C_s t$$

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

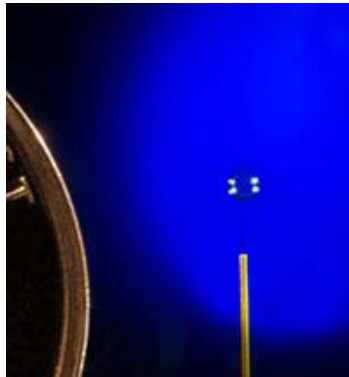
Summary



- Possible fuel assembly for 1MJ ICF driver

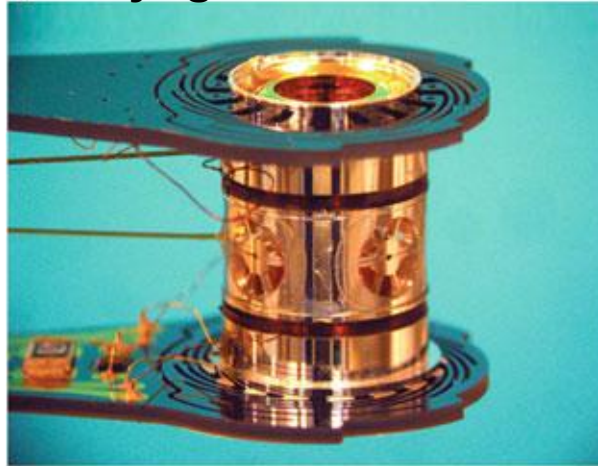


Targets used in ICF

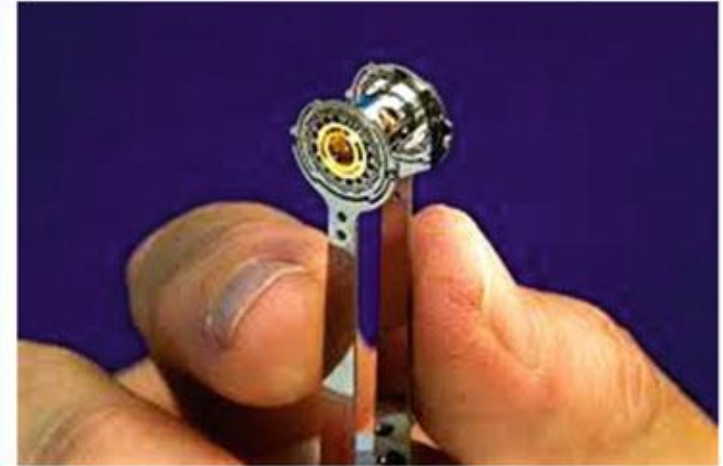


Cryogenic shroud

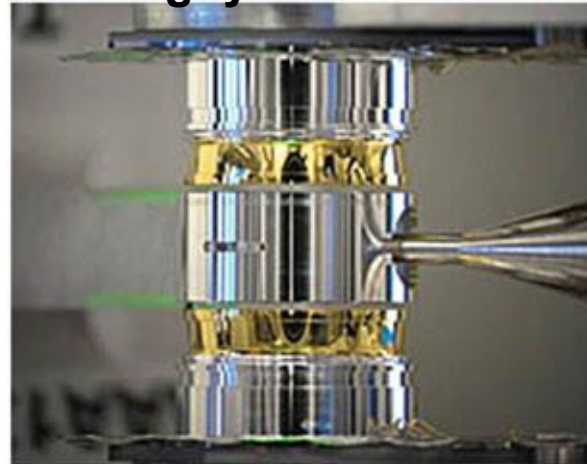
a Cryogenic hohlraum



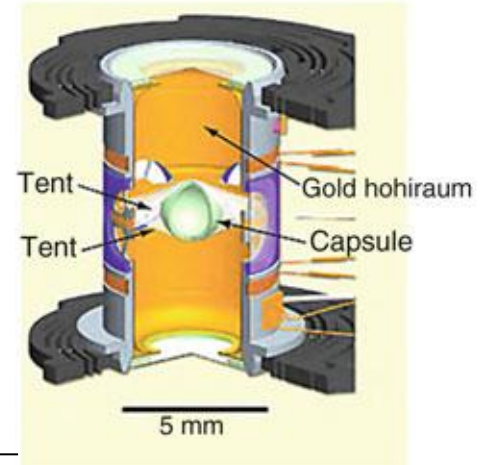
b



c Rugby hohlraum

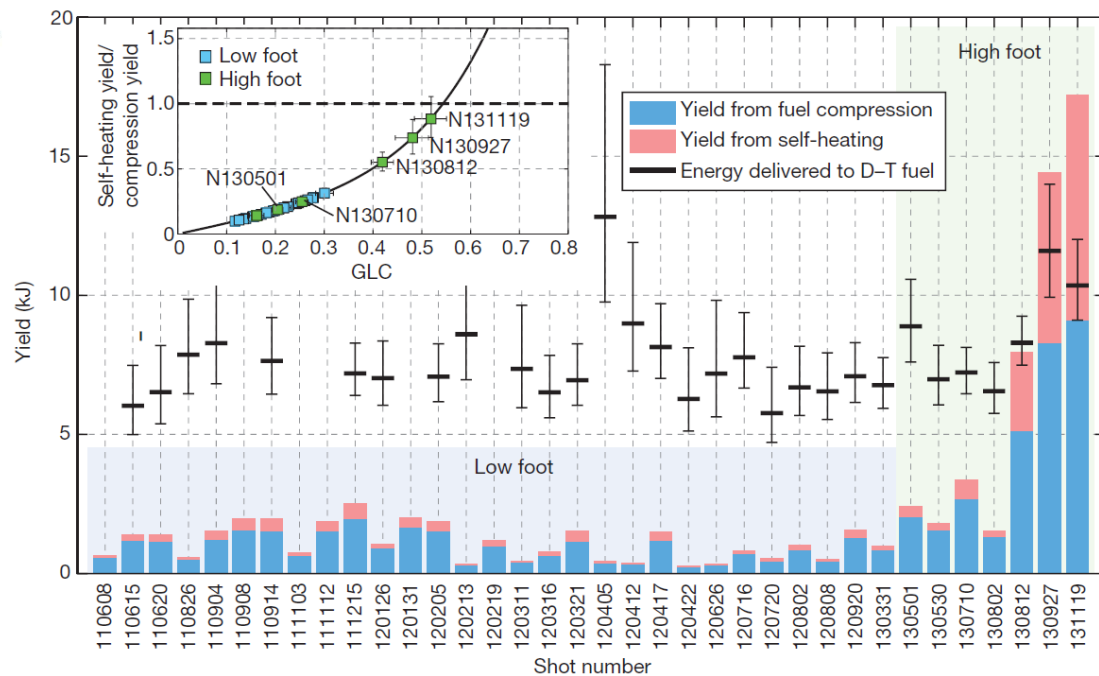
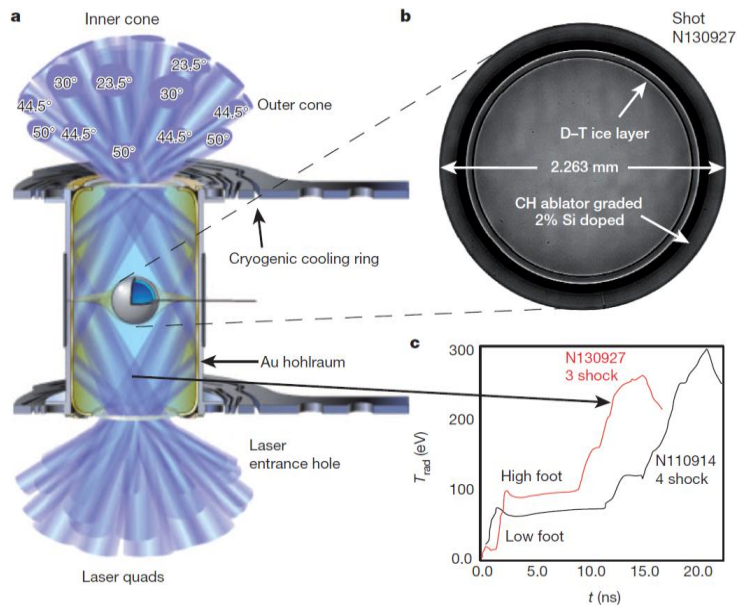


d Tent holder



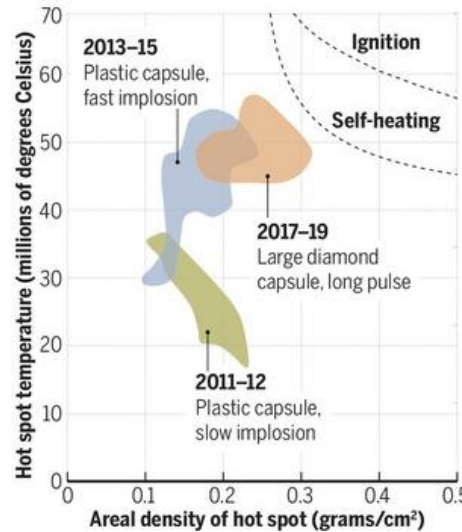
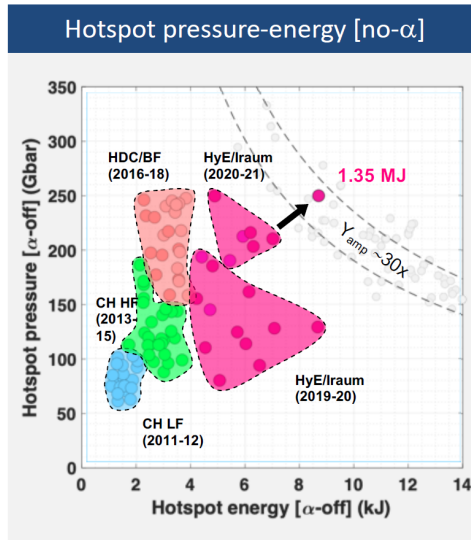
<https://www.lle.rochester.edu/index.php/2014/11/10/next-generation-cryo-target/>
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen
<https://www.llnl.gov/news/nif-shot-lights-way-new-fusion-ignition-phase>

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

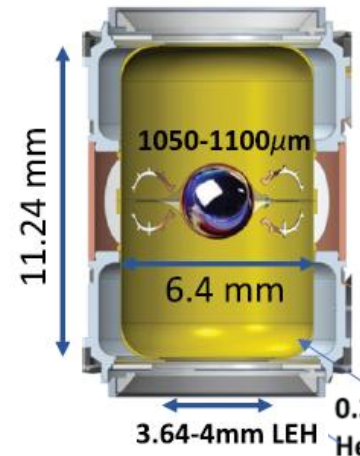


- Fuel gain exceeding unity was demonstrated for the first time.

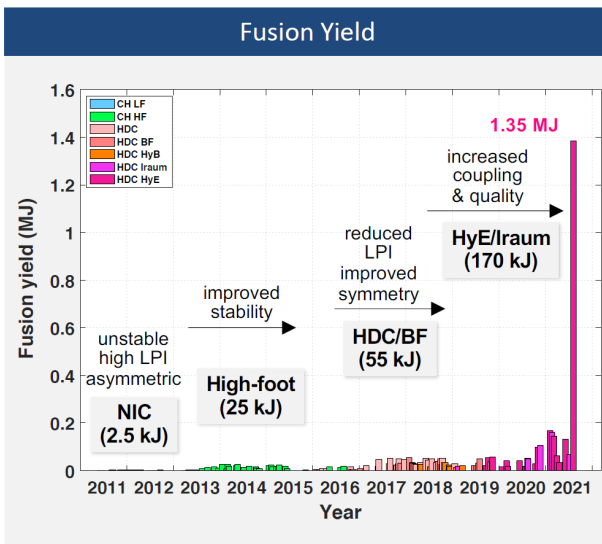
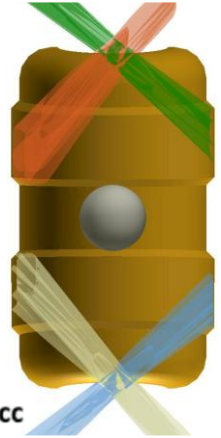
The hot spot has entered the burning plasma regime



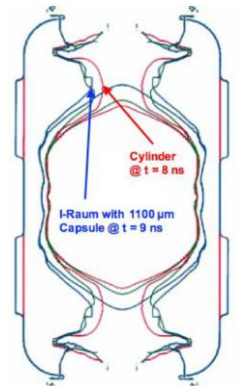
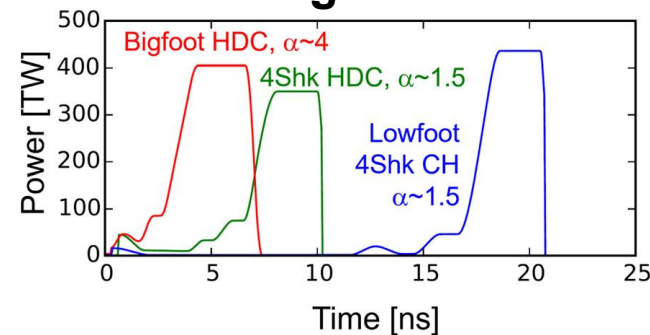
• Hybrid-E



• I-raum



• Big foot



T. Ma, ARPA-E workshop, April 26, 2022

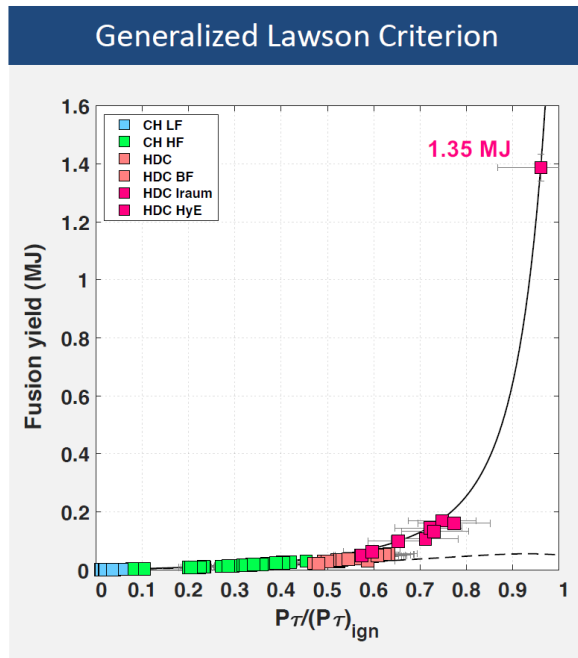
Science 370, p1019, 2020

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)

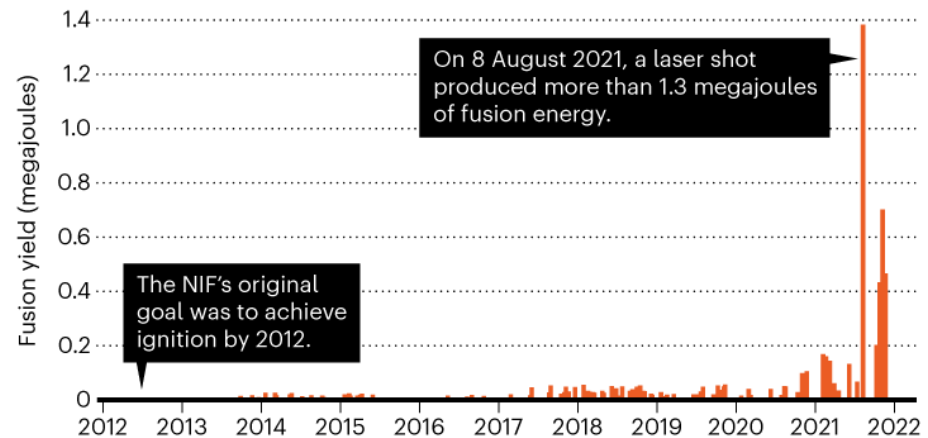
National Ignition Facility (NIF) achieved a yield of more than 1.3 MJ from ~1.9 MJ of laser energy in 2021 (Q~0.7)



- 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.

THE ROAD TO IGNITION

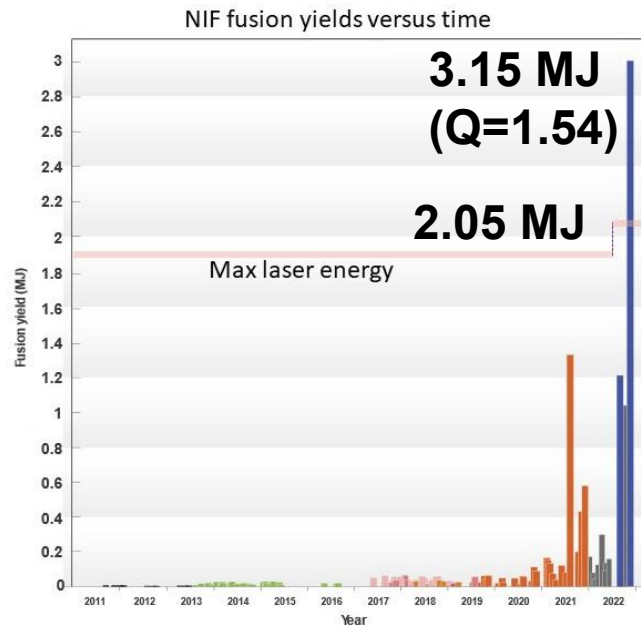
The National Ignition Facility (NIF) struggled for years before achieving a high-yield fusion reaction (considered ignition, by some measures) in 2021. Repeat experiments, however, produced less than half the energy of that result.



©nature

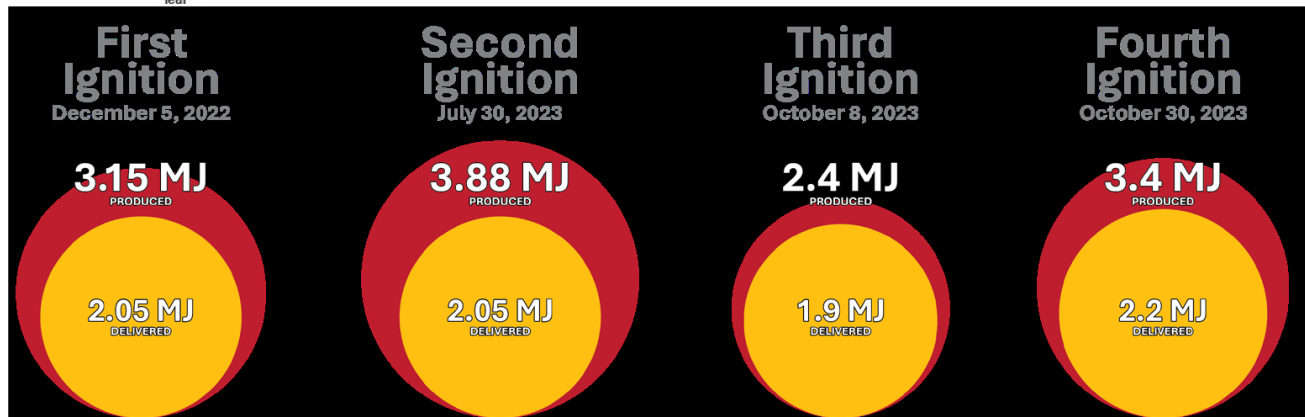
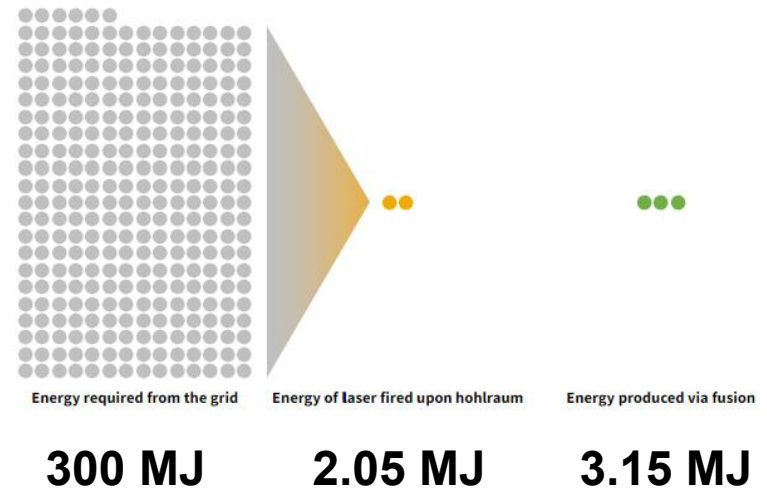
- Laser-fusion facility heads back to the drawing board.

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

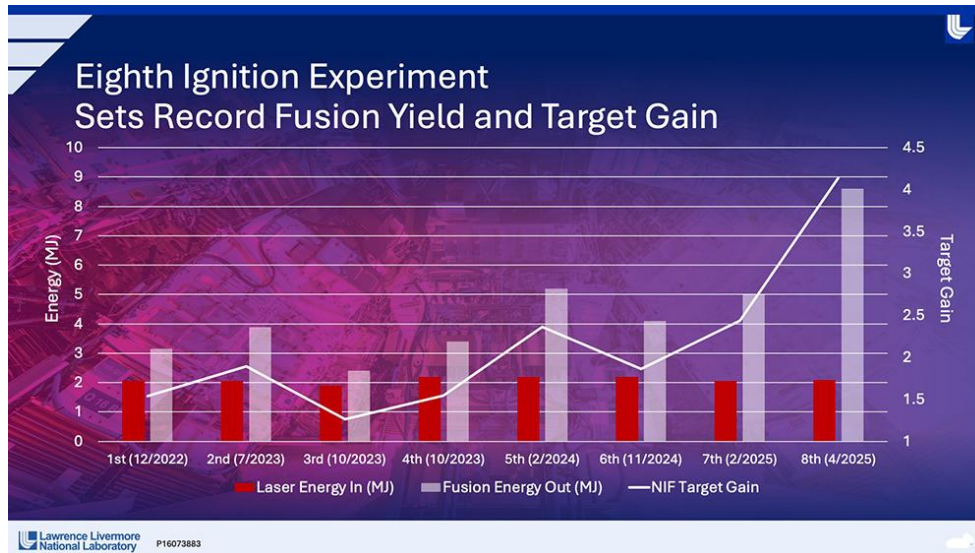


NIF's ignition achievement in perspective

Energy in megajoules ● = 1

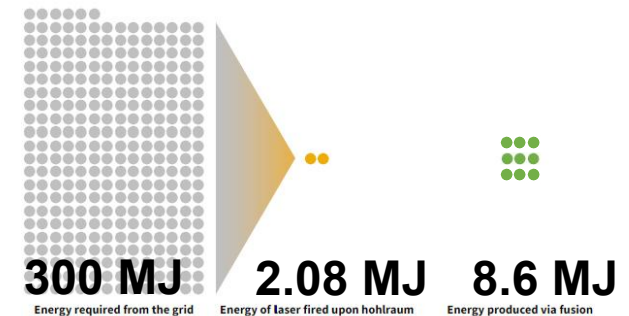


A gain over 4 has been achieved



NIF's ignition achievement in perspective

Energy in megajoules ● = 1



- 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.

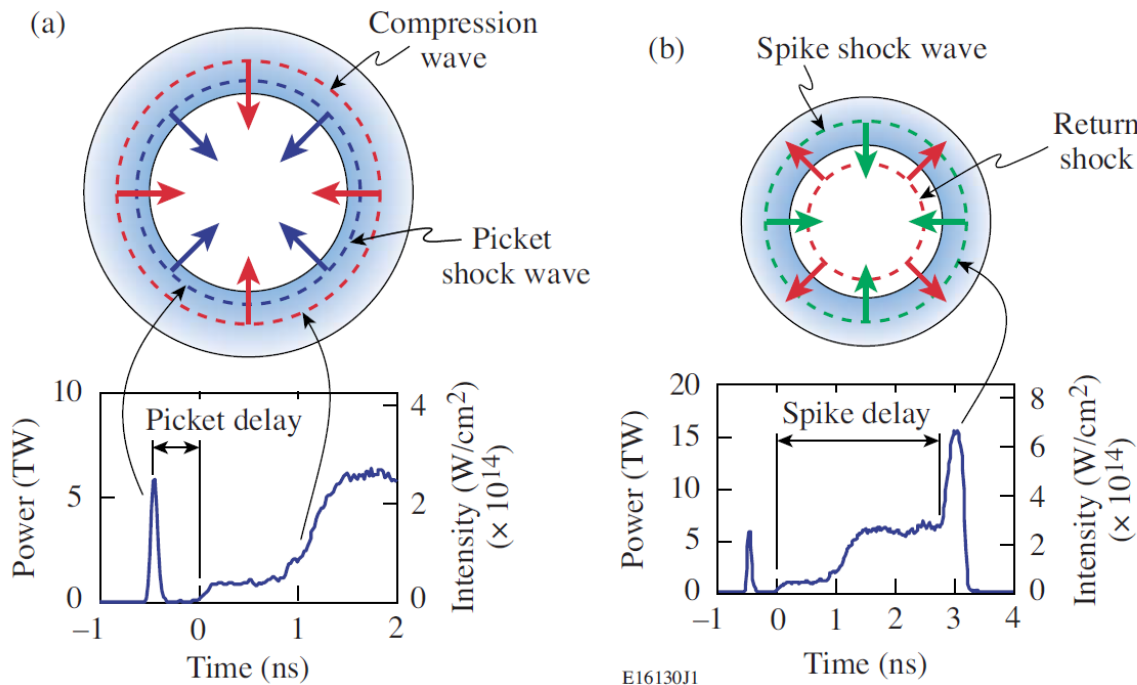
<https://physicstoday.scitation.org/doi/10.1063/PT.6.2.20221213a/full/>

<https://lasers.llnl.gov/science/achieving-fusion-ignition>

External “spark” can be used for ignition

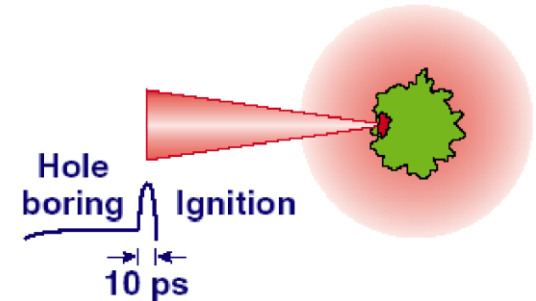


- Shock ignition

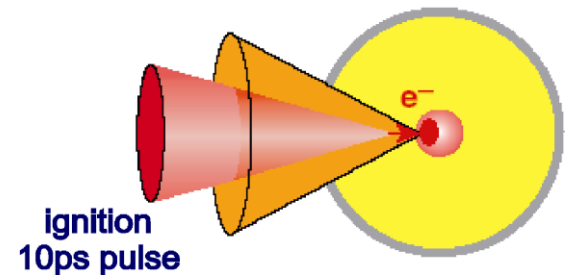


- Fast ignition

- a) channeling FI concept



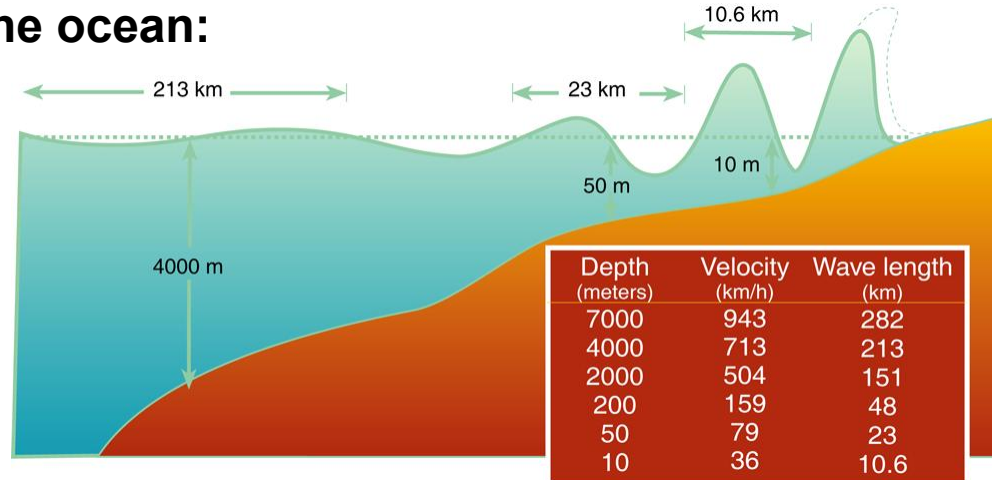
- b) cone-in-shell FI concept



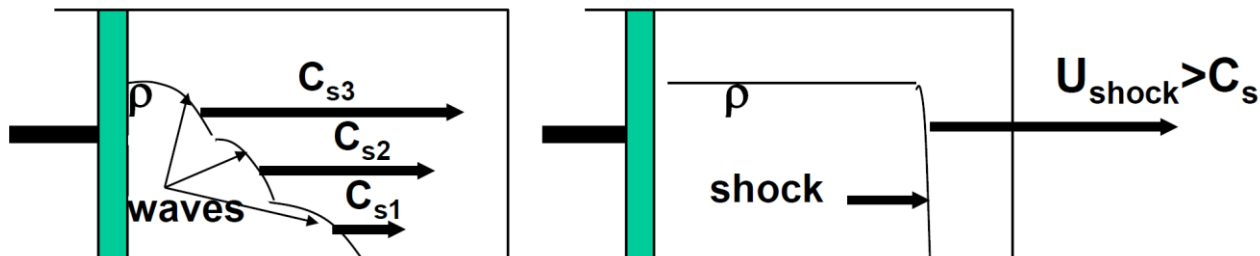
A shock is formed due to the increasing sound speed of a compressed gas/plasma



- Wave in the ocean:**



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



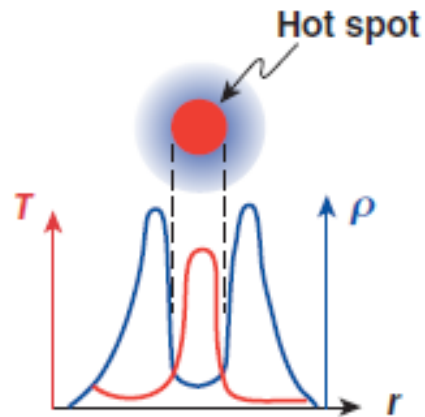
$$C_s \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha \rho^{5/3}}{\rho}} \sim \sqrt{\alpha} \rho^{1/3}$$

Ignition can happen by itself or being triggered externally



Self-ignition

Conventional ICF

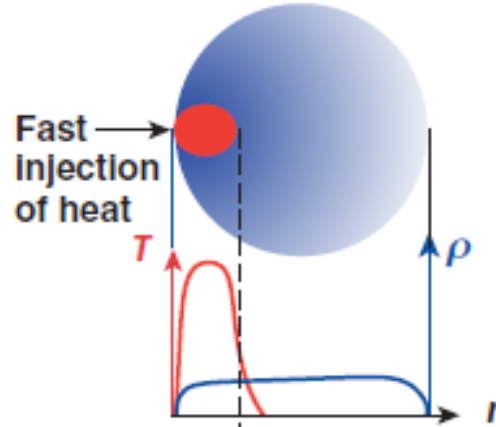


Low-density central spot ignites
a high-density cold shell

$$\rho T_{\text{hot}} \approx \rho T_{\text{cold}} \text{ (isobaric)}$$

External “spark” for fast ignition

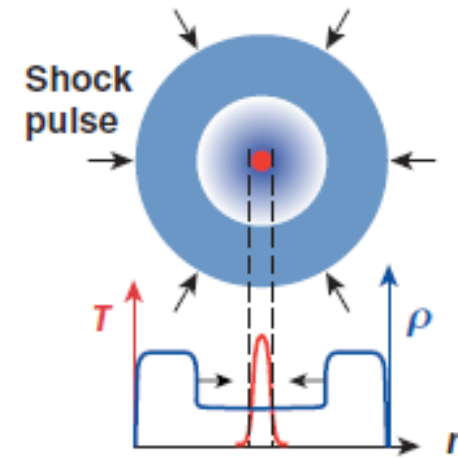
Fast Ignition



Fast-heated side spot ignites
a high-density fuel ball

$$\rho_{\text{hot}} \approx \rho_{\text{cold}} \text{ (isochoric)}$$

Shock Ignition



Spherical shock wave ignites
a high-density fuel ball

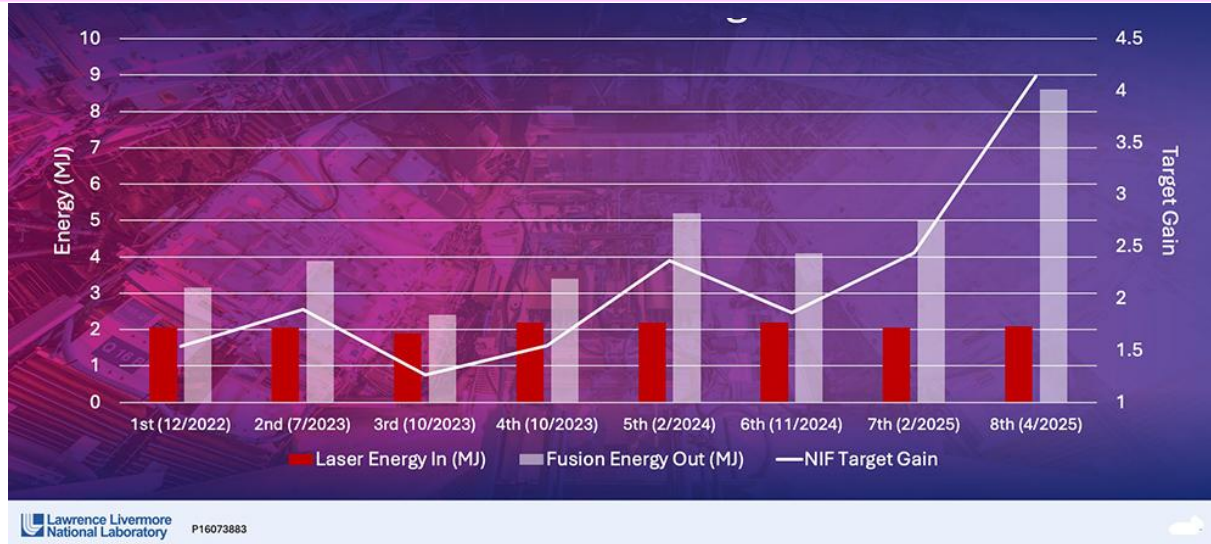
$$\rho T_{\text{hot}} \gg \rho T_{\text{cold}}$$

Reference for ICF



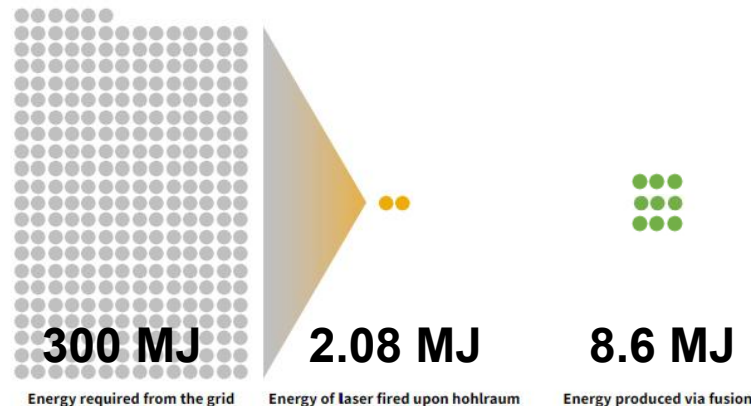
- **Riccardo Betti, University of Rochester, HEDSA HEDP summer school, San Diego, CA, August 16-21, 2015**
- **ICF lectures for course PHY558/ME533**
- **The physics of inertial fusion, by S. Atzeni, J. Meyer-Ter-Vehn**

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



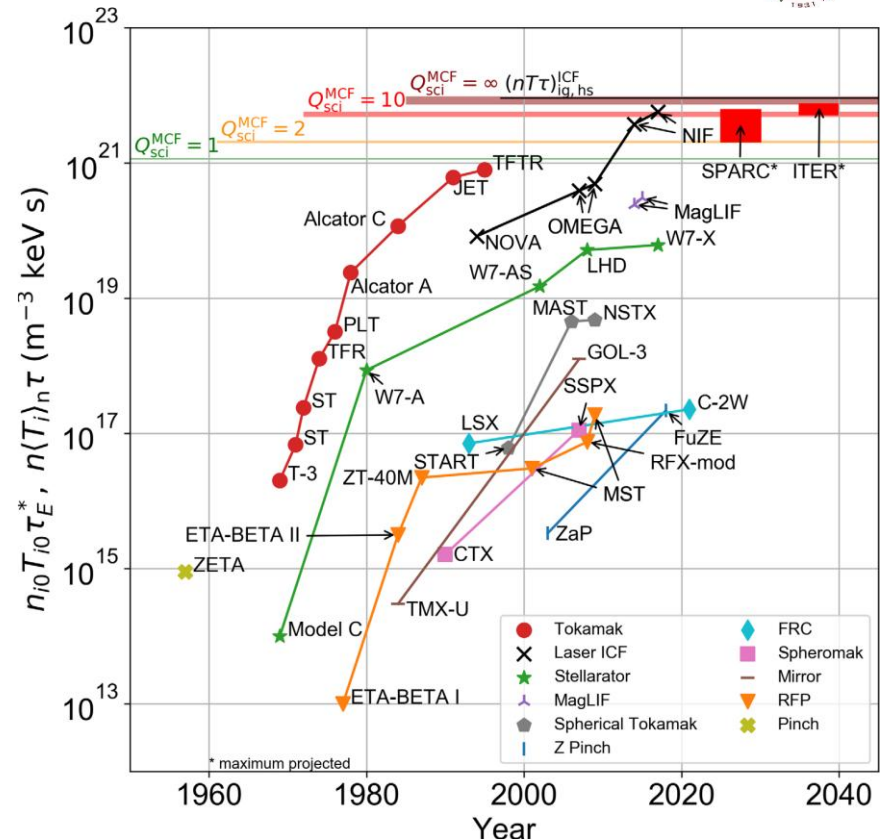
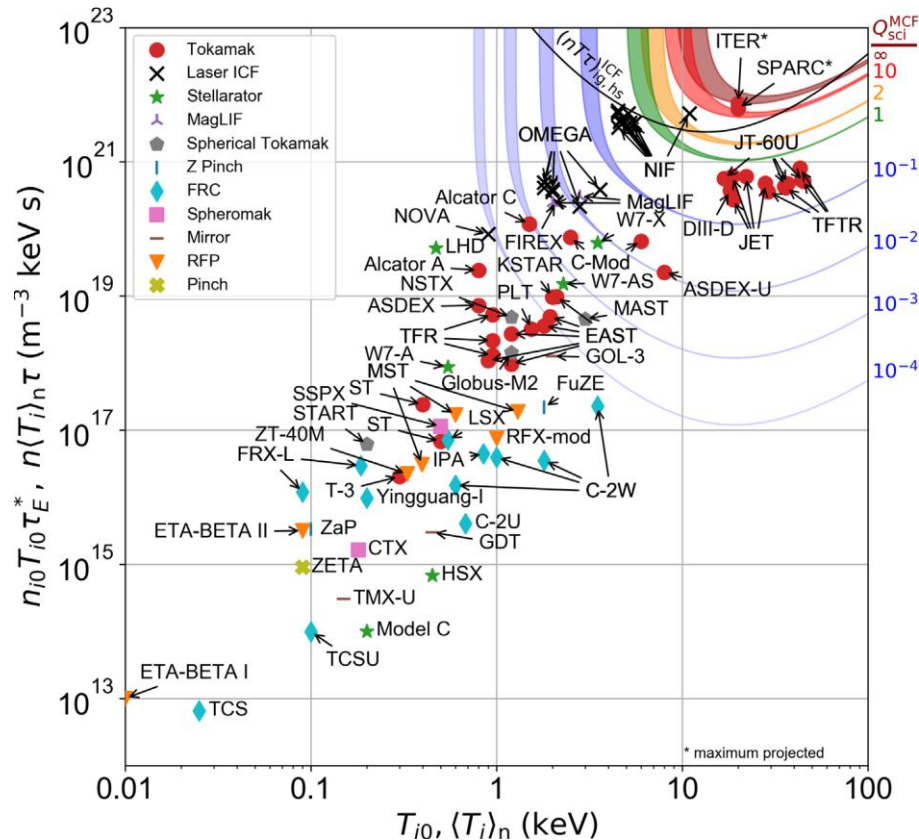
NIF's ignition achievement in perspective

Energy in megajoules ● = 1



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

We are closed to ignition!



• **Lawson criteria (Ignition condition): $P\tau > 10 \text{ atm-s} = 10 \text{ Gbar - ns}$**

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

There are alternative

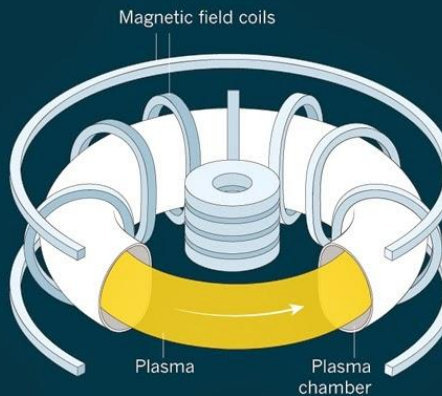


TRAPPING FUSION FIRE

When a superhot, ionized plasma is trapped in a magnetic field, it will fight to escape. Reactors are designed to keep it confined for long enough for the nuclei to fuse and produce energy.

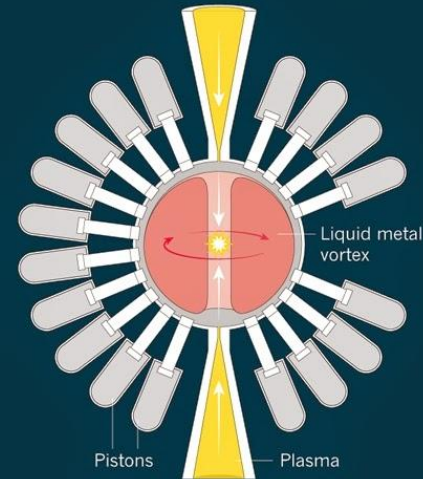
A CHOICE OF FUELS

Many light isotopes will fuse to release energy. A deuterium-tritium mix ignites at the lowest temperature, roughly 100 million kelvin, but produces neutrons that make the reactor radioactive. Other fuels avoid that, but ignite at much higher temperatures.



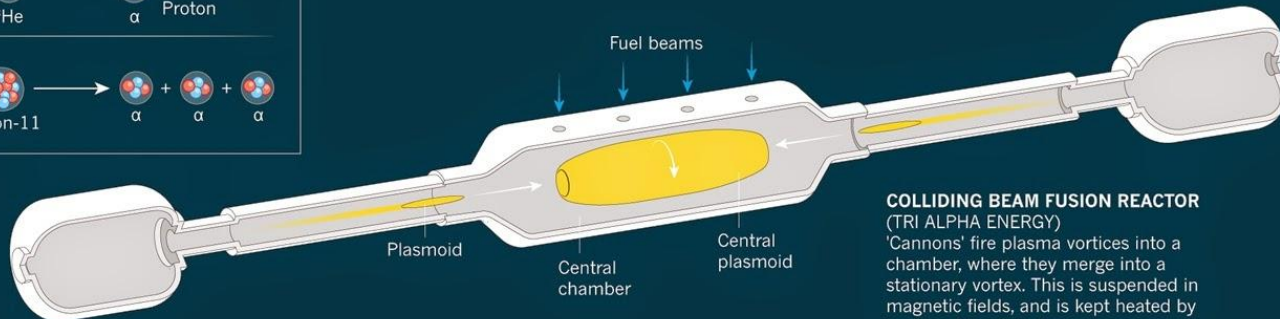
TOKAMAK

(ITER AND MANY OTHERS)
Multiple coils produce magnetic fields that hold the plasma in the chamber. A coil through the centre drives a current through the plasma to keep it hot.



MAGNETIZED TARGET REACTOR (GENERAL FUSION)

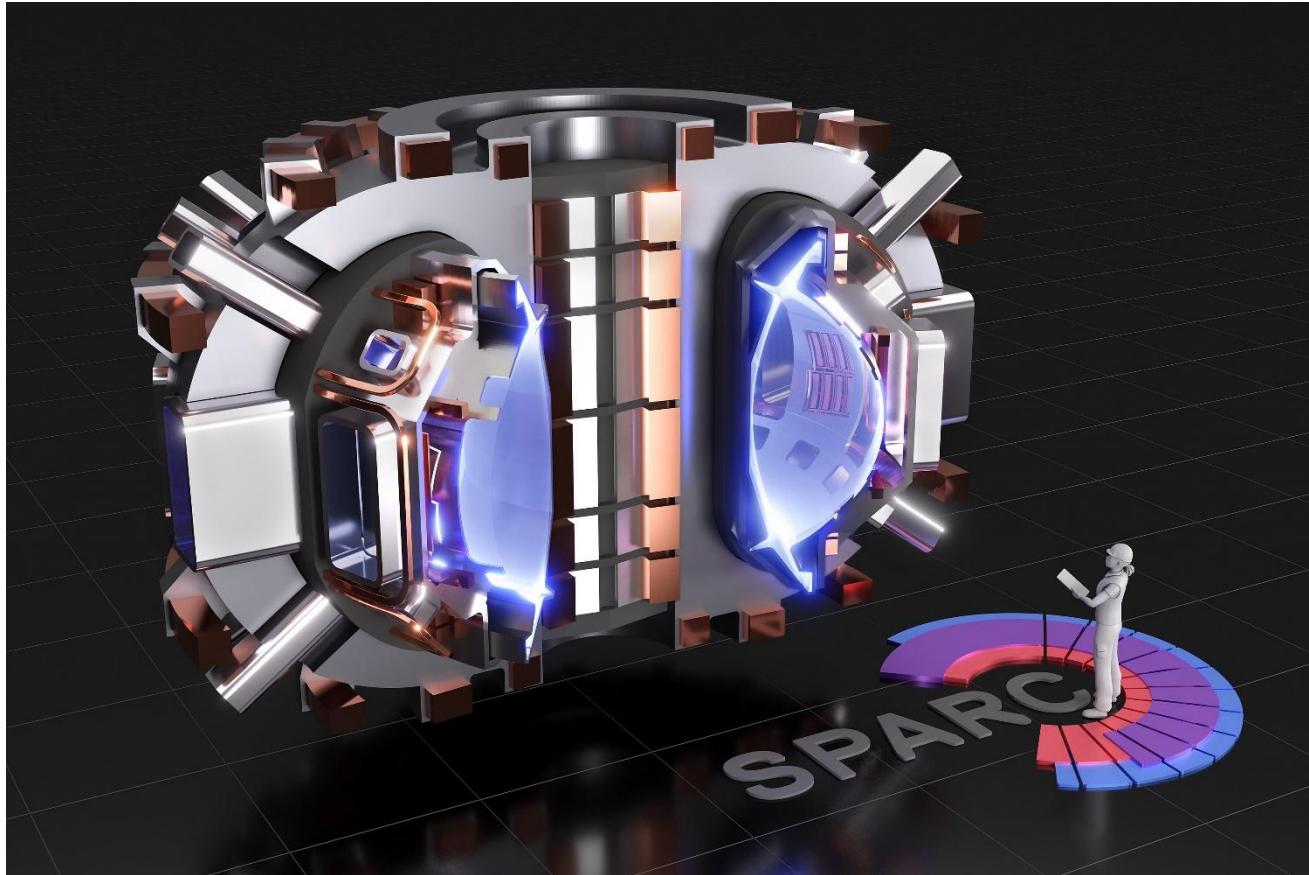
Magnetized rings of plasma are injected into a vortex of liquid metal. Pistons punch the metal inwards, compressing the plasma to ignite fusion.



COLLIDING BEAM FUSION REACTOR (TRI ALPHA ENERGY)

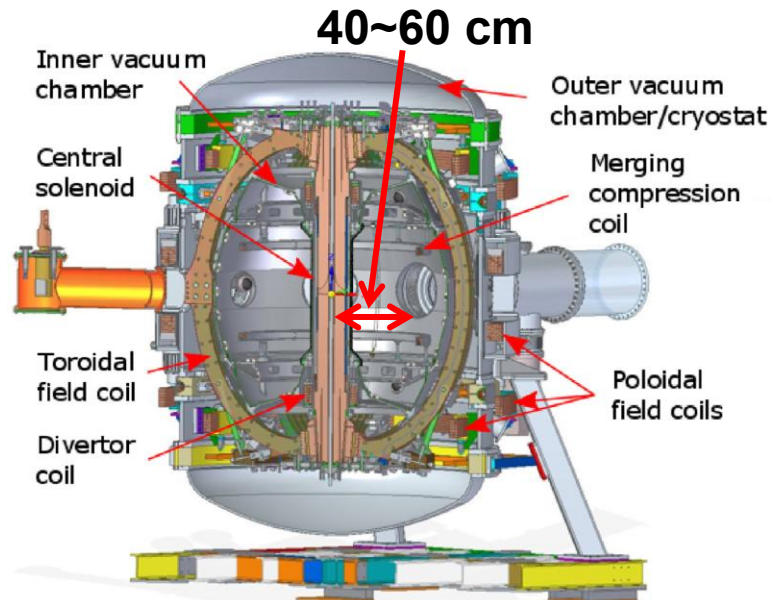
'Cannons' fire plasma vortices into a chamber, where they merge into a stationary vortex. This is suspended in magnetic fields, and is kept heated by beams of fresh fuel.

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



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

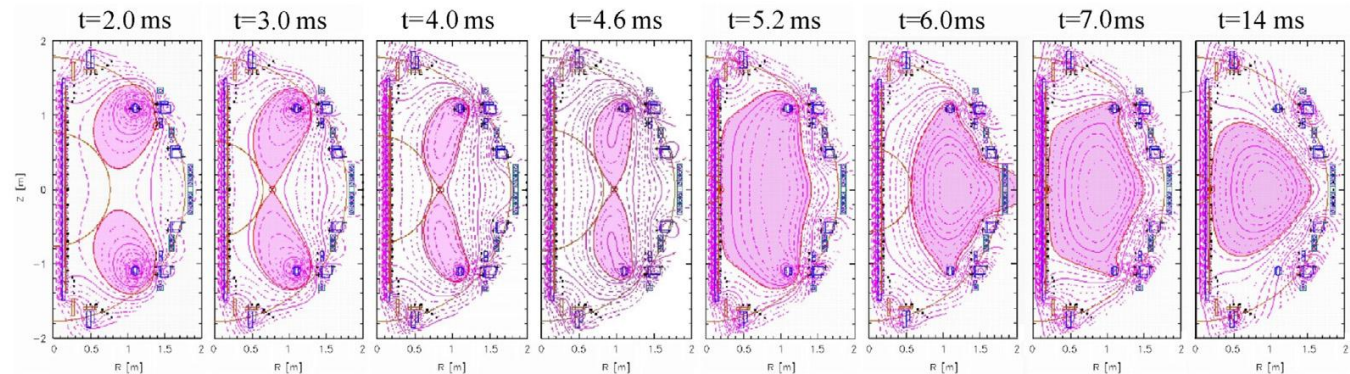
Merging compression is used to heat the tokamak at the start-up process in ST40 Tokamak at Tokamak Energy Ltd



- High temperature superconductors are used.
- $B_T \sim 3 \text{ T}$



- Merging compression

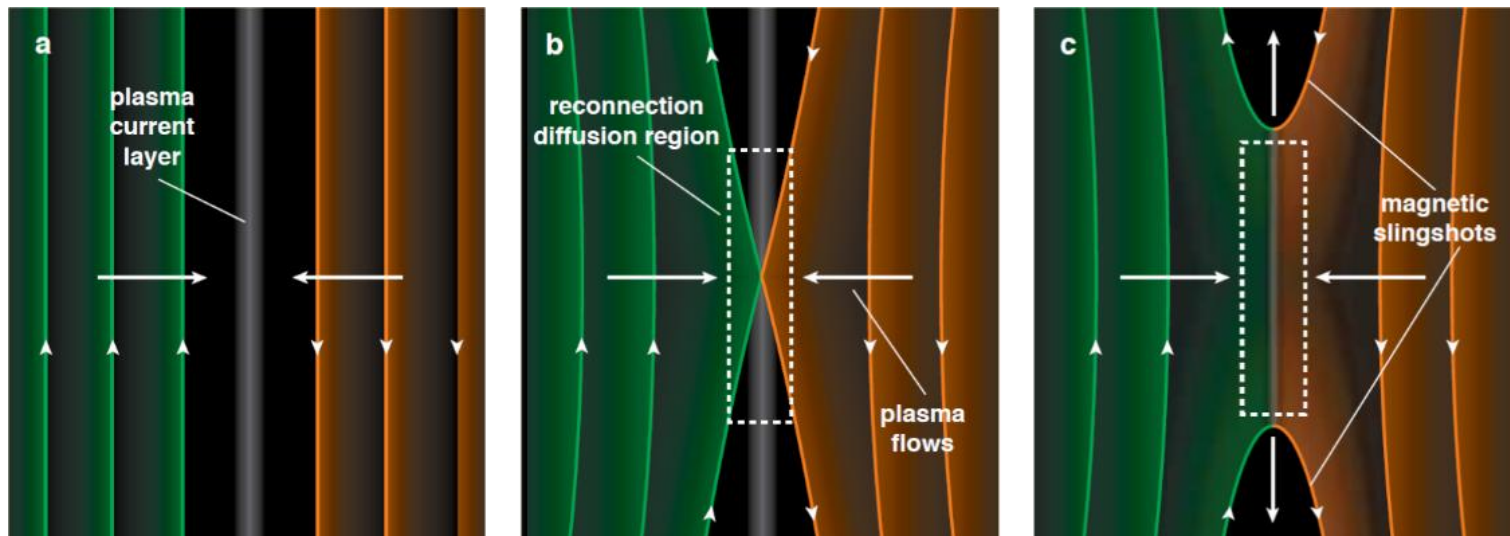


M. Gryaznevich, etc., Fusion Eng. Design, **123**,177 (2017)

<https://www.tokamakenergy.co.uk/>

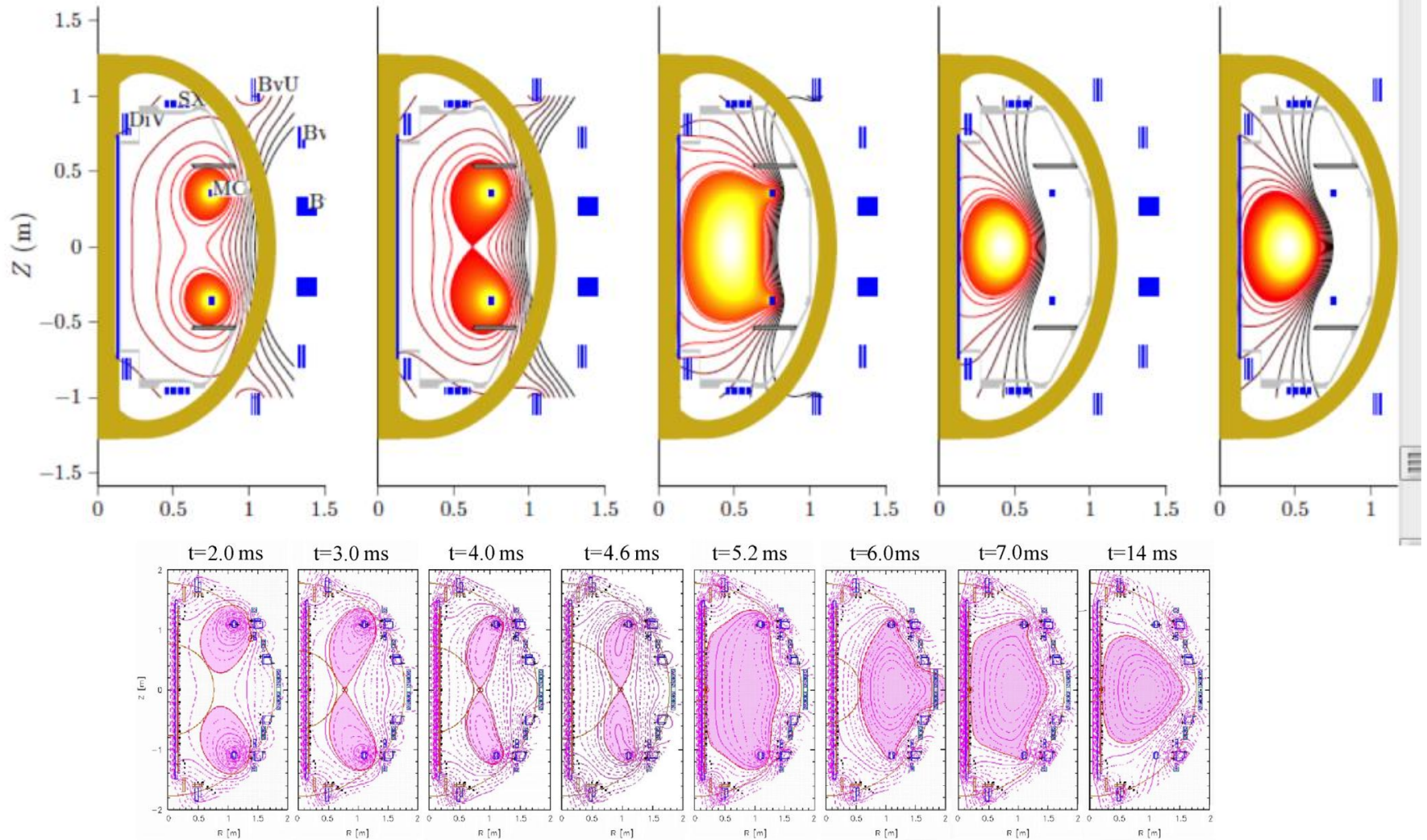
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

Reconnection

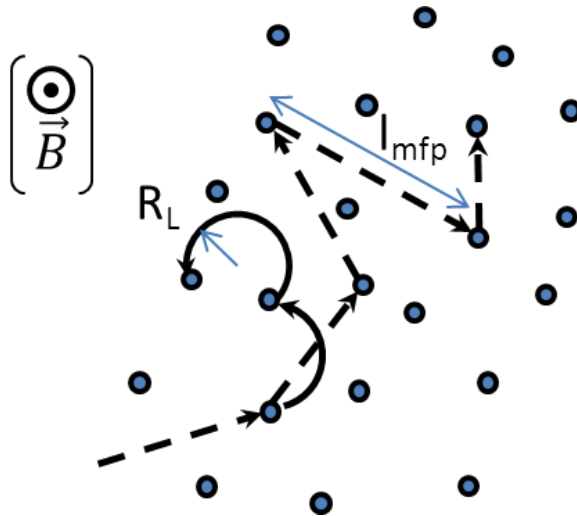


<https://www.youtube.com/watch?v=7sS3Lpzh0Zw>

Merging compression is used to heat the plasma



A strong magnetic field reduces the heat flux



$$\mathbf{q}_T = -\kappa_{\parallel} \nabla_{\parallel} T - \kappa_{\perp} \nabla_{\perp} T$$

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

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

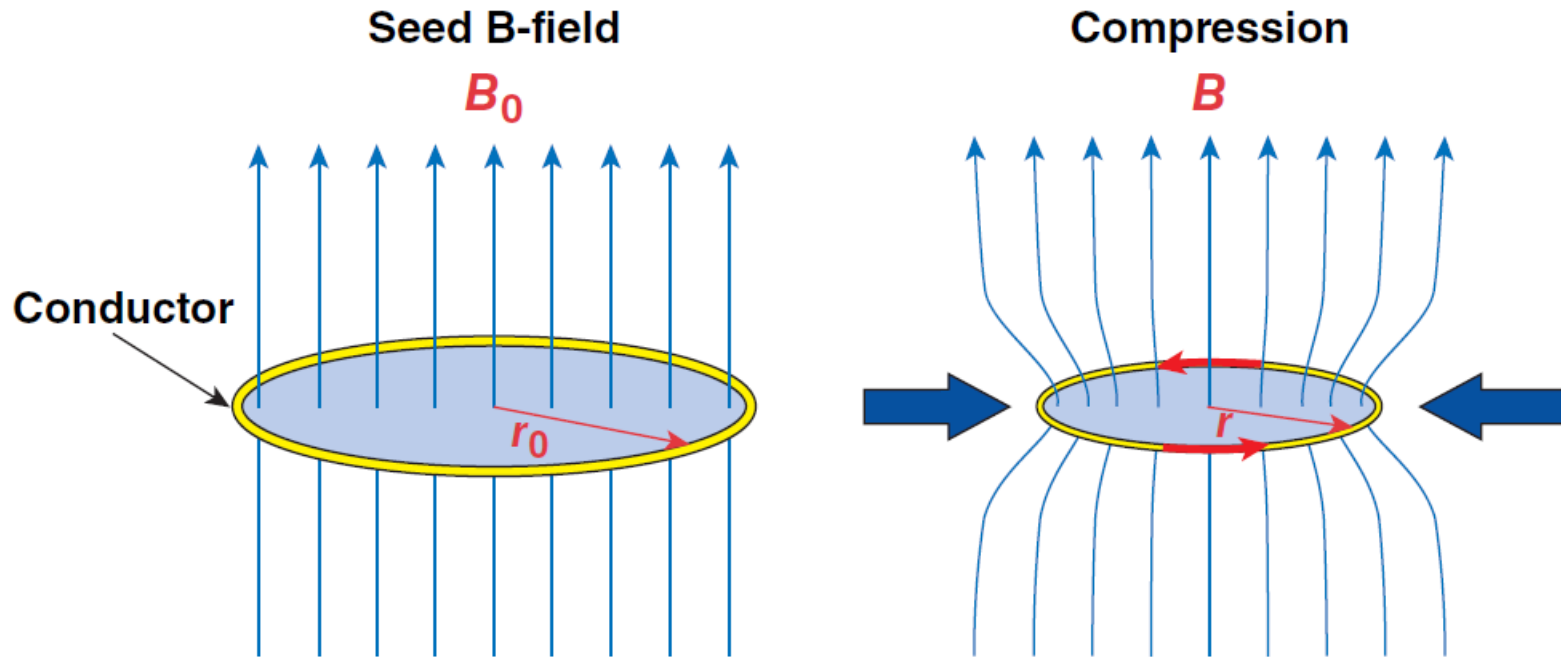
- Typical hot spot conditions:

$R_{\text{hs}} \sim 40 \mu\text{m}$, $\rho \sim 20 \text{ g/cm}^3$, $T \sim 5 \text{ keV}$:

$B > 10 \text{ MG}$ is needed for $\chi > 1$

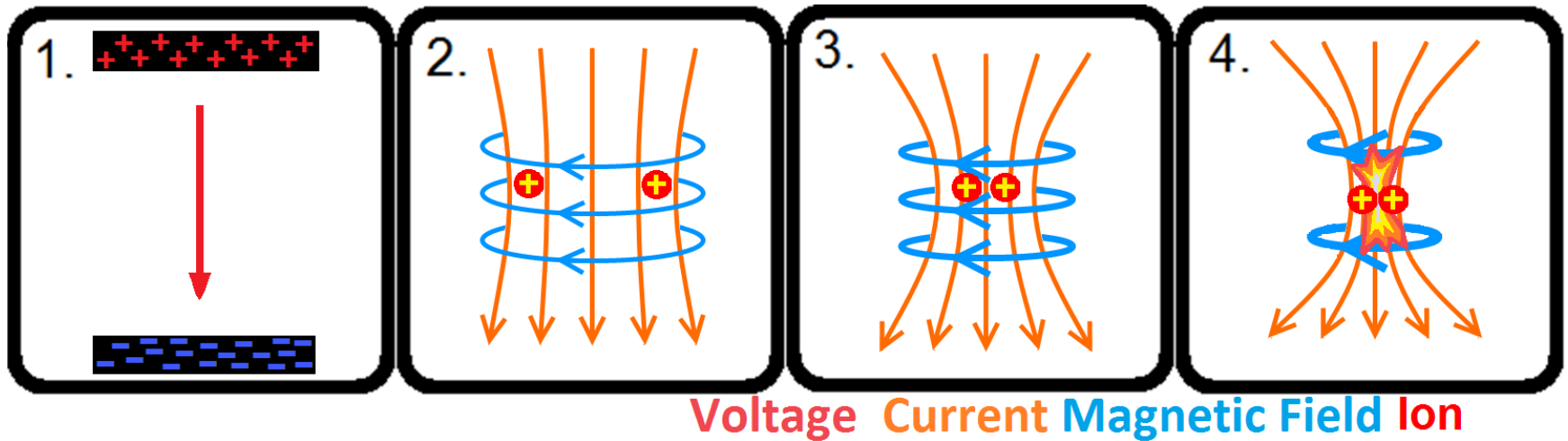
Magnetic-flux compression can be used to provide the needed magnetic field.

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



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

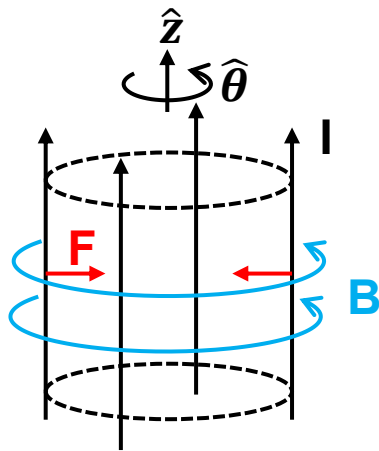
Plasma can be pinched by parallel propagating plasmas



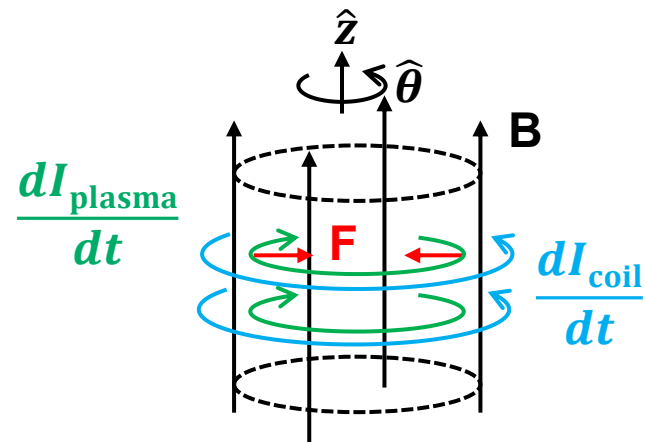
Plasma can be heated via pinches



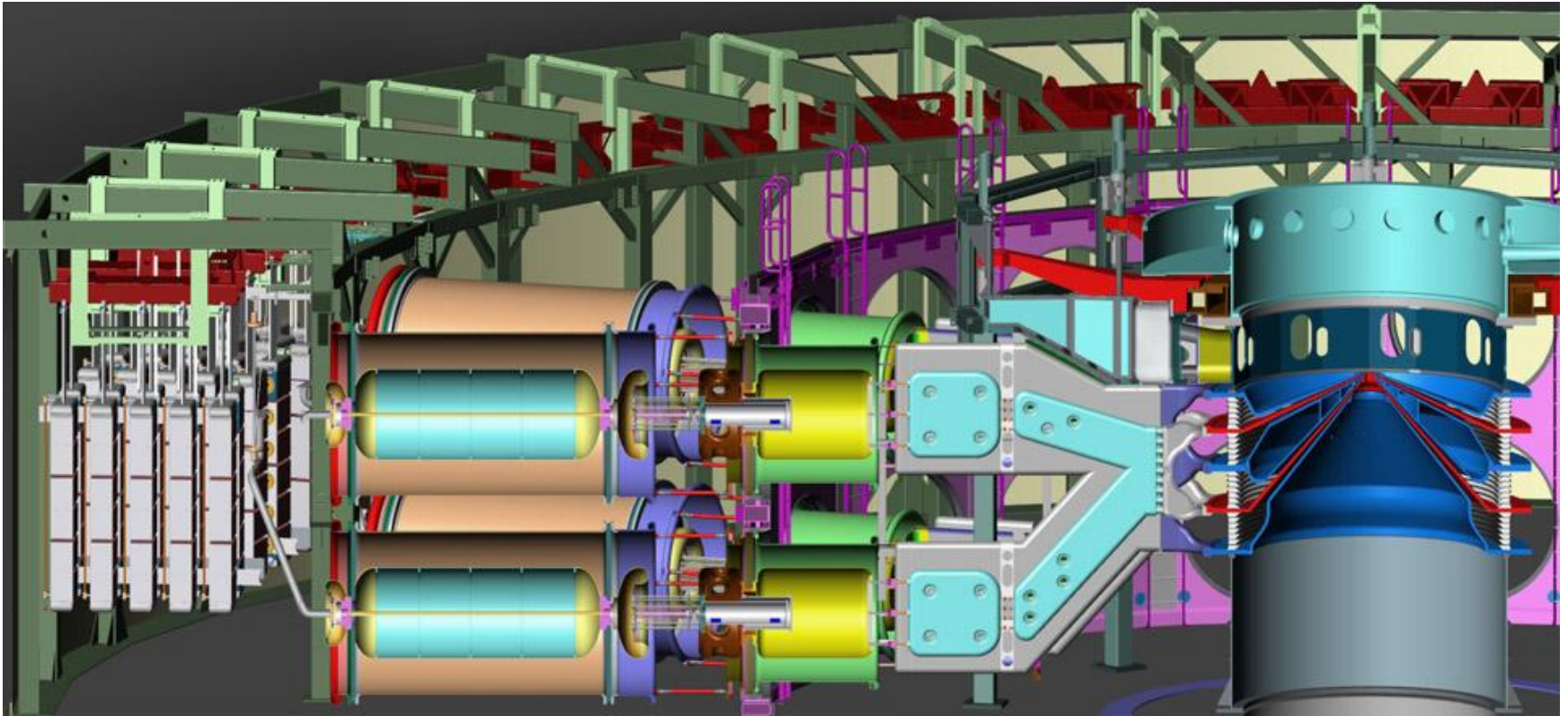
Z pinch



Theta pinch

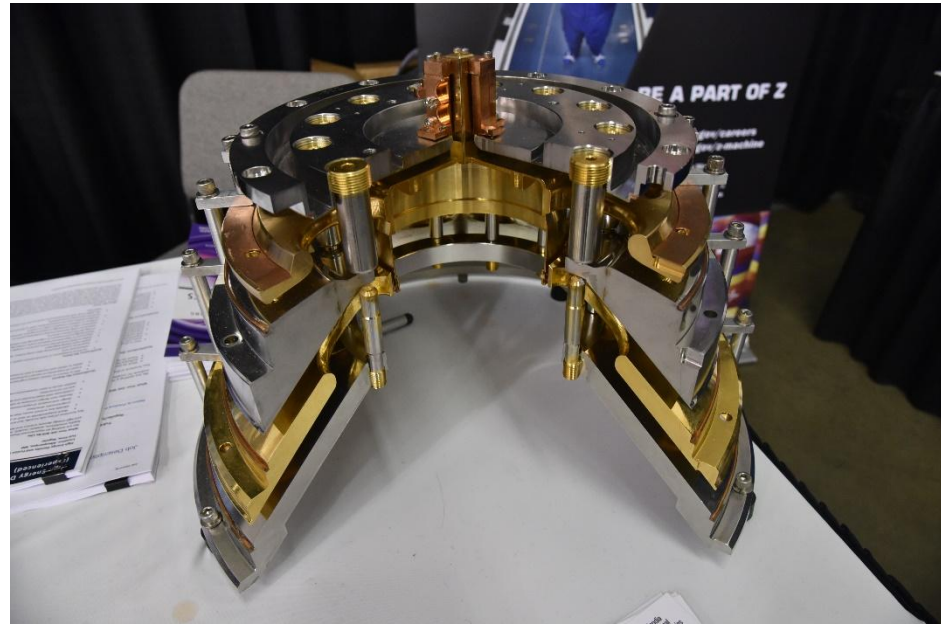


Sandia's Z machine is the world's most powerful and efficient laboratory radiation source

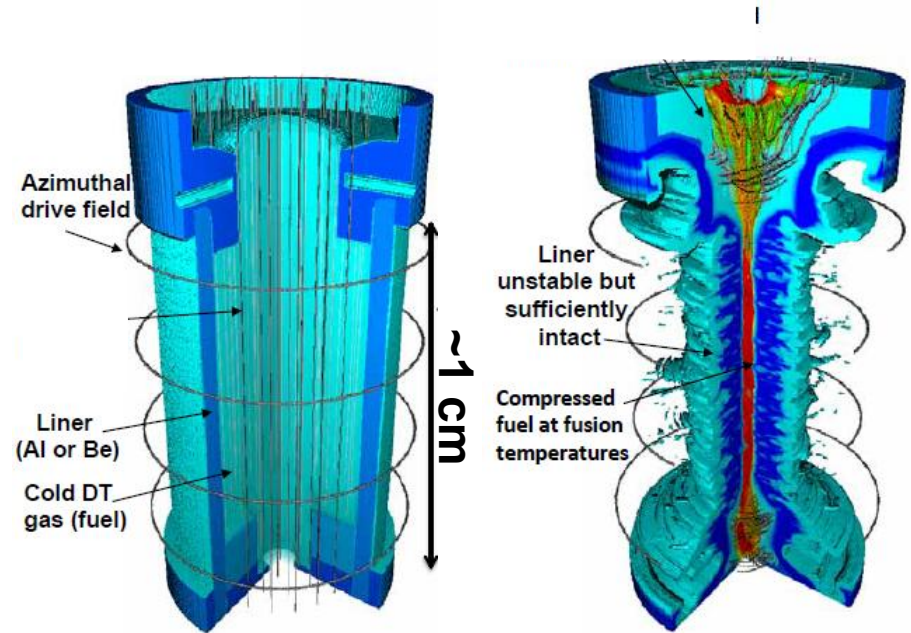


- **Stored energy: 20 MJ**
- **Marx charge voltage: 85 kV**
- **Peak electrical power: 85 TW**
- **Peak current: 26 MA**
- **Rise time: 100 ns**
- **Peak X-ray emissions: 350 TW**
- **Peak X-ray output: 2.7 MJ**

Z machine



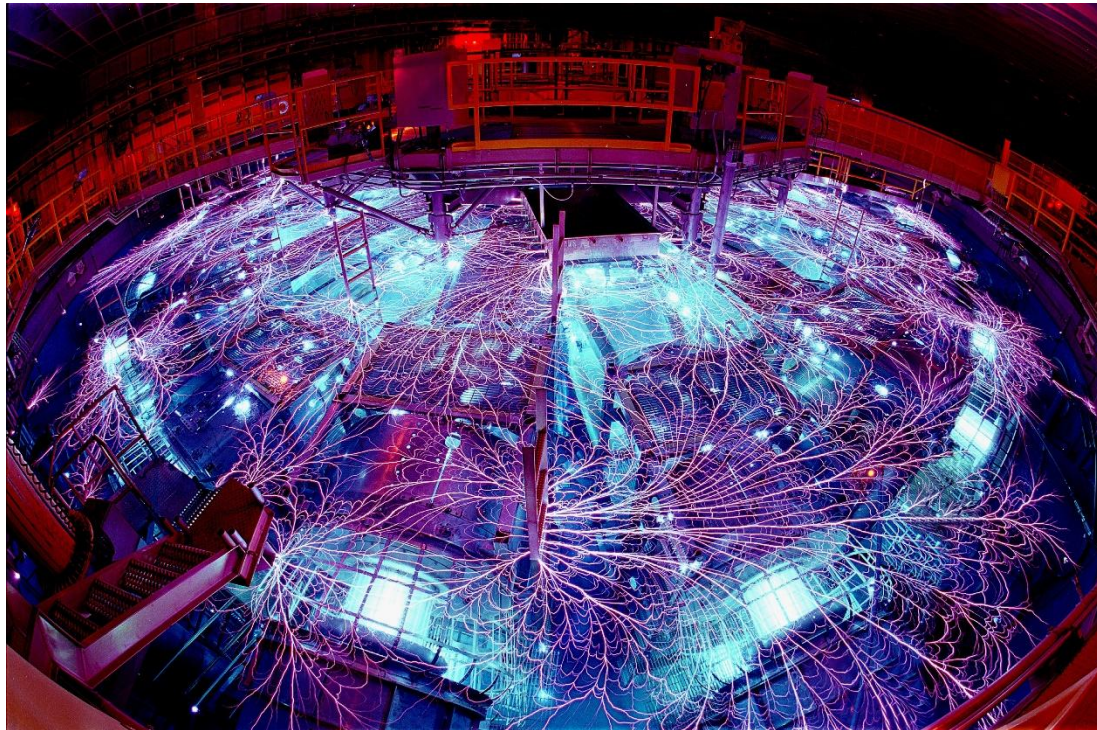
Z machine



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

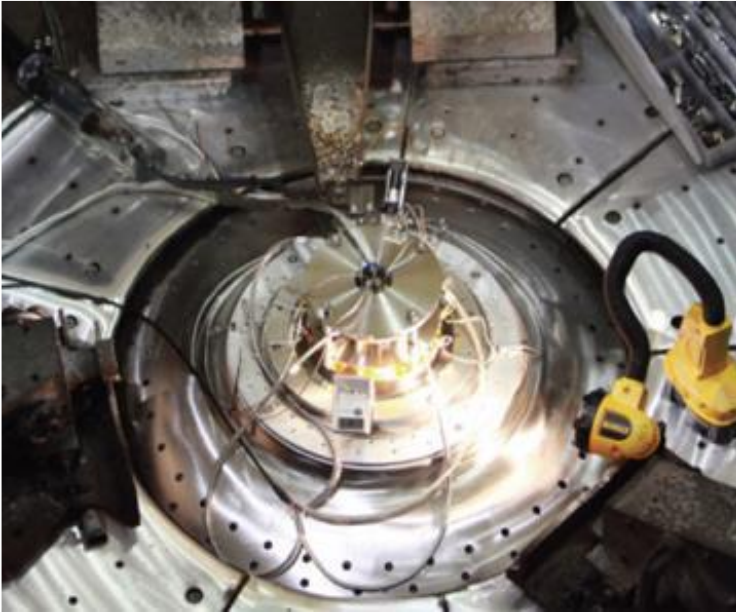
- **Peak current: 26 MA**
- **Rise time: 100 ns**
- **Peak X-ray output: 2.7 MJ**

Z machine discharge



Before and after shots

- Before shots

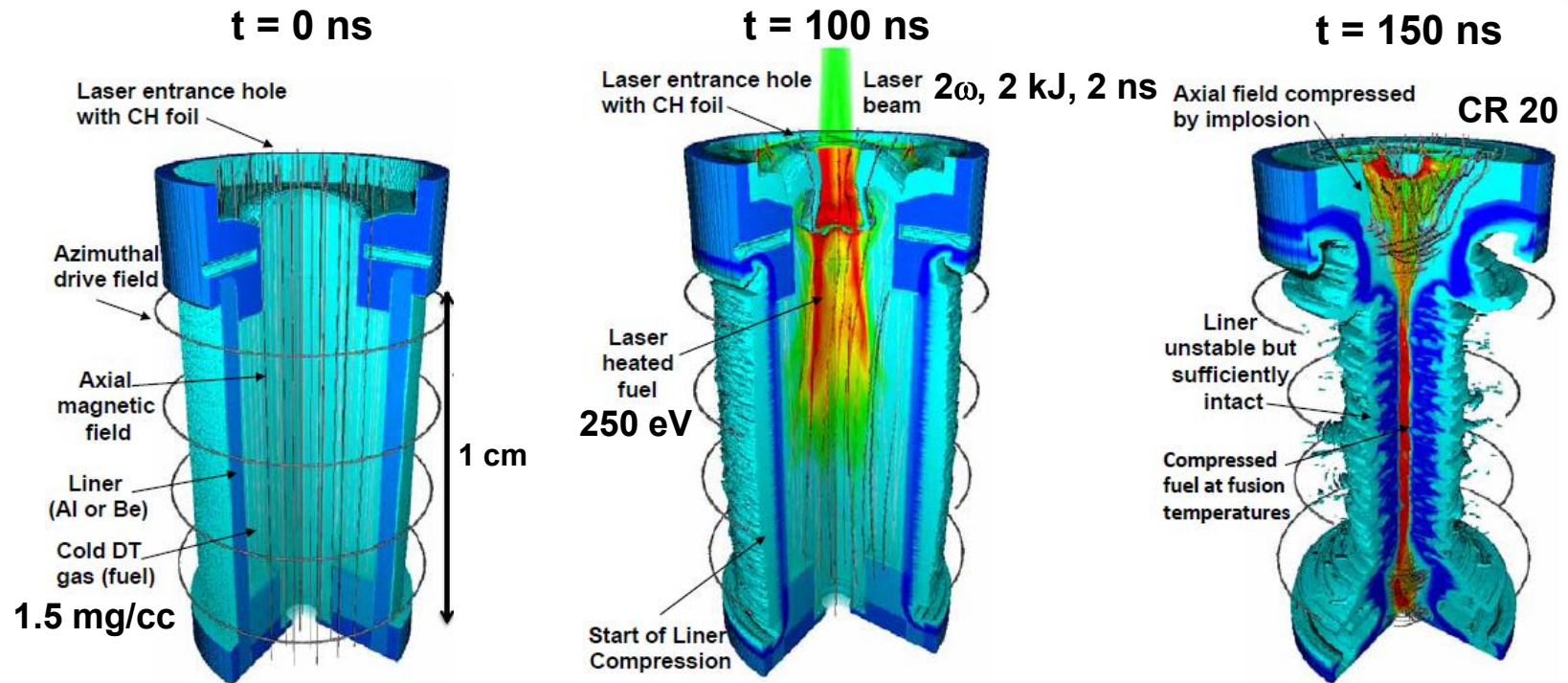


- After shots



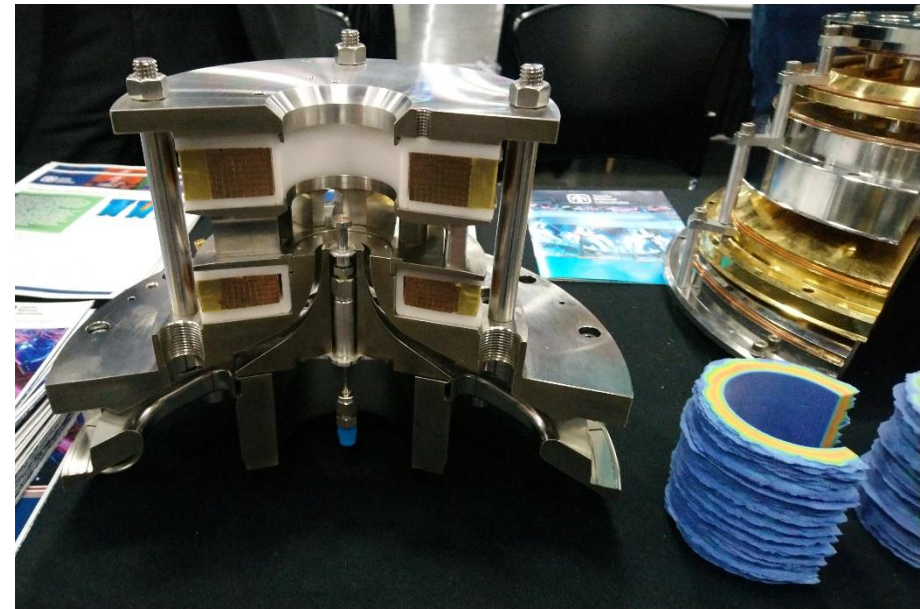
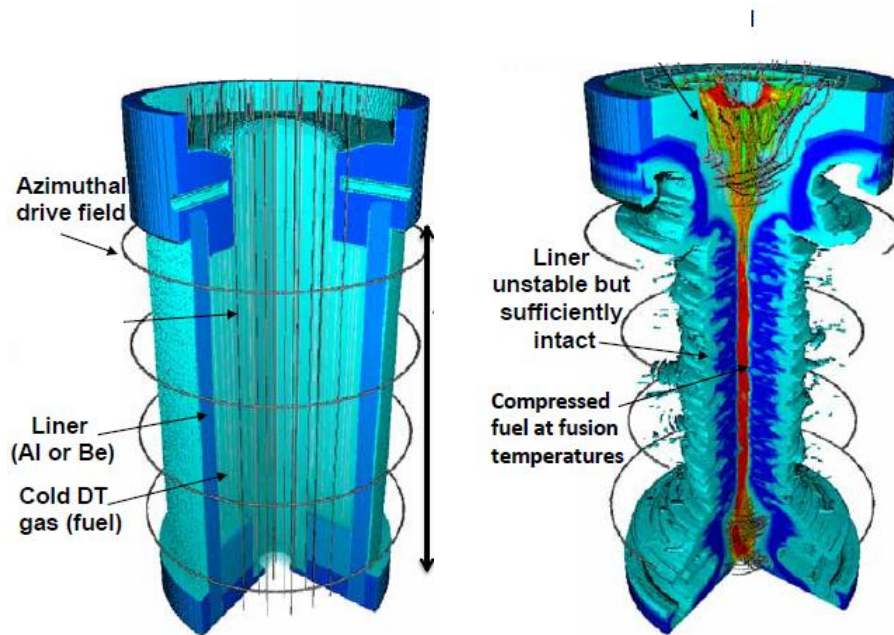
SAND2017-0900PE_The sandia z machine - an overview of the world's most powerful pulsed power facility.pdf

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

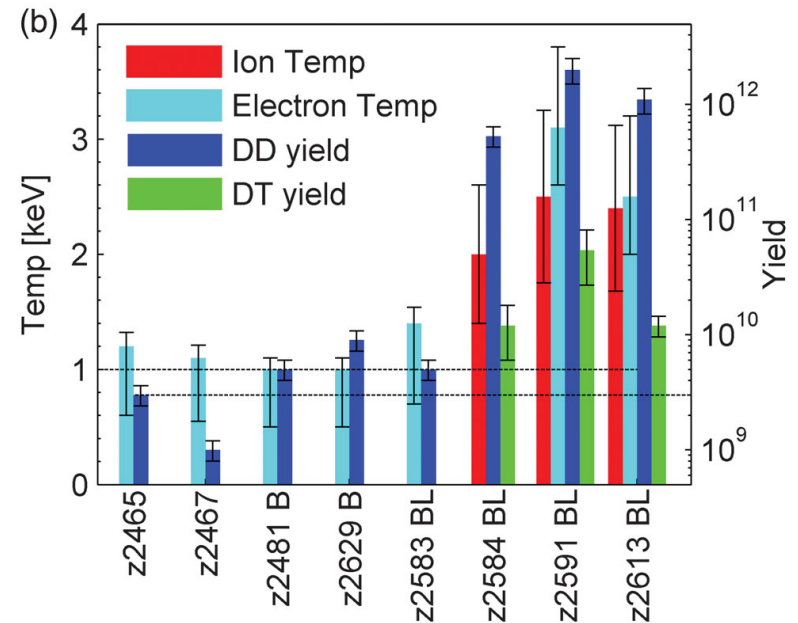
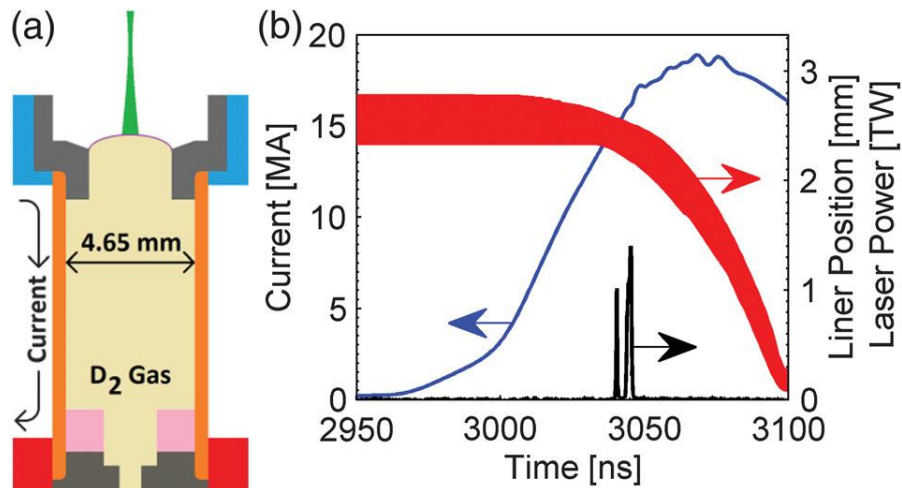


The stagnation plasma reached fusion-relevant temperatures with a 70 km/s implosion velocity

MagLIF target



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

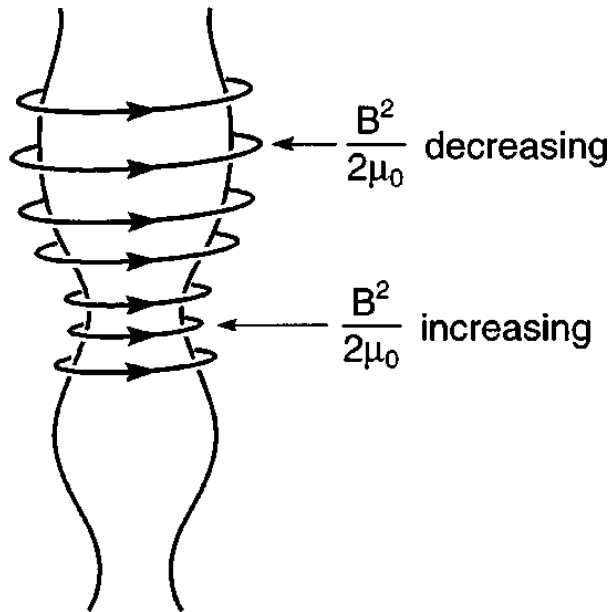


Sheared flow stabilizes MHD instabilities

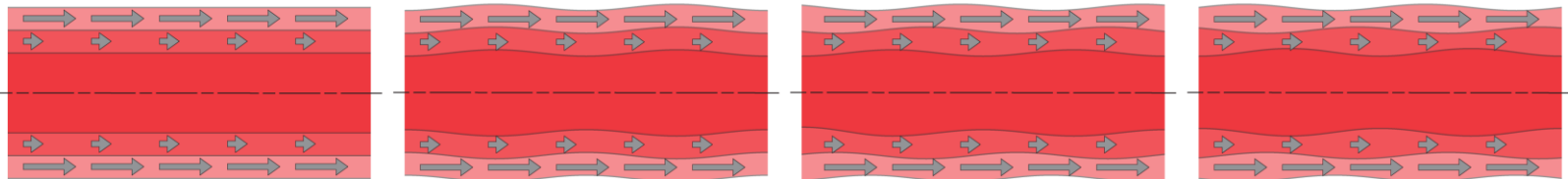
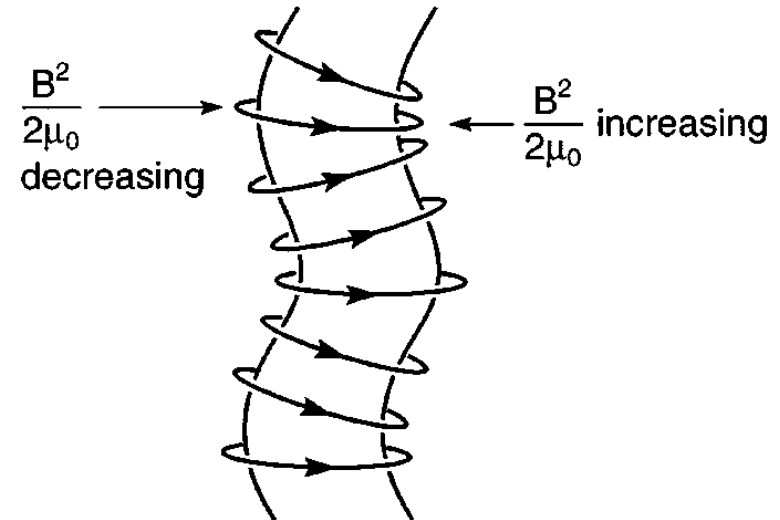


$m = 0$ (sausage)

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



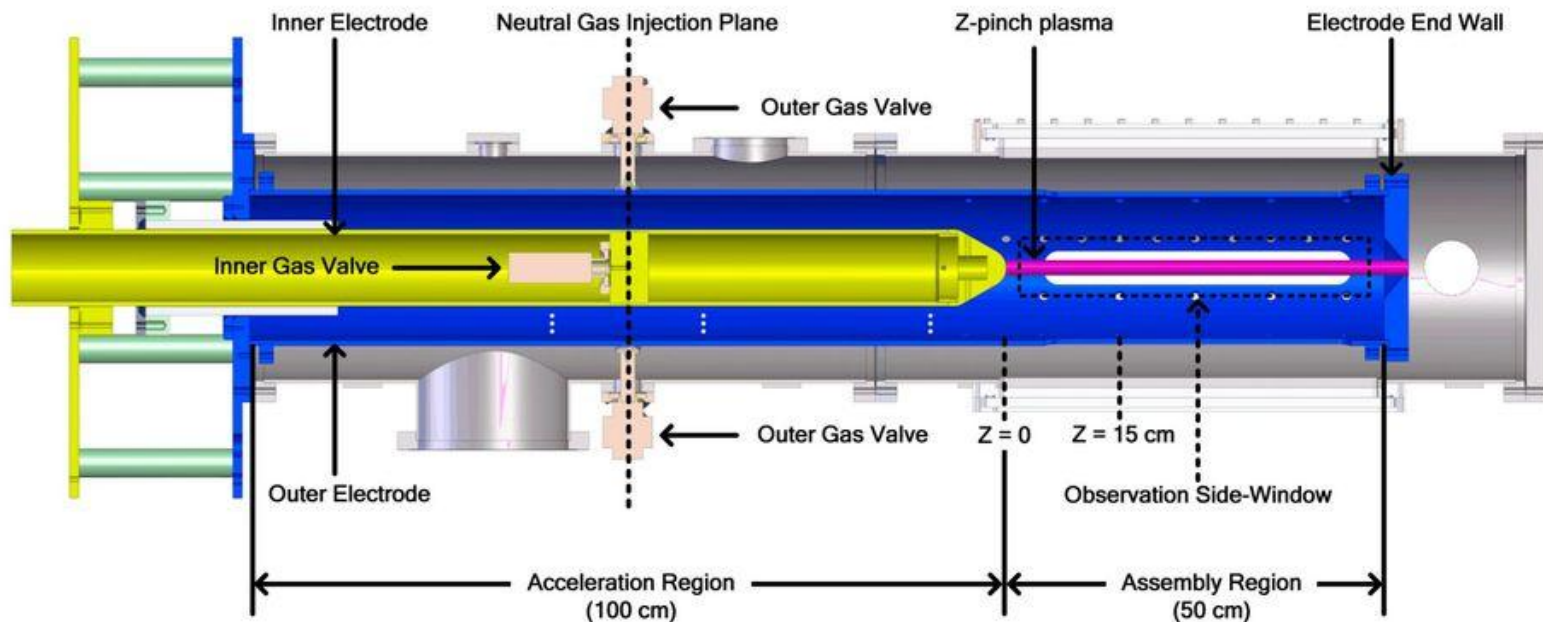
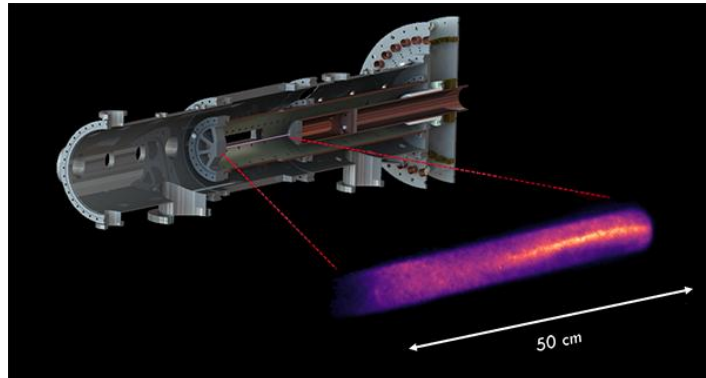
$m = 1$ (kink)



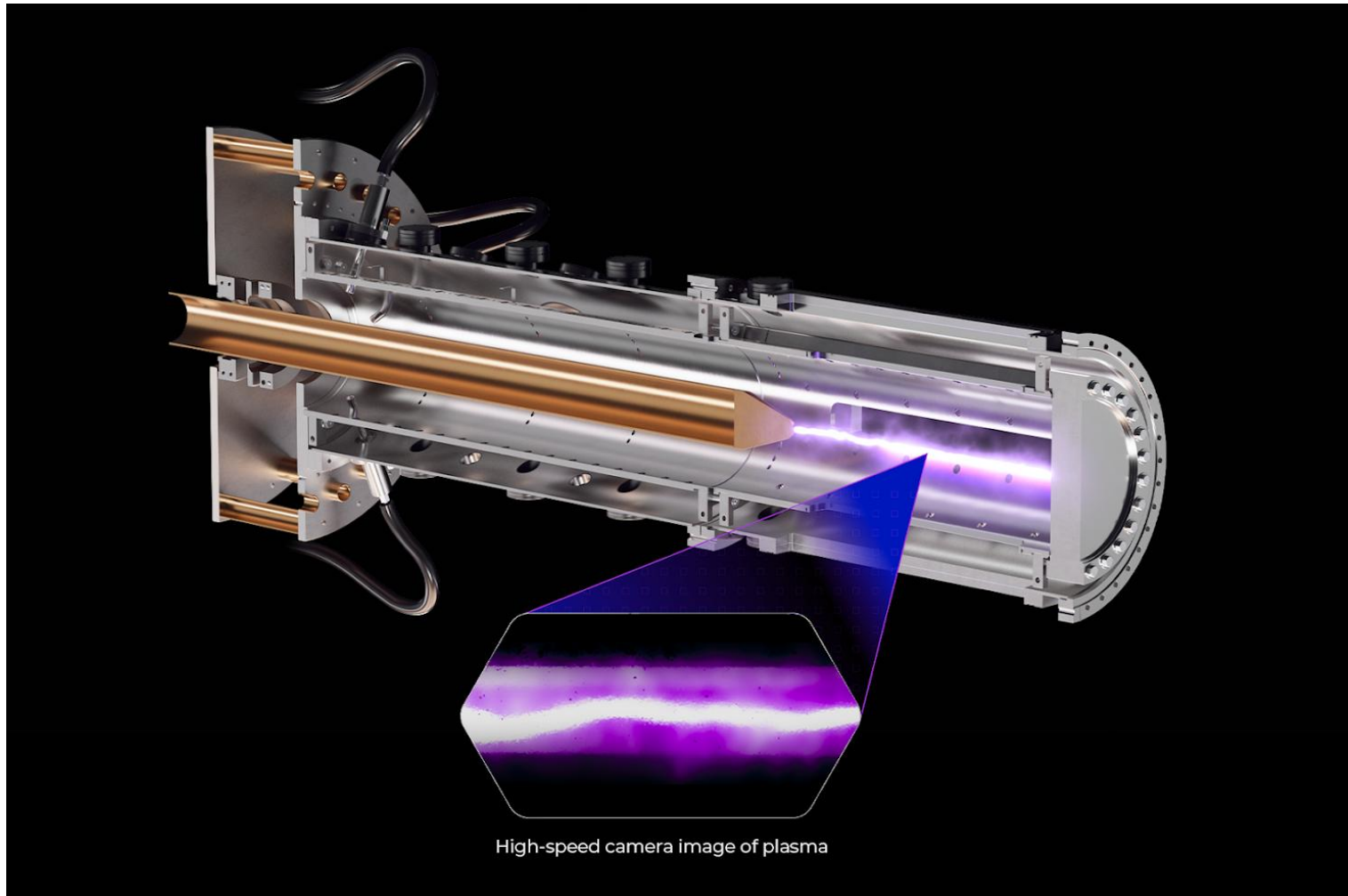
$$\frac{dV_z}{dr} \neq 0$$

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

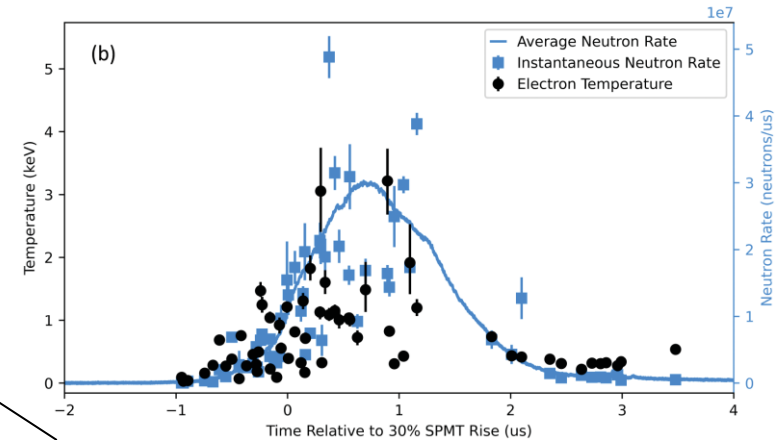
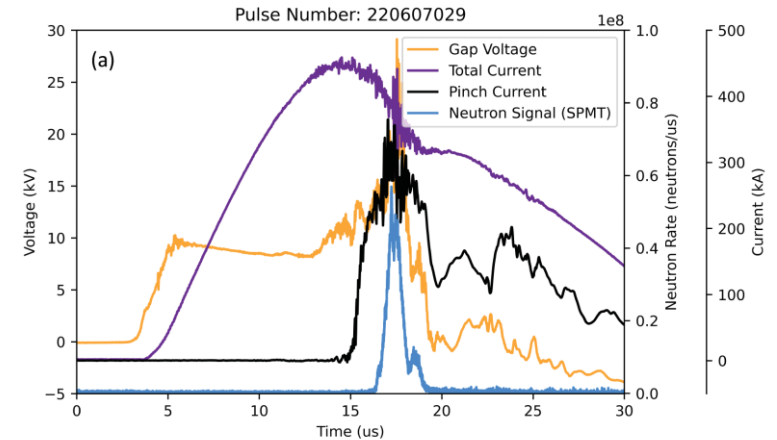
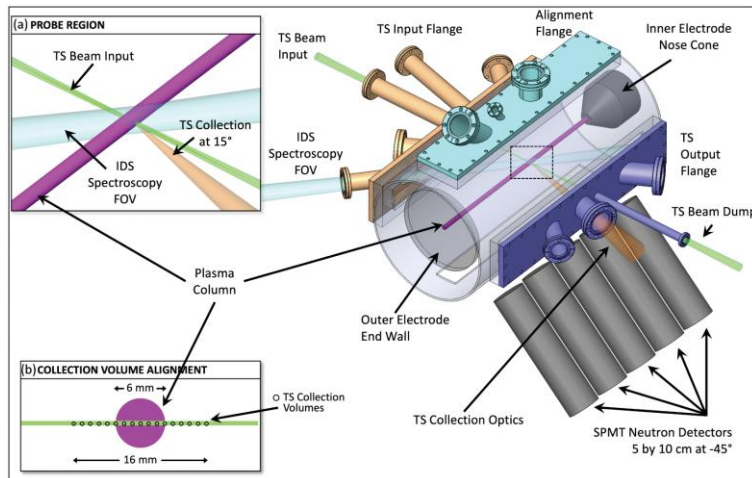
A z-pinch plasma can be stabilized by sheared flows



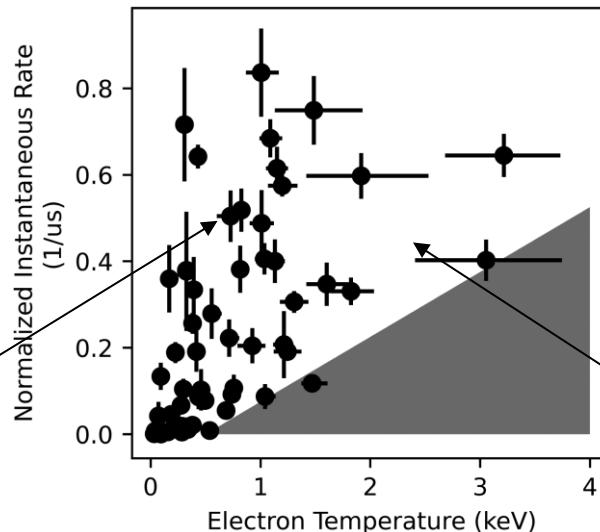
<https://www.zapenergyinc.com/about>
A. D. Stepanov, etc., Phys. Plasmas 27, 112503 (2020)



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

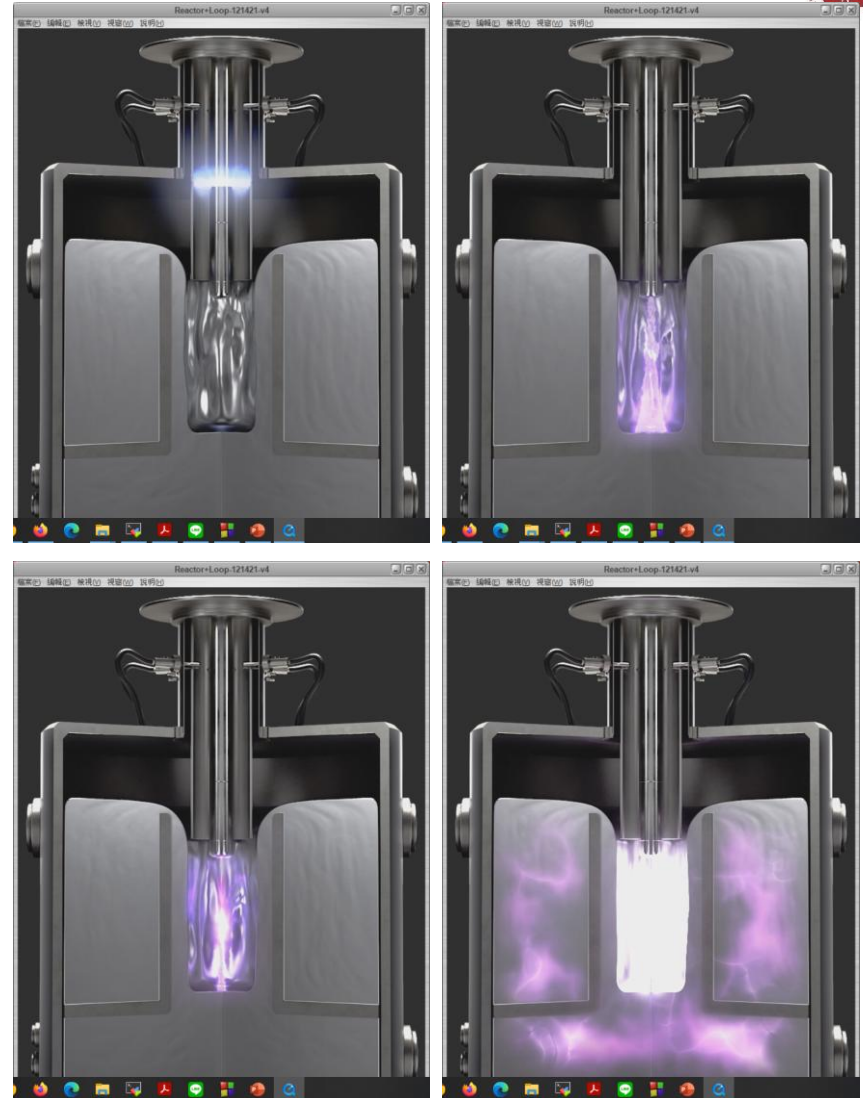
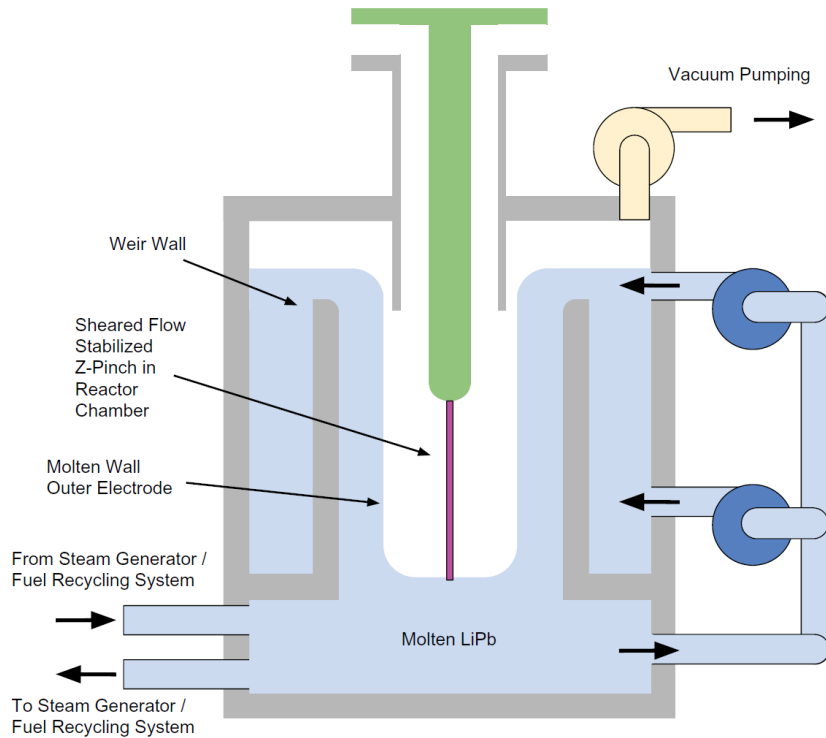


- Thomson scattering measurement missed the high temperature region.



- High temperature coincide with high rate.

Fusion reactor concept by ZAP energy

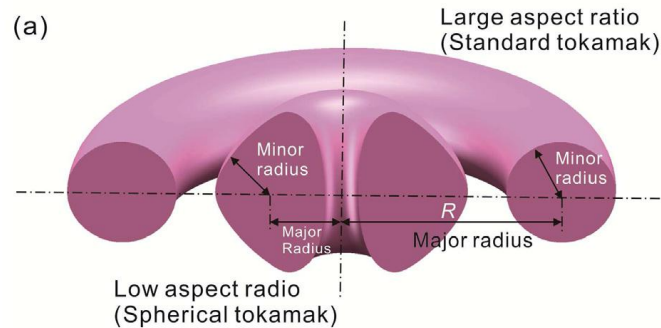


<https://www.zapenergyinc.com/about>
 E. G. Forbes, etc., Fusion Sci. Tech. 75, 599 (2019)

Spherical torus (ST) and compact torus (CT)

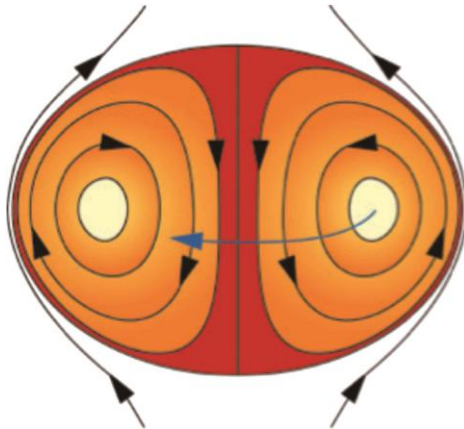


- Spherical torus (ST)

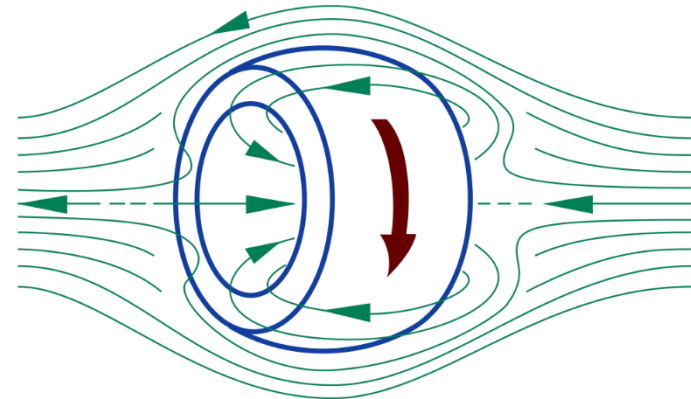


- Compact torus (CT)

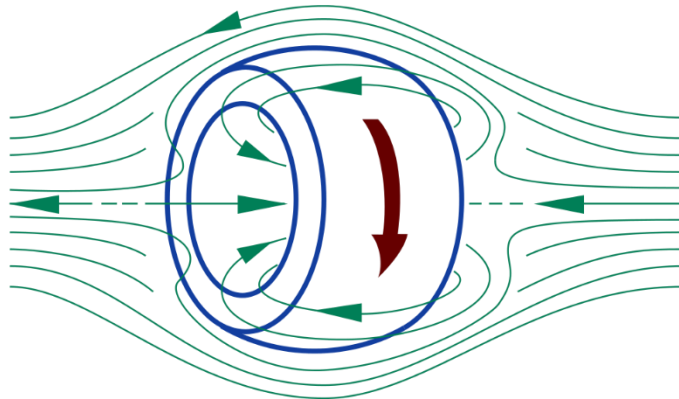
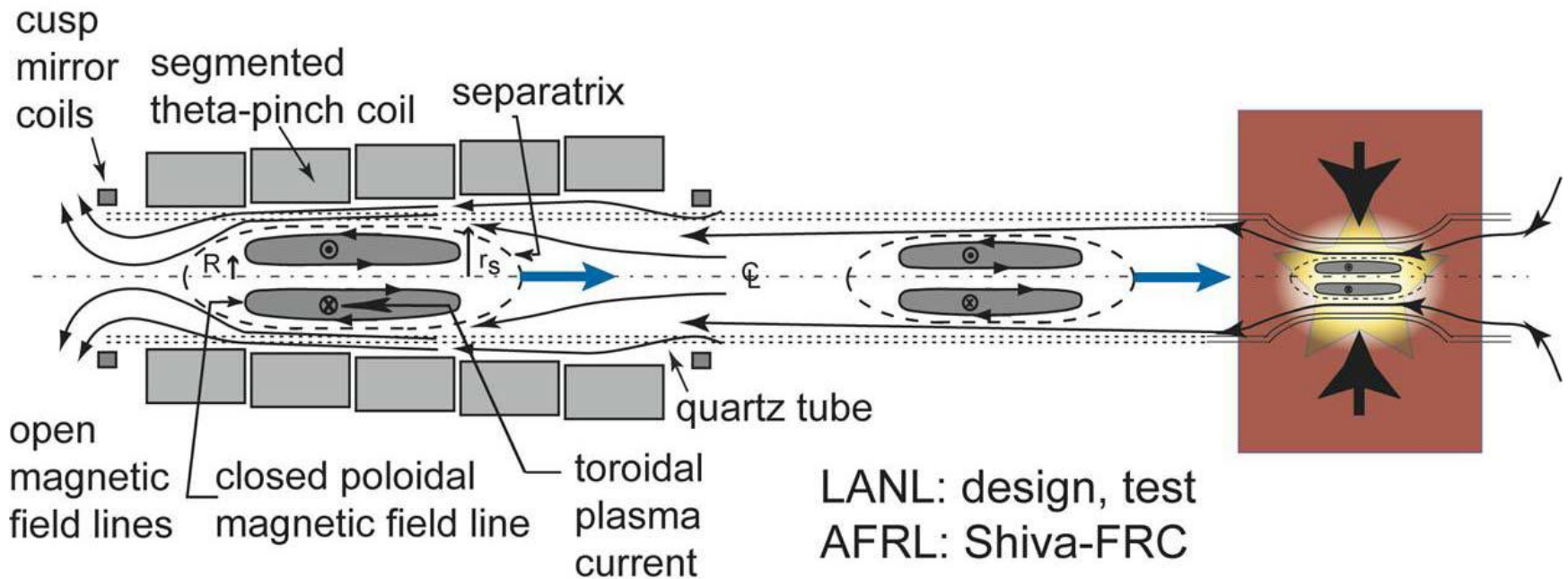
- Spheromak



- Field reversed configuration (FRC)



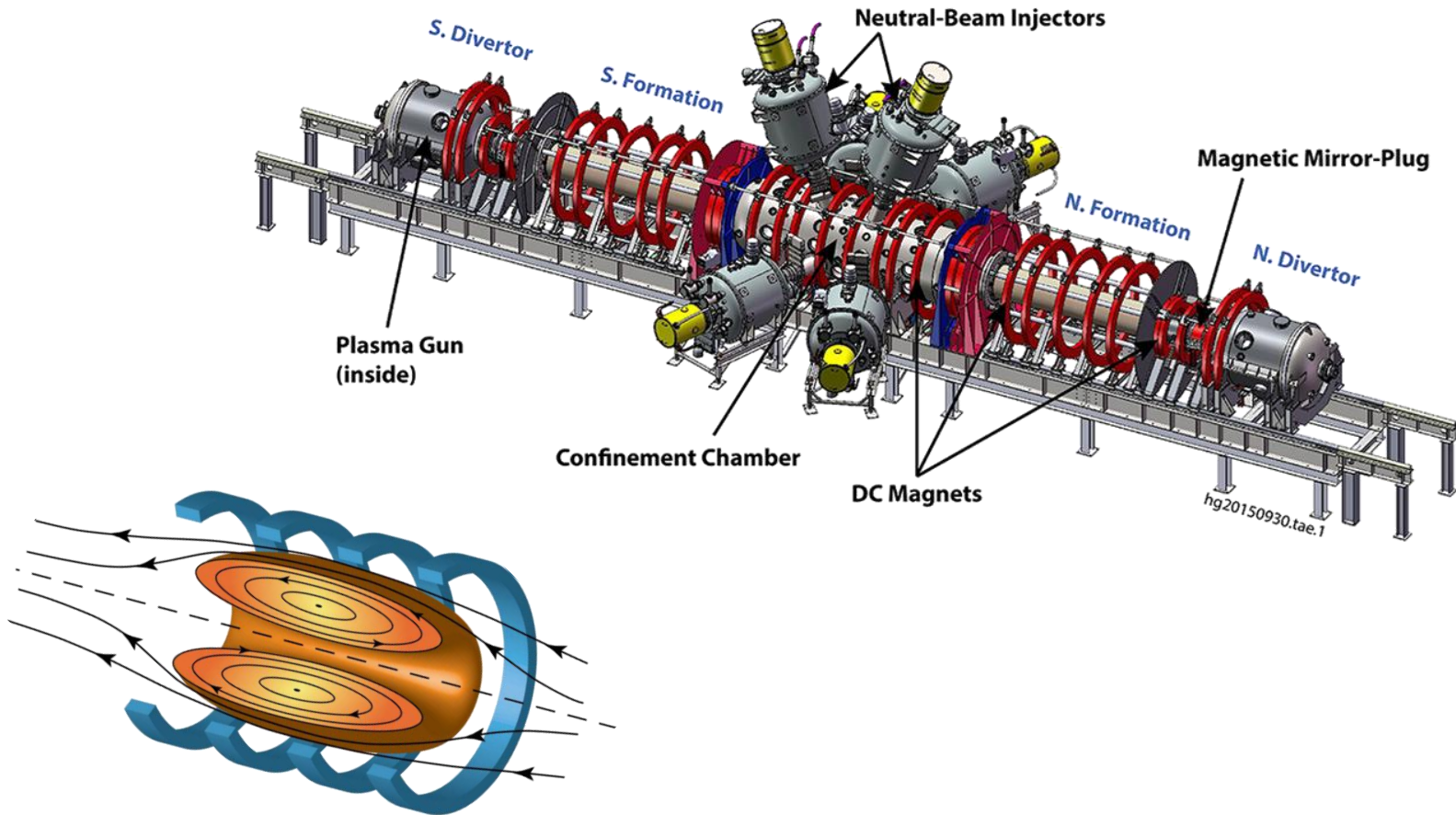
Field reverse configuration is used in Tri-alpha energy



*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



NBI for Tri-Alpha Energy Technologies

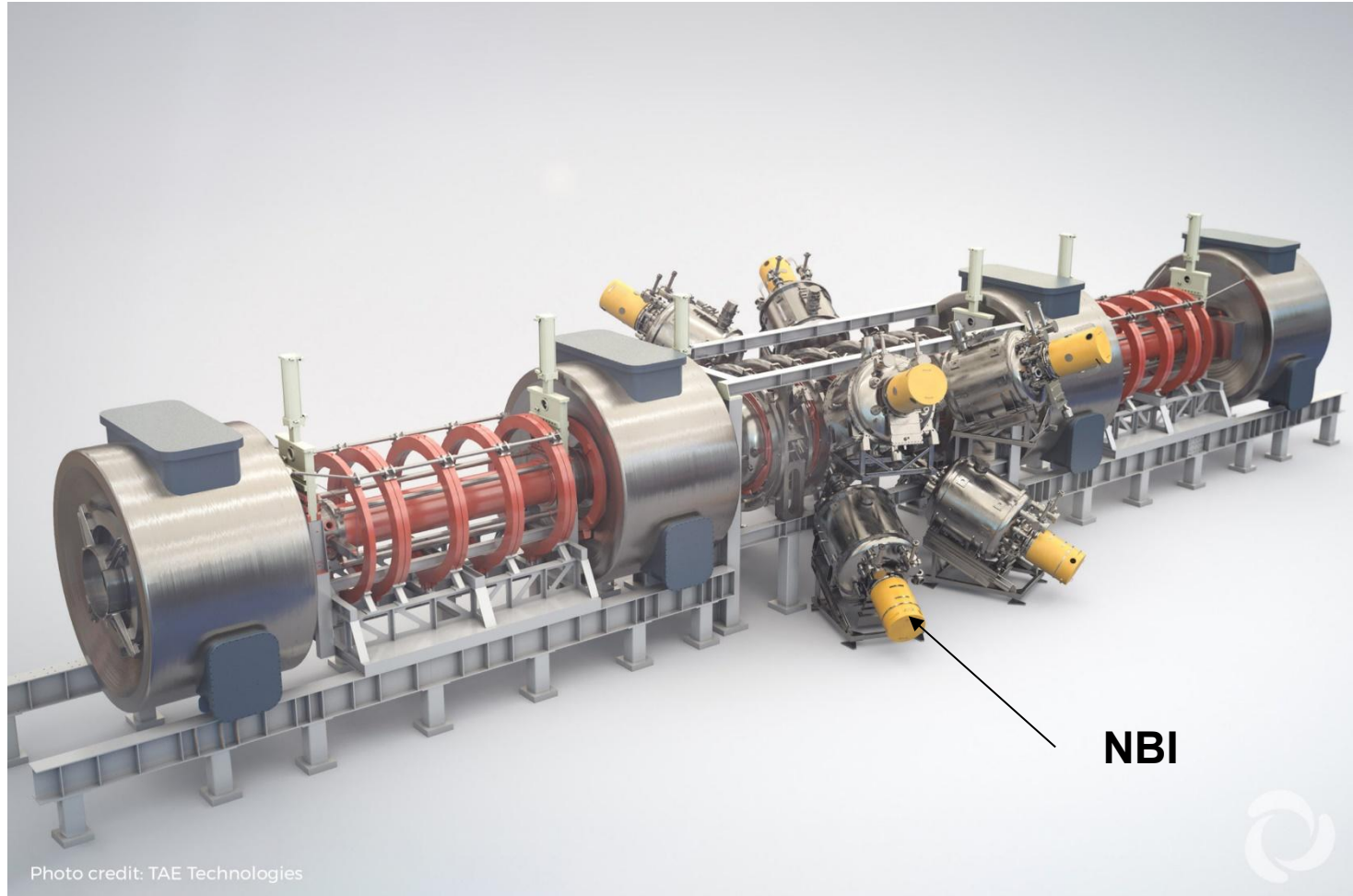


Photo credit: TAE Technologies

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

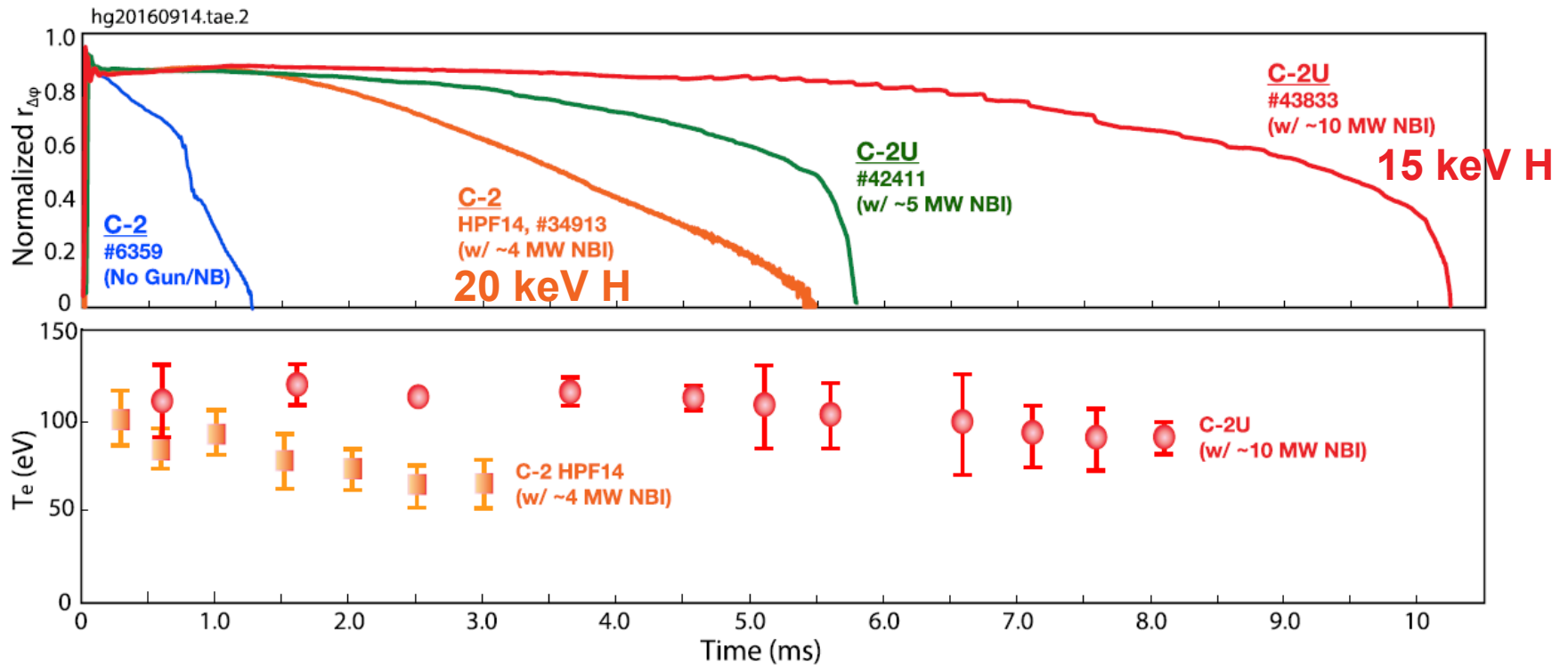


Photo credit: TAE Technologies

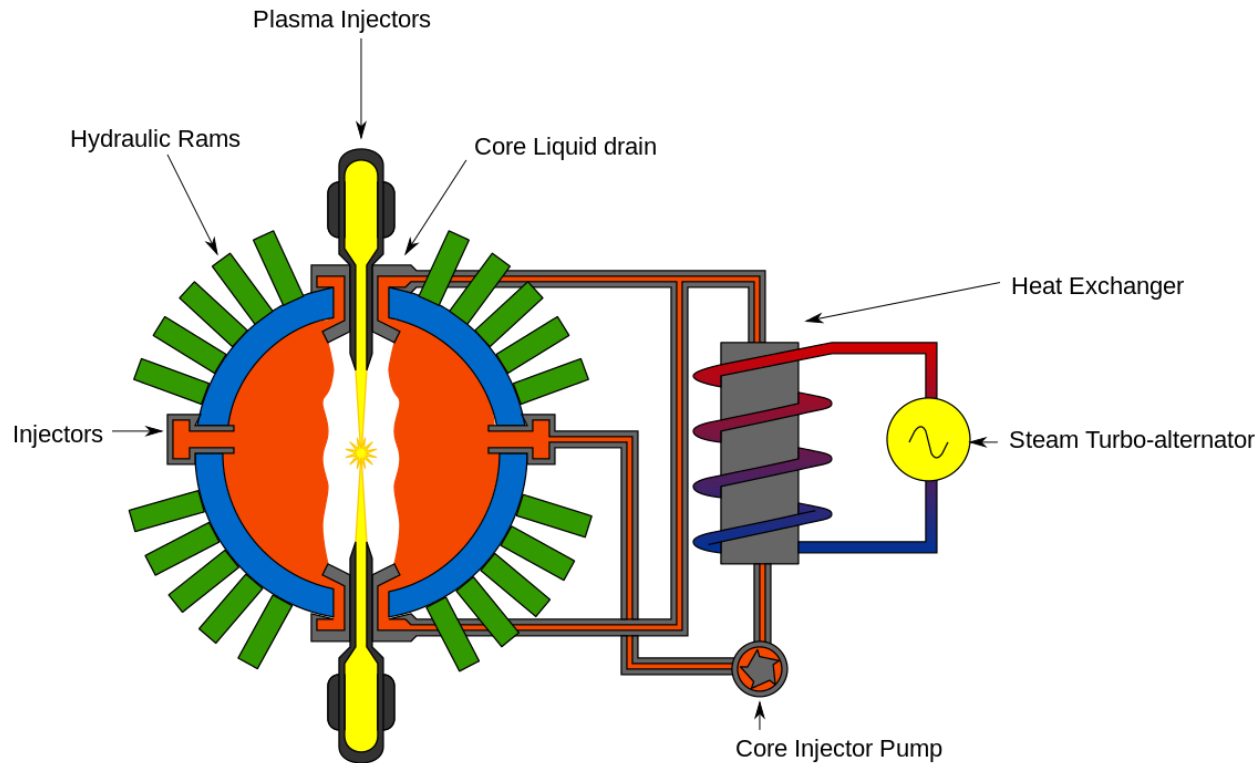
<https://tae.com/media/>

<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>

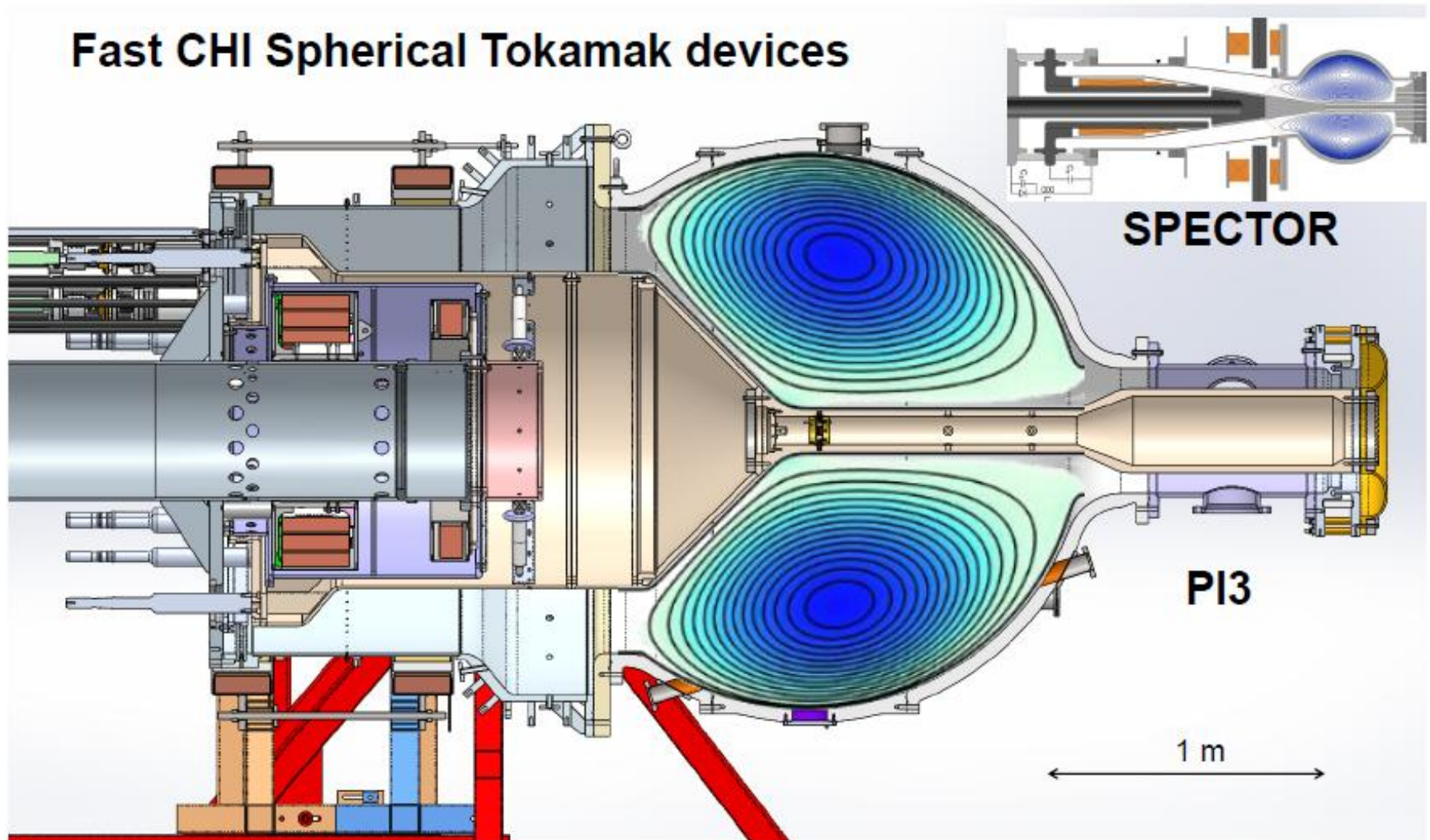
FRC sustain longer with neutral beam injection



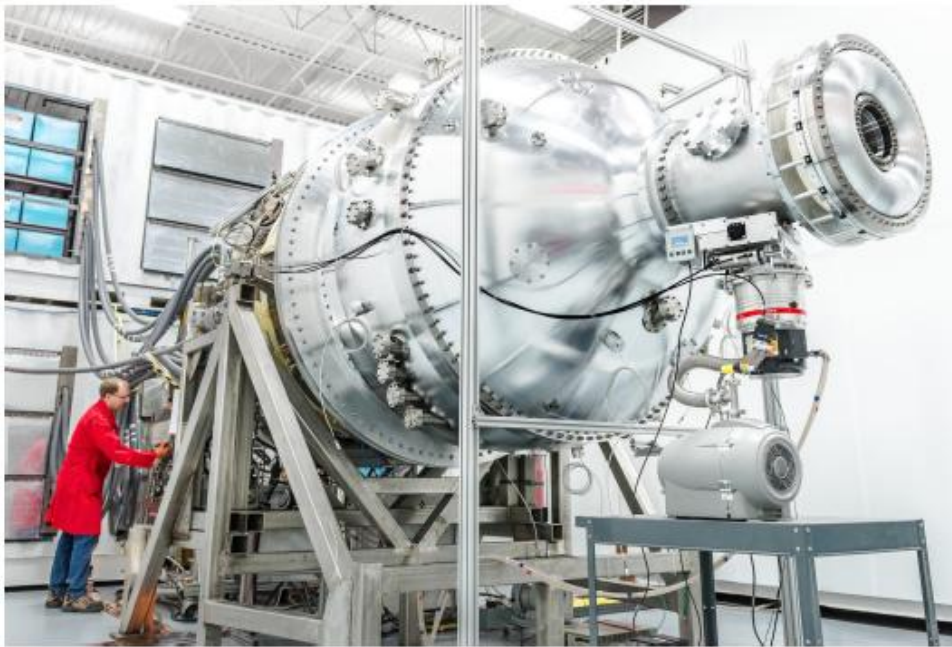
General fusion is a design ready to be migrated to a power plant



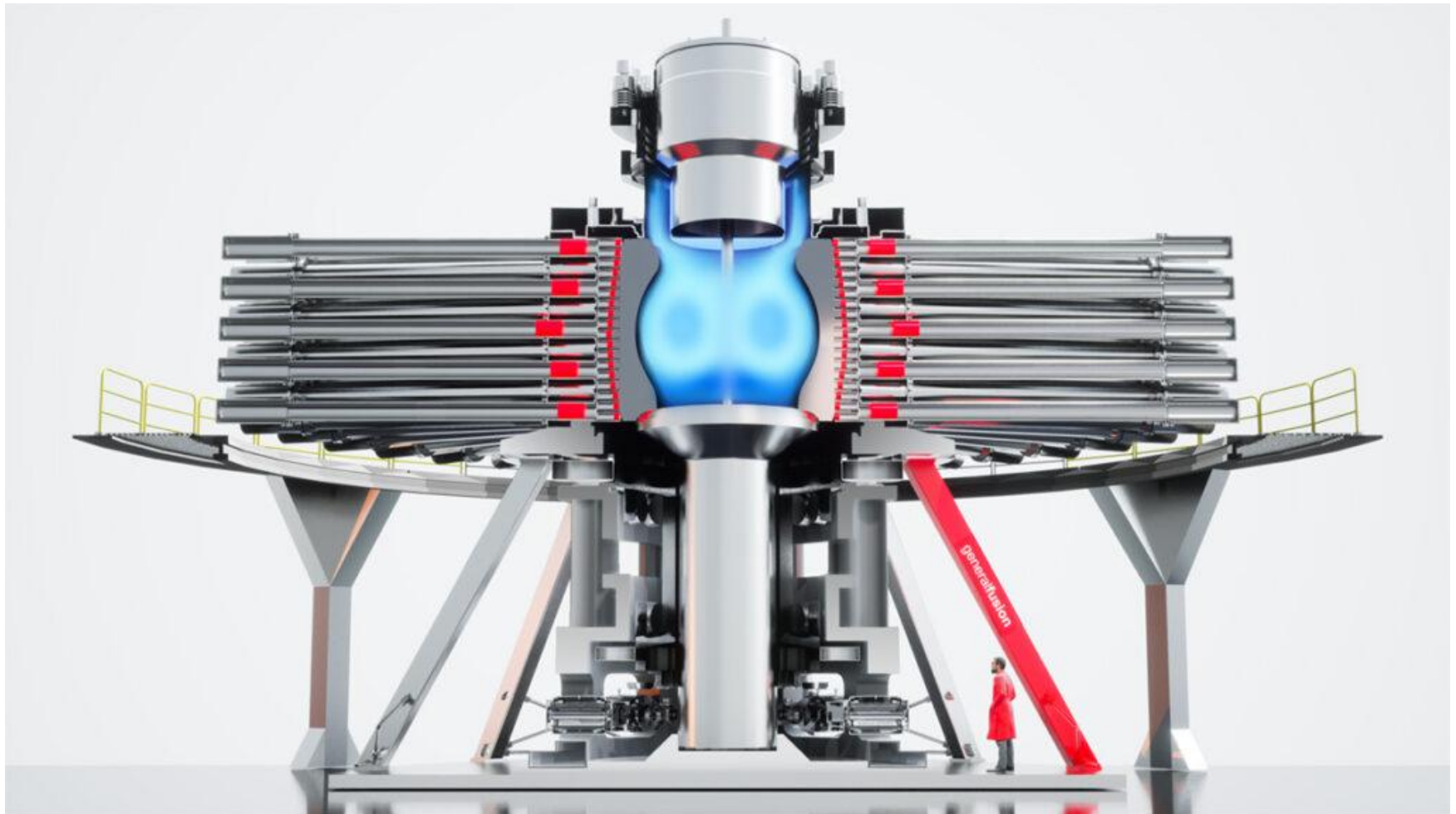
A spherical tokamak is first generated



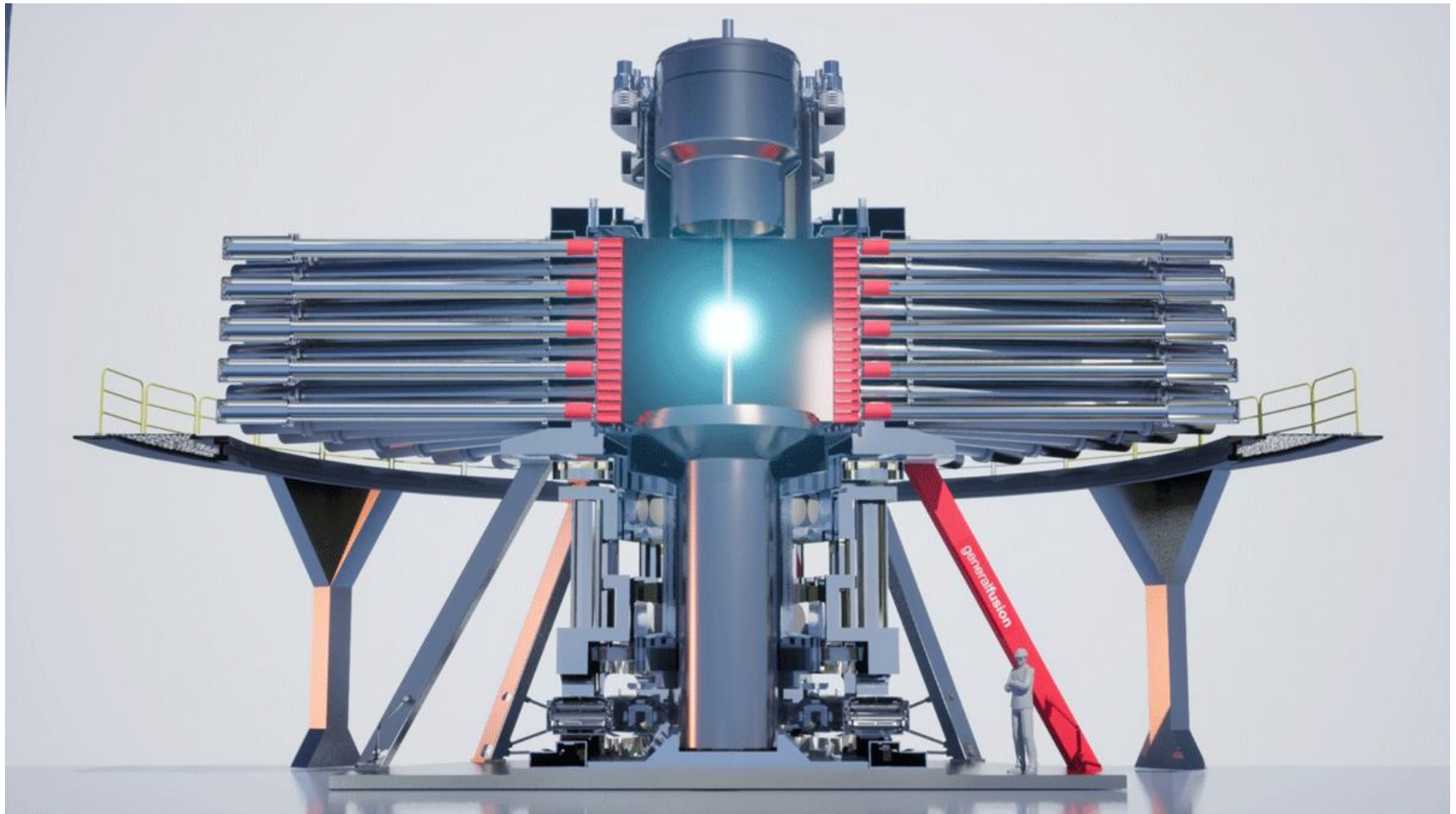
Plasma injector for the spherical tokamak



A spherical tokamak is generated in a liquid metal vortex



The spherical tokamak is compressed by the pressure provided by the surrounding 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

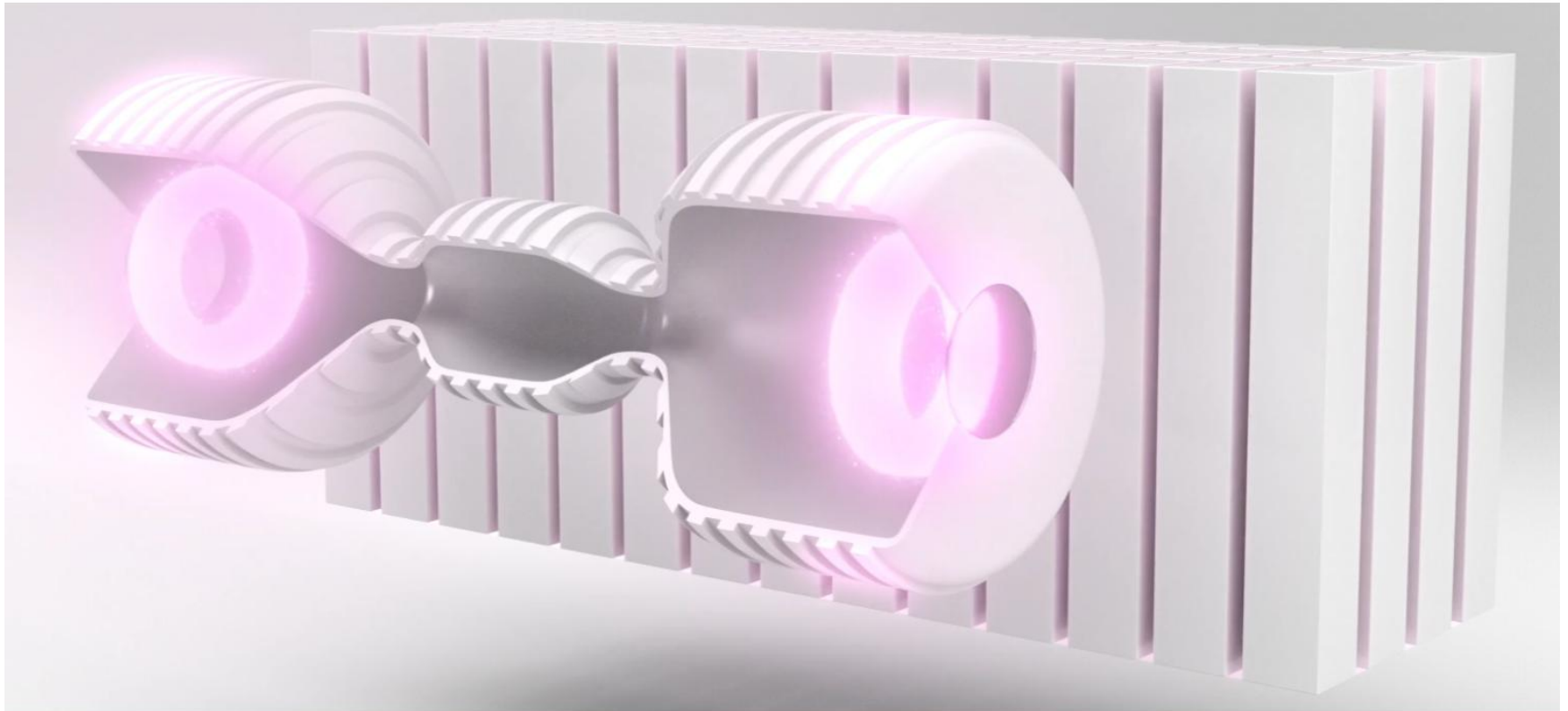


An artist's impression of what the new demonstration plant might look like

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

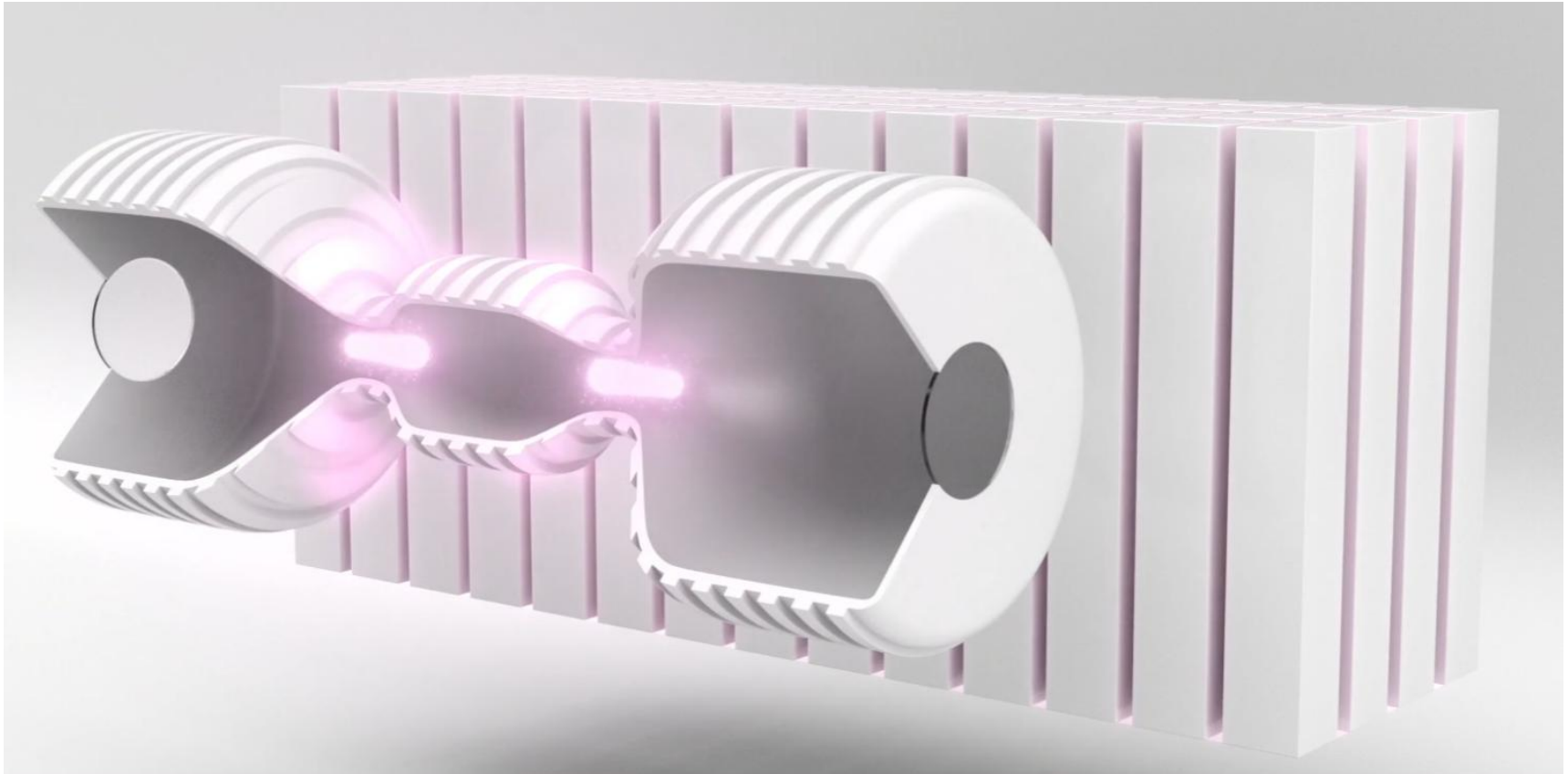
Helion energy is compressing the two merging FRCs



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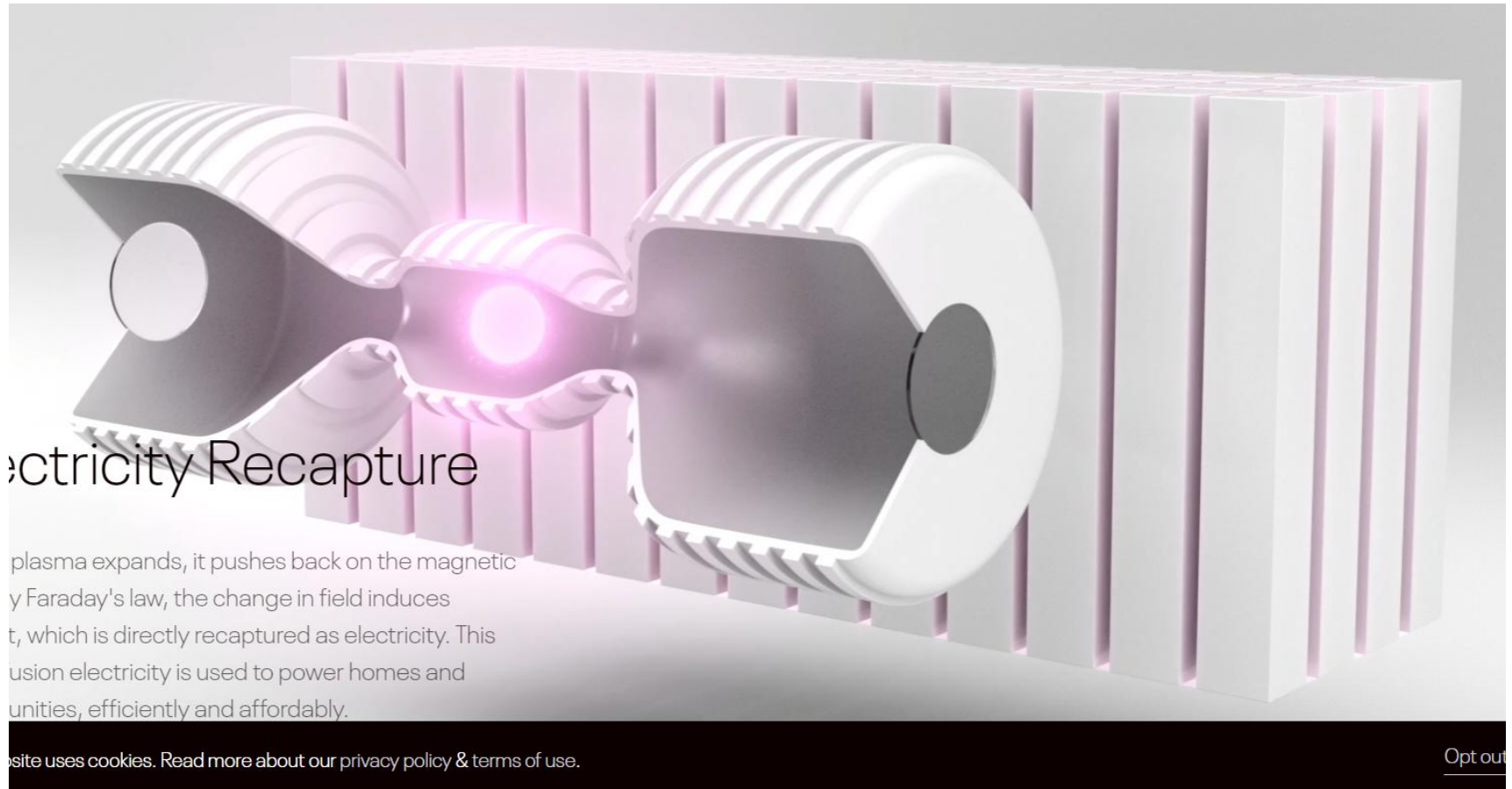
Two FRCs are accelerated toward each other



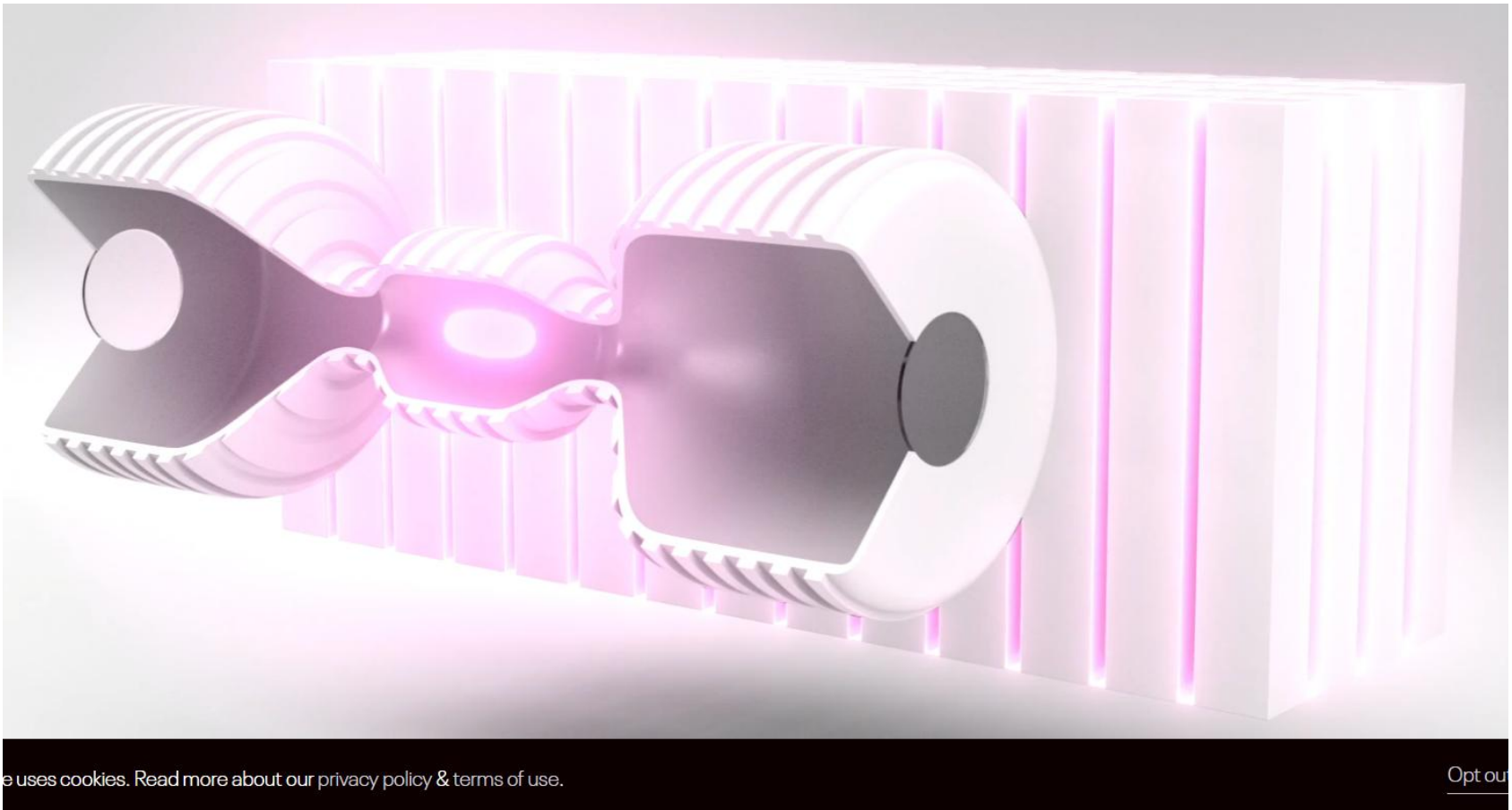
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Two FRCs merge with each other



The merged FRC is compressed electrically to high temperature



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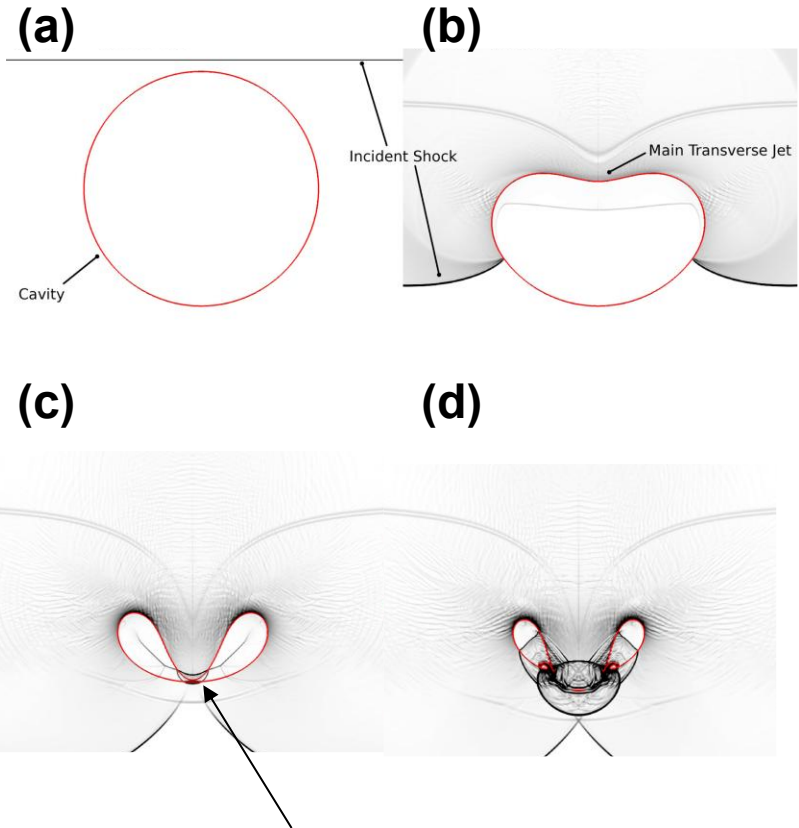
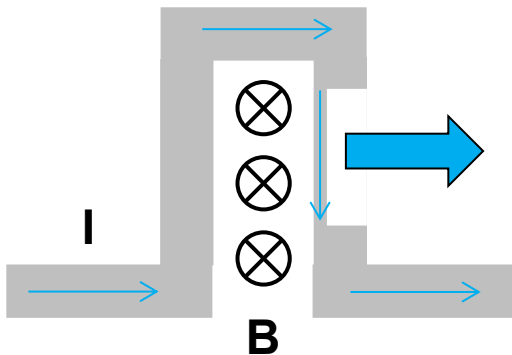
[Opt out](#)

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

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



- Stored energy: 2.5 MJ @ 200 kV ($C_{\text{tot}}=125 \text{ uF}$)
- $I_{\text{peak}}=14 \text{ MA}$ w/ $T_{\text{rise}} \sim 2 \mu\text{s}$.



- 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



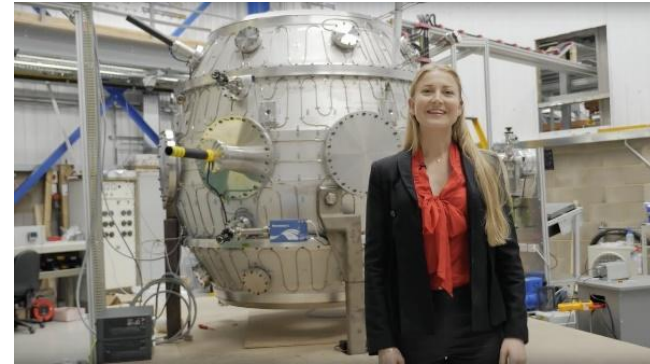
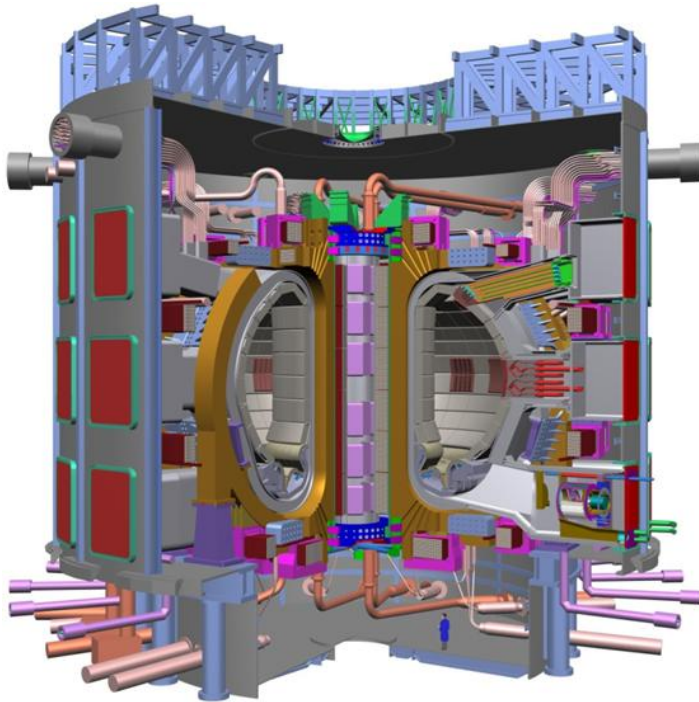
<https://www.youtube.com/watch?v=JN7lyxC11n0>

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

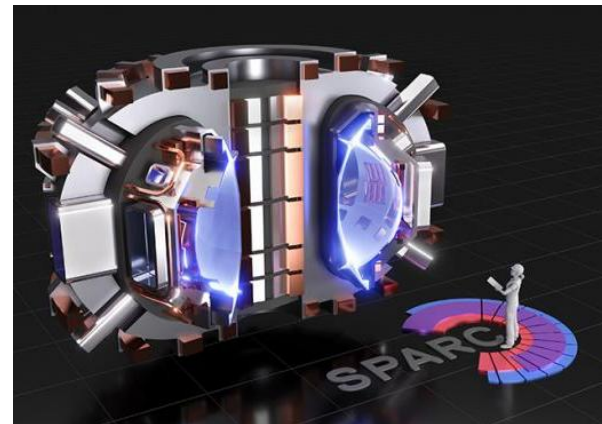
Many groups aim to achieve ignition in the MCF regime in the near future



- **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



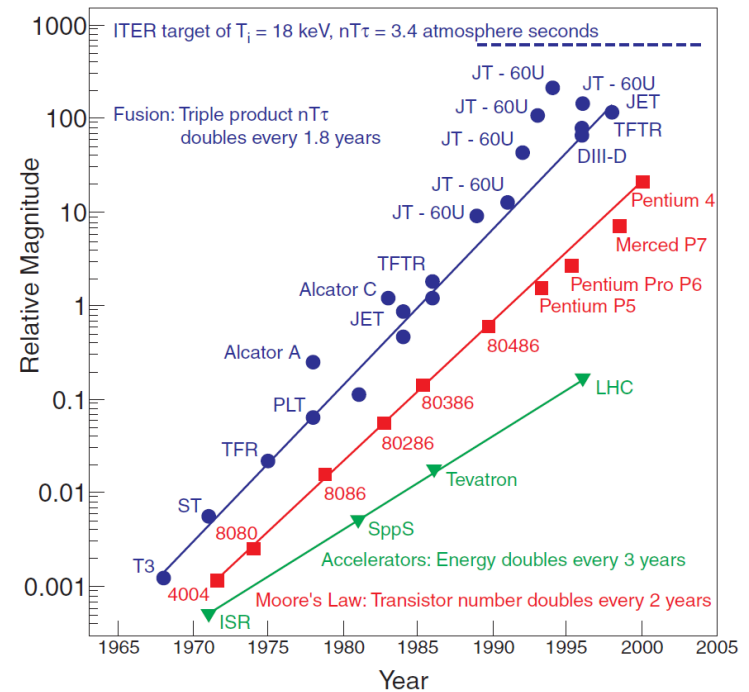
<https://www.iter.org>
<https://www.tokamakenergy.co.uk/>
<https://www.psfc.mit.edu/sparc>

Fusion is blooming



FUSION INDUSTRY ASSOCIATION



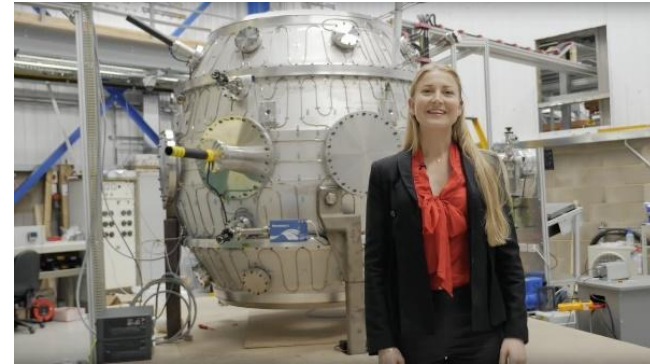
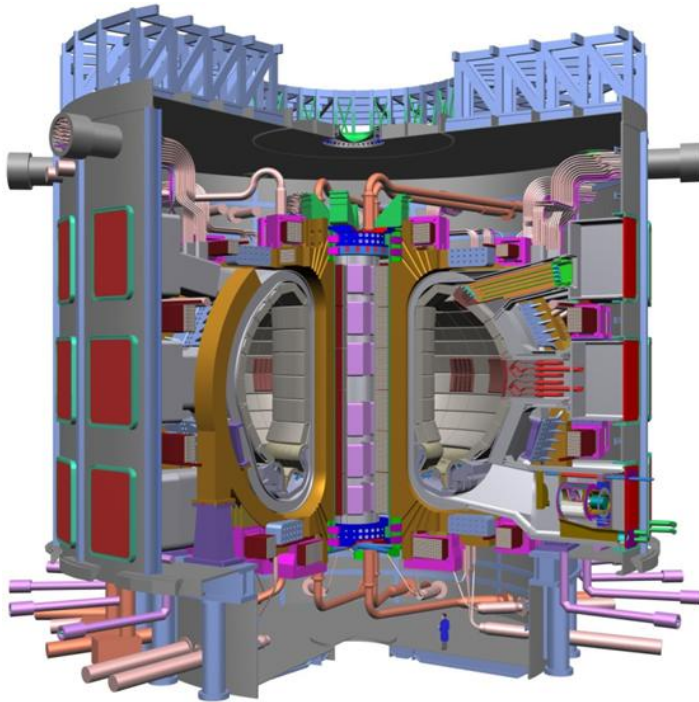


108

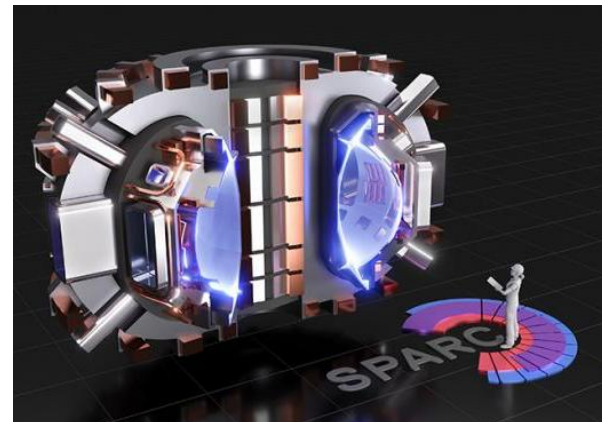
Many groups aim to achieve ignition in the MCF regime in the near future



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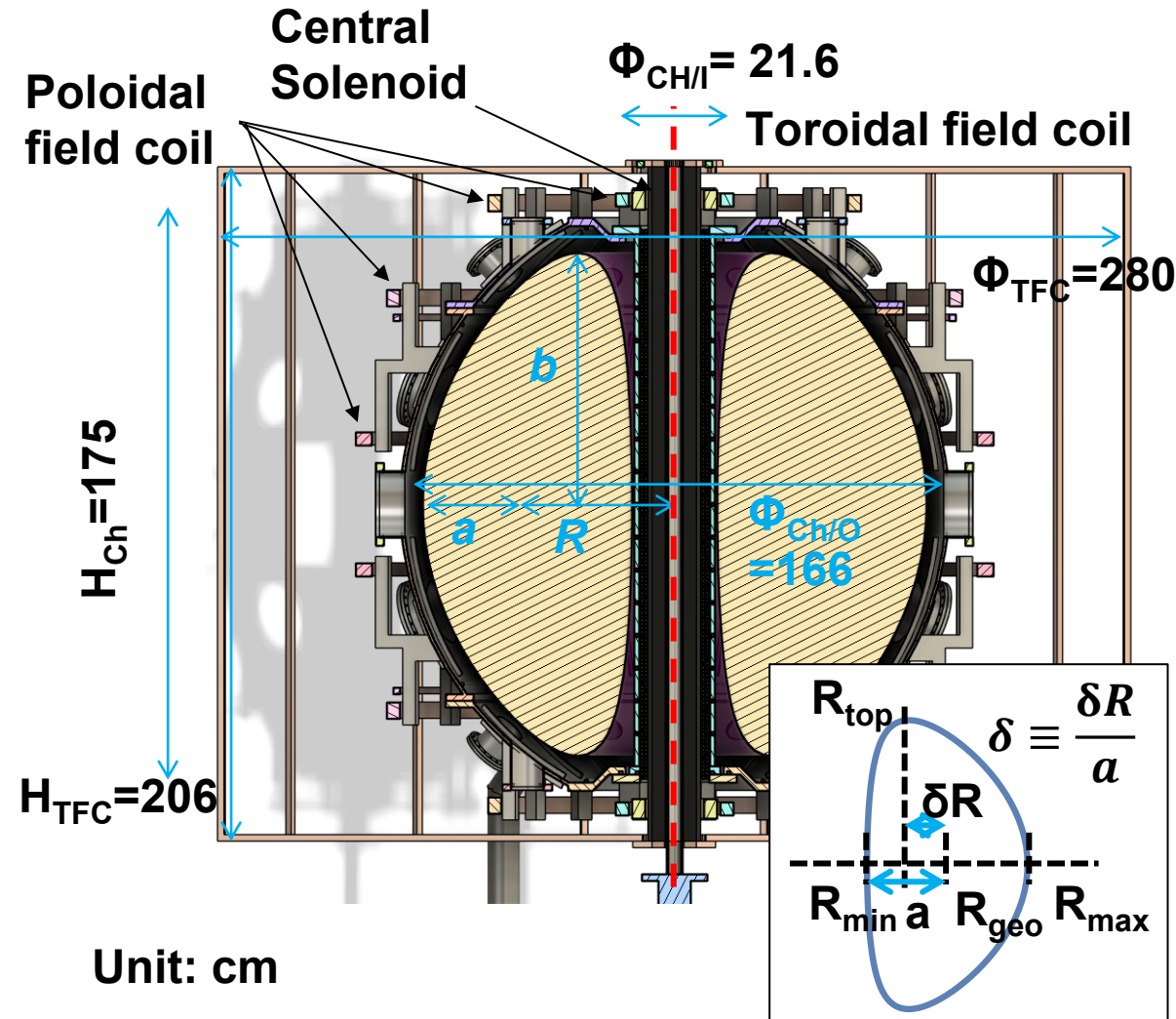


- **Commonwealth Fusion Systems, USA**
– 2025 Gain



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

Formosa Integrated Research Spherical Tokamak (FIRST)



- $R/a/b = 45/32/76.8$ cm
- Aspect ratio $= R/a = 1.5$
- $k = b/a = 2.4$
- $\delta = 0.5$
- $B_T = 0.1 \sim 0.5$ 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!