Introduction to Nuclear Fusion as An Energy Source

Po-Yu Chang

Institute of Space and Plasma Sciences, National Cheng Kung University

Lecture 14

2024 spring semester

Wednesday 9:10-12:00

Materials:

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

Online courses:

https://nckucc.webex.com/nckucc/j.php?MTID=ma76b50f97b1c6d72db61de9eaa9f0b27

2024/6/19 updated

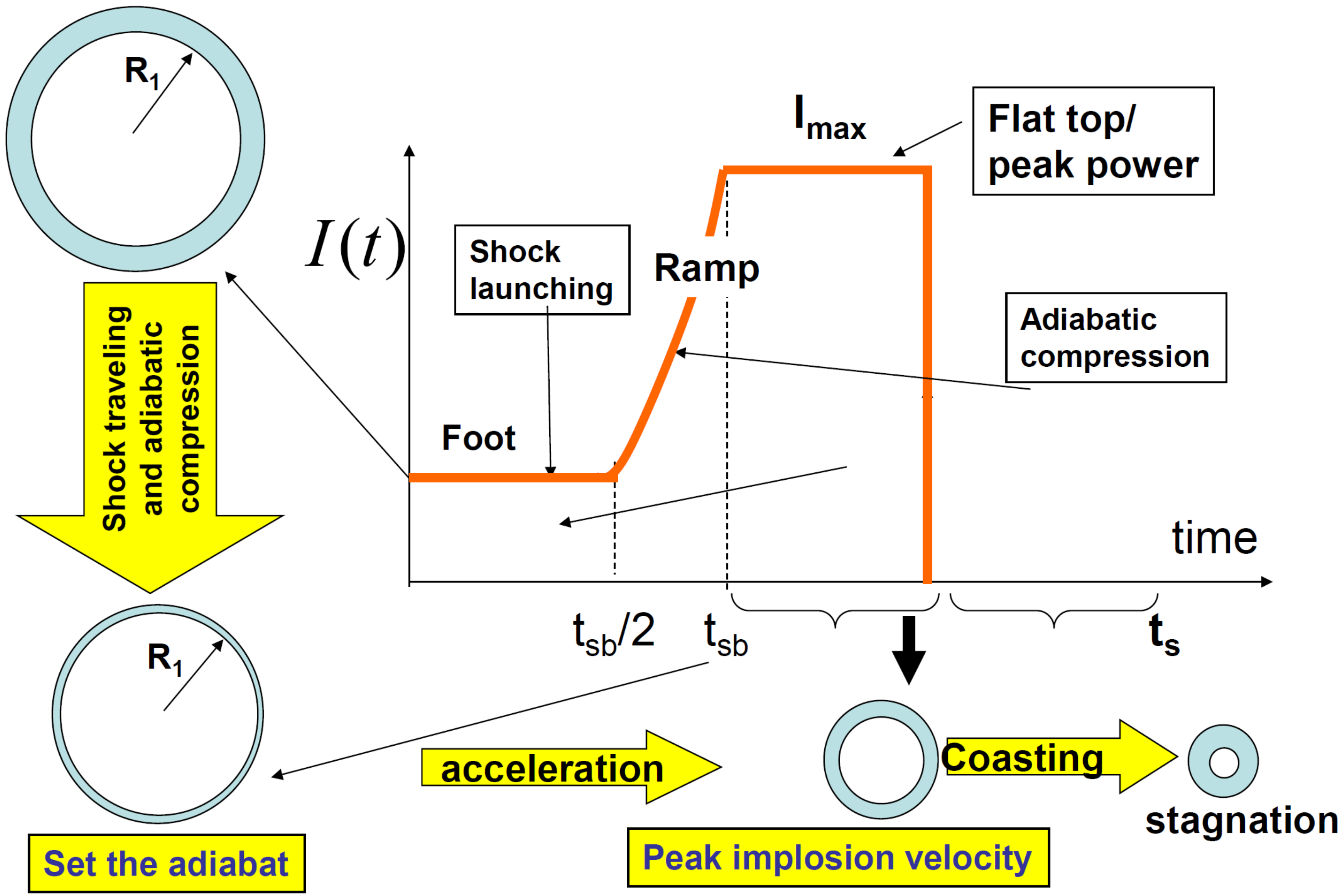
Course Outline

- **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)**

Reference for ICF

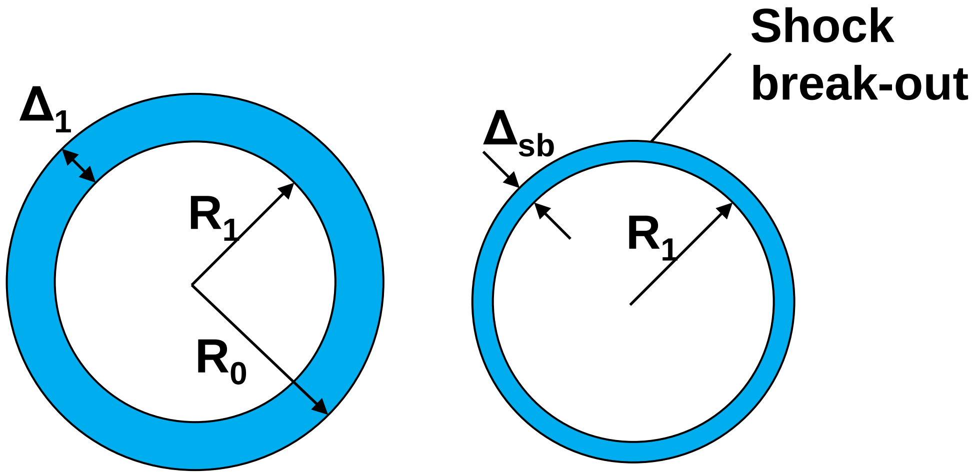
- Riccardo Betti, University of Rochester, HEDSA HEDP summer school, San Diego, CA, August 16-21, 2015
- ICF lectures for course PHY558/ME533
- The physics of inertial fusion, by S. Atzeni, J. Meyer-Ter-Vehn

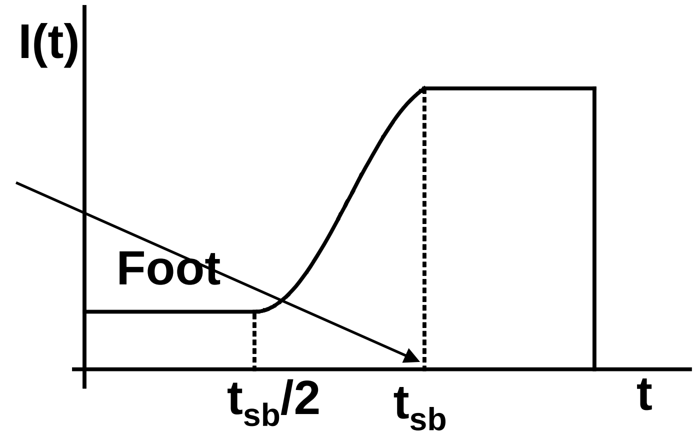
There are three stages in the laser pulse: foot, ramp, and flat top



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

$$\rho_1 = \text{initial density}$$





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

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

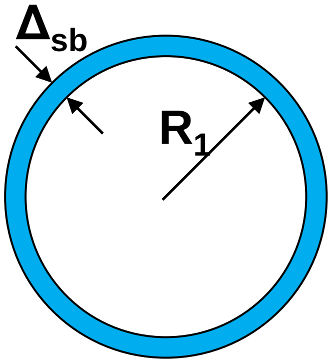
$$m_{\text{sb}} \sim 4\pi {R_1}^2 \Delta_1 \rho_1 = 4\pi {R_1}^2 \Delta_{\text{sb}} \rho_{\text{sb}}$$

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

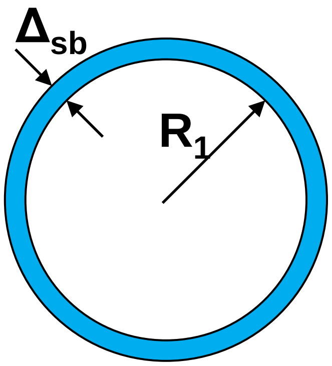
$$\Delta_{\text{sb}} = \Delta_1 \frac{\rho_1}{\rho_{\text{sb}}} \sim \Delta_1 \frac{\rho_1}{4\rho_1 \left(\frac{p_{\max}}{p_{\text{foot}}}\right)^{3/5}} = \frac{\Delta_1}{4} \left(\frac{p_{\text{foot}}}{p_{\max}}\right)^{3/5}$$

Density and thickness at shock break out time are expressed in laser intensity

- Use $p \sim I^{2/3}$
- Shell density $$\rho_{\mathrm{sb}} \sim \rho_1 \left(\frac{p_{\mathrm{max}}}{p_{\mathrm{foot}}}\right)^{5/3} = 4\rho_1 \left(\frac{I_{\mathrm{max}}}{I_{\mathrm{foot}}}\right)^{2/5}$$
- Shell thickness $$\Delta_{\mathrm{sb}} \sim \frac{\Delta_1}{4} \left(\frac{p_{\mathrm{foot}}}{p_{\mathrm{max}}}\right)^{3/5} = \frac{\Delta_1}{4} \left(\frac{I_{\mathrm{foot}}}{I_{\mathrm{max}}}\right)^{2/5}$$
- Shell radius $$R \approx R_1$$



The aspect ratio is maximum at shock break out



$$\text{Aspect ratio} \equiv \frac{R}{\Delta}$$

$$A_1 = \frac{R_1}{\Delta_1} = \text{initial aspect ratio}$$

$$A_{\mathrm{sb}} = IFAR = \frac{R_1}{\Delta_{\mathrm{sb}}} = 4A_1\left(\frac{I_{\mathrm{max}}}{I_{\mathrm{foot}}}\right)^{2/5}$$

$$A_{\mathrm{sb}} = A_{\mathrm{max}}$$

IFAR ≡ Maximum In-Flight-Aspect-Ratio = aspect ratio at shock break-out

The IFAR scales with the Mach number

- The shell kinetic energy = the work done on the shell

$$Mu_{max}^2 \sim -\int_{R_1}^{R} pr^2 dr \sim p\left(R_1^3 - R^3\right) \approx pR_1^3 \qquad R_1^3 = \frac{Mu_{max}^2}{p}$$

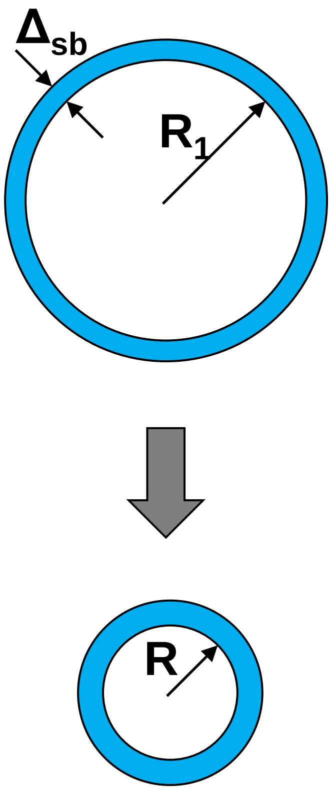
$$M \sim \rho_{sb}\Delta_{sb}R_1^2 \qquad \Delta_{sb} \sim \frac{M}{\rho_{sb}R_1^2} \qquad R_1 >> R$$

$$IFAR = \frac{R_1}{\Delta_{sb}} = \frac{R_1}{\frac{M}{\rho_{sb}R_1^2}} = \frac{\rho_{sb}R_1^3}{M} = \frac{\rho_{sb}}{M}\frac{Mu_{max}^2}{p}$$

$$= \frac{u_{max}^2}{p/\rho_{sb}} \sim Mach_{max}^2$$

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

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



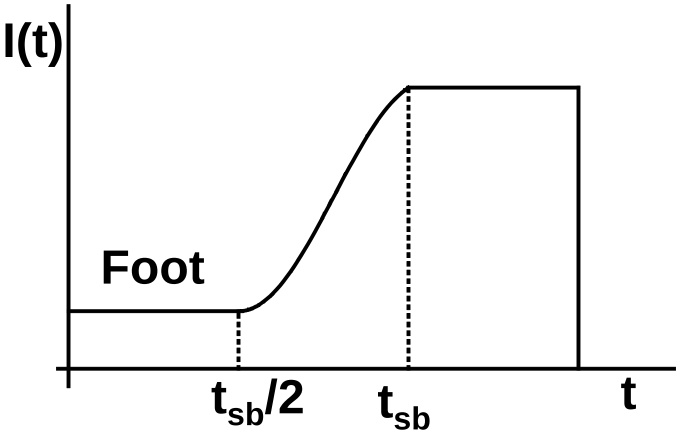
The final implosion velocity can be found using IFAR

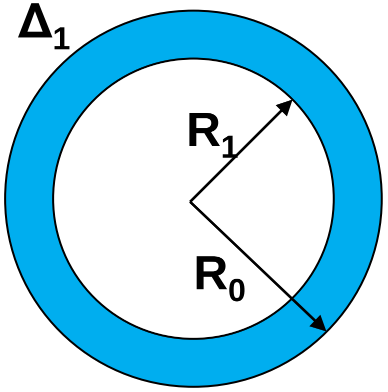
$$u_{\max}{}^{2} \sim IFAR \times \alpha^{3/5} I^{4/15}$$

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

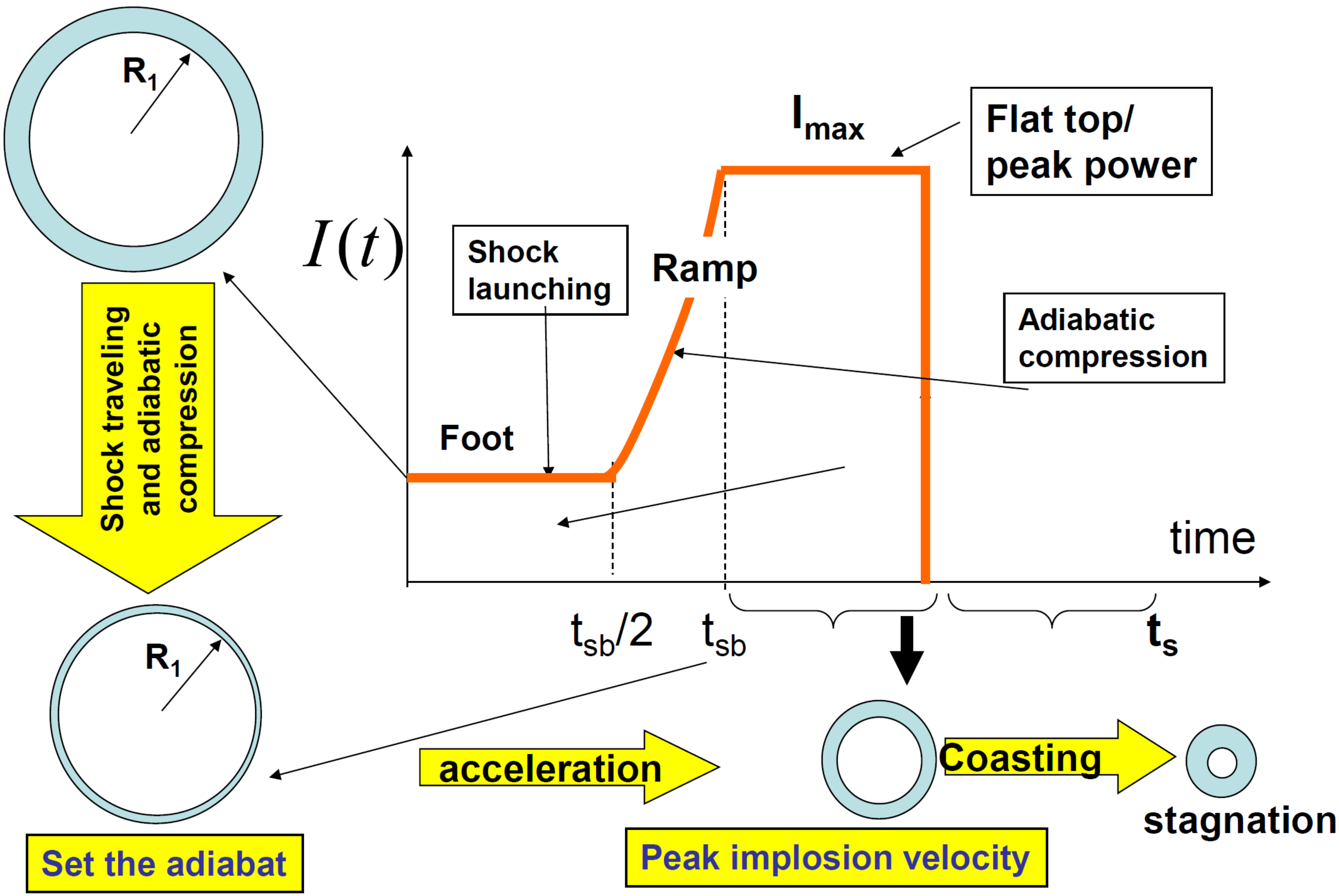
$$A_1 = \frac{R_1}{\Delta_1}$$

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





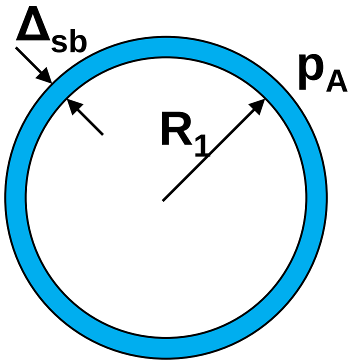
There are three stages in the laser pulse: foot, ramp, and flat top



A simple implosion theory can be derived in the limit of infinite initial aspect ratio

- Start from a high aspect ratio shell (thin shell) at the beginning of the acceleration phase
  - Constant ablated pressure
  - The adiabat is set and kept fixed by the first and the only shock

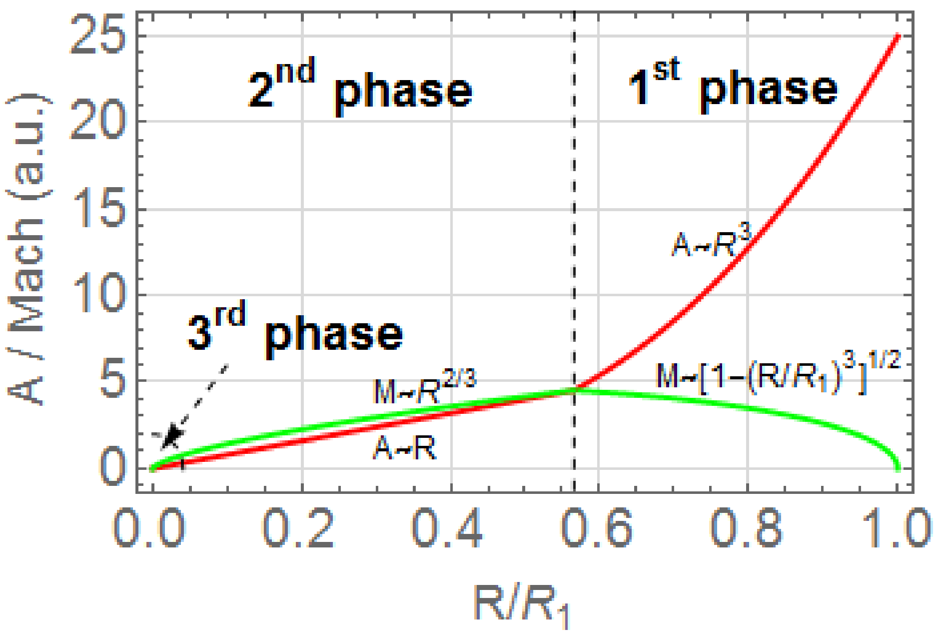
$$IFAR = A_{sb} = \frac{R_1}{\Delta_{sb}} \gg 1$$

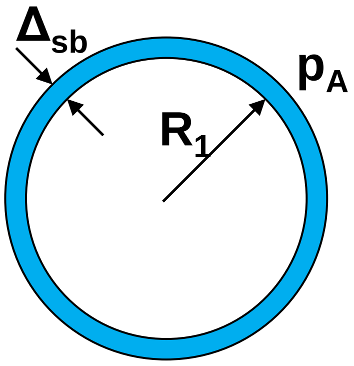


Basko and Meyer-ter-vehn, Phys. Rev. Lett. *88*, 244502-1, 2002

The implosion are divided in 3 phases after the shock break out

$\Delta \simeq \text{constant}$ $\rho \approx \text{const}$

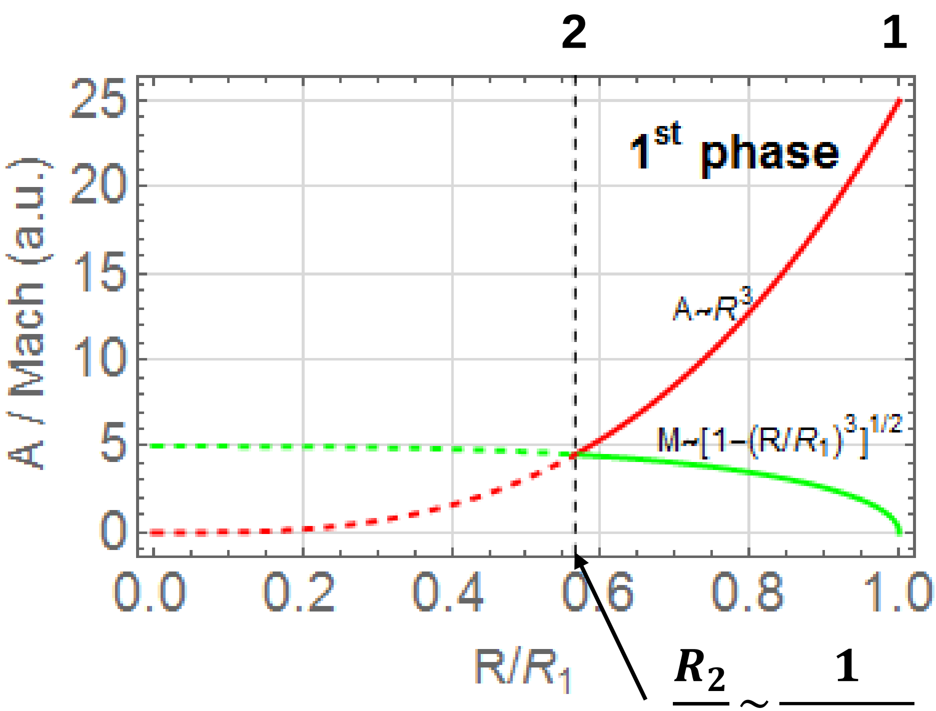




$$\text{Aspect ratio} = A \equiv \frac{R}{\Delta}$$

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

Summary of phase 1 (acceleration phase)



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

$$\frac{1}{{A_{sb}}^{1/6}} < \frac{R}{R_1} \leq 1$$

$$A = A_{sb}\left(\frac{R}{R_1}\right)^3 = \mathrm{IFAR}\left(\frac{R}{R_1}\right)^3$$

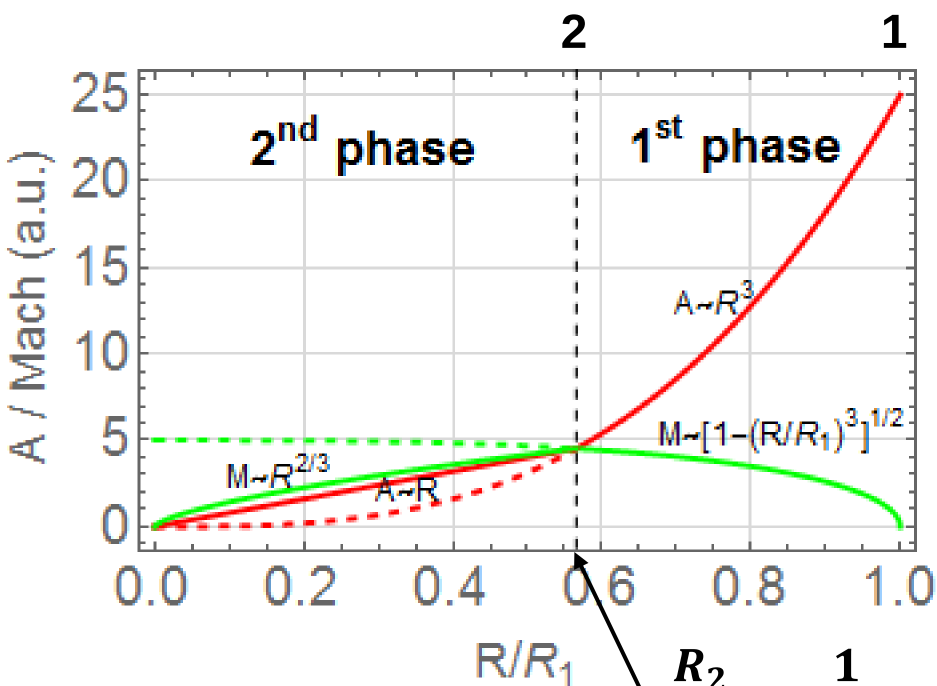
$$Mach = Mach_{max}\left[1 - \left(\frac{R}{R_1}\right)^3\right]^{1/2}$$

$$M \sim 4\pi R^2 \Delta\rho \quad \Rightarrow \quad \Delta \sim R^{-2}$$

$$A = \frac{R}{\Delta} \sim R^3 \Rightarrow \quad A = A_{sb}\left(\frac{R}{R_1}\right)^3$$

$$Mach_2 \simeq Mach_{\max}\left(1 - \frac{1}{\sqrt{A_{sb}}}\right)^{1/2} \simeq Mach_{\max} = \sqrt{A_{sb}} \qquad A_2 \sim \sqrt{A_{sb}}$$

Summary of phase 2 (coasting phase)



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

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

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

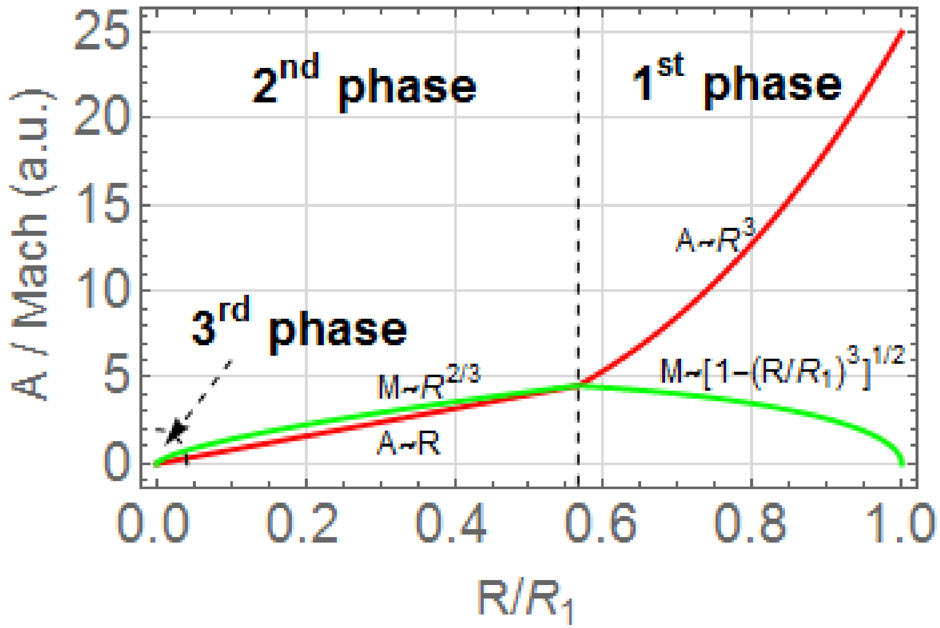
$$A = A_2\left(\frac{R}{R_2}\right) \sim \sqrt{A_{sb}}\left(\frac{R}{R_2}\right)$$

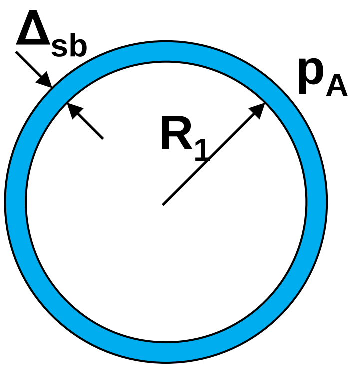
$$Mach \sim Mach_2\left(\frac{R}{R_2}\right)^{2/3} \sim \sqrt{A_{sb}}\left(\frac{R}{R_2}\right)^{2/3}$$

$$Mach_2 = Mach_{\max} \simeq A_2 = \sqrt{A_{sb}}$$

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

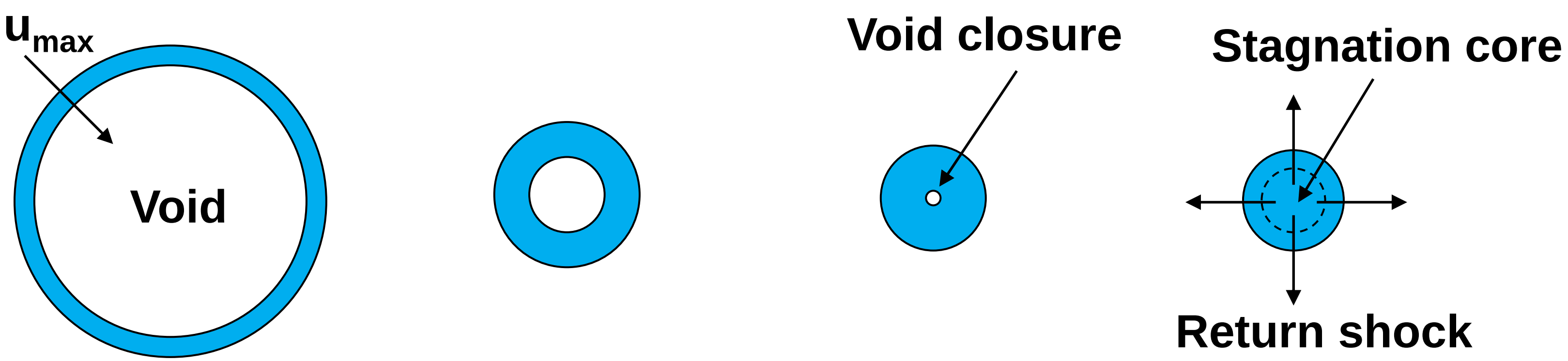
How about the 3rd phase where A~1 ?





- 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

$\rho_{st} \sim 4\rho_3 \sim \rho_3$ where ρ_3 is the density right before the void closure

The stagnated density scales with square of the maximum Mach number

$$\rho_3 \sim \rho_2 \left(\frac{R_2}{R_3}\right)^2 \sim \rho_{\mathrm{sb}} \left(\frac{R_2}{R_3}\right)^2$$

$$\bar{\rho} \simeq \rho_2 \left(\frac{R_2}{R}\right)^2$$

$$A = A_3 \sim 1 \Rightarrow \frac{R_3}{\Delta_3} \sim \frac{R_3}{\Delta_2} \sim 1 \Rightarrow R_3 \sim \Delta_2$$

$$\rho_{\mathrm{st}} \sim \rho_3 \sim \rho_{\mathrm{sb}} \left(\frac{R_2}{\Delta_2}\right)^2 \sim \rho_{\mathrm{sb}} {A_2}^2 \sim \rho_{\mathrm{sb}} {Mach_2}^2 \sim \rho_{\mathrm{sb}} {Mach_{\mathrm{max}}}^2$$

$$\frac{\rho_{\mathrm{st}}}{\rho_{\mathrm{sb}}} \sim {Mach_{\mathrm{max}}}^2$$

← **Density compression scaling law.**

The stagnated pressure scales to the 4th power of the maximum Mach number

- **Conservation of energy at stagnation:**

$$p_{\mathrm{st}} R_{\mathrm{st}}{}^{3} \sim m u_{\mathrm{max}}{}^{2} \qquad R_{\mathrm{st}} \sim R_3 \sim \Delta_3 \sim \Delta_2 \quad \Rightarrow \quad p_{\mathrm{st}} \Delta_2{}^{3} \sim \underline{m} u_{\mathrm{max}}{}^{2} \sim \underline{\rho_2 R_2{}^{2} \Delta_2} u_{\mathrm{max}}{}^{2}$$

$$\Rightarrow p_{\mathrm{st}} \sim \rho_2 \left(\frac{R_2}{\Delta_2}\right)^2 u_{\mathrm{max}}{}^{2} = \rho_2 A_2{}^{2} u_{\mathrm{max}}{}^{2} \sim p_2 Mach_2{}^{2} \frac{u_{\mathrm{max}}{}^{2}}{p_2/\rho_2} \sim p_A Mach_2{}^{4} \sim p_A Mach_{\mathrm{max}}{}^{4}$$

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

$$\frac{p_{\mathrm{st}}}{p_{\mathrm{A}}} \sim Mach_{\mathrm{max}}{}^{4}$$

$$\alpha_{\mathrm{st}} \sim \frac{p_{\mathrm{st}}}{\rho_{\mathrm{st}}{}^{5/3}} \sim \frac{p_A Mach_{\mathrm{max}}{}^{4}}{\rho_{\mathrm{sb}}{}^{5/3} Mach_{\mathrm{max}}{}^{10/3}} = \alpha_{\mathrm{sb}} Mach_{\mathrm{max}}{}^{2/3}$$

$$\frac{\rho_{\mathrm{st}}}{\rho_{\mathrm{sb}}} \sim Mach_{\mathrm{max}}{}^{2}$$

$$\frac{\alpha_{\mathrm{st}}}{\alpha_{\mathrm{sb}}} \sim Mach_{\mathrm{max}}{}^{2/3}$$

Scaling of the areal density of the compressed core

$$\rho_{st}R_{st} \sim \rho_{st}\Delta_2 \sim \left(\frac{p_{st}}{\alpha_{st}}\right)^{3/5} \frac{\Delta_2}{R_2}\frac{R_2}{R_1}R_1 \sim \left(\frac{p_A\, Mach_{\max}{}^4}{\alpha_{sb}\, Mach_{\max}{}^{2/3}}\right)^{3/5} \frac{1}{A_2}\frac{1}{A_{sb}{}^{1/6}}R_1$$

$$A_2 \sim Mach_{\max} \qquad A_{sb} \sim Mach_{\max}{}^2 \qquad \frac{R_2}{R_1} \sim \frac{1}{A_{sb}{}^{1/6}}$$

$$\rho_{st}R_{st} \sim \left(\frac{p_A}{\alpha_{sb}}\right)^{3/5} Mach_{\max}{}^2 \frac{1}{Mach_{\max}}\frac{1}{Mach_{\max}{}^{1/3}}R_1$$

$$\sim \left(\frac{p_A}{\alpha_{sb}}\right)^{3/5} Mach_{\max}{}^{2/3}R_1 \sim \left(\frac{p_A}{\alpha_{sb}}\right)^{3/5} \frac{u_{\max}{}^{2/3}}{(p_A/\rho_{sb})^{1/3}}\frac{p_A{}^{1/3}R_1}{p_A{}^{1/3}}$$

$$\sim \left(\frac{p_A}{\alpha_{sb}}\right)^{3/5} \frac{u_{\max}{}^{2/3}}{(p_A{}^{2/5}\alpha_{sb}{}^{3/5})^{1/3}}\frac{(p_A R_1{}^3)^{1/3}}{p_A{}^{1/3}} \sim \frac{p_A{}^{2/15}}{\alpha_{sb}{}^{4/5}}u_{\max}{}^{2/3}E_k{}^{1/3}$$

$$E_k \sim p_A R_1{}^3$$

$$E_k \sim E_{las} \Rightarrow \quad \boxed{\rho_{st}R_{st} \sim \frac{p_A{}^{2/15}u_{\max}{}^{2/3}E_{las}{}^{1/3}}{\alpha_{sb}{}^{4/5}}}$$

Amplification of areal density

$$\rho_{st}R_{st} \sim \rho_{st}^{2/3}\left(\underline{\rho_{st}R_{st}^{3}}\right)^{1/3} \sim \rho_{sb}^{2/3}Mach_{max}^{4/3}\underline{Mass}^{1/3}$$

$$\frac{\rho_{st}}{\rho_{sb}} \sim Mach_{max}^{2}$$

$$\sim \frac{\rho_{sb}^{2/3}}{\rho_1^{2/3}}Mach_{max}^{4/3}\rho_1^{2/3}\left(\rho_1 R_1^{2}\Delta_1\right)^{1/3}$$

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

$$\rho_{st}R_{st} \sim (\rho_1\Delta_1)Mach_{max}^{4/3}A_1^{2/3}\left(\frac{\rho_{sb}}{\rho_1}\right)^{2/3}$$

$$\frac{\rho_{sb}}{\rho_1} = 4\left(\frac{I_{max}}{I_{foot}}\right)^{2/5}$$

$$(\rho R)_{st} \sim (\rho_1\Delta_1)IFAR^{2/3}A_1^{2/3}\left(\frac{I_{max}}{I_{foot}}\right)^{4/15}$$

$$IFAR \sim Mach_{max}^{2}$$

$$E_{las} = 4\pi R_1^{2}I_{max}t_{imp} \approx 4\pi R_1^{2}I_{max}\frac{R_1}{u_{max}}$$

$$E_{las} \approx \frac{4\pi R_1^{3}I_{max}}{u_{max}}$$

Summary

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

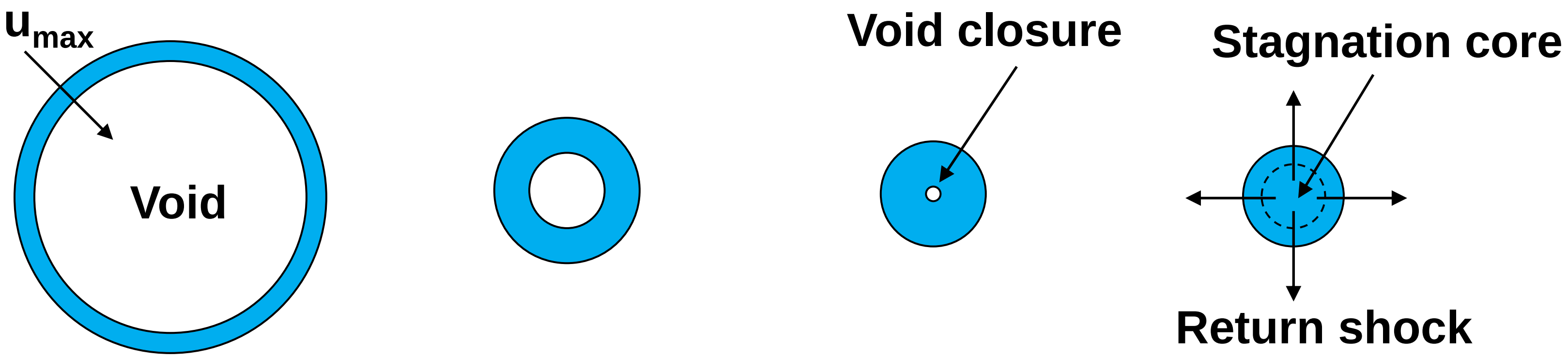
$$\rho_{\mathrm{st}} \sim \rho_{\mathrm{sb}} Mach_{\mathrm{max}}{}^{2} \sim \rho_1 IFAR\left(\frac{I_{\mathrm{max}}}{I_{\mathrm{foot}}}\right)^{2/5}$$

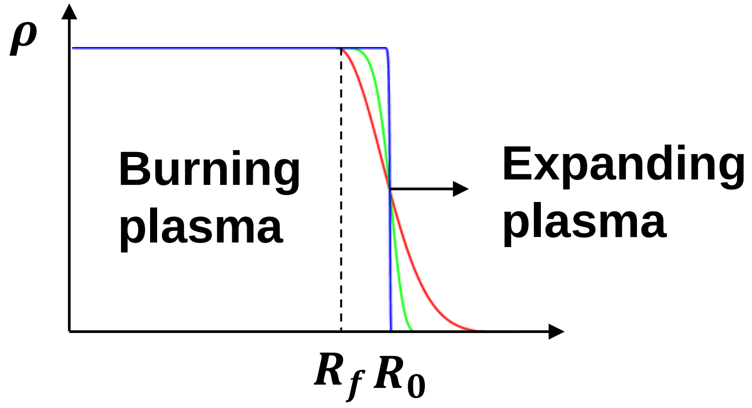
$$p_{\mathrm{st}} \sim p_A Mach_{\mathrm{max}}{}^{4} \sim p_A IFAR^2$$

$$\alpha_{\mathrm{st}} \sim \alpha_{\mathrm{sb}} Mach_{\mathrm{max}}{}^{2/3} \sim \alpha_{\mathrm{sb}} IFAR^{1/3}$$

$$(\rho R)_{\mathrm{st}} \sim (\rho_1 \Delta_1) IFAR^{2/3} A_1{}^{2/3}\left(\frac{I_{\mathrm{max}}}{I_{\mathrm{foot}}}\right)^{4/15}$$

Calculation of the burn-up fraction



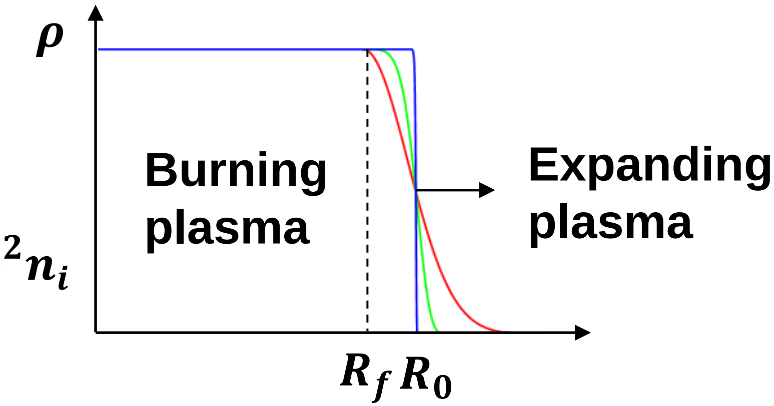


$$R_f = R_0 - C_s t$$

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

Calculation of the burn-up fraction - continue

$$4\pi \int_0^{R_f} r^2 dr \left(\frac{\partial n_i}{\partial t} = -\nabla \cdot (n_i v) - \frac{{n_i}^2}{2} \langle \sigma v \rangle \right)$$



$$4\pi \int_0^{R_f} r^2 \frac{\partial n_i}{\partial t} dr = 4\pi \frac{d}{dt} \int_0^{R_f} r^2 n_i dr - 4\pi \dot{R}_f {R_f}^2 n_i$$

$$= -n_i v 4\pi {R_f}^2 - \frac{{n_i}^2}{2} \langle \sigma v \rangle V_f$$

(neglect)

$$\frac{d}{dt}\left(\int_{a(t)}^{b(t)} f(x,t) dx \right) = f(b(t),t) \frac{db(t)}{dt} - f(a(t),t) \frac{da(t)}{dt} + \int \frac{\partial}{\partial t} f(x,t) dx$$

(Leibniz integral rule)

$$N_f \equiv \frac{4\pi}{3} {R_f}^3 n_i \equiv V_f n_i$$

$$\frac{dN_f}{dt} - 3N_f \frac{\dot{R}_f}{R_f} = -\frac{{N_f}^2}{V_f} \frac{\langle \sigma v \rangle}{2}$$

$$\frac{d_t N_f}{{N_f}^2} - \frac{3\dot{R}_f}{N_f R_f} = -\frac{\langle \sigma v \rangle}{2V_f}$$

$$\frac{d}{dt}\left(\frac{1}{N_f} \right) + \frac{3\dot{R}_f}{N_f R_f} = \frac{\langle \sigma v \rangle}{2V_f}$$

$${R_f}^3 \frac{d}{dt}\left(\frac{1}{N_f} \right) + 3{R_f}^2 \frac{\dot{R}_f}{N_f} = \frac{d}{\mathrm{dt}} \left(\frac{{R_f}^3}{N_f} \right) = \frac{\langle \sigma v \rangle}{2V_f} {R_f}^3$$

Calculation of the burn-up fraction - continue

$$\frac{d}{dt}\left(\frac{{R_f}^3}{N_f}\right) = \frac{\langle\sigma v\rangle}{2V_f}{R_f}^3$$

$$\frac{{R_f}^3}{N_f} = \int_0^t \frac{\langle\sigma v\rangle}{2V_f}{R_f}^3 dt + \frac{{R_0}^3}{N_0}$$

$$R_f = R_0 - C_s t \qquad dt = -\frac{dR_f}{C_s} \qquad V_f = \frac{4\pi}{3}{R_f}^3$$

$$\frac{{R_f}^3}{N_f} = -\int_{R_0}^{R_f} \frac{\langle\sigma v\rangle}{2\times 4\,\pi/3}\frac{dR_f}{C_s} + \frac{{R_0}^3}{N_0}$$

$$n_0 = \frac{N_0}{V_0}$$

$$\frac{{R_f}^3}{N_f} = -\int_{R_0}^{R_f} \frac{\langle\sigma v\rangle}{2C_s}\frac{3}{4\pi}dR_f + \frac{{R_0}^3}{N_0}$$

$$\frac{V_f}{N_f} = \frac{V_0}{N_0}\left[1 + \frac{\langle\sigma v\rangle}{2C_s}n_0 R_0\left(1 - \frac{R_f}{R_0}\right)\right]$$

$$\frac{{R_f}^3}{N_f} = \frac{\langle\sigma v\rangle}{2C_s}\frac{3}{4\pi}(R_0 - R_f) + \frac{{R_0}^3}{N_0}$$

$$\xi \equiv \frac{\langle\sigma v\rangle}{2C_s}n_0 R_0$$

$$\frac{V_f}{N_f} = \frac{\langle\sigma v\rangle}{2C_s}R_0\left(1 - \frac{R_f}{R_0}\right) + \frac{V_0}{N_0}$$

$$\frac{V_f}{N_f} = \frac{1}{n_0}\left[1 + \xi\left(1 - \frac{R_f}{R_0}\right)\right]$$

Calculation of the burn-up fraction - continue

$$\frac{V_f}{N_f} = \frac{1}{n_0}\left[1 + \xi\left(1 - \frac{R_f}{R_0}\right)\right]$$

$$n_i = \frac{N_f}{V_f}$$

#Burned ions $= \int_0^t \frac{\langle \sigma v \rangle}{2} n_i^2 V_f dt = \int_0^t \frac{\langle \sigma v \rangle}{2} \frac{N_f^{\,2}}{V_f} dt = -\int_{R_0}^{R_f} \frac{\langle \sigma v \rangle}{2} \left(\frac{N_f}{V_f}\right)^2 V_f \frac{dR_f}{C_s}$

$$= \int_{R_f}^{R_0} \frac{\langle \sigma v \rangle}{2} \frac{n_0^{\,2}}{\left[1 + \xi\left(1 - \frac{R_f}{R_0}\right)\right]^2} \left(\frac{R_f}{R_0}\right)^3 V_0 R_0 \frac{dR_f/R_0}{C_s}$$

$$V_{f,0} = \frac{4\pi}{3} R_{f,0}^{\,3}$$

$$= \int \frac{\langle \sigma v \rangle}{2} \frac{n_0^{\,2}}{[1 + \xi(1 - x)]^2} x^3 V_0 \frac{R_0}{C_s} dx = N_0 \xi \int_0^1 \frac{x^3 dx}{[1 + \xi(1 - x)]^2}$$

$$= N_0 \frac{\xi[6 + \xi(9 + 2\xi)] - 6(1 + \xi)^2 Ln[1 + \xi]}{2\xi^3}$$

$$\xi \equiv \frac{\langle \sigma v \rangle}{2C_s} n_0 R_0$$

#Burn-up Fraction

$$\Theta(\xi) = \frac{\xi[6 + \xi(9 + 2\xi)] - 6(1 + \xi)^2 \mathrm{Ln}[1 + \xi]}{2\xi^3}$$

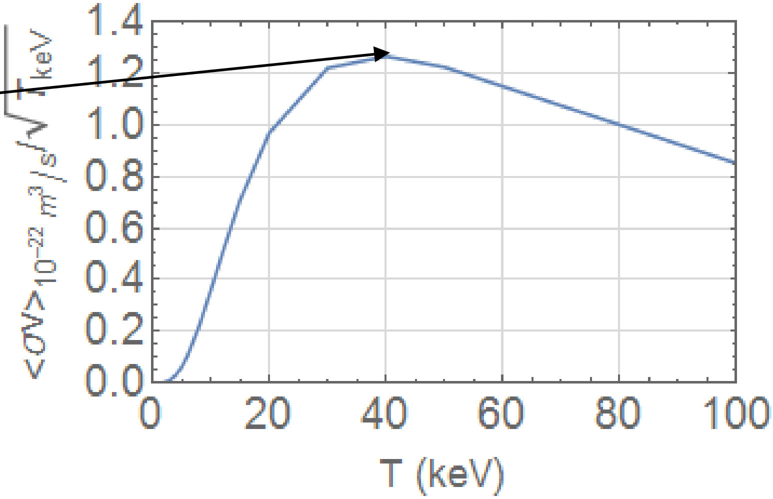
Calculation of the burn-up fraction - continue

$$C_s = \sqrt{\frac{T_e + T_i}{m_i}} = \sqrt{\frac{2T}{m_i}} \qquad \rho = n_0 m_i \quad m_i = \frac{m_D + m_T}{2} = 2.5 \times 1.67 \times 10^{-27}\text{kg}$$

$$\xi = \frac{\langle\sigma v\rangle}{\sqrt{T}}(\rho R_0)\frac{1}{2\sqrt{2m_i}} = \frac{\langle\sigma v\rangle_{m^3/s}}{\sqrt{T_{keV} \times 1.6 \times 10^{-16}}}\frac{(\rho R_0)_{g/cm^2} \times 10}{2\sqrt{5 \times 1.67 \times 10^{-27}}}$$

$$\xi \simeq \frac{1.25 \times 10^{-22}}{\sqrt{1.6 \times 10^{-16}}}\frac{10(\rho R_0)_{g/cm^2}}{2\sqrt{5 \times 1.67 \times 10^{-27}}} = 0.54(\rho R_0)_{g/cm^2}$$

$$\left.\frac{\langle\sigma v\rangle}{\sqrt{T_{keV}}}\right|_{\max} = 1.25 \times 10^{-22} \quad @\ T = 40\ \text{keV}$$



H.-S. Bosch and G.M. HaleNucl. Fusion ***32*** (1992) 611

Smallest areal density (ρR)

#Burned-up Fraction

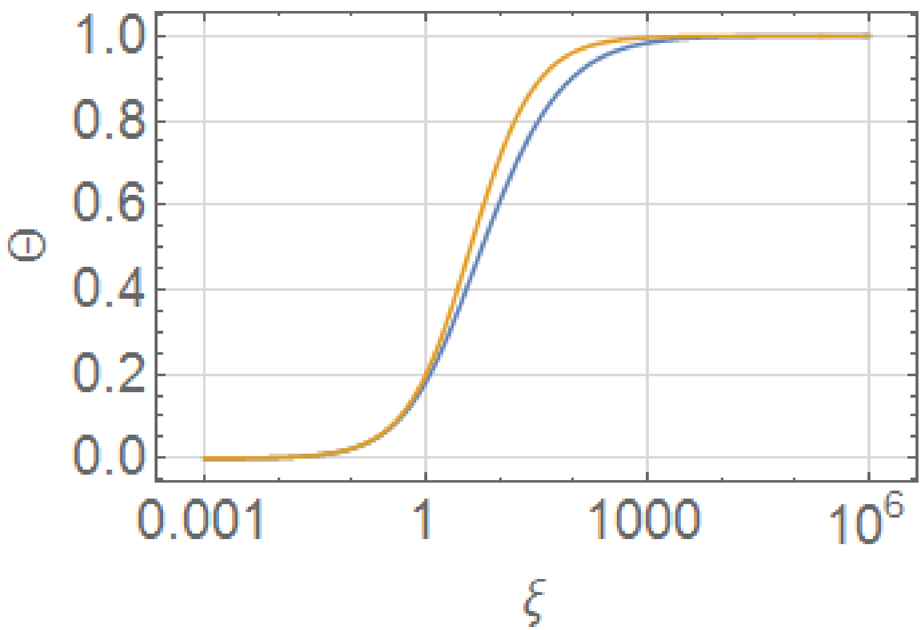
$$\Theta(\xi) = \frac{\xi[6+\xi(9+2\xi)] - 6(1+\xi)^2 \mathrm{Ln}[1+\xi]}{2\xi^3}$$

$$\lim_{\xi\to 0}\Theta(\xi) = \frac{\xi}{4} \qquad \lim_{\xi\to\infty}\Theta(\xi) = 1 \qquad \Theta(\xi) \approx \frac{\xi}{4+\xi} \qquad \xi \simeq 0.54(\rho R_0)_{g/cm^2}$$

$$\Theta(\xi) \approx \frac{0.54\rho R}{4+0.54\rho R}$$

$$\Theta(\xi) \approx \frac{(\rho R)_{g/cm^2}}{7+(\rho R)_{g/cm^2}}$$

Large *ρR* is needed to have high burn-up fraction.



For energy applications:

$$\Theta \gtrsim 0.3 \qquad \rho R \geq 3\ g/\mathrm{cm}^2$$

Energy gain

Fusion energy $= \dfrac{M_0}{2m_i}\epsilon_f \Theta$

$\epsilon_f = 17.6\text{MeV}$

Energy gain $= \dfrac{\text{Fusion Energy}}{\text{Input Energy}}$

Mass = M_0
Temp = T
DT
Volume = V_0

- Input energy: the sphere is heated to the temperature T

Thermal energy in sphere: $\dfrac{3}{2}(n_{i0}T_i + n_{e0}T_e)V_0$

$n_{i0} = n_{e0} \equiv n_0 \qquad T_e = T_i \Rightarrow 3n_0\text{TV}_0 = 3\dfrac{M_0}{m_i}T$

Set heating efficiency: $\eta = \dfrac{\text{Thermal Energy}}{\text{Input Energy}}$

$$\text{Gain} = \frac{\frac{M_0}{2m_i}\epsilon_f\Theta}{3\frac{M_0}{m_i}T/\eta} = \eta\frac{M_0}{2m_i}\frac{\epsilon_f\Theta}{3\frac{M_0}{m_i}T} = \frac{\eta}{6}\frac{\epsilon_f}{T}\Theta$$

$$\text{Gain} = \eta\, 293\left(\frac{10}{T_{\text{keV}}}\right)\Theta$$

The power to heat the plasma is enormous

- **Consider the small T limit:**

$$\Theta(\xi) \approx \frac{\xi}{4+\xi} \qquad \xi \equiv \frac{\langle \sigma v\rangle}{2C_s} n_0 R_0 = \frac{\langle \sigma v\rangle}{\sqrt{T}} (\rho R_0) \frac{1}{2\sqrt{2m_i}}$$

$$\langle \sigma v\rangle \sim T^4 \text{ for } T \to 0 \text{ , then } \quad \xi \sim T^{7/2} \quad \text{and} \quad Gain \sim T^{5/2} \to 0$$

- **Required input power:**

$$P_w = \frac{E_{\text{input}}}{\tau_{\text{input}}} \qquad \tau_{\text{input}} \ll \tau_{\text{burn}} = \frac{R}{C_s}$$ **(Heat out before it runs away)**

$$P_w = \frac{E_{\text{input}}}{\mu R/C_s} = \frac{E_{\text{thermal}}}{\eta\mu R/C_s} = 3\frac{M_0}{m_i} T \frac{1}{R} \frac{C_s}{\eta\mu} \qquad \tau_{\text{input}} = \mu \frac{R}{C_s}$$ Ex: $\mu \sim 0.1$

$$\frac{P_w}{M_0} = \frac{3}{m_i}\frac{T}{R}\frac{C_s}{\eta\mu} = \frac{3}{m_i}\frac{T}{R}\sqrt{\frac{2T}{m_i}}\frac{1}{\eta\mu}$$

$$\frac{P_w}{M_0} = 10^{18}\left(\frac{T_{\text{keV}}}{10}\right)^{3/2} \frac{0.1}{\mu}\frac{1}{R_{\text{cm}}}\frac{1}{\eta} \text{ Watts}/g$$

A clever way is needed to ignite a target

- **For T = 10 keV**

$$\xi \approx 0.18(\rho R) \qquad Gain|_{10\text{keV}} \approx 293\eta \frac{0.18\rho R}{4 + 0.18\rho R} \approx 293\eta \frac{\rho R_{g/\text{cm}^2}}{22 + \rho R_{g/\text{cm}^2}}$$

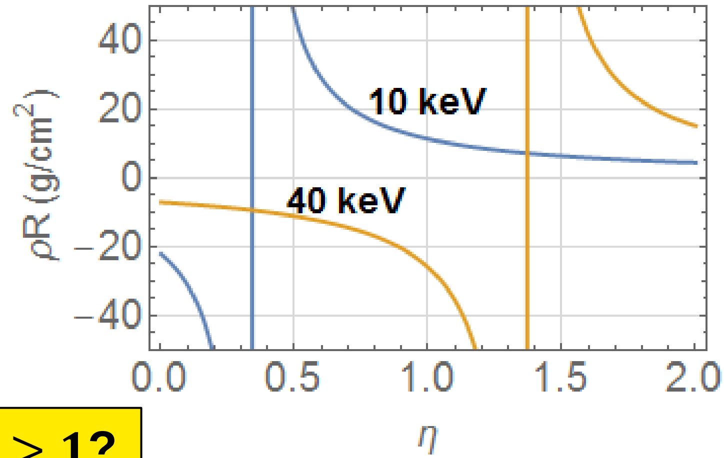
- **For T=40 keV**

$$\xi \approx 0.54(\rho R) \qquad Gain|_{40\text{keV}} \approx 73\eta \frac{\rho R_{g/\text{cm}^2}}{7 + \rho R_{g/\text{cm}^2}}$$

- **For Gains $\gtrsim$ 100**
  - **T = 10 keV** $\qquad \rho R_{g/\text{cm}^2} \gtrsim \dfrac{22}{2.93\eta - 1}$

    $\rho R \gtrsim 22\ g/\text{cm}^2 \qquad \eta > 1$
  - **T = 40 keV** $\qquad \rho R_{g/\text{cm}^2} \gtrsim \dfrac{7}{0.73\eta - 1}$

    $\rho R \gtrsim 7\ g/\text{cm}^2 \qquad \eta > 1$



How do we get $\eta > 1$?

Requirement to ignite a target

- **For T=10 keV and $\rho R \gtrsim 22$ g/cm²**

$$\rho R = \frac{4\pi}{3}\frac{\rho R^3}{4\,\pi R^2/3} = \frac{M_0}{\frac{4\pi}{3}R^2} = \frac{3}{4\pi}\frac{M_0}{R^2} \gtrsim 22\; g/\mathrm{cm}^2$$

$$\frac{M_0}{R^2} \gtrsim 92\; g/\mathrm{cm}^2$$

$$P_w\Big|_{10keV} = 10^{18}\left(\frac{T_{\mathrm{keV}}}{10}\right)^{3/2}\frac{0.1}{\mu}\frac{M_0}{R_{\mathrm{cm}}}\frac{1}{\eta} = 10^{18}\frac{0.1}{\mu}\frac{1}{\eta}92R_{\mathrm{cm}} \quad \mathrm{Watts}$$

$$P_w\Big|_{10keV} \approx 10^{20}\frac{0.1}{\mu}\frac{R_{\mathrm{cm}}}{\eta}\mathrm{Watts}$$

- **For T=40keV**

$$\rho R \gtrsim 7 \;\; \Rightarrow \;\; \frac{M_0}{R^2} \gtrsim 30\; g/\mathrm{cm}^2$$

$$P_w\Big|_{40keV} \approx 2.4\times 10^{20}\frac{0.1}{\mu}\frac{R_{\mathrm{cm}}}{\eta}\mathrm{Watts}$$

- **Needed:**

$R_{\mathrm{cm}} \ll 1$

$\eta \gg 1$

$\mu \gg 0.1$

Requirements to ignite a target

$$P_w\Big|_{10keV} \approx 10^{20}\,\frac{0.1}{\mu}\,\frac{R_{\rm cm}}{\eta}\,\text{Watts}$$

- $R_{\rm cm} \ll 1$ **: sphere size in the order of 100's um**
- $\eta \gg 1$ **: input energy amplification**
- $\mu \gg 0.1$ **: energy delivery time decoupled from burn time. Need longer energy delivery time. Need to bring down power to ~10^{15} W**

Math….#!@%$$#&^%$#

$$P_w = 10^{18}\frac{M_{0,g}}{\eta}\left(\frac{T_{\text{keV}}}{10}\right)^{3/2}\frac{0.1}{\mu}\frac{1}{R_{\text{cm}}}\ \text{Watts}/g$$

$$\tau_{\text{input}} = \mu\frac{R}{C_s}\quad \text{Ex: } \mu\sim 0.1 \qquad \eta = \frac{\text{Thermal Energy}}{\text{Input Energy}}$$

$$\text{Gain} = 293\eta\left(\frac{10}{T_{\text{keV}}}\right)\Theta(\xi) \qquad \Theta(\xi)\approx\frac{\xi}{4+\xi} \qquad \xi = \frac{\langle\sigma v\rangle}{2m_i C_s}(\rho R_0)$$

$$G_{\max} \equiv 293\eta\left(\frac{10}{T_{\text{keV}}}\right) \qquad G = G_{\max}\frac{\xi}{4+\xi} \Longrightarrow \xi = \frac{4G}{G_{\max}-G}$$

$$P_w = \frac{10^{18}}{\eta}\left(\frac{T_{\text{kev}}}{10}\right)^{3/2}\frac{0.1}{\mu}\frac{4\pi}{3}\frac{\rho {R_0}^3}{R_0} = \frac{10^{18}}{\eta}\left(\frac{T_{\text{kev}}}{10}\right)^{3/2}\frac{0.1}{\mu}\frac{4\pi}{3}(\rho R_0)R_0$$

More math…!#$%%^&*&^(*&%)(#%!@$#%%^*&*%(

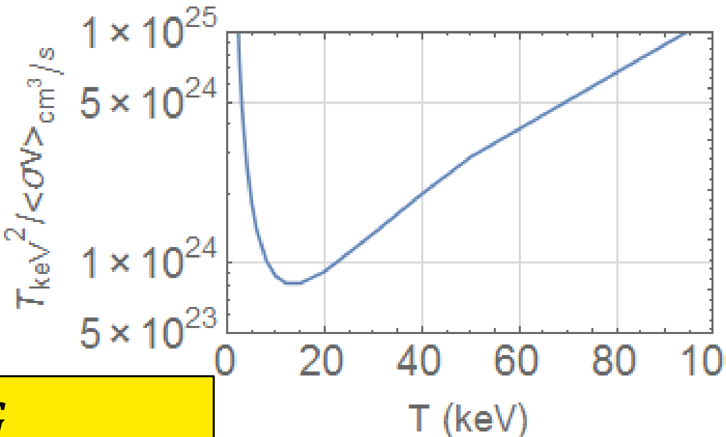
$$P_w = \frac{10^{18}}{\eta}\left(\frac{T_{kev}}{10}\right)^{3/2}\frac{0.1}{\mu}\frac{4\pi}{3}\frac{\rho {R_0}^3}{R_0} = \frac{10^{18}}{\eta}\left(\frac{T_{kev}}{10}\right)^{3/2}\frac{0.1}{\mu}\frac{4\pi}{3}(\rho R_0)R_0$$

$$= \frac{10^{18}}{\eta}\left(\frac{T_{kev}}{10}\right)^{3/2}\frac{0.1}{\mu}\frac{4\pi}{3}R_0\frac{2m_iC_s}{<\sigma v>}\xi \qquad \text{where} \quad \xi \equiv \frac{\langle\sigma v\rangle}{2m_iC_s}(\rho R)$$

$$= \frac{10^{18}}{\eta}\left(\frac{T_{kev}}{10}\right)^{3/2}\frac{0.1}{\mu}\frac{32\pi}{3}R_{0,cm}\frac{\sqrt{Tm_i}}{<\sigma v>}\frac{G}{G_{max}-G} \qquad \text{where} \quad C_s = \sqrt{\frac{2T}{m_i}}$$

$$P_w = \frac{10^{18}}{\eta}\frac{{T_{kev}}^2}{\langle\sigma v\rangle_{cm^2/s}}\frac{0.1}{\mu}R_{0,cm}\frac{G}{G_{max}-G} \quad \text{Watts}$$

$$\left.\frac{{T_{kev}}^2}{\langle\sigma v\rangle_{cm^2/s}}\right|_{min} = 8\times 10^{23} \quad \text{for} \quad T = 14\text{keV}$$



$$\frac{G}{G_{max}-G} \approx \frac{G}{G_{max}}$$

$$P_w \approx \frac{7\times 10^{19}}{\eta}\frac{0.1}{\mu}R_{0,cm}\frac{G}{G_{max}}\text{Watts}$$

Need to lower the power by 5 orders of magnitude

$$P_w \approx \frac{7\times 10^{19}}{\eta}\frac{0.1}{\mu}R_{0,\mathrm{cm}}\frac{G}{G_{\max}}\,\mathrm{Watts}$$

- $\mu\uparrow$:
- $\eta\uparrow$: require the fuel ignition from a "spark." Ignite only a small portion of the DT plasma, i.e., $M_h << M_0$
- $R_0\downarrow$: smaller system size

$$P_w = P_w(M_0)\frac{M_h}{M_0}$$

$$P_w{}^{\min} = \frac{7\times 10^{15}}{\eta_h}\left(\frac{M_h/M_0}{0.01}\right)\left(\frac{R_{0,\mu\mathrm{m}}}{100}\right)\left(\frac{0.1}{\mu}\right)\left(\frac{G}{G_{\max}}\right)\mathrm{Watts}$$

Effective increase in η

Target design using an 1MJ laser

$$P_w{}^{\min} = \frac{7\times10^{15}}{\eta_h}\left(\frac{M_h/M_0}{0.01}\right)\left(\frac{R_{0,\mu\mathrm{m}}}{100}\right)\left(\frac{0.1}{\mu}\right)\left(\frac{G}{G_{\max}}\right)\mathrm{Watts}$$

- **For the case of using a huge laser, ex: 1MJ.**
- **The ignition requires temperatures $T \gtrsim 5\mathrm{keV}$, then the energy required for ignition is**

$$E_{\mathrm{ign}} \approx 3\frac{M_h}{m_i}\frac{T}{\eta_h}$$

$$M_h \approx \frac{m_i}{3}\frac{\eta_h E_{\mathrm{ign}}}{T}$$

$$M_{h,\mu\mathrm{g}} \approx 17\left(\frac{5}{T_{\mathrm{keV}}}\right)E_{\mathrm{igm,MJ}}\left(\frac{\eta_h}{0.01}\right) \qquad M_h \approx 20\mu\mathrm{g}$$

Target design using an 1MJ laser - continue

- For "inefficient" heating mechanism $(\eta_h \approx 1\%)$, the mass that can be heated to $T \approx 5$ keV is in the order of $M_h \approx 20$ μg.
- If $M_h/M_0 \approx 0.01$, then $M_0 \approx 2$ mg .
- Assuming that the burned-up fraction $\Theta \approx \frac{\rho R}{7+\rho R}$

for $\Theta \approx 30\% \rightarrow \rho R \approx 3\ g/cm^2$

$$M_0 = \frac{4\pi}{3}\rho R^3 = \frac{4\pi}{3}R^2(\rho R) \qquad R = \sqrt{\frac{4\pi}{3}\frac{M_0}{\rho R}} = 126\sqrt{\frac{M_{0,mg}}{2}}\sqrt{\frac{3}{\rho R}}\,\mu m$$

$$\rho = \frac{3M_0}{4\pi R^3} = 240\sqrt{\frac{M_{0,mg}}{2}}\left(\frac{126}{R_{\mu m}}\right)^3 g/cm^3 \xleftarrow[\times 1000]{} \rho_{DT} = 0.25\ g/cm^3$$

- DT must be compressed ~1000 times
- The initial radius of a 2 mg sphere of *DT* is $R_{init} \simeq 2.6$ mm while the final radius $R_{final} \simeq 100\ \mu m$, the convergence ratios of 30 ~ 40 are required.

Requirements of the density and size of the ignition mass

$$M_h \approx 20\mu\text{g}$$

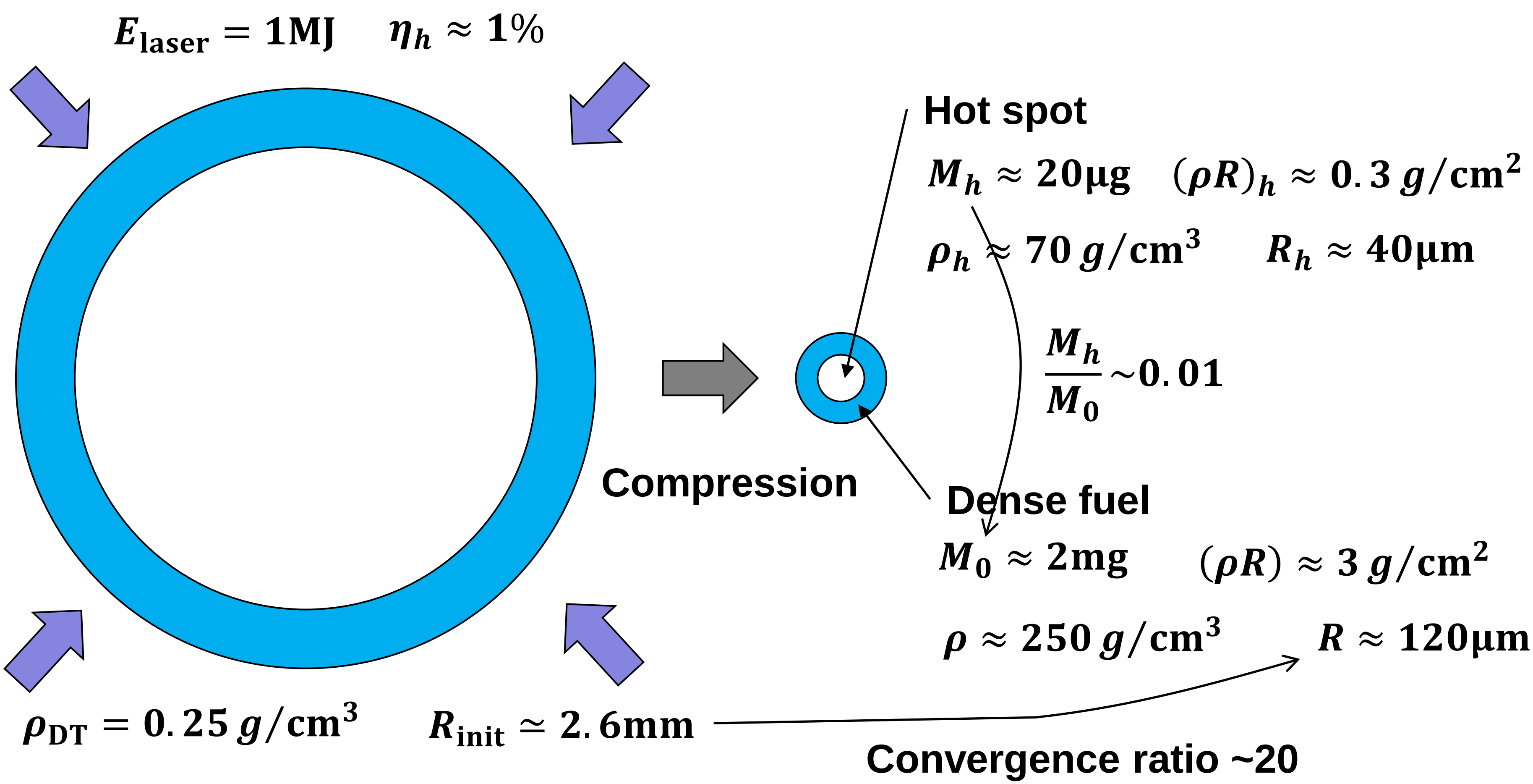
$$\rho_h R_h \approx 0.3\ g/\text{cm}^2 \longleftarrow$$ **To stop 3.5 MeV α particles**

$$R_h \simeq \sqrt{\frac{3}{4\pi}\frac{M_h}{\rho_h R_h}} \approx 40\mu\text{m}$$

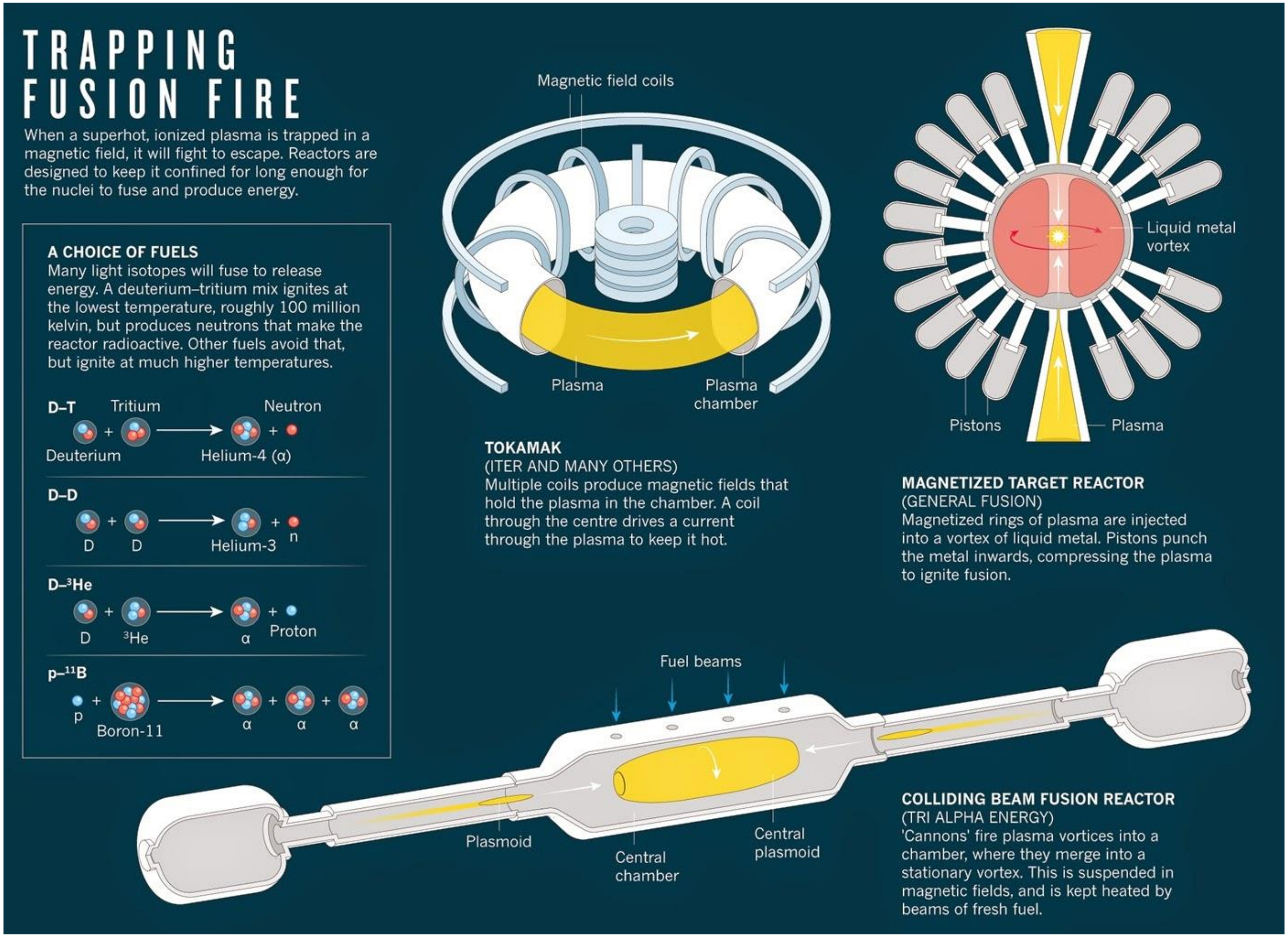
$$\rho_h \approx \frac{(\rho_h R_h)}{R_h} = \frac{0.3}{40 * 10^{-4}} = 75\ g/\text{cm}^3$$

Summary

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

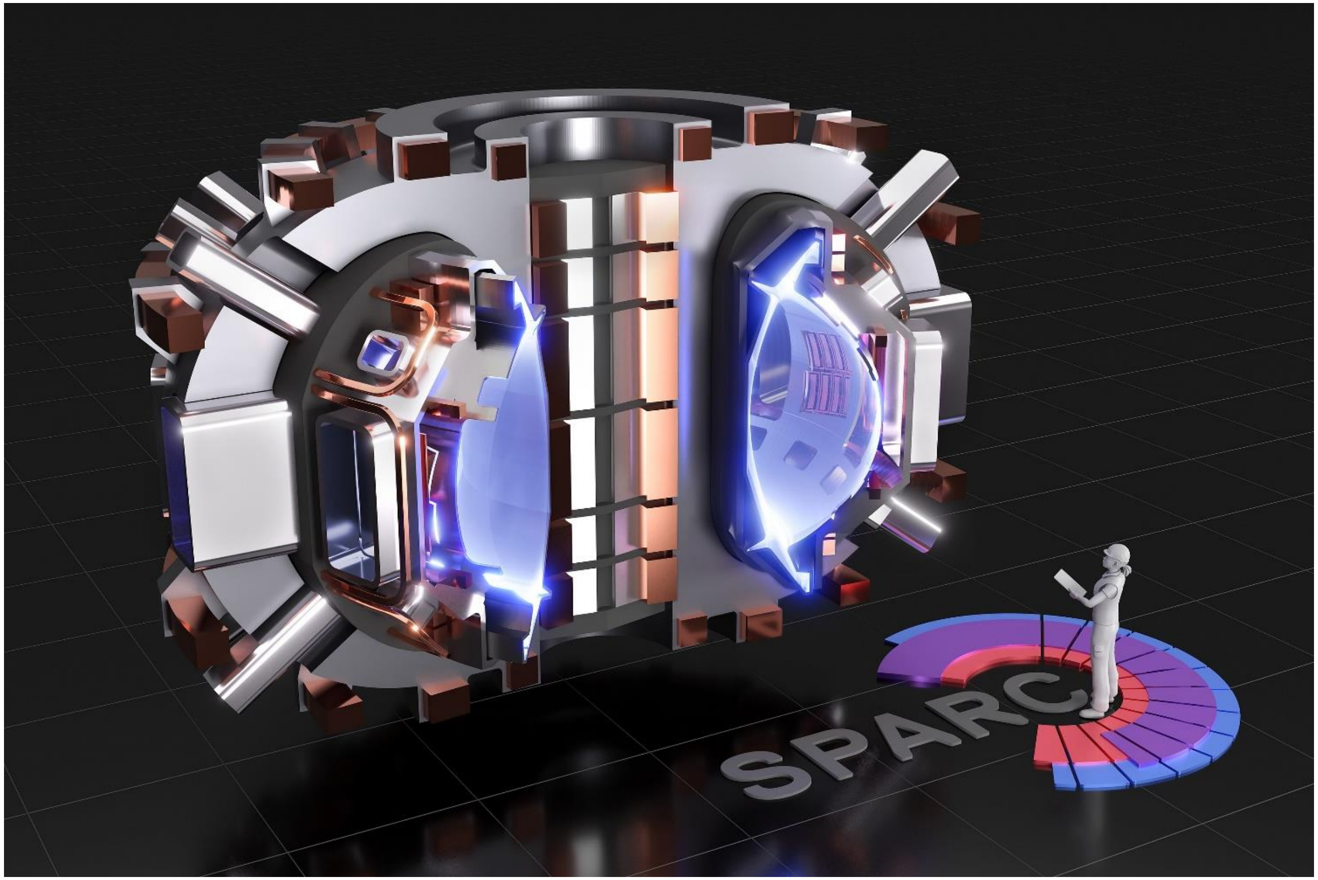


There are alternative



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

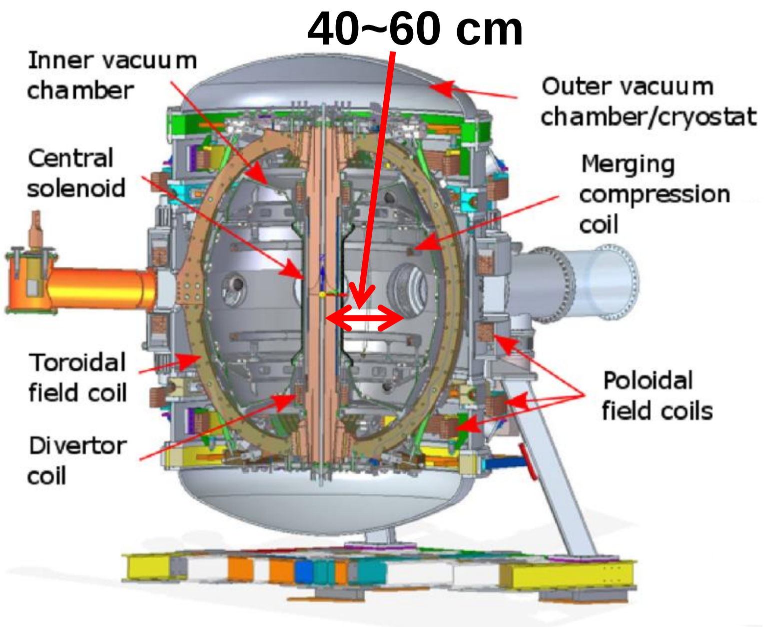
Commonwealth Fusion Systems, a MIT spin-out company, is building a high-magnetic field tokamak



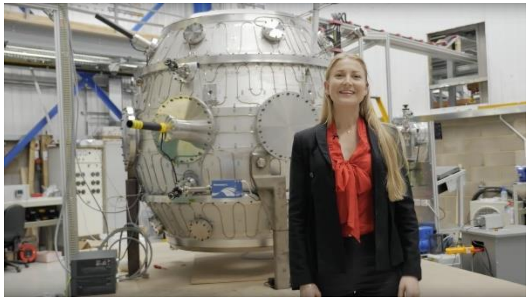
- **Fusion power ∝ B^4.**
- **The fusion gain Q > 2 is expected for SPARC tokamak.**

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

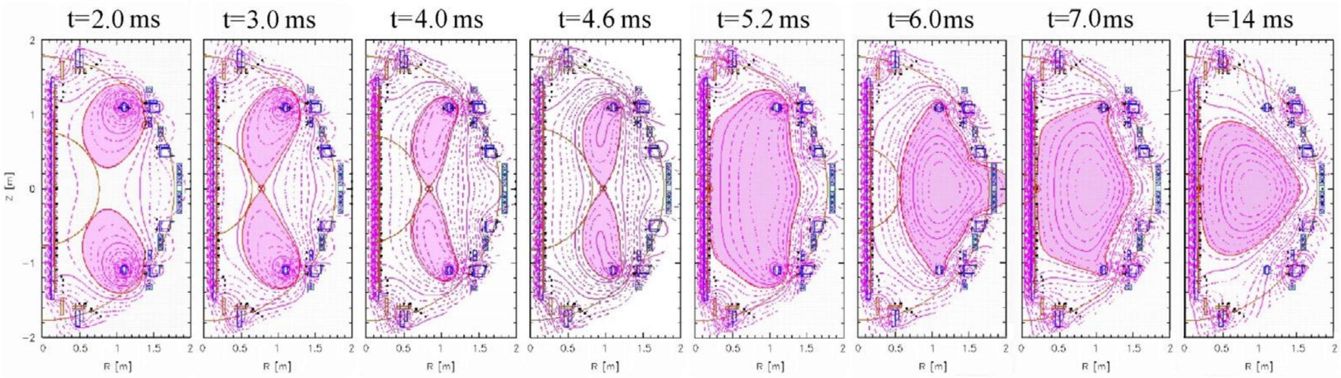
Merging compression is used to heat the tokamak at the start-up process in ST40 Tokamak at Tokamak Energy Ltd



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

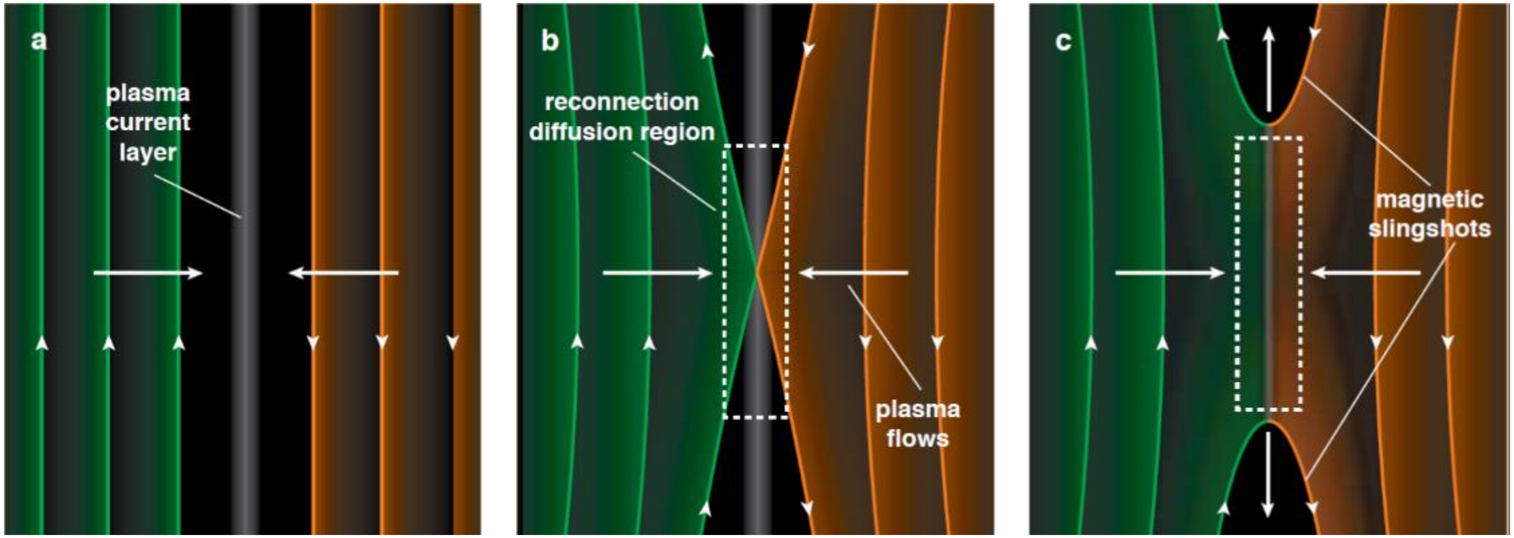


- **Merging compression**



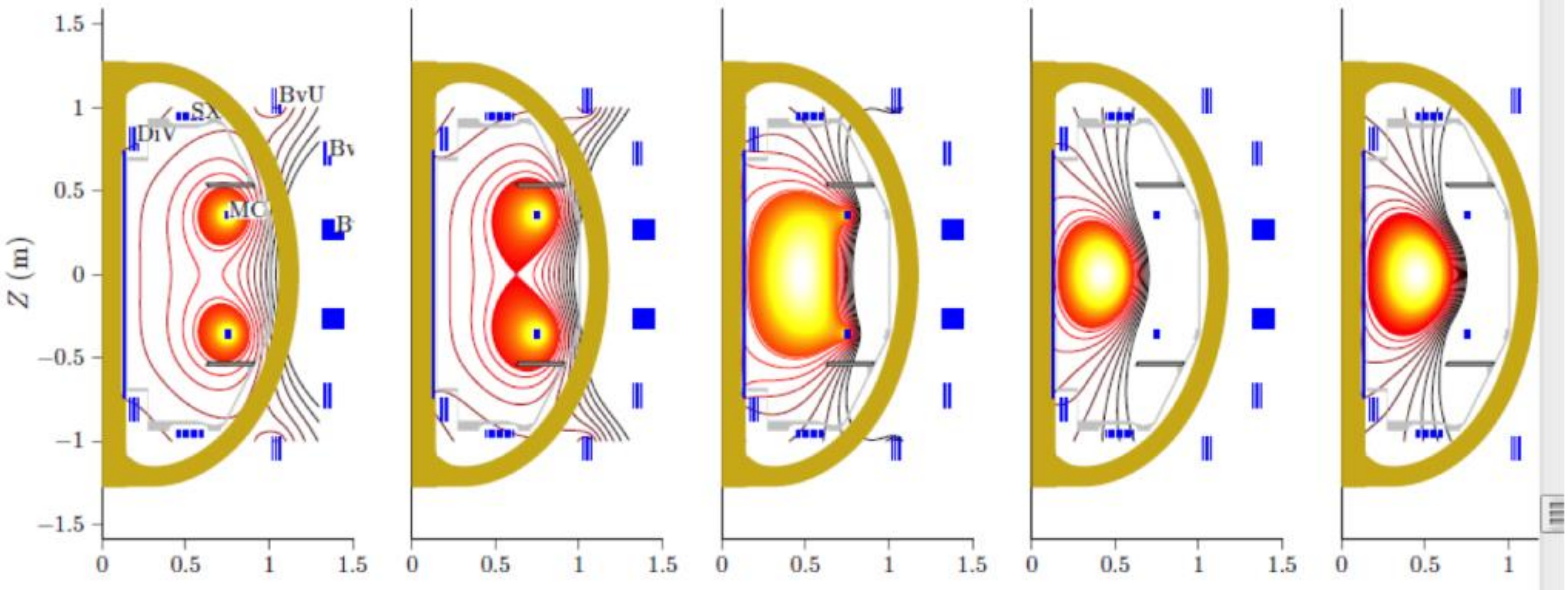
M. Gryaznevich, etc., Fusion Eng. Design, **123**,177 (2017)
https://www.tokamakenergy.co.uk/
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

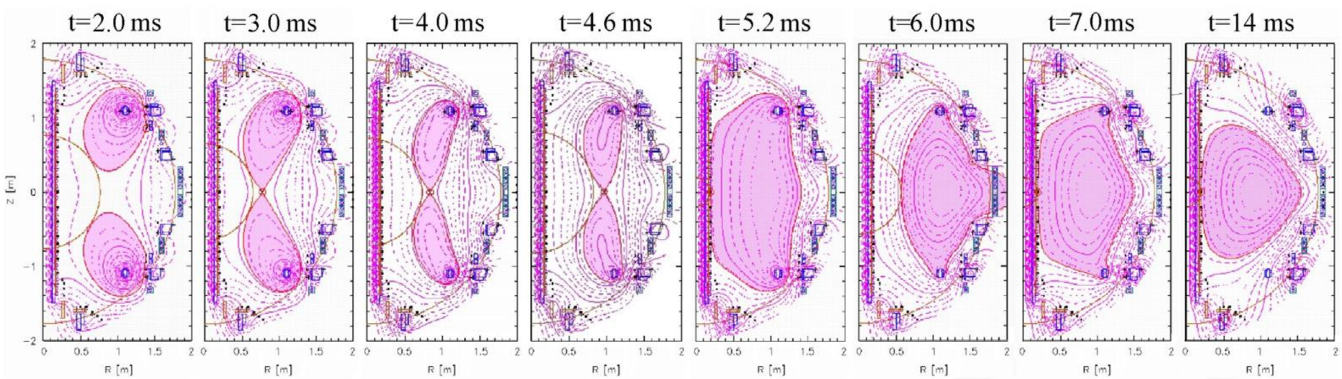
Reconnection



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

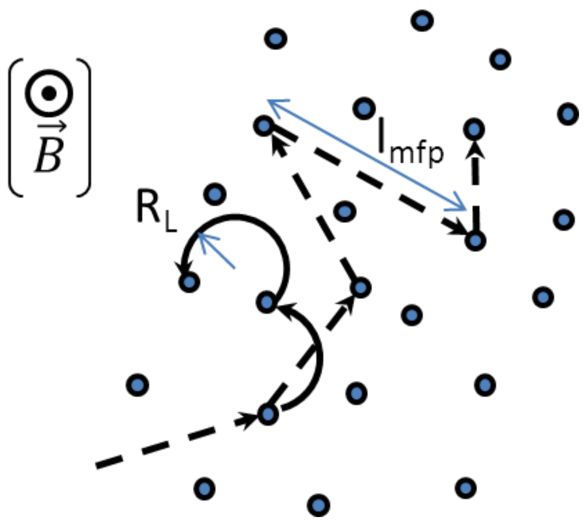
Merging compression is used to heat the plasma





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

A strong magnetic field reduces the heat flux



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

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

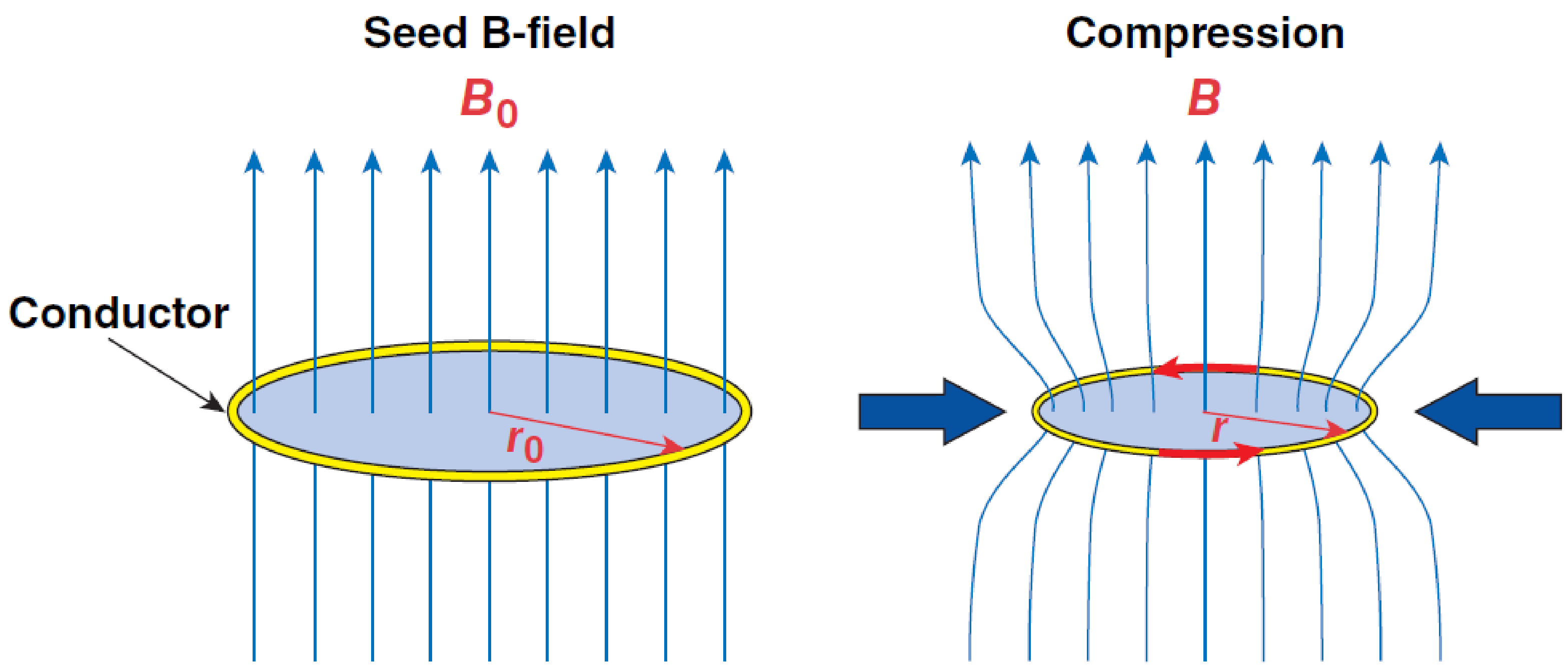
$$\kappa_{\perp} = \frac{\kappa_{||}}{\chi^2} \quad \text{for large Hall parameter } \chi \propto \frac{l_{mfp}}{R_L} >> 1$$

- **Typical hot spot conditions:**
  R_{hs} ~ 40 μm, ρ ~ 20 g/cm³, T ~ 5 keV:

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

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

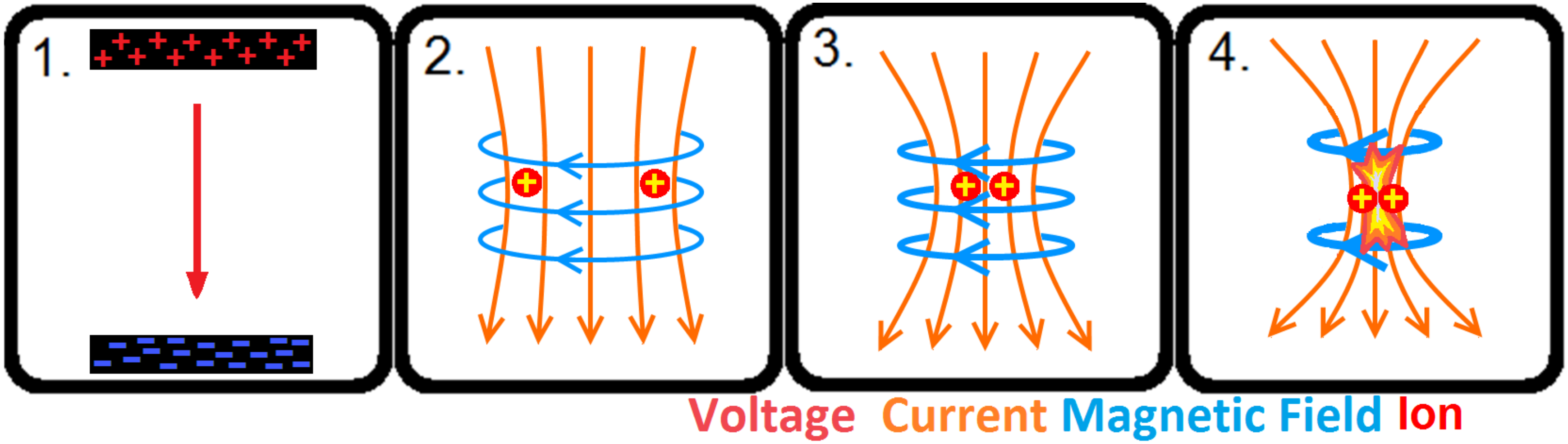
Principle of frozen magnetic flux in a good conductor is used to compress fields



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

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

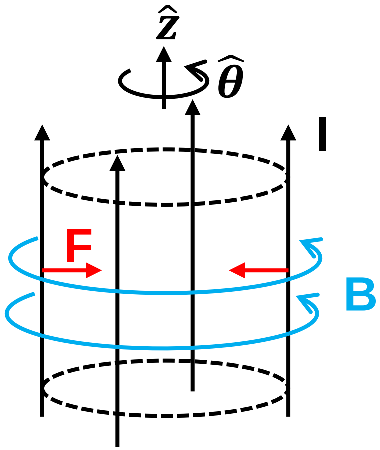
Plasma can be pinched by parallel propagating plasmas



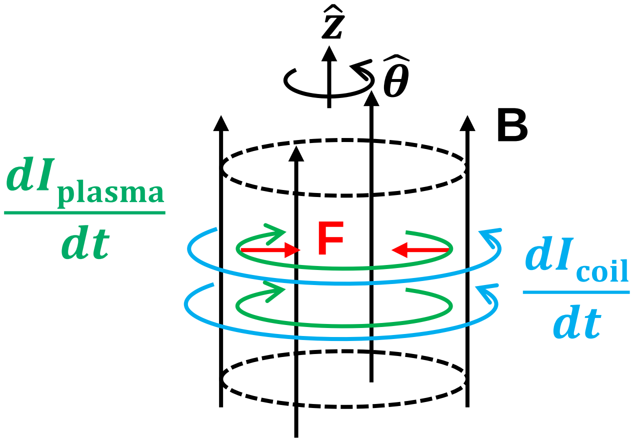
https://en.wikipedia.org/wiki/Pinch_(plasma_physics)

Plasma can be heated via pinches

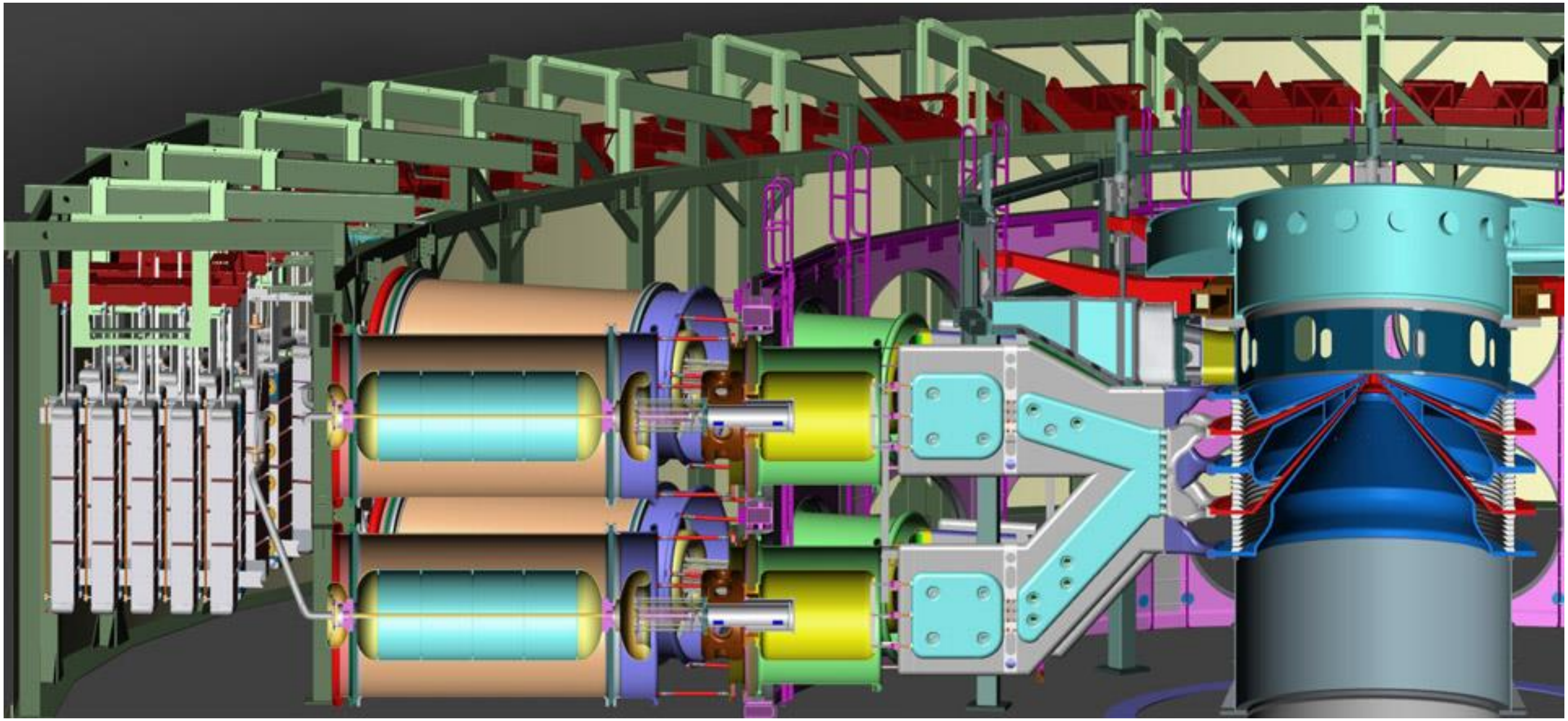
Z pinch



Theta pinch

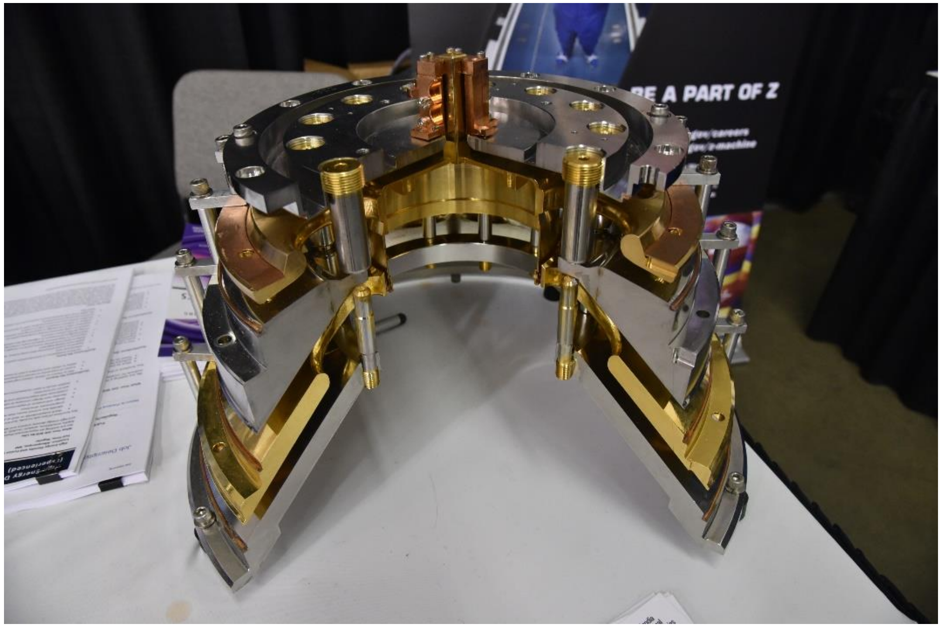


Sandia's Z machine is the world's most powerful and efficient laboratory radiation source

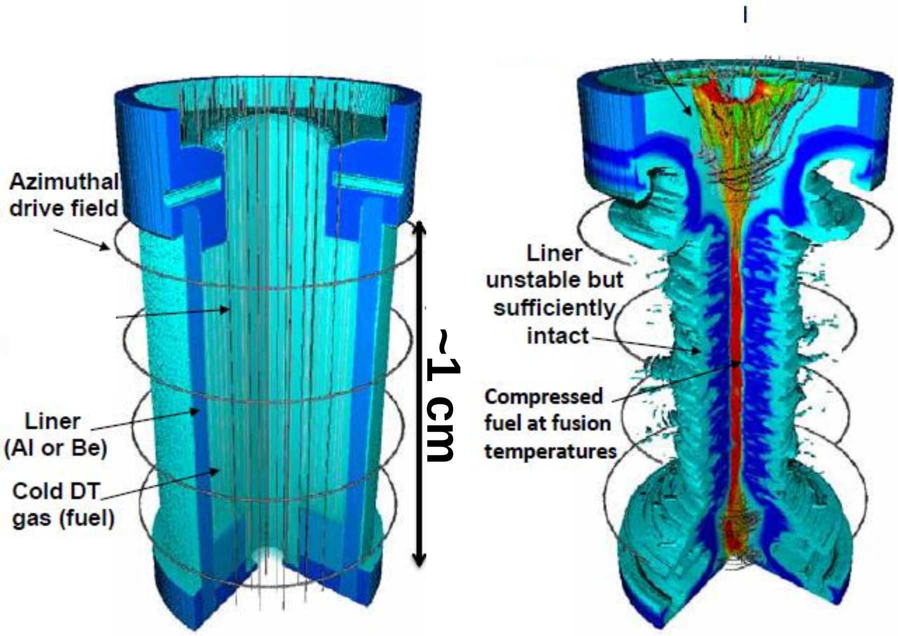


- Stored energy: 20 MJ
- Marx charge voltage: 85 kV
- Peak electrical power: 85 TW
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray emissions: 350 TW
- Peak X-ray output: 2.7 MJ

Z machine



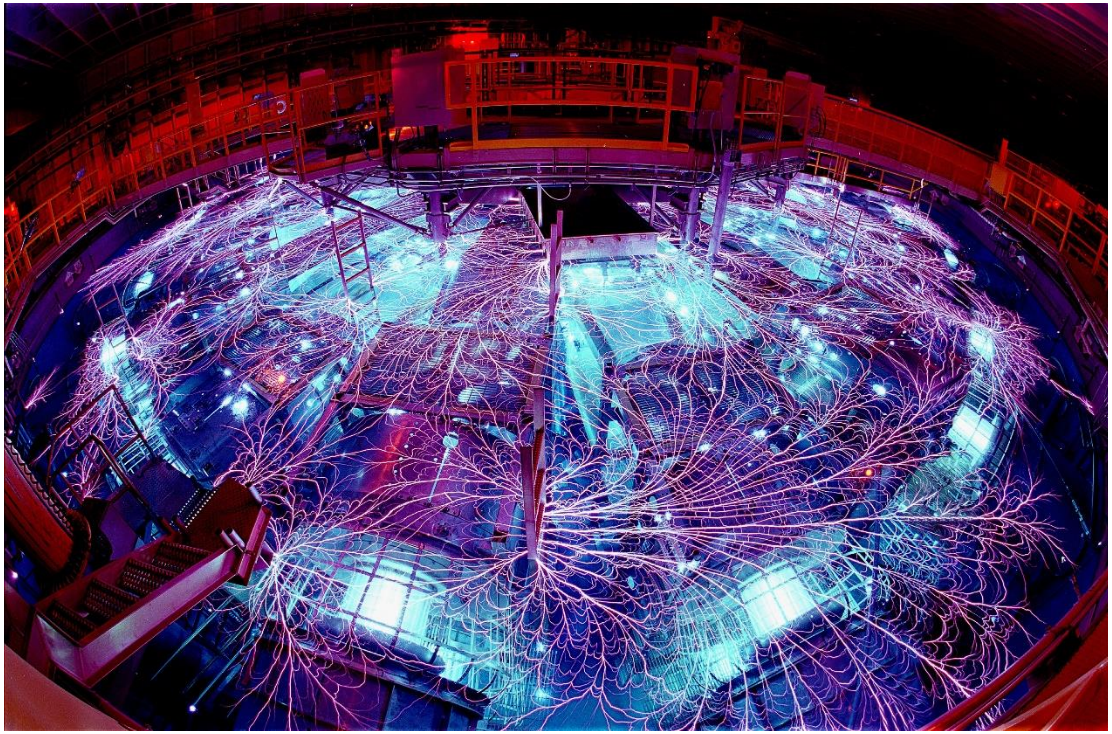
Z machine



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

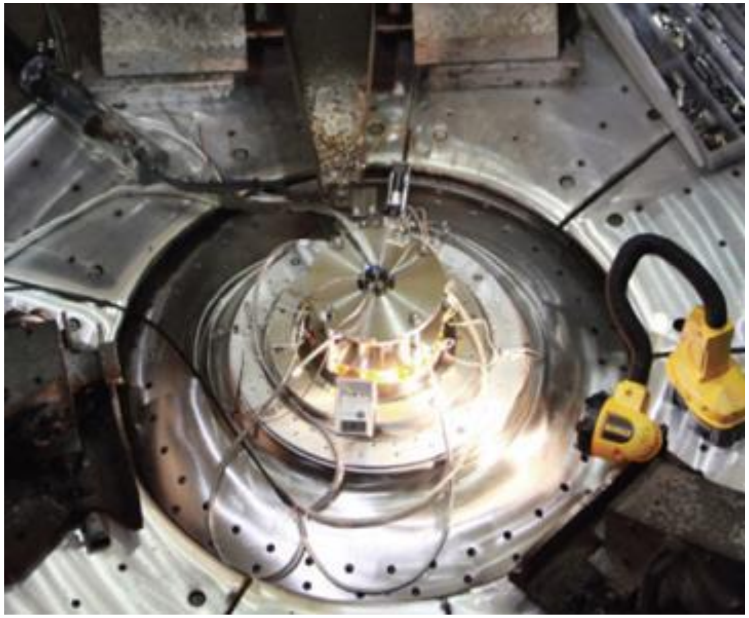
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray output: 2.7 MJ

Z machine discharge



Before and after shots

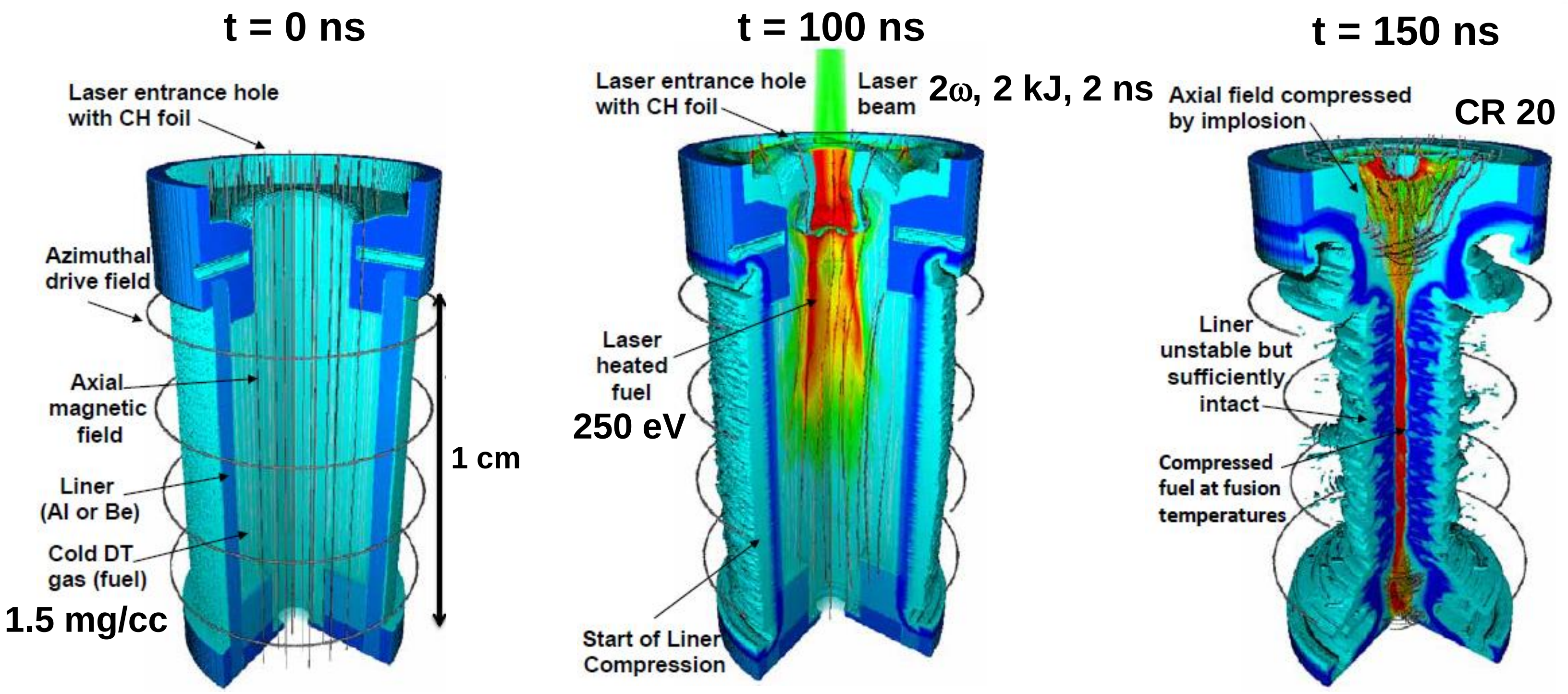
- **Before shots**



- **After shots**

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

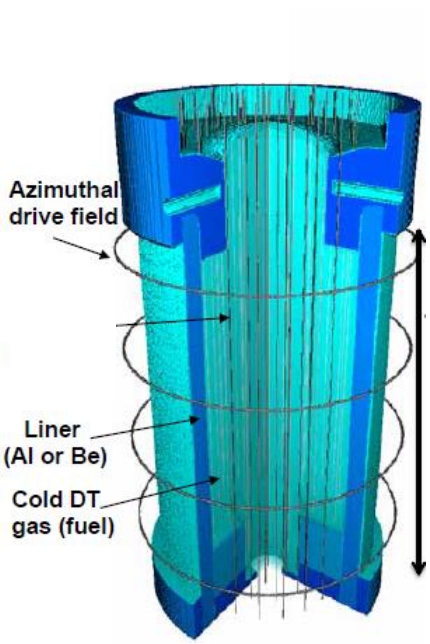
Promising results were shown in MagLIF concept conducted at the Sandia National Laboratories

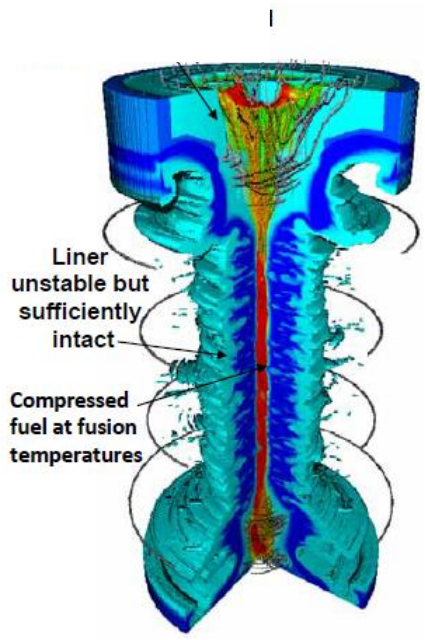


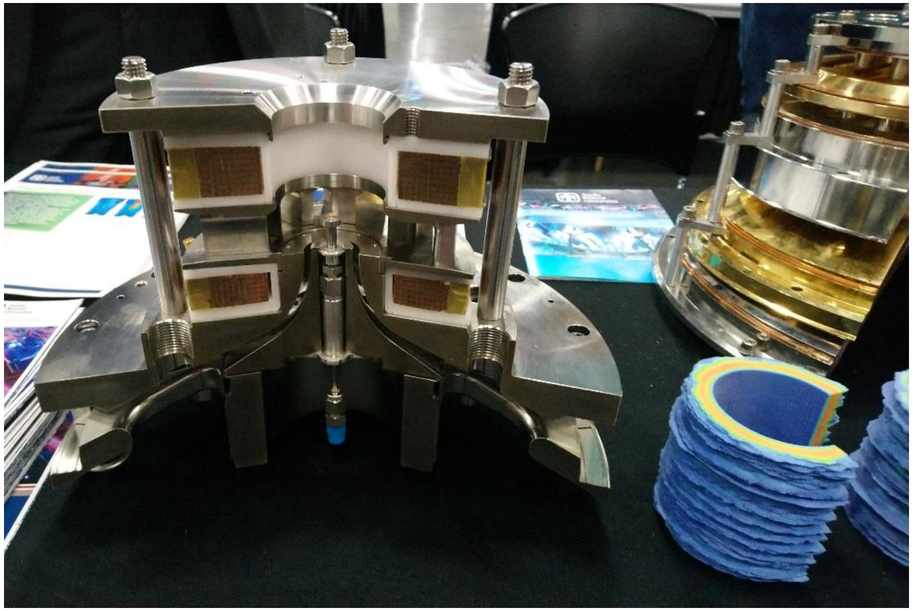
The stagnation plasma reached fusion-relevant temperatures with a 70 km/s implosion velocity

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

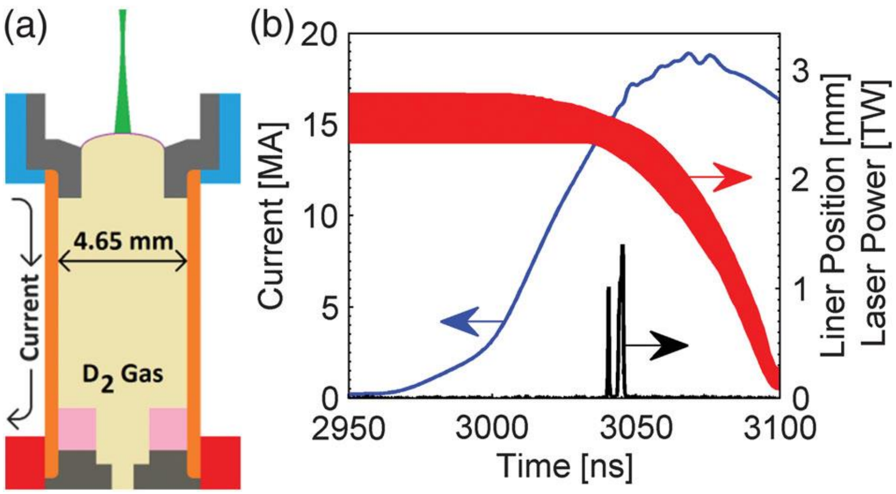
MagLIF target

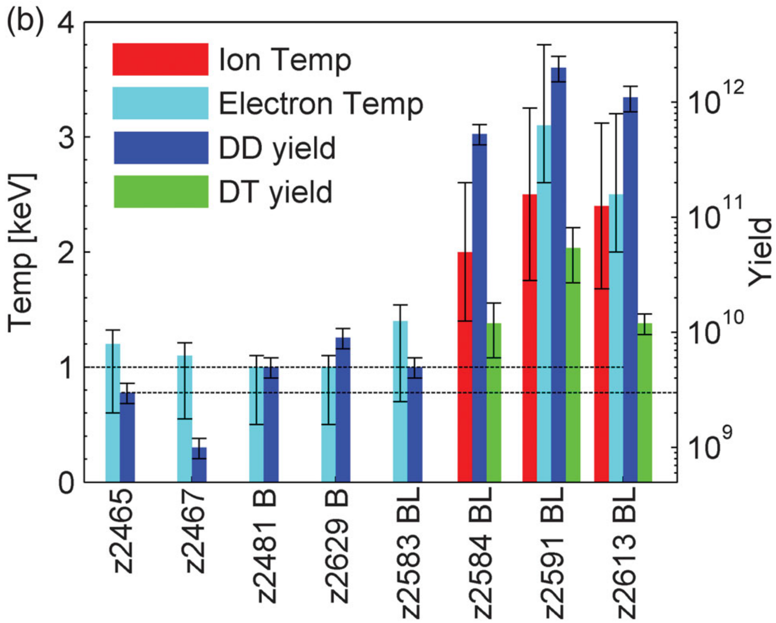






Neutron yield increased by 100x with preheat and external magnetic field.





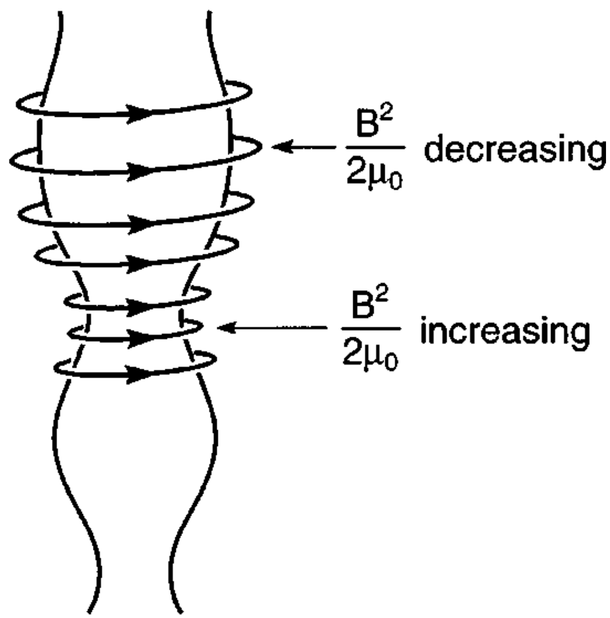
M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)

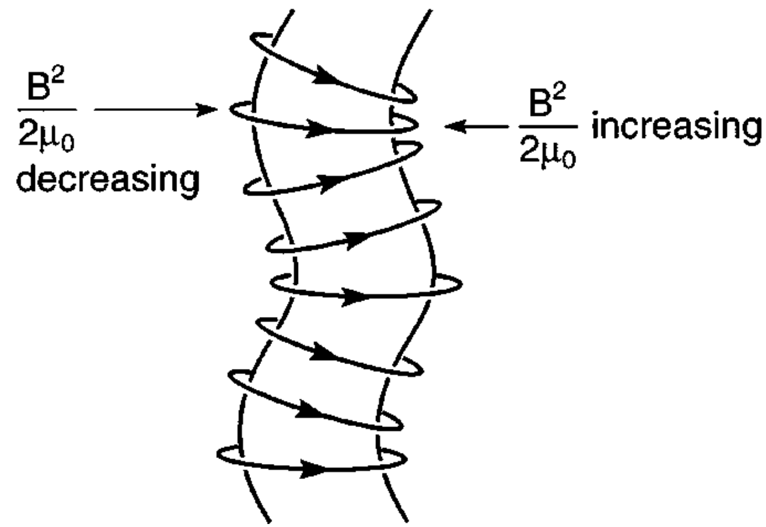
Sheared flow stabilizes MHD instabilities

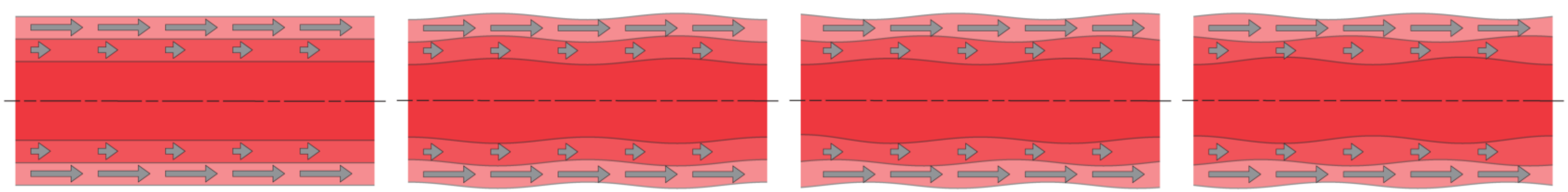
m = 0 (sausage)

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

m = 1 (kink)



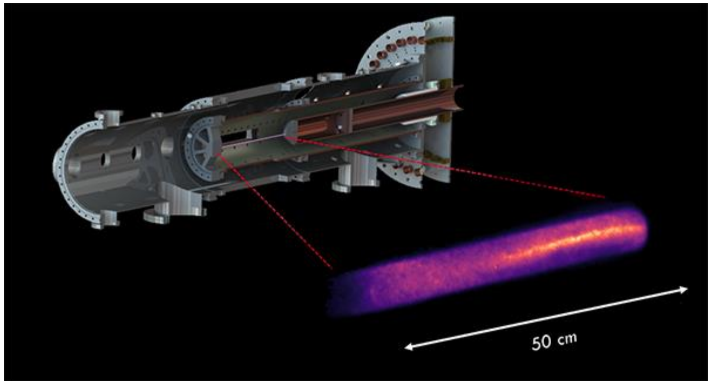




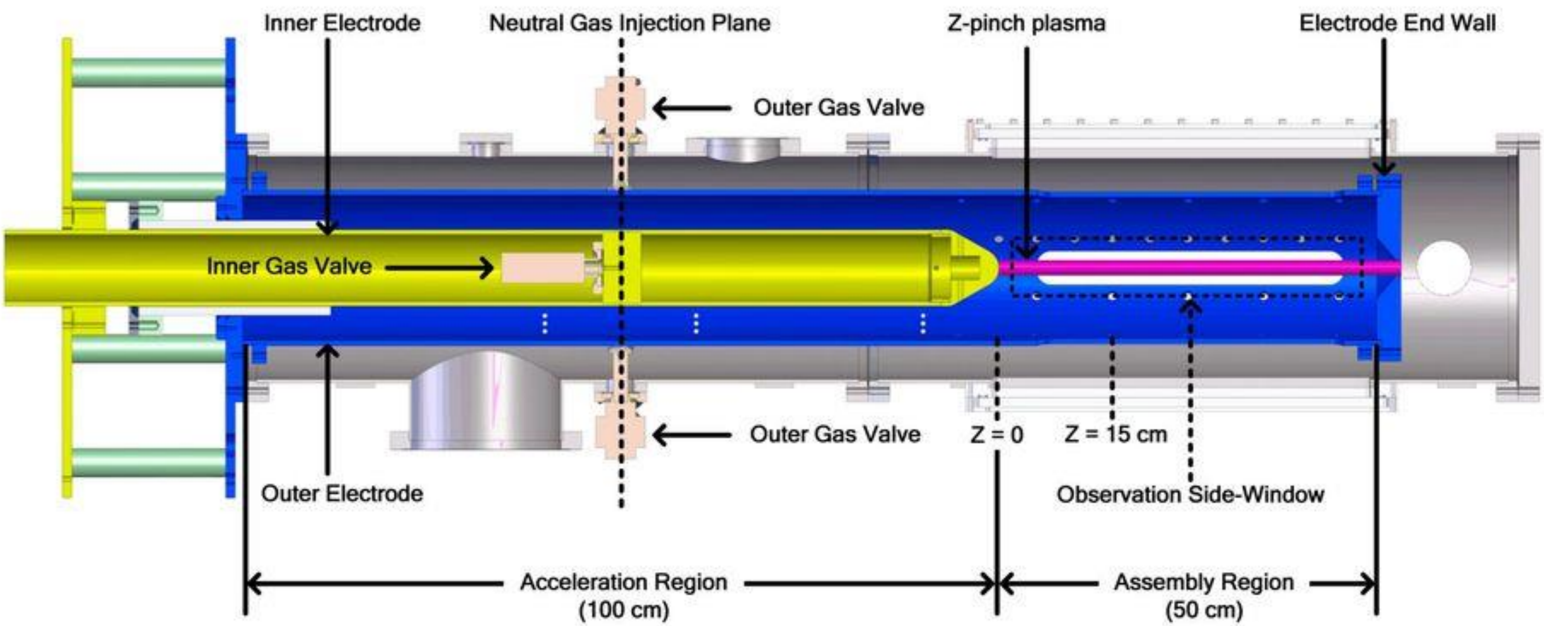
$$\frac{dV_Z}{dr} \neq 0$$

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

A z-pinch plasma can be stabilized by sheared flows

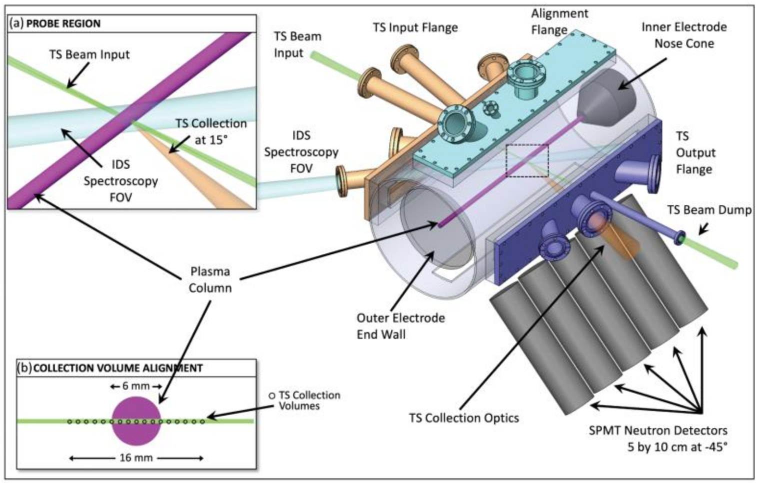


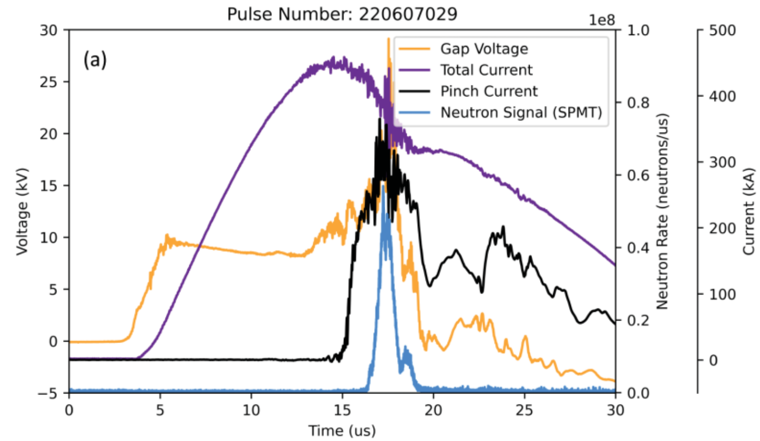
ZAP ENERGY™

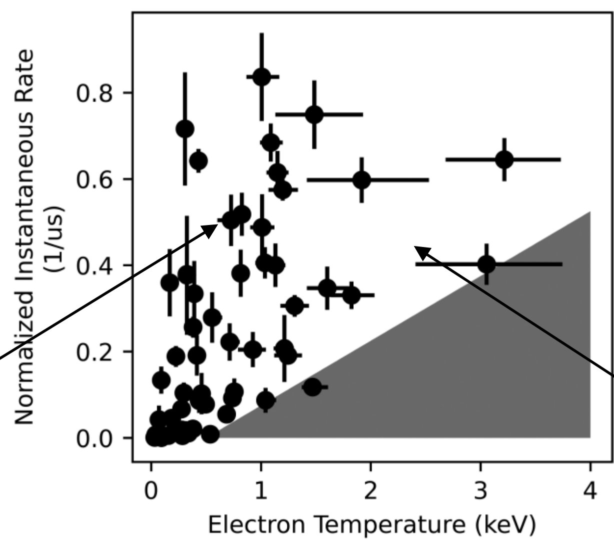


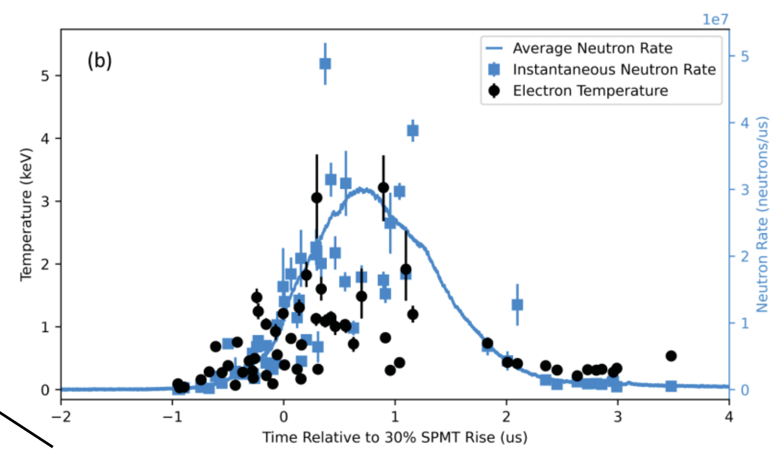
https://www.zapenergyinc.com/about
A. D. Stepanov, etc., Phys. Plasmas 27, 112503 (2020)

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





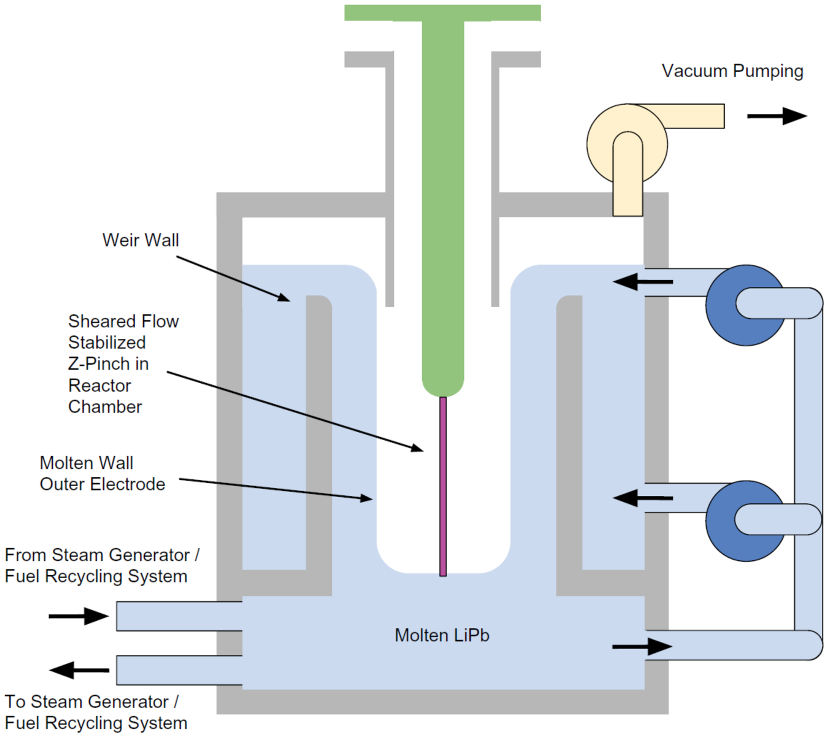


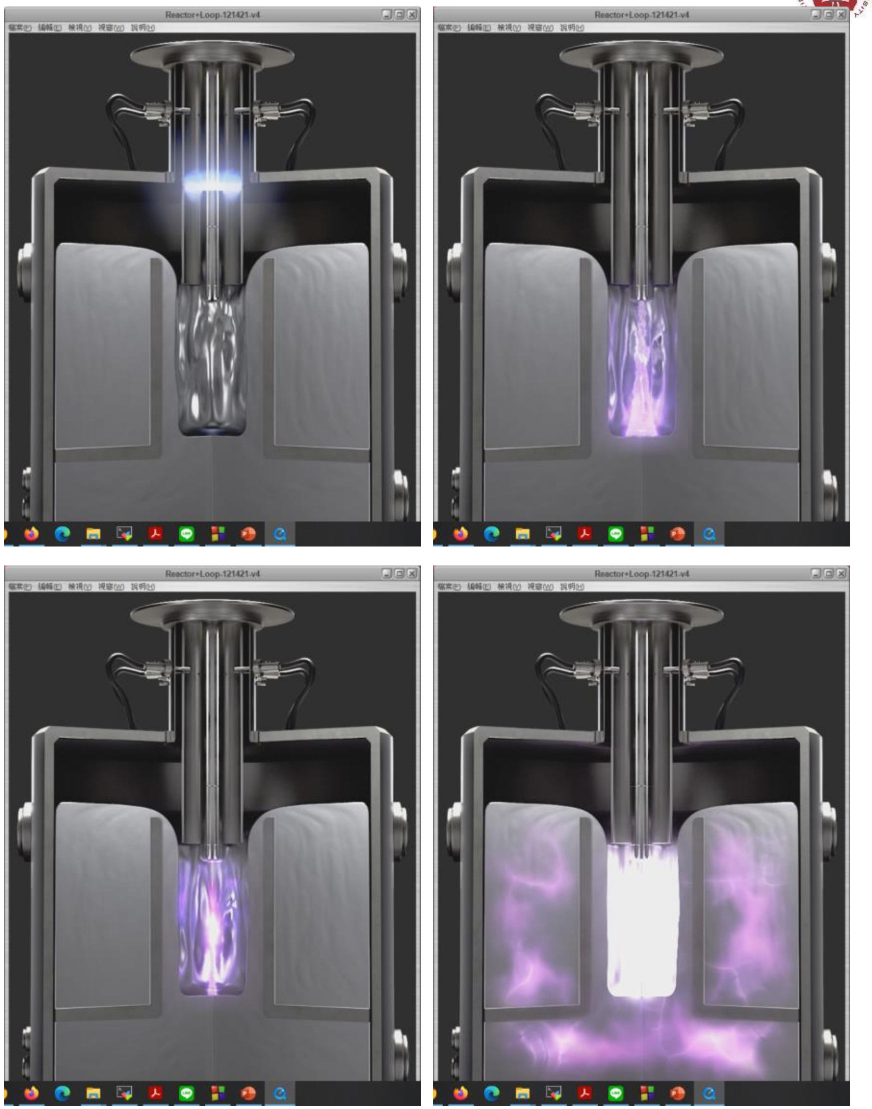


- **Thomson scattering measurement missed the high temperature region.**
- **High temperature coincide with high rate.**

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

Fusion reactor concept by ZAP energy

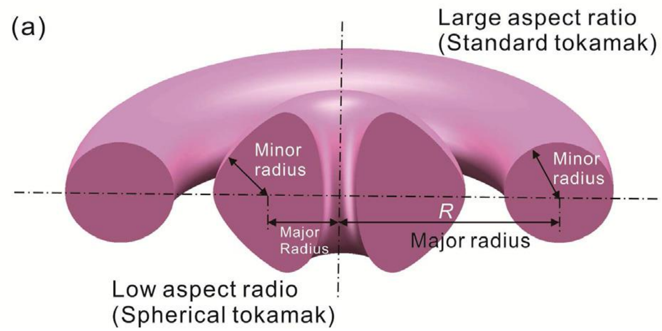




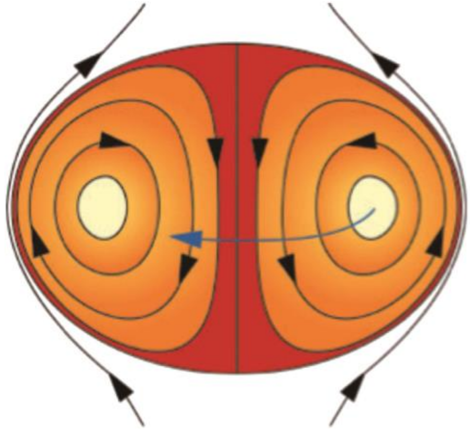
https://www.zapenergyinc.com/about
E. G. Forbes, etc., Fusion Sci. Tech. 75, 599 (2019)

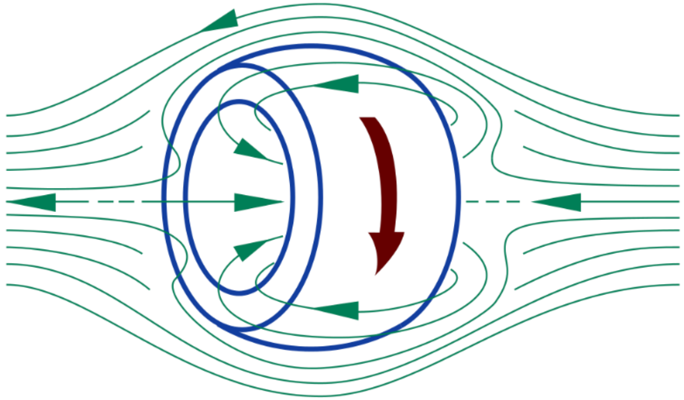
Spherical torus (ST) and compact torus (CT)

- **Spherical torus (ST)**



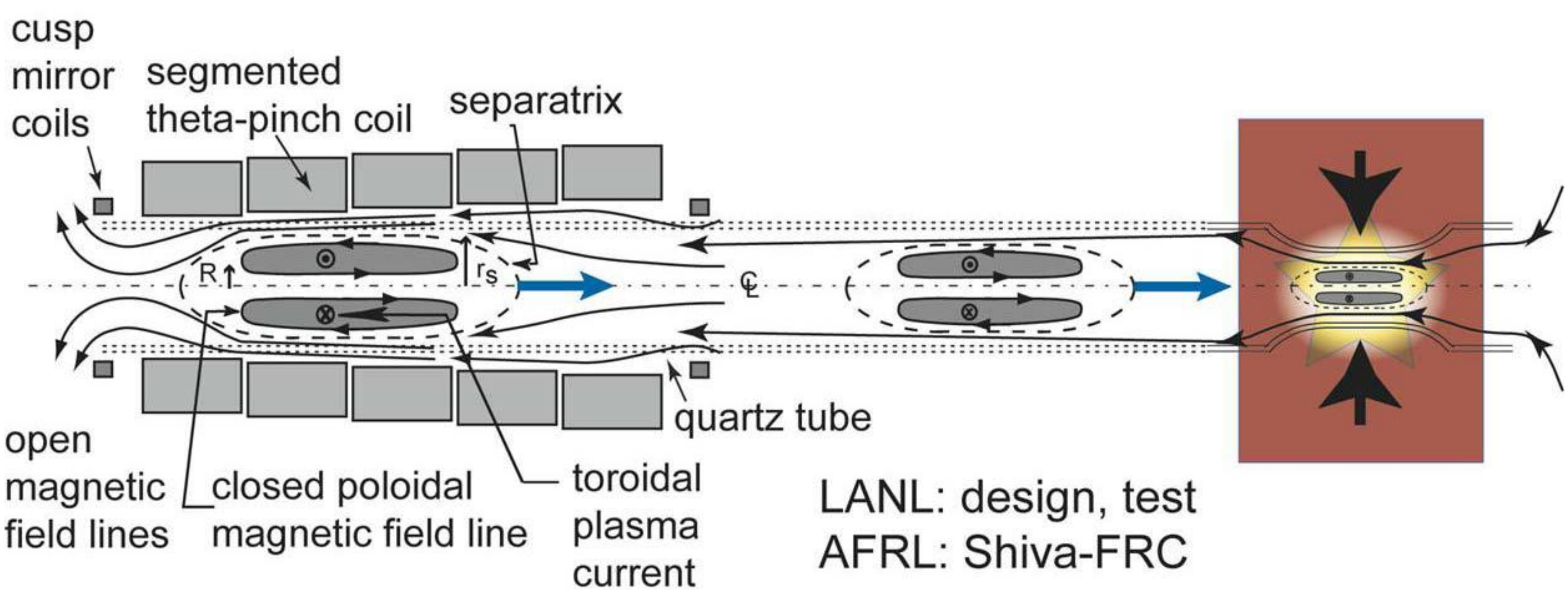
- **Compact torus (CT)**
  - **Spheromak**
  - **Field reversed configuration (FRC)**



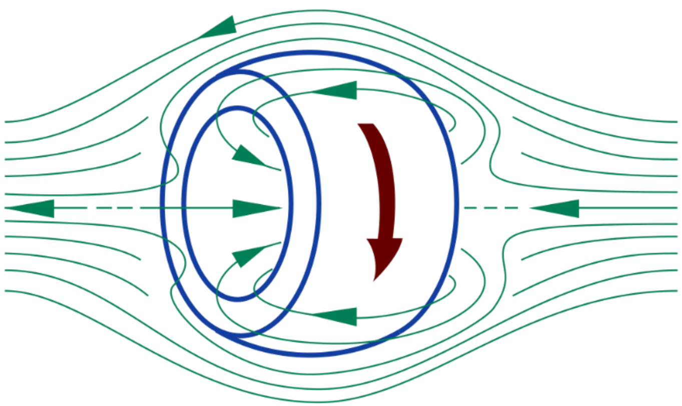


Zhe Gao, Matter Radiat. Extremes **1**, 153 (2016)
https://en.wikipedia.org/wiki/Field-reversed_configuration

Field reverse configuration is used in Tri-alpha energy

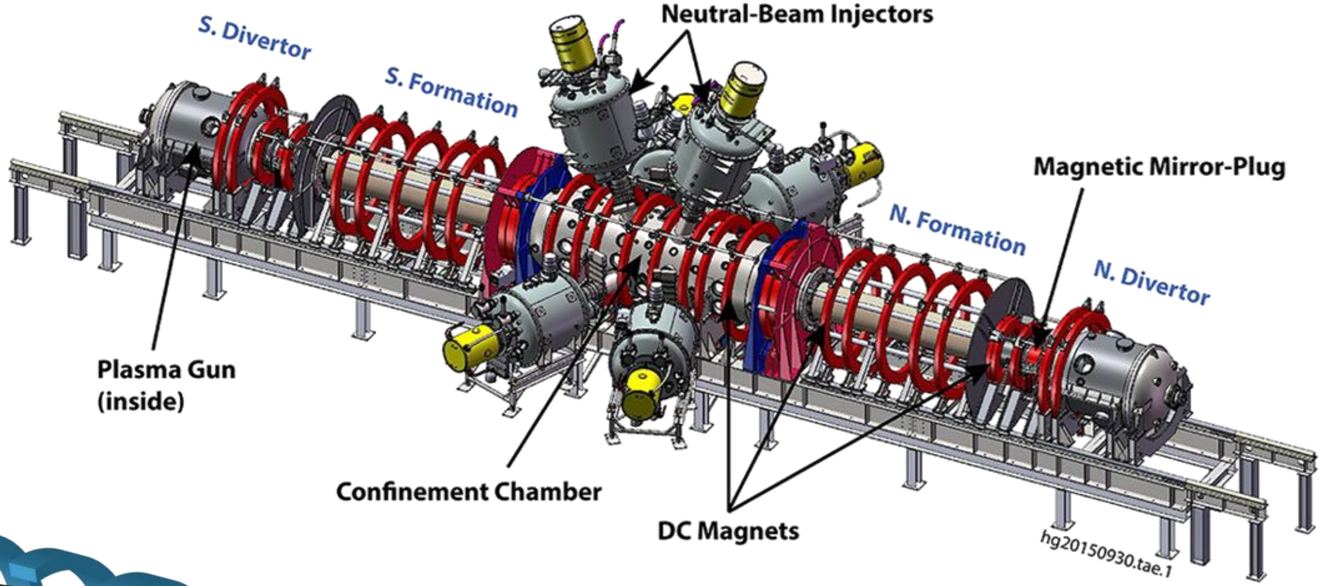


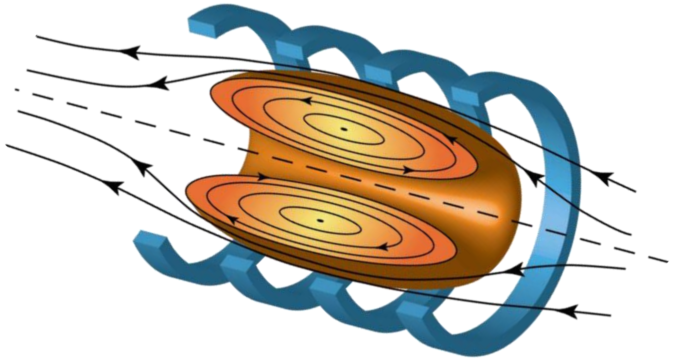
LANL: design, test
AFRL: Shiva-FRC



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

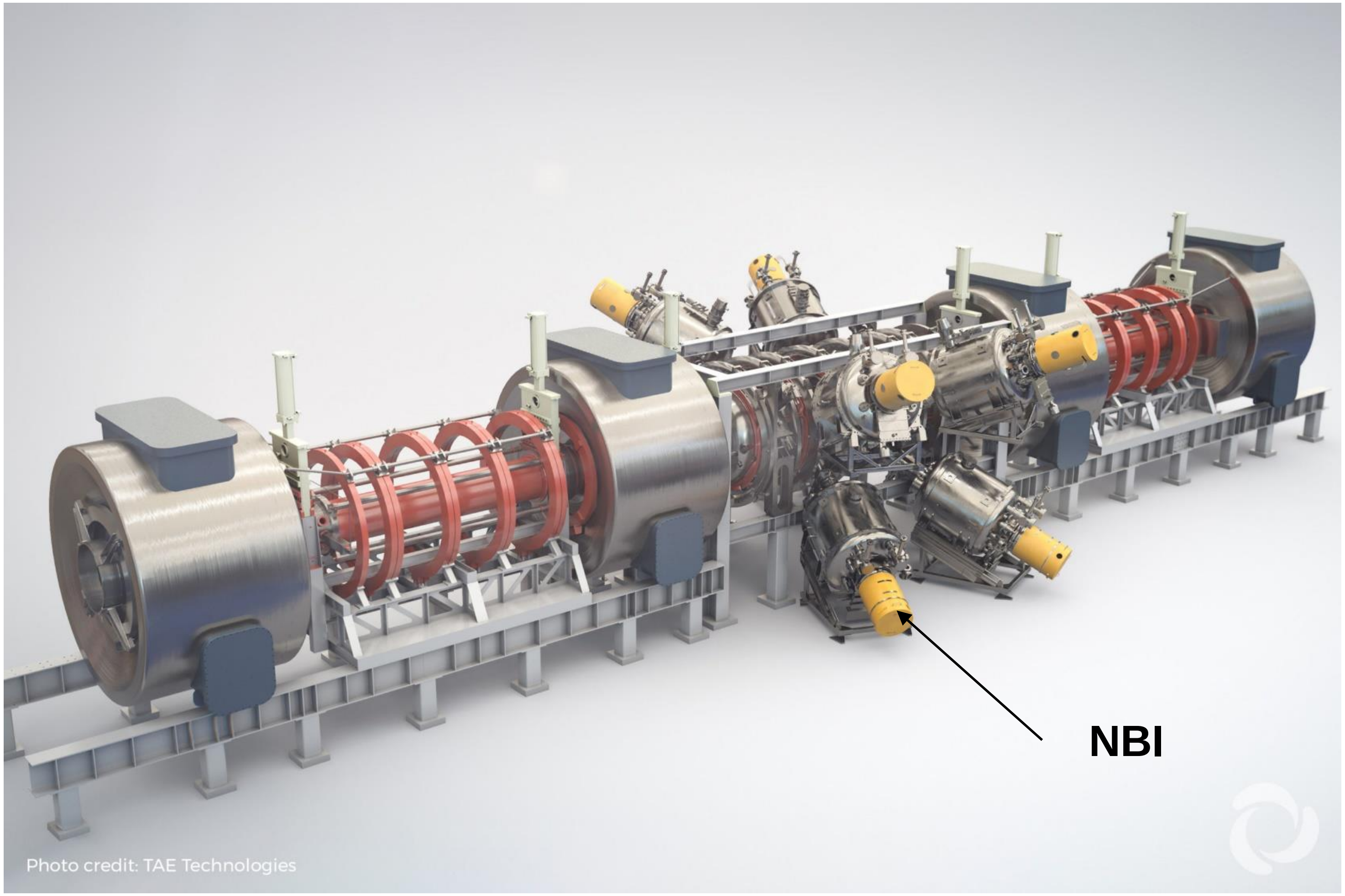
Field reverse configuration is used in Tri-alpha energy





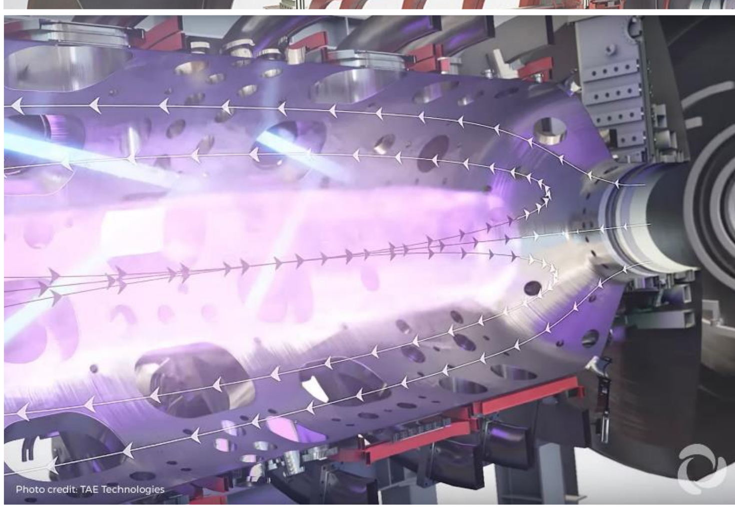
http://trialphaenergy.com/
Zhe Gao, Matter Radiat. Extremes **1**, 153 (2016)

NBI for Tri-Alpha Energy Technologies



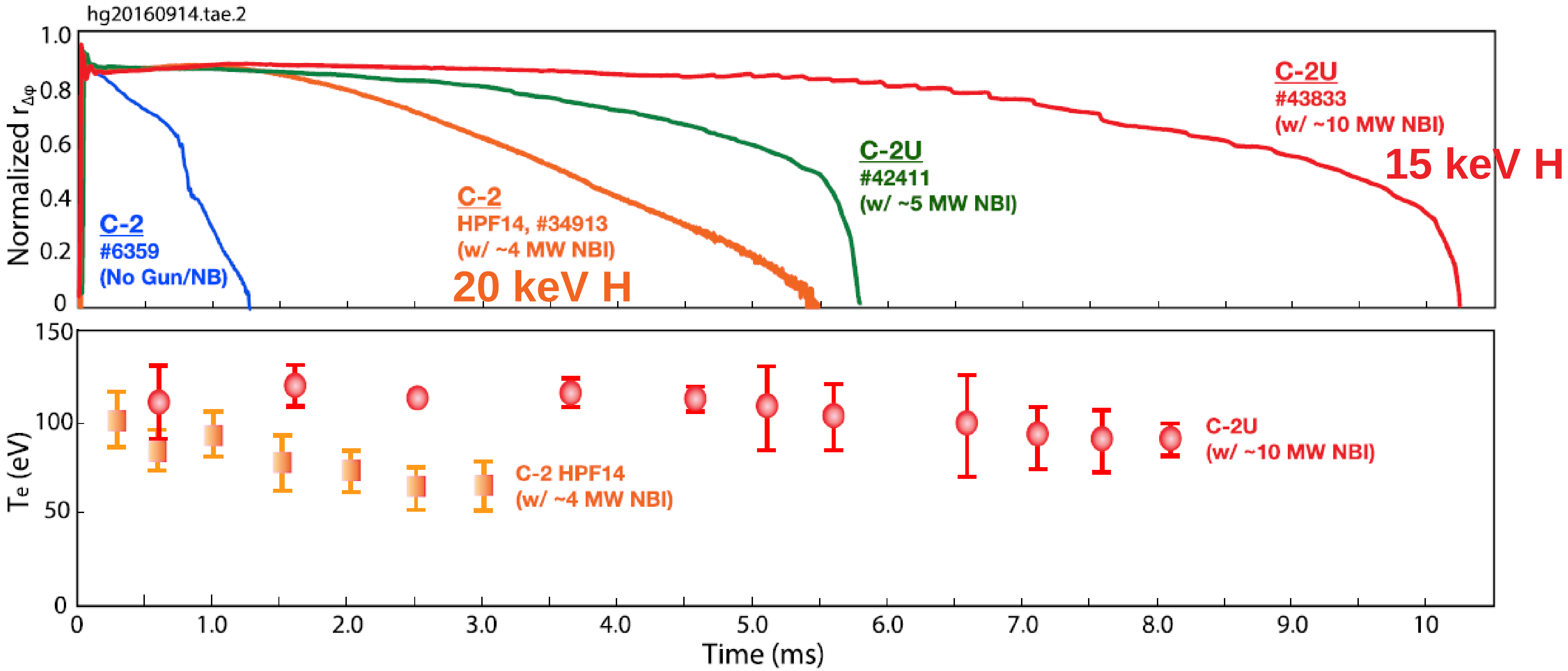
https://tae.com/media/

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



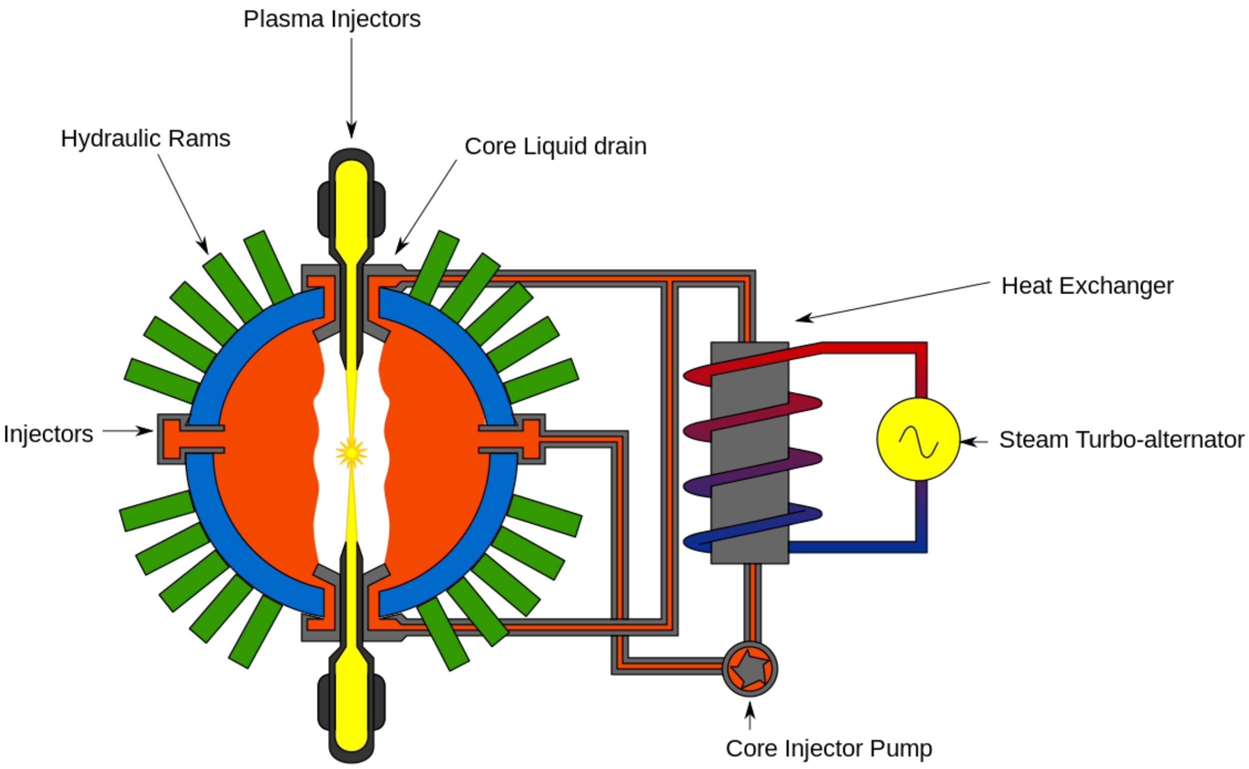
https://tae.com/media/
https://zh.wikihow.com/%E5%9C%A8%E6%89%8B%E6%8C%87%E4%B8%8A%E8%BD%AC%E7%AF%AE%E7%90%83

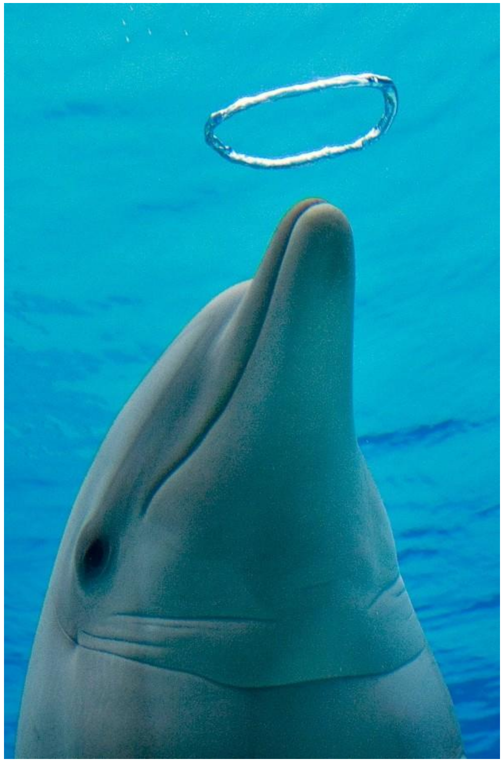
FRC sustain longer with neutral beam injection



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

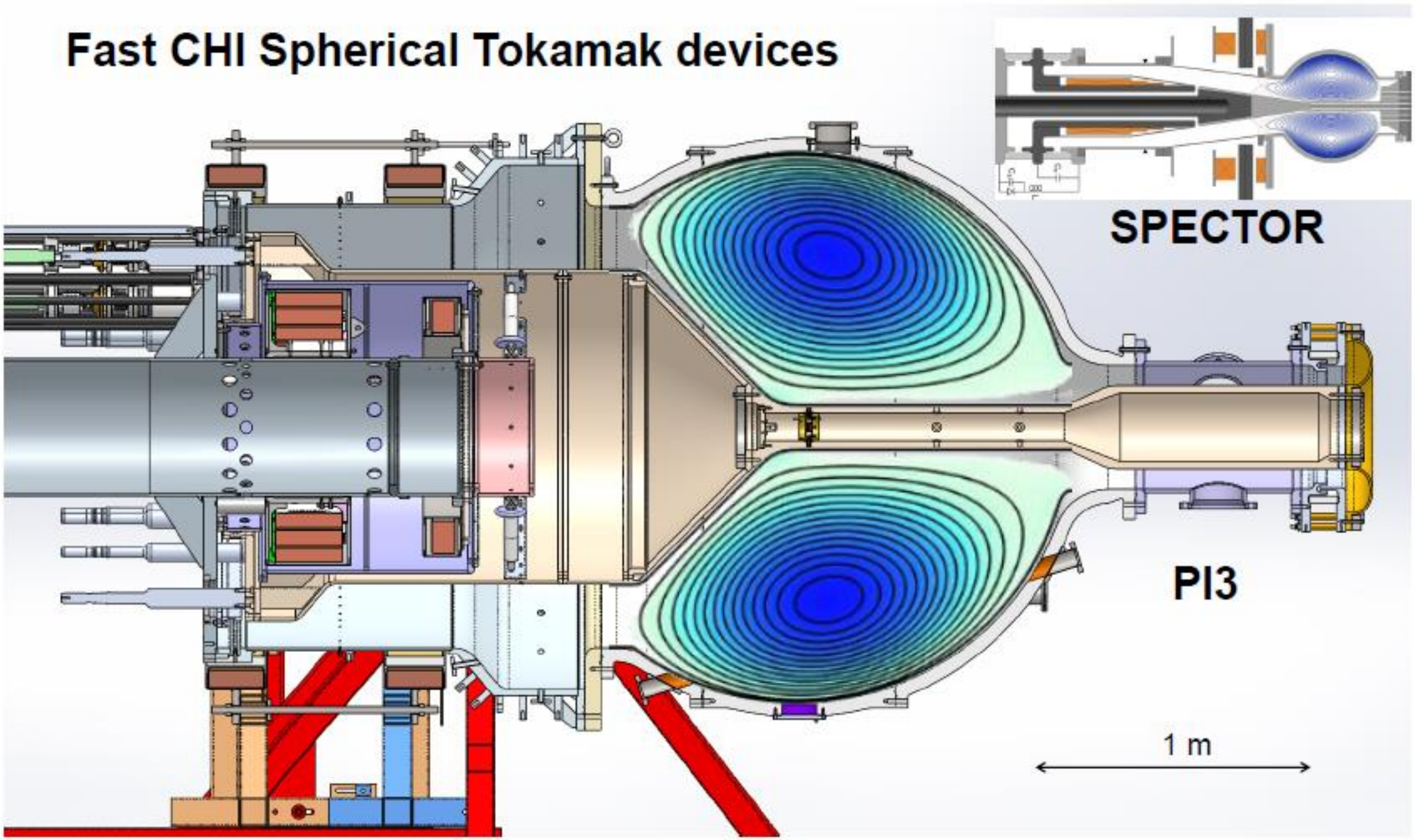
General fusion is a design ready to be migrated to a power plant





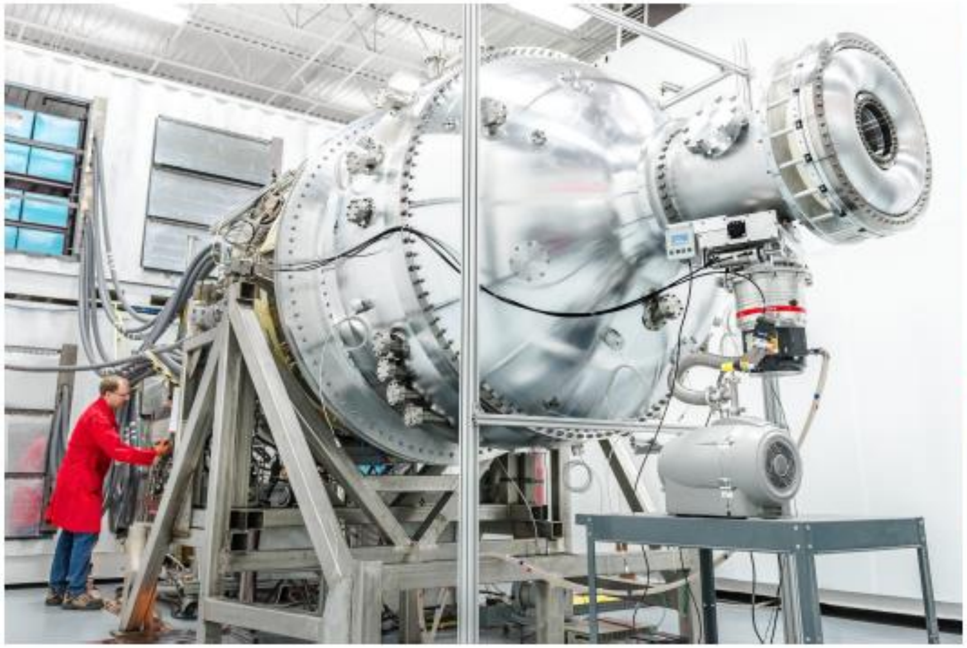
https://en.wikipedia.org/wiki/General_Fusion

A spherical tokamak is first generated



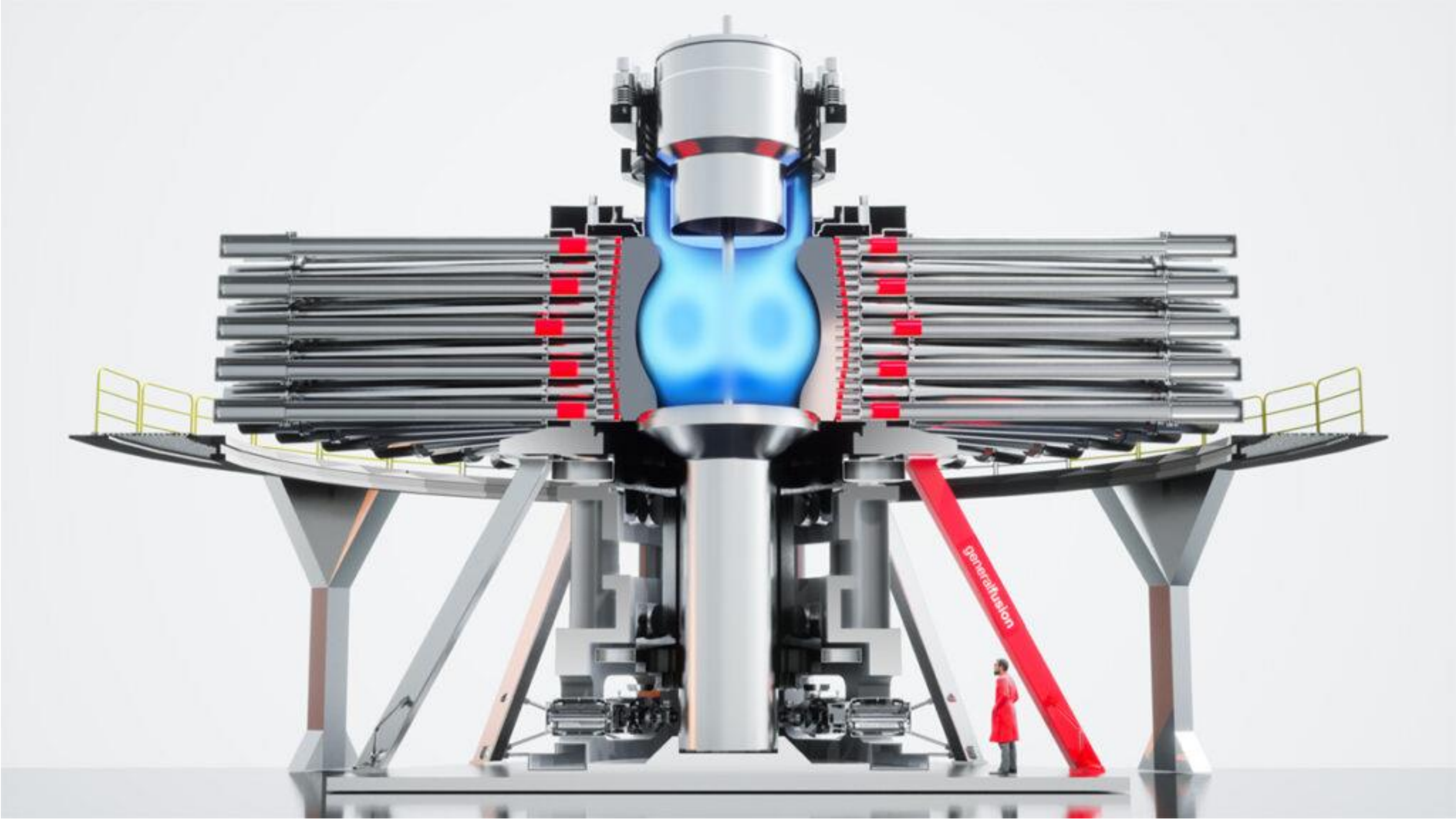
K. EPP, etc., 60th APS-DPP, CP11.00192

Plasma injector for the spherical tokamak

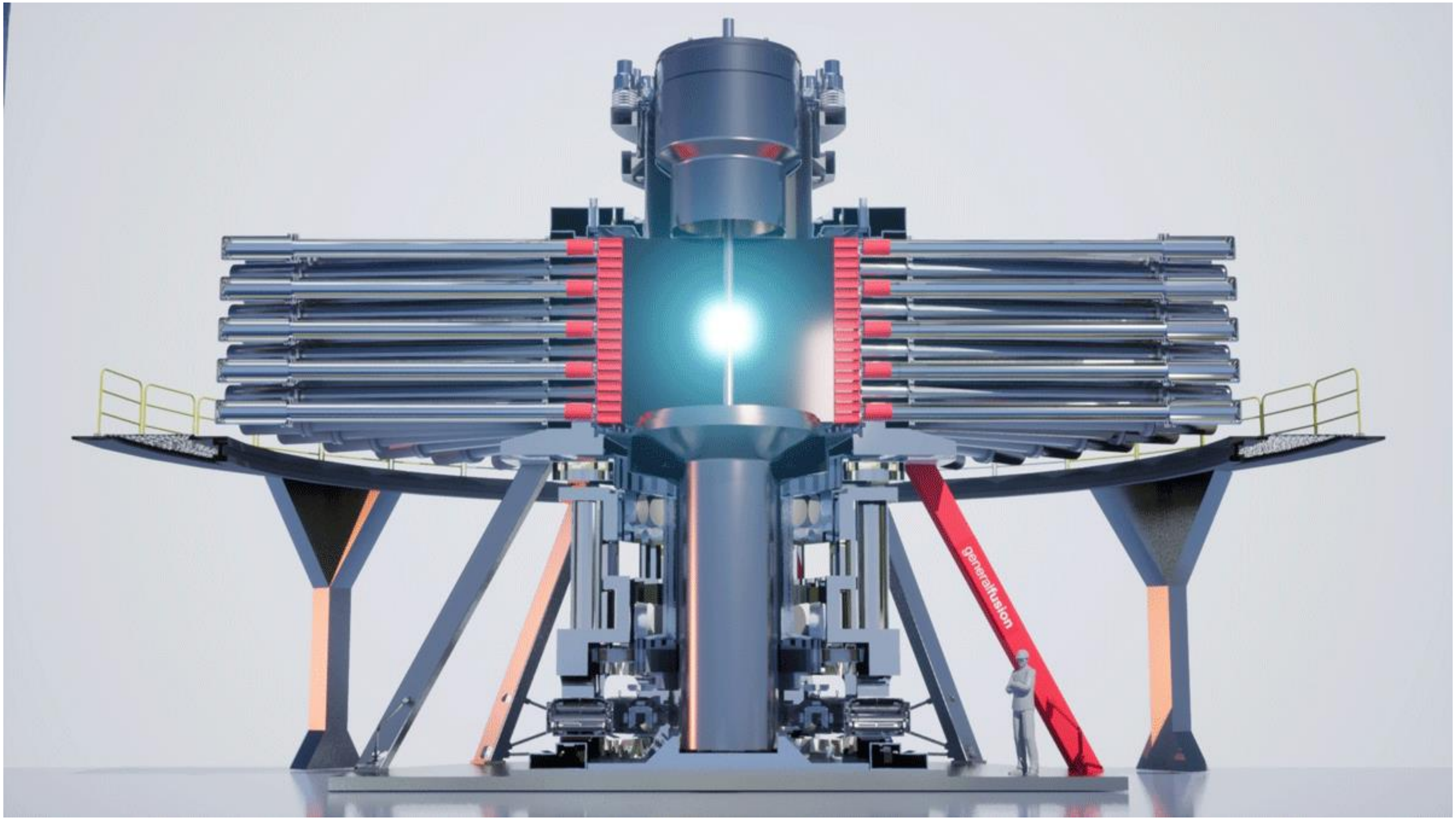


K. EPP, etc., 60th APS-DPP, CP11.00192

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

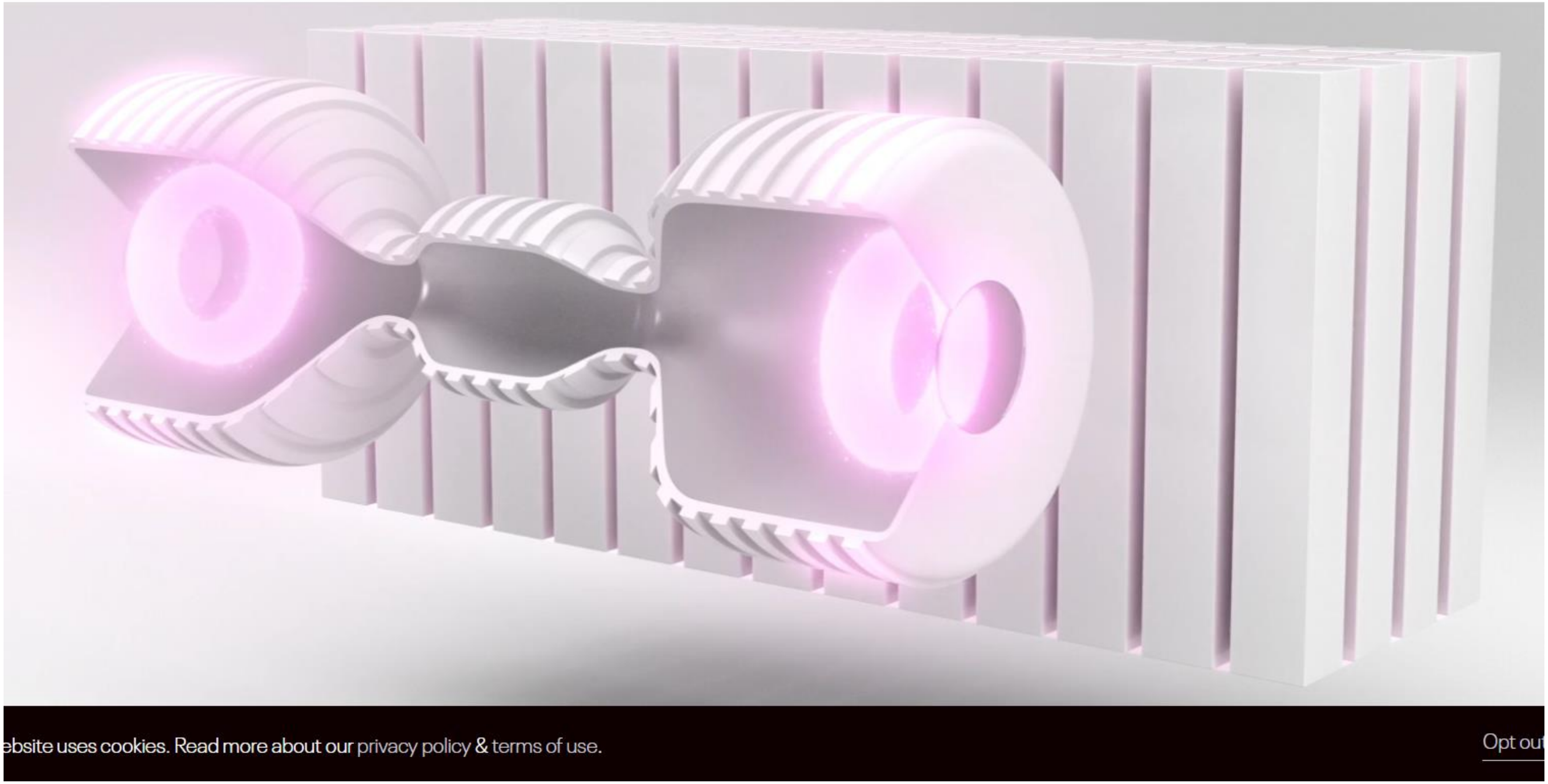
An artist's impression of what the new demonstration plant might look like

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

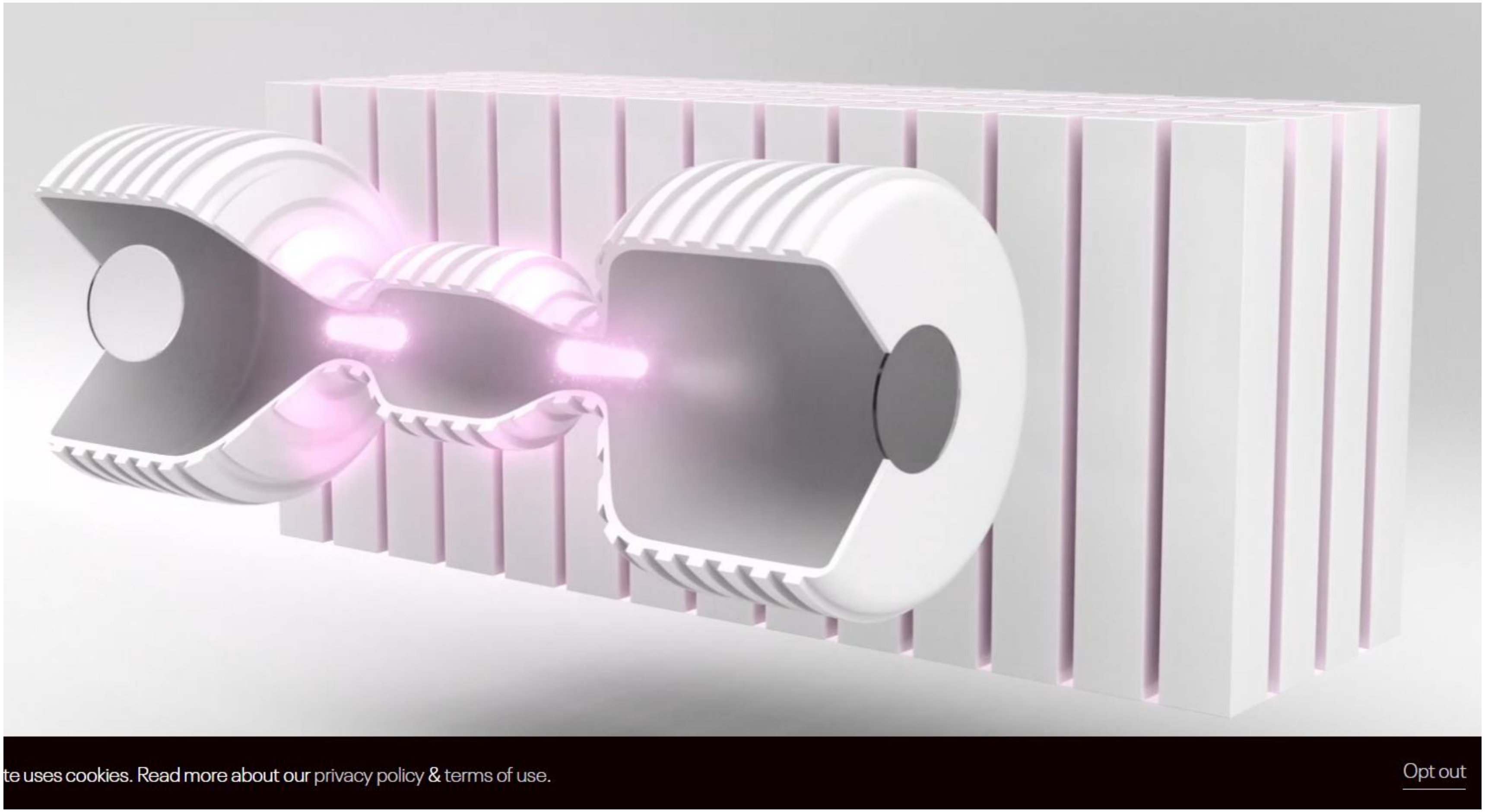
https://www.bbc.com/news/science-environment-57512229

Helion energy is compressing the two merging FRCs



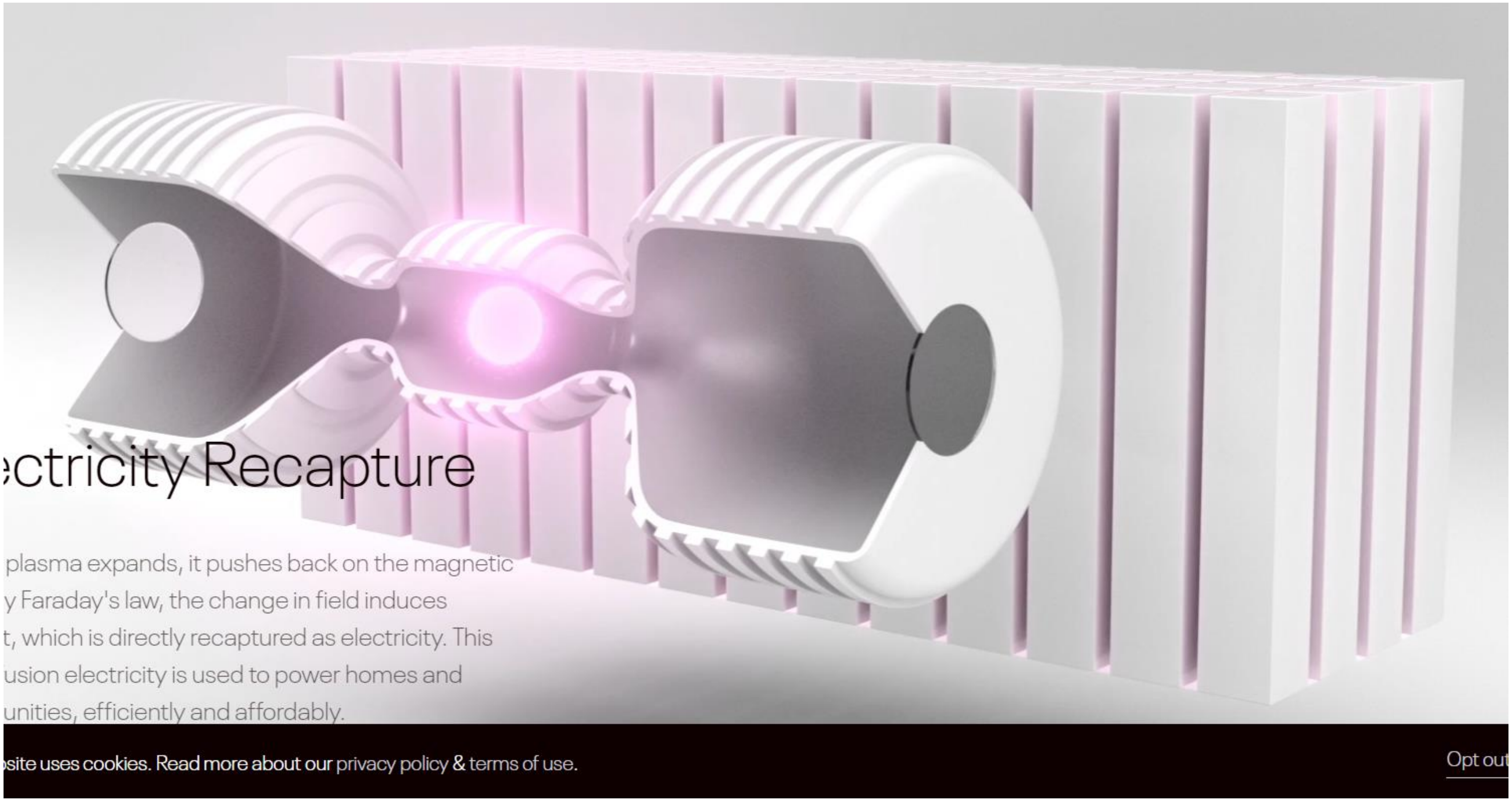
https://www.helionenergy.com/

Two FRCs are accelerated toward each other



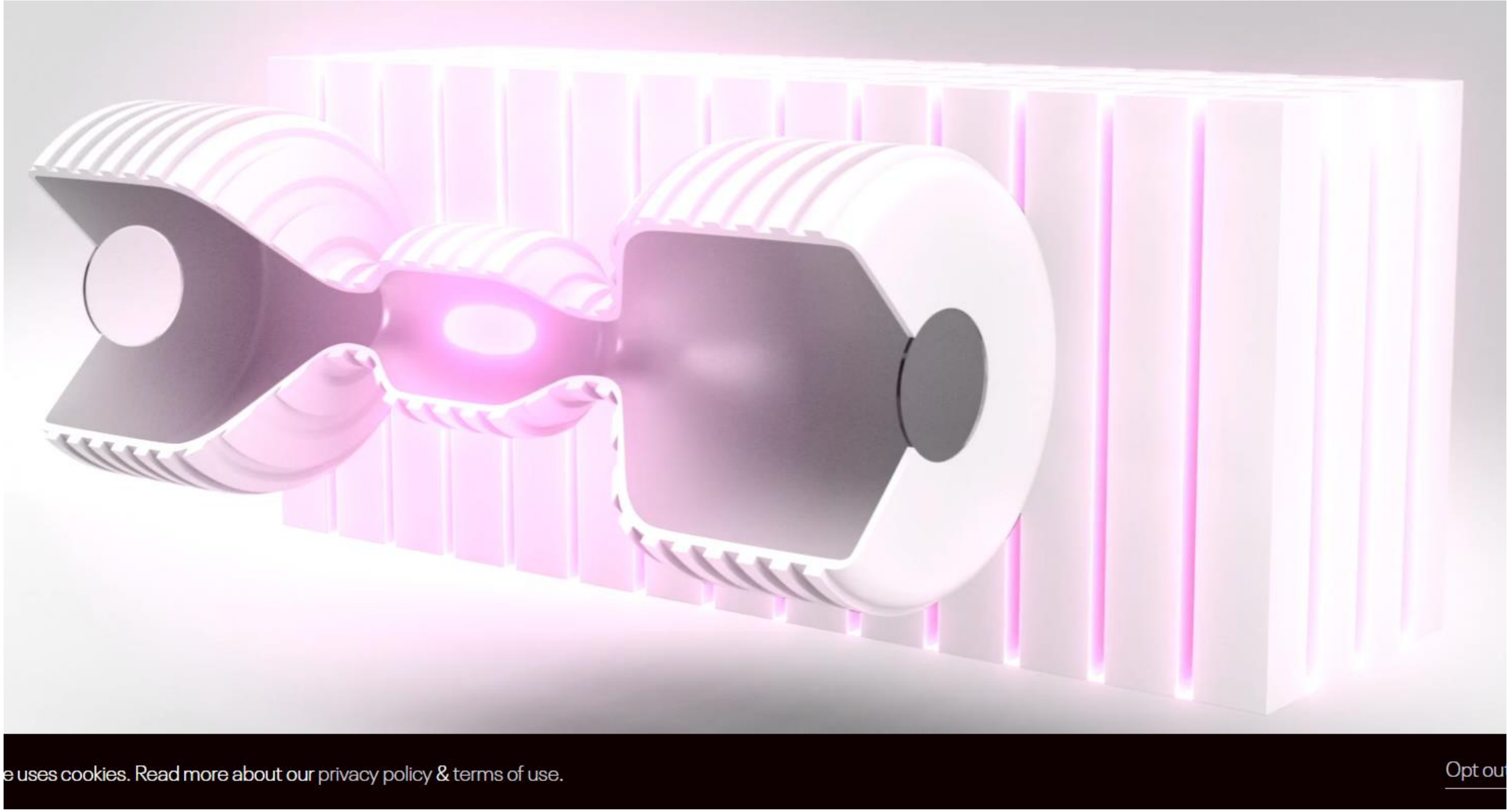
https://www.helionenergy.com/

Two FRCs merge with each other



https://www.helionenergy.com/

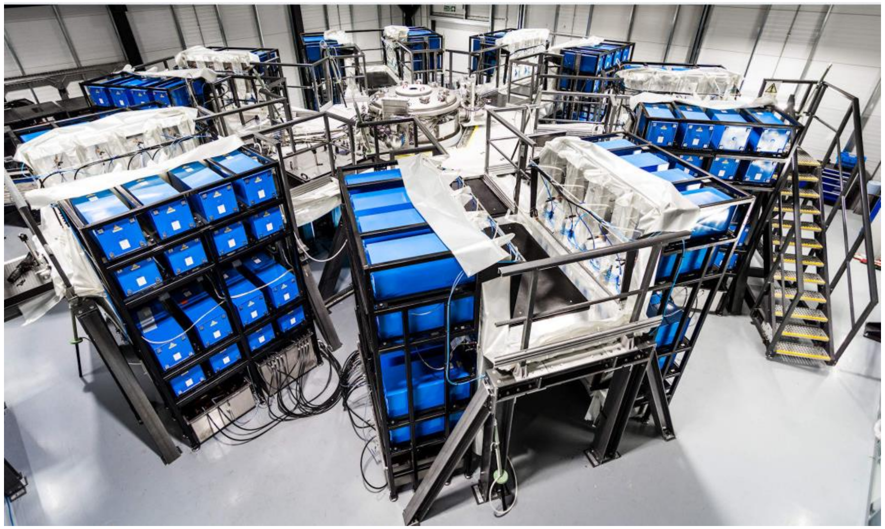
The merged FRC is compressed electrically to high temperature



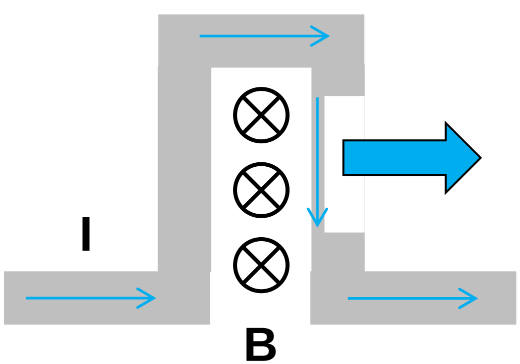
- **Similar concept will be studied in our laboratory.**

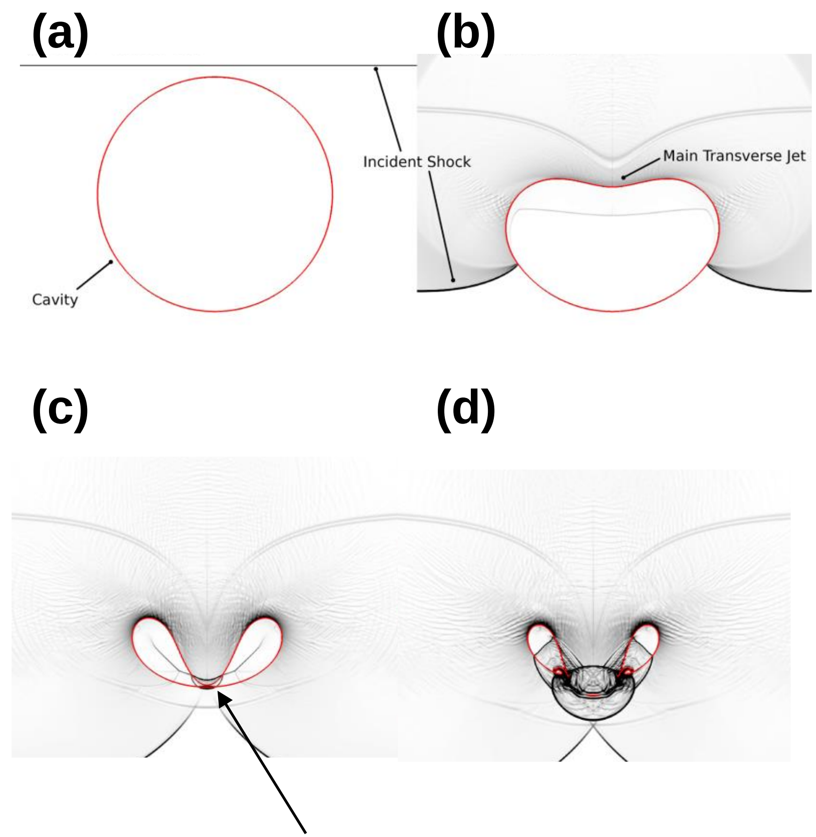
https://www.helionenergy.com/

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/

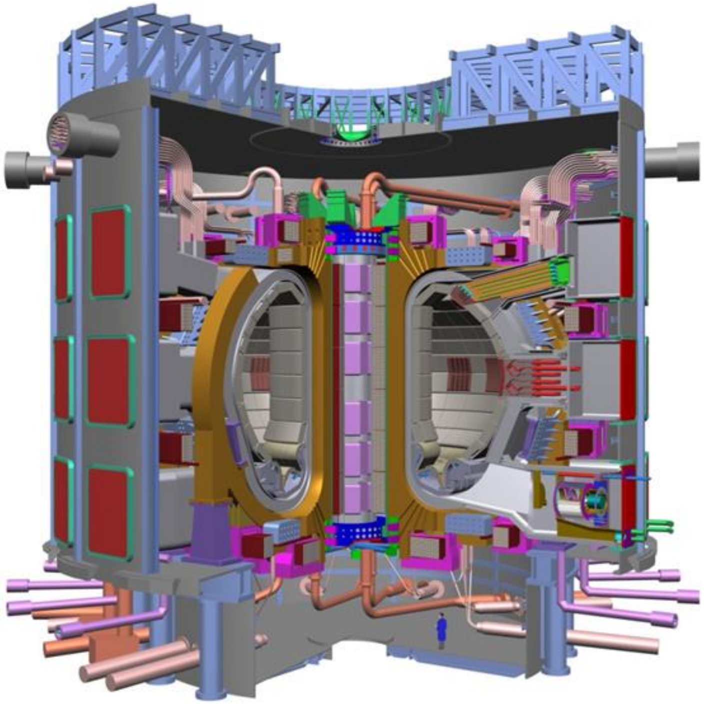
B. Tully and N. Hawker, Phys. Rev. **E93**, 053105 (2016)

A gas gun is used to eject the projectile

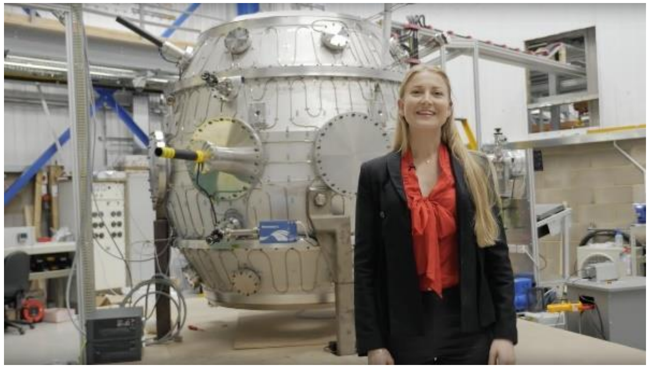
https://www.youtube.com/watch?v=JN7lyxC11n0
https://www.youtube.com/watch?v=aW4eufacf-8

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

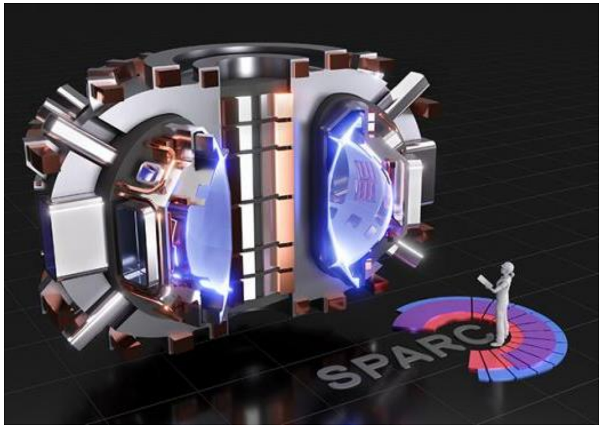
- **ITER – 2025 First Plasma**
  2035 D-T Exps
  2050 DEMO



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



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



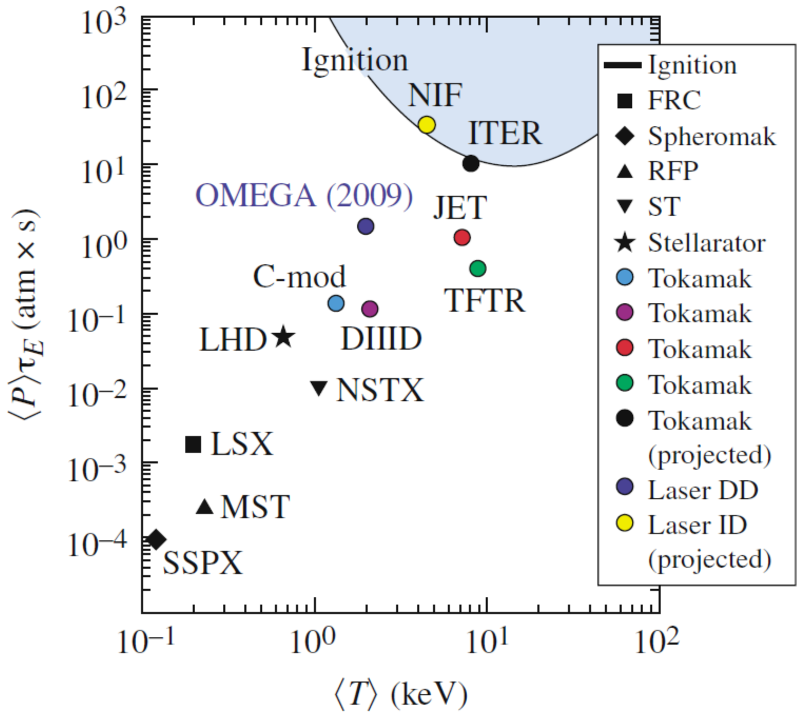
https://www.iter.org
https://www.tokamakenergy.co.uk/
https://www.psfc.mit.edu/sparc

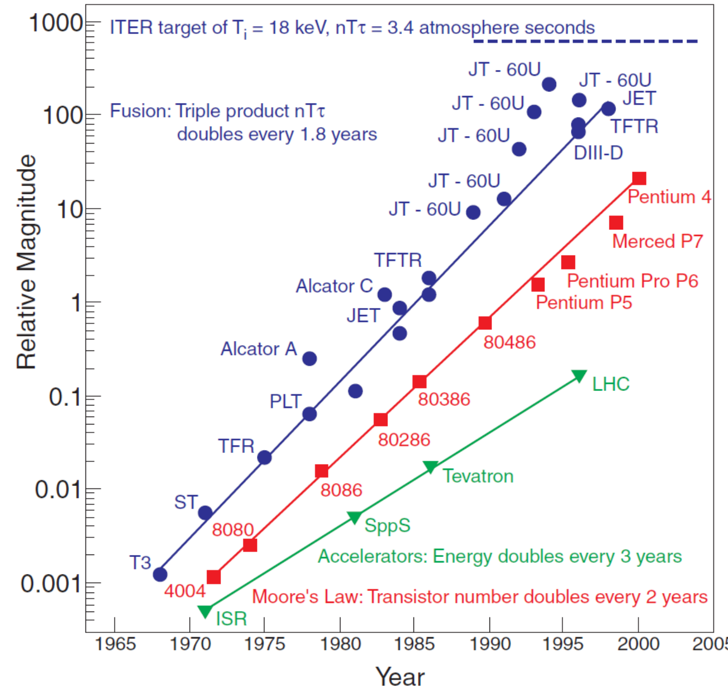
Fusion is blooming

⋮

https://www.fusionindustryassociation.org/members

We are closed to ignition!





- **Other private companies:**

generalfusion

first light

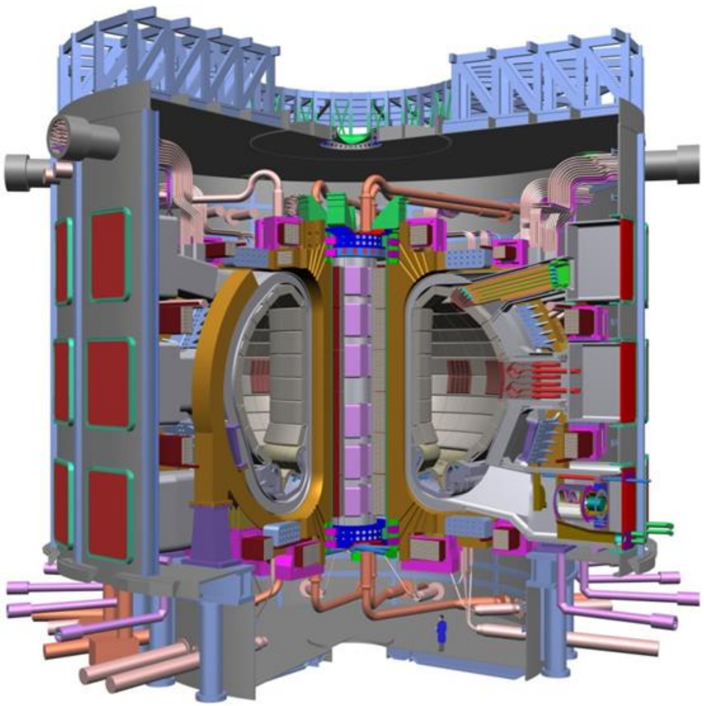
…

Tokamak **MTF** **ICF**

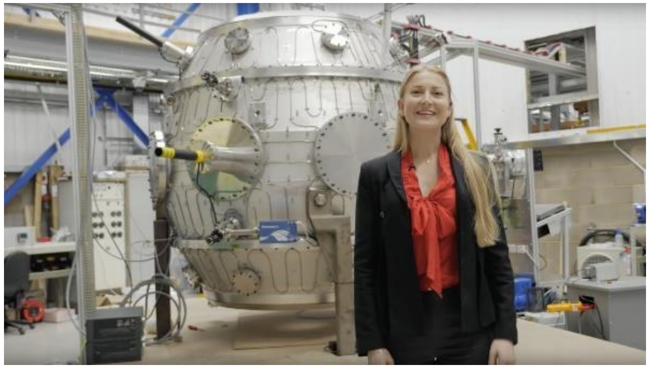
A. J. Webster, Phys. Educ. **38**, 135 (2003)
R. Betti, etc., Phys. Plasmas, **17**, 058102 (2010)

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

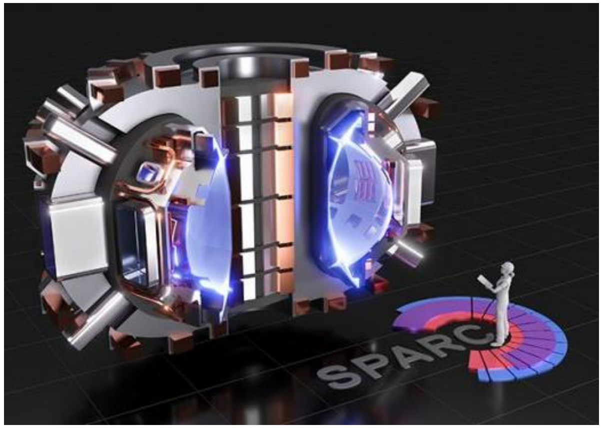
- **ITER – 2025 First Plasma**
  2035 D-T Exps
  2050 DEMO



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

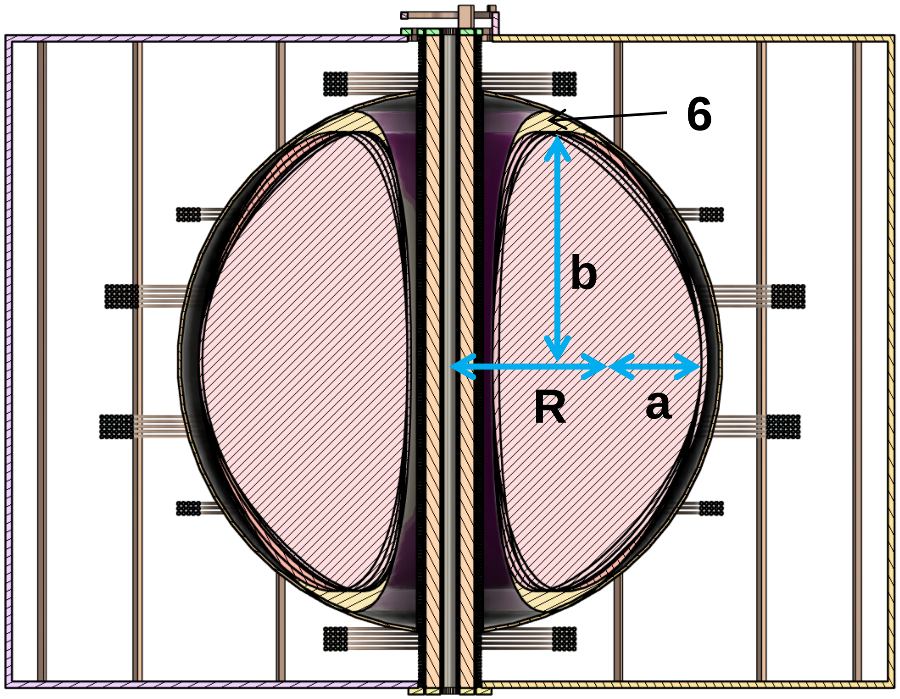


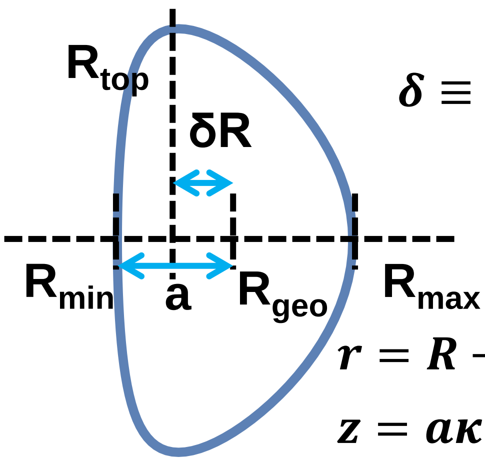
- **Commonwealth Fusion Systems, USA – 2025 Gain**



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

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





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

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

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

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

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

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