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Aspects of Advanced Fuel FRC Fusion Reactors

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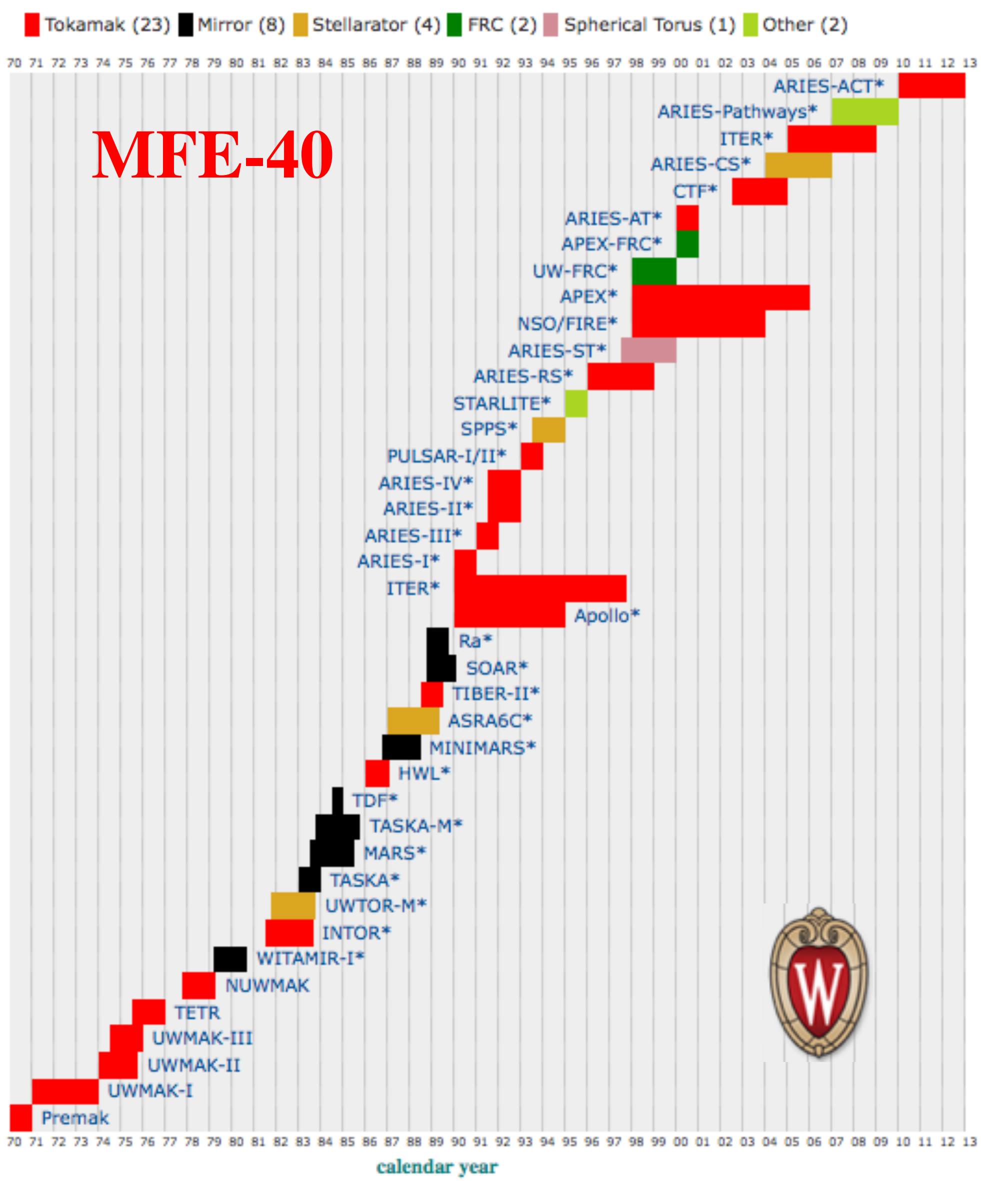
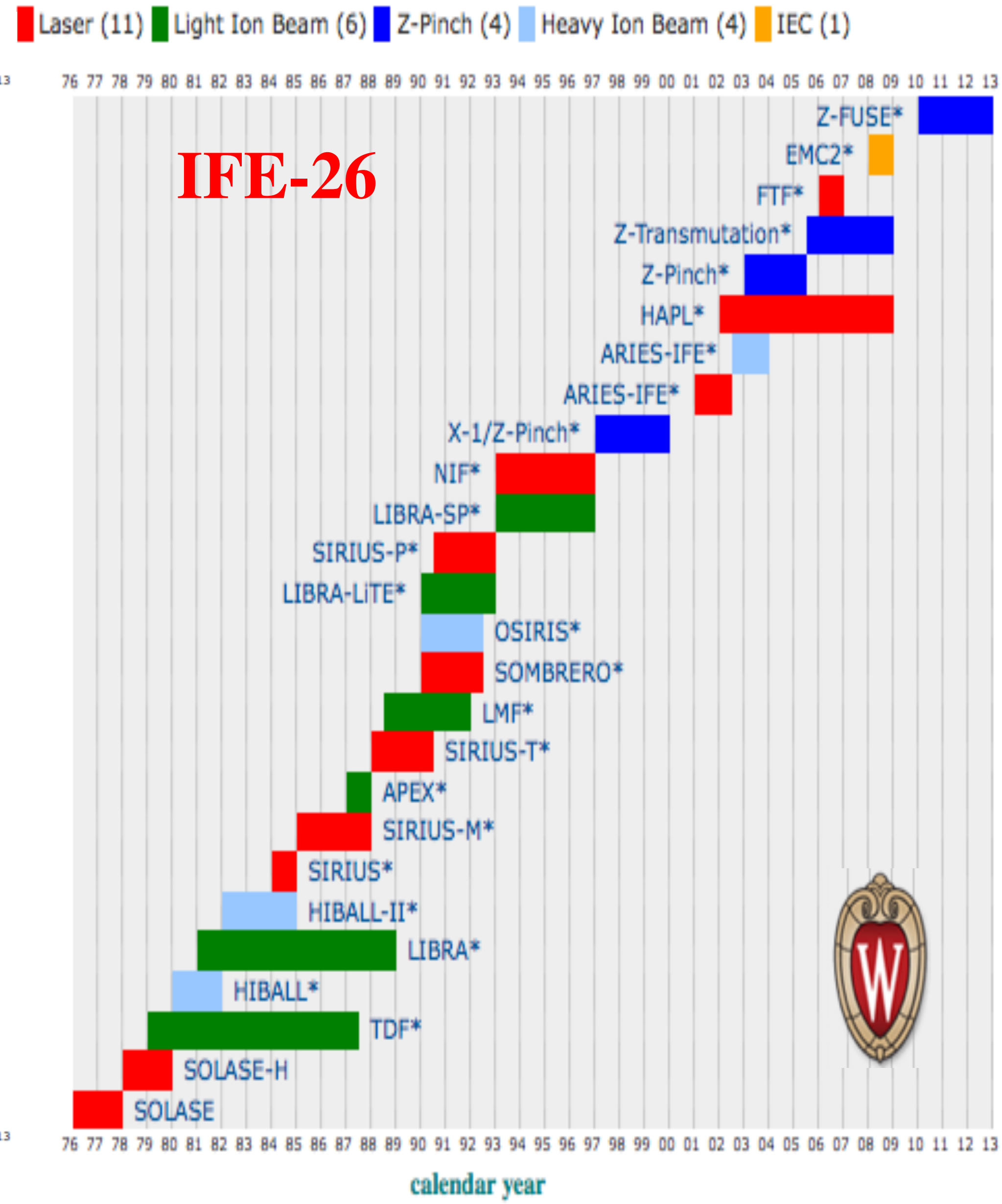
Laundry List of Fusion Reactor Development Issues

- Plasma physics of fusion fuel cycles
  - Cross sections and Maxwellian reactivity
  - Beta and B-field utilization
  - Plasma fusion power density
  - Plasma energy and particle confinement
  - Neutron production vs Ti for various fuel ion ratios
- Geometry implications for engineering design
  - Power flows
  - Direct energy conversion
  - Magnet configuration
  - Radiation shielding
  - Maintenance in a highly radioactive environment
  - Coolant piping accessibility
- Plasma-surface interactions
- Engineering issues unique or more important for DT fuel
  - Tritium-breeding blanket design
  - Neutron damage to materials
  - Radiological hazard (afterheat and waste disposal)
- Safety
- Environment
- Licensing
- Economics
- Nuclear non-proliferation
- Non-electric applications
- ^{3}He fuel supply

UW Developed and/or Participated in 40 MFE & 26 IFE Power Plant and Test Facility Studies in Past 46 years





Total *Fusion Reactivities* for Key Fusion Fuels

1st generation fuels:

$D + T \rightarrow n\ (14.07\ MeV) + {}^4He\ (3.52\ MeV)$

$D + D \rightarrow n\ (2.45\ MeV) + {}^3He\ (0.82\ MeV)$

$\rightarrow p\ (3.02\ MeV) + T\ (1.01\ MeV)$

{50% each channel}

2nd generation fuel:

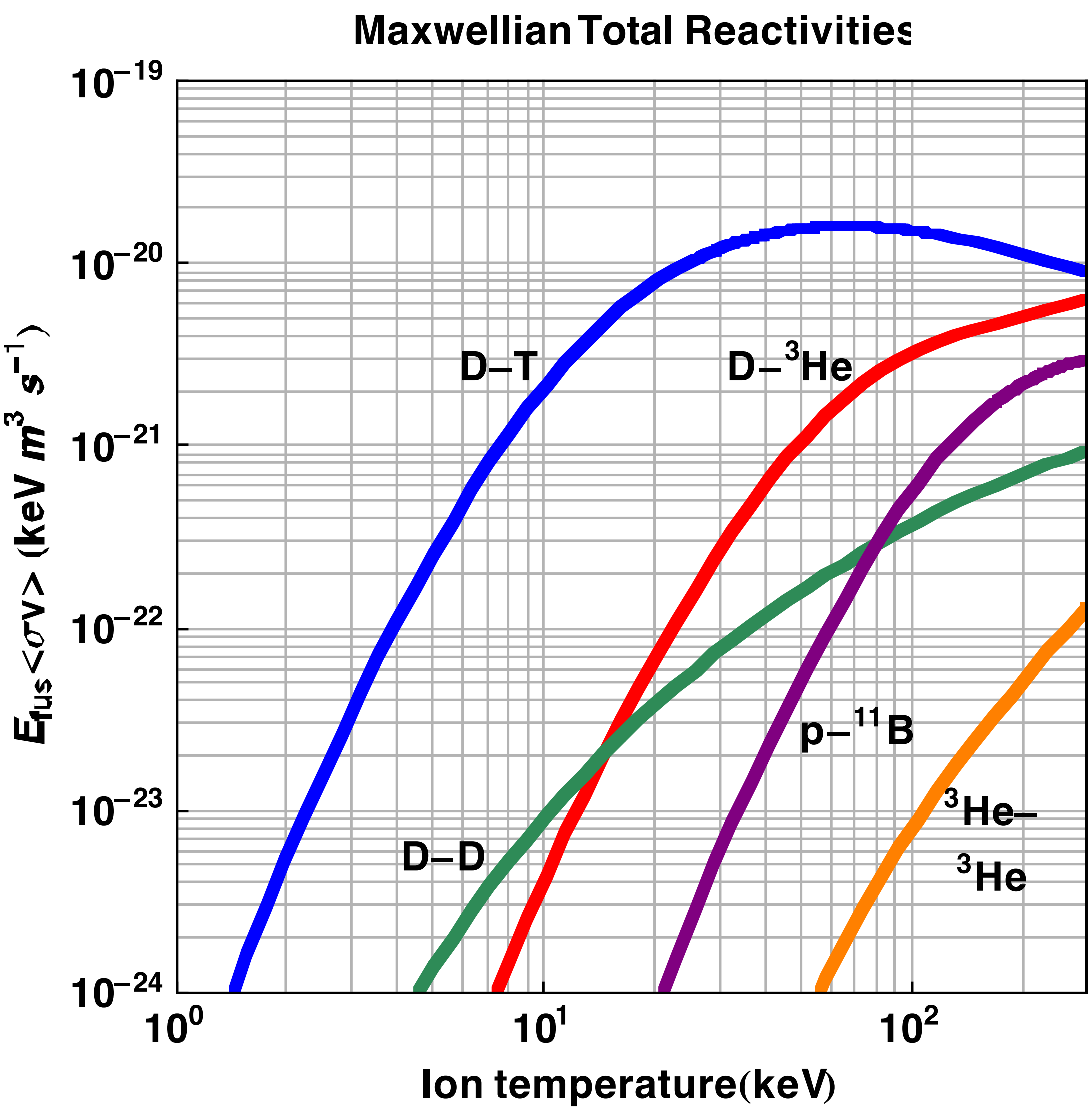
$D + {}^3He \rightarrow p\ (14.68\ MeV) + {}^4He\ (3.67\ MeV)$

3rd generation fuels:

${}^3He + {}^3He \rightarrow 2\ p + {}^4He\ (12.86\ MeV)$

$p + {}^{11}B \rightarrow 3\ {}^4He\ (8.68\ MeV)$

Total Energy Production Rate



What Are the Solar System ^{3}He Resources?

- ~100 kg ^{3}He accessible on Earth
  - ~2 GW-y fusion energy for R&D
- ~10^9 kg ^{3}He on lunar surface for the 21st & 22nd centuries
  - ~1000 y world energy supply
- ~10^{23} kg ^{3}He in gas-giant planets for the indefinite future
  - ~10^{17} y of world energy supply

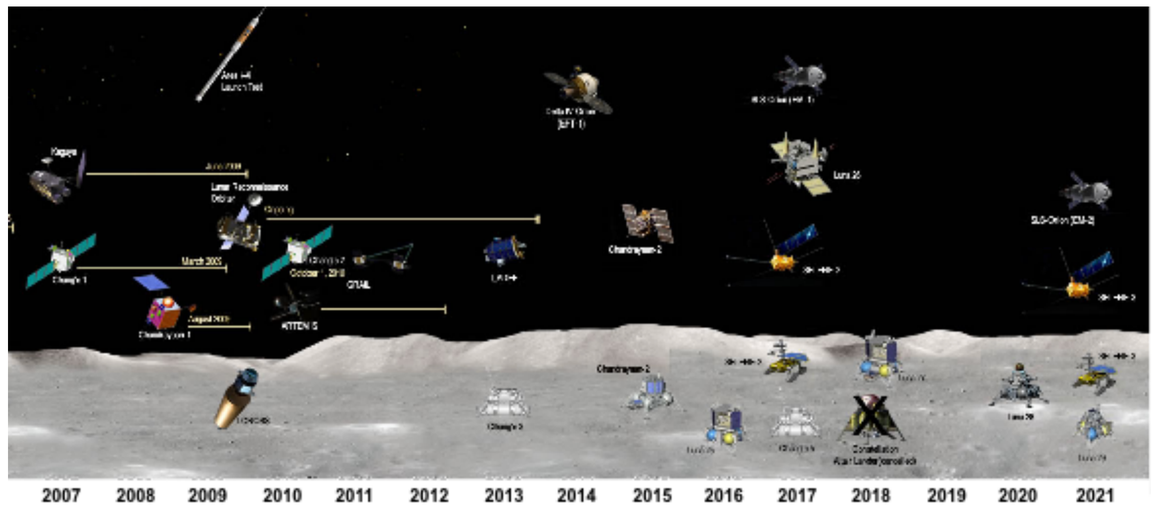
L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, "Lunar Source of ^{3}He for Commercial Fusion Power," *Fusion Technology* **10**, 167 (1986).

Private Enterprise Has Discovered the Moon

Companies with Lunar Plans as of 2014

Company	Country
Angelicum	Chile
Astrobotic Technology	
Bigelow Aerospace*	United States
Earthrise Space: Omega Envoy	
Euroluna	Europe
Excalibur Almaz*	United Kingdom#
Galactic Suite: Barcelona Moon Team	Spain
Golden Spike Company*	United States
Hakuto	Japan
Independence-X	Malaysia
Moon Express	United States
OpenLuna*	
Part-Time Scientists	Germany
Penn State Lunar Lion Team	United States
Puli Space Technologies	Hungary
Shackleton Energy Company*	
Space Adventures*	United States
STELLAR	
Synergy Moon	International
Team Indus	India
Team Italia	Italy
Team Plan B	Canada
Team Space IL	Israel
Team SpaceMETA	Brazil

Lunar Missions 2003-2021



At a Minimum, the Fusion Power Must Sustain the Plasma against Charged-Particle and Bremsstrahlung Losses

- Ignition against bremsstrahlung (only) is calculated using

$$P^{q}_{\text{fus}} = P_{\text{brem}} + \frac{n_e}{\tau_{eE}} \frac{3}{2} T_e + \sum_k \frac{n_i n_k}{(n\tau)_{kE}} \frac{3}{2} T_i$$

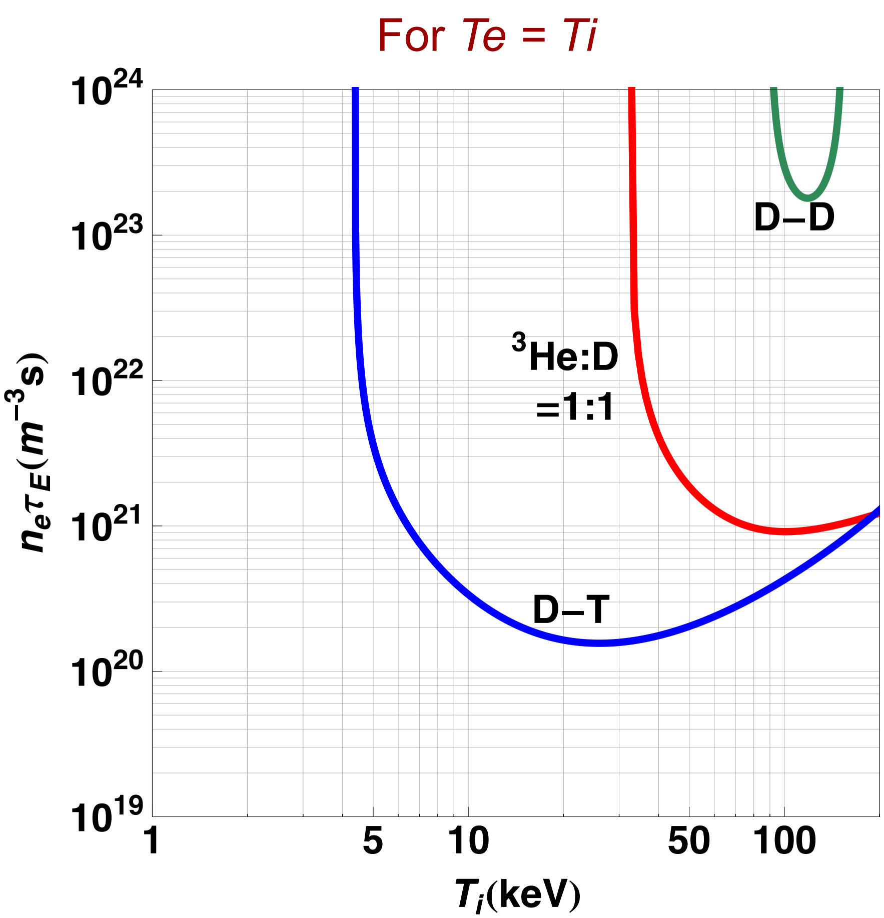
- Relativistic

$$P_{\text{brem}} = 5.36 \times 10^{-43} n_e^2 T_e^{0.5} \left[0.00414\, T_e + 0.071\, Z_3^{\text{eff}} T_e^{-0.5} + Z^{\text{eff}} \left(1 + 0.00155\, T_e + 7.15 \times 10^{-6} T_e^2 \right) \right]$$

- Definitions

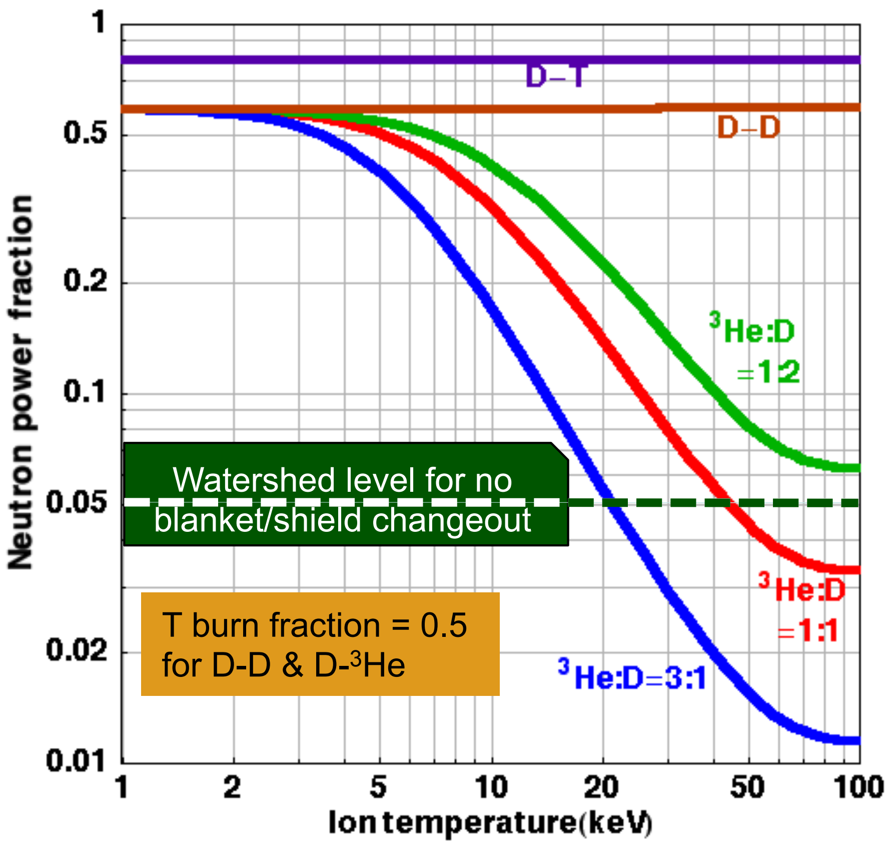
$$Z^{\text{eff}} \equiv \sum_i \frac{z_i^2 n_i}{n_e} \quad \text{and} \quad Z_3^{\text{eff}} \equiv \sum_i \frac{z_i^3 n_i}{n_e}$$

- Note: fusion ash accumulation, an issue for all reactor plasmas, possibly will be mitigated in FRCs due to nonadiabicity of the several MeV energy of the fusion-product alphas (and protons for D^3He).

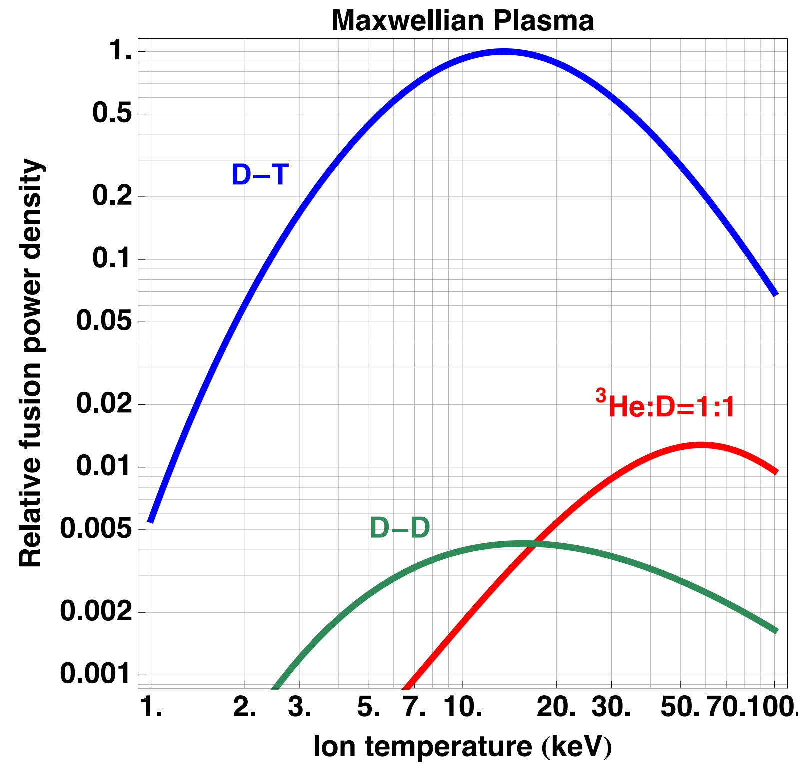


Neutron Production & Plasma Fusion Power Density

Neutron Production



Relative Power Density at Constant B & β

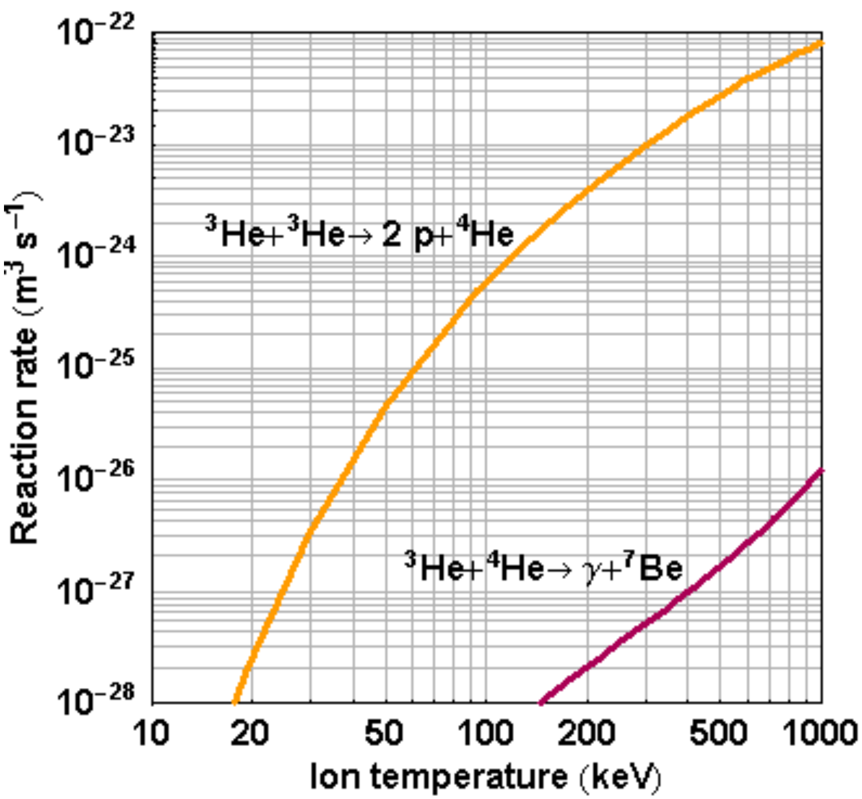


$$\beta \equiv \frac{P_{plasma}}{P_{Bfield}} \approx \frac{2nk_B T}{B^2/2\mu_0} \Rightarrow n \propto \beta B^2$$

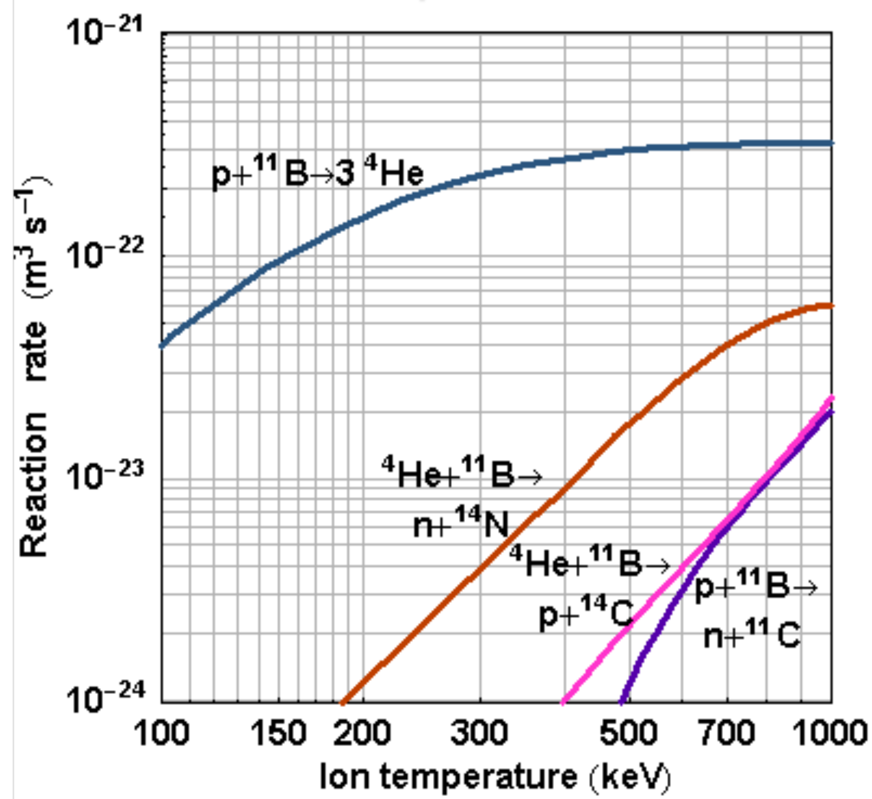
$$\frac{P_{fus}}{V} = n_1 n_2 E_{fus} < \sigma v > \propto \beta^2 B^4$$

^3He-^3He Reactions Will Produce Less Radioactivity than p-^{11}B Reactions in Maxwellian Plasmas

^3He-^3He

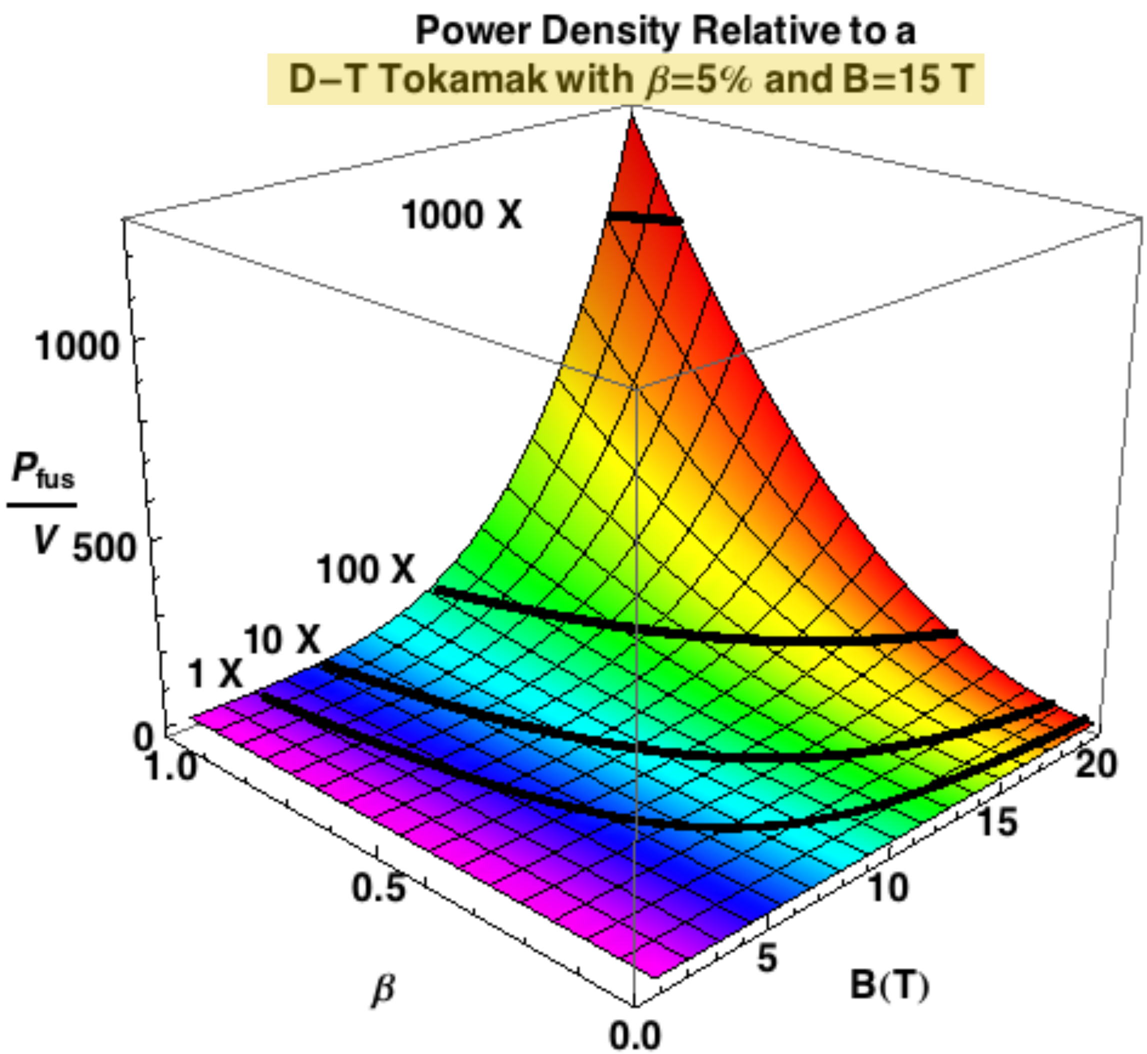


p-^{11}B



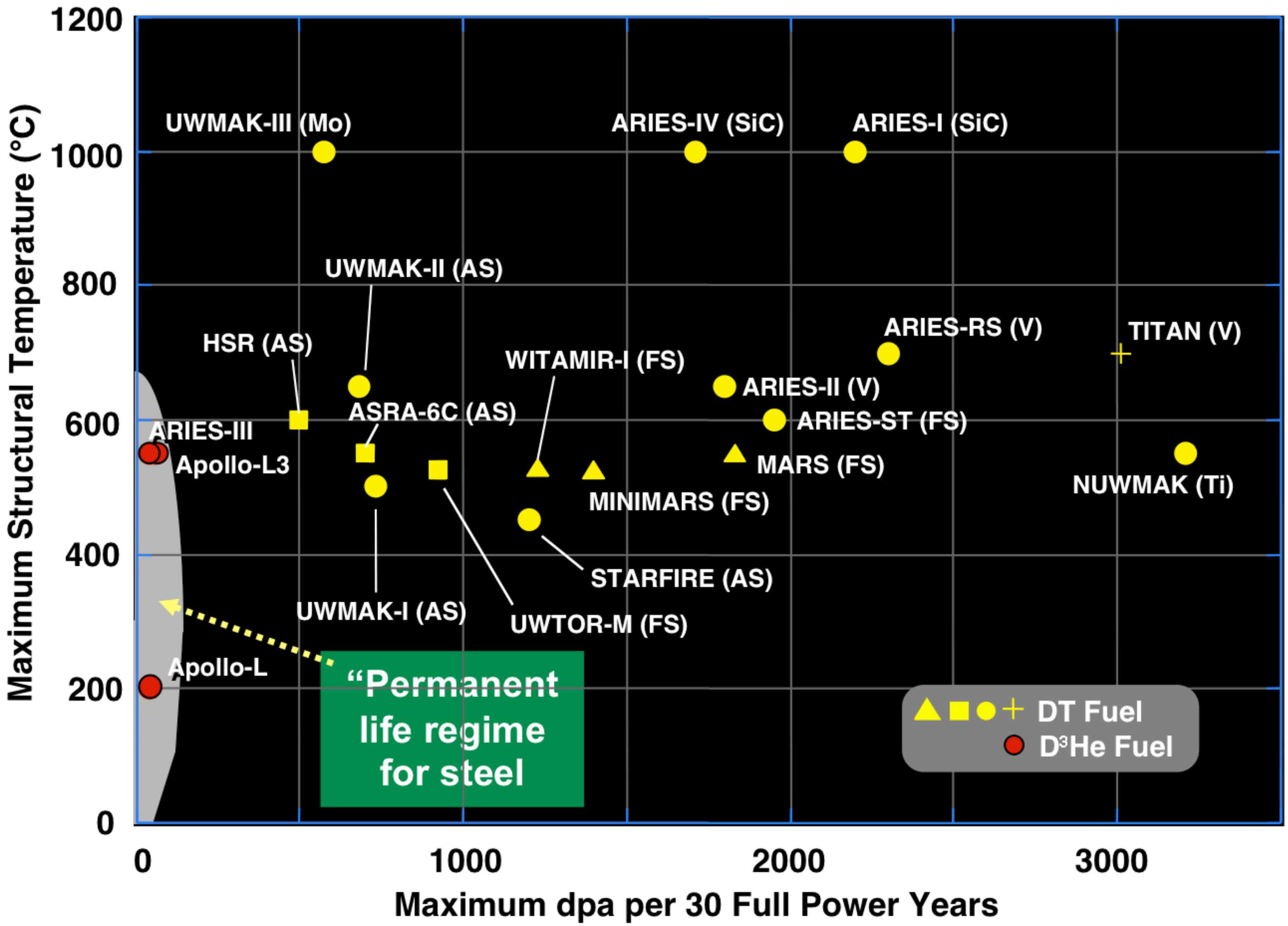
Maxwellian-averaged reaction rates are shown.

Advanced Fuel Fusion Power Density Can Improve Greatly through Increasing β and B-Field



- Low tokamak and stellarator β limits cause optimized reactor design B-fields to approach the technological limits (~20 T) on magnet coils, leaving little room to gain power density by increasing B.
- High-β concepts optimize at low B, because neutron damage requires frequent blanket and shield changeout, leaving a large technical margin for increasing B.

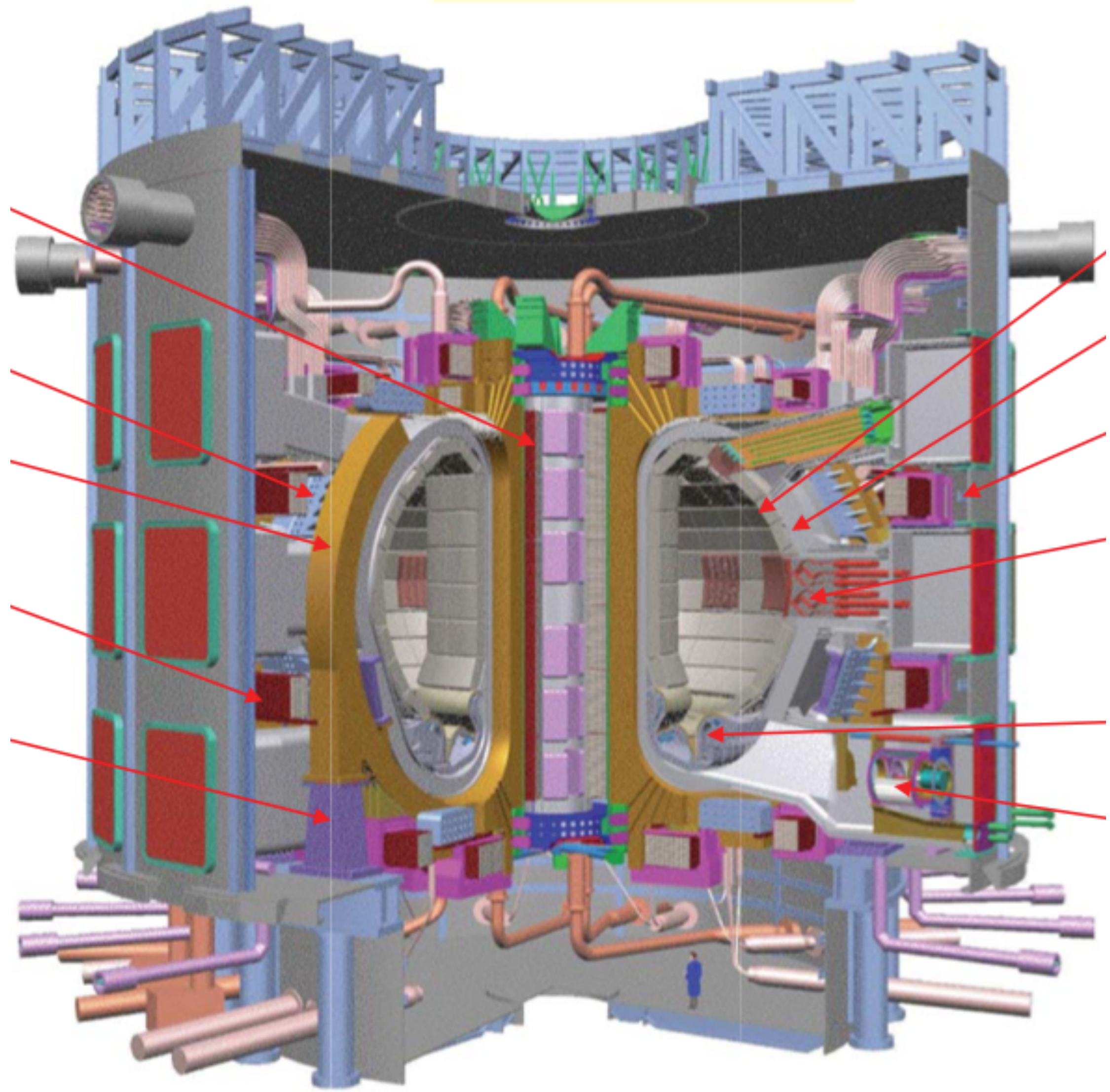
Advancd-Fuel Full-Lifetime Structure Gives a More Robust System and Reduces Maintenance Frequency



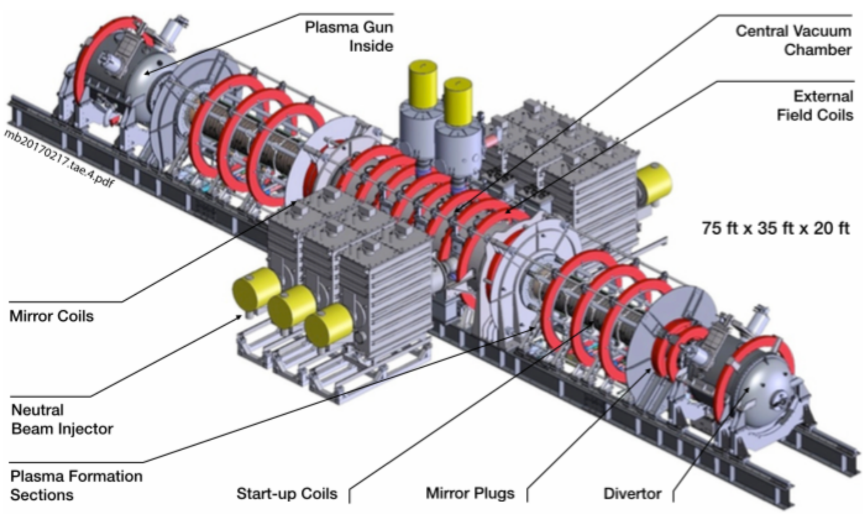
Linear Geometry Allows Much Easier Maintenance and Plumbing

- Some advantages of linear geometry:
  - ➢ Few interlocking systems
  - ➢ Modularity
  - ➢ Easier routing of plumbing

ITER Fusion Core

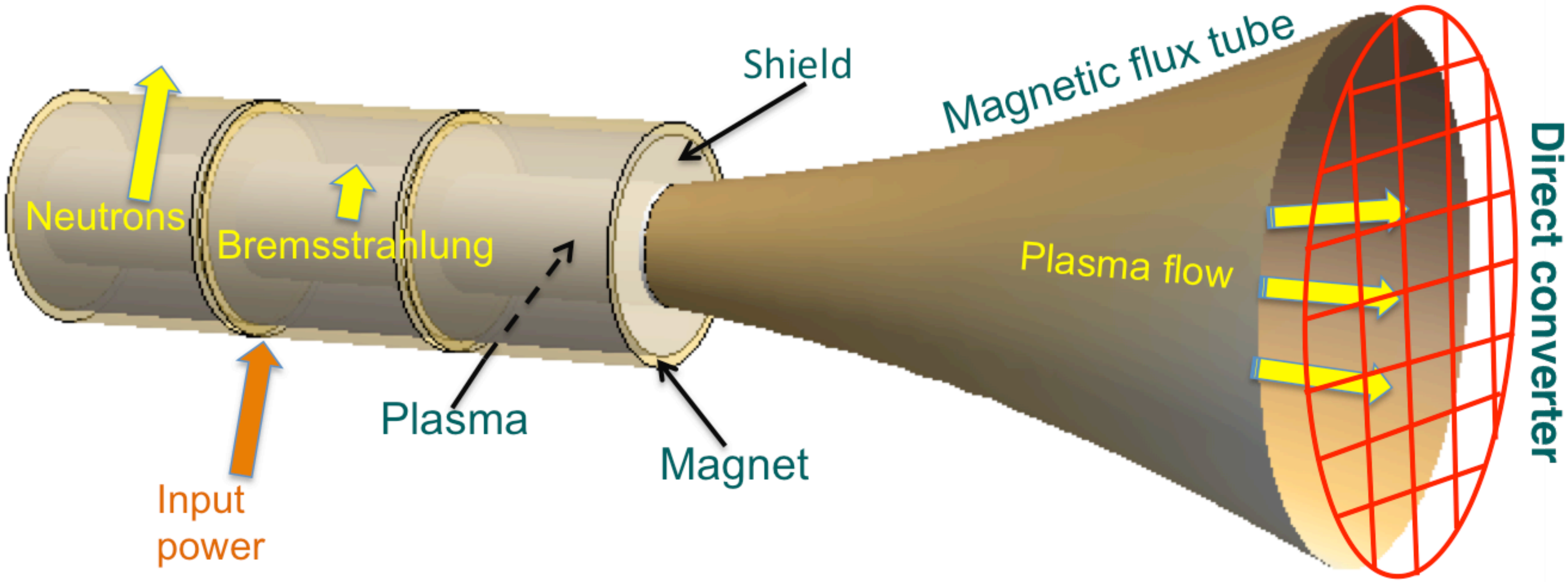


Tri Alpha Energy C-2 Experiment



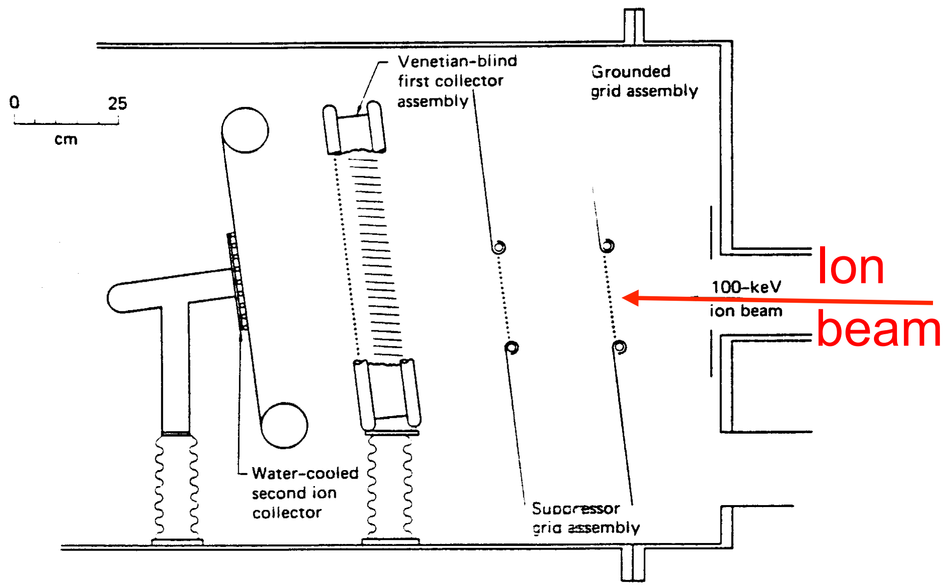
Power Flows Can Be Handled Much More Easily in Linear Geometry

- Charged-particle power transports from internal plasmoid (in an FRC or spheromak) to edge region and then out ends of fusion core.
- Expanded flux tube in end chamber reduces heat and particle fluxes.
- Mainly bremsstrahlung power contributes to first-wall surface heat.
- Relatively small peaking factor along axis for bremsstrahlung and neutrons.

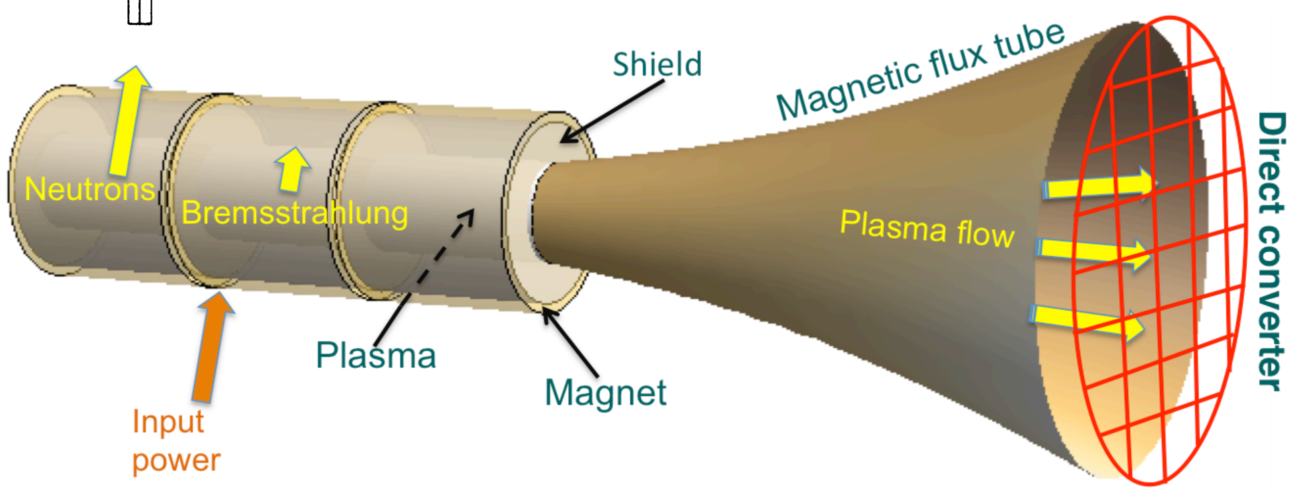


Direct Energy Conversion Can Be Applied to End-Loss Plasma

Barr-Moir experiment, LLNL
(*Fusion Technology*, 1973)



- Experiment and theory agreed within 2%.
- Direct conversion would provide 60-80% efficiency for escaping fusion products.
- Bremsstrahlung (x-rays) require thermal energy conversion.



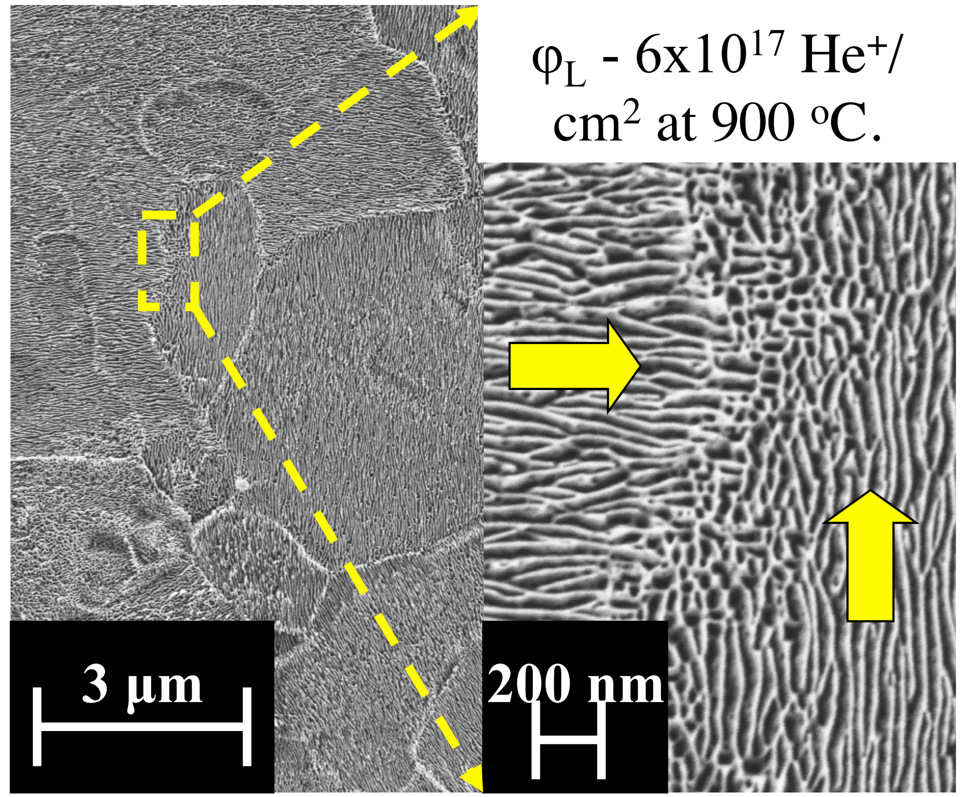
Plasma Surface Interactions Can Create Damage

- Linear geometry devices can handle high heat fluxes, caused by charged particles escaping the core, by expanding the flux tube in the end tank.

- Tokamaks take that heat and those particles mainly in a thin strip along the divertor, leading to surface heat fluxes of 10-20 MW m^{-2}.

30 keV He^+ Irradiation of Polycrystalline Tungsten

φ_L - 6x10^{17} He^+/cm^2 at 900 ^oC.



From S. J. Zenobia, L. M. Garrison, G. L. Kulcinski. "The response of polycrystalline tungsten to 30 keV helium ion implantation at normal incidence and high temperatures." *Journal of Nuclear Materials* **425**, 83 (2012).

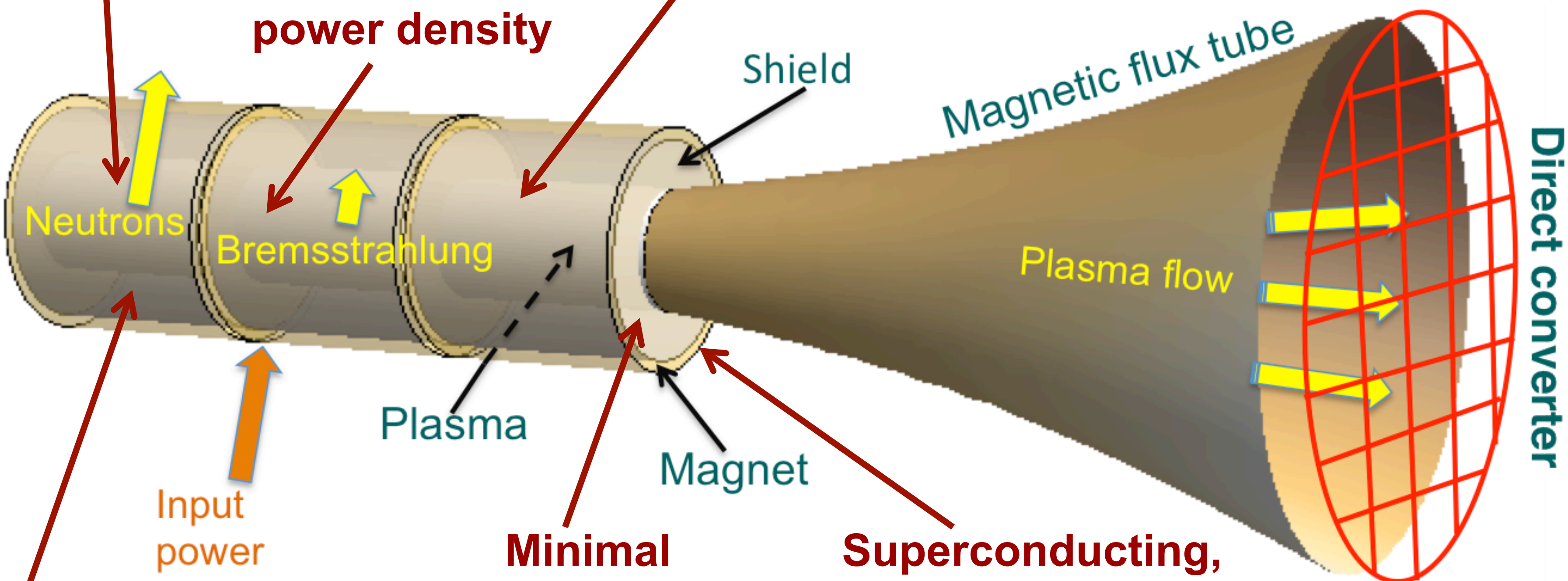
Can We Design Proliferation-Proof Advanced Fuel FRCs?

Advanced fuel for low neutron wall loading

Large α particle & D^3He proton gyroradii contribute to macroscopic stability

Direct converter for increased electric power per unit fusion power

High β for high fusion power density



Organic coolant to make high-flux DT operation difficult

Minimal radiation shield to reduce space for DT shielding

Superconducting, high-field magnet for high fusion power density

Summary

- DT fuel is the easiest to burn, whereas burning advanced fuels requires continued, modest plasma physics progress, especially in energy confinement.
- Physics development path typically costs less than engineering development path => advanced fuels.
- Considerations of engineering, safety, environment, and licensing favor advanced fuels, while cost remains to be determined.
- Advanced fuels require the development of the FRC or another suitable high-β, innovative concept.

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^{3}He Plays a Key Role in the Advanced Fusion Fuels

Key Fusion Fuels

1st Generation

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3rd Generation

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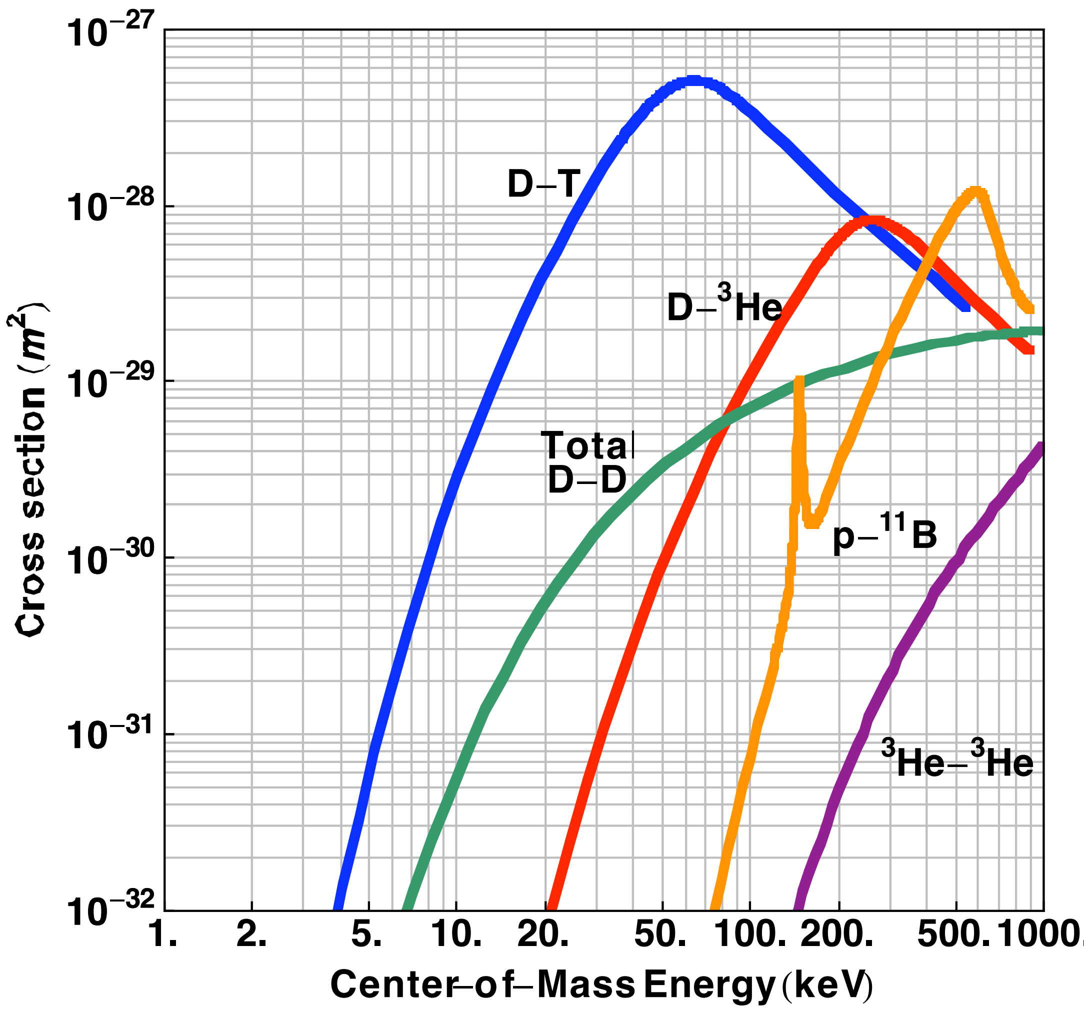
^{3}He + ^{3}He → 2 p + ^{4}He (12.86 MeV)



Advanced Fuels Could Lower R&D Costs

Engineering R&D costs typically dominate physics R&D costs.