氫硼核融合實作
Practical course on proton-boron nuclear fusion

Po-Yu Chang (pchang@mail.ncku.edu.tw)

Institute of Space and Plasma Sciences, National Cheng Kung University

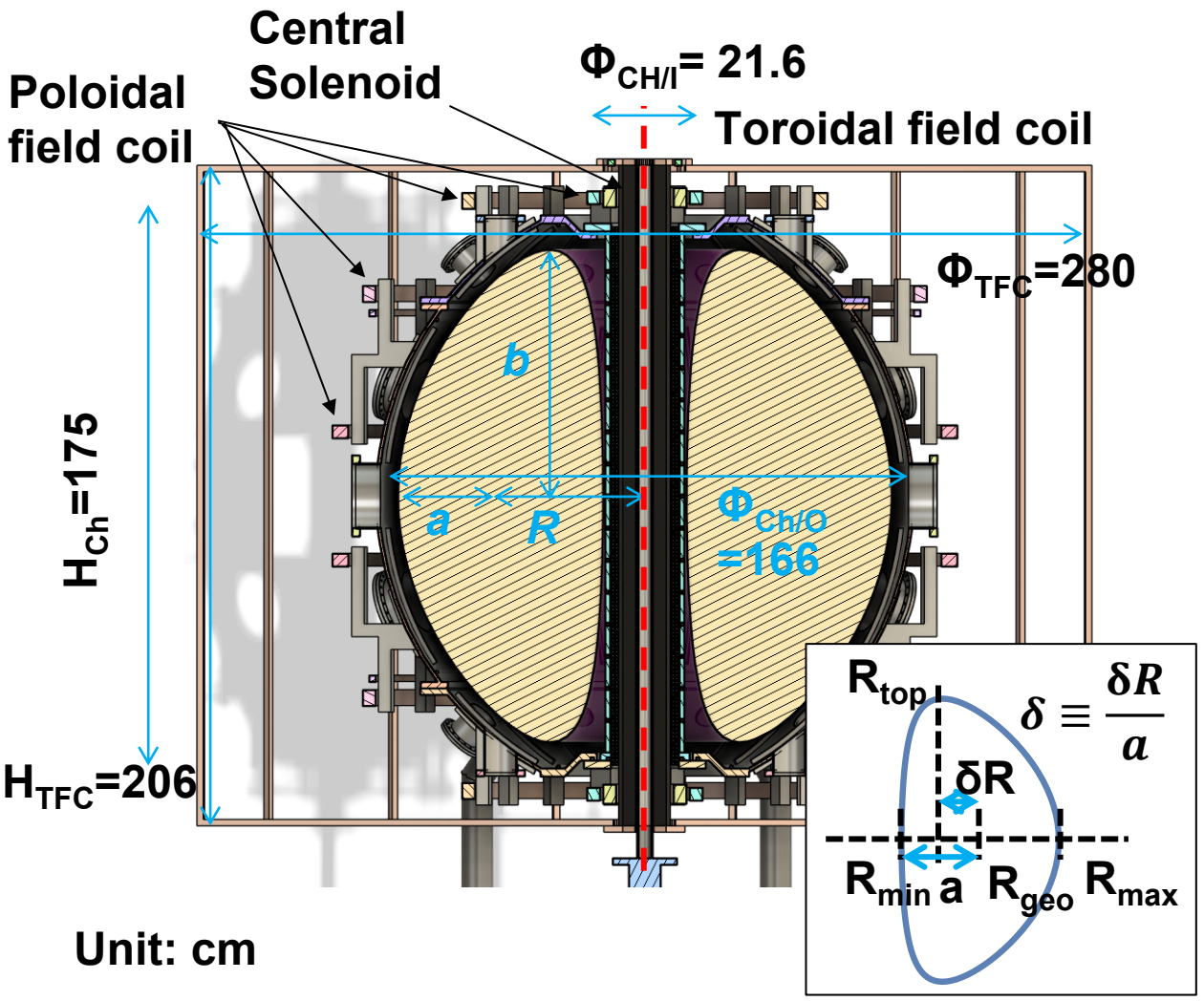
2025 summer break

7/14(Mon.) – 7/18(Fri.) 14:00-17:40

Lecture 5

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

Formosa Integrated Research Spherical Tokamak (FIRST) aiming for the first plasma in 2026



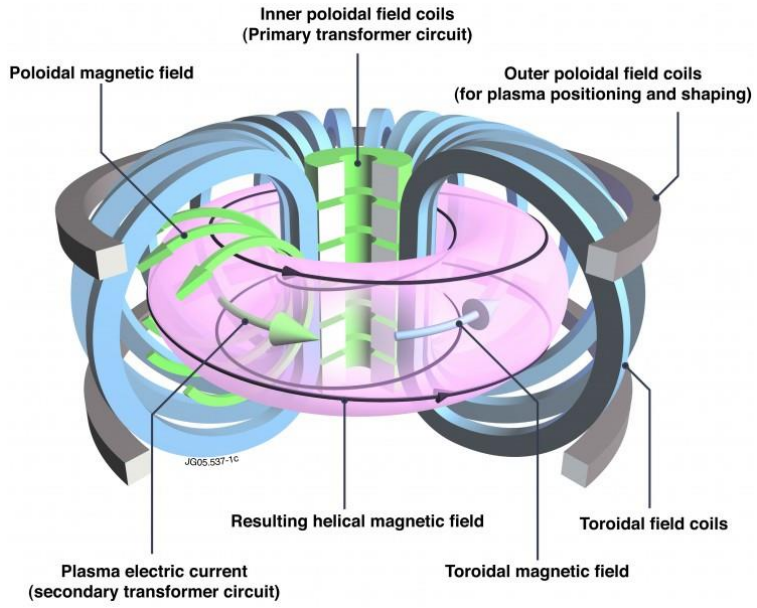
Unit: cm

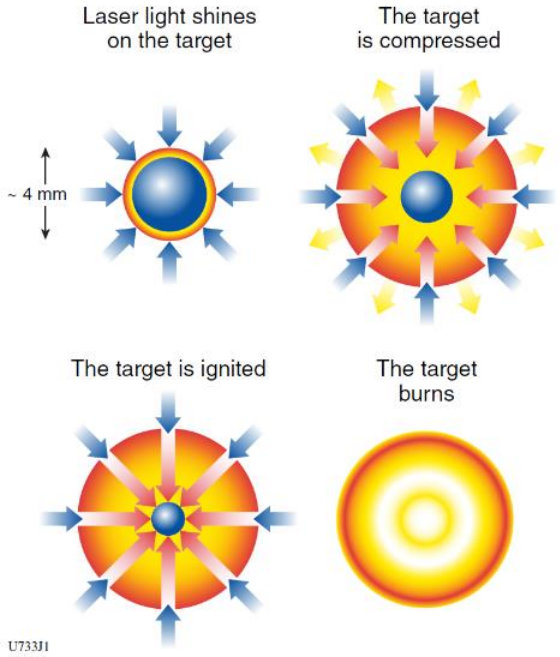
- *R*/*a*/*b*=45/32/76.8 cm
- Aspect ratio = *R*/*a* = 1.5
- *k* = *b*/*a* = 2.4
- δ = 0.5
- B_T = 0.1 ~ 0.5 T
- $T \geq 100$ eV
- $I_p \geq 100$ kA
- Gas: H_2
- Ohmic heating
- Duration: 100 ms
- FIRST is targeted for
  - Low aspect ratio
  - High beta
  - High bootstrap current

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

Nuclear fusion as an energy source is being developed

- **Magnetic confinement fusion (MCF)**
- **Inertial confinement fusion (ICF)**

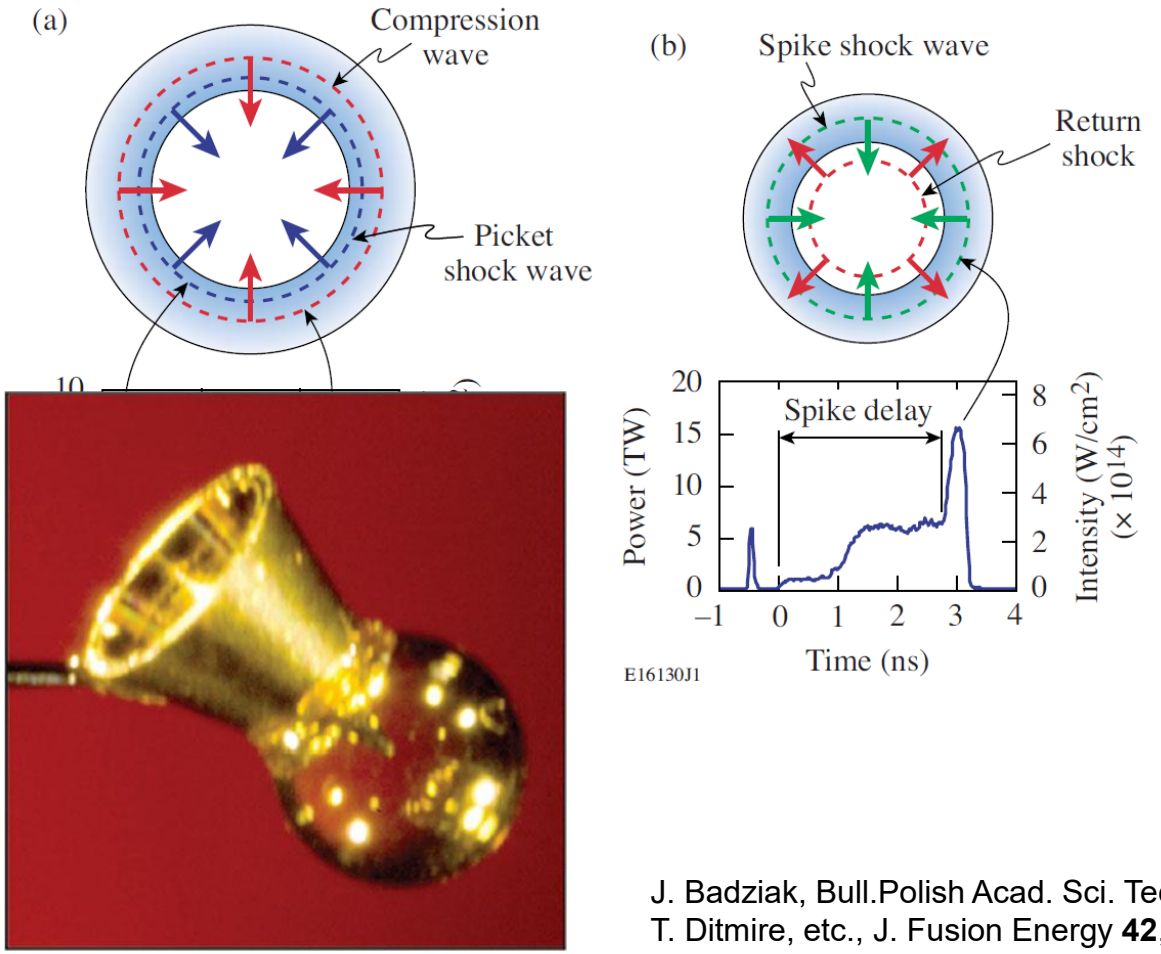




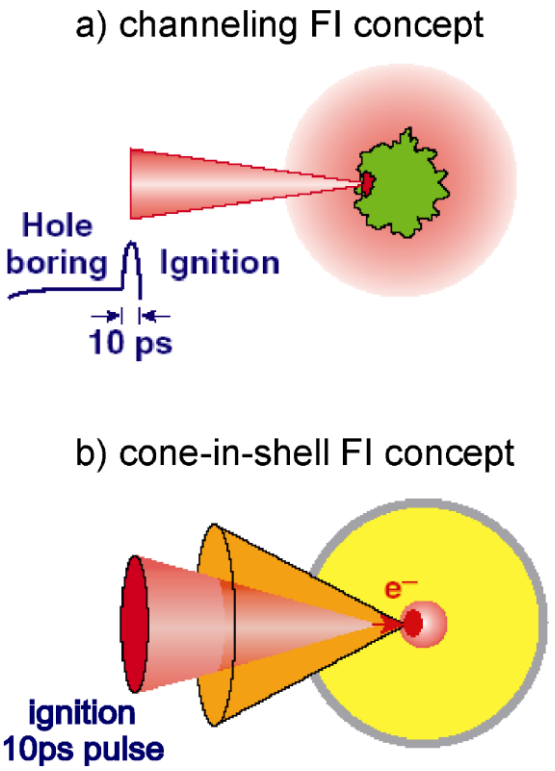
https://www.euro-fusion.org/2011/09/tokamak-principle-2/
Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

External “spark” can be used for ignition

- **Shock ignition**



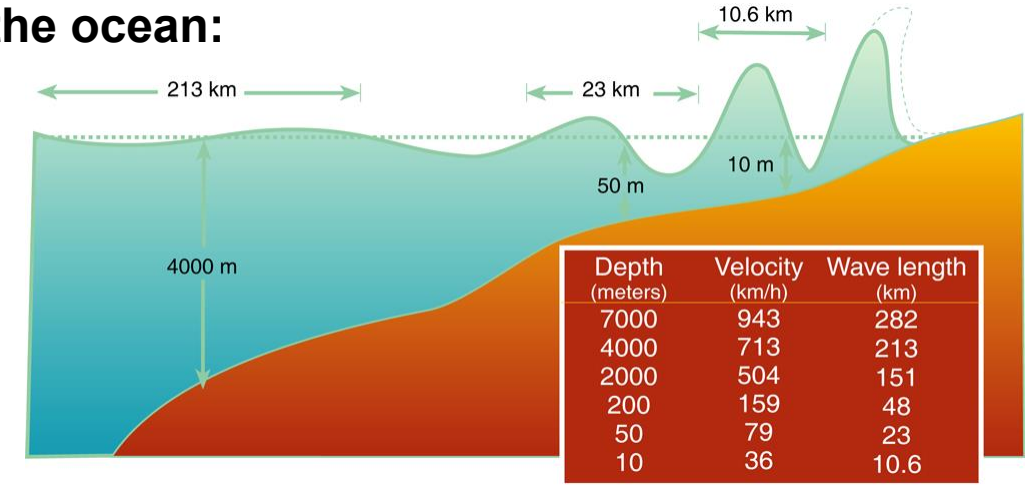
- **Fast ignition**



J. Badziak, Bull.Polish Acad. Sci. Tech. Sci.Phys. Plasmas 15, 056306 (2008)
T. Ditmire, etc., J. Fusion Energy **42**, 27 (2023)

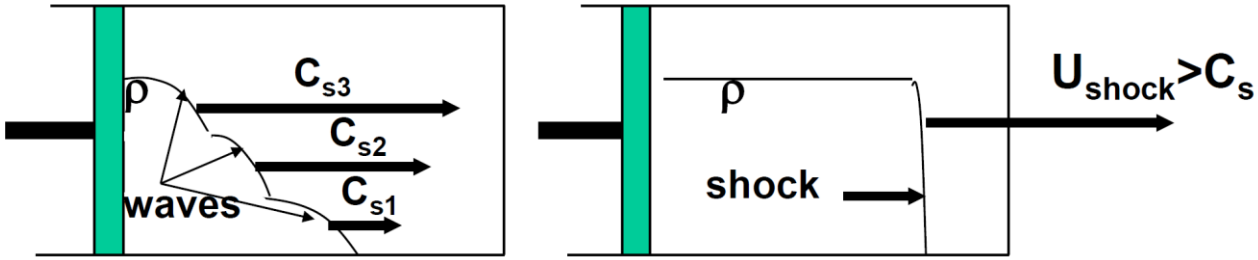
A shock is formed due to the increasing sound speed of a compressed gas/plasma

- **Wave in the ocean:**



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

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



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

http://neamtic.ioc-unesco.org/tsunami-info/the-cause-of-tsunamis

*R. Betti, HEDSA HEDP Summer School, 2015

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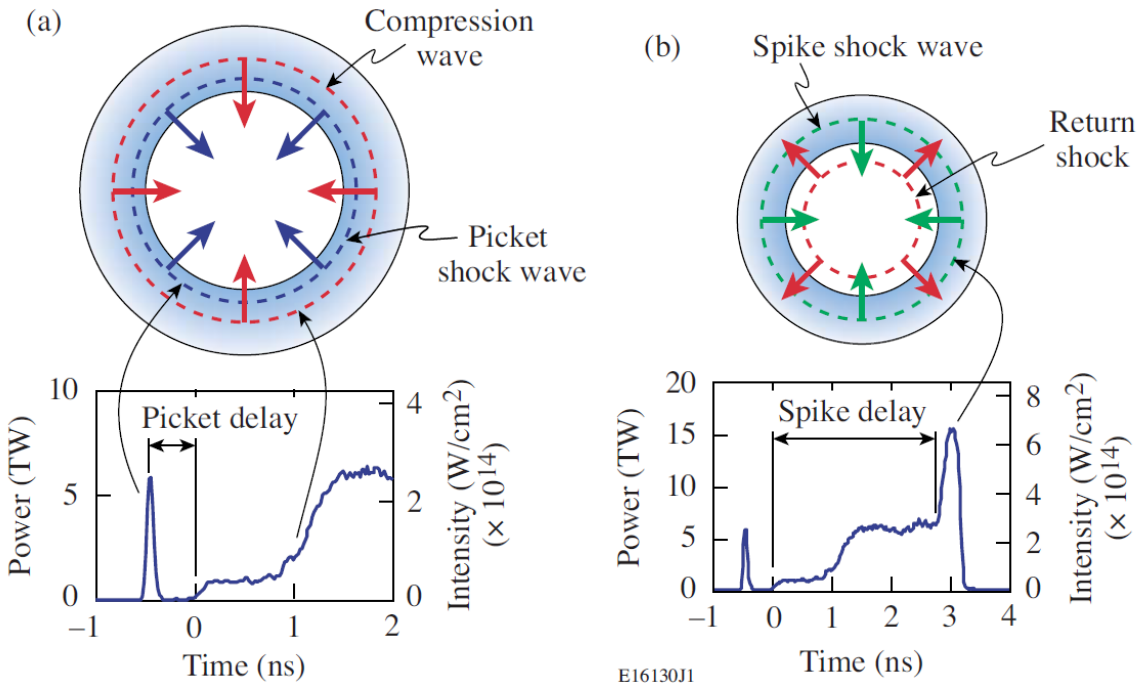
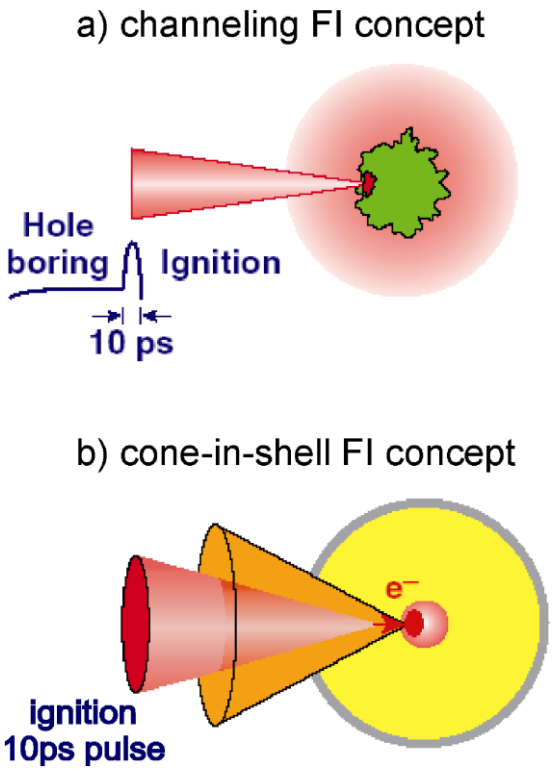
- **Shock ignition**

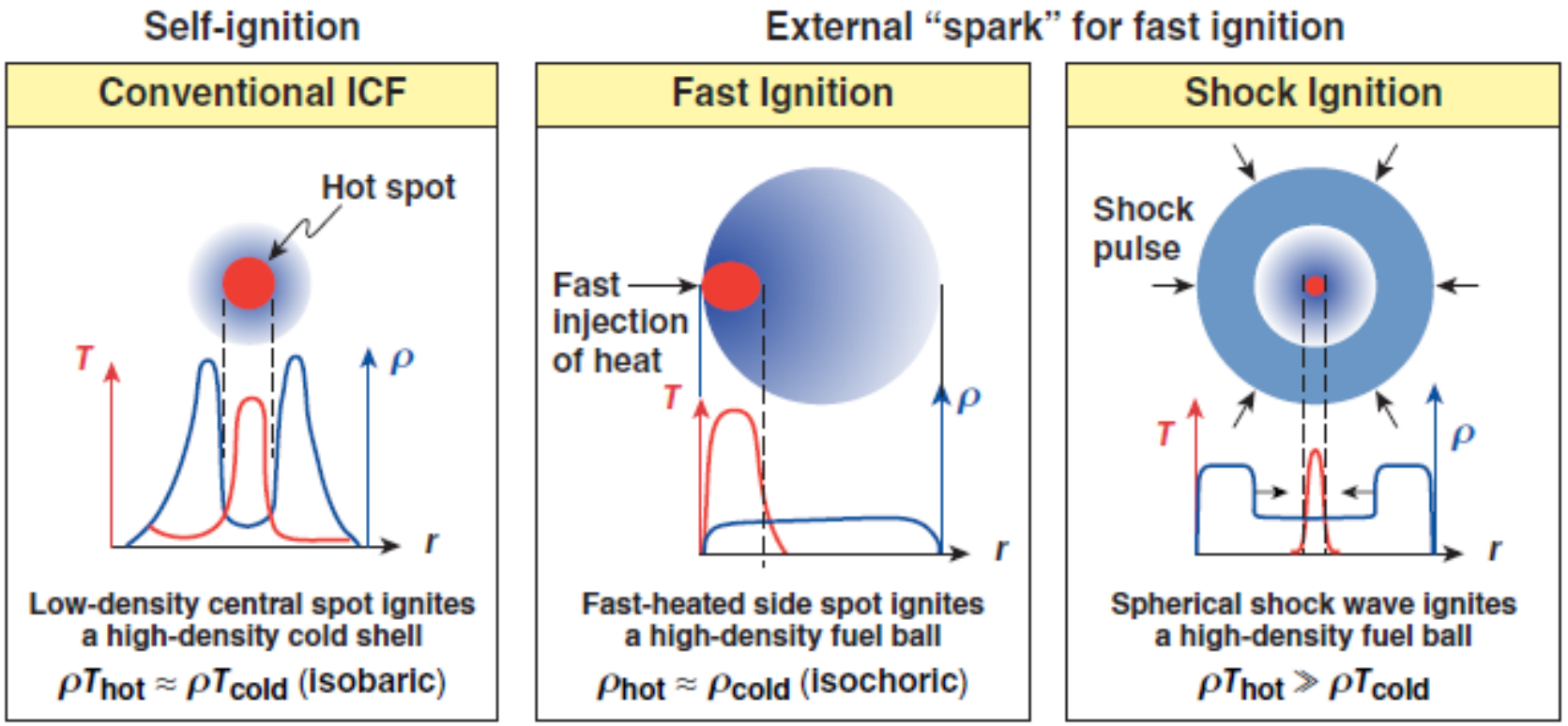


- **Fast ignition**



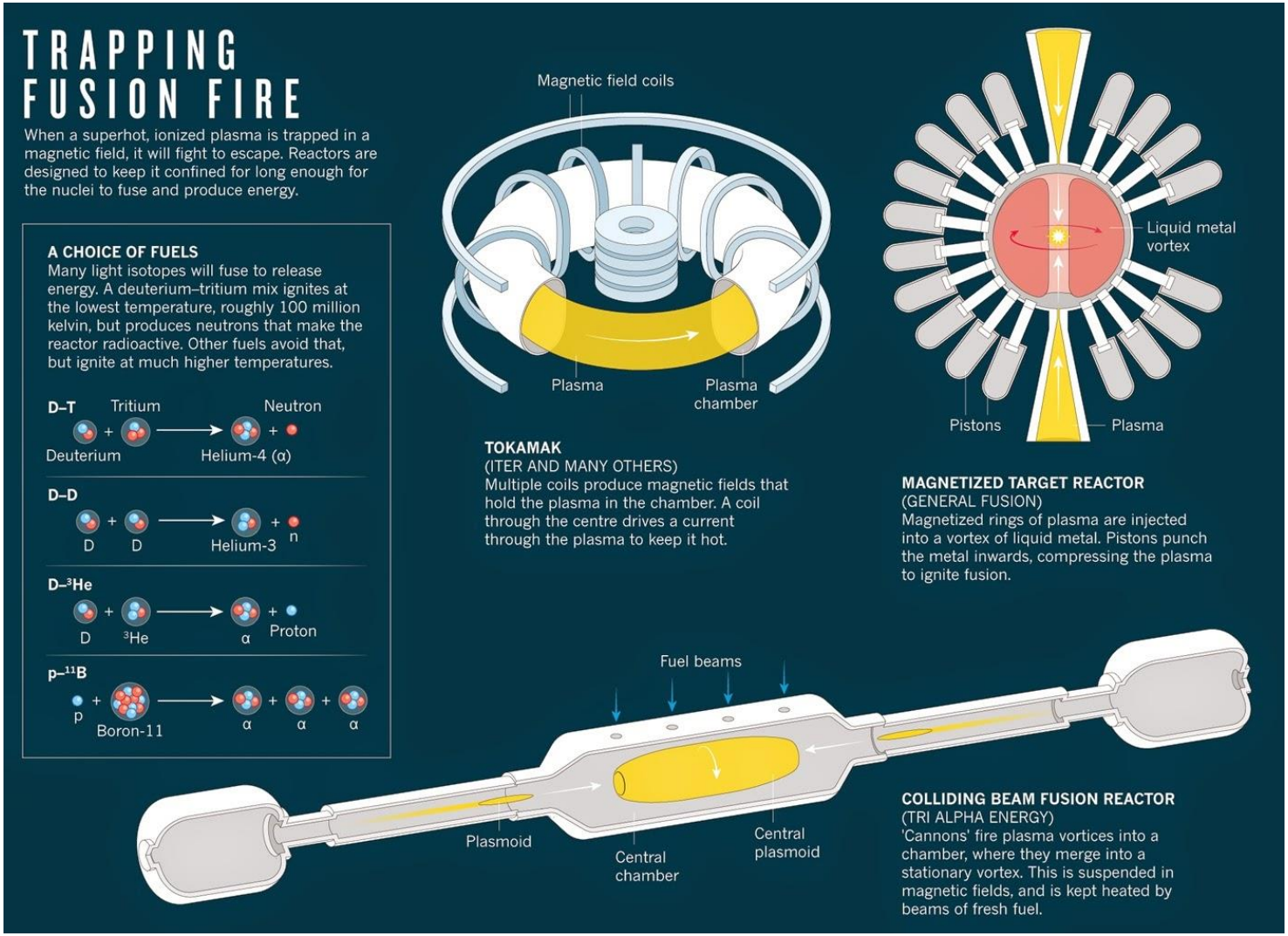
J. Badziak, Bull.Polish Acad. Sci. Tech. Sci.Phys. Plasmas 15, 056306 (2008)

Ignition can happen by itself or being triggered externally



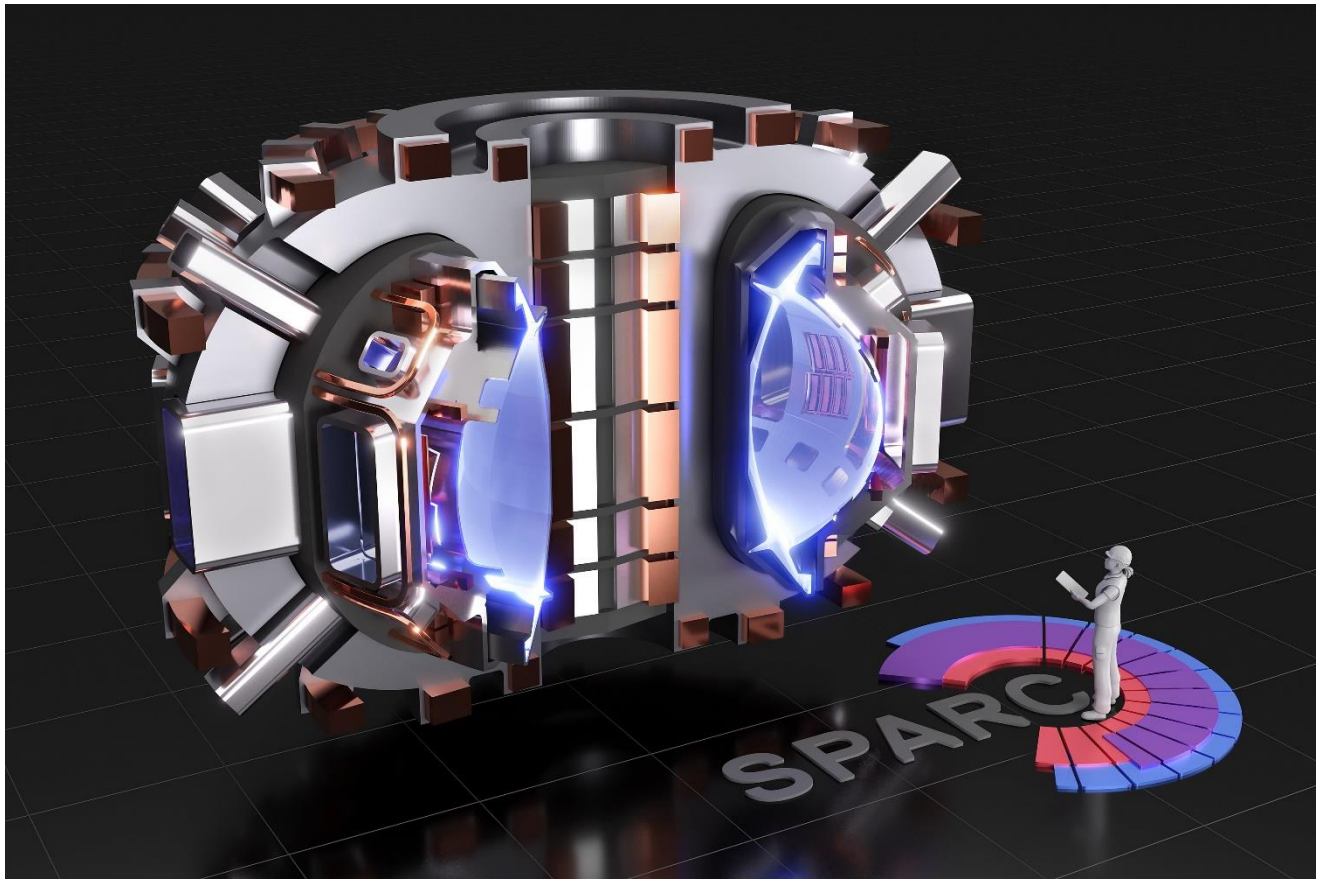
P. B. Radha, Fusion Energy Conference,2018

There are alternative



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

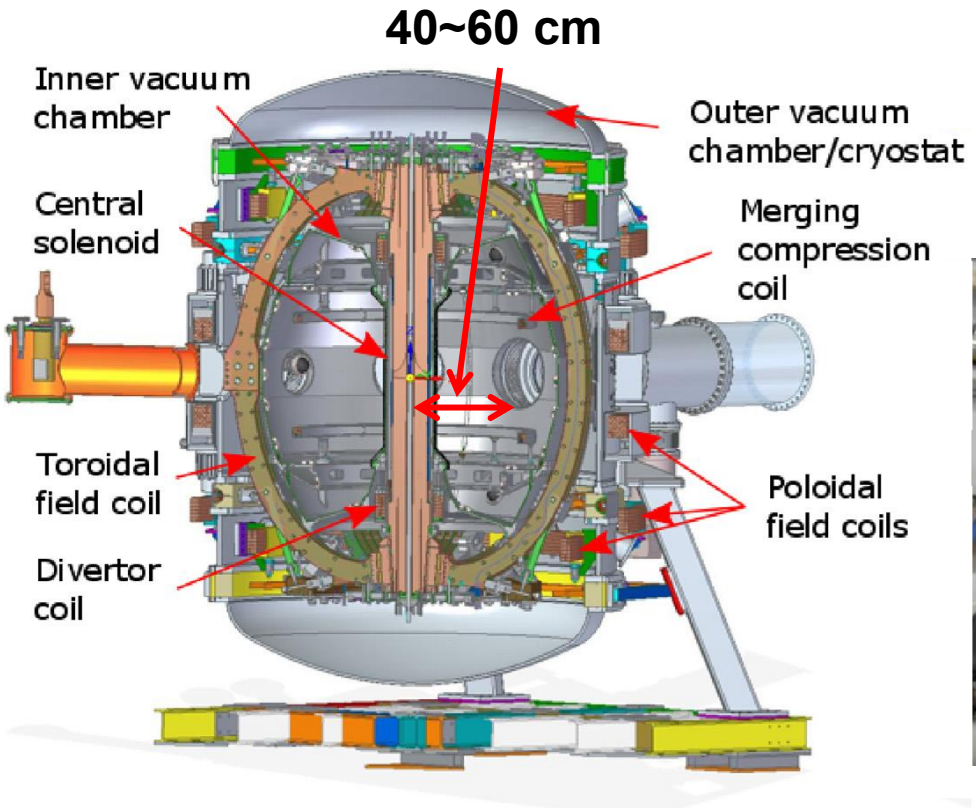
Commonwealth Fusion Systems, a MIT spin-out company, is building a high-magnetic field tokamak



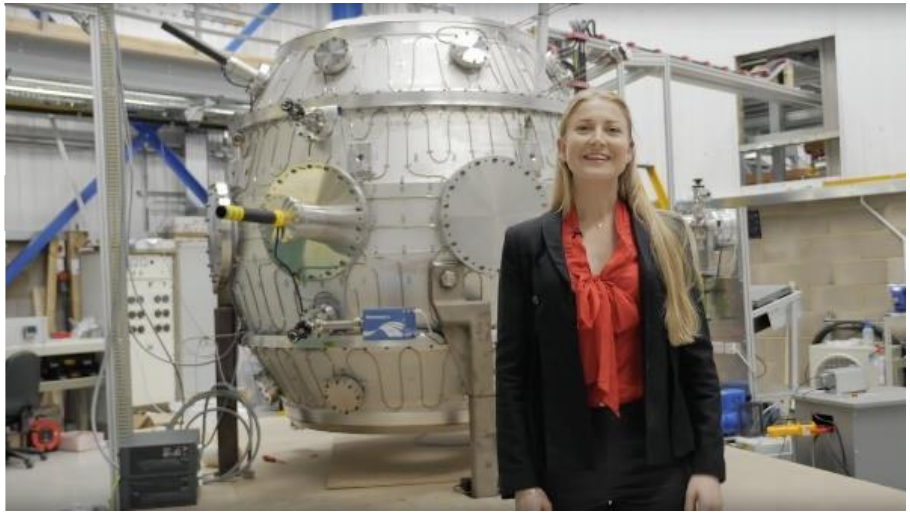
- **Fusion power $\propto B^4$.**
- **The fusion gain Q > 2 is expected for SPARC tokamak.**

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

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

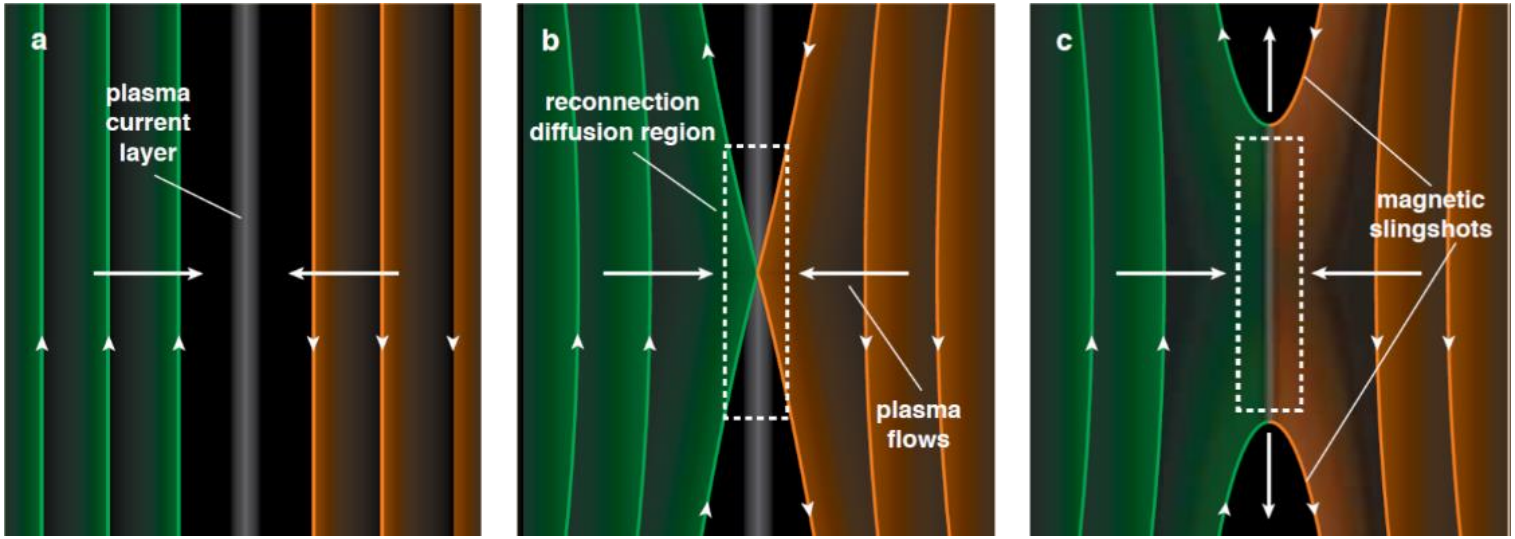


- **High temperature superconductors are used.**
- **B_T ~ 3 T**



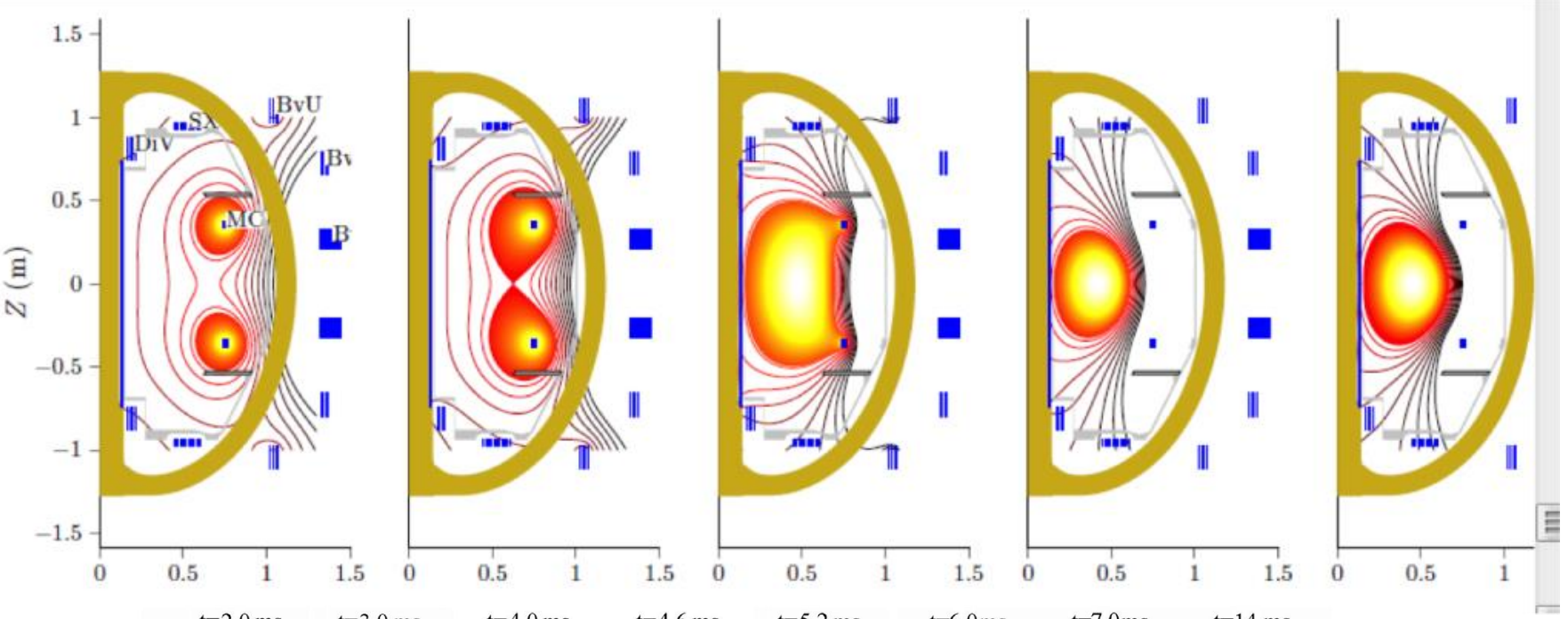
M. Gryaznevich, etc., Fusion Eng. Design, **123**,177 (2017)
https://www.tokamakenergy.co.uk/
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

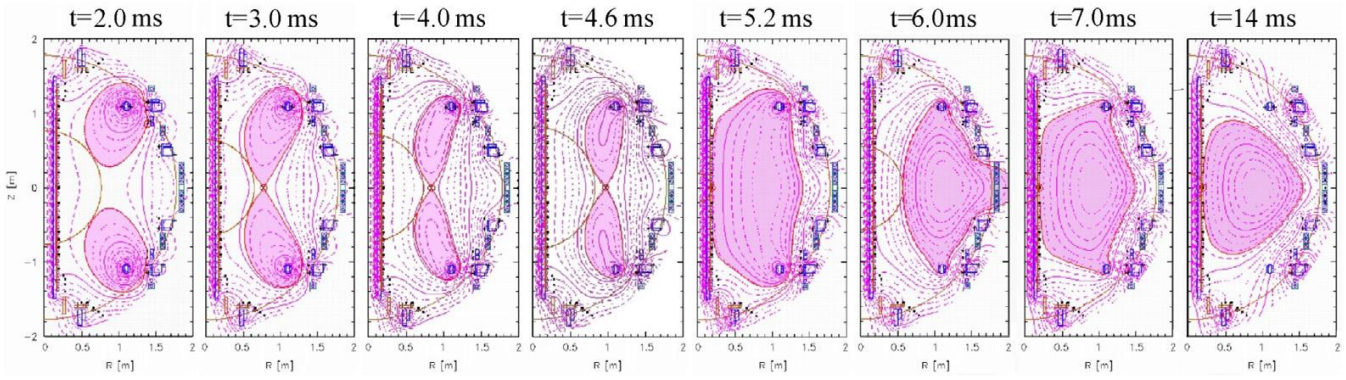
Reconnection



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

Merging compression is used to heat the plasma

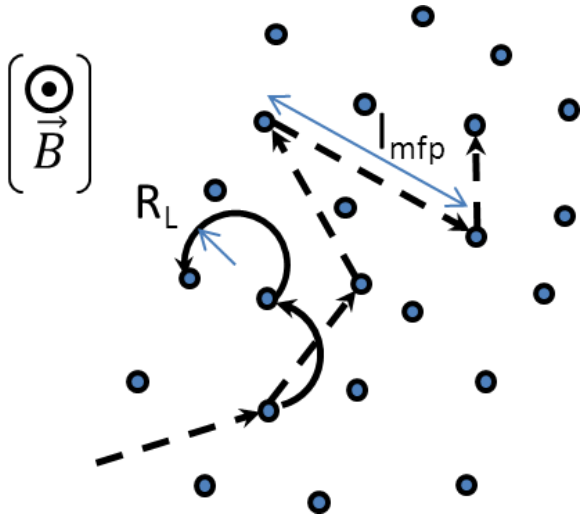




http://www.100milliondegrees.com/merging-compression/

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

A strong magnetic field reduces the heat flux



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

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

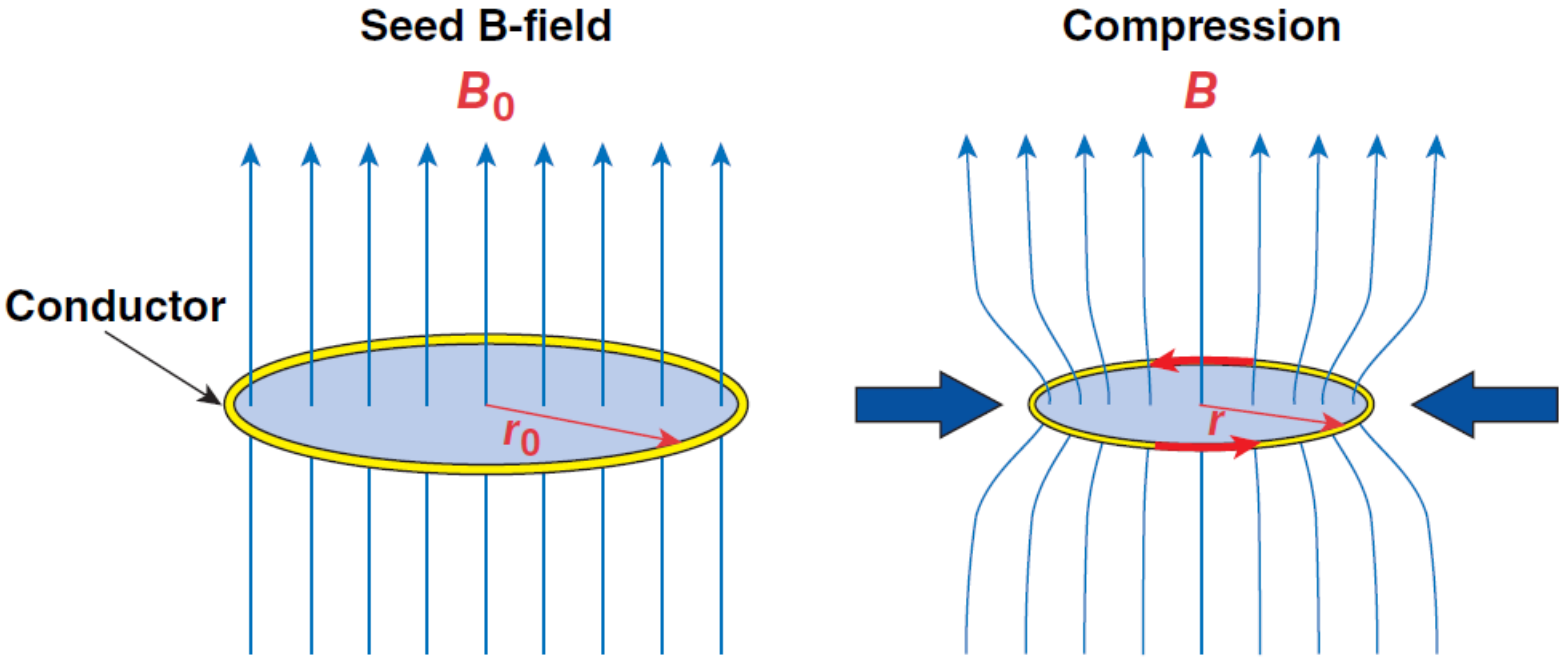
$$\kappa_{\perp} = \frac{\kappa_{||}}{\chi^2} \quad \text{for large Hall parameter } \chi \propto \frac{l_{mfp}}{R_L} >> 1$$

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

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

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

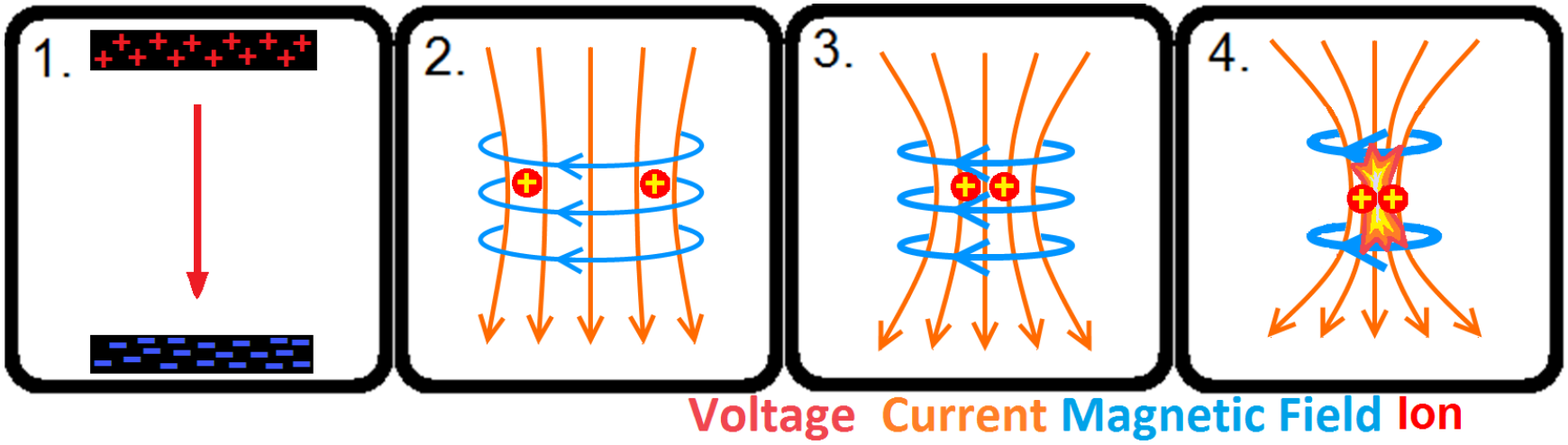
Principle of frozen magnetic flux in a good conductor is used to compress fields



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

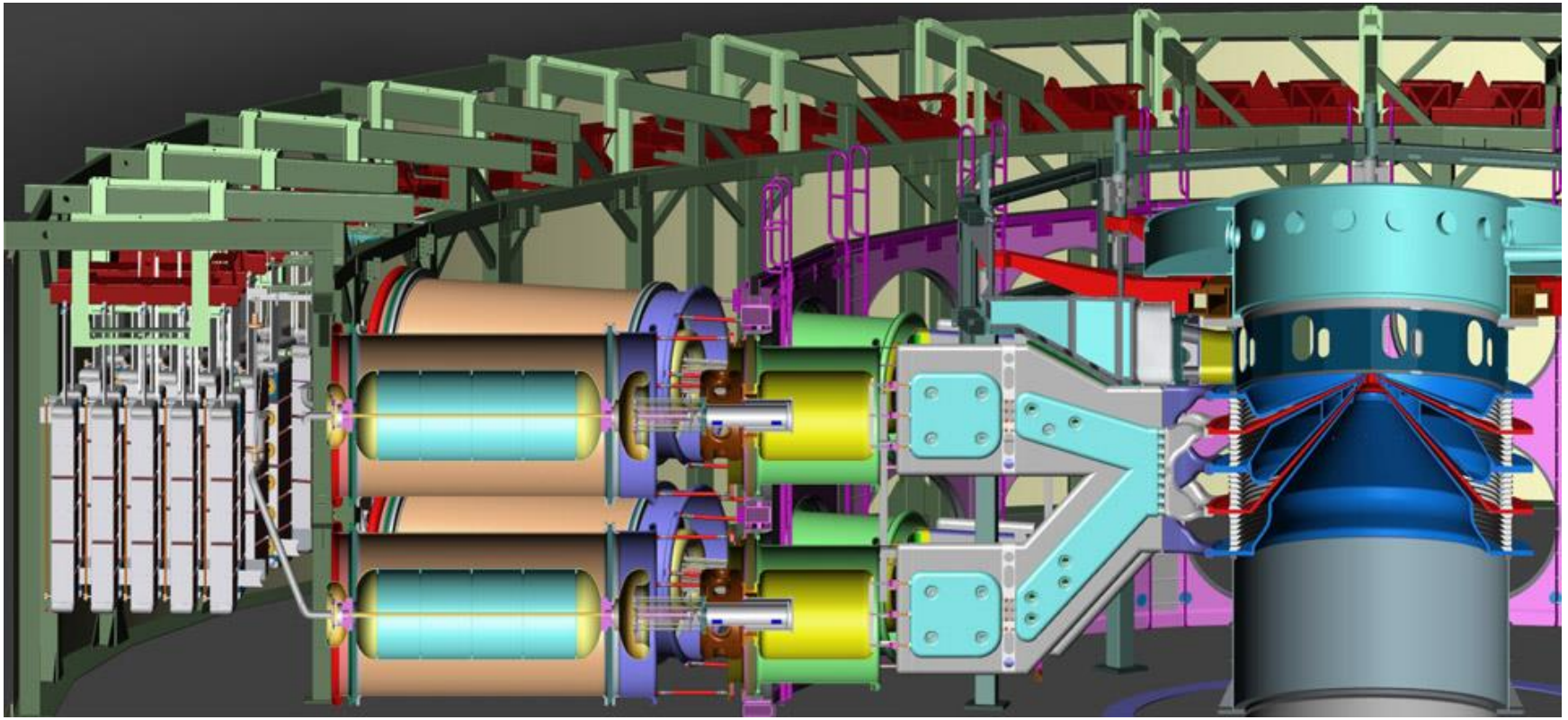
M. Hohenberger, P.-Y. Chang, *et al*., Phys. Plasmas 19, 056306 (2012).

Plasma can be pinched by parallel propagating plasmas



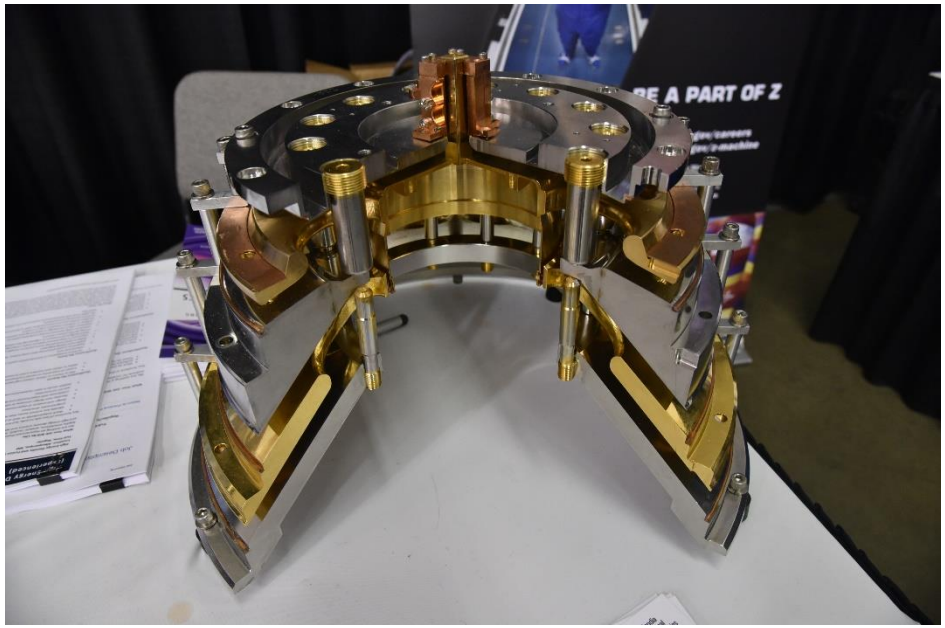
https://en.wikipedia.org/wiki/Pinch_(plasma_physics)

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

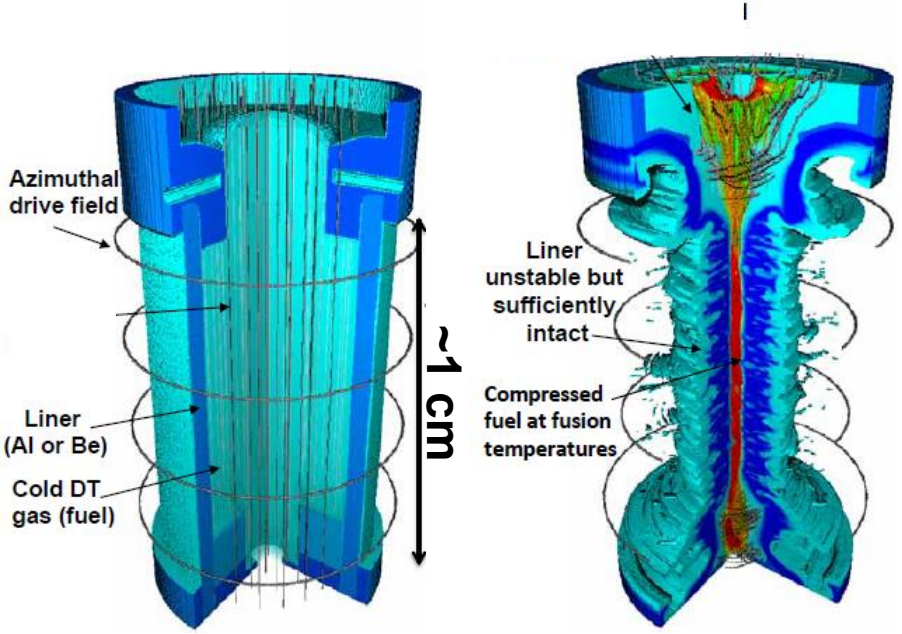


- Stored energy: 20 MJ
- Marx charge voltage: 85 kV
- Peak electrical power: 85 TW
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray emissions: 350 TW
- Peak X-ray output: 2.7 MJ

Z machine



Z machine



- **Stored energy: 20 MJ**
- **Peak electrical power: 85 TW**
- **Peak current: 26 MA**
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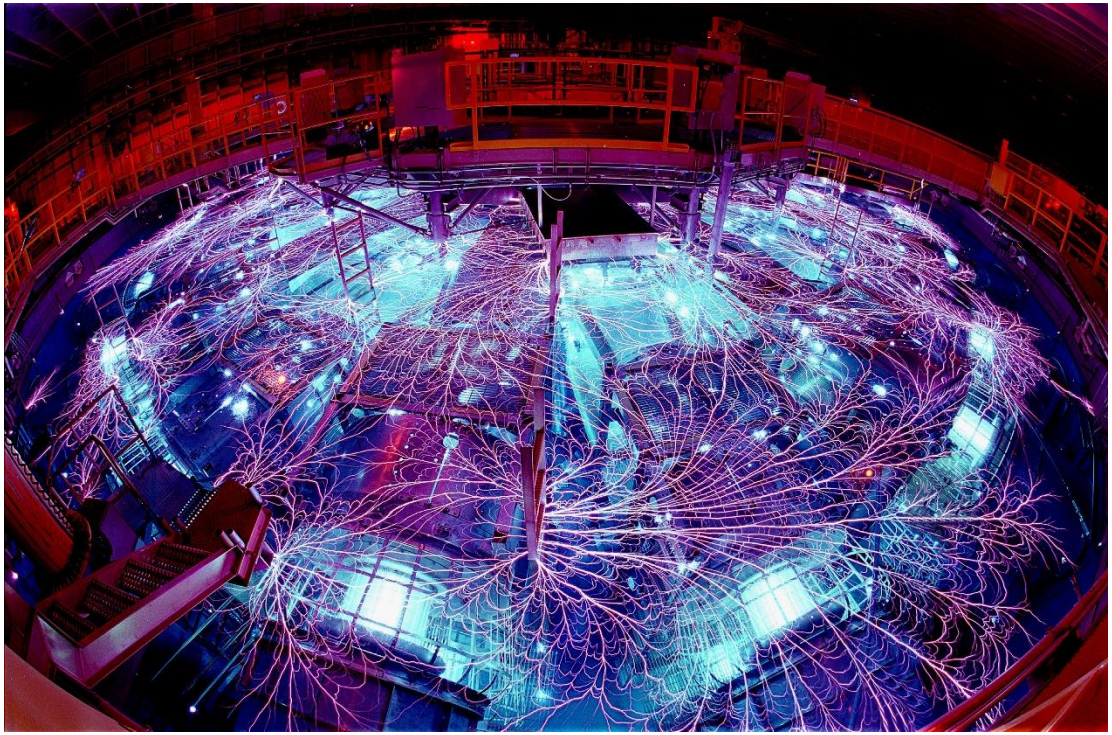
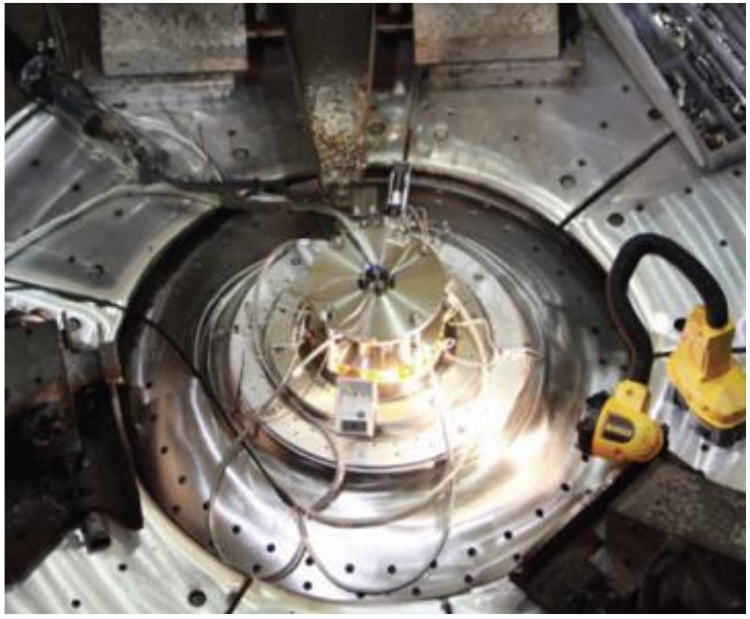
Z machine discharge

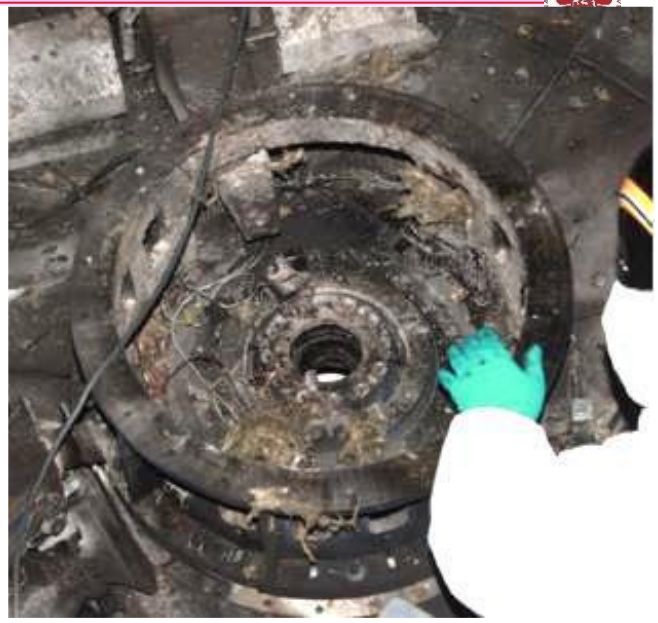


Before and after shots

- **Before shots**

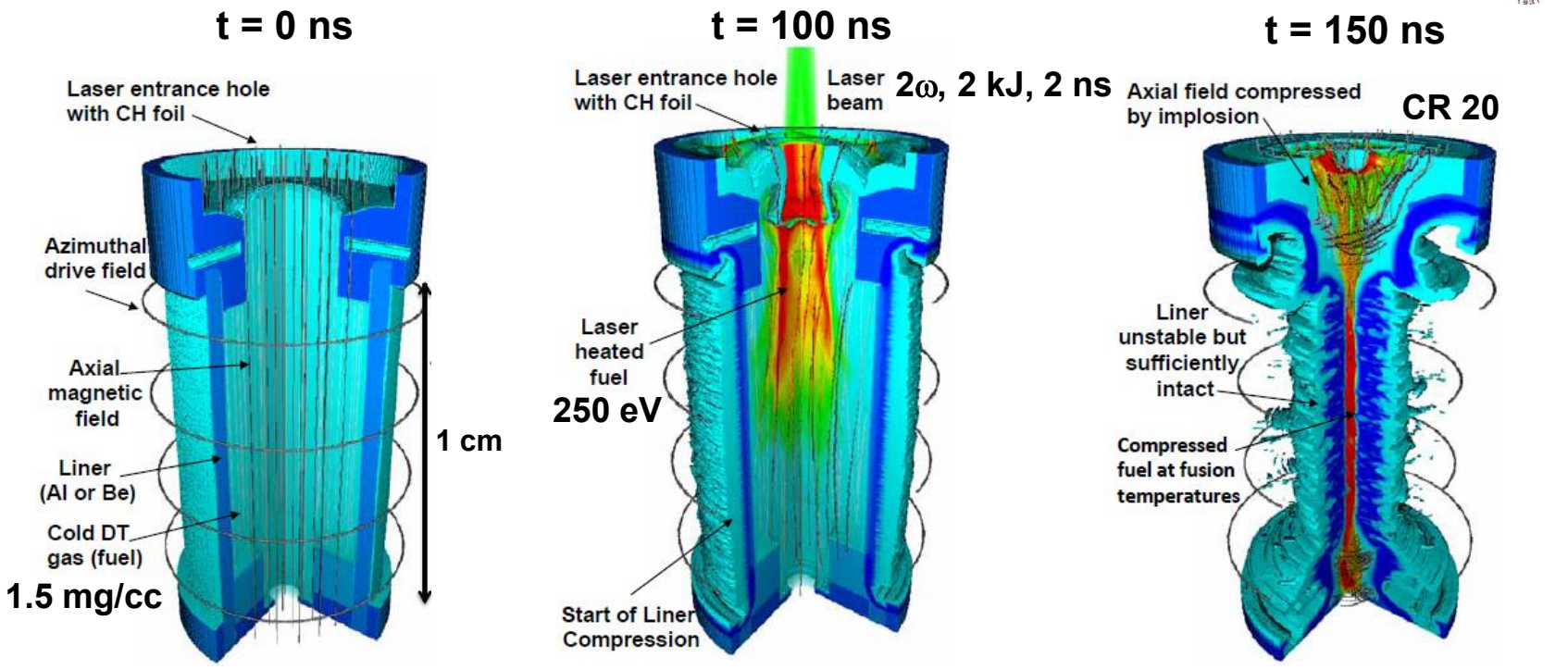


- **After shots**



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

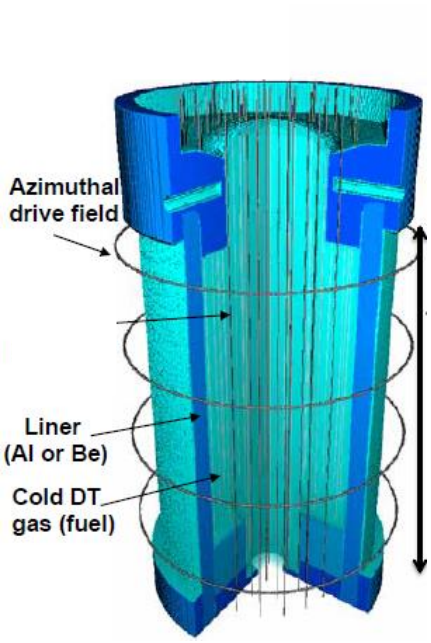
Promising results were shown in MagLIF concept conducted at the Sandia National Laboratories

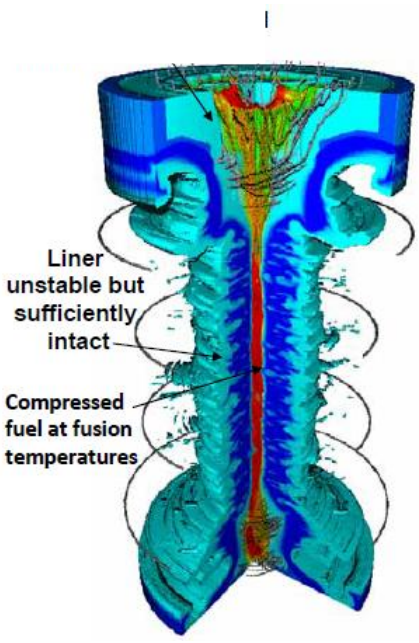


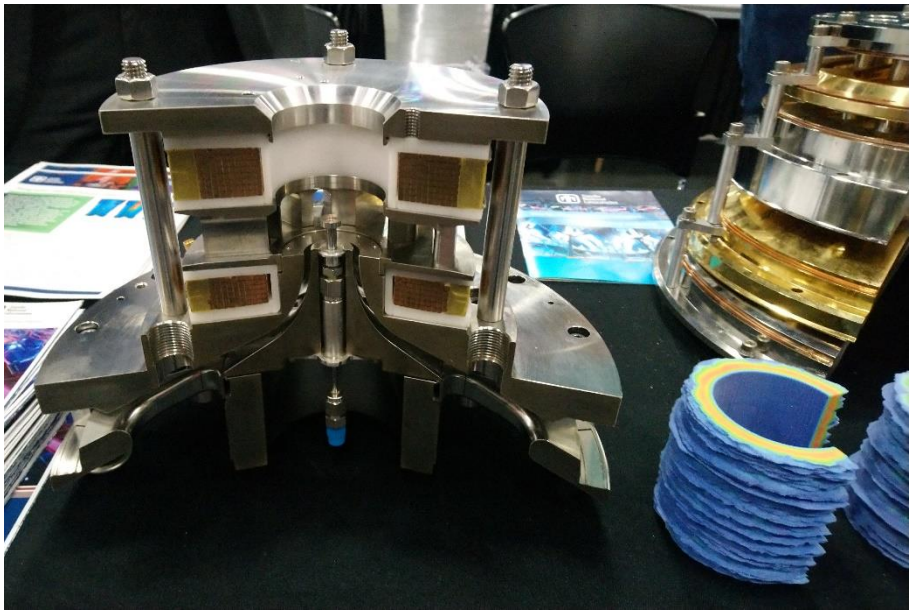
The stagnation plasma reached fusion-relevant temperatures with a 70 km/s implosion velocity

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

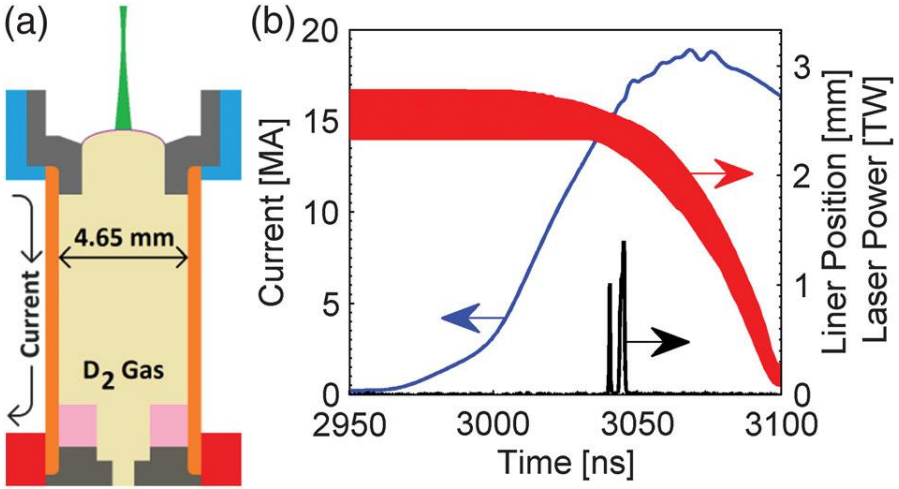
MagLIF target

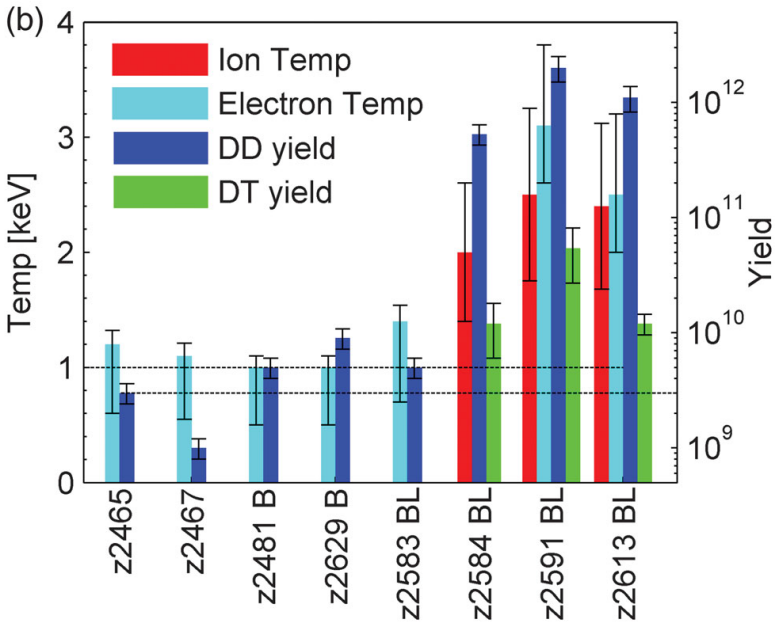






Neutron yield increased by 100x with preheat and external magnetic field.



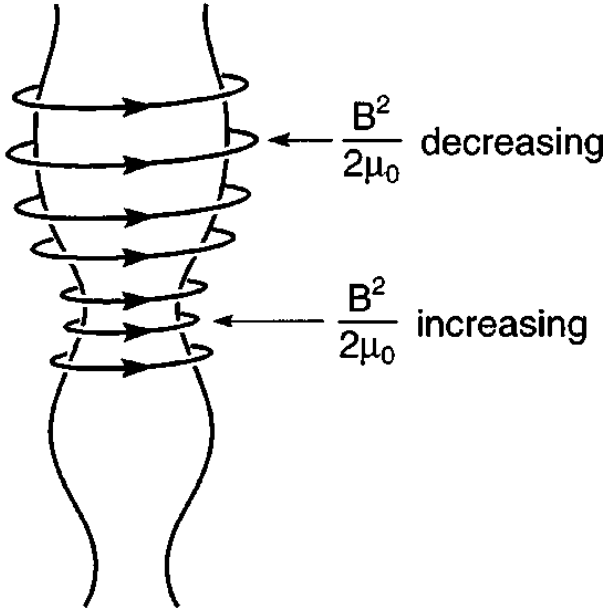


M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)

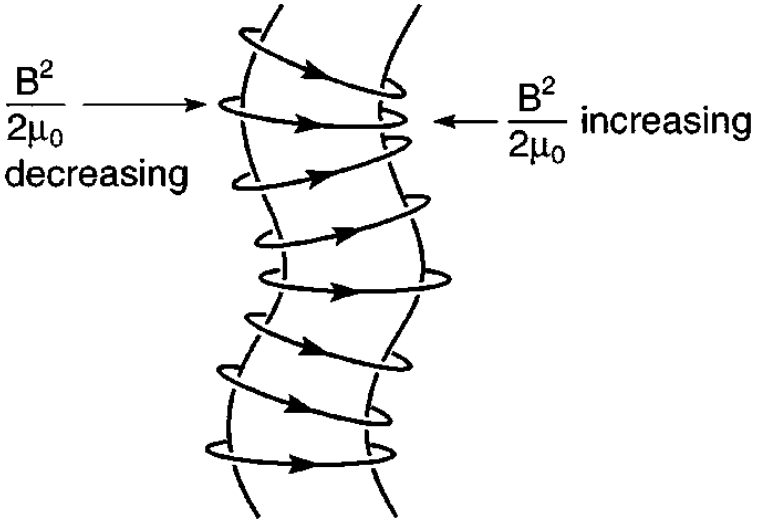
Sheared flow stabilizes MHD instabilities

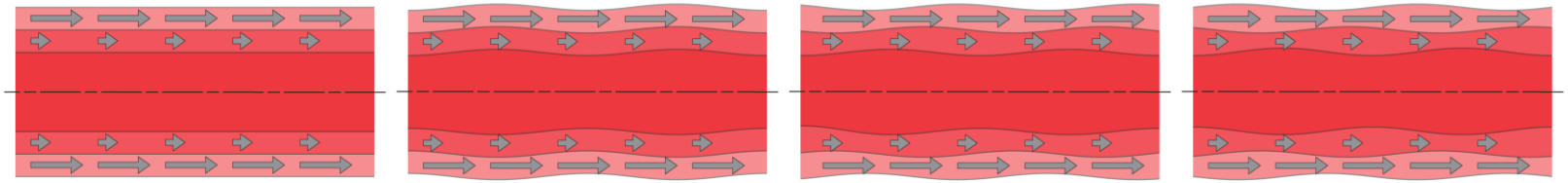
m = 0 (sausage)

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



m = 1 (kink)

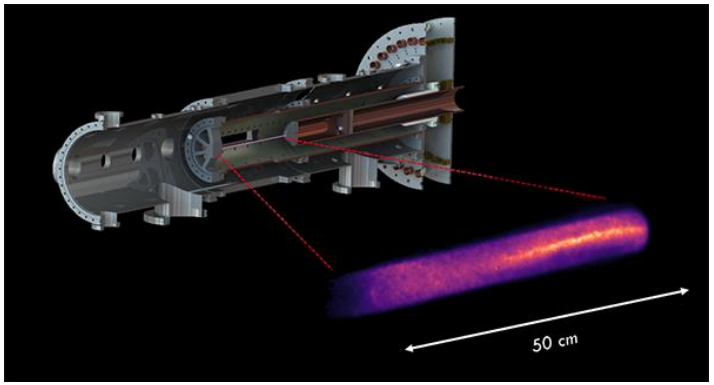




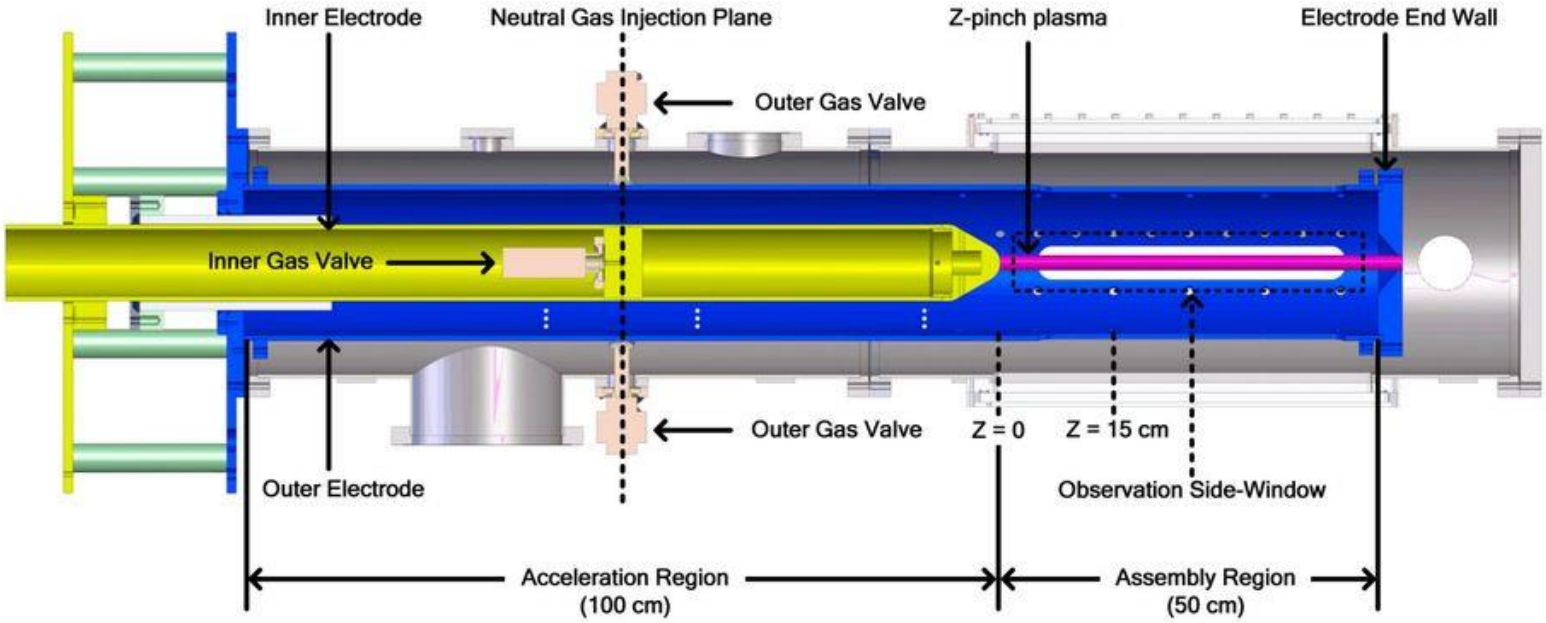
$$\frac{dV_Z}{dr} \neq 0$$

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

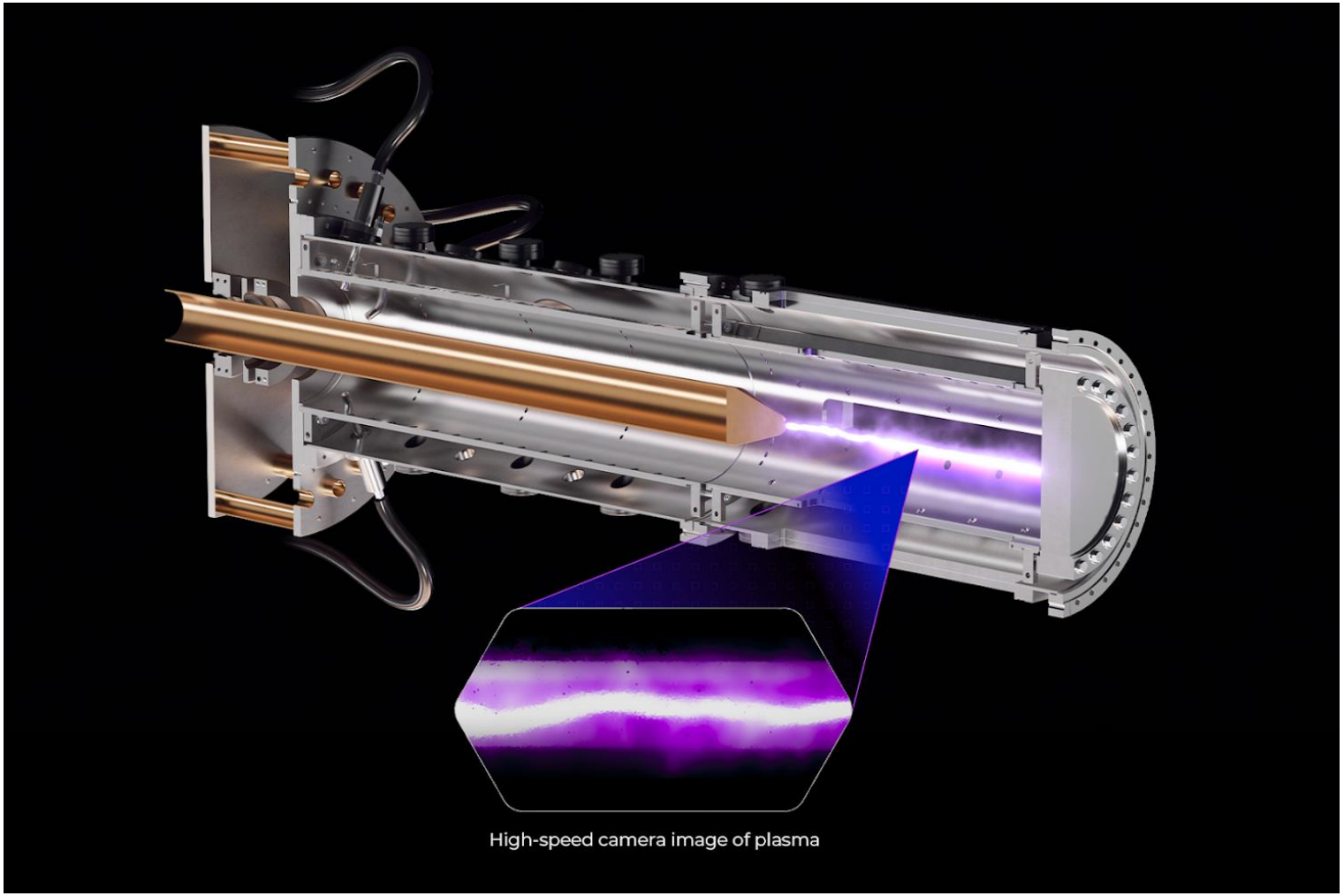


ZAP ENERGY™



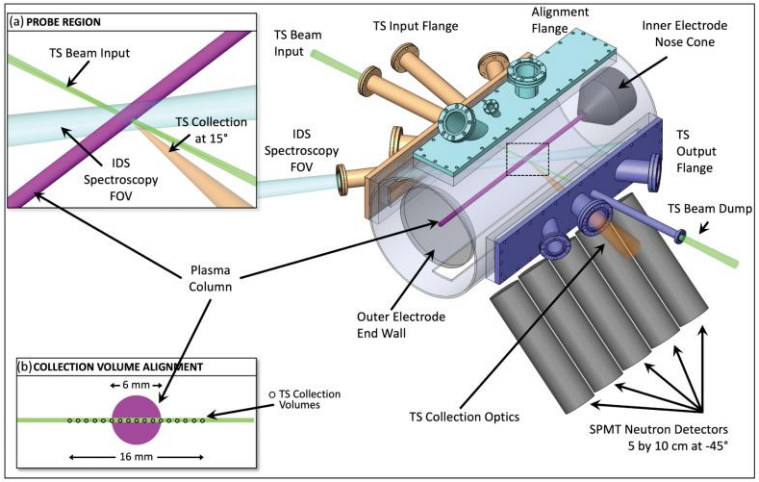
https://www.zapenergyinc.com/about

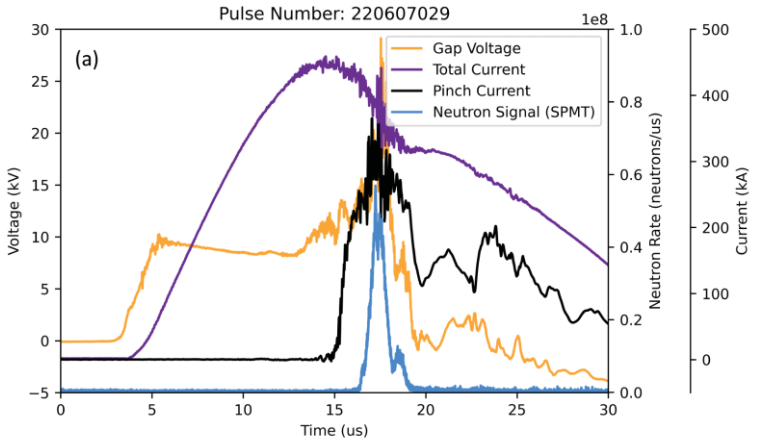
A. D. Stepanov, etc., Phys. Plasmas 27, 112503 (2020)



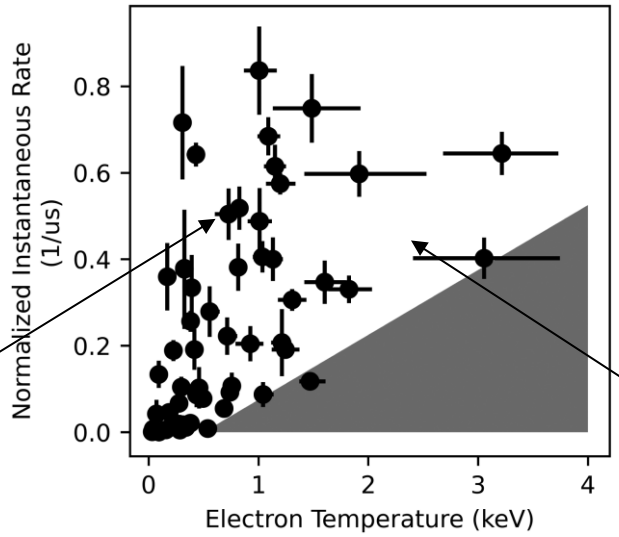
https://www.powerelectronicsnews.com/zap-energys-vision-for-fusion-power/

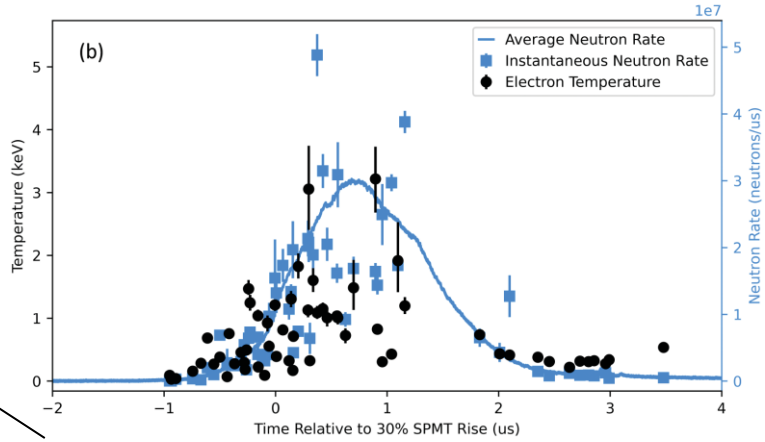
Elevated electron temperature coincident with observed fusion reactions in a sheared-flow-stabilized z pinch





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

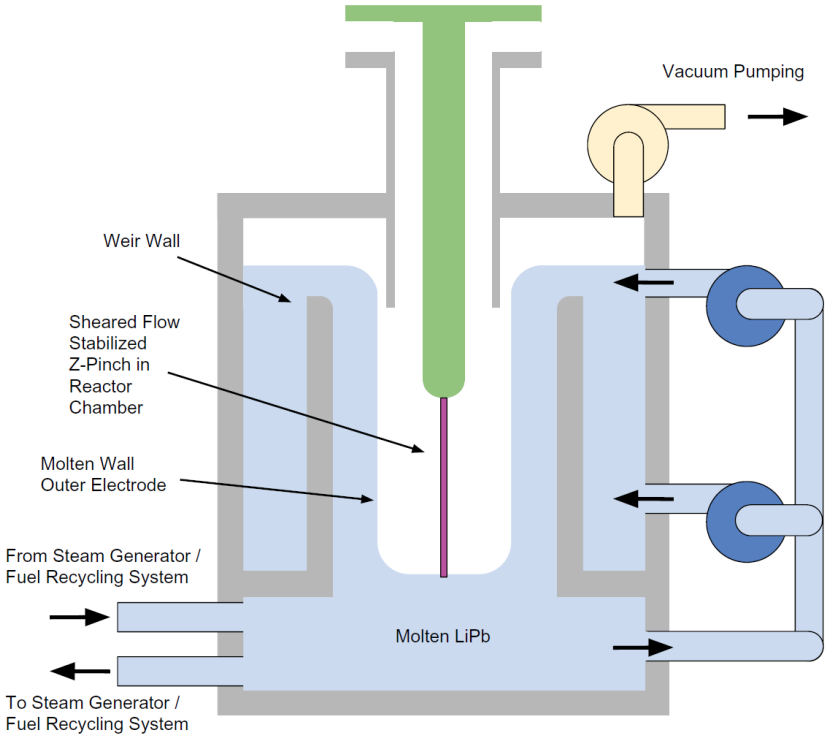


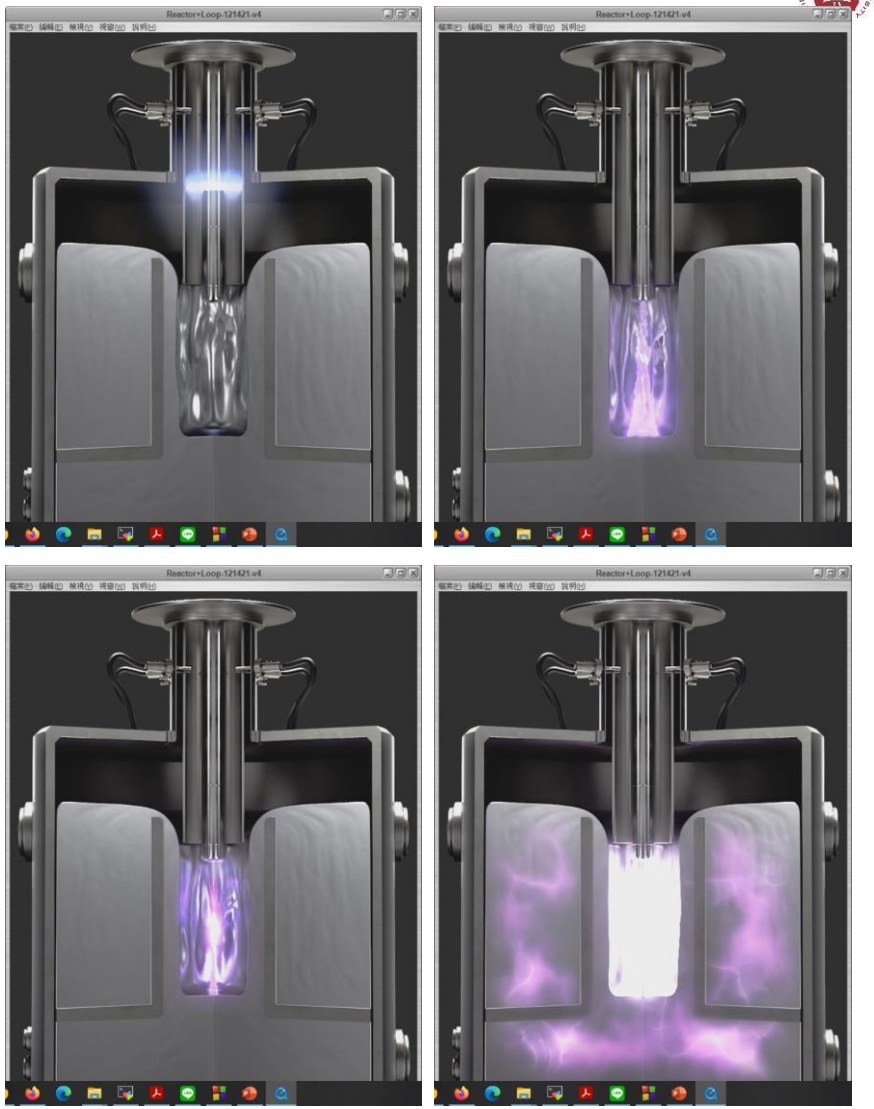


- **High temperature coincide with high rate.**

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

Fusion reactor concept by ZAP energy

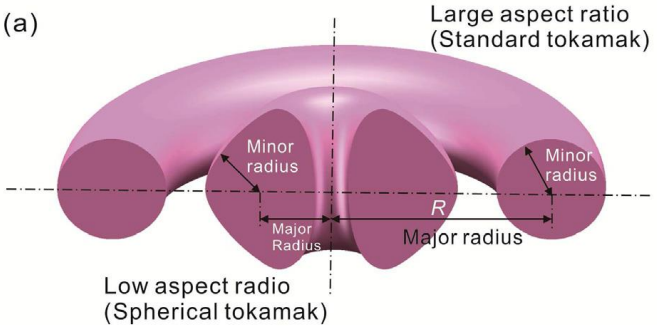




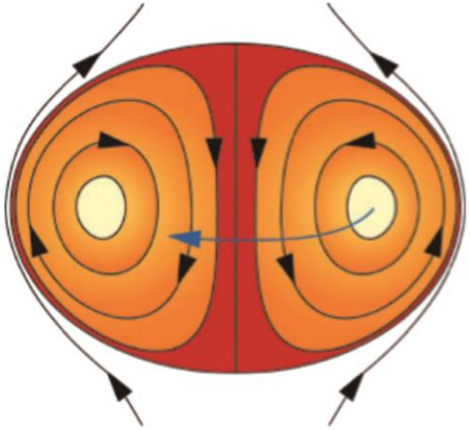
https://www.zapenergyinc.com/about
E. G. Forbes, etc., Fusion Sci. Tech. 75, 599 (2019)

Spherical torus (ST) and compact torus (CT)

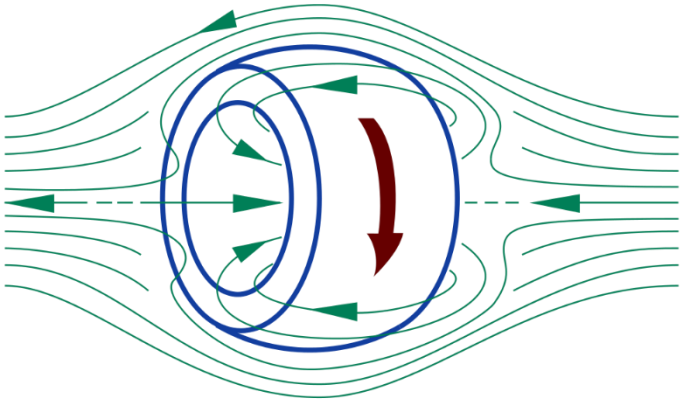
- **Spherical torus (ST)**



- **Compact torus (CT)**
  - **Spheromak**

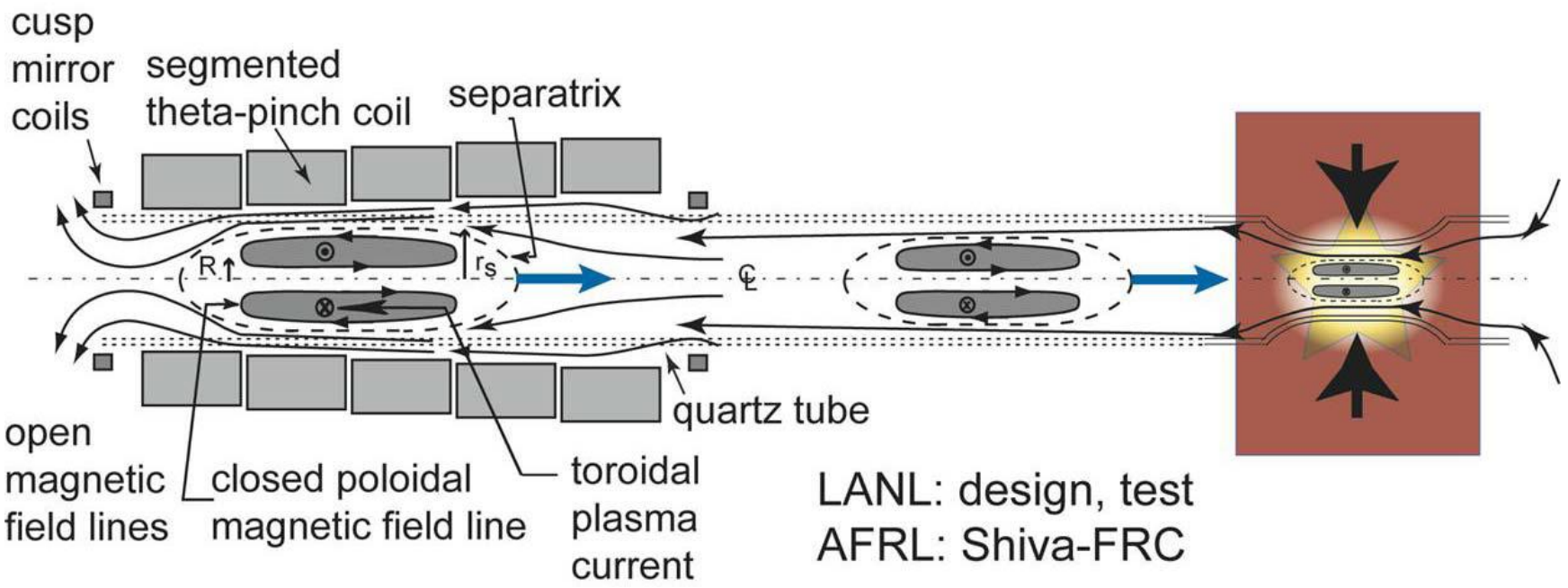


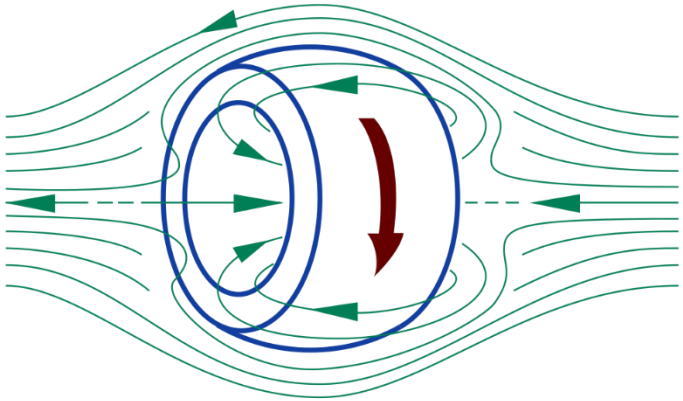
  - **Field reversed configuration (FRC)**



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

Field reverse configuration is used in Tri-alpha energy

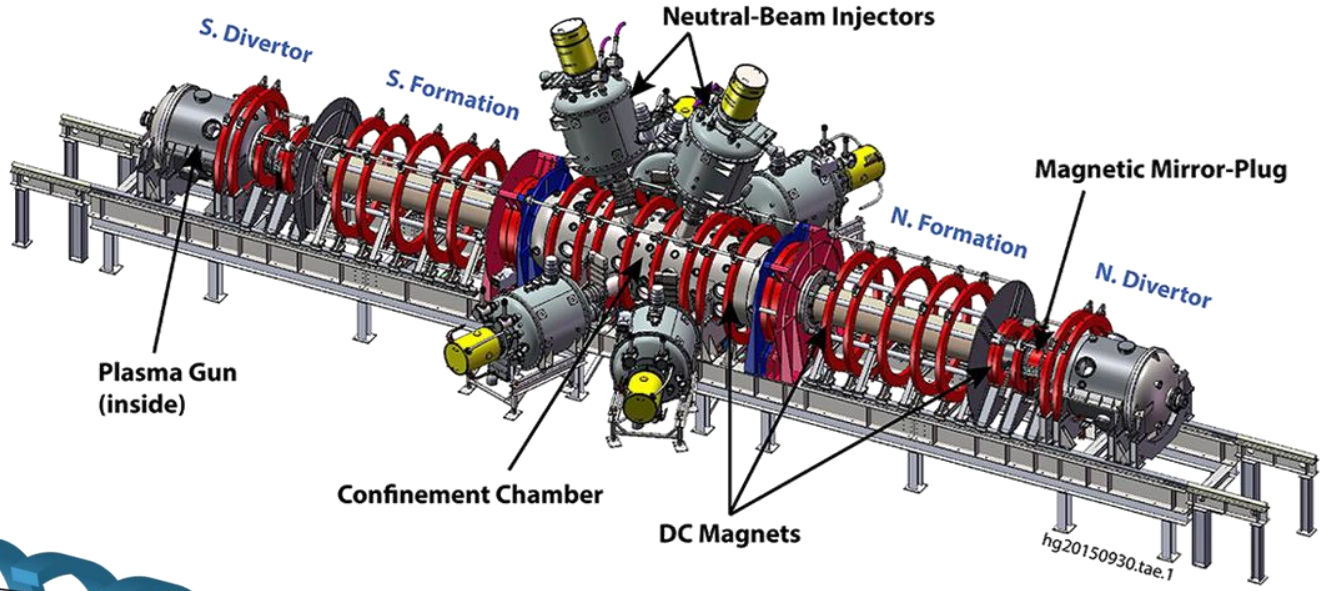


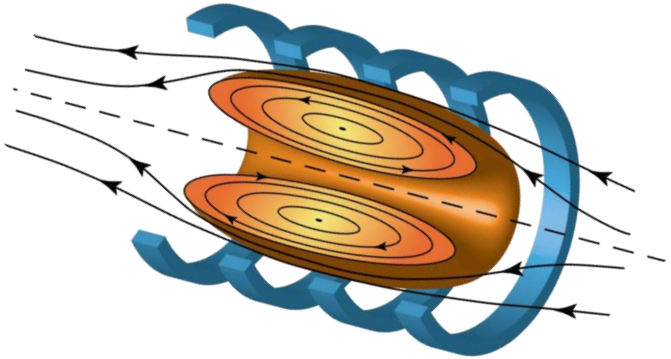


*Magneto-Inertial Fusion& Magnetized HED Physics by Bruno S. Bauer, UNR & Magneto-Inertial Fusion Community

**https://en.wikipedia.org/wiki/Field-reversed_configuration

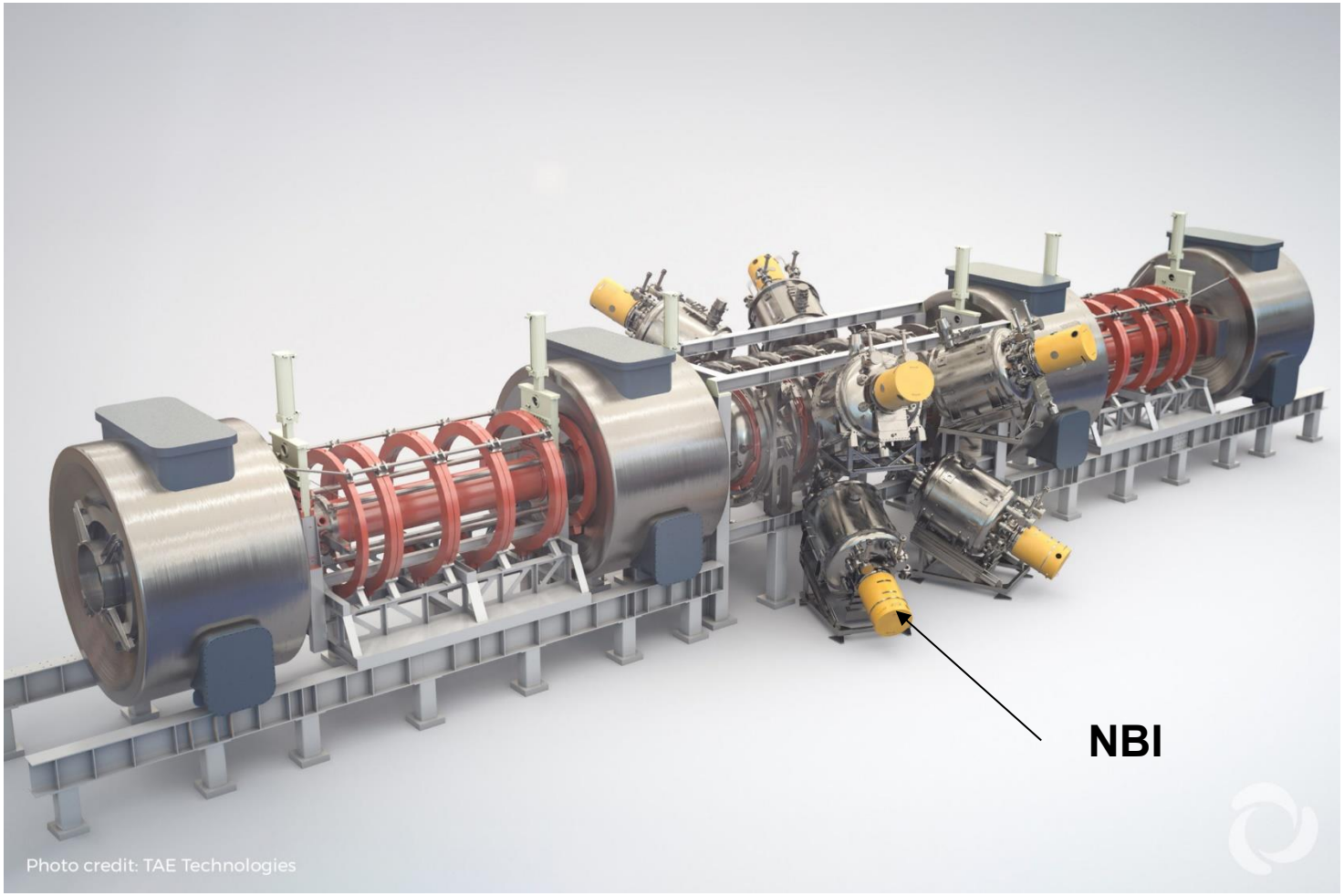
Field reverse configuration is used in Tri-alpha energy





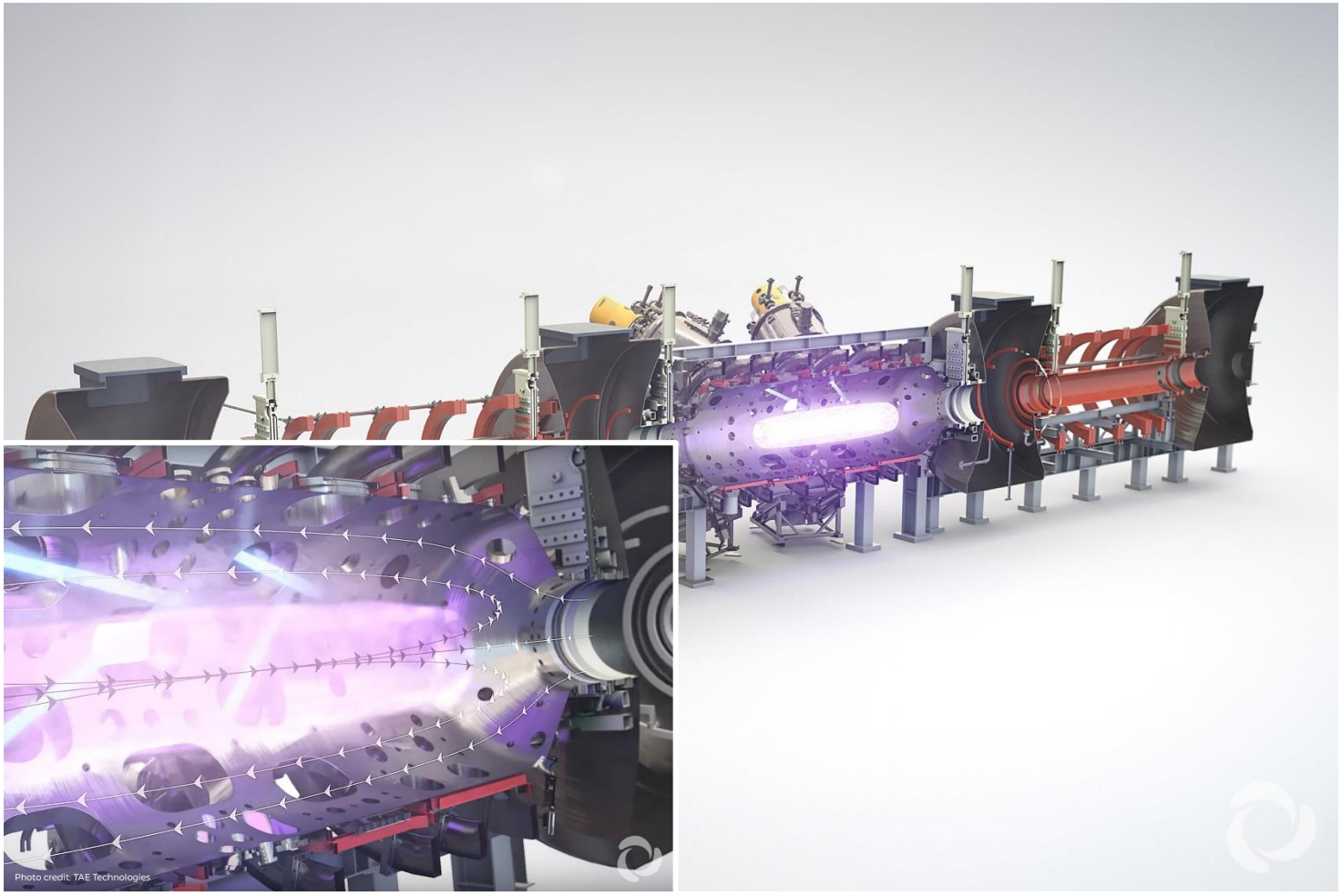
http://trialphaenergy.com/

NBI for Tri-Alpha Energy Technologies



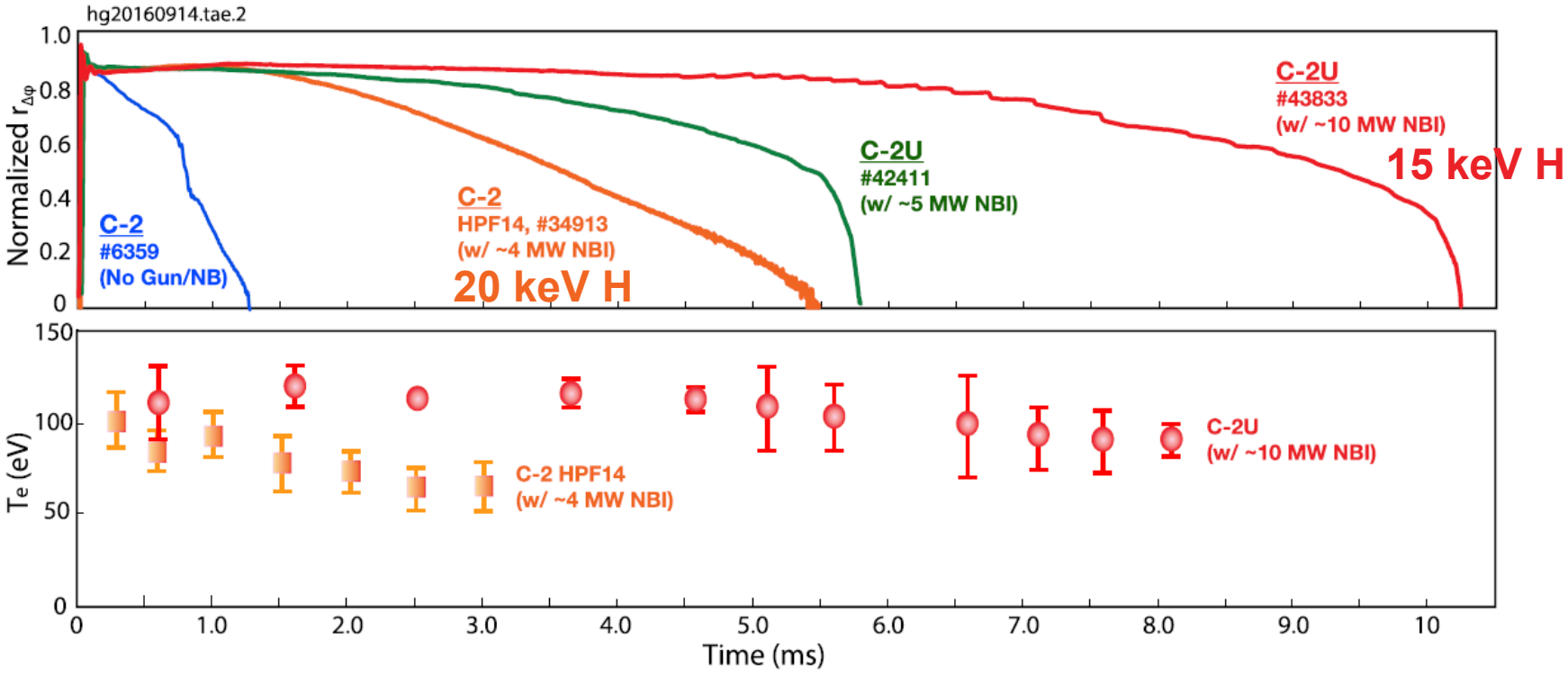
https://tae.com/media/

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



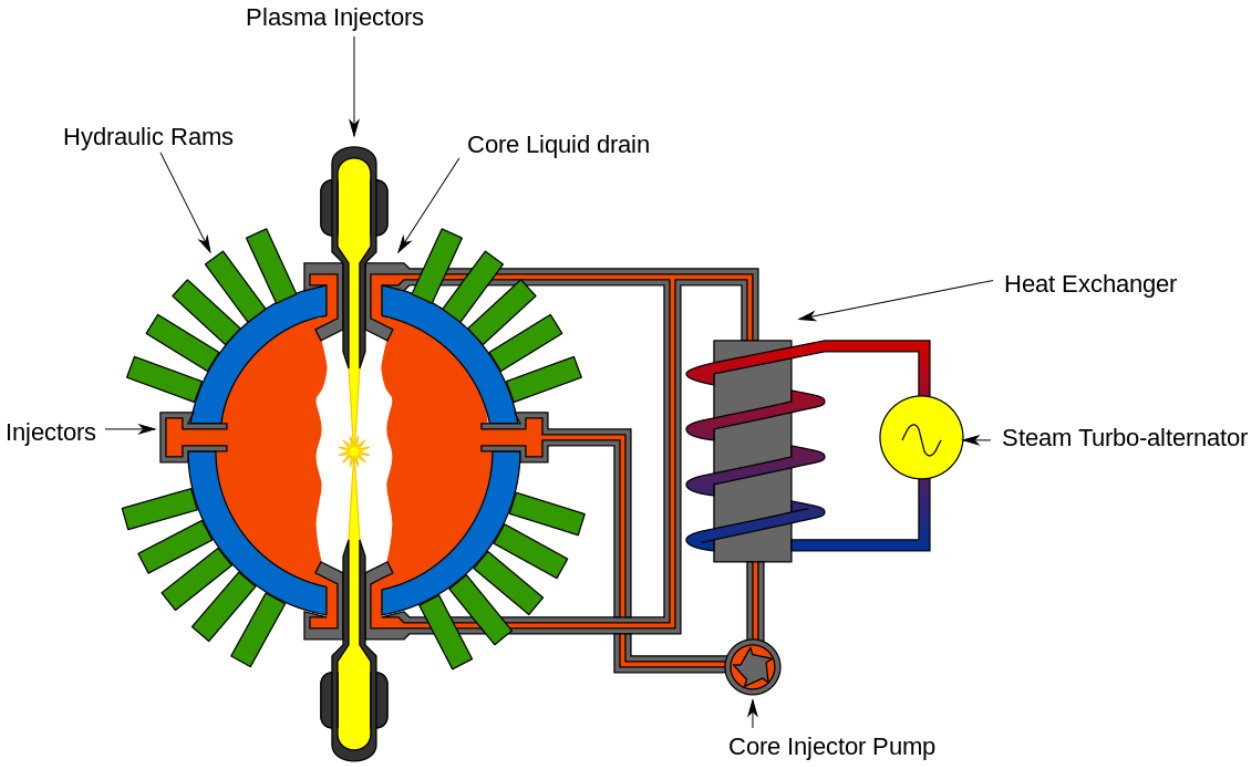
https://tae.com/media/

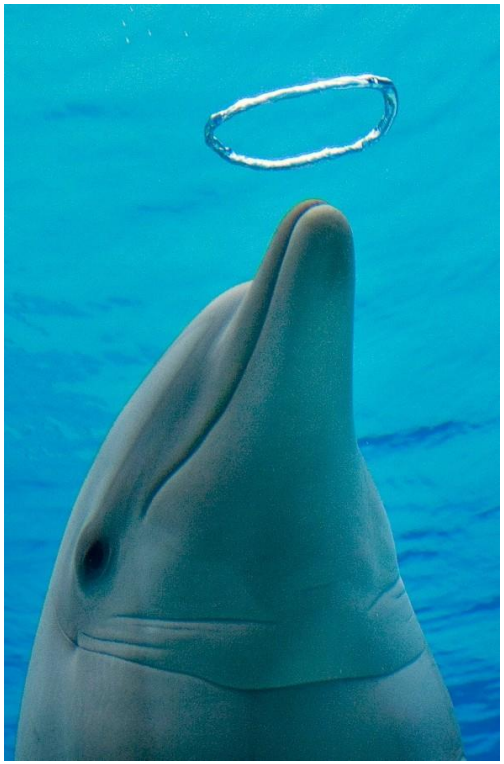
FRC sustain longer with neutral beam injection



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

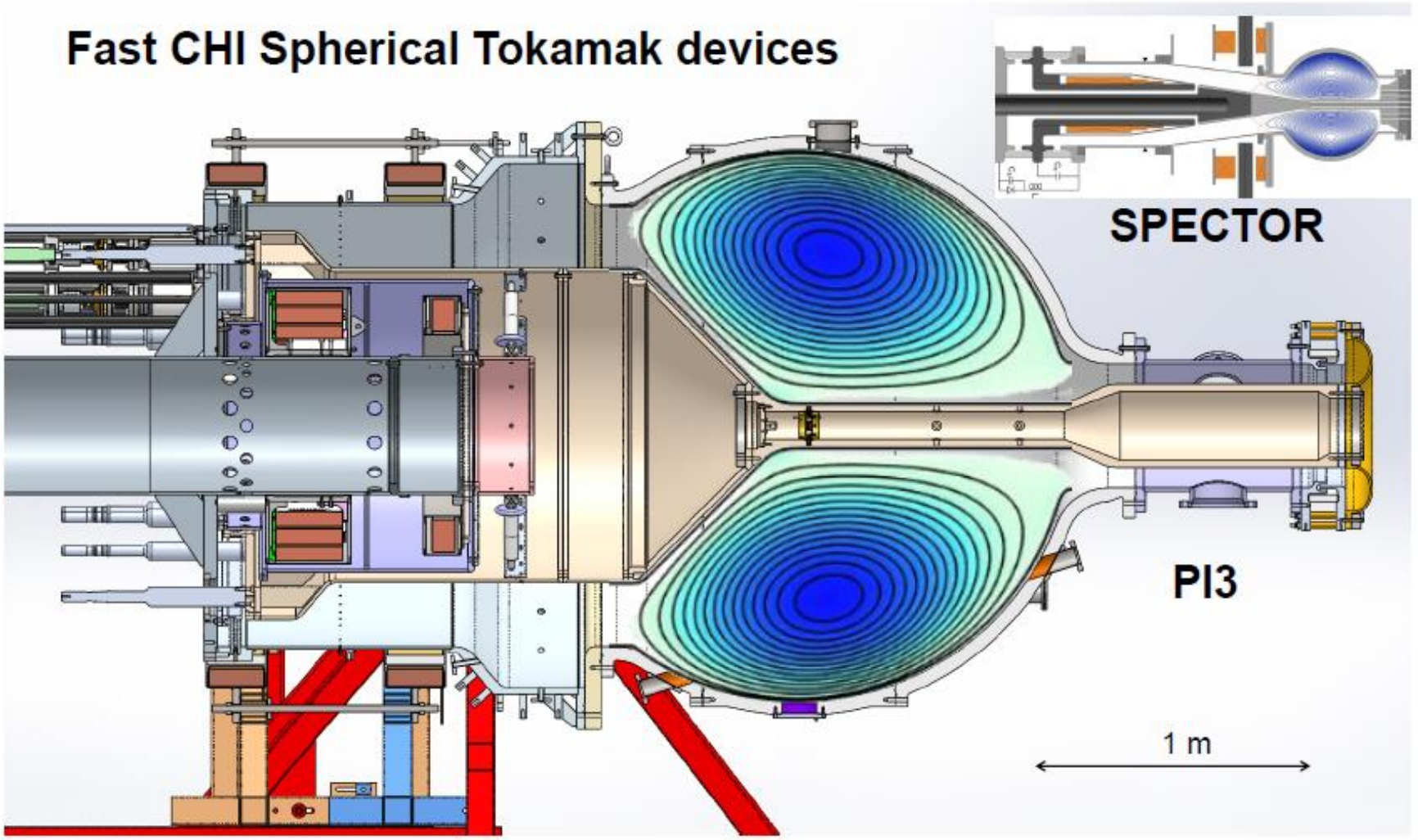
General fusion is a design ready to be migrated to a power plant





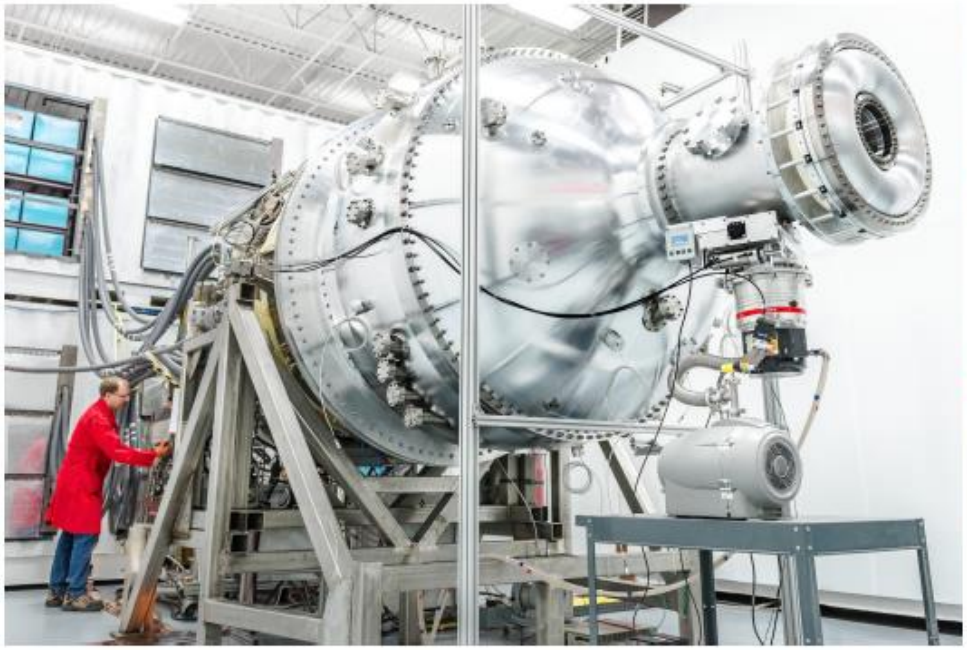
https://en.wikipedia.org/wiki/General_Fusion

A spherical tokamak is first generated



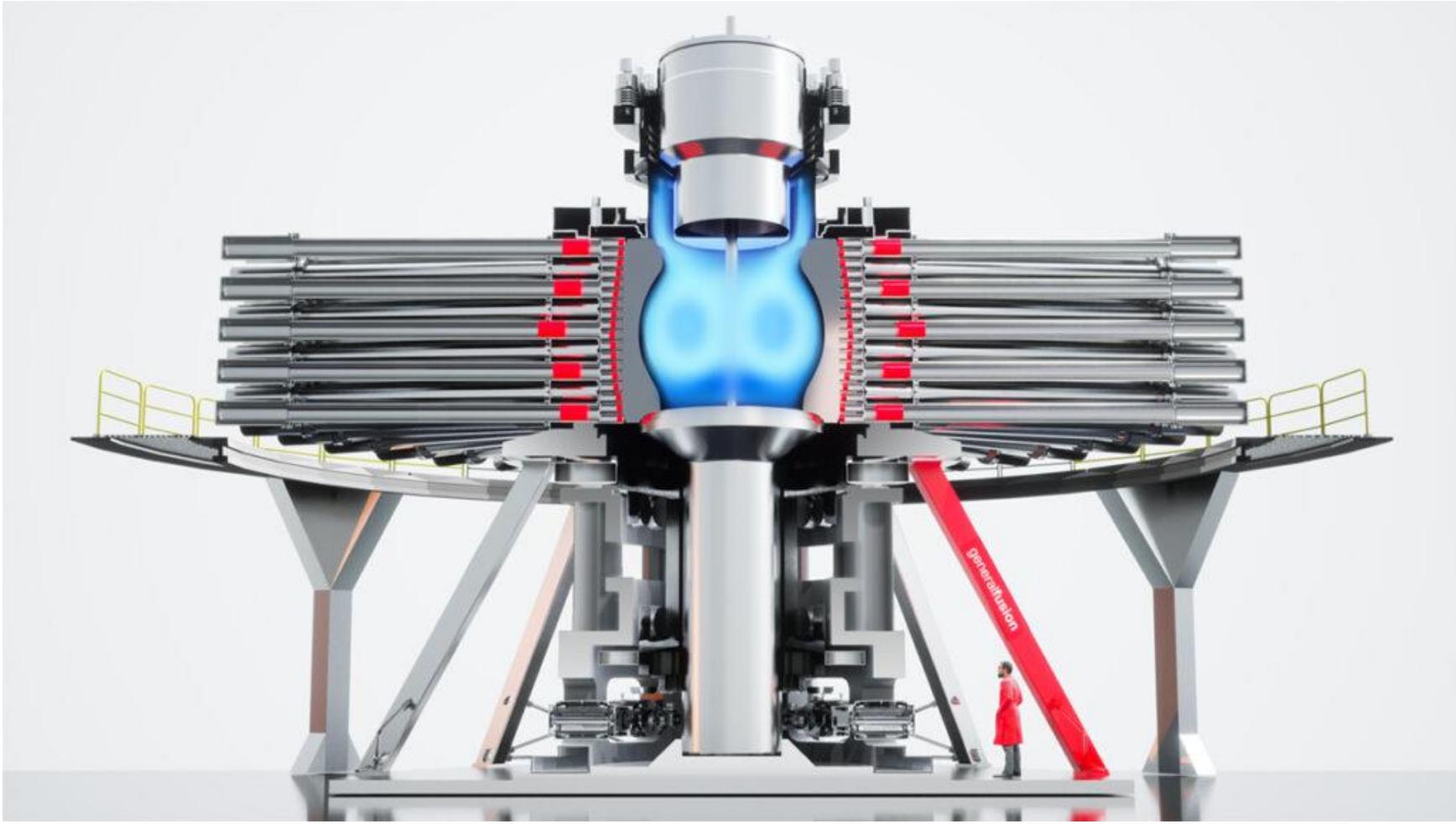
K. EPP, etc., 60th APS-DPP, CP11.00192

Plasma injector for the spherical tokamak

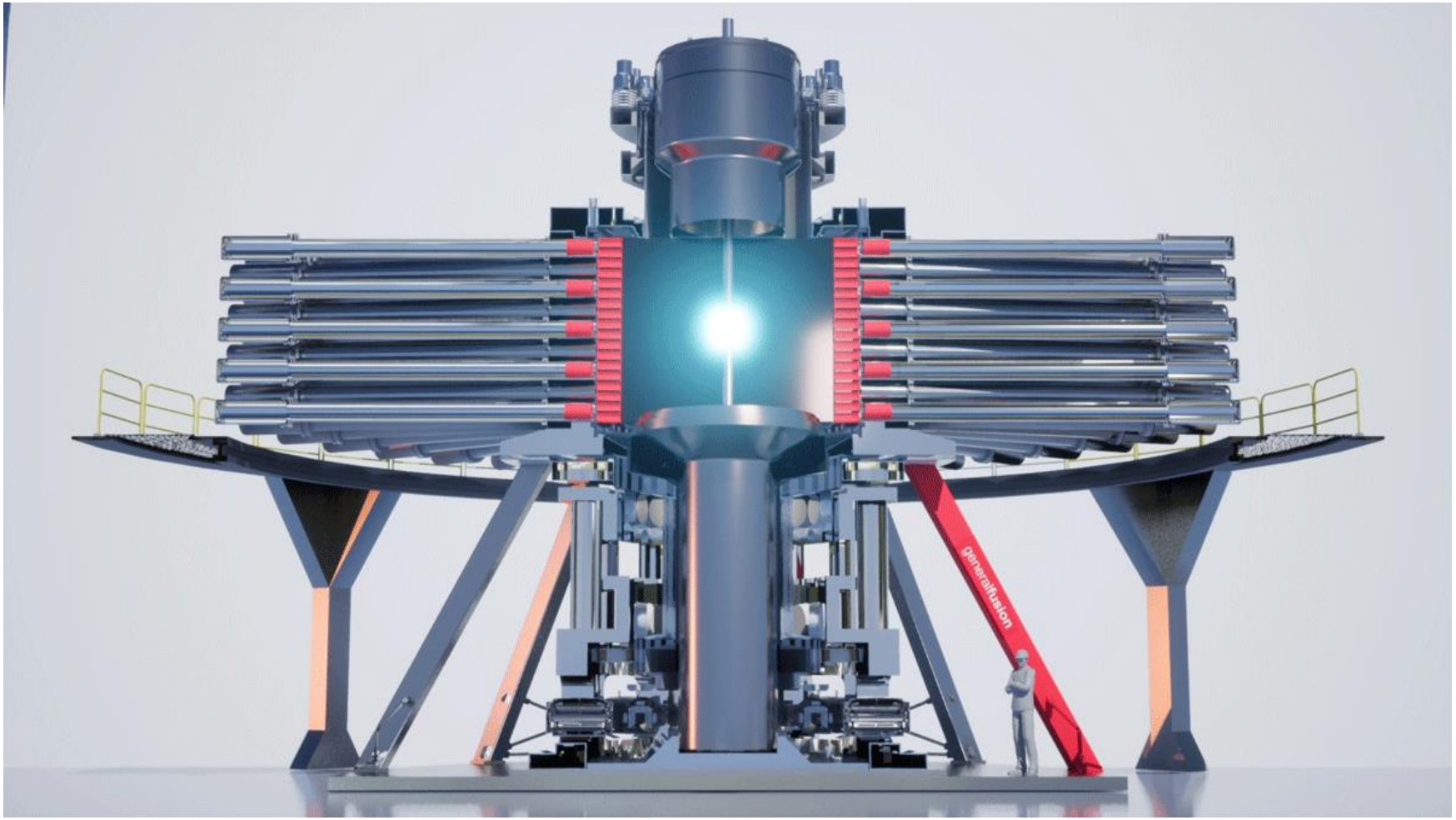


K. EPP, etc., 60th APS-DPP, CP11.00192

A spherical tokamak is generated in a liquid metal vortex



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



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

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

By Matt McGrath
Environment correspondent

17 June

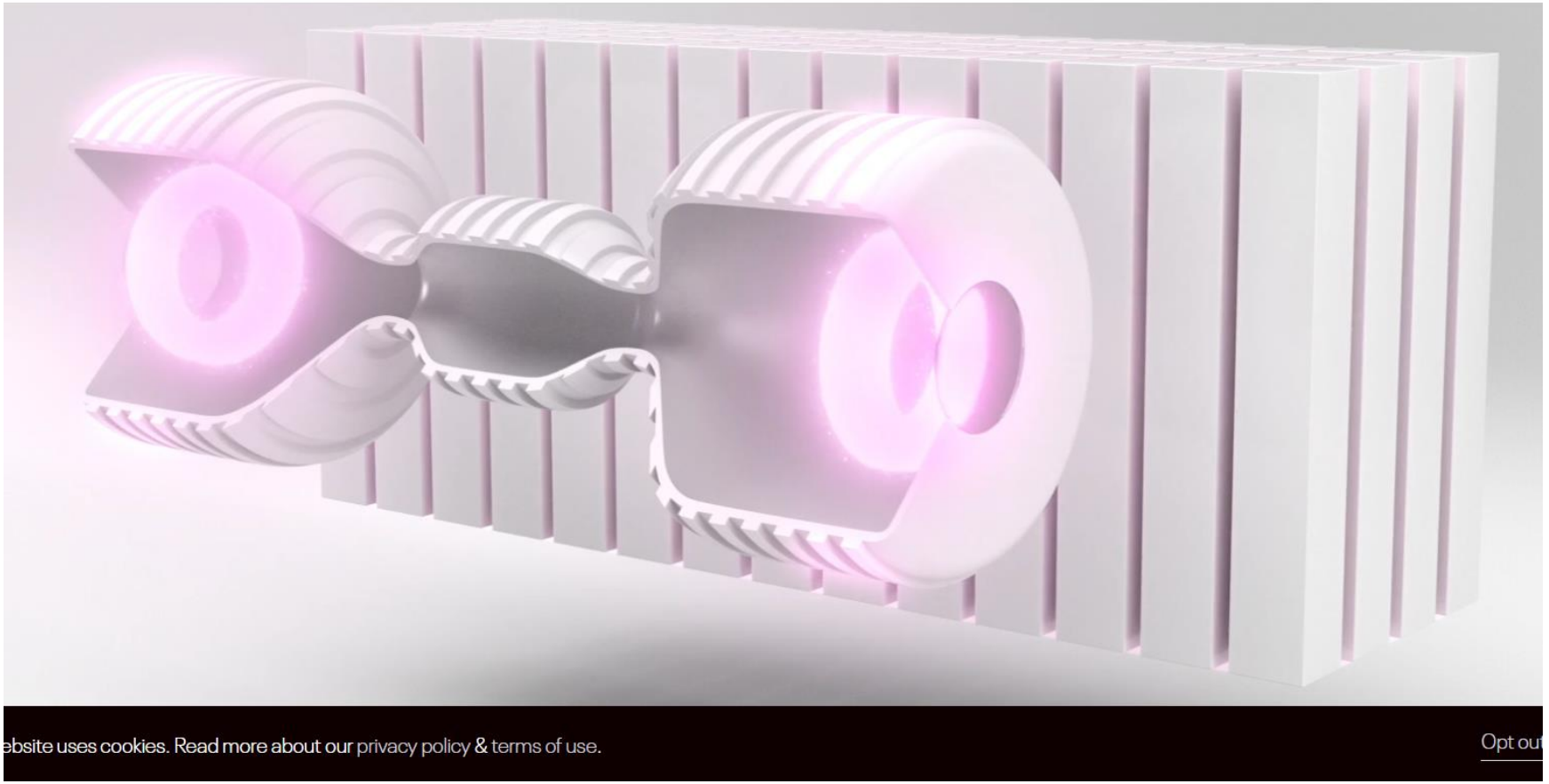
An artist's impression of what the new demonstration plant might look like

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

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

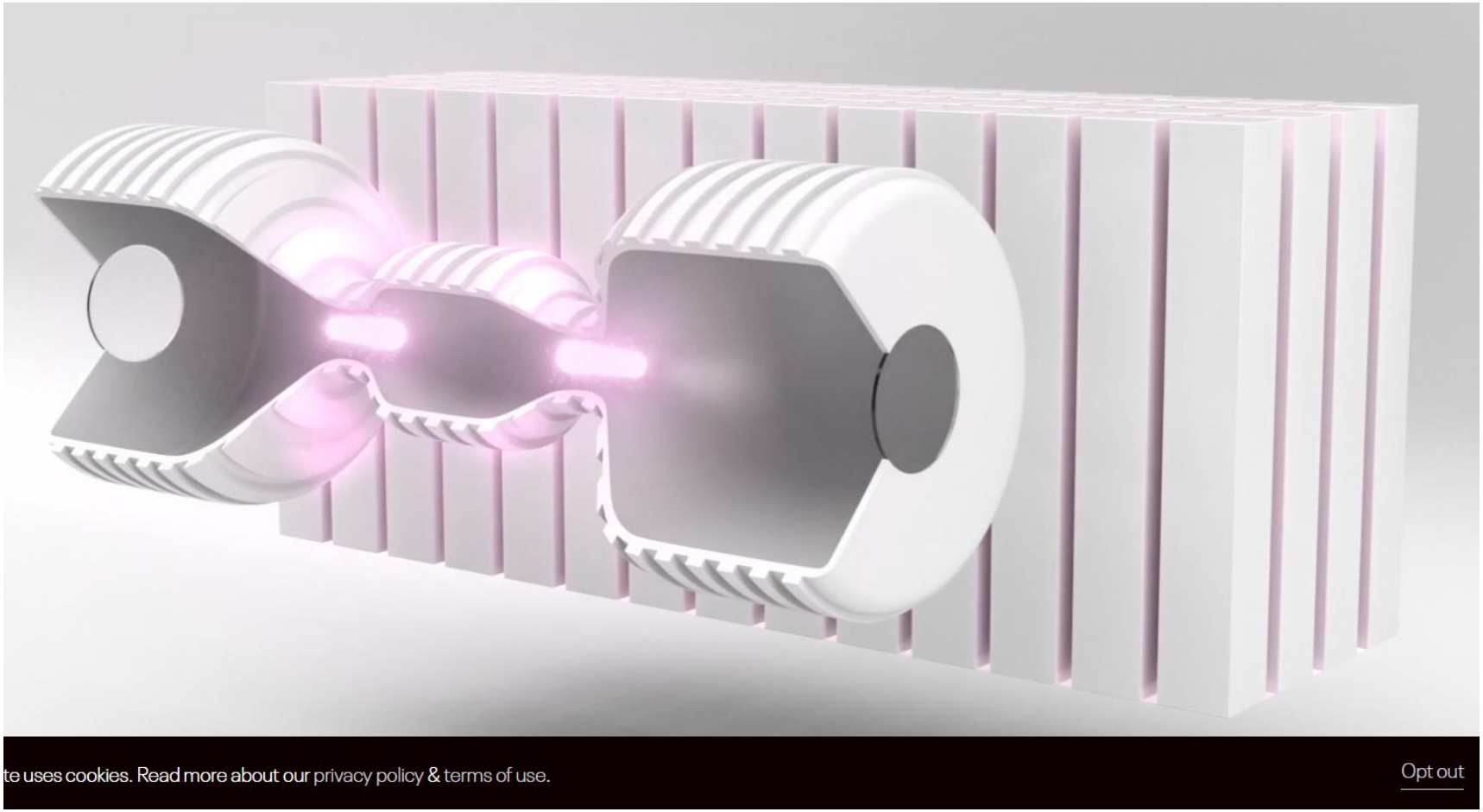
https://www.bbc.com/news/science-environment-57512229

Helion energy is compressing the two merging FRCs



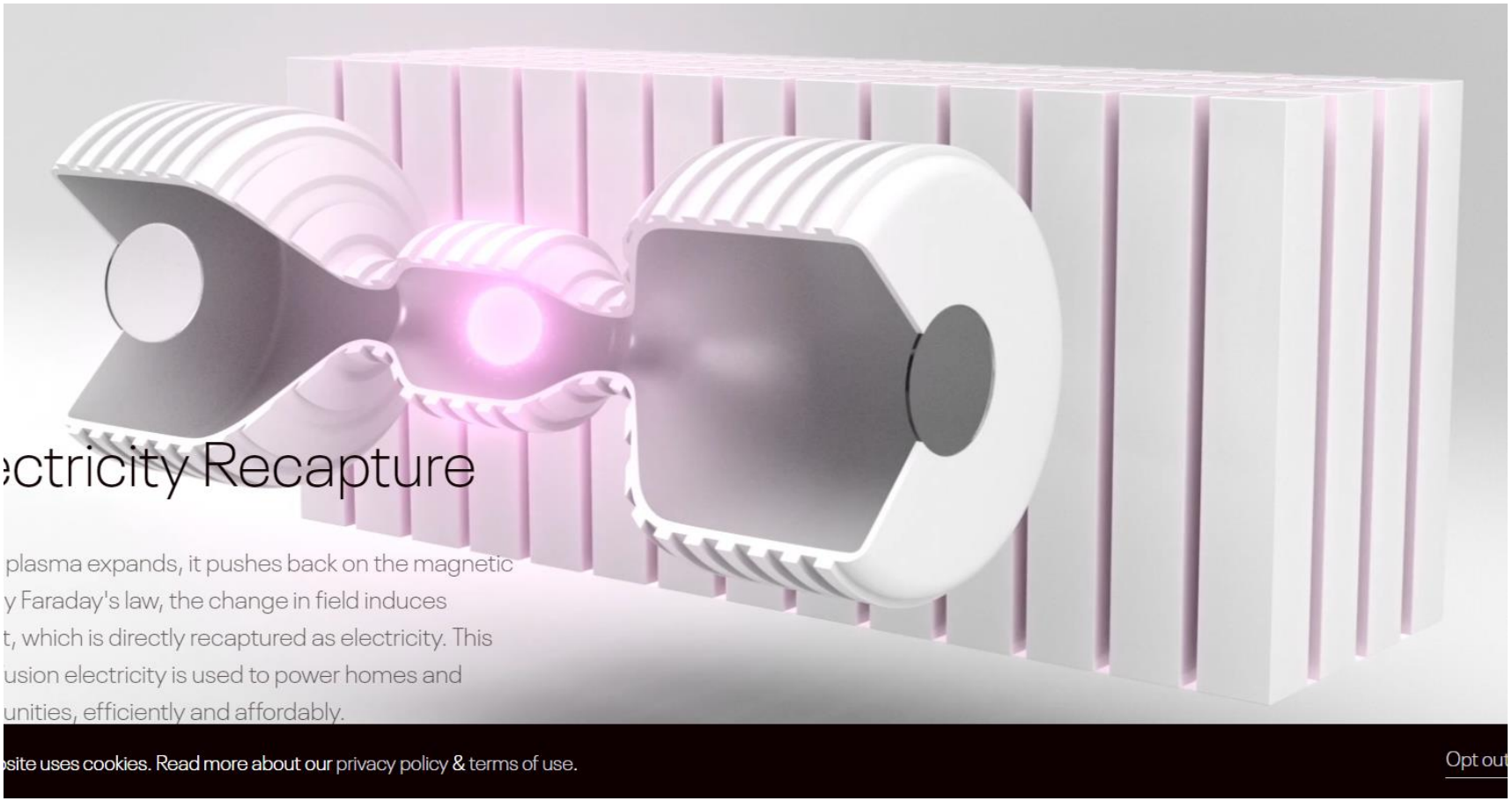
https://www.helionenergy.com/

Two FRCs are accelerated toward each other



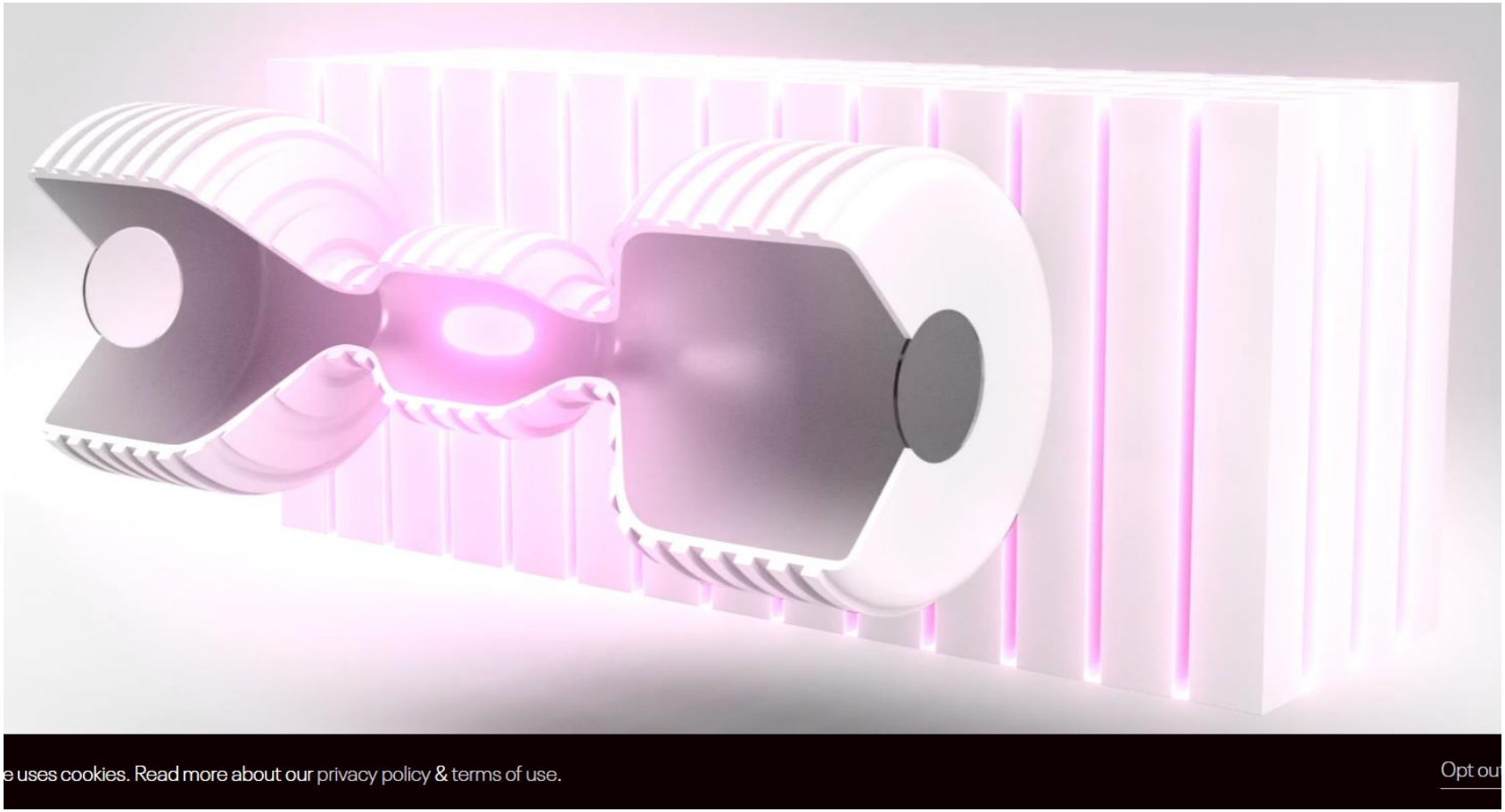
https://www.helionenergy.com/

Two FRCs merge with each other



https://www.helionenergy.com/

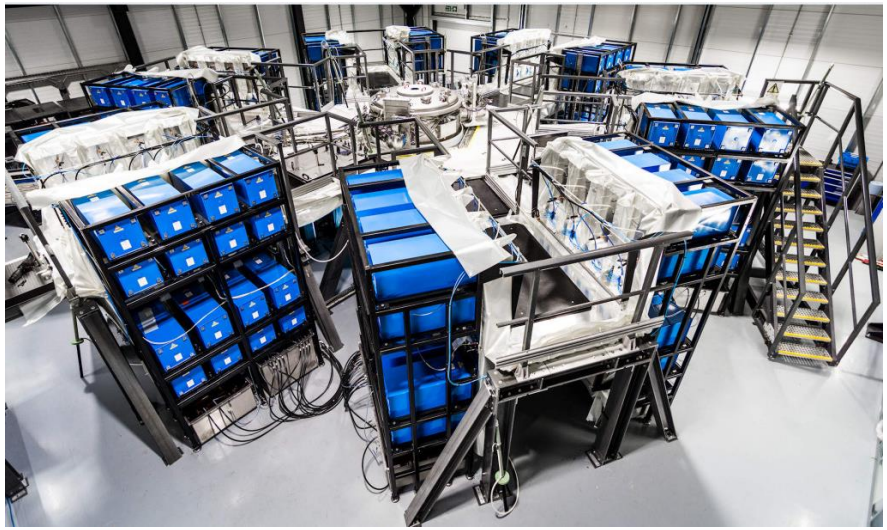
The merged FRC is compressed electrically to high temperature



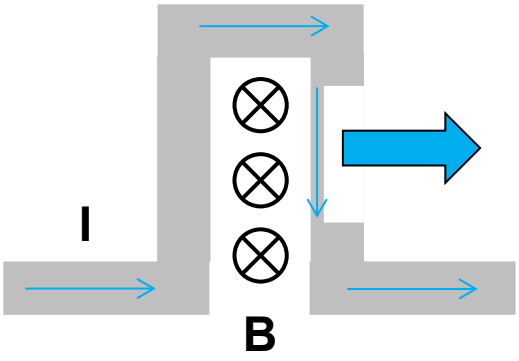
- **Similar concept will be studied in our laboratory.**

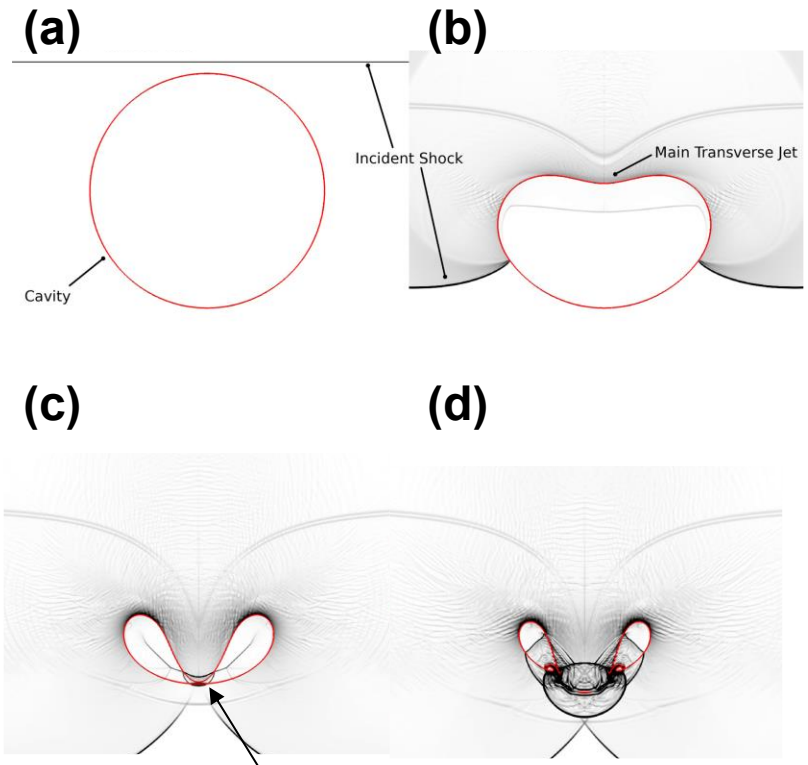
https://www.helionenergy.com/

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



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





- High pressure is generated by the colliding shock.

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

https://firstlightfusion.com/

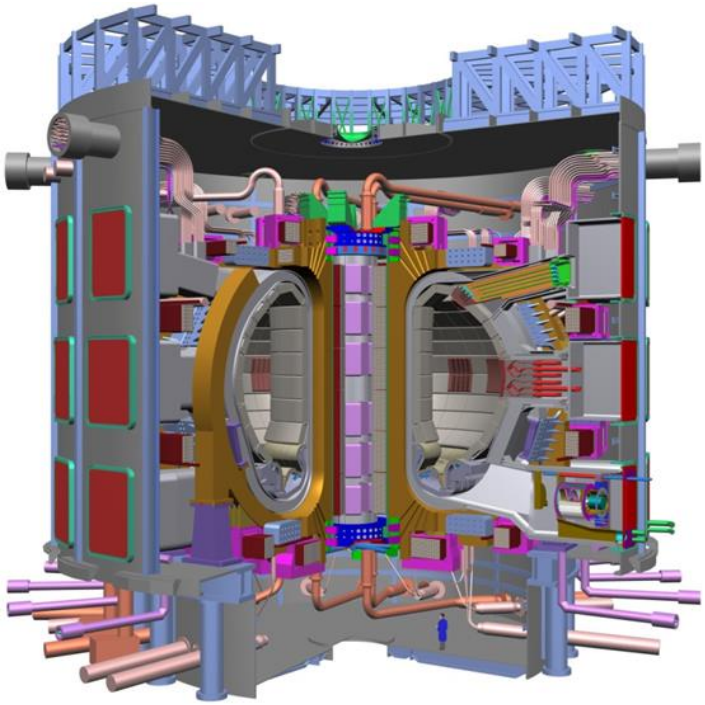
B. Tully and N. Hawker, Phys. Rev. **E93**, 053105 (2016)

A gas gun is used to eject the projectile

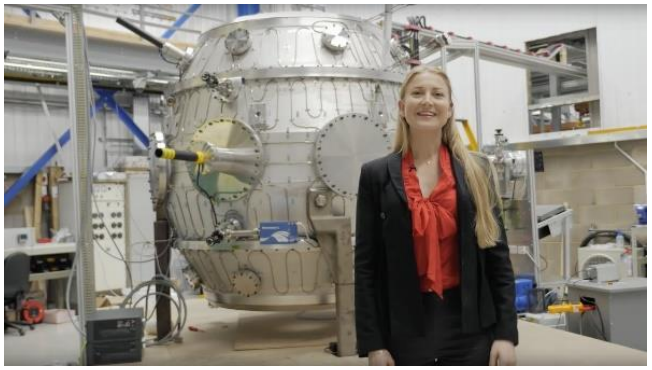
https://www.youtube.com/watch?v=JN7lyxC11n0
https://www.youtube.com/watch?v=aW4eufacf-8

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

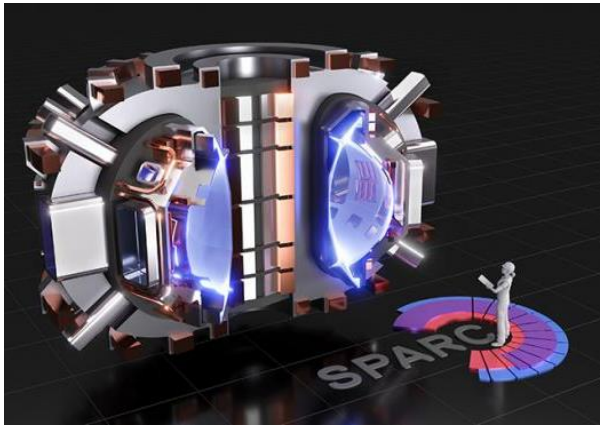
- ITER – 2025 First Plasma
  2035 D-T Exps
  2050 DEMO



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



- Commonwealth Fusion Systems, USA – 2025 Gain



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

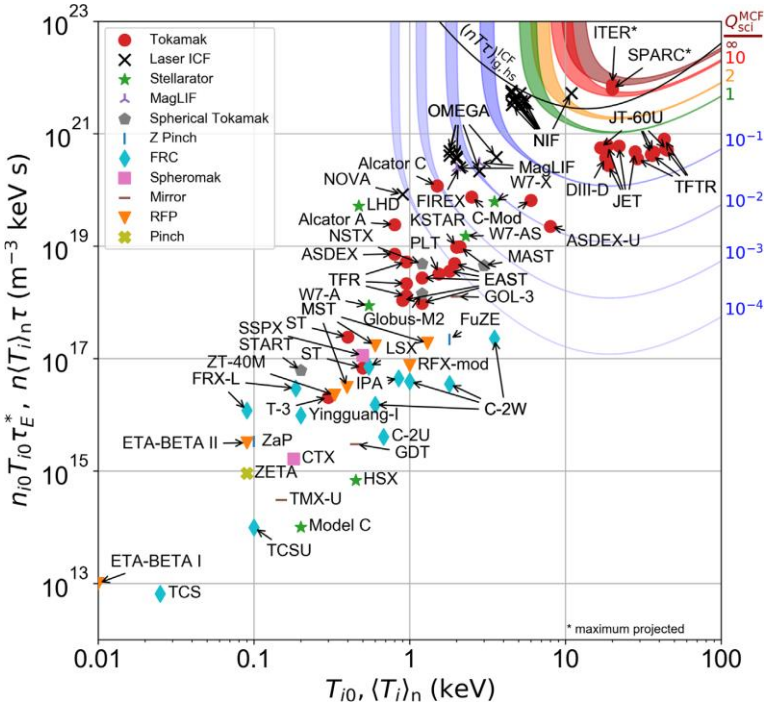
Fusion is blooming

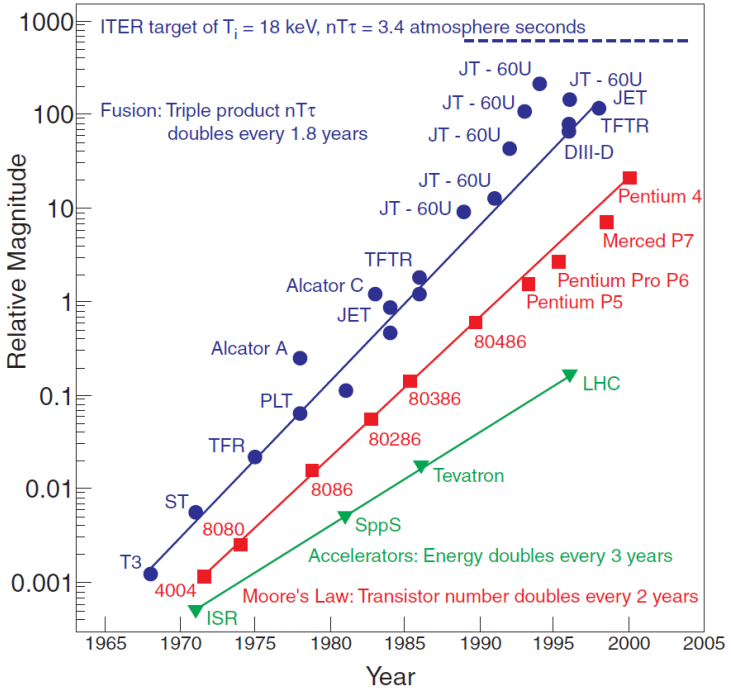
FUSION INDUSTRY ASSOCIATION

MCF MTF ICF

https://www.fusionindustryassociation.org/members

We are closed to ignition!





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