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

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Institute of Space and Plasma Sciences, National Cheng Kung University

2023 summer break

8/28(Mon.) – 9/1(Fri.) 14:00-17:40

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

Lecture 5

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：

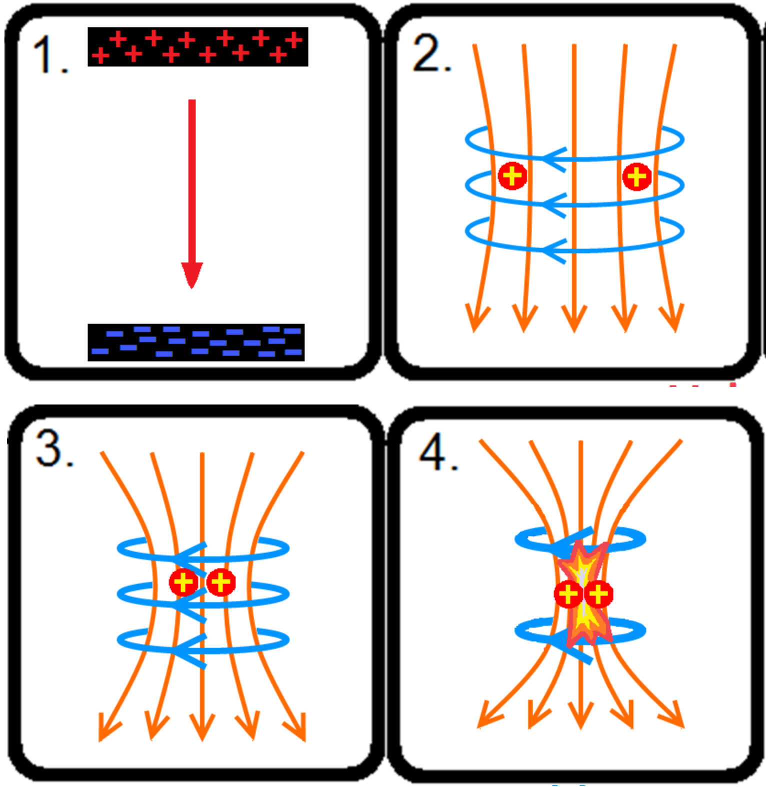
https://i-ocw.ctld.ncku.edu.tw/site/course_content/FTqT2RS1h7j

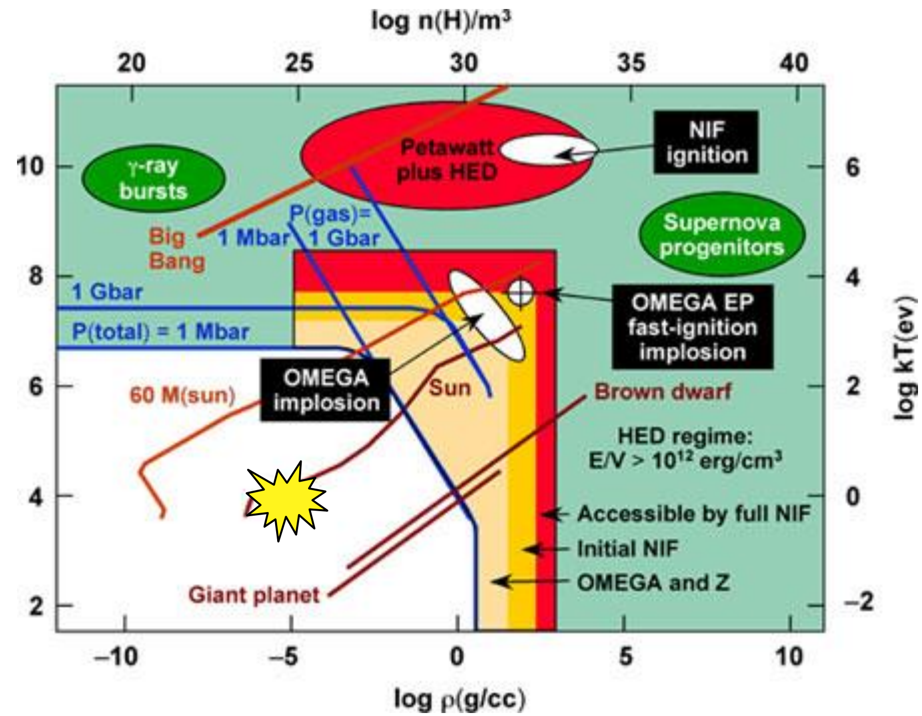
2023/9/1 updated

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**

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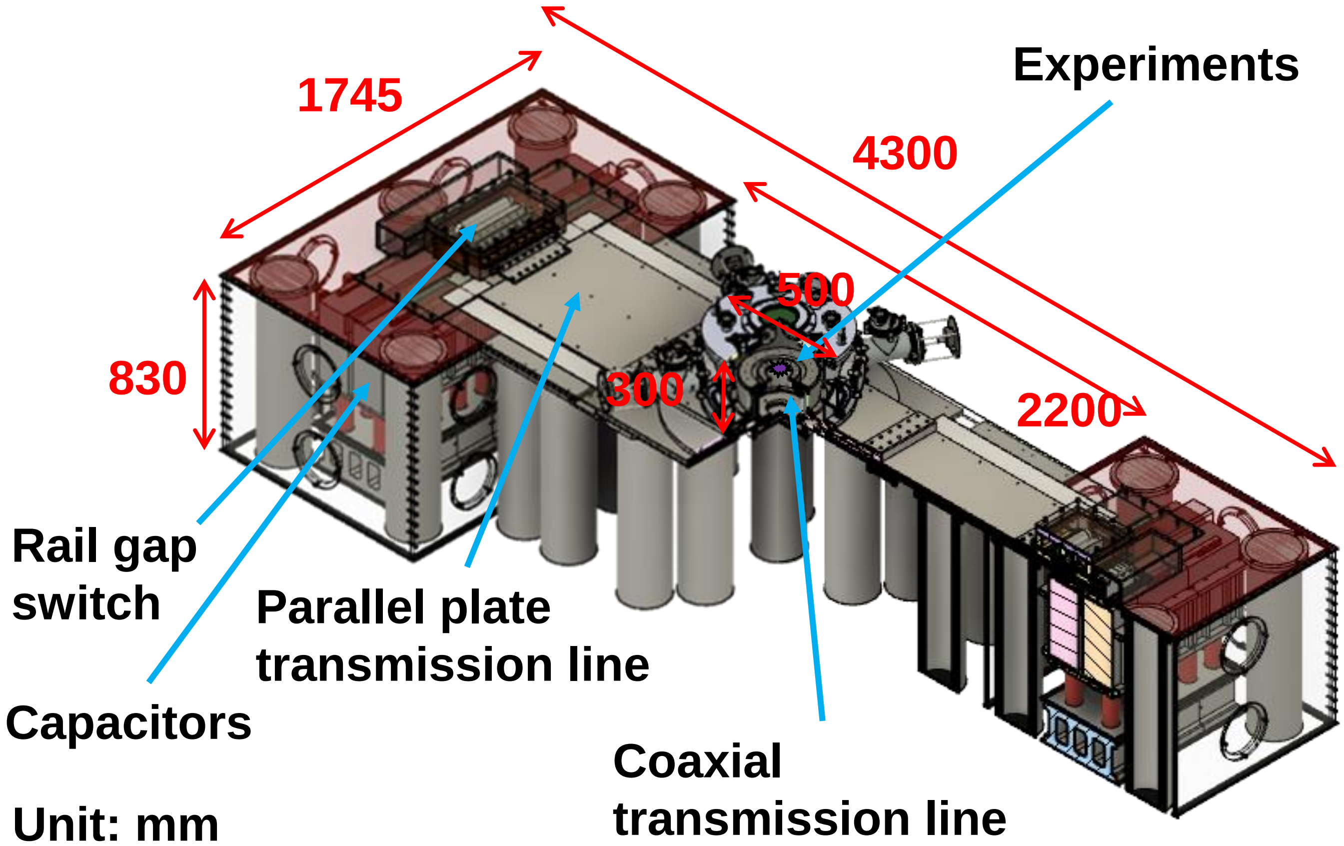
*https://en.wikipedia.org/wiki/Pinch_(plasma_physics)

**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

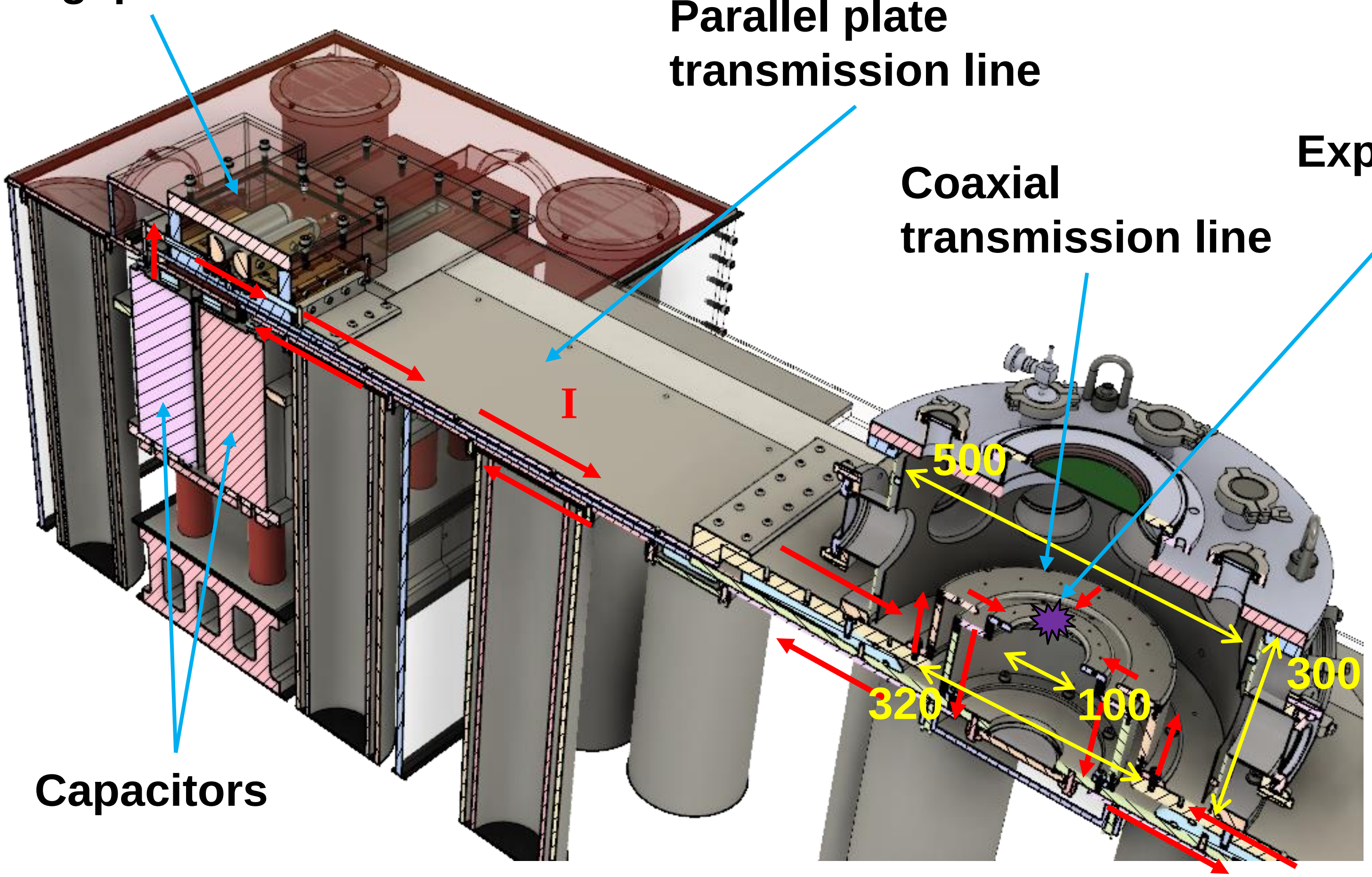
Facility	Budgets (NTD)
OMEGA at University of Rochester	~1.8 billion
National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL)	~100 billion
Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory in Berkeley (LBNL)	~3 billion
Taiwan Photon Source (TPS) at National 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.**

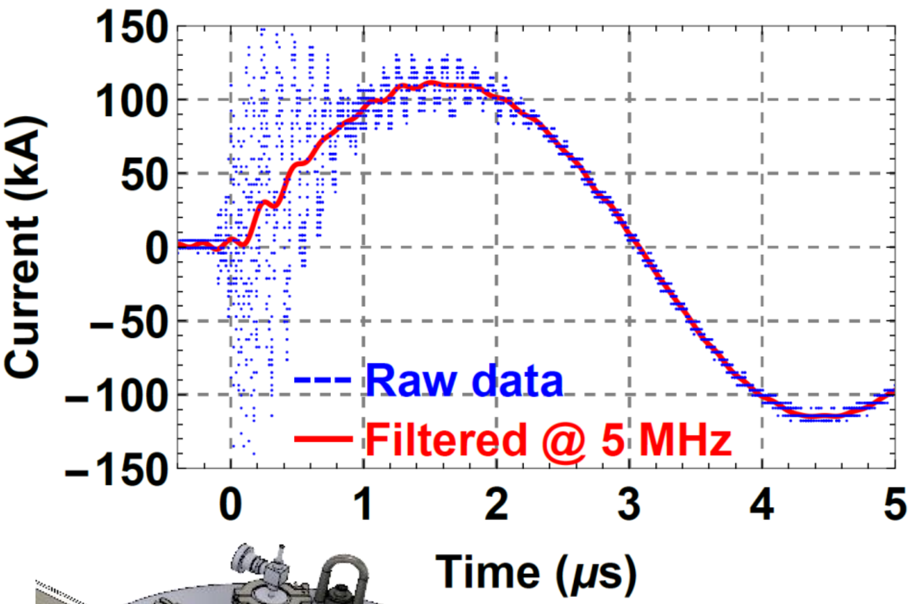
Experiments will be taken placed at the center of the vacuum chamber

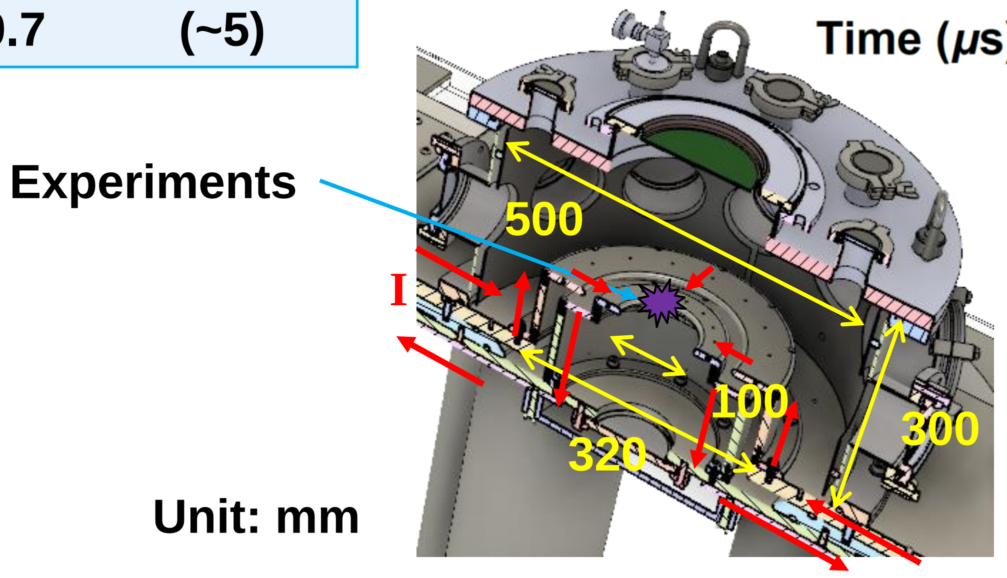


Unit: mm

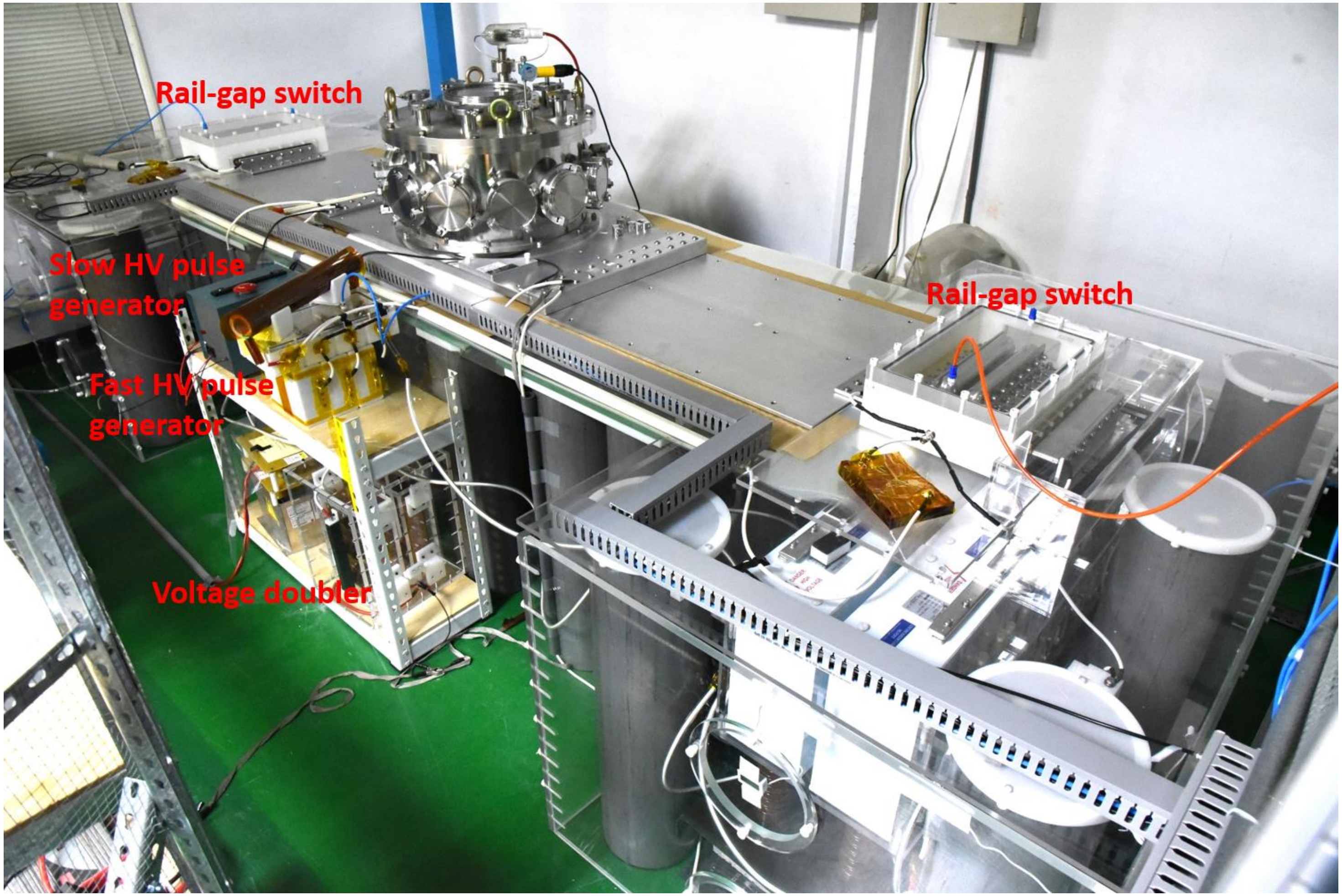
A peak current of 110 kA with a rise time of 1.5 us is provided by the pulsed-power system

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)

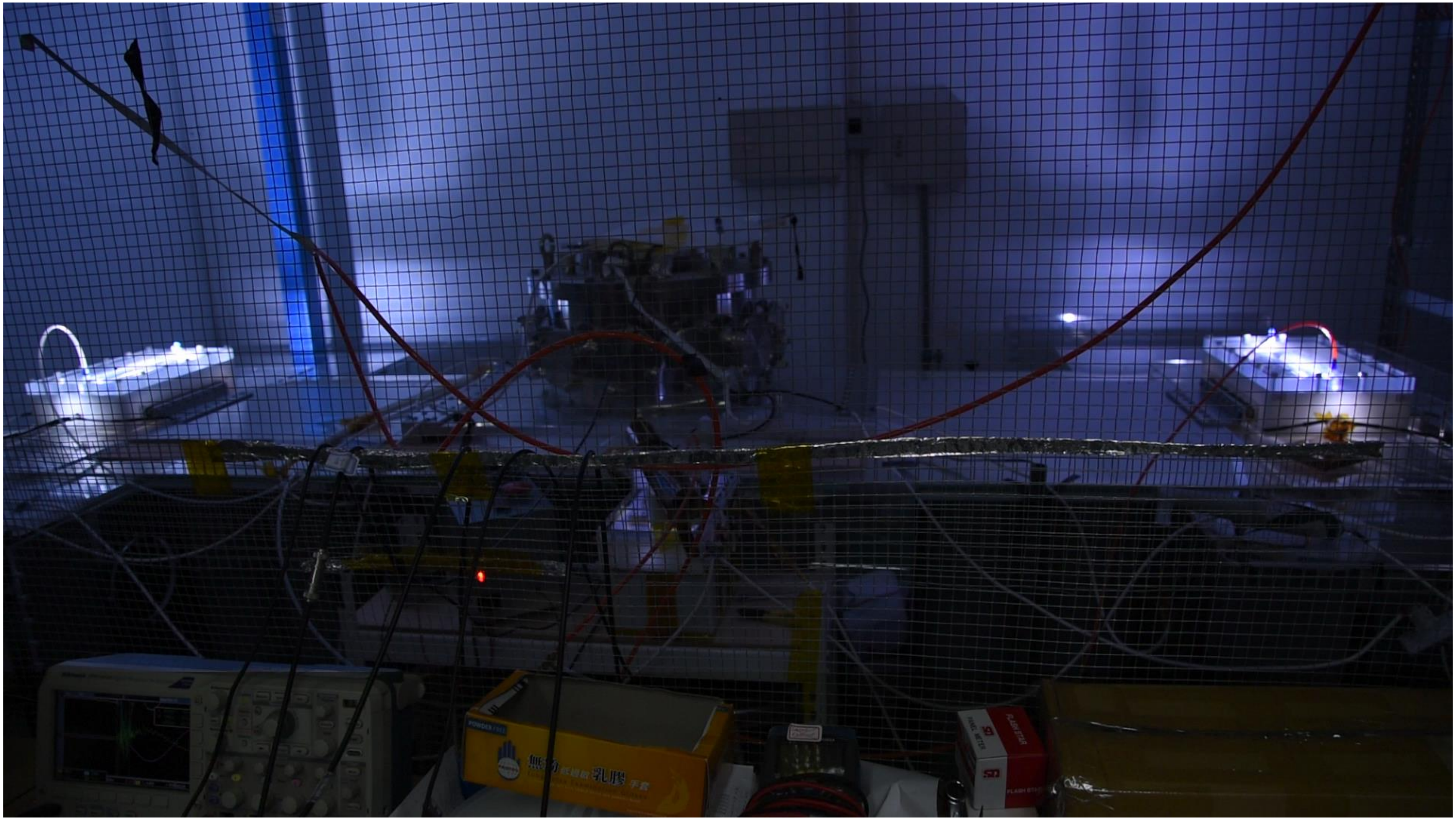




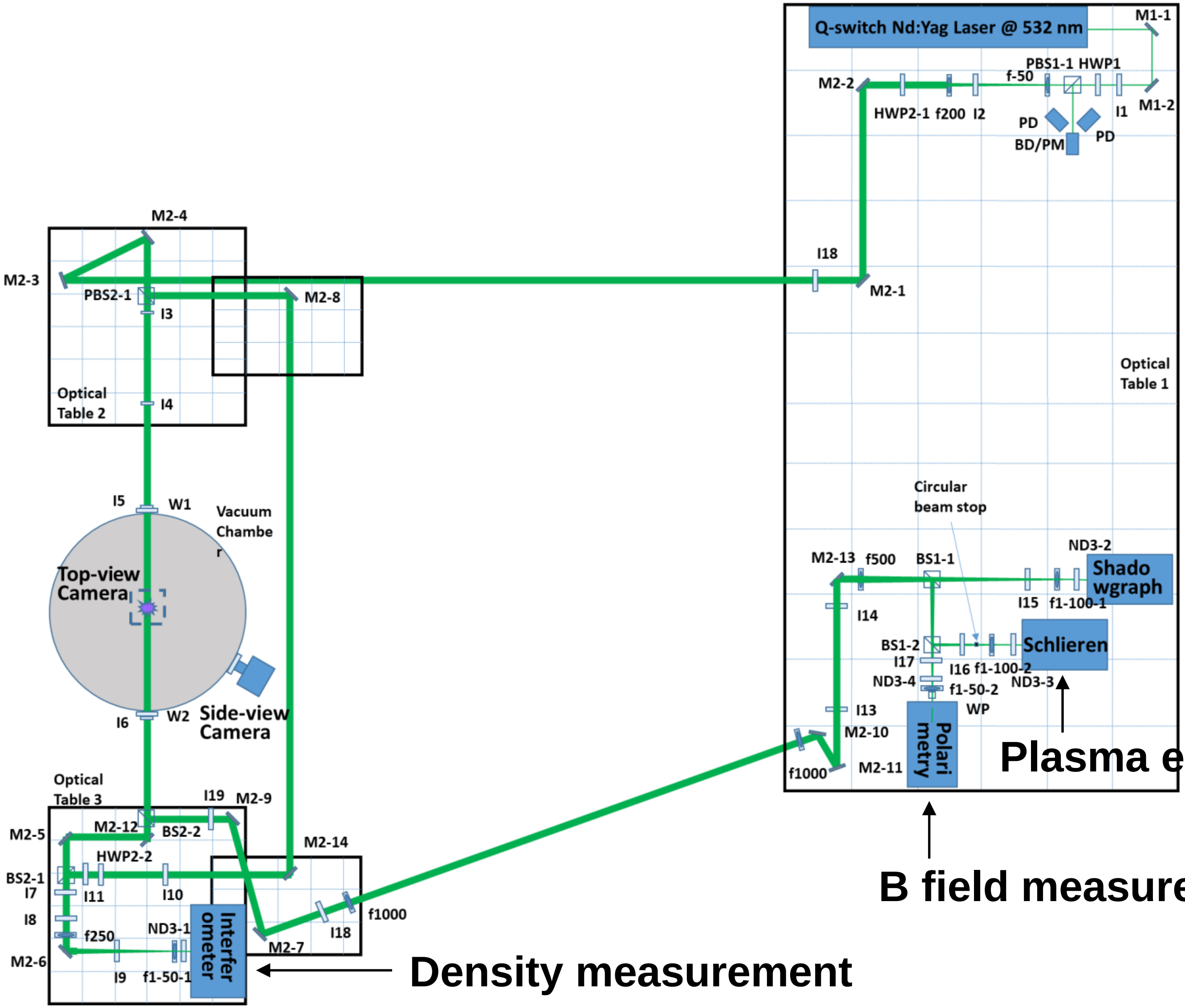
The pulsed-power system has been built



First shot with two synchronized rail-gap switches



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

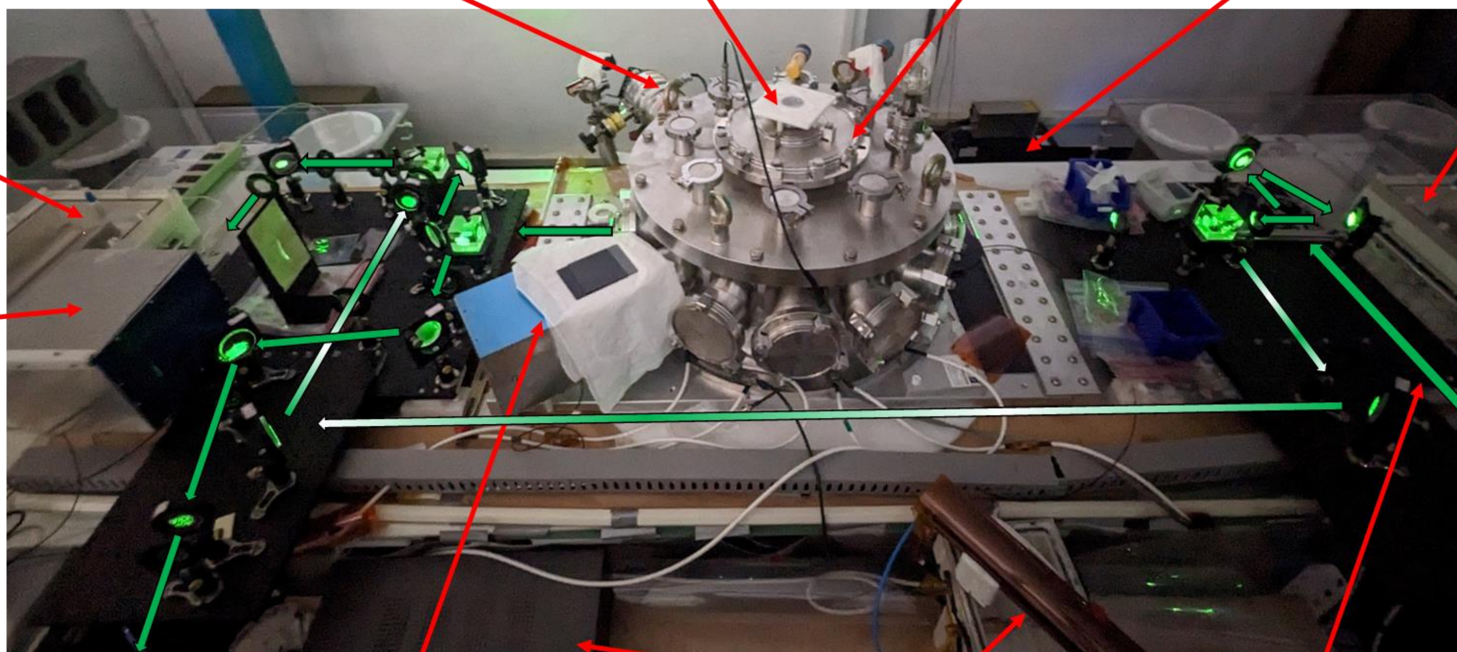


Plasma edge detection

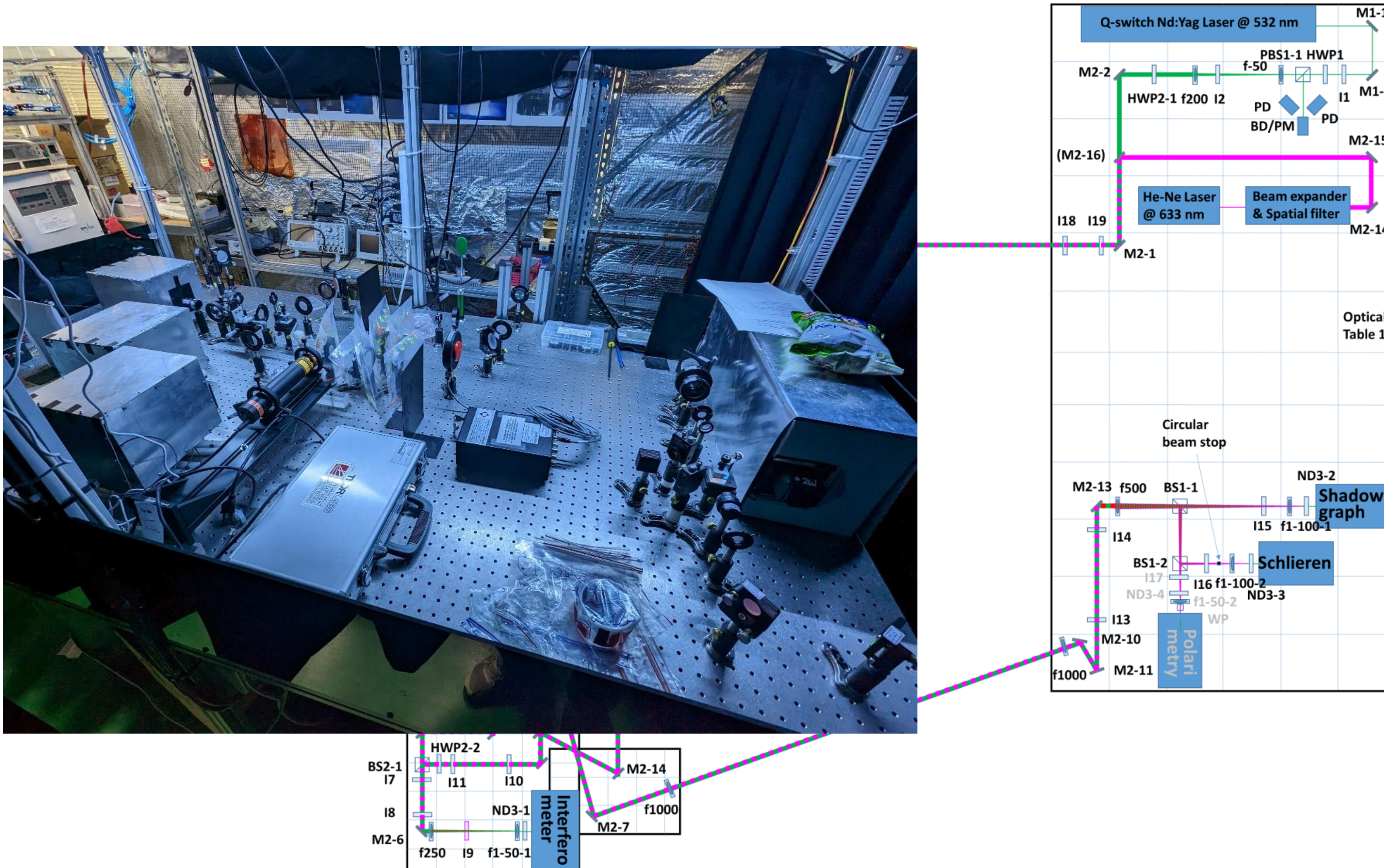
B field measurement

Density measurement

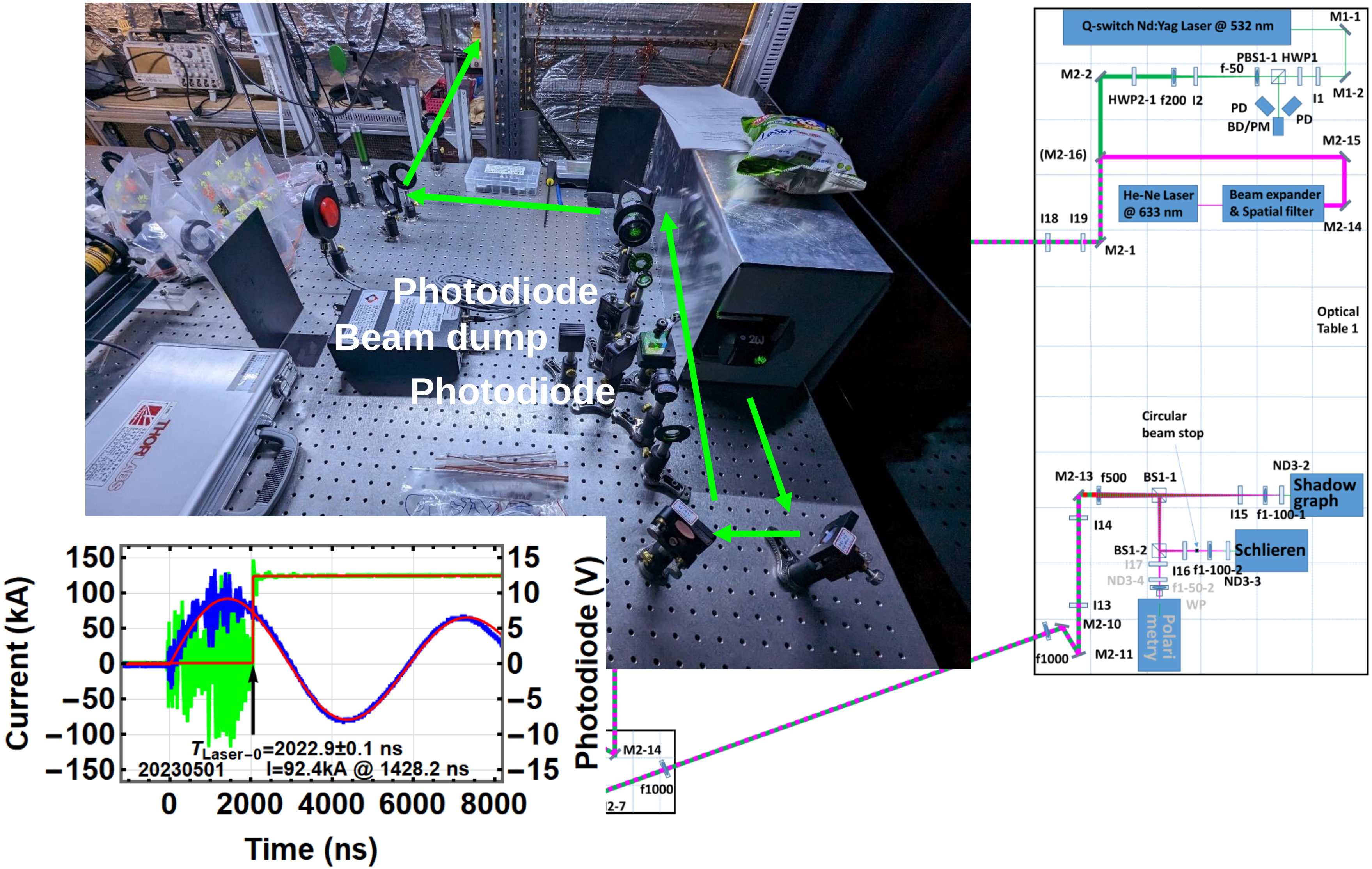
Varies diagnostics were integrated to the system



Beam path


Q-switch Nd:Yag Laser @ 532 nm
M1-1
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
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
ND3-3
f1-50-2
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
THORLABS
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
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He-Ne Laser @ 633 nm
Beam expander & Spatial filter
I18
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Circular beam stop
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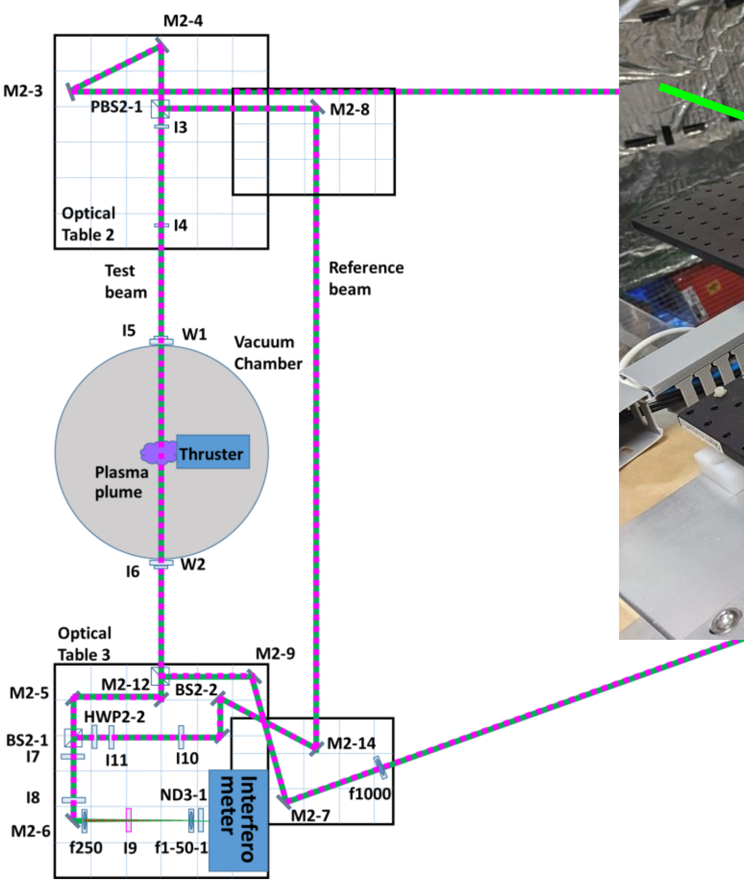
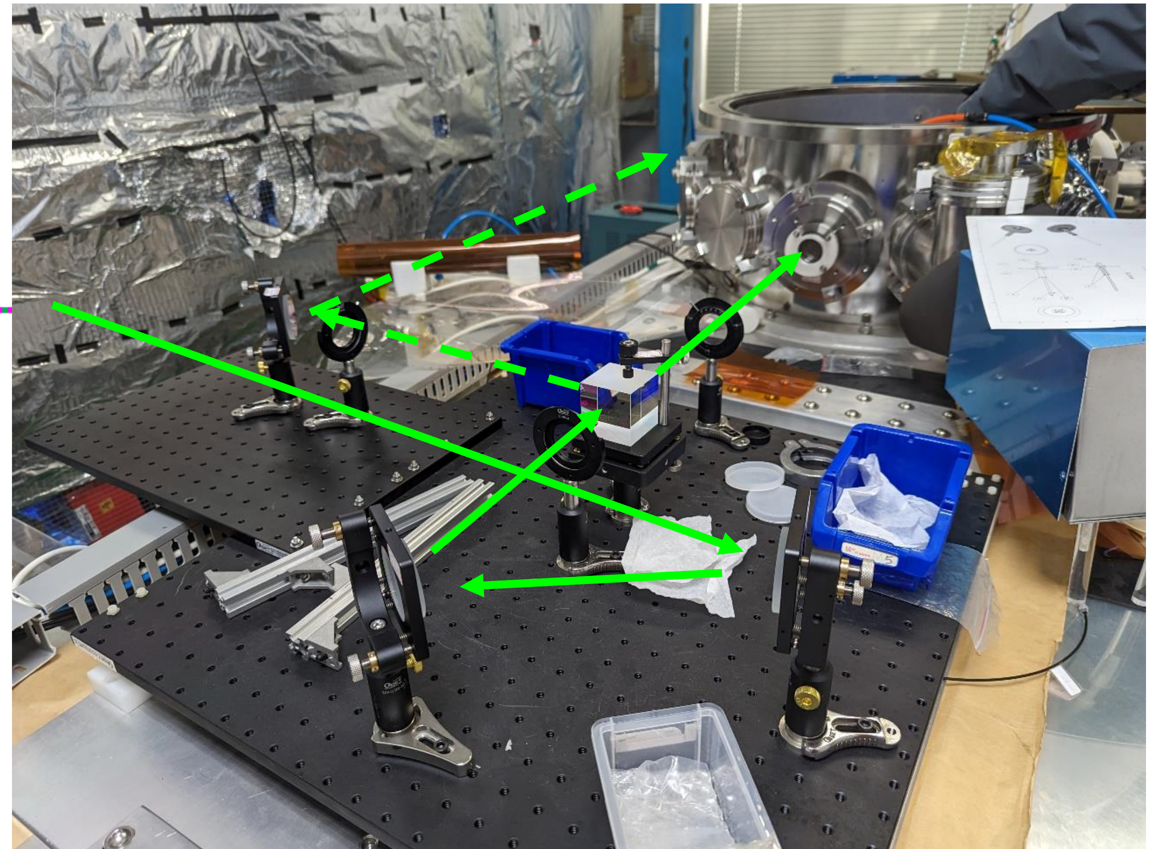
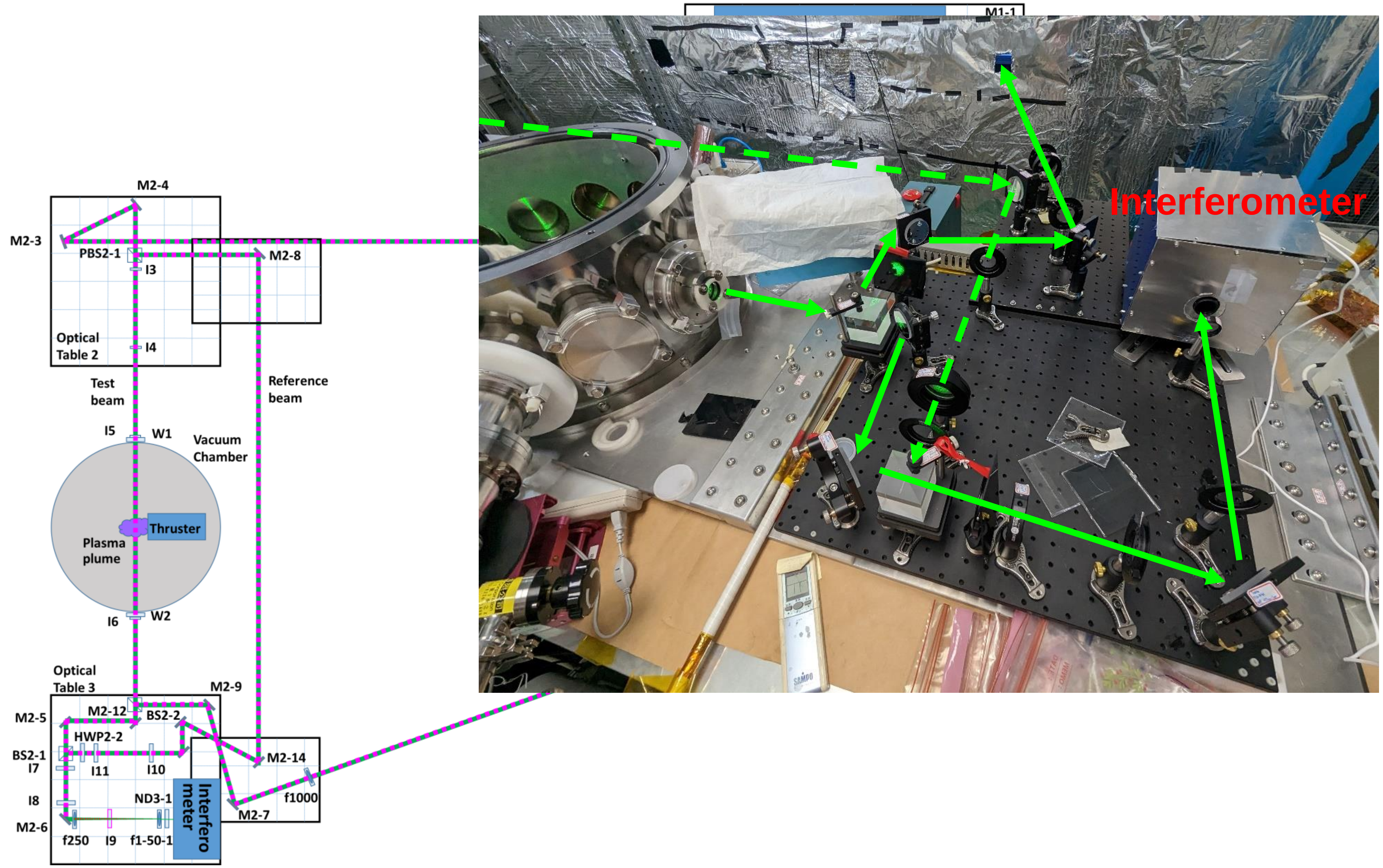
WP
I13
M2-10
Polari metry
f1000
M2-11
M2-14
f1000
2-7

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
Interfero meter
f1000
M2-7
M2-6
f250
I9
f1-50-1



Beam path


M1-1
Interferometer
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
Interfero
meter
f1000
M2-7
M2-6
f250
I9
f1-50-1

Beam path

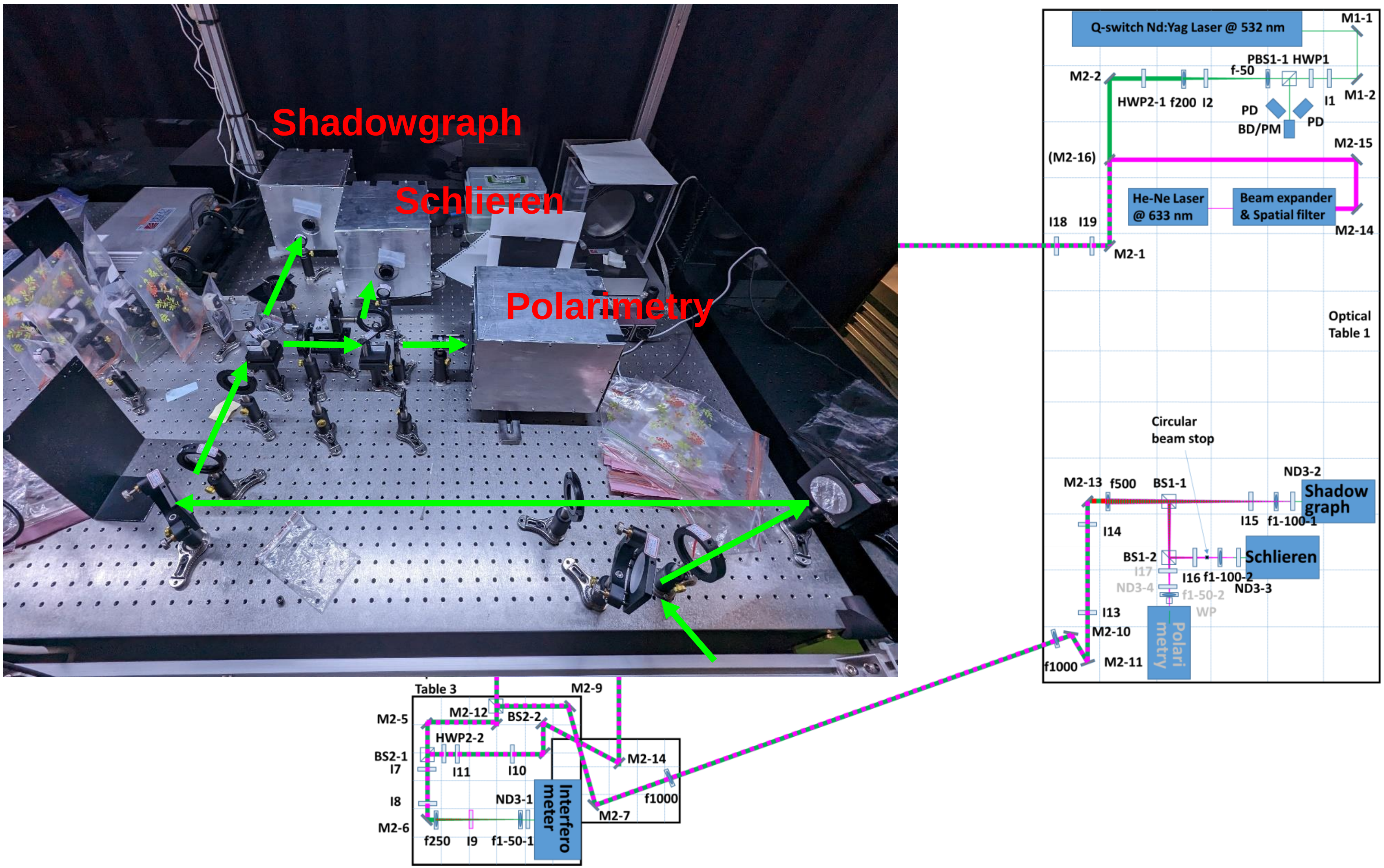

Shadowgraph
Schlieren
Polarimetry
Q-switch Nd:Yag Laser @ 532 nm
M1-1
PBS1-1 HWP1
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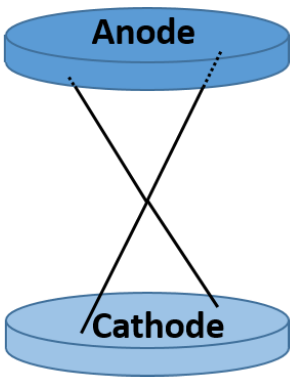
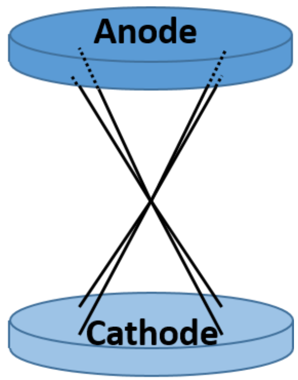
Table 3
M2-9
M2-5
M2-12
BS2-2
HWP2-2
BS2-1
I7
I11
I10
M2-14
I8
ND3-1
Interfero meter
f1000
M2-6
f250 I9 f1-50-1
M2-7

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

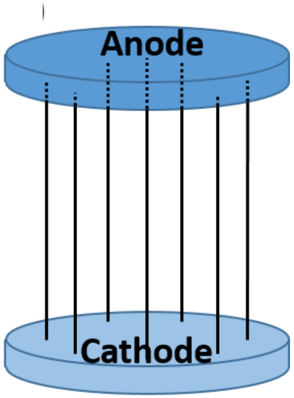
- x pinch



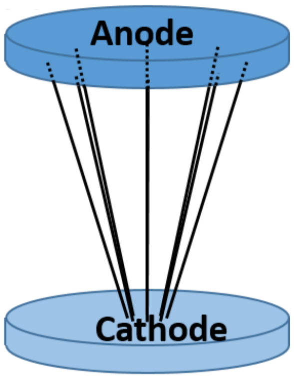
- multi-wires x pinch



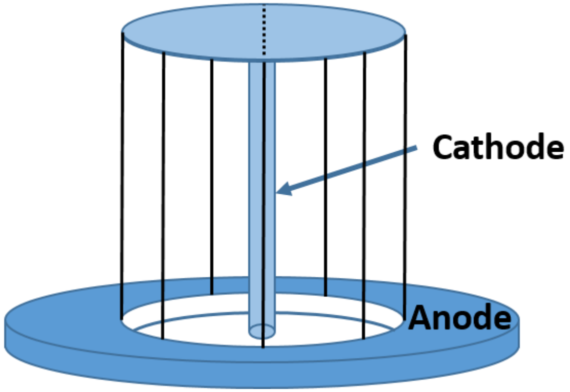
- wire array



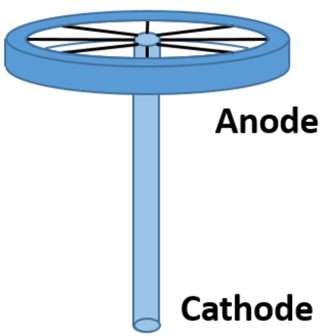
- conical-wire array



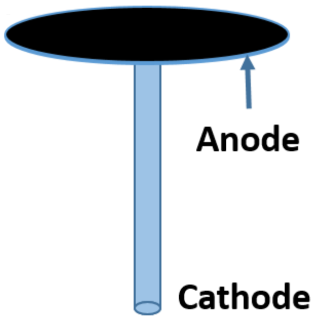
- inverse-wire array



- radial-wire array

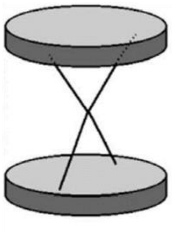


- radial foil

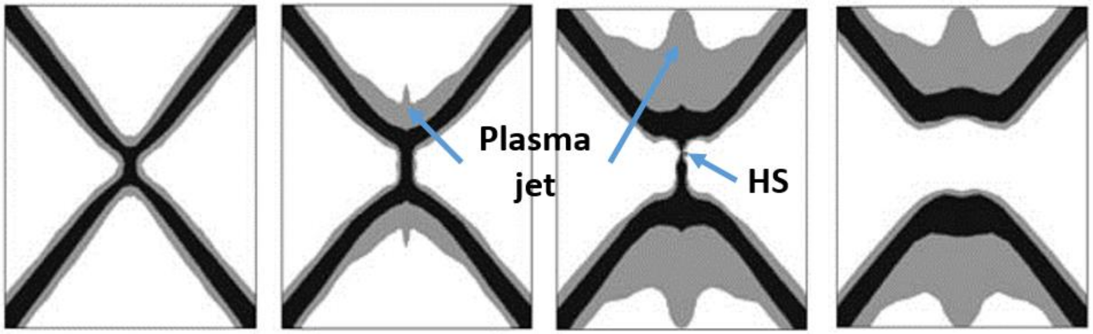


Spatial coherent hard x rays can be generated using x pinches for point-projection x-ray radiography

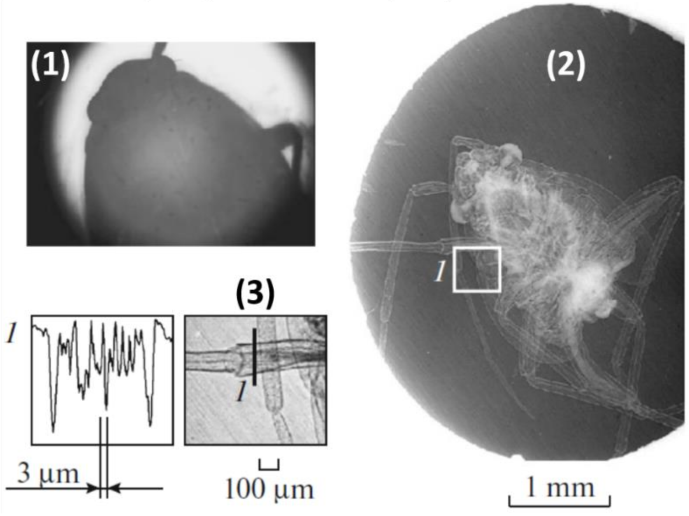
- **x pinch**



- **The process of an exploded x pinch**



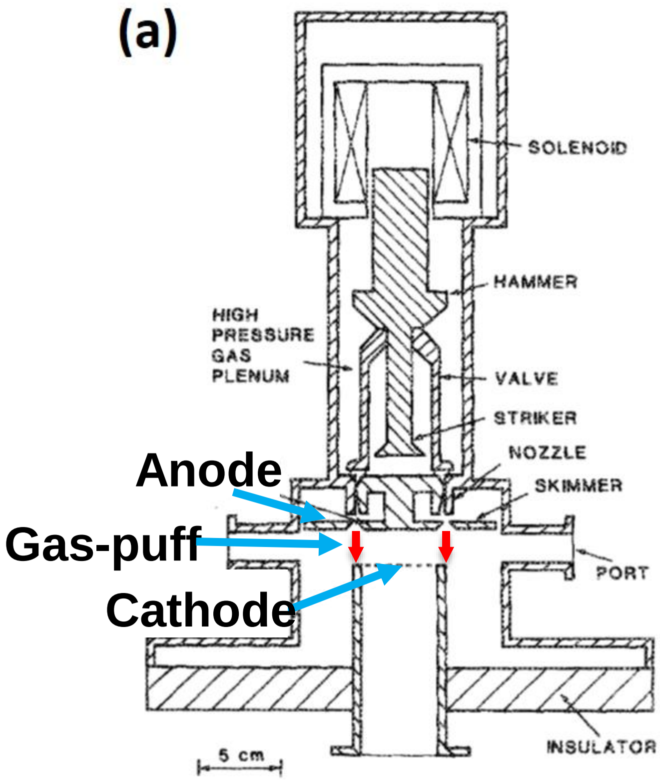
- **Point-projection x-ray radiography**



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

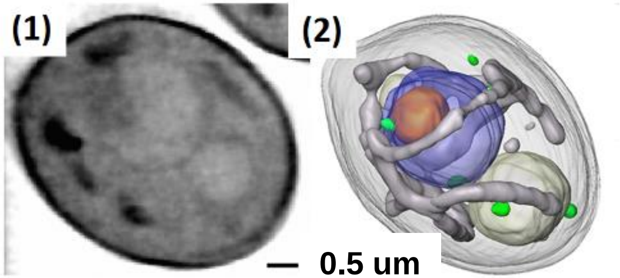
* G. V. Ivanenkov *et al.* Plasma Physics Reports 34, 619 (2008)
* T. A. Shelkovenko *et al.* Plasma Physics Reports 42, 226 (2016)
* T. A. Shelkovenko *et al.* IEEE Trans. Plasma Sci. 34, 2336 (2006)
* D. H. Kalantar *et al.* J. Applied Physics 73, 8134 (1993)

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.

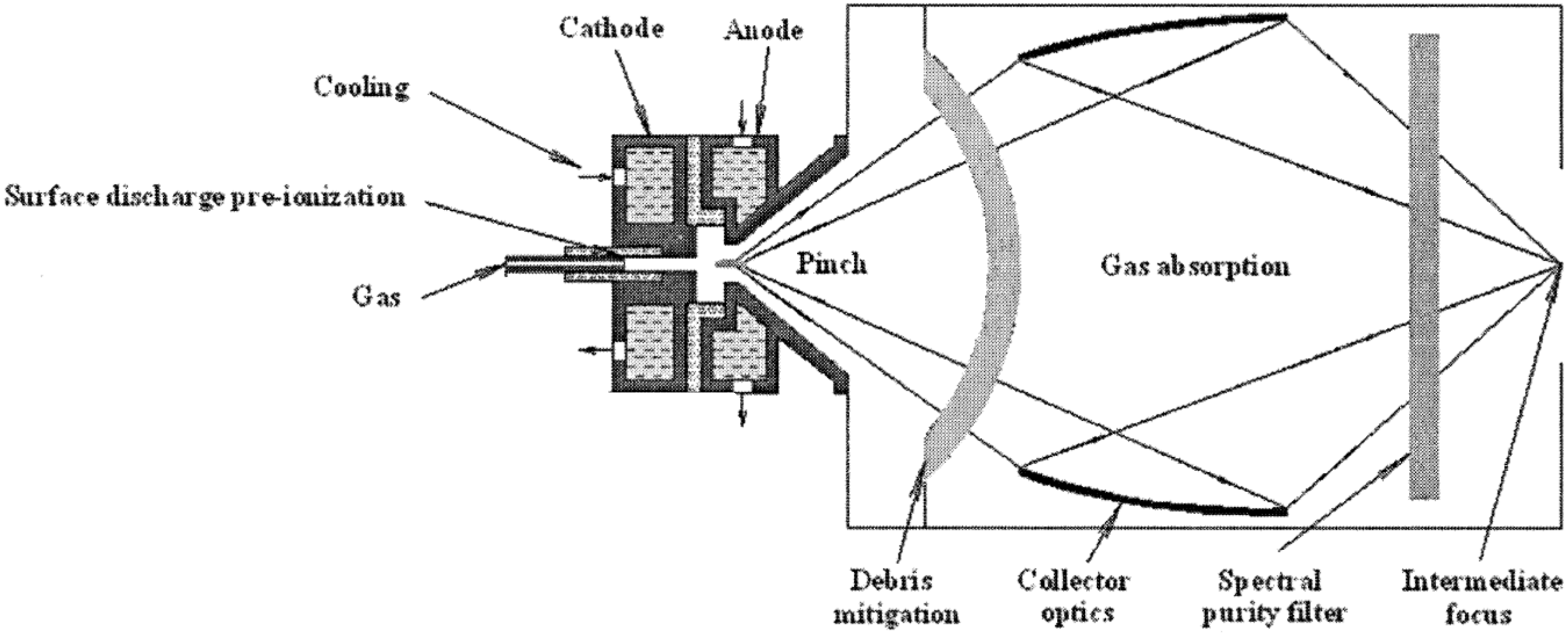
- Soft x rays (~520eV) from synchrotron radiation at Advanced Light Source (ALS) is used for 3-D x-ray tomographic microscopy.



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

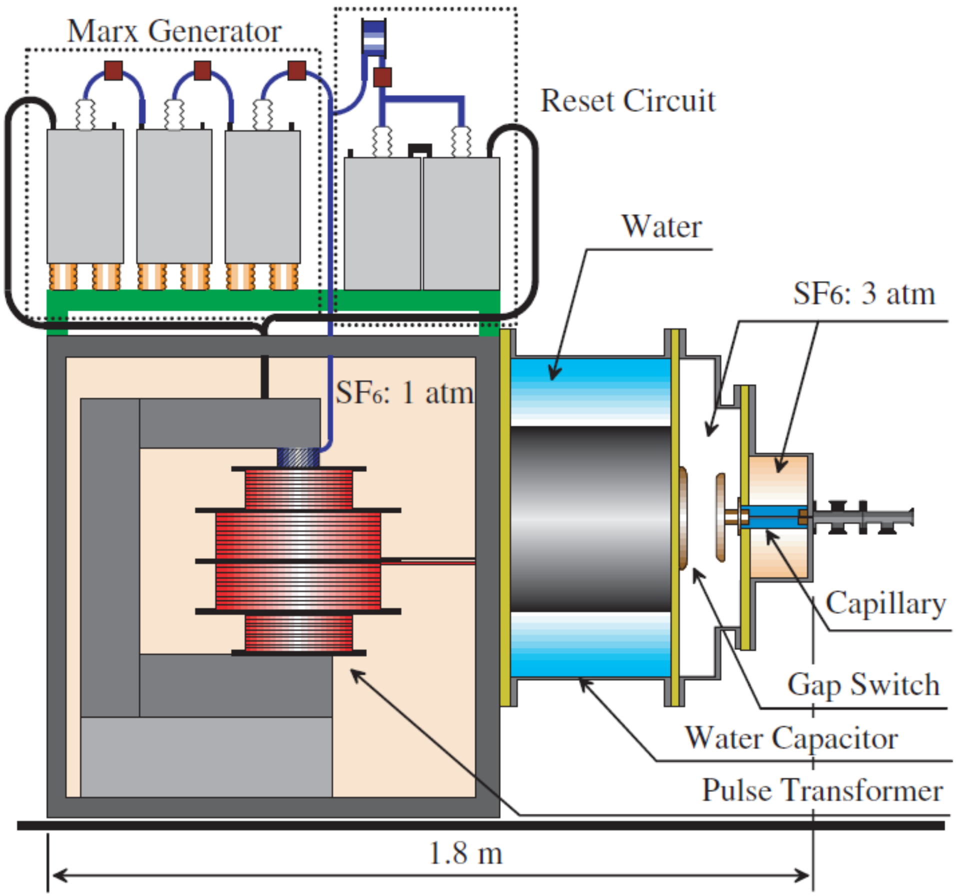
*P. Choi *et al.* Rev. Sci. Instru. 57, 2162 (1986)
*G. Nave *et al.* J. Appl. Phys. 65, 3385 (1989)
*M. Uchida *et al. Proc. National Acad. Sci.* 106, 19375 (2009)

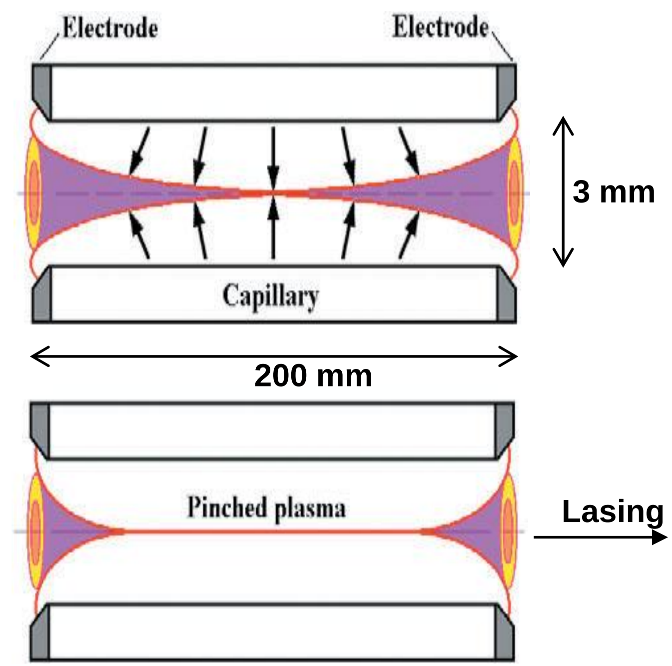
Discharge produced plasma can generate EUV light for EUV lithography



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



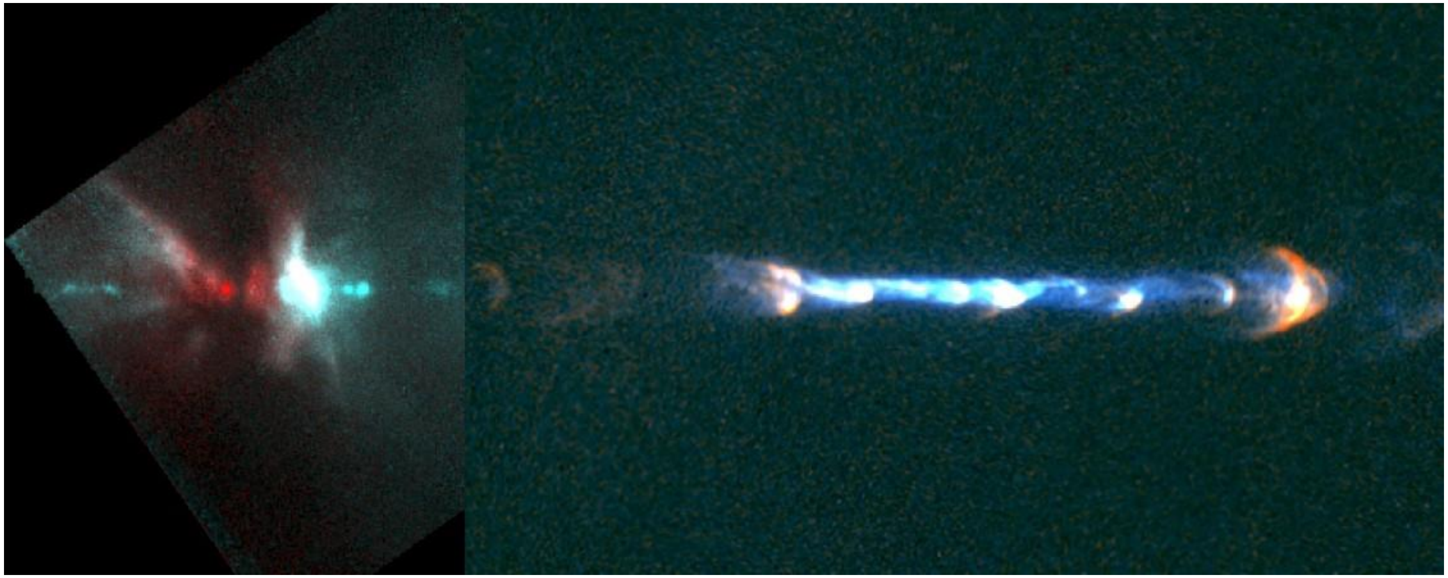


- **If 200～500 mTorr Ar is used as the filled gas, 46.9 nm (26.5 eV) Ne-like Ar laser can be built.**

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

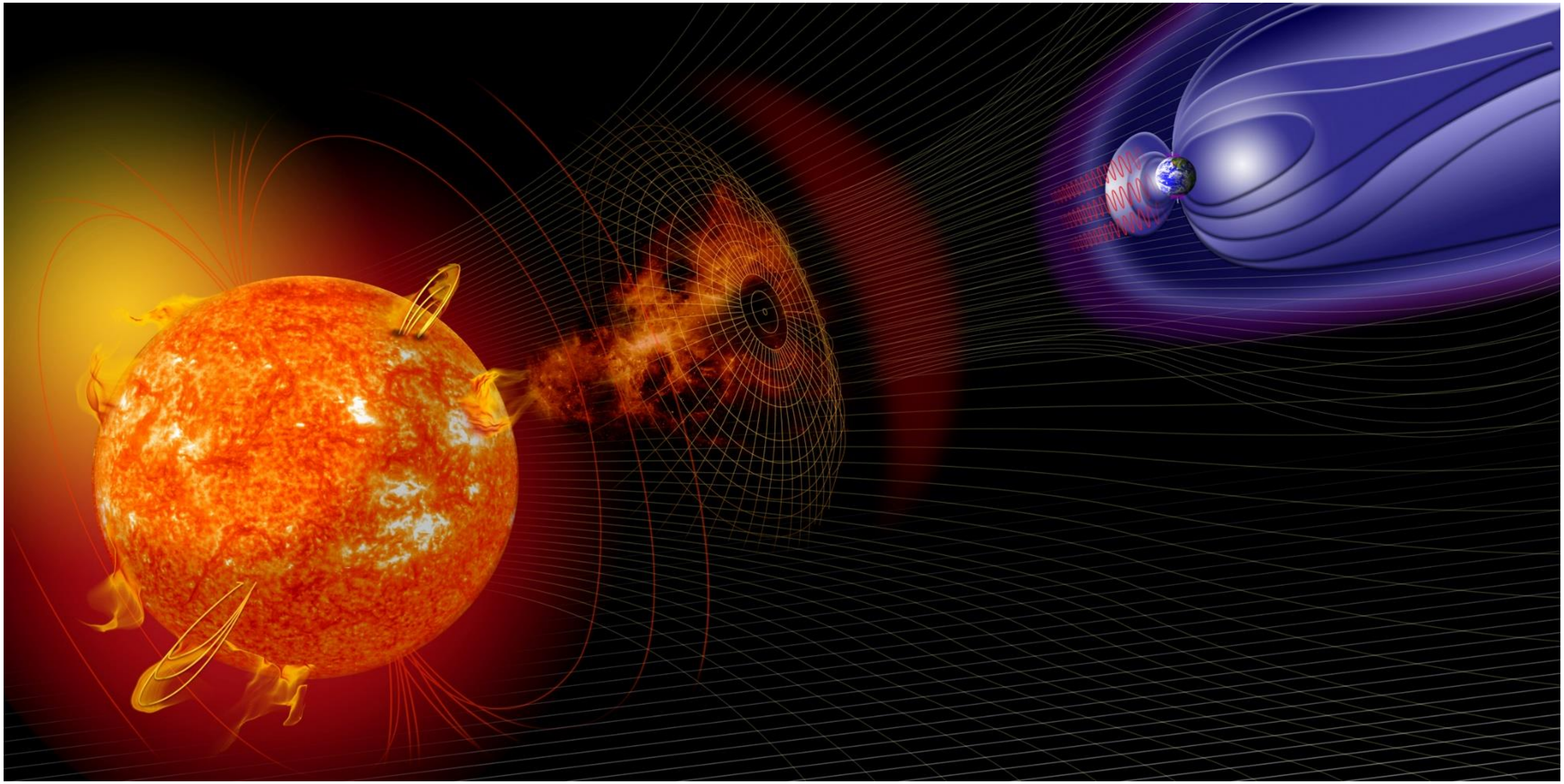
Astrophysics and space science can be studied in laboratory environments.

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



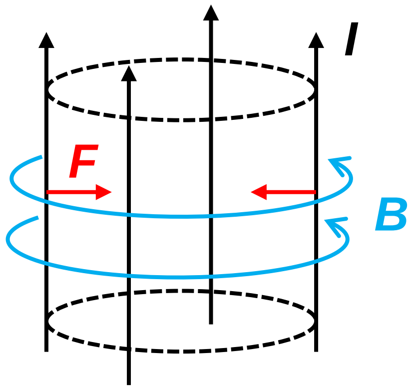
B. Reipurth and J. BallyAnnu. Rev. Astron. Astrophys., **39**, 403 (2001)

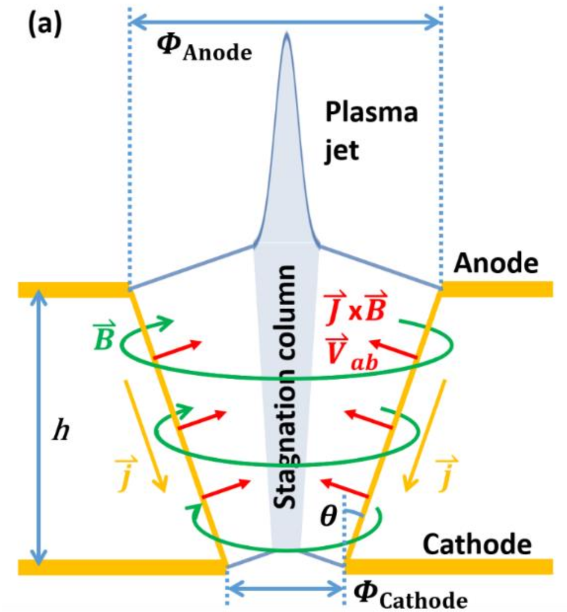
Solar wind is a supersonic plasma plume coming from the sun



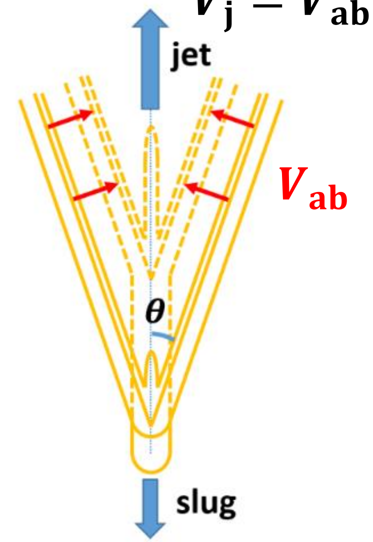
https://www.nasa.gov/mission_pages/sunearth/spaceweather/index.html

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





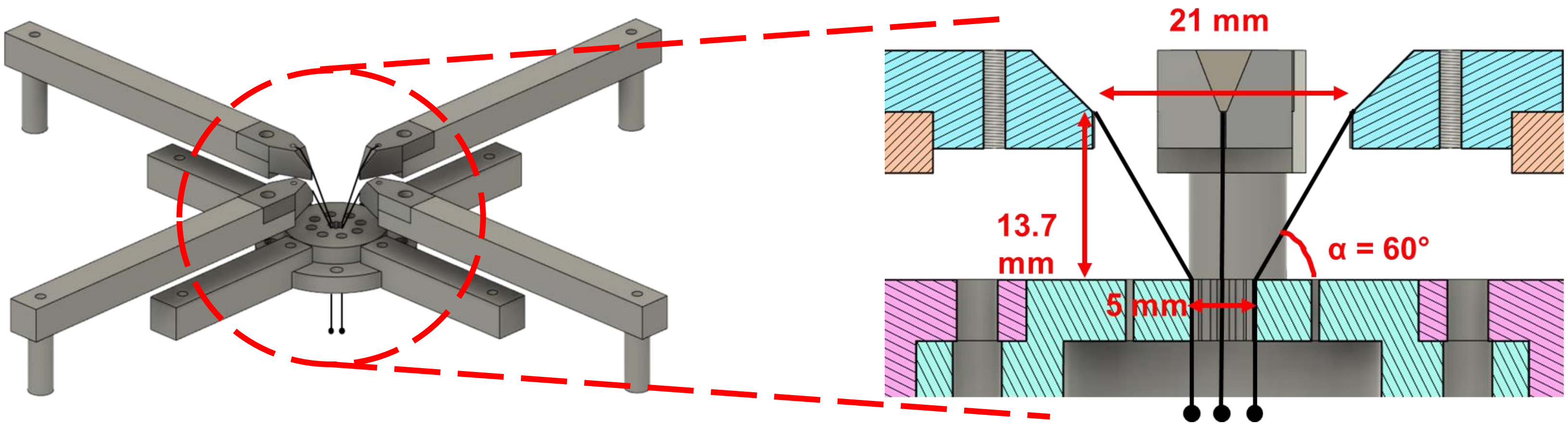
$$V_j = V_{ab} \frac{1 + \cos\theta}{\sin\theta}$$



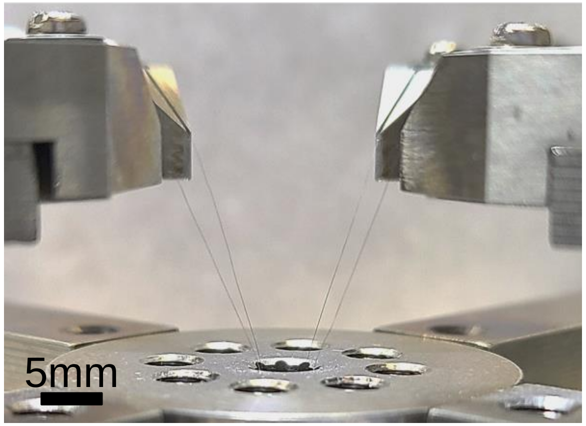
1. Wire ablation : corona plasma is generated by wire ablations.
2. Precursor : corona plasma is pushed by the $\vec{J} \times \vec{B}$ force and accumulated on the axis forming a precursor.
3. Plasma jet is formed by the nonuniform z-pinch effect due to the radius difference between the top and the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

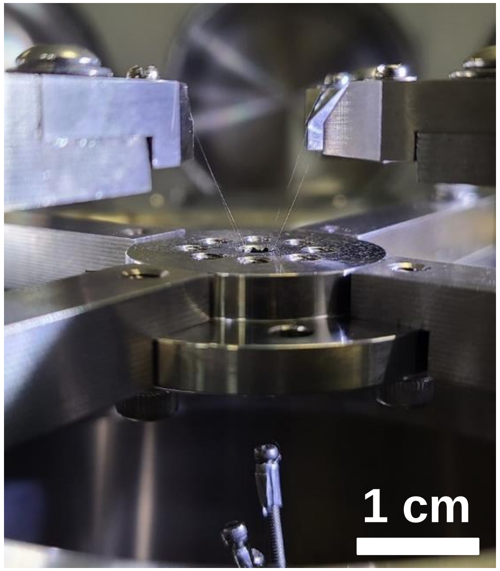
D. J. Ampleforda, et al., Phys. Plasmas 14, 102704 (2007)
G. Birkhoff, et al., J. Applied Physics 19, 563 (1948)

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



• Conical-wire array

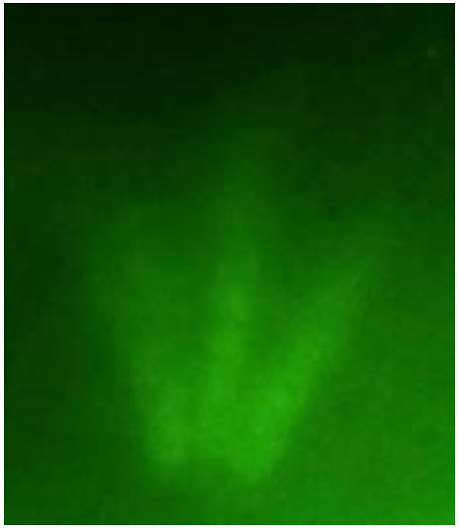




- Material : Tungsten
- Number of wires : 4
- Diameter : 0.02 mm

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

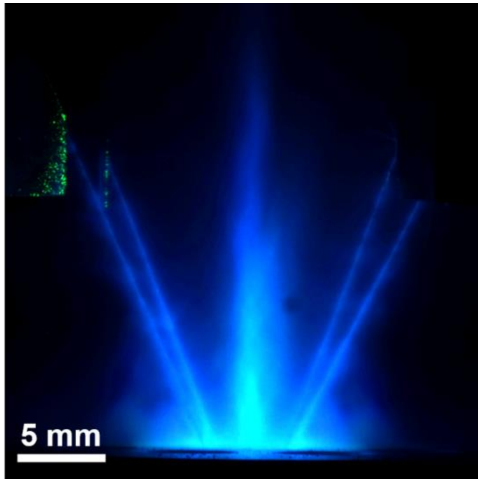
- Image in UV/soft x ray



(Brightness is increased by 40 %.)

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

- Image in visible light



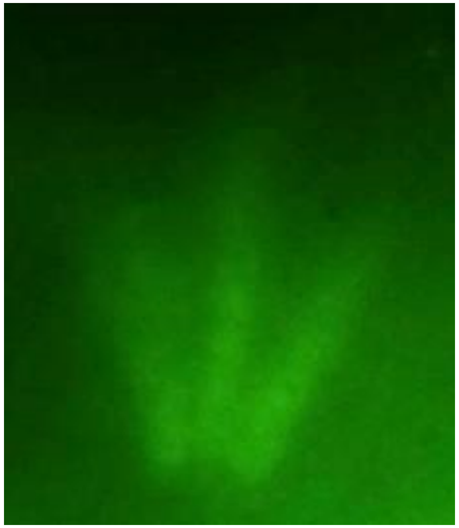
(Enhanced by scaling the intensity range linearly from 0 − 64 to 0 − 255.)

- 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



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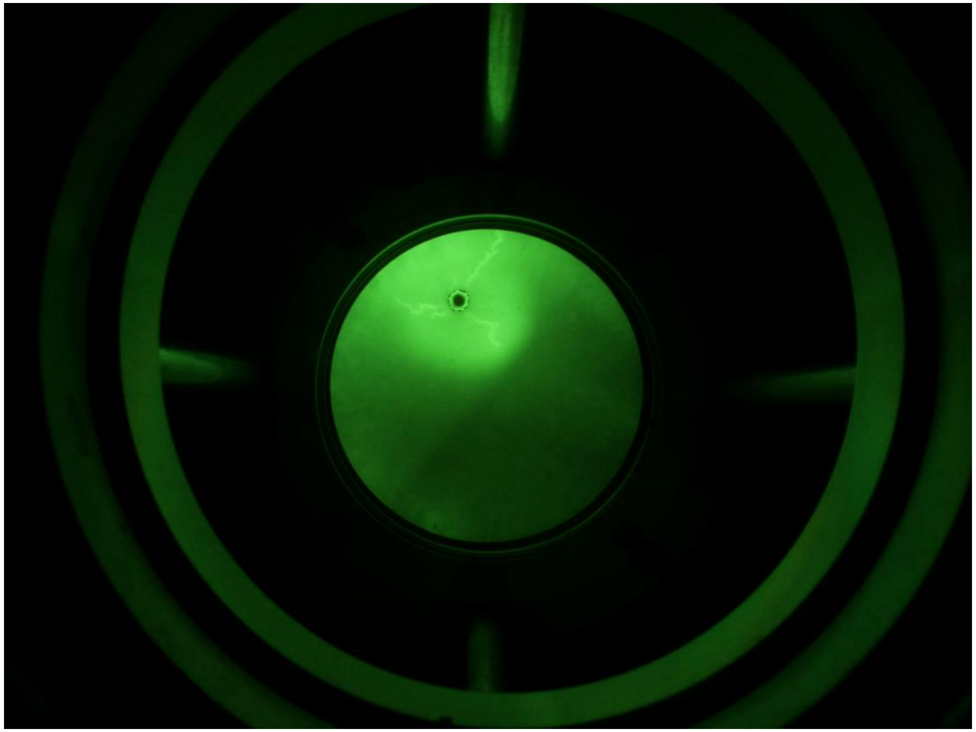
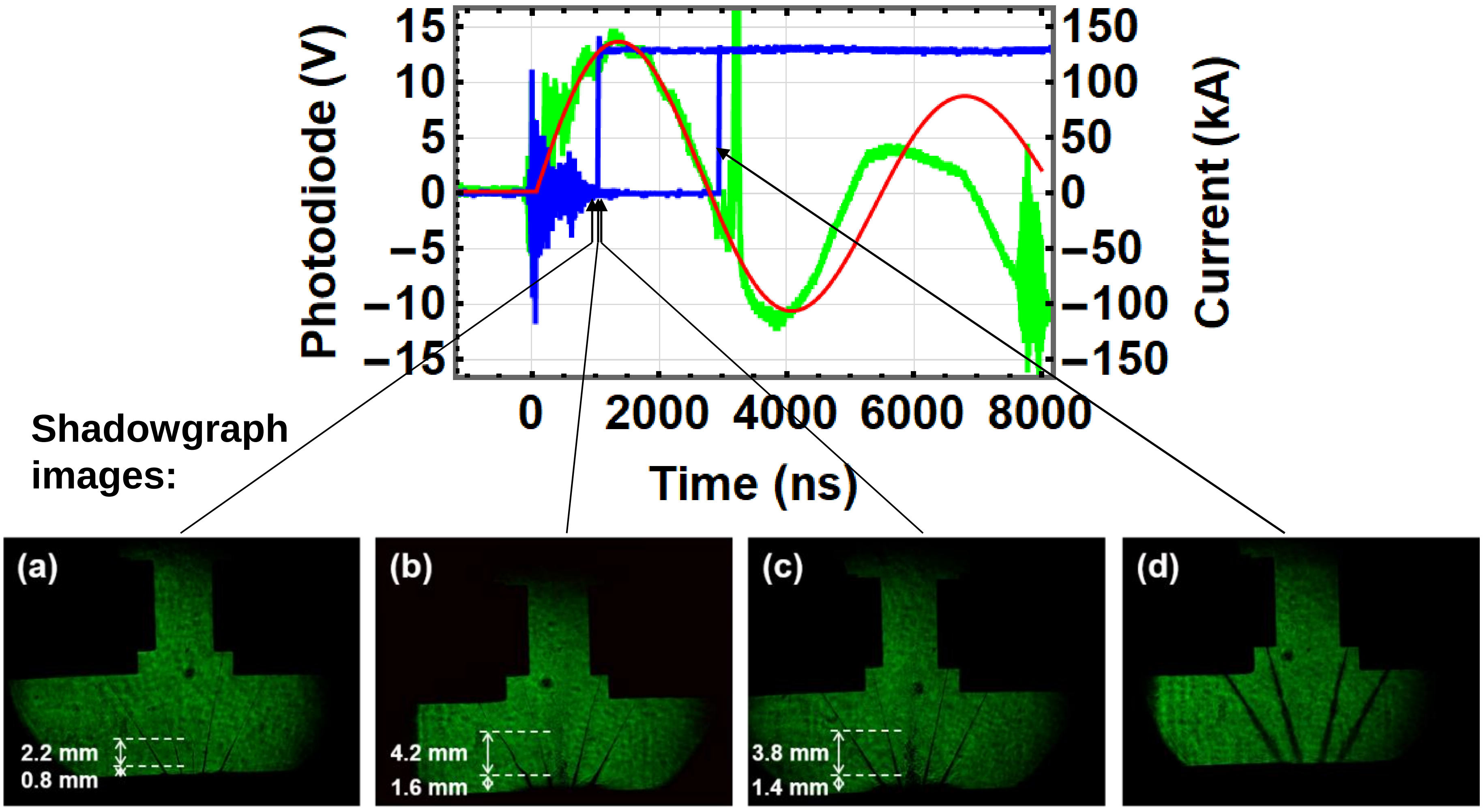


- Pinhole diameter: 0.5 mm, i.e., spatial resolution: 1 mm.

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

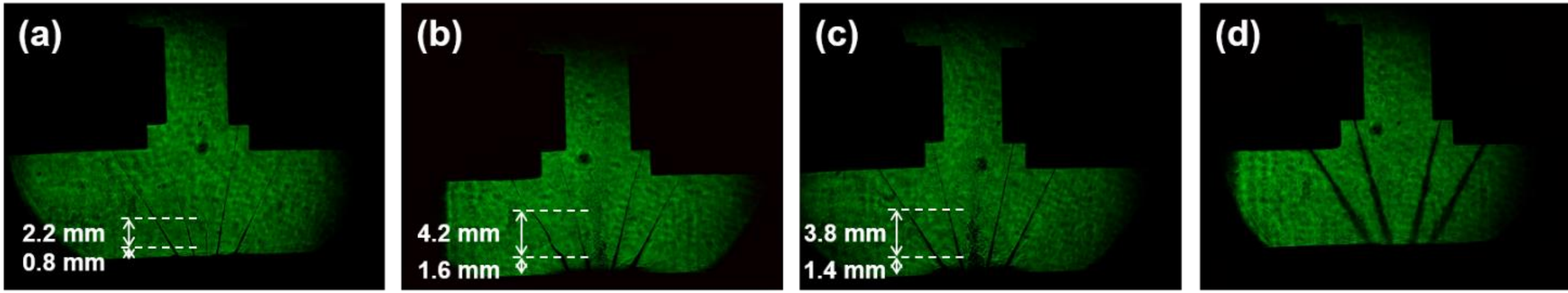
- **Shadowgraph images:**



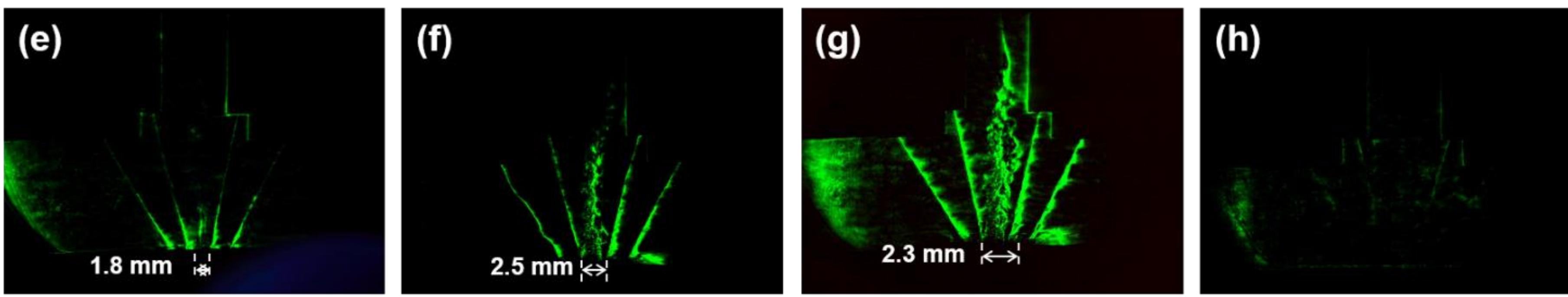
930 ± 20 ns | 975 ± 2 ns | 985 ± 3 ns | 2945 ± 2 ns

Plasma jet propagation was observed using laser diagnostics

- **Shadowgraph images:**

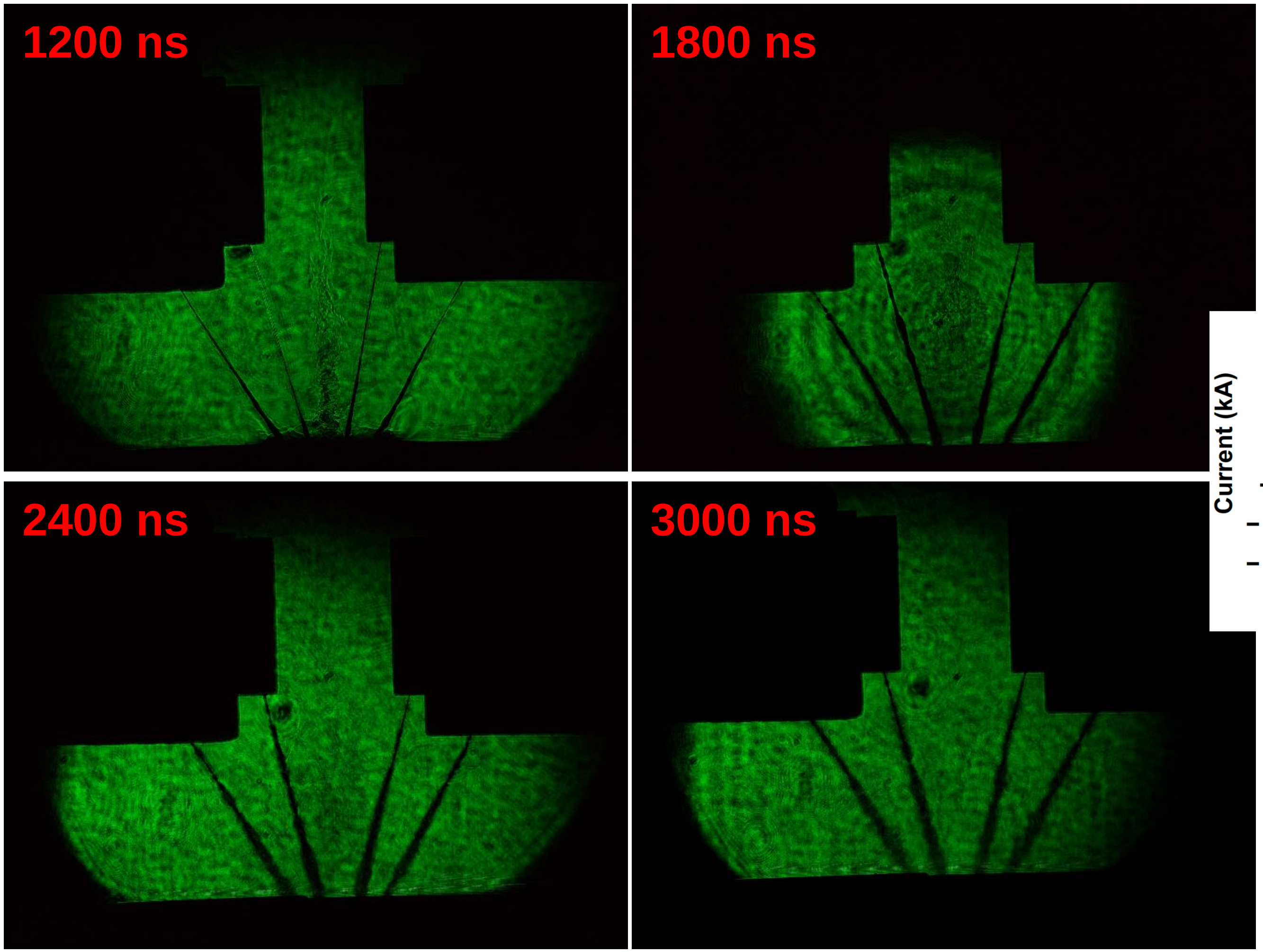


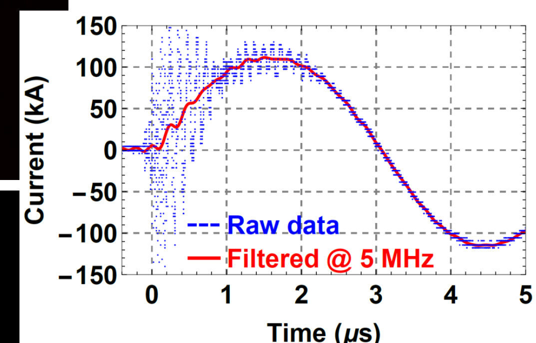
- **Schlieren images:**



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

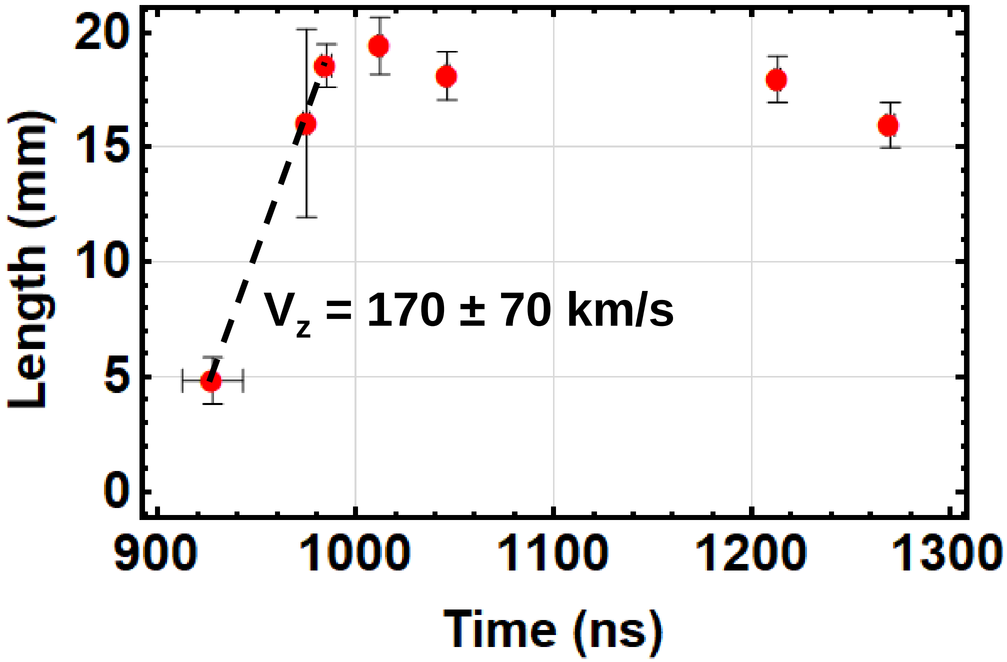
Tungsten wires are being evaporated by the pulsed current

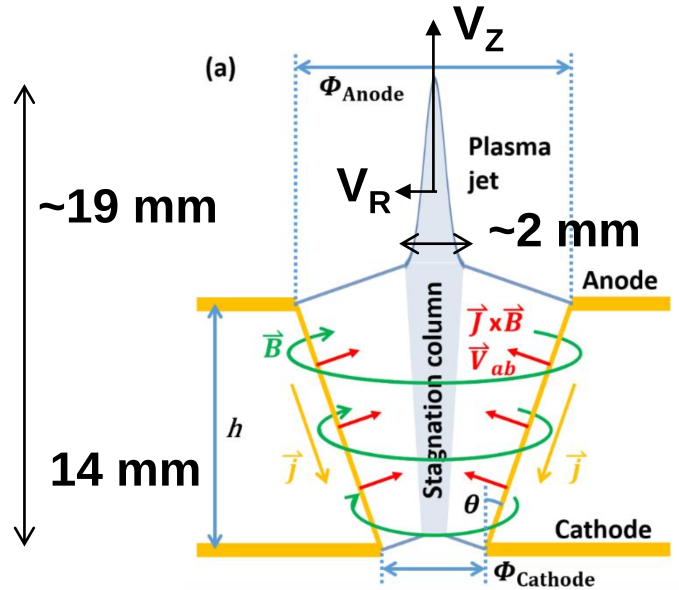




To be continued…..

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



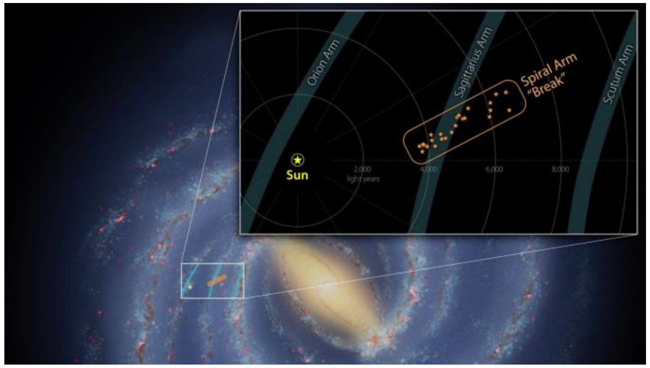


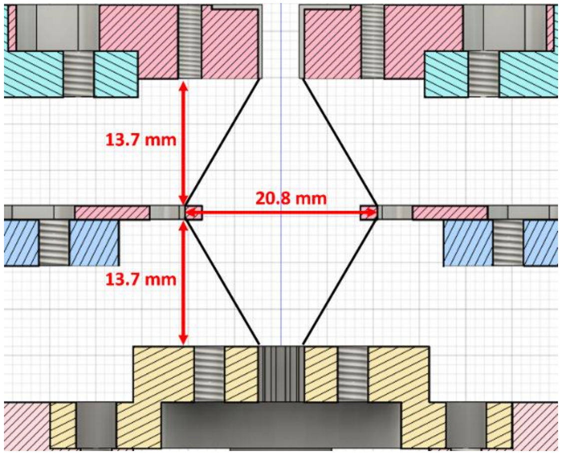
$$M = \frac{V_Z}{V_R} \leq \frac{Z}{r} \approx \frac{(19-14)\text{ mm}}{\frac{2\text{ mm}}{2}} = 5$$

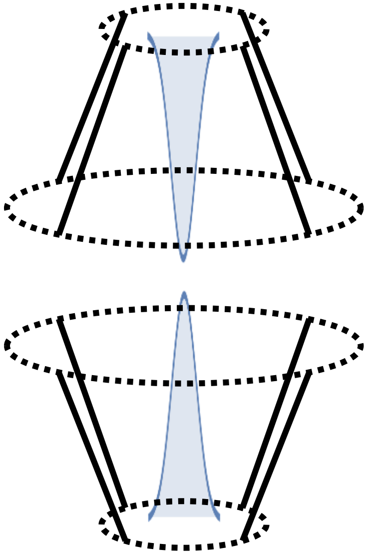
$$V_{ab} = V_j \frac{\sin\theta}{1+\cos\theta} = 50 \pm 20\text{ km/s}$$

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.**



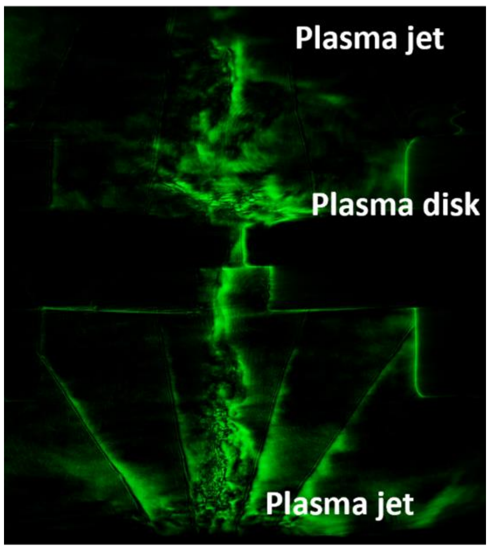




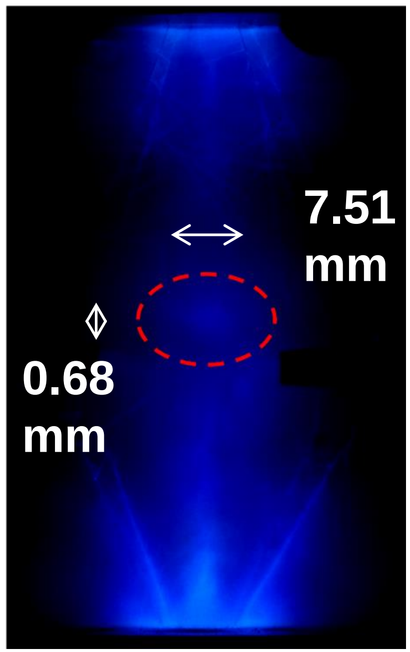
Jet Propulsion Laboratory [NASA/JPL] Astronomers Find a ‘Break’ in One of the Milky Way’s Spiral Arms (Aug 17, 2021)

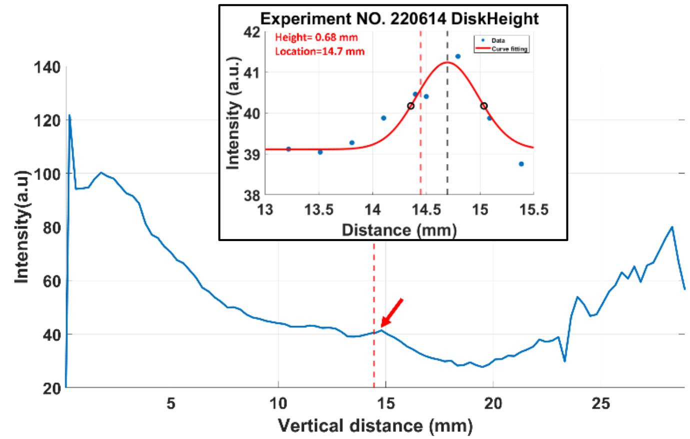
A plasma disk with a height of ~0.68 mm and a width of ~7.51 mm was generated ~0.15 mm above the middle plane

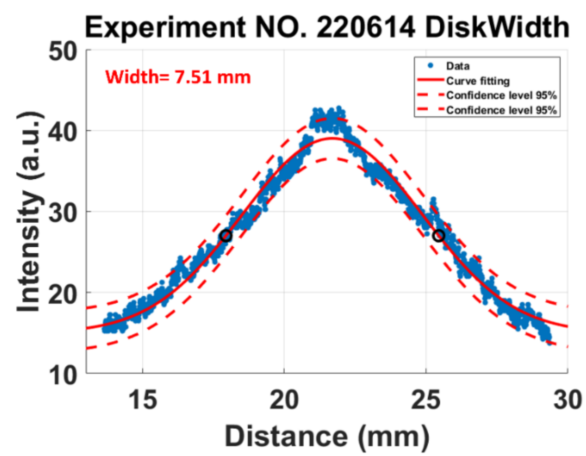
- **Schlieren image:**



- **Time-integrated image:**



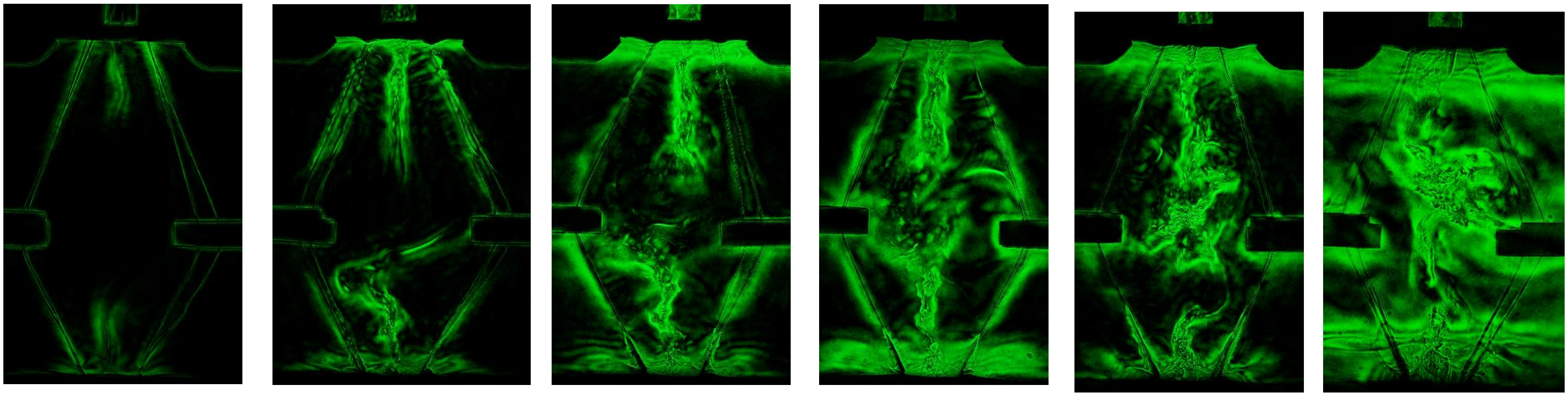




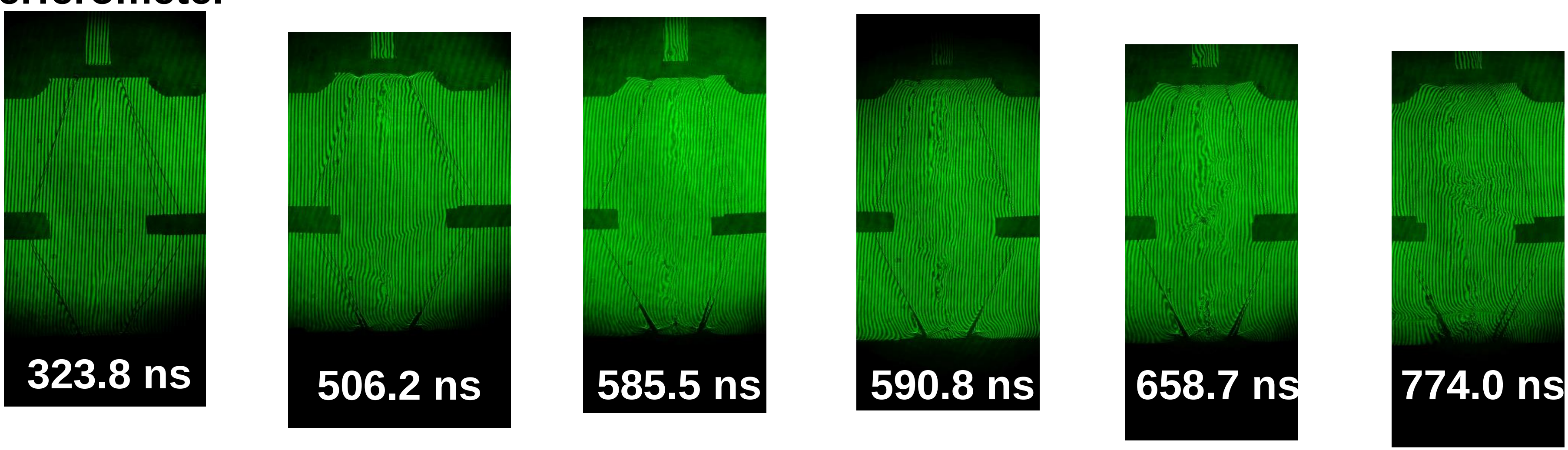
M.-S. Kuo, NCKU Master Thesis 2022

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

Schlieren

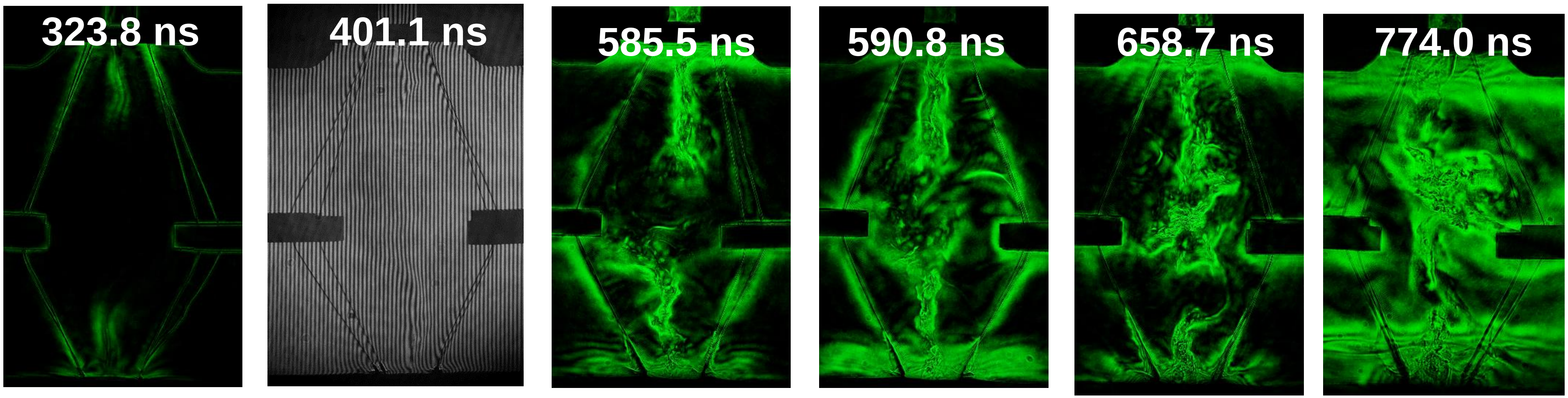


Interferometer

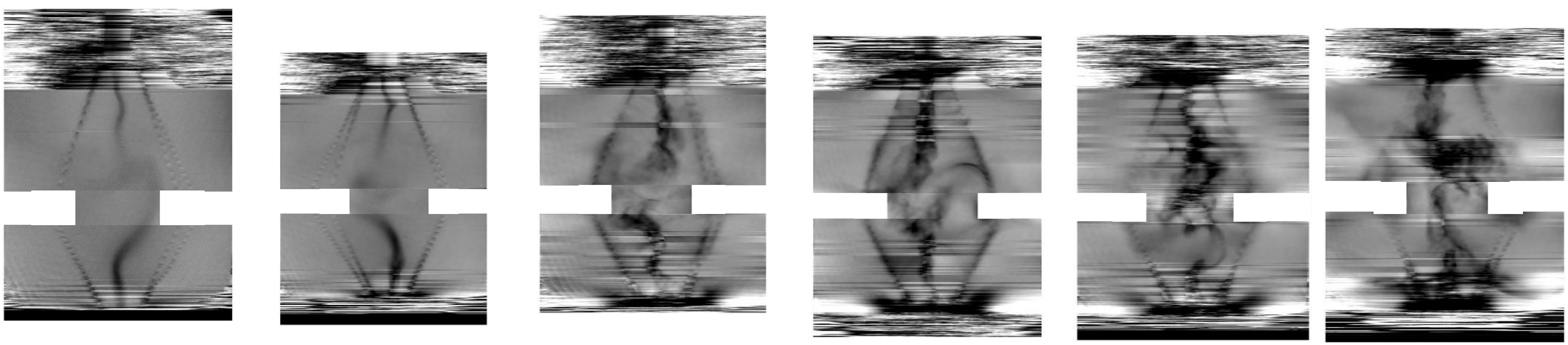


The plasma disk with a number density of ~ 10^{18} cm^{-3} was generated

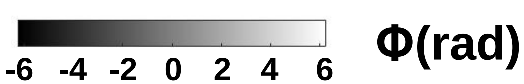
Schlieren



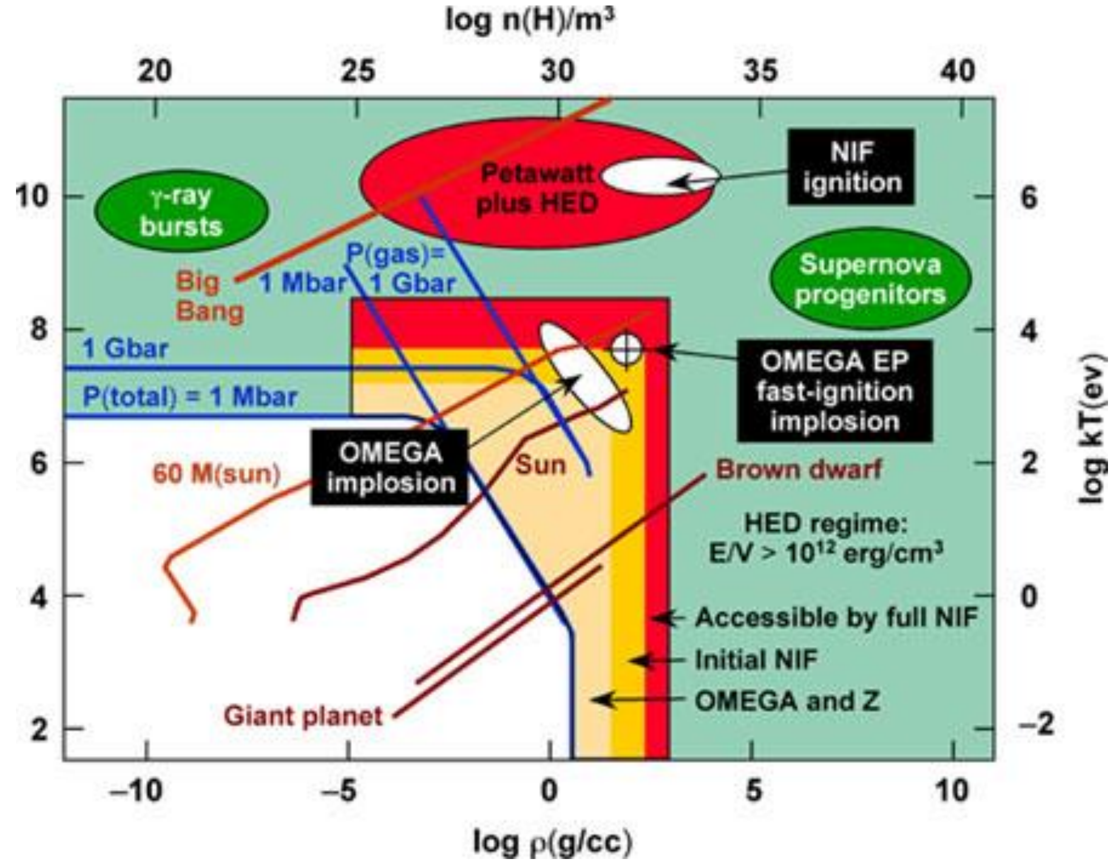
Interferometer



$-2\pi \sim 2\pi \Rightarrow 0 \sim 4.2 \times 10^{17}\ cm^{-2}$
$\Rightarrow 8.4 \times 10^{17}\ cm^{-3}$ for L= 5mm



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

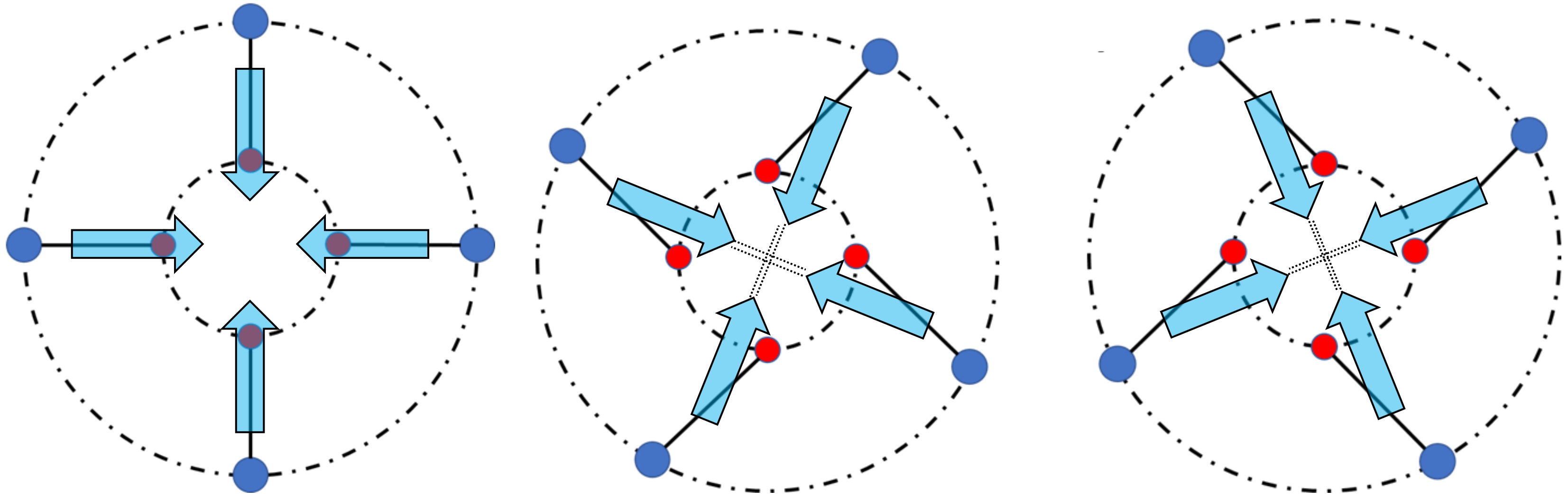


- **The energy density of HEDP regime is higher than 1 kJ of energy per 10 mm³.**

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?

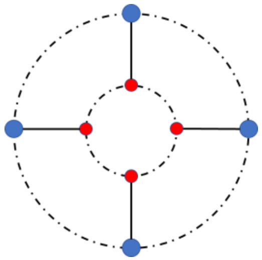
- **Non-rotation**
- **Clockwise 45°**
- **CCW 45°**

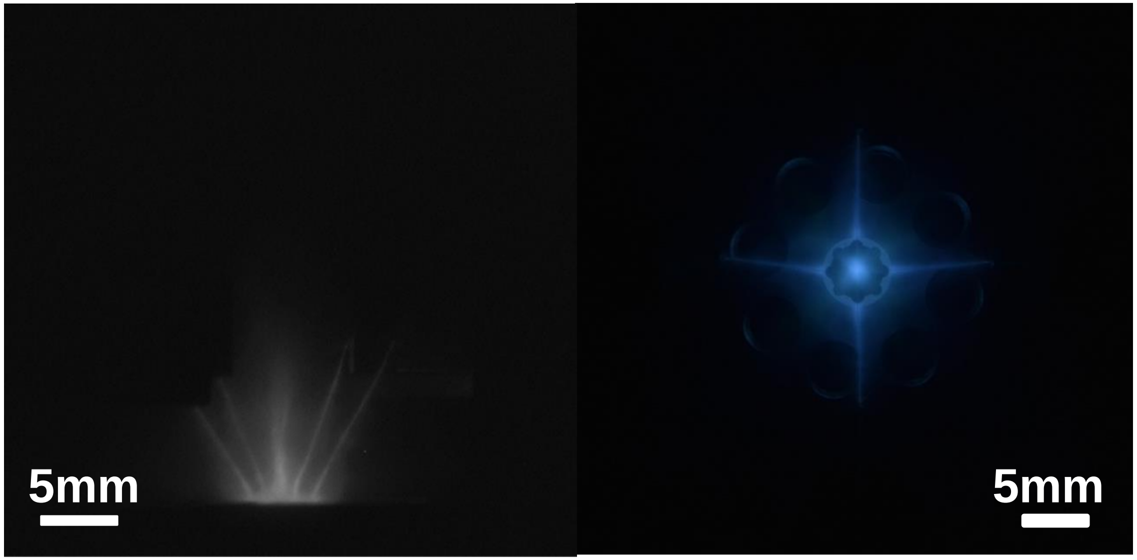


Y.-C. Lin, NCKU Master Thesis 2021

The plasma jet is a bright spot from the top view

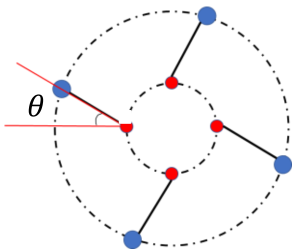
- **Non-rotation**

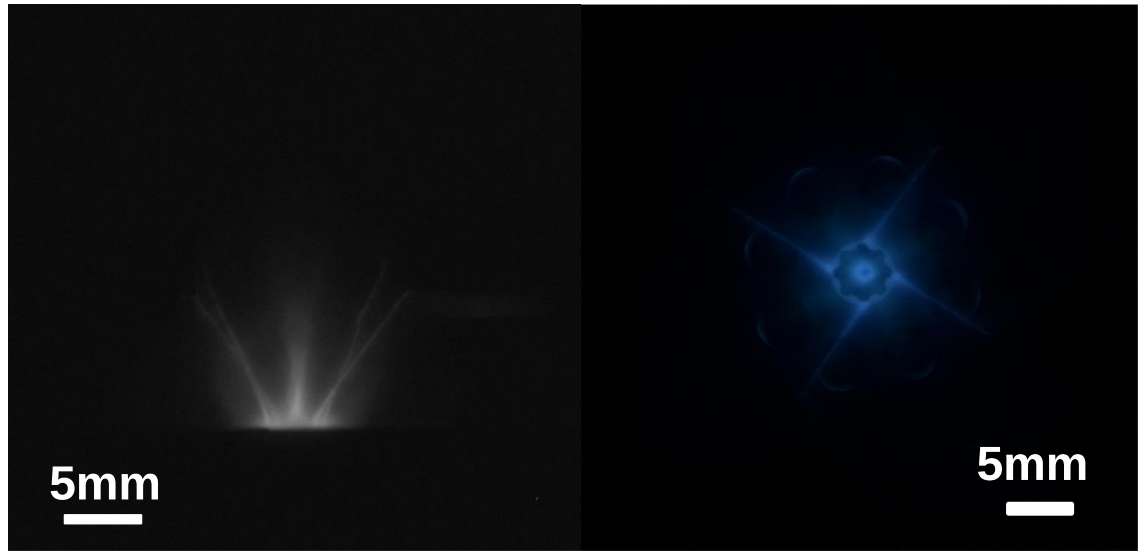




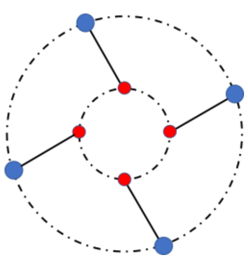
Hollow plasma jets were generated when the conical-wire arrays were twisted

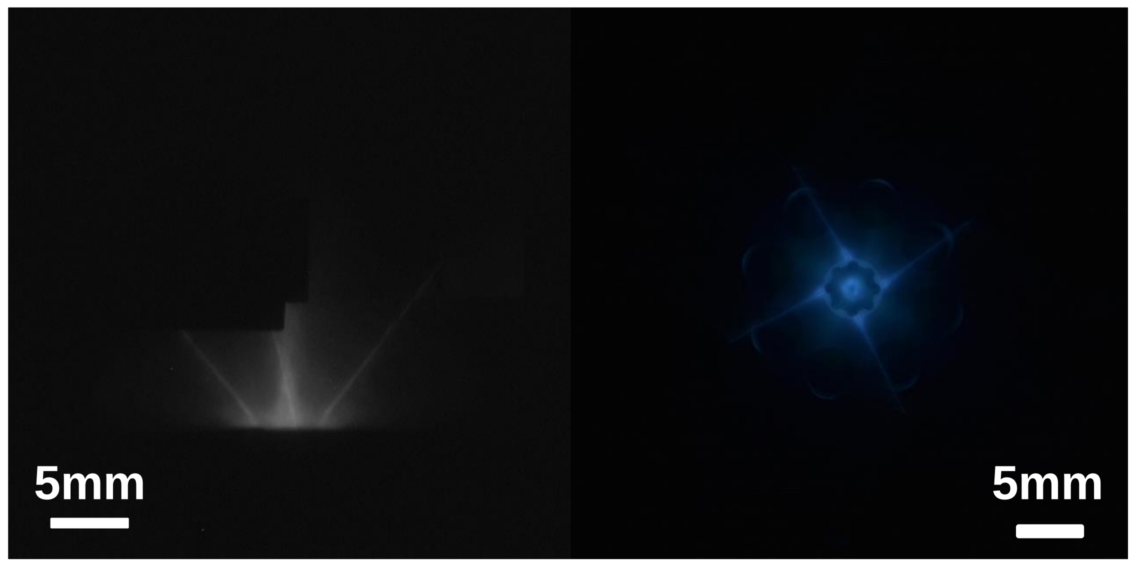
- **Clockwise 30 °**



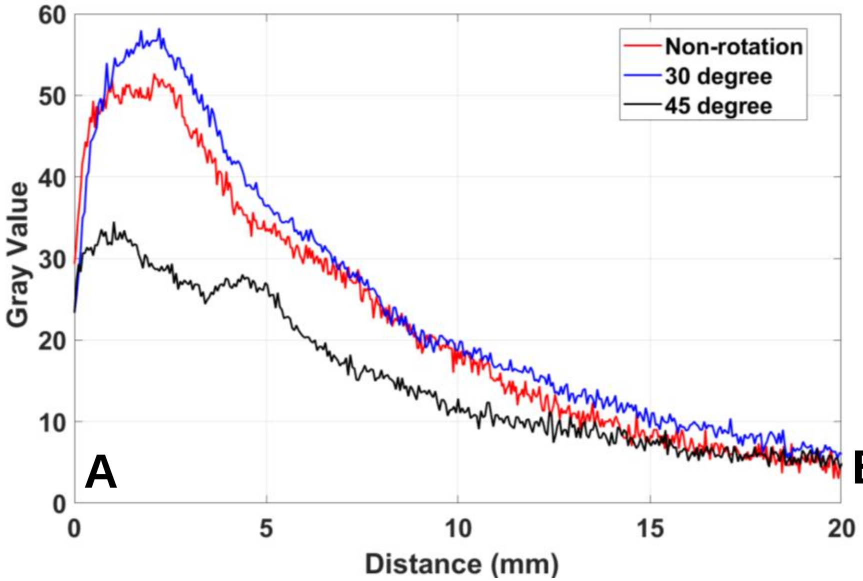


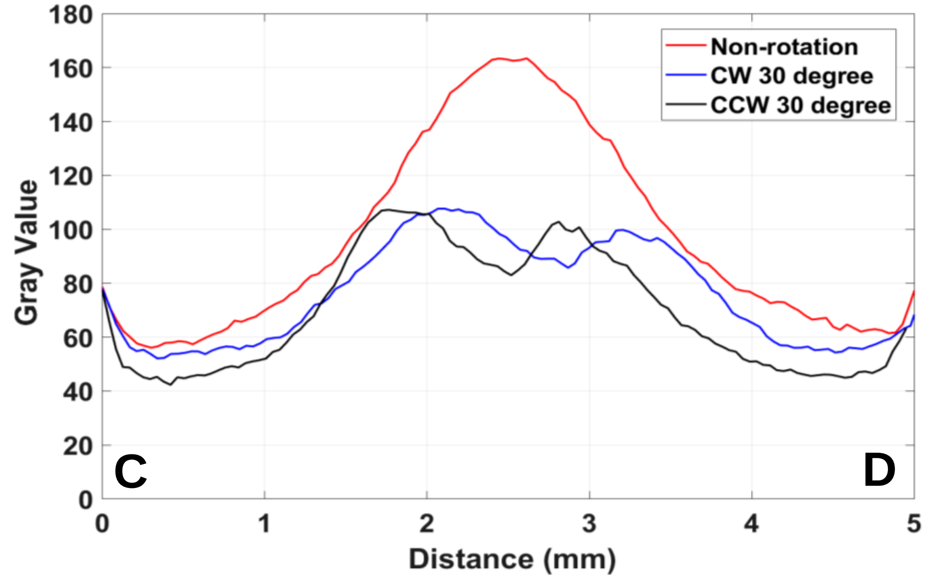
- **Counter clockwise 30 °**

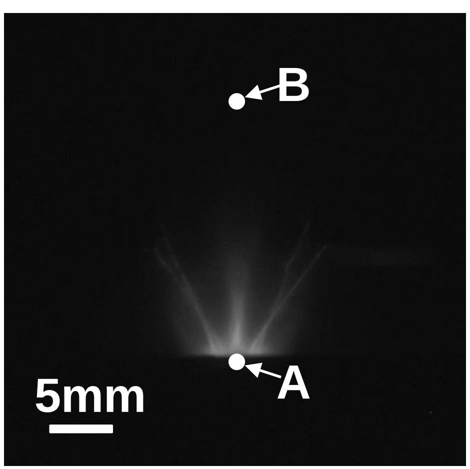




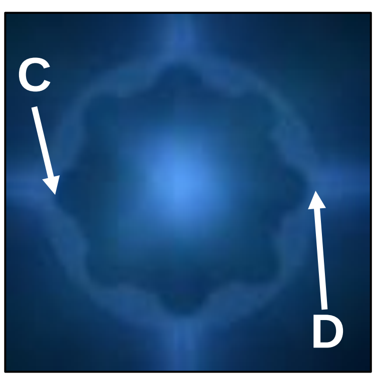
The hollow region at the center was due to angular momentum conservation of the in-coming plasma flow



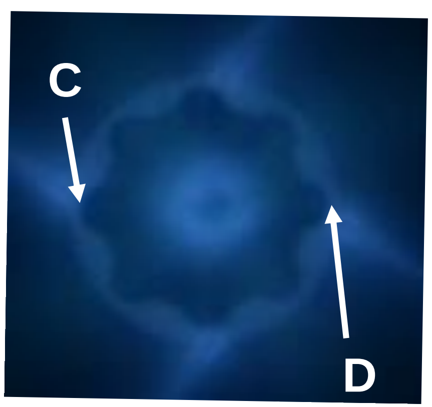




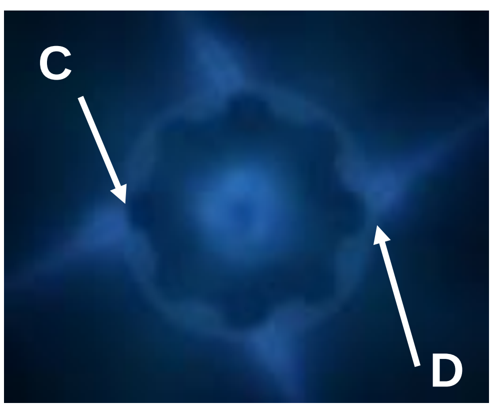
- 0 °



- CW 30 °



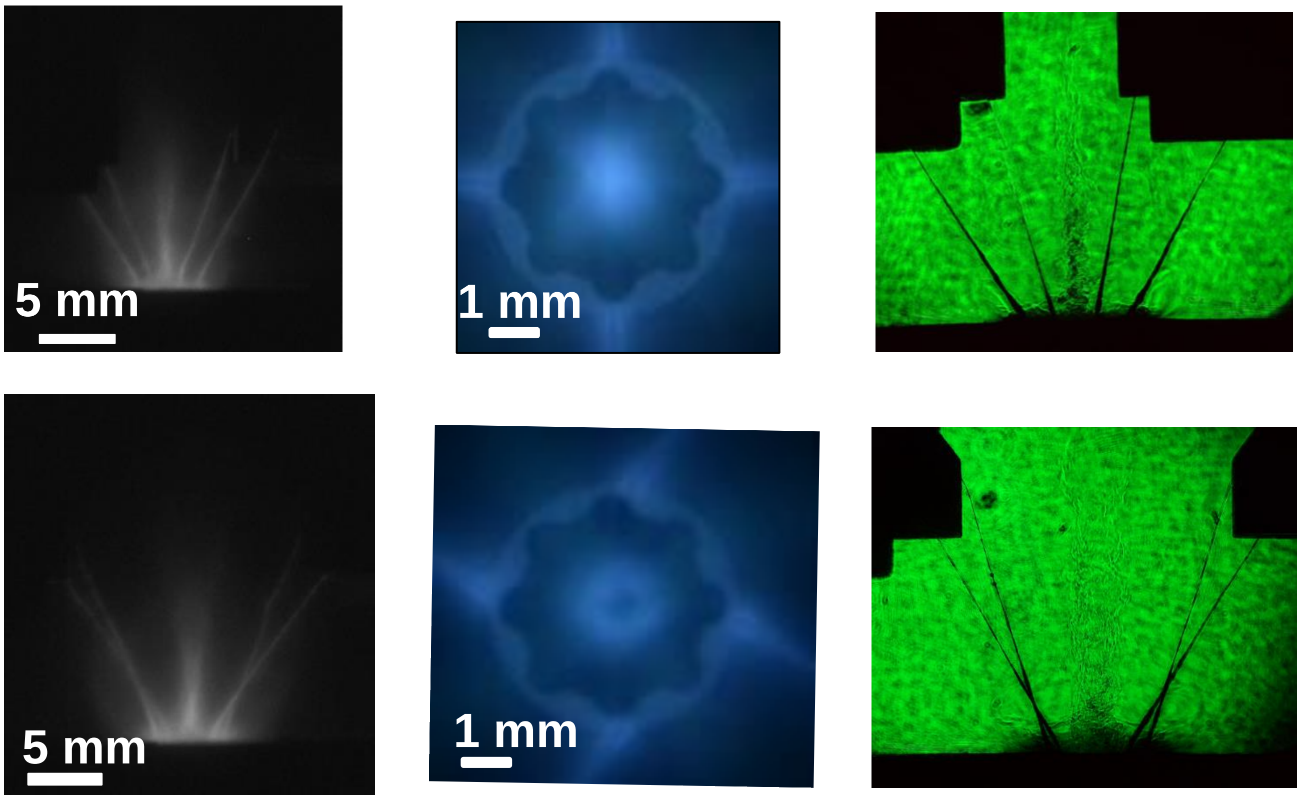
- CCW 30 °



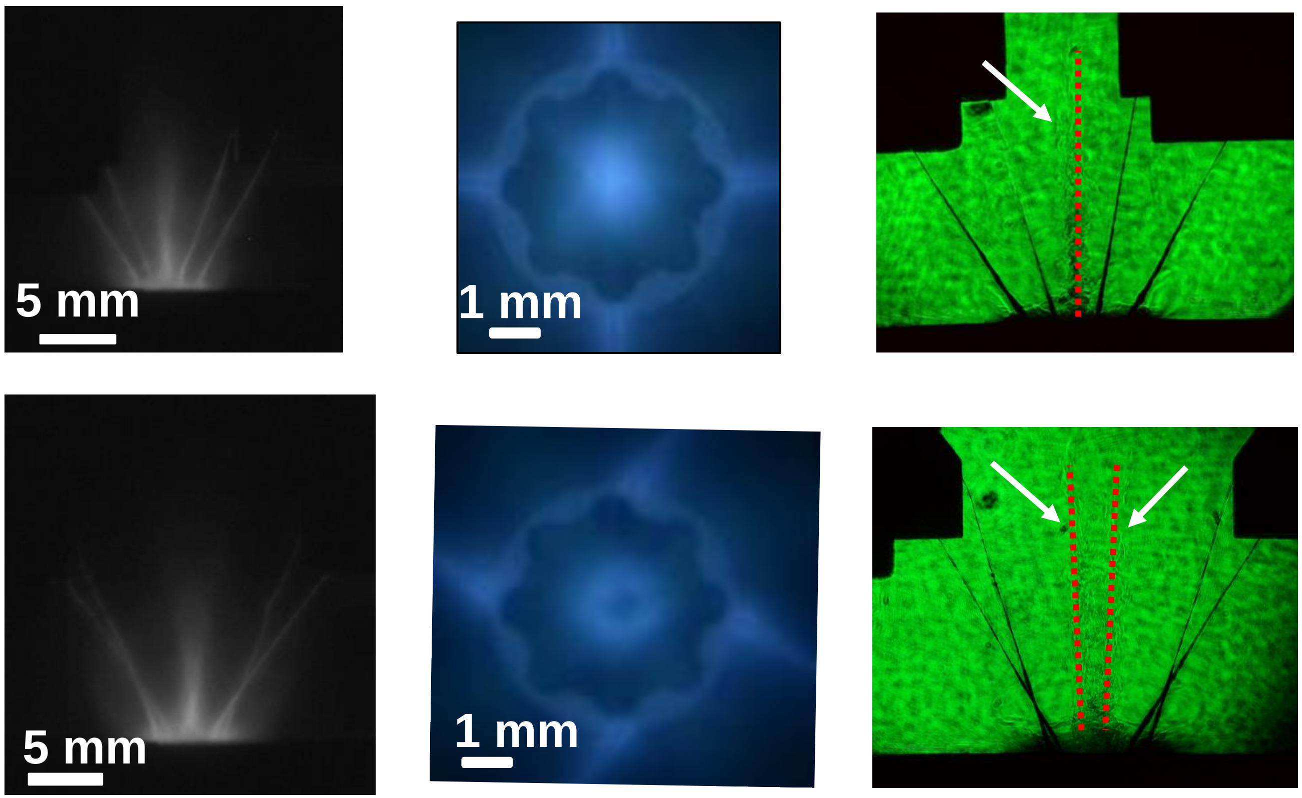
5mm

D. J. Ampleforda, et al., PRL 100, 035001 (2008)

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

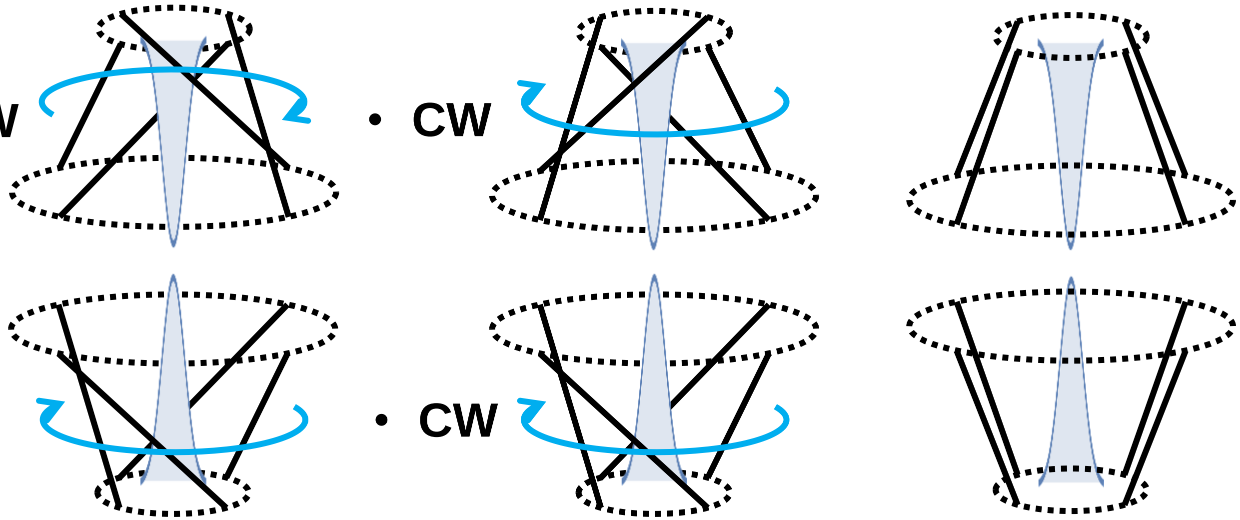


A “tornado” is generated by the twisted conical-wire array

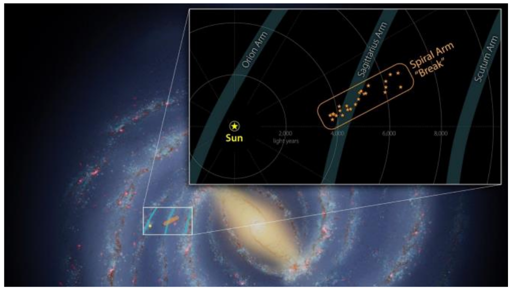


Can a rotating plasma disk be formed?
To be continue…

- CCW
- CW
- CW
- CW



- No rotation

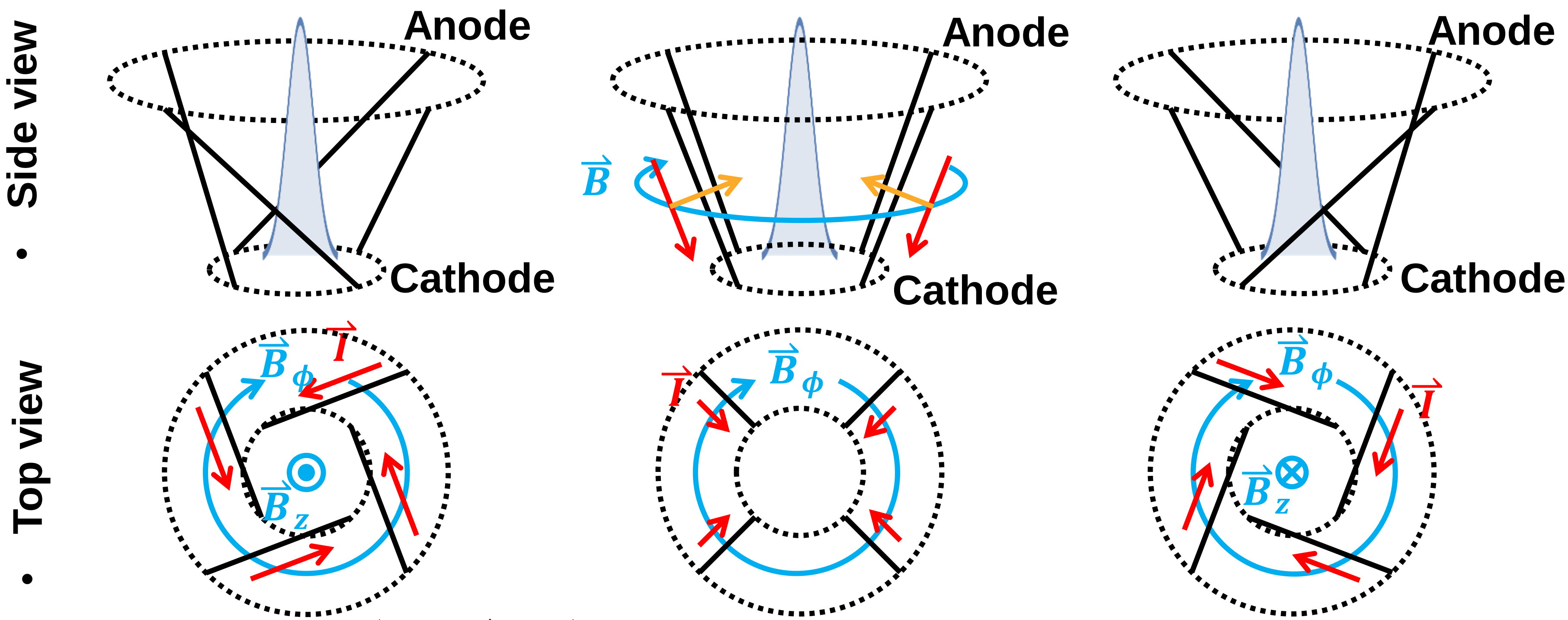


- **Astronomers Find a 'Break' in One of the Milky Way's Spiral Arms.**

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

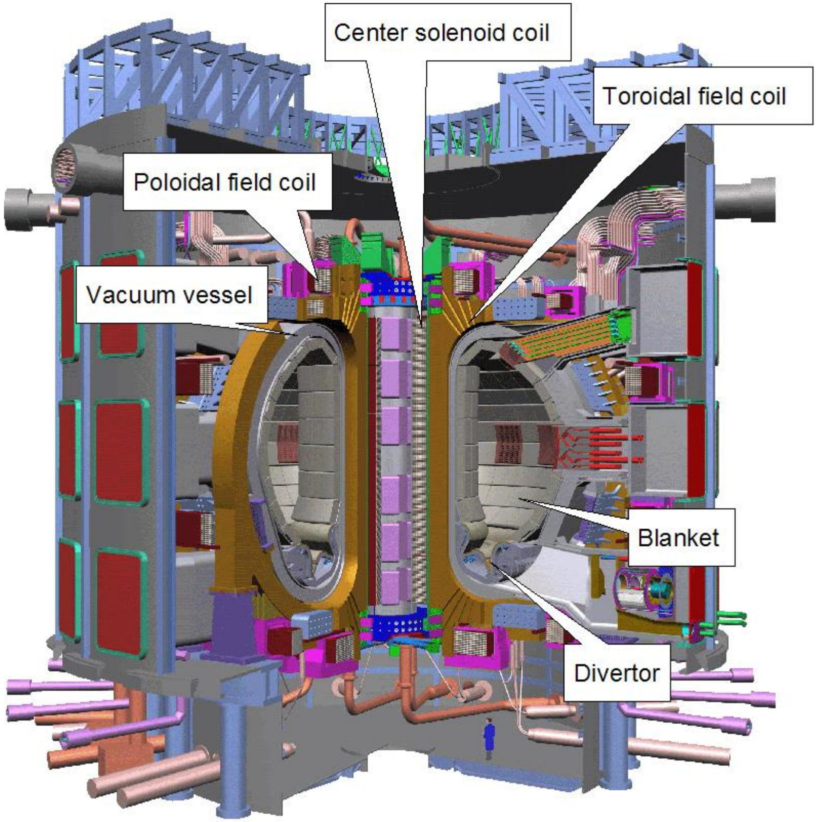
- CW: + + | - - | - + | - + | - - | + +
- CCW: - - | - - | - - | - - | - - | - -

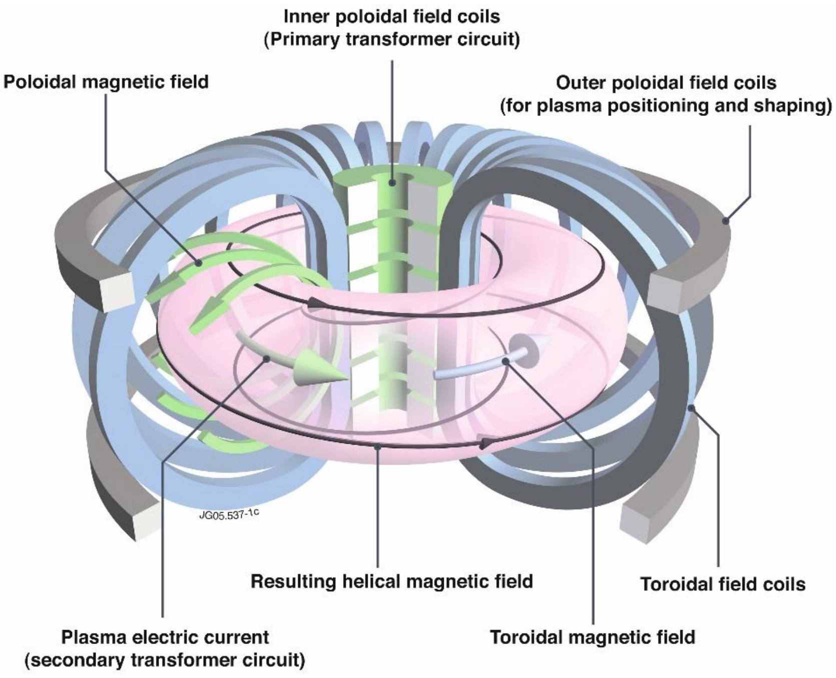
Neutral beam source

- **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**

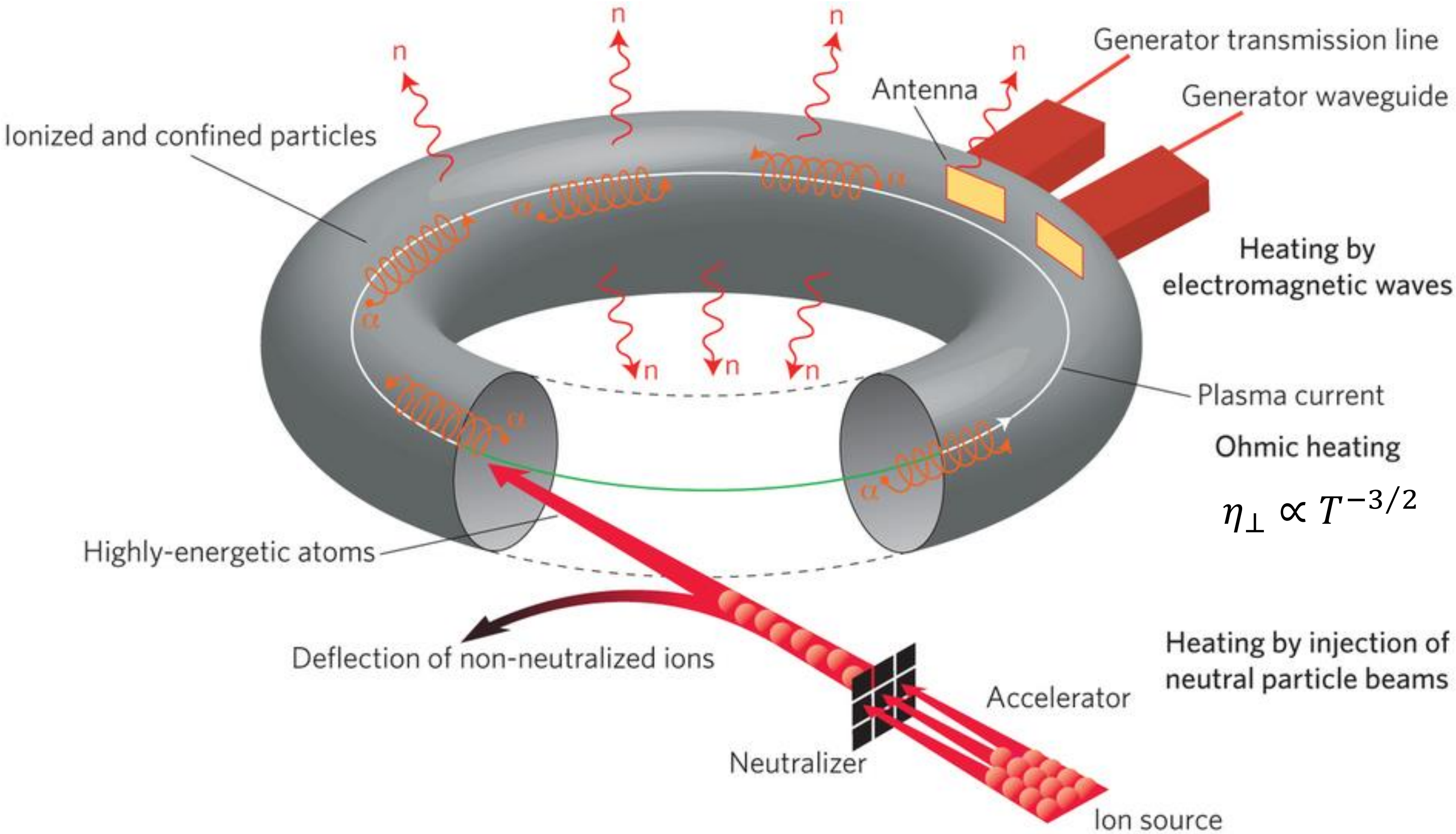
Hot plasma is confined by the magnetic field in magnetic confinement fusion





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

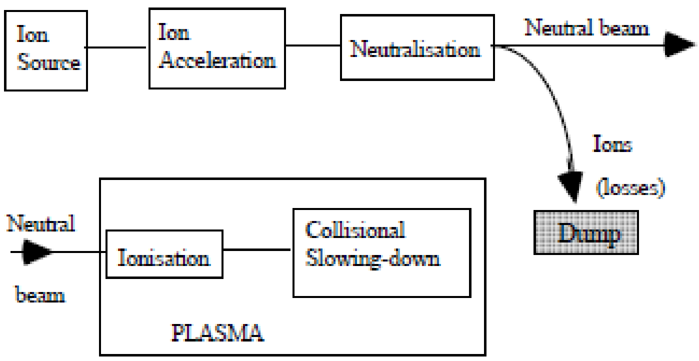
Varies way of heating a MCF device

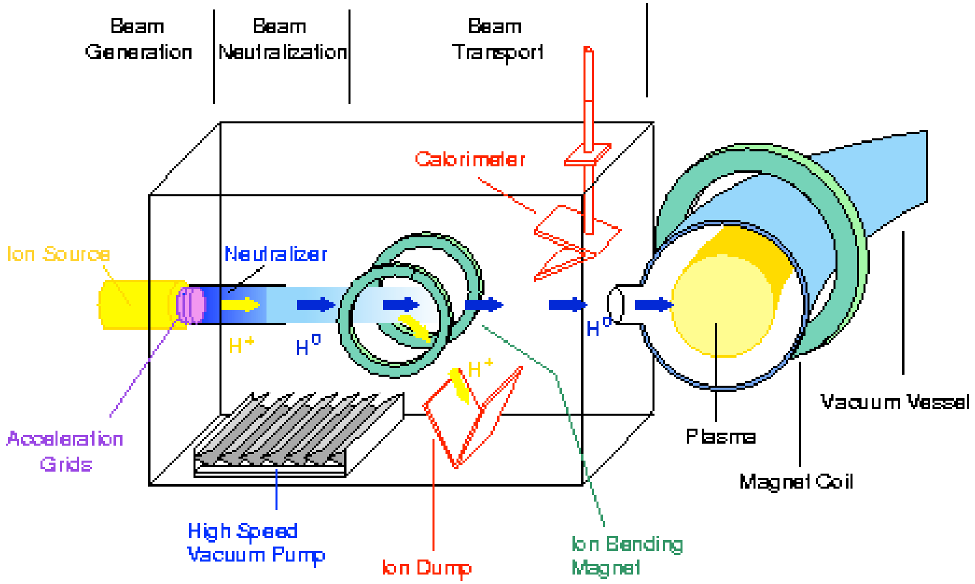
System		Frequency/ energy	Maximum power coupled to plasma	Overall system efficiency	Development/ demonstration required	Remarks
ECRF	Demonstrated in tokamaks	28–157 GHz	2.8 MW, 0.2 s	30–40%	Power sources and windows, off-axis CD	Provides off-axis CD
	ITER needs	150–170 GHz	50 MW, S S			
ICRF	Demonstrated 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

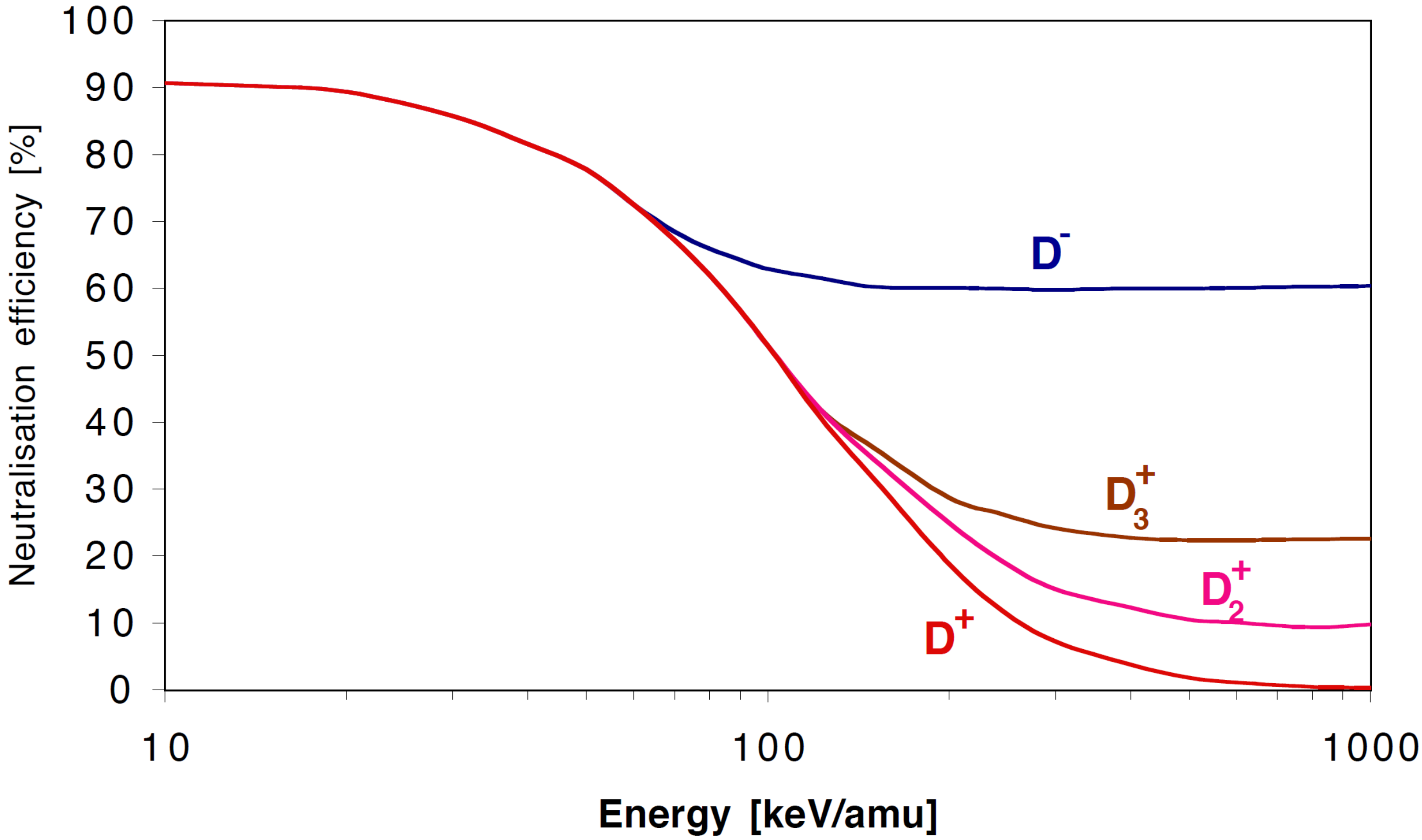
Neutral particles heat the plasma via coulomb collisions





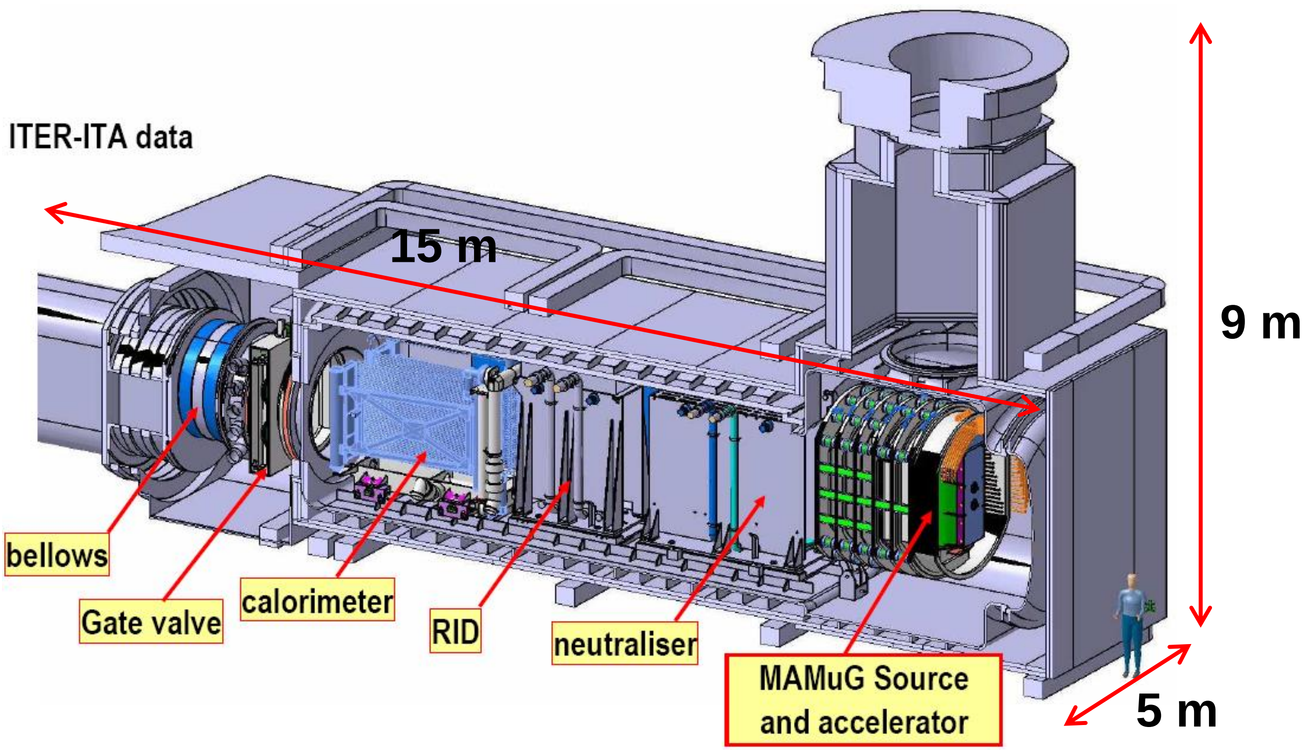
1. create energetic (fast) neutral ions
2. ionize the neutral particles
3. heat the plasma (electrons and ions) via Coulomb collisions

Negative ion source is preferred due to higher neutralization efficiency



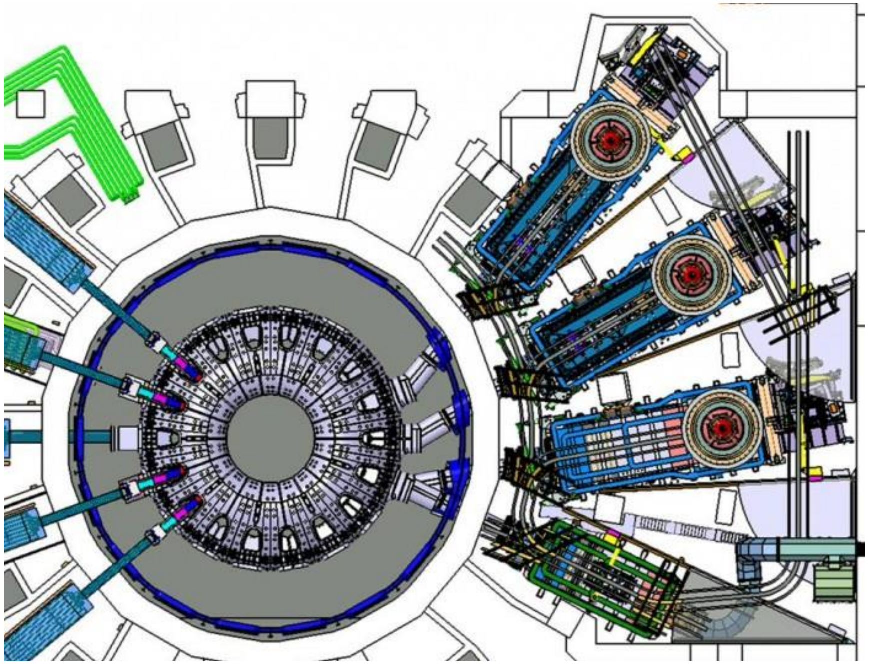
NBI for ITER

- **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

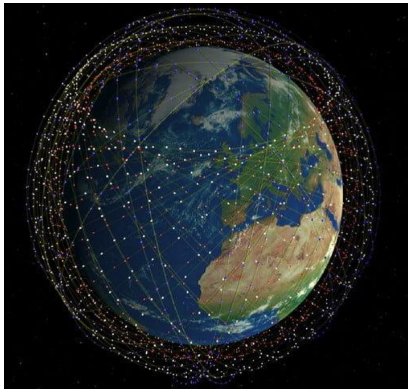
Neutral beam source

- 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

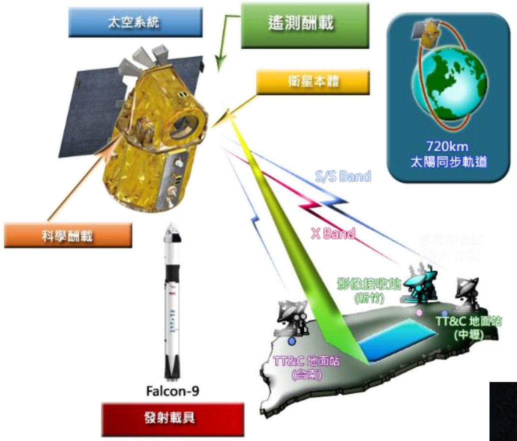
- **Electric propulsion (plasma thrusters)**
  - **D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters**

Satellites are widely used in our daily life

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

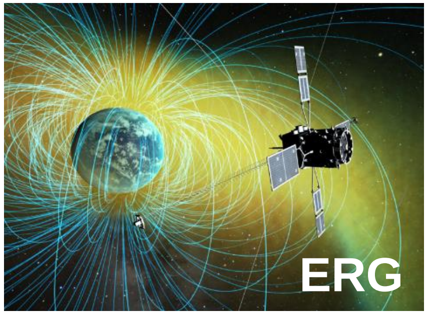


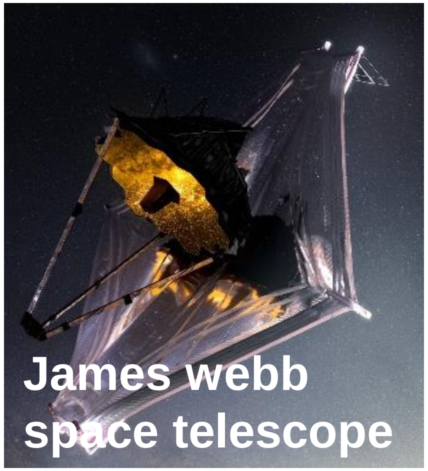
- **Foromsa 5 – Optical remote sensing**



- **GPS signal**

- **Science**



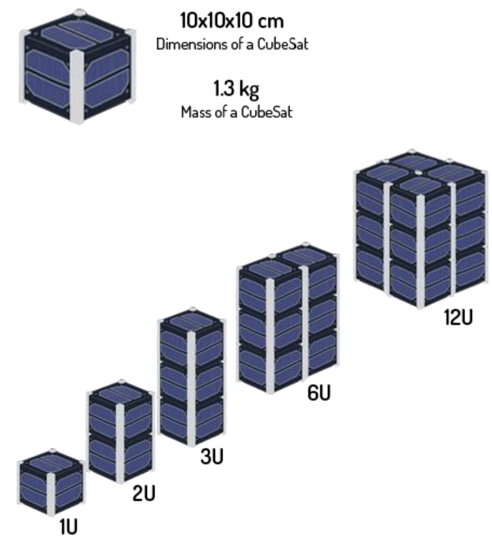


https://phys.org/news/2019-05-starlink-satellites-orbiting-altitude-space.html
https://www.nspo.narl.org.tw/inprogress.php?c=20021501
https://www.theengineeringcommunity.org/satellite-positioning-gps-advantages-and-disadvantages-for-site-engineers/
https://en.wikipedia.org/wiki/Arase_%28satellite%29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

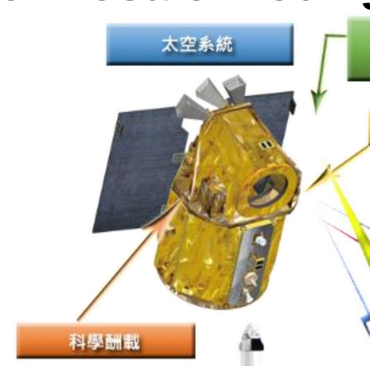
Satellites are classified by their weights and sizes

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

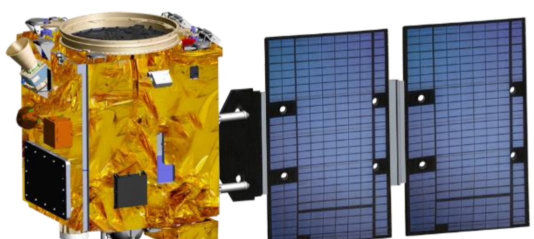
- **CubeSat**



- **Formosa 5: 450 kg**

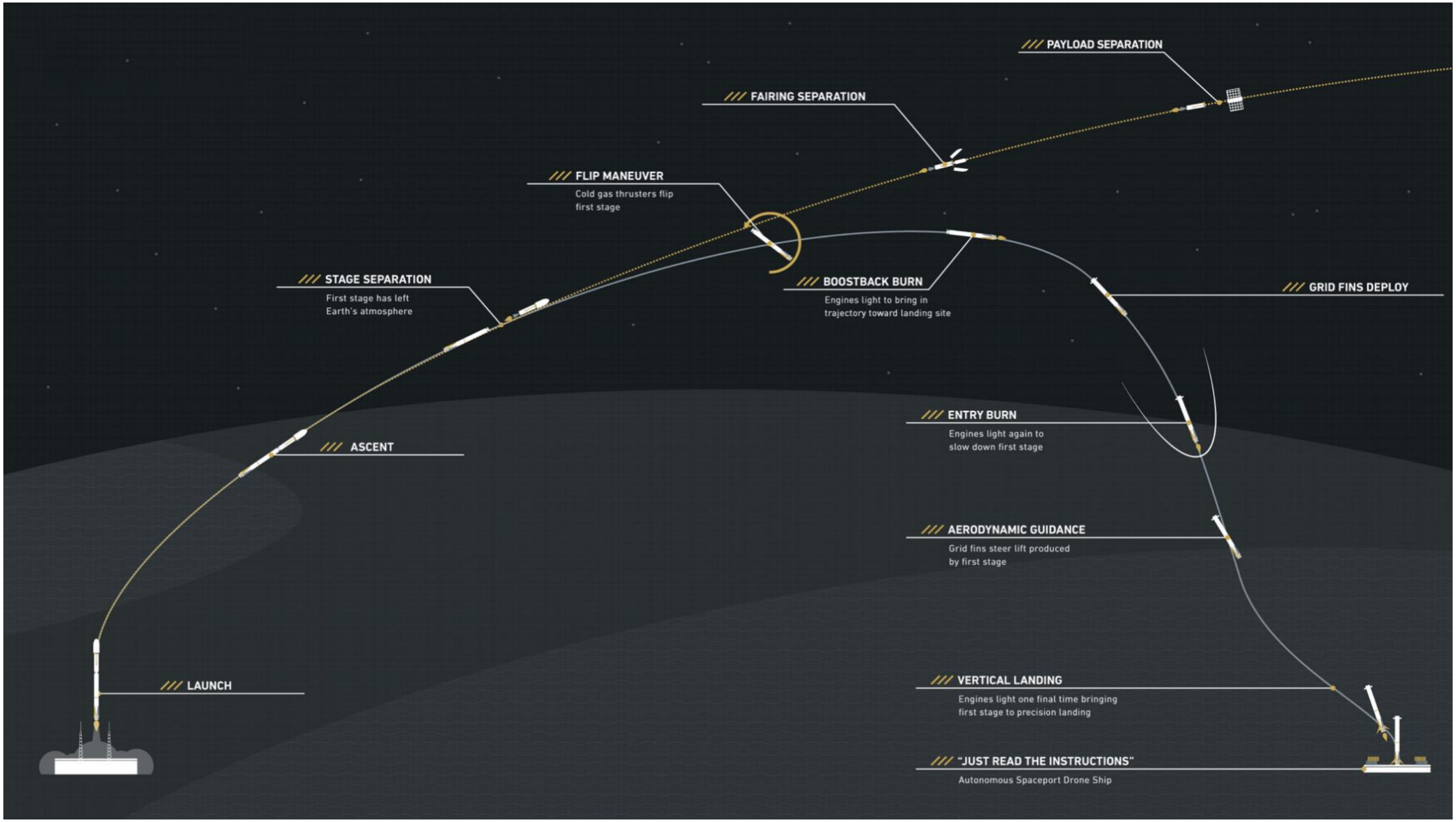


- **Triton: 300 kg**



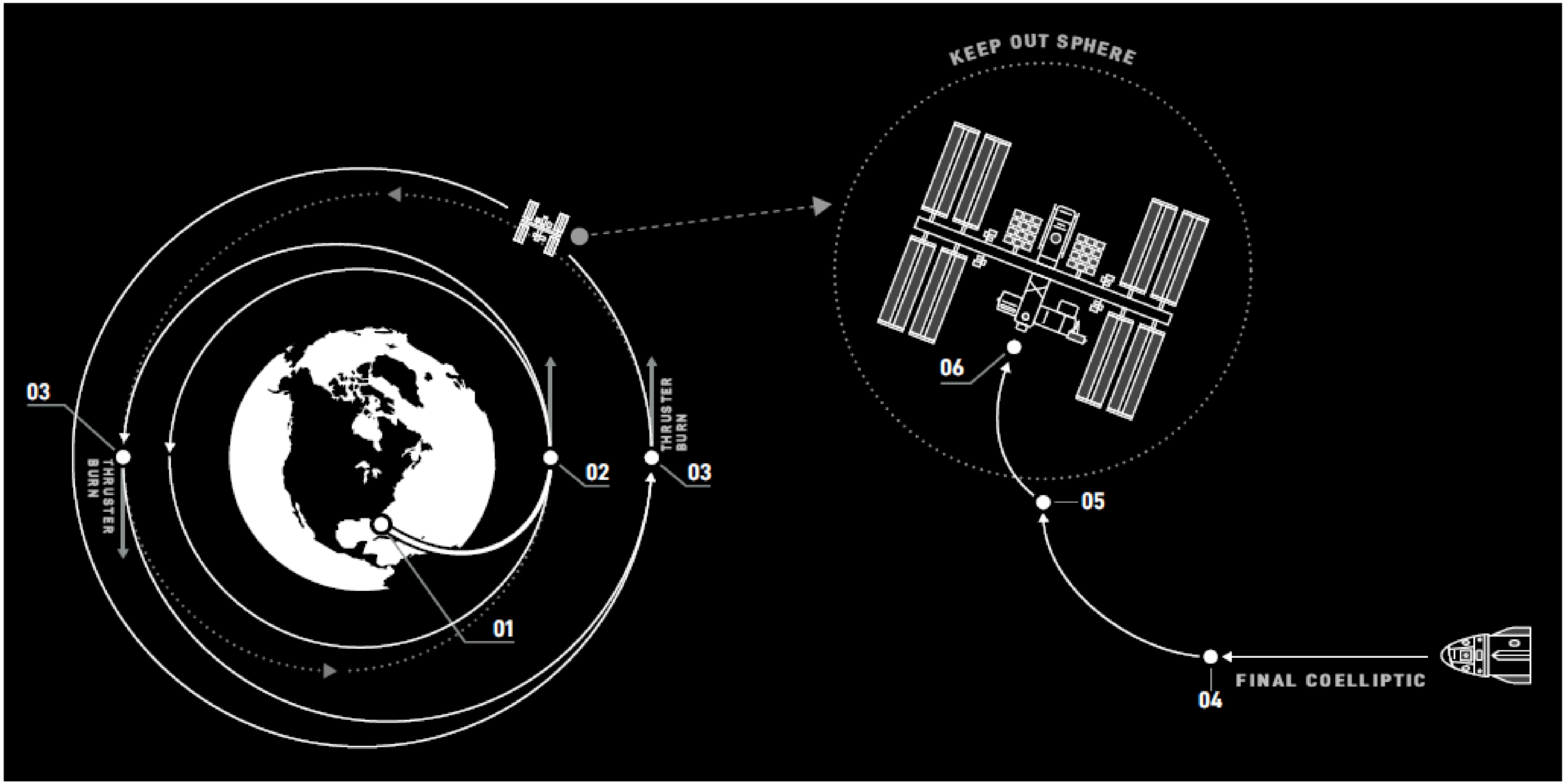
https://www.nspo.narl.org.tw/index.php?ln=zh_TW
https://alen.space/basic-guide-nanosatellites/

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

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

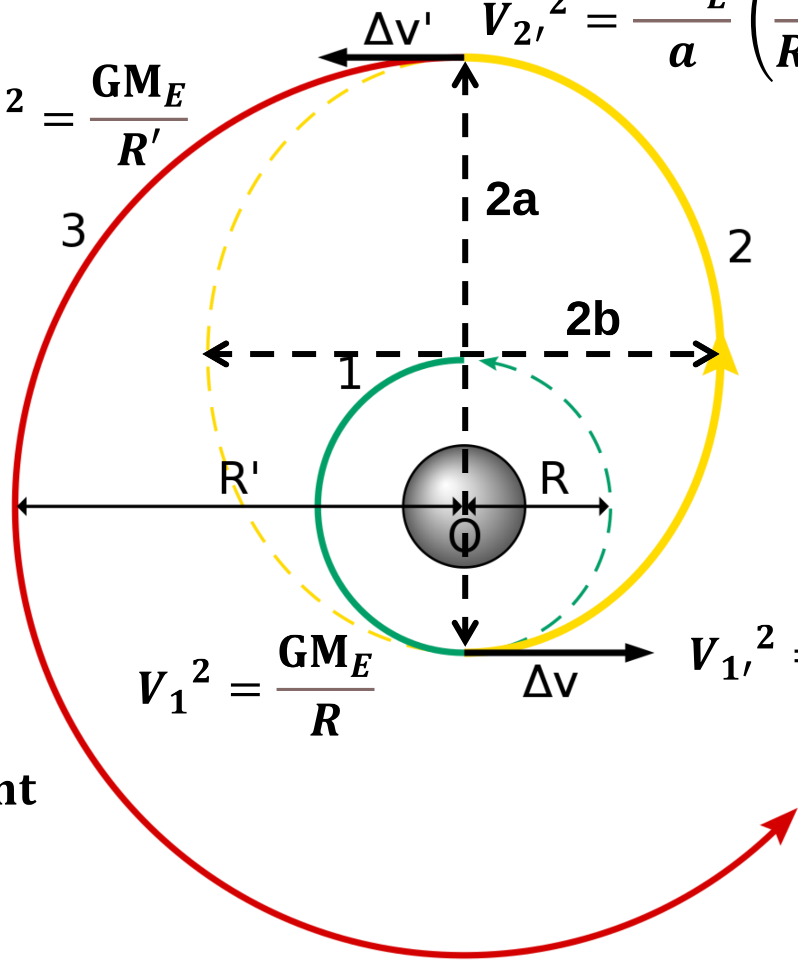
$$V^2 = \frac{\text{GM}}{r}$$

- **Energy conservation:**

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

- **Angular momentum conservation:**

$$mV_{1'}R = \text{mV}_2R'$$



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

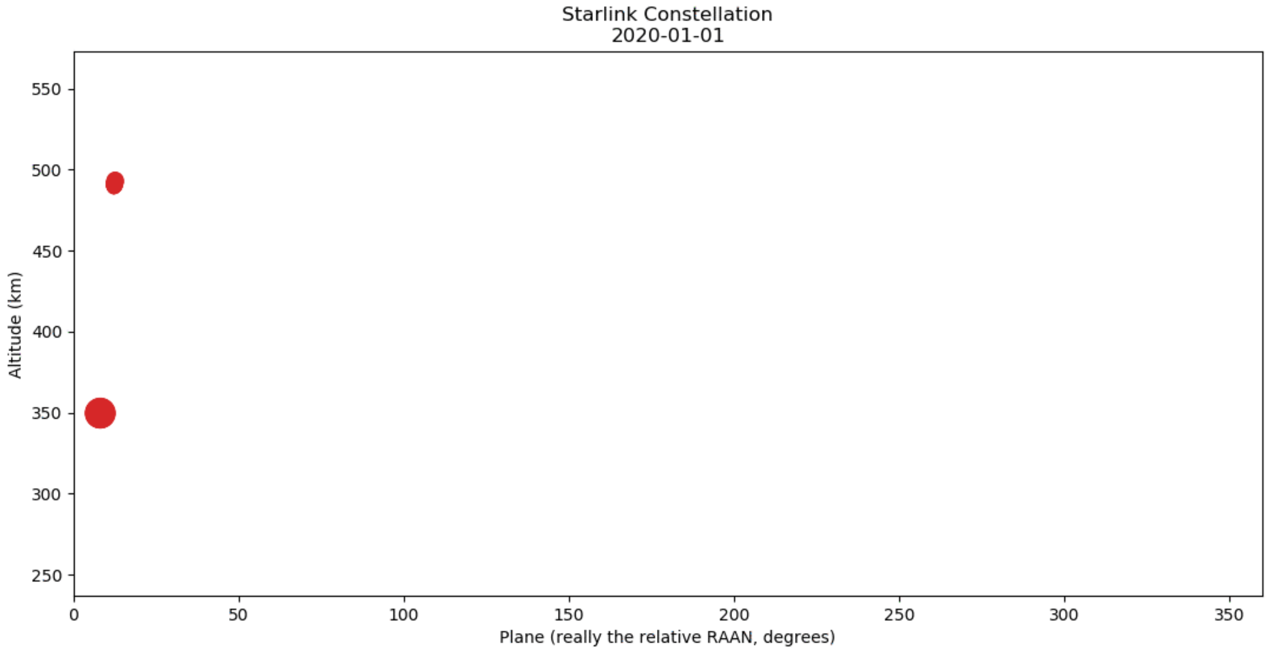
$$V_3^{\ 2} = \frac{\text{GM}_E}{R'}$$

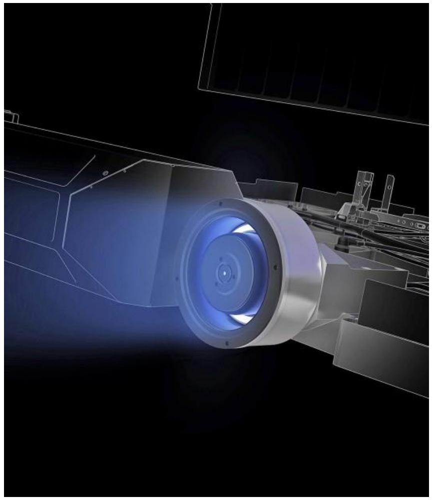
$$V_1^{\ 2} = \frac{\text{GM}_E}{R}$$

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

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

Satellites are slowly deployed for Starlink constellation

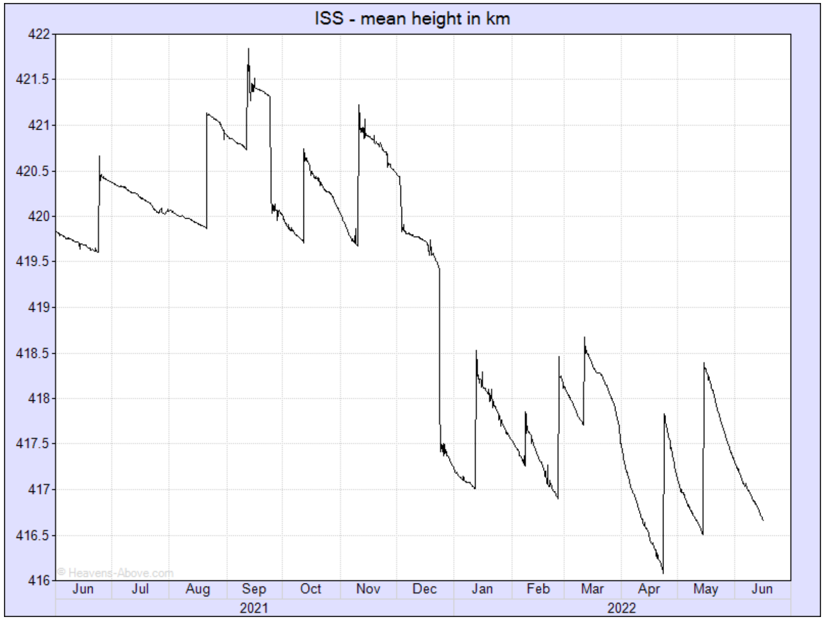


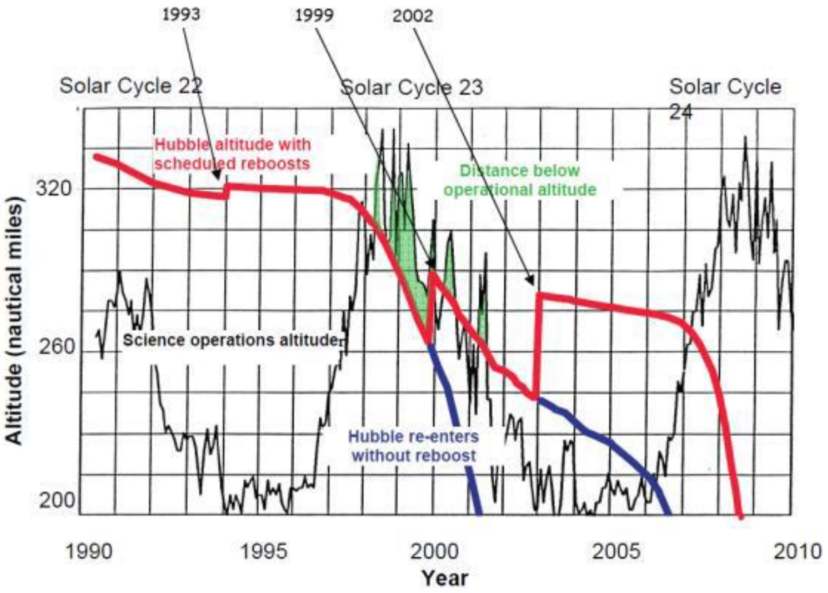


https://www.nasaspaceflight.com/2020/06/evaluating-spacexs-starlink-push/
https://www.space.com/spacex-starlink-satellites.html
https://metro.co.uk/2020/04/24/starlink-satellites-work-12604227/

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**





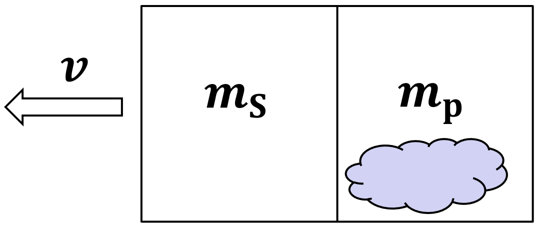
https://www.heavens-above.com/IssHeight.aspx
V. Nwankwo and S. Chakrabarti, Trans. JSASS Aero. Tech. Japan 12, 47 (2014)

Trajectories including the gravitational force needs to be solved numerically

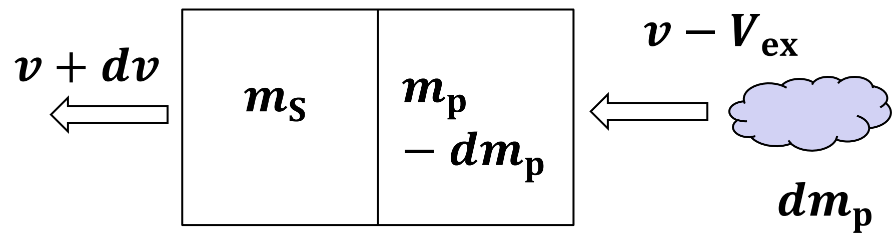
- **Force on exhaust propellant from the thruster**

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

$$= v_{\mathrm{ex}}\frac{dm_{\mathrm{p}}}{dt} = -v_{\mathrm{ex}}\dot{M}_{\mathrm{p}}$$



- **Force on the vehicle**



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

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

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

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

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

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

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

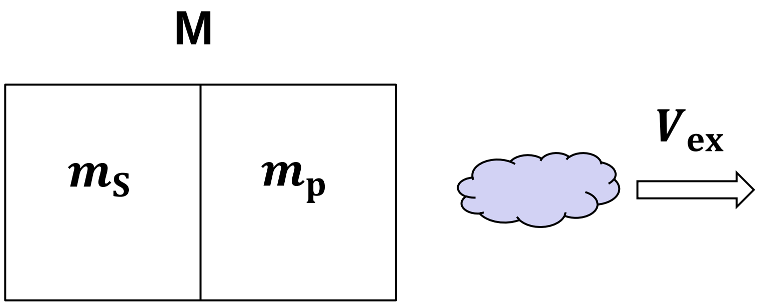
$$Mv = Mv + Mdv - dm_p v - dm_p dv + dm_p v - dm_p V_{\mathrm{ex}}$$

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

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

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

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



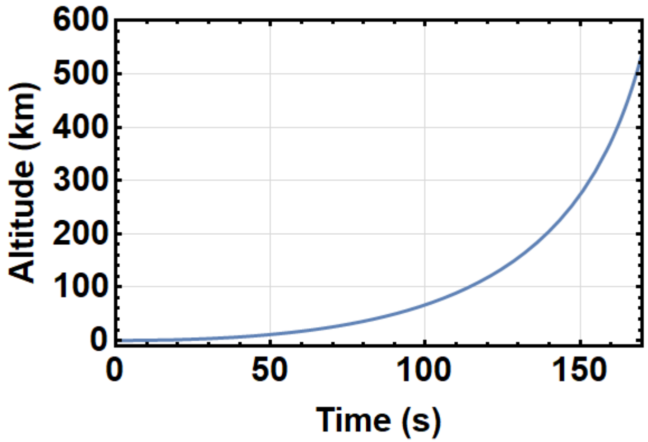
$$m_{\mathrm{p}} = m_S[e^{\Delta \mathrm{v}/v_{\mathrm{ex}}} - 1]$$
$$= m_S[e^{\Delta \mathrm{v}/(\mathrm{Isp} \times g)} - 1]$$

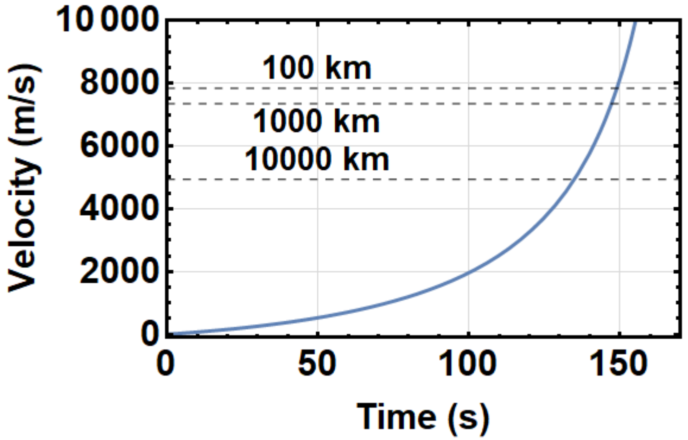
- **Specific impulse represents how efficient a thruster is.**

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**
  - $\dot{M}_p$ **= 2700 kg/s**



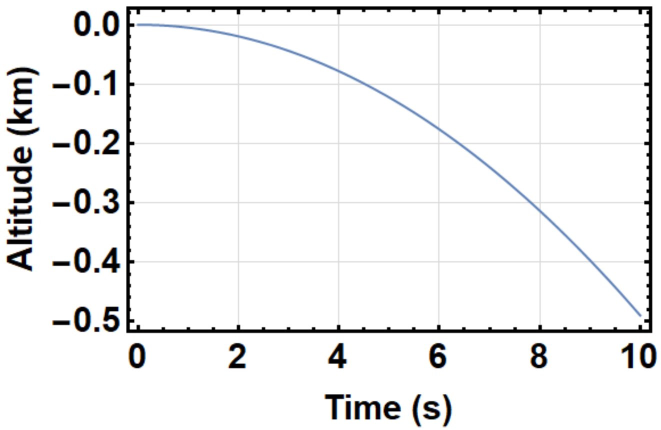


*https://en.wikipedia.org/wiki/Falcon_9#cite_note-falcon9-v1.1-si-14

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

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

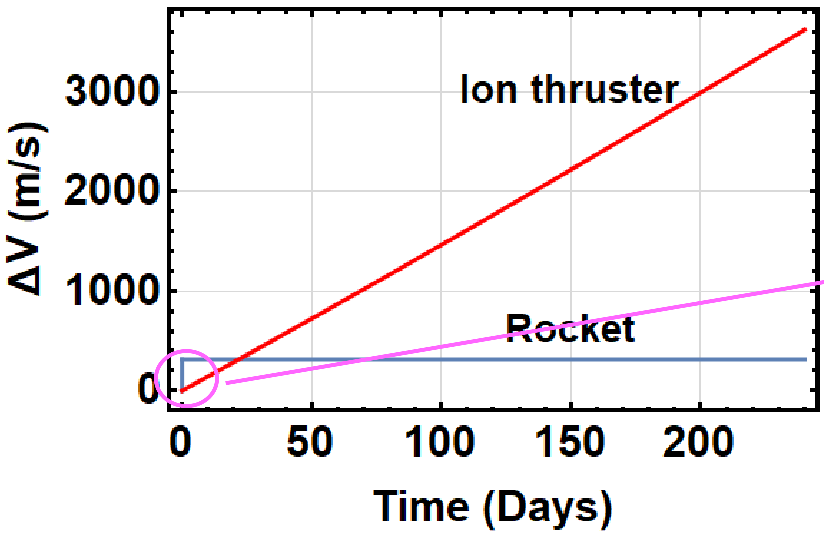
- **Electrical propulsion (similar to 500 25-cm XIPS*):**
  - M_{Sat} **= 1000 kg**
  - V_{ex} **= 34790 m/s (Isp = 3550 sec)**
  - M_{p} **= 5 x 10^5 kg**
  - $\dot{M}_{\mathrm{p}}$ **= 2.4 x 10^{-3} kg/s**

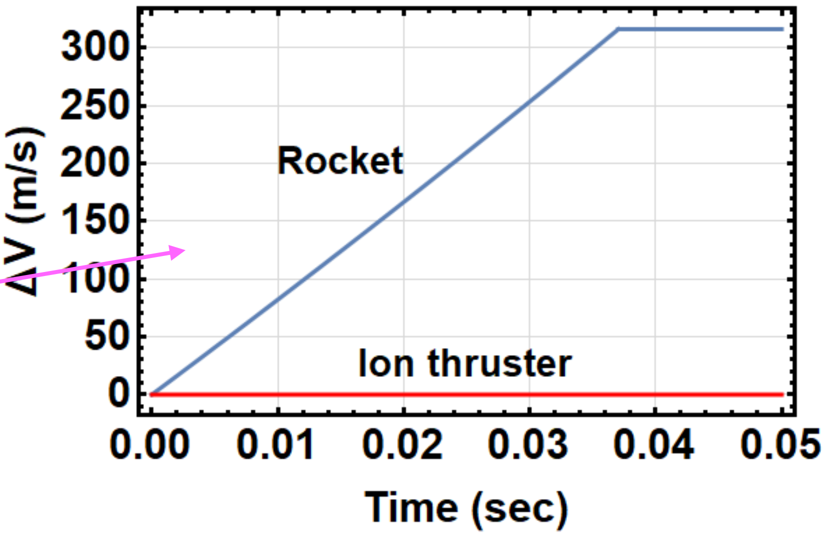


*Dan M. Geobel and I. Katz, Fundamentals of electric propulsion – ion and hall thrusters

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

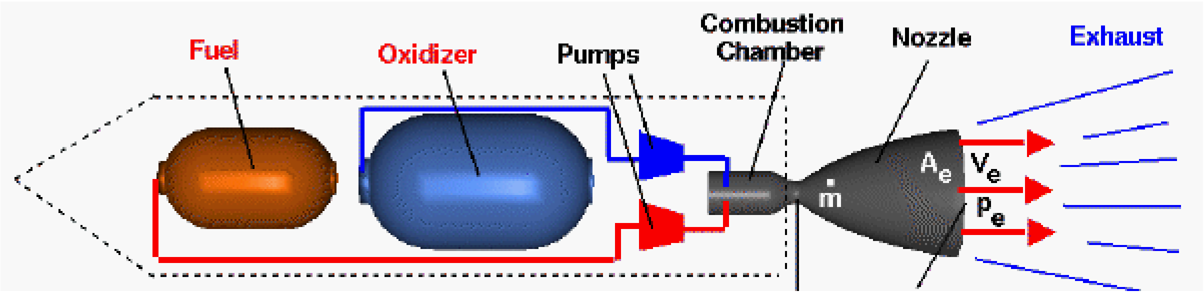
- Rocket (similar to Falcon 9*):
  - M_{Sat} = 900 kg
  - V_{ex} = 3000 m/s (Isp = 306 sec)
  - M_{p} = 100 kg
  - $\dot{M}_{\mathrm{p}}$ = 2700 kg/s
  - T_{total} = 37 ms
- Electrical propulsion (similar to 25-cm XIPS*):
  - M_{Sat} = 900 kg
  - V_{ex} = 34790 m/s (Isp = 3550 sec)
  - M_{p} = 100 kg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



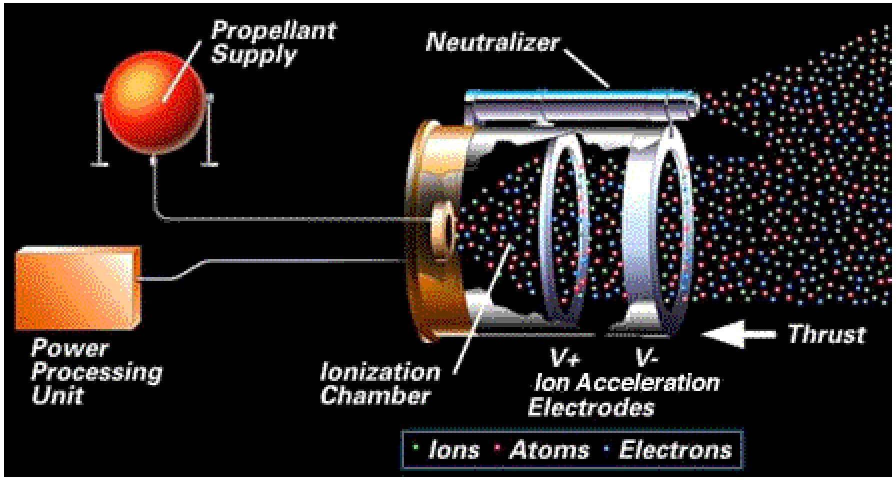


Comparison between liquid rockets and ion thrusters

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

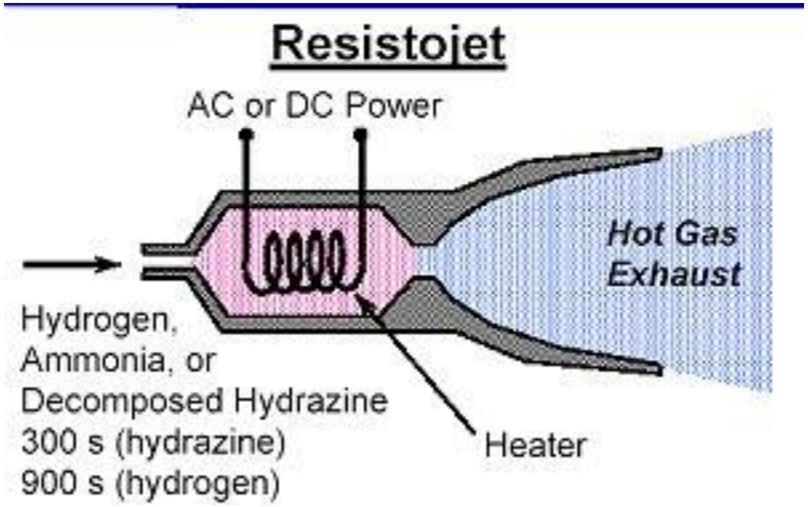


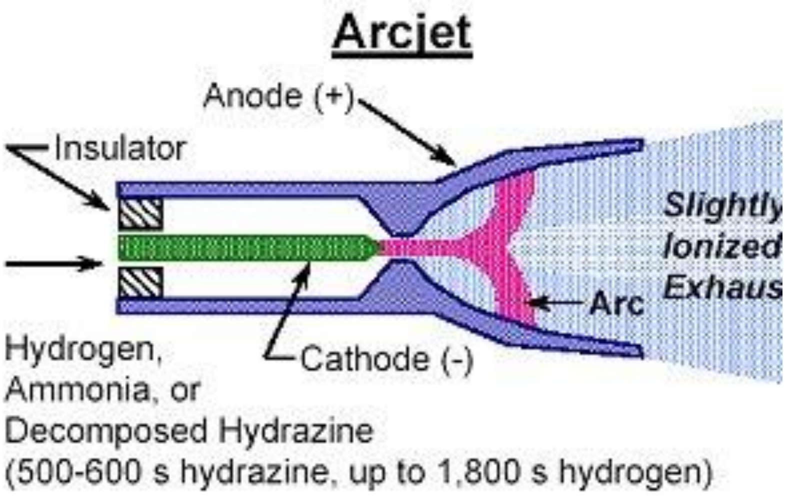
- Ion thrusters
  - u~30000 m/s
  - Isp~3000 s
  - Energy ~ 1000GJ
  - Power ~ 1kW
  - Thrust ~ 0.1 N



Electric thruster types - electrothermal

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

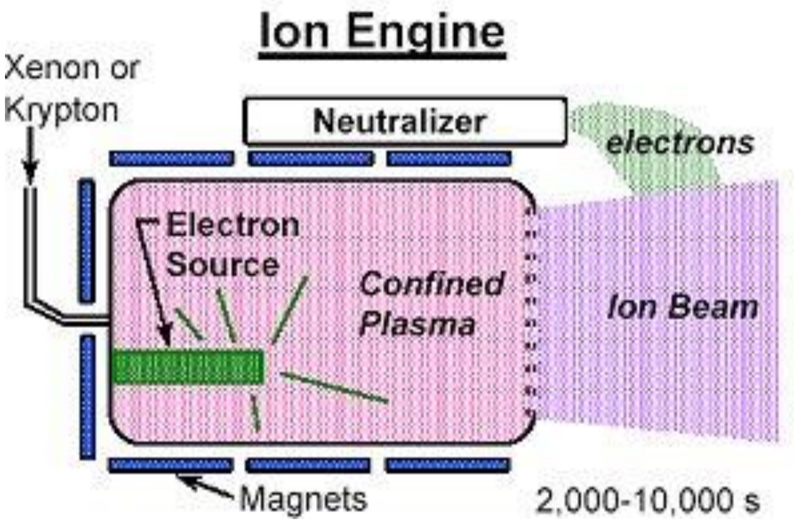




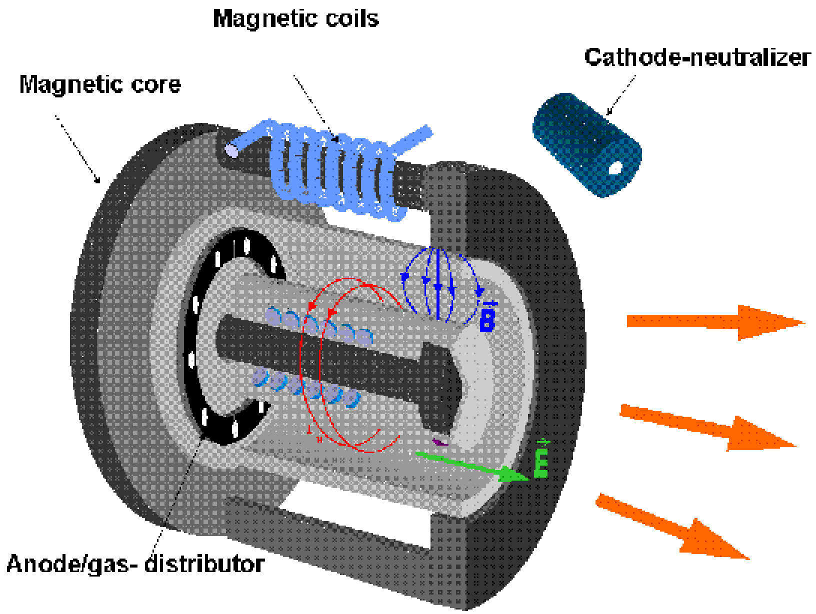
http://pages.erau.edu/~ericksol/courses/sp300/ch5/propul_ch5.html

Electric thruster types - electrostatic

- **Ion thruster**



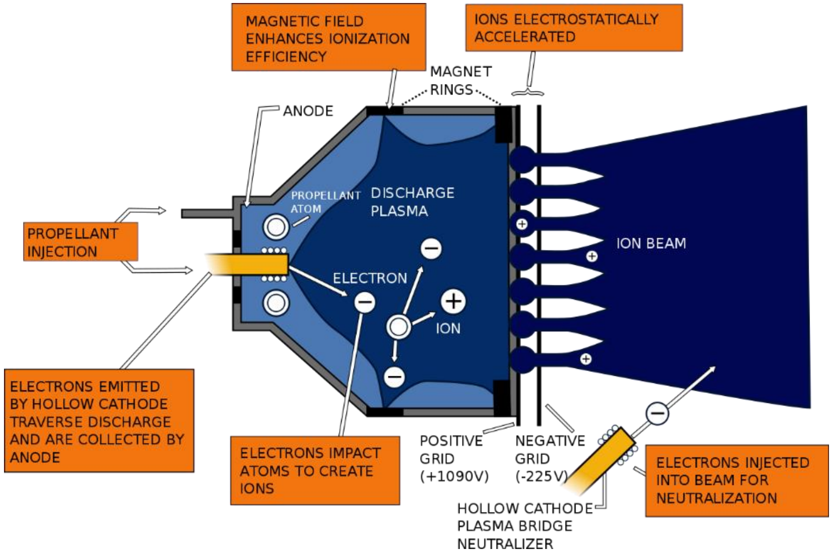
- **Hall thruster**



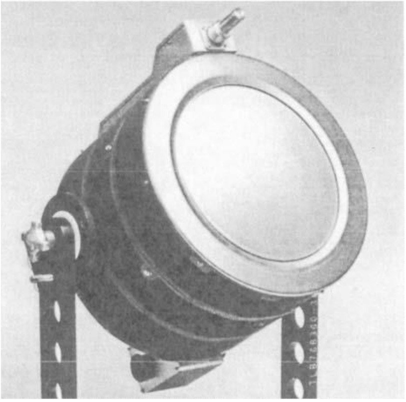
Ions are accelerated by the electric field in an ion thruster

- 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



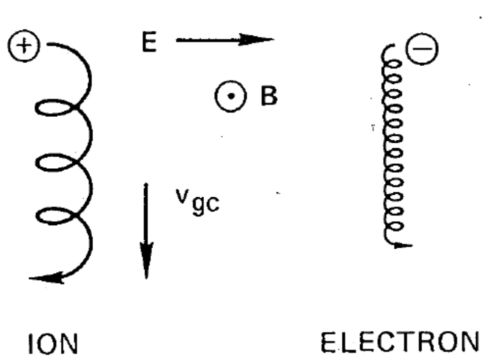
Parameters	Performance
Diameter	25 cm
Power	4.3 kW
Isp	3550 sec
Thrust	166 mN
Beam voltage	1215 V
Beam current	3.05 A

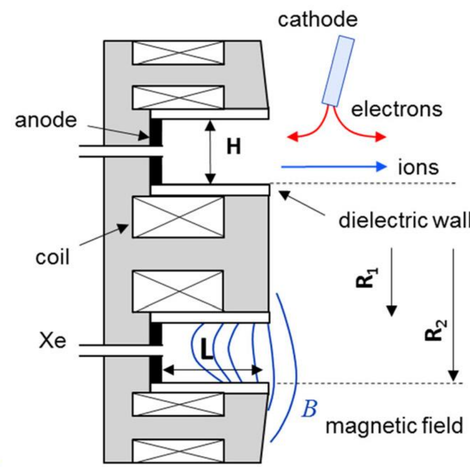
https://en.wikipedia.org/wiki/Ion_thruster
Dan M. Geobel and I. Katz, Fundamentals of electric propulsion – ion and hall thrusters

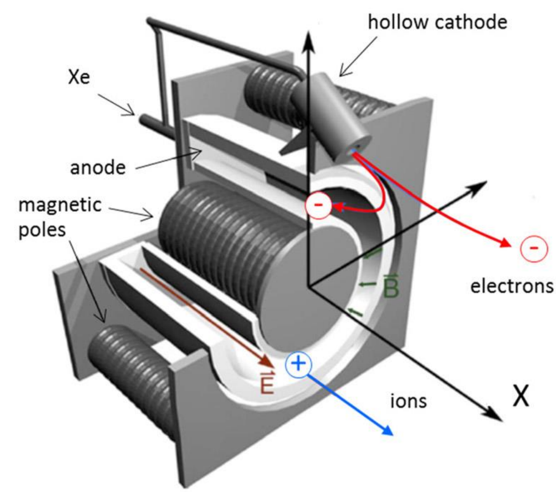
Electrons are confined by magnetic field so that ionization fraction increases in a Hall thruster

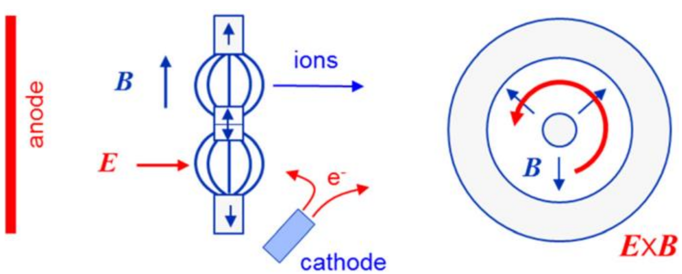
- **Ion thrusters consist of:**
  - **Ionization chamber – to generate ions.**
  - **Radial magnetic field is used to confine electrons.**
  - **Acceleration electrodes – to accelerate ions.**
  - **Single electron gun is used as the neutralizer and for ionization.**

- **ExB drift**





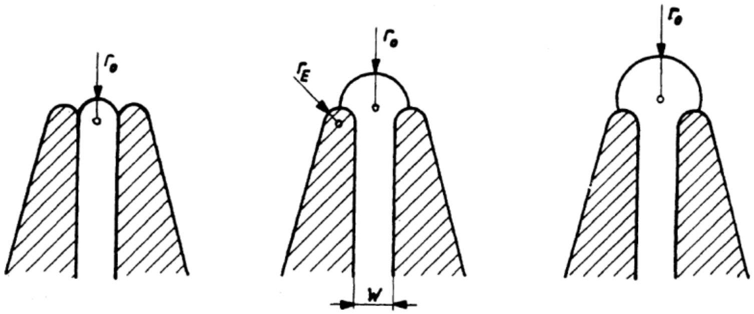


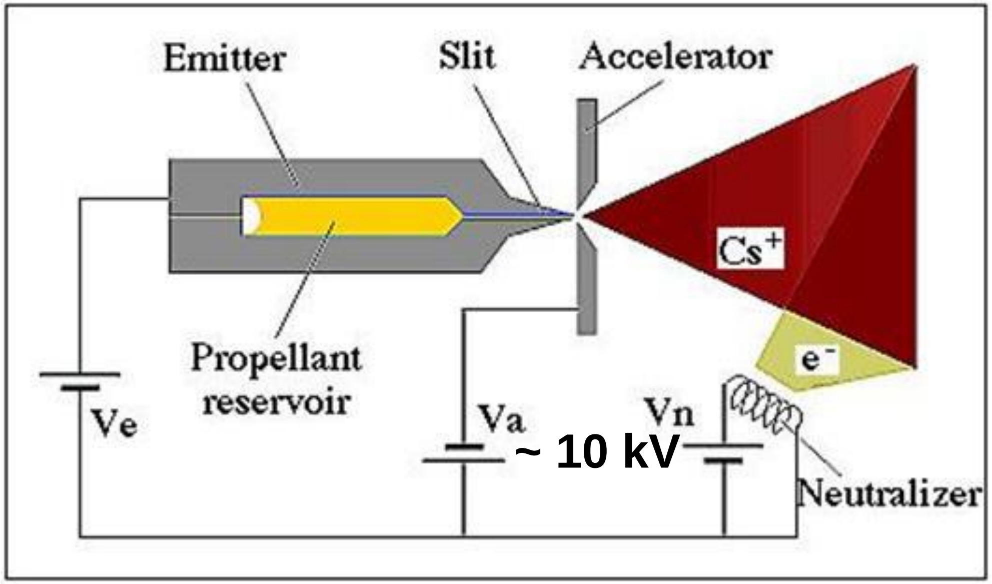


J.-P Boeuf, J. Appl. Phys. 212, 011101 (2017)

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

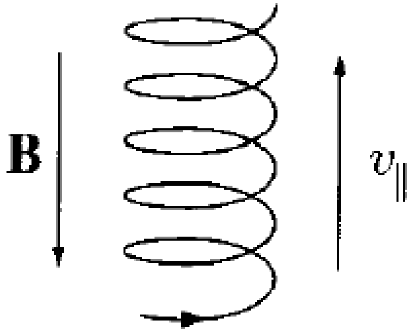
- **A Taylor cone is formed when the liquid metal's surface tension is balanced by the applied electric field.**
- **If the evaporation field strength of about 10^{10} V/m is reached at the needle tip, the liquid metal is evaporated and ionized.**
- **Thrust: 0.1~100 uN.**
- **Isp = 1600~8000 sec.**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





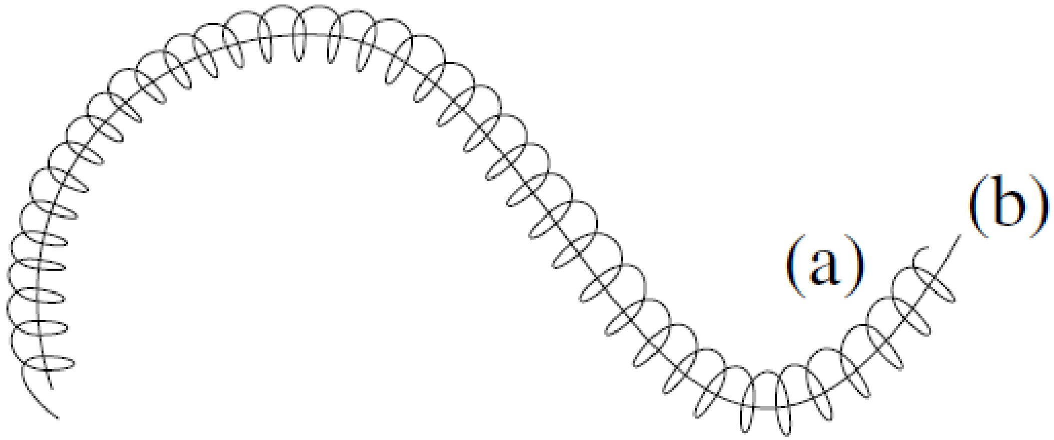
M. K. Bharti and S. Chalia, I. Res. J. Engin. Tech., 4, p2777 (2017)
J. Mitterauer, IEEE Trans. Plas. Sci., PS-15, 593 (1987)
M. Taimar, etc., J. Propulsion and Power, 20, 211 (2004)

Charged particles gyro around the magnetic fields



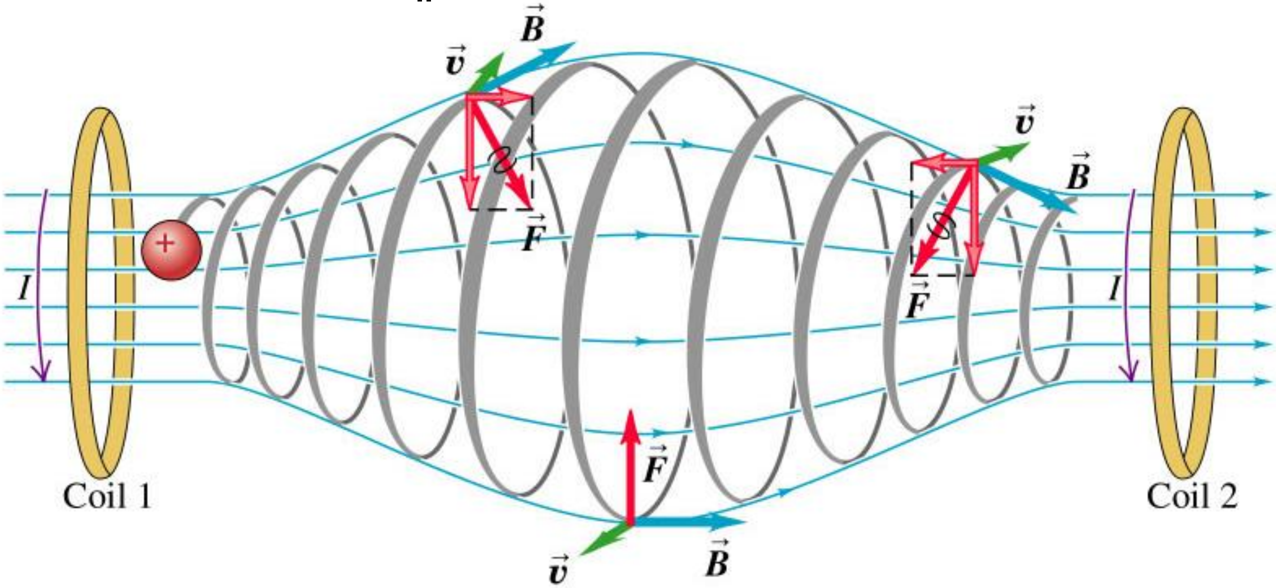
$$r_L = \frac{mv_\perp}{|q|B}$$

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



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.**



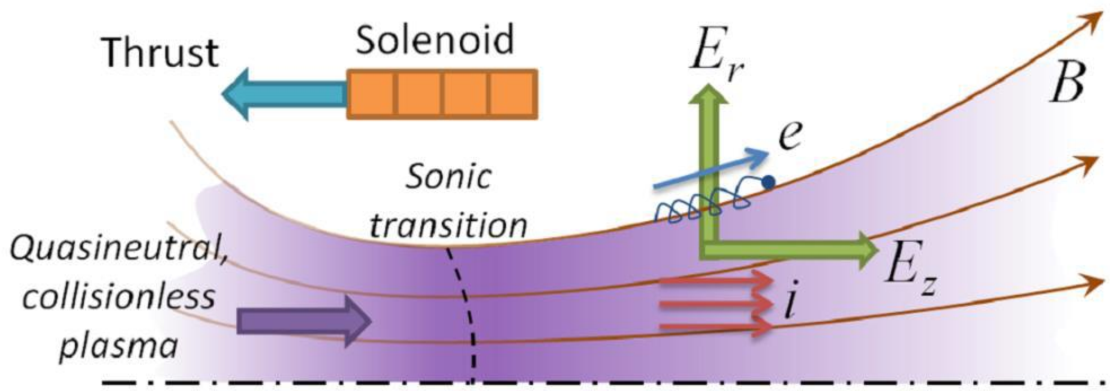
$$\frac{1}{2}mv^2 = \frac{1}{2}m{v_{||}}^2 + \frac{1}{2}m{v_{\perp}}^2$$

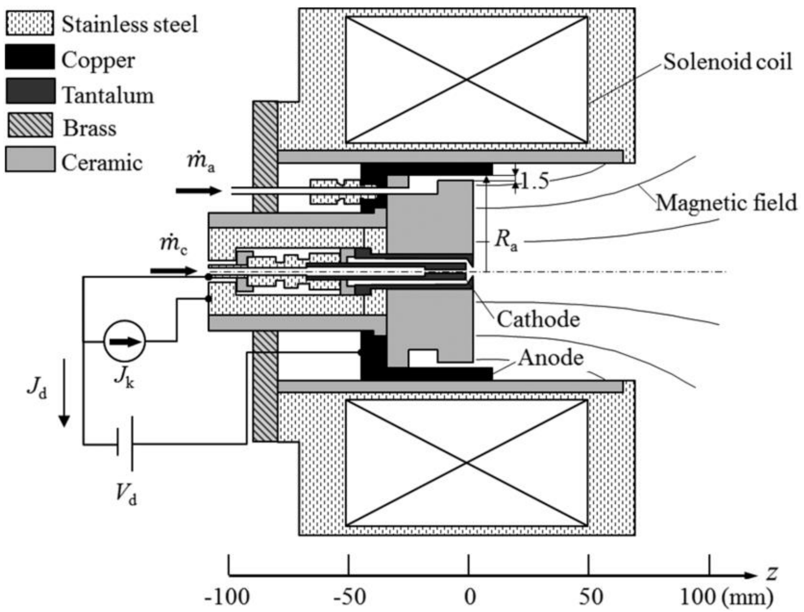
- **Large $v_{||}$ may occur from collisions between particles.**

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

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

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

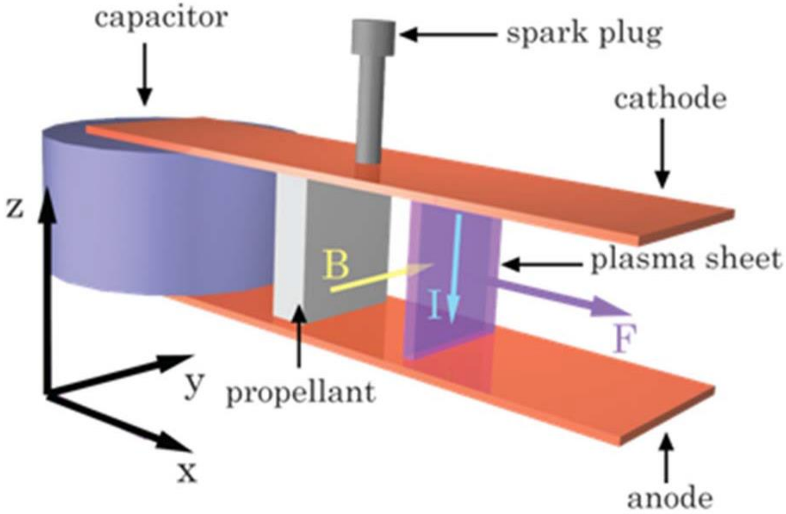




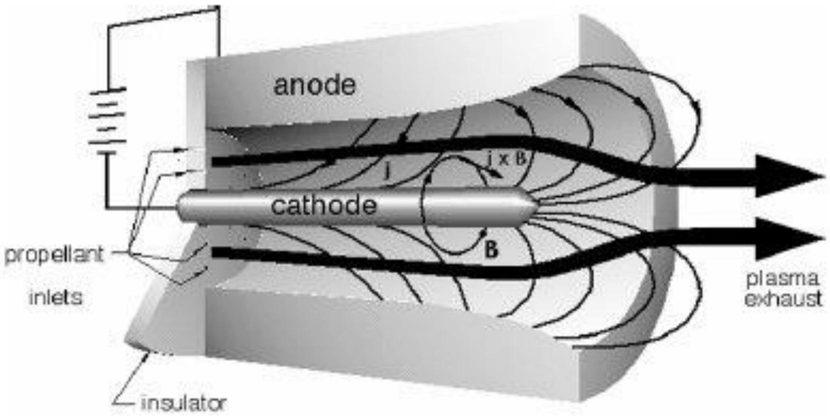
A. Sasoh, etc., AIP Advances 7, 065204 (2017)

Electric thruster types - Electromagnetic

- **Pulsed plasma thruster**

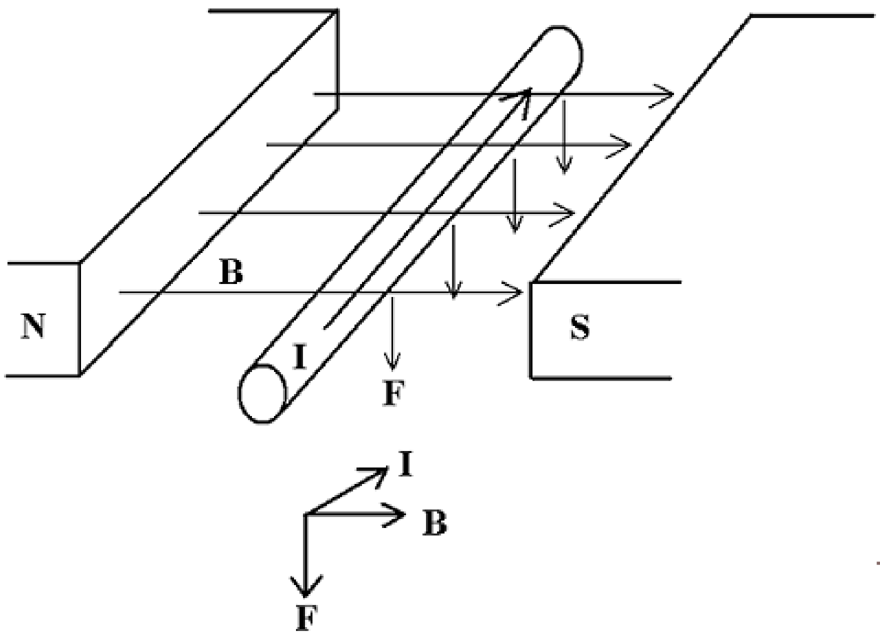


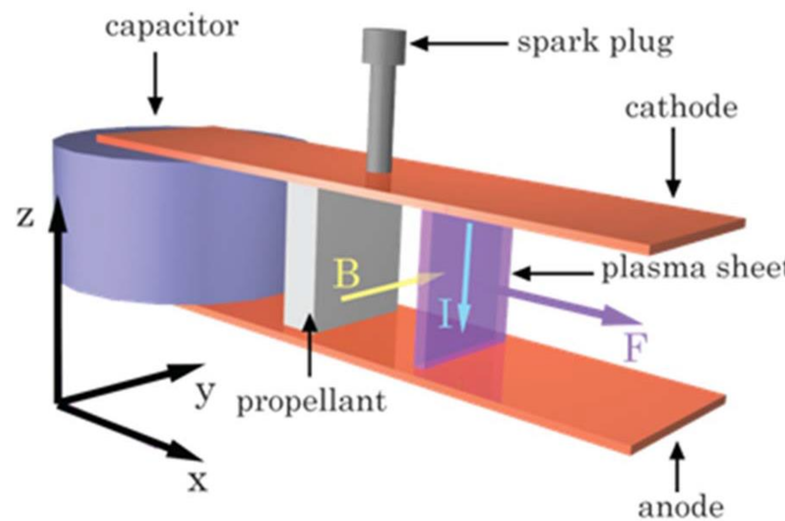
- **Magnetoplasmadynamic thruster (MPD)**



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

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





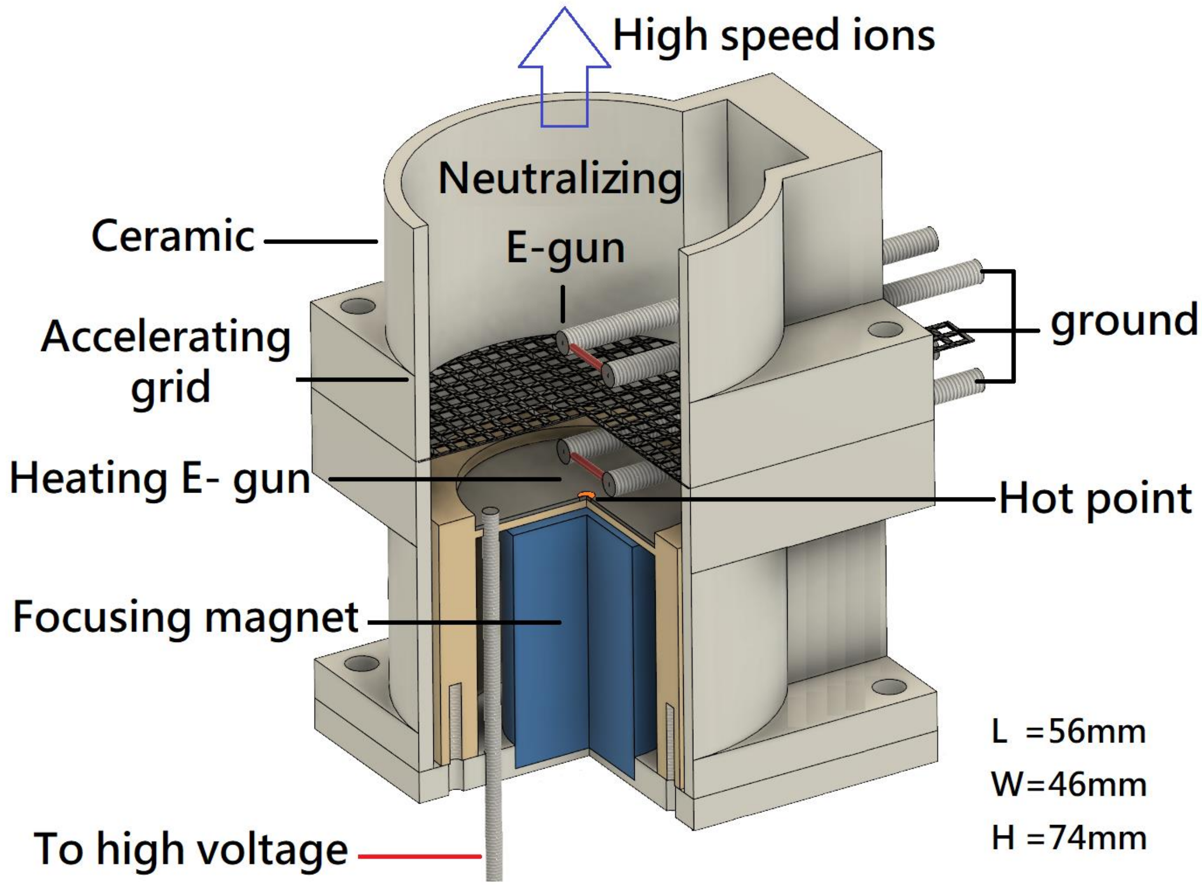
$$\vec{F} = q\,\vec{v} \times \vec{B}$$

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

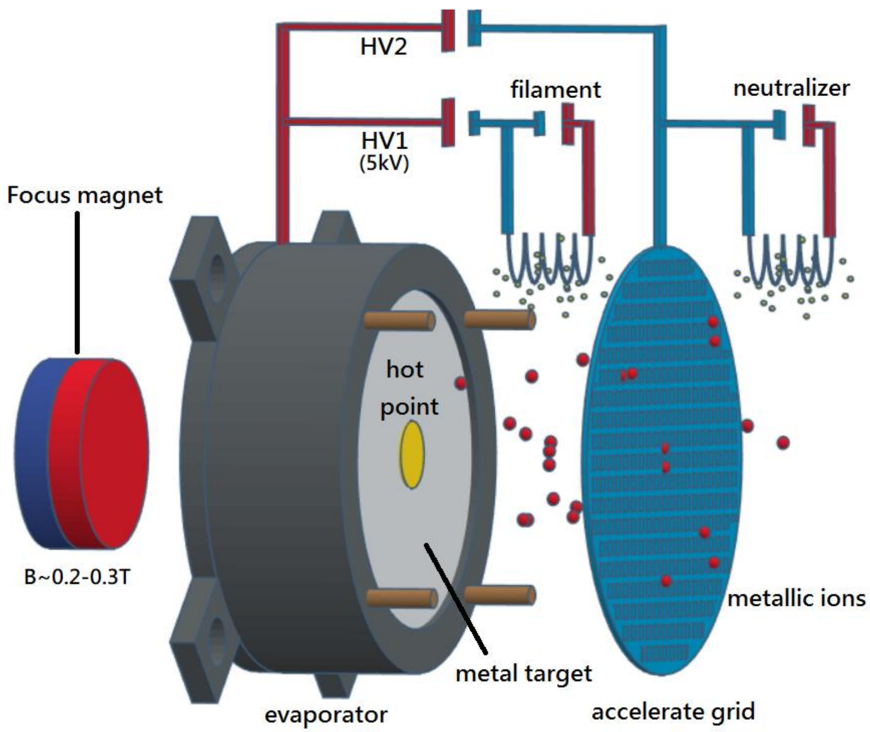
Ion thruster has the highest specific impulse (Isp)

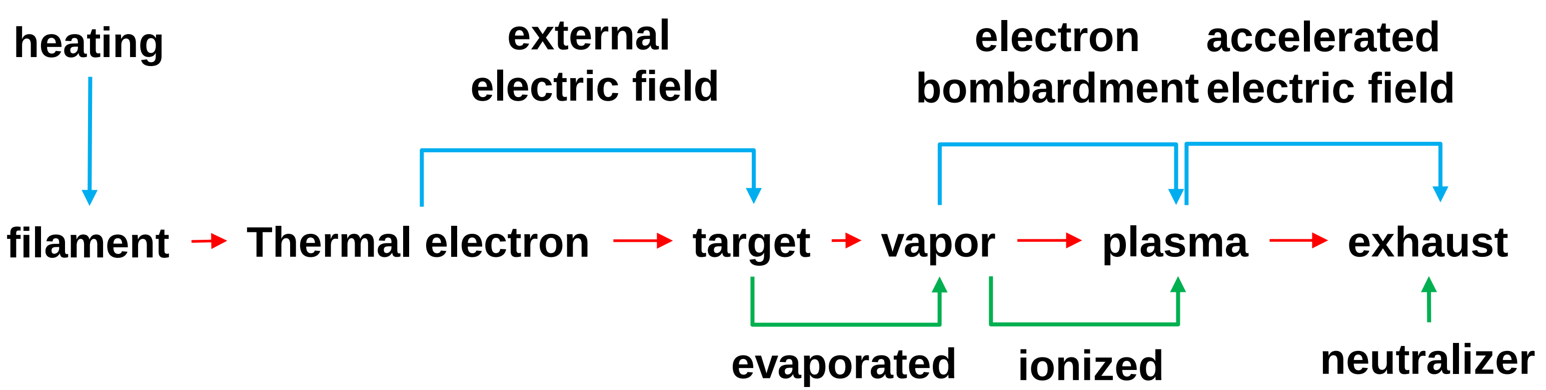
Thruster	Specific Impulse (s)	Input Power (kW)	Efficiency Range (%)	Propellant
Cold gas	50–75	—	—	Various
Chemical (monopropellant)	150–225	—	—	N_2H_4 H_2O_2
Chemical (bipropellant)	300–450	—	—	Various
Resistojet	300	0.5–1	65–90	N_2H_4 monoprop
Arcjet	500–600	0.9–2.2	25–45	N_2H_4 monoprop
Ion thruster	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)

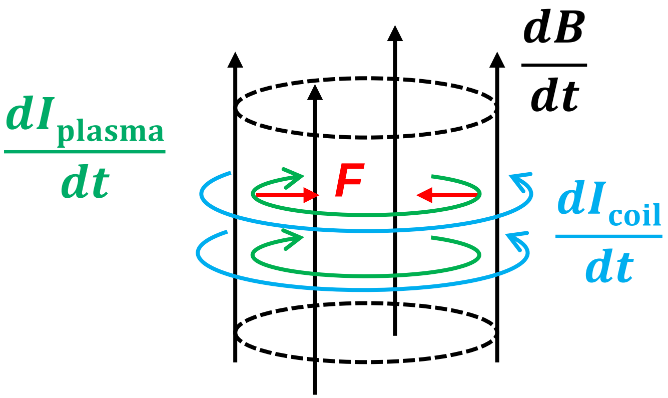


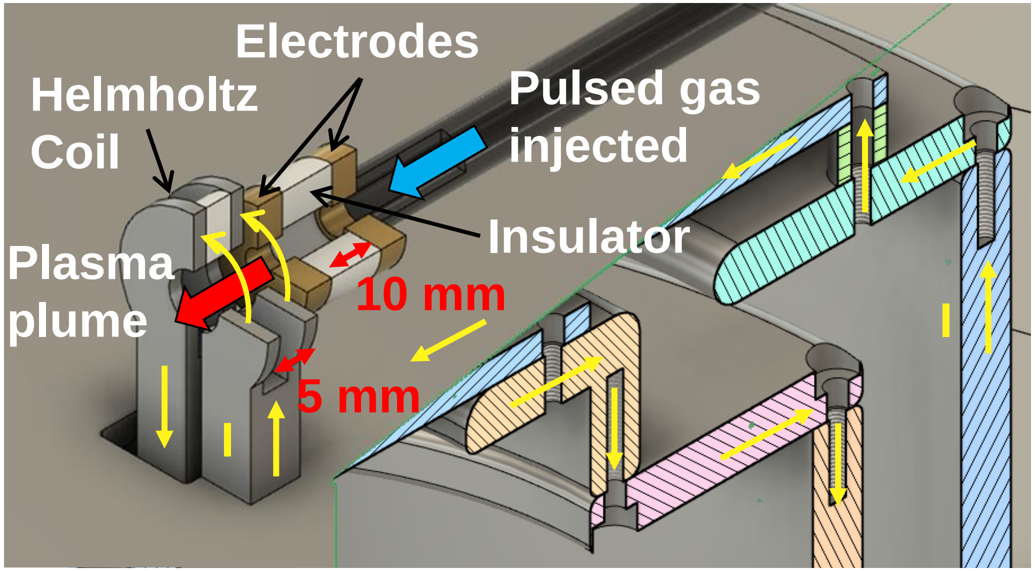
Electrons are used to generate metallic gas, metallic plasma and to neutralize ions

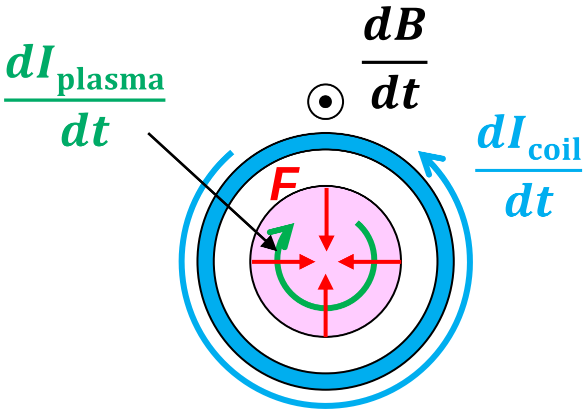


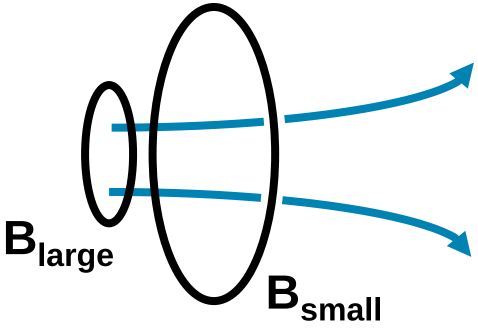


An unbalanced theta pinch can be used as the propulsion



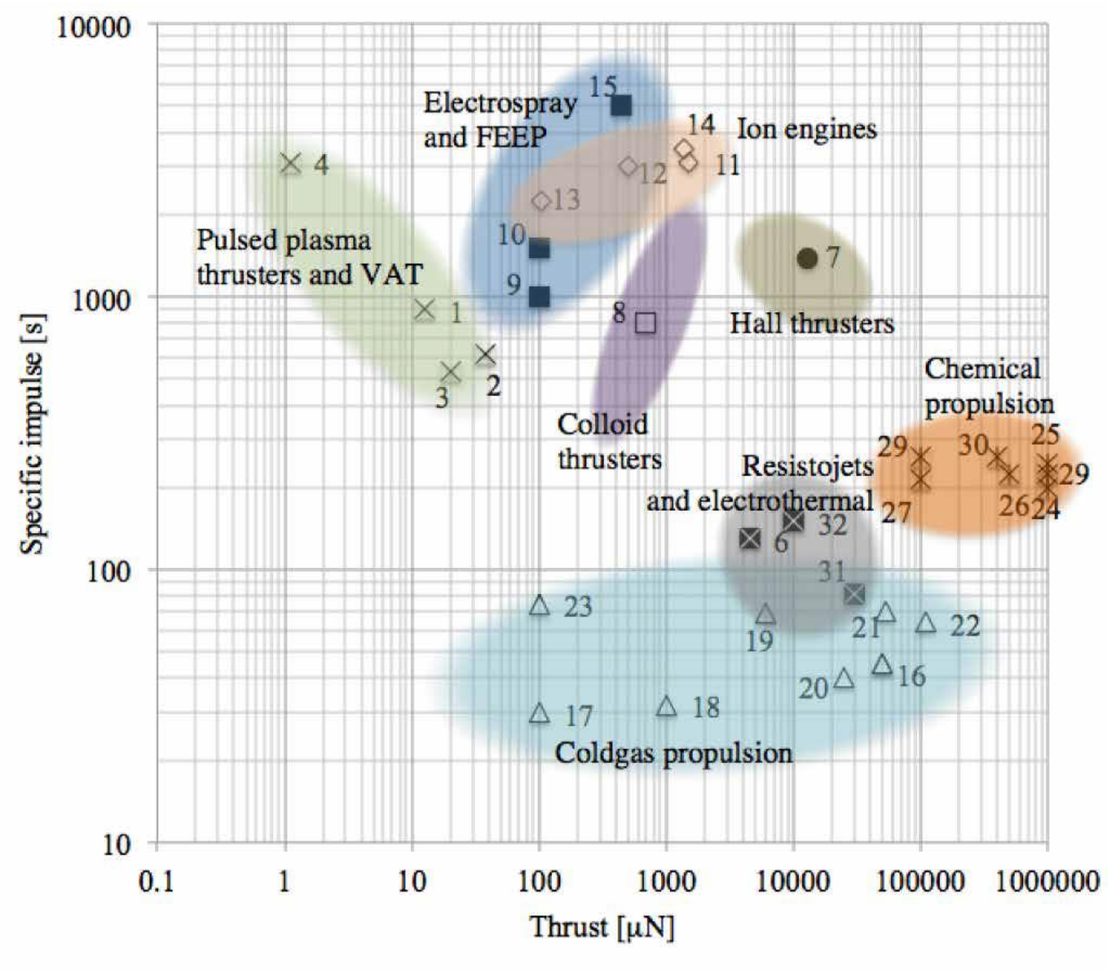






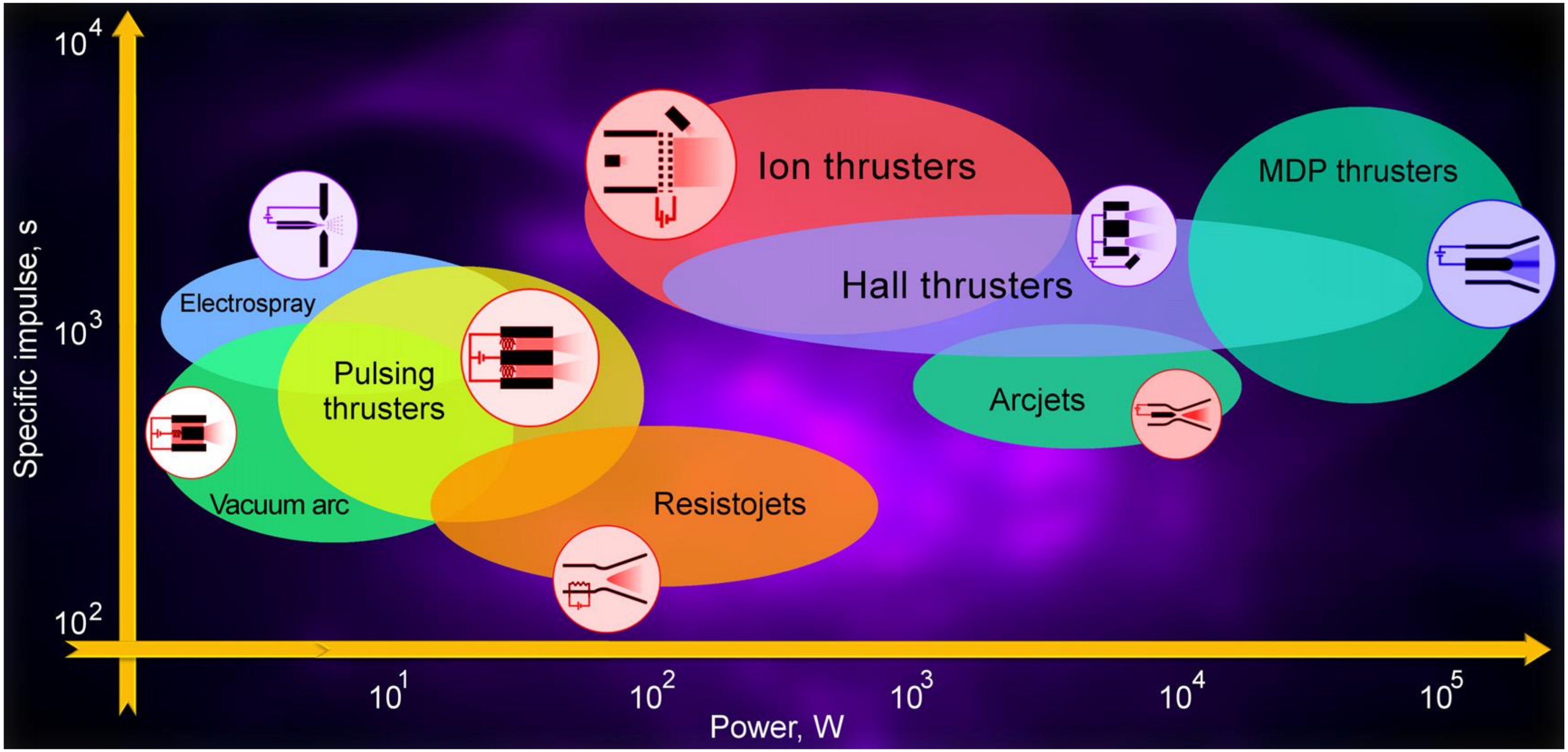
- **We are looking for students who are interested in electrical propulsion.**

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 /**

Summary

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)

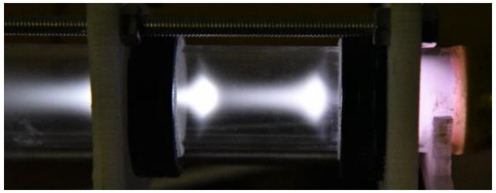
d. Magnetic mirror

e. Tesla coil

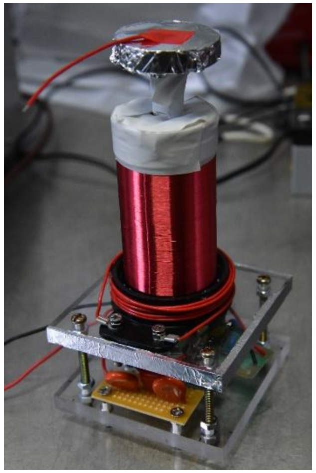
Planeterrella

Magnetron sputtering

DBD plasma

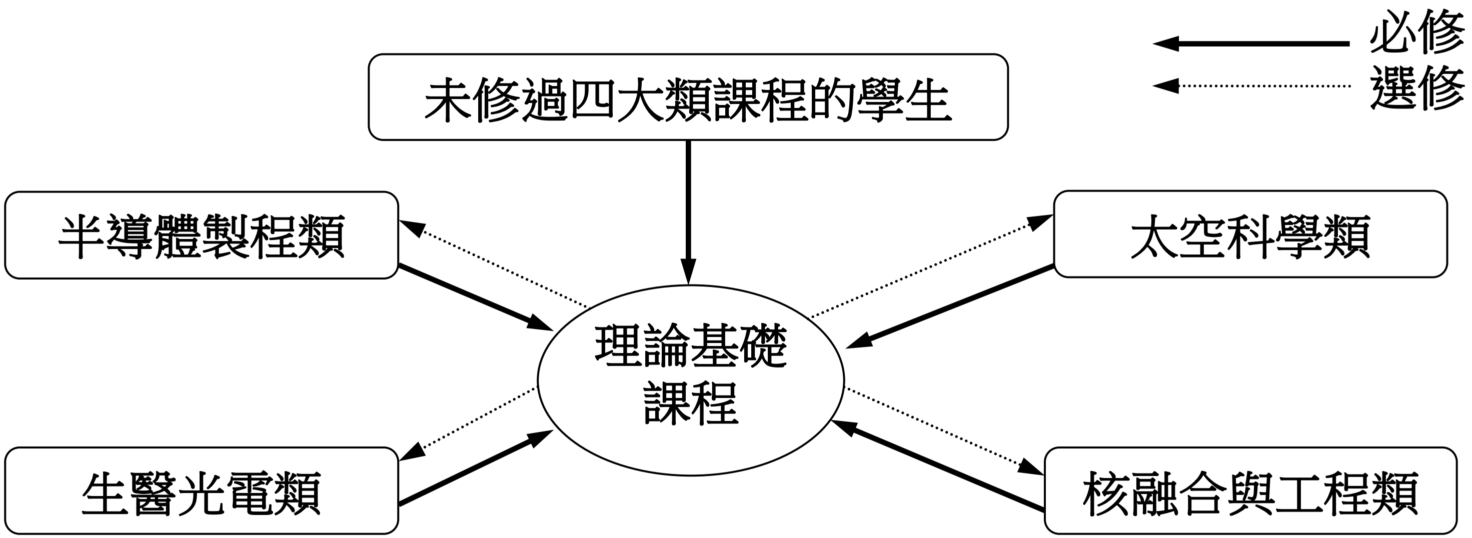


Magnetic mirror



Tesla Coil

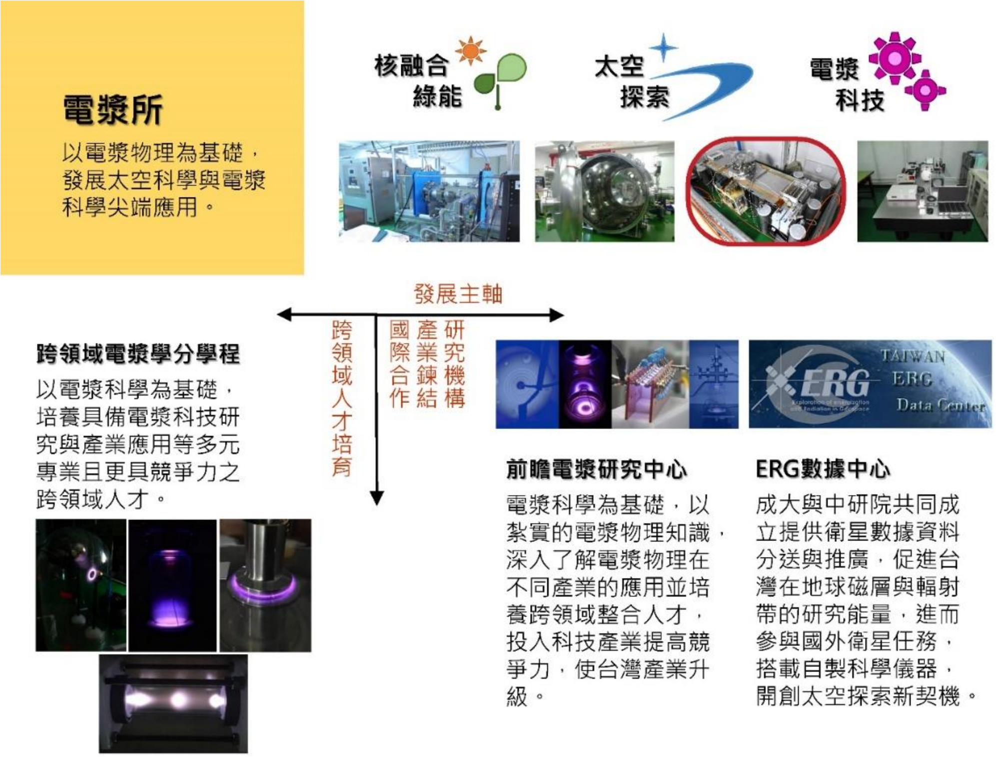
深入的電漿知識請選修 電漿學分學程



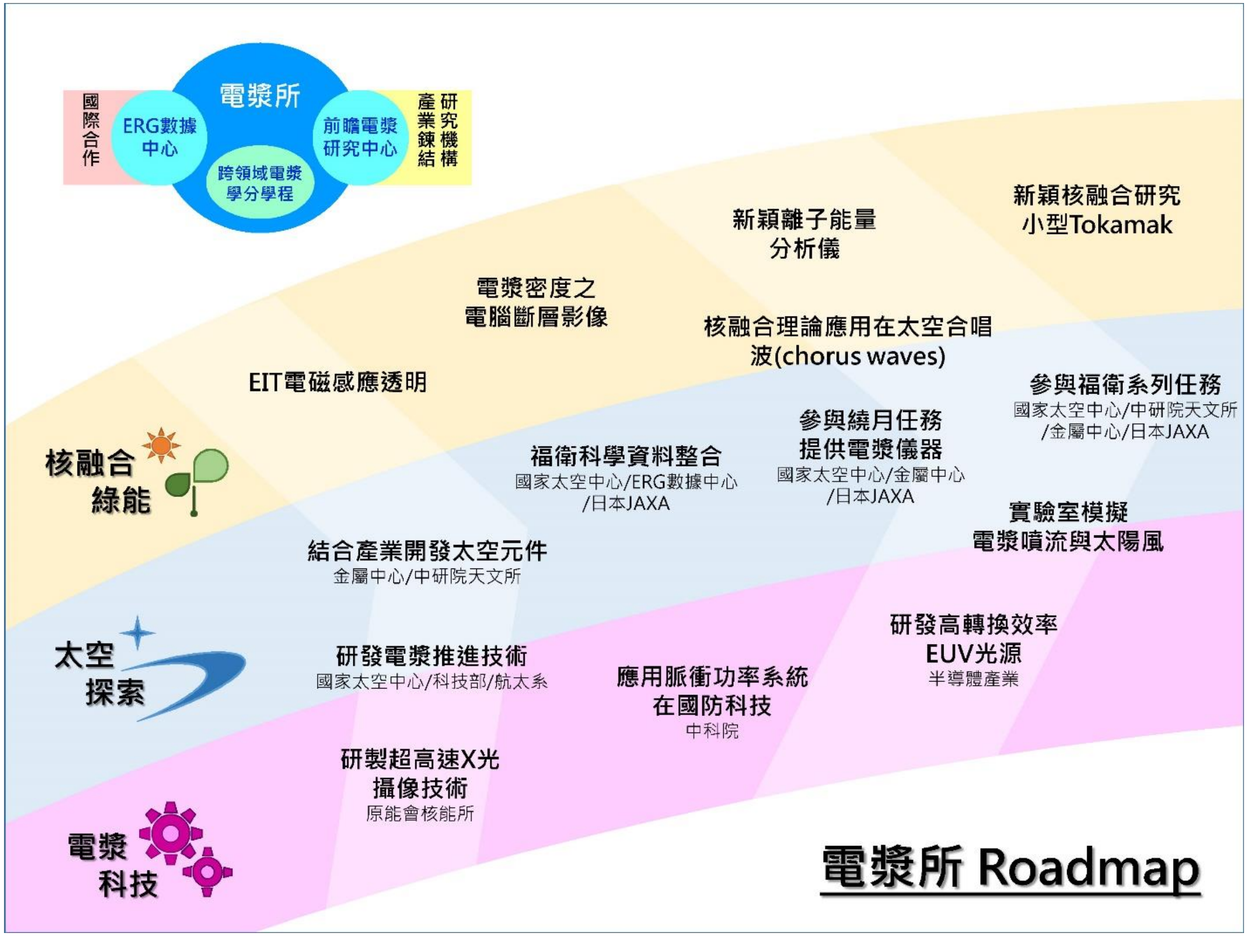
- 將培養具備電漿科技研究與產業應用等多元專業且更具競爭力之跨領域人才.

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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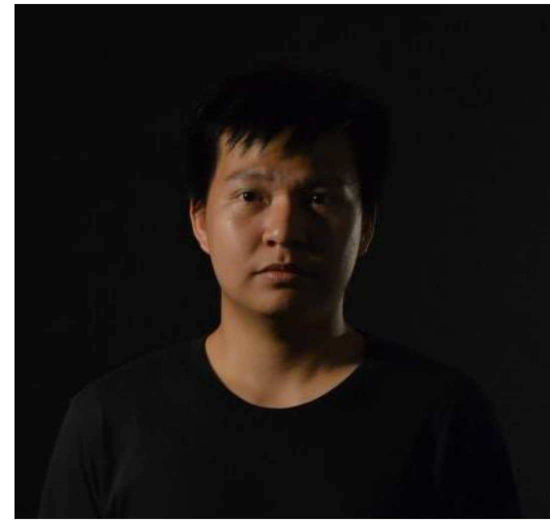

Grading

- **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**