Introduction to plasma theory and demonstration
電漿基礎理論與實作

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2023 summer break

8/28(Mon.) – 9/1(Fri.) 14:00-17:40

Except: 8/29(Tue.) 13:30-17:10

Lecture 4

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

https://nckucc.webex.com/nckucc/j.php?MTID=mb9ccf65ba2c981ce1f0f02ea60e1dbf2

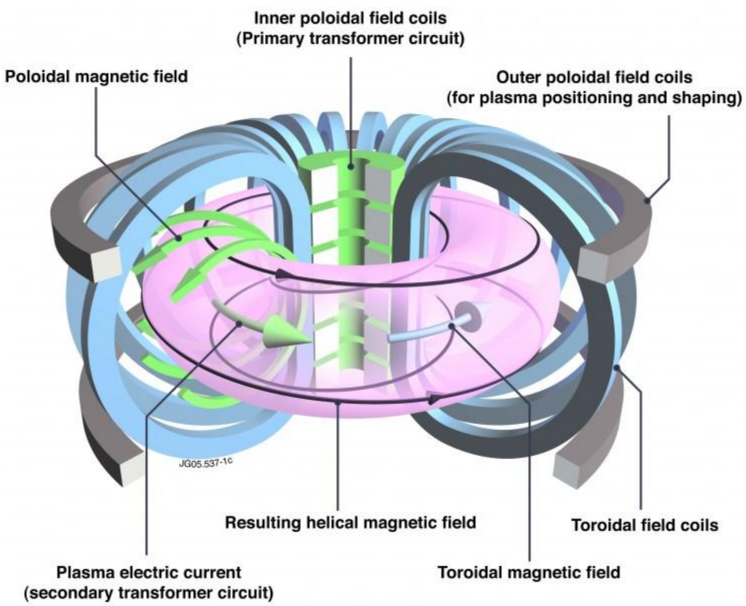
開放式教育平台：

https://i-ocw.ctld.ncku.edu.tw/site/course_content/FTqT2RS1h7j

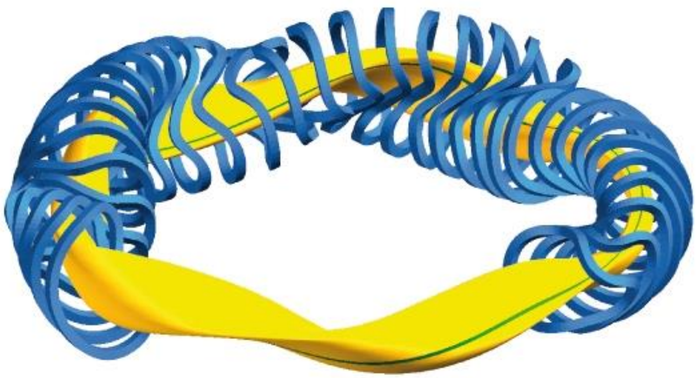
2023/8/31 updated

Stellarator uses twisted coil to generate poloidal magnetic field

Tokamak

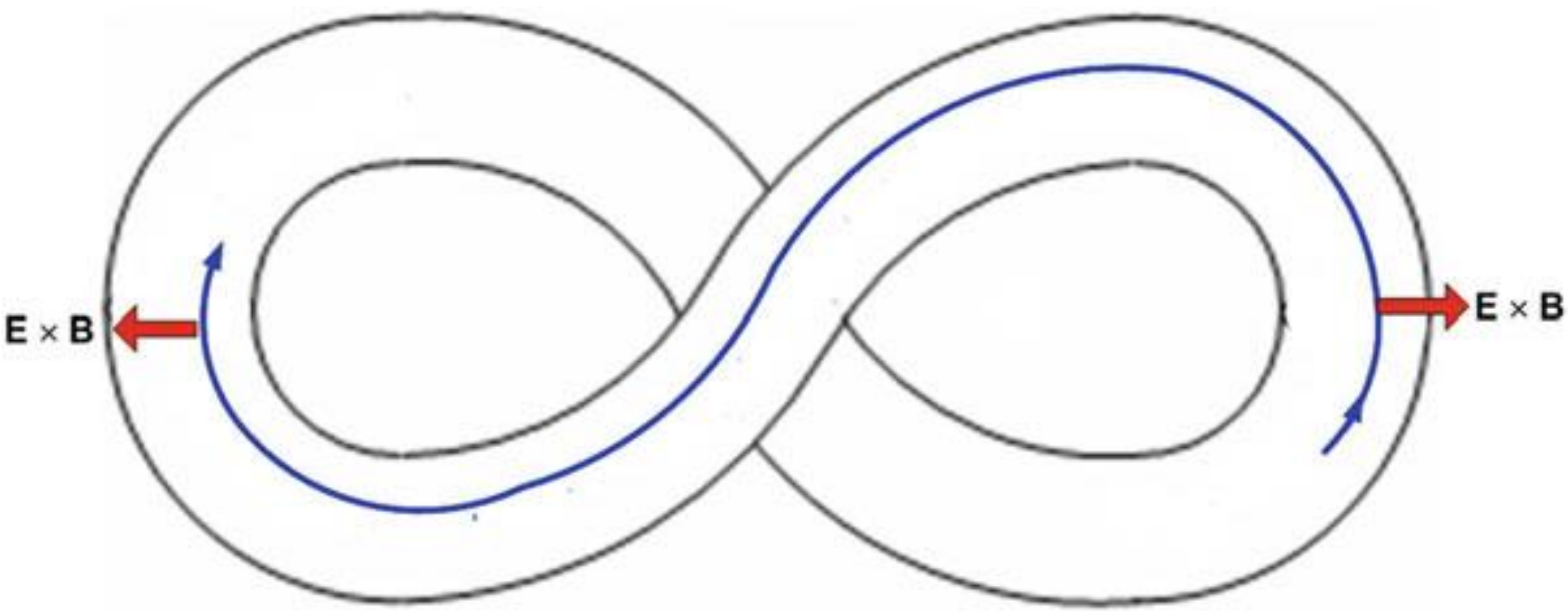


Stellarator



https://www.euro-fusion.org/2011/09/tokamak-principle-2/
https://en.wikipedia.org/wiki/Stellarator

A figure-8 stellarator solved the drift issues



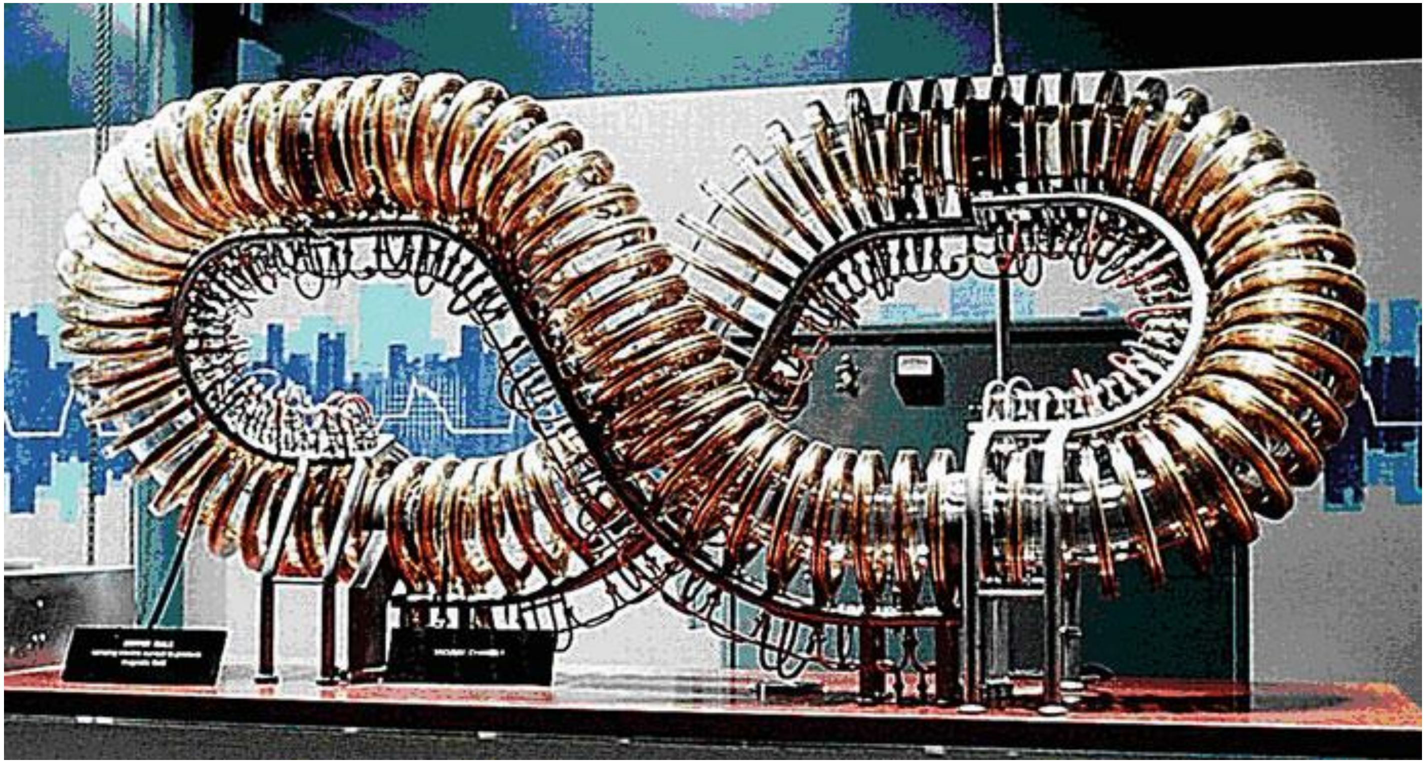
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

A figure-8 stellarator solved the drift issues

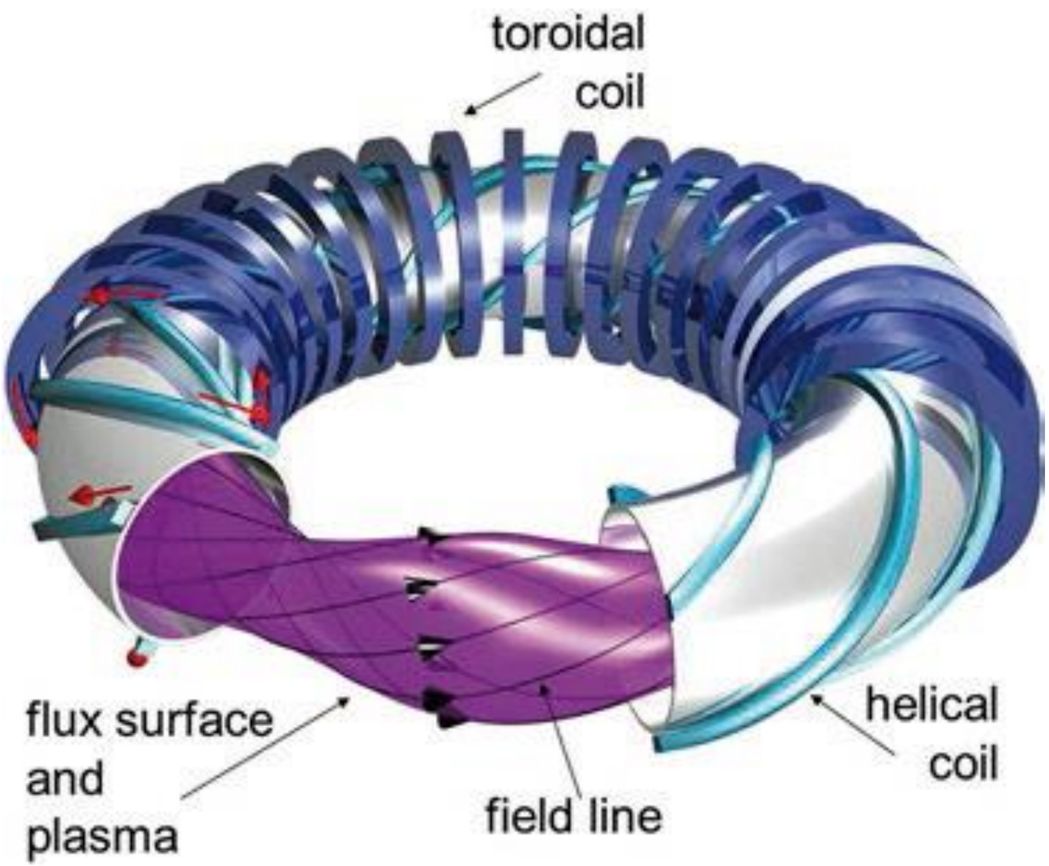
Lyman Spitzer, Jr. came out the idea during a long ride on a ski lift at Garmisch-Partenkirchen

https://www.snowtrex.de/magazin/skigebiete/garmisch-classic-zugspitze/

Exhibit model of a figure-8 stellarator for the Atoms for Peace conference in Geneva in 1958

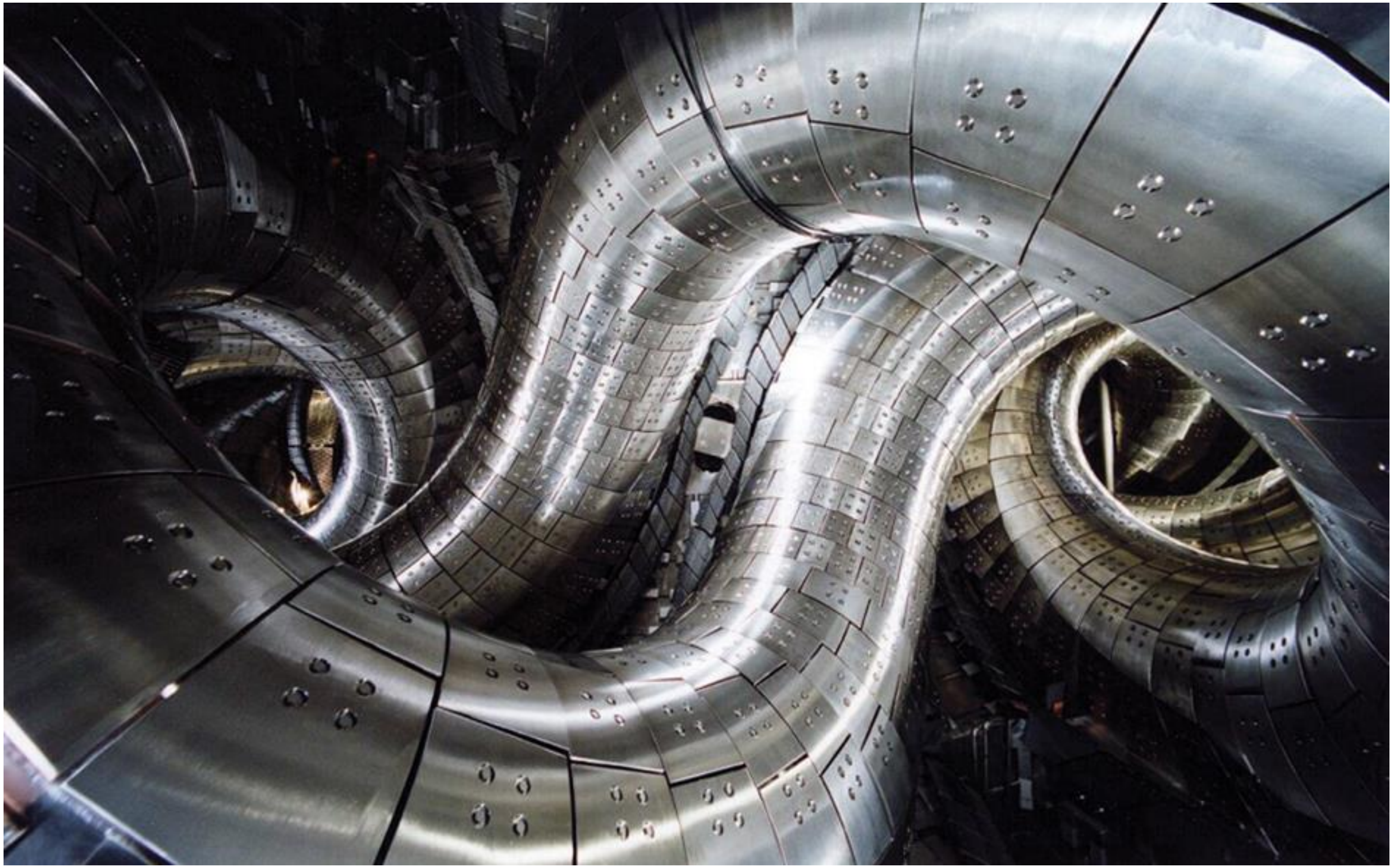


Twisted magnetic field lines can be provided by toroidal coils with helical coils



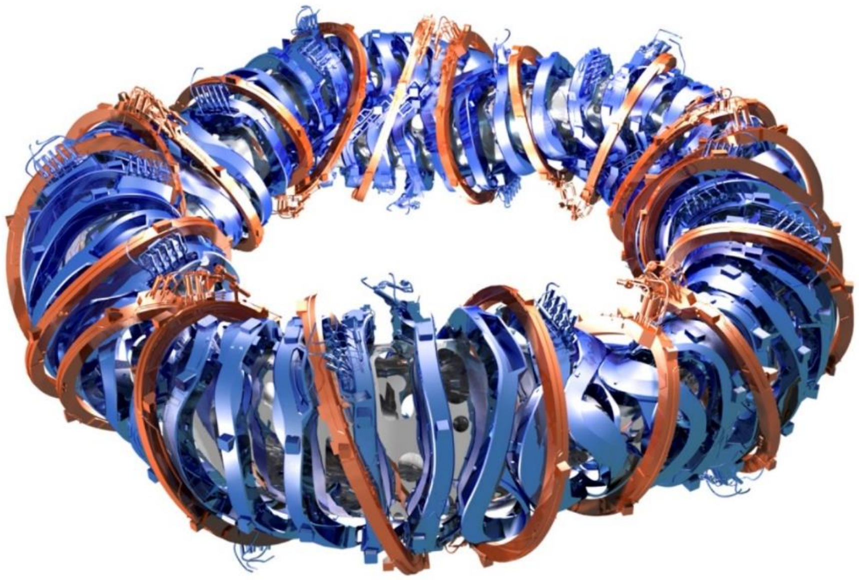
Wagner, F., Fusion energy. MRS Energy & Sustainability, 5, E8 (2018)

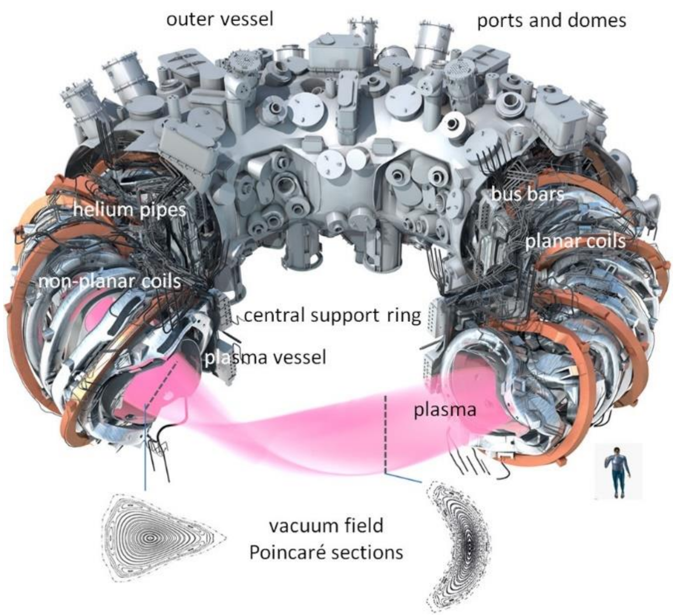
LHD stellarator in Japan



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

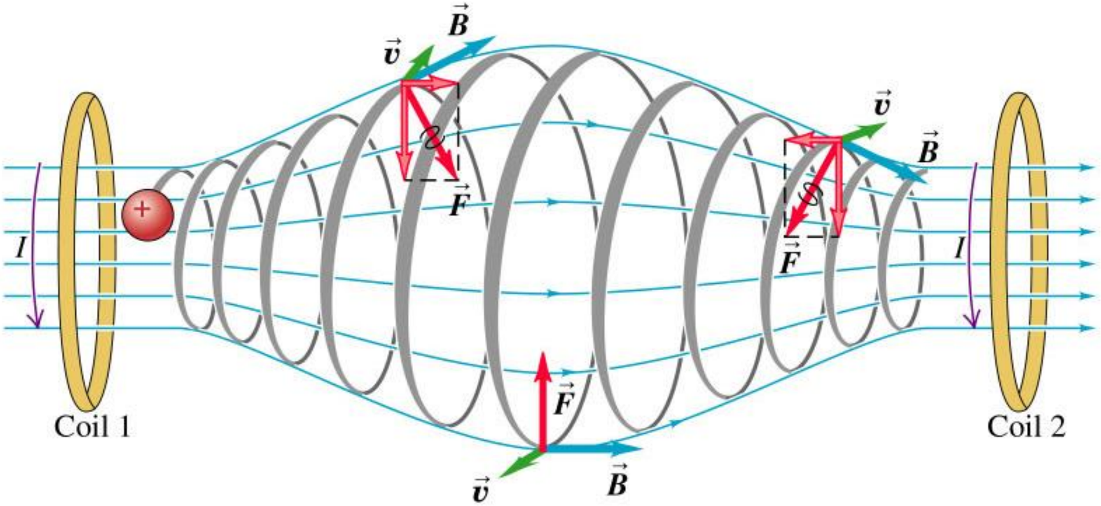
Wendelstein 7-X is a stellarator built by Max Planck Institute for Plasma Physics (IPP)

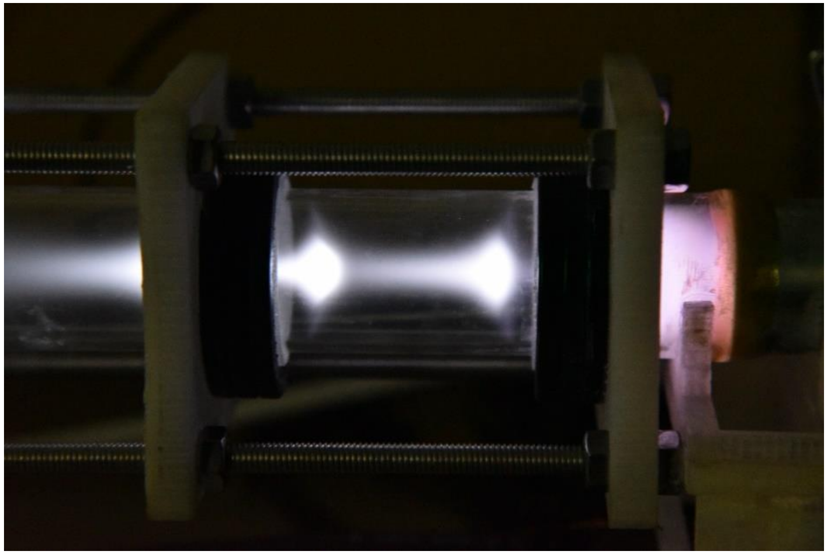




- **Wemdelstein 7-x is now installing new diverters.**

Demonstration of a magnetic mirror machine

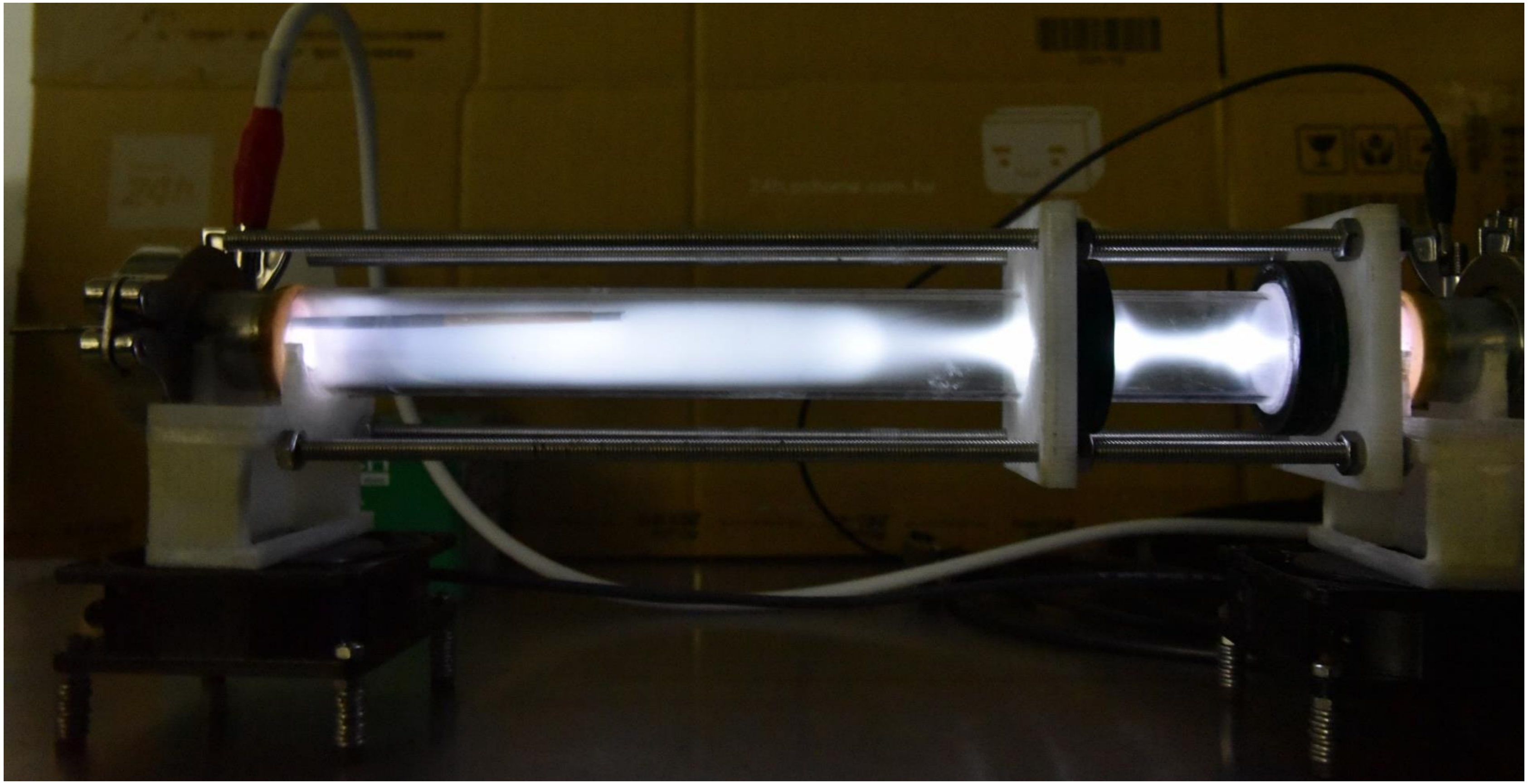




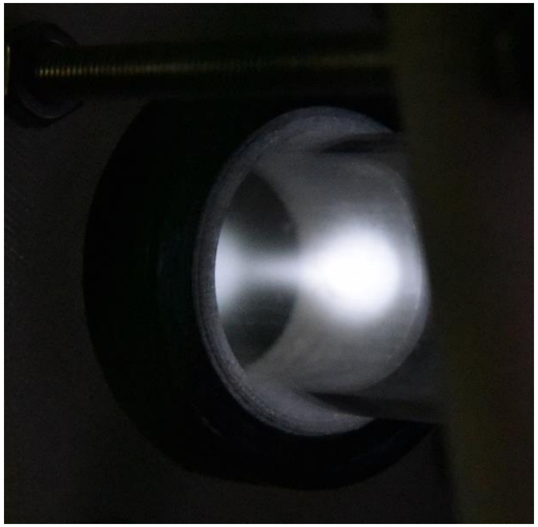
Show video.

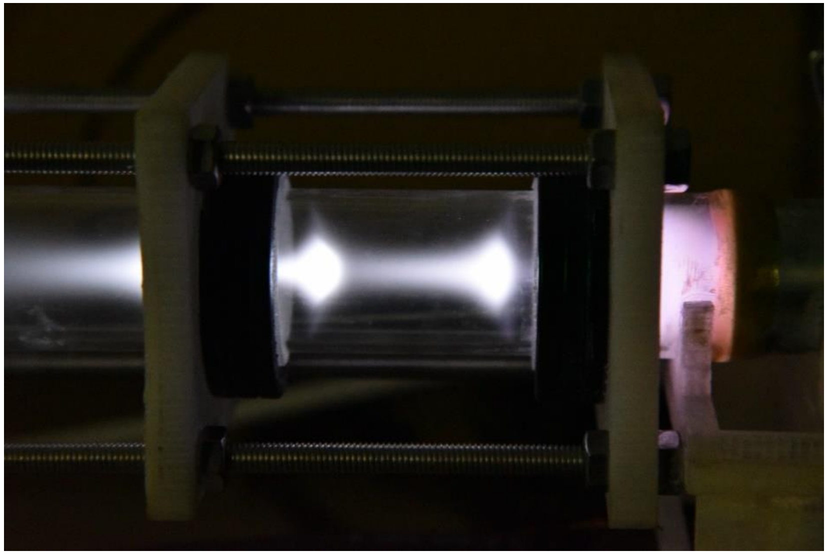
https://i.stack.imgur.com/GlzGZ.jpg

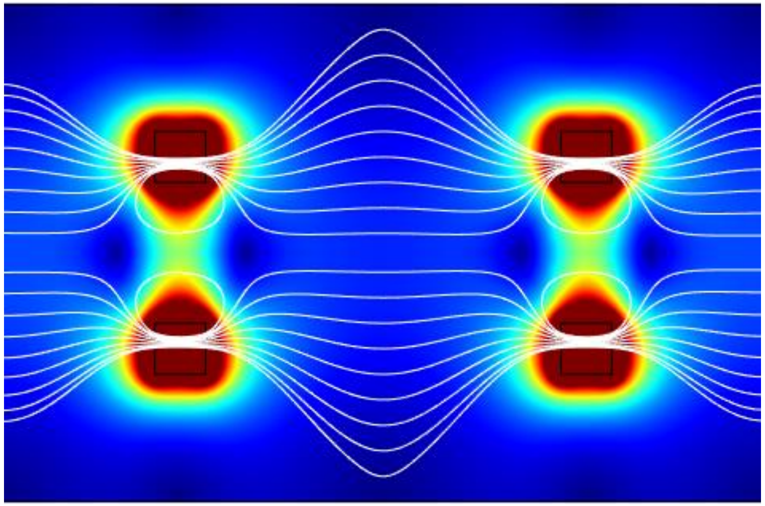
Plasma is partially confined by the magnetic field



Many mirror points are provided by a pair of ring-type magnets



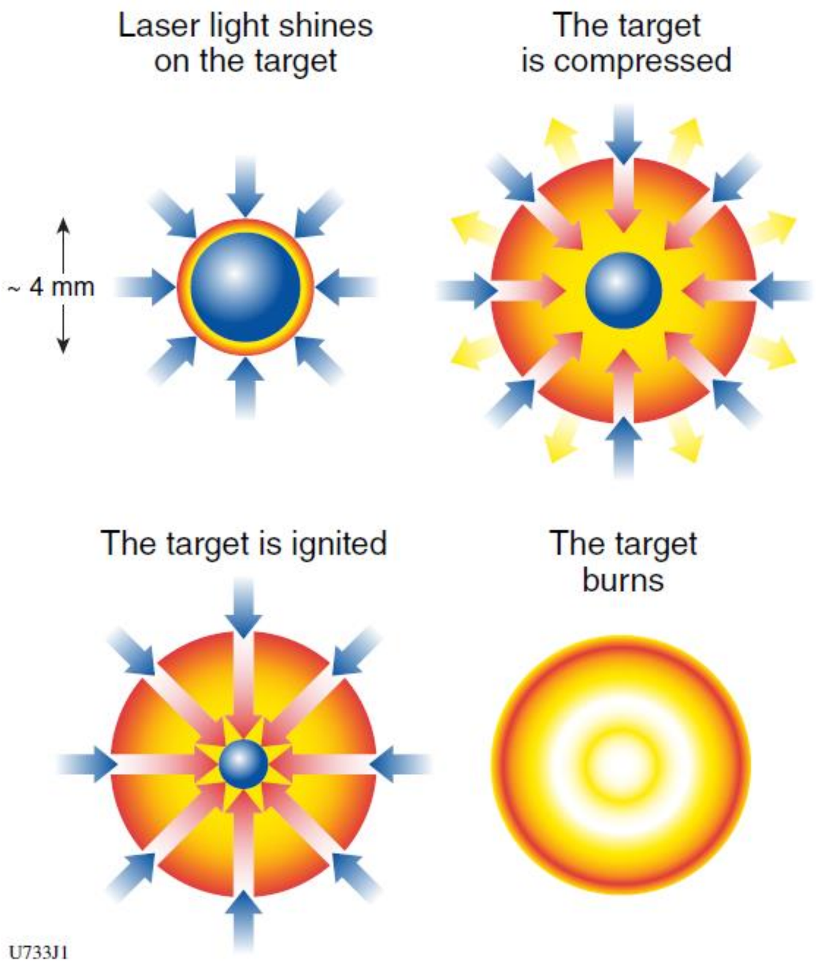




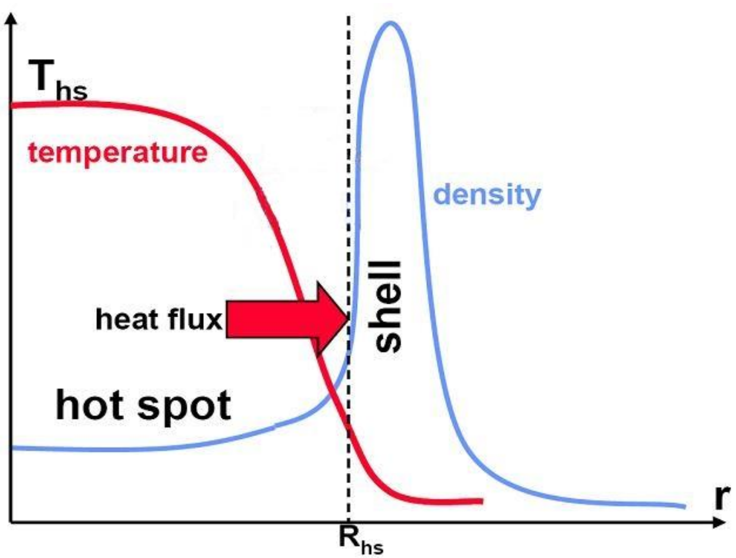
Outline

- Introduction to nuclear fusion
- Magnetic confinement fusion (MCF)
  - Tokamak
  - Stellarator
- **Inertial confinement fusion (ICF)**
  - **Indirection drive ICF**
  - **Direct drive ICF**
- Innovation idea – MCF + ICF
- Pulsed-power system at NCKU

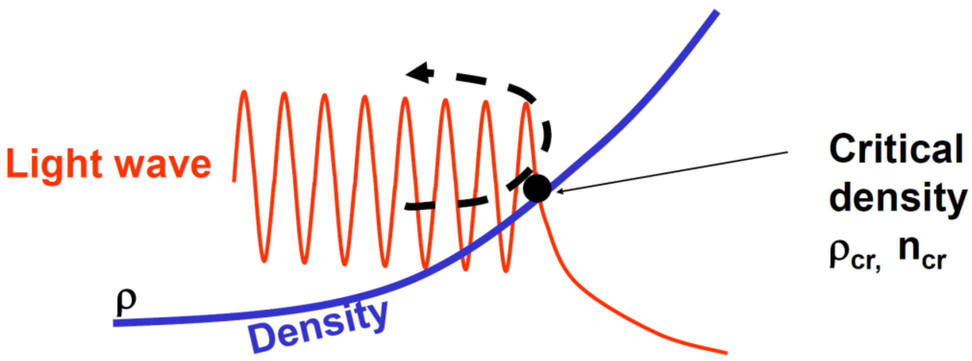
Plasma is confined by its own inertia in inertial confinement fusion (ICF)

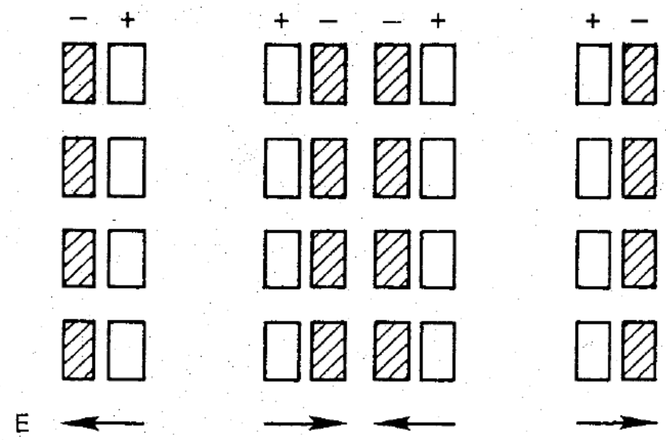


Spatial profile at stagnation



The laser light cannot propagate past a critical density





Mechanism of plasma oscillations.

- **Critical density is given by plasma frequency=laser frequency**

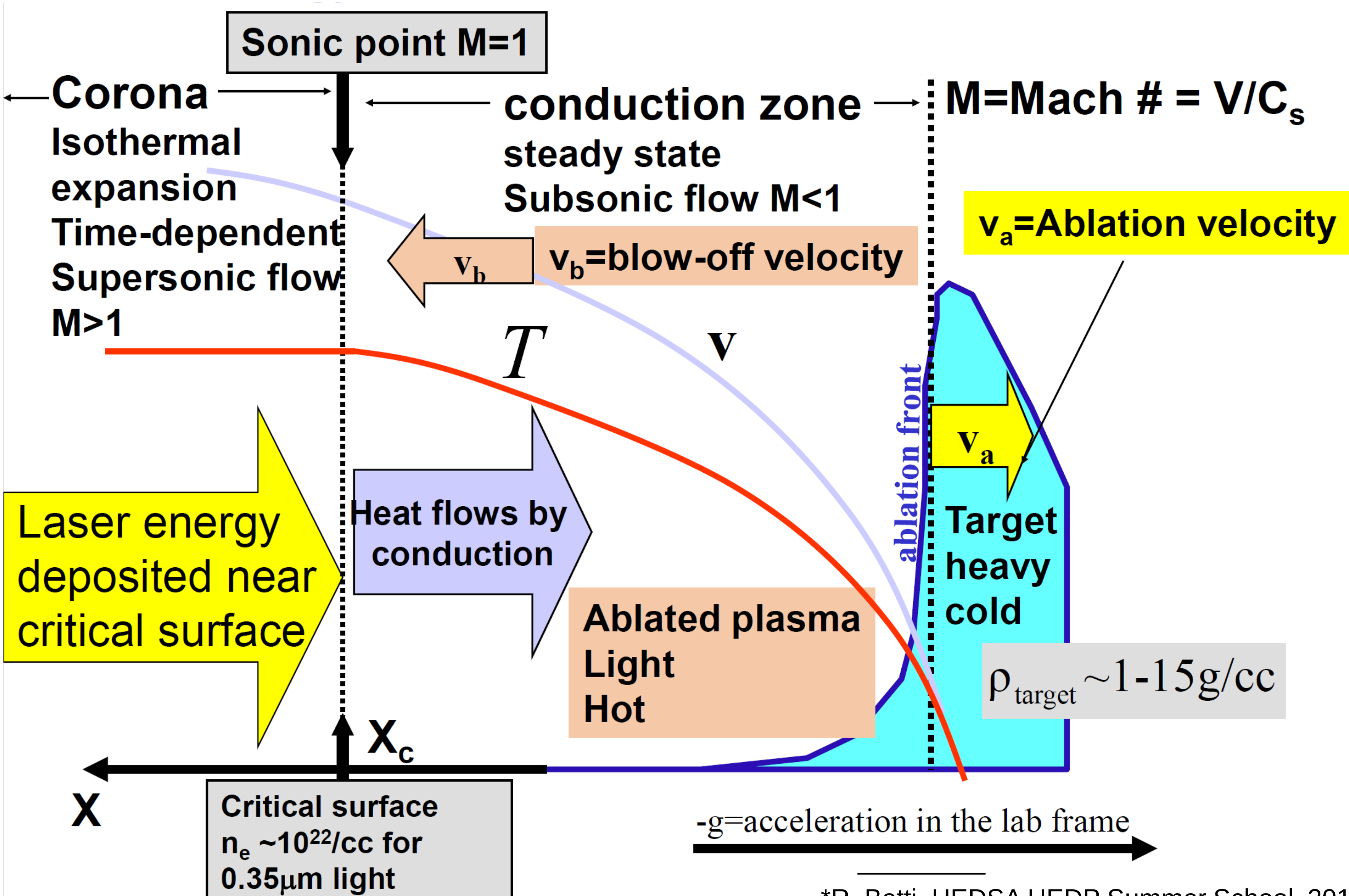
$$\omega_{\mathrm{L}} = \frac{2\pi c}{\lambda_{\mathrm{L}}} \qquad \omega_{\mathrm{pe}} = \sqrt{\frac{4\pi n_{\mathrm{e}} e^2}{m_{\mathrm{e}}}}$$

$$\omega_{\mathrm{L}}^2 = \omega_{\mathrm{pe}}^2$$

$$\boxed{n_{\mathrm{e}}{}^{\mathrm{cr}} = \frac{1.1 \times 10^{21}}{\lambda_{\mathrm{L},\mu\mathrm{m}}{}^2}\,\mathrm{cm}^{-3}}$$

*R. Betti, HEDSA HEDP Summer School, 2015

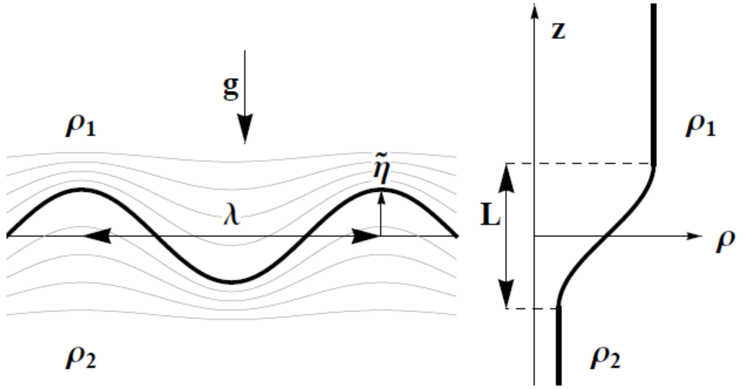
The laser generates a pressure by depositing energy at the critical surface



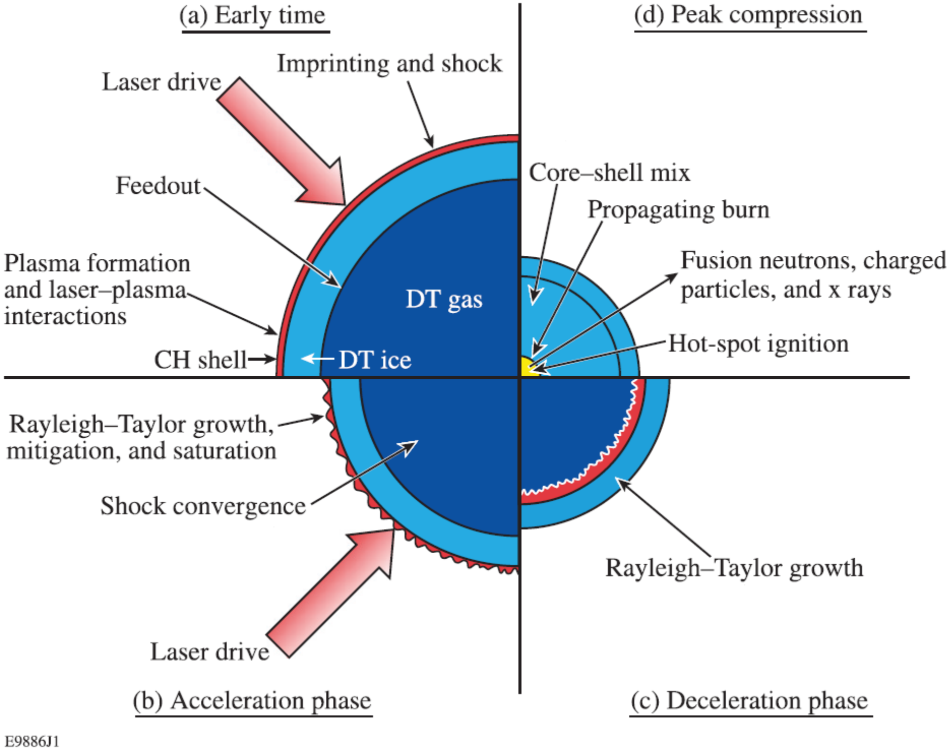
*R. Betti, HEDSA HEDP Summer School, 2015

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

- **Rayleigh-Taylor instability**

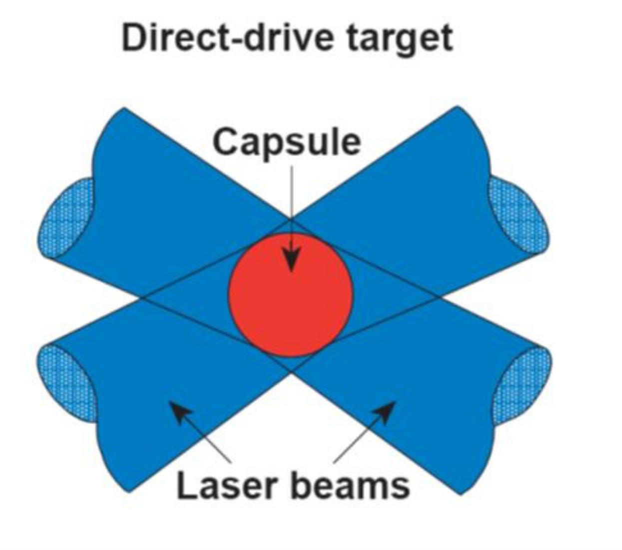


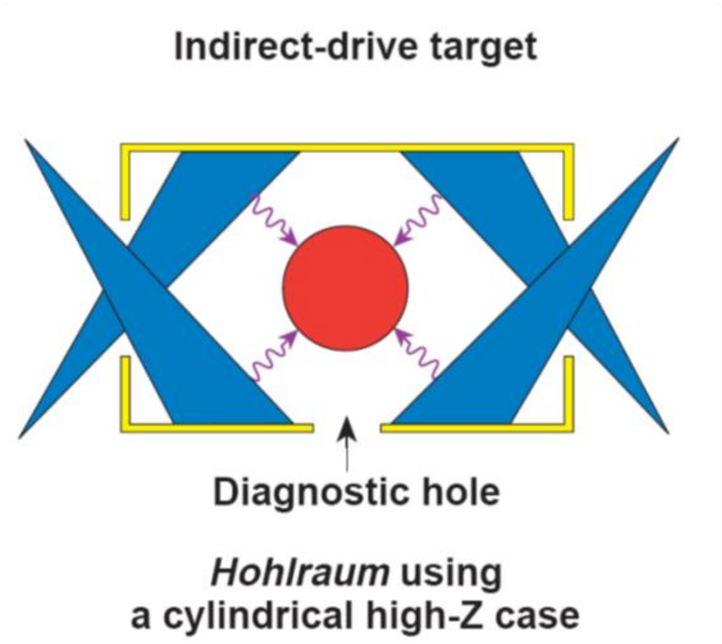
- **Stages of a target implosion**



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

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





*R. Betti, HEDSA HEDP Summer School, 2015

Rochester is known as “The World's Image Center”

There are many famous optical companies at Rochester

Kodak

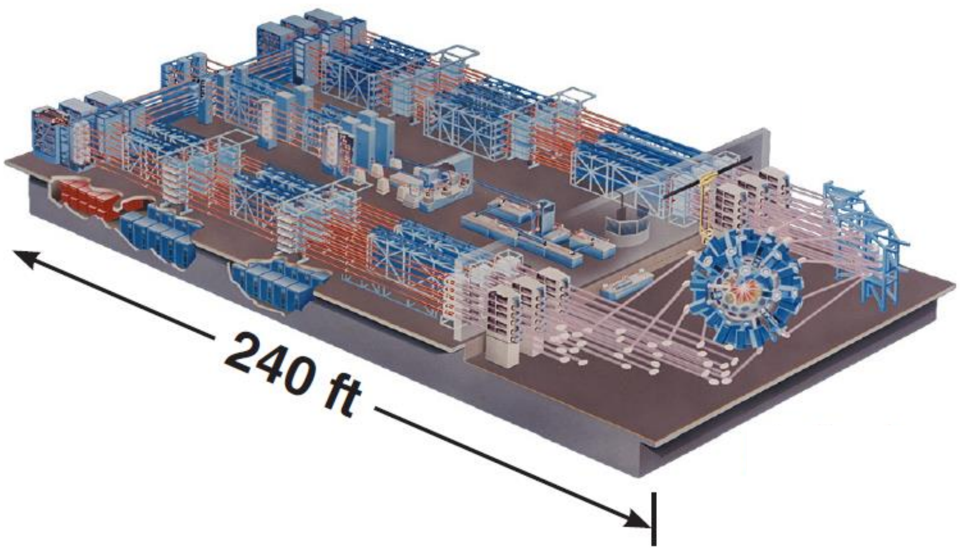
xerox ®

Eastman school of music

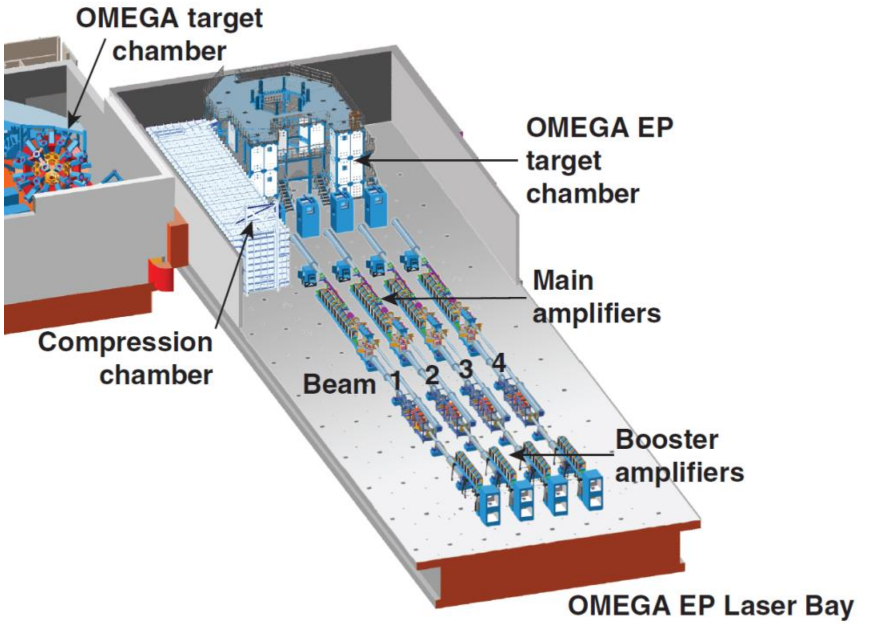
BAUSCH + LOMB

Laboratory for Laser Energetics, University of Rochester is a pioneer in laser fusion

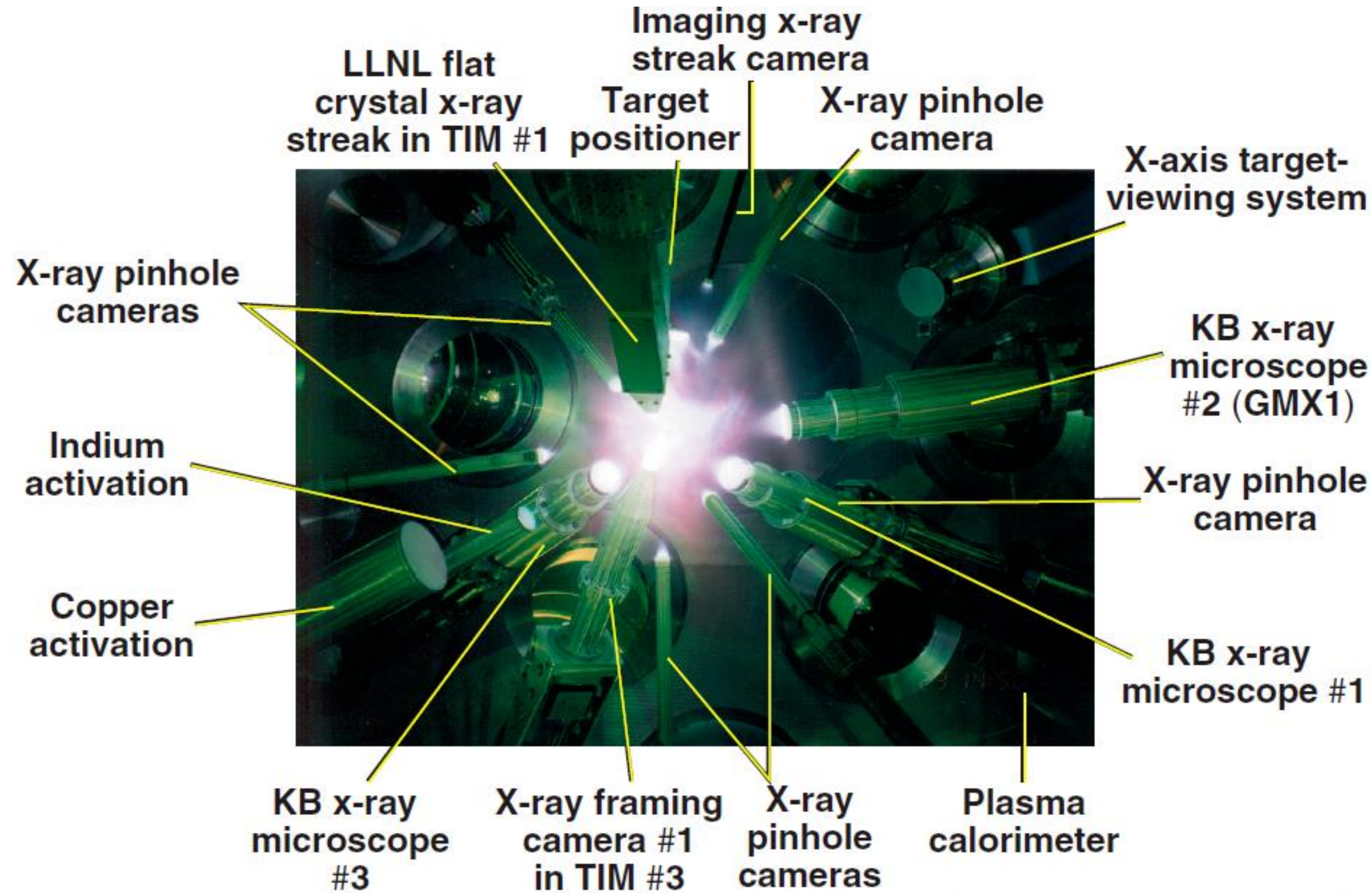
- **OMEGA Laser System**
  - **60 beams**
  - **>30 kJ UV on target**
  - **1%~2% irradiation nonuniformity**
  - **Flexible pulse shaping**



- **OMEGA EP Laser System**
  - **4 beams; 6.5 kJ UV (10ns)**
  - **Two beams can be high-energy petawatt**
    - **2.6 kJ IR in 10 ps**
    - **Can propagate to the OMEGA or OMEGA EP target chamber**



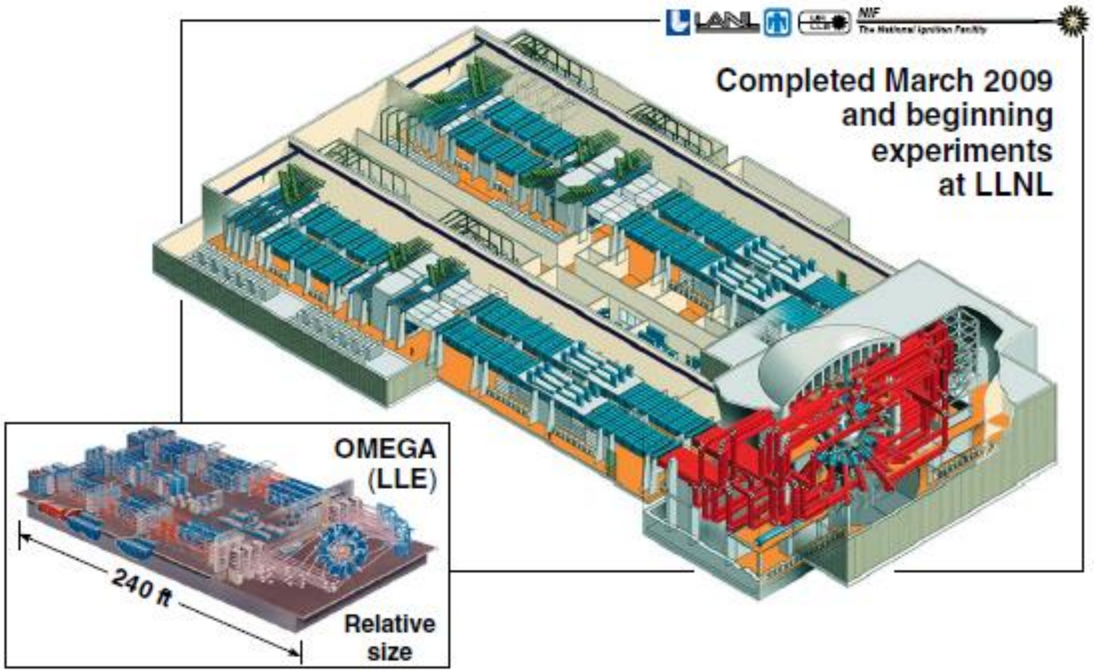
The OMEGA Facility is carrying out ICF experiments using a full suite of target diagnostics



E8012b

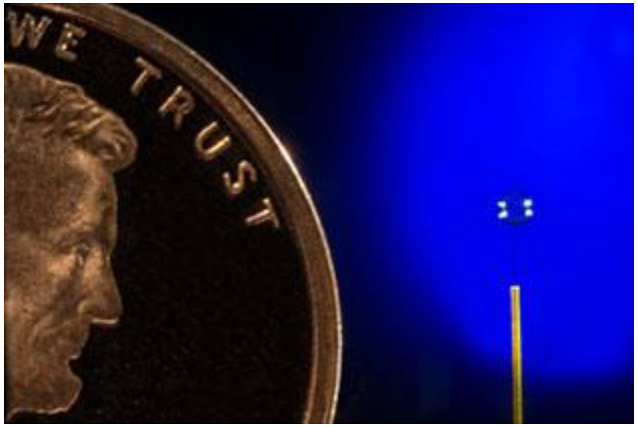
Photo taken from port H11B

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

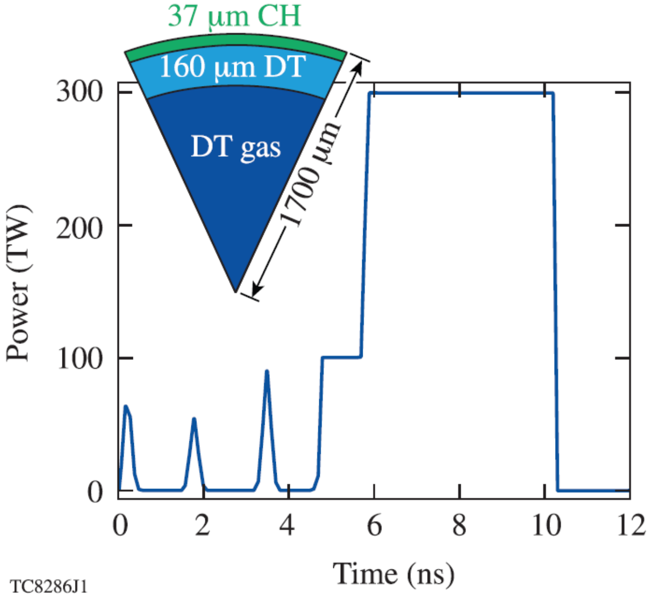


OMEGA experiments are integral to an ignition demonstration on the NIF.

Targets used in ICF



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

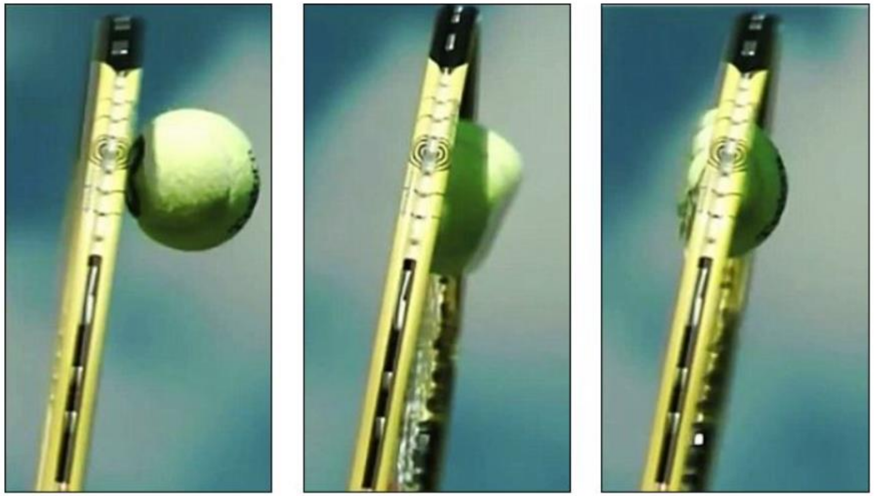


http://www.lle.rochester.ed
https://en.wikipedia.org/wiki/Inertial_confinement_fusion
R. S. Craxton, etc., *Phys. Plasmas* **22**, 110501 (2015)

Softer material can be compressed to higher density

- **Compression of a baseball**

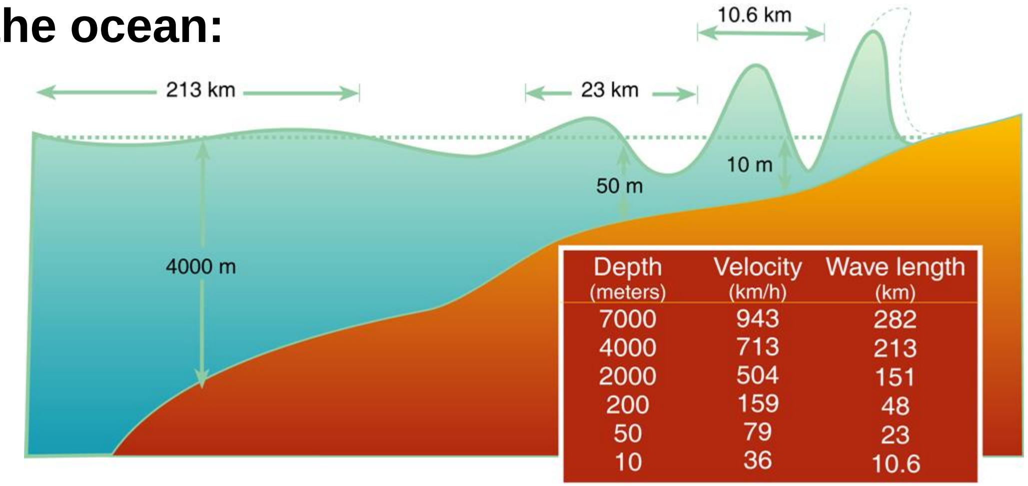
- **Compression of a tennis ball**



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

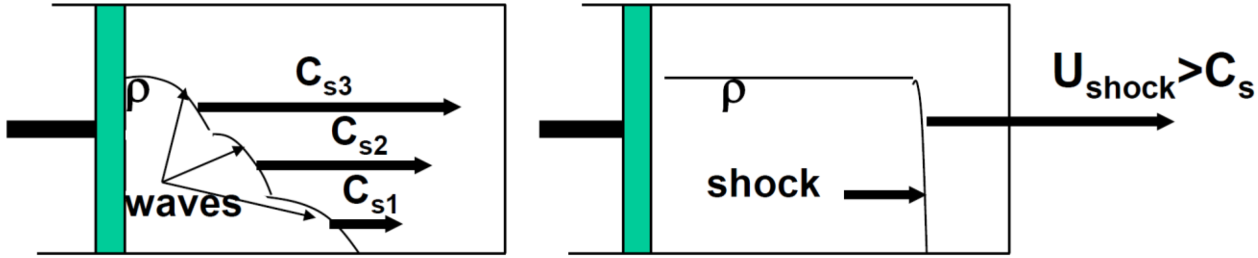
A shock is formed due to the increasing sound speed of a compressed gas/plasma

- **Wave in the ocean:**



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

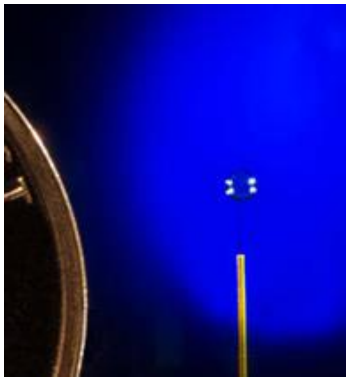
- **Acoustic/compression wave driven by a piston:**



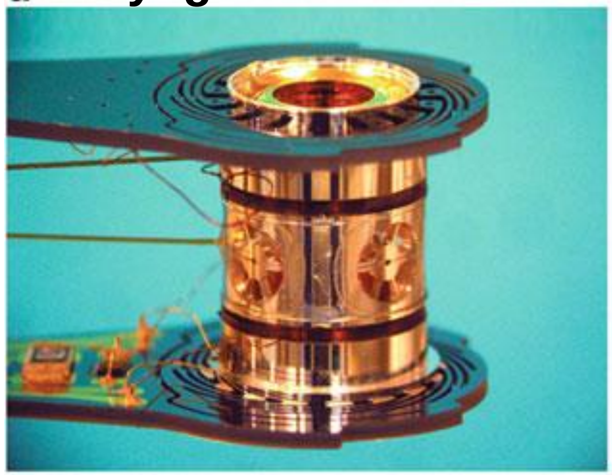
$$C_\mathrm{s} \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha\rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\rho^{1/3}$$

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

Targets used in ICF



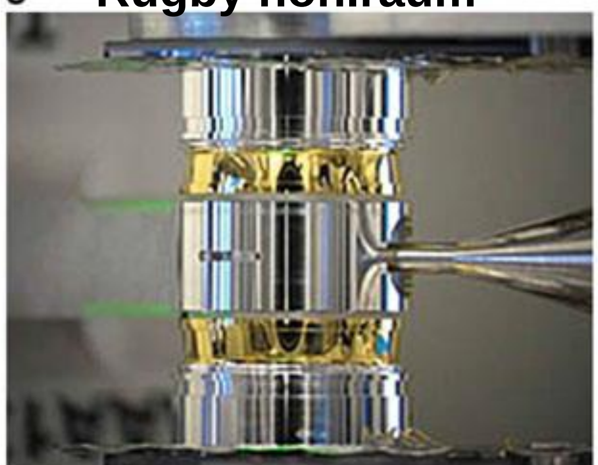
a Cryogenic hohlraum



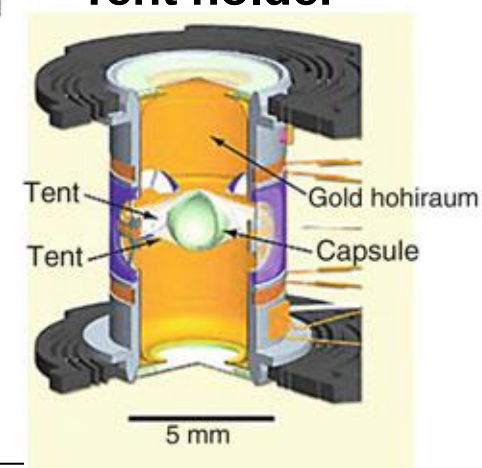
b

Cryogenic shroud

c Rugby hohlraum

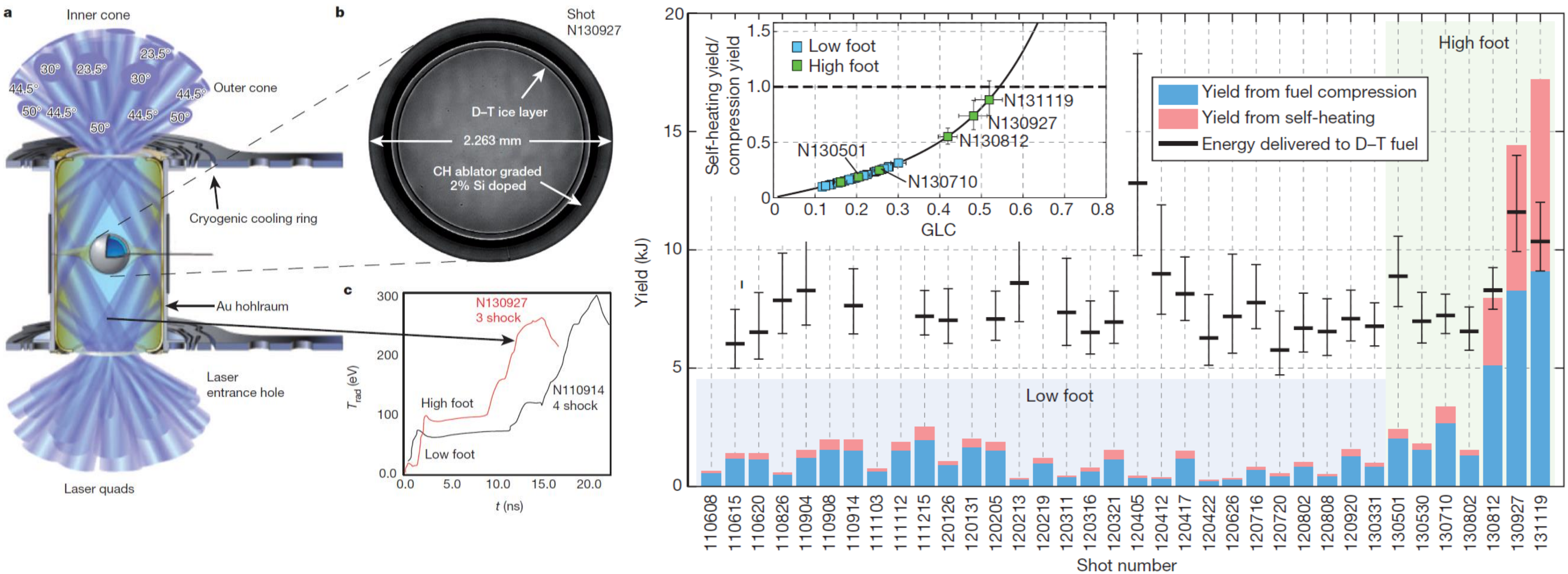


d Tent holder



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

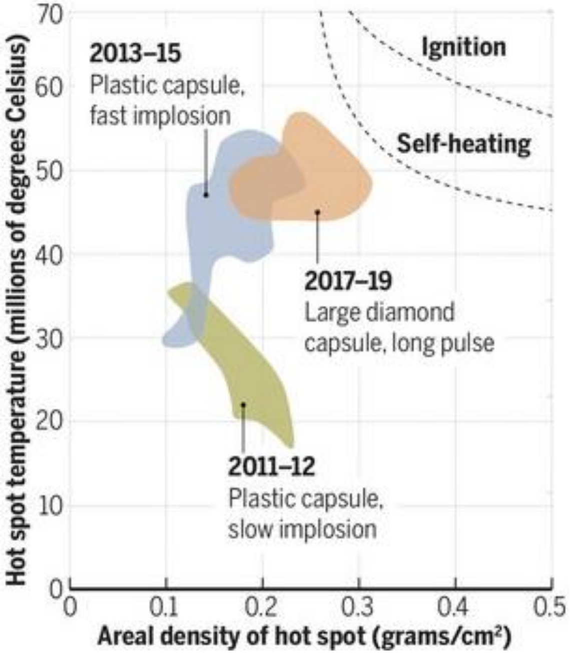
Nature letter “Fuel gain exceeding unity in an inertially confined fusion implosion”



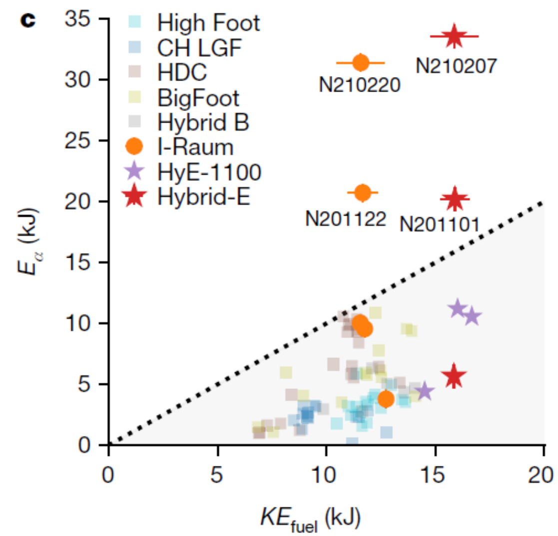
- **Fuel gain exceeding unity (scientific breakeven) was demonstrated for the first time.**

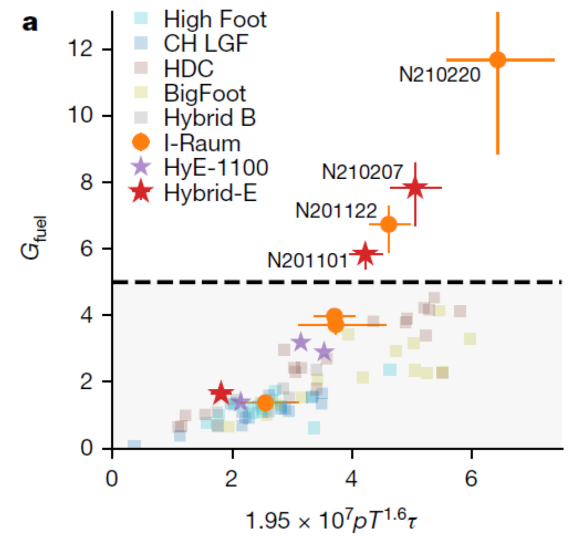
Nature 506, p343, 2014

The hot spot has entered the burning plasma regime



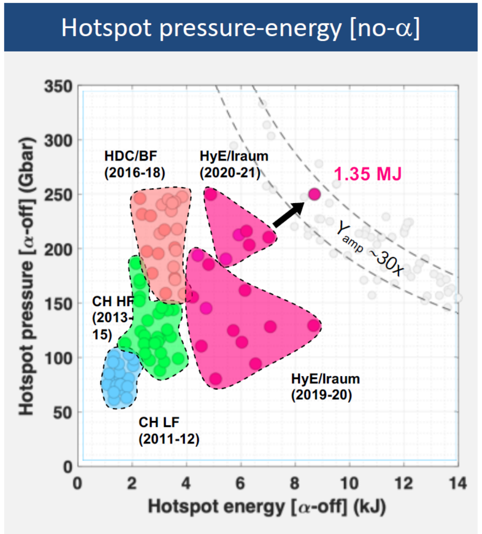
Science 370, p1019, 2020

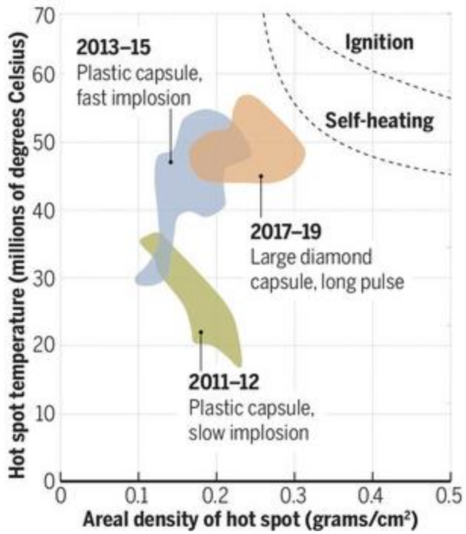




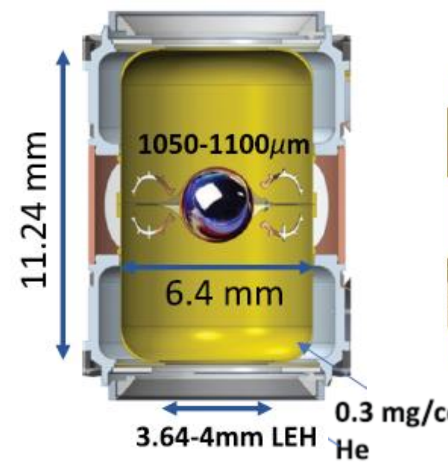
Nature 601, p542, 2022

The hot spot has entered the burning plasma regime

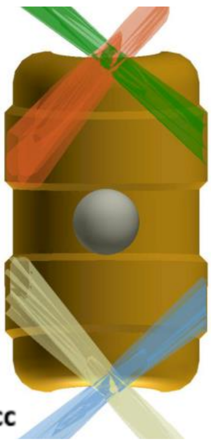


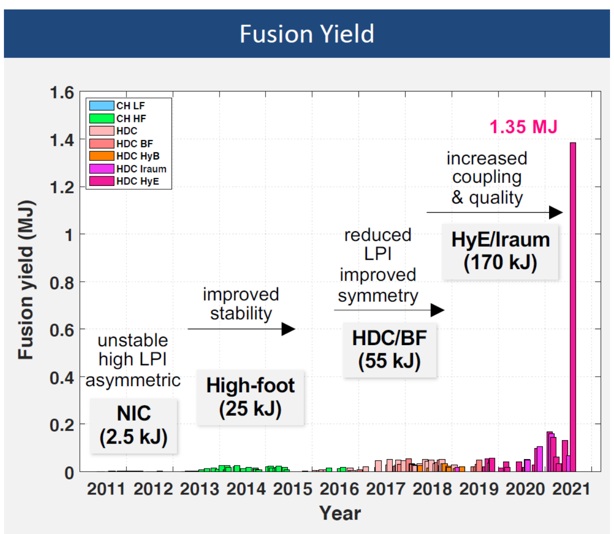


- **Hybrid-E**

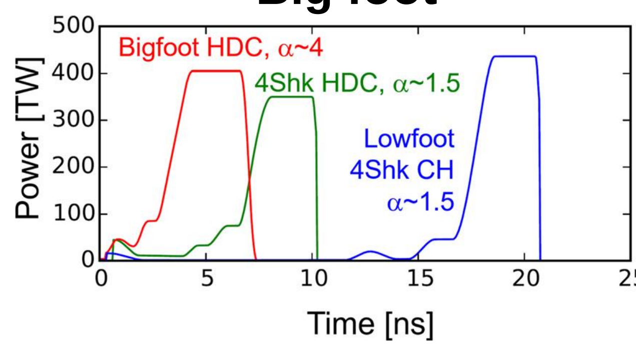


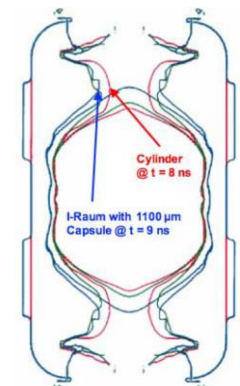
- **I-raum**





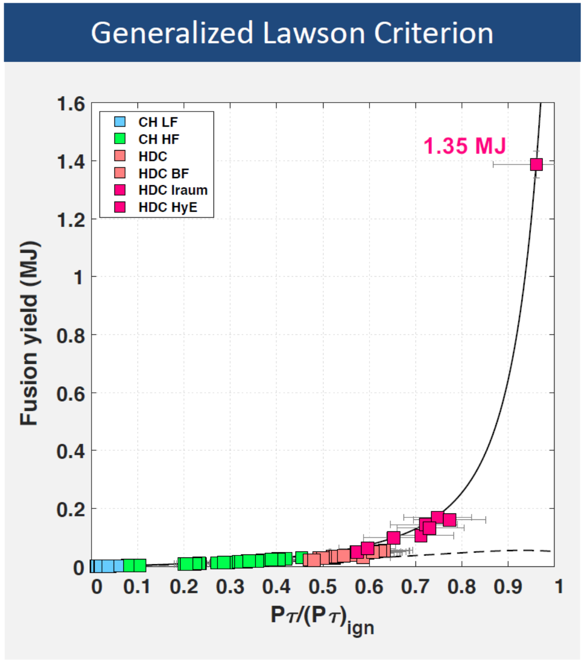
- **Big foot**

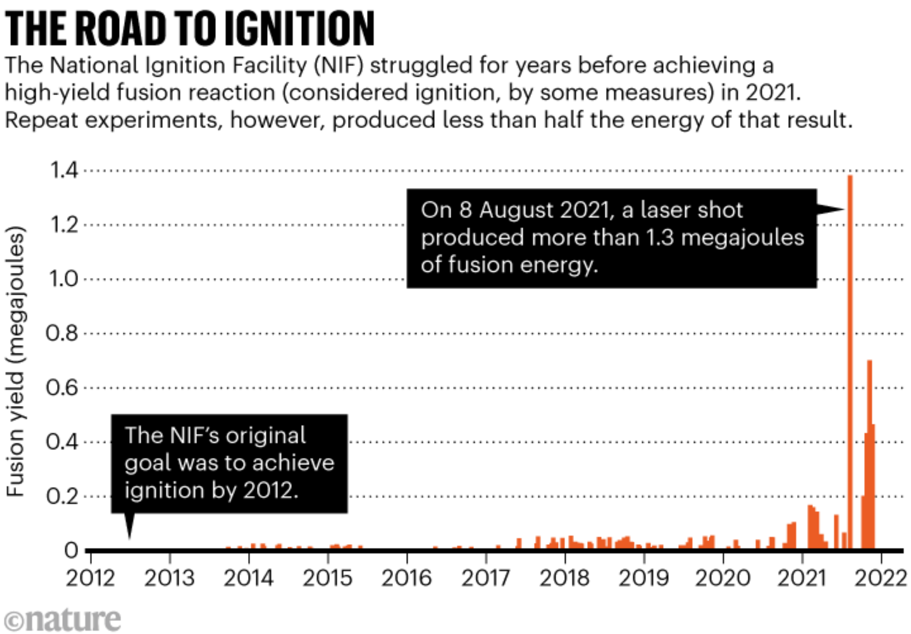




T. Ma, ARPA-E workshop, April 26, 2022
Science 370, p1019, 2020
D. T. Casey, etc., Phys. Plasmas, 25, 056308 (2018)
A. L. Kritcher, etc., Phys. Plasmas, 28, 072706 (2021)
H. F. Robey, etc., Phys. Plasmas, 25, 012711 (2018)

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

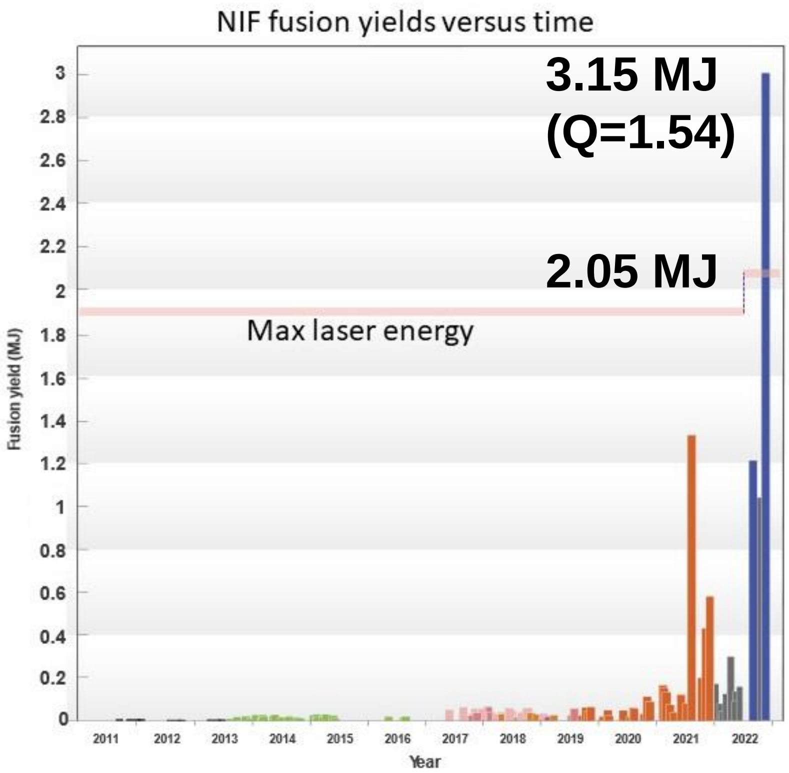


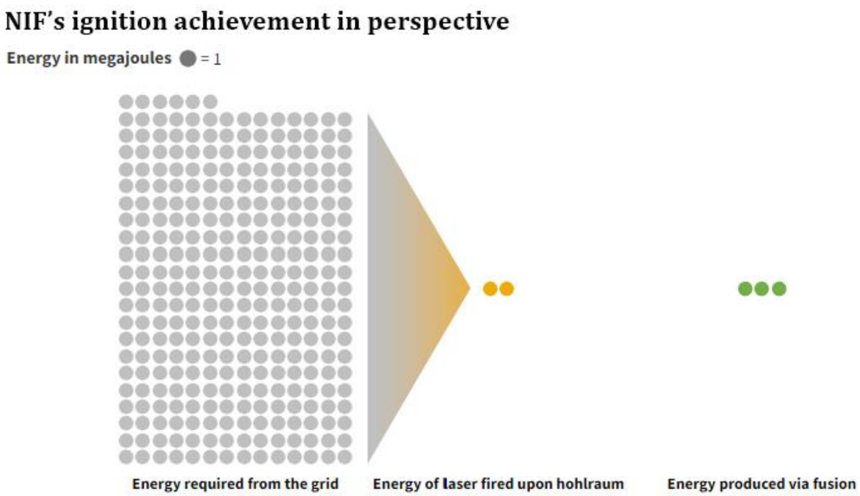


- **National Ignition Facility (NIF) achieved a yield of more than 1.3 MJ (Q~0.7). This advancement puts researchers at the threshold of fusion ignition.**
- **Laser-fusion facility heads back to the drawing board.**

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

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



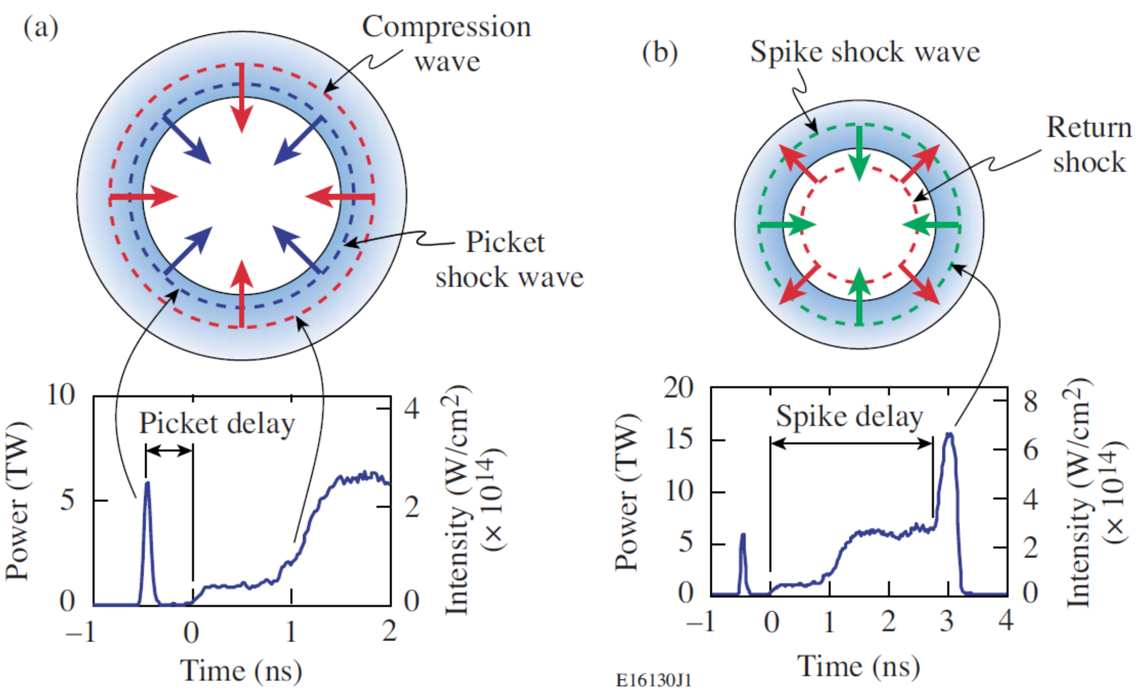


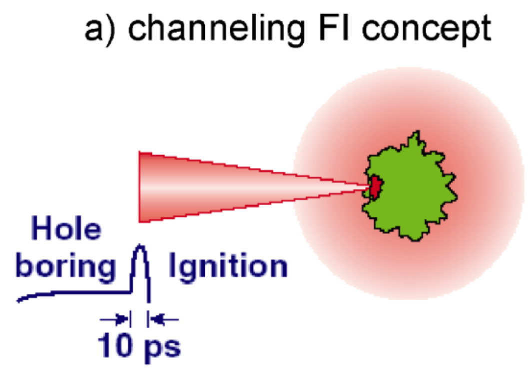
300 MJ **2.05 MJ** **3.15 MJ**

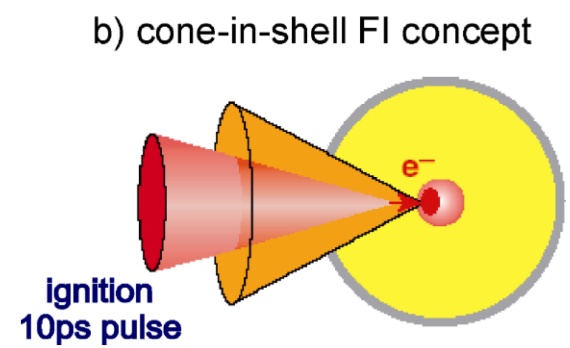
https://physicstoday.scitation.org/do/10.1063/PT.6.2.20221213a/full/

External “spark” can be used for ignition

- **Shock ignition**
- **Fast ignition**



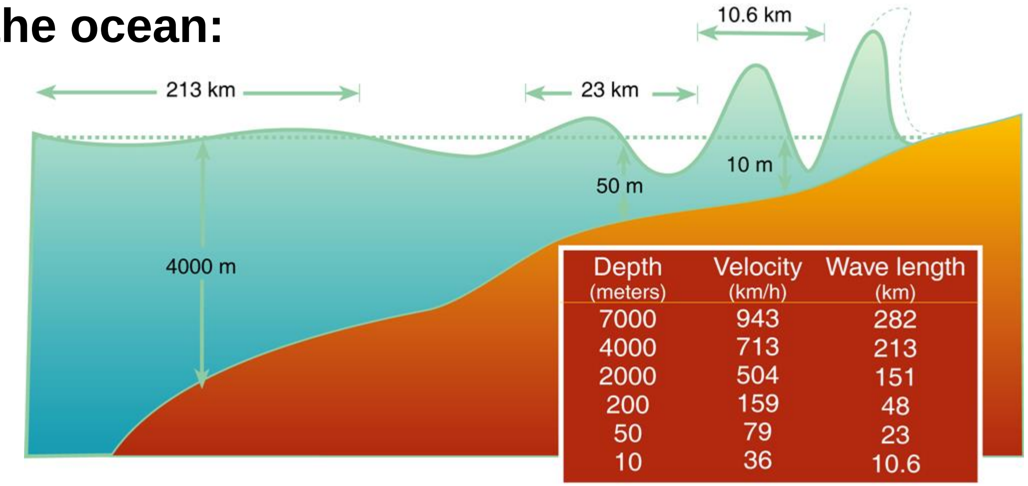




J. Badziak, Bull.Polish Acad. Sci. Tech. Sci.Phys. Plasmas 15, 056306 (2008)

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

- **Wave in the ocean:**



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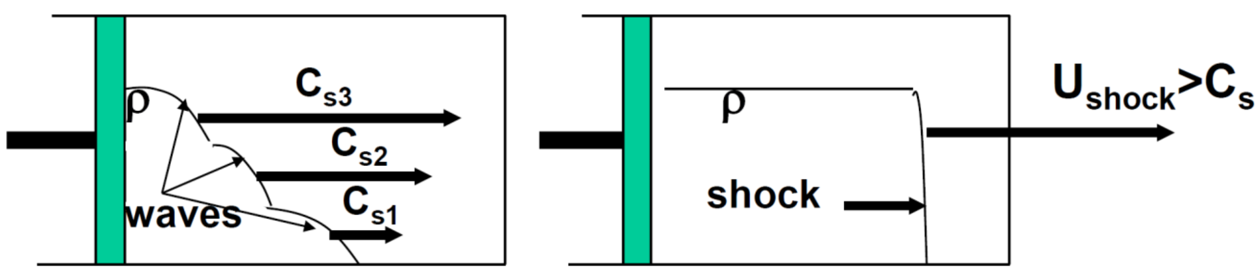
10	36	10.6

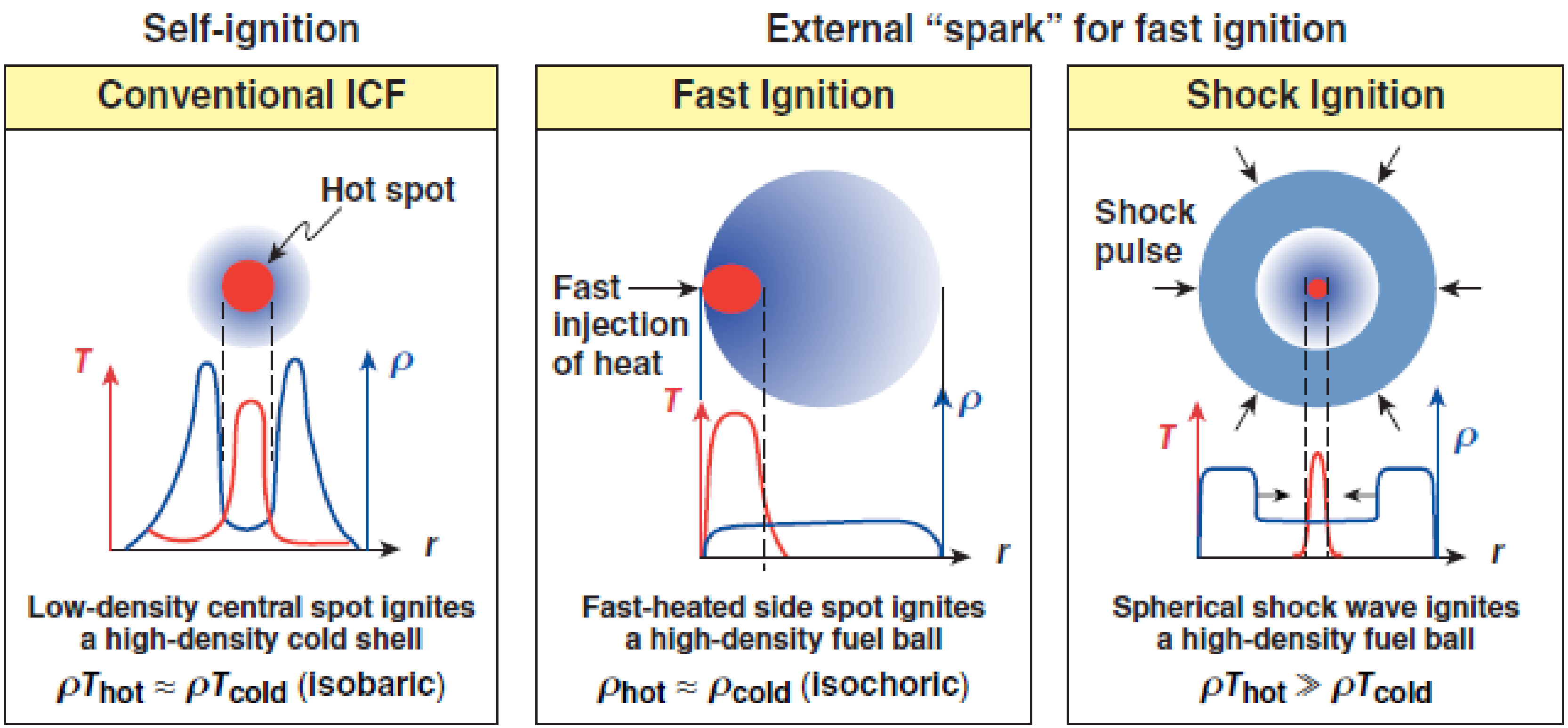
- **Acoustic/compression wave driven by a piston:**



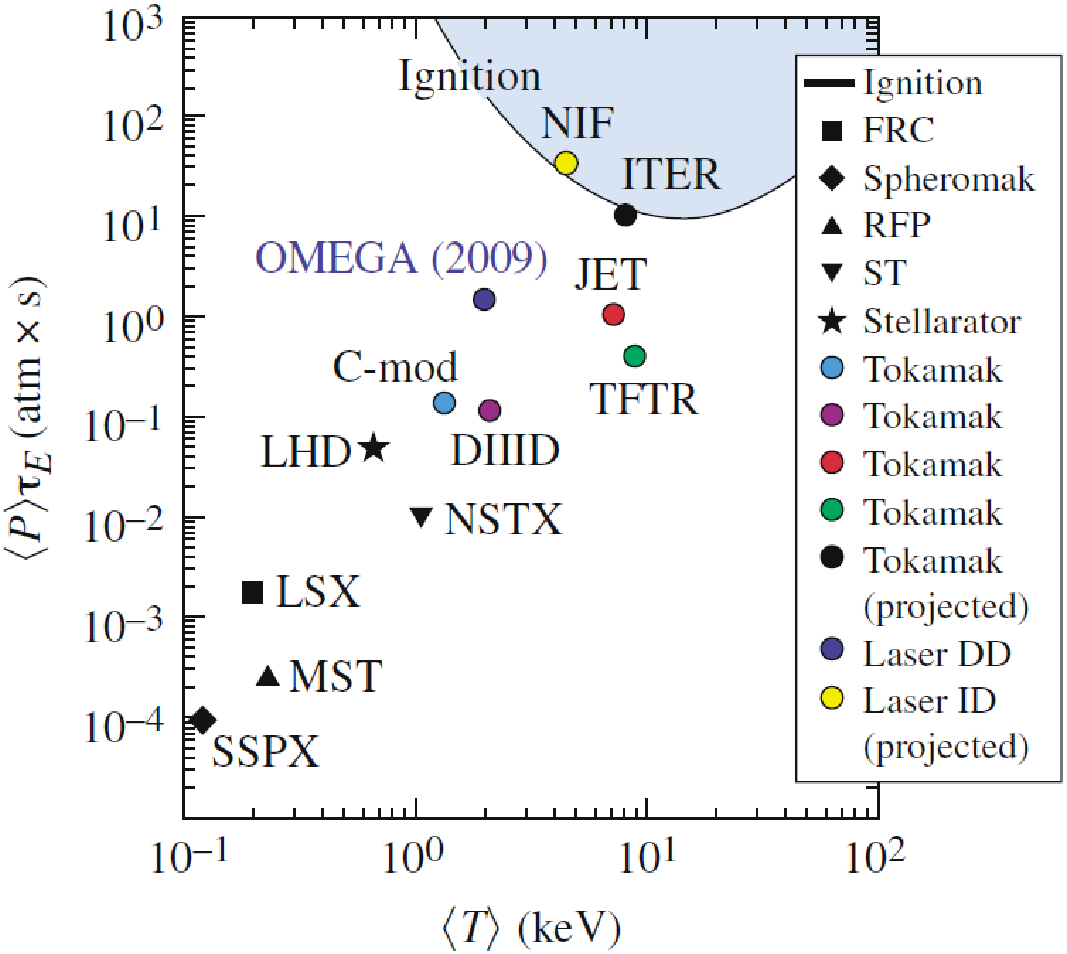
$$C_s \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha\rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\rho^{1/3}$$

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

Ignition can happen by itself or being triggered externally



We are closed to ignition!

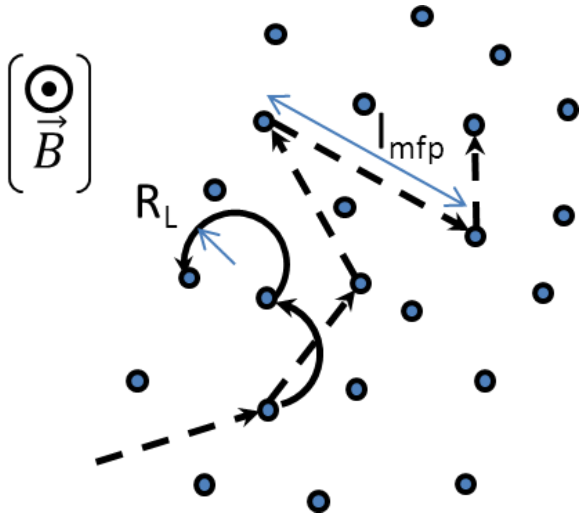


R. Betti, etc., Phys. Plasmas, **17**, 058102 (2010)

Outline

- Introduction to nuclear fusion
- Magnetic confinement fusion (MCF)
  - Tokamak
  - Stellarator
- Inertial confinement fusion (ICF)
  - Indirection drive ICF
  - Direct drive ICF
- **Innovation idea – MCF + ICF**
- Pulsed-power system at NCKU

A strong magnetic field reduces the heat flux



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

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

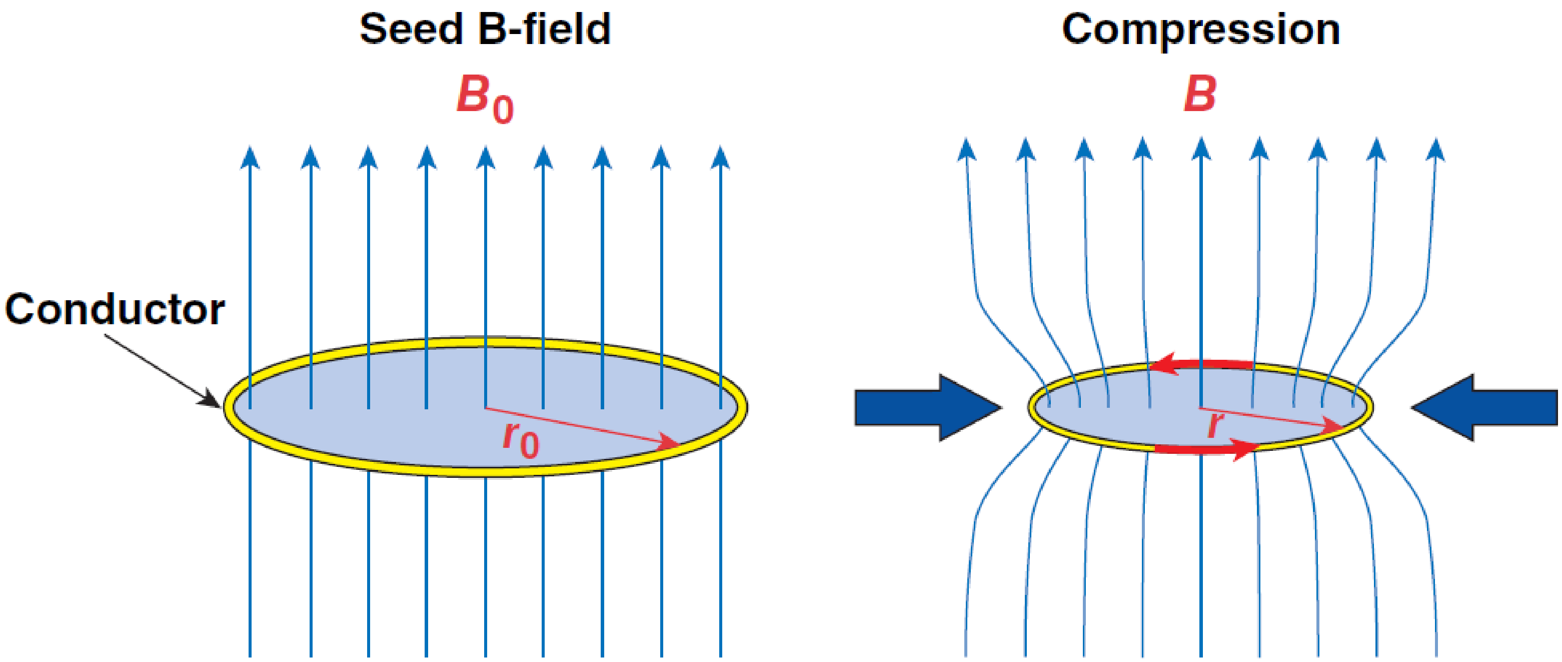
$$\kappa_{\perp} = \frac{\kappa_{||}}{\chi^2} \quad \text{for large Hall parameter } \chi \propto \frac{l_{mfp}}{R_L} >> 1$$

- **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.

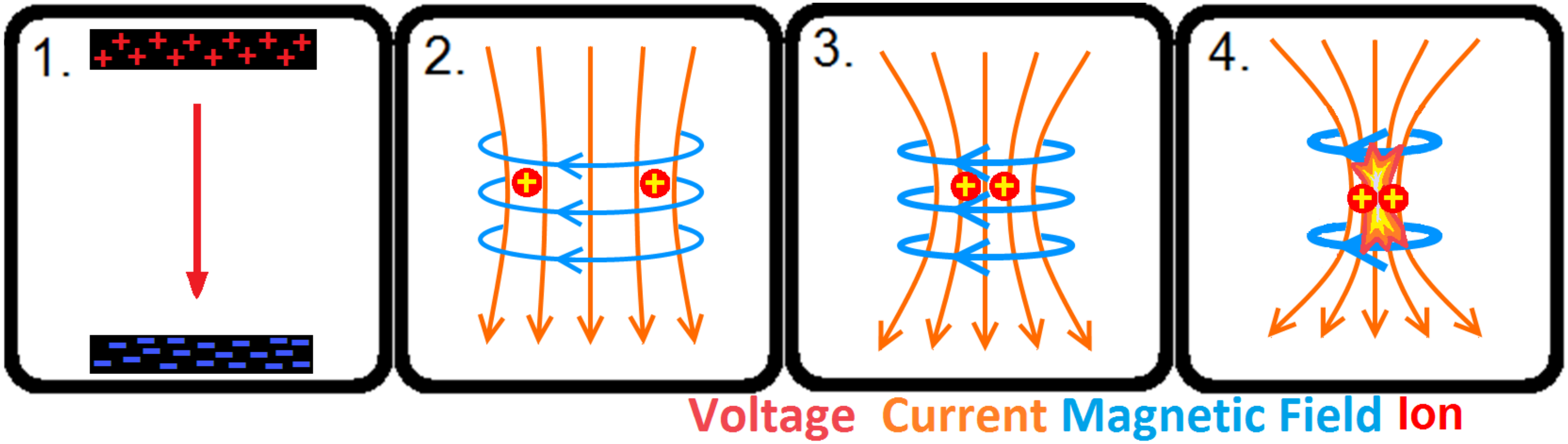
Principle of frozen magnetic flux in a good conductor is used to compress fields



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

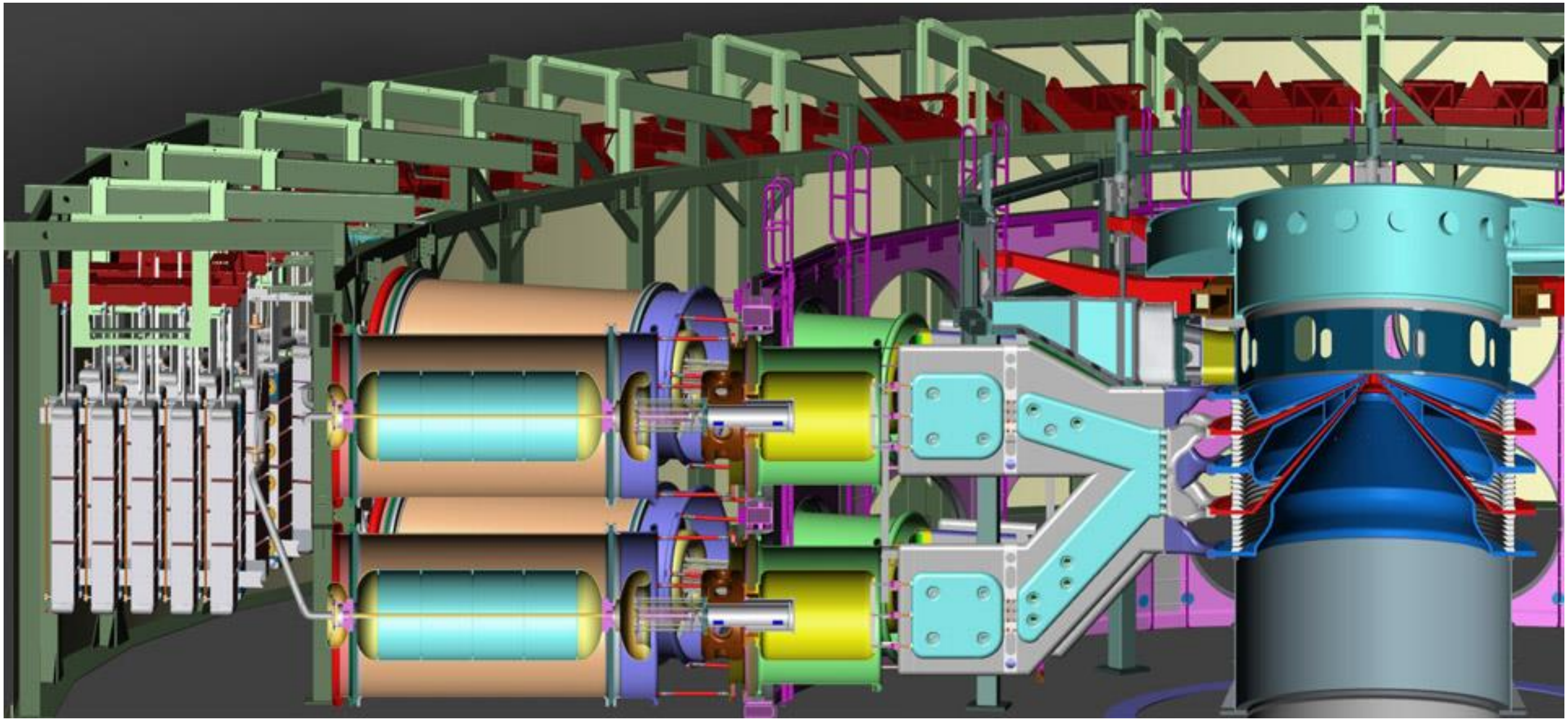
M. Hohenberger, P.-Y. Chang, *et al*., Phys. Plasmas 19, 056306 (2012).

Plasma can be pinched by parallel propagating plasmas



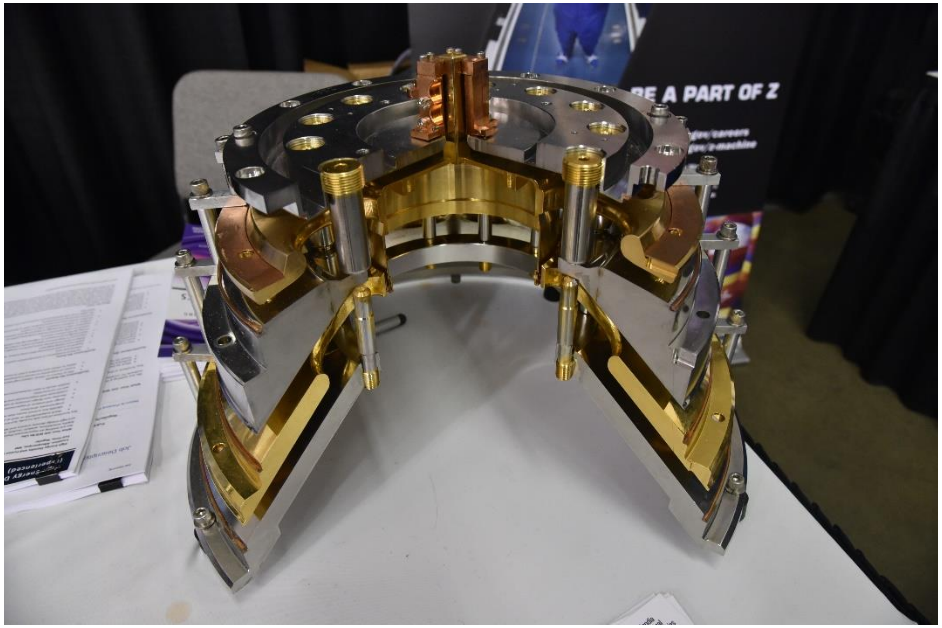
https://en.wikipedia.org/wiki/Pinch_(plasma_physics)

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



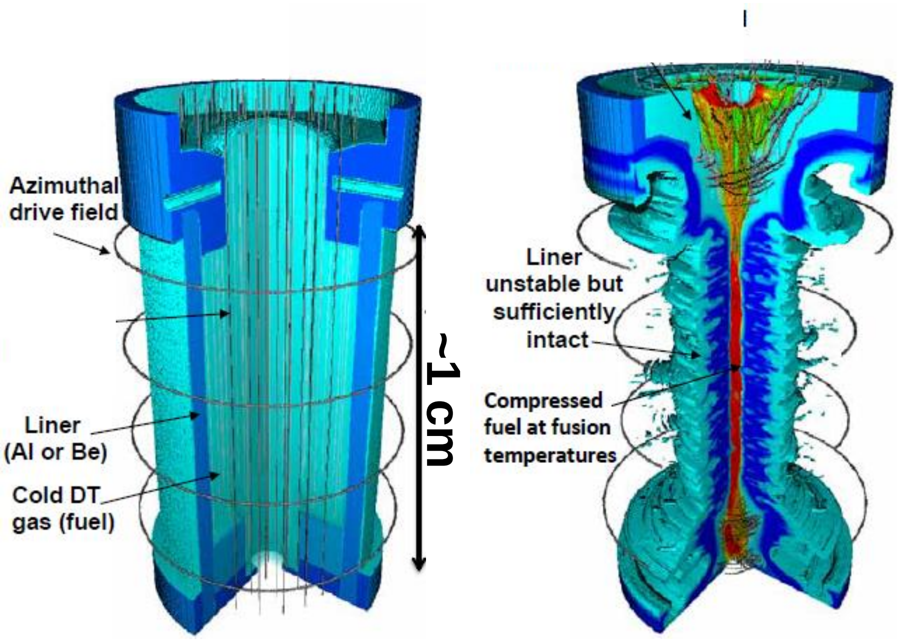
- Stored energy: 20 MJ
- Marx charge voltage: 85 kV
- Peak electrical power: 85 TW
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray emissions: 350 TW
- Peak X-ray output: 2.7 MJ

Z machine



- Stored energy: 20 MJ
- Peak electrical power: 85 TW
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray output: 2.7 MJ

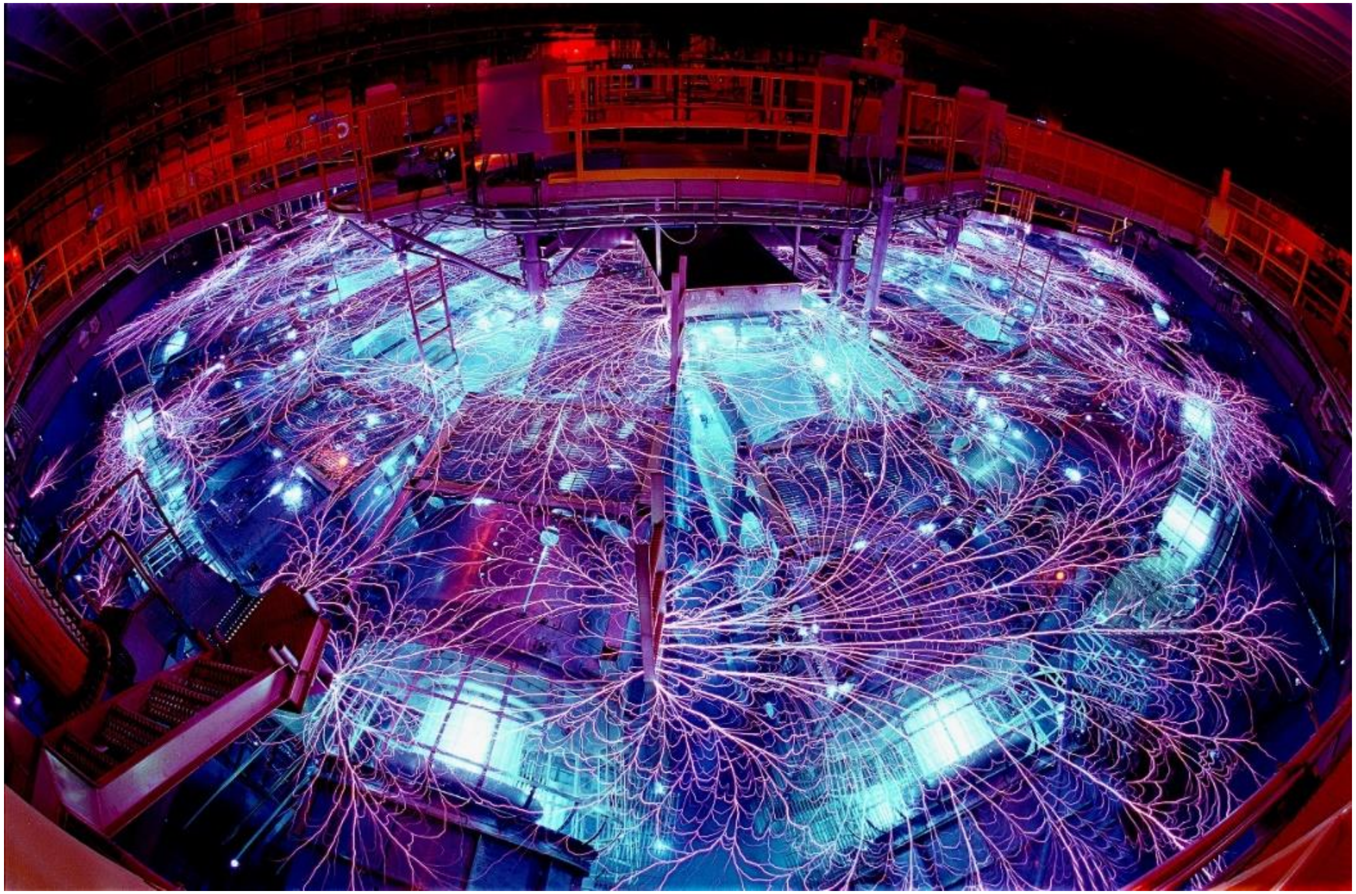
Z machine



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

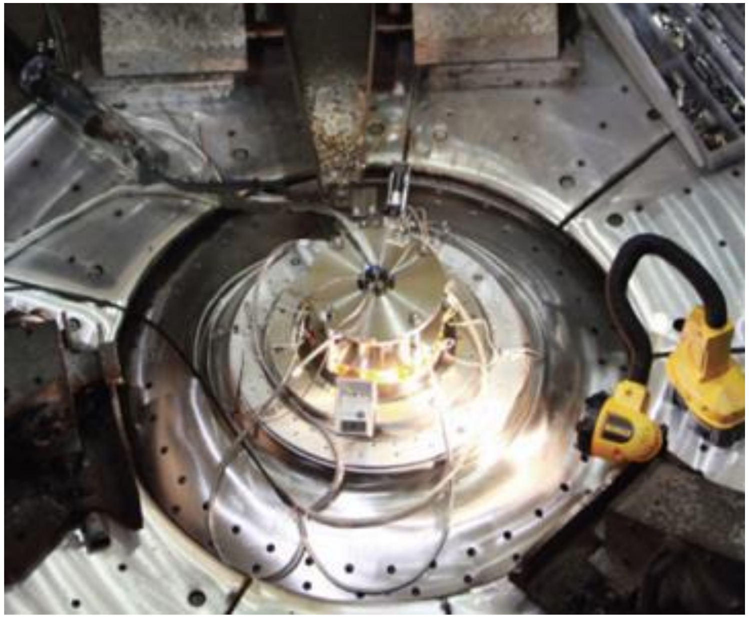
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray output: 2.7 MJ

Z machine discharge



Before and after shots

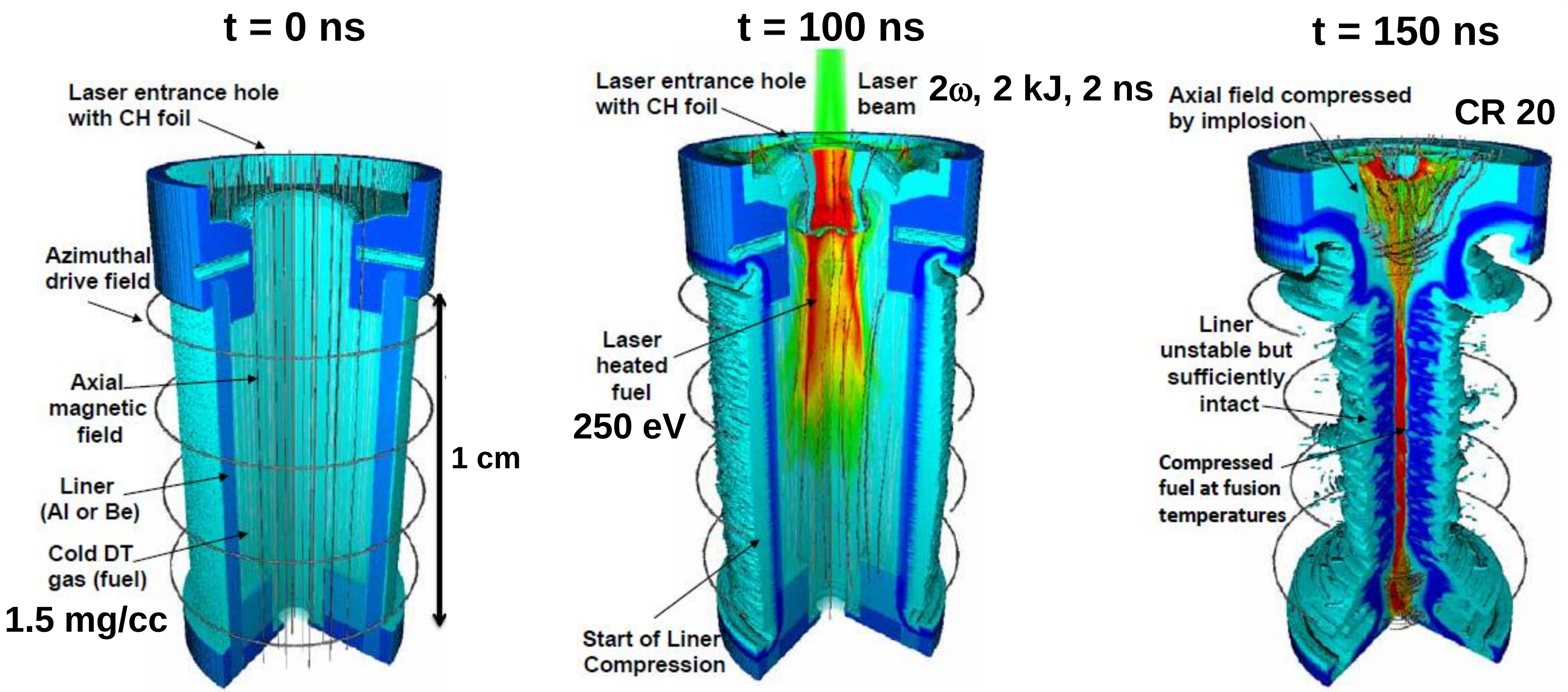
- **Before shots**



- **After shots**

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

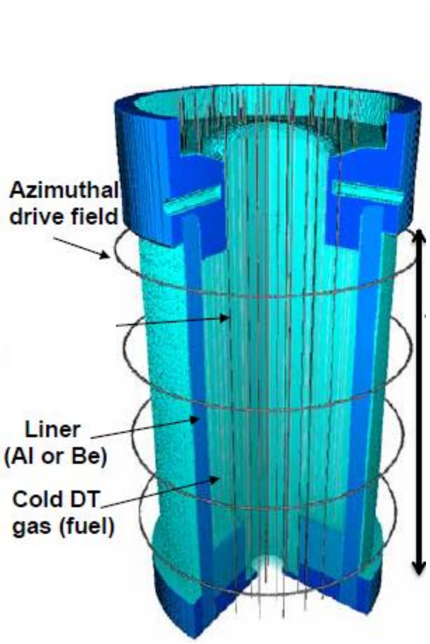
Promising results were shown in MagLIF concept conducted at the Sandia National Laboratories

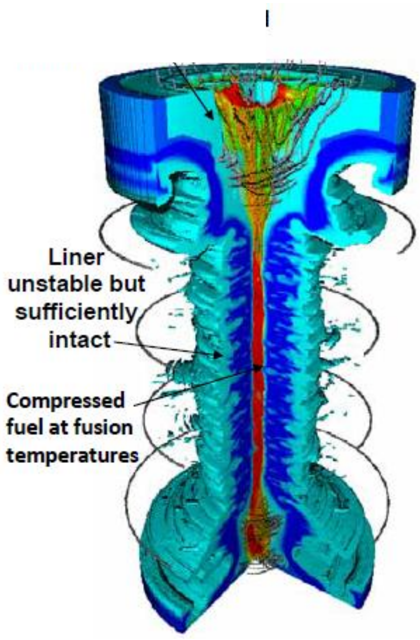


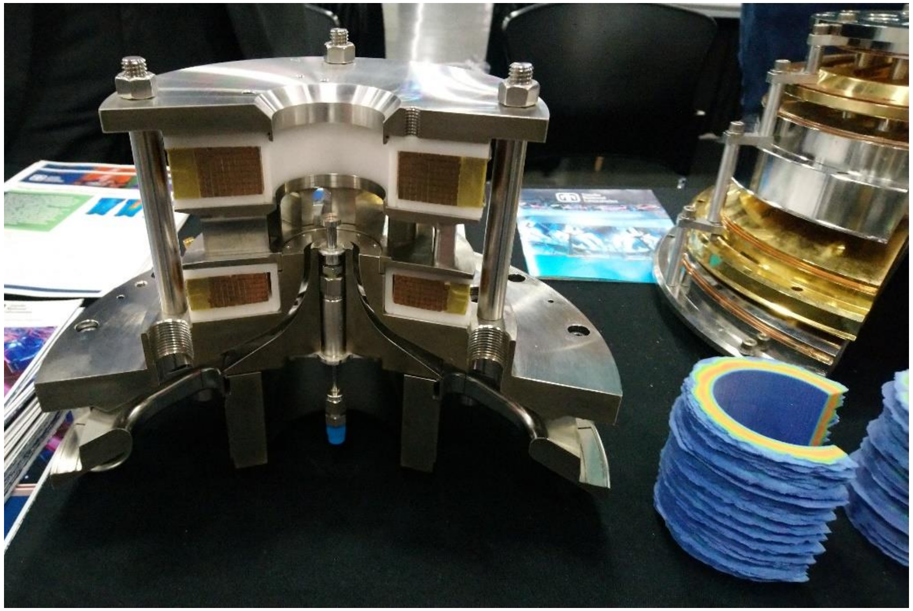
The stagnation plasma reached fusion-relevant temperatures with a 70 km/s implosion velocity

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

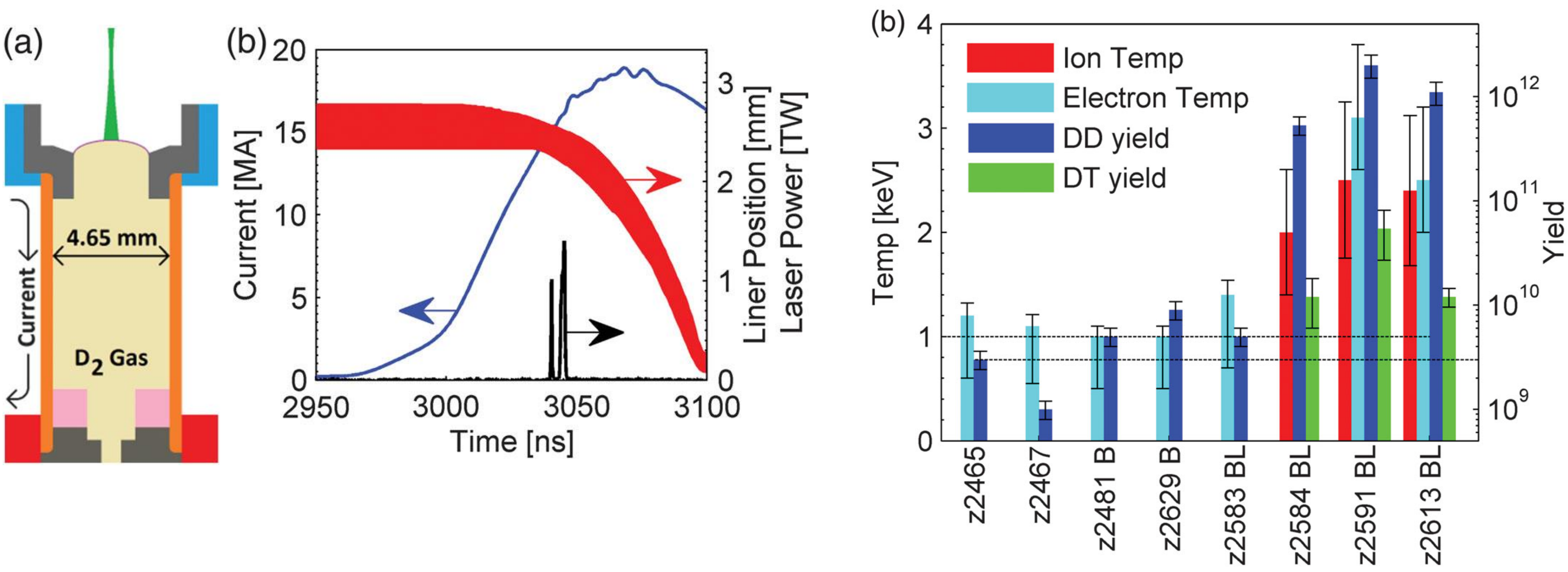
MagLIF target







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



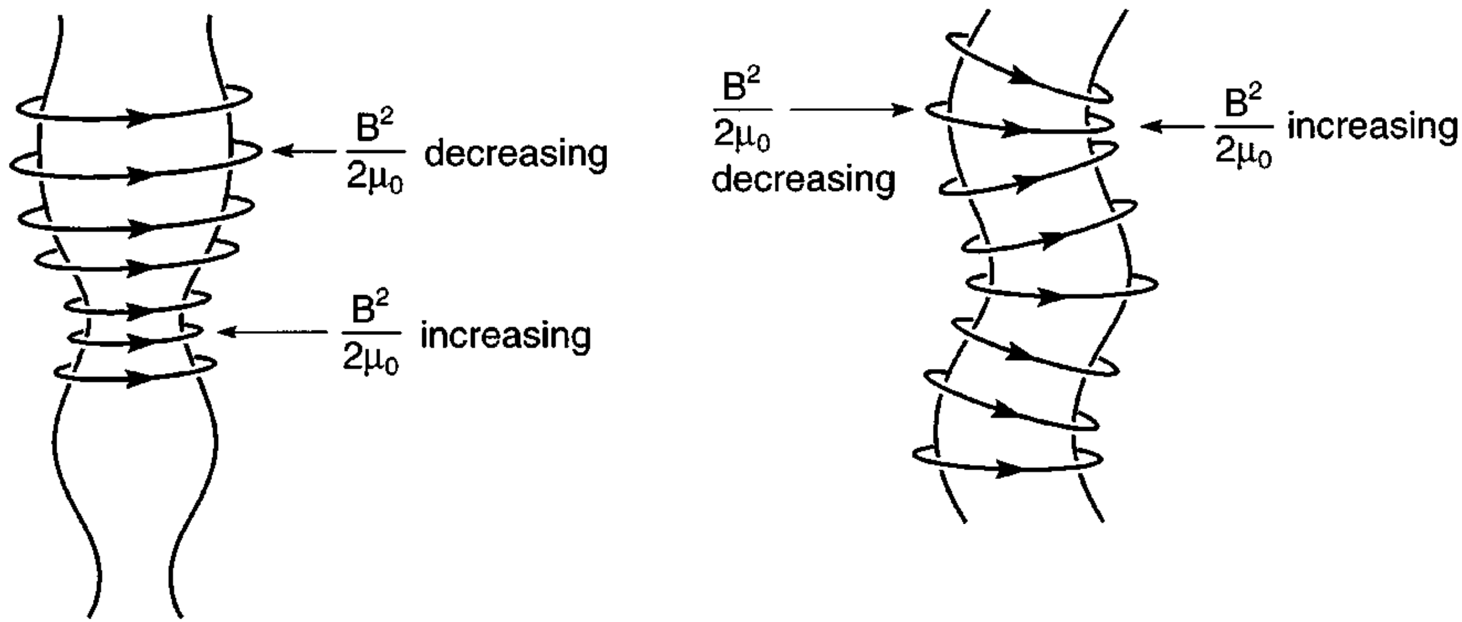
M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)

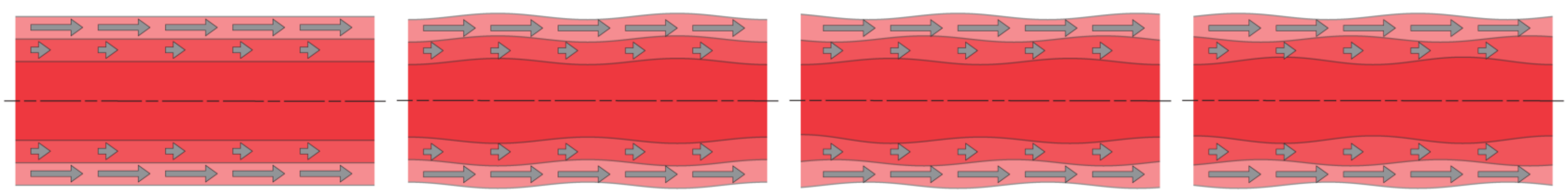
Sheared flow stabilizes MHD instabilities

m = 0 (sausage)

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

m = 1 (kink)

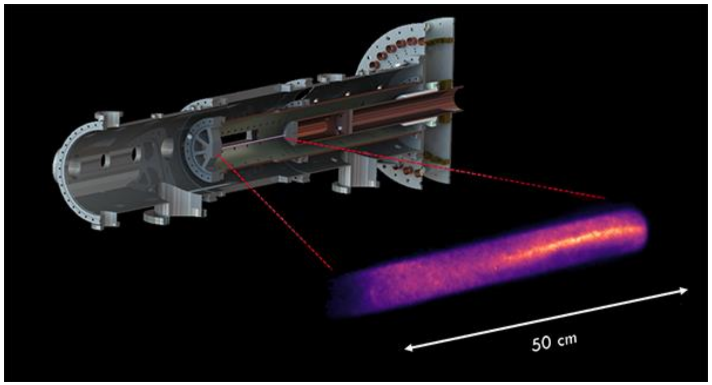




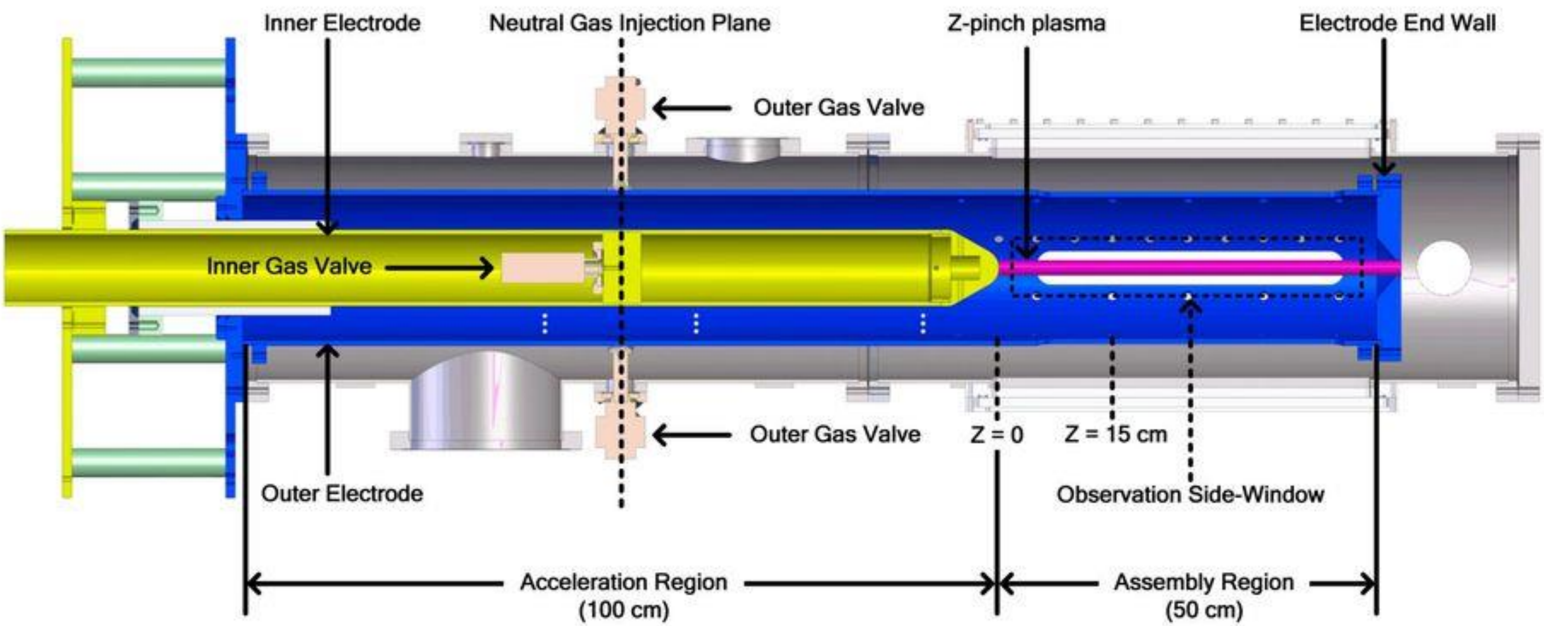
$$\frac{dV_Z}{dr} \neq 0$$

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

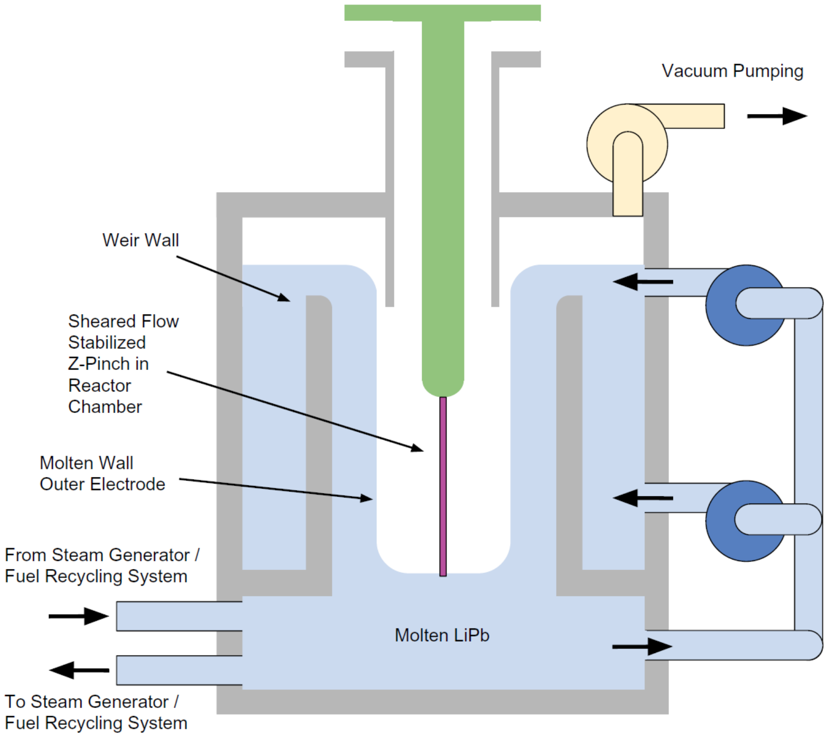


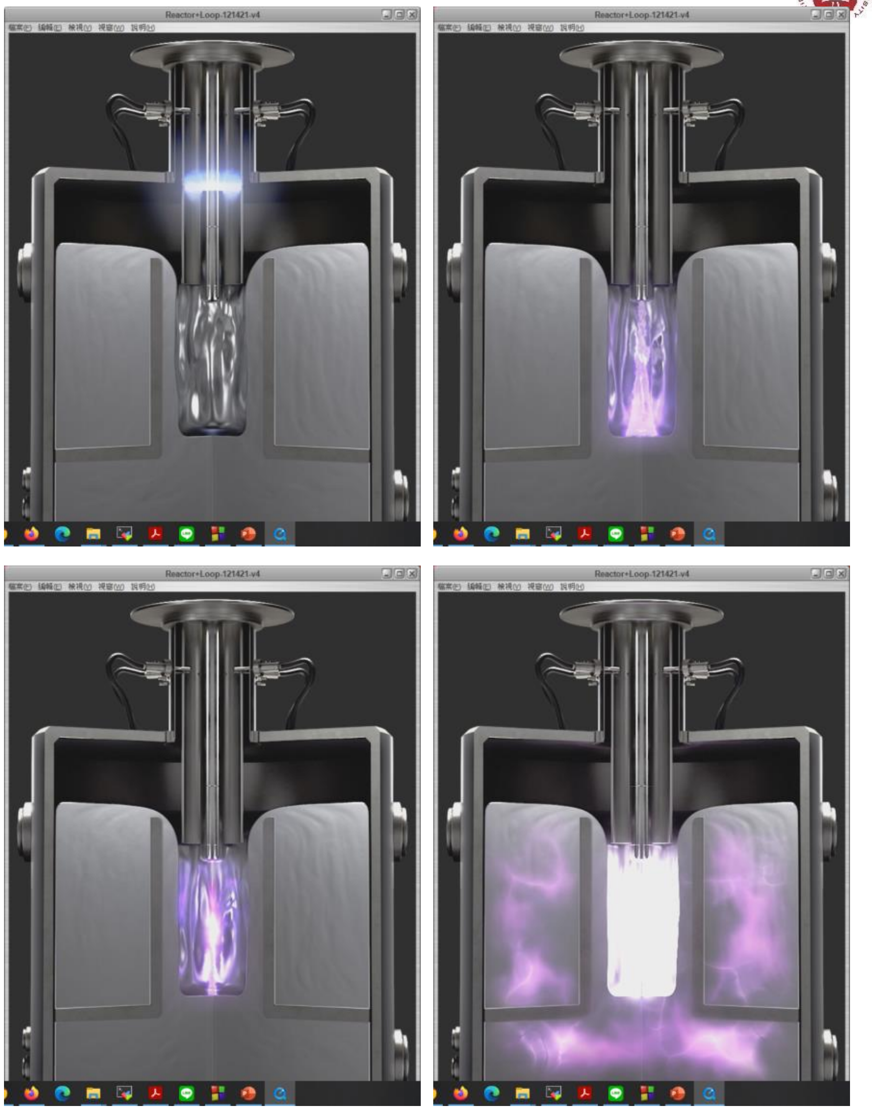
ZAP ENERGY



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

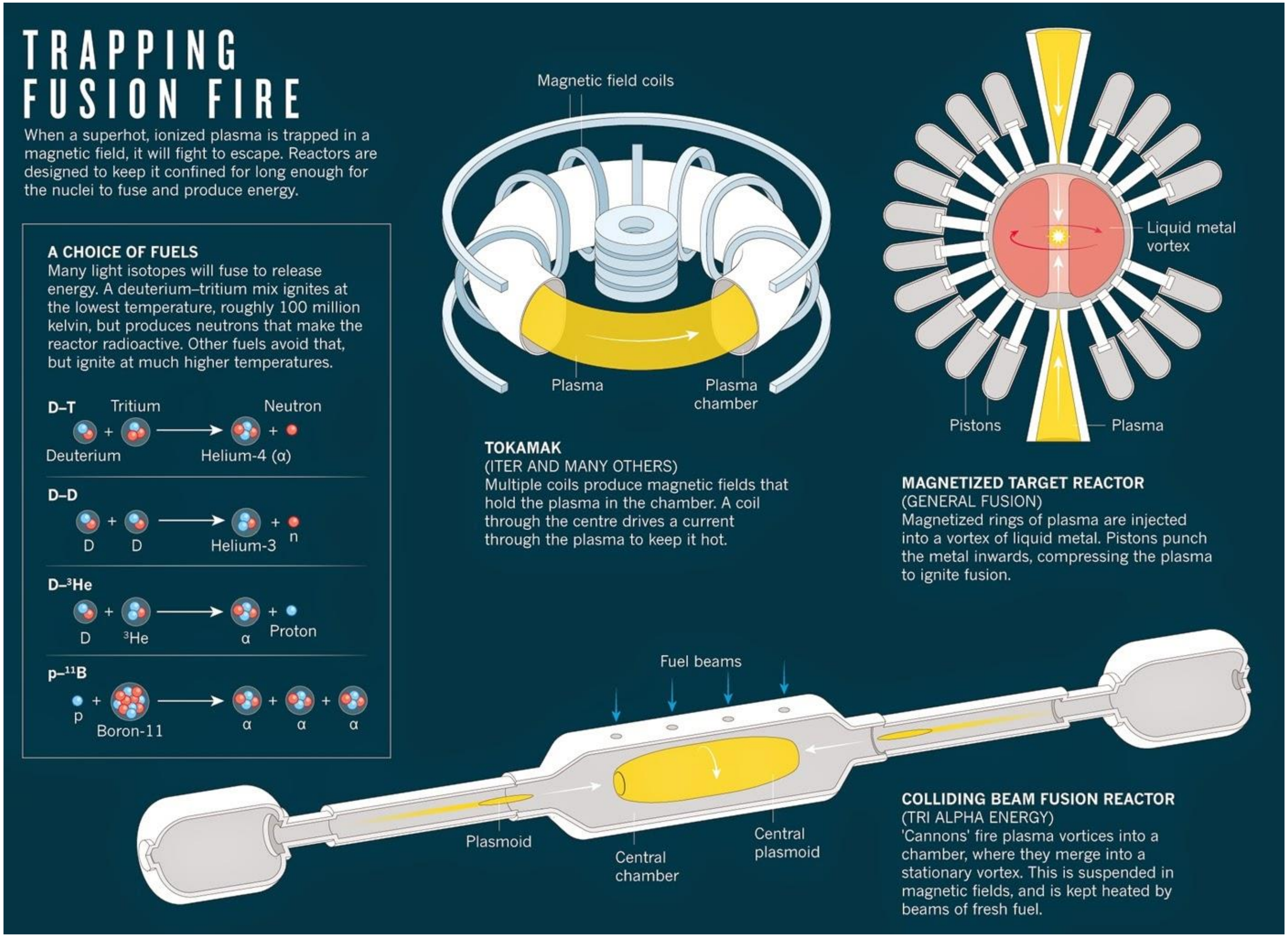
Fusion reactor concept by ZAP energy





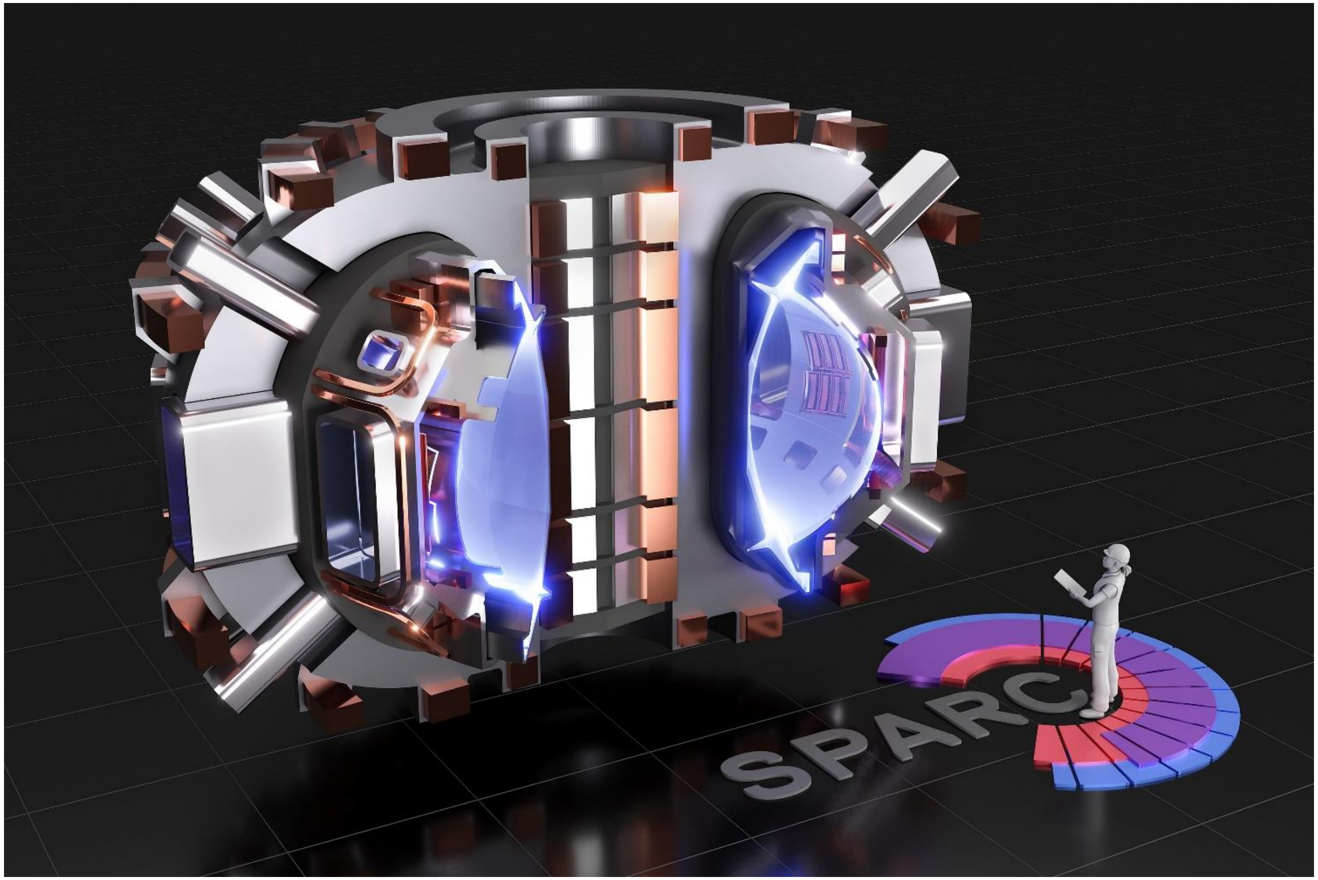
https://www.zapenergyinc.com/about
E. G. Forbes, etc., Fusion Sci. Tech. 75, 599 (2019)

There are alternative



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

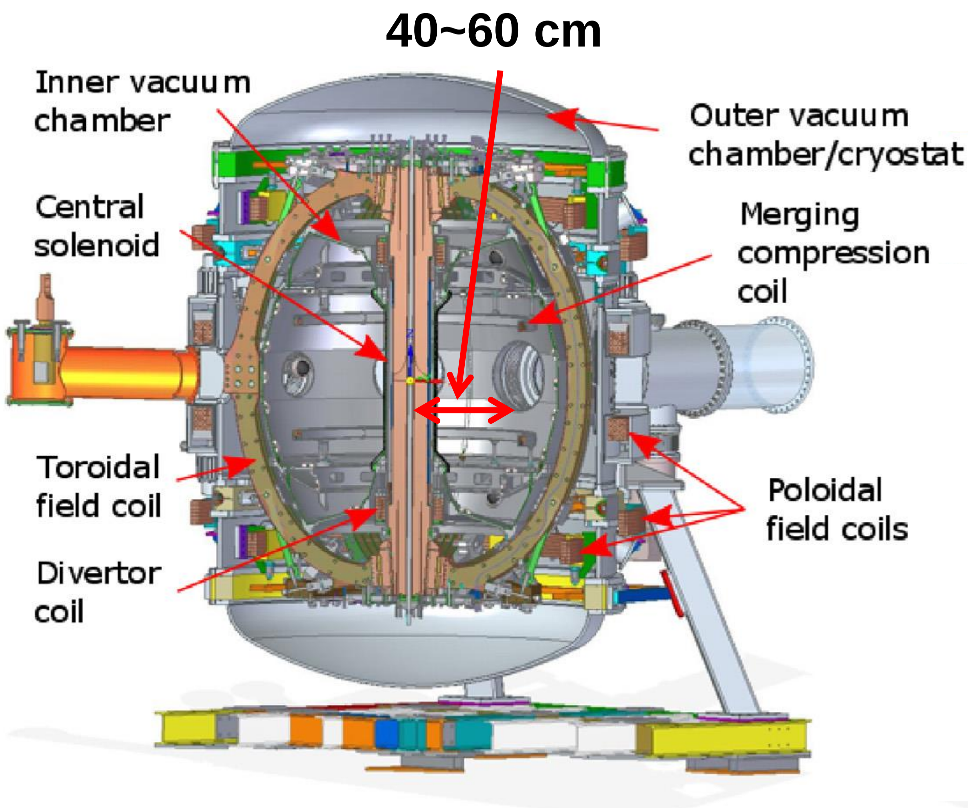
Commonwealth Fusion Systems, a MIT spin-out company, is building a high-magnetic field tokamak



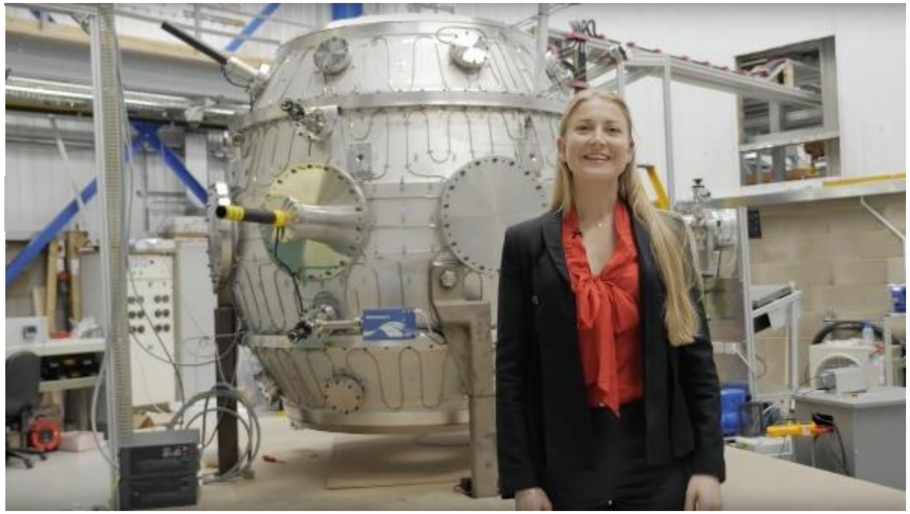
- **Fusion power ∝ B^4.**
- **The fusion gain Q > 2 is expected for SPARC tokamak.**

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

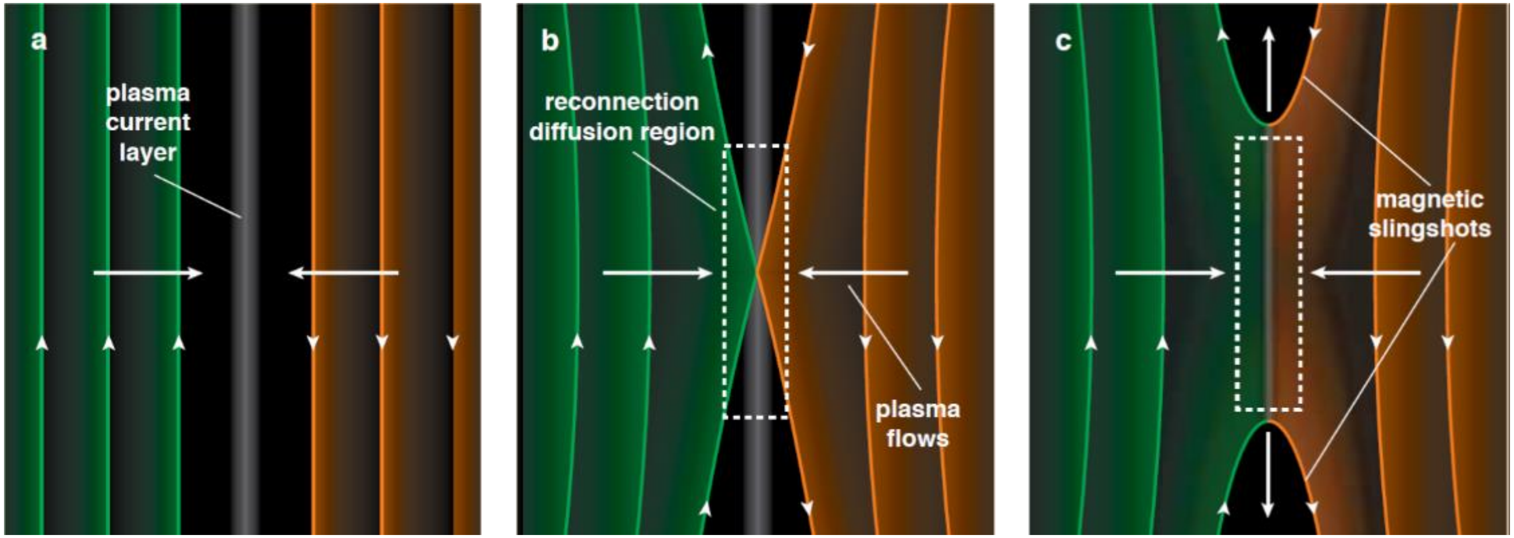


- **High temperature superconductors are used.**
- **B_T ~ 3 T**



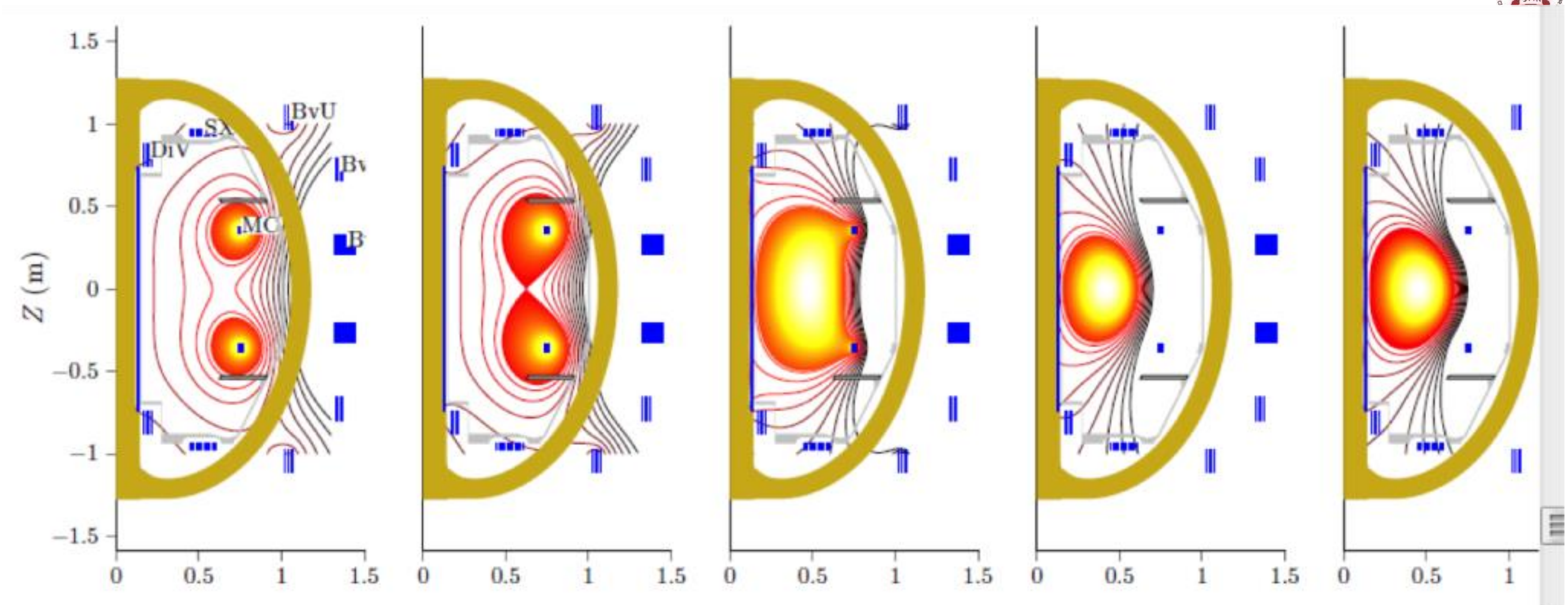
M. Gryaznevich, etc., Fusion Eng. Design, **123**,177 (2017)
https://www.tokamakenergy.co.uk/
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

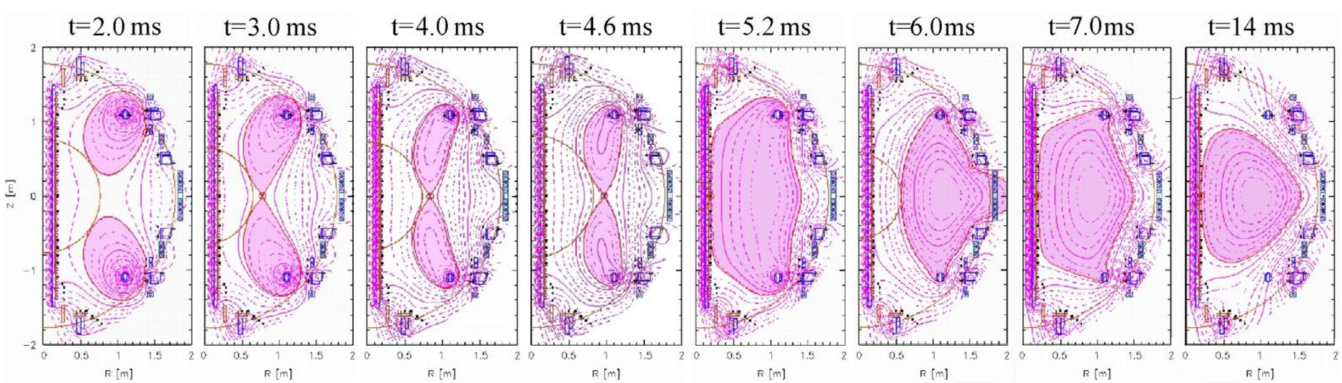
Reconnection



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

Merging compression is used to heat the plasma

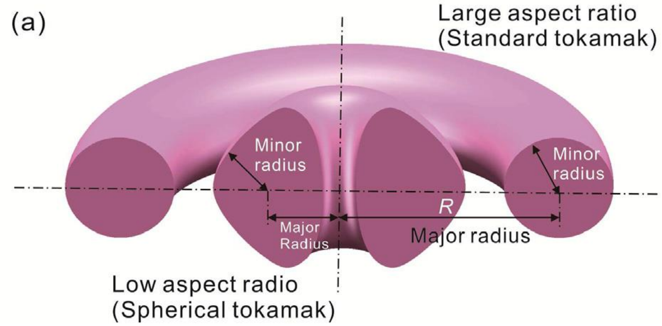




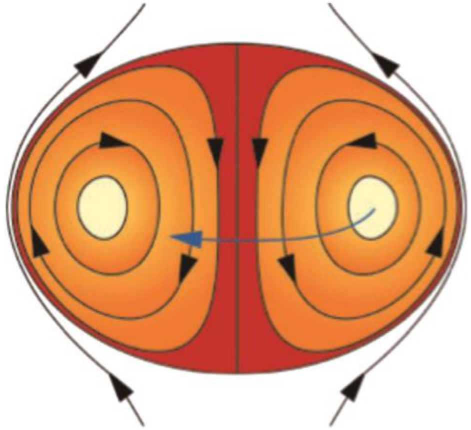
http://www.100milliondegrees.com/merging-compression/
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

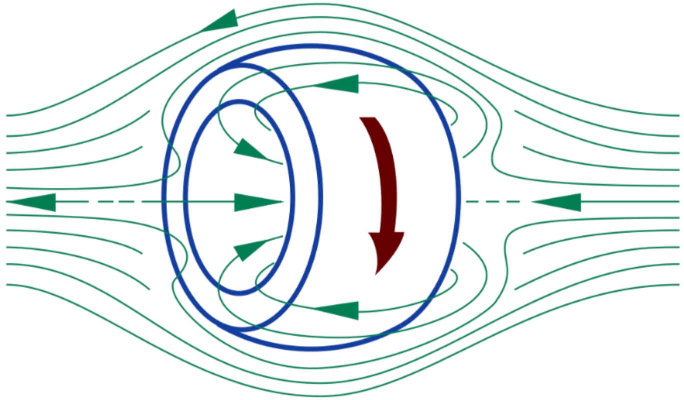
Spherical torus (ST) and compact torus (CT)

- **Spherical torus (ST)**



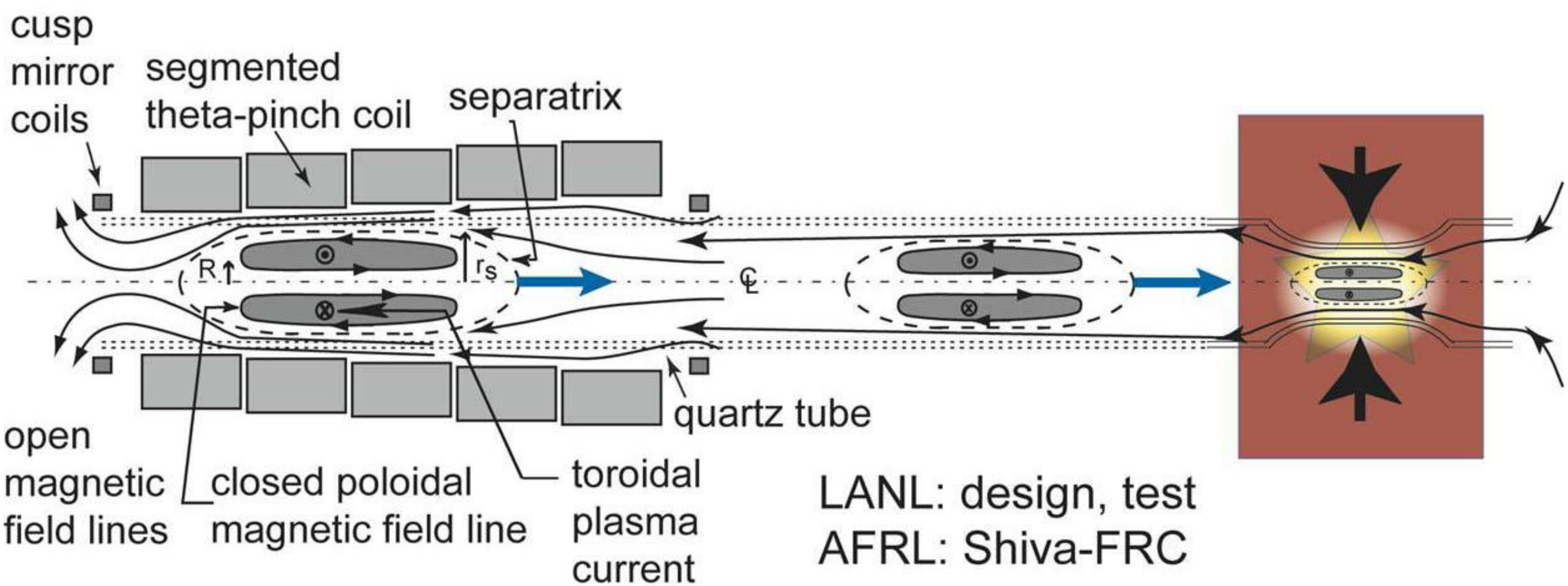
- **Compact torus (CT)**
  - **Spheromak**
  - **Field reversed configuration (FRC)**

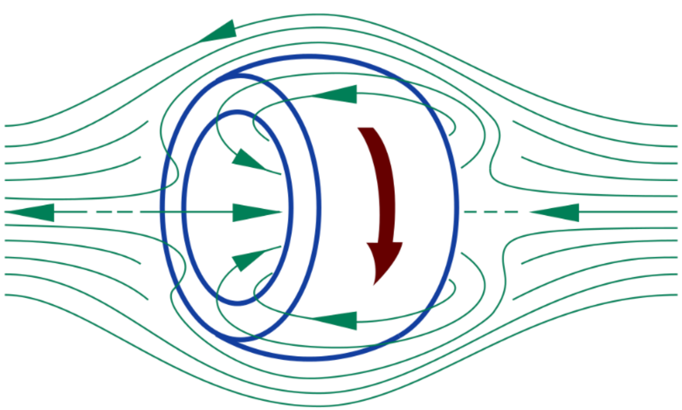




Zhe Gao, Matter Radiat. Extremes **1**, 153 (2016)
https://en.wikipedia.org/wiki/Field-reversed_configuration

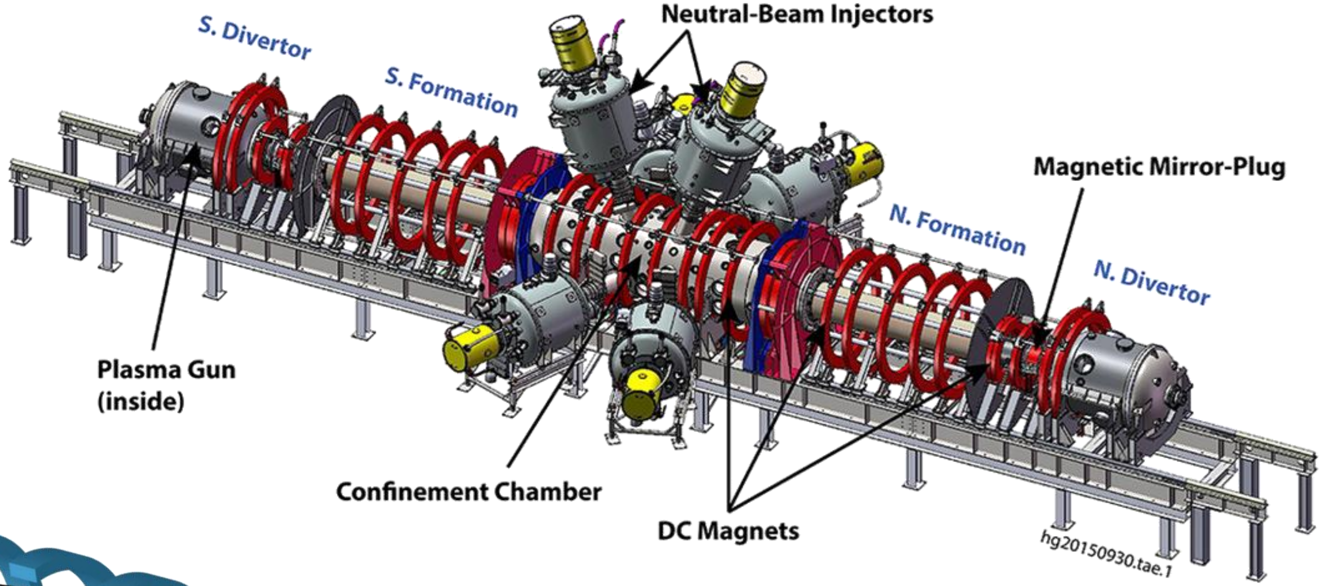
Field reverse configuration is used in Tri-alpha energy

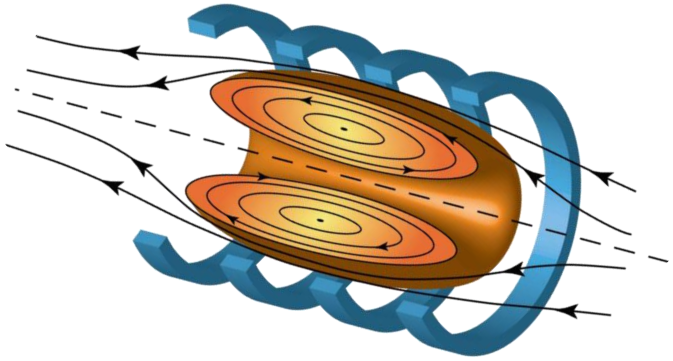




*Magneto-Inertial Fusion& Magnetized HED Physics by Bruno S. Bauer, UNR & Magneto-Inertial Fusion Community
**https://en.wikipedia.org/wiki/Field-reversed_configuration

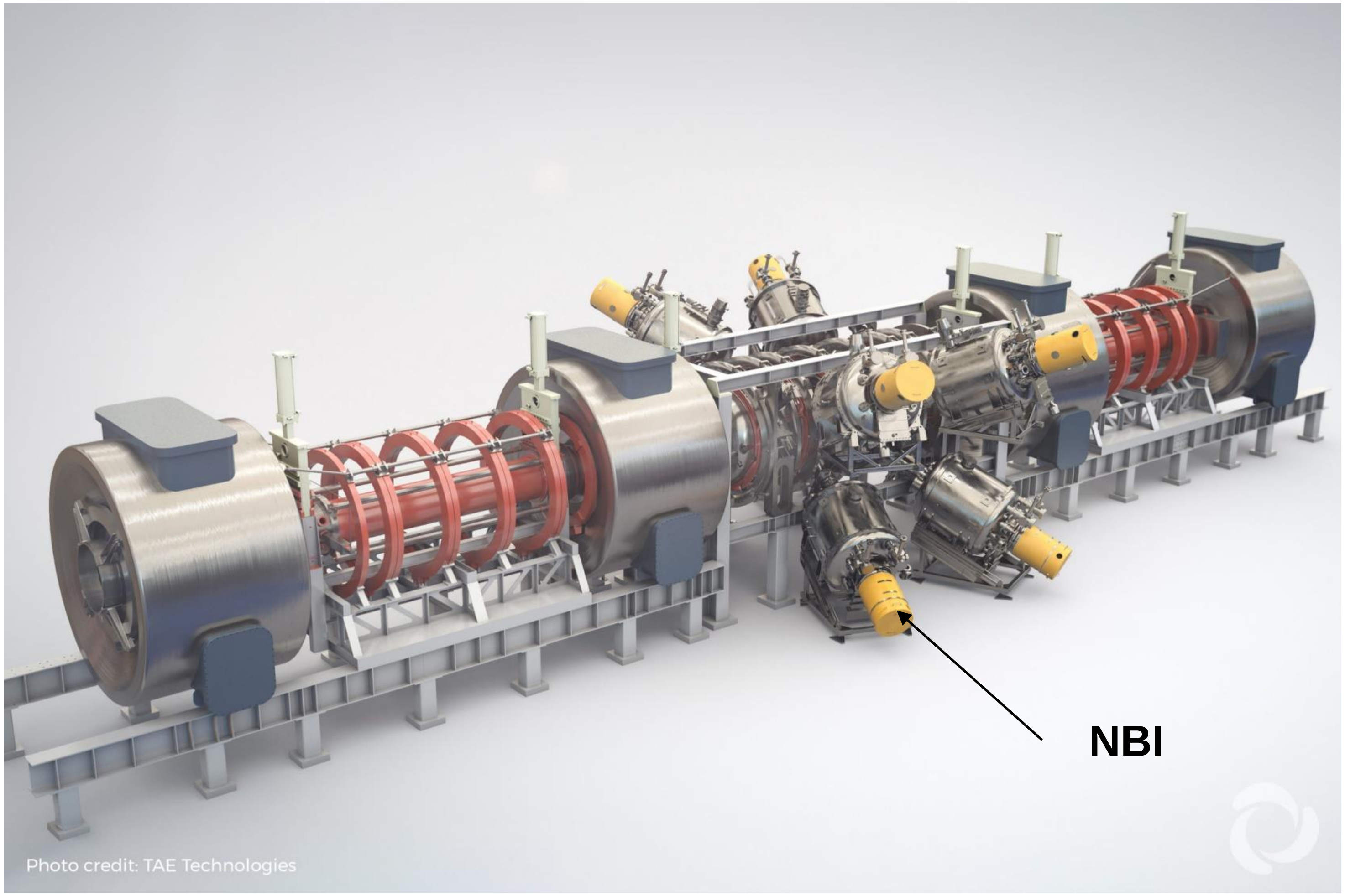
Field reverse configuration is used in Tri-alpha energy





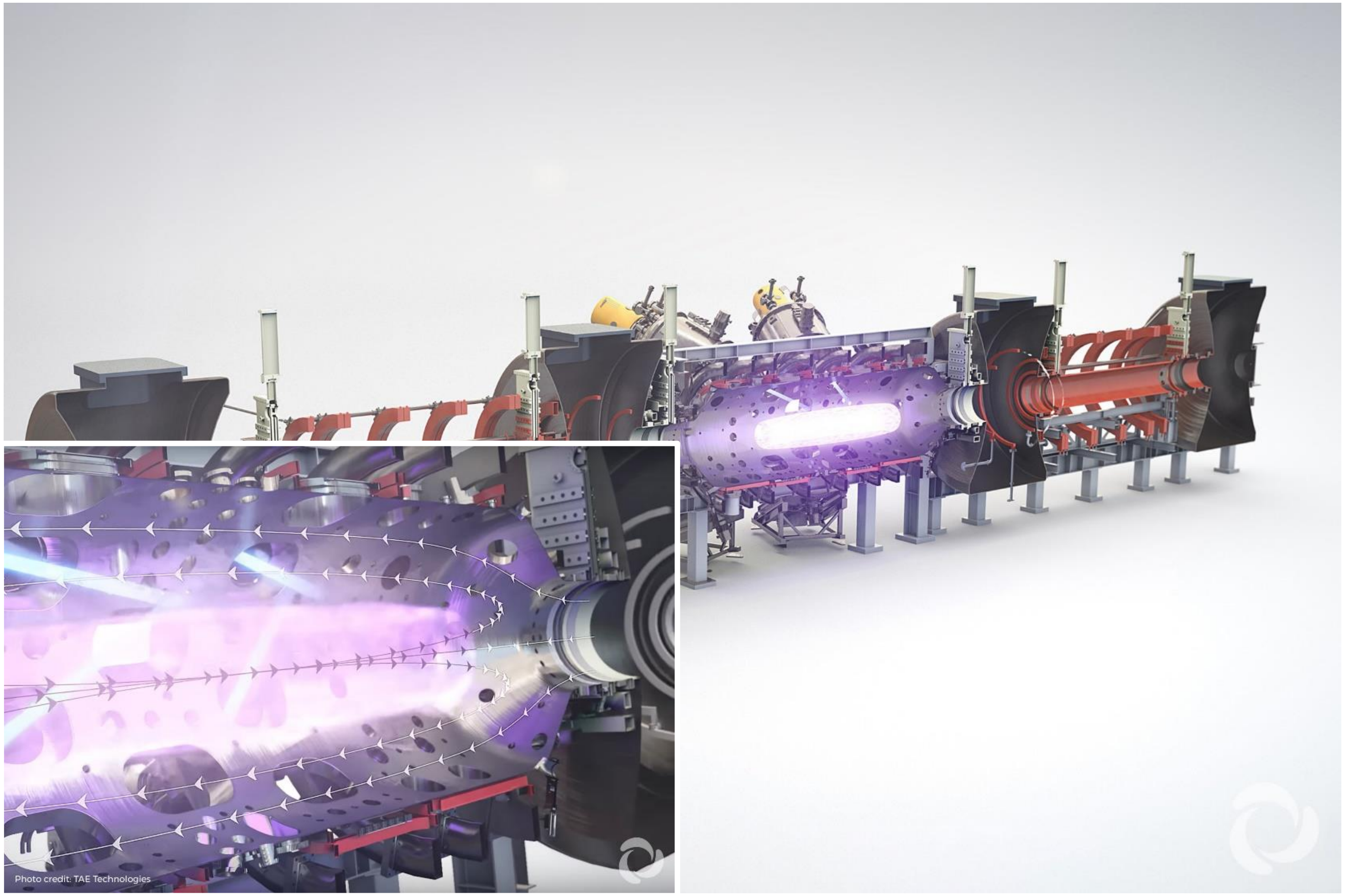
http://trialphaenergy.com/

NBI for Tri-Alpha Energy Technologies



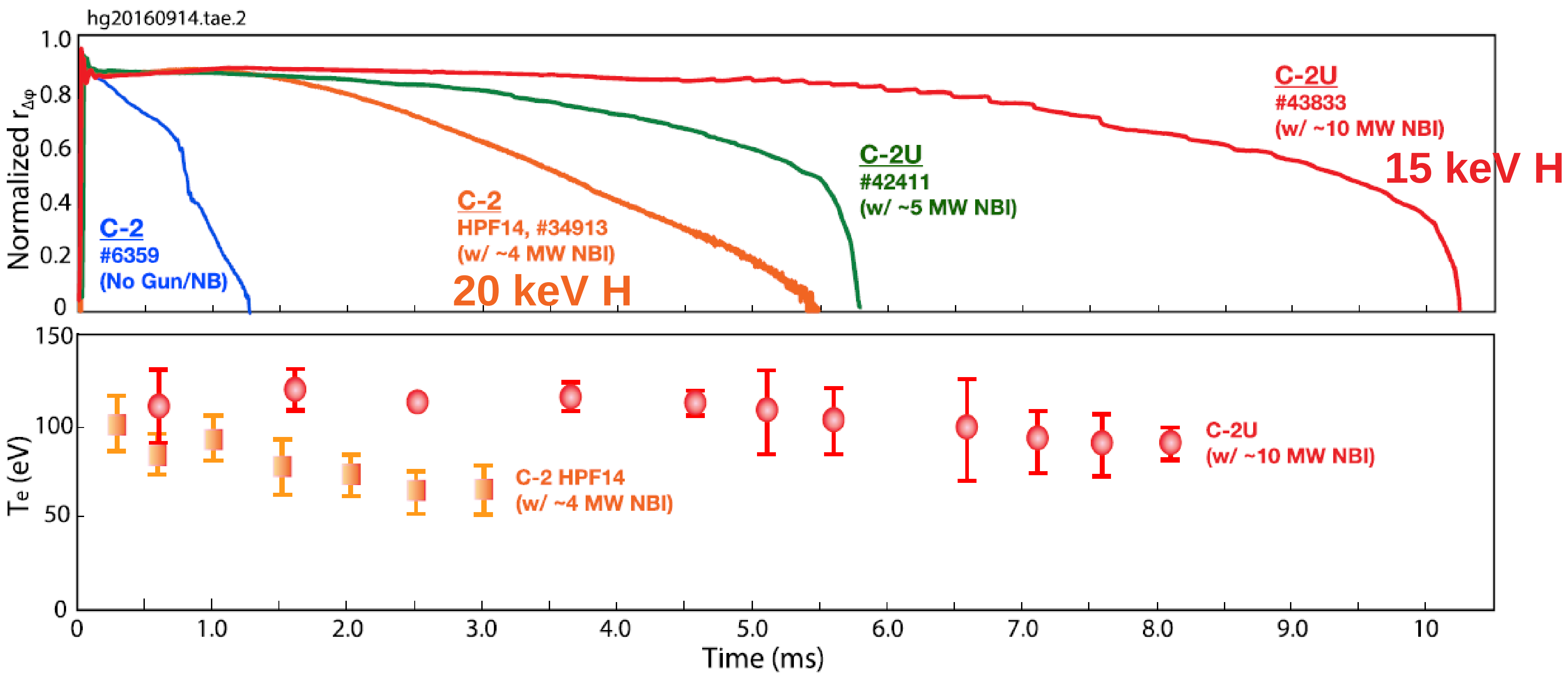
https://tae.com/media/

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



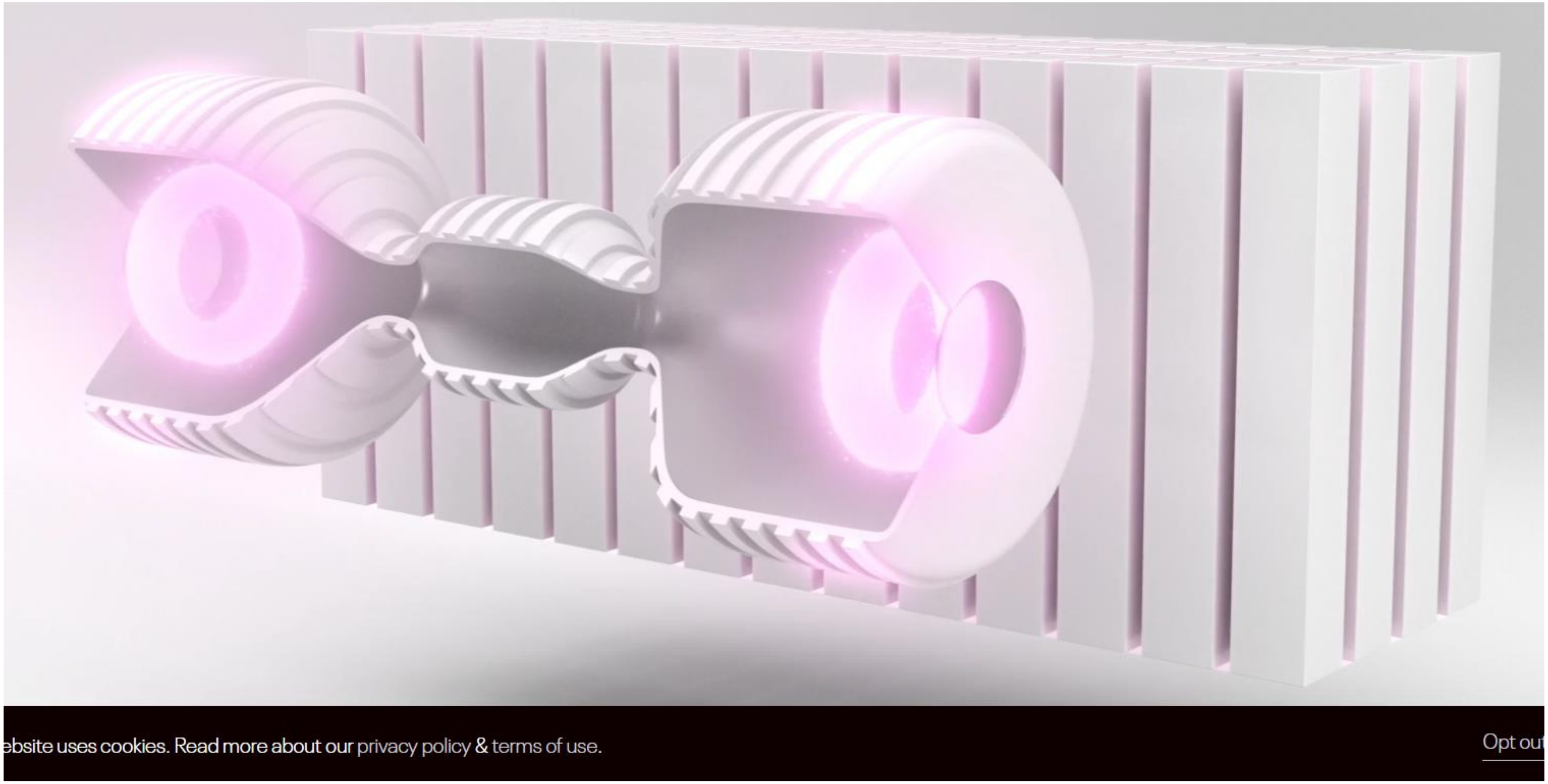
https://tae.com/media/

FRC sustain longer with neutral beam injection



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

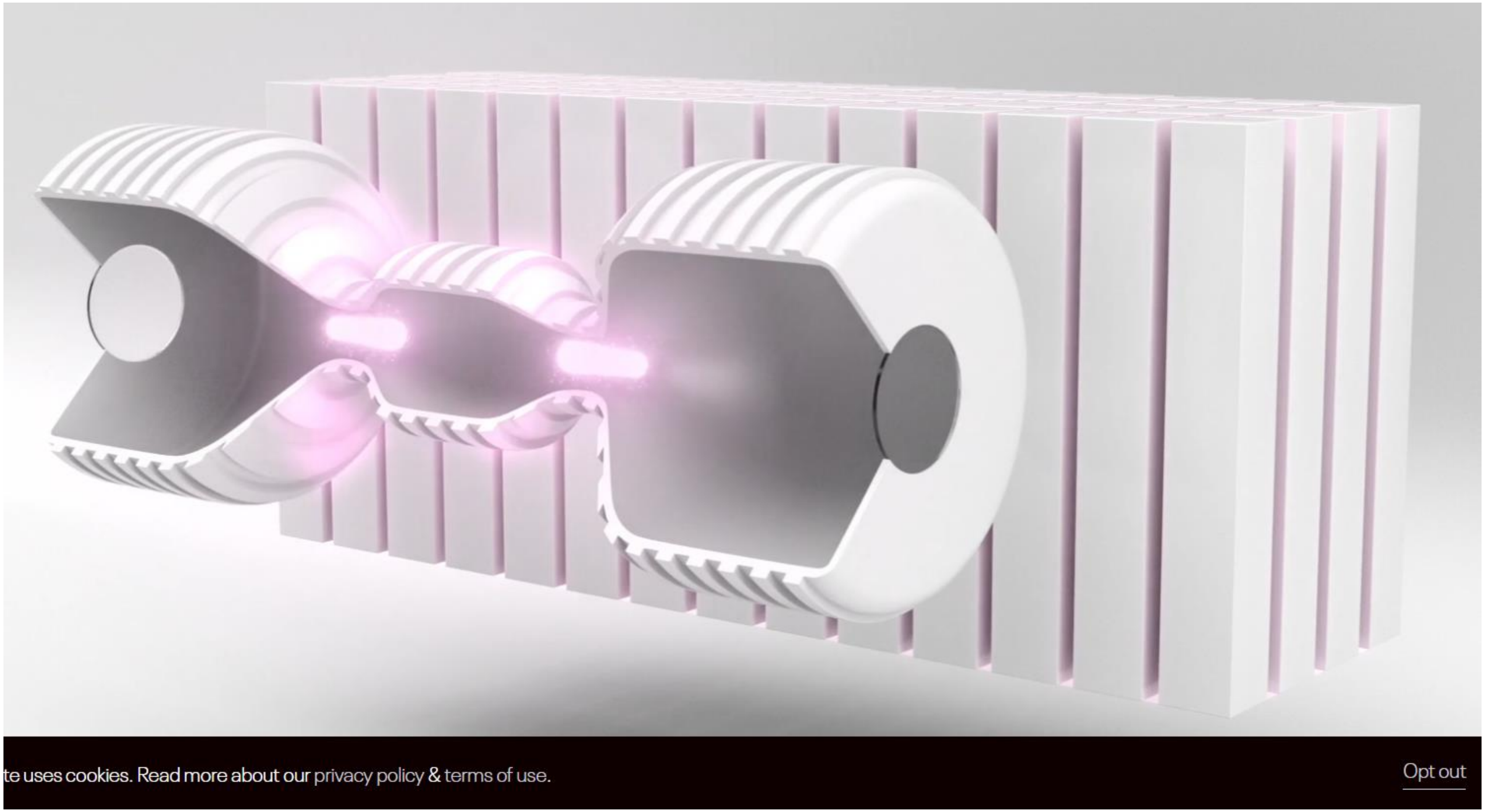
Helion energy is compressing the two merging FRCs



https://youtu.be/HlNfP3iywvI

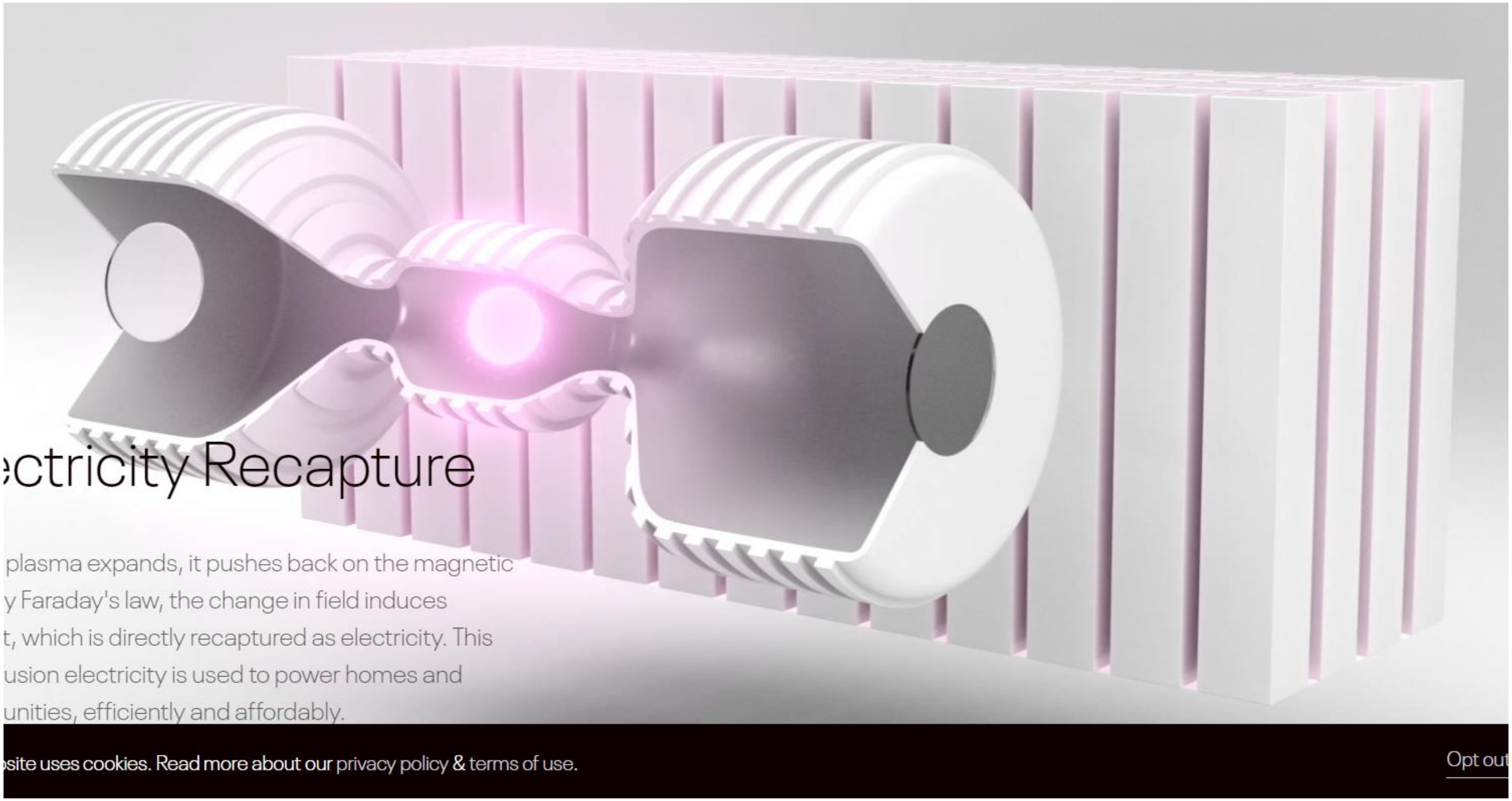
https://www.helionenergy.com/

Two FRCs are accelerated toward each other



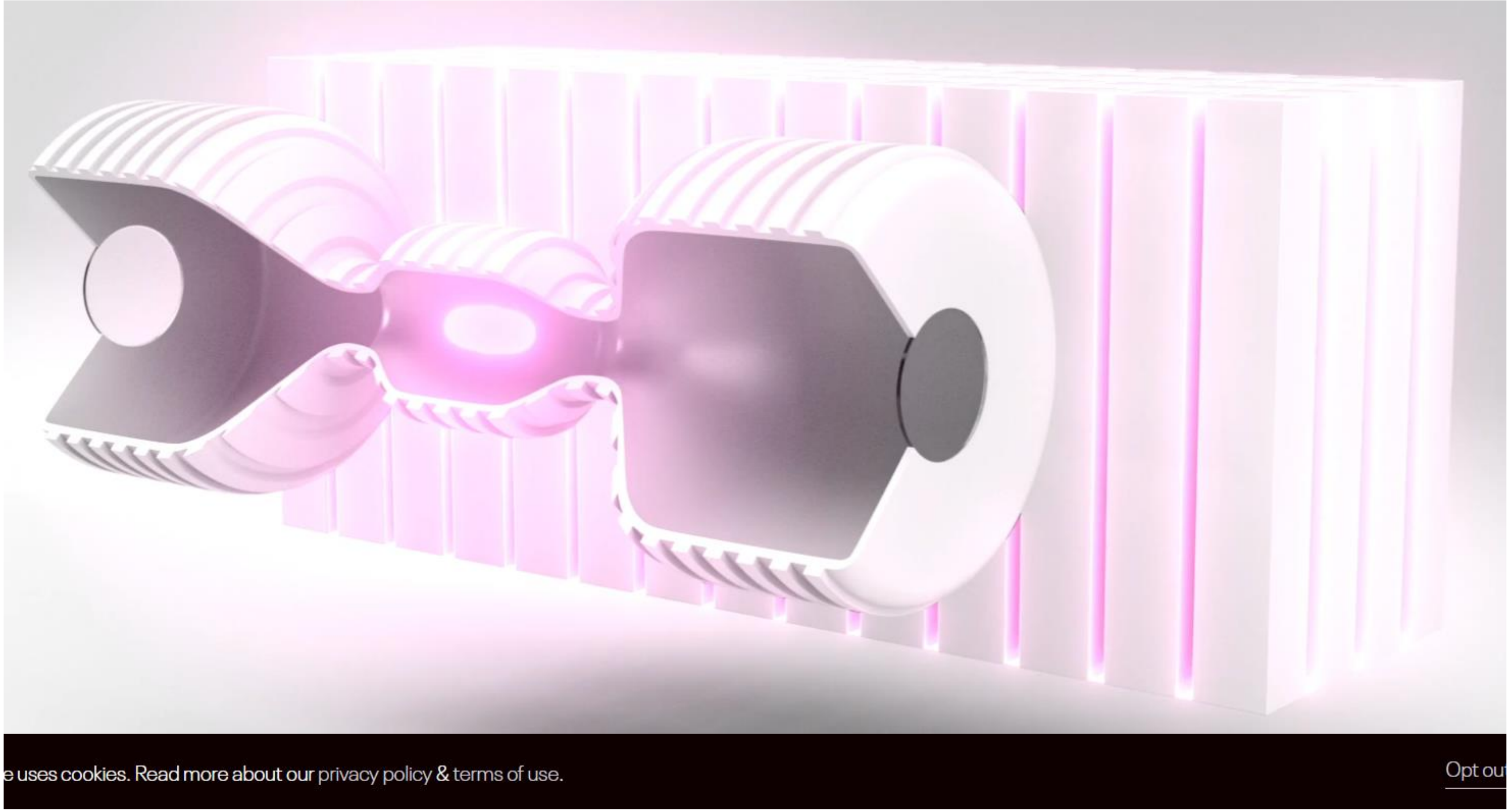
https://www.helionenergy.com/

Two FRCs merge with each other



https://www.helionenergy.com/

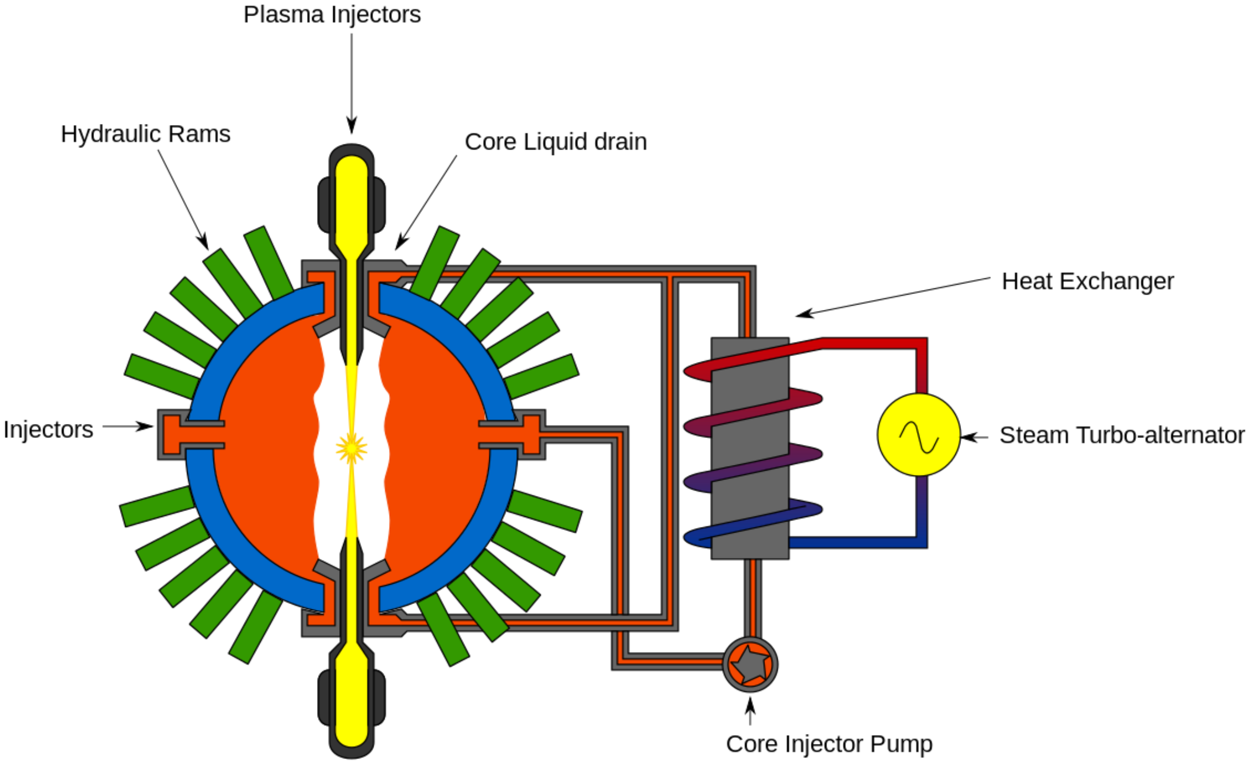
The merged FRC is compressed electrically to high temperature

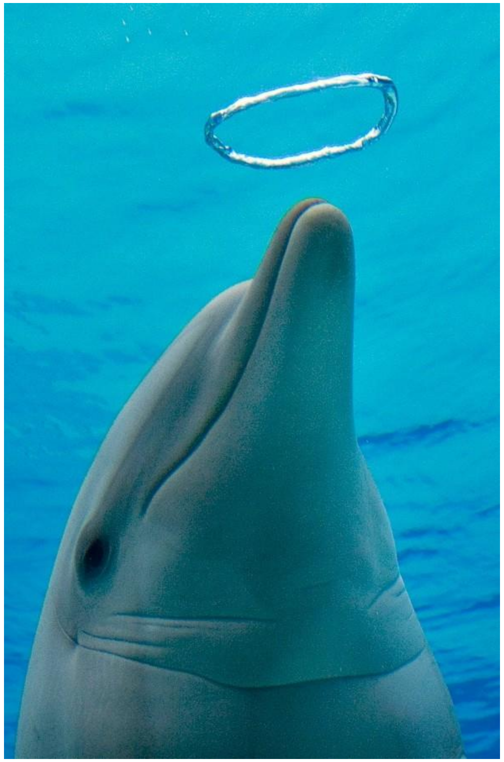


- **Similar concept will be studied in our laboratory.**

https://www.helionenergy.com/

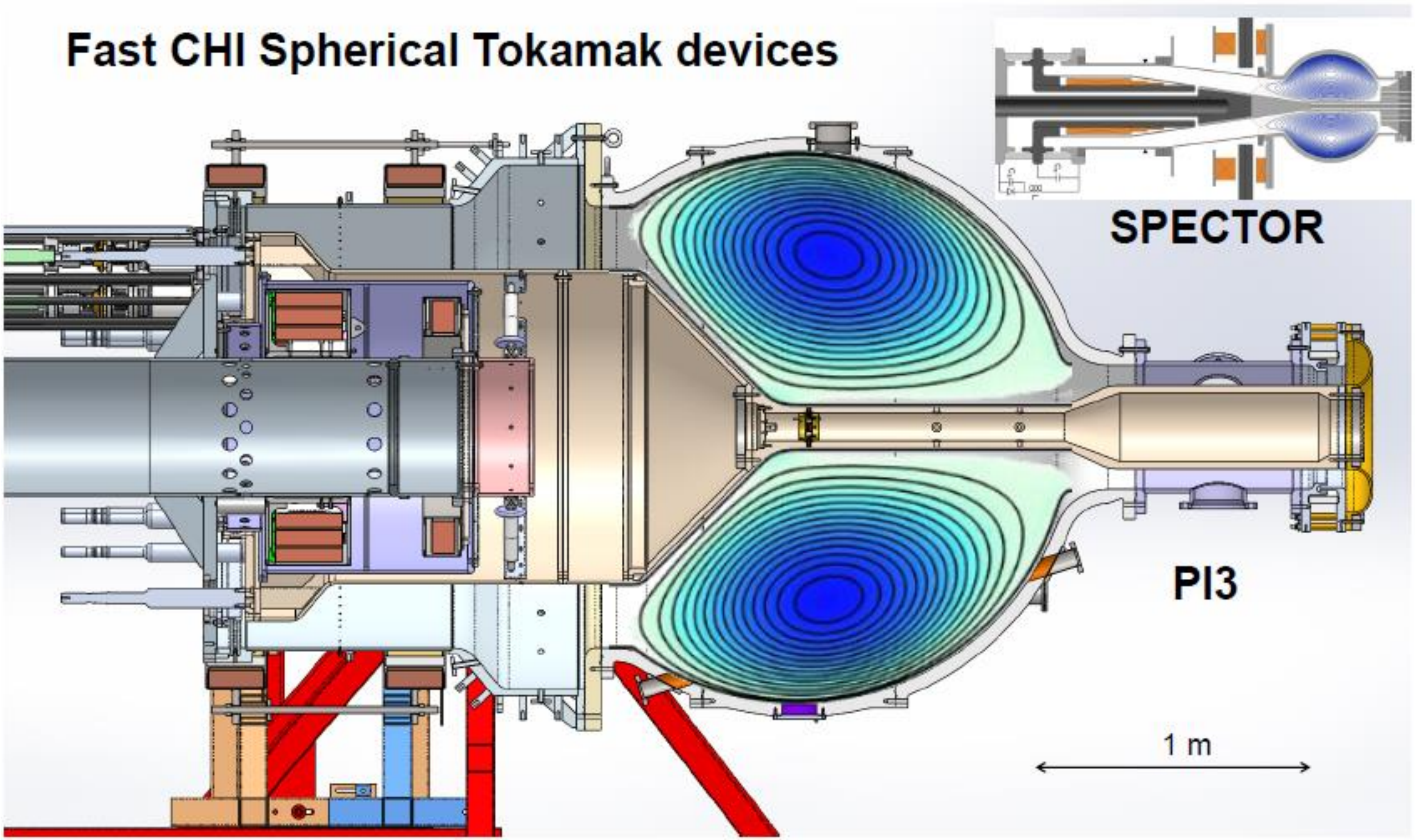
General fusion is a design ready to be migrated to a power plant





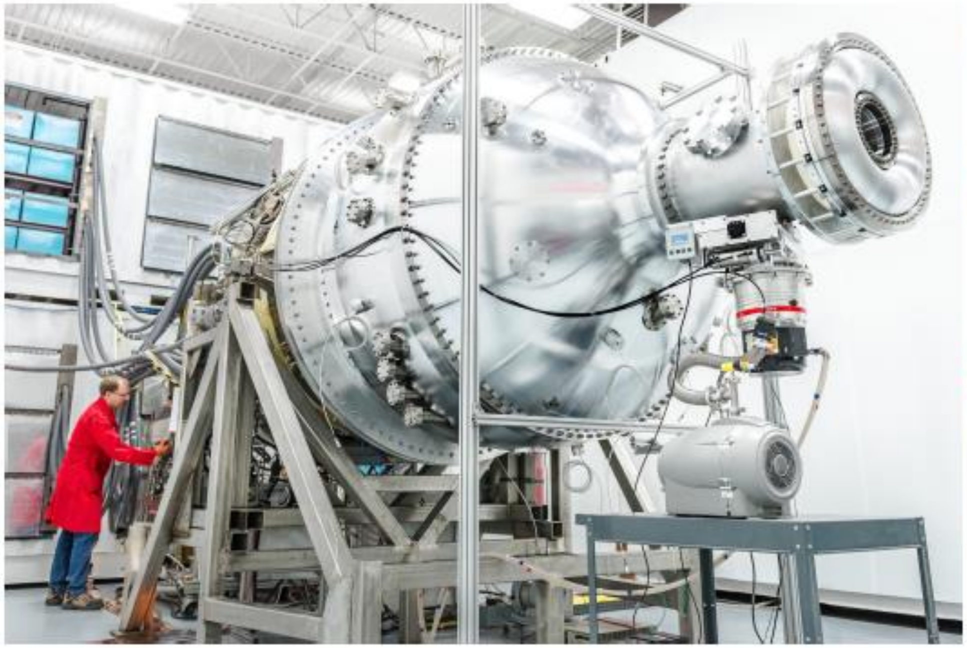
https://en.wikipedia.org/wiki/General_Fusion

A spherical tokamak is first generated



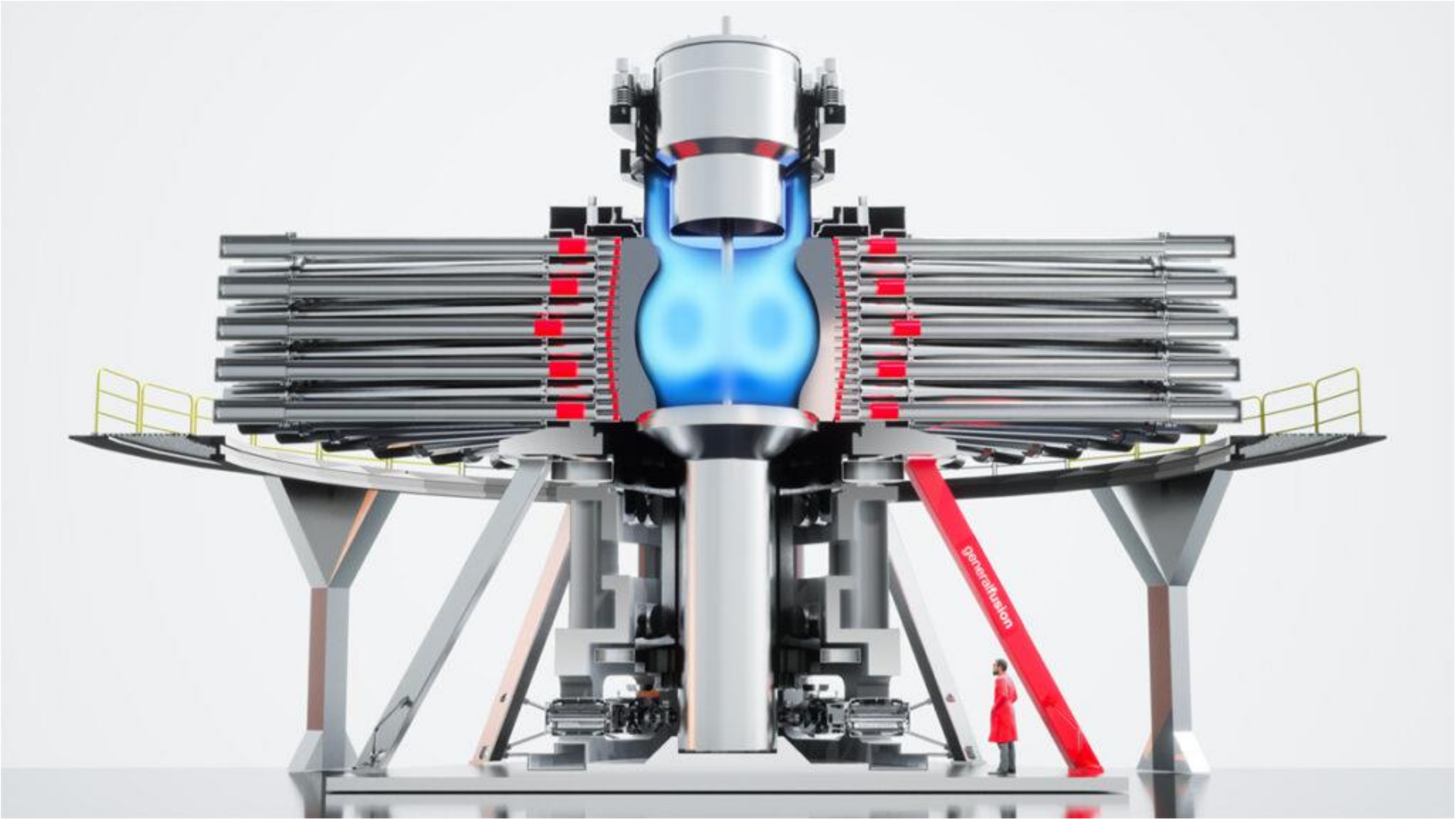
K. EPP, etc., 60th APS-DPP, CP11.00192

Plasma injector for the spherical tokamak

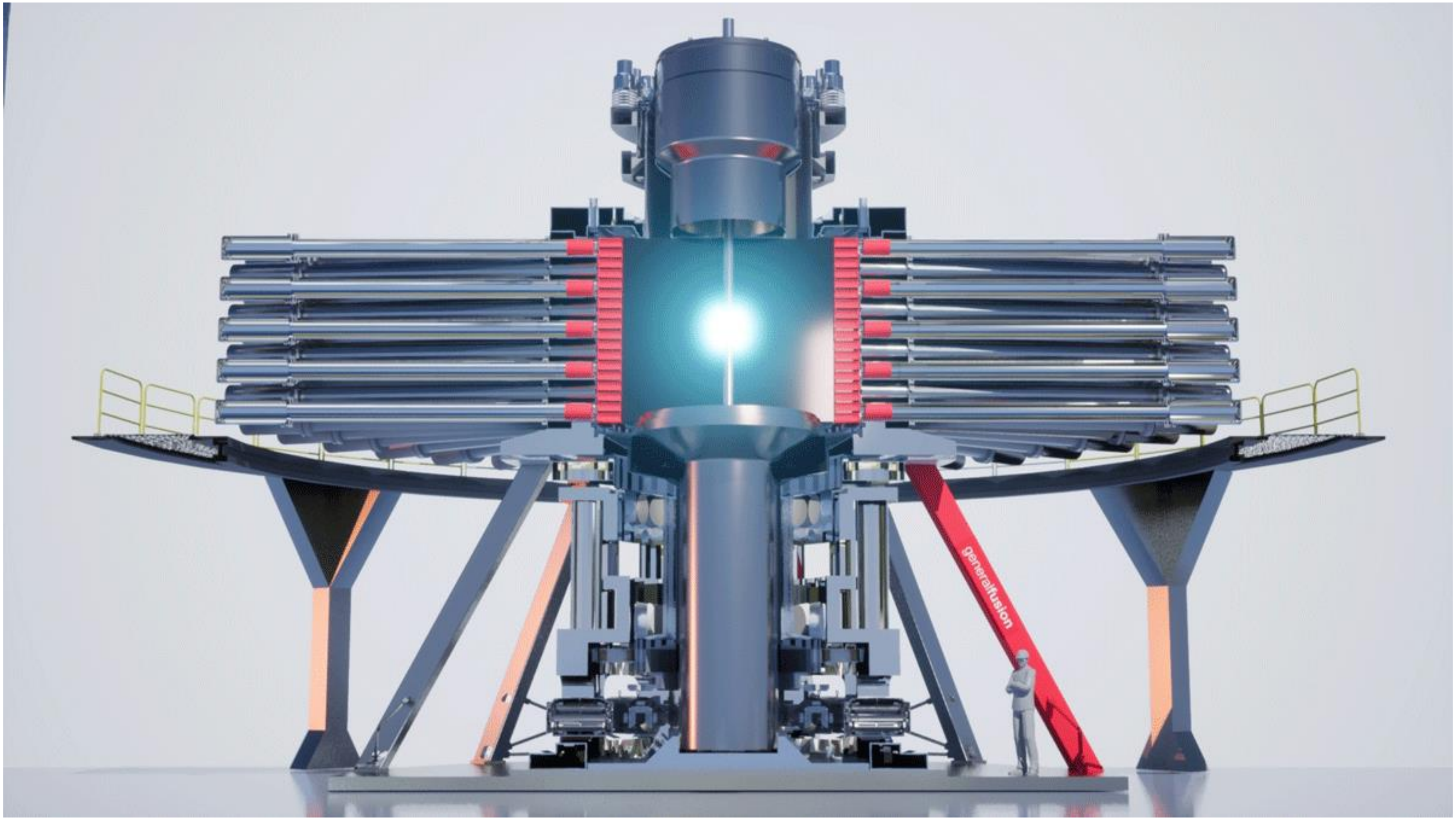


K. EPP, etc., 60th APS-DPP, CP11.00192

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

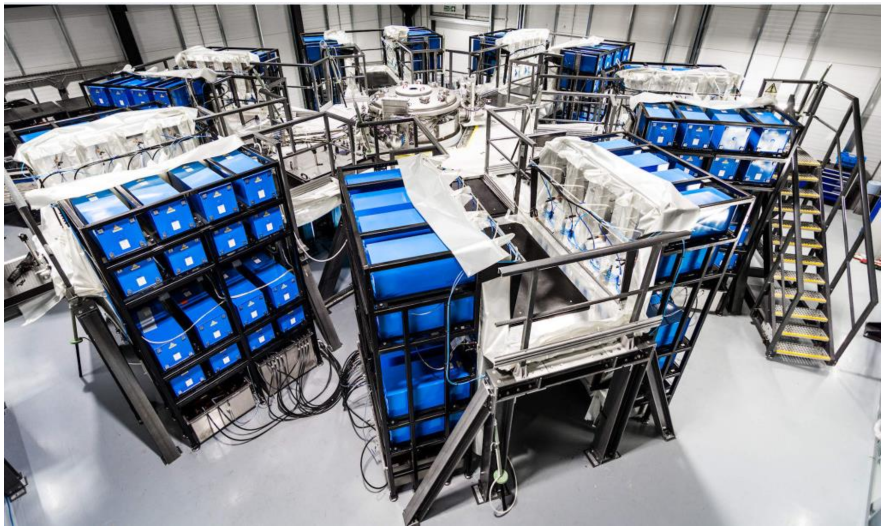
An artist's impression of what the new demonstration plant might look like

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

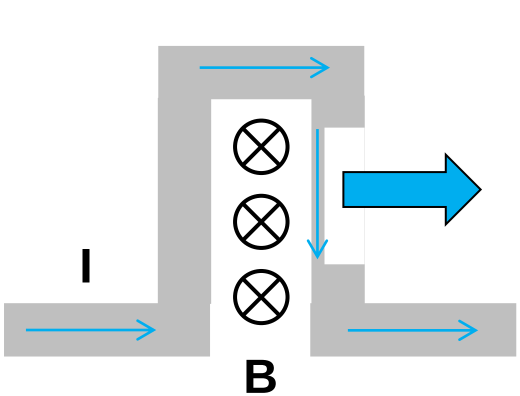
Canada's **General Fusion** is one of the leading private firms aiming to turn the

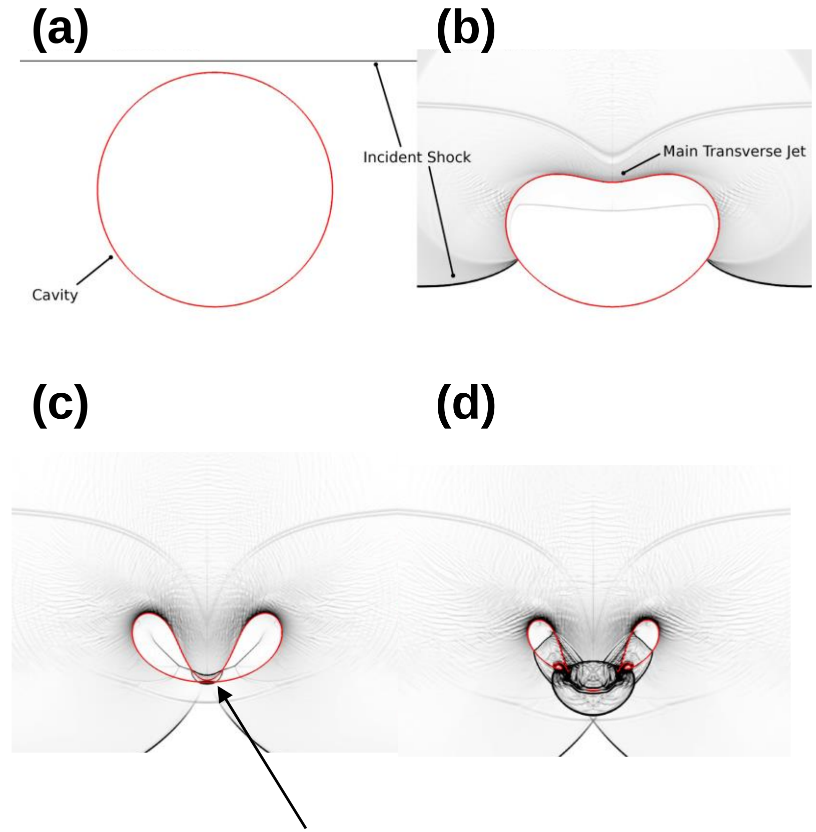
https://www.bbc.com/news/science-environment-57512229

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.**

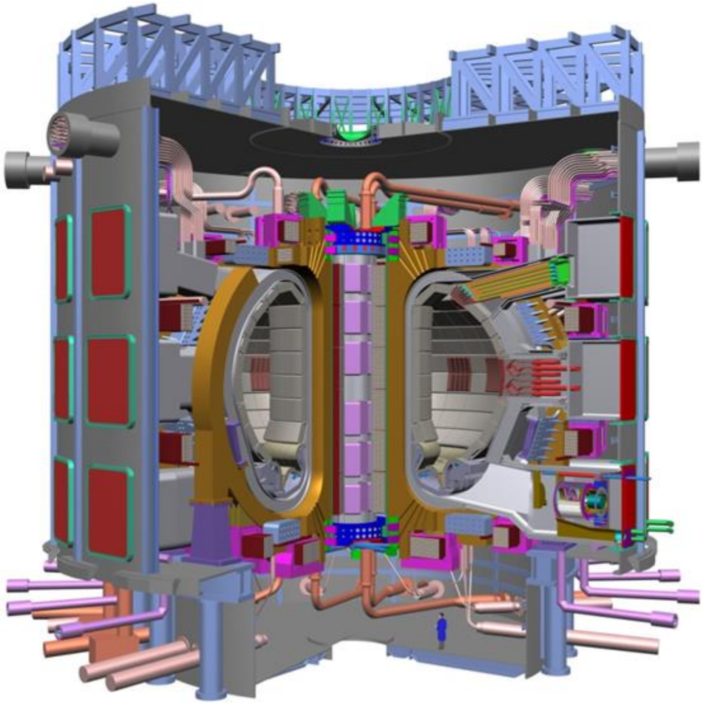
https://firstlightfusion.com/
B. Tully and N. Hawker, Phys. Rev. **E93**, 053105 (2016)

A gas gun is used to eject the projectile

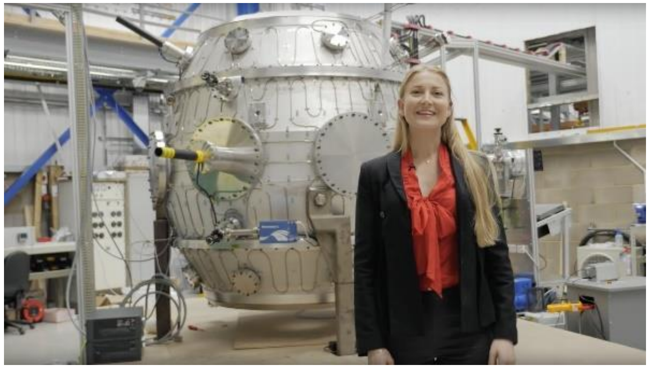
https://www.youtube.com/watch?v=JN7lyxC11n0
https://www.youtube.com/watch?v=aW4eufacf-8

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

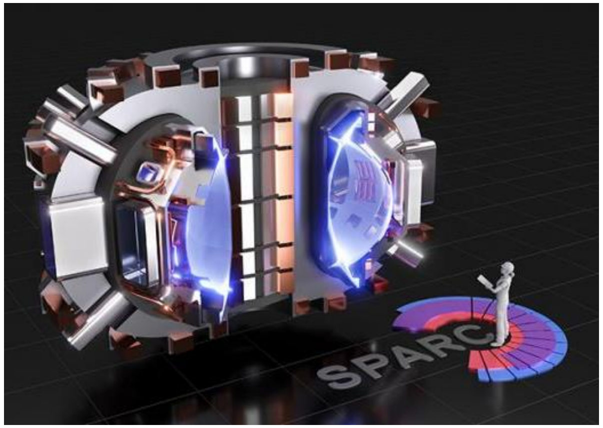
- **ITER – 2025 First Plasma**
  2035 D-T Exps
  2050 DEMO



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



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



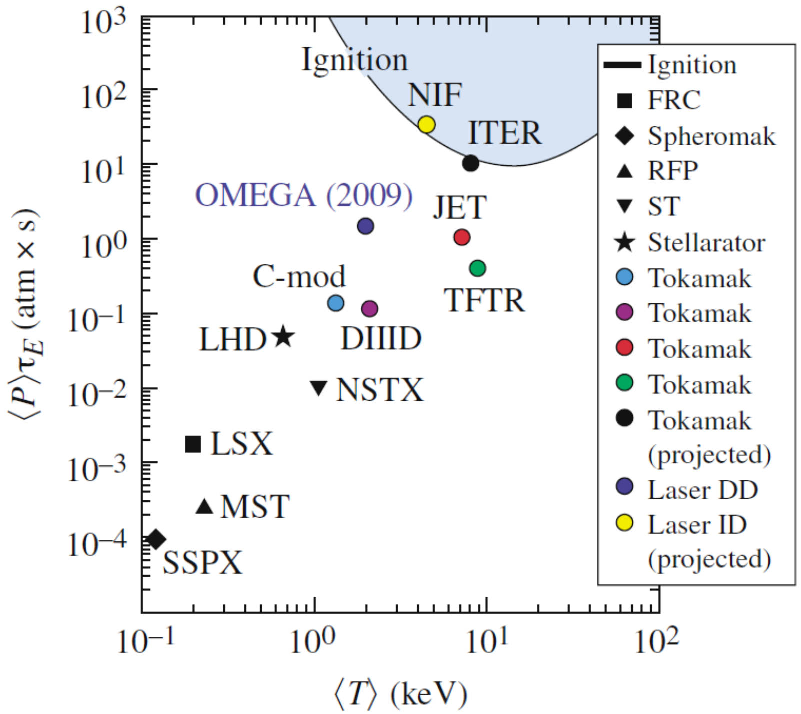
https://www.iter.org
https://www.tokamakenergy.co.uk/
https://www.psfc.mit.edu/sparc

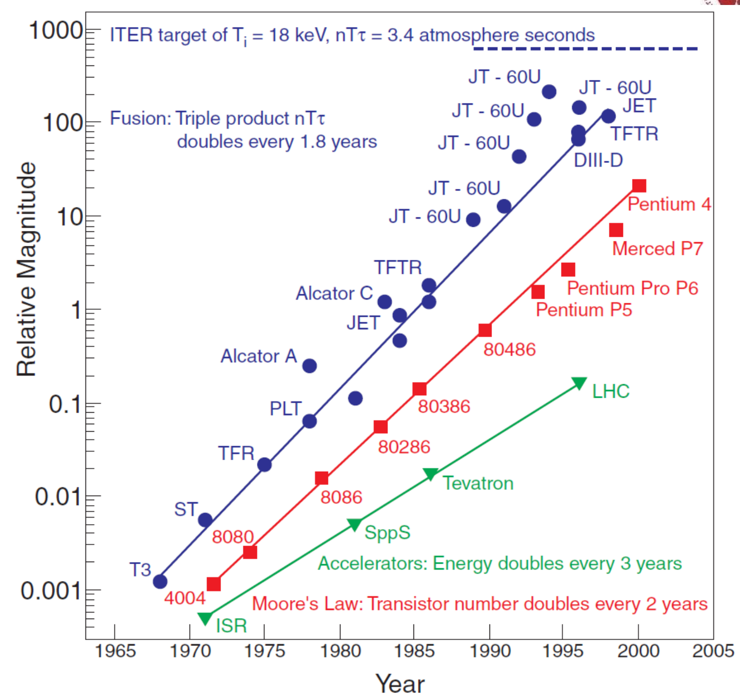
Fusion is blooming!

⋮

https://www.fusionindustryassociation.org/members

We are closed to ignition!





- **Other private companies:**

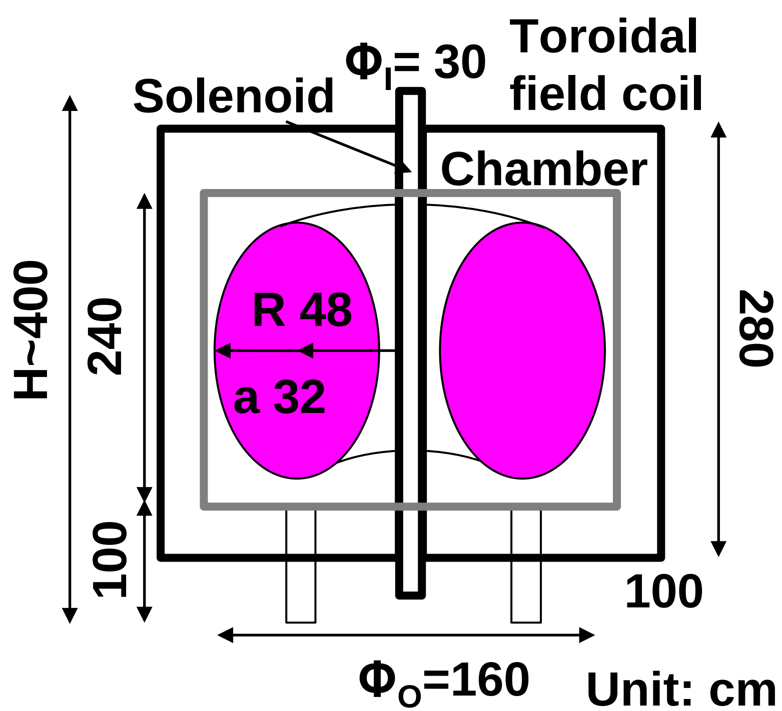
Tokamak **MTF** **ICF**

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

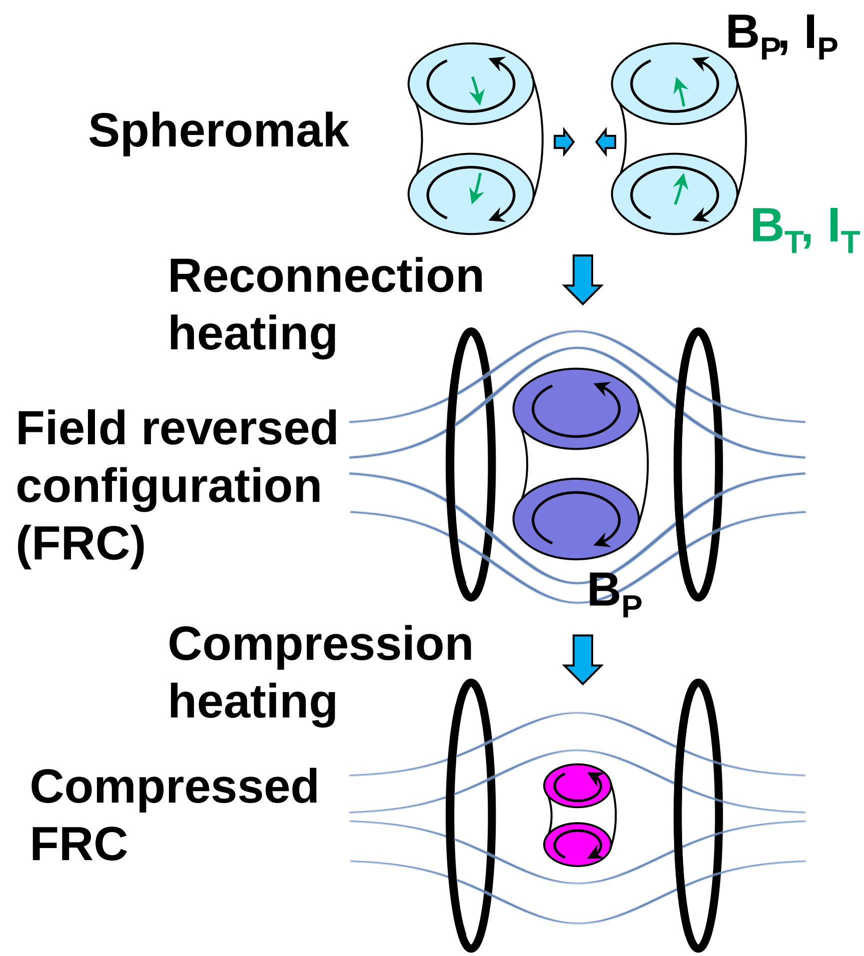
Fusion projects in Inst. Space and Plasma Sciences , National Cheng Kung University

- 國科會計畫 - 磁約束高溫電漿研究

Formosa Integrated Research Spherical Tokamak (FIRST)



- Magneto-inertial fusion (MIF)

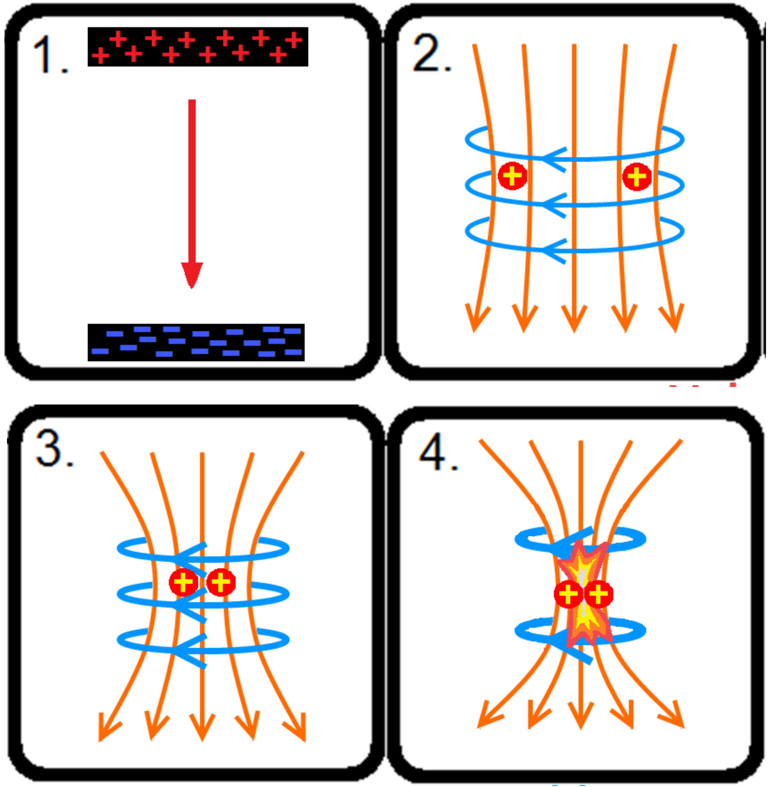


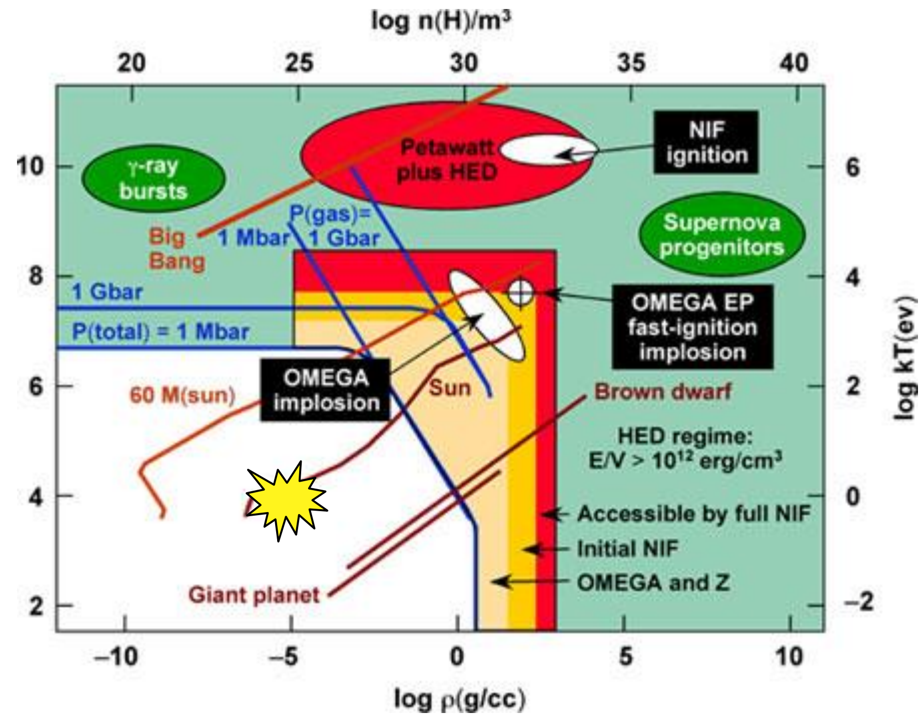
- **We welcome anyone interested in fusion research to join our team!**

Outline

- Introduction to nuclear fusion
- Magnetic confinement fusion (MCF)
  - Tokamak
  - Stellarator
- Inertial confinement fusion (ICF)
  - Indirection drive ICF
  - Direct drive ICF
- Innovation idea – MCF + ICF
- **Pulsed-power system at NCKU**

Plasma can be compressed when parallel propagating current occurs





- **High energy density plasma (HEDP) regime: P > 1 Mbar**

---

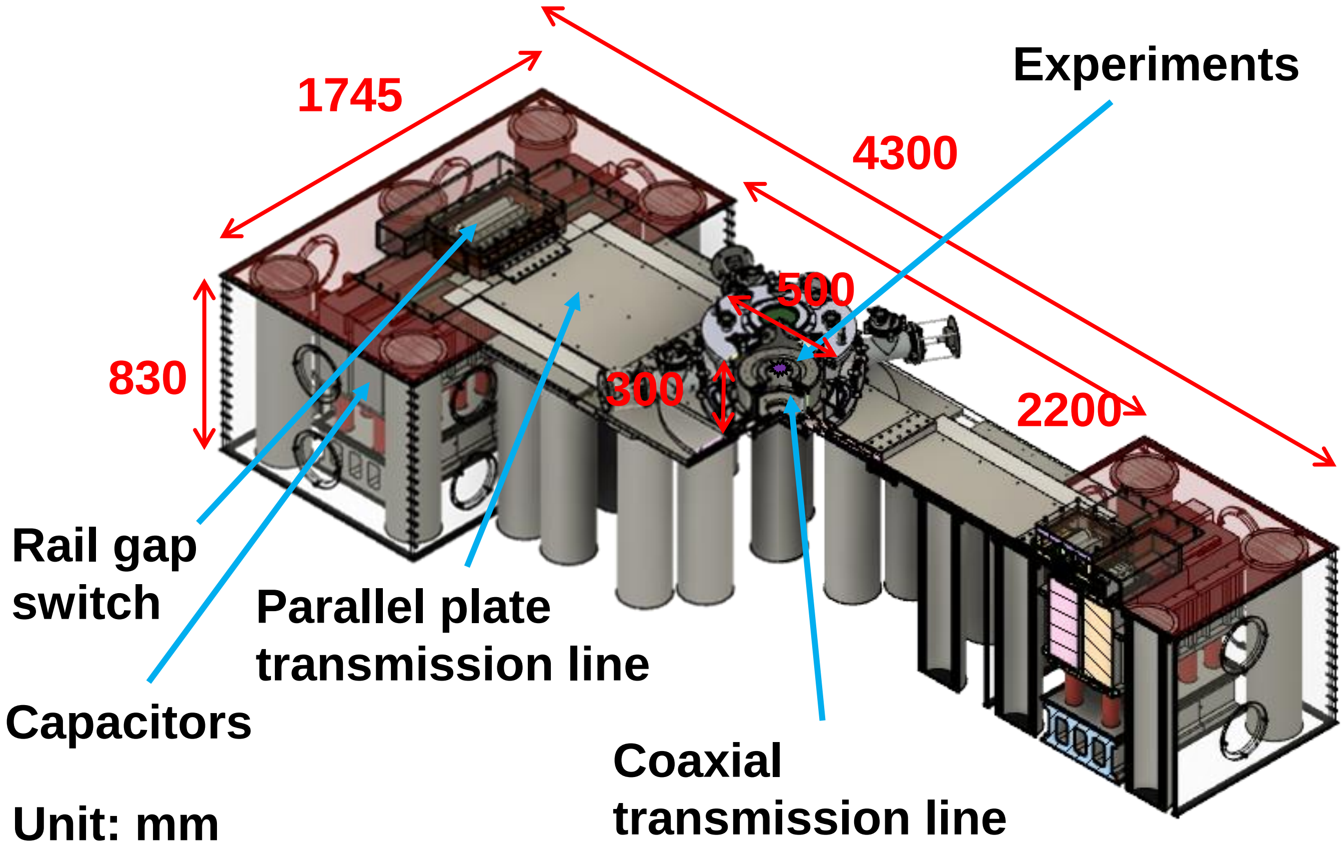
*https://en.wikipedia.org/wiki/Pinch_(plasma_physics)

**Frontiers in High Energy Density Physics: The X-Games of Contemporary Science © (2003) by the National Academy of Sciences, courtesy of the National Academies Press, Washington, D.C.

A pulsed-power system is much cheaper than a laser facility

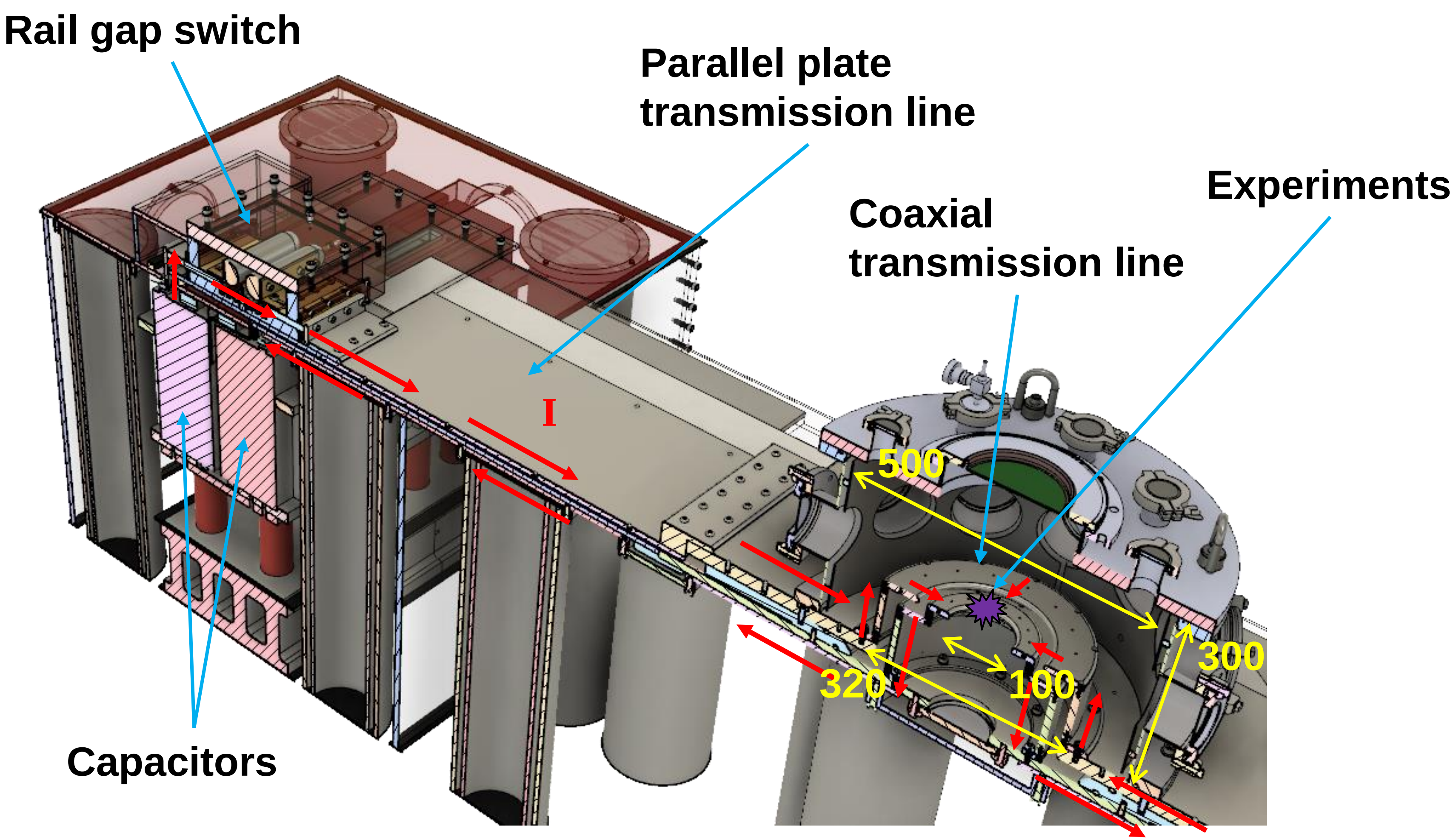
Facility	Budgets (NTD)
OMEGA at University of Rochester	~1.8 billion
National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL)	~100 billion
Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory in Berkeley (LBNL)	~3 billion
Taiwan Photon Source (TPS) at National Synchrotron Radiation Research Center (NSRRC)	~7 billion
Pulsed-power system at ISAPS, NCKU	~0.002 billion (<0.1 %)!!!

The pulsed-power system was built by only students



- **A 1 kJ pulsed-power system has been built in ISAPS, NCKU in September, 2019.**

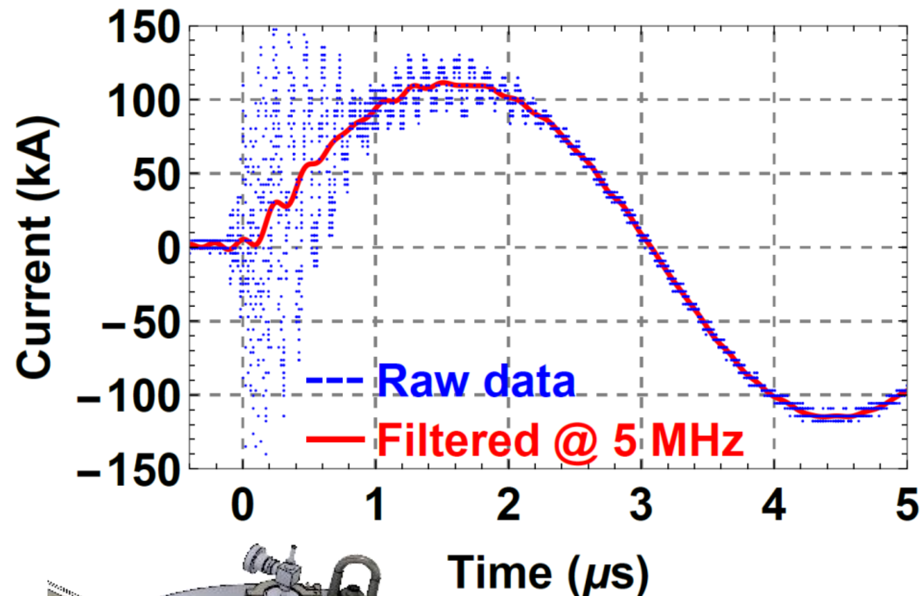
Experiments will be taken placed at the center of the vacuum chamber



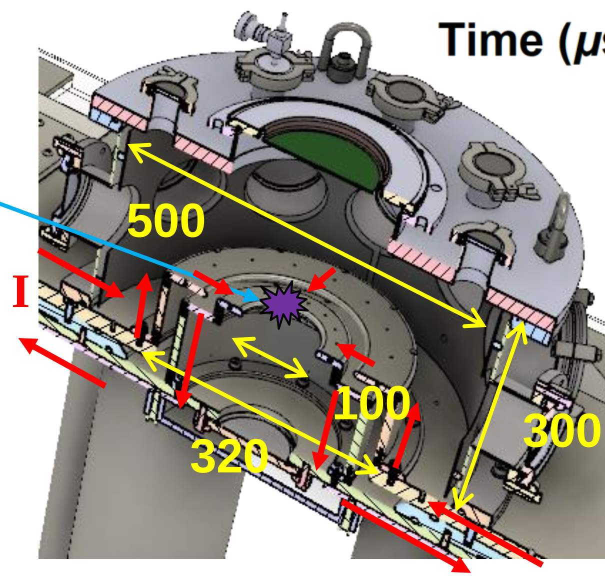
Unit: mm

A peak current of 110 kA with a rise time of 1.5 us is provided by the pulsed-power system

Capacitance (μF)	5	
V_{charge} (kV)	20	(50)
Energy (kJ)	1	(6.25)
Inductance (nH)	150 ± 50	
Rise time (quarter period, μs)	1.5 ± 0.1	
I_{peak} (kA)	110 ± 20	(~275)
Power (GW)	~0.7	(~5)

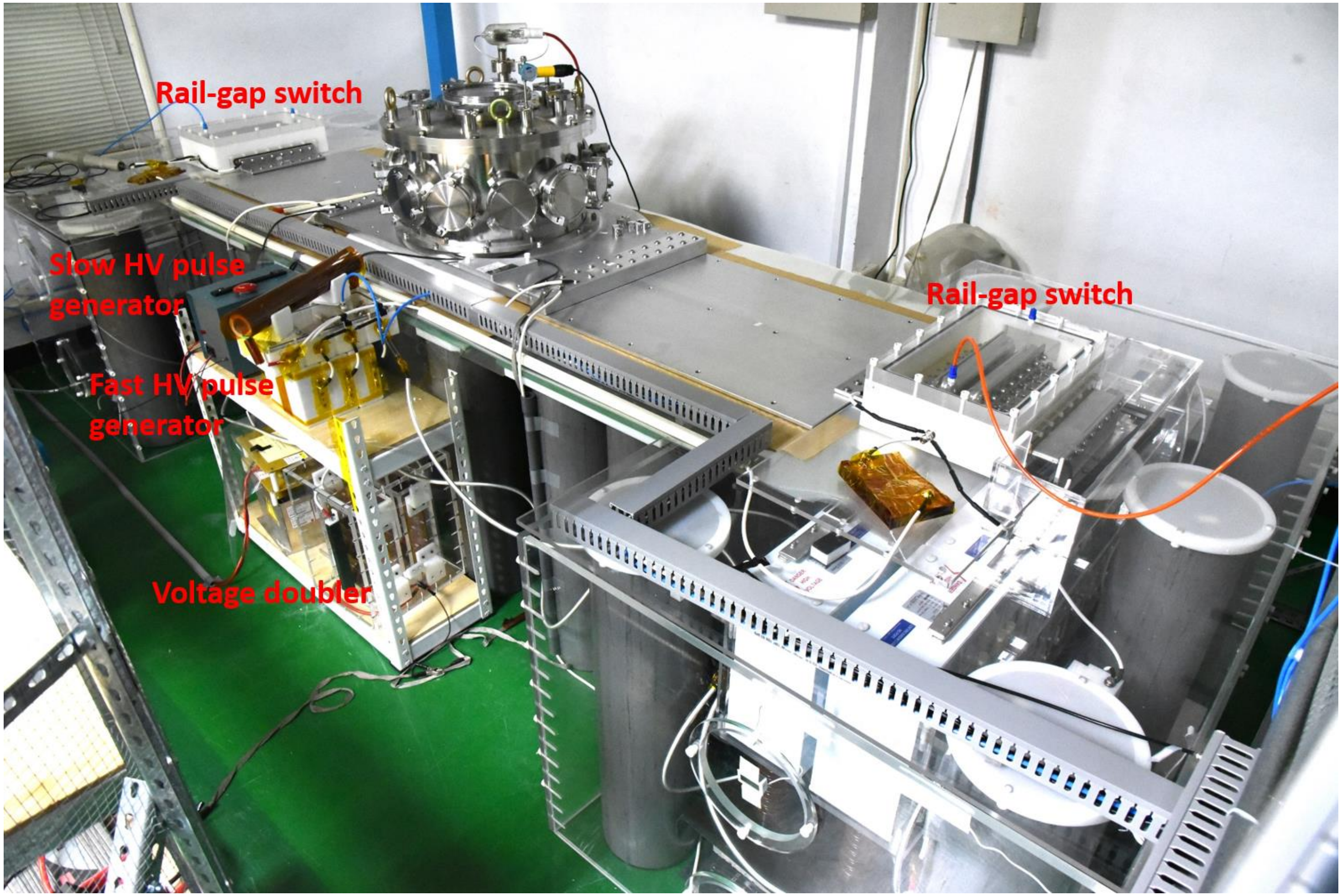


Experiments

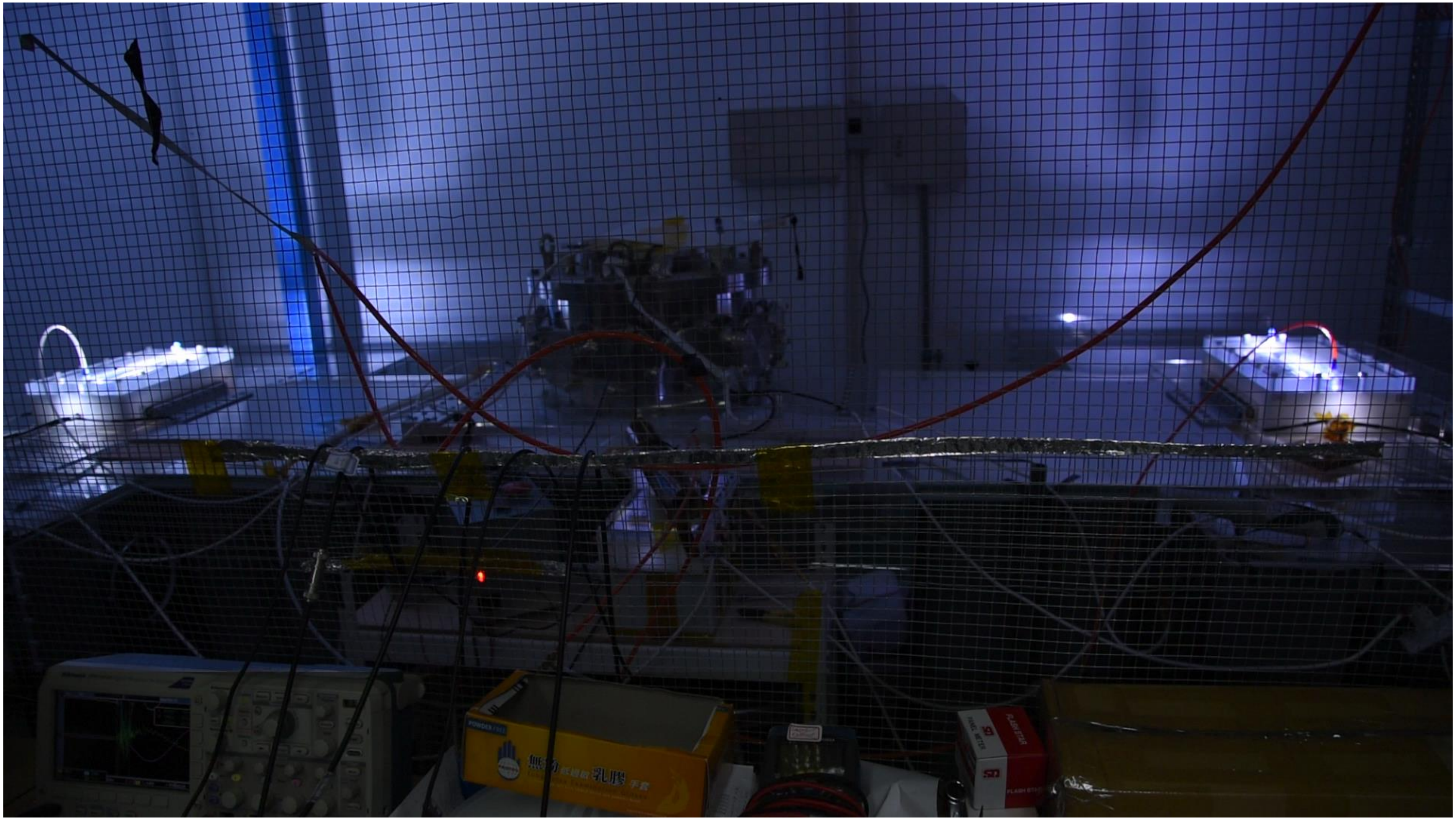


Unit: mm

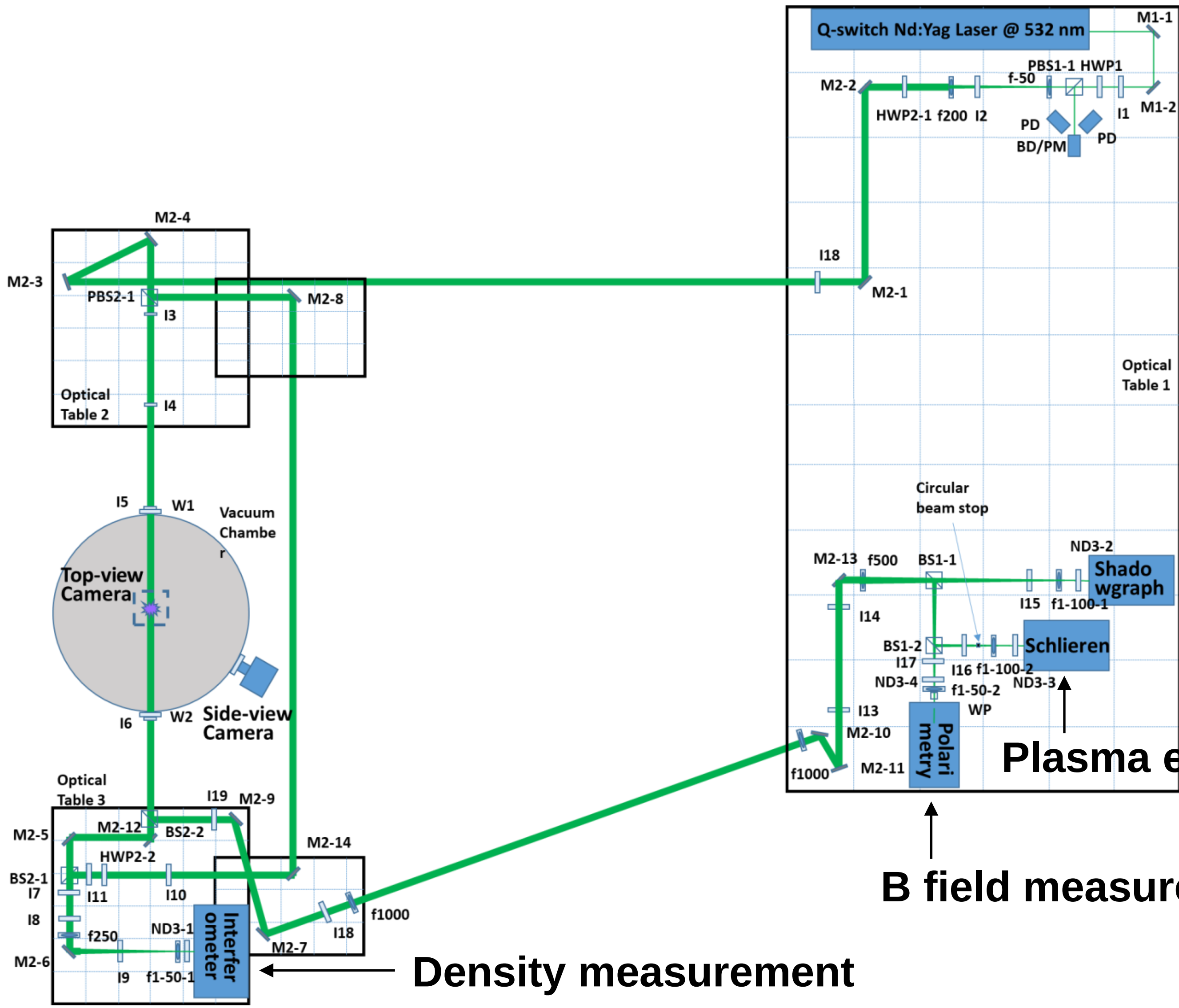
The pulsed-power system has been built



First shot with two synchronized rail-gap switches



Time-resolved imaging system with temporal resolution in the order of nanoseconds was implemented

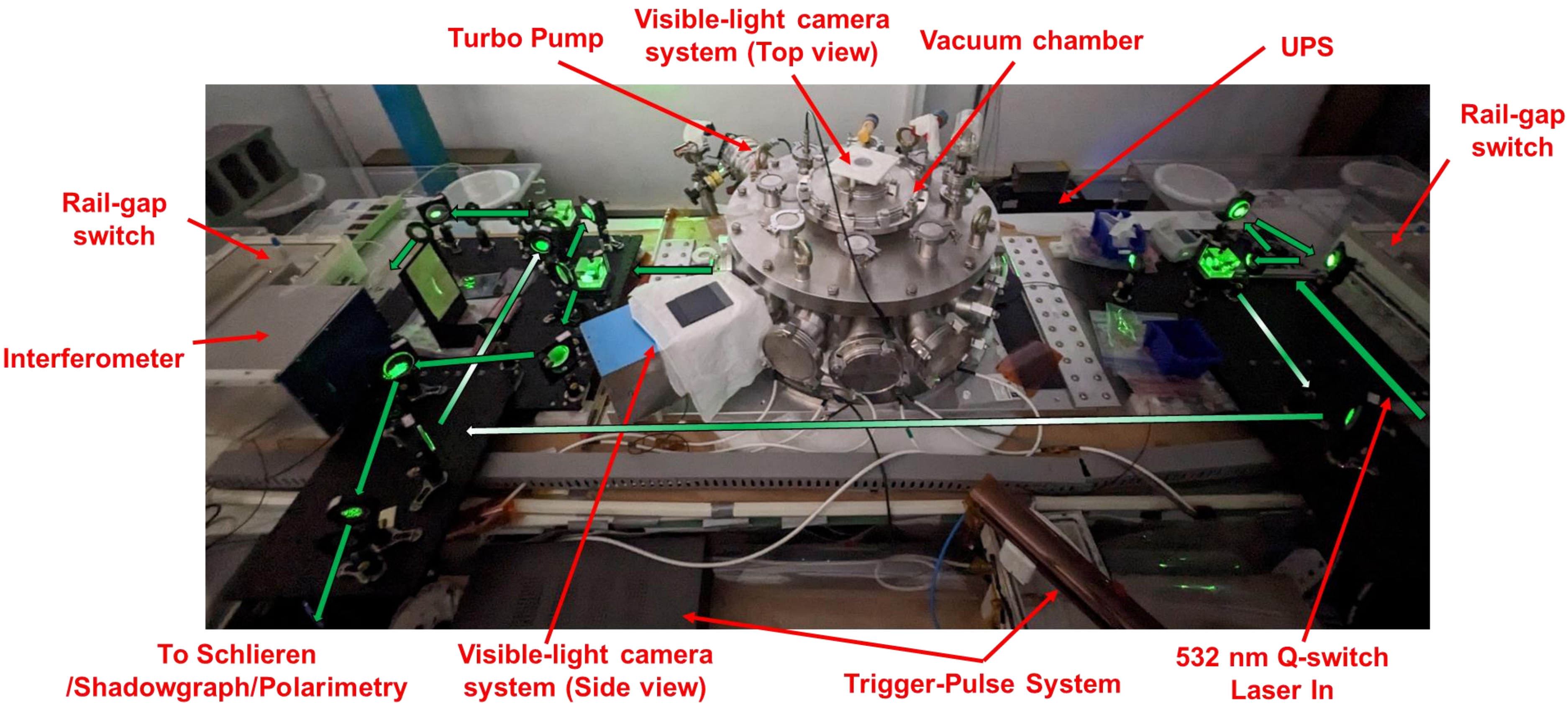


Plasma edge detection

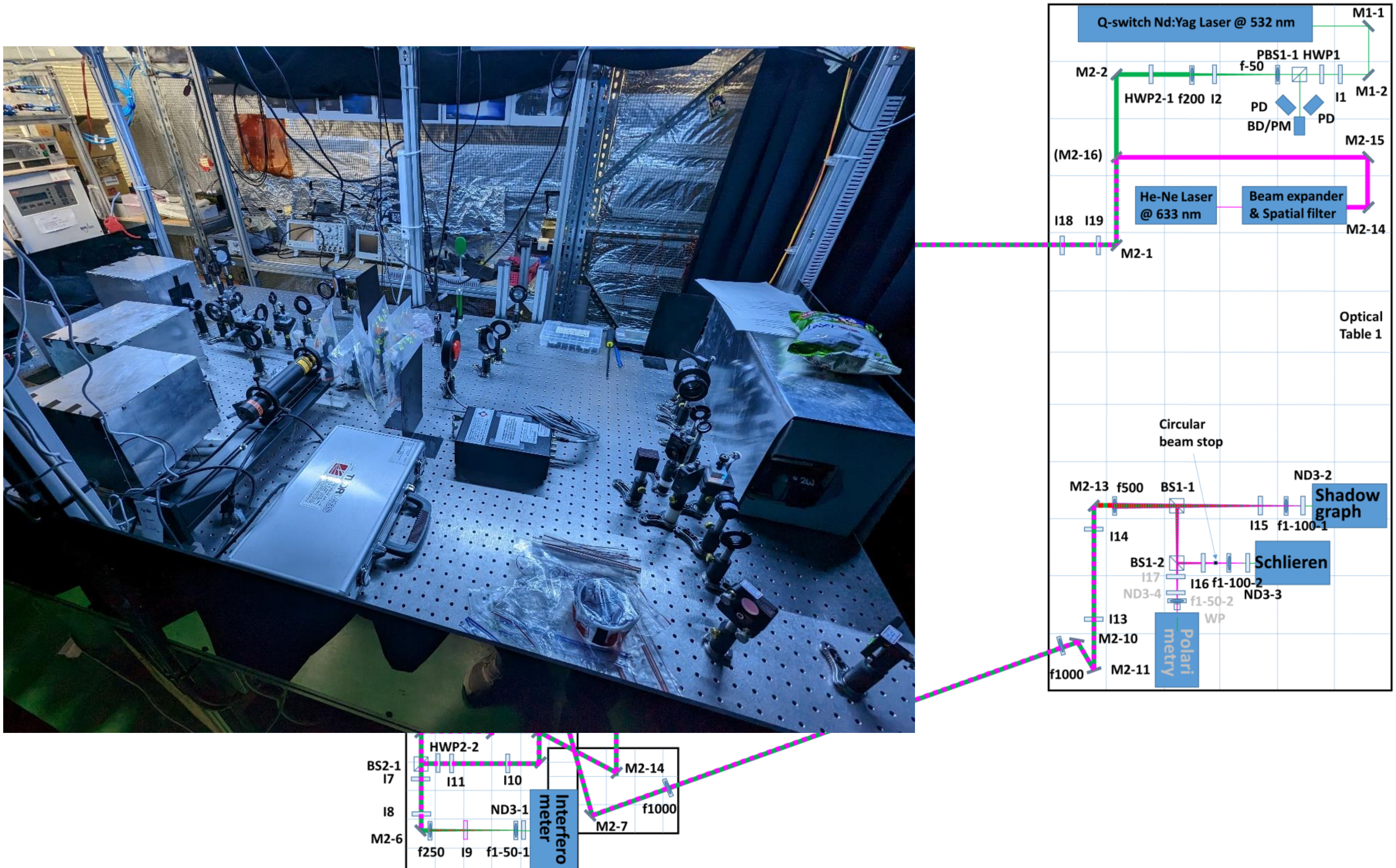
B field measurement

Density measurement

Varies diagnostics were integrated to the system

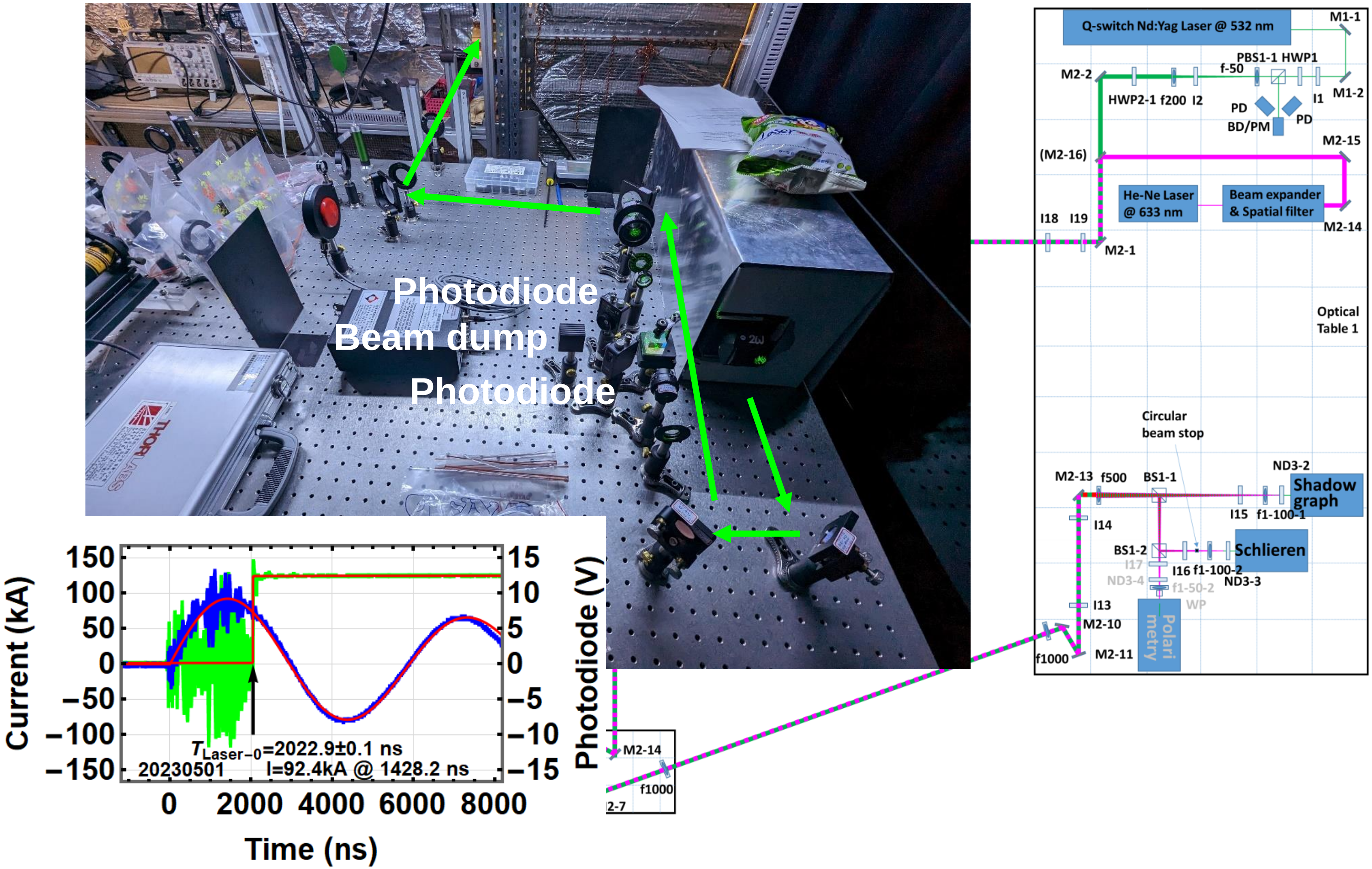


Beam path



Q-switch Nd:Yag Laser @ 532 nm
M1-1
M2-2
PBS1-1 HWP1
f-50
M1-2
HWP2-1 f200 I2
I1
PD
PD
BD/PM
M2-15
(M2-16)
He-Ne Laser
@ 633 nm
Beam expander
& Spatial filter
I18 I19
M2-14
M2-1
Optical
Table 1
Circular
beam stop
ND3-2
M2-13 f500 BS1-1
Shadow
graph
I15 f1-100-1
I14
BS1-2
Schlieren
I17
I16 f1-100-2
ND3-4
f1-50-2
ND3-3
WP
I13
M2-10
Polari
metry
f1000
M2-11
HWP2-2
BS2-1
I7
I11
I10
M2-14
I8
ND3-1
Interfero
meter
f1000
M2-7
M2-6
f250
I9
f1-50-1

Beam path


Photodiode
Beam dump
Photodiode
Current (kA)
Photodiode (V)
Time (ns)
$T_{Laser-0}$=2022.9±0.1 ns
20230501
I=92.4kA @ 1428.2 ns
Q-switch Nd:Yag Laser @ 532 nm
M1-1
PBS1-1 HWP1
M2-2
f-50
HWP2-1 f200 I2
I1
M1-2
PD
PD
BD/PM
M2-15
(M2-16)
He-Ne Laser @ 633 nm
Beam expander & Spatial filter
I18 I19
M2-14
M2-1
Optical Table 1
Circular beam stop
ND3-2
M2-13 f500
BS1-1
Shadow graph
I15 f1-100-1
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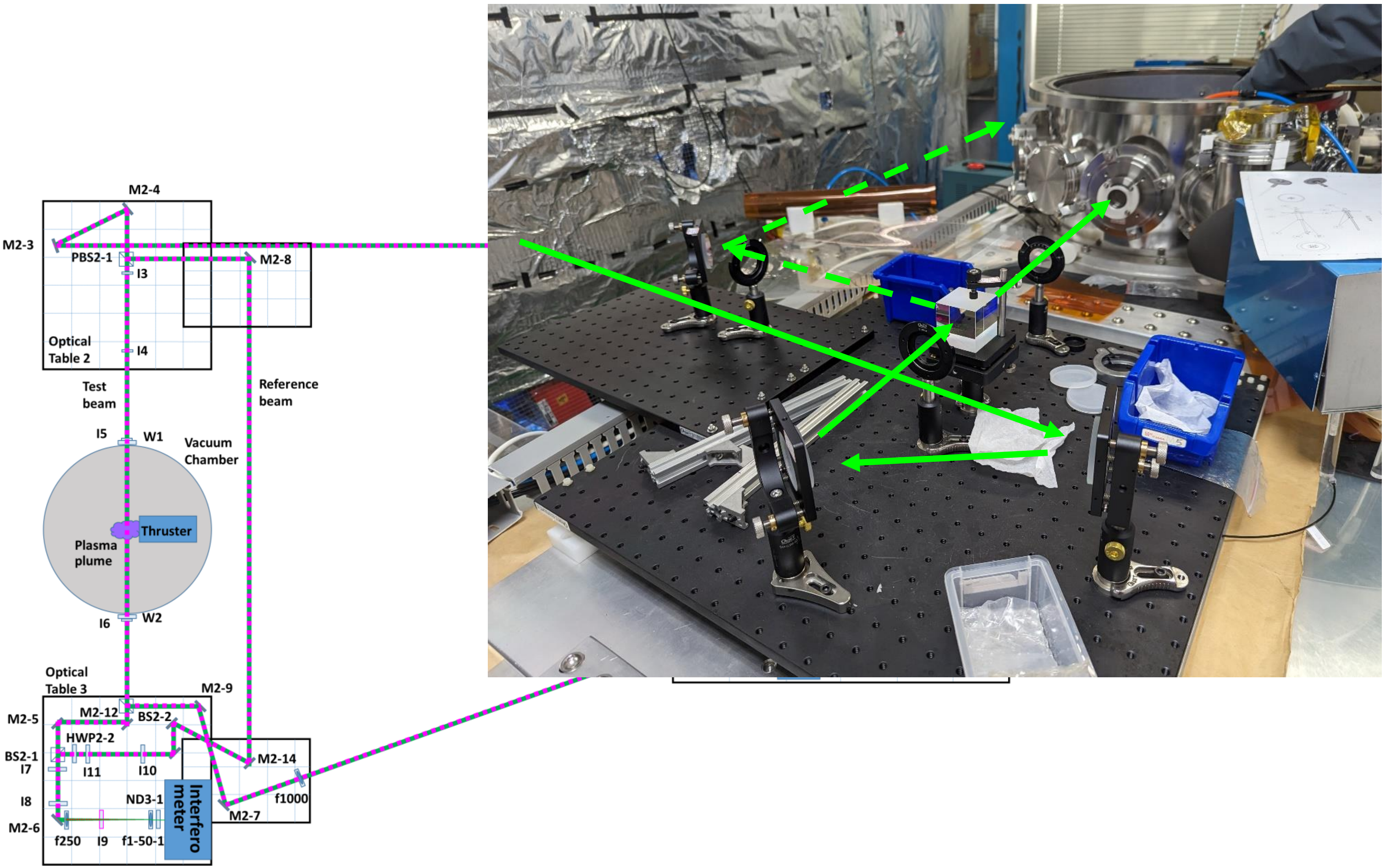
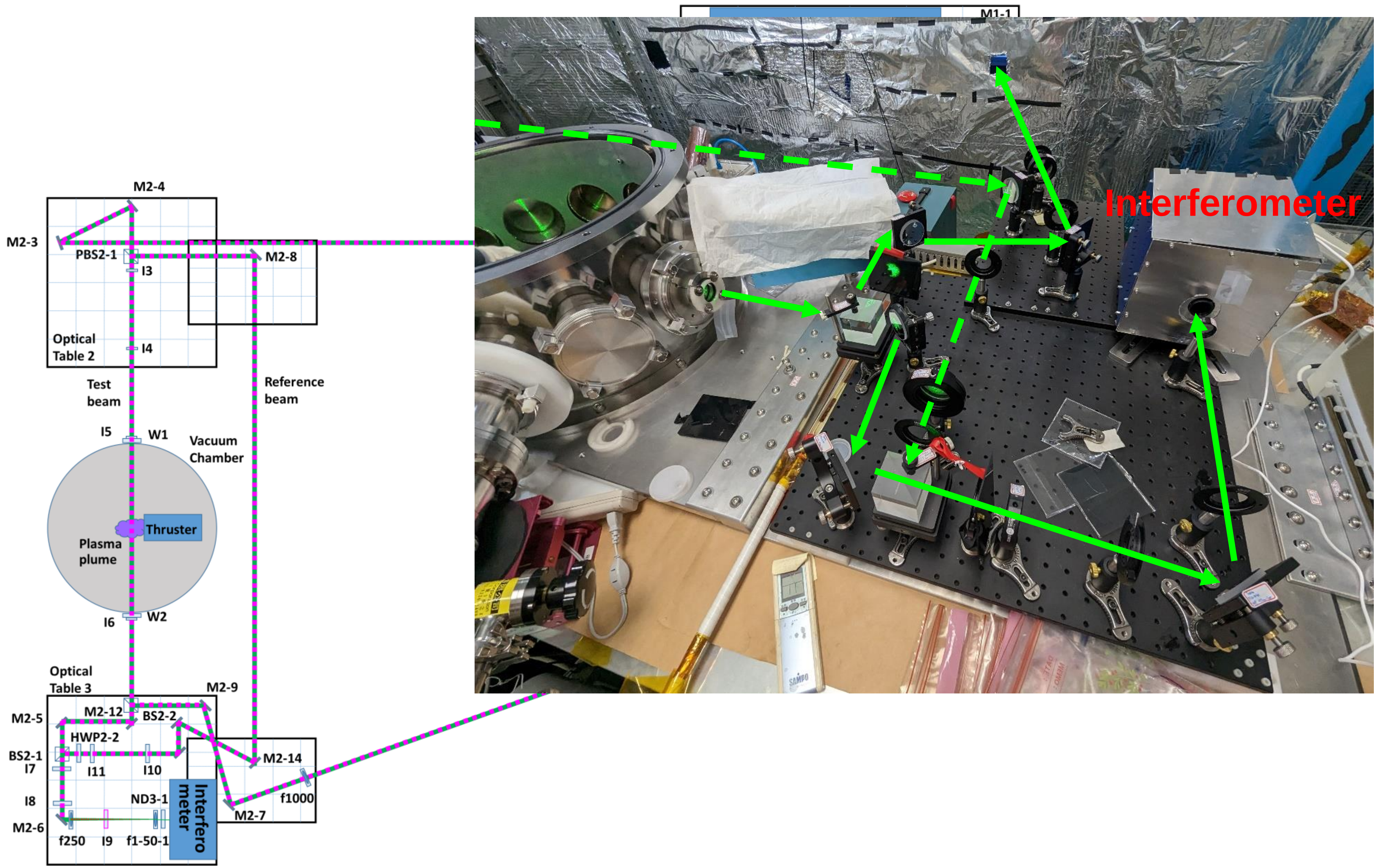
ND3-4
f1-50-2
ND3-3
WP
I13
M2-10
Polari metry
f1000
M2-11
M2-14
f1000
2-7

Beam path

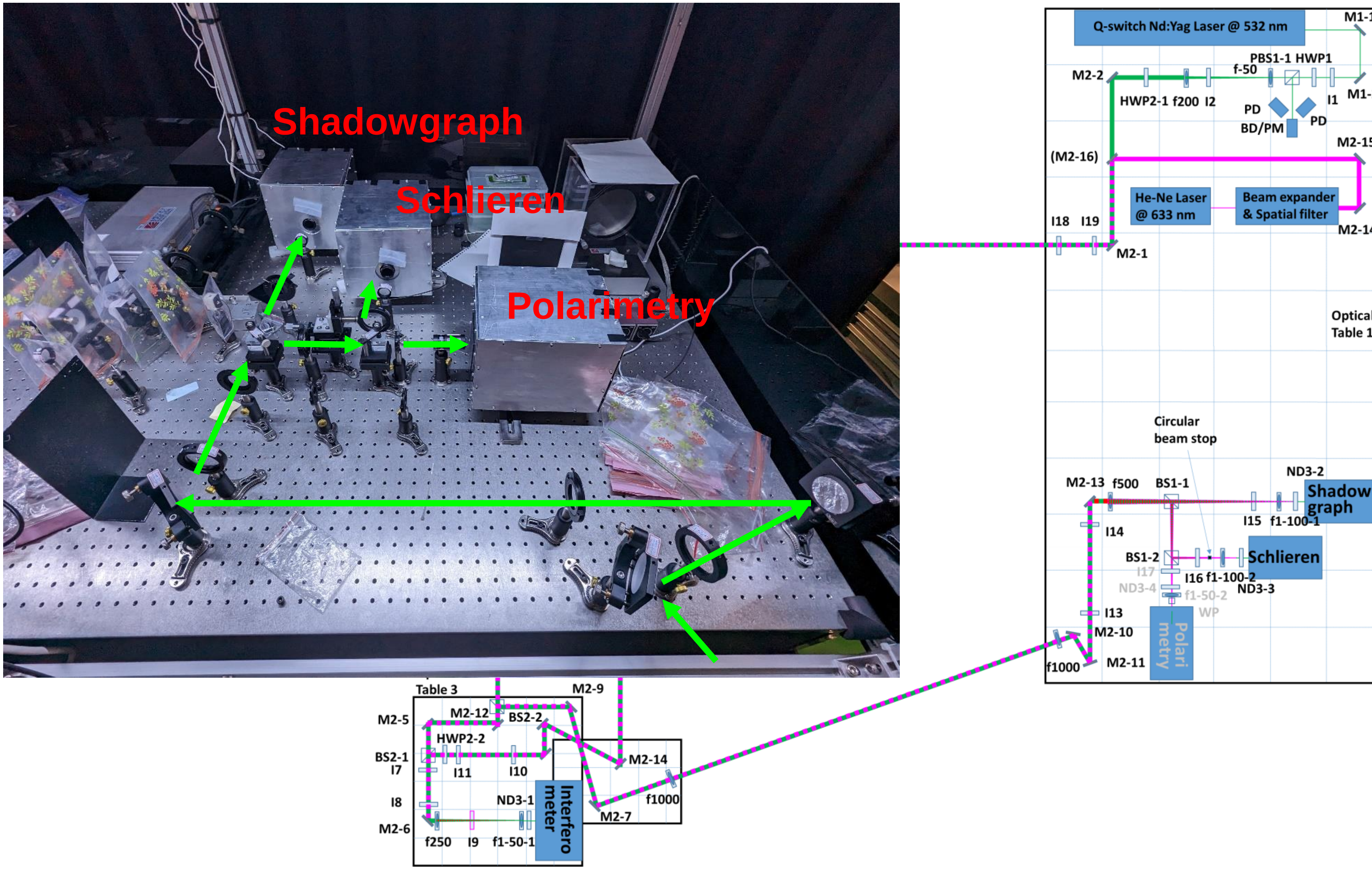


M2-4
M2-3
PBS2-1
M2-8
I3
Optical Table 2
I4
Test beam
Reference beam
I5
W1
Vacuum Chamber
Thruster
Plasma plume
I6
W2
Optical Table 3
M2-9
M2-5
M2-12
BS2-2
HWP2-2
BS2-1
I7
I11
I10
M2-14
I8
ND3-1
f1000
M2-7
M2-6
f250
I9
f1-50-1
Interferometer

Beam path


M1-1
M2-4
M2-3
PBS2-1
I3
M2-8
Optical Table 2
I4
Test beam
Reference beam
I5
W1
Vacuum Chamber
Thruster
Plasma plume
W2
I6
Optical Table 3
M2-9
M2-12
BS2-2
M2-5
HWP2-2
BS2-1
I7
I11
I10
M2-14
I8
ND3-1
f1000
Interfero meter
M2-7
M2-6
f250
I9
f1-50-1
Interferometer

Beam path



Shadowgraph
Schlieren
Polarimetry
Q-switch Nd:Yag Laser @ 532 nm
M1-1
PBS1-1 HWP1
f-50
M2-2
M1-2
HWP2-1 f200 I2
I1
PD
PD
BD/PM
M2-15
(M2-16)
He-Ne Laser
@ 633 nm
Beam expander
& Spatial filter
I18 I19
M2-14
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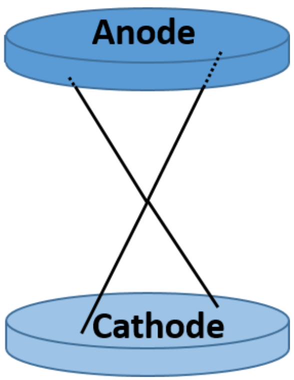
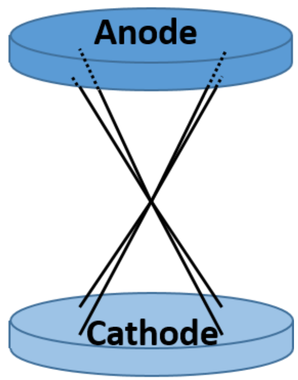
I17
I16 f1-100-2
ND3-4
f1-50-2
ND3-3
WP
I13
M2-10
Polari
metry
f1000
M2-11
Table 3
M2-9
M2-5
M2-12
BS2-2
HWP2-2
BS2-1
I7
I11
I10
M2-14
I8
ND3-1
Interfero
meter
f1000
M2-6
M2-7
f250 I9 f1-50-1

Different wire configurations can be used to generate plasma jets and hard x rays

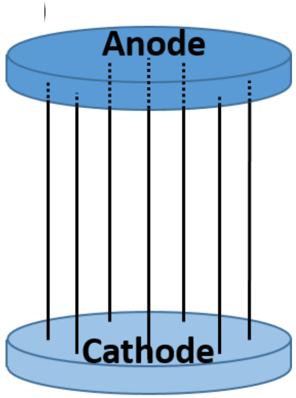
- x pinch



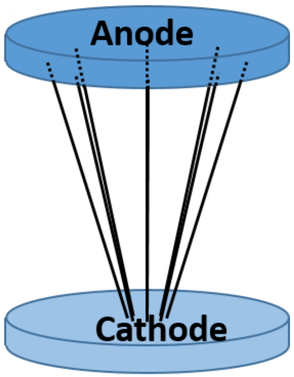
- multi-wires x pinch



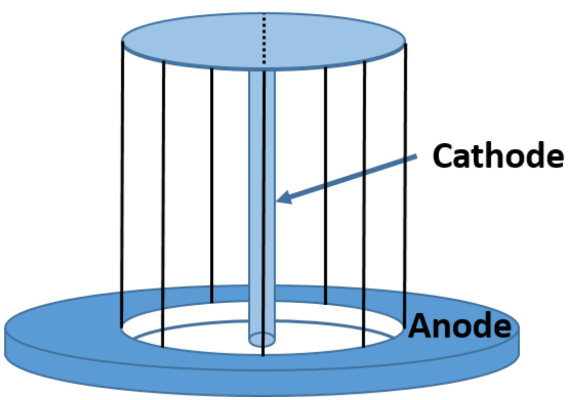
- wire array



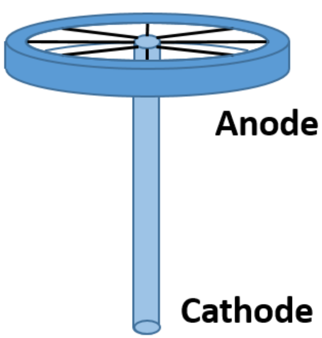
- conical-wire array



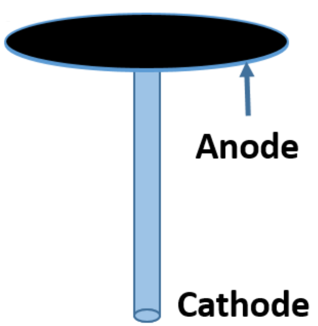
- inverse-wire array



- radial-wire array

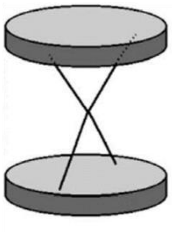


- radial foil

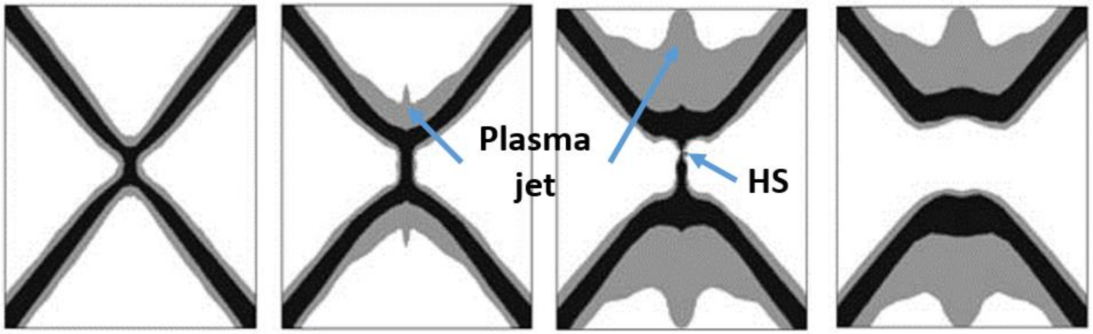


Spatial coherent hard x rays can be generated using x pinches for point-projection x-ray radiography

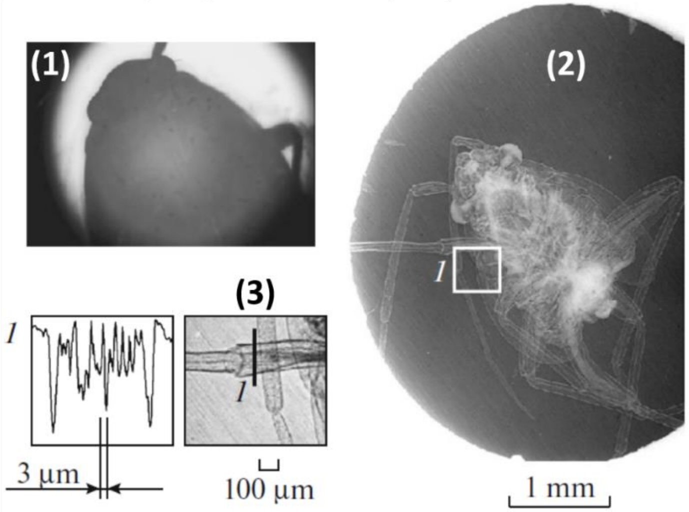
- x pinch



- The process of an exploded x pinch



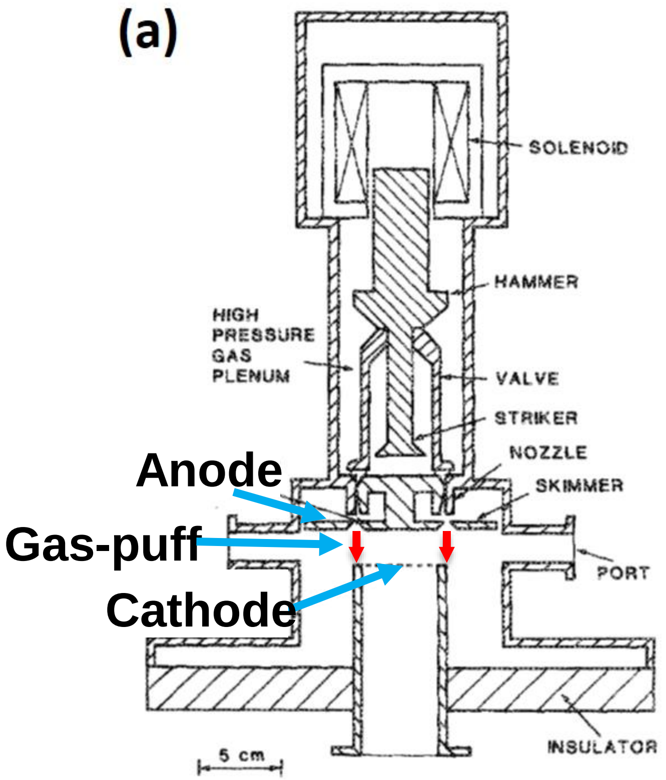
- Point-projection x-ray radiography



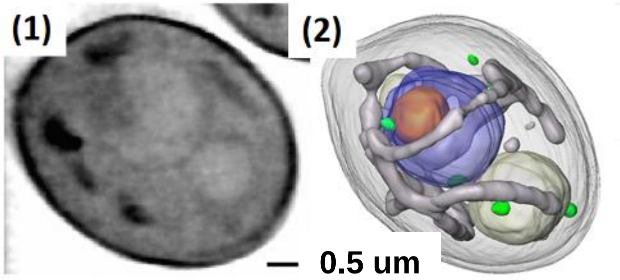
- **We are expecting x-ray yields of couple keV, < 1ns, <10 um, ~5 J in total energy generated in our system.**

* G. V. Ivanenkov *et al.* Plasma Physics Reports 34, 619 (2008)
* T. A. Shelkovenko *et al.* Plasma Physics Reports 42, 226 (2016)
* T. A. Shelkovenko *et al.* IEEE Trans. Plasma Sci. 34, 2336 (2006)
* D. H. Kalantar *et al.* J. Applied Physics 73, 8134 (1993)

Soft x rays for 3-D x-ray tomographic microscopy can be generated using gas-puff z pinches



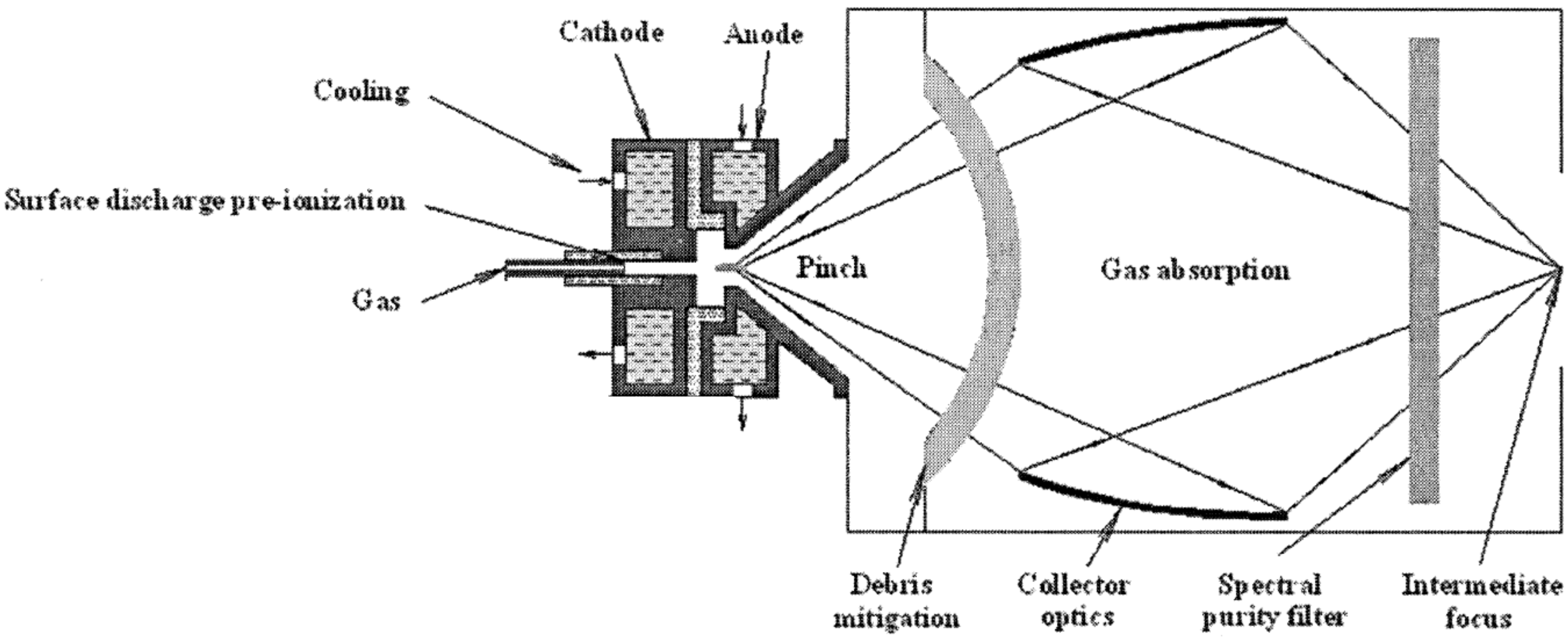
- **Line radiation in the range of 40-15 Å (310-830 eV) with a total energy of 10 J using CO_2 is expected.**
- **Soft x rays (~520eV) from synchrotron radiation at Advanced Light Source (ALS) is used for 3-D x-ray tomographic microscopy.**



- **Single line emission in 41.8 / 32.8 nm is expected using Xenon or Krypton.**

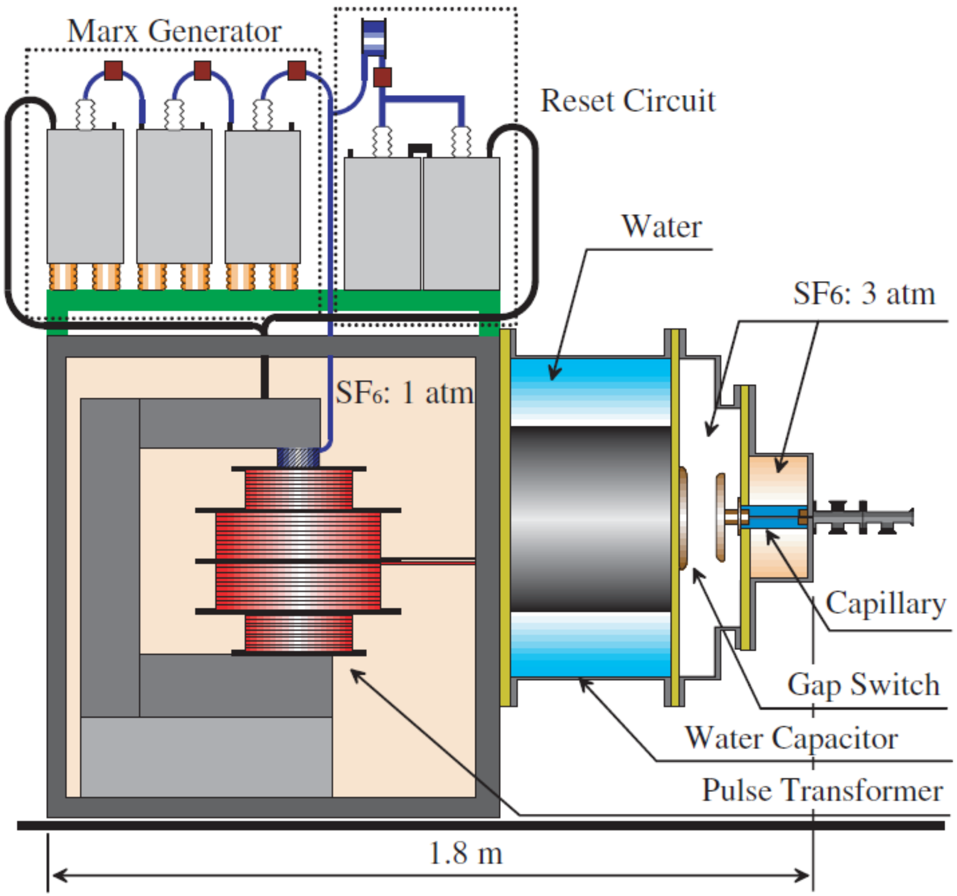
*P. Choi *et al.* Rev. Sci. Instru. 57, 2162 (1986)
*G. Nave *et al.* J. Appl. Phys. 65, 3385 (1989)
*M. Uchida *et al.* *Proc. National Acad. Sci.* 106, 19375 (2009)

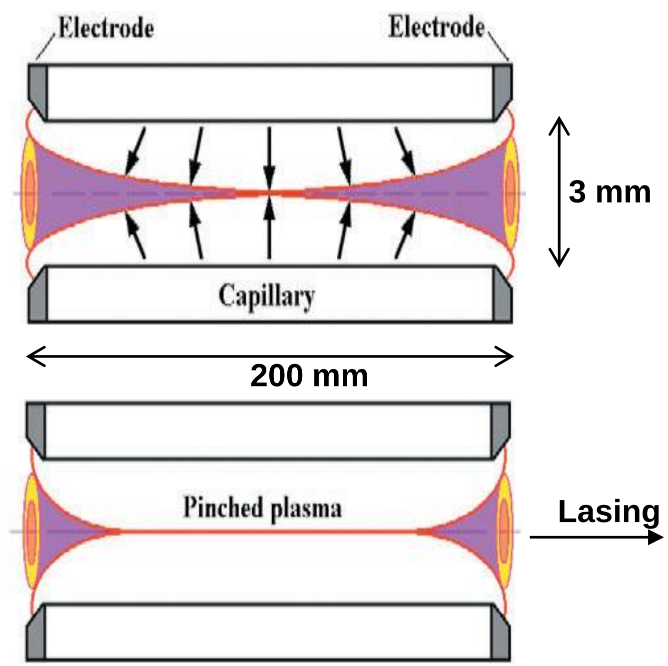
Discharge produced plasma can generate EUV light for EUV lithography



V. Borisov, etc., Proc. SPIE 6611, Laser Optics 2006: High-Power Gas Lasers, 66110B (12 April 2007)

Soft x-ray laser can be generated using a capillary z-pinch discharge



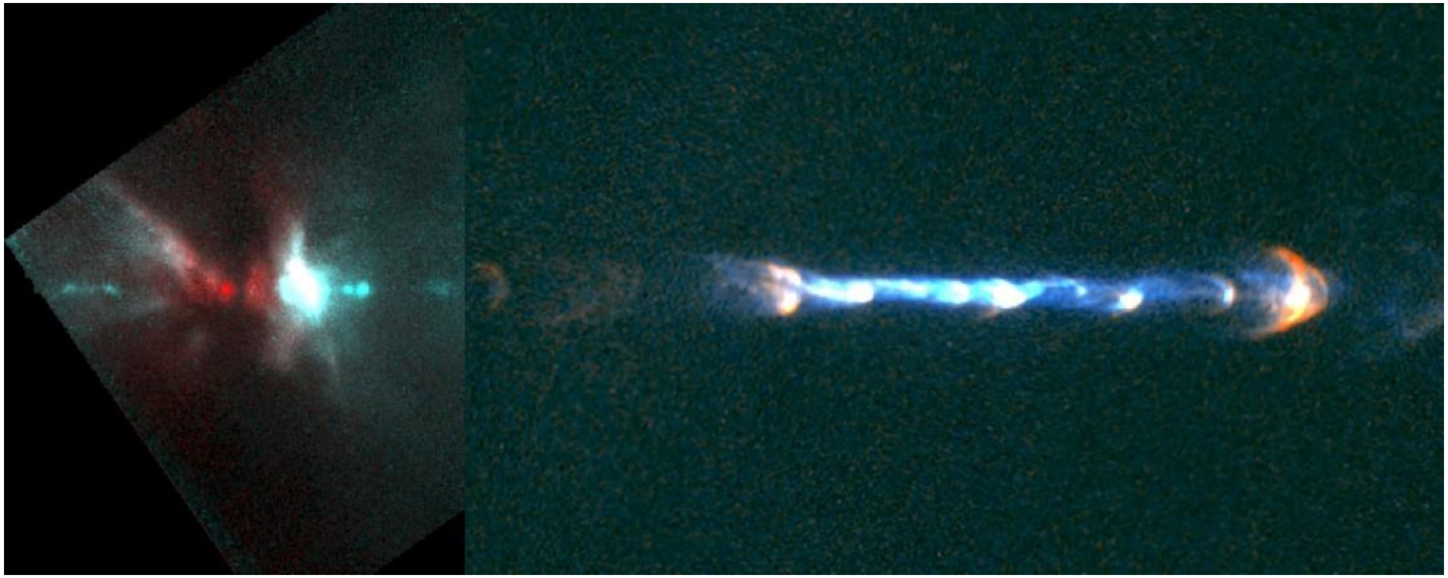


- **If 200～500 mTorr Ar is used as the filled gas, 46.9 nm (26.5 eV) Ne-like Ar laser can be built.**

Y. Hayashi, etc., Plasma Sources Sci. Technol. 13, 675 (2004)

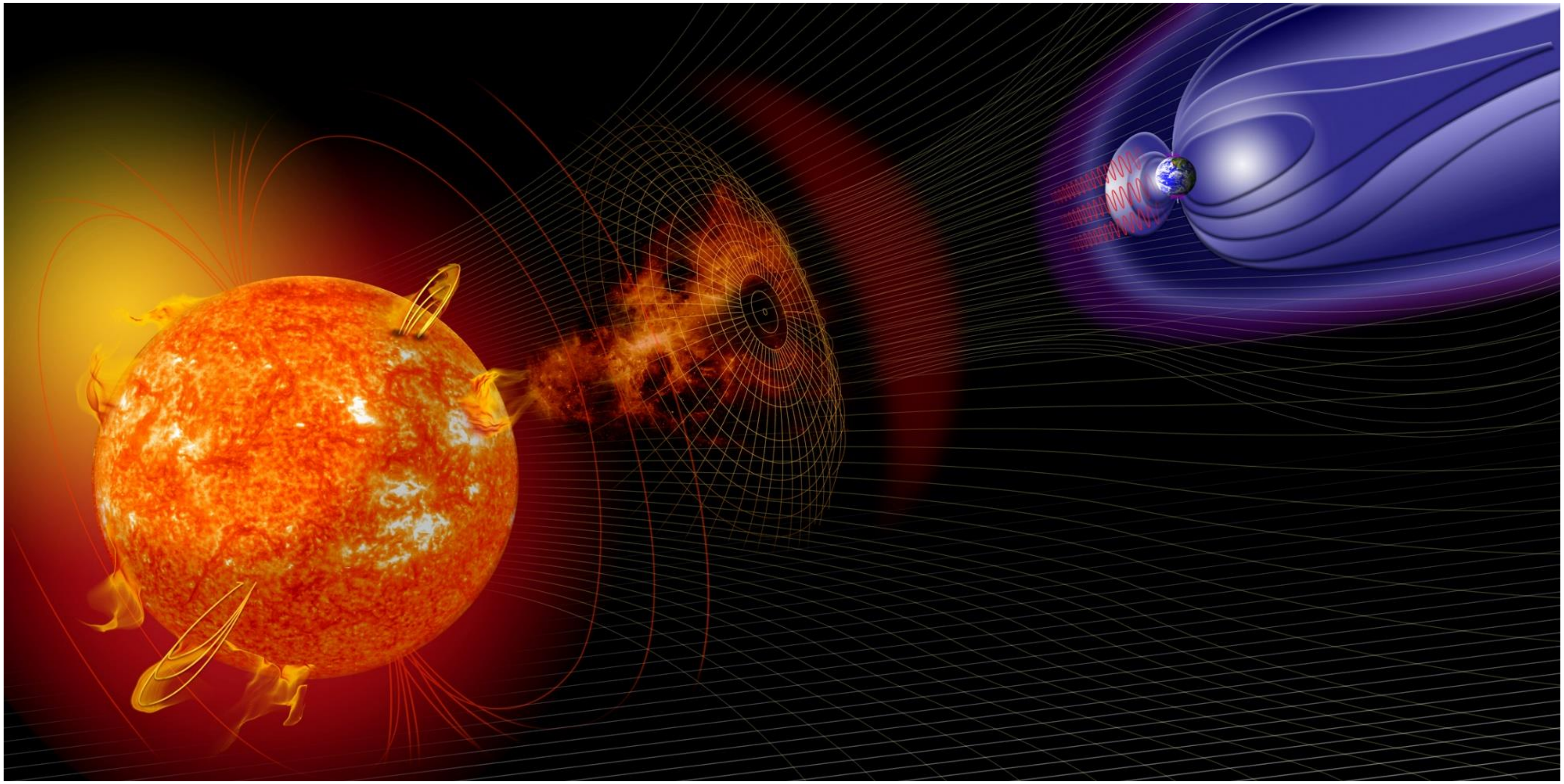
Astrophysics and space science can be studied in laboratory environments.

- **Plasma jets in Herbig-Haro 111 taken by Hubble space telescope.**



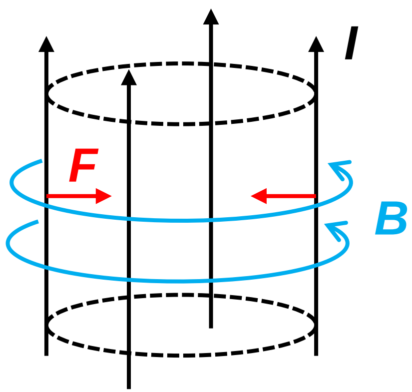
B. Reipurth and J. BallyAnnu. Rev. Astron. Astrophys., **39**, 403 (2001)

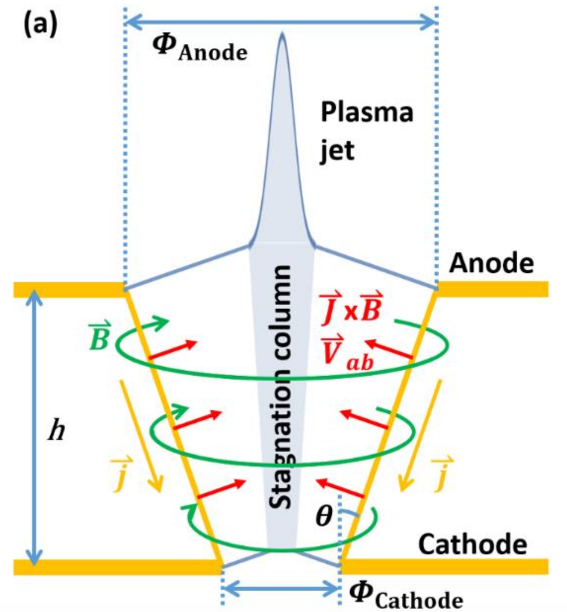
Solar wind is a supersonic plasma plume coming from the sun



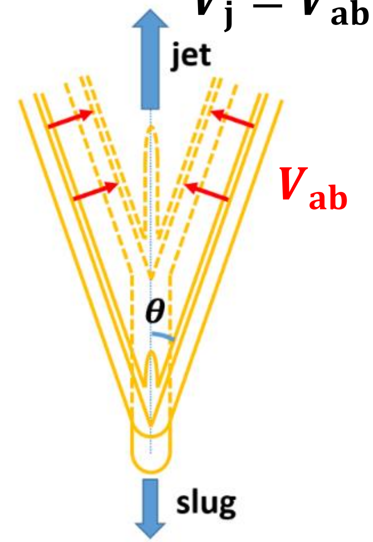
https://www.nasa.gov/mission_pages/sunearth/spaceweather/index.html

A plasma jet can be generated by a conical-wire array due to the nonuniform z-pinch effect





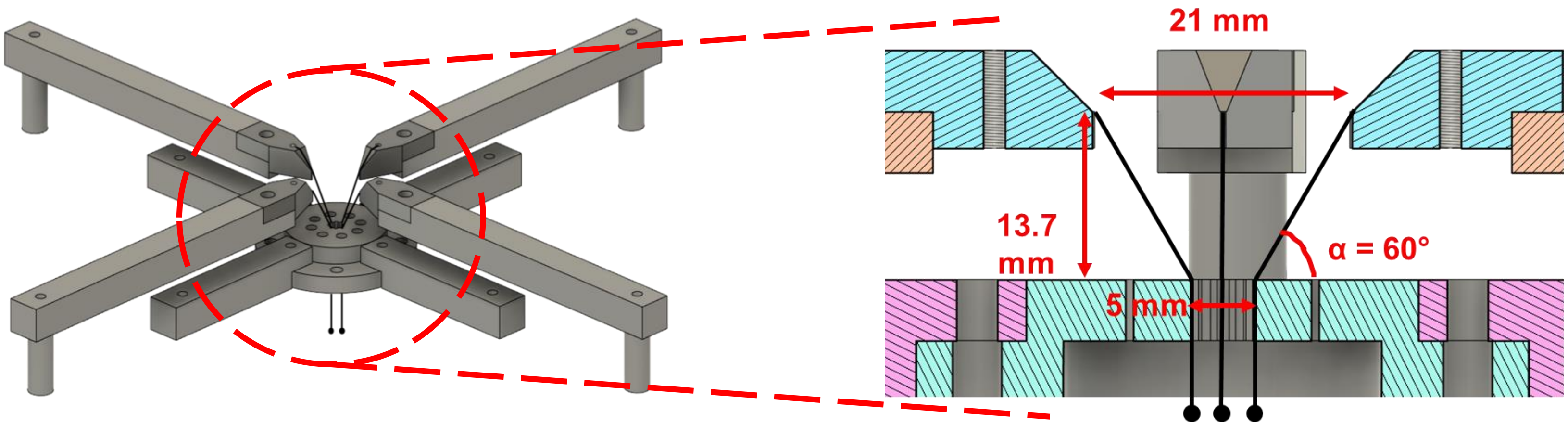
$$V_{\mathrm{j}} = V_{\mathrm{ab}}\frac{1+\cos\theta}{\sin\theta}$$



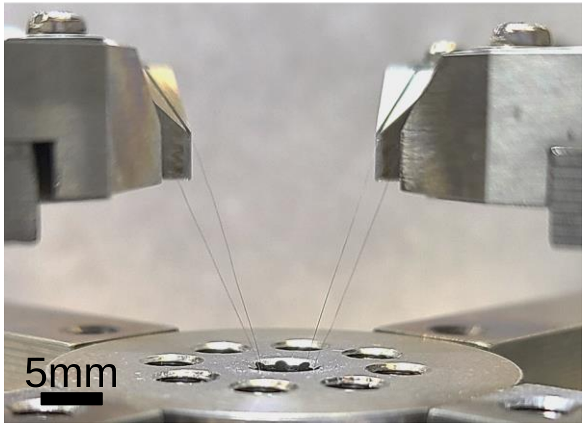
1. **Wire ablation : corona plasma is generated by wire ablations.**
2. **Precursor : corona plasma is pushed by the $\vec{J}\times\vec{B}$ force and accumulated on the axis forming a precursor.**
3. **Plasma jet is formed by the nonuniform z-pinch effect due to the radius difference between the top and the bottom of the array.**

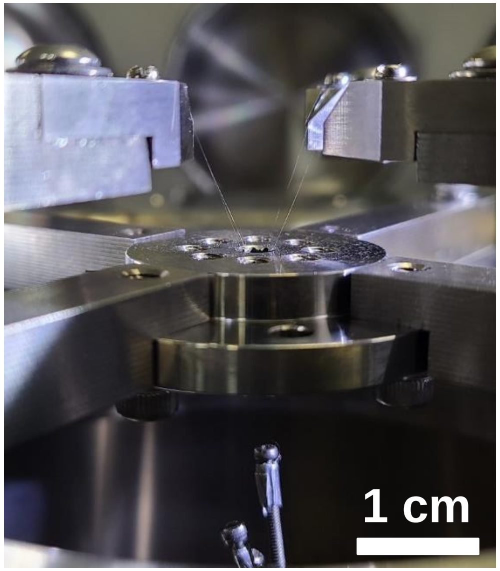
D. J. Ampleforda, et al., Phys. Plasmas 14, 102704 (2007)
G. Birkhoff, et al., J. Applied Physics 19, 563 (1948)

Our conical-wire array consists of 4 tungsten wires with an inclination angle of 30° with respect to the axis



- **Conical-wire array**

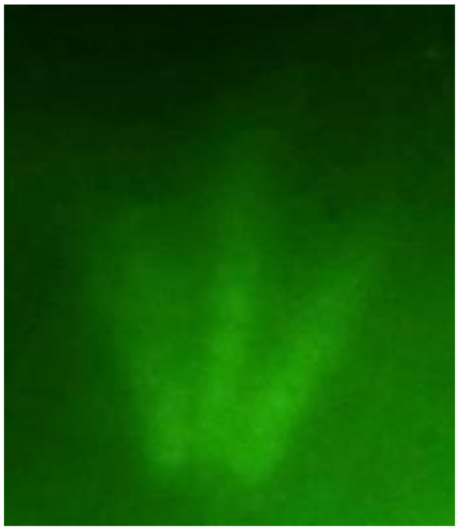




- **Material : Tungsten**
- **Number of wires : 4**
- **Diameter : 0.02 mm**

Self-emission of the plasma jet in the UV to soft x-ray regions was captured by the pinhole camera

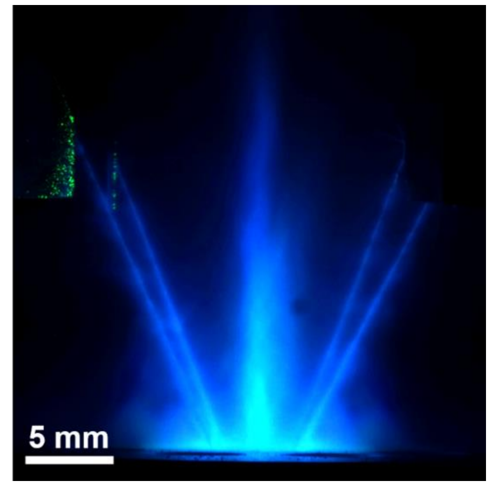
- Image in UV/soft x ray



(Brightness is increased by 40 %.)

- Pinhole diameter: 0.5 mm, i.e., spatial resolution: 1 mm.

- Image in visible light



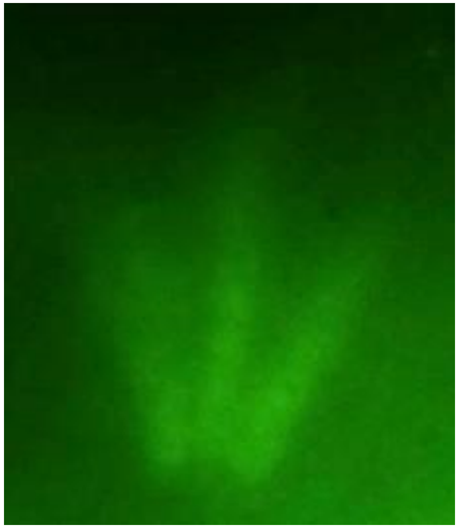
(Enhanced by scaling the intensity range linearly from 0 − 64 to 0 − 255.)

- P08 Ming-Hsiang Kuo

Y.-C. Lin, NCKU Master Thesis 2021

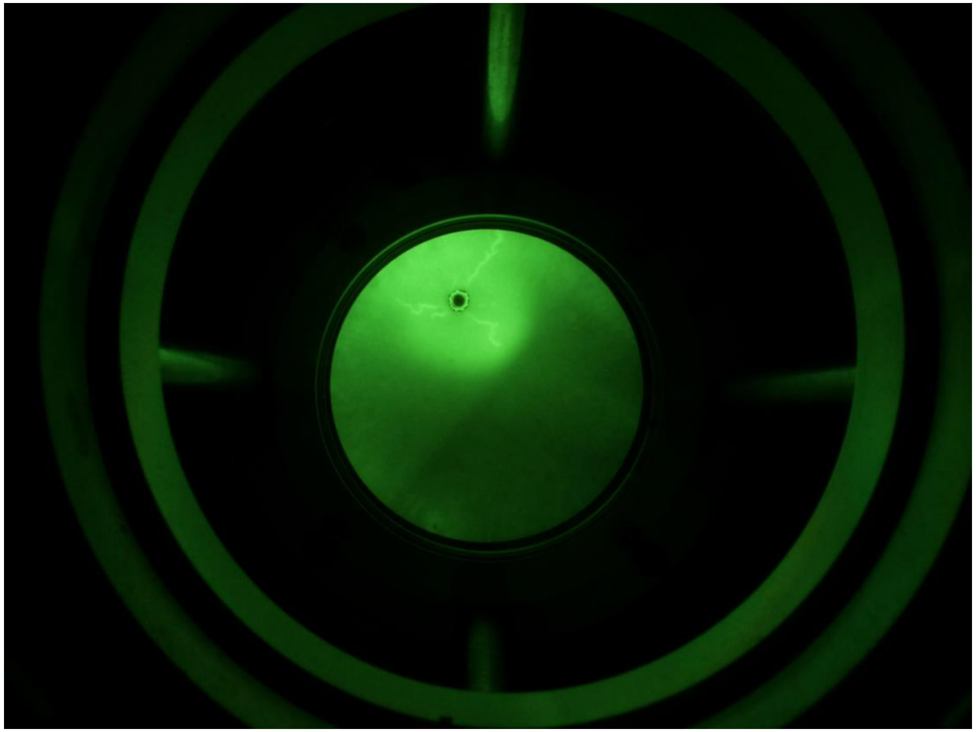
The MCP was burned due to the higher DC voltage supply

- **Image in UV/soft x ray**



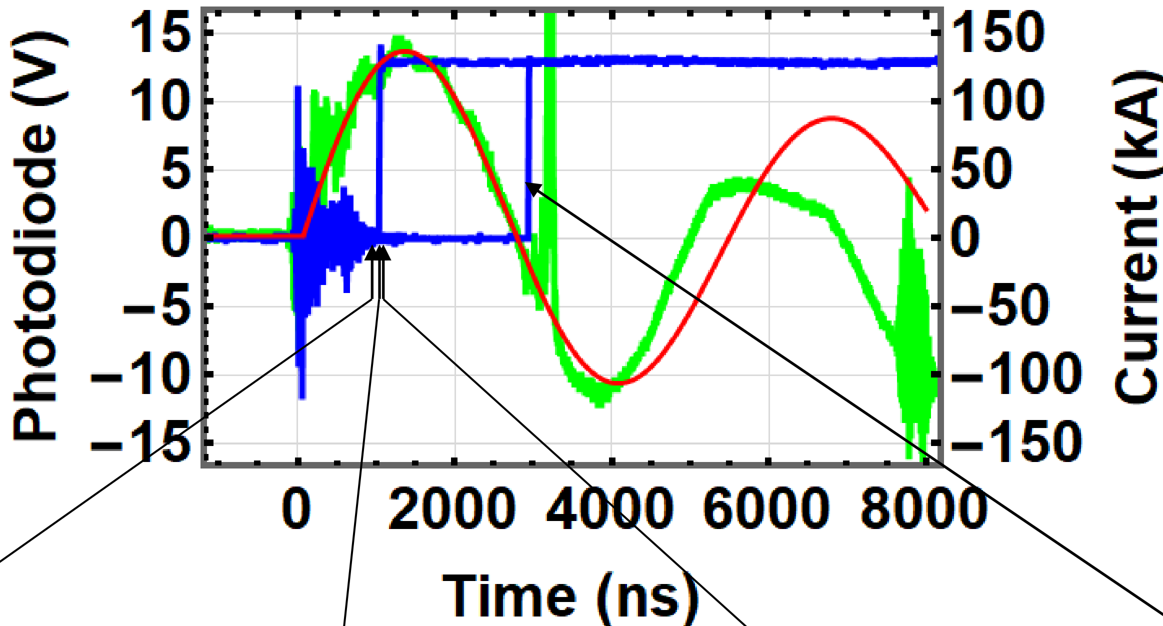
(Brightness is increased by 40 %.)

- **Pinhole diameter: 0.5 mm, i.e., spatial resolution: 1 mm.**

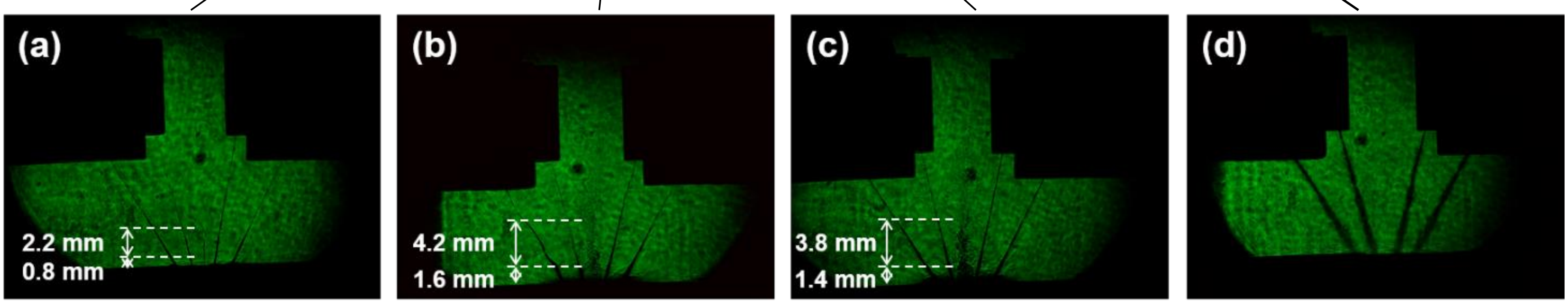


Y.-C. Lin, 2021/8/31 Final report
P.-Y. Chang, etc, Rev. Sci. Instrum., 93, 043505 (2022)

Plasma jet propagation was observed using laser diagnostics



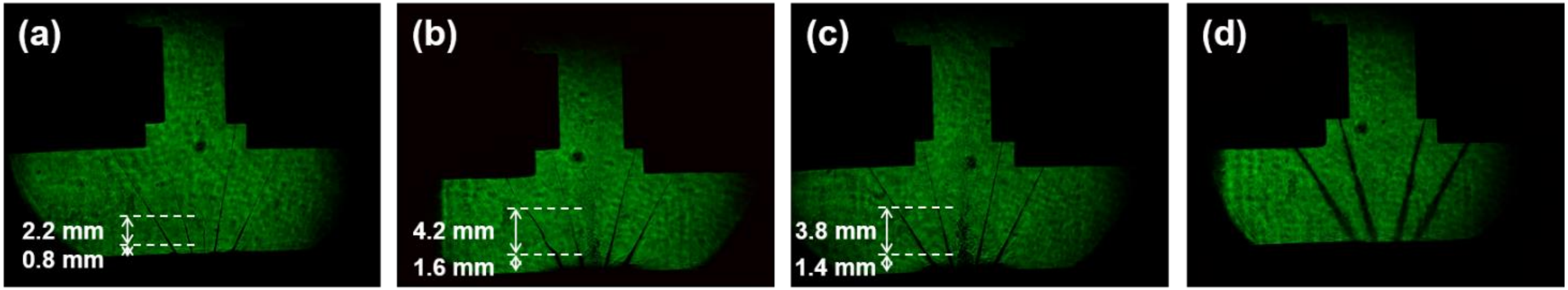
- **Shadowgraph images:**



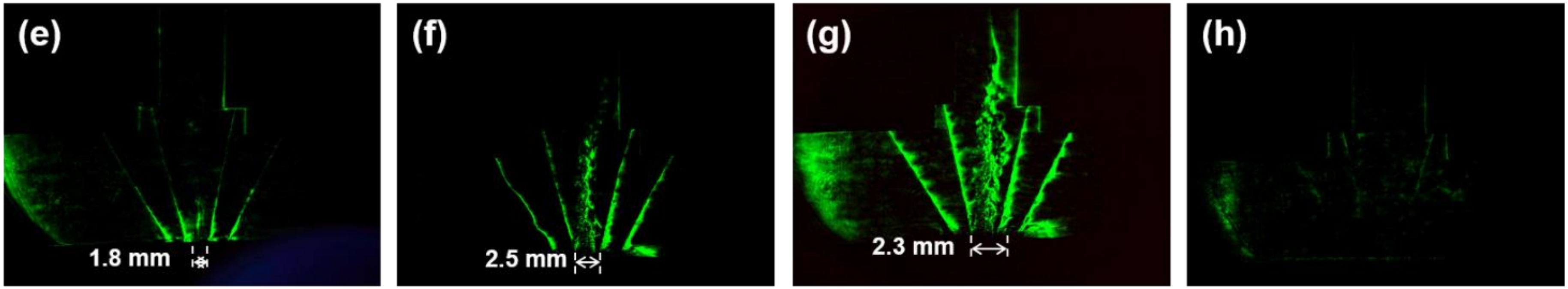
930 ± 20 ns | **975** ± 2 ns | **985** ± 3 ns | **2945** ± 2 ns

Plasma jet propagation was observed using laser diagnostics

- **Shadowgraph images:**

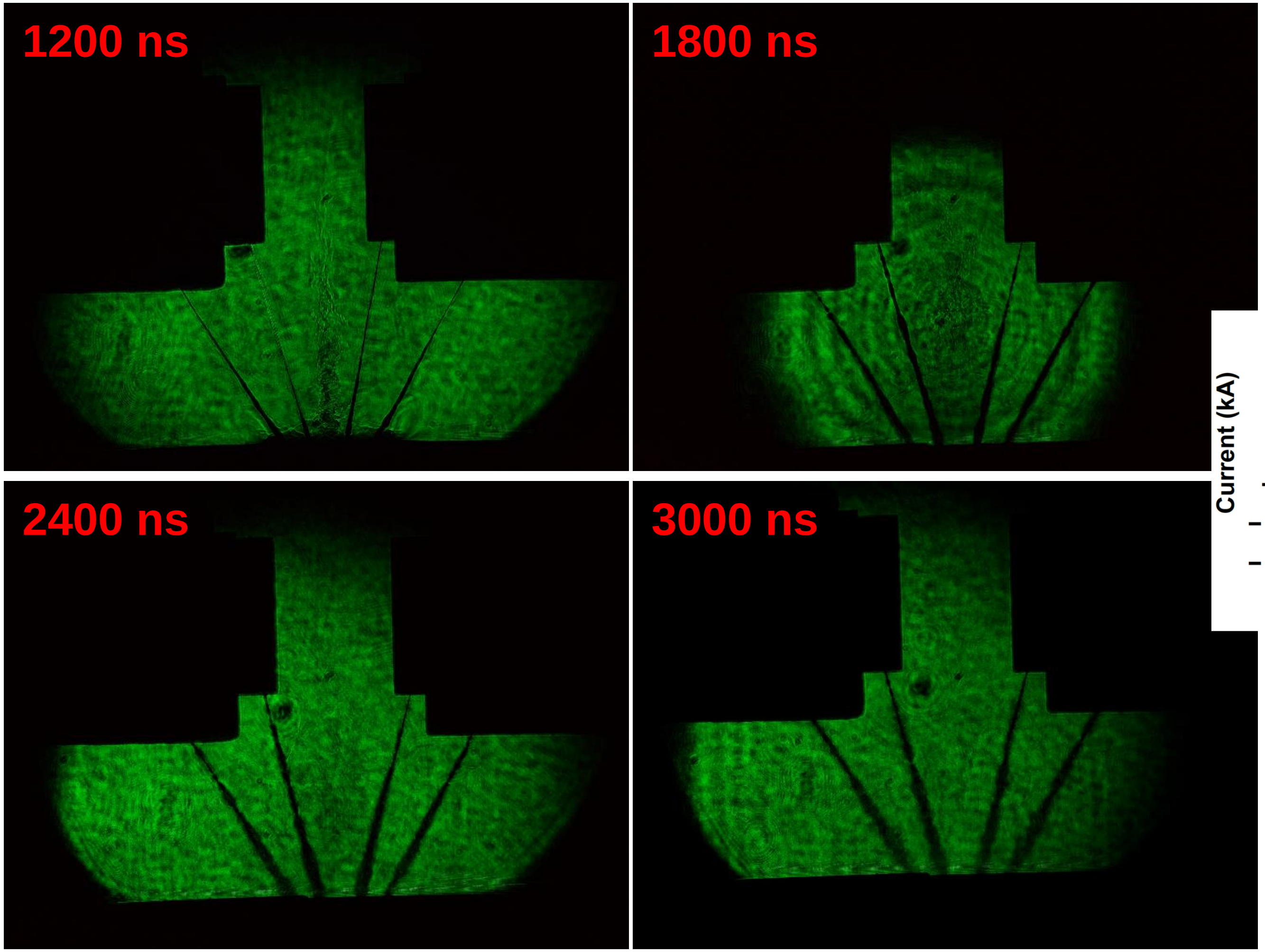


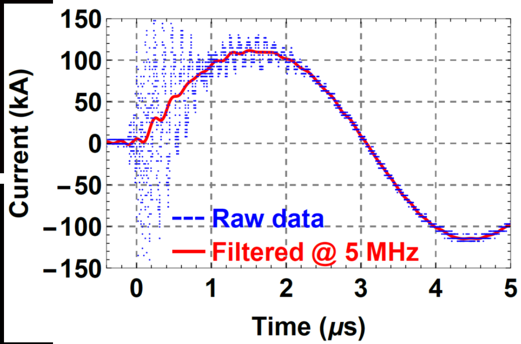
- **Schlieren images:**



930 $\pm$ 20 ns | **975 $\pm$ 2 ns** | **985 $\pm$ 3 ns** | **2945 $\pm$ 2 ns**

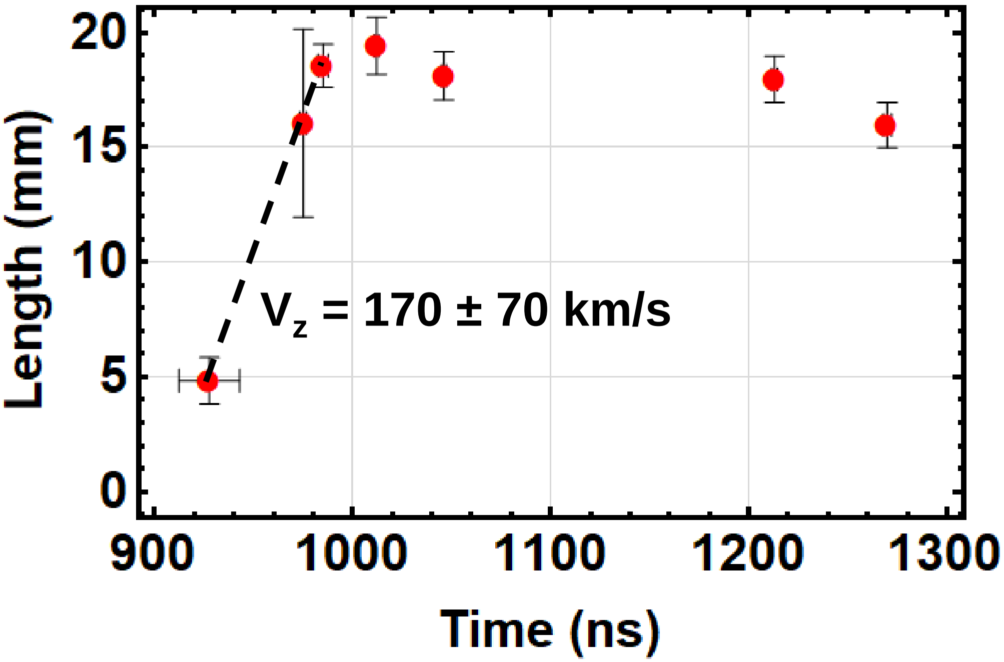
Tungsten wires are being evaporated by the pulsed current

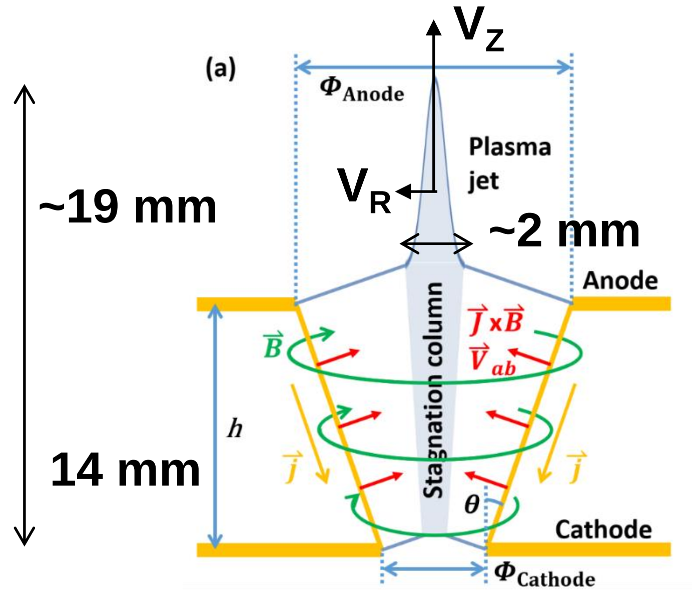




To be continued…..

The measured plasma jet speed is 170 ± 70 km/s with the corresponding Mach number greater than 5



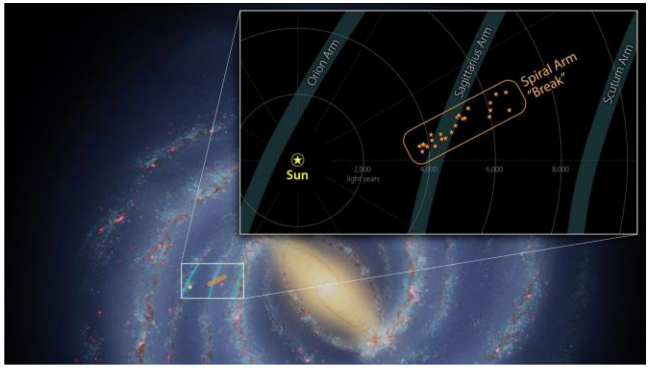


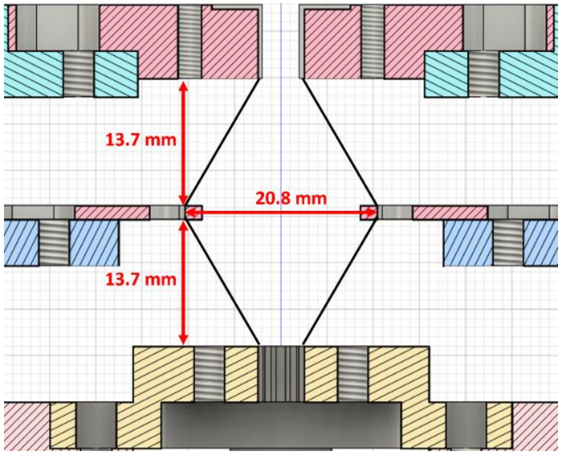
$$M = \frac{V_Z}{V_R} \leq \frac{Z}{r} \approx \frac{(19 - 14)\ \mathrm{mm}}{\frac{2\ \mathrm{mm}}{2}} = 5$$

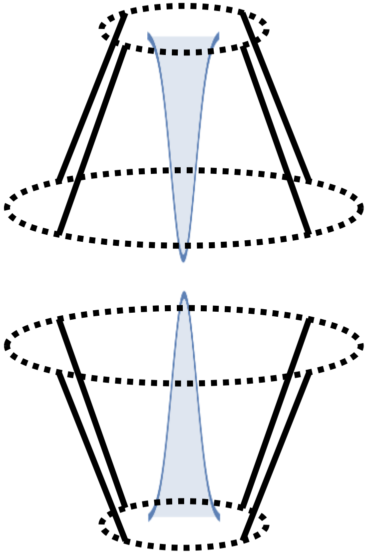
$$V_{\mathrm{ab}} = V_{\mathrm{j}} \frac{\sin\theta}{1 + \cos\theta} = 50\ \pm 20\ \mathrm{km/s}$$

Plasma disk can be formed when two head-on plasma jets collide with each other

- **Astronomers Find a ‘Break’ in One of the Milky Way’s Spiral Arms.**



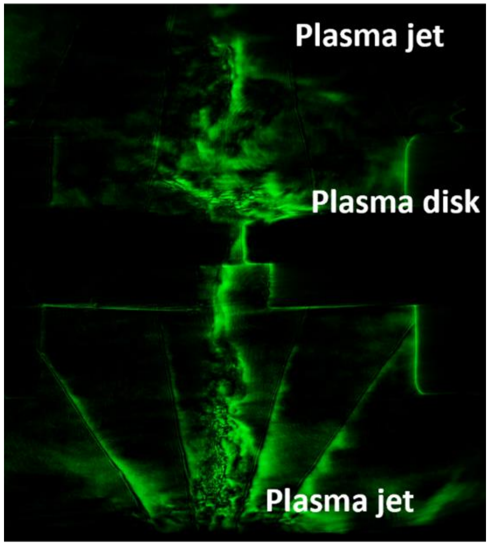




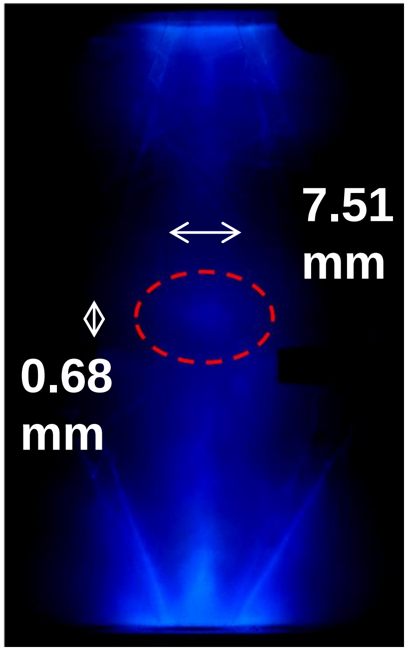
Jet Propulsion Laboratory [NASA/JPL] Astronomers Find a ‘Break’ in One of the Milky Way’s Spiral Arms (Aug 17, 2021)

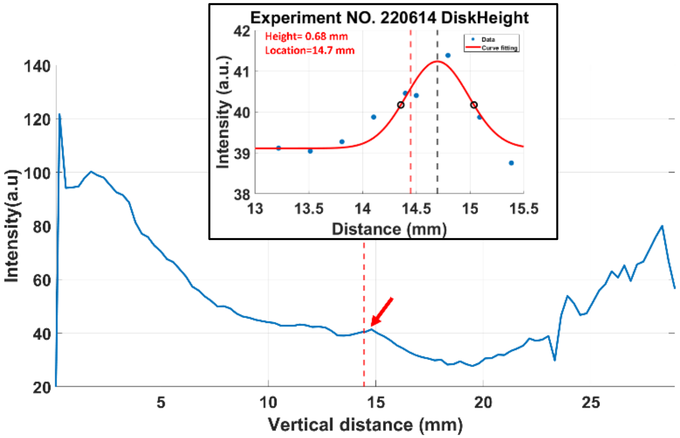
A plasma disk with a height of ~0.68 mm and a width of ~7.51 mm was generated ~0.15 mm above the middle plane

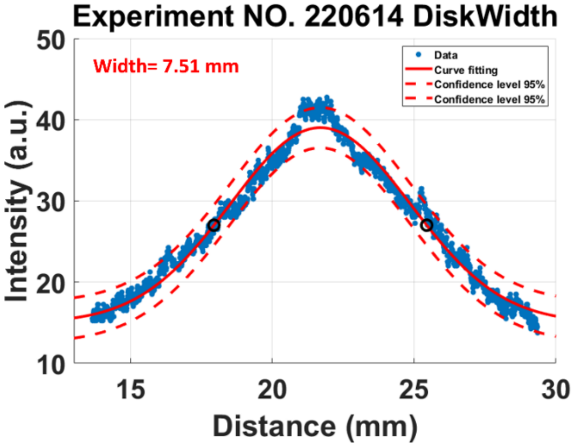
- **Schlieren image:**



- **Time-integrated image:**



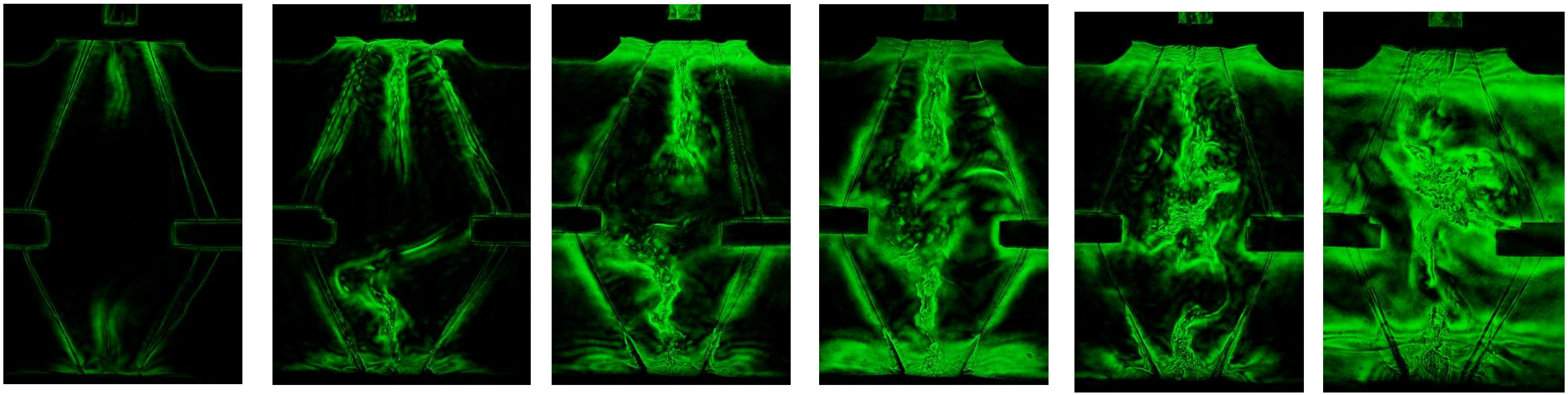




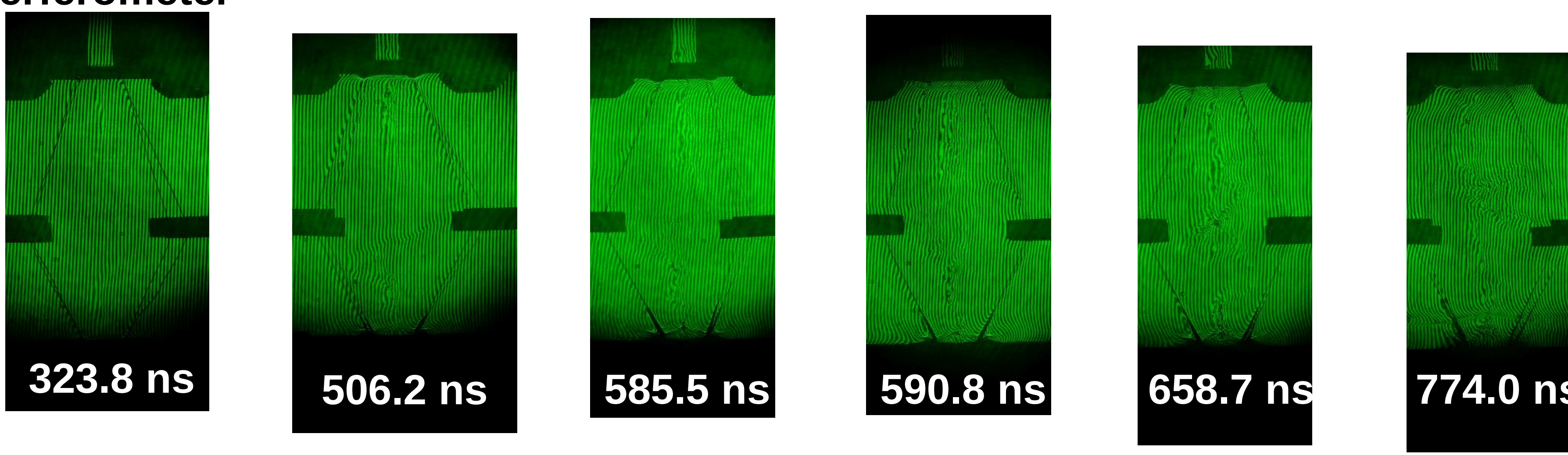
M.-S. Kuo, NCKU Master Thesis 2022

Plasma disk can be formed when two head-on plasma jets collide with each other

Schlieren

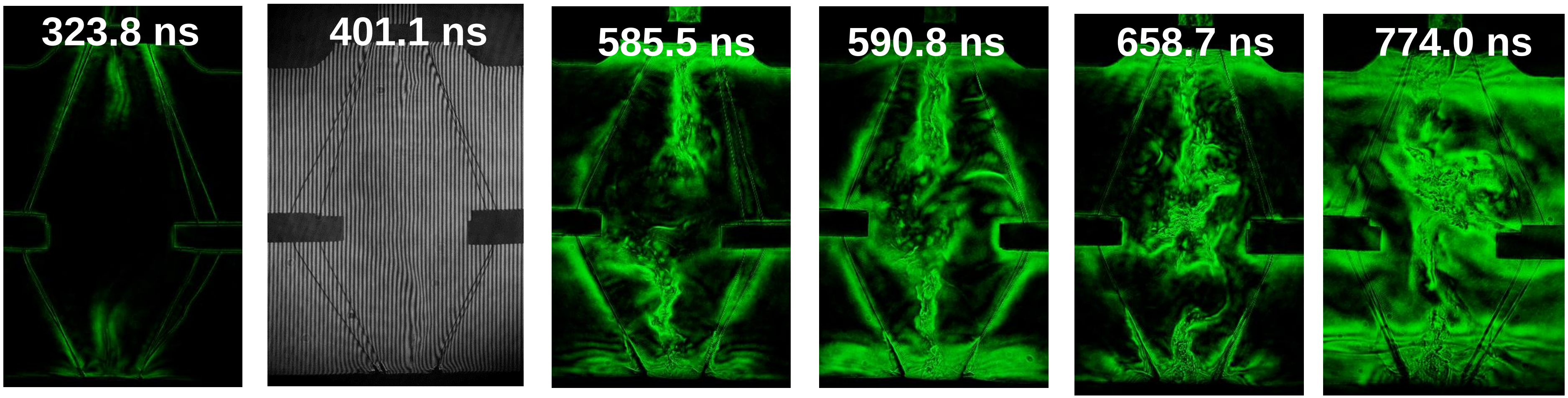


Interferometer

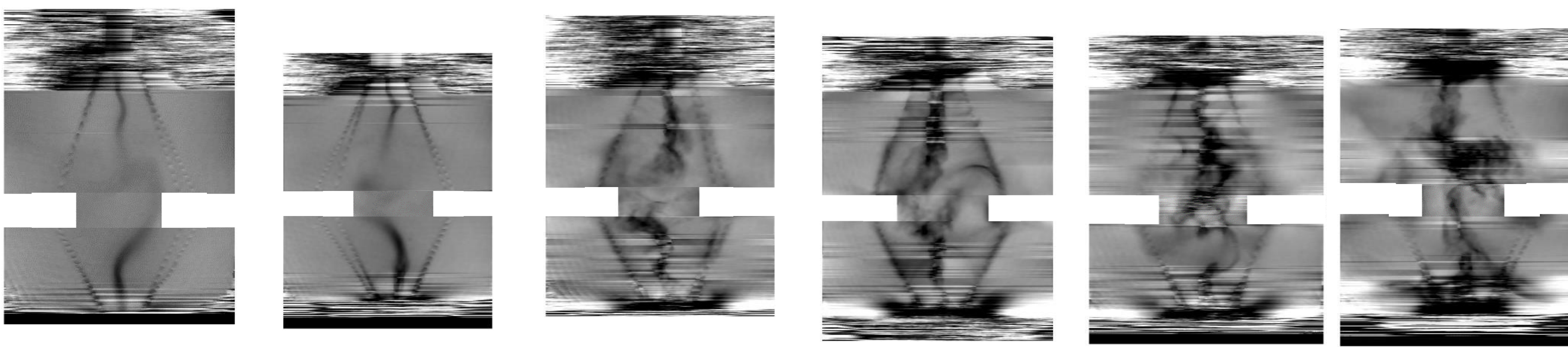


The plasma disk with a number density of ~ 10^{18} cm^{-3} was generated

Schlieren

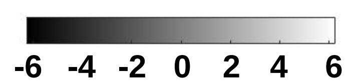


Interferometer



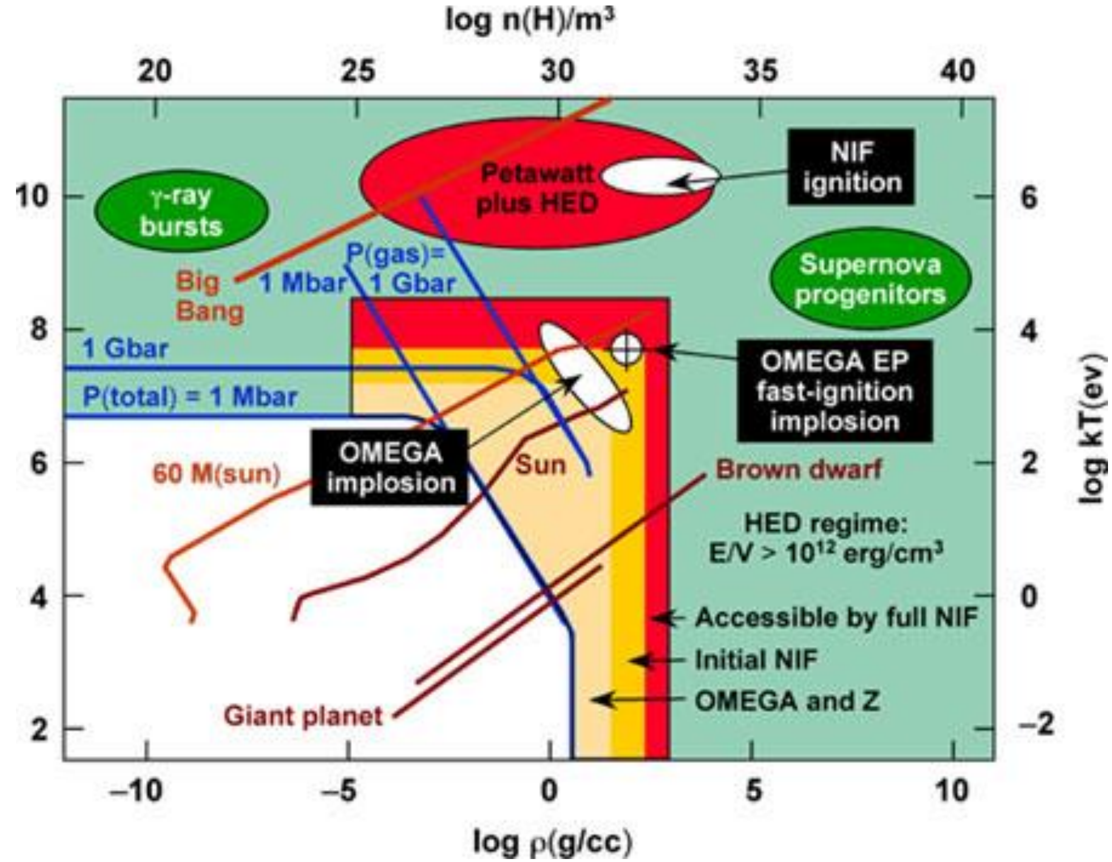
$-2\pi \sim 2\pi \Rightarrow 0 \sim 4.2 \times 10^{17}$ cm^{-2}

$\Rightarrow 8.4 \times 10^{17}$ cm^{-3} for L= 5mm



Φ(rad)

High energy density plasma (HEDP) is the regime where the pressure is greater than 1 Mbar

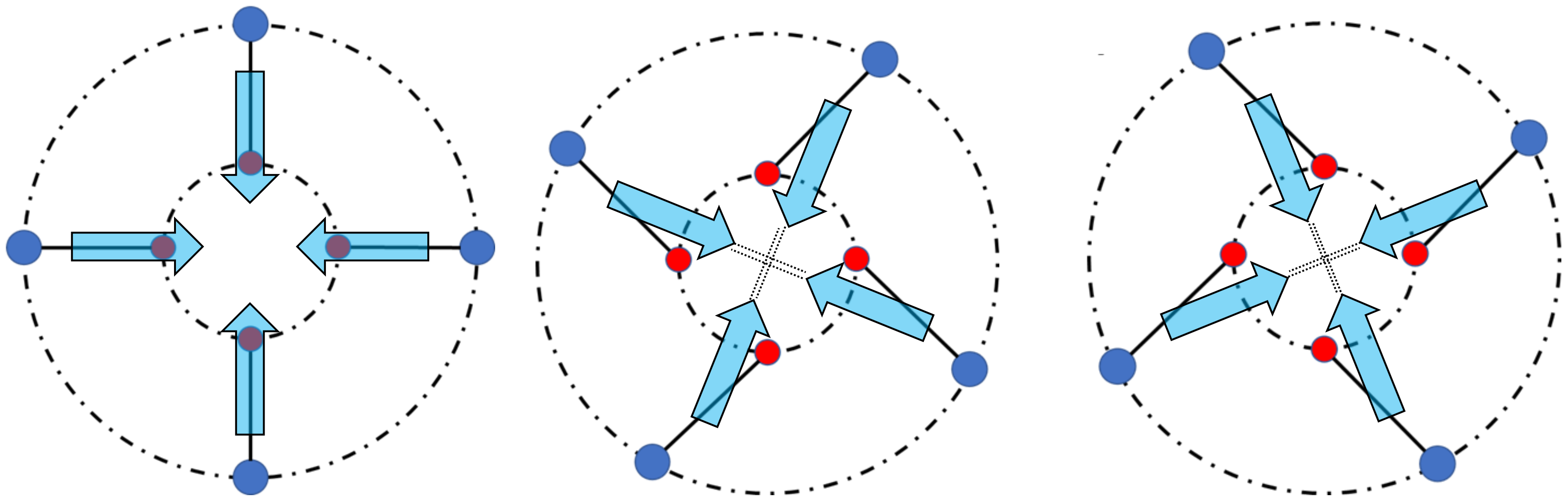


- **The energy density of HEDP regime is higher than 1 kJ of energy per 10 mm^3.**

Frontiers in High Energy Density Physics: The X-Games of Contemporary Science © (2003) by the National Academy of Sciences, courtesy of the National Academies Press, Washington, D.C.

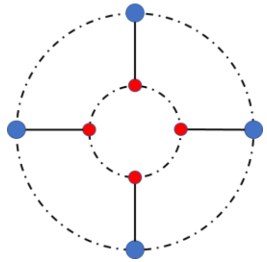
What if we twist the conical-wire array?

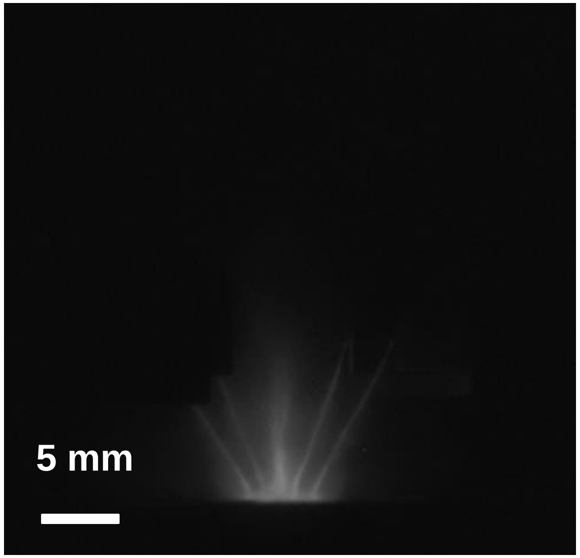
- **Non-rotation**
- **Clockwise 45°**
- **CCW 45°**

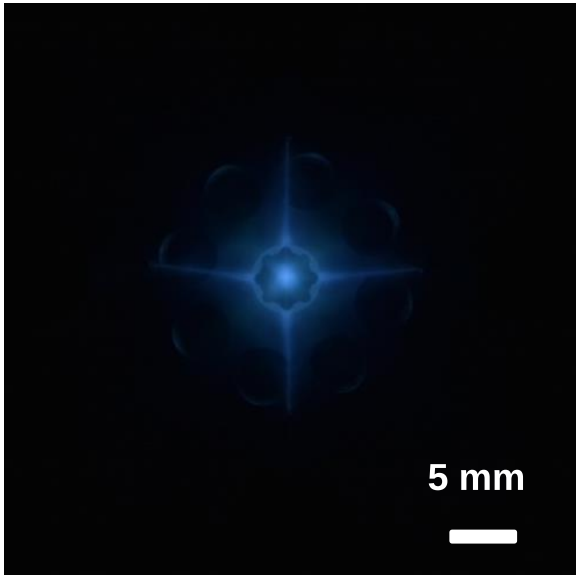


The plasma jet is a bright spot from the top view

- **Non-rotation**

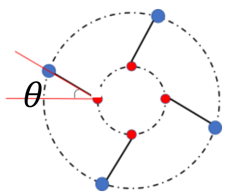


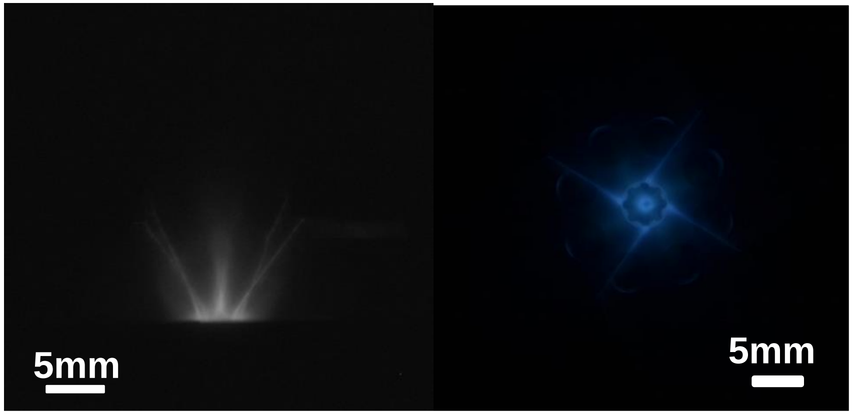




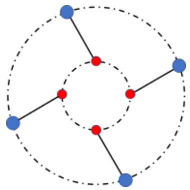
Hollow plasma jets were generated when the conical-wire arrays were twisted

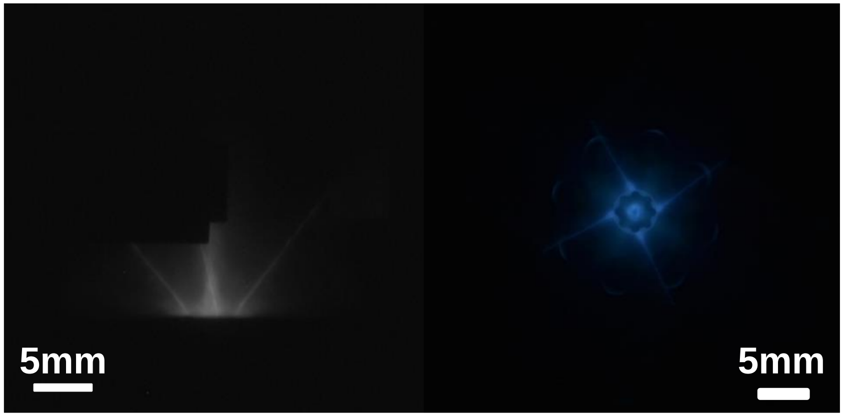
- **Clockwise 30 °**





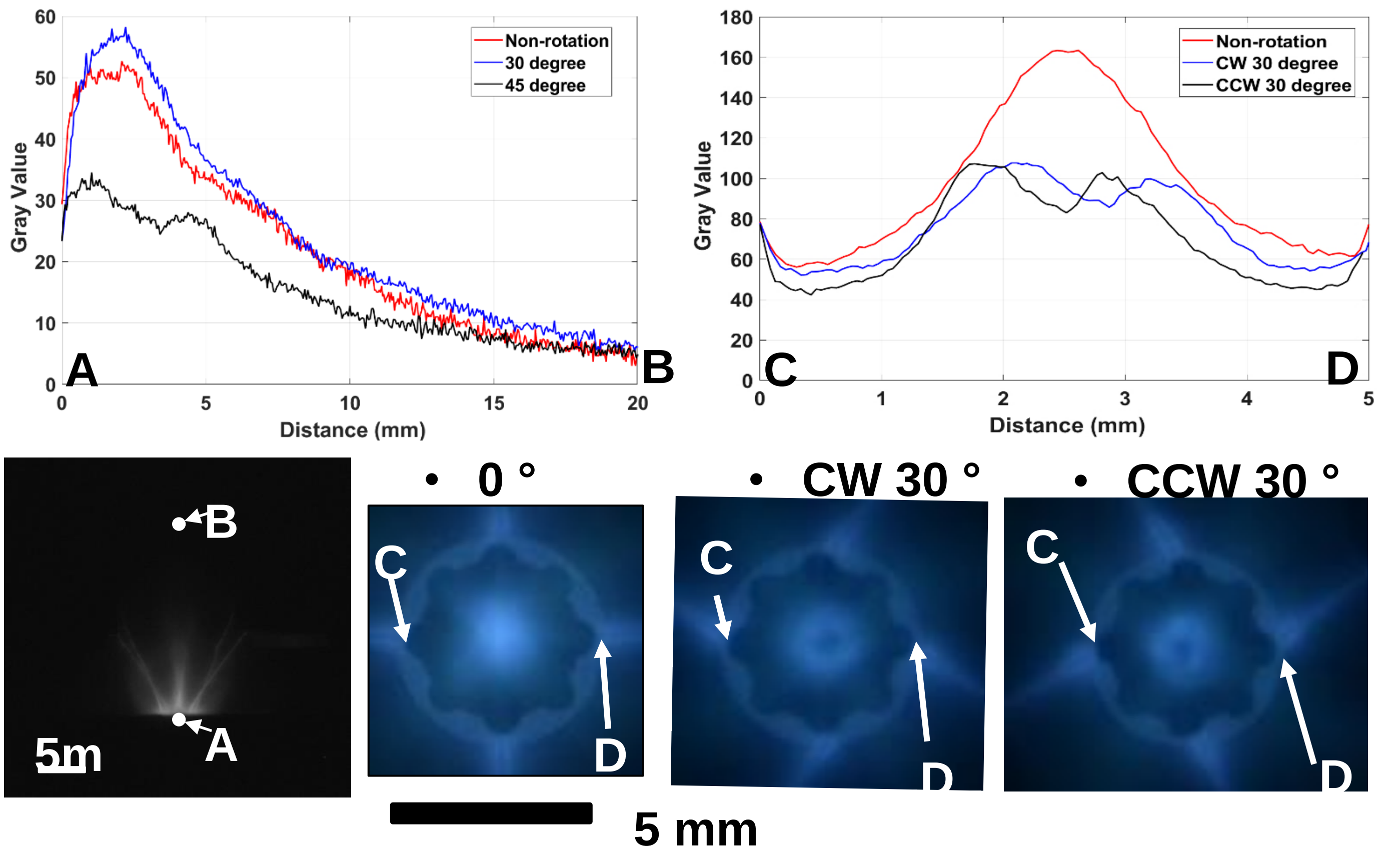
- **Counter clockwise 30 °**





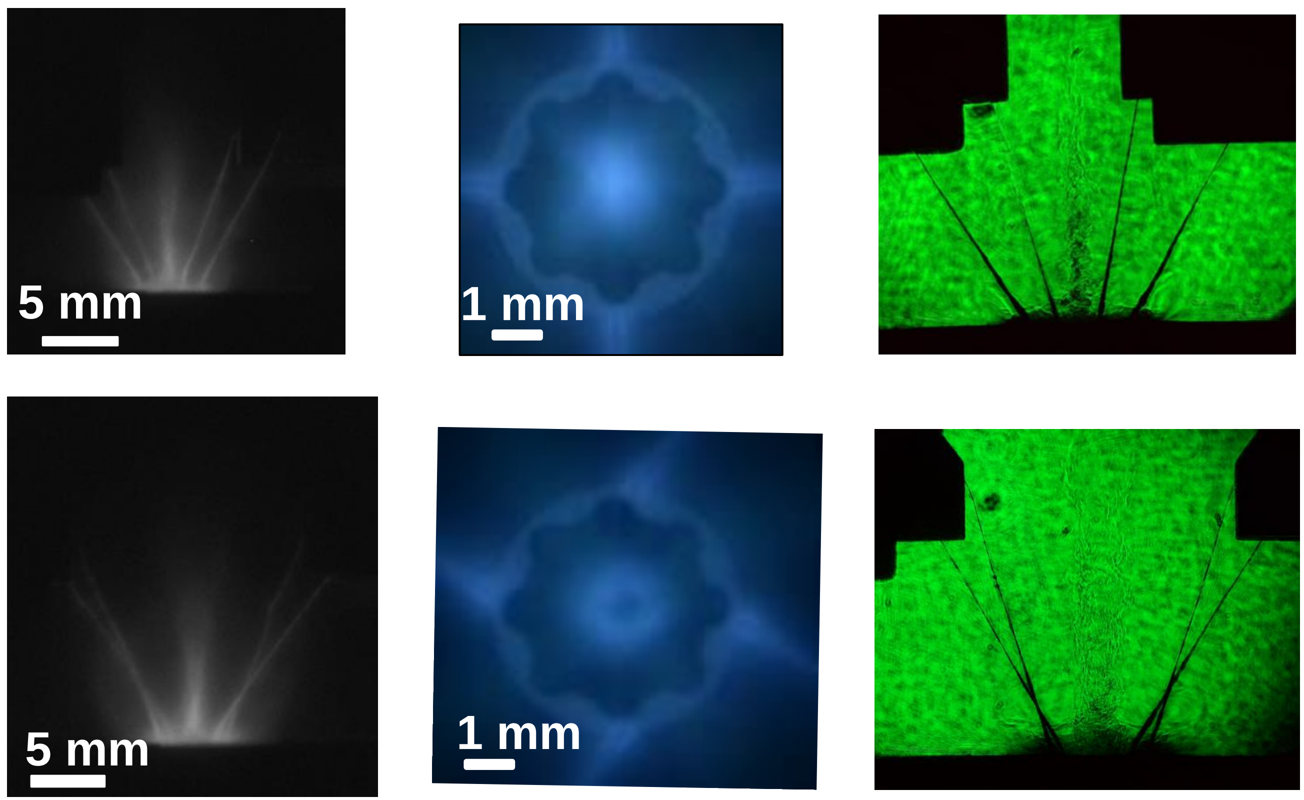
Y.-C. Lin, NCKU Master Thesis 2021

The hollow region at the center was due to angular momentum conservation of the in-coming plasma flow

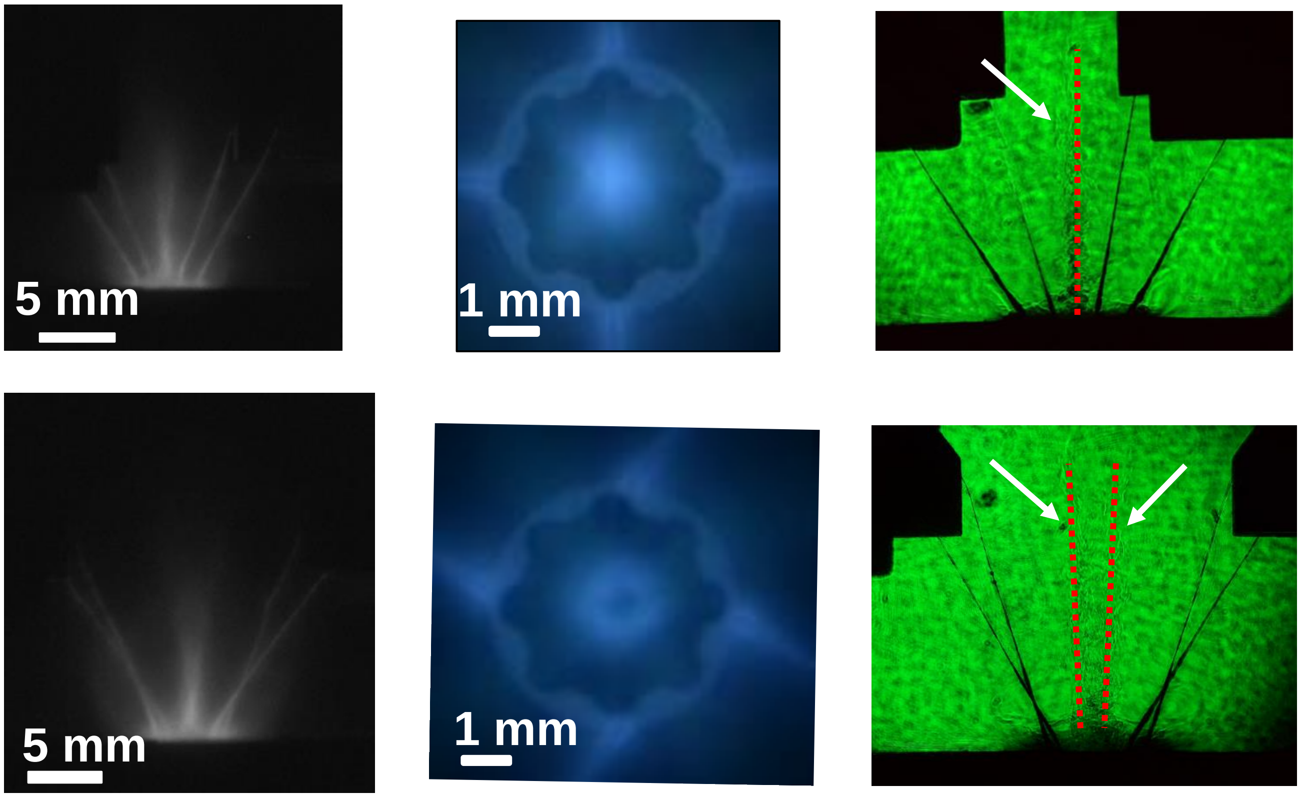


D. J. Ampleforda, et al., PRL 100, 035001 (2008)
Y.-C. Lin, NCKU Master Thesis 2021

A “tornado” is generated by the twisted conical-wire array

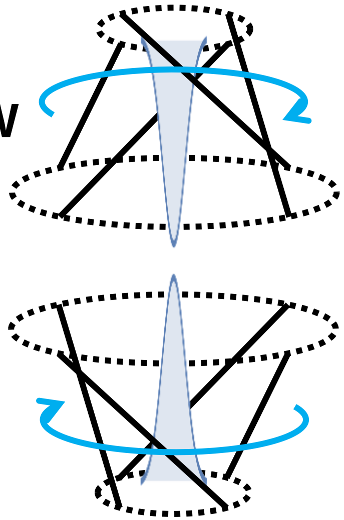


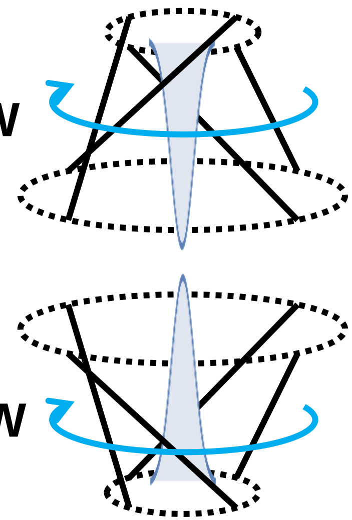
A “tornado” is generated by the twisted conical-wire array

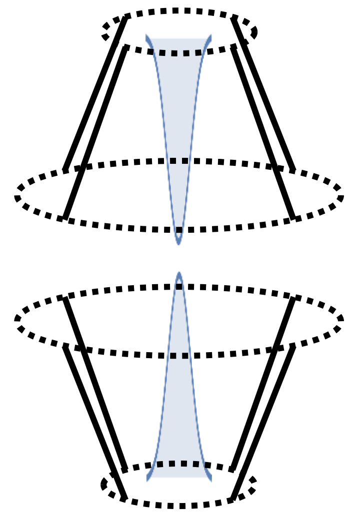


Can a rotating plasma disk be formed?
To be continue…

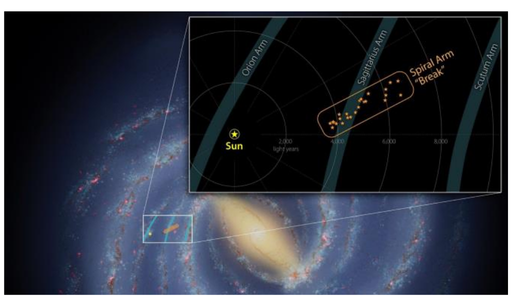
- CCW
- CW







- CW
- CW
- No rotation

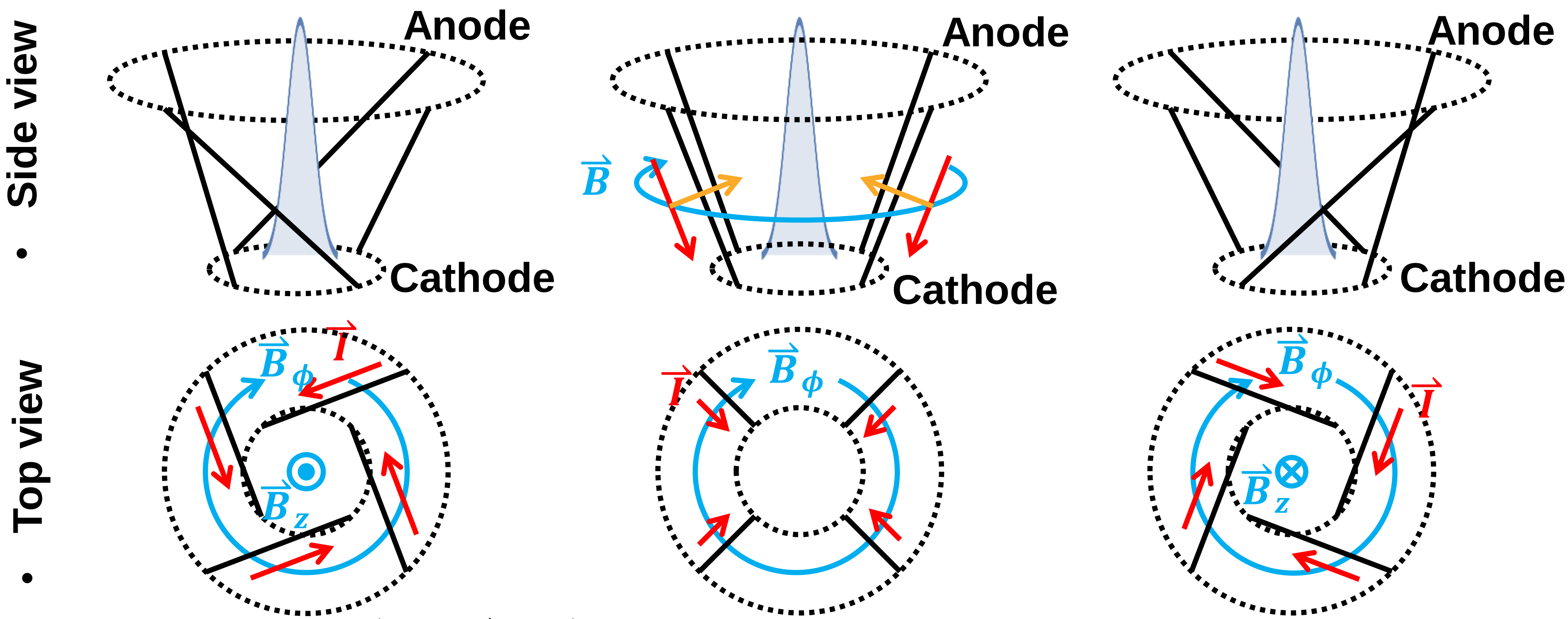


- **Astronomers Find a 'Break' in One of the Milky Way's Spiral Arms.**

https://www.nasa.gov/feature/jpl/astronomers-find-a-break-in-one-of-the-milky-way-s-spiral-arms

The rotational plasma jet produced by a twisted-conical-wire array is being studied

- Clockwise
- No rotation
- Counterclockwise



- **No rotation:** $\vec{F}_V = \vec{j} \times \vec{B} = (J_r, 0, J_z) \times (0, B_\phi, 0) = \hat{r}(-J_z B_\phi) + \hat{z}(J_r B_\phi)$
- **With rotation:** $\vec{F}_V = \vec{j} \times \vec{B} = (J_r, J_\phi, J_z) \times (B_r, B_\phi, B_z)$

$$= \hat{r}(J_\phi B_z - J_z B_\phi) + \hat{\phi}(J_z B_r - J_r B_z) + \hat{z}(J_r B_\phi - J_\phi B_z)$$

Compression Rotation

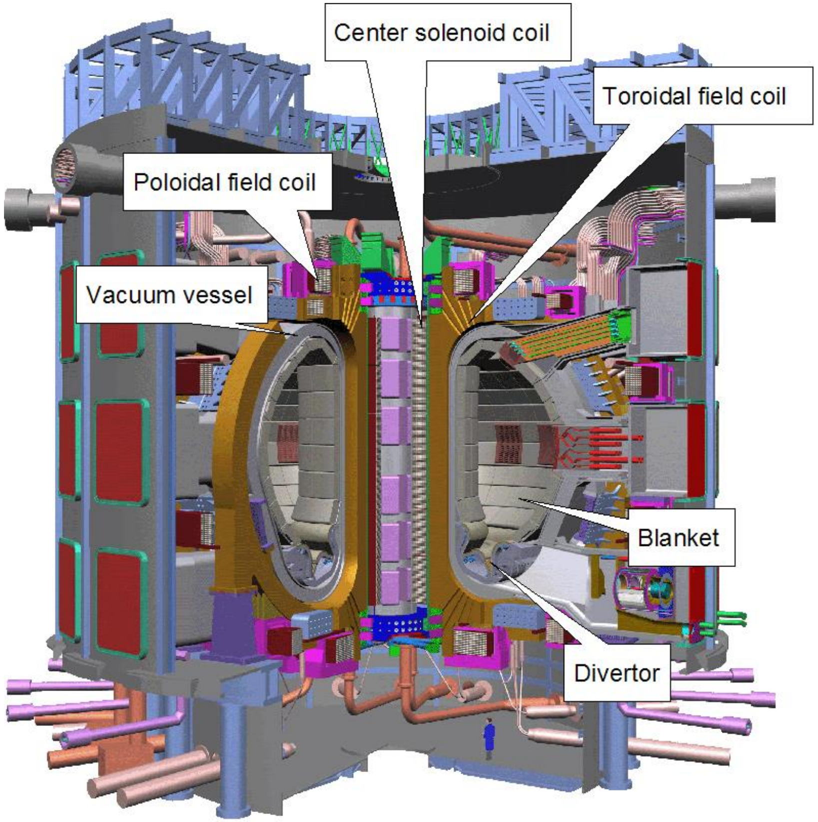
- CW: + + - - - + - + - - + +
- CCW: - - - - - - - - - - - -

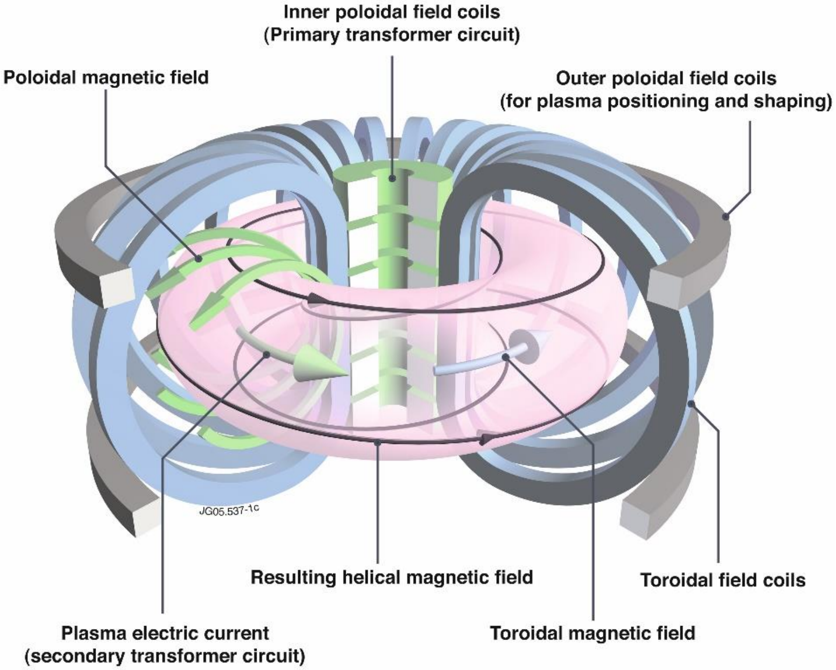
Neutral beam source

- **Neutral beam injection for heating plasma in Tokamak**
  - **Jure Maglica, Seminar at University in Ljubljana**
  - **Ian G. Brown, The Physics and Technology of Ion Sources**

- **Electric propulsion (plasma thrusters)**
  - **D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters**

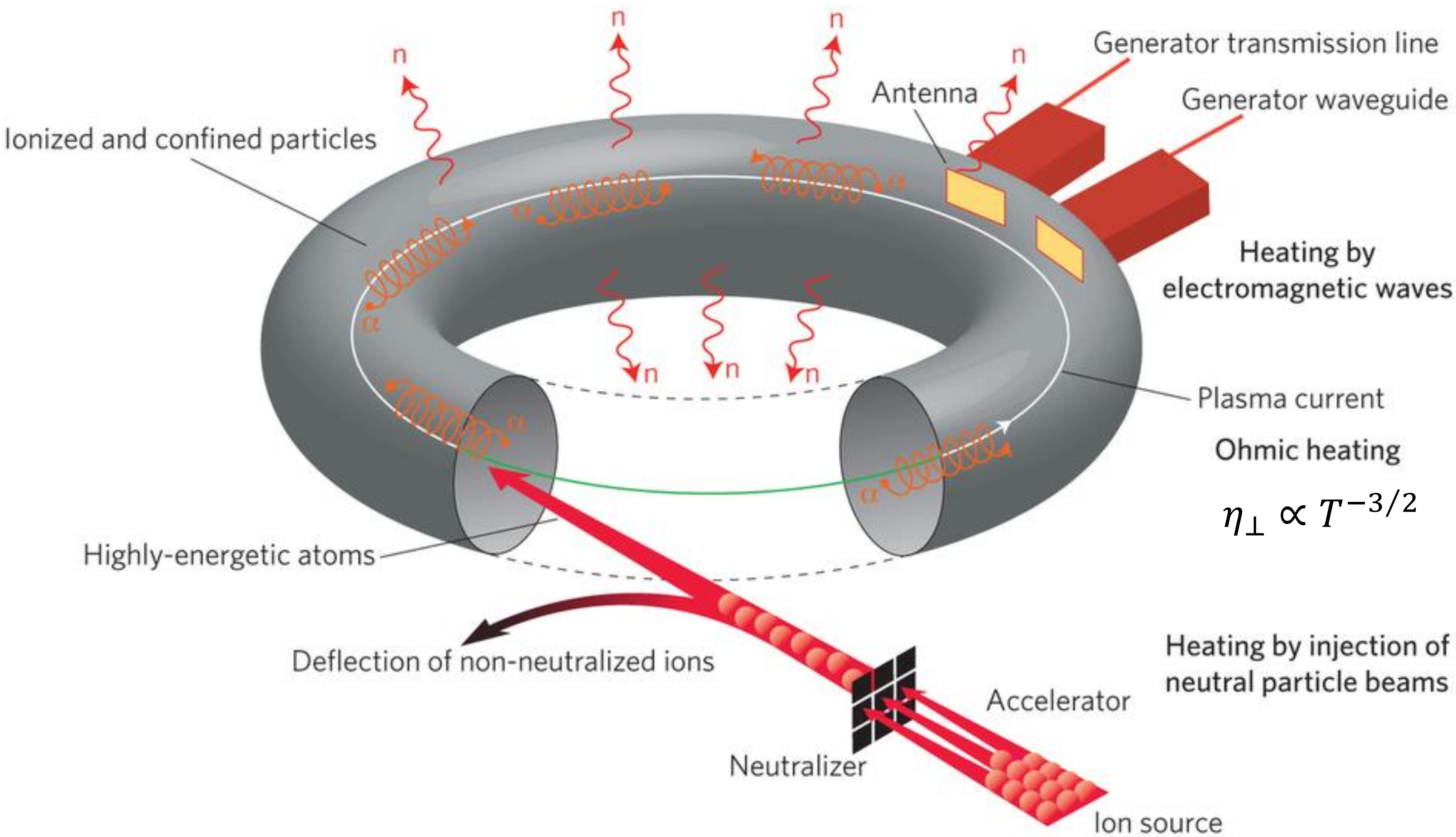
Hot plasma is confined by the magnetic field in magnetic confinement fusion





http://www.dailykos.com/story/2010/5/24/869588/-
https://www.euro-fusion.org/jet/

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



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

D. Mazon, etc., NATURE PHYSICS, 12, 14, 2016

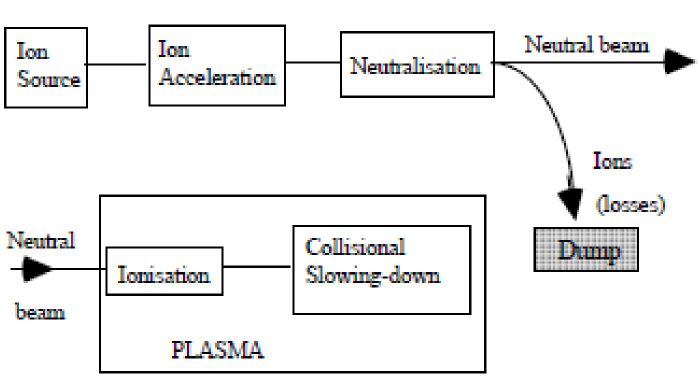
Varies way of heating a MCF device

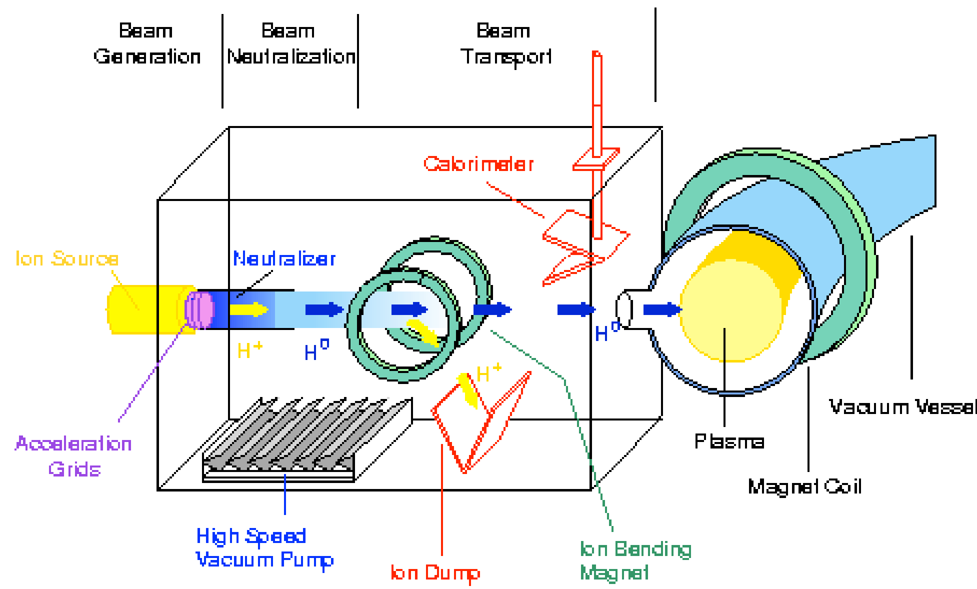
System		Frequency/ energy	Maximum power coupled to plasma	Overall system efficiency	Development/ demonstration required	Remarks
ECRF	Demonstrated in tokamaks	28–157 GHz	2.8 MW, 0.2 s	30–40%	Power sources and windows, off-axis CD	Provides off-axis CD
	ITER needs	150–170 GHz	50 MW, S S			
ICRF	Demonstrated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

'S S' indicates steady state

Nuclear Fusion, 39, 2495, 1999

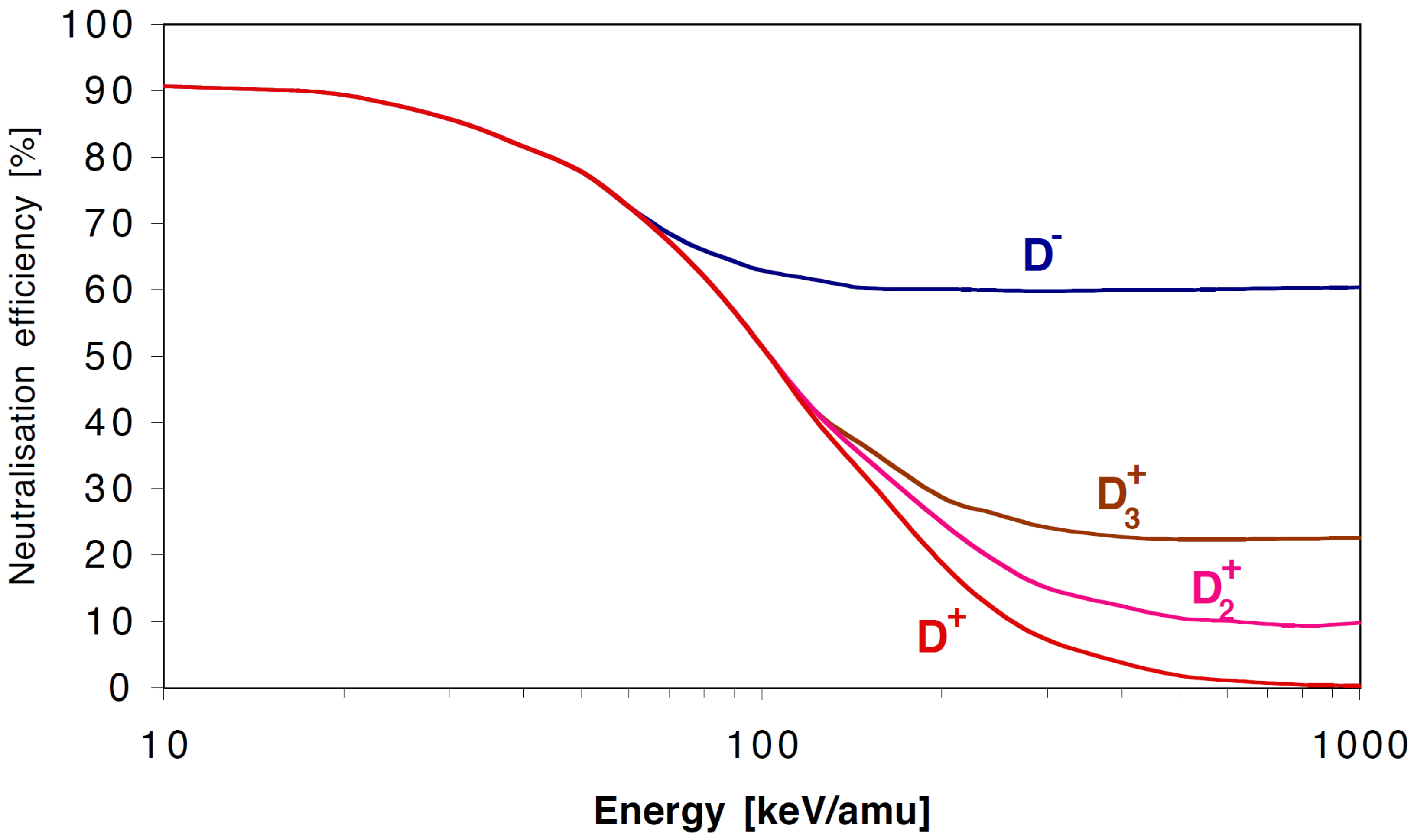
Neutral particles heat the plasma via coulomb collisions





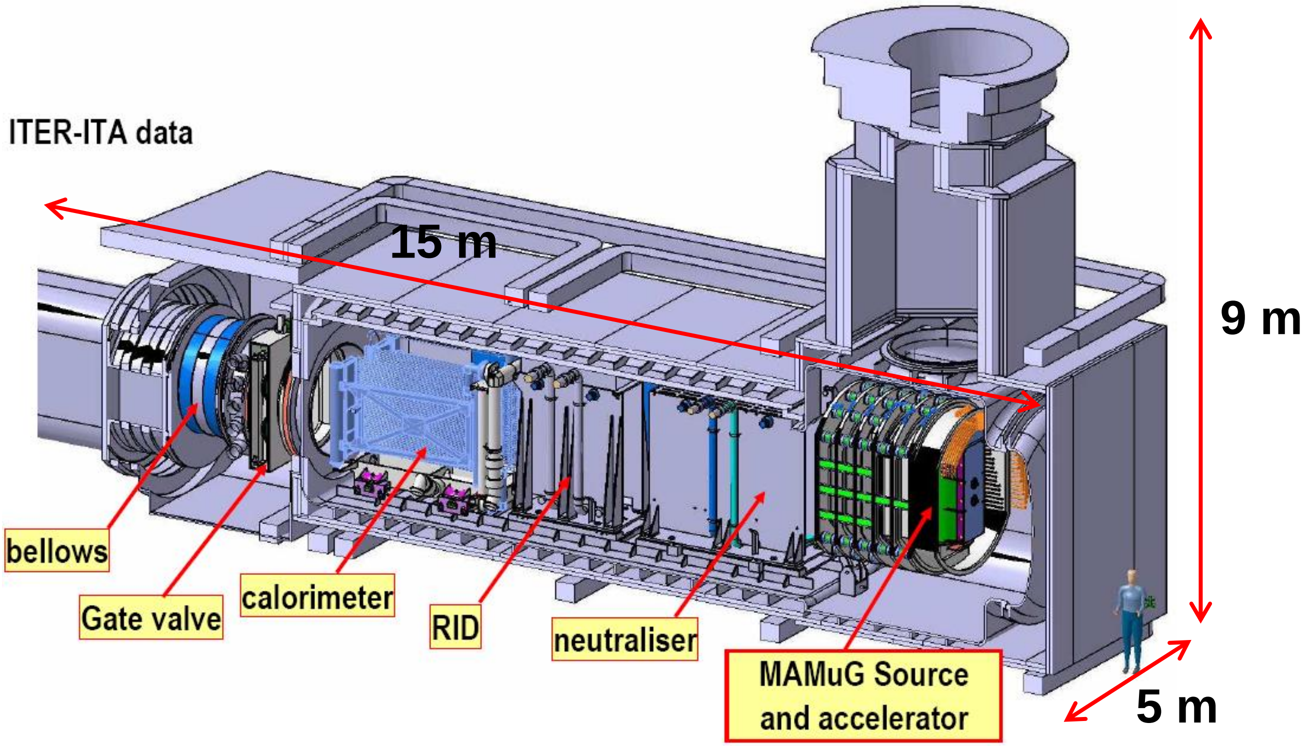
1. **create energetic (fast) neutral ions**
2. **ionize the neutral particles**
3. **heat the plasma (electrons and ions) via Coulomb collisions**

Negative ion source is preferred due to higher neutralization efficiency



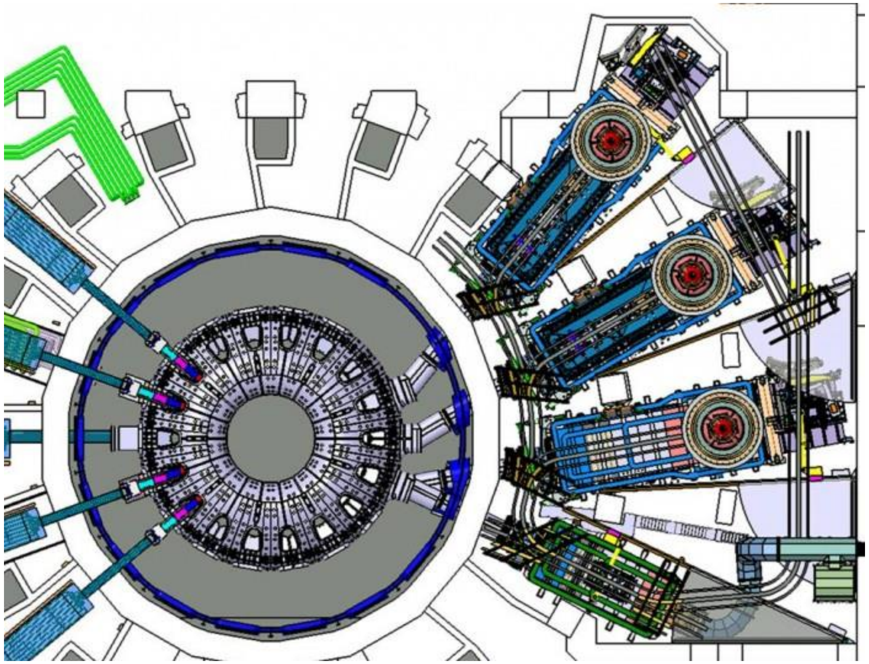
NBI for ITER

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



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

Neutral beam penetration



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

https://www.iter.org

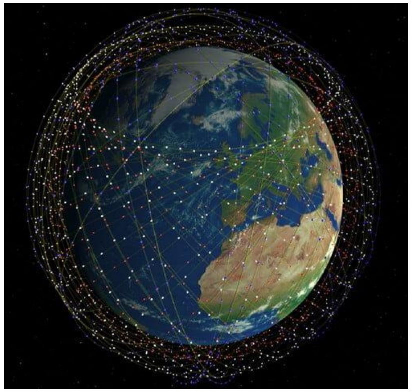
Neutral beam source

- Neutral beam injection for heating plasma in Tokamak
  - Jure Maglica, Seminar at University in Ljubljana
  - Ian G. Brown, The Physics and Technology of Ion Sources

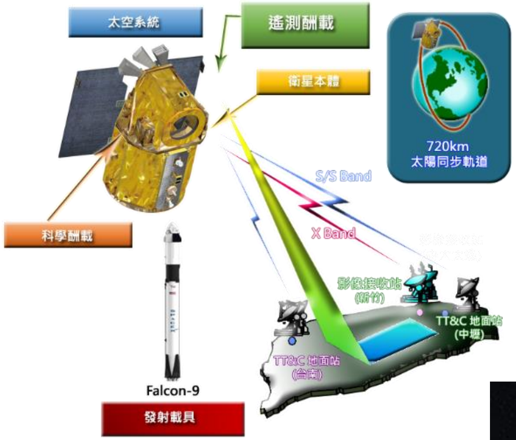
- **Electric propulsion (plasma thrusters)**
  - **D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters**

Satellites are widely used in our daily life

- **SpaceX's Starlink – 12,000 satellites**

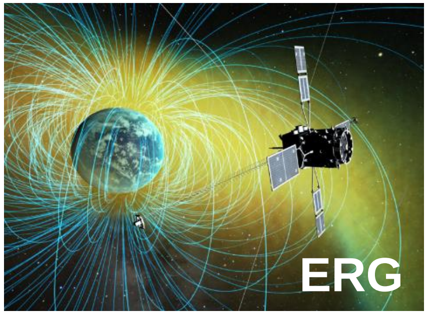


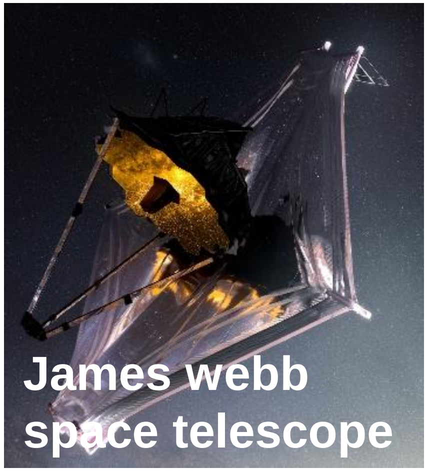
- **Foromsa 5 – Optical remote sensing**



- **GPS signal**

- **Science**



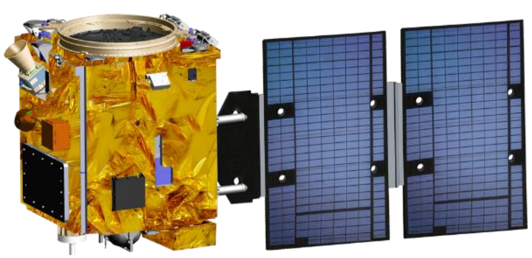


https://phys.org/news/2019-05-starlink-satellites-orbiting-altitude-space.html
https://www.nspo.narl.org.tw/inprogress.php?c=20021501
https://www.theengineeringcommunity.org/satellite-positioning-gps-advantages-and-disadvantages-for-site-engineers/
https://en.wikipedia.org/wiki/Arase_%28satellite%29
https://www.nasa.gov/feature/goddard/2022/first-images-from-nasa-s-webb-space-telescope-coming-soon

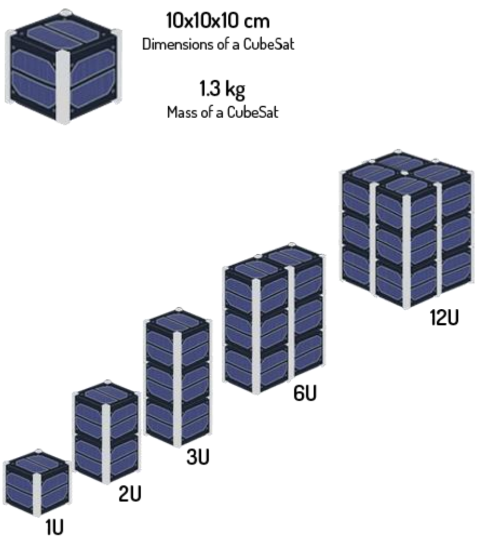
Satellites are classified by their weights and sizes

Mass	Classification
≥ 1000 kg	Large satellite
500 ~ 1000 kg	Medium satellite
≤ 500 kg	Small satellite
100 ~ 500 kg	Mini satellite
10 ~ 100 kg	Micro satellite
1 ~ 10 kg	Nano satellite
0.1 ~ 1 kg	Pico satellite
≤ 0.1 kg	Femto satellite

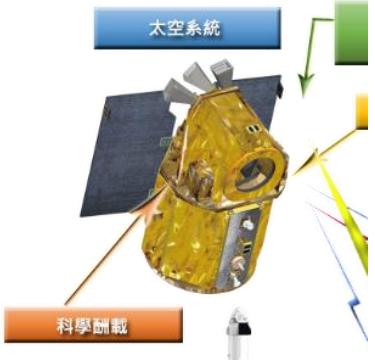
- Triton: 300 kg



- CubeSat

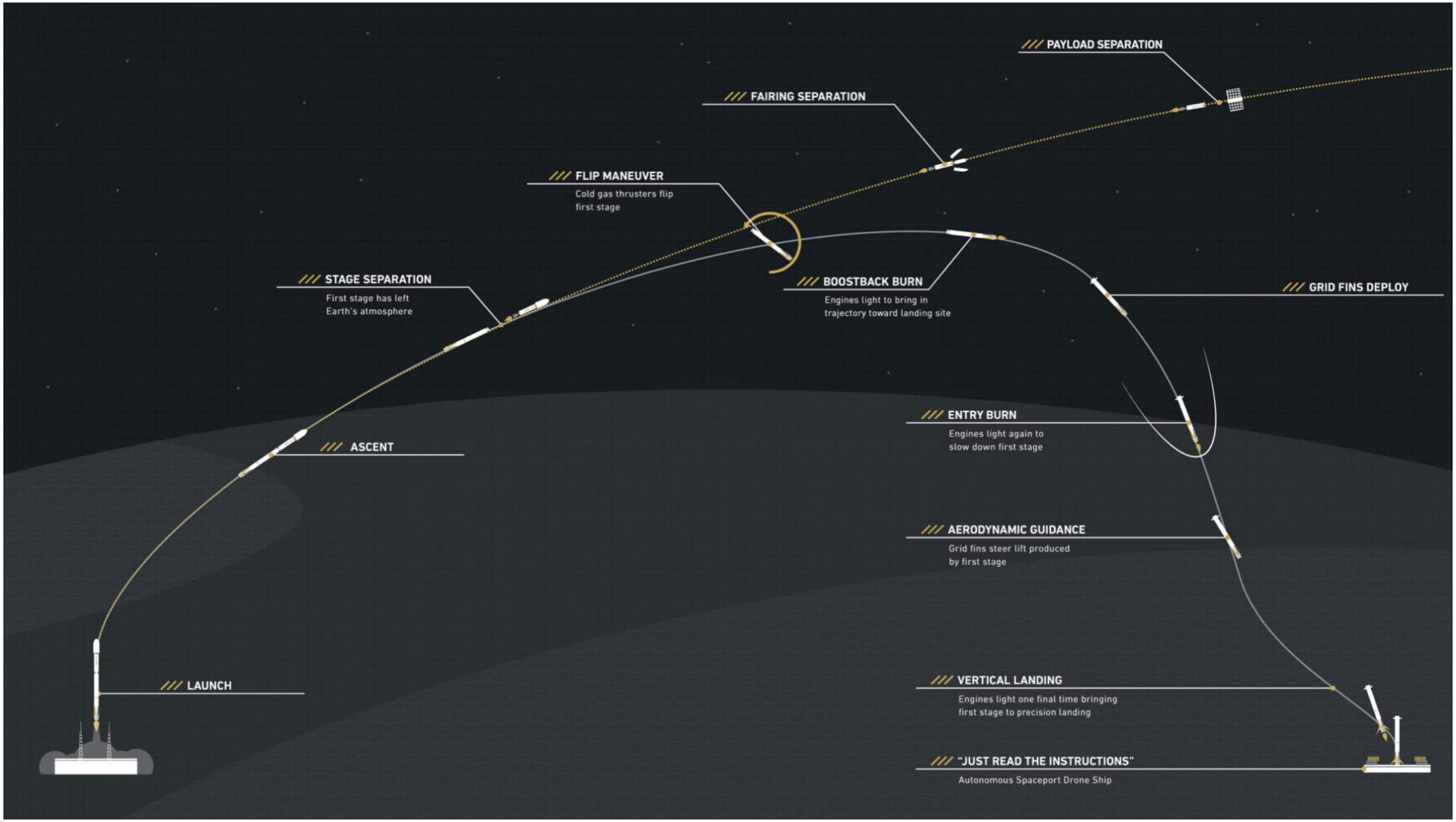


- Formosa 5: 450 kg



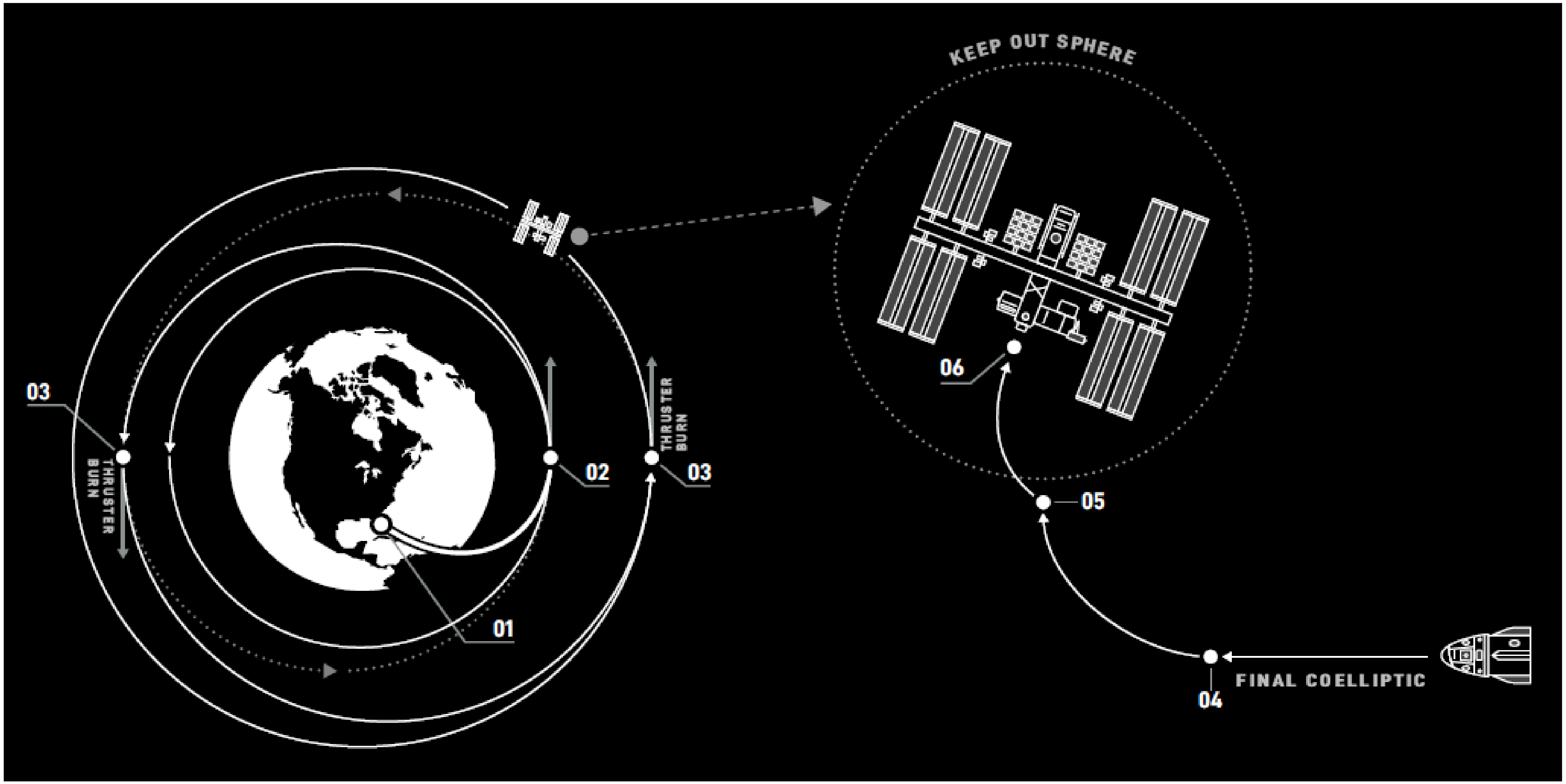
https://www.nspo.narl.org.tw/index.php?ln=zh_TW
https://alen.space/basic-guide-nanosatellites/

A rocket is used to deploy a satellite to orbit



Falcon user's guide, Sep. 2021

SpaceX Dragon reaches the international space station with several steps



https://www.space.com/spacex-demo-2-astronaut-launch-delay-explained.html (Image credit: SpaceX)

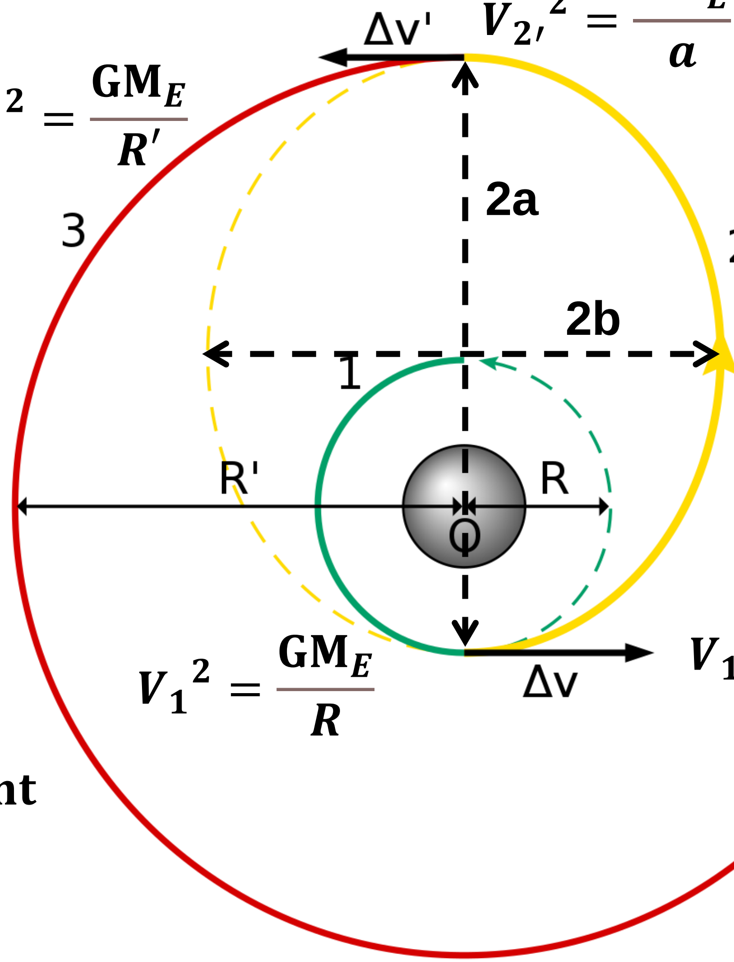
Hohmann orbit transformation uses two impulses to transfer the vehicle between two circular orbits with different altitudes

$$F = m\frac{V^2}{r} = \frac{\mathrm{GMm}}{r^2}$$

$$V^2 = \frac{\mathrm{GM}}{r}$$

$$V_{2'}{}^2 = \frac{\mathrm{GM}_E}{a}\left(\frac{b}{R'}\right)^2 < V_3{}^2$$

$$V_3{}^2 = \frac{\mathrm{GM}_E}{R'}$$



$$V_1{}^2 = \frac{\mathrm{GM}_E}{R}$$

$$V_{1'}{}^2 = \frac{\mathrm{GM}_E}{a}\left(\frac{b}{R}\right)^2 > V_1{}^2$$

- **Energy conservation:**

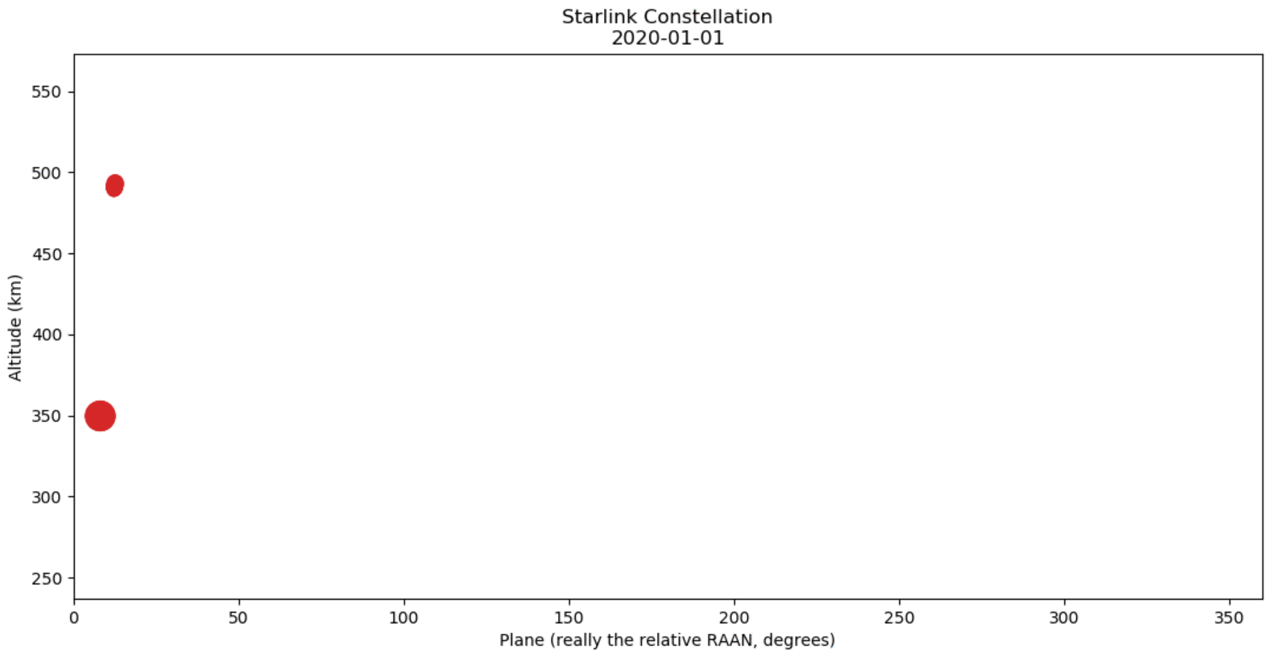
$$\frac{1}{2}mV^2 - \frac{GMm}{\mathrm{r}} = \mathrm{constant}$$

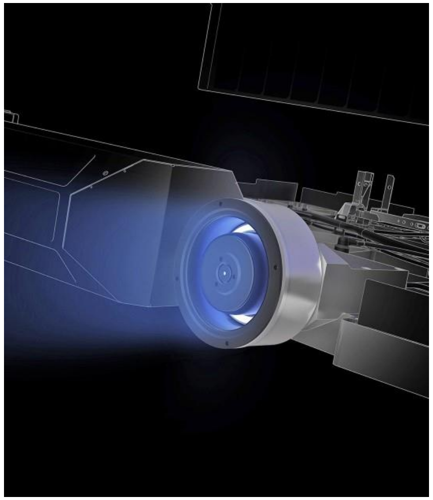
- **Angular momentum conservation:**

$$mV_{1'}R = \mathrm{mV_2}R'$$

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

Satellites are slowly deployed for Starlink constellation

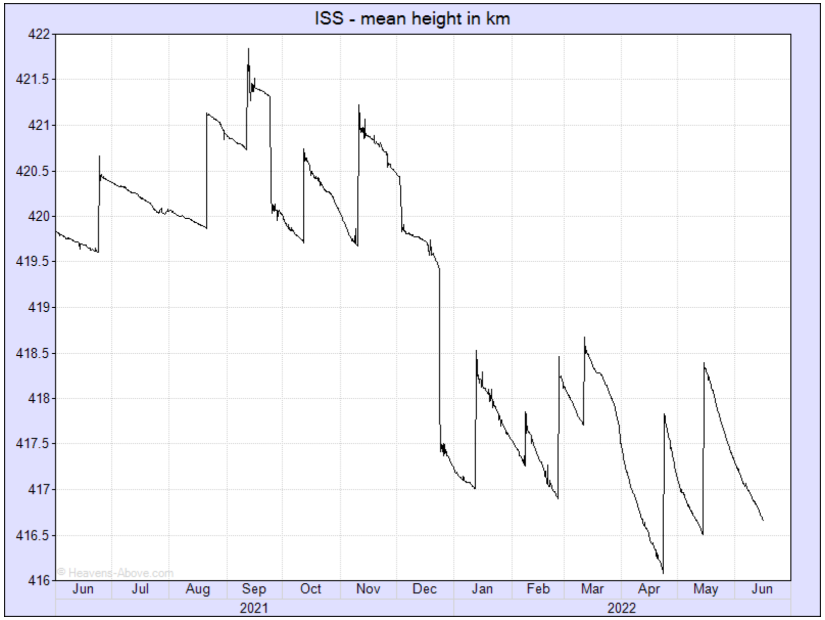




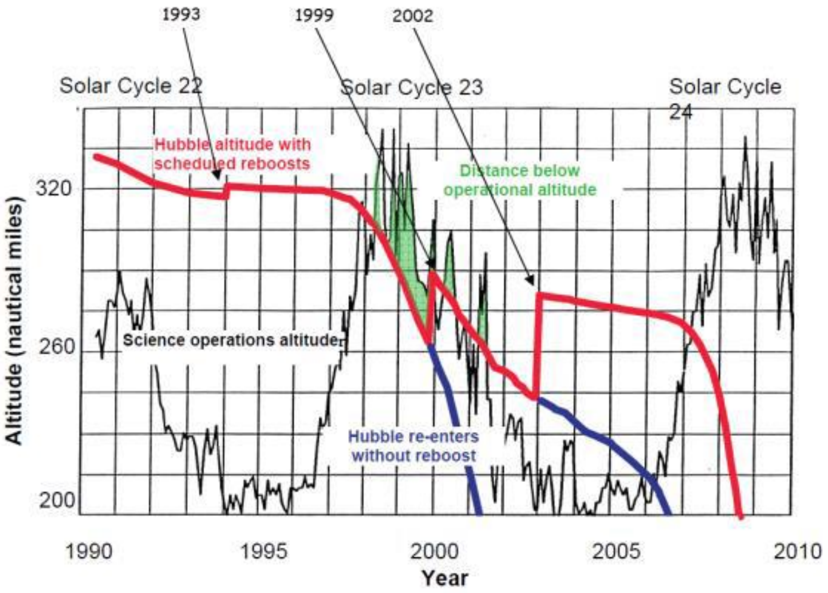
https://www.nasaspaceflight.com/2020/06/evaluating-spacexs-starlink-push/
https://www.space.com/spacex-starlink-satellites.html
https://metro.co.uk/2020/04/24/starlink-satellites-work-12604227/

Satellite may encounter air drag so that reboost is needed to remain the altitude

- **Altitude of the international space station**



- **Altitude of the Hubble telescope**

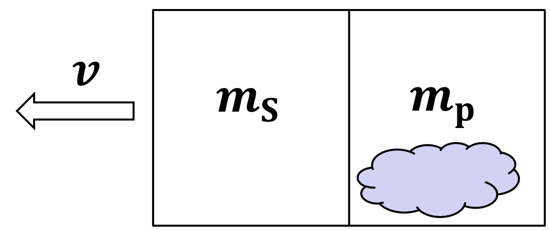


https://www.heavens-above.com/IssHeight.aspx
V. Nwankwo and S. Chakrabarti, Trans. JSASS Aero. Tech. Japan 12, 47 (2014)

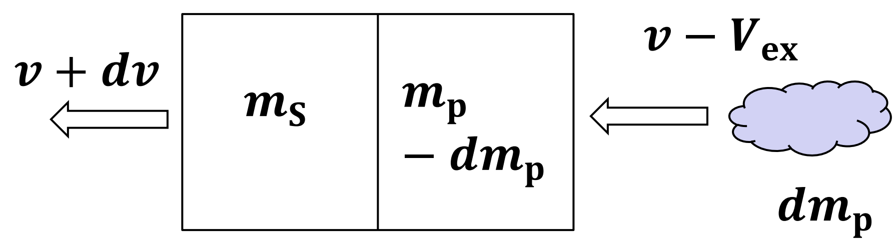
Trajectories including the gravitational force needs to be solved numerically

- **Force on exhaust propellant from the thruster**

$$F = \frac{d(mv)}{dt} = \frac{dm_{\mathrm{p}}(v - v_{\mathrm{ex}}) - dm_{\mathrm{p}}v}{dt}$$
$$= v_{\mathrm{ex}}\frac{dm_{\mathrm{p}}}{dt} = -v_{\mathrm{ex}}\dot{M}_{\mathrm{p}}$$



- **Force on the vehicle**



$$F = T - F_g = \dot{M}_{\mathrm{p}}V_{\mathrm{ex}} - \frac{GM_{\mathrm{E}}m}{r^2}$$

$$\frac{d(mv)}{dt} = \dot{M}_{\mathrm{p}}V_{\mathrm{ex}} - \frac{GM_{\mathrm{E}}m}{(x + r_{\mathrm{E}})^2}$$

$$m\frac{dv}{dt} + \frac{dm}{dt}v = \dot{M}_{\mathrm{p}}V_{\mathrm{ex}} - \frac{GM_{\mathrm{E}}m}{(x + r_{\mathrm{E}})^2}$$

$$\begin{cases} m\dfrac{d^2x}{dt^2} - \dot{M}_{\mathrm{p}}\dfrac{dx}{dt} + \dfrac{GM_{\mathrm{E}}m}{(x + r_{\mathrm{E}})^2} = \dot{M}_{\mathrm{p}}V_{\mathrm{ex}} \\ m = M_{\mathrm{sat}} + M_P = \left(M_{\mathrm{sat}} + M_{\mathrm{p0}}\right) - \dot{M}_p t \end{cases}$$

The final velocity of a vehicle in gravitational-free space is proportional to the exhaust velocity of the propolant

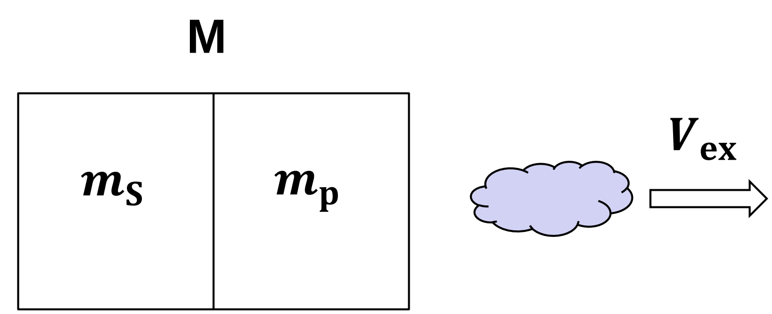
$$\boldsymbol{p(t) = p(t + \mathrm{dt})}$$

$$\boldsymbol{Mv = \left(M - dm_{\mathrm{p}}\right)(v + dv) + dm_{\mathrm{p}}(v - V_{\mathrm{ex}})}$$

$$\boldsymbol{\cancel{Mv} = \cancel{Mv} + Mdv - \cancel{dm_p v} - dm_p dv + \cancel{dm_p v} - dm_p V_{\mathrm{ex}}}$$

$$\boldsymbol{dv \sim -V_{\mathrm{ex}} \frac{dM}{M}} \quad \textbf{where } \boldsymbol{dm_{\mathrm{p}} dv} \textbf{ is neglected and } \boldsymbol{dm_{\mathrm{p}} = -dM}$$

$$\int_{v_i}^{v_f} dv = -V_{\mathrm{ex}} \int_{m_d + m_p}^{m_d} \frac{dM}{M}$$



Specific impulse: $\boldsymbol{\mathrm{Isp} \equiv \frac{V_{\mathrm{ex}}}{g}}$

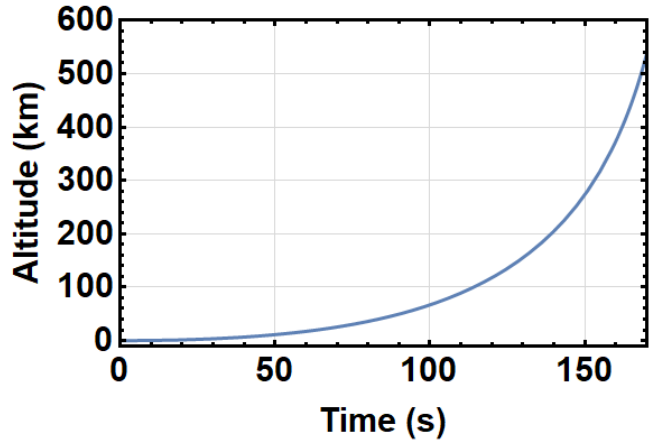
$$\boldsymbol{\Delta \mathrm{v} = (\mathrm{Isp} \times g) \ln \left(\frac{m_S + m_{\mathrm{p}}}{m_S} \right)}$$

$$\boldsymbol{m_{\mathrm{p}} = m_S\left[e^{\Delta \mathrm{v}/v_{\mathrm{ex}}} - 1\right]}$$
$$\boldsymbol{= m_S\left[e^{\Delta \mathrm{v}/(\mathrm{Isp} \times g)} - 1\right]}$$

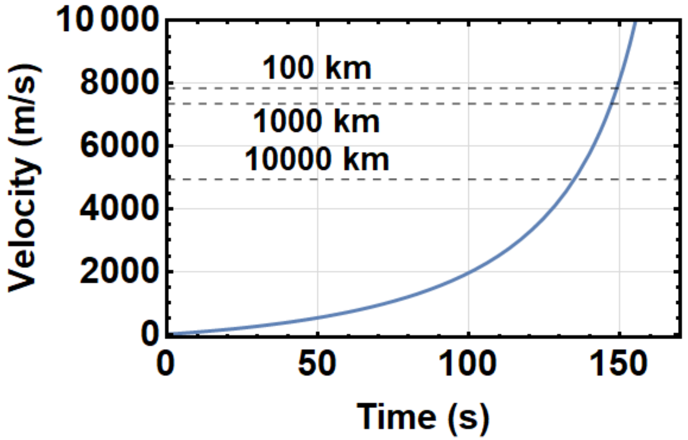
- **Specific impulse represents how efficient a thruster is.**

A thrust larger than gravitational force is needed to bring the vehicle to the space

- **Assumptions:**
  - **Only vertical motion**
  - **No air resistance**



- **Rocket (similar to Falcon 9*):**
  - M_{Sat} **= 1000 kg**
  - V_{ex} **= 3000 m/s (Isp = 306 sec)**
  - M_{p} **= 5 x 10^5 kg**
  - $\dot{M}_{\mathrm{p}}$ **= 2700 kg/s**

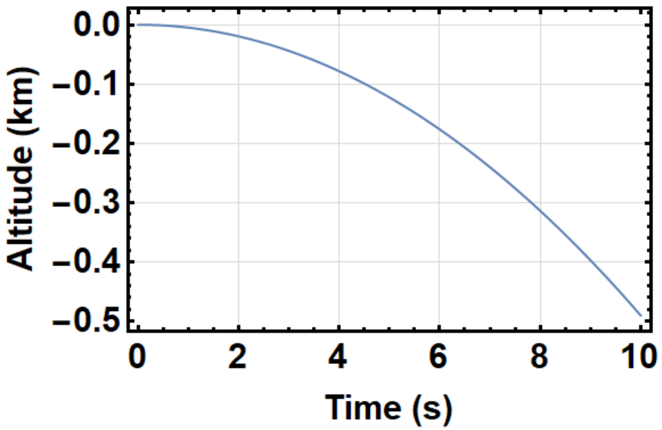


*https://en.wikipedia.org/wiki/Falcon_9#cite_note-falcon9-v1.1-si-14

A thrust larger than gravitational force is needed to bring the vehicle to the space

- **Assumptions:**
  - **Only vertical motion**
  - **No air resistance**

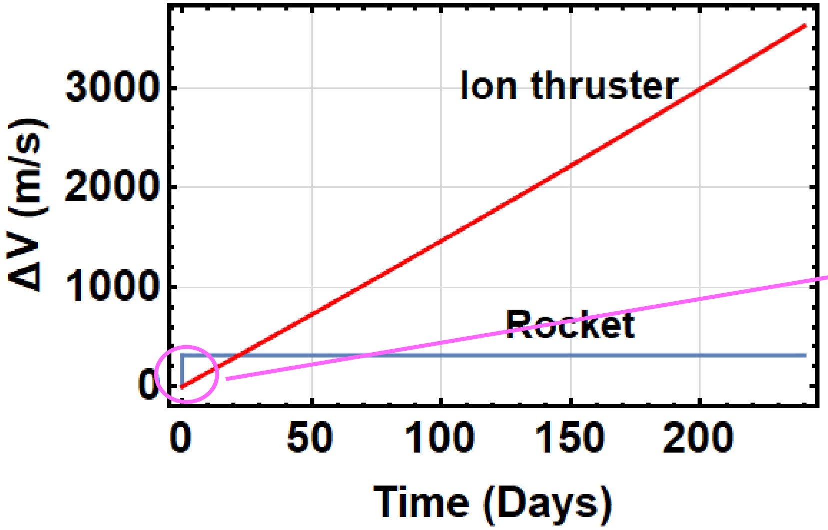
- **Electrical propulsion (similar to 500 25-cm XIPS*):**
  - M_{Sat} **= 1000 kg**
  - V_{ex} **= 34790 m/s (Isp = 3550 sec)**
  - M_{p} **= 5 x 10^5 kg**
  - $\dot{M}_{\mathrm{p}}$ **= 2.4 x 10^{-3} kg/s**

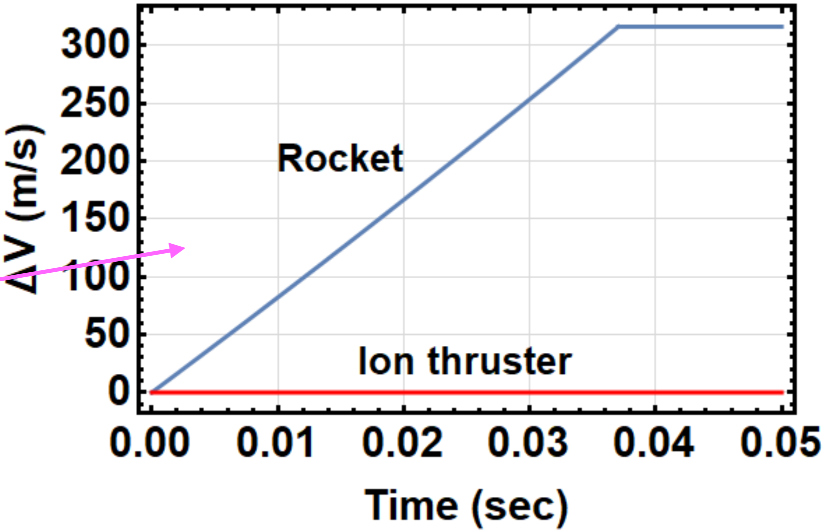


*Dan M. Geobel and I. Katz, Fundamentals of electric propulsion – ion and hall thrusters

An ion thruster provides much higher Δv than that provided by a rocket

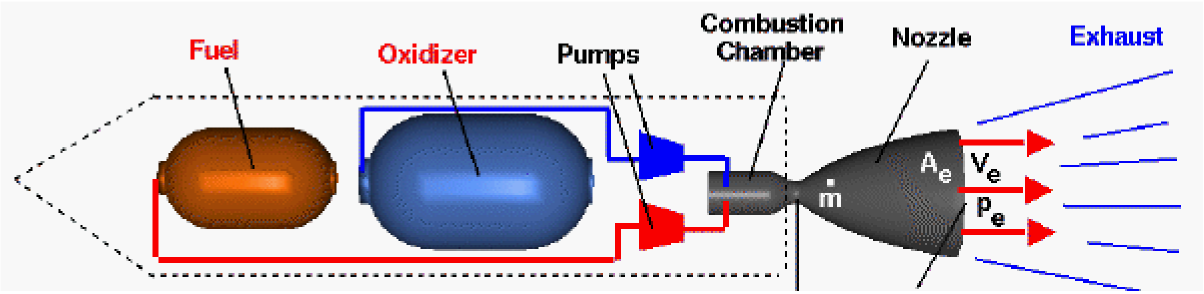
- Rocket (similar to Falcon 9*):
  - M_{Sat} = 900 kg
  - V_{ex} = 3000 m/s (Isp = 306 sec)
  - M_{p} = 100 kg
  - $\dot{M}_{\mathrm{p}}$ = 2700 kg/s
  - T_{total} = 37 ms
- Electrical propulsion (similar to 25-cm XIPS*):
  - M_{Sat} = 900 kg
  - V_{ex} = 34790 m/s (Isp = 3550 sec)
  - M_{p} = 100 kg
  - $\dot{M}_{\mathrm{p}}$ = 4.77 x 10^{-6} kg/s
  - T_{total} = 246 days



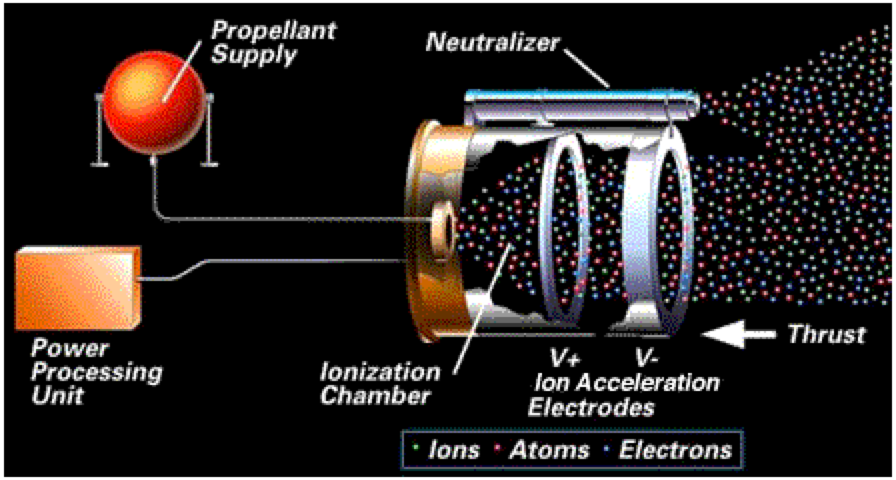


Comparison between liquid rockets and ion thrusters

- **Liquid rockests**
  - **u~4500 m/s**
  - **Isp~450 s**
  - **Energy ~ 100GJ**
  - **Power ~ 300MW**
  - **Thrust ~ 2x10^6 N**

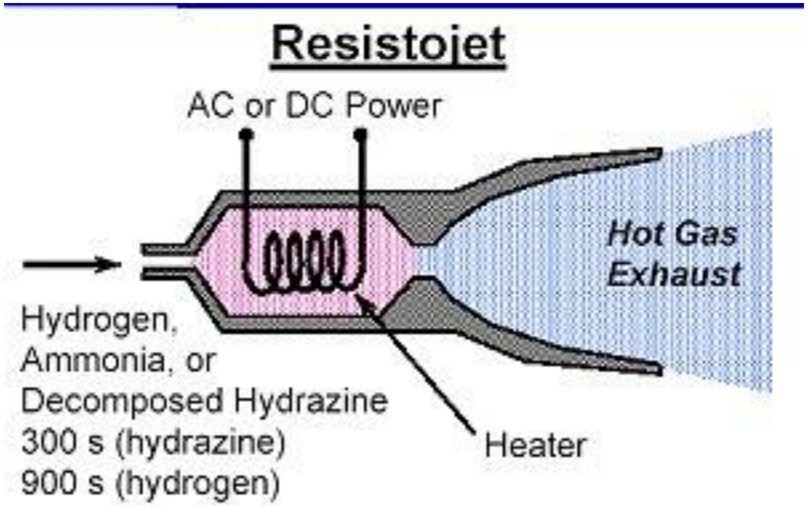


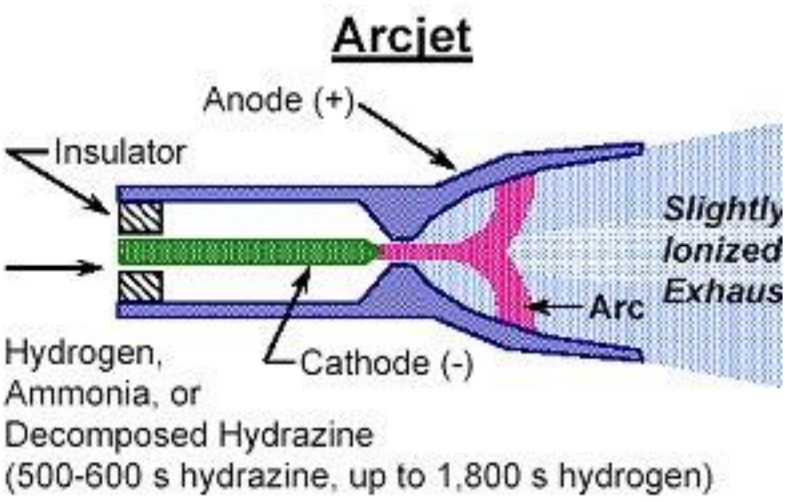
- **Ion thrusters**
  - **u~30000 m/s**
  - **Isp~3000 s**
  - **Energy ~ 1000GJ**
  - **Power ~ 1kW**
  - **Thrust ~ 0.1 N**



Electric thruster types - electrothermal

- **Resistojet**
- **Arcjet**

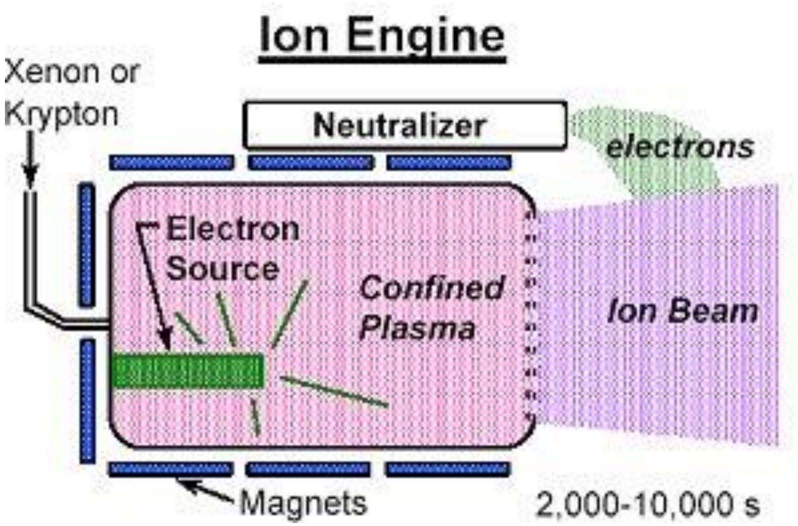


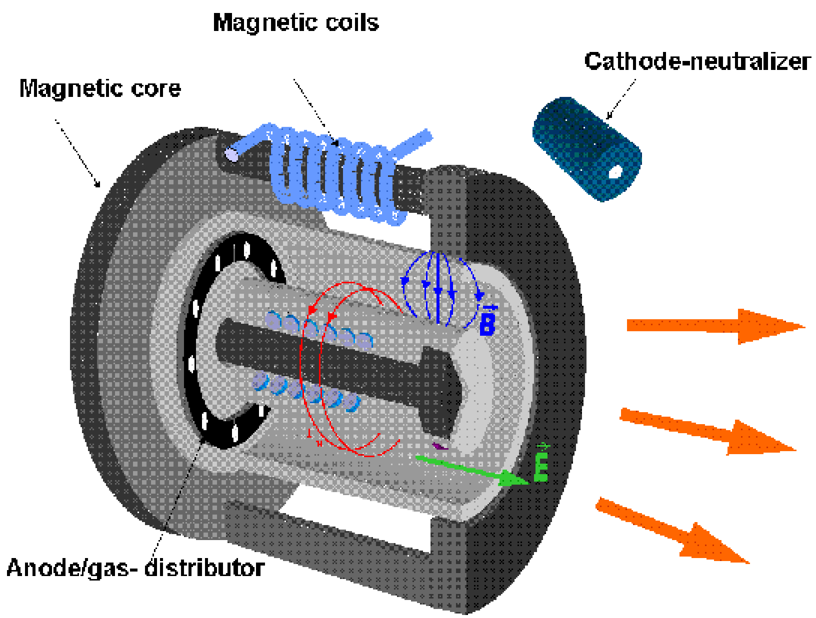


http://pages.erau.edu/~ericksol/courses/sp300/ch5/propul_ch5.html

Electric thruster types - electrostatic

- Ion thruster
- Hall thruster

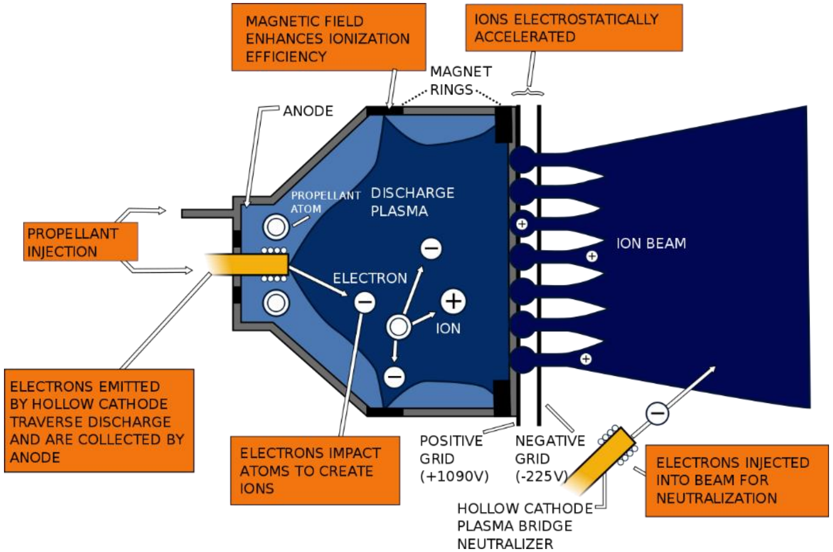




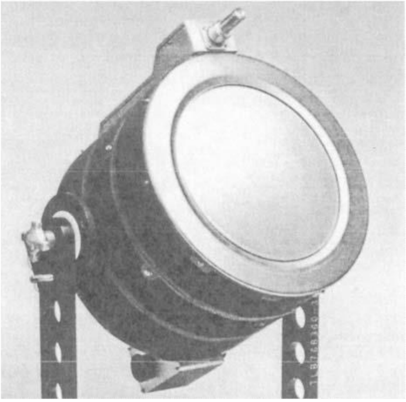
Ions are accelerated by the electric field in an ion thruster

- Ion thrusters consist of:
  - Ionization chamber – to generate ions.
  - Acceleration electrodes – to accelerate ions.
  - Neutralizer – to neutralize the ions.

$$\frac{1}{2}mv^2 = e\Delta V \qquad v = \sqrt{\frac{2e\Delta V}{m}}$$



- 25-cm XIPS



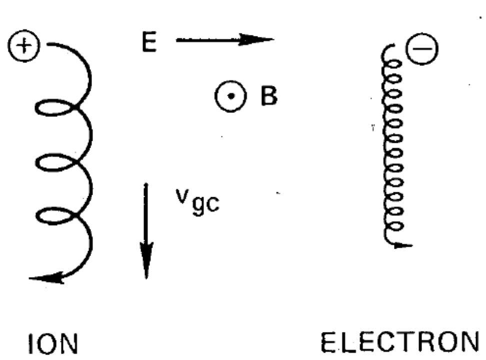
Parameters	Performance
Diameter	25 cm
Power	4.3 kW
Isp	3550 sec
Thrust	166 mN
Beam voltage	1215 V
Beam current	3.05 A

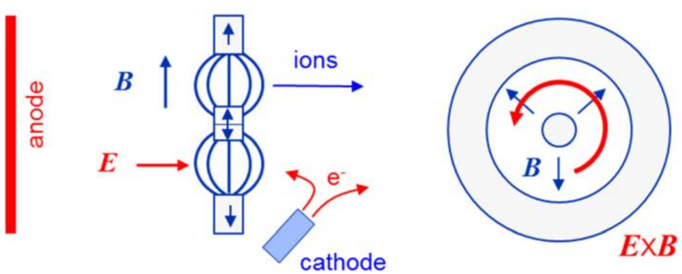
https://en.wikipedia.org/wiki/Ion_thruster
Dan M. Geobel and I. Katz, Fundamentals of electric propulsion – ion and hall thrusters

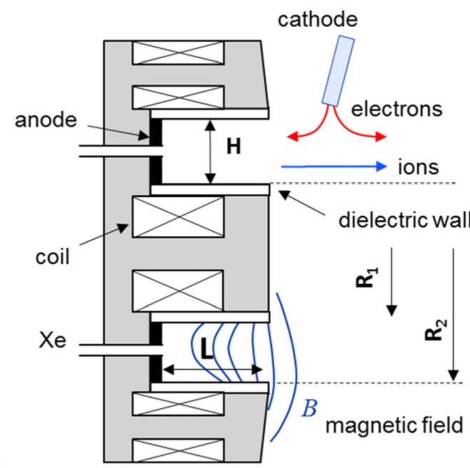
Electrons are confined by magnetic field so that ionization fraction increases in a Hall thruster

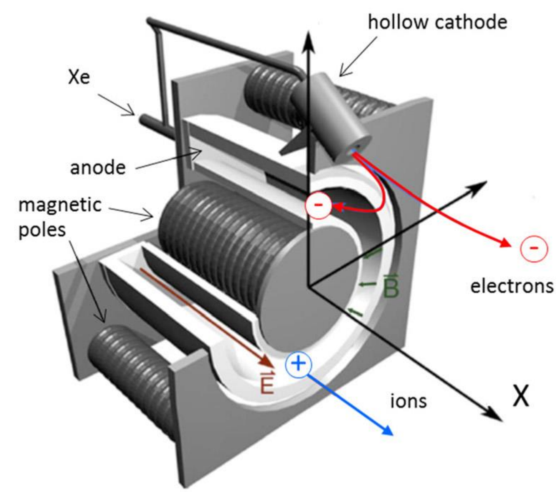
- **Ion thrusters consist of:**
  - **Ionization chamber – to generate ions.**
  - **Radial magnetic field is used to confine electrons.**
  - **Acceleration electrodes – to accelerate ions.**
  - **Single electron gun is used as the neutralizer and for ionization.**

  - **ExB drift**





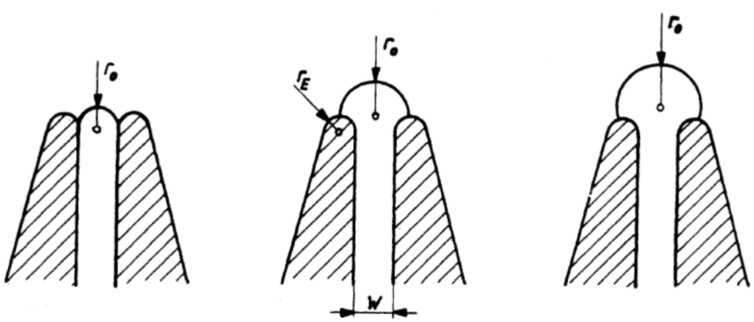


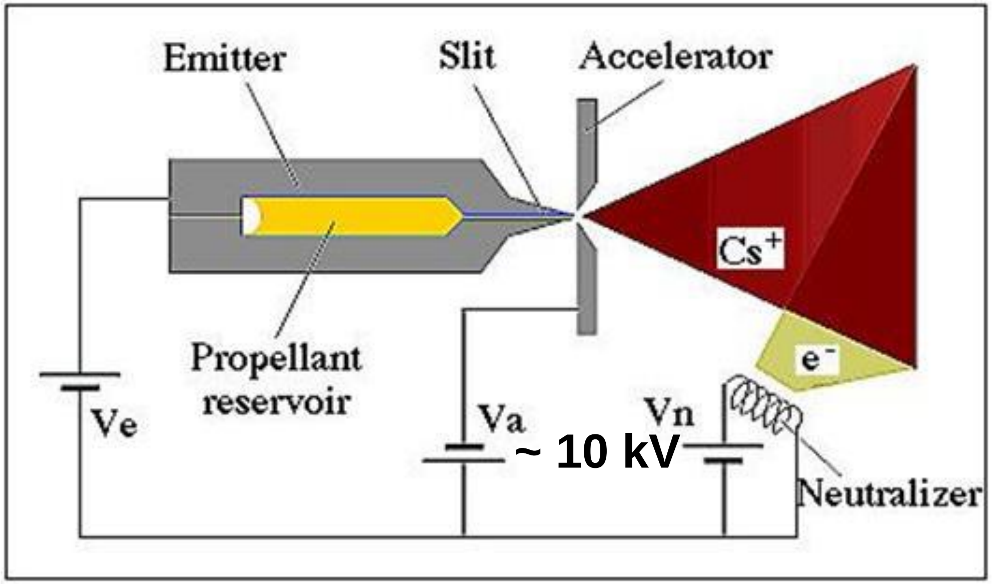


J.-P Boeuf, J. Appl. Phys. 212, 011101 (2017)

Ions are ejected by strong electric field applied on a liquid metal tip in a field-emission-electric propulsion (FEEP)

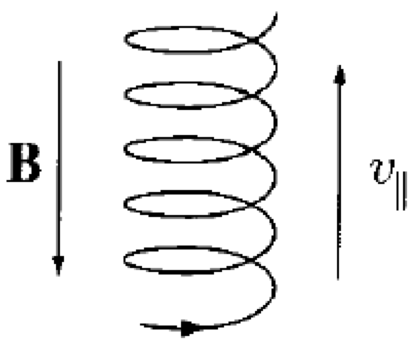
- **A Taylor cone is formed when the liquid metal's surface tension is balanced by the applied electric field.**
- **If the evaporation field strength of about 10^{10} V/m is reached at the needle tip, the liquid metal is evaporated and ionized.**
- **Thrust: 0.1~100 uN.**
- **Isp = 1600~8000 sec.**
- **Power = 13 W**

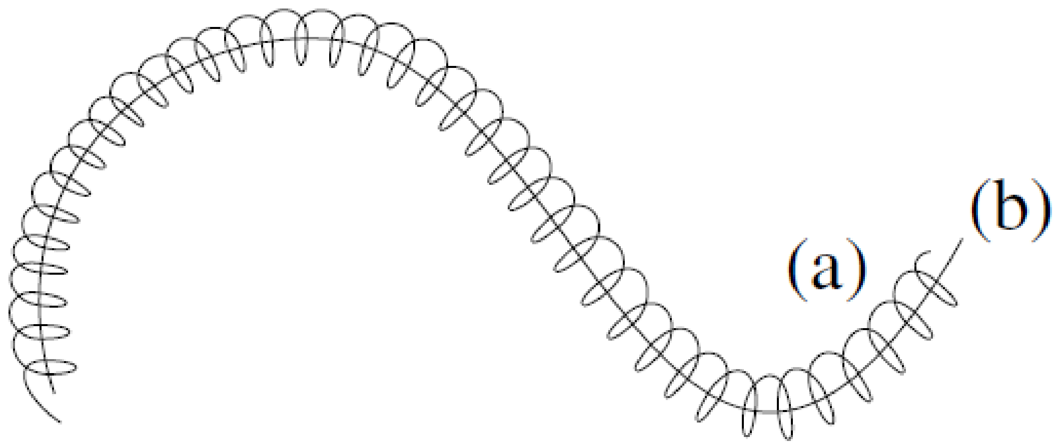




M. K. Bharti and S. Chalia, I. Res. J. Engin. Tech., 4, p2777 (2017)
J. Mitterauer, IEEE Trans. Plas. Sci., PS-15, 593 (1987)
M. Taimar, etc., J. Propulsion and Power, 20, 211 (2004)

Charged particles gyro around the magnetic fields



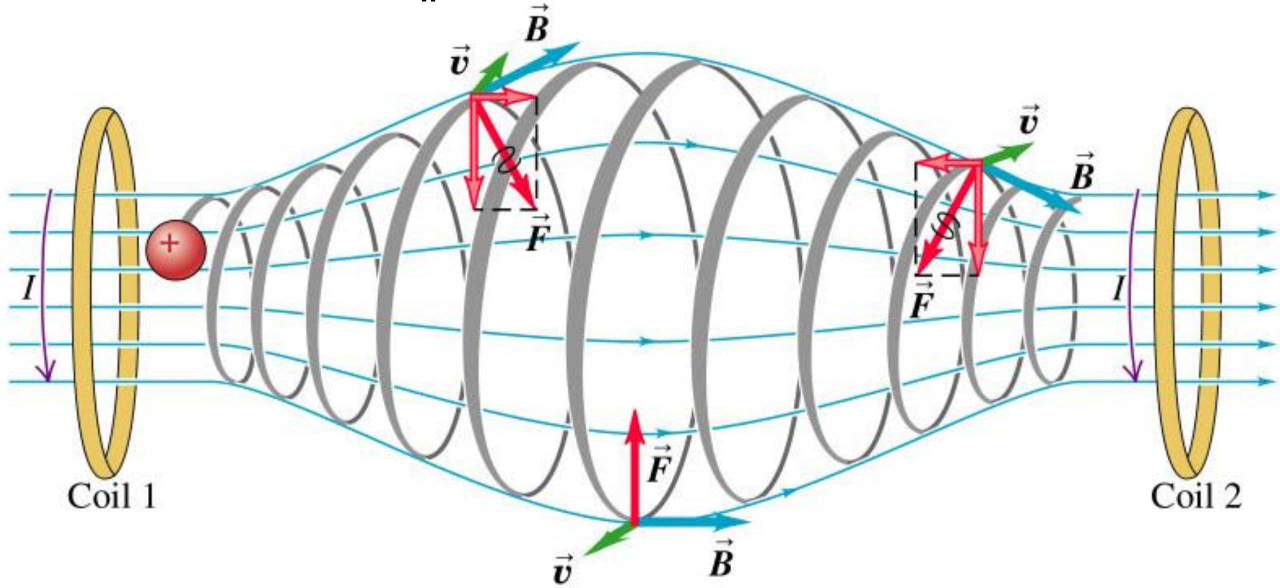


$$r_L = \frac{mv_\perp}{|q|B}$$

$$\vec{F} = q\,\vec{v} \times \vec{B}$$

Charged particles can be partially confined by a magnetic mirror machine

- **Charged particles with small $v_{||}$ eventually stop and are reflected while those with large $v_{||}$ escape.**



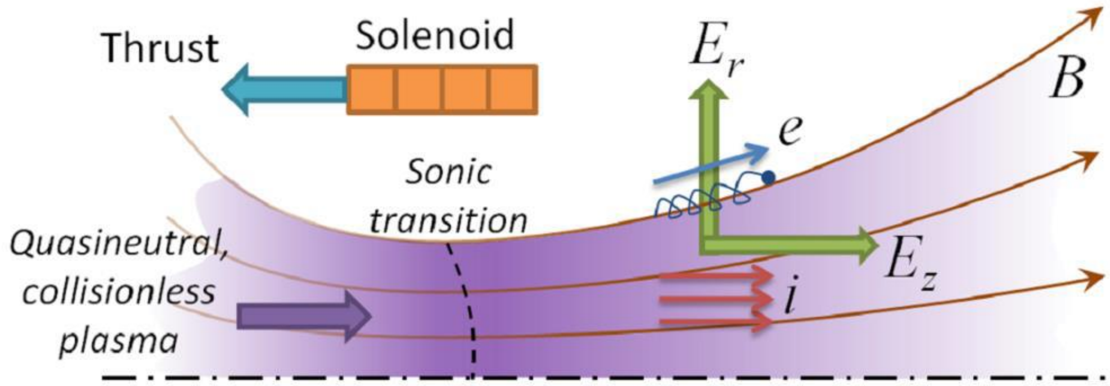
$$\frac{1}{2}mv^2 = \frac{1}{2}m{v_{||}}^2 + \frac{1}{2}m{v_{\perp}}^2$$

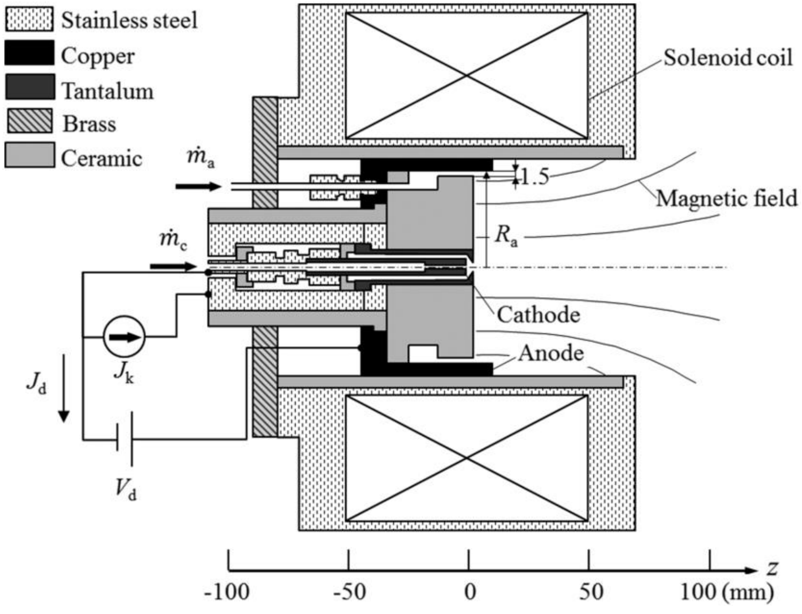
- **Large $v_{||}$ may occur from collisions between particles.**

- **Those confined charged particle are eventually lost due to collisions.**

https://i.stack.imgur.com/GlzGZ.jpg

Ions are accelerated by the ambipolar electric field created by electrons in a magnetic nozzle

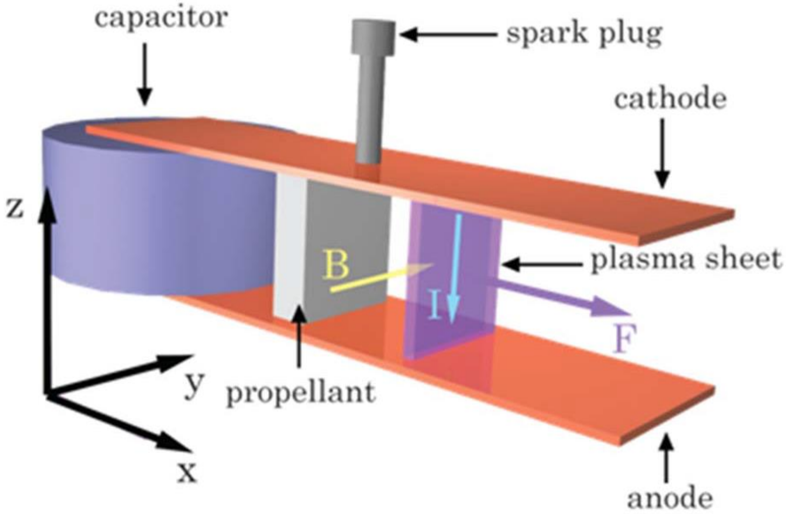




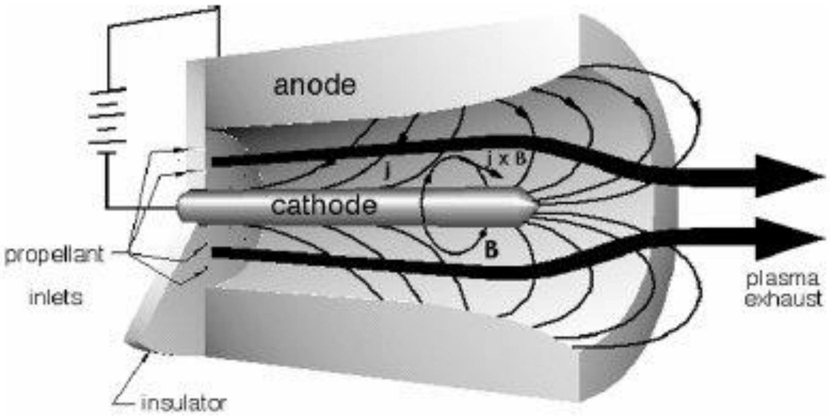
A. Sasoh, etc., AIP Advances 7, 065204 (2017)

Electric thruster types - Electromagnetic

- **Pulsed plasma thruster**

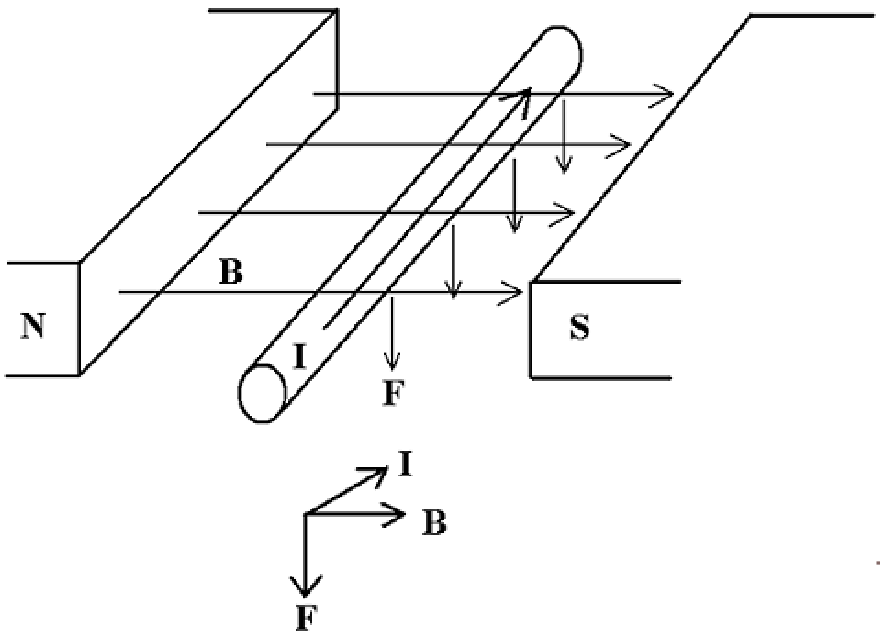


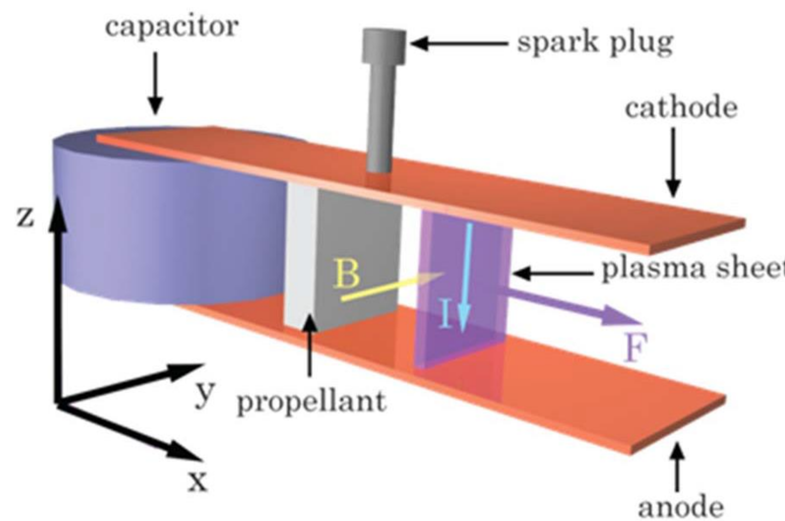
- **Magnetoplasmadynamic thruster (MPD)**



Current carries are accelerated by the Lorentz force in a pulsed-plasma thruster

- **A pulsed-plasma thruster (PPT) is suitable for small satellite.**





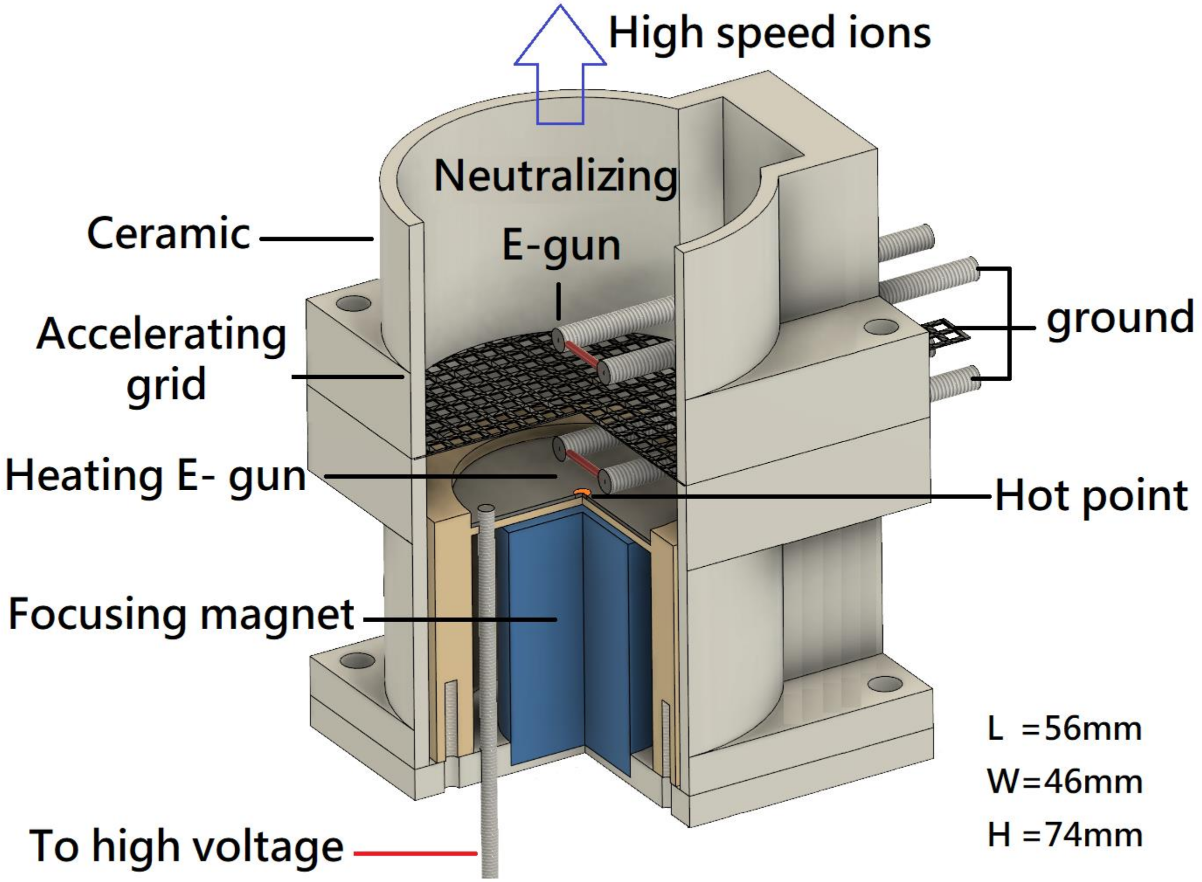
$$\vec{F} = q\,\vec{v} \times \vec{B}$$

A. Nawaz, etc., Acta Astro. 67, 440 (2010)

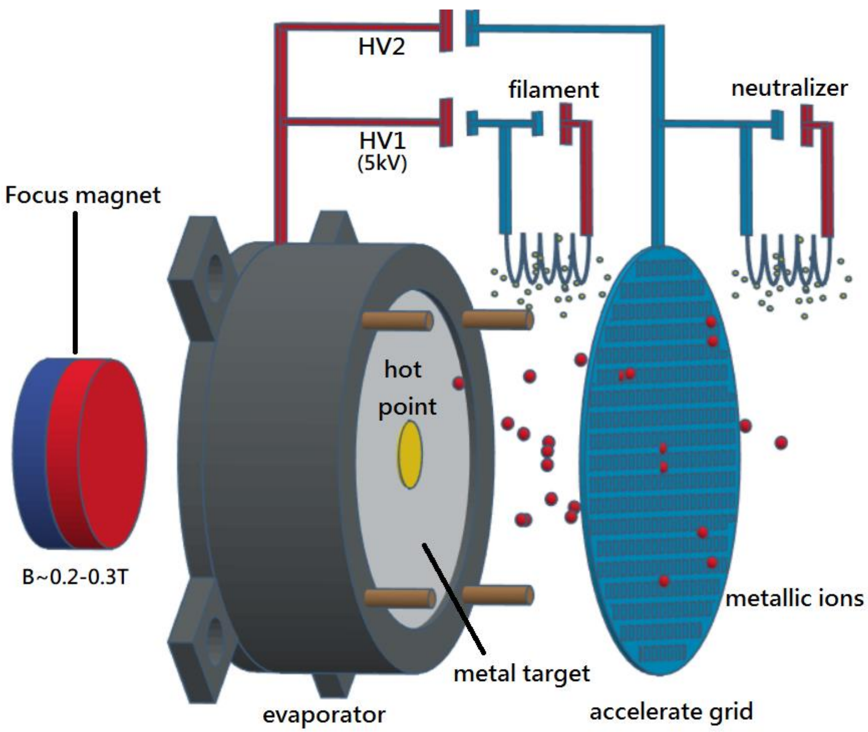
Ion thruster has the highest specific impulse (Isp)

Thruster	Specific Impulse (s)	Input Power (kW)	Efficiency Range (%)	Propellant
Cold gas	50–75	—	—	Various
Chemical (monopropellant)	150–225	—	—	N_2H_4 H_2O_2
Chemical (bipropellant)	300–450	—	—	Various
Resistojet	300	0.5–1	65–90	N_2H_4 monoprop
Arcjet	500–600	0.9–2.2	25–45	N_2H_4 monoprop
Ion thruster	2500–3600	0.4–4.3	40–80	Xenon
Hall thrusters	1500–2000	1.5–4.5	35–60	Xenon
PPTs	850–1200	<0.2	7–13	Teflon

Metallic Ion Thruster Using Magnetron E-Beam Bombardment (MIT-MEB)



Electrons are used to generate metallic gas, metallic plasma and to neutralize ions

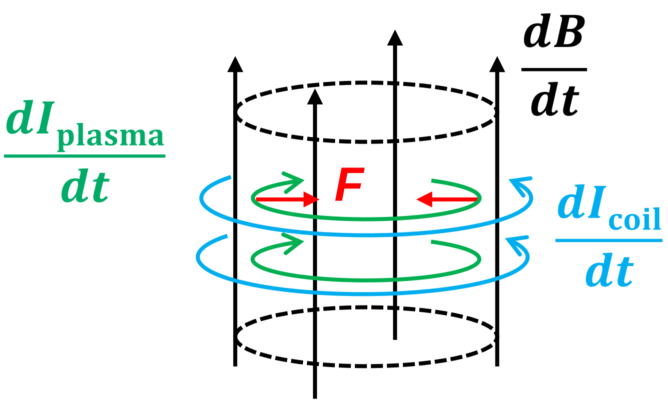


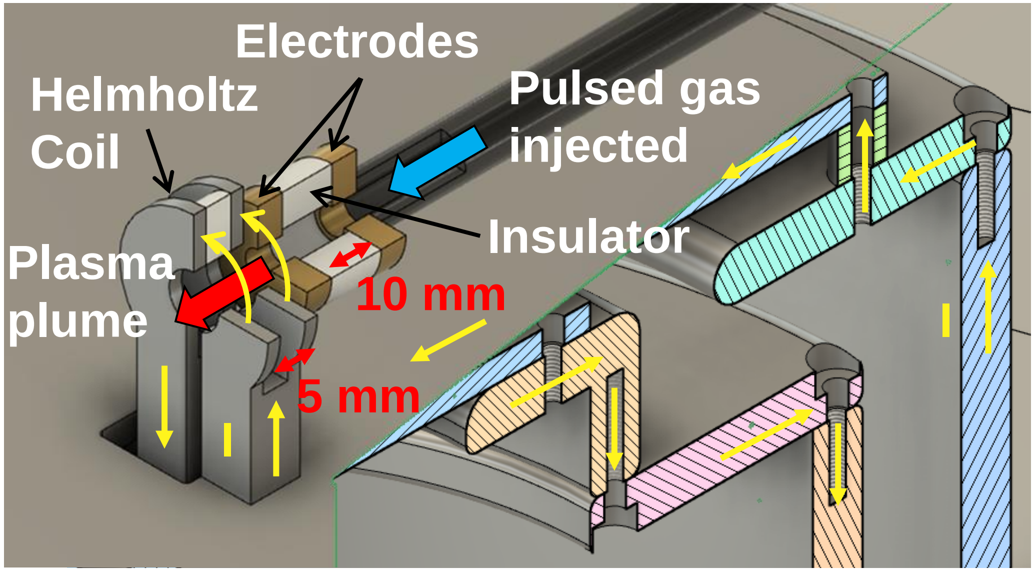
heating ↓

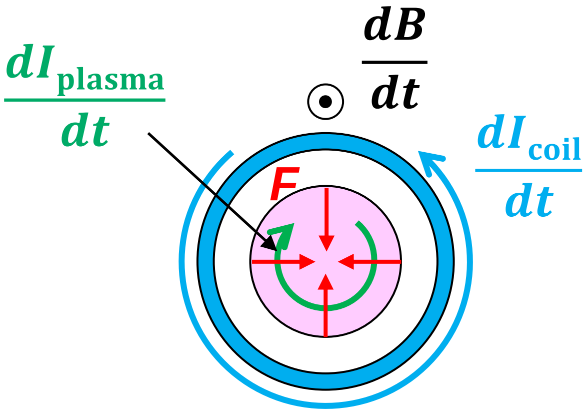
filament → Thermal electron → target → vapor → plasma → exhaust

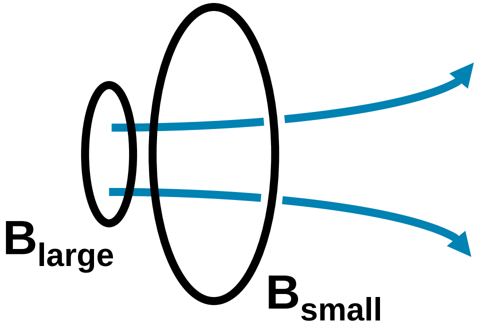
- **external electric field**: Thermal electron → target
- **evaporated**: target → vapor
- **electron bombardment**: vapor → plasma
- **ionized**: vapor → plasma
- **accelerated electric field**: plasma → exhaust
- **neutralizer**: → exhaust

An unbalanced theta pinch can be used as the propulsion



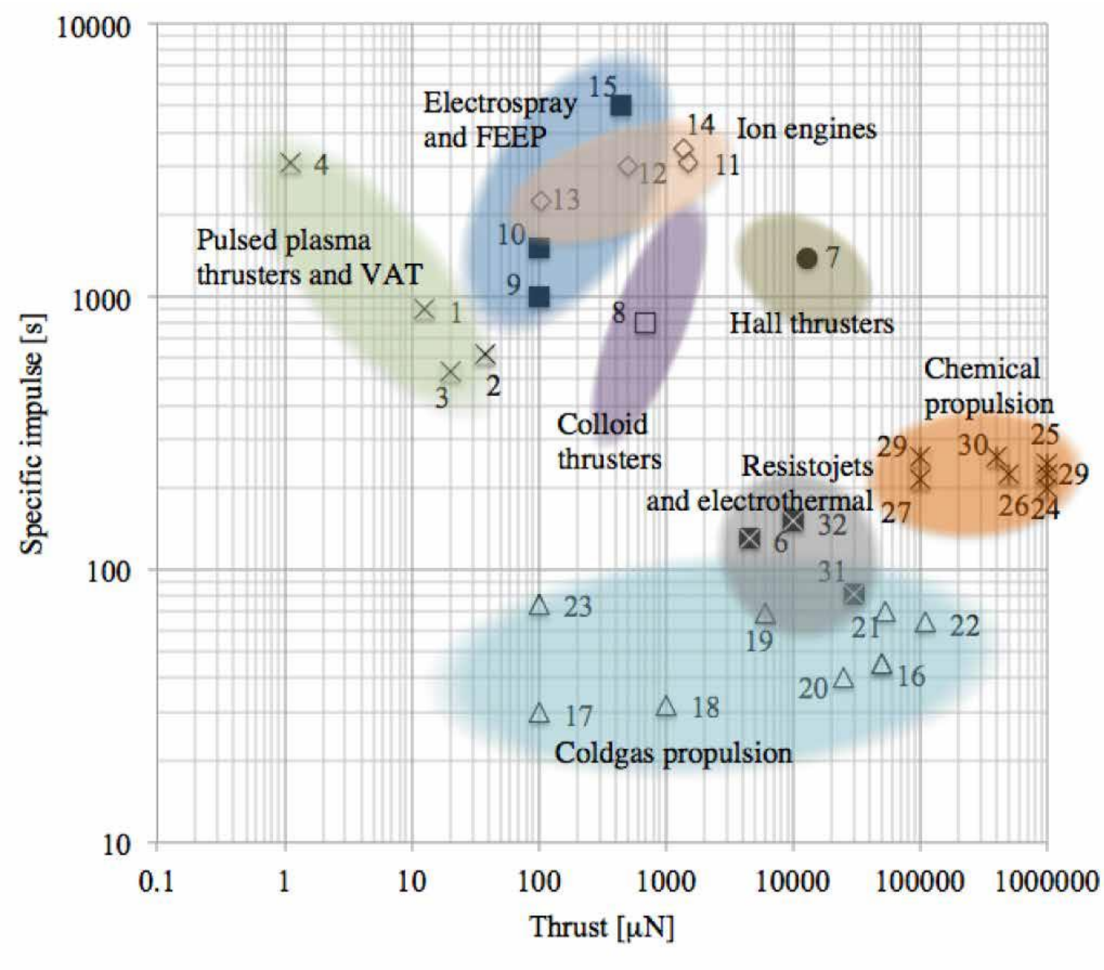






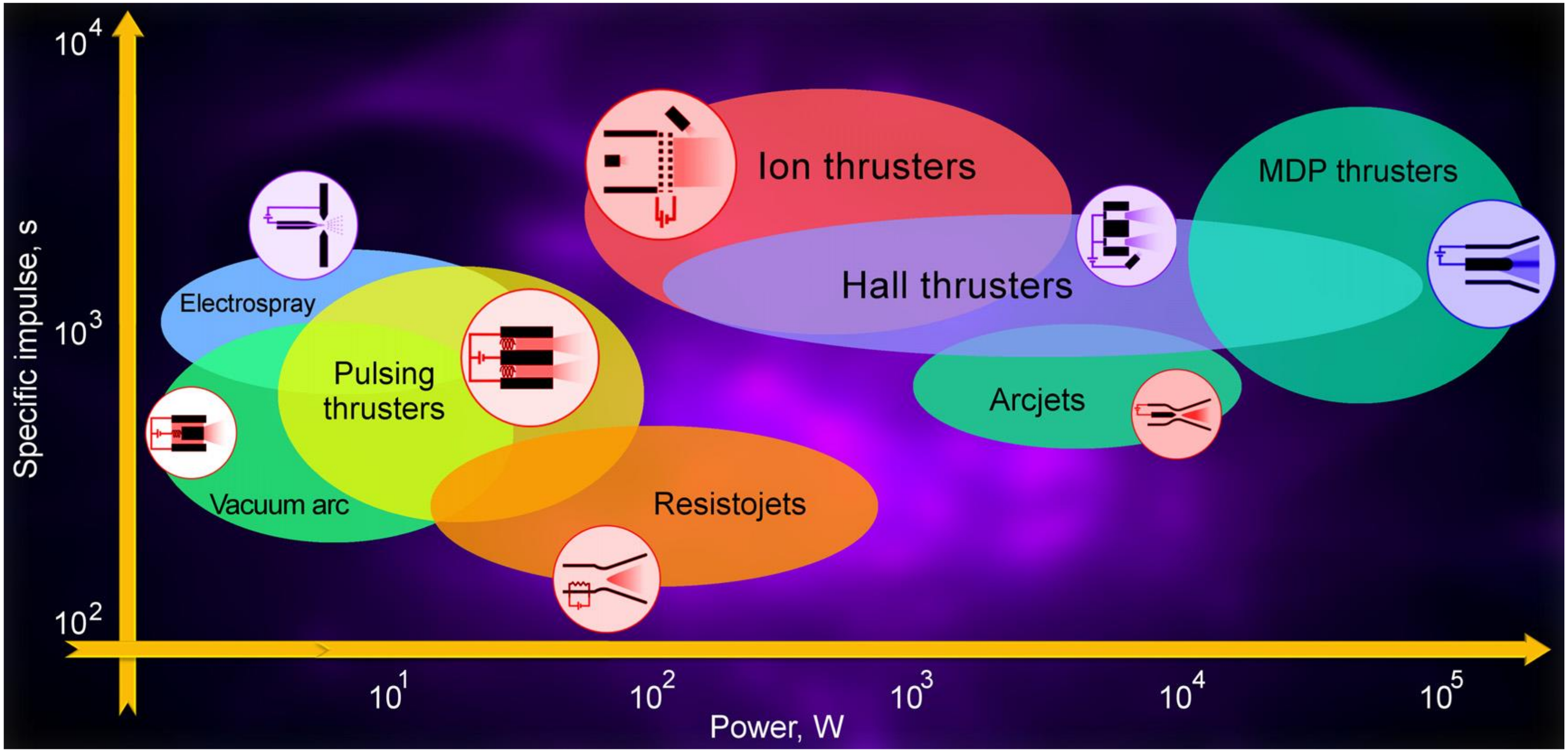
- **We are looking for students who are interested in electrical propulsion.**

Thrusters are picked by their specific impulses and thrusts



D. Krejci and R. Lozano, Proc. of the IEEE, 106, p362 (2018)

Thrusters are also picked by their powers



I. Levchenko, etc., Phys. Plasmas 27, 020601 (2020)

Plasma is everywhere and has many applications

- What is a plasma?
- Important plasma parameters
  - Debye length, Plasma parameter, Plasma frequency
- DC electrical discharges
  - Dark / glow / arc discharges
- AC electrical discharges
  - RF / Microwave discharges / Electron cyclotron resonance (ECR) plasma
- Space science
  - Aurora / Reconnection / Corona mass ejection /

Plasma is everywhere and has many applications

- Semiconductor device fabrication
  - etching / deposition / implantation
- Plasma medicine – dielectric barrier discharge (DBD)
- Nuclear fusion
  - MCF / ICF / Innovation
- Neutral beam source
  - Neutral beam injection (NBI) / Electric propulsion
- High energy particle accelerator
- Pulsed-power system in ISAPS, NCKU

Course Outline

4. Demonstration

a. Planeterrella

b. Magnetron sputtering

c. Dielectric barrier discharge (DBD)

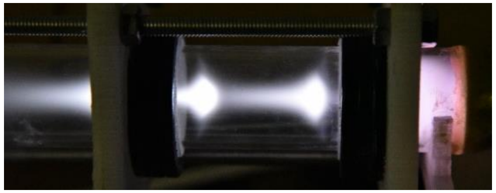
d. Magnetic mirror

e. Tesla coil

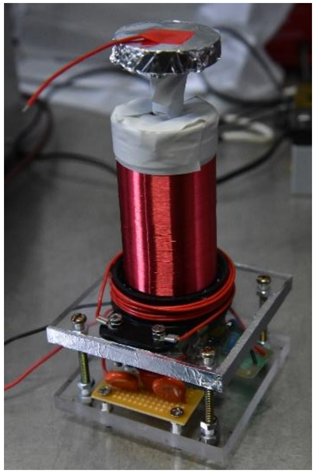
Planeterrella

Magnetron sputtering

DBD plasma

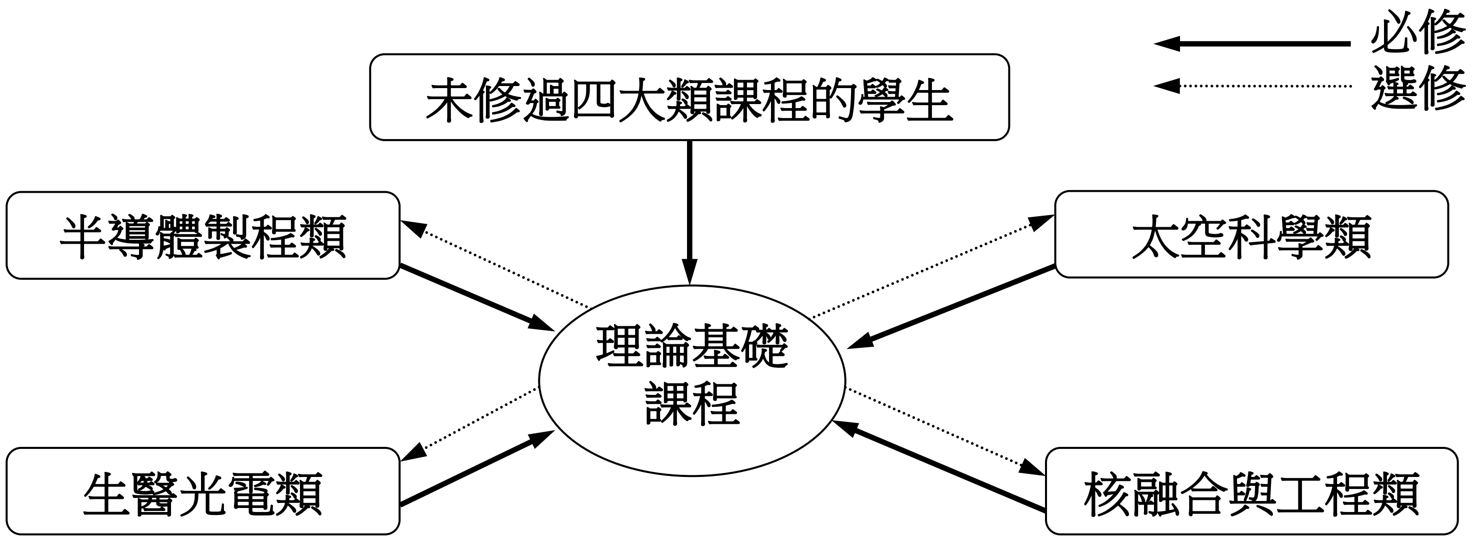


Magnetic mirror



Tesla Coil

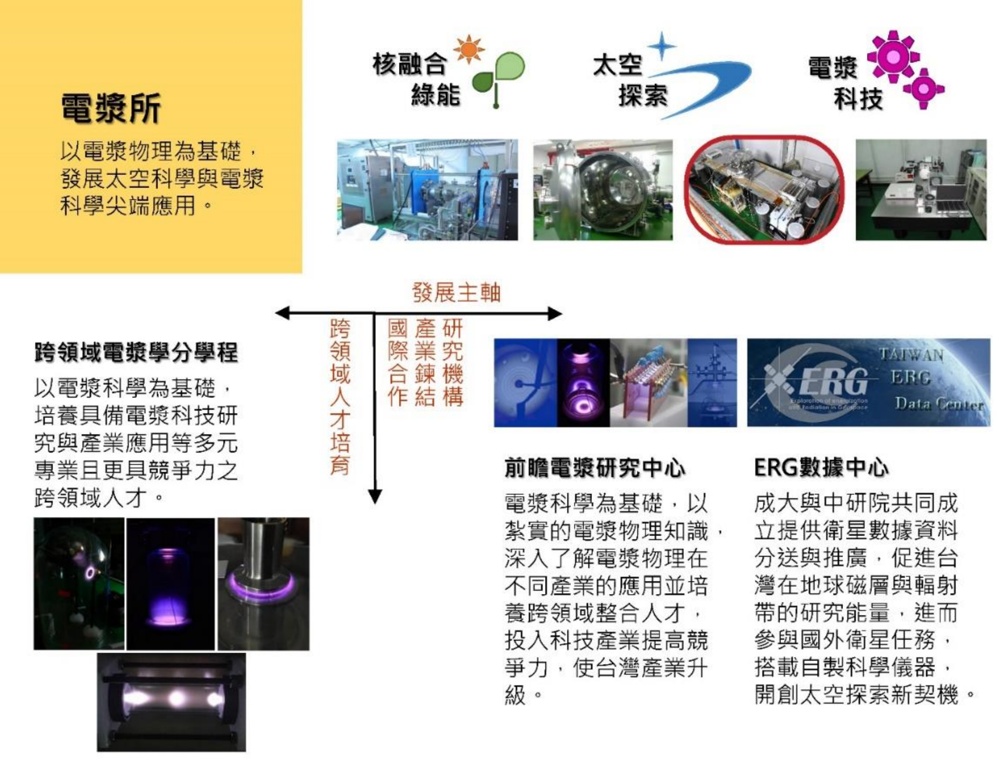
深入的電漿知識請選修 電漿學分學程



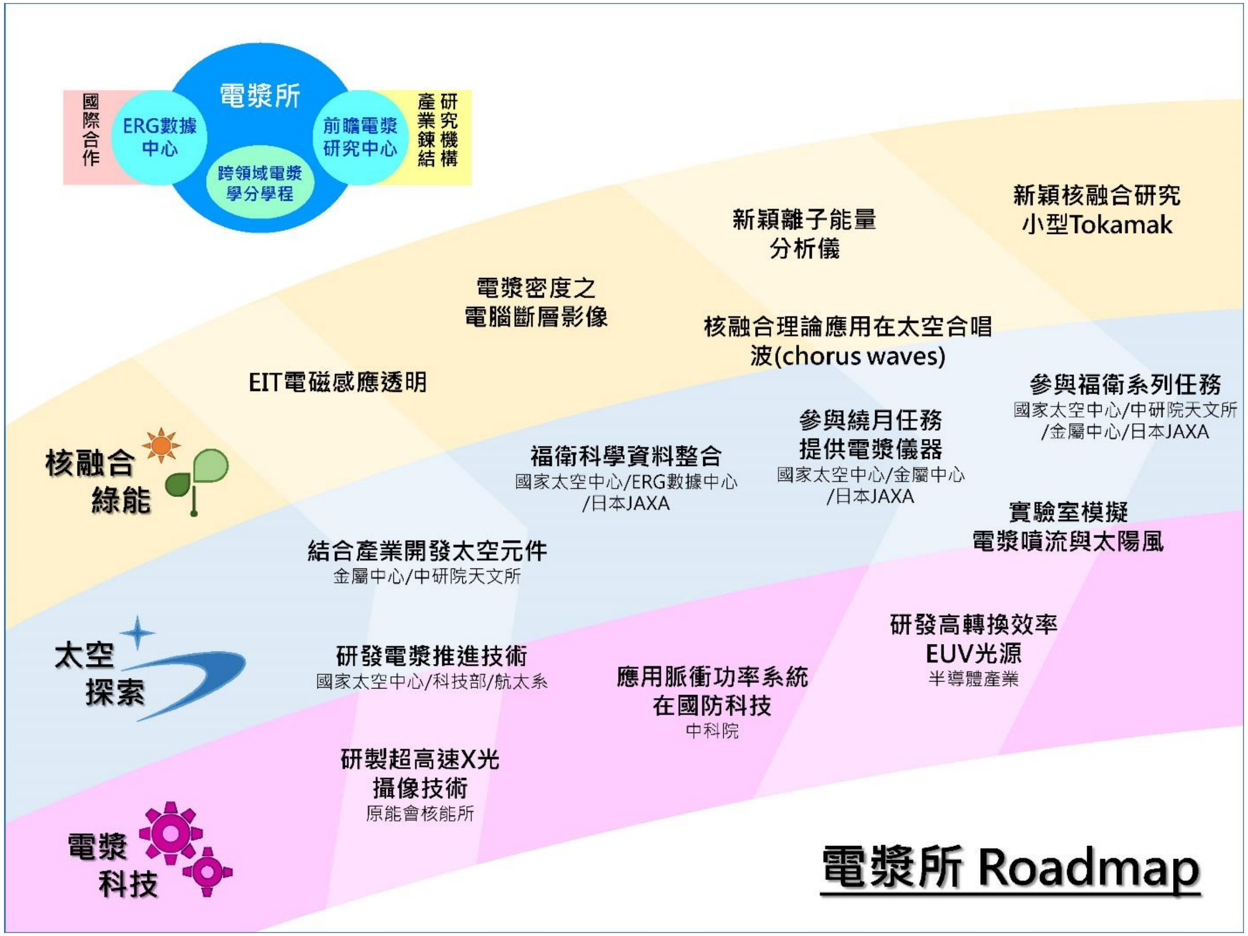
- 將培養具備電漿科技研究與產業應用等多元專業且更具競爭力之跨領域人才.

成大電漿所是全台唯一以電漿為基礎的研究所。

- **You are welcome to join Prof. Chang’s lab, Pulsed-Plasma Laboratory (PPL), if you are interested in**
  - **Plasma physics**
  - **Nuclear fusion, Magneto-inertial fusion in particular**
  - **Laboratory astrophysics and space sciences**
  - **EUV light generation**
  - **Electrical propulsion**
  - **Pulsed-power system**



電漿所有在進行核融合相關的研究



- 成大電漿所是全台唯一針對電漿及核融合做研究的研究所。

Acknowledgement - all experimental demonstrations were developed by my students from scratch

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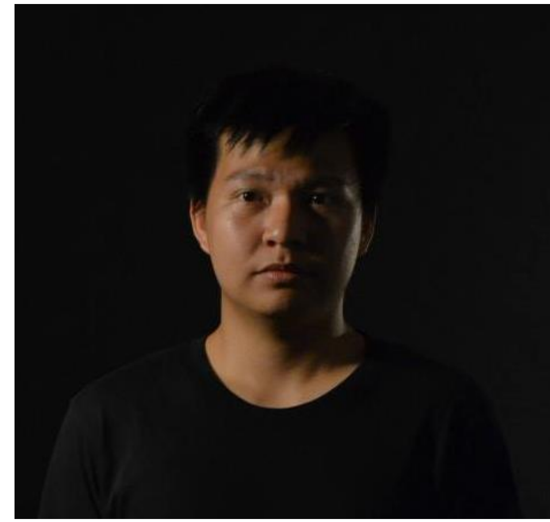

Grading

- Presentations 40 %
- Final report 60 %
  - Pick a plasma application or plasma application/phenomenon.
  - Explain in details how the application/phenomenon works.
  - Where the application/phenomenon is used or occurs?
  - How is the plasma generated in the application/phenomenon?
  - What role does the plasma play in the application/phenomenon?
  - The writing part of the report needs to be longer than two full pages with font size 14 and single-line spacing.
  - Please send your report to Prof. Chang's email address: pchang@mail.ncku.edu.tw

- Deadline: 9/9 (Saturday) 0:00