Introduction to Nuclear Fusion as An Energy Source

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Institute of Space and Plasma Sciences, National Cheng Kung University

Lecture 13

2025 spring semester

Tuesday 9:00-12:00

Materials:

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

Online courses:

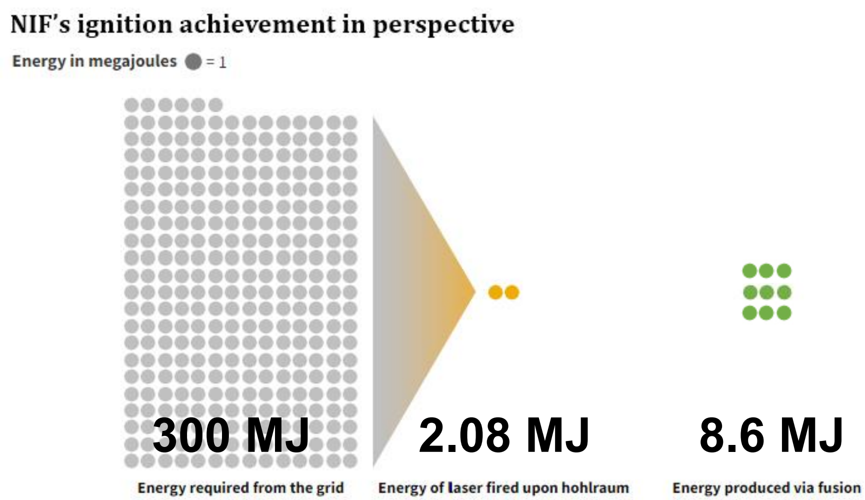
https://nckucc.webex.com/nckucc/j.php?MTID=mf1a33a5dab5eb71de9da4380ae888592

2025/6/10 updated

Note!

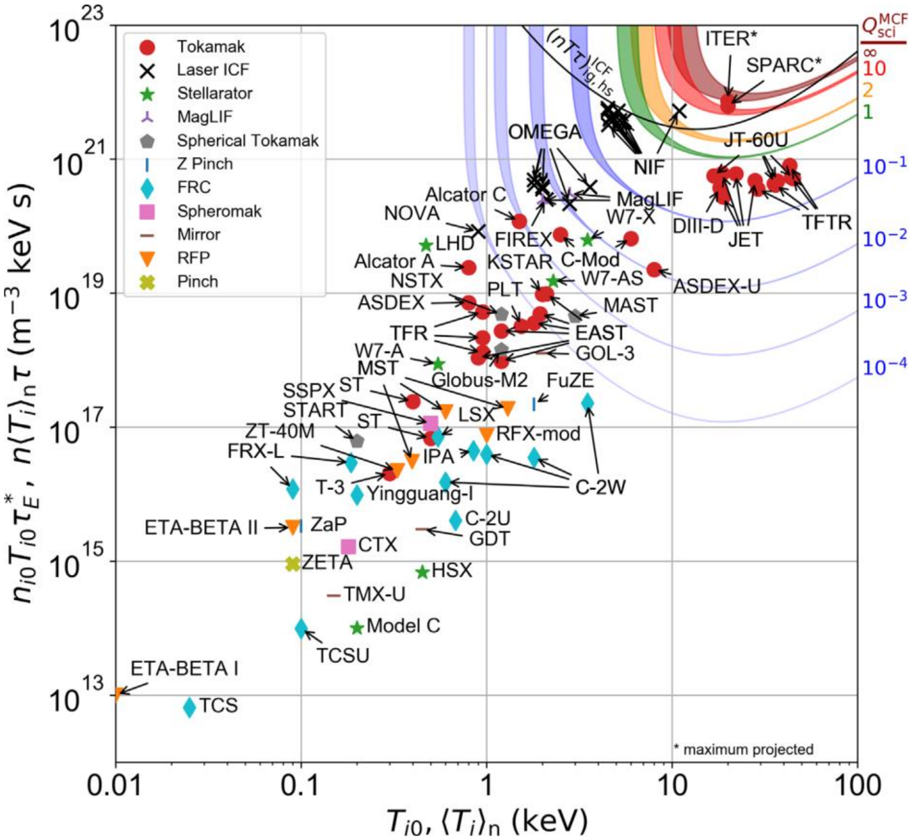
- 6/10
  - Introduction to Formosa Integrated Research Spherical Tokamak (FIRST), First Tokamak being developed in Taiwan.
  - Alternative approaches to achieve nuclear fusion as an energy source.
- 6/17 Q&A

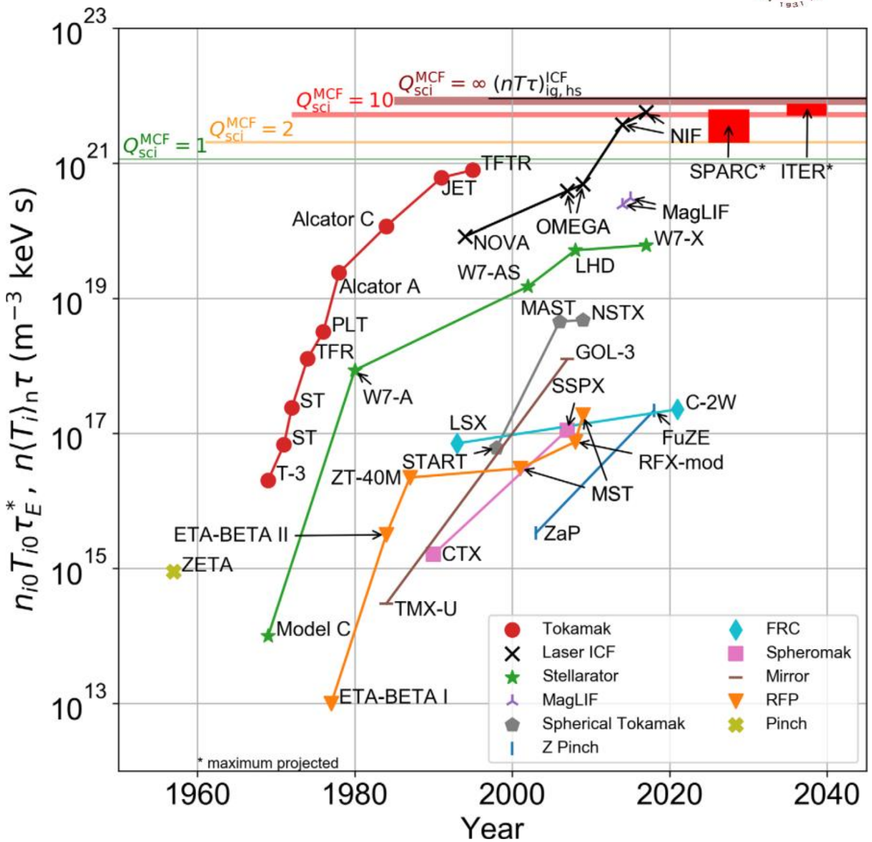
"Ignition" (target gain larger than one) was achieved in National Ignition Facility (NIF) on 2022/12/5



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

We are closed to ignition!

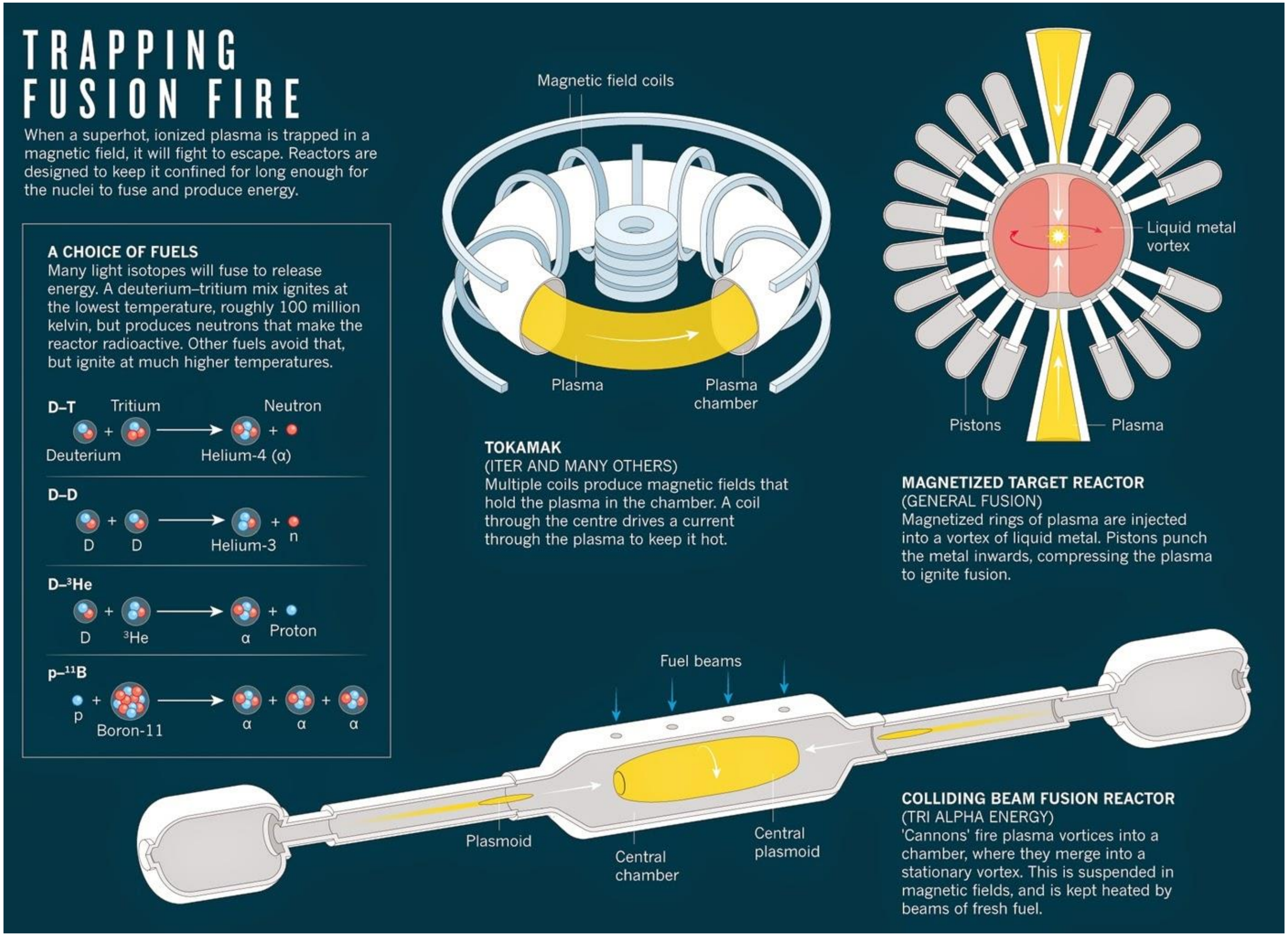




- **Lawson criteria (Ignition condition): Pτ > 10 atm-s = 10 Gbar - ns**
  - **P: pressure, or called energy density**
  - **τ is confinement time**

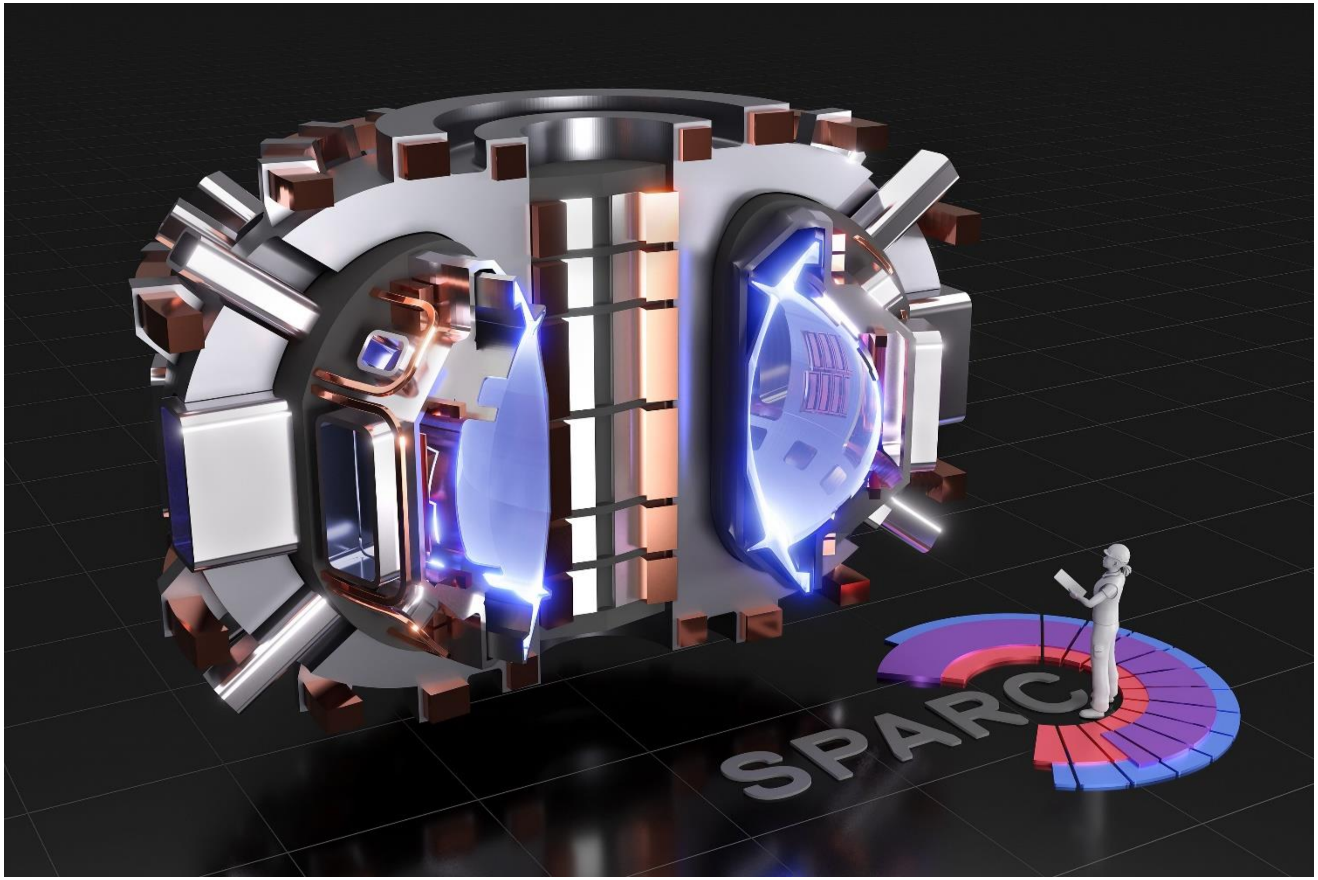
Samuel E. Wurzel and Scott C. Hsu, Phys. Plasmas, **29**, 062103 (2022)

There are alternative



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

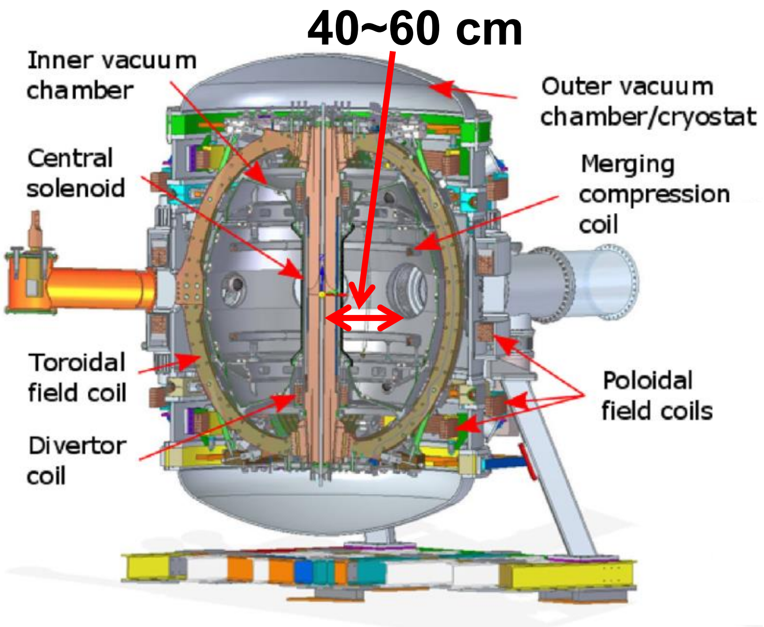
Commonwealth Fusion Systems, a MIT spin-out company, is building a high-magnetic field tokamak



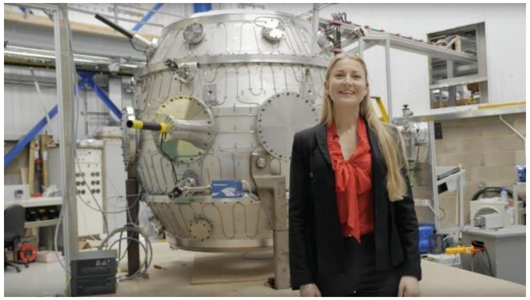
- **Fusion power ∝ B^4.**
- **The fusion gain Q > 2 is expected for SPARC tokamak.**

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

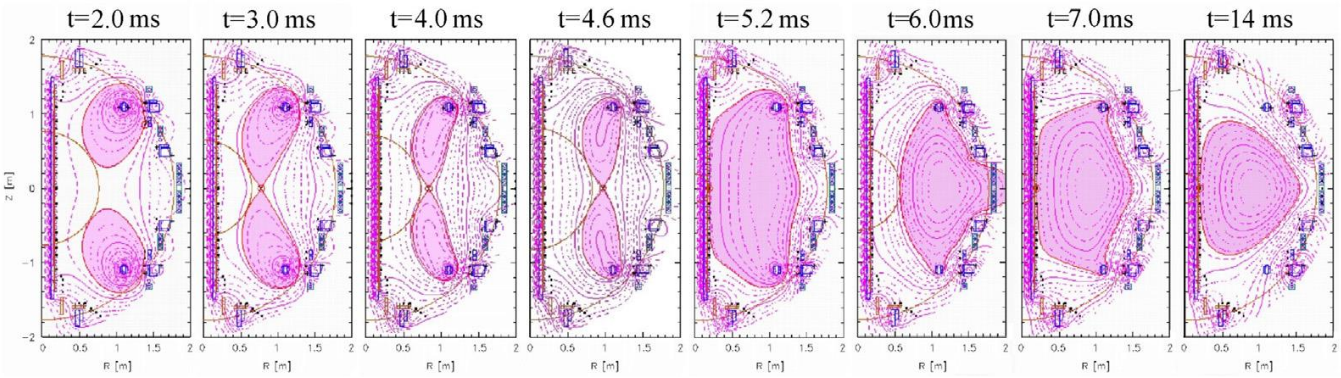
Merging compression is used to heat the tokamak at the start-up process in ST40 Tokamak at Tokamak Energy Ltd



- **High temperature superconductors are used.**
- **$B_T \sim 3$ T**

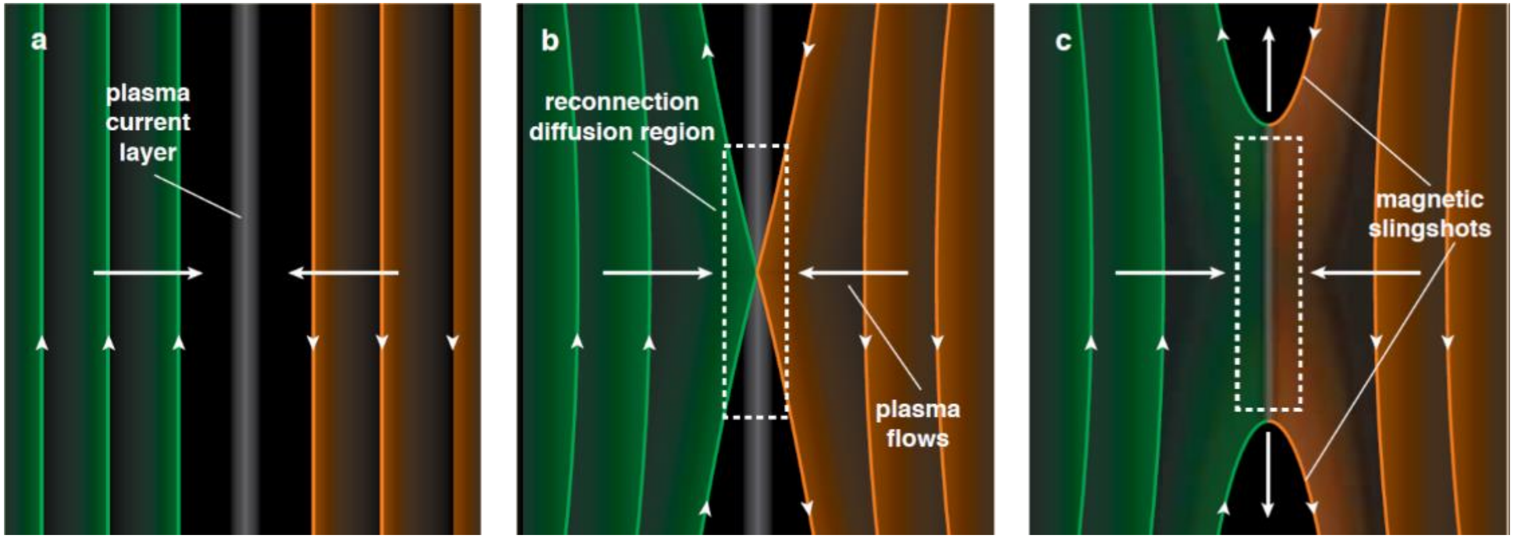


- **Merging compression**



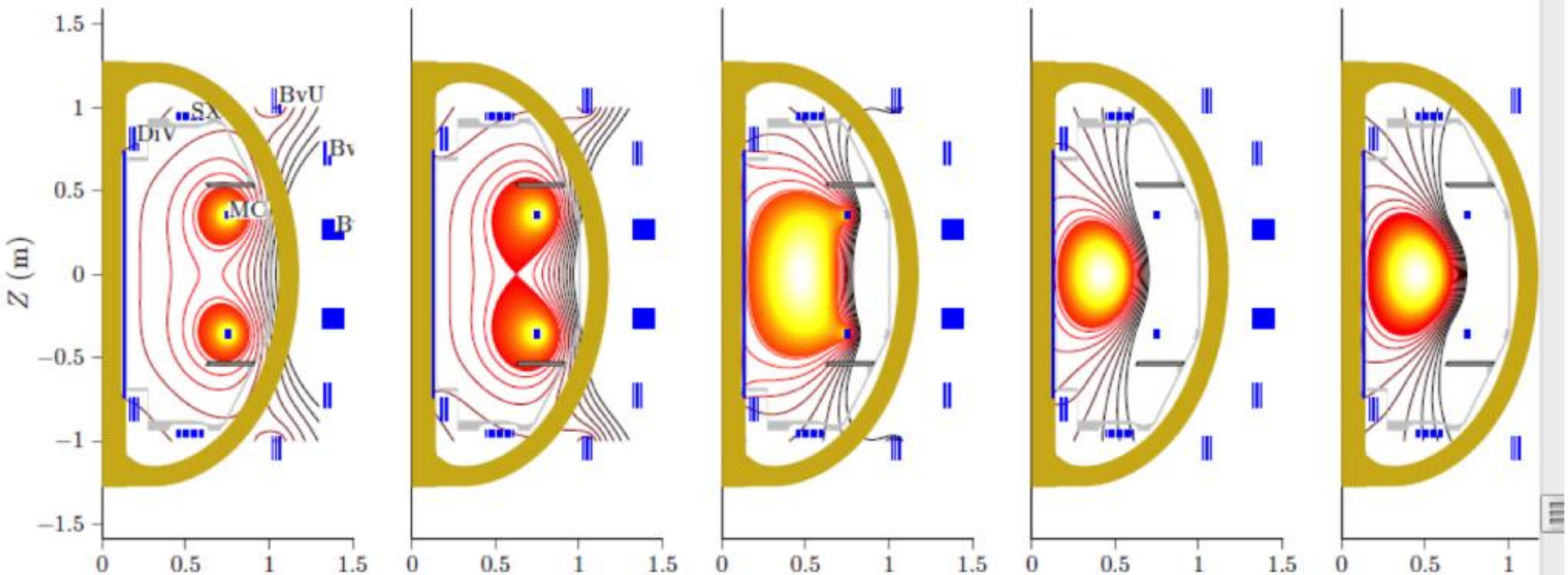
M. Gryaznevich, etc., Fusion Eng. Design, **123**,177 (2017)
https://www.tokamakenergy.co.uk/
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

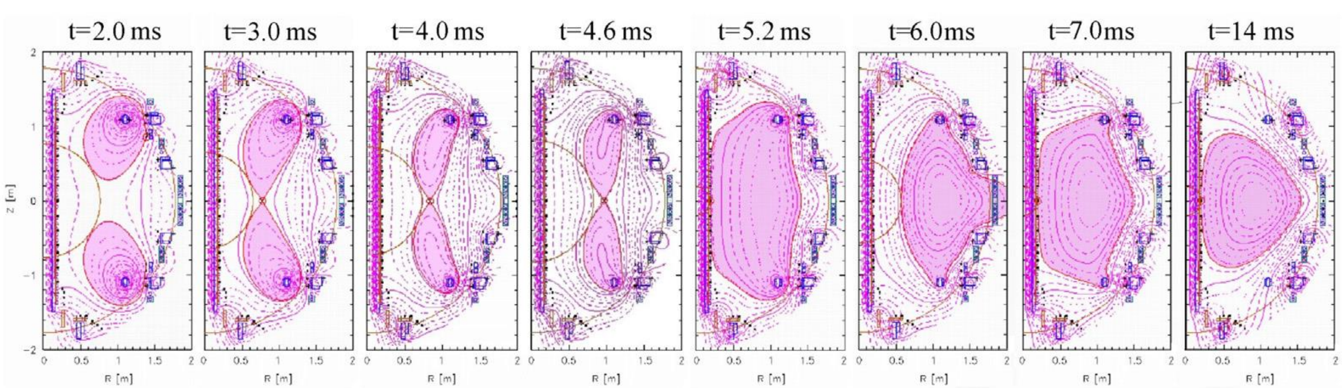
Reconnection



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

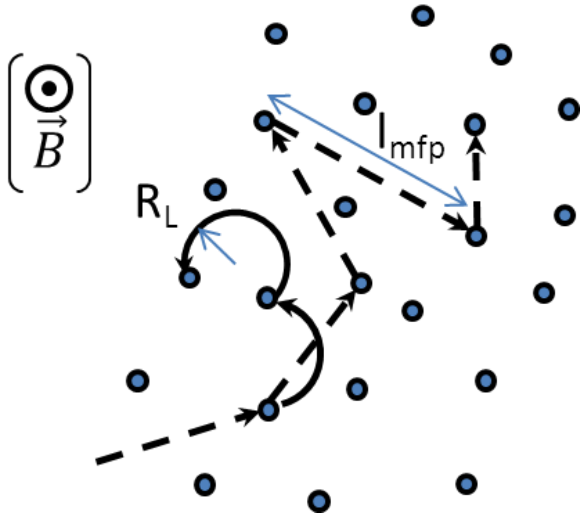
Merging compression is used to heat the plasma





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

A strong magnetic field reduces the heat flux



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

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

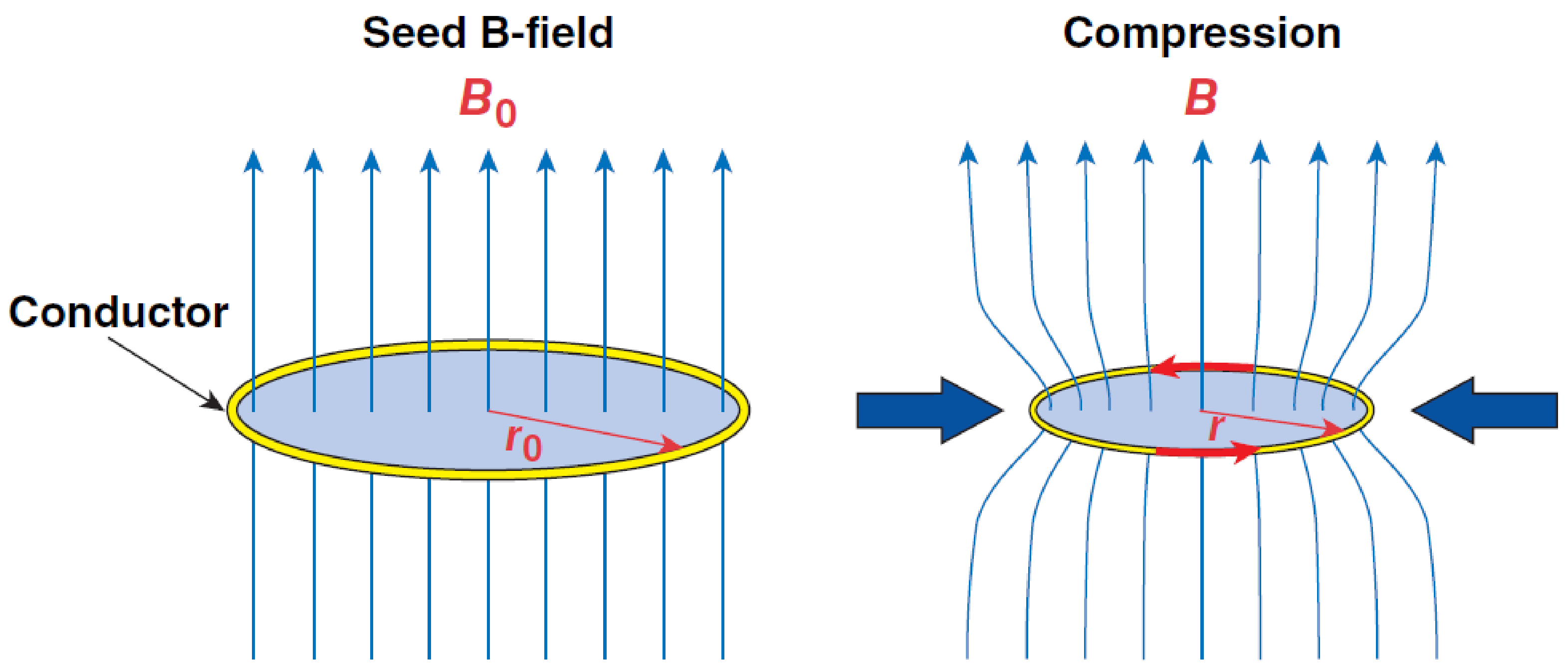
$$\kappa_{\perp} = \frac{\kappa_{||}}{\chi^2} \quad \text{for large Hall parameter } \chi \propto \frac{l_{mfp}}{R_L} >> 1$$

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

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

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

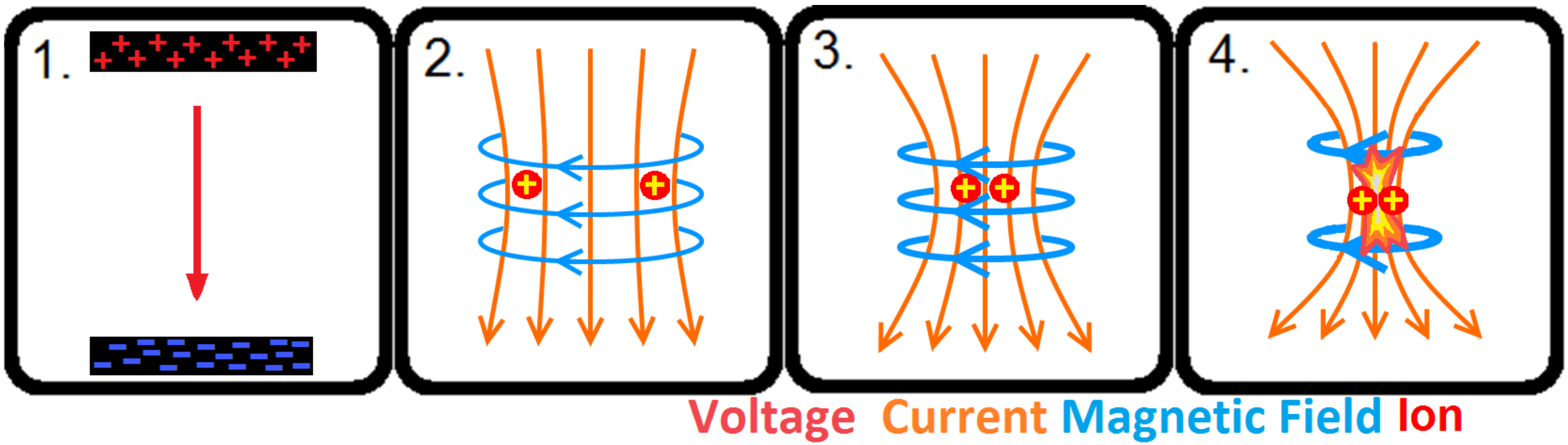
Principle of frozen magnetic flux in a good conductor is used to compress fields



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

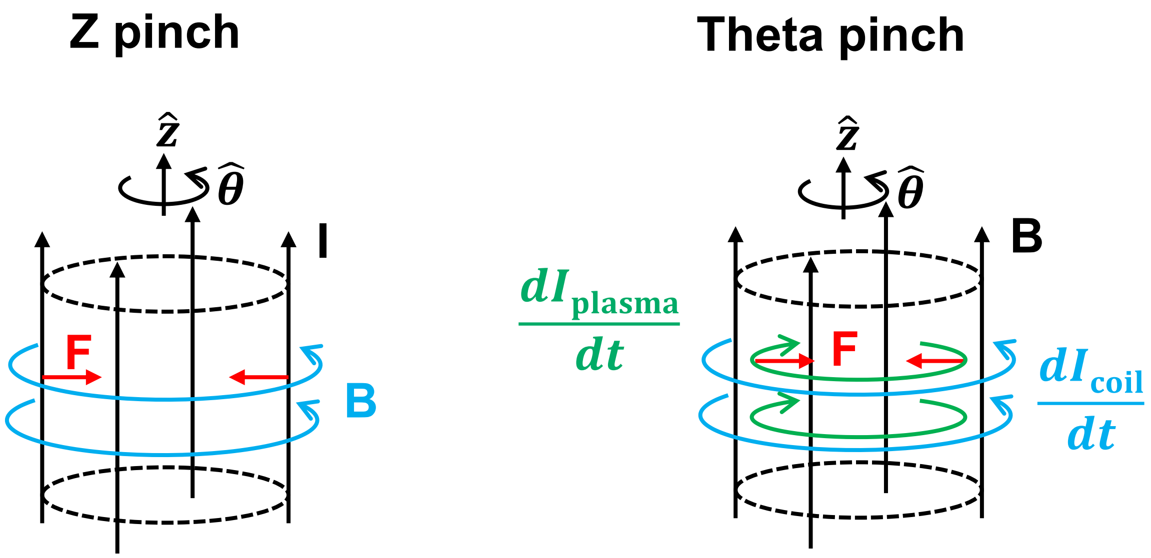
M. Hohenberger, P.-Y. Chang, *et al.*, Phys. Plasmas 19, 056306 (2012).

Plasma can be pinched by parallel propagating plasmas

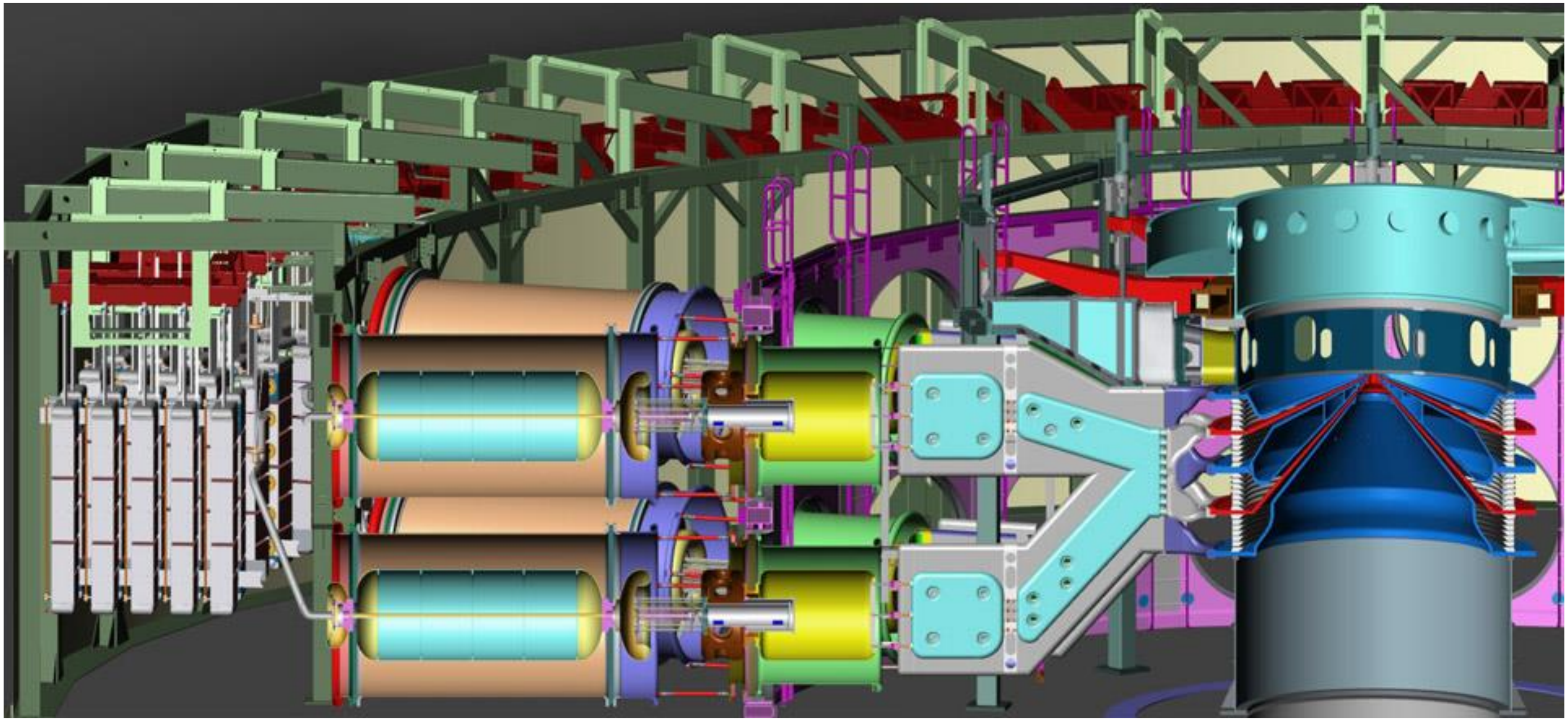


https://en.wikipedia.org/wiki/Pinch_(plasma_physics)

Plasma can be heated via pinches



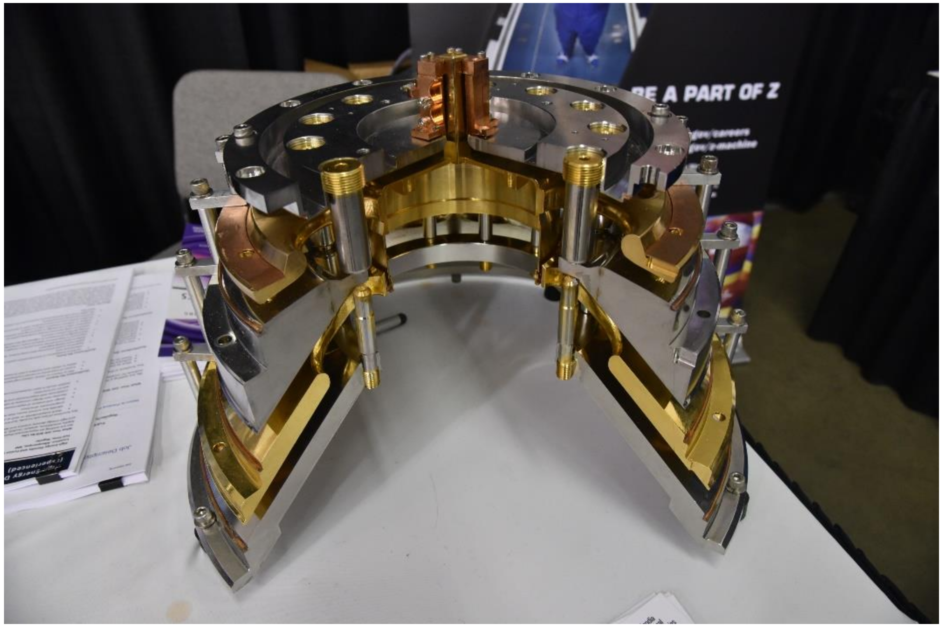
Sandia's Z machine is the world's most powerful and efficient laboratory radiation source



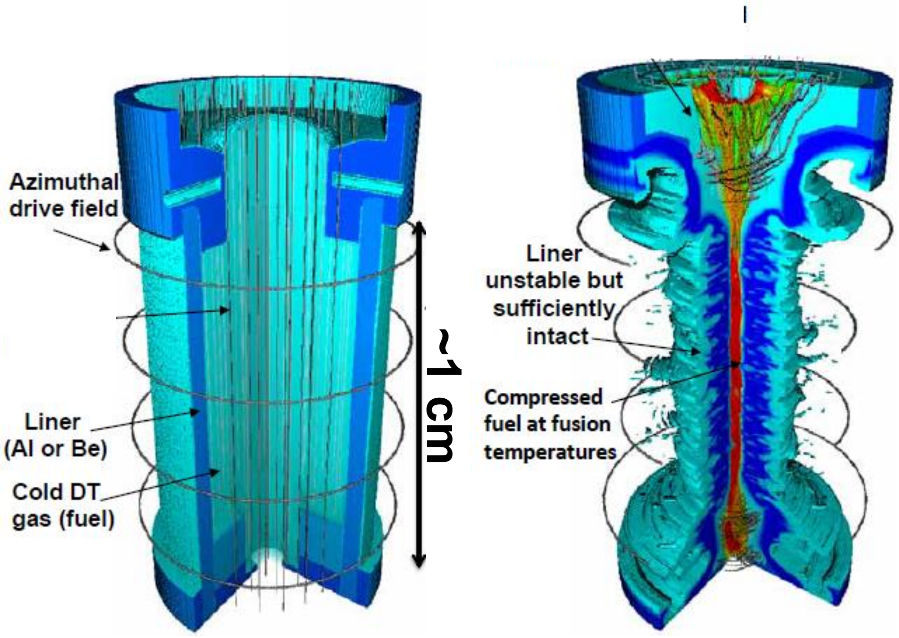
- Stored energy: 20 MJ
- Marx charge voltage: 85 kV
- Peak electrical power: 85 TW

- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray emissions: 350 TW
- Peak X-ray output: 2.7 MJ

Z machine



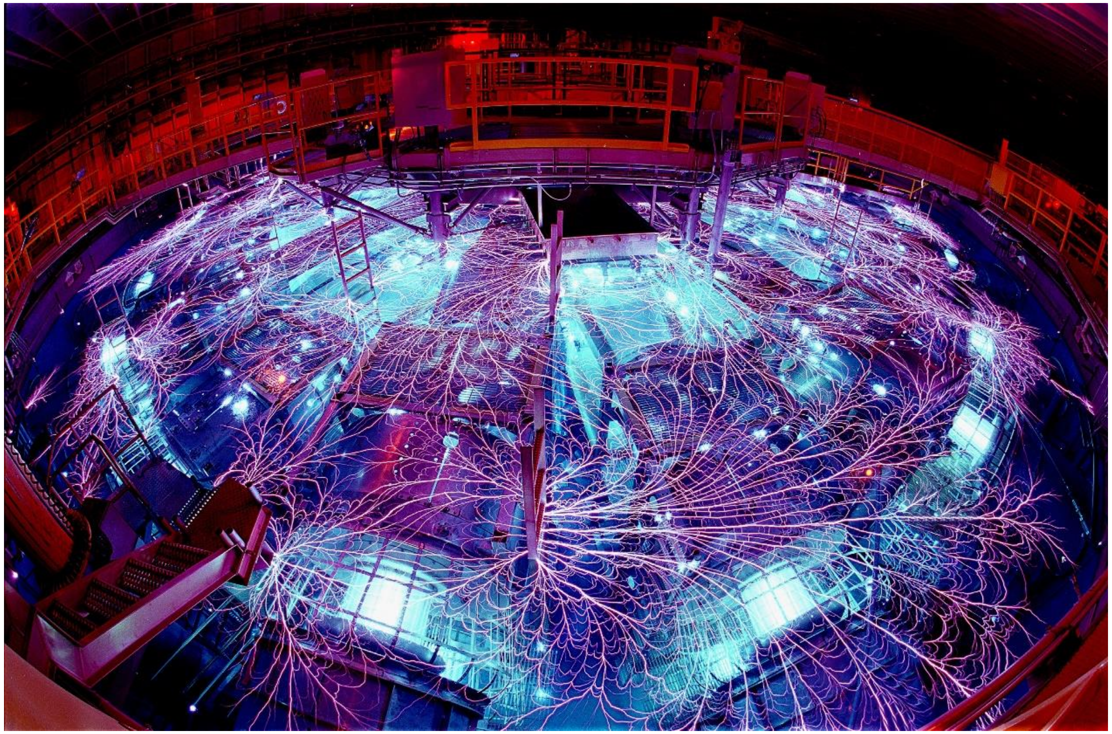
Z machine



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

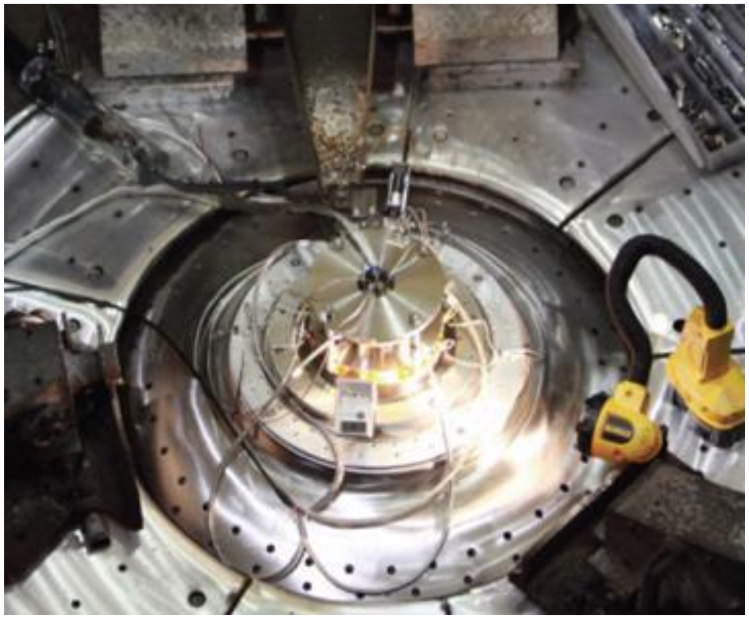
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray output: 2.7 MJ

Z machine discharge



Before and after shots

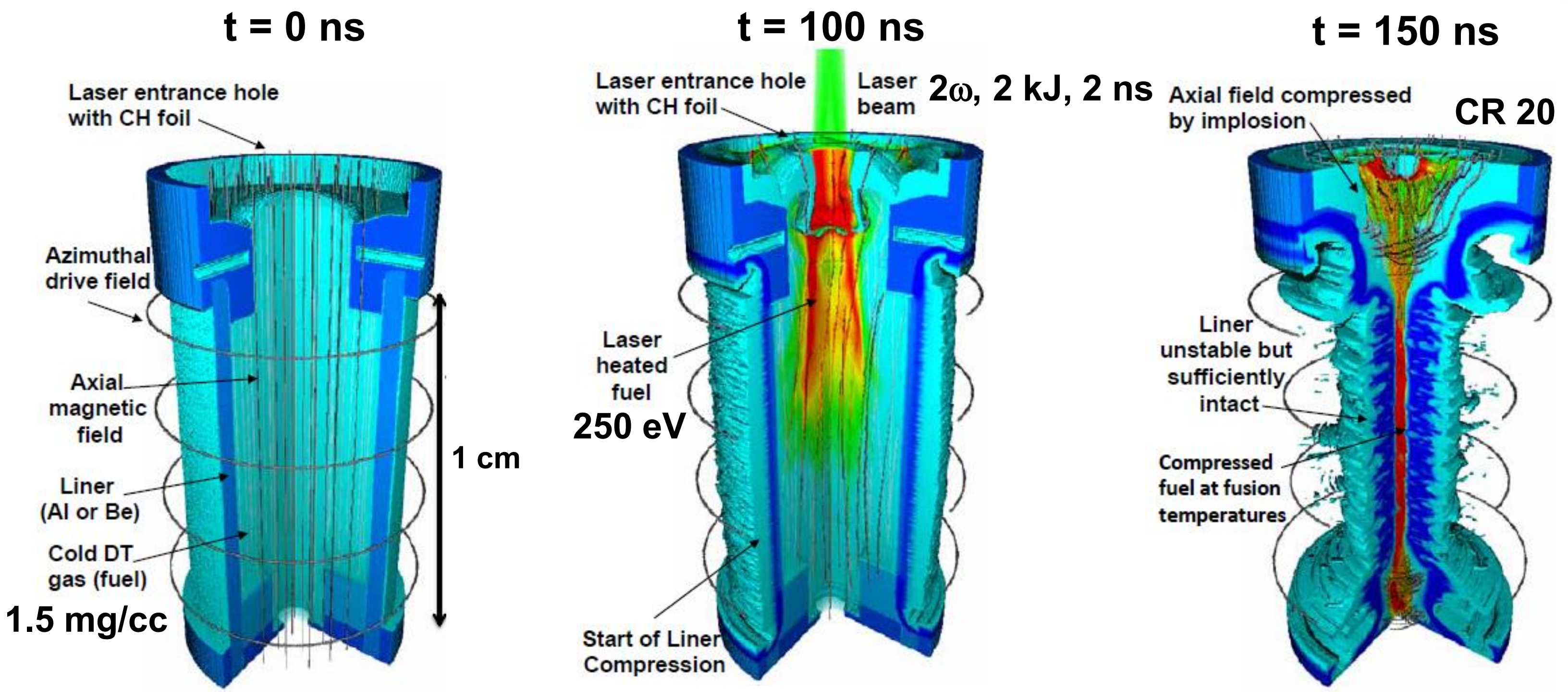
- **Before shots**



- **After shots**

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

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



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

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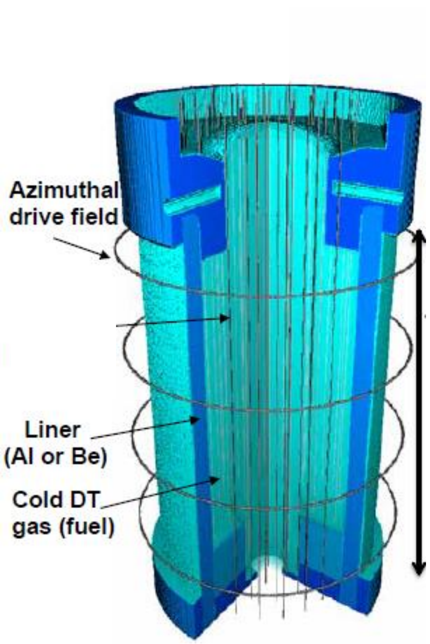
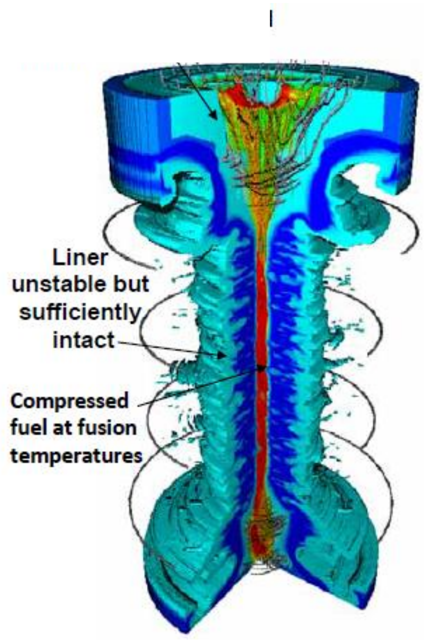
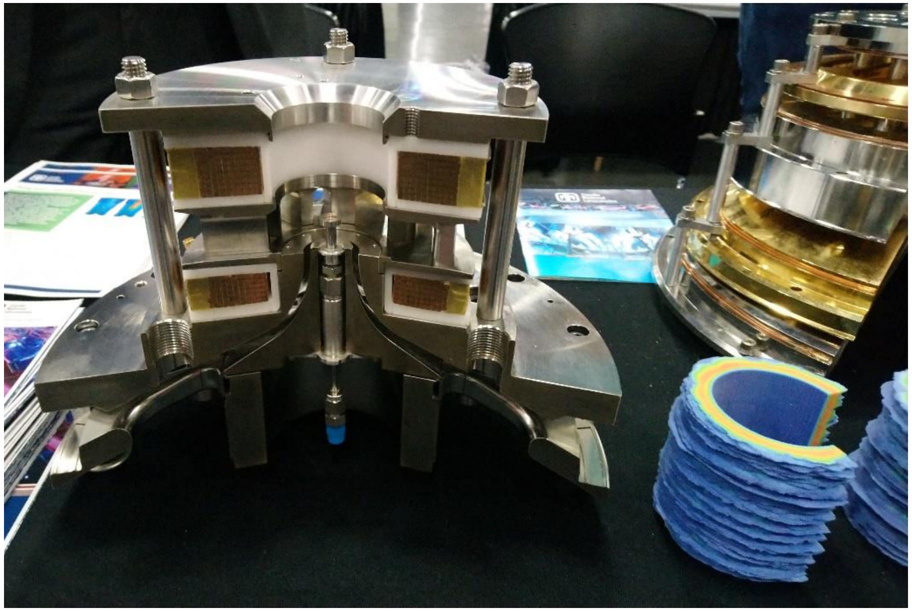
S. A. Slutz *et al* Phys. Plasmas 17 056303 (2010)
M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)

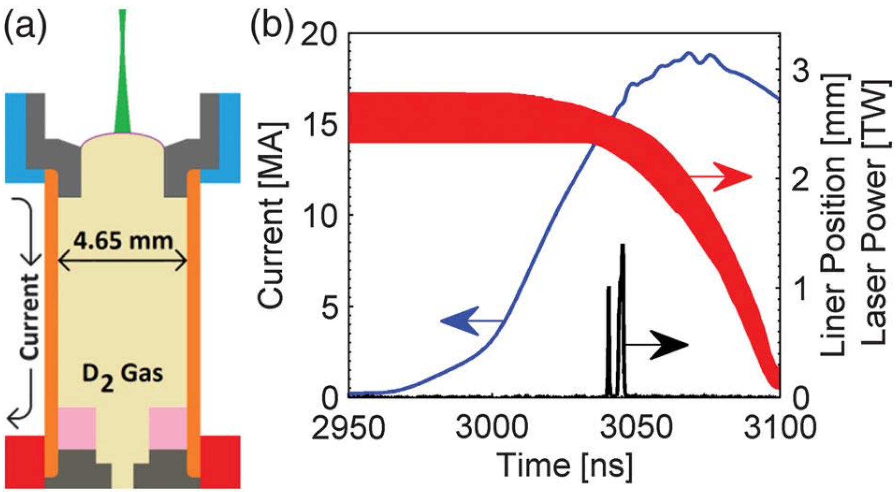
MagLIF target

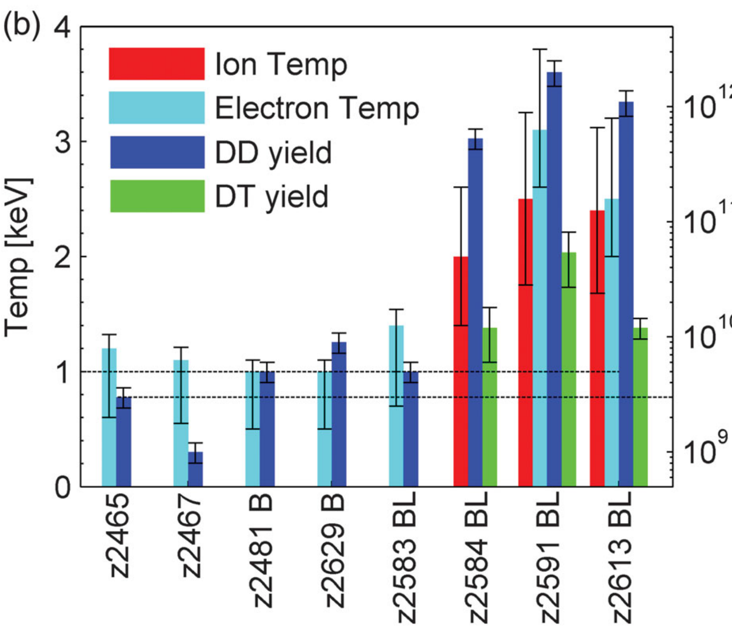






Neutron yield increased by 100x with preheat and external magnetic field.





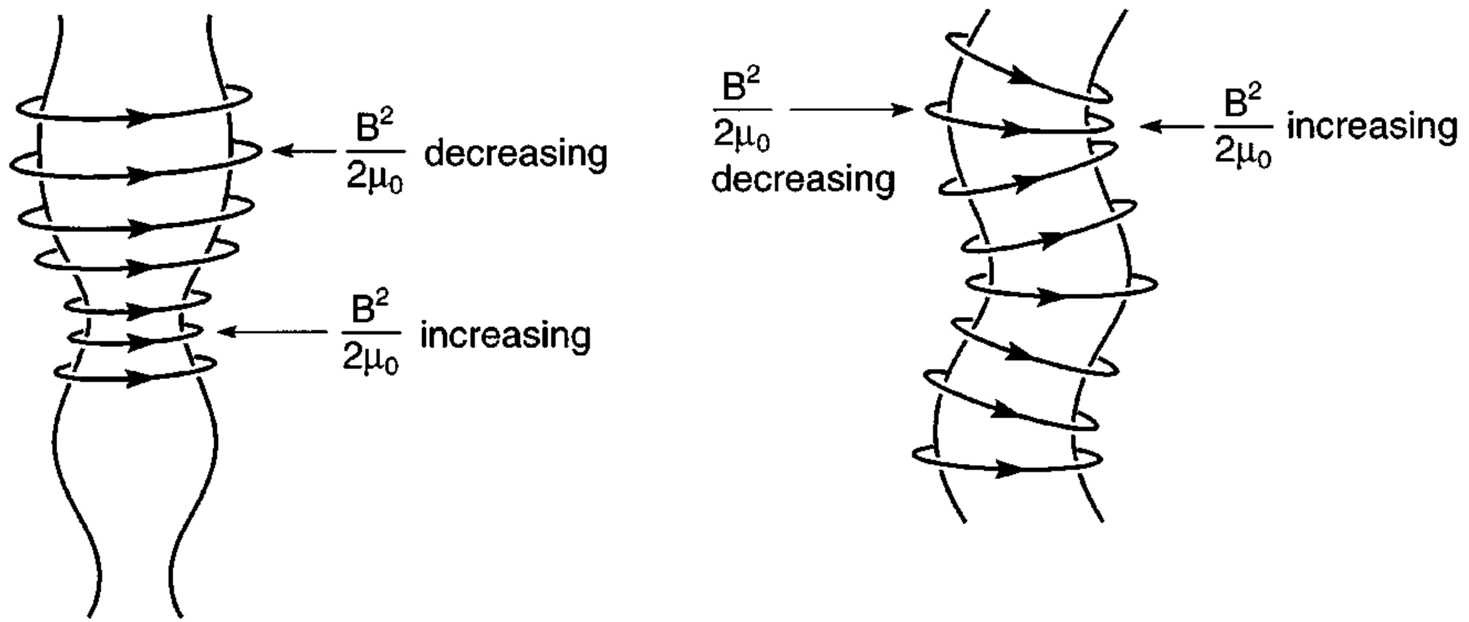
M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)

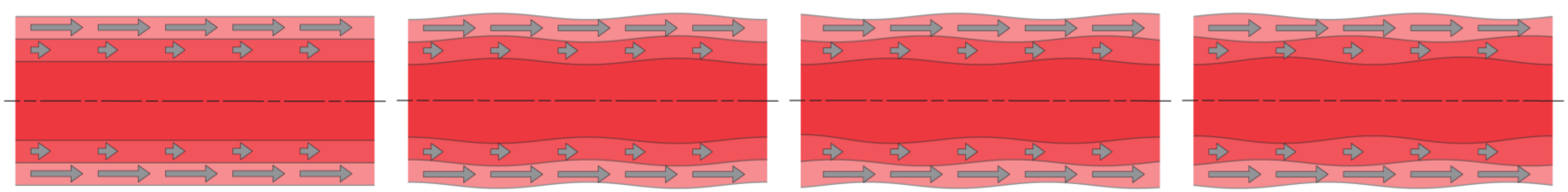
Sheared flow stabilizes MHD instabilities

m = 0 (sausage)

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

m = 1 (kink)

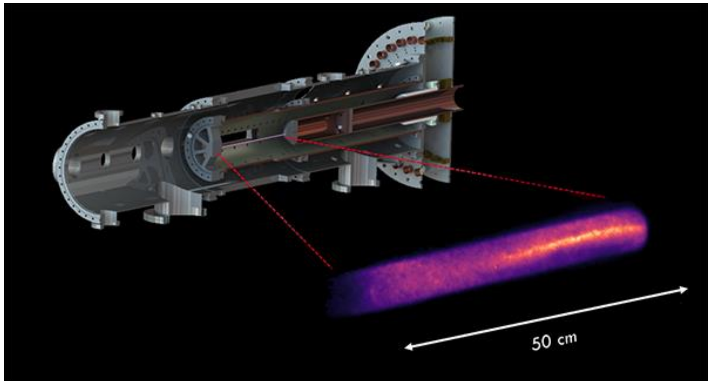


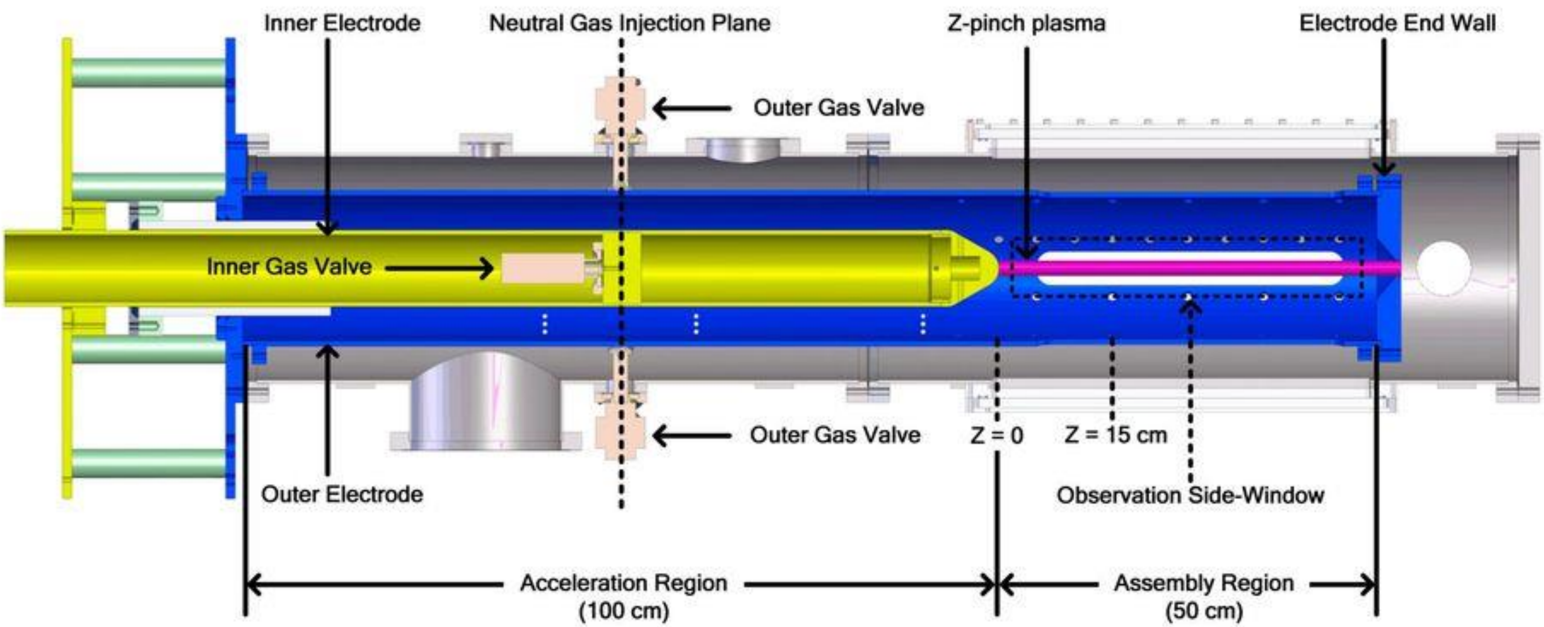


$$\frac{dV_Z}{dr} \neq 0$$

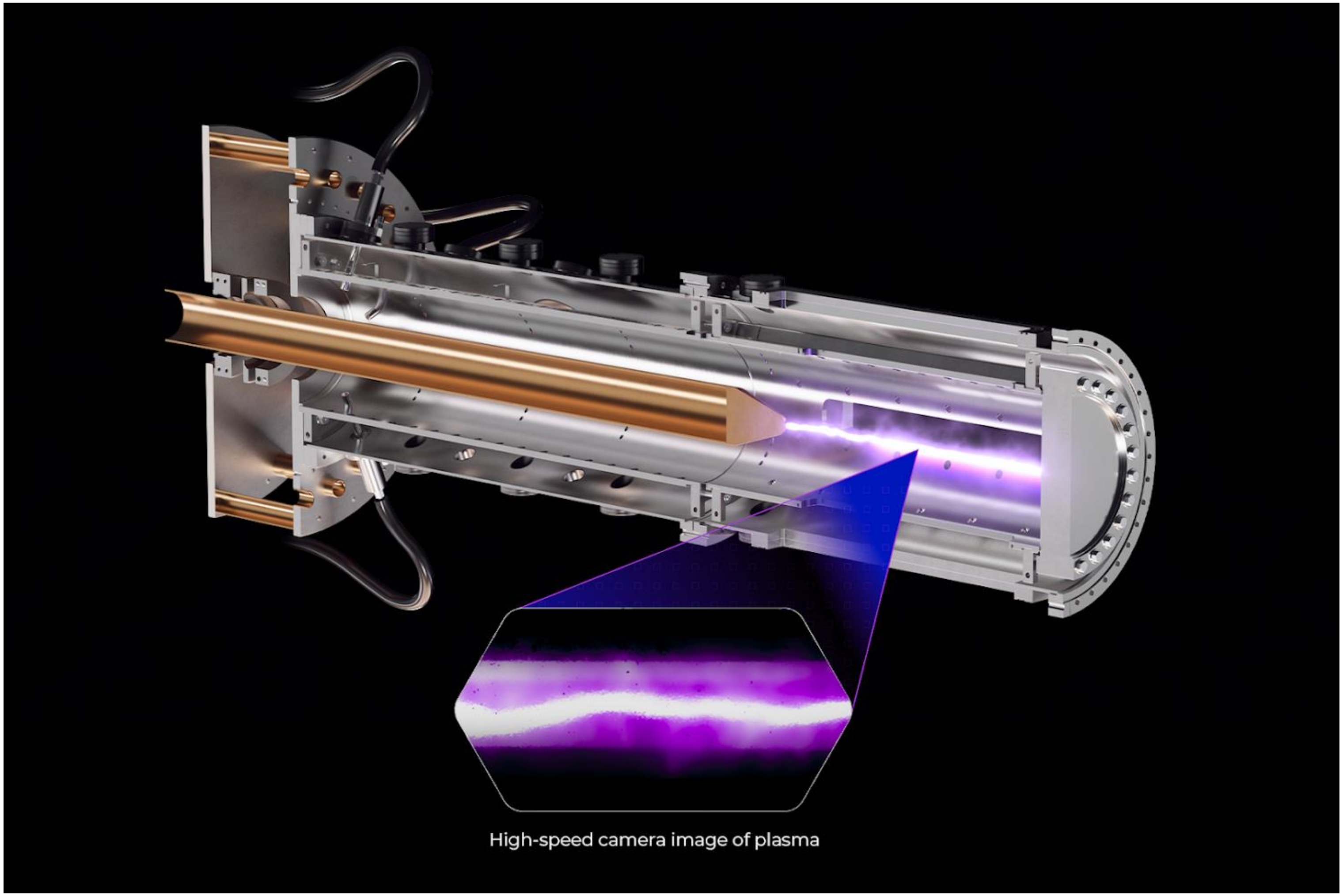
M. G. Haines, etc., Phys. Plasmas 7, 1672 (2000)
U. Shumlak, etc., Physical Rev. Lett. 75, 3285 (1995)
U. Shumlak, etc., ALPHA Annual Review Meeting 2017

A z-pinch plasma can be stabilized by sheared flows



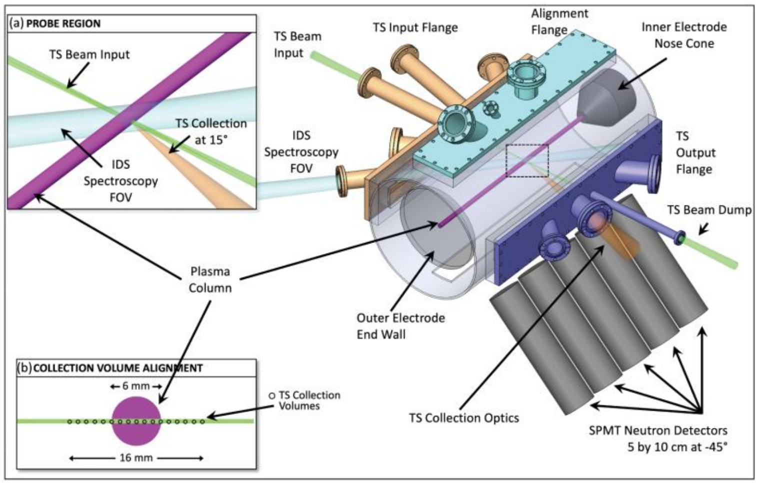


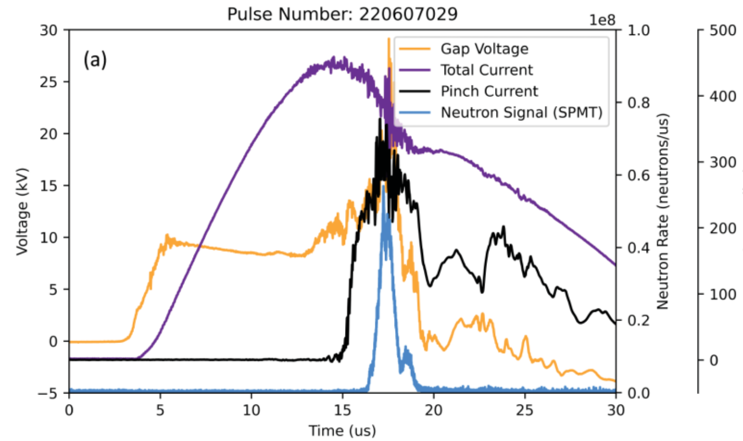
https://www.zapenergyinc.com/about
A. D. Stepanov, etc., Phys. Plasmas 27, 112503 (2020)

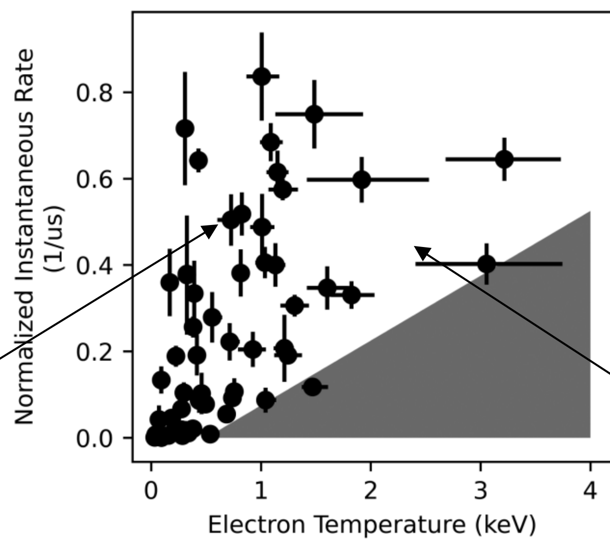


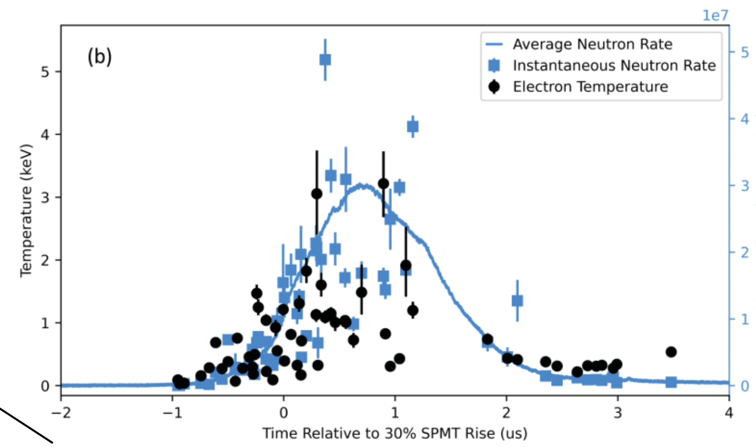
https://www.powerelectronicsnews.com/zap-energys-vision-for-fusion-power/

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







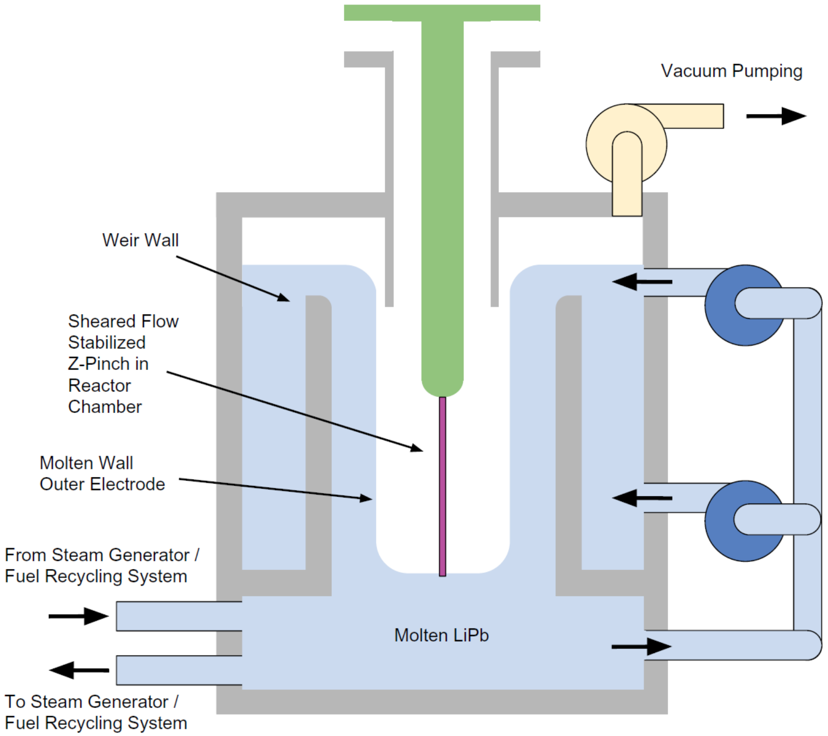


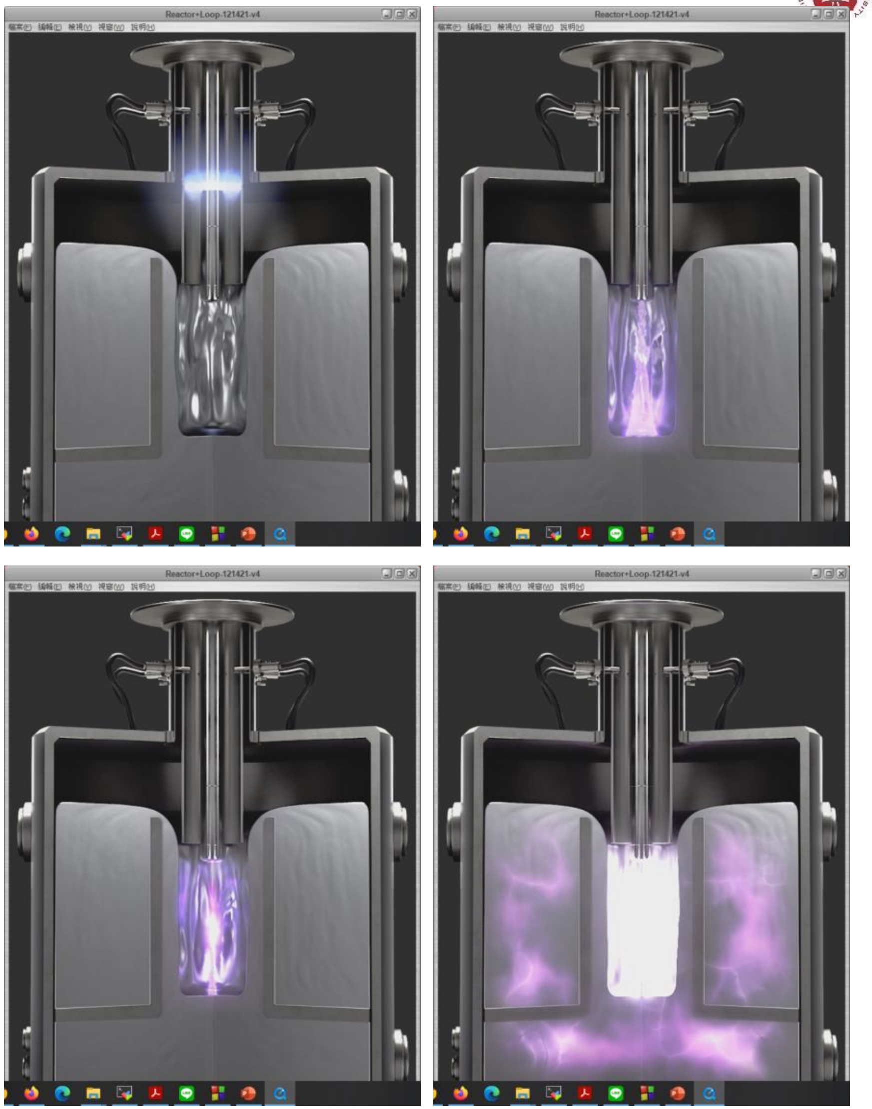
- Thomson scattering measurement missed the high temperature region.

- High temperature coincide with high rate.

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

Fusion reactor concept by ZAP energy

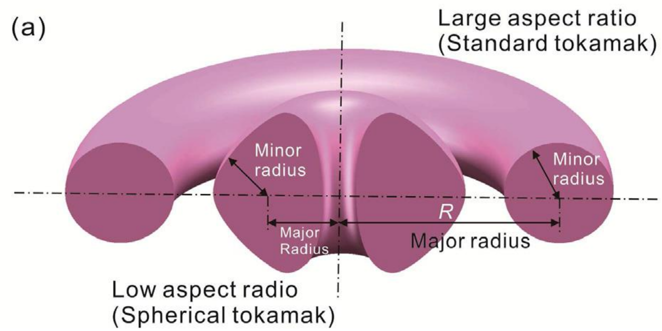




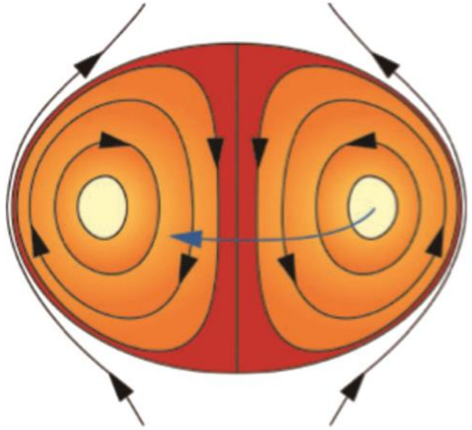
https://www.zapenergyinc.com/about
E. G. Forbes, etc., Fusion Sci. Tech. 75, 599 (2019)

Spherical torus (ST) and compact torus (CT)

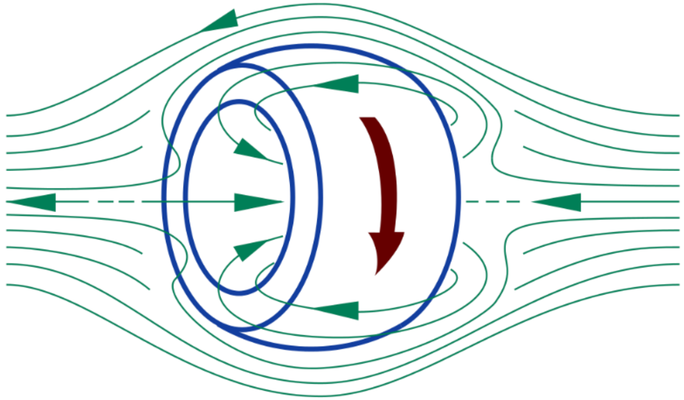
- **Spherical torus (ST)**



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

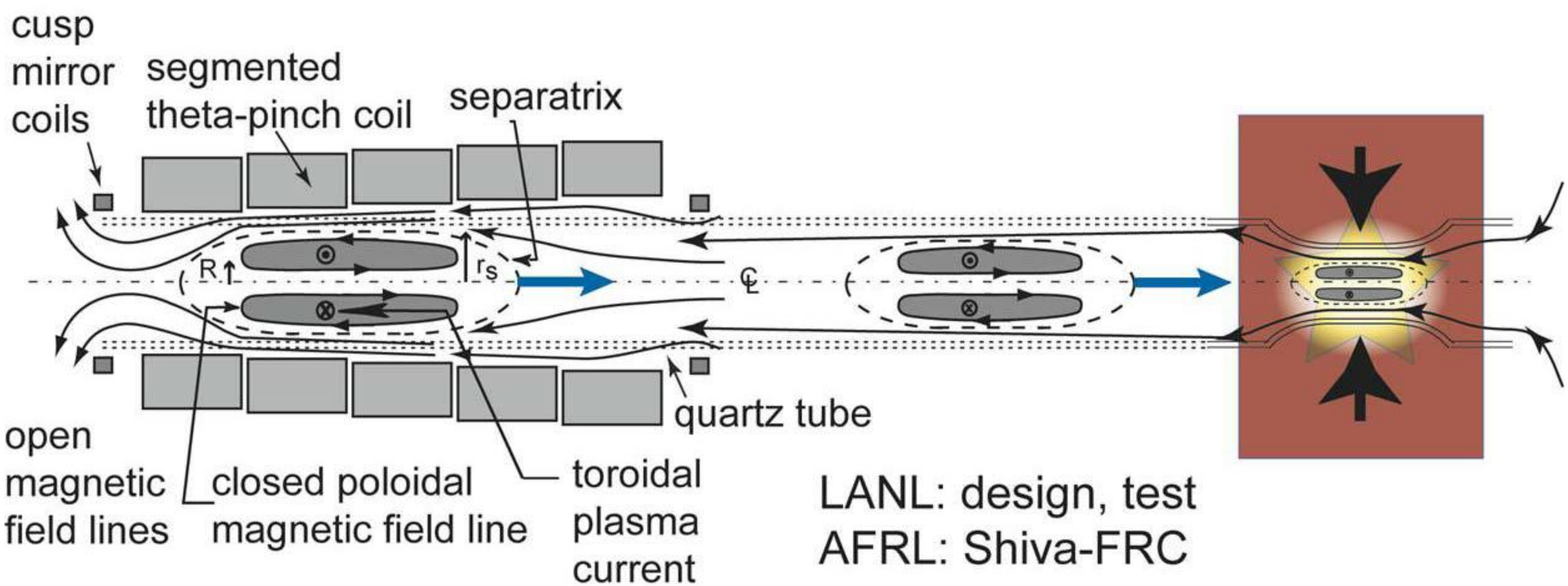


  - **Field reversed configuration (FRC)**

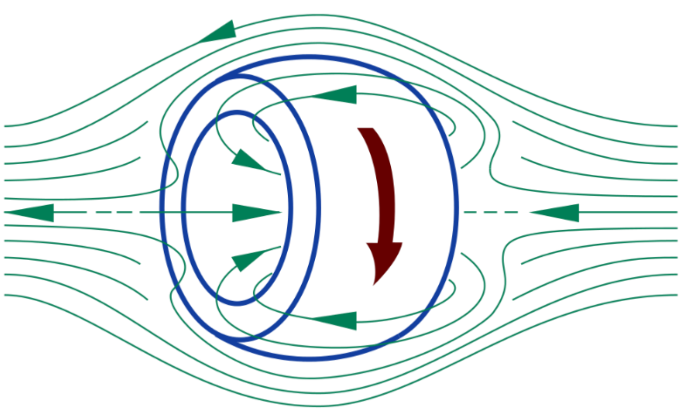


Zhe Gao, Matter Radiat. Extremes **1**, 153 (2016)
https://en.wikipedia.org/wiki/Field-reversed_configuration

Field reverse configuration is used in Tri-alpha energy



LANL: design, test
AFRL: Shiva-FRC



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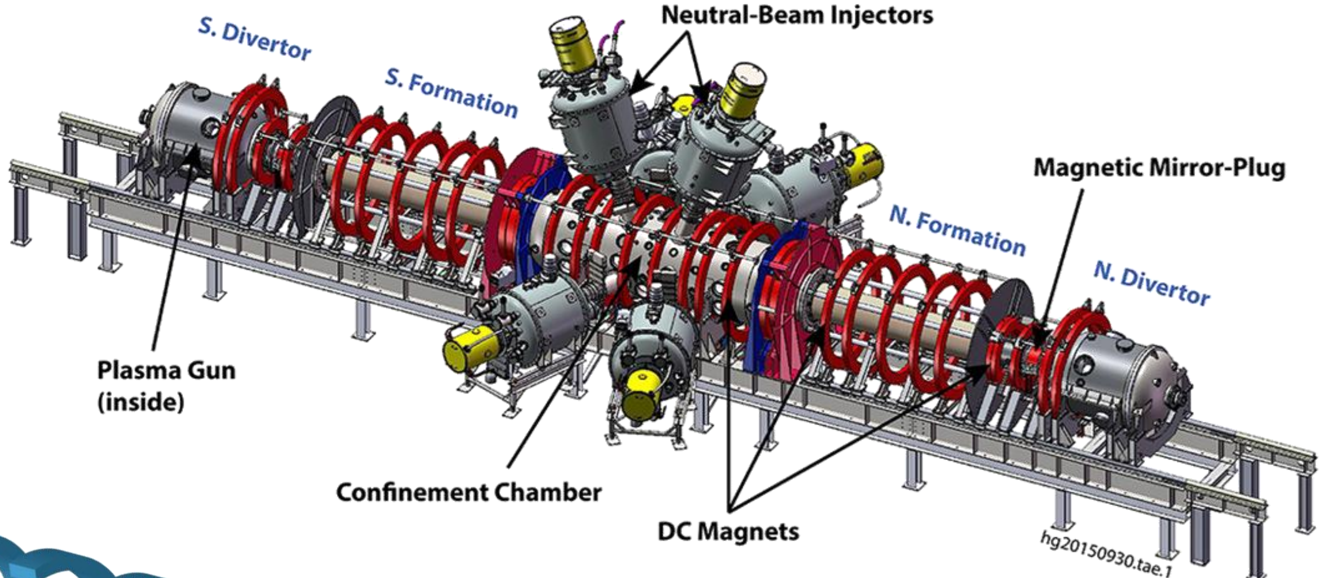
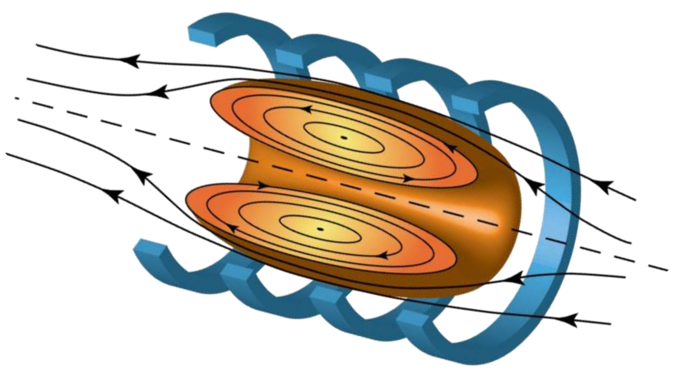
*Magneto-Inertial Fusion& Magnetized HED Physics by Bruno S. Bauer, UNR & Magneto-Inertial Fusion Community
**https://en.wikipedia.org/wiki/Field-reversed_configuration

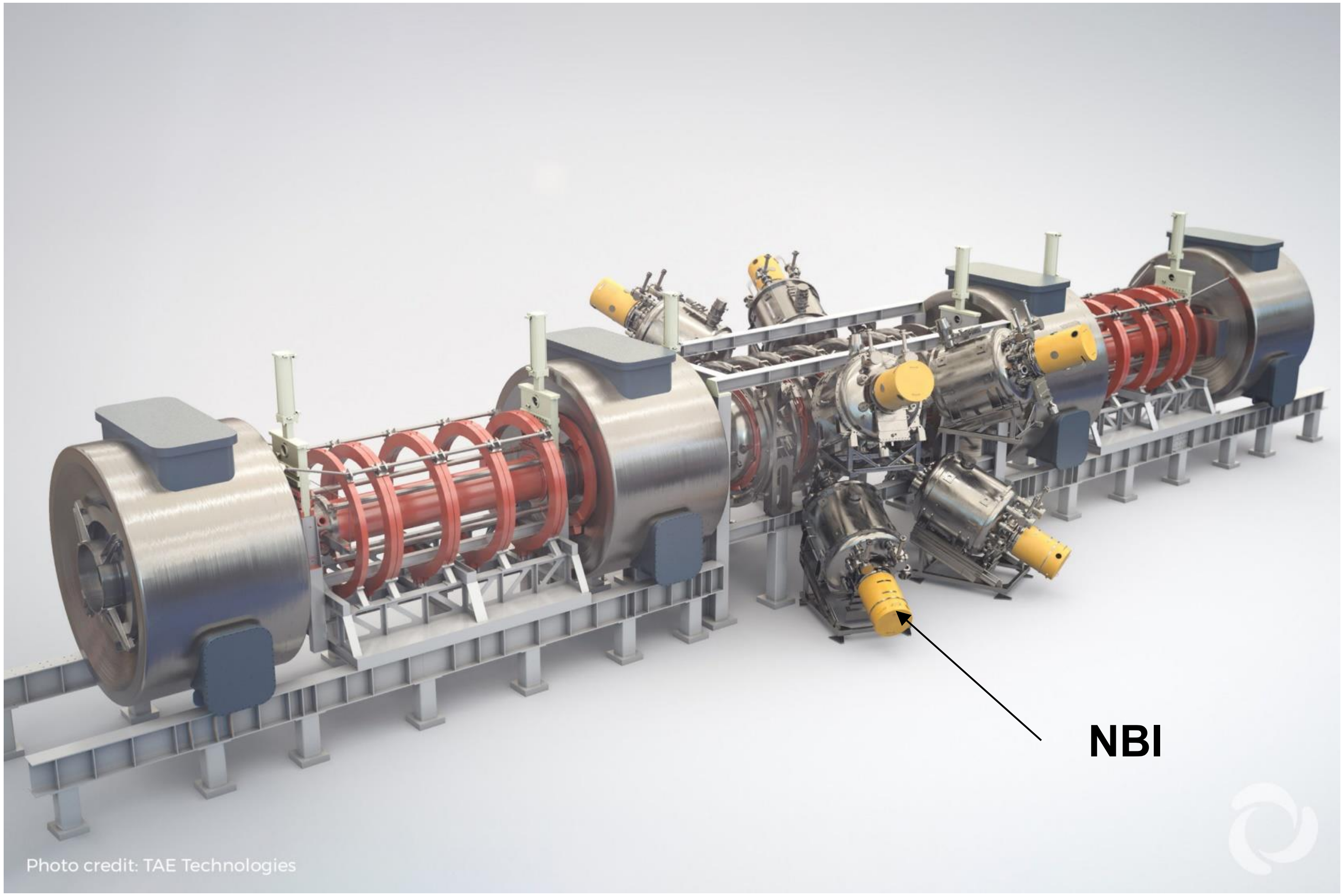
Field reverse configuration is used in Tri-alpha energy





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

NBI for Tri-Alpha Energy Technologies

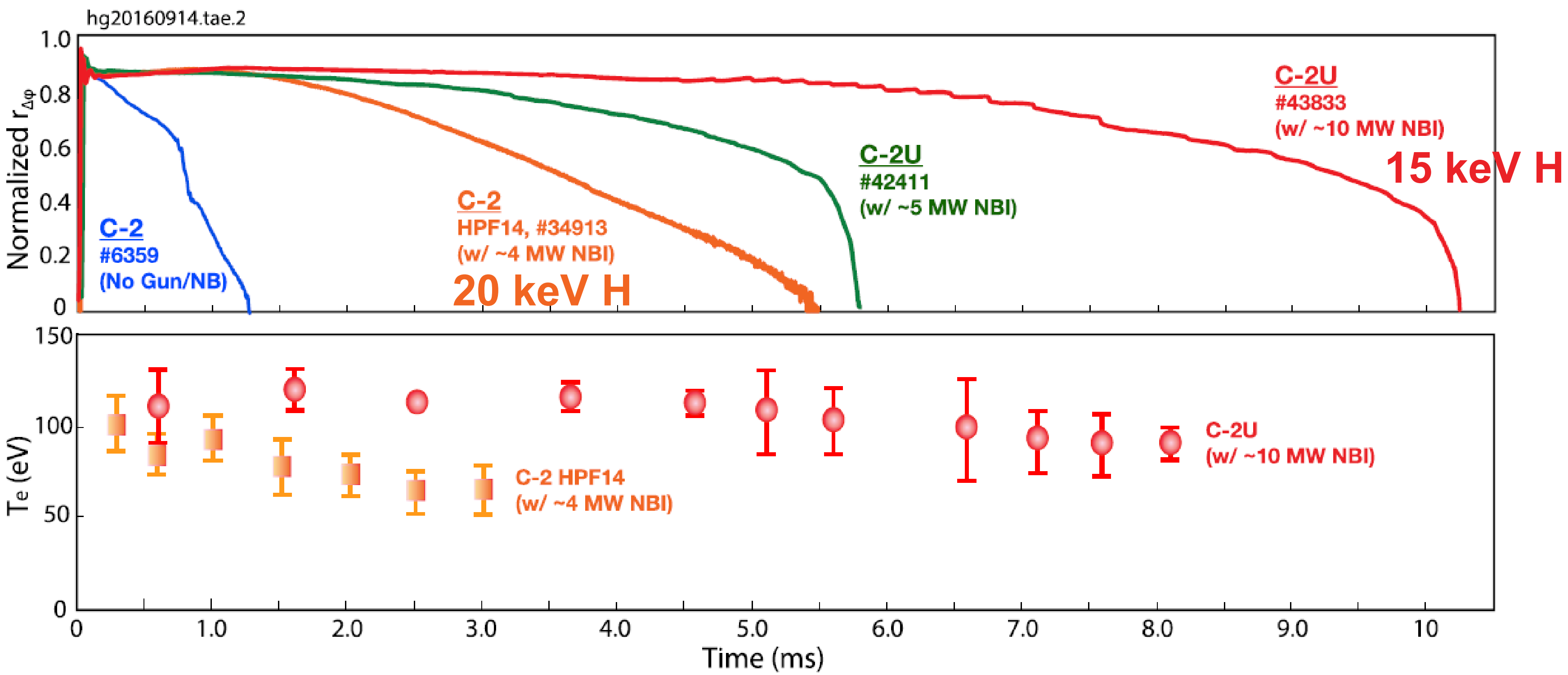


https://tae.com/media/

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

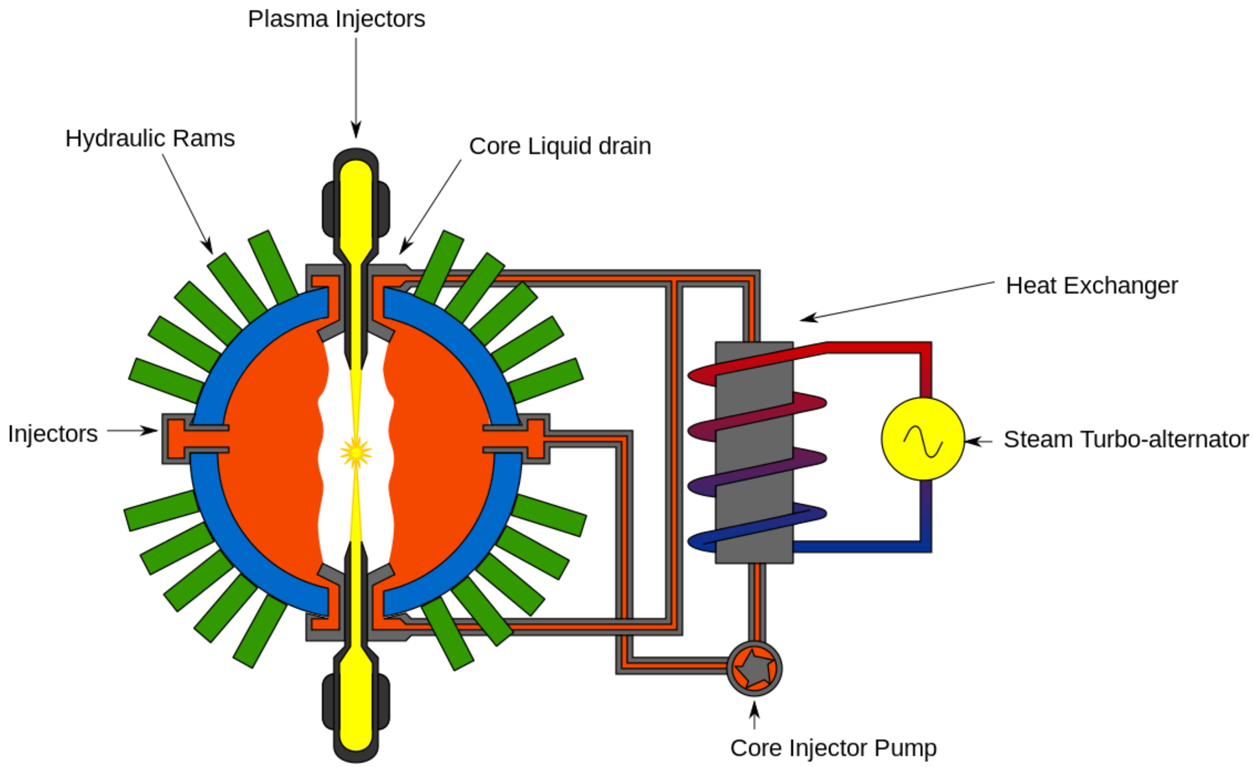
https://tae.com/media/
https://zh.wikihow.com/%E5%9C%A8%E6%89%8B%E6%8C%87%E4%B8%8A%E8%BD%AC%E7%AF%AE%E7%90%83

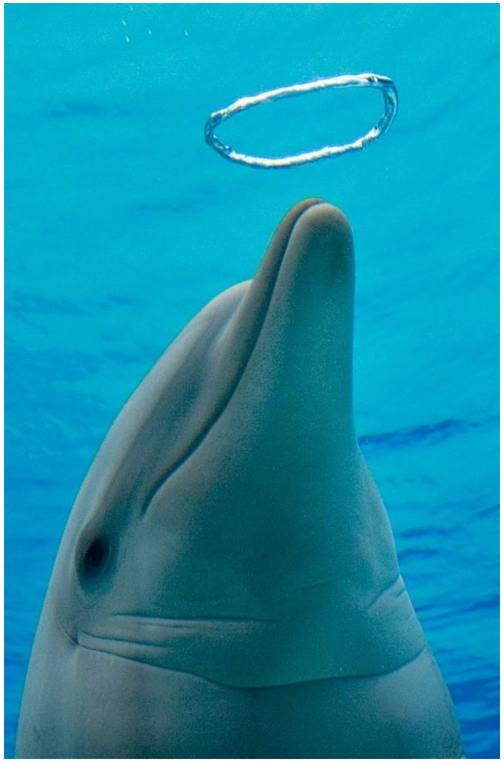
FRC sustain longer with neutral beam injection



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

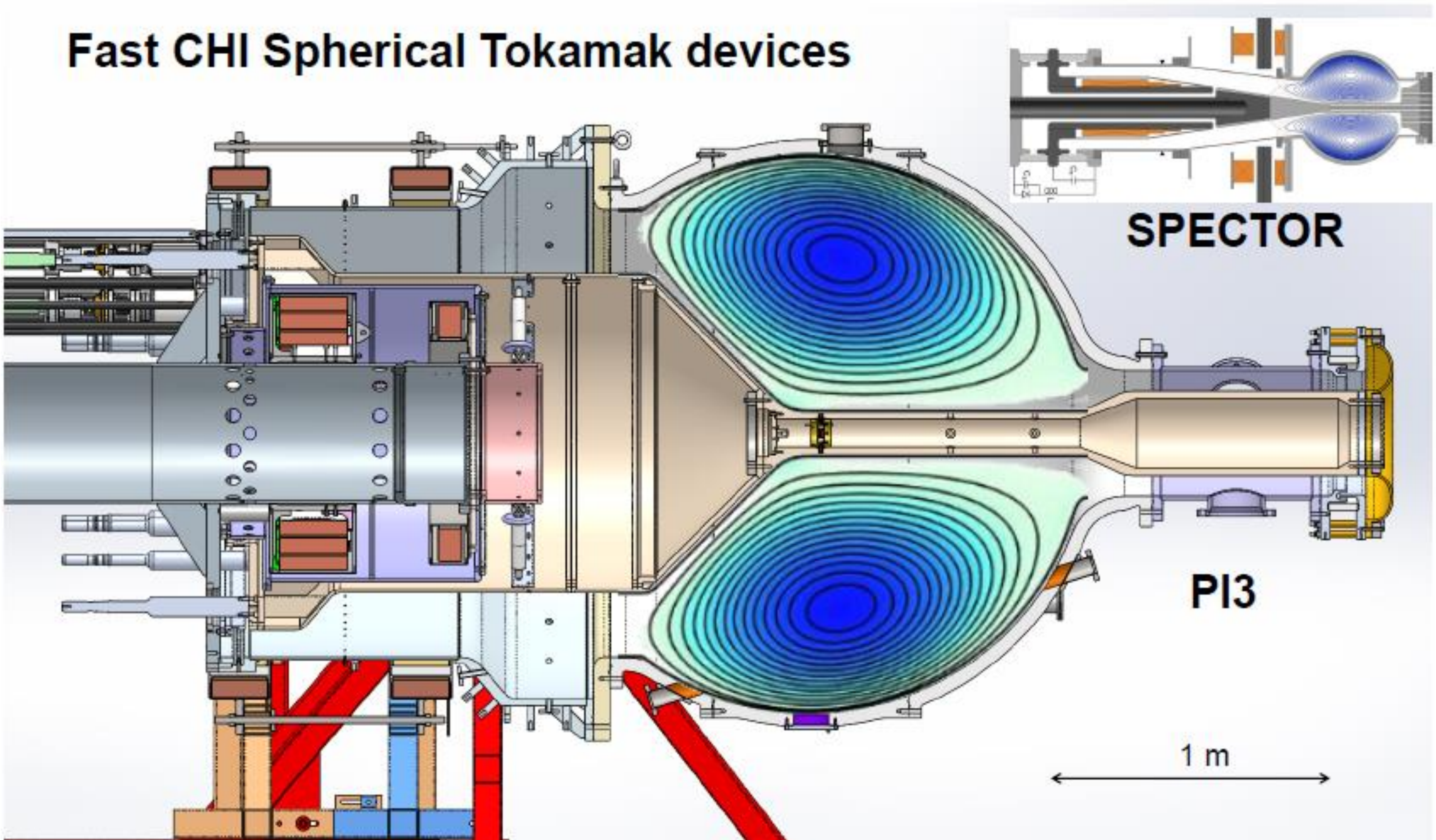
General fusion is a design ready to be migrated to a power plant





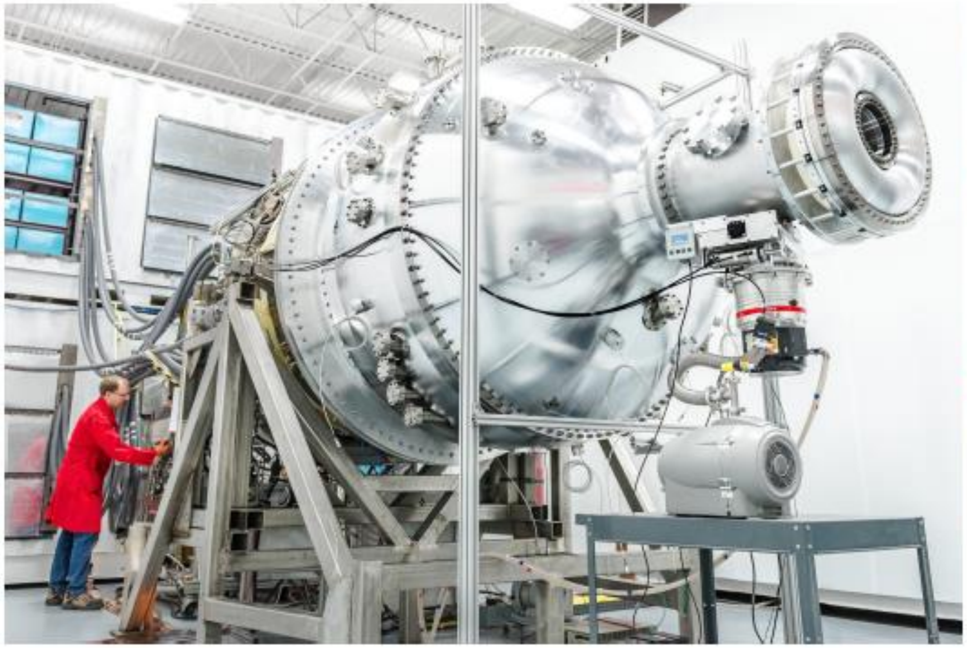
https://en.wikipedia.org/wiki/General_Fusion

A spherical tokamak is first generated



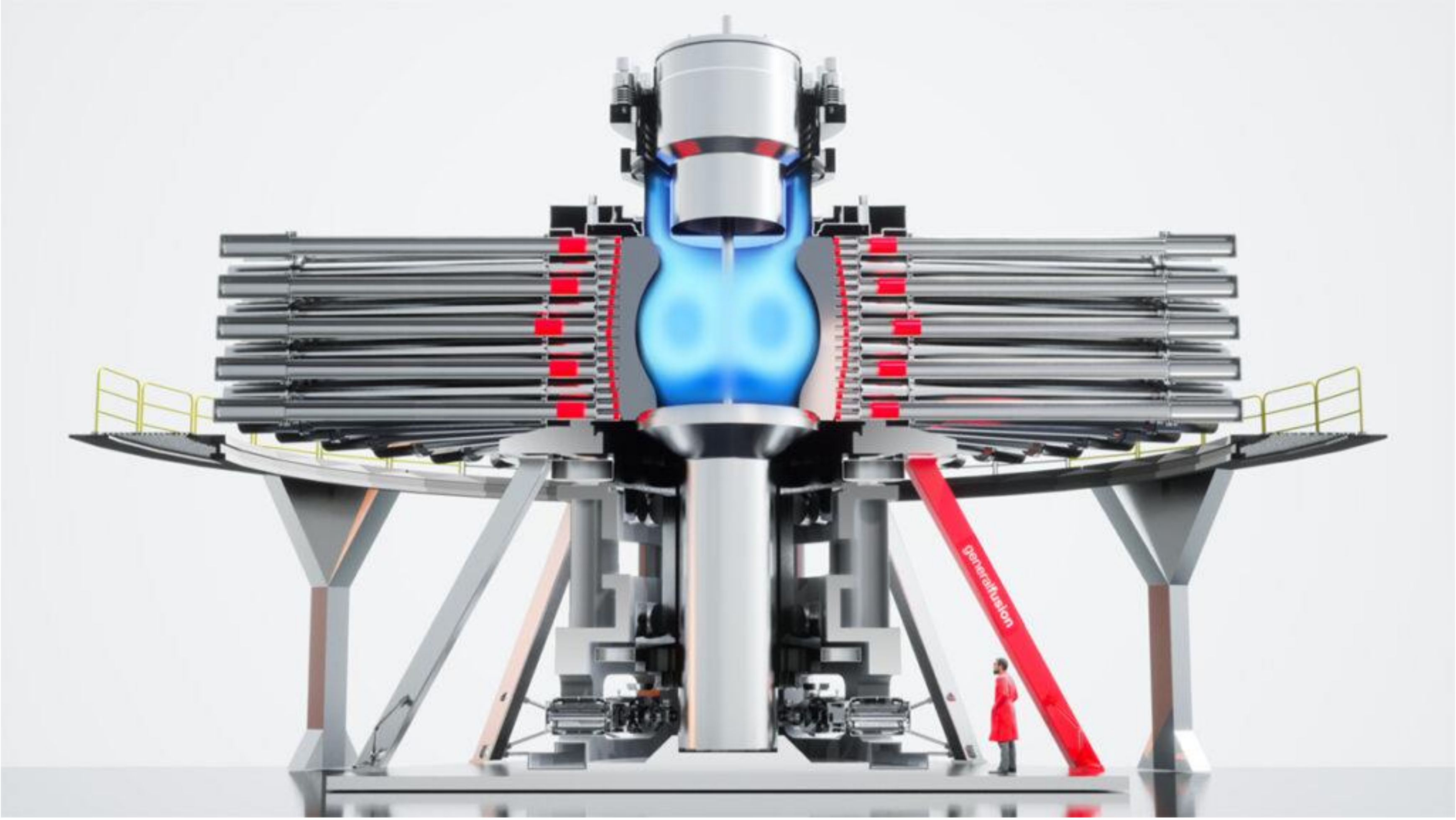
K. EPP, etc., 60th APS-DPP, CP11.00192

Plasma injector for the spherical tokamak

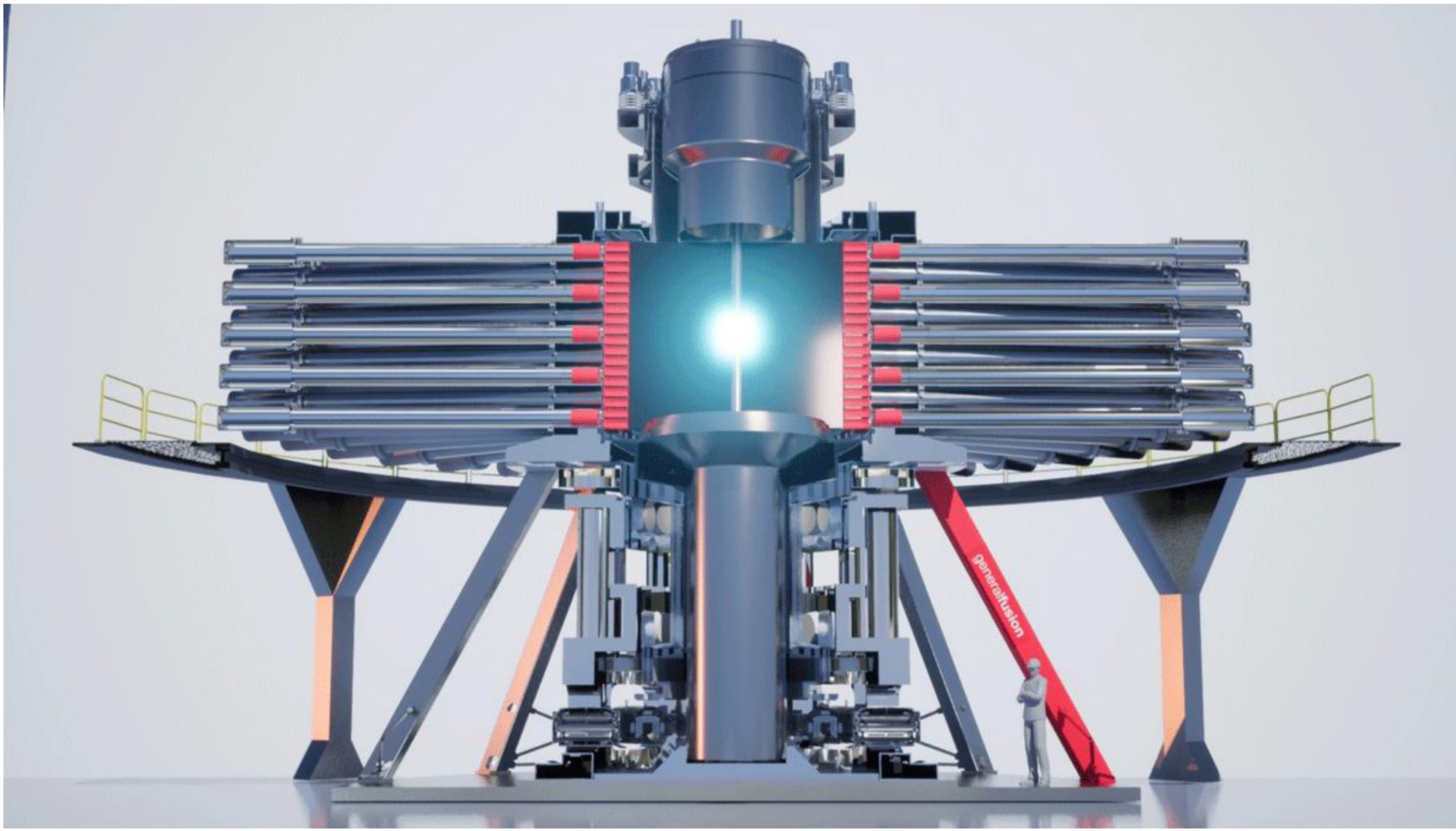


K. EPP, etc., 60th APS-DPP, CP11.00192

A spherical tokamak is generated in a liquid metal vortex



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



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

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

By Matt McGrath
Environment correspondent

17 June

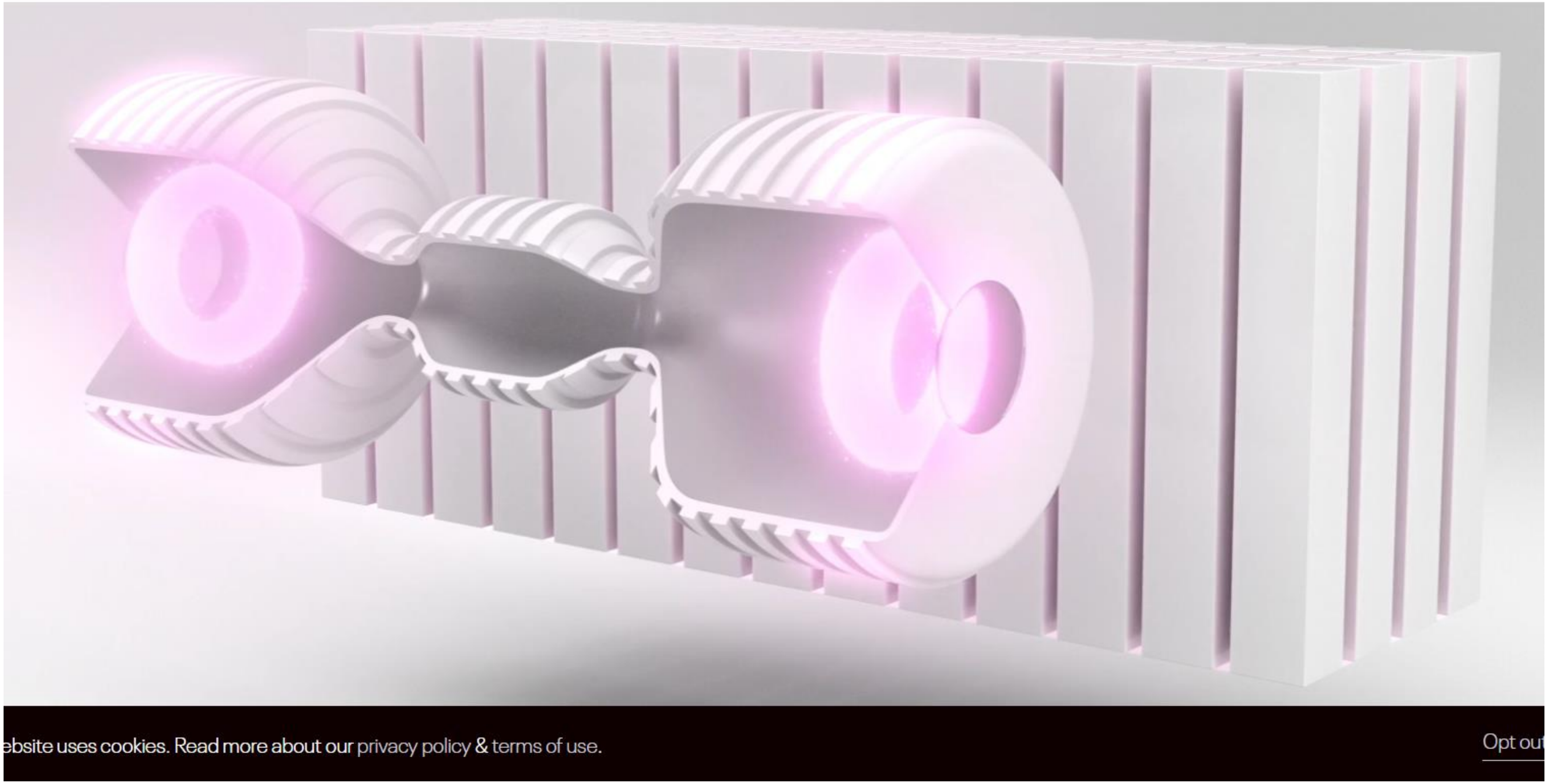
An artist's impression of what the new demonstration plant might look like

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

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

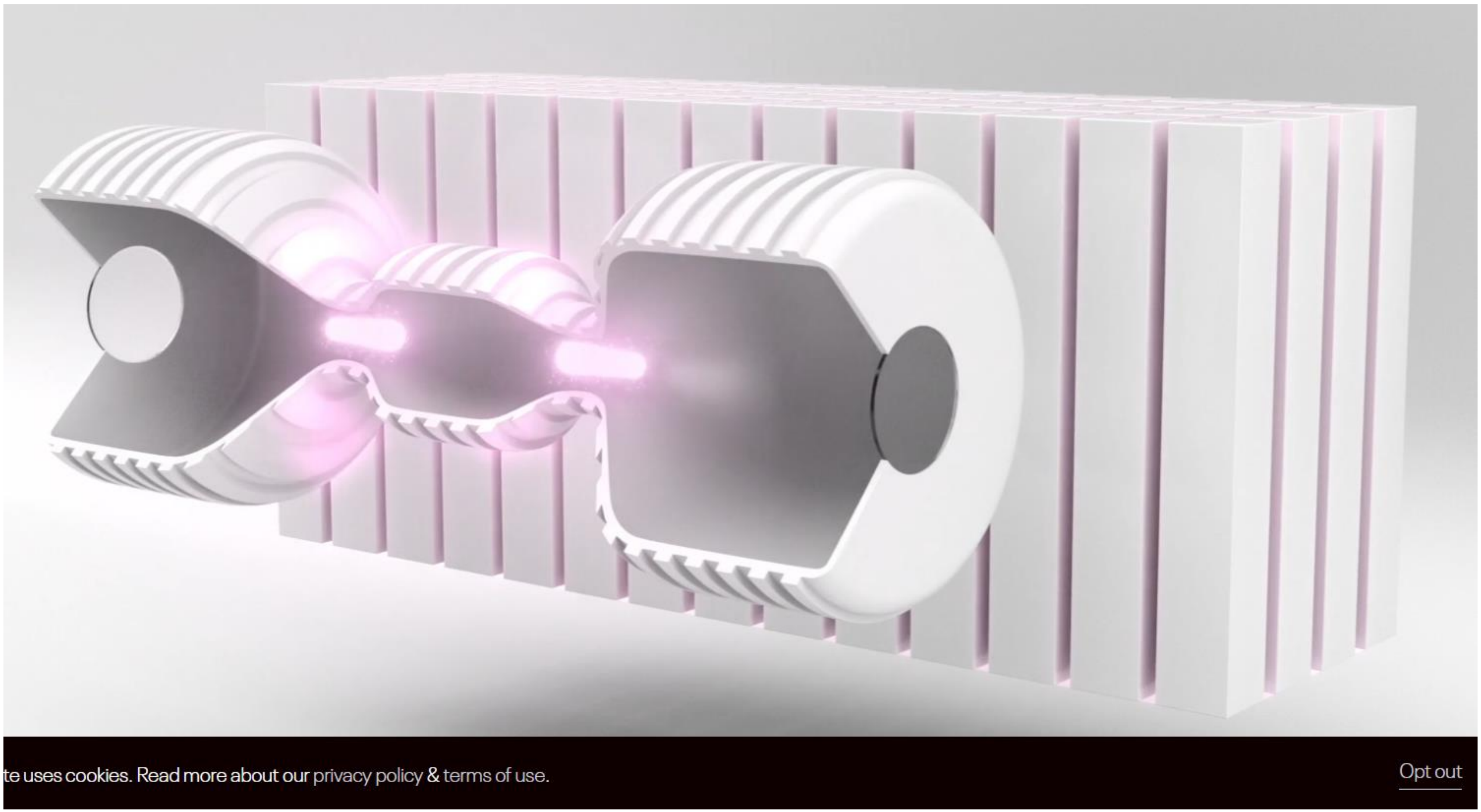
https://www.bbc.com/news/science-environment-57512229

Helion energy is compressing the two merging FRCs



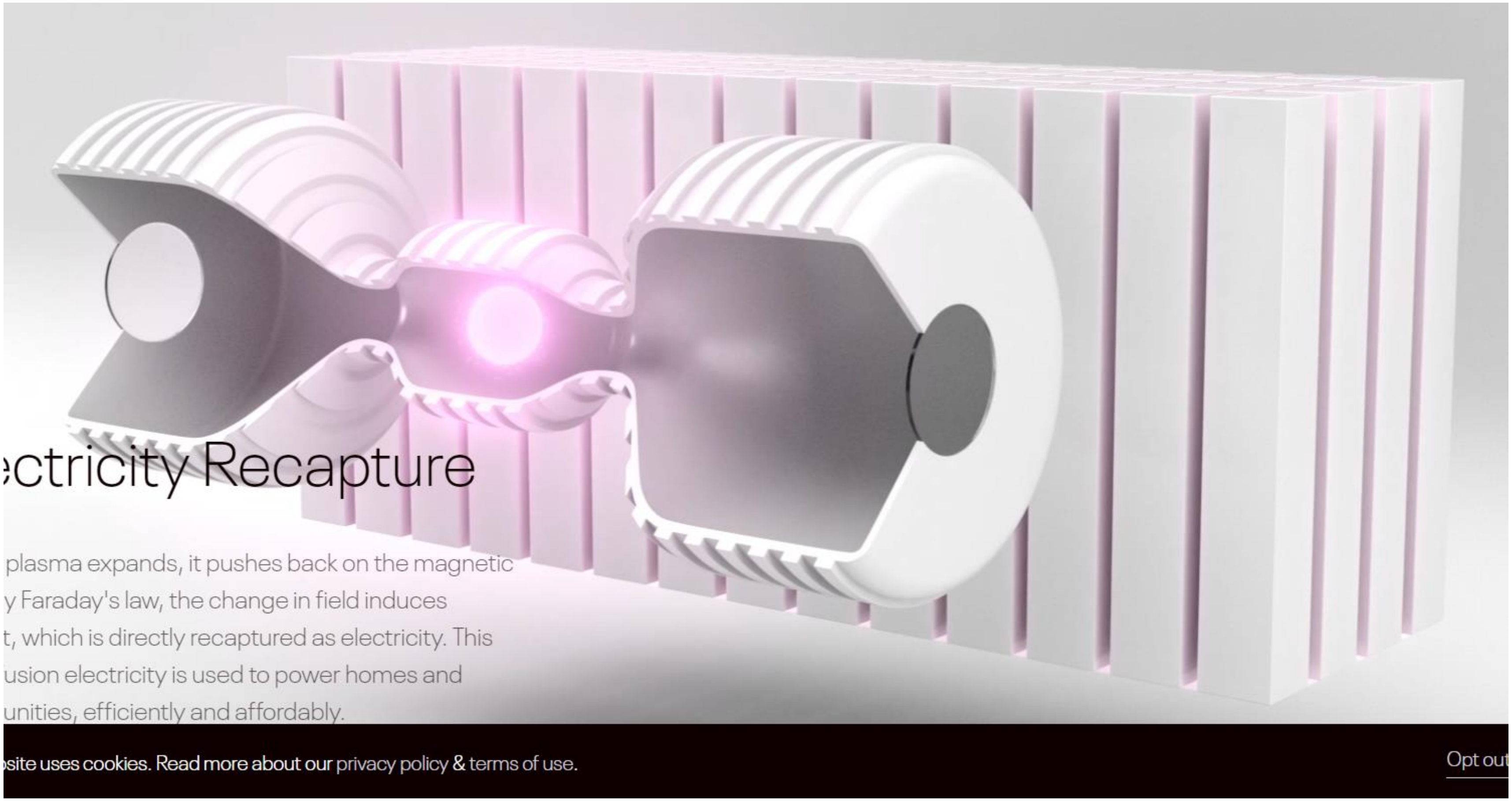
https://www.helionenergy.com/

Two FRCs are accelerated toward each other



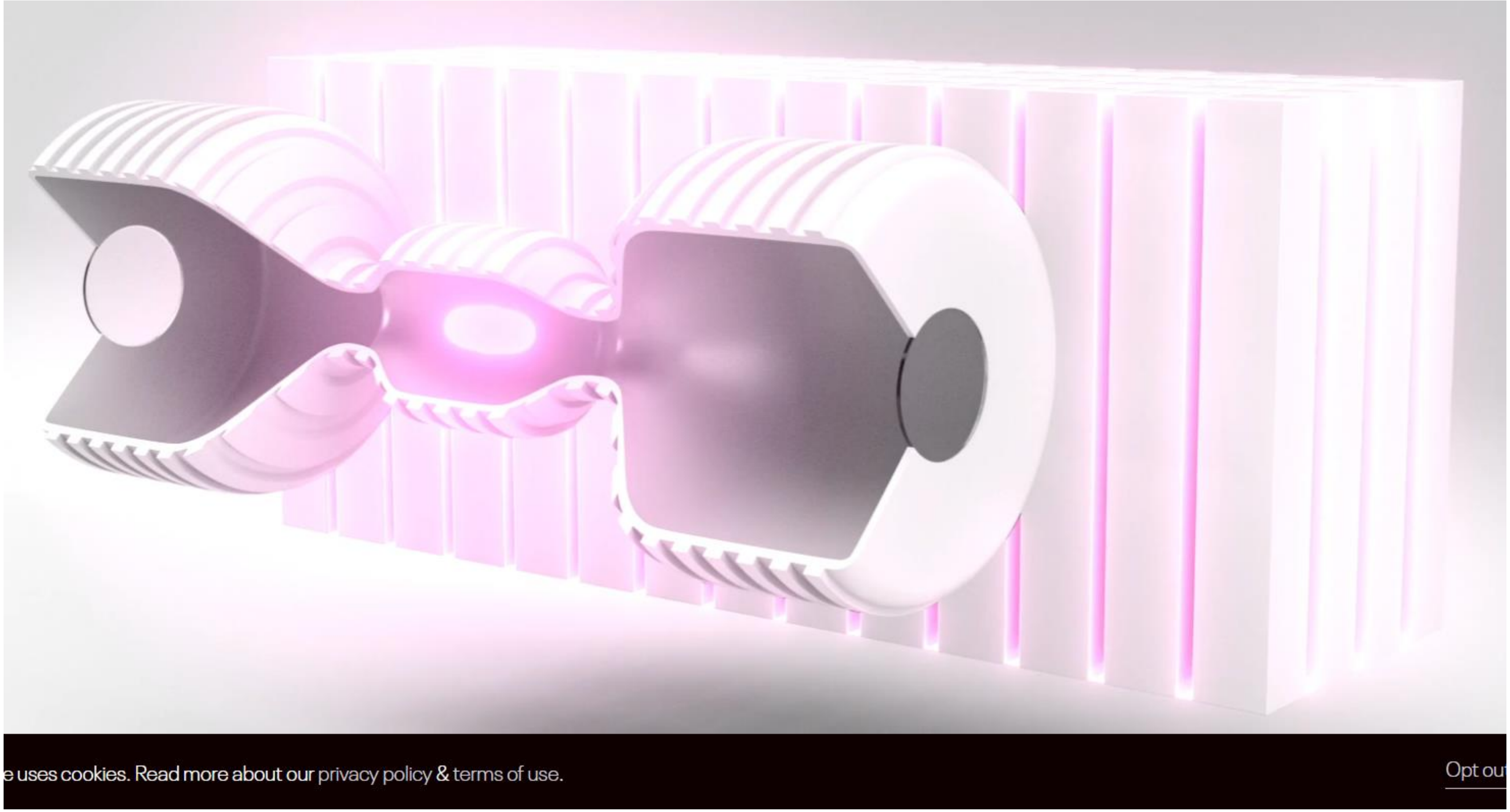
https://www.helionenergy.com/

Two FRCs merge with each other



https://www.helionenergy.com/

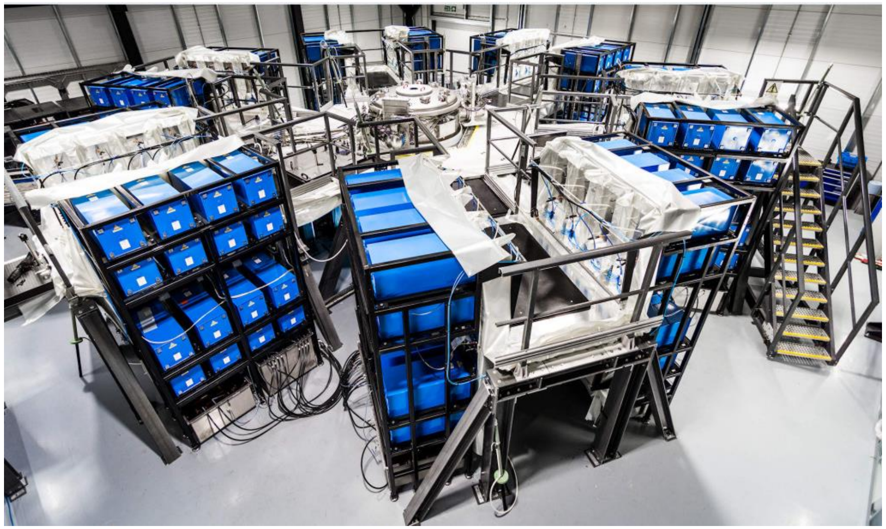
The merged FRC is compressed electrically to high temperature



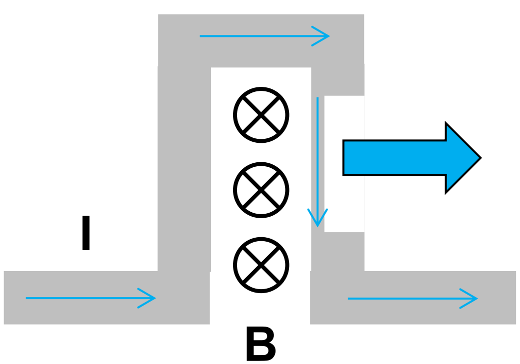
- **Similar concept will be studied in our laboratory.**

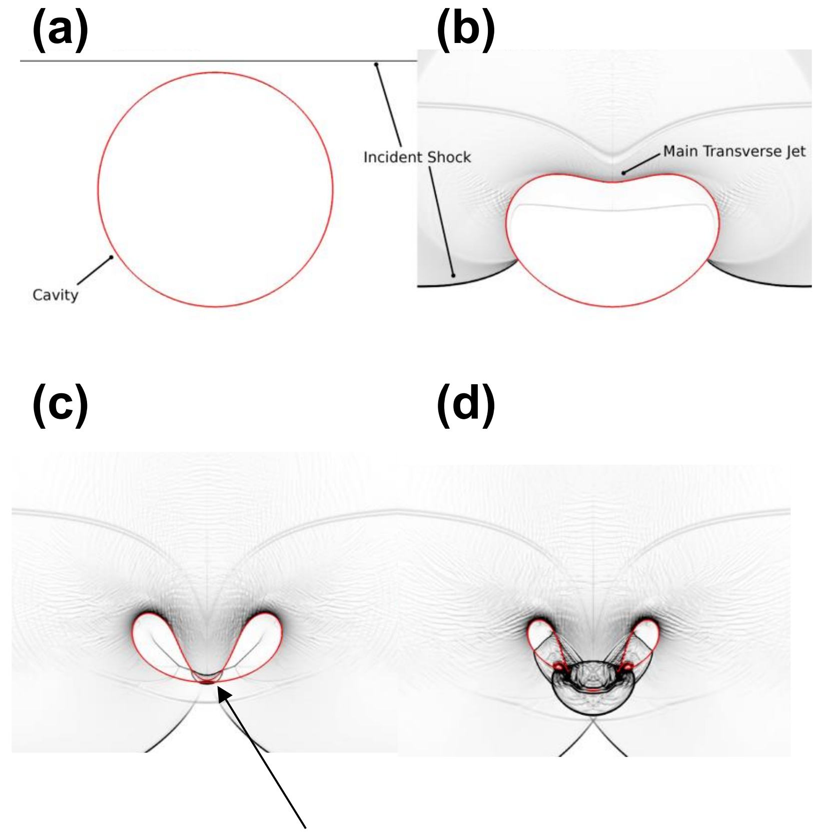
https://www.helionenergy.com/

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



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





- **High pressure is generated by the colliding shock.**

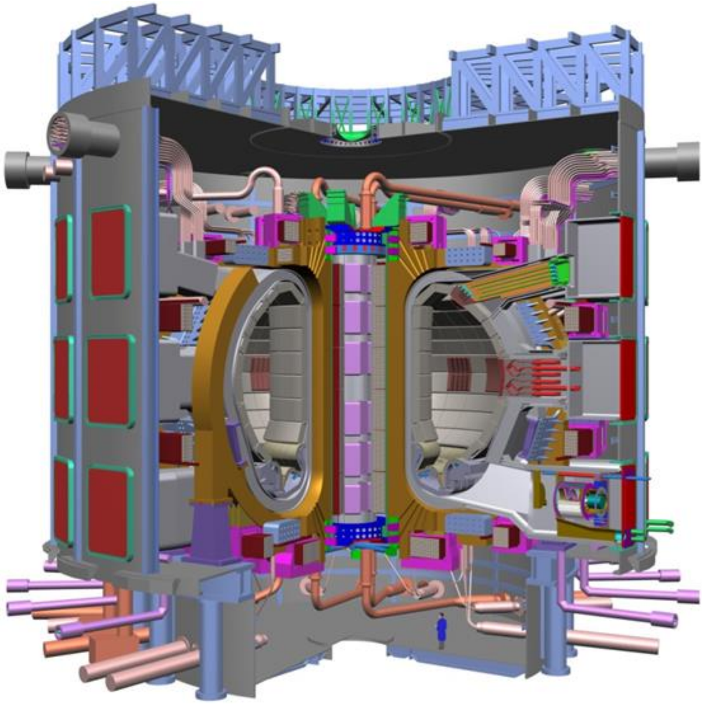
https://firstlightfusion.com/
B. Tully and N. Hawker, Phys. Rev. **E93**, 053105 (2016)

A gas gun is used to eject the projectile

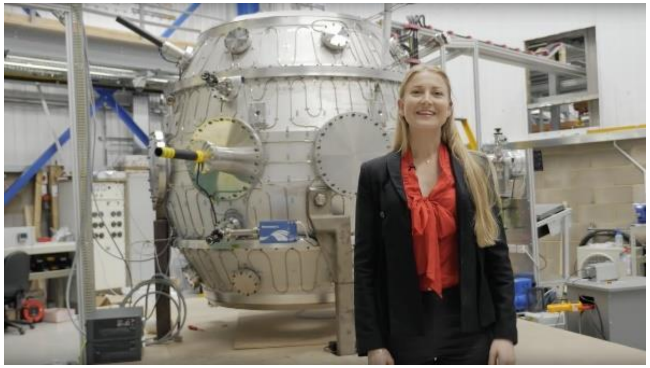
https://www.youtube.com/watch?v=JN7IyxC11n0
https://www.youtube.com/watch?v=aW4eufacf-8

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

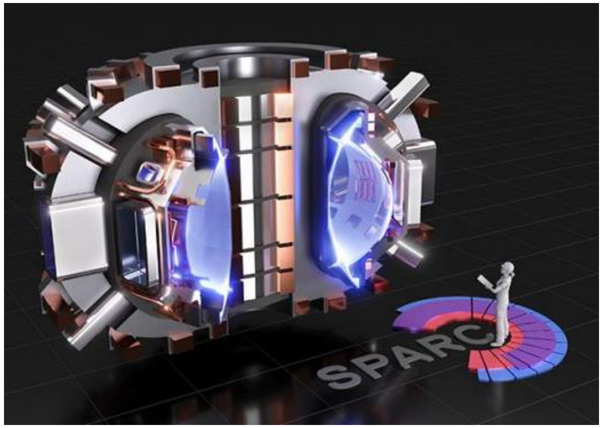
- **ITER – 2025 First Plasma**
  2035 D-T Exps
  2050 DEMO



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



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



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

Fusion is blooming

FUSION INDUSTRY ASSOCIATION

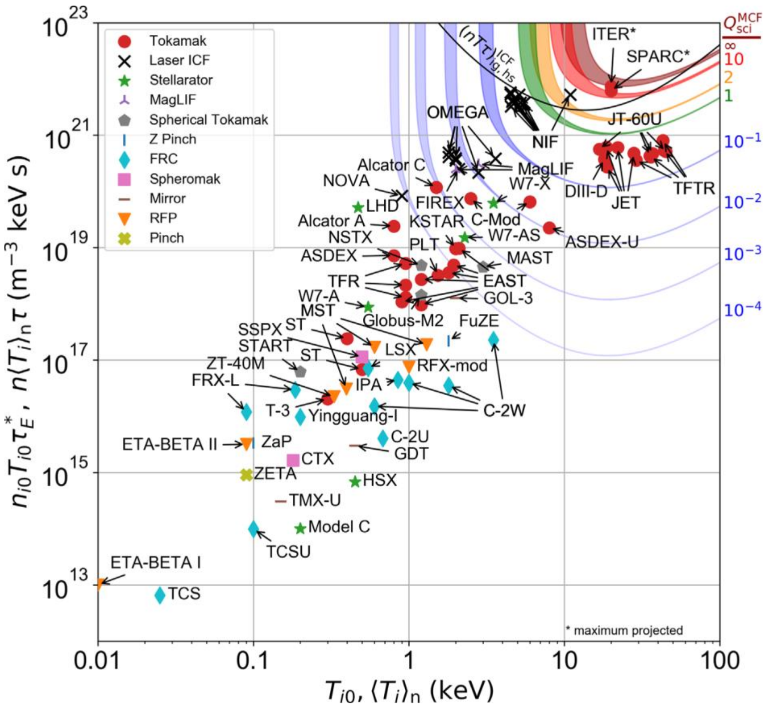
generalfusion
Commonwealth Fusion Systems
tae
ZAP ENERGY
TYPE ONE ENERGY
HELION
OPENSTAR
REALTA FUSION
THEA ENERGY
Tokamak Energy
XCIMER ENERGY CORPORATION
acceleron
ANUBAL FUSION
BLUE LASER FUSION
ELECTRIC FUSION SYSTEMS
Helical Fusion
HelicitySpace
HORNE TECHNOLOGIES
PRANOS FUSION ENERGY
RENAISSANCE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

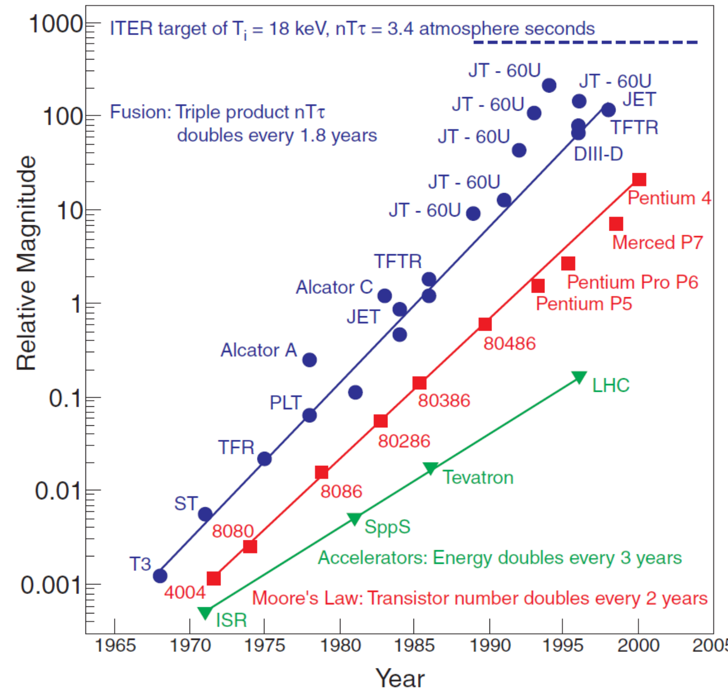
AVALANCHE
Proxima Fusion
PACIFIC FUSION
EX-Fusion
first light
FOCUSED
fuse
GAUSS FUSION
HB11 ENERGY
KYOTO FUSIONEERING
Marvel Fusion
LaserFusionX
LONGVIEW FUSION
LPP FUSION
MARITIME FUSION
MIFTI
nearstar FUSION
NOVATRON
nT-tao Compact Fusion Power

MCF
MTF
ICF

https://www.fusionindustryassociation.org/members

We are closed to ignition!





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

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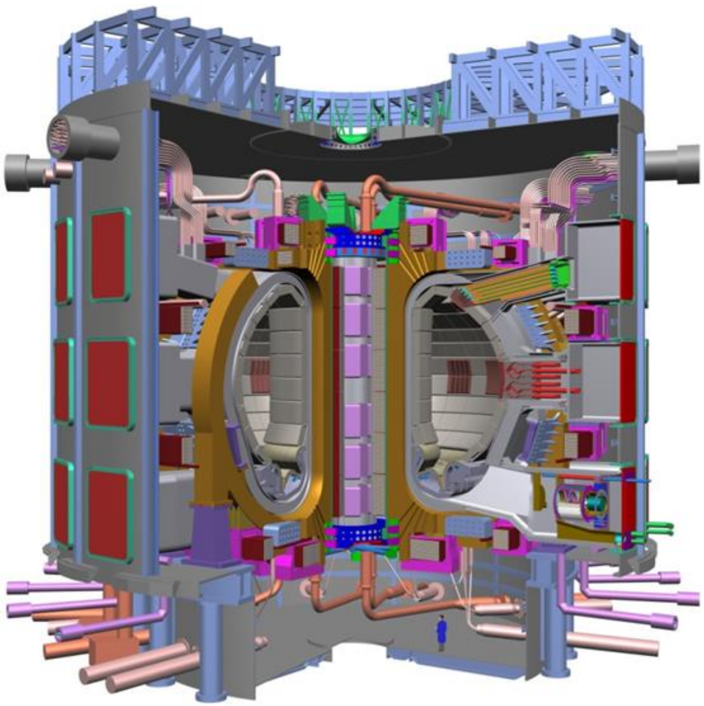
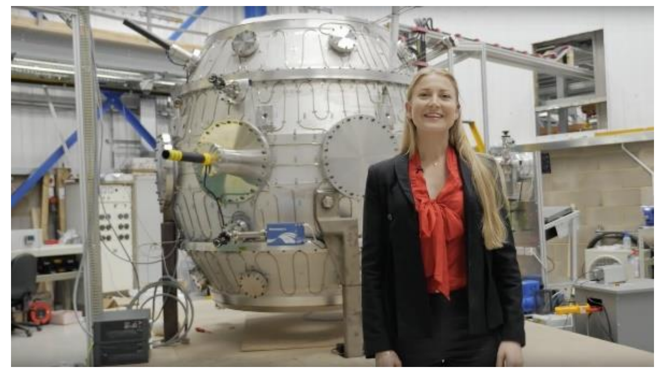


- **Tokamak energy, UK**
  - **2025 Gain**
  - **2030 to power grid**



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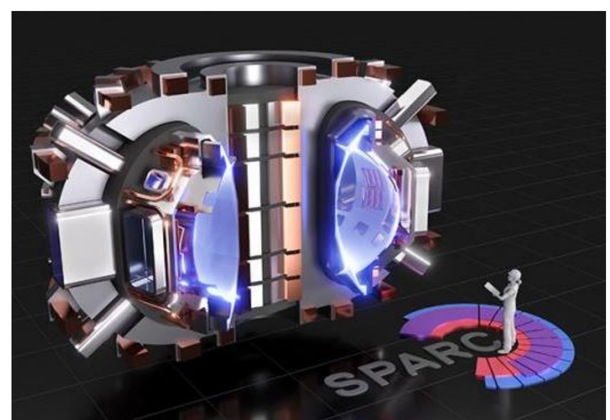
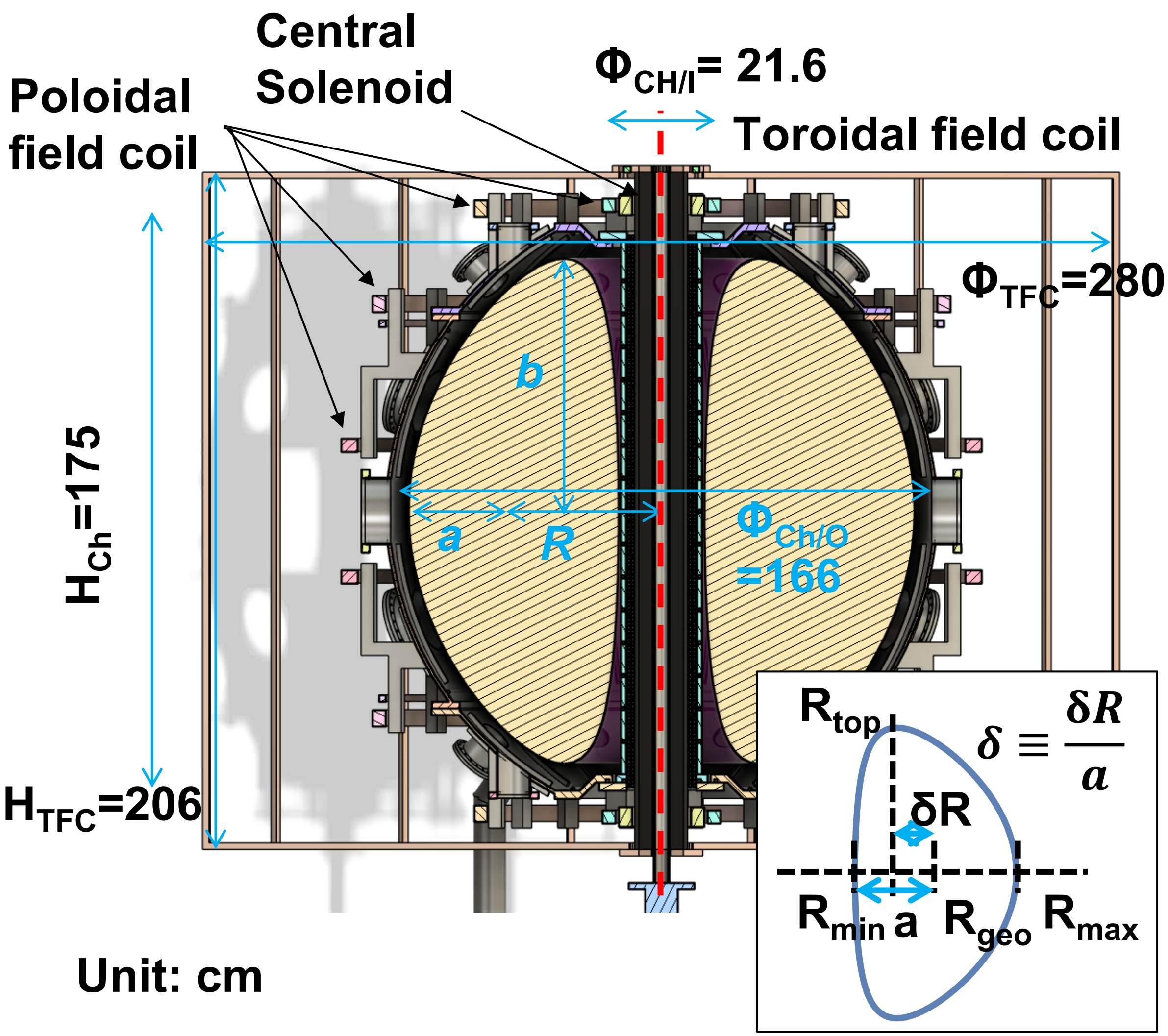


https://www.iter.org
https://www.tokamakenergy.co.uk/
https://www.psfc.mit.edu/sparc

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!**