Introduction to Nuclear Fusion as An Energy Source

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Institute of Space and Plasma Sciences, National Cheng Kung University

Lecture 10

2025 spring semester

Tuesday 9:00-12:00

Materials:

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

Online courses:

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

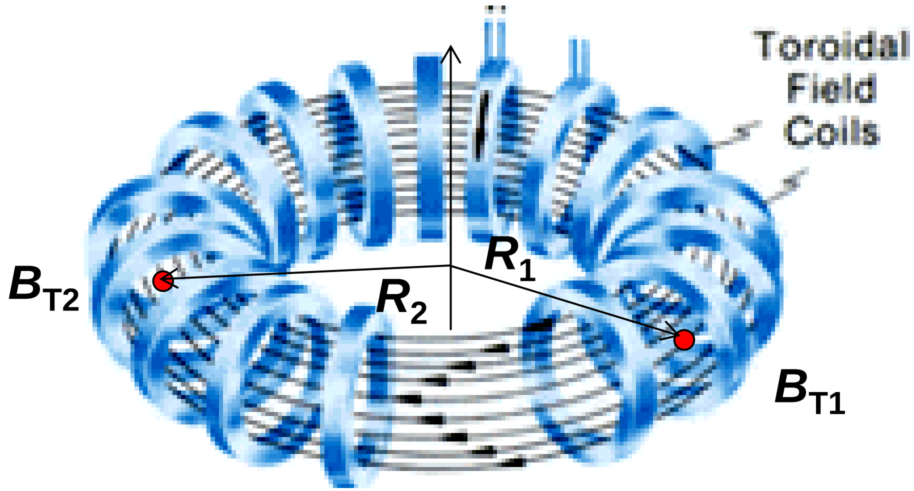
2025/5/13 updated

With poloidal fields, charged particles see nonuniform toroidal magnetic field

- **W/o poloidal field**

$$R_1 = R_2$$

$$B_{T1} = B_{T2}$$



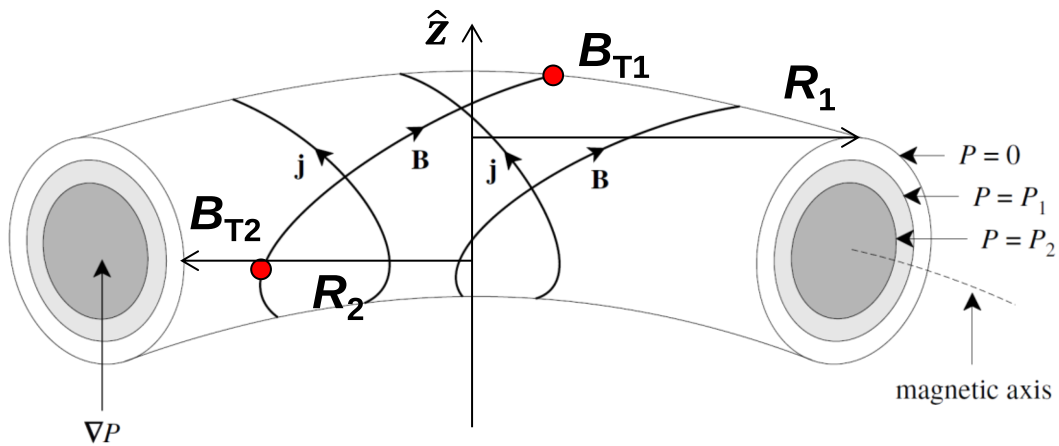
$$B_T \propto \frac{1}{R}$$

$$B_T \gg B_p$$

- **W/ poloidal field**

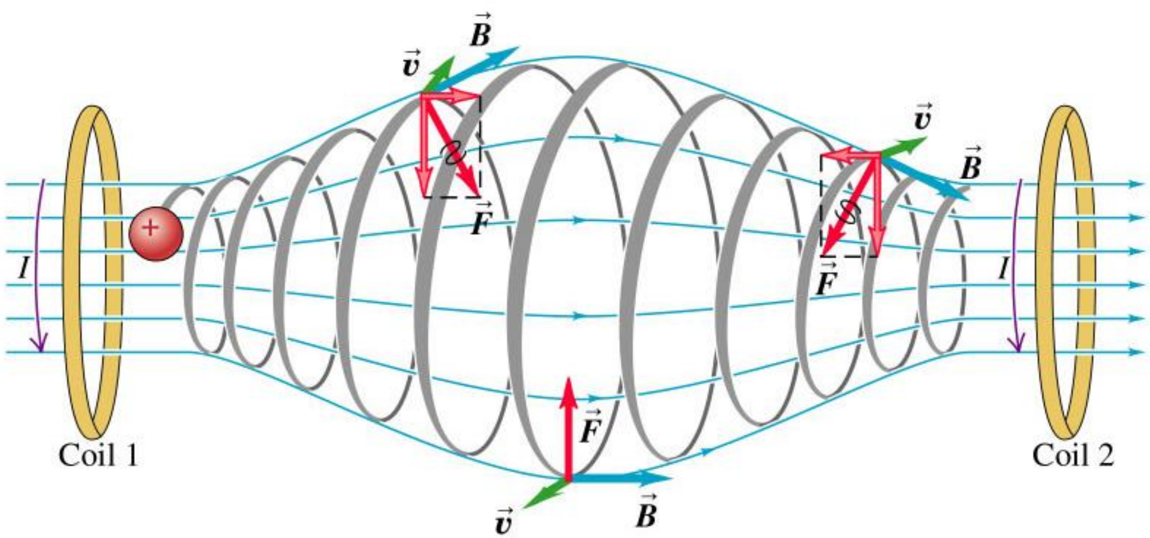
$$R_1 > R_2$$

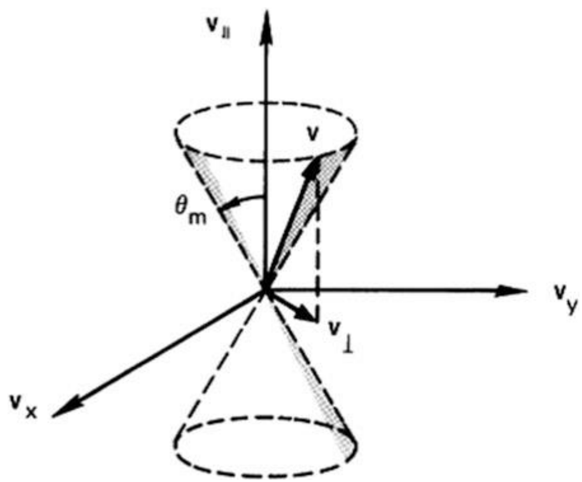
$$B_{T1} < B_{T2}$$



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.**





$${v'_\perp}^2 = {v_{\perp o}}^2 + {v_{||o}}^2 \equiv {v_o}^2$$

$$\frac{B_o}{B'} = \frac{{v_{\perp o}}^2}{{v'_\perp}^2} = \frac{{v_{\perp o}}^2}{{v_o}^2} \equiv sin^2\theta$$

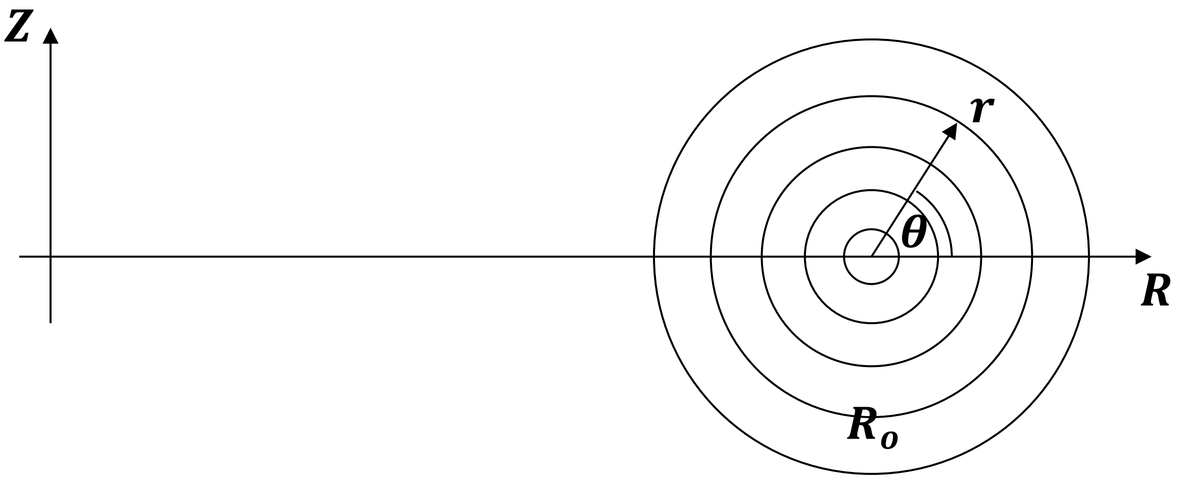
$$\frac{1}{2}mv^2 = \frac{1}{2}m{v_{||}}^2 + \frac{1}{2}m{v_\perp}^2 \quad \text{Invarient: } \mu \equiv \frac{1}{2}\frac{m{v_\perp}^2}{B}$$

$$\frac{B_o}{B_m} \equiv \frac{1}{R_m} = sin^2\theta_m$$

- **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

Parallel velocity changes when particles follow field the field line



$R \gg r$

$B_{\mathrm{T}} \gg B_{\mathrm{p}}$

$R = R_{\mathrm{o}} + r\cos\theta = R_{\mathrm{o}}(1 + \epsilon\cos\theta)$ **Inverse aspect ratio:** $\epsilon \equiv \dfrac{r}{R_{\mathrm{o}}}$

$$B \simeq \frac{B_{\mathrm{o}}}{1 + \epsilon\cos\theta} \simeq B_{\mathrm{o}}(1 - \epsilon\cos\theta)$$

Invarient: $\mu \equiv \dfrac{1}{2}\dfrac{m{v_\perp}^2}{B}$ $\quad \dfrac{{v_\perp}^2}{B_o(1 - \epsilon cos\theta)} = \dfrac{{v_{\perp 0}}^2}{B_o(1 - \epsilon)}$ $\quad {v_\perp}^2 = \dfrac{{v_{\perp 0}}^2(1 - \epsilon cos\theta)}{1 - \epsilon}$

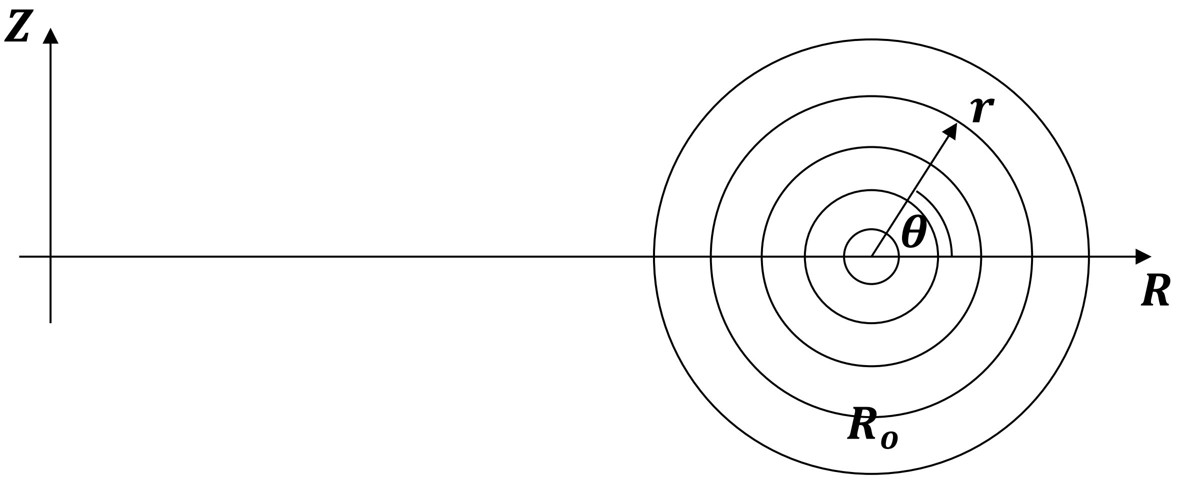
$$v^2 = {v_\perp}^2 + {v_{||}}^2 = {v_{\perp o}}^2 + {v_{||o}}^2$$

$$v_{||}{}^2 = v^2\left(1 - \frac{{v_{\perp 0}}^2}{v^2}\frac{(1 - \epsilon\cos\theta)}{1 - \epsilon}\right)$$

$$v_{||}{}^2 = v^2\left(1 - \frac{{v_\perp}^2}{v^2}\right)$$

$$\approx v^2\left(1 - \frac{{v_{\perp 0}}^2}{v^2}\left(1 + 2\epsilon\sin^2\left(\frac{\theta}{2}\right)\right)\right)$$

Particles may be trapped by nonuniform magnetic field



$$R \gg r$$

$$B_{\mathrm{T}} \gg B_{\mathrm{p}}$$

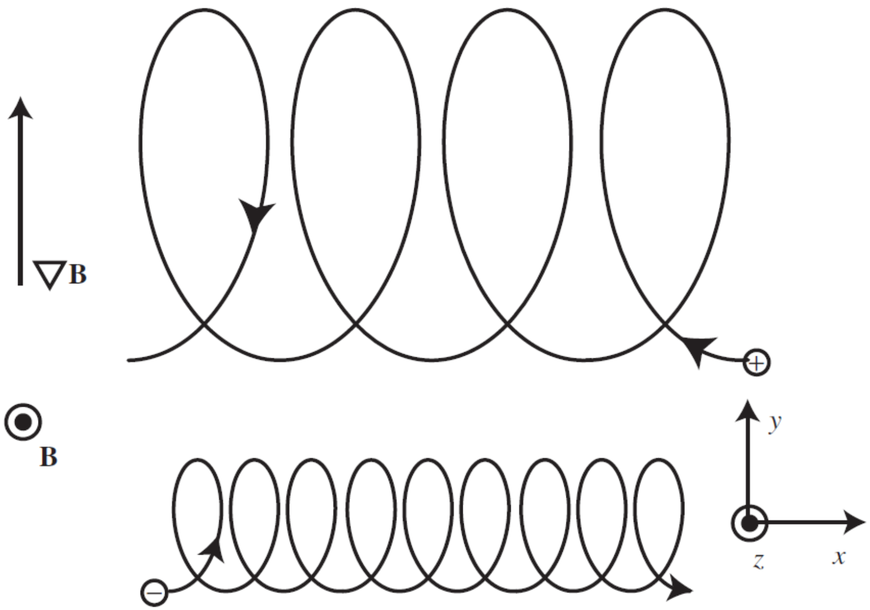
$$\epsilon \equiv \frac{r}{R_{\mathrm{o}}}$$

$$v_{||}{}^{2} \approx v^{2}\left(1-\frac{v_{\perp 0}{}^{2}}{v^{2}}\left(1+2\epsilon\sin^{2}\left(\frac{\theta}{2}\right)\right)\right)$$

- For $v_{||}{}^{2} \geq 0$, particles are passing.
- For $v_{||}{}^{2} \leq 0$, particles are trapped.

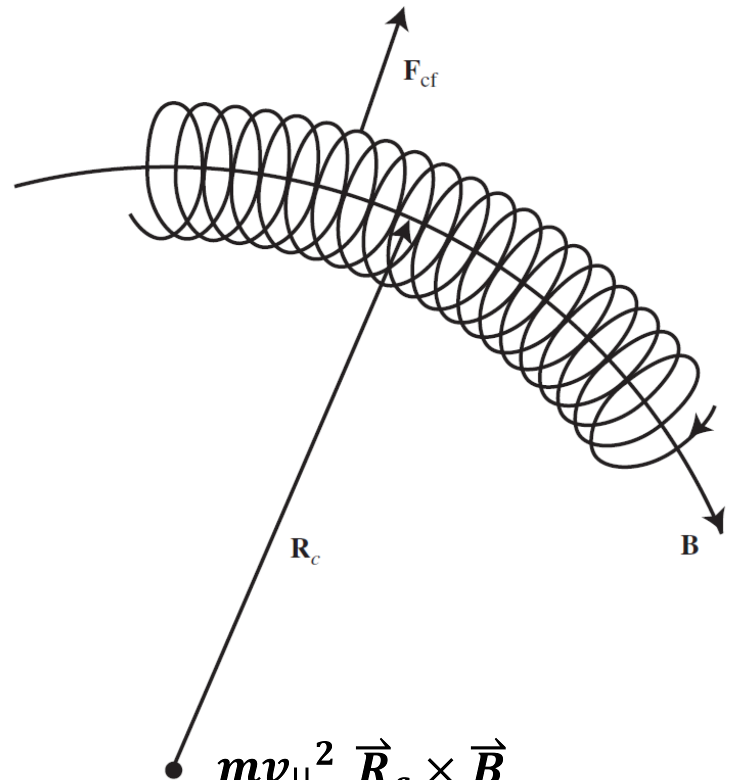
Charge particles drift across magnetic field lines when the magnetic field is not uniform or curved

- **Gradient-B drift**



$$\vec{v}_{\nabla} = \frac{m{v_{\perp}}^2}{2q}\frac{\vec{B}\times\nabla B}{B^3}$$

- **Curvature drift**

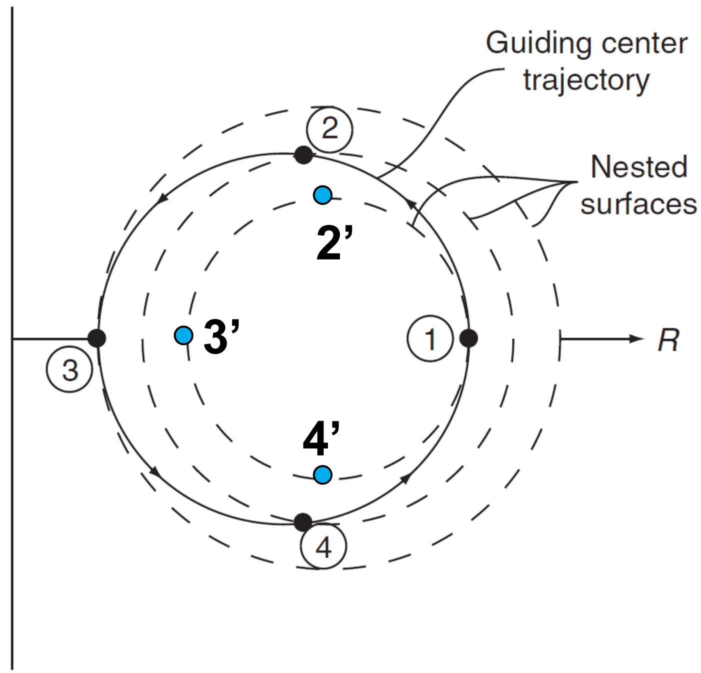


$$\vec{v}_{R} = \frac{m{v_{||}}^2}{2q}\frac{\vec{R}_c\times\vec{B}}{R_c B^2}$$

$$\vec{v}_{\text{total}} = \vec{v}_{R} + \vec{v}_{\nabla} = \frac{\vec{B}\times\nabla B}{\omega_c B^2}\left({v_{||}}^2 + \frac{1}{2}{v_{\perp}}^2\right) = \frac{m}{q}\frac{\vec{R}_c\times\vec{B}}{{R_c}^2 B^2}\left({v_{||}}^2 + \frac{1}{2}{v_{\perp}}^2\right)$$

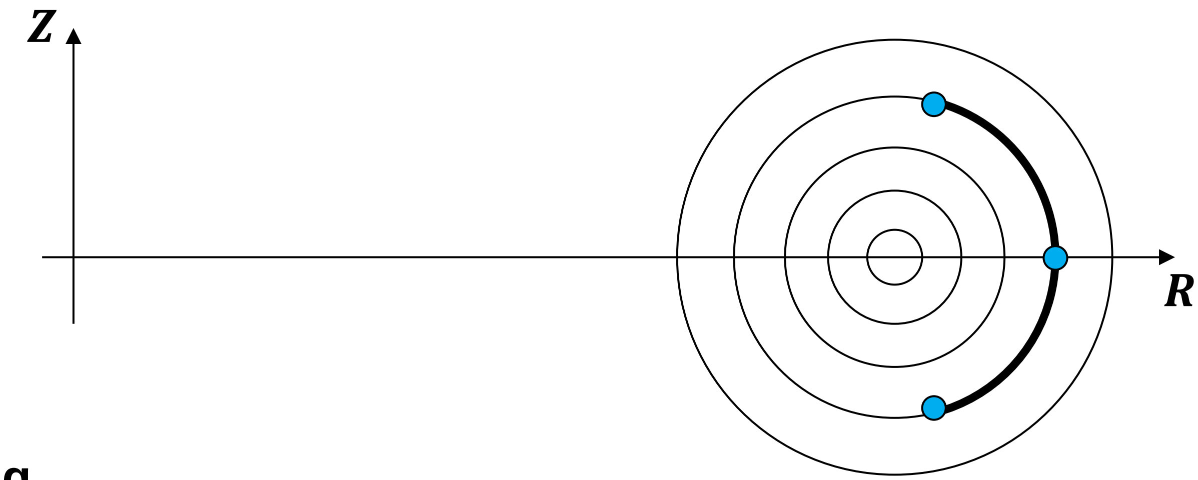
For passing particles, they drift back to the original position with a “semicircle” orbit

$$\vec{v}_{\text{total}} = \vec{v}_{\text{R}} + \vec{v}_{\nabla} = \frac{\vec{B} \times \nabla B}{\omega_c B^2}\left(v_{||}^2 + \frac{1}{2}v_{\perp}^2\right) = \frac{m}{q}\frac{\vec{R}_c \times \vec{B}}{R_c^2 B^2}\left(v_{||}^2 + \frac{1}{2}v_{\perp}^2\right)$$

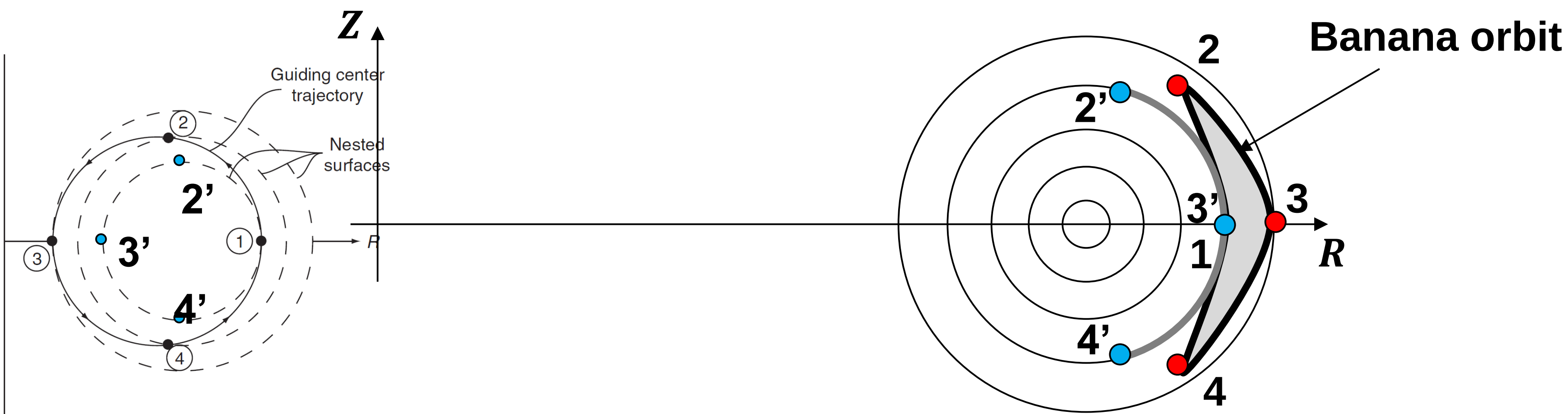


For trapped particles, they drift back to the original position with a banana orbit

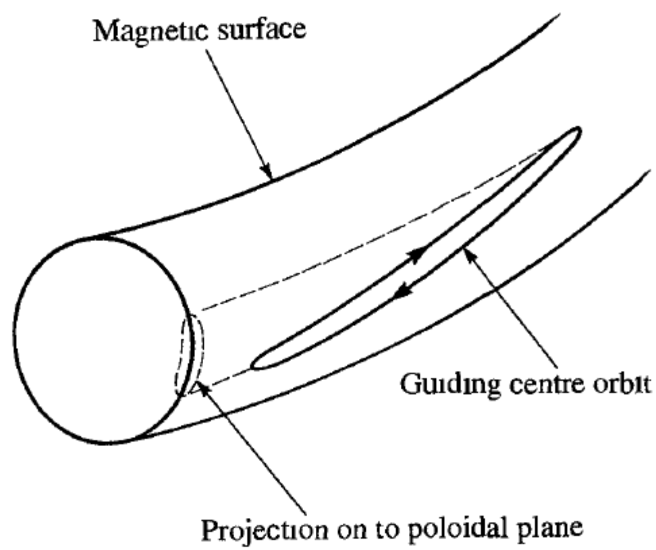
- W/o drifting

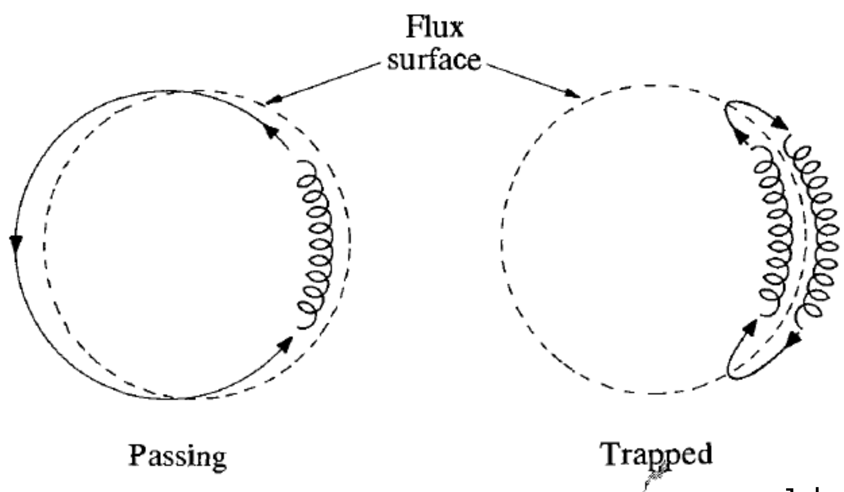


- W/ drifting



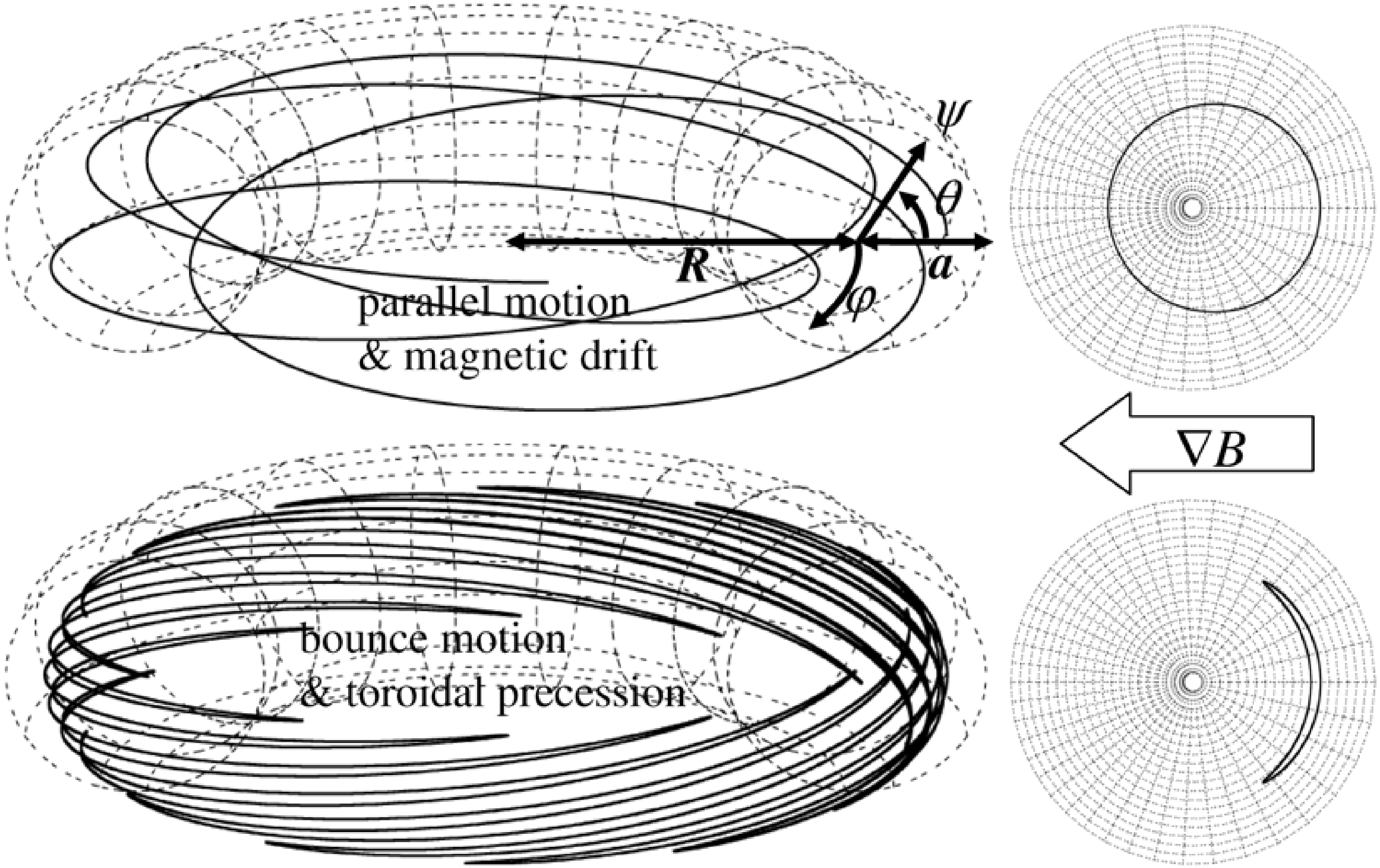
Trajectories of charged particles





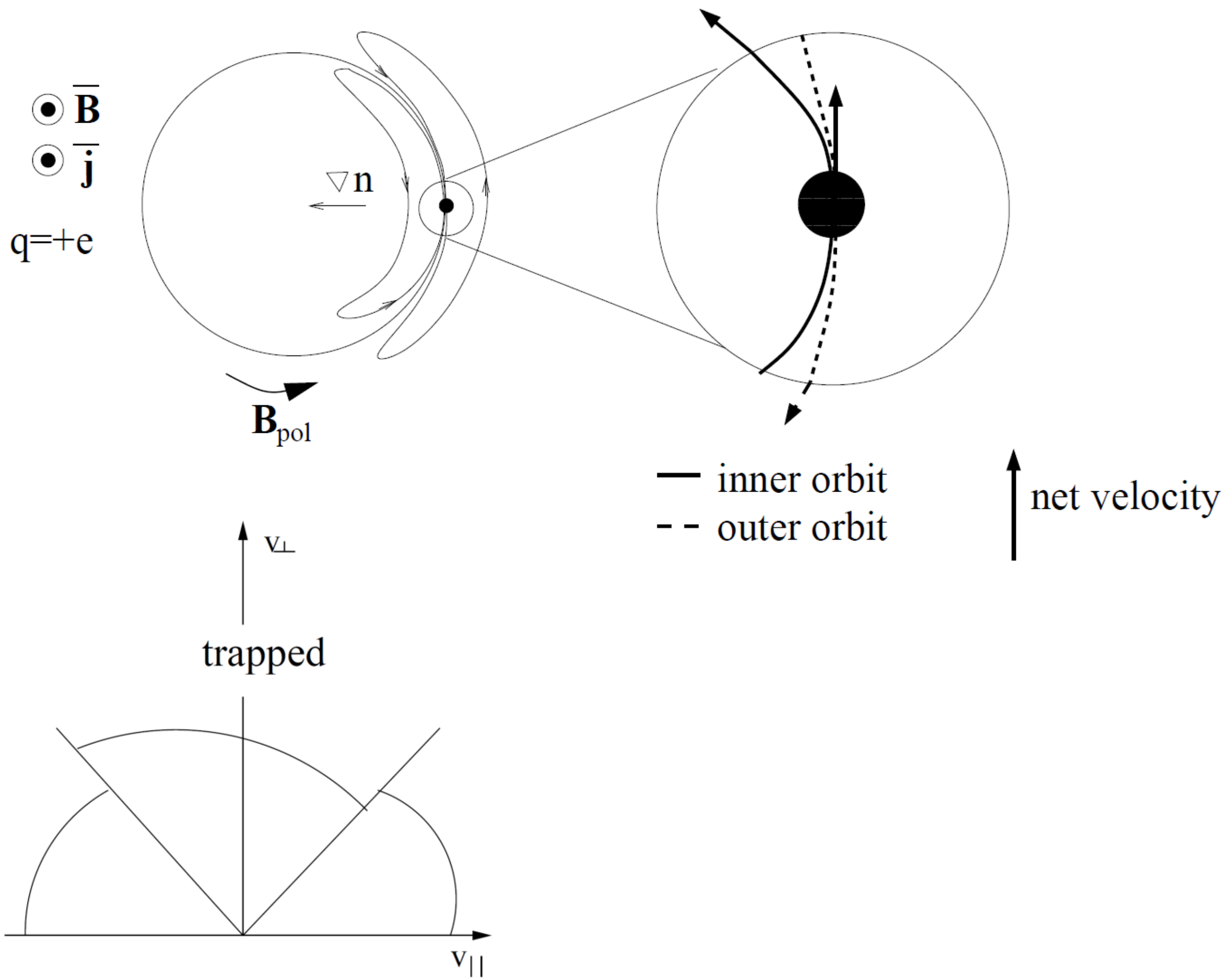
John Wesson, Tokamaks 3rd edition

The trajectories of charged particles follow the toroidal field lines



X. Garbet et al, Nucl. Fusion **50**, 043002 (2010)

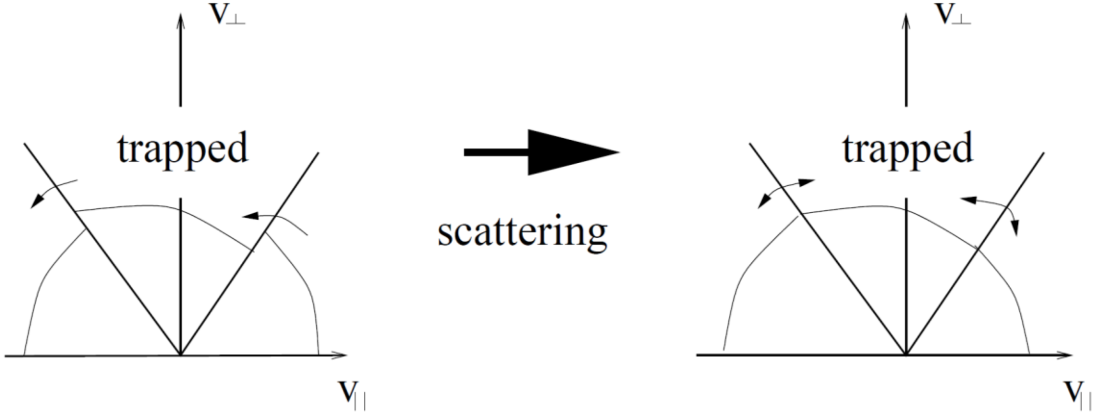
A banana current is generated when there is a pressure gradient in the plasma

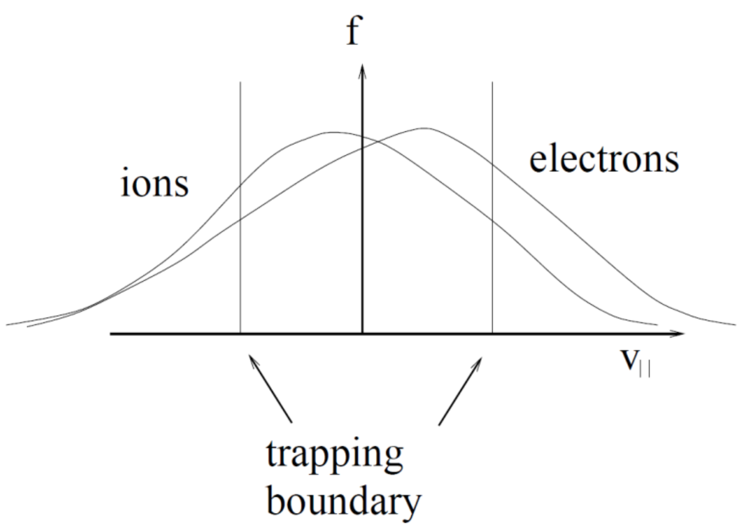


Samuli Saarelma, Helsinki University of Technology, PhD Thesis 2015

Bootstrap current is generated when passing particles are scattered by the trapped particles

- **Scattering smooths the velocity distribution and shifts it in the parallel direction, i.e., a current is generated. It is called the bootstrap current.**



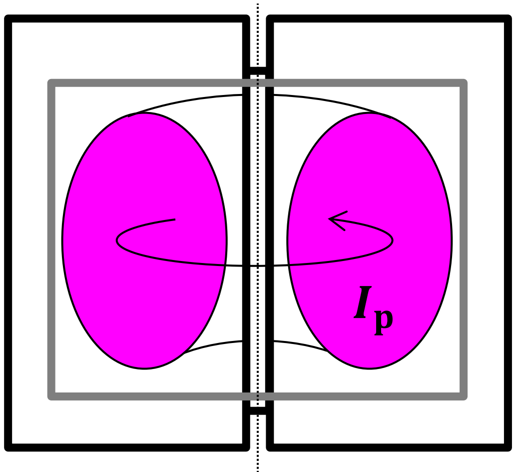


$$\boldsymbol{j = -enu_{||\mathrm{e}} + enu_{||\mathrm{i}} = 4\epsilon^{3/2}\frac{1}{B_{\mathrm{p}}}T\frac{dn}{dr}}$$

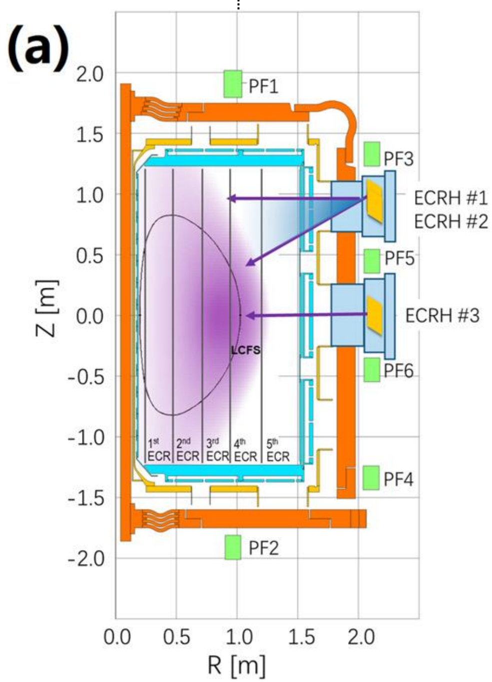
- **The bootstrap current is vital for steady-state operation.**

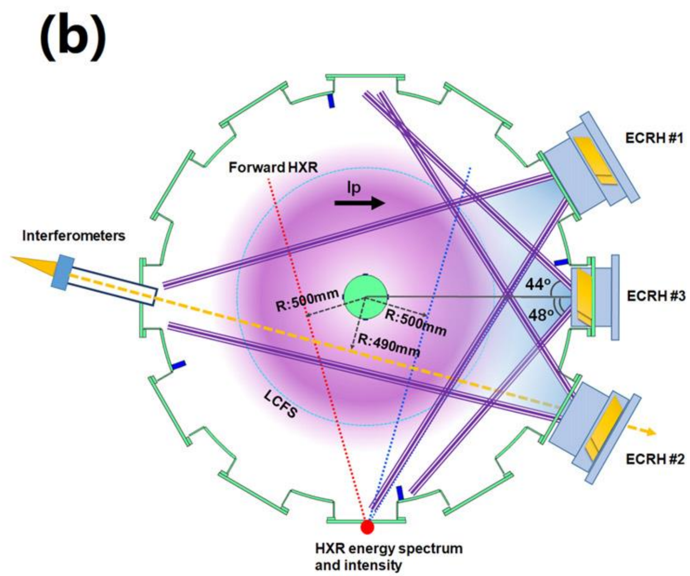
Samuli Saarelma, Helsinki University of Technology, PhD Thesis 2015

Momentum exchange may be needed to drive plasma current



$$\vec{j}_{\mathbf{p}} = \Sigma q n \vec{v} = -e n_{\mathbf{e}} \vec{v}_{\mathbf{e}} + e n_{\mathbf{i}} \vec{v}_{\mathbf{i}}$$

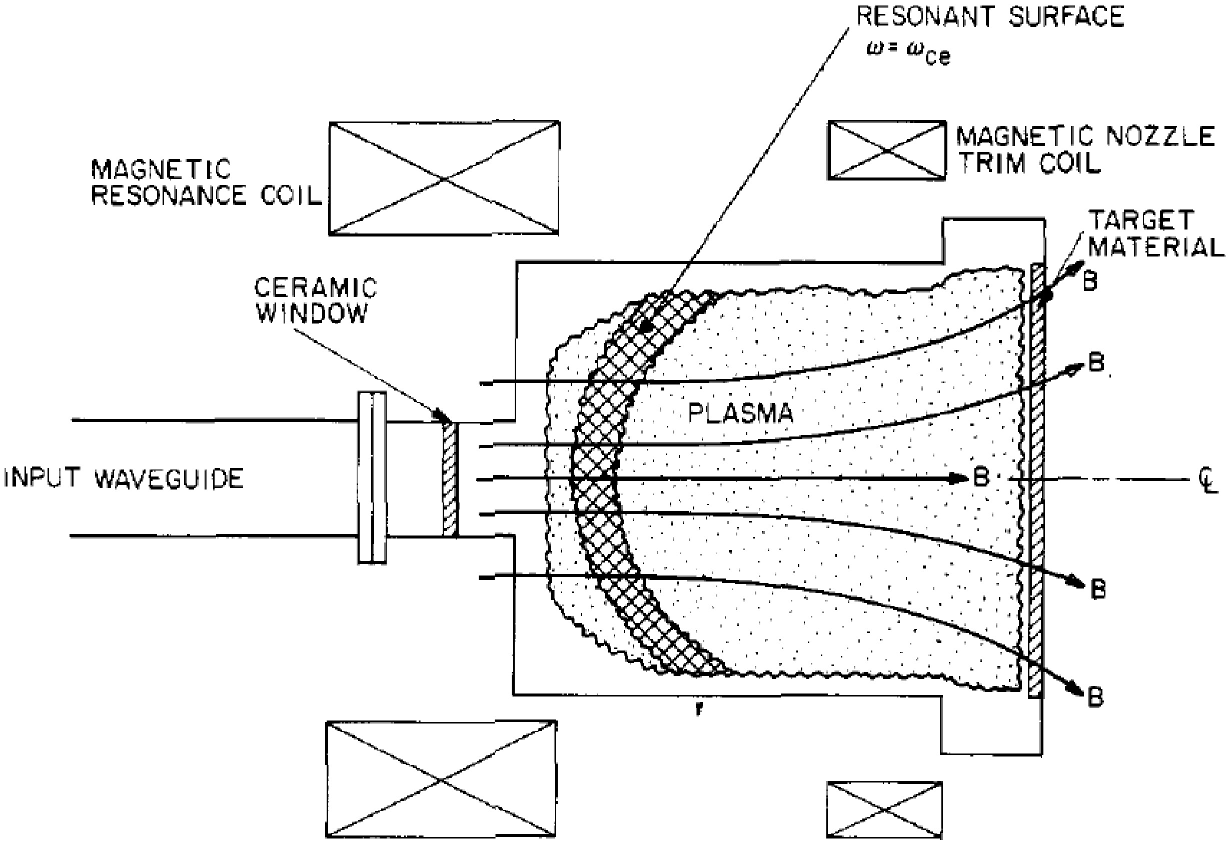




Yuejiang Shi et al, Nucl. Fusion **62**, 086047 (2022)

Strong absorption occurs when the frequency matches the electron cyclotron frequency

- **Electron cyclotron resonance (ECR) plasma reactor**



Electron cyclotron frequency depends on magnetic field only

$$m_e \frac{d\,\vec{v}}{\mathrm{dt}} = -\frac{e}{c}\,\vec{v} \times \vec{B}$$

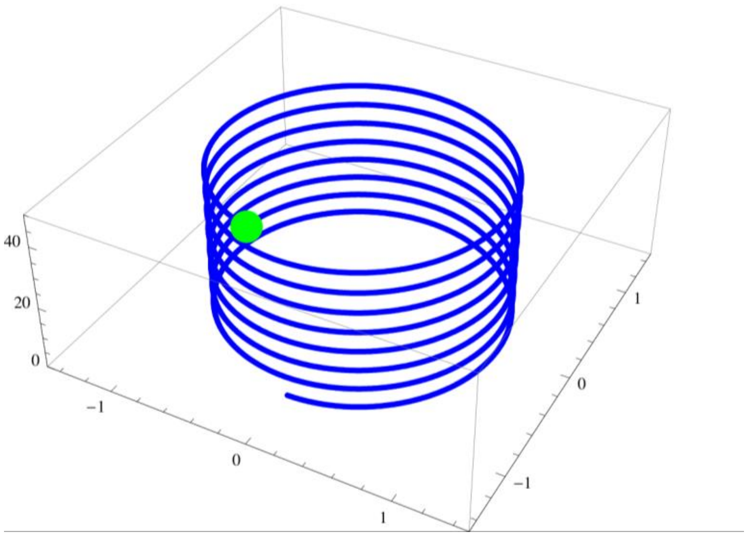
- **Assuming $\vec{B} = B\hat{z}$ and the electron oscillates in x-y plane**

$$m_e \dot{v}_x = -\frac{e}{c} B v_y \qquad m_e \dot{v}_z = 0$$

$$m_e \dot{v}_y = \frac{e}{c} B v_x$$

$$\ddot{v}_x = -\frac{eB}{m_e c}\dot{v}_y = -\left(\frac{eB}{m_e c}\right)^2 v_x$$

$$\ddot{v}_y = -\frac{eB}{m_e c}\dot{v}_x = -\left(\frac{eB}{m_e c}\right)^2 v_y$$



- **Therefore**

$$\omega_{\mathrm{ce}} = \frac{eB}{m_e c}$$

Electrons keep getting accelerated when a electric field rotates in electron's gyrofrequency

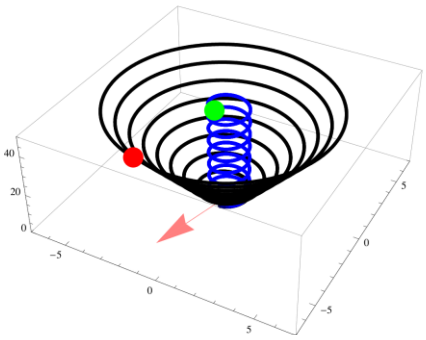
$$m_e \frac{d\vec{v}}{\mathrm{dt}} = -\frac{e}{c}\vec{v} \times \vec{B} - e\vec{E} \qquad \vec{B} = B_0\hat{z} \qquad \vec{E} = E_0[\hat{x}\cos(\omega t) + \hat{y}\sin(\omega t)]$$

$$m_e\dot{v}_x = -\frac{e}{c}Bv_y + E_0\cos(\omega t) \qquad m_e\dot{v}_y = \frac{e}{c}Bv_x + E_0\cos(\omega t) \qquad m_e\dot{v}_z = 0$$

$$\ddot{v}_x = -\frac{eB}{m_e c}\dot{v}_y - \frac{E_0}{m_e}\omega\cos(\omega t) = -\omega_{ce}{}^2 v_x - \frac{E_0}{m_e}(\omega_{ce} + \omega)\cos(\omega t)$$

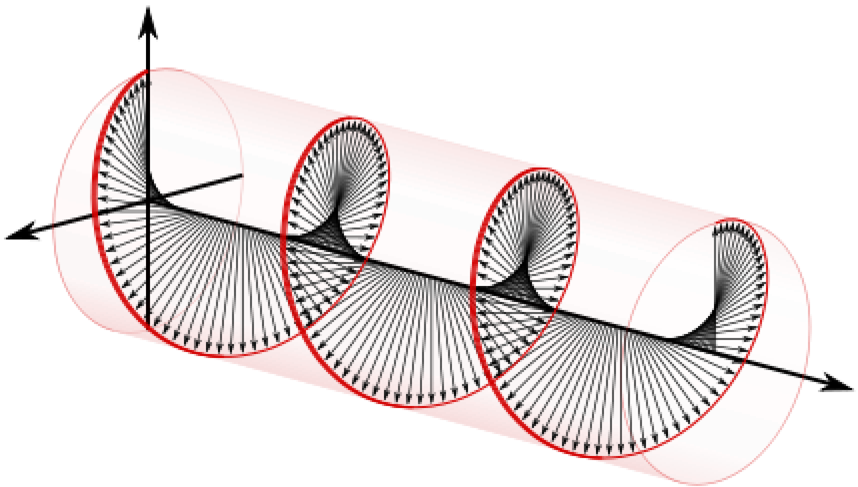
$$\ddot{v}_y = -\frac{eB}{m_e c}\dot{v}_x + \frac{E_0}{m_e}\omega\sin(\omega t) = -\omega_{ce}{}^2 v_y + \frac{E_0}{m_e}(\omega_{ce} + \omega)\sin(\omega t)$$

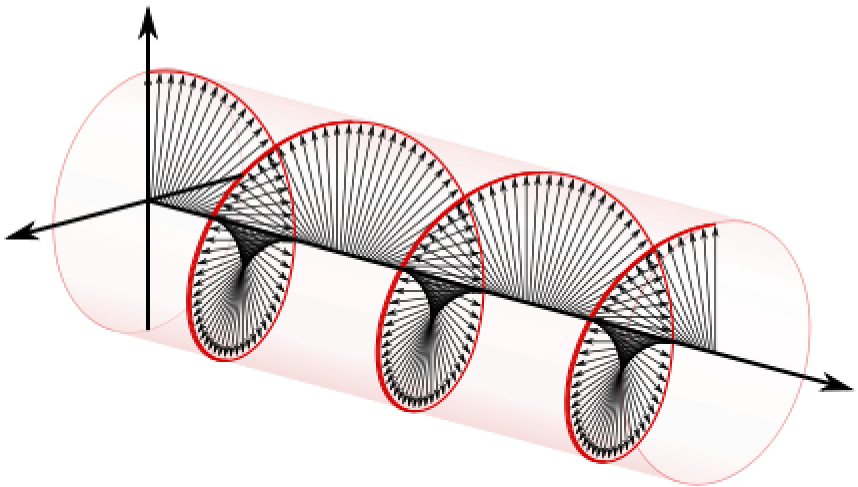
$$\omega_{ce} = \frac{eB}{m_e c}$$



Electric field in a circular polarized electromagnetic wave keeps rotating as the wave propagates

- **Right-handed polarization**
- **Left-handed polarization**





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

Only right-handed polarization can resonance with electron's gyromotion

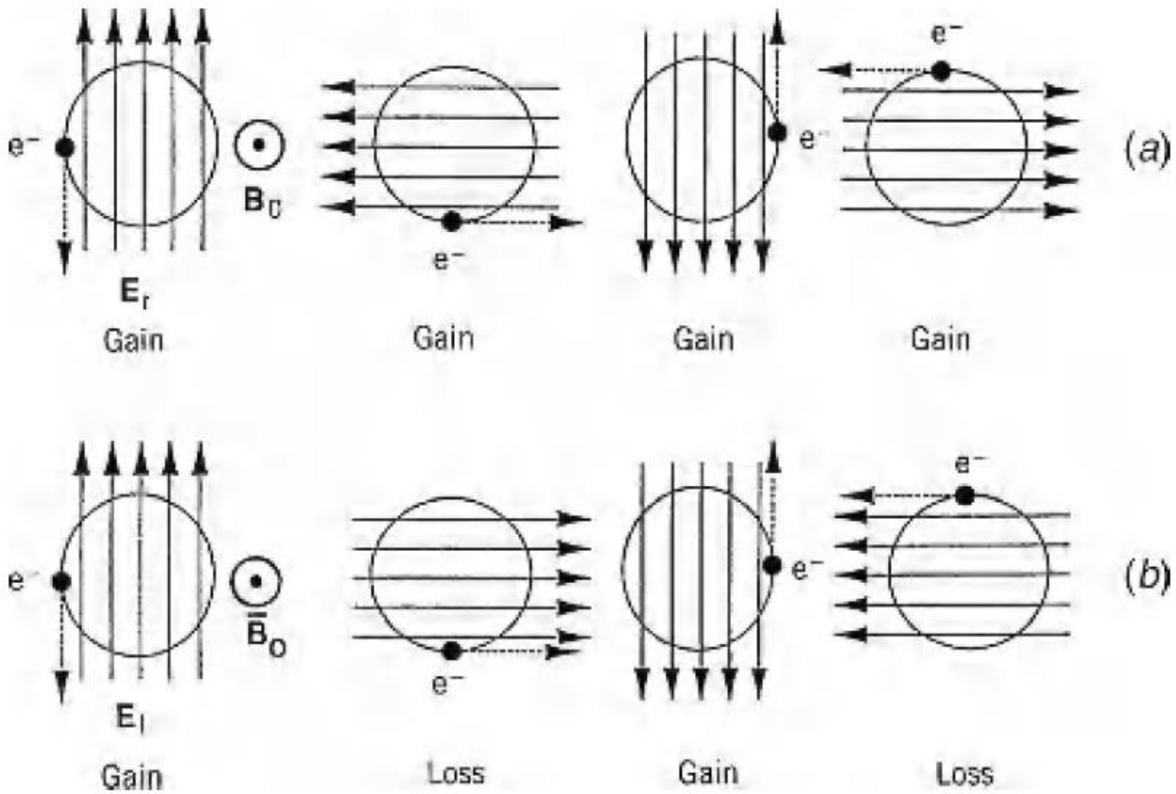
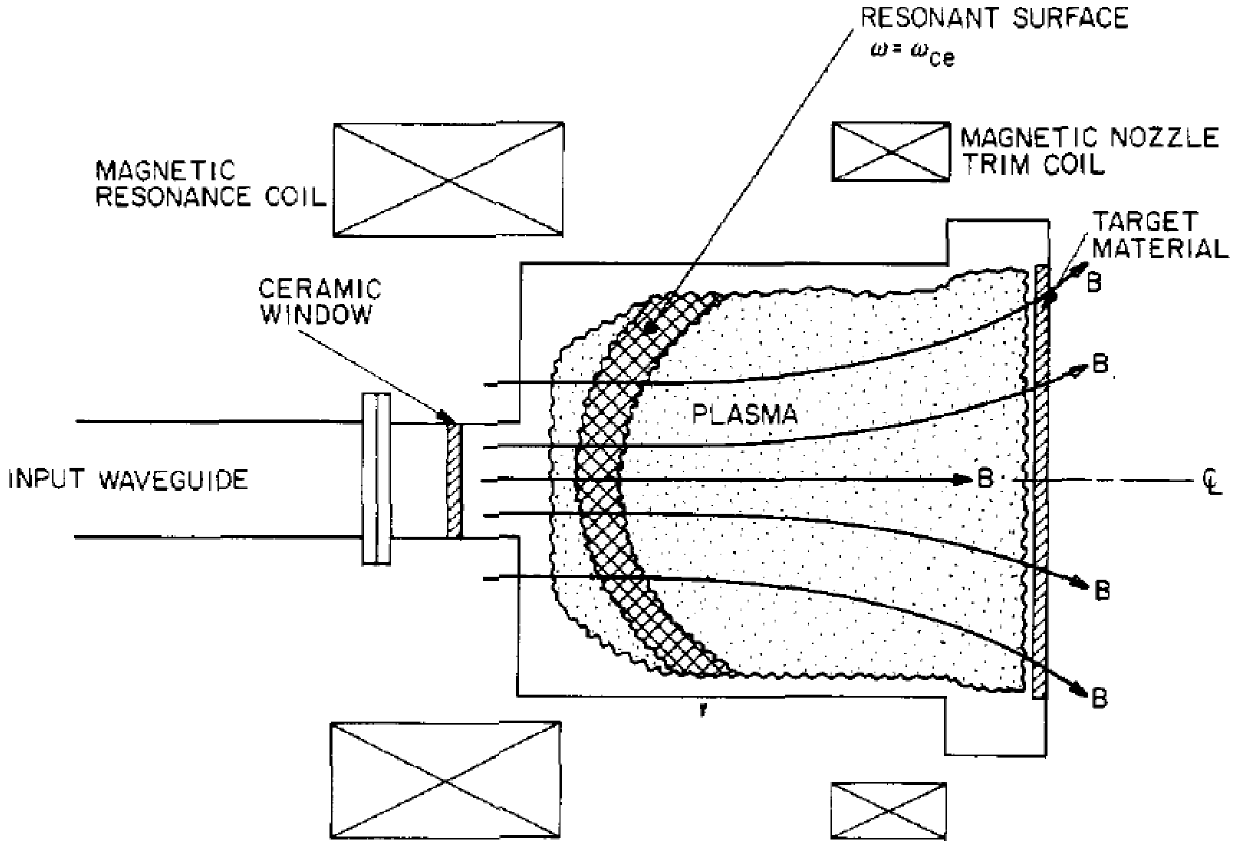


FIGURE 13.5. Basic principle of ECR heating: (*a*) continuous energy gain for right-hand polarization; (*b*) oscillating energy for left-hand polarization (after Lieberman and Gottscho, 1994).

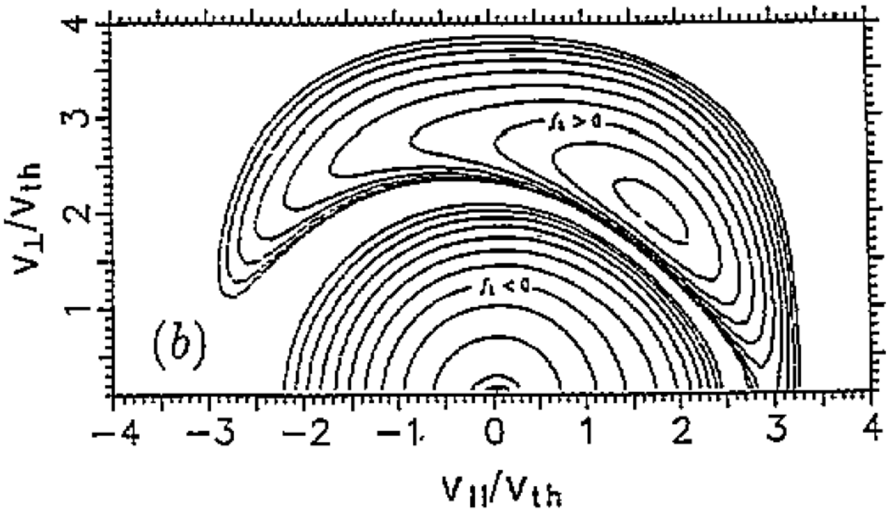
Strong absorption occurs when the frequency matches the electron cyclotron frequency

- **Electron cyclotron resonance (ECR) plasma reactor**



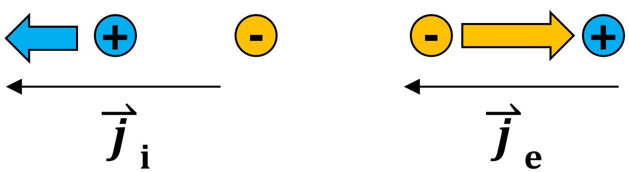
The collisional re-distribution of the ECRH-driven anisotropy in $E_\perp$ causes some parallel momentum to flow from e^- to ions

- **Coulomb collisions are more efficient at lower energies.**

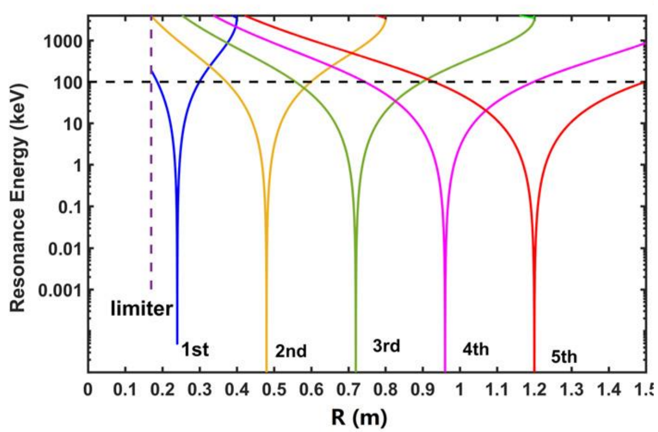


Velocity: $v_2 > v_1$

Collisions: $\nu_2 < \nu_1$



- **Electron cyclotron current drive:**



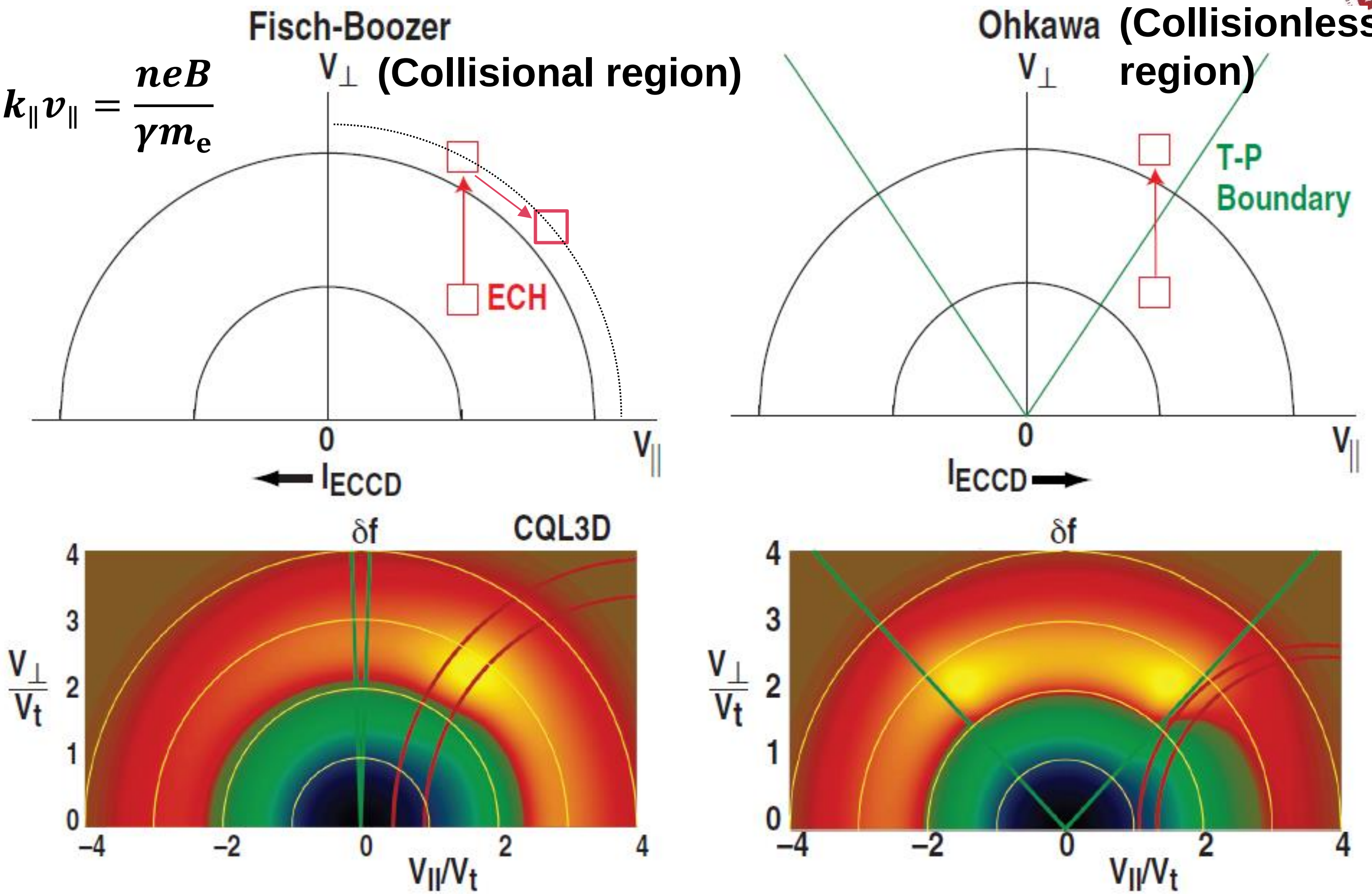
$$\vec{j}_{\mathrm{p}} = -en_{\mathrm{e}}\,\vec{v}_{\mathrm{e}} + en_{\mathrm{i}}\,\vec{v}_{\mathrm{i}}$$

$$\vec{P} = n_{\mathrm{e}}m_{\mathrm{e}}\,\vec{v}_{\mathrm{e}} + n_{\mathrm{i}}m_{\mathrm{i}}\,\vec{v}_{\mathrm{i}} \approx 0$$

V. Erckmann and U. Gasparion, Plasma Phys. Control. Fusion **36**, 1869 (1994)
Yuejiang Shi et al, Nucl. Fusion **62**, 086047 (2022)

Passing electrons can be trapped if the $v_\perp$ is increased by heating

$$\omega - k_\parallel v_\parallel = \frac{neB}{\gamma m_e}$$



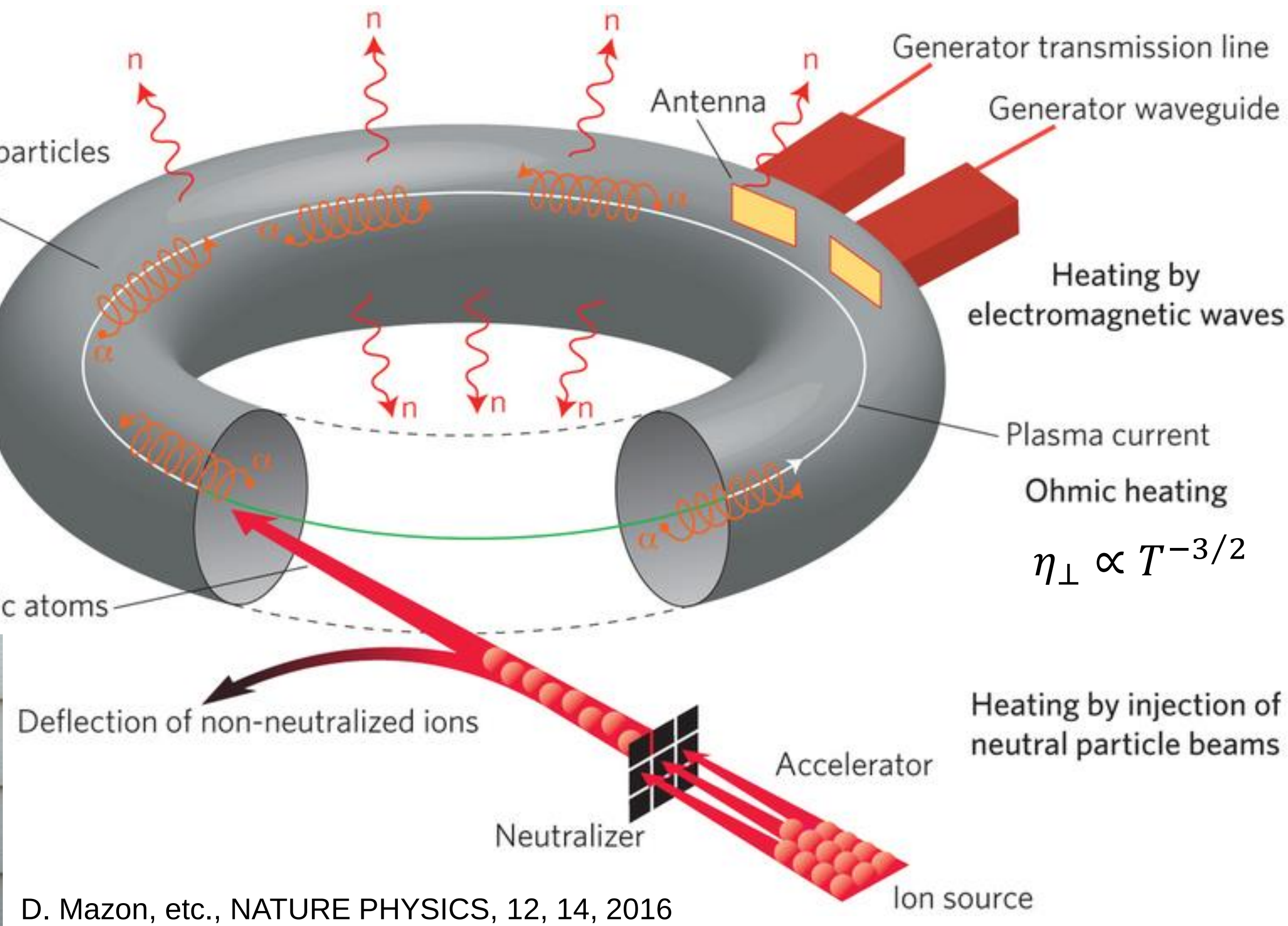
Lecture note "Physics and Applications of Electron Cyclotron Heating and Current Drive" by R. Prater from GA at 6th ITER International School 2012, Institute for Plasma Research, Gandhinagar Ahmedabad, India, December 2-6, 2012

Comparison of Fisch-Boozer Mechanism and Ohkawa Mechanism

Aspect	Fisch–Boozer Mechanism[1]	Ohkawa Mechanism[2]
Physical Process	Asymmetric heating of passing electrons with subsequent collisional momentum transfer	Selective de-trapping of barely trapped electrons into passing orbits (collisionless mechanism)
Requires collisions?	Yes (collisional mechanism)	No (collisionless pitch-angle scattering)
Key Particle Population	Passing electrons	Trapped (or barely trapped) electrons
Wave absorption location	Depends on Doppler-shifted resonance; typically near magnetic axis or mid-radius	Usually near edge where barely trapped particles are abundant

1 N. J. Fisch and A. H. Boozer, Phys. Rev. Lett. 45, 720 (1980).
2 T. Ohkawa, "Steady state operation of tokamaks by rf heating," General Atomics Report No. GA-A13847 (1976).

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

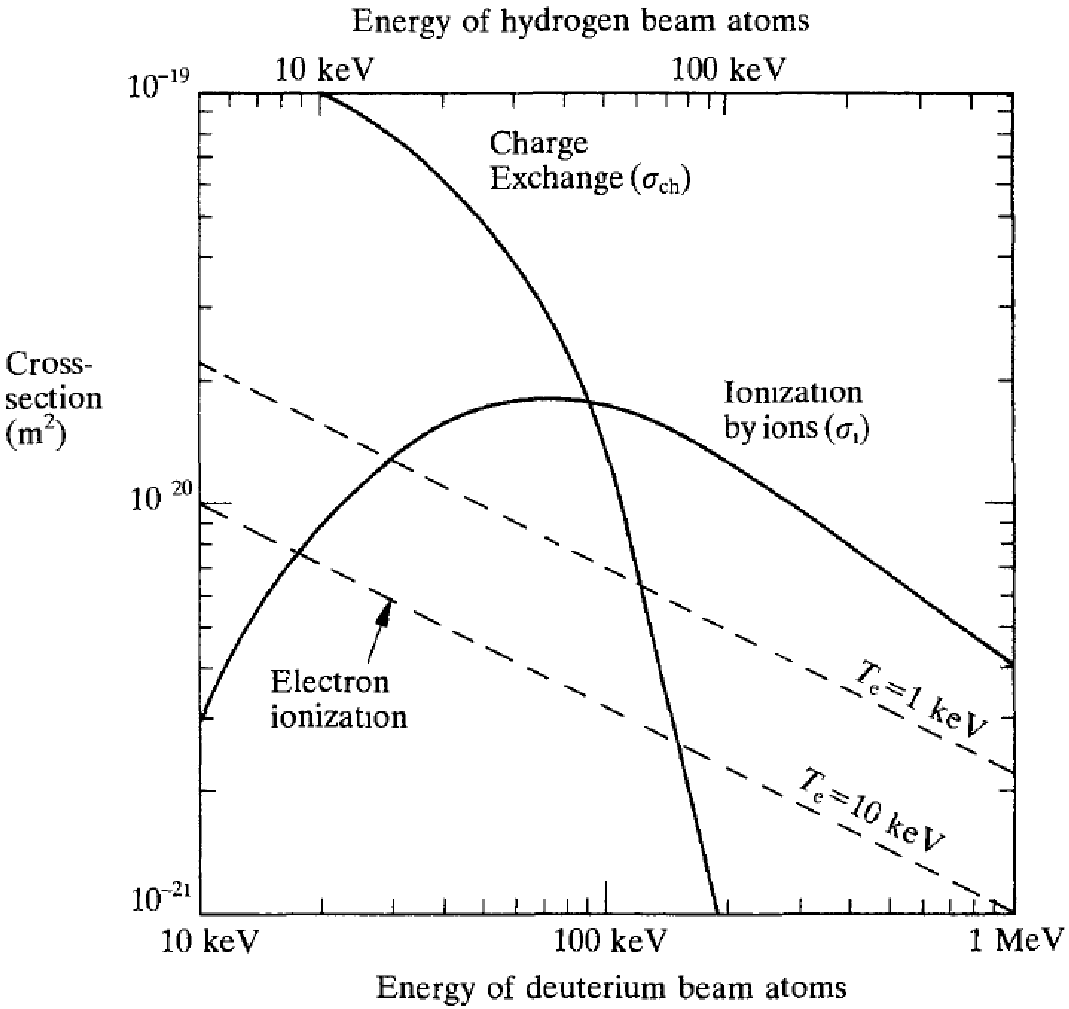
Varies way of heating a MCF device

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			
	−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 atoms are ionized by collisions in the plasma



- **Charge exchange:**

  $\mathbf{H_b + H_p^+ \rightarrow H_b^+ + H_p}$

- **Ionization by ions**

  $\mathbf{H_b + H_p^+ \rightarrow H_b^+ + H_p^+ + e^-}$

- **Ionization by electrons**

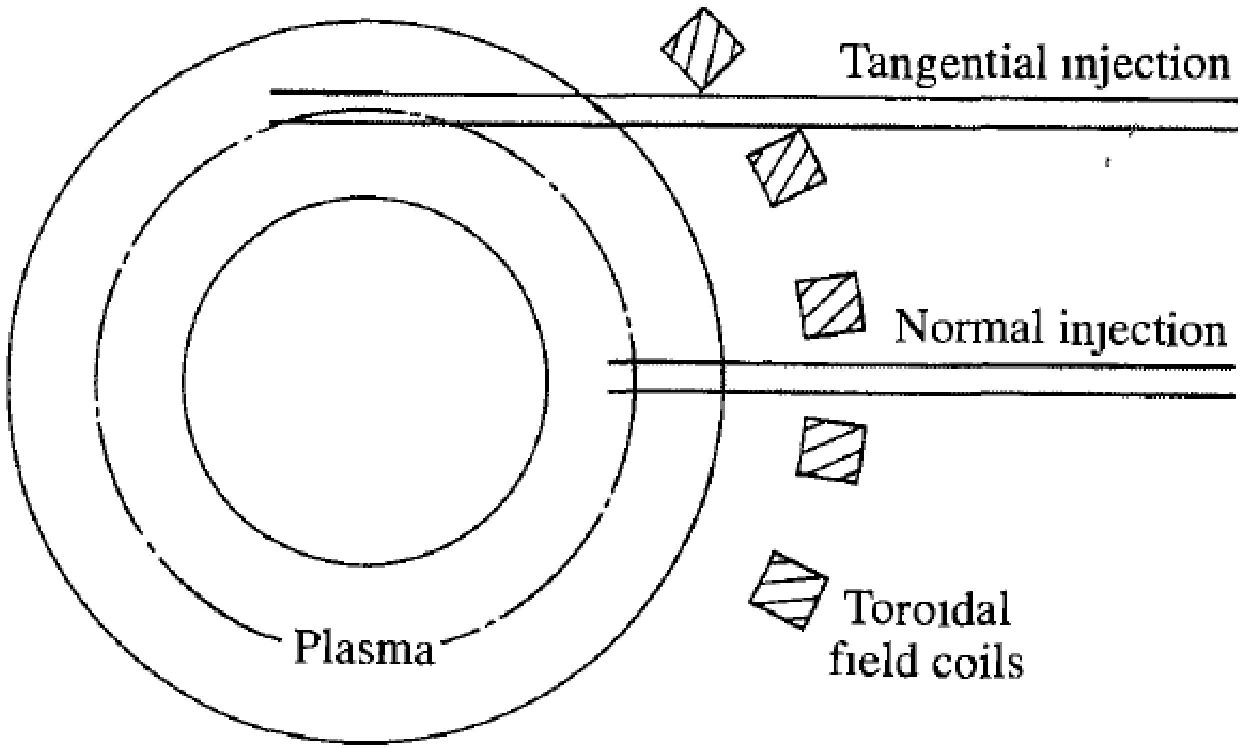
  $\mathbf{H_b + e^- \rightarrow H_b^+ + 2e^-}$

b: beam
p: plasma

John Wesson, Tokamaks 3rd edition

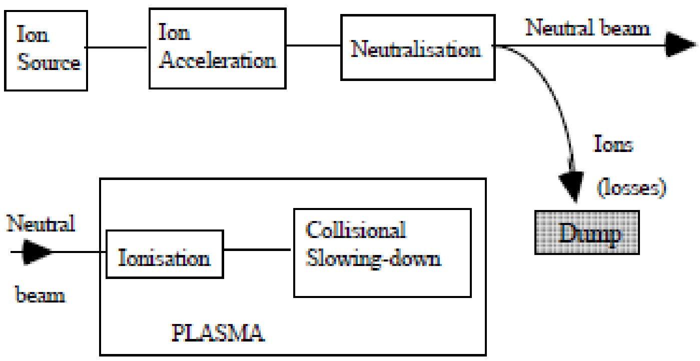
Neutral beam absorption length increases with tangential injection

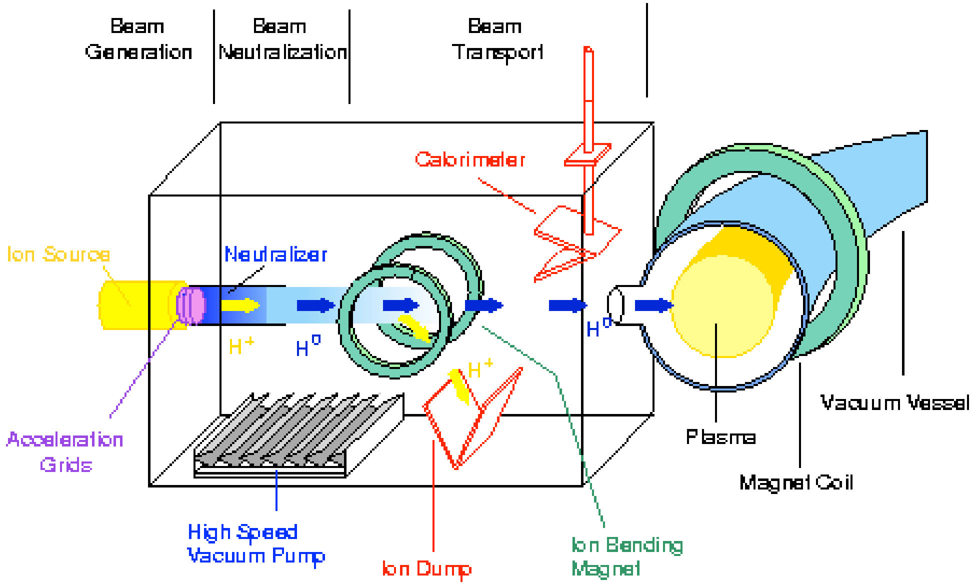
- **It is more difficult to access through the toroidal field coils with tangential injection.**



John Wesson, Tokamaks 3rd edition

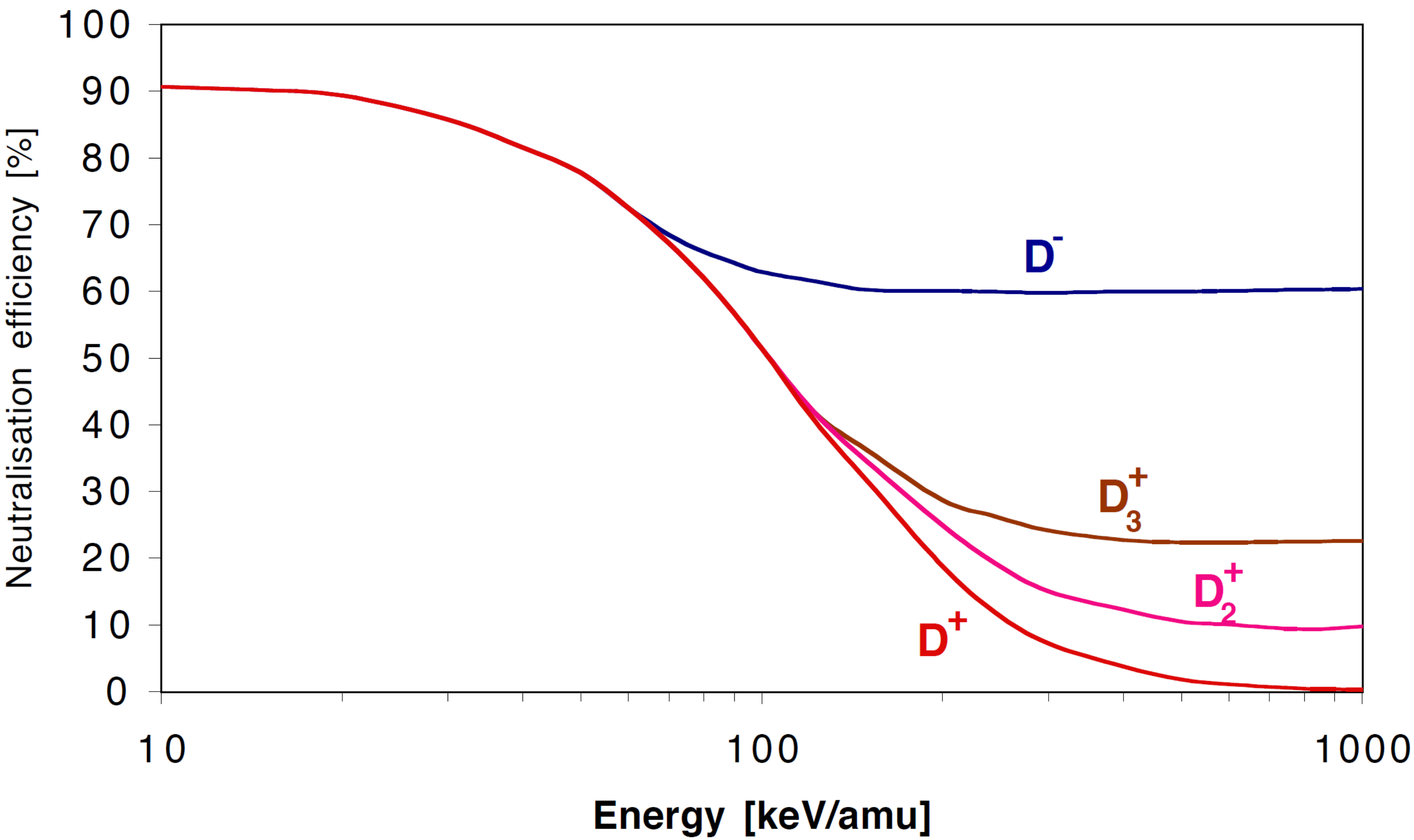
Neutral particles heat the plasma via coulomb collisions





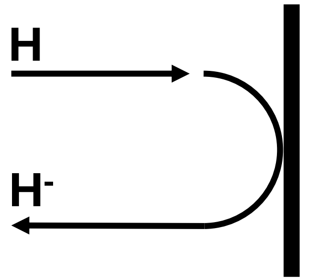
1. create energetic (fast) neutral ions
2. ionize the neutral particles
3. heat the plasma (electrons and ions) via Coulomb collisions

Negative ion source is preferred due to higher neutralization efficiency



There are two ways to make negative ions – surface and volume production

- **Surface production, depends on :**
  - **Work function Φ**
  - **Electron affinity level, 0.75 eV for H^-**
  - **Perpendicular velocity**
  - **Work function can be reduced by covering the metal surface with cesium**



$$H + e^- \longrightarrow H^-$$

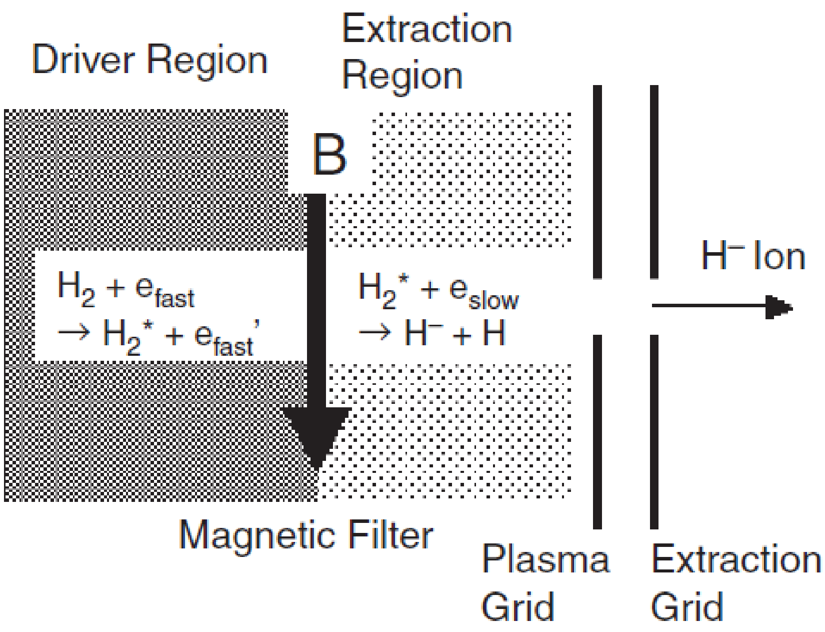
$$H^+ + 2e^- \longrightarrow H^-$$

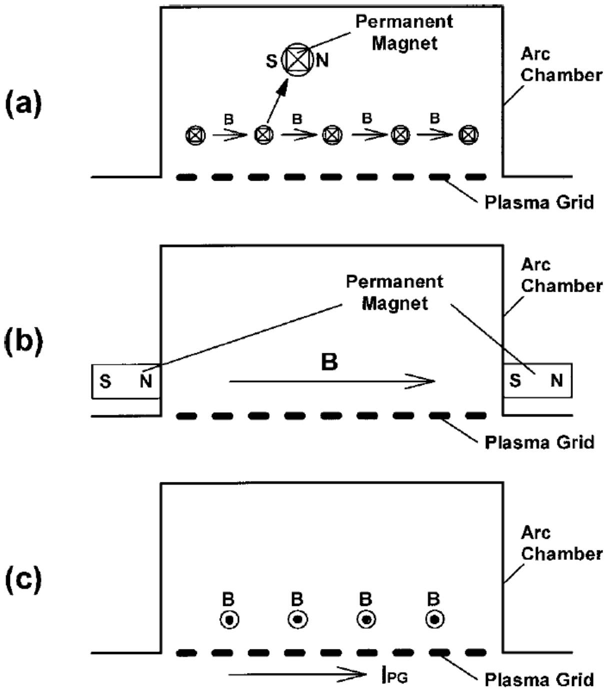
- **Volume production:**

$$H_2 + e_{fast}(>20\ \mathrm{eV}) \rightarrow H_2^*(\text{excited state}) + e_{fast},$$

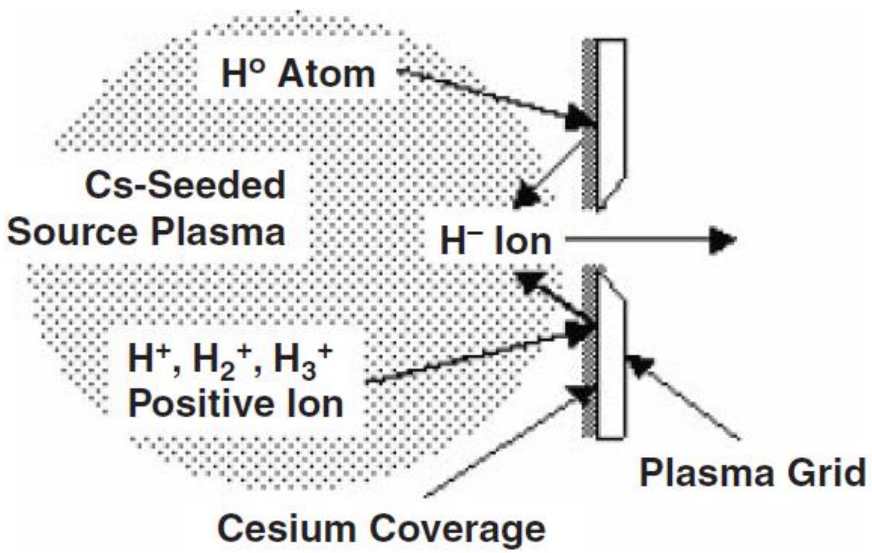
$$H_2^*(\text{excited state}) + e_{slow}(\approx 1\ \mathrm{eV}) \rightarrow H^- + H.$$

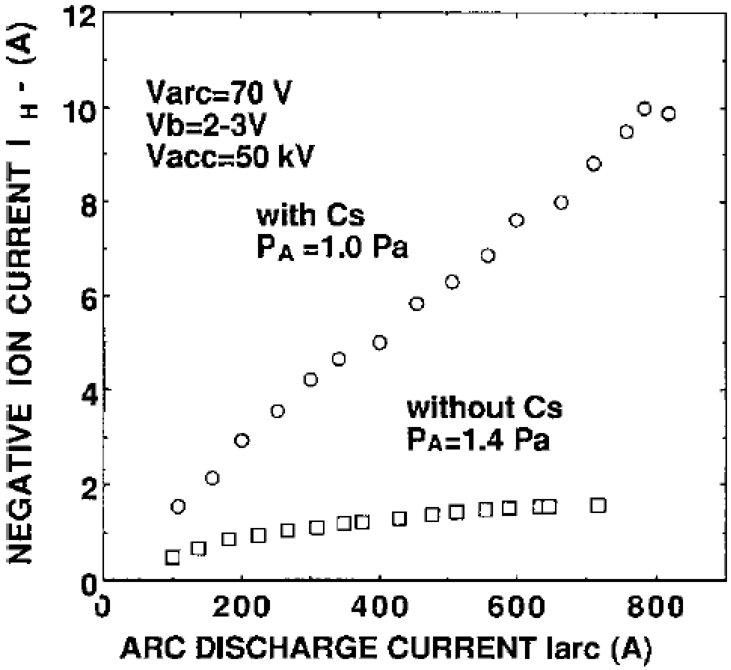
Two-chamber method of negative ions in volume production with a magnetic filter



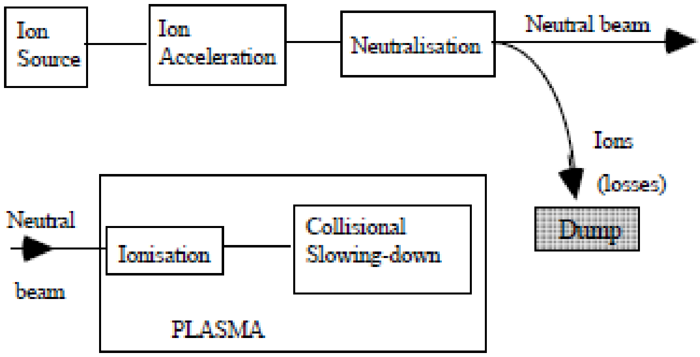


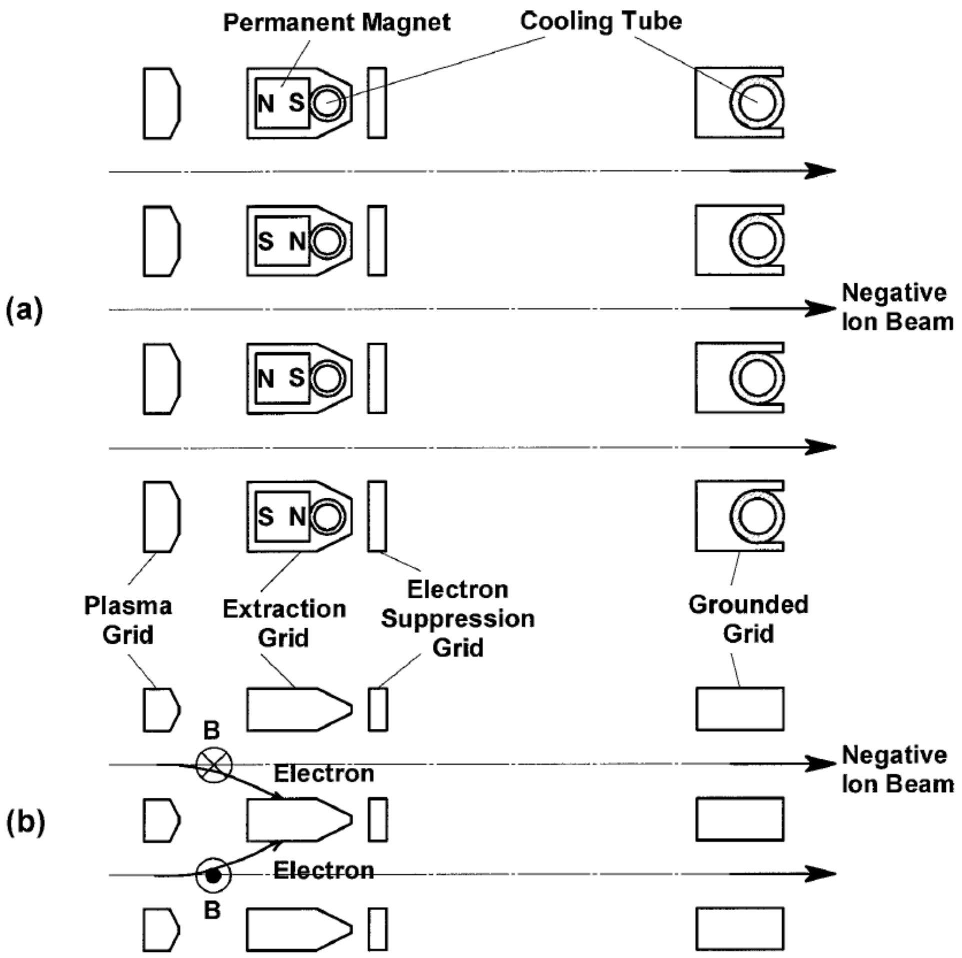
Adding cesium increases negative ion current





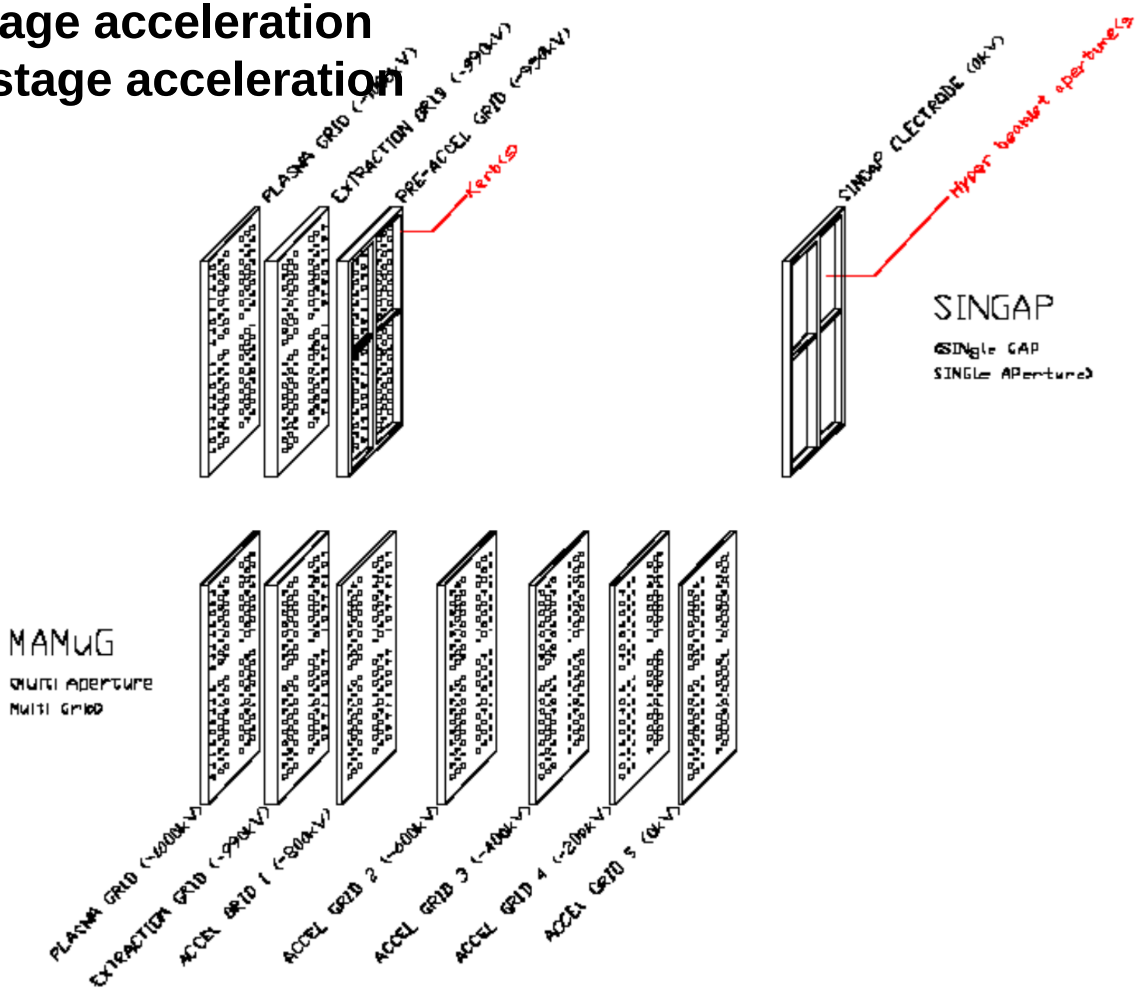
Electrons need to be filtered out since they are extracted together with negative ions





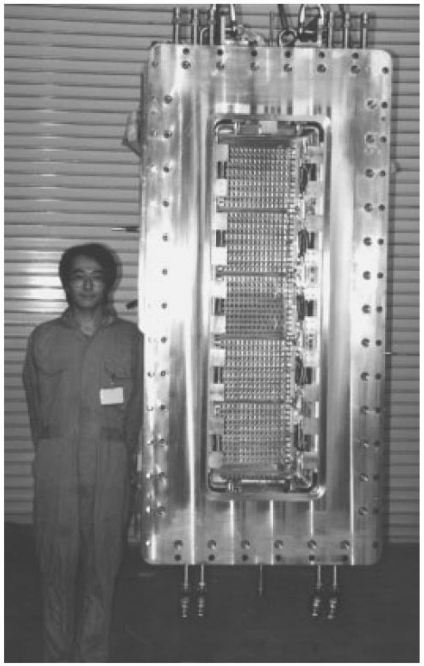
Acceleration

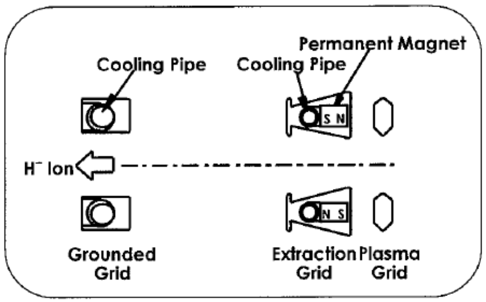
- **Multi-stage acceleration**
- **Single-stage acceleration**



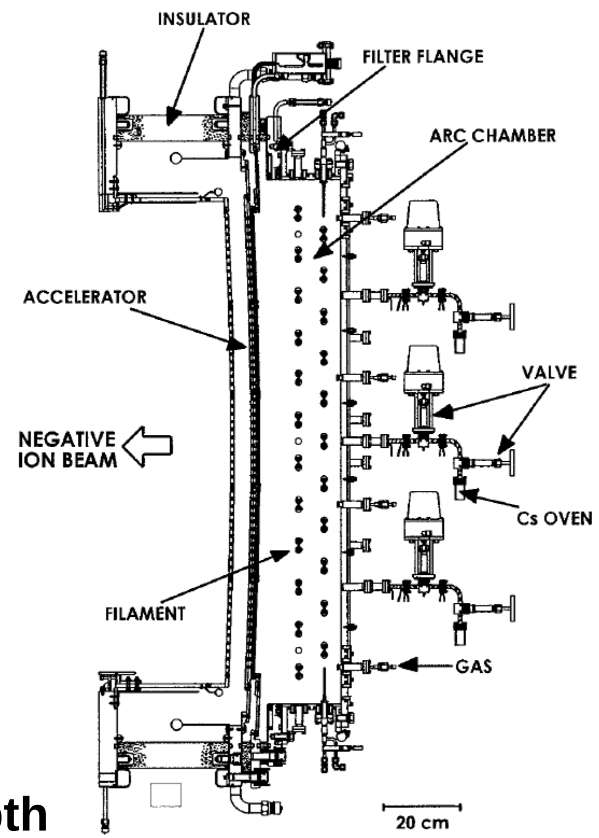
The ITER neutral beam system: status of the project and review of the main technological issues, presented by V. Antoni

NBI system of the LHD fusion machine





Negative Ion Accelerator

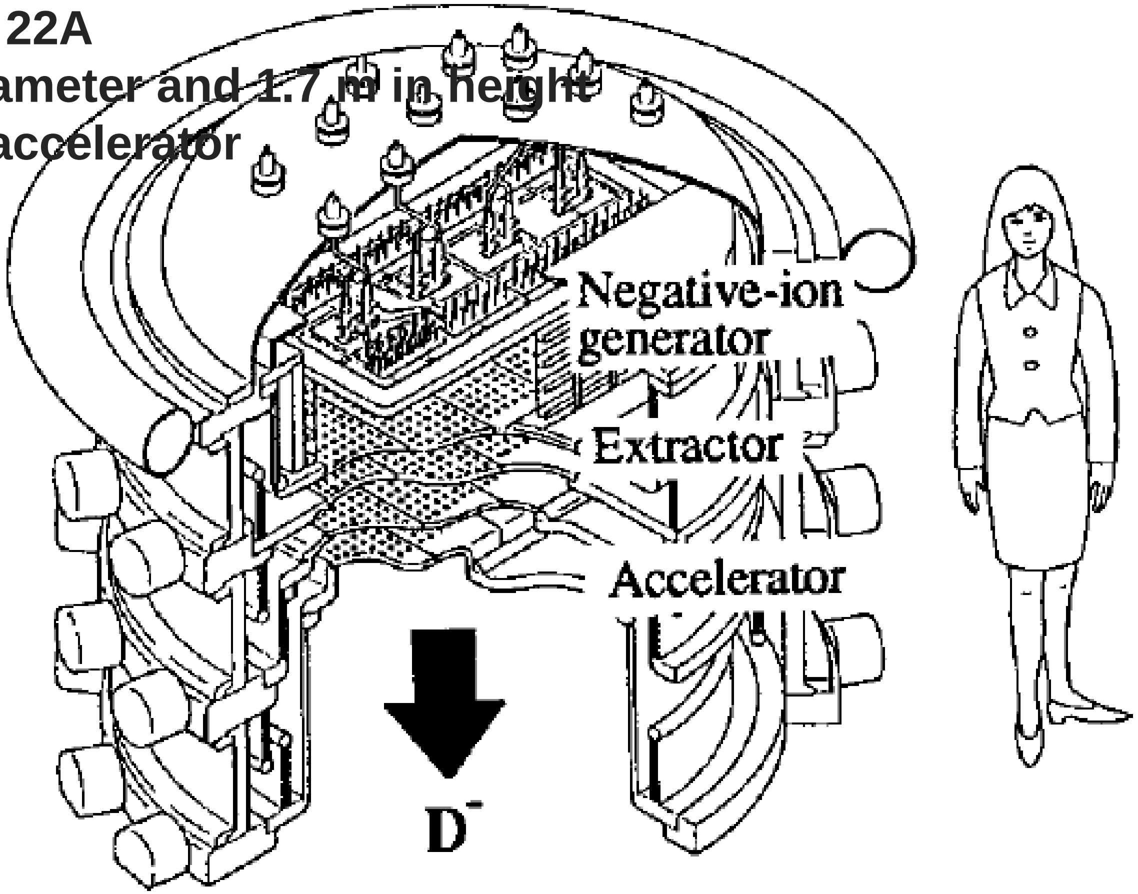


- **180 keV and 30 A**
- **Arc chamber: 35 cm x 145 cm, 21cm in depth**
- **Single stage accelerator**

Y. Takeiri, etc., Nucl. Fusion, 46, S199, 2006

JT60U NBI system

- JT-60 (Japan-Torus) is a tokamak in Japan.
- 550 keV, 22A
- 2m in diameter and 1.7 m in height
- 3-stage accelerator



Neutralization

- Gas neutralization
  - Collisions between fast negative ions and atoms

$$H^- + H_2 \longrightarrow H + H_2 + e^-$$

  - Fast ions can lose another electron after neutralized

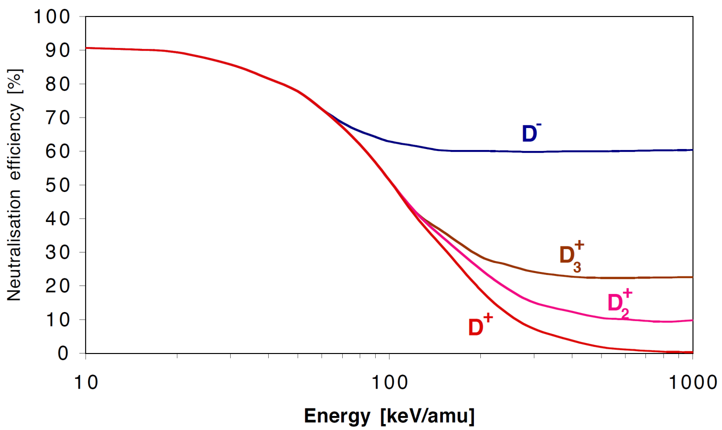
$$H + H_2 \longrightarrow H^+ + H_2 + e^-$$

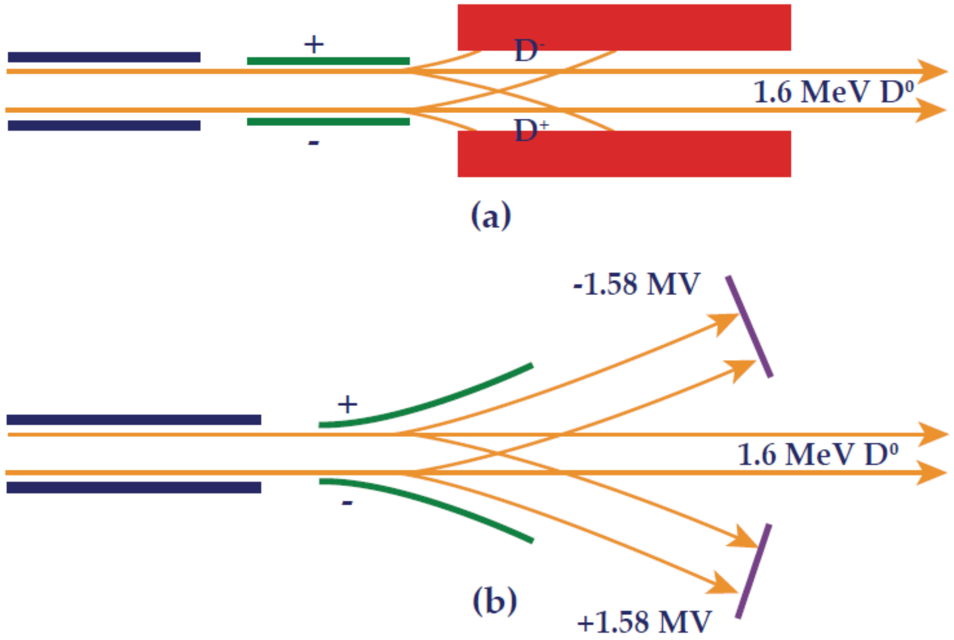
- Plasma neutralization
  - Collisions with charged particles in plasma

$$H^- + X(e, \mathrm{Ar}, H^+, {H_2}^+) \longrightarrow H + X + e^-$$

  - The efficiencies reach up to 85% for fully ionized hydrogen plasma

Beam dump

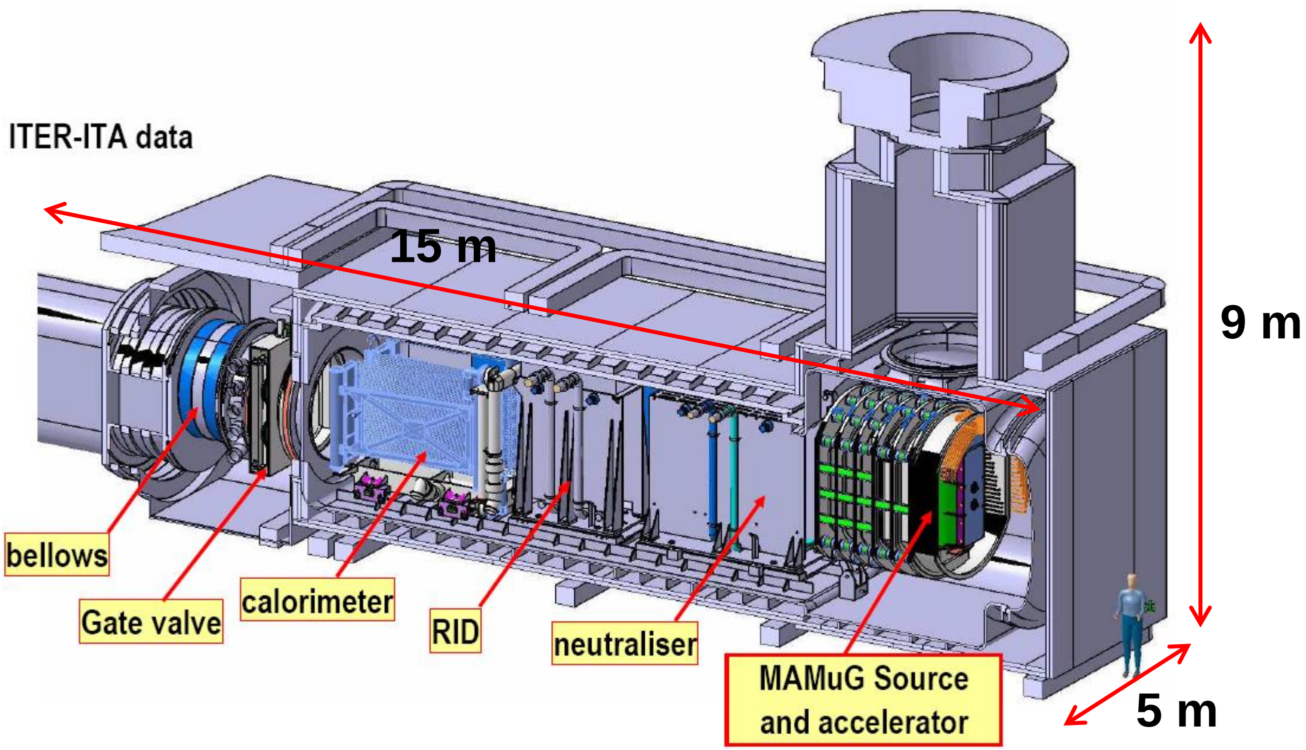




R. W. Moir, Fusion Technology, 25, 129, 1994

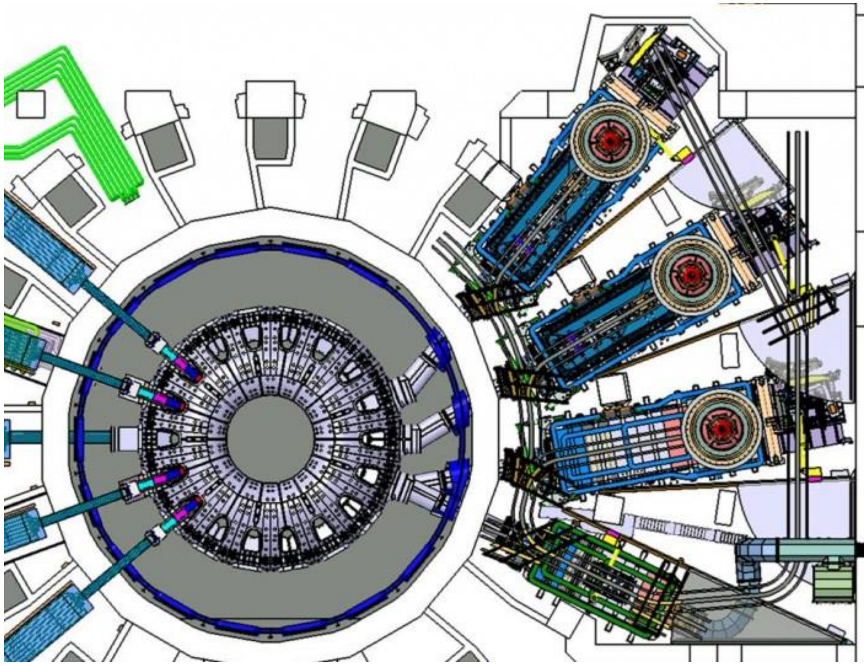
NBI for ITER

- **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

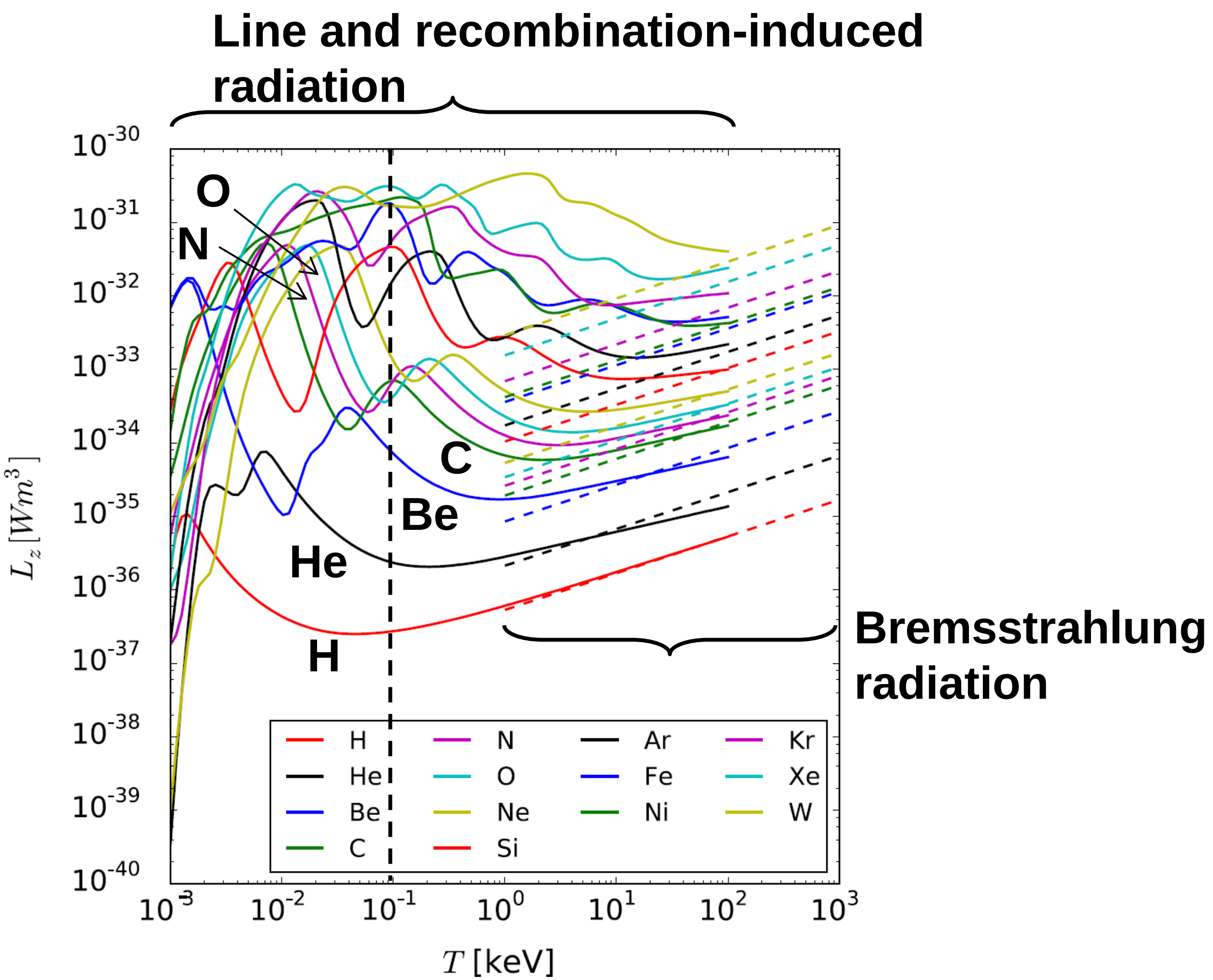
Neutral beam penetration



- **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

Temperature of 100 eV is the threshold of radiation barrier by impurities



H. Lux, etc., Fusion Eng. Des. **42**, 101 (2015)

Course Outline

- **Inertial confinement fusion (ICF)**
  - **Plasma frequency and critical density**
  - **Direct- and indirect- drive**
  - **Laser generated pressure (Inverse bremsstrahlung and Ablation pressure)**
  - **Burning fraction, why compressing a capsule?**
  - **Implosion dynamics**
  - **Shock (Compression with different adiabat)**
  - **Laser pulse shape**
  - **Rocket model, shell velocity**
  - **Laser-plasma interaction (Stimulated Raman Scattering, SRS; Stimulated Brillouin Scattering, SBS; Two-plasmon decay)**
  - **Instabilities (Rayleigh-taylor instability, Kelvin-Helmholtz instability, Richtmeyer-Meshkov instability)**

Under what conditions the plasma keeps itself hot?

- Steady state 0-D power balance:

  $S_\alpha + S_h = S_B + S_k$

  S_α: α particle heating

  S_h: external heating

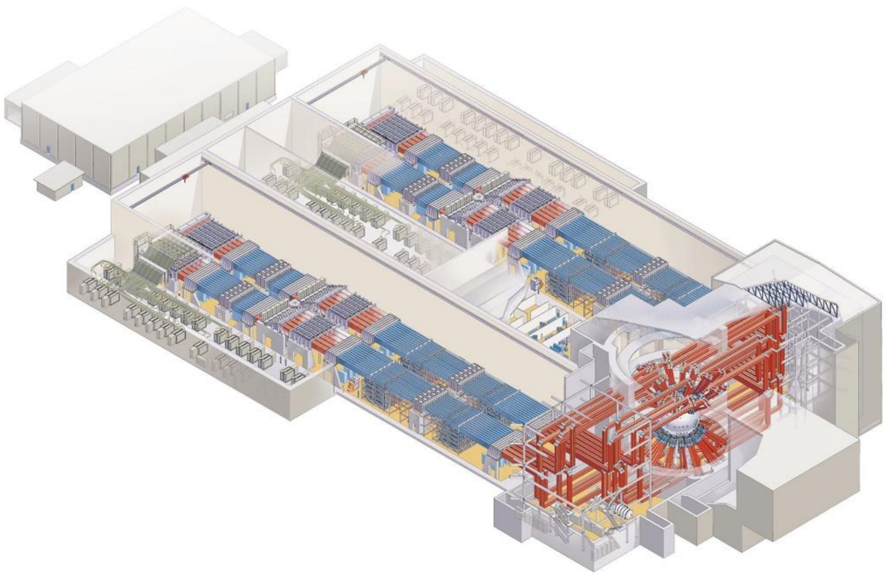
  S_B: Bremsstrahlung radiation

  S_k: heat conduction lost

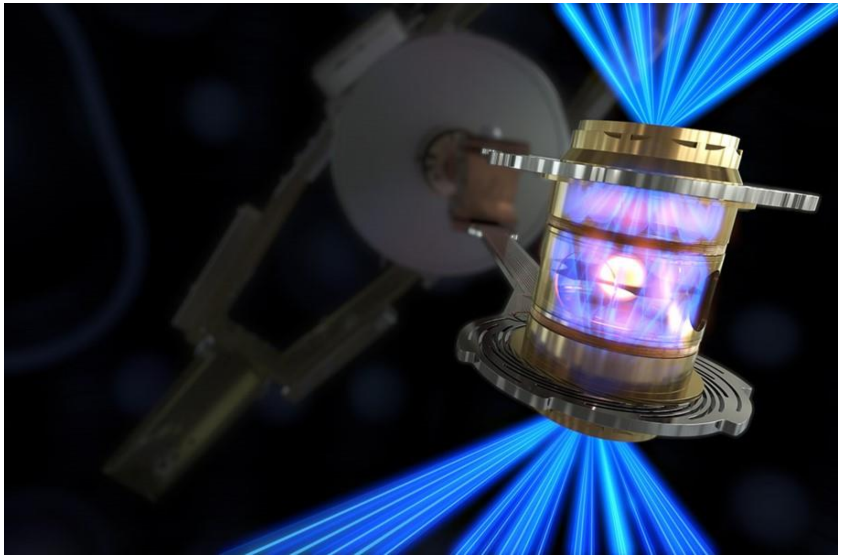
Ignition condition: Pτ > 10 atm-s = 10 Gbar - ns

- P: pressure, or called energy density
- τ is confinement time

Significant breakthrough was achieved in ICF recently



- **Inertial confinement fusion (ICF)**

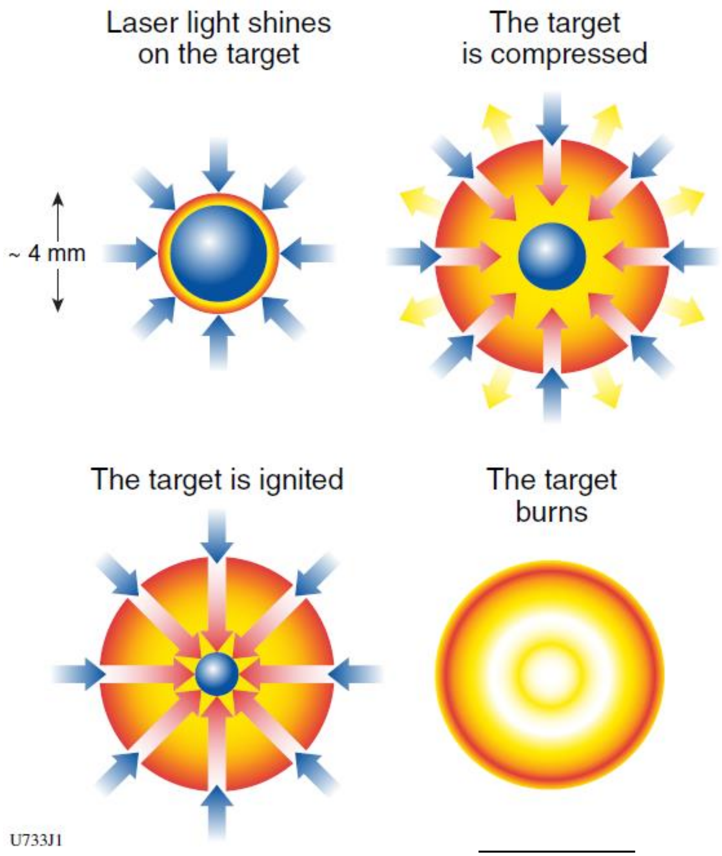


- **National Ignition Facility (NIF) demonstrated a gain grater than 1 for the first time on 2022/12/5. The yield of 3.15 MJ from the 2.05-MJ input laser energy, i.e., Q=1.5.**

https://zh.wikipedia.org/wiki/國家點火設施
https://www.science.org/content/article/historic-explosion-long-sought-fusion-breakthrough

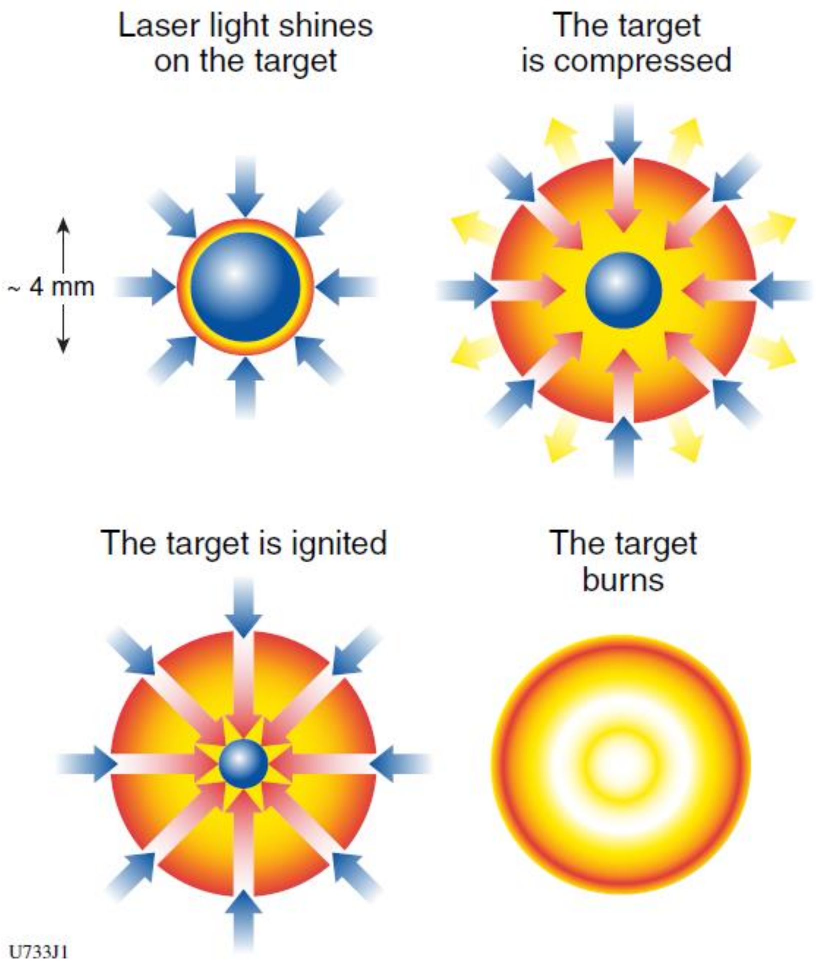
Don’t confine it!

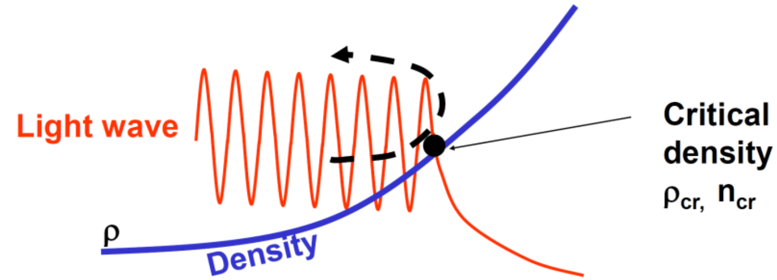
- **Solution 2: Inertial confinement fusion (ICF). Or you can say it is confined by its own inertia: P~Gigabar, τ~nsec, T~10 keV (10^8 ⁰C)**

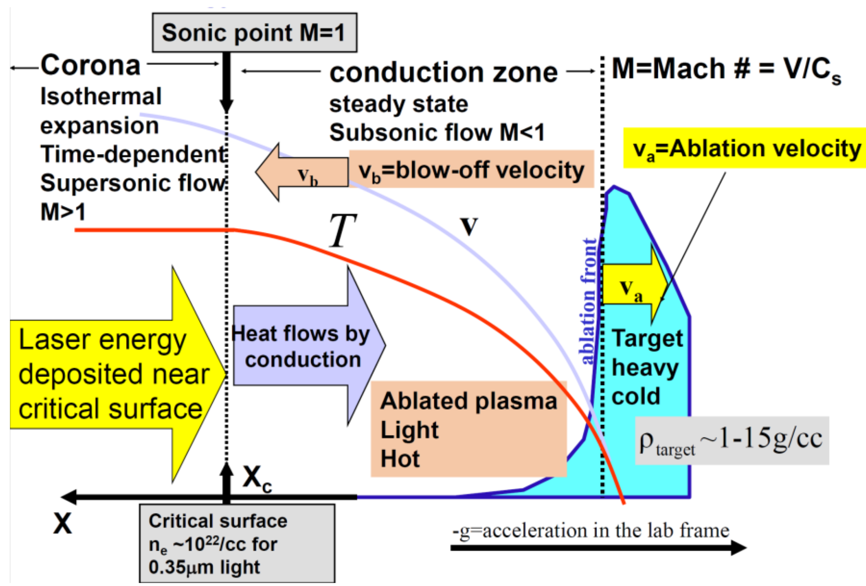


Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

Compression happens when outer layer of the target is heated by laser and ablated outward

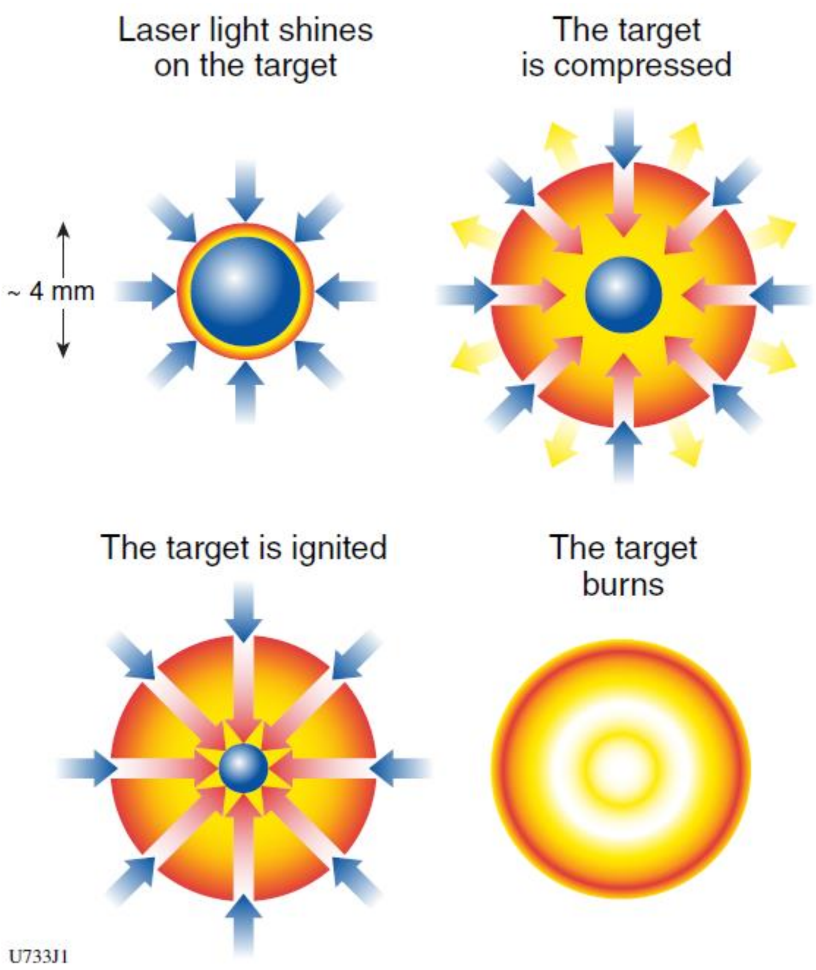




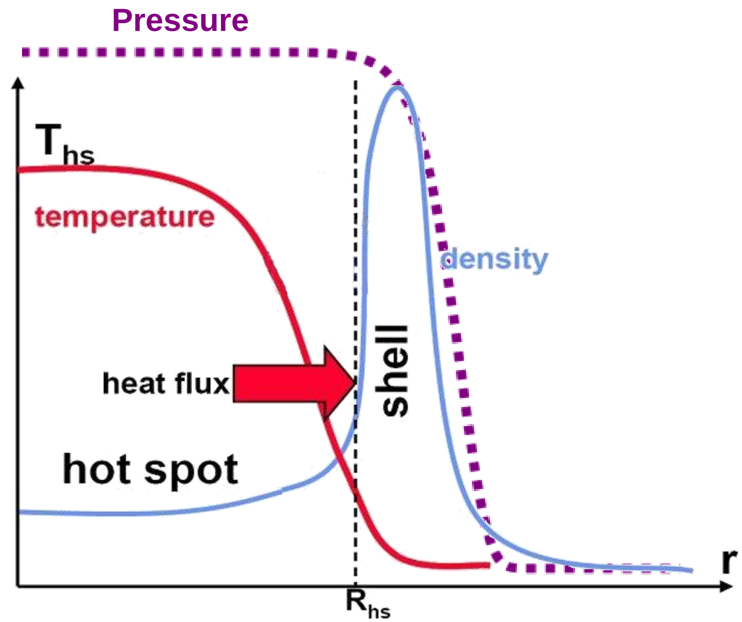


Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester
R. Betti, HEDSA HEDP Summer School, 2015

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



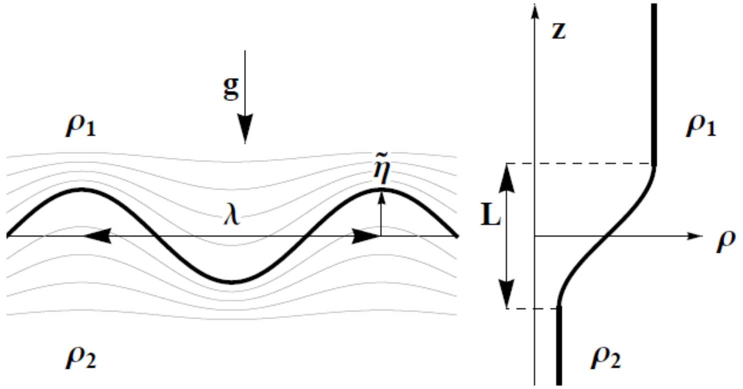
Spatial profile at stagnation



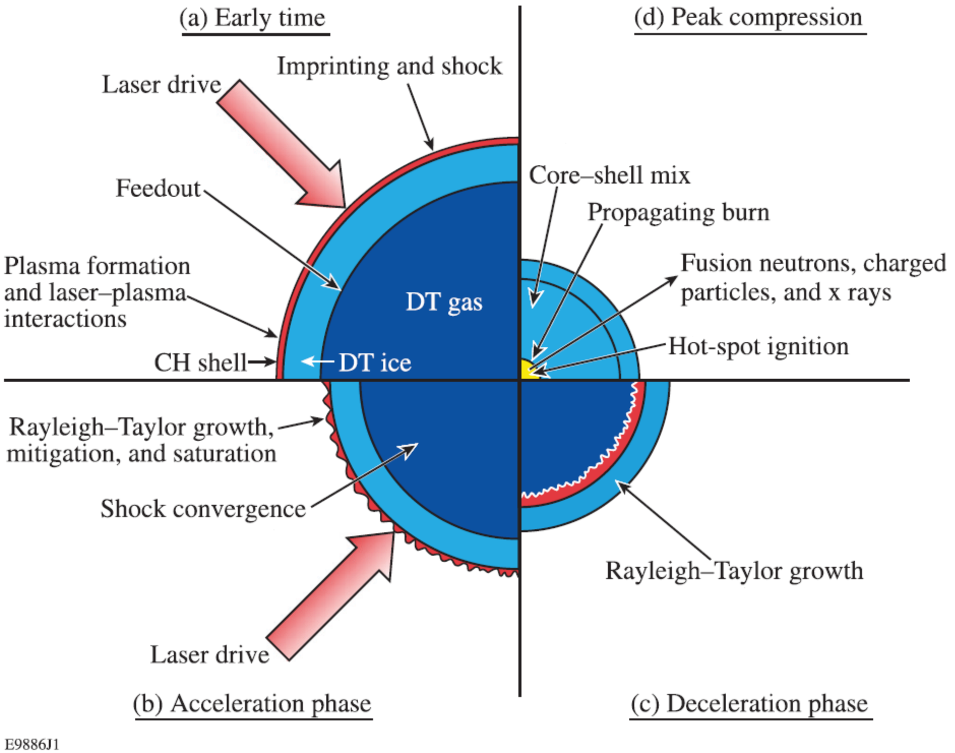
Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

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

- **Rayleigh-Taylor instability**

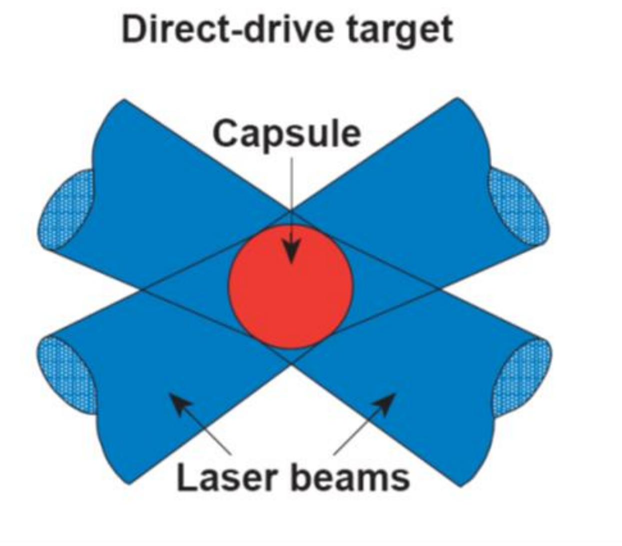


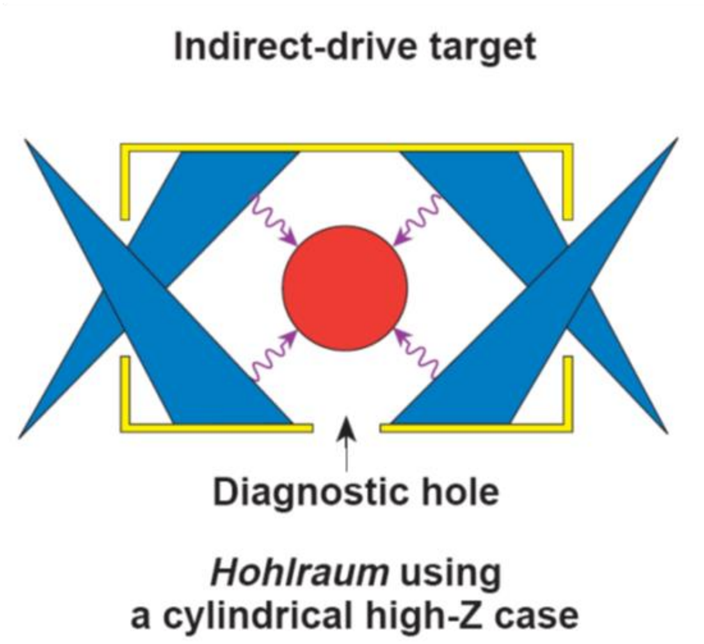
- **Stages of a target implosion**



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

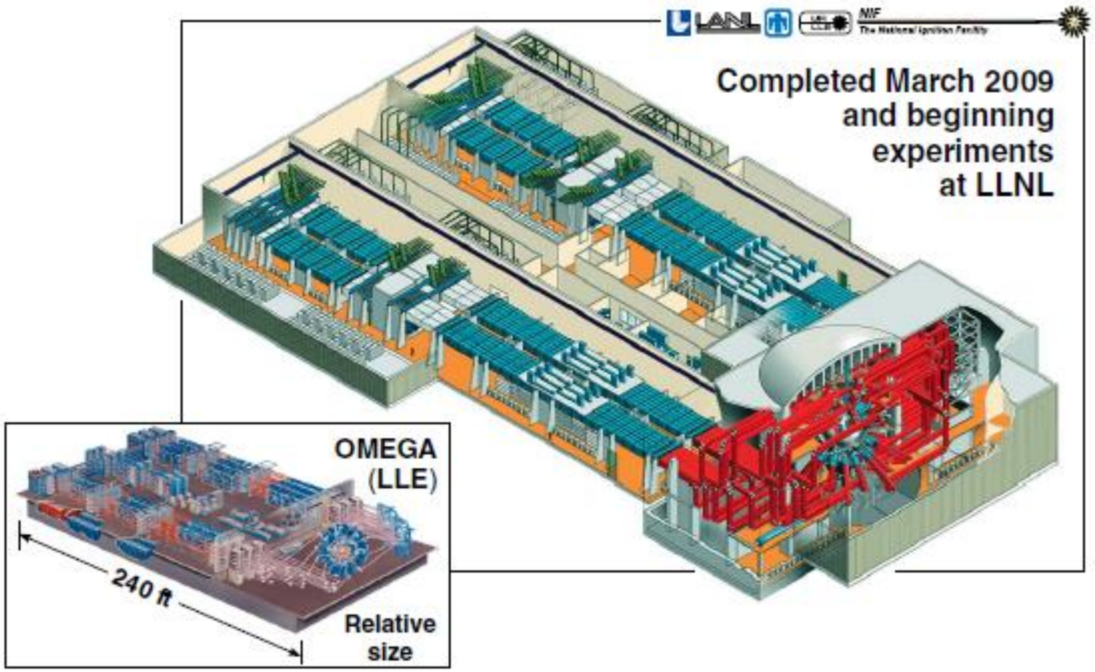
A spherical capsule can be imploded through directly or indirectly laser illumination





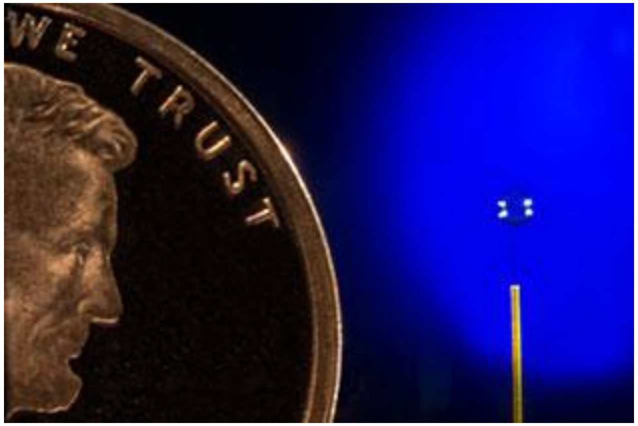
*R. Betti, HEDSA HEDP Summer School, 2015

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

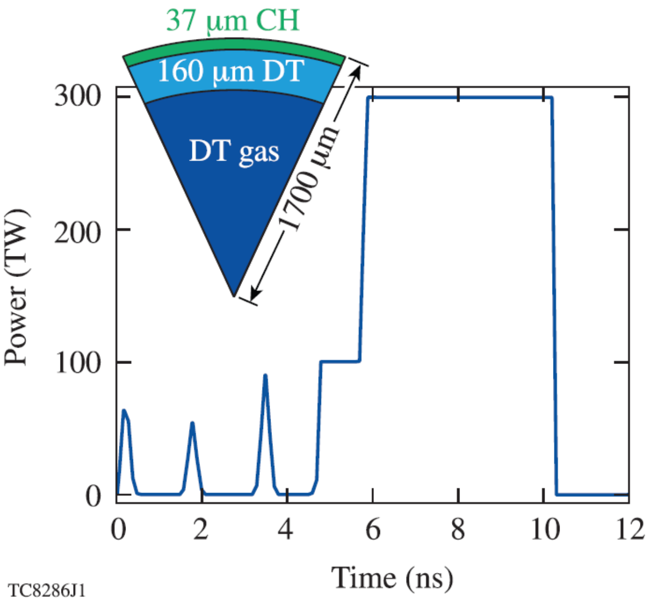


OMEGA experiments are integral to an ignition demonstration on the NIF.

Targets used in ICF



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

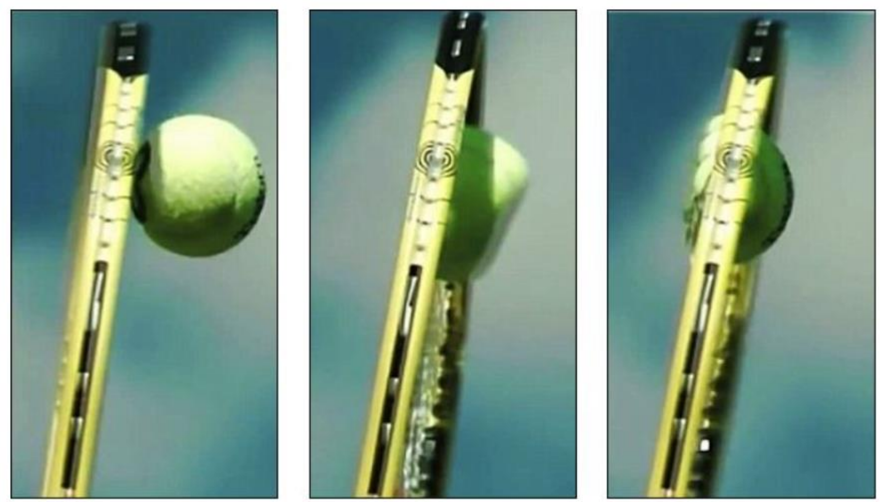


http://www.lle.rochester.ed
https://en.wikipedia.org/wiki/Inertial_confinement_fusion
R. S. Craxton, etc., *Phys. Plasmas* **22**, 110501 (2015)

Softer material can be compressed to higher density

- **Compression of a baseball**

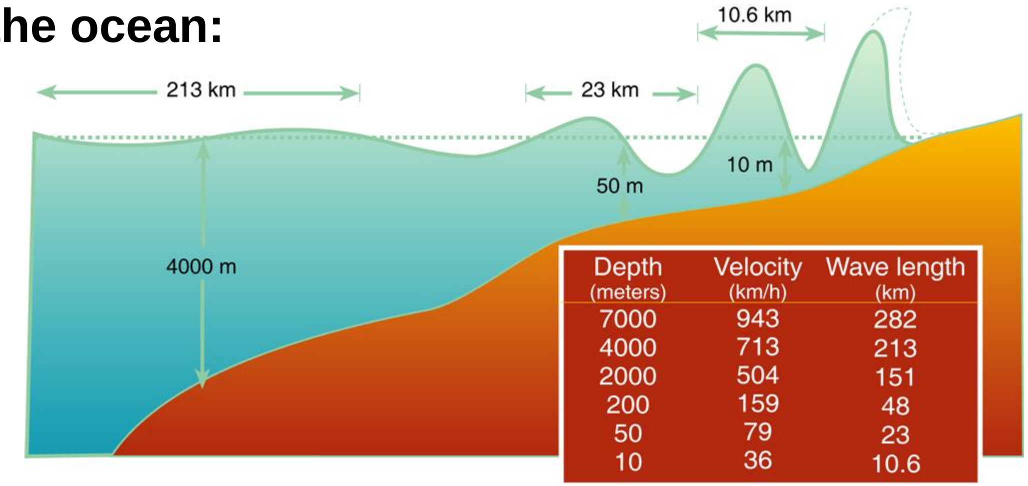
- **Compression of a tennis ball**



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/

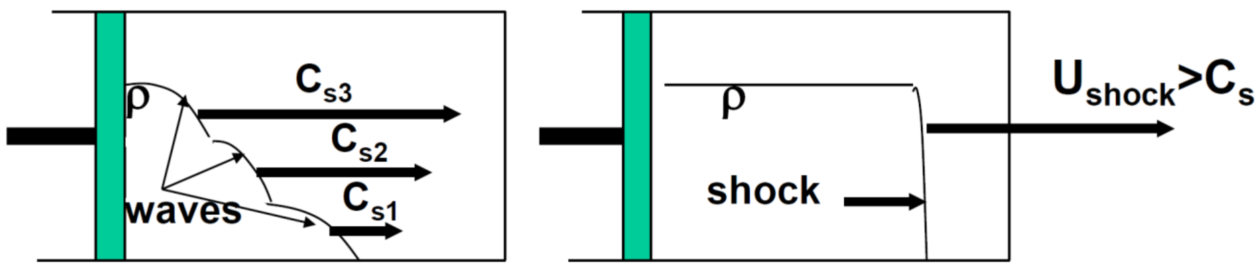
A shock is formed due to the increasing sound speed of a compressed gas/plasma

- **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

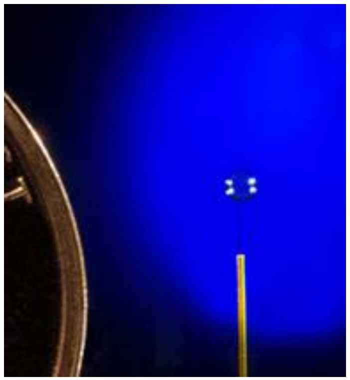
- **Acoustic/compression wave driven by a piston:**



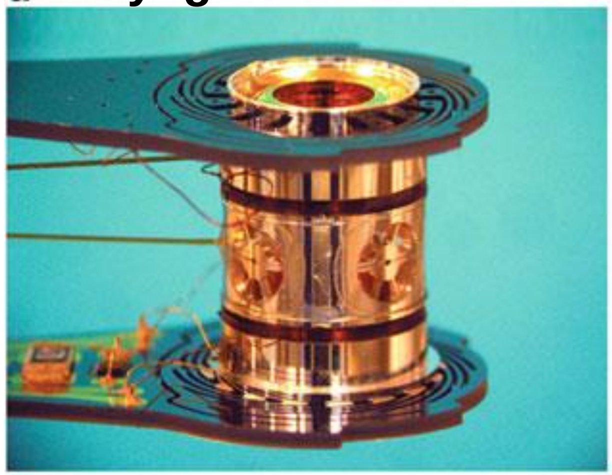
$$C_s \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha \rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\rho^{1/3}$$

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

Targets used in ICF



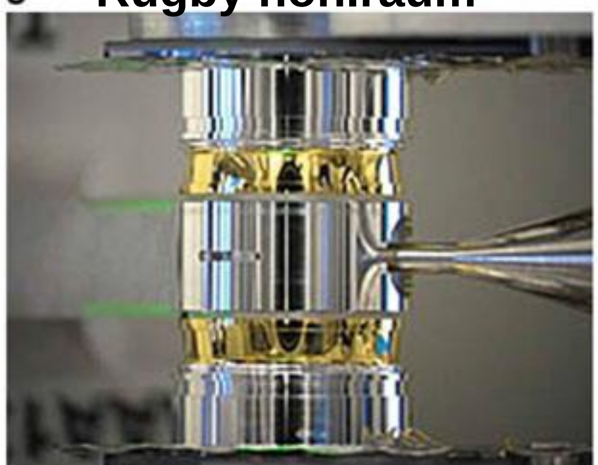
a **Cryogenic hohlraum**



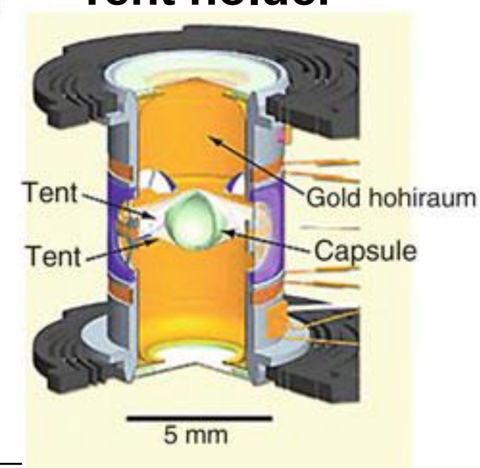
b

Cryogenic shroud

c **Rugby hohlraum**

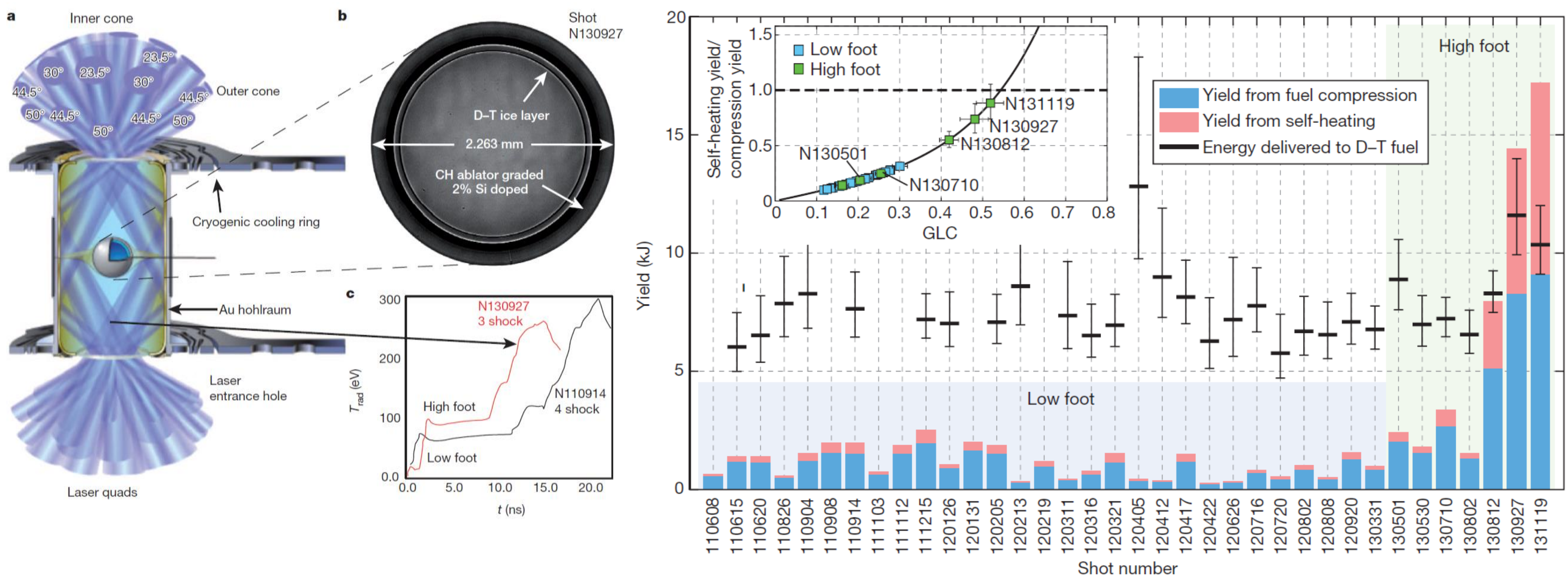


d **Tent holder**



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

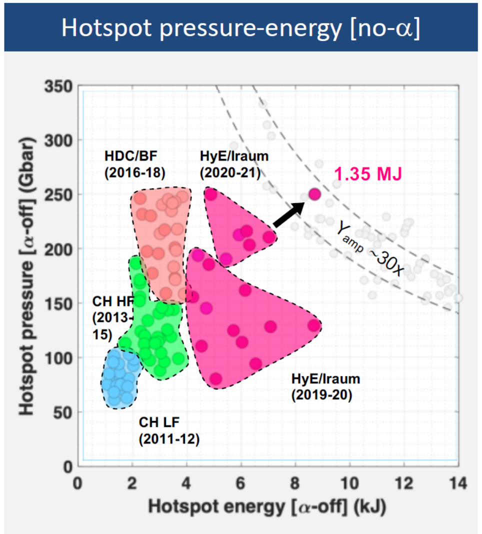
Nature letter “Fuel gain exceeding unity in an inertially confined fusion implosion”

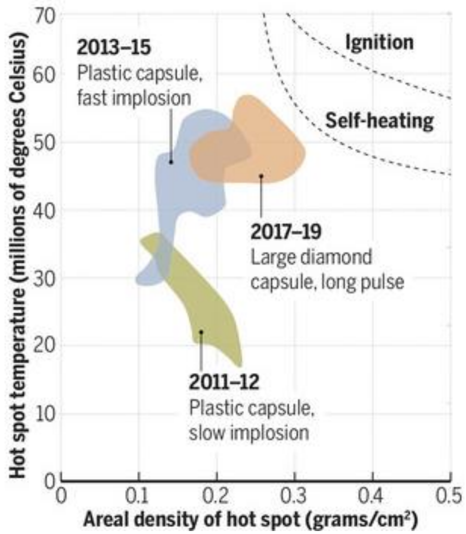


- **Fuel gain exceeding unity was demonstrated for the first time.**

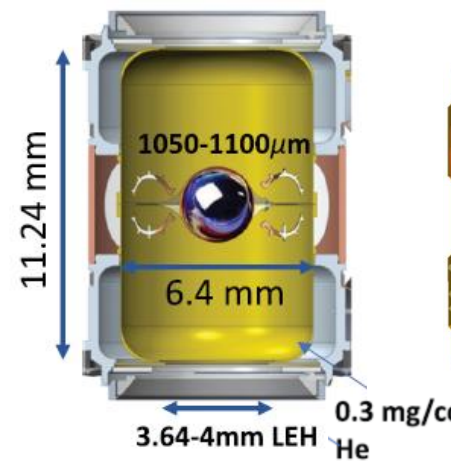
Nature 506, p343, 2014

The hot spot has entered the burning plasma regime

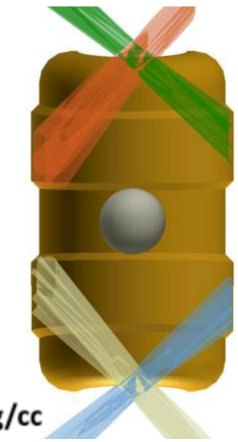


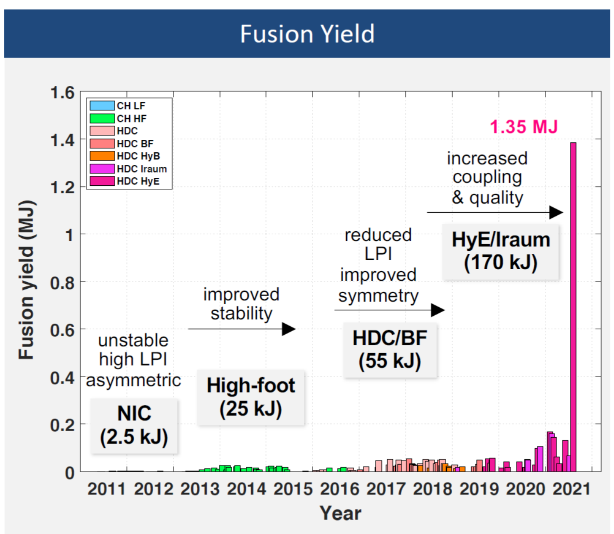


- **Hybrid-E**

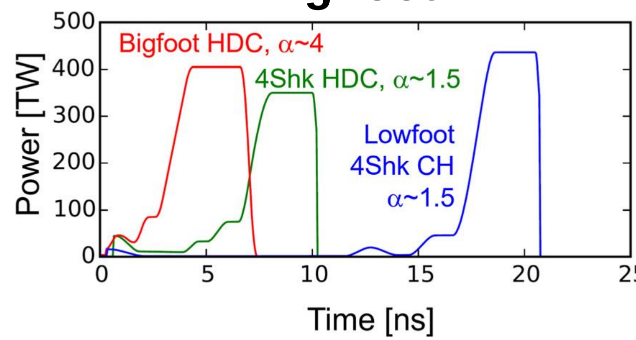


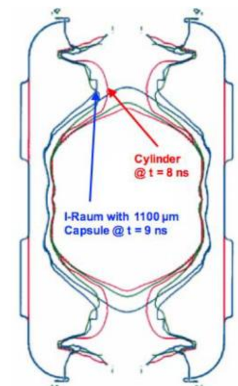
- **I-raum**





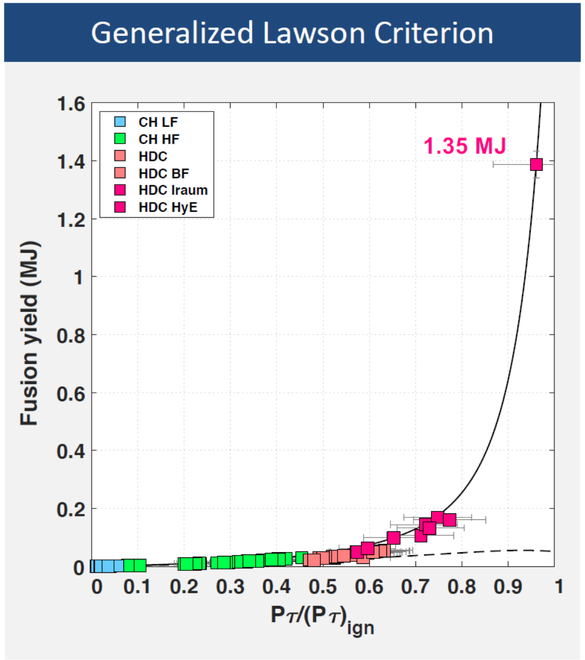
- **Big foot**

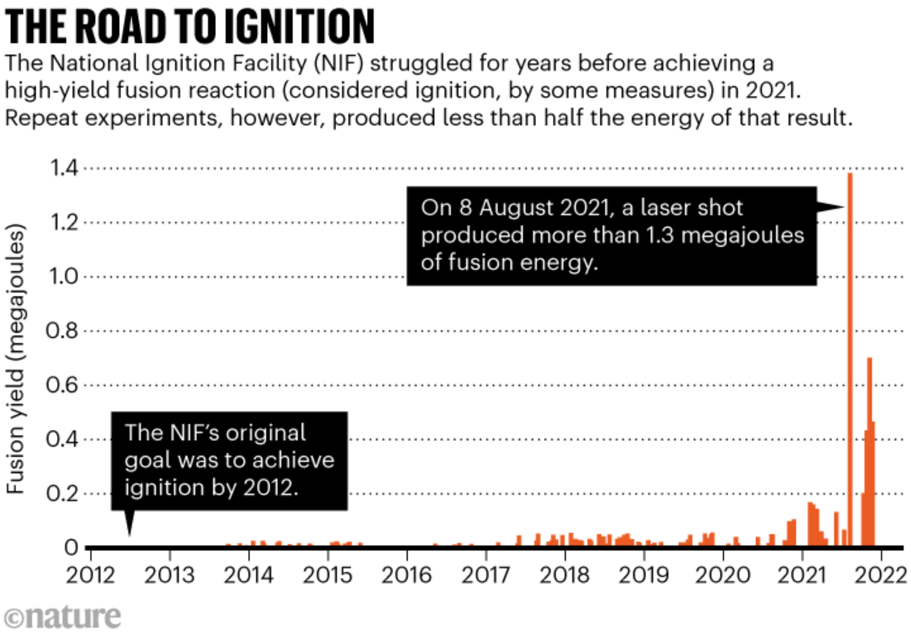




T. Ma, ARPA-E workshop, April 26, 2022
Science 370, p1019, 2020
D. T. Casey, etc., Phys. Plasmas, 25, 056308 (2018)
A. L. Kritcher, etc., Phys. Plasmas, 28, 072706 (2021)
H. F. Robey, etc., Phys. Plasmas, 25, 012711 (2018)

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)

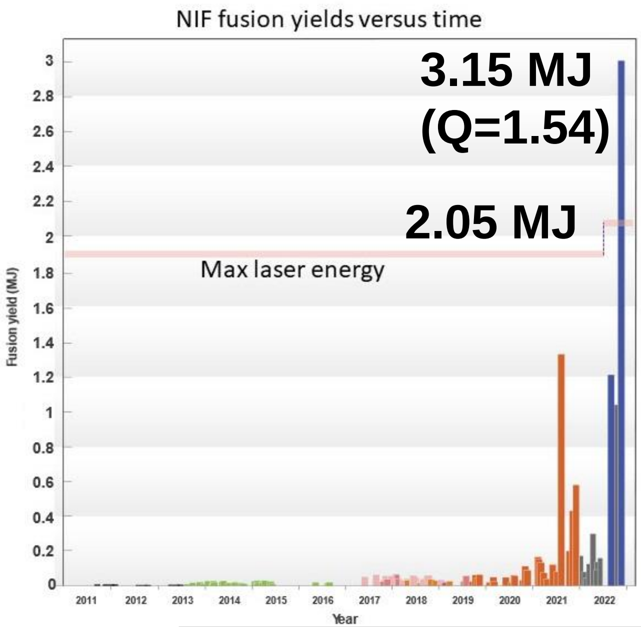


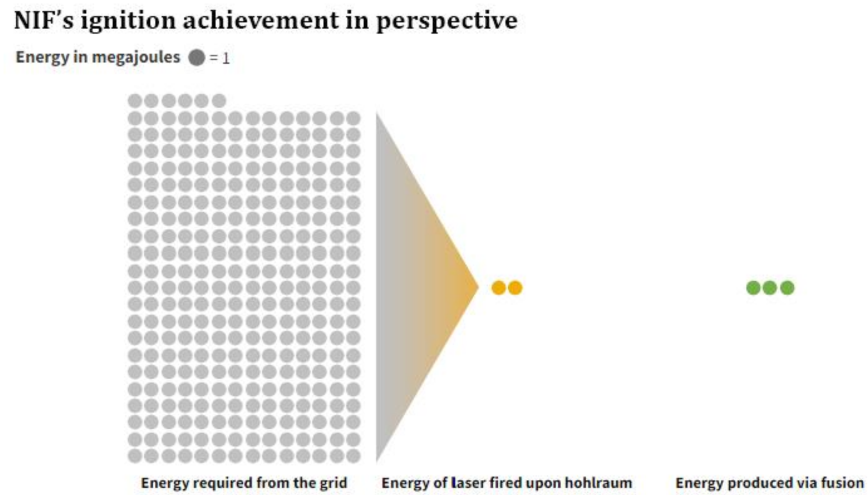


- **National Ignition Facility (NIF) achieved a yield of more than 1.3 MJ (Q~0.7). This advancement puts researchers at the threshold of fusion ignition.**
- **Laser-fusion facility heads back to the drawing board.**

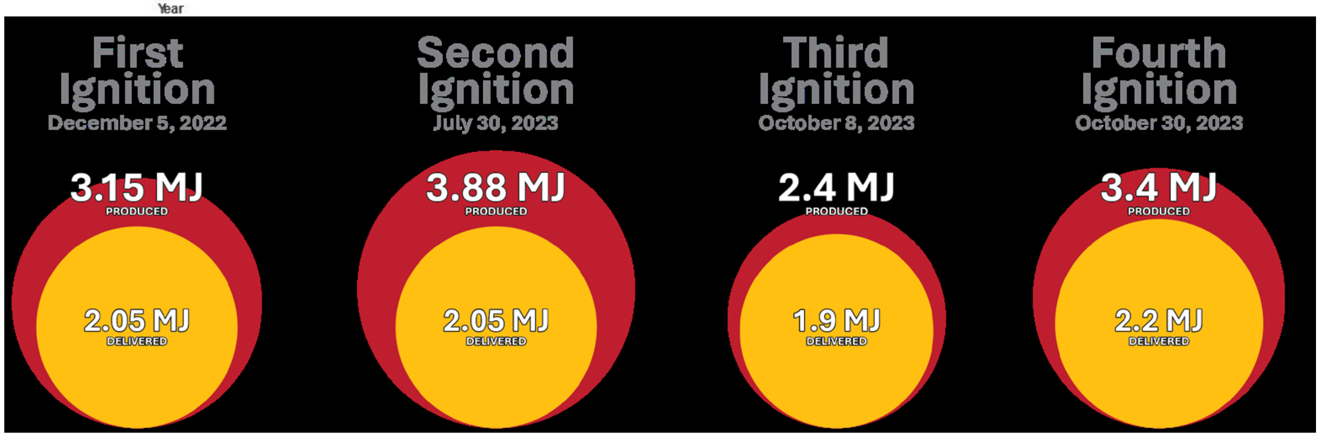
T. Ma, ARPA-E workshop, April 26, 2022
J. Tollefson, Nature (News) 608, 20 (2022)

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





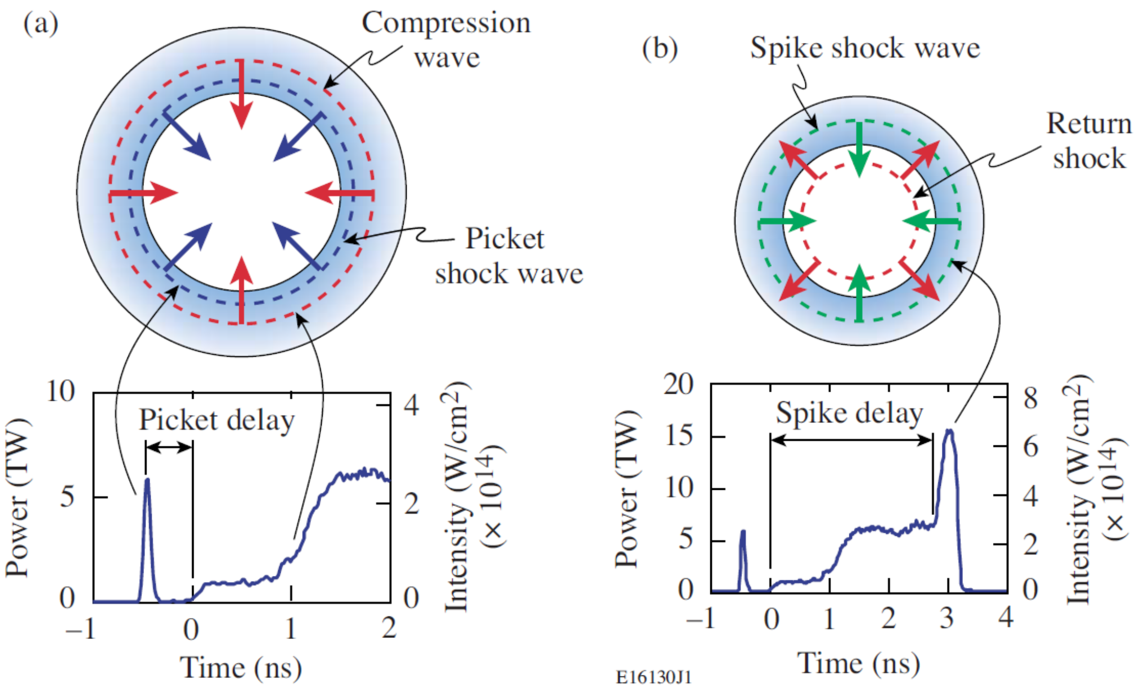
300 MJ 2.05 MJ 3.15 MJ

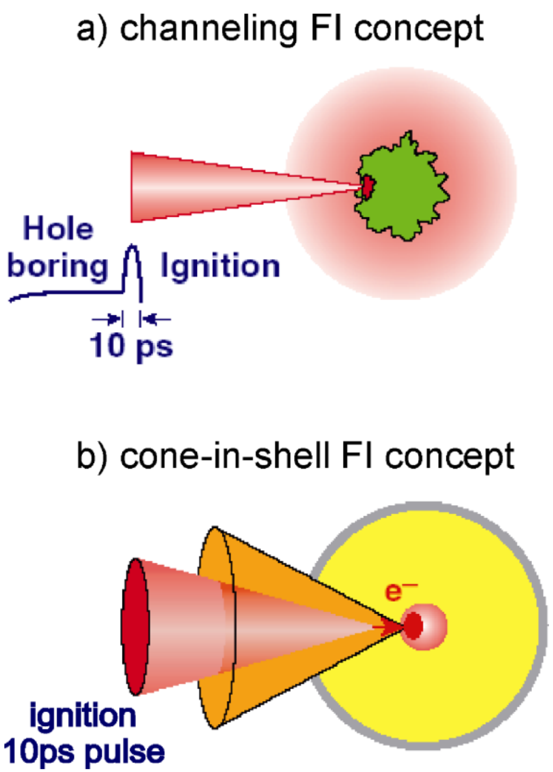


https://physicstoday.scitation.org/do/10.1063/PT.6.2.20221213a/full/
The age of ignition: anniversary edition, LLNL-BR-857901

External "spark" can be used for ignition

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

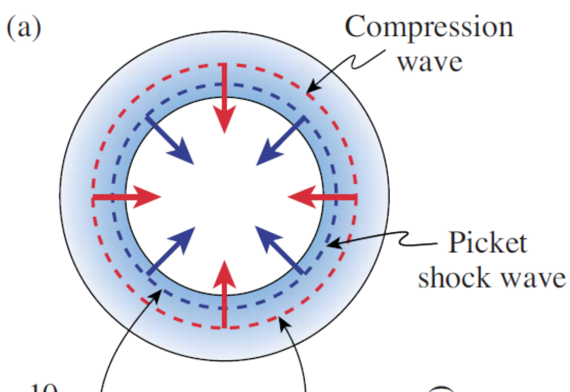


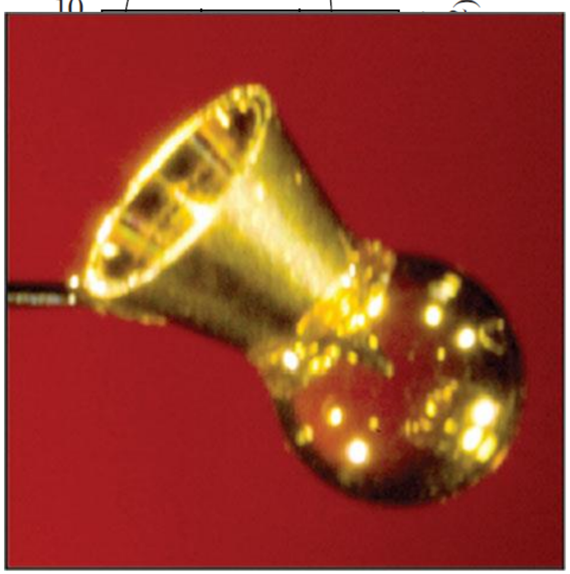


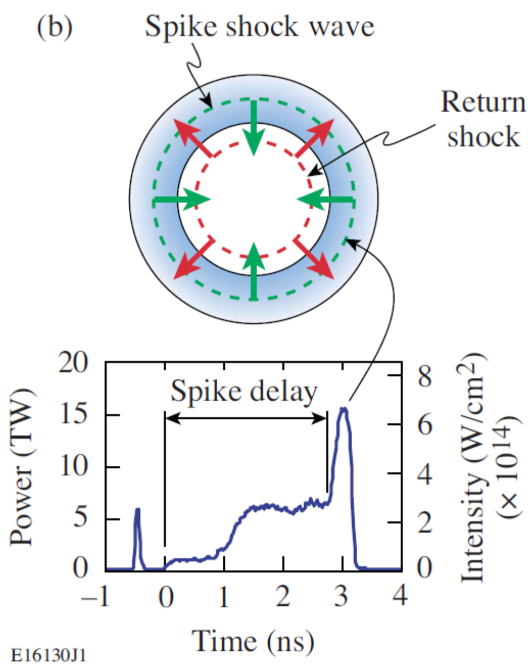
J. Badziak, Bull.Polish Acad. Sci. Tech. Sci.Phys. Plasmas 15, 056306 (2008)

External "spark" can be used for ignition

- **Shock ignition**

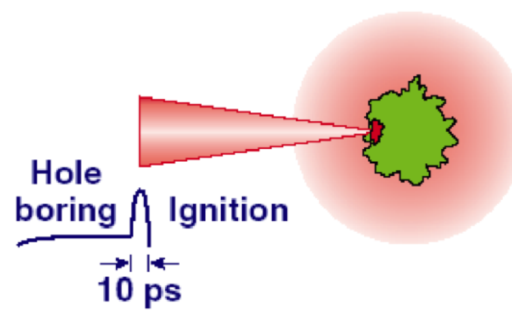




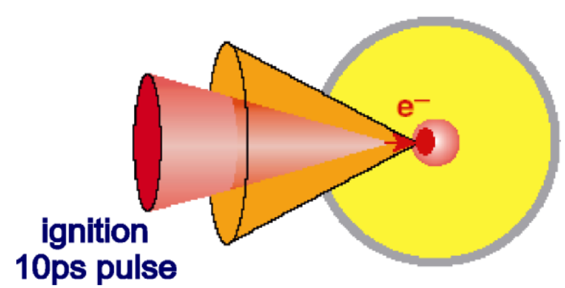


- **Fast ignition**

a) channeling FI concept



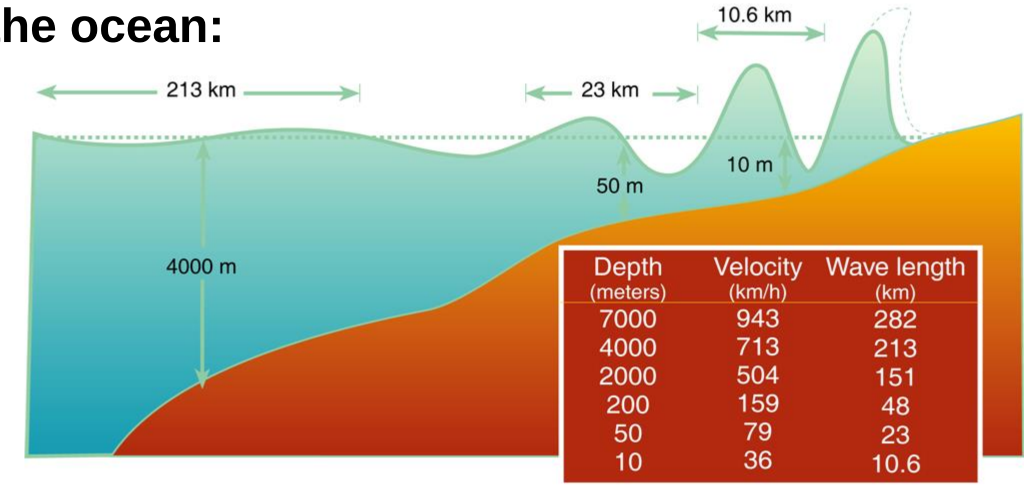
b) cone-in-shell FI concept



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

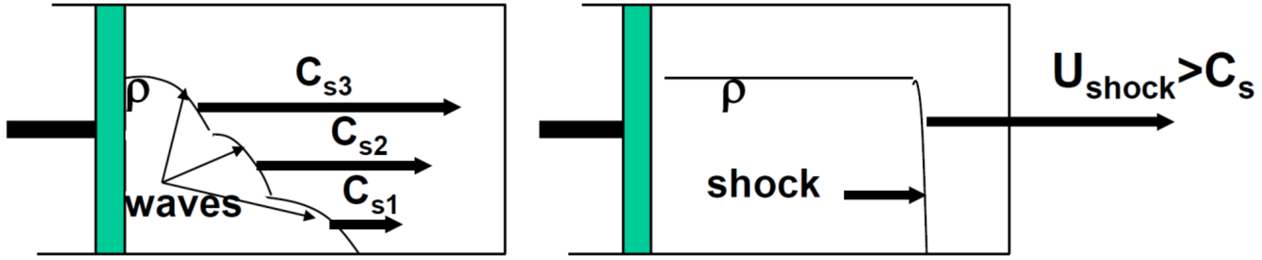
A shock is formed due to the increasing sound speed of a compressed gas/plasma

- **Wave in the ocean:**



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

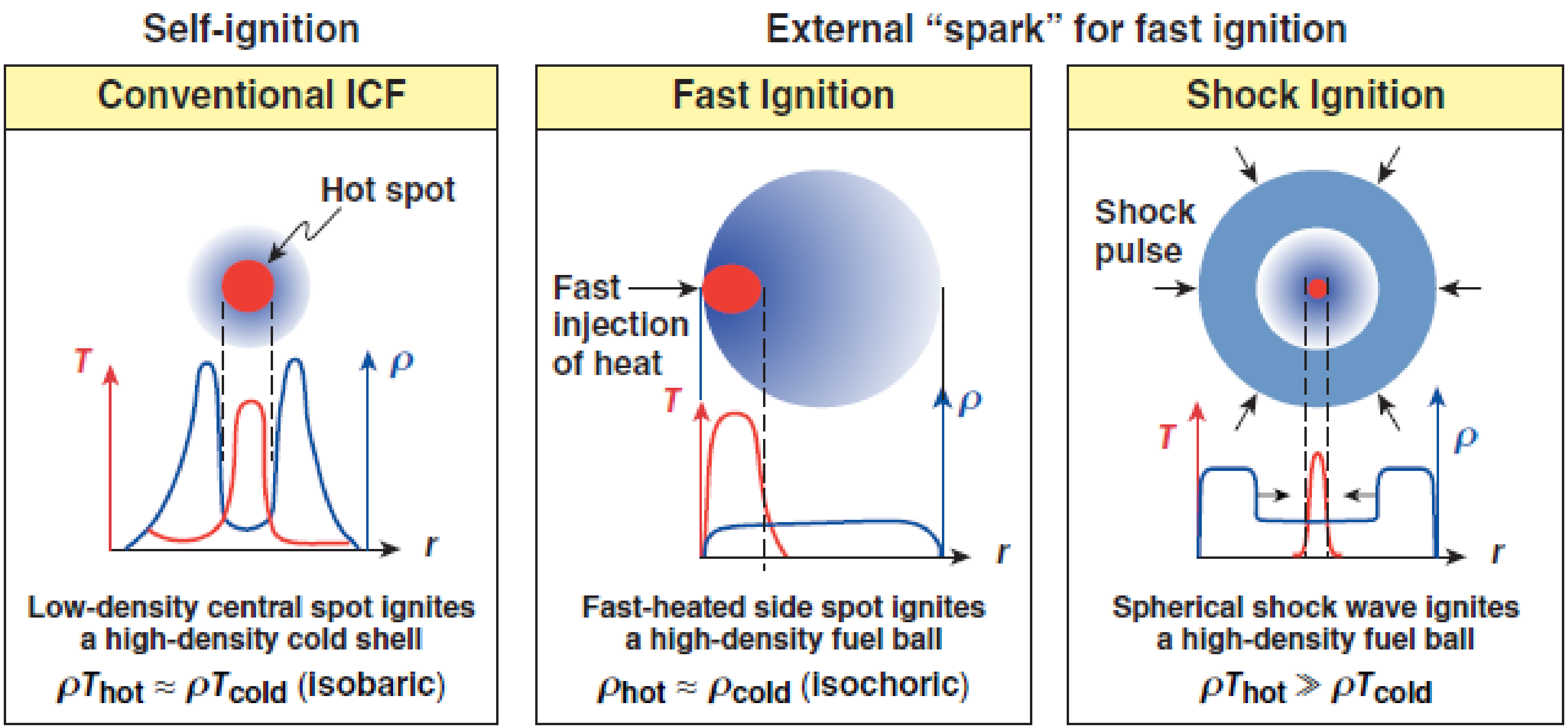
- **Acoustic/compression wave driven by a piston:**



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

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

Ignition can happen by itself or being triggered externally



P. B. Radha, Fusion Energy Conference,2018