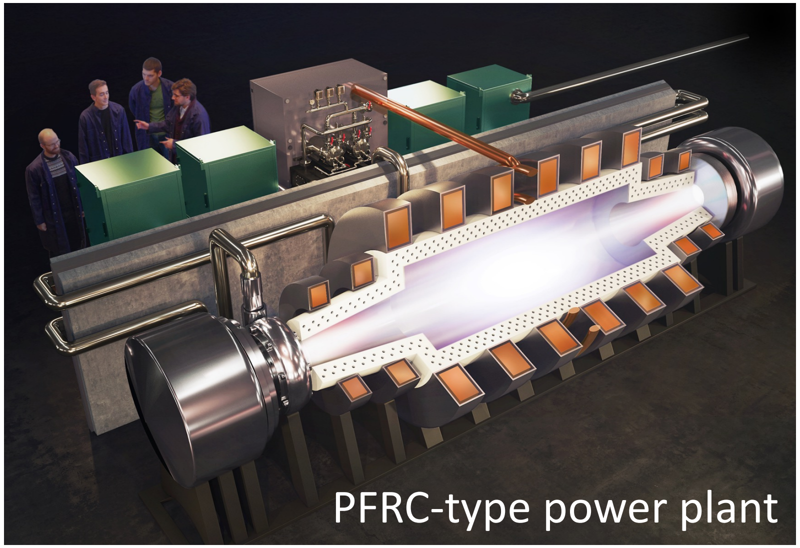
Field-Reversed Configuration (FRC) Reactors for Power and Propulsion

S.A. Cohen, Princeton Plasma Physics Laboratory

June 2023

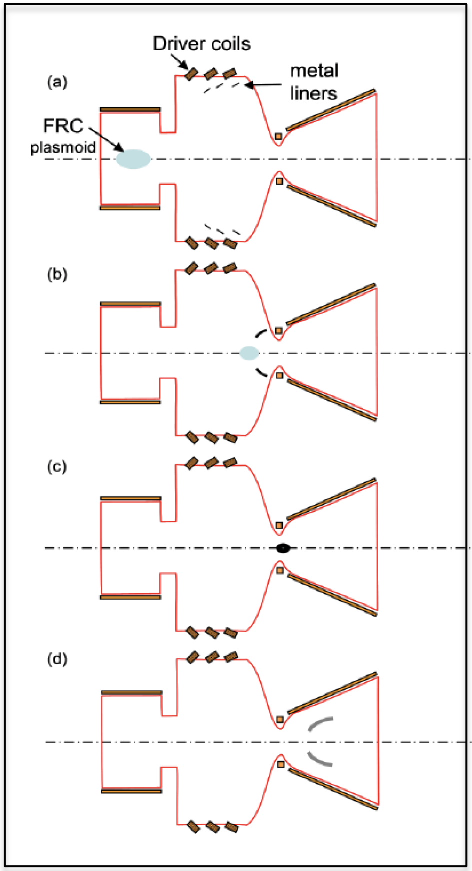
Research performed under DOE *Contract Number DE-AC02-09CH11466*


PFRC-type power plant

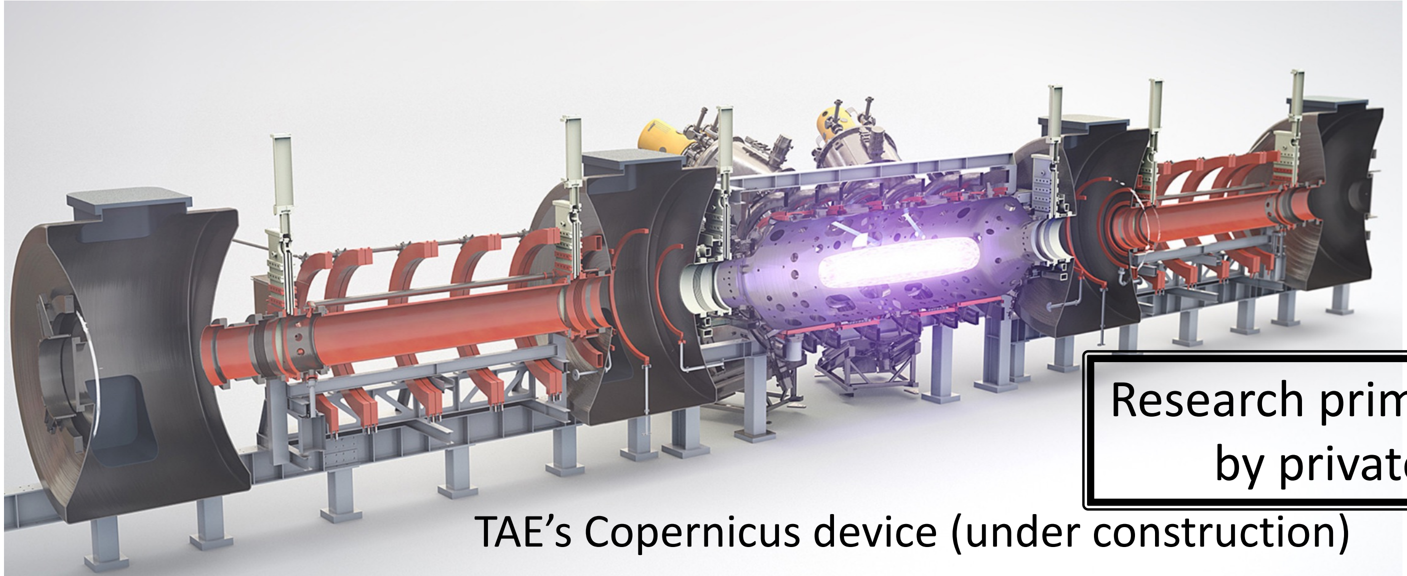
FRC Science

&

Technology



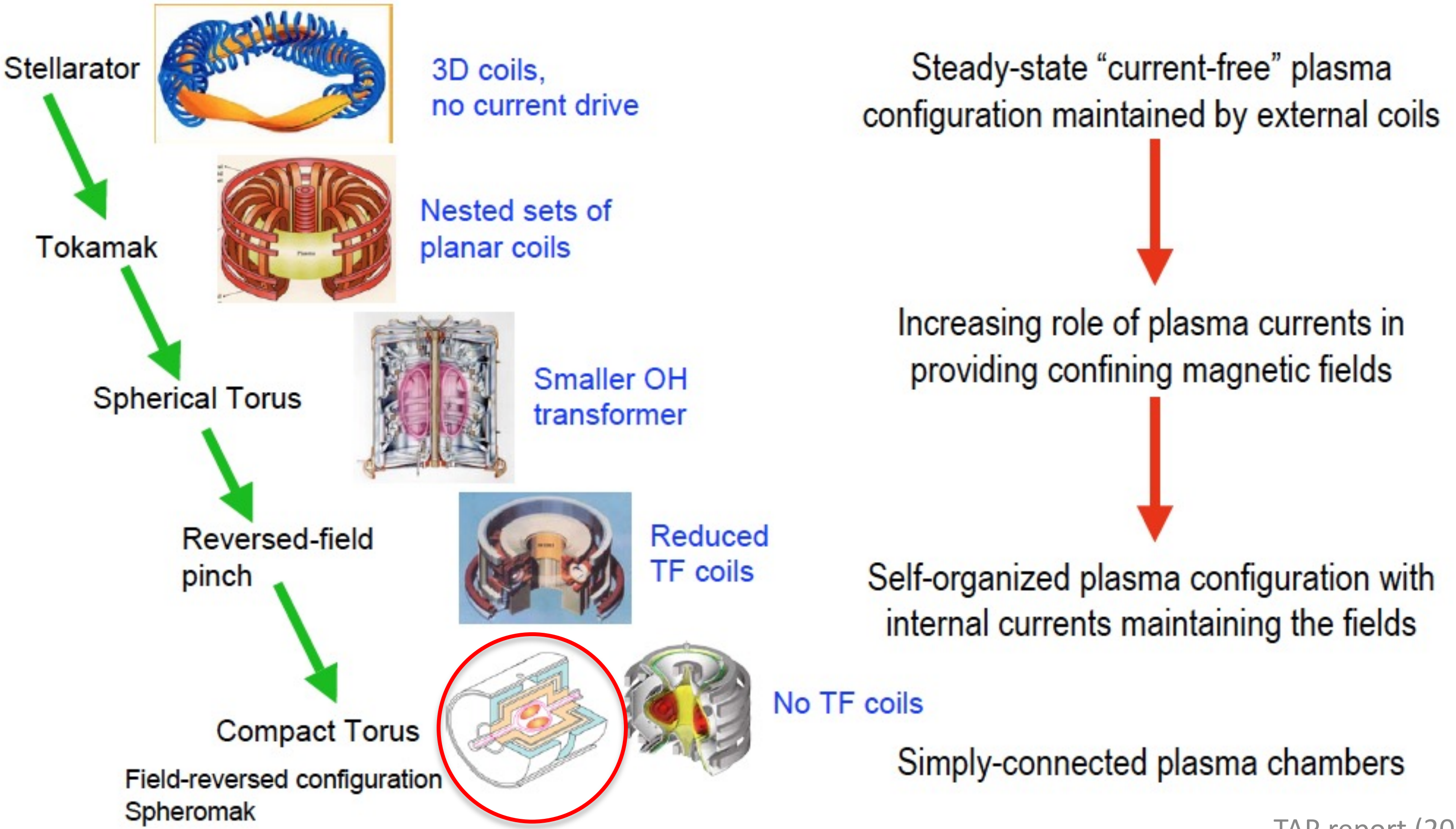
Helion rocket concept


TAE's Copernicus device (under construction)

Research primarily funded by private sector

The FRC: one of 7+ families of magnetic fusion reactor concepts

Which *toroidal* device for burning ^{3}He?



Stellarator

3D coils,
no current drive

Tokamak

Nested sets of
planar coils

Spherical Torus

Smaller OH
transformer

Reversed-field
pinch

Reduced
TF coils

Compact Torus

Field-reversed configuration
Spheromak

No TF coils

Steady-state "current-free" plasma configuration maintained by external coils

Increasing role of plasma currents in providing confining magnetic fields

Self-organized plasma configuration with internal currents maintaining the fields

Simply-connected plasma chambers

TAP report (2008)

Self-organized →

Some international FRC research efforts

- Osaka University: Okada *et al.*, Experiments (FIX) on neutral beam & RF (compressional) plasma heating
  - T_e+T_i ~ 120 eV; τ ~ 150 ms
- Tokyo U: Kaminou *et al.*, Experiments (TS-4) on merging spheromaks -> FRCs
  - Hall effect; PIC >> MHD; Low S*; n_e to 7e14/cc; T_e ~ 5eV
- Nihon U: Hirano *et al.*, D-T FRC reactor design
  - 3 GW; 40-m long; r_s =4.3 m.; 1.5 MW/m^2 n; Cu coils
- Gunma U & Hyogo U: Watanabe *et al.*, MHD & PIC FRC modeling
  - CT "neutralization" for tokamak fueling
- ENN (Langfang): RF Experiments on plasma heating and current drive
  - RMF_o studies
- USTC (Hefei) KMAX device: Sun *et al.*, Theta-pinch and RMF FRC formation, stabilization
  - Azimuthal electric fields, RMF_o, shear flow

PFRC researchers, collaborators, co-authors,…

PU: A. Dogariu (Tex A&M), A. Landsman, E. Schwarzmann, T. Kornak, N. Ferraro, K. Ghantous, A. Roach, D. Lundberg, C. Myers, A. Stepanov, J. Mitrani, C. Liu, Y. Zhou, N. McGrievy, J. Matteucci, C. Swanson, **E. Evans**, P. Jandovitz, A. Glasser, E. Palmerduca, **L. David**, R. Katz, E. Torbert, S. Fahmy, J. Sapan, E. Lieberman, T. O'Neil, D. Levit , T. Gudmundsen, S. Pollard, A. Hazony, W. Herlands, V. Solomon, E. Coleman, M. Edwards, K. Griffin, M. Walsh, **M. Chu-Cheong**, M. Khodak, J. Pearcy, H. Winarto, A. Raja, A. Creely, E. Paul, A. McDonagh, E. Kolmes, J. Liu, E. Ham, G. Gaitin, M. Yeh, J. Abbate, F. Zheng, H. Khan, H. Santhanam, J. de Wetering, M. Penza, J. Zhou, G. Rutherford, S. Polson, K. Alkin, T. Ahsan, M. Chitoto, B. Allesio, N. Notis, C. Arens, T. Qian, T. Rubin, K. Torrens, H. Chen, A. Ateyeh, D. Singh, G. Nucci, S. Capili, S. Morel, M. Bates

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Sandia: M. Campbell

NYU: M. Edelman, G. Zaslavsky

UTenn: Z. Zhang, Z. He

MIT: J. Minervini, J. Wright, M. Breton

ORNL: N. Kafle, T. Biewer, D. Elliot

FTC, Inc: A.H. Glasser

General Atomics: P. Parks, T. Evans

Voss Sci: D. Welch, T. Genoni, R. Clark

U Rochester: A. Sefkow, S. Zhai, A. Kish, Lavell

UW: R. Milroy

PSS: M. Paluszek, **S. Thomas**, J. Mueller, Y. Raizin, A.J. Knutson, G. Pajer, C. Swanson, **C. Galea**

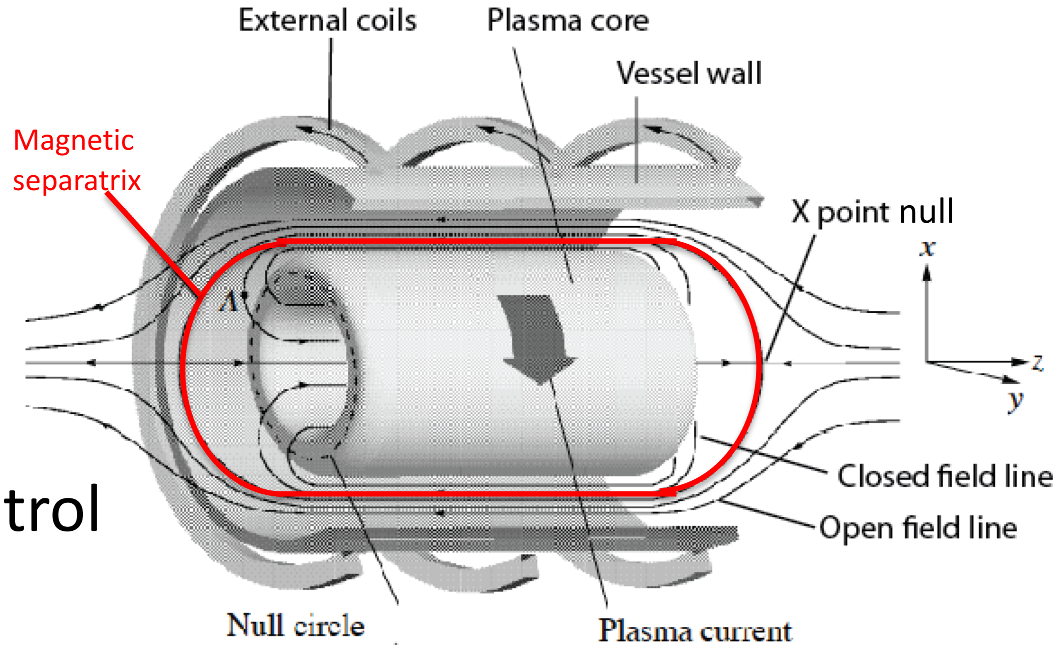
Other: J. Kollasch, S. Newbury, G. Player, R. Oliver, A. Kaptanoglu, B. Pelc, N. Cannon, A. Sexton C. Jakuback, **G. Jusino**, J. Cohen, C. Biava, P. Hooda, M. Kim, H. Doucet, J. Turchi, J. Cassibry

Foreign visitors: M. Demir (Turkey), W. Li (China)

Red = undergraduate students
Green = graduate students
Black = professionals

Notable FRC attributes: *new science*

- High $\langle\beta\rangle = 8\pi knT/B^2$, 0.5-1.0 ; high T_i at moderate n_e
  - Aneutronic fuels + …..
- Highly kinetic: non-equilibrium f(E); $\rho_i/r_s > 0.1$
  - Classical transport? Stability?
- B = 0 in parts of plasma
- $J \perp B$ **(not Taylor, not Beltrami)**
- q = 0
  - Classical transport?
- Linear magnet array
  - Easy field expansion
  - Active edge plasma control
- Compact
  - Ash exhaust



$S^* \sim \omega_{pi} r_s/c \sim 3s$

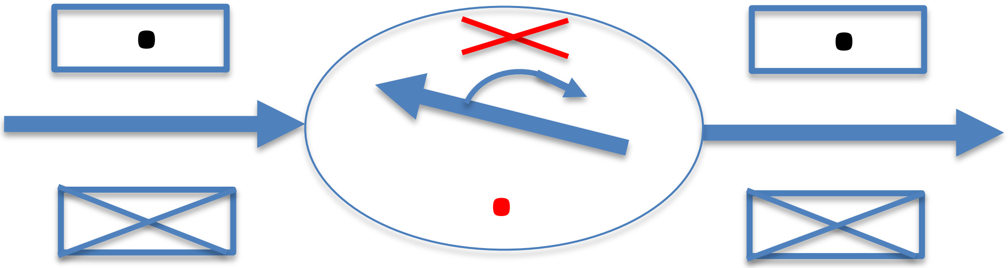
$s \equiv 0.3\, r_s/\rho_i$

$\kappa \equiv 2\, r_s/L$

Early criticisms of FRC

Instability

Macro: internal tilt mode (see next slide)



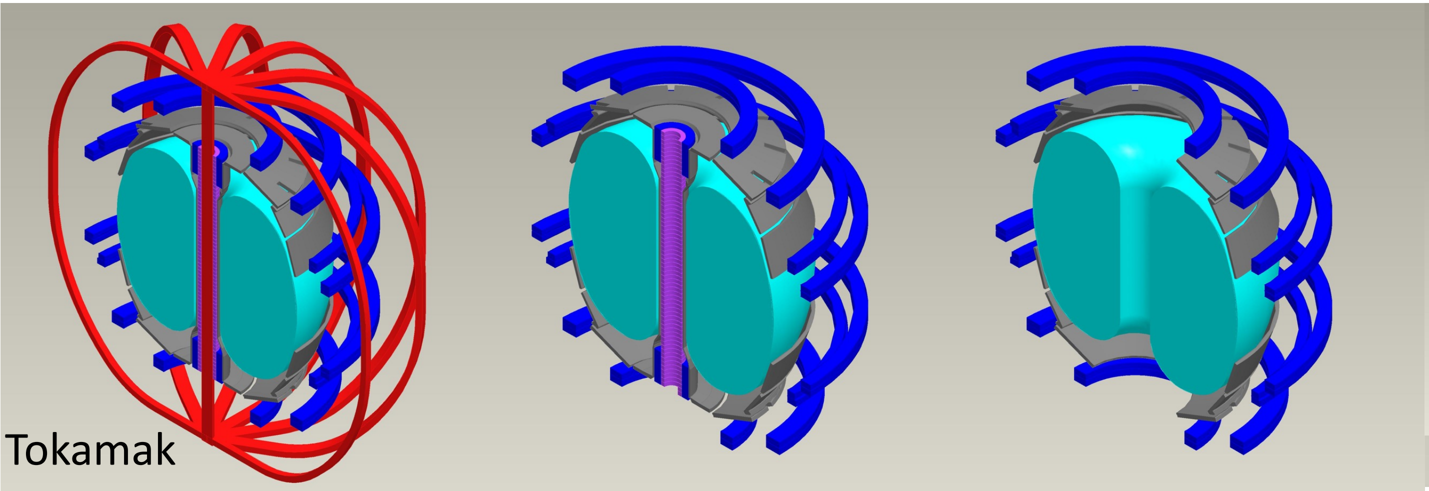
$\tau_A \sim 1\text{-}10\ \mu\text{s}$

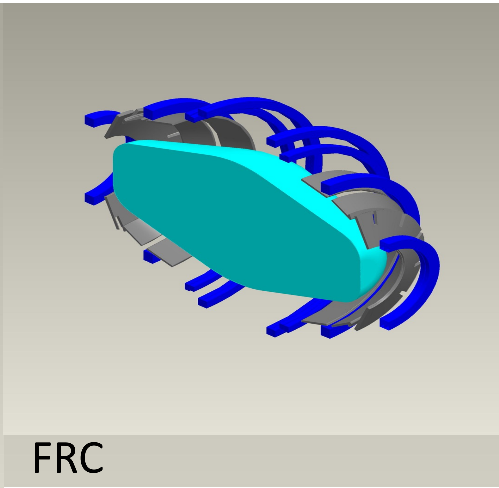
Micro: LHDI – poor energy confinement
(see slide 20)

Poor ^{3}He fuel supply (think Musk!)

The Tokamak and the FRC

Tokamak	**FRC**
$\langle\beta\rangle \ll 1$	$\langle\beta\rangle \sim 1$
Toroidal magnets	Linear solenoid
Strong B_t at coils	$B_t = 0$
$q \sim 3$	$q = 0$
Strong B on minor axis	B = 0 on minor axis
Current || to **B**	Current ⊥ to **B**
Hole and coils in middle	No hole or coils in middle
Field lines cover surface	Field lines stay lines
Bigger	Smaller
Burns D-T	**Could burn advanced fuel – no neutrons**
Extensive neutron shielding needed	Less neutron shielding needed
Extensive database	Weak database
MHD stability known	MHD relevance?

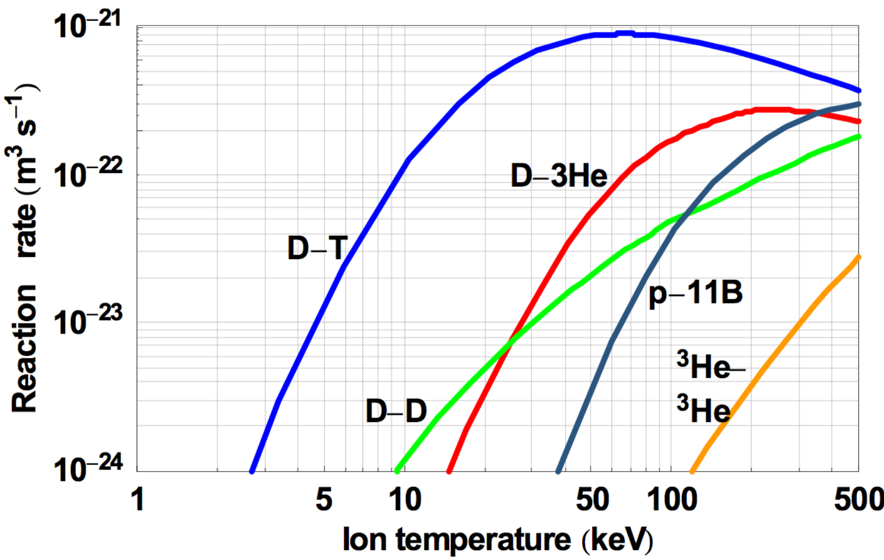




Why and how "clean:" *Aneutronic*

Bad aspects of neutrons

- Damage materials' electrical & thermo-mechanical properties
- Activate materials
- Tritium breeding is difficult
  - ITER's base program will use up 3/4 of the world's available tritium
- Required shielding increases weight, size, & cost
- Materials development is costly, slow, & questionable



$D + T \rightarrow {}^4He(3.5\ MeV) + n(14.1\ MeV)$

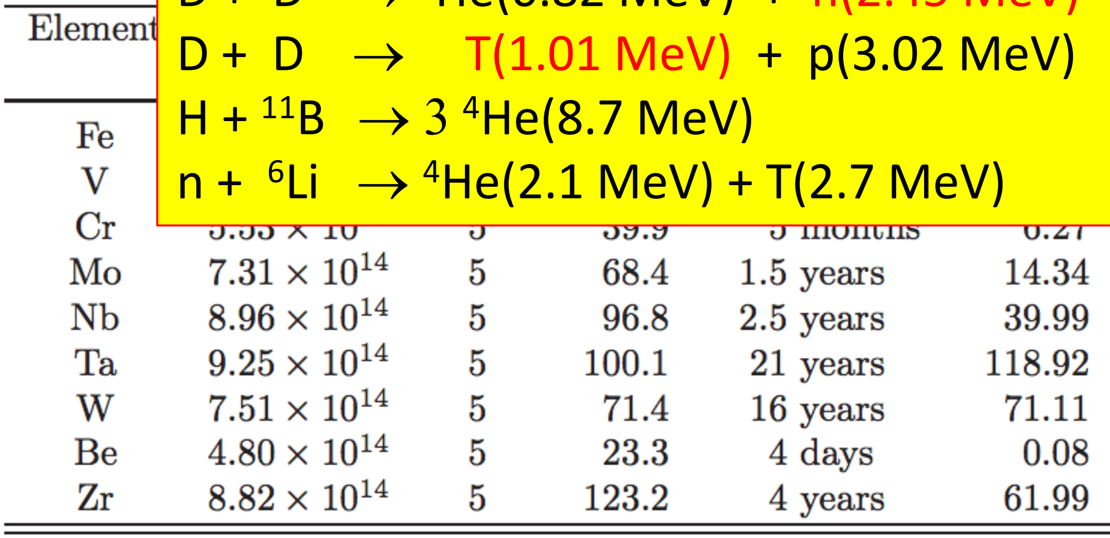
$D + {}^3He \rightarrow {}^4He(3.6\ MeV) + p(14.7\ MeV)$

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

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

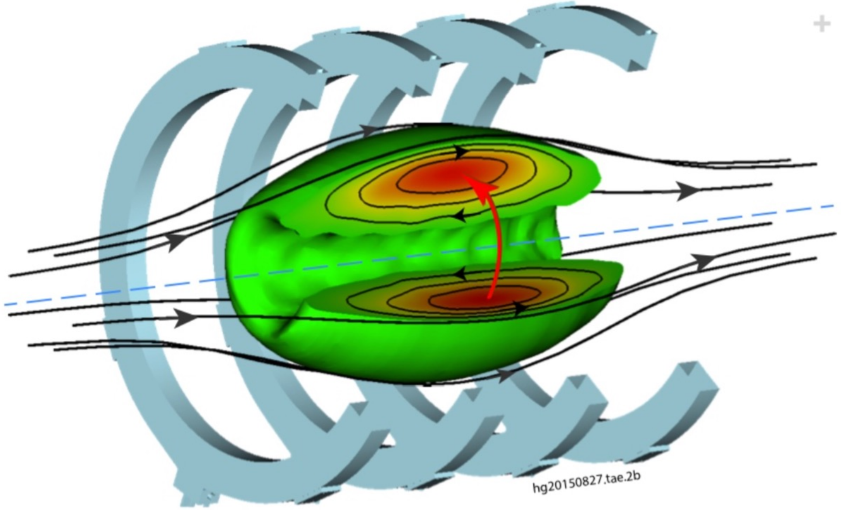
$H + {}^{11}B \rightarrow 3\ {}^4He(8.7\ MeV)$

$n + {}^6Li \rightarrow {}^4He(2.1\ MeV) + T(2.7\ MeV)$



Element					
Fe					
V					
Cr	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Mo	7.31×10^{14}	5	68.4	1.5 years	14.34
Nb	8.96×10^{14}	5	96.8	2.5 years	39.99
Ta	9.25×10^{14}	5	100.1	21 years	118.92
W	7.51×10^{14}	5	71.4	16 years	71.11
Be	4.80×10^{14}	5	23.3	4 days	0.08
Zr	8.82×10^{14}	5	123.2	4 years	61.99

Gilbert, Dudarev, Zheng,…



Pulsed *vs* Steady state

Beam *vs* RF *vs* Compression

D-T *vs* p-^{11}B *vs* D-^{3}He

Small *vs* Medium *vs* Large

54 Combinations

BUT only 3 FRC reactor concepts considered

- 50 MW, pulsed, compression-heated: D-D+^{3}He fuel

  Helion $r_s = 0.02$ m

- 0.5-1 GW, steady-state, beam-heated: p-^{11}B fuel

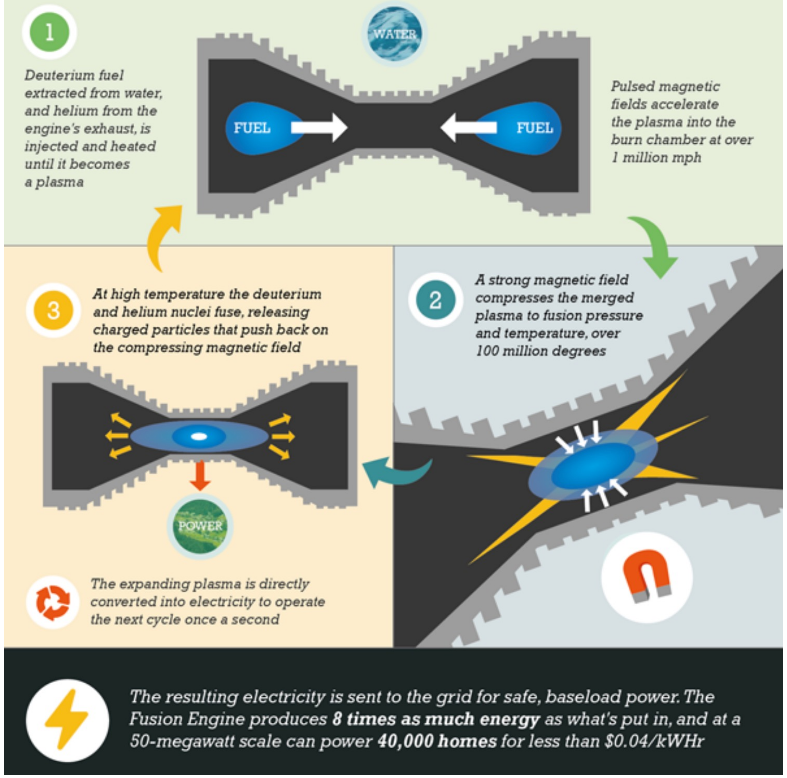
  TriAlpha (TAE) $r_s = 2$ m

- 1-10 MW, steady-state, RF-heated: D-^{3}He fuel

  Princeton $r_s = 0.25$ m

Helion Energy: not neutron free

Several Helion approaches: mostly using compressional heating



Deuterium fuel extracted from water, and helium from the engine's exhaust, is injected and heated until it becomes a plasma

Pulsed magnetic fields accelerate the plasma into the burn chamber at over 1 million mph

A strong magnetic field compresses the merged plasma to fusion pressure and temperature, over 100 million degrees

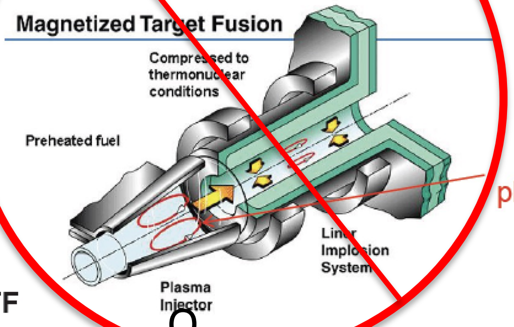
At high temperature the deuterium and helium nuclei fuse, releasing charged particles that push back on the compressing magnetic field

The expanding plasma is directly converted into electricity to operate the next cycle once a second

The resulting electricity is sent to the grid for safe, baseload power. The Fusion Engine produces **8 times as much energy** as what's put in, and at a 50-megawatt scale can power **40,000 homes** for less than $0.04/kWHr

Magnetized target fusion

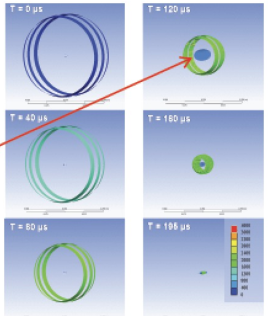
Shell (liner) implosion driven by B_θ from large axial currents in shell.



MTF Issues: Q

Fusion Rocket Drive

Liner implosion from **j×B** force between external coil and induced liner currents



FDR Advantages:

(2012)

NIAC I, Final report

D-T
For space craft propulsion

$$D + T \rightarrow {}^4He(3.5\ MeV) + n(14.1\ MeV)$$
$$D + {}^3He \rightarrow {}^4He(3.6\ MeV) + p(14.7\ MeV)$$
$$D + D \rightarrow {}^3He(0.82\ MeV) + n(2.45\ MeV)$$
$$D + D \rightarrow T(1.01\ MeV) + p(3.02\ MeV)$$

^{3}He-catalyzed D-D
For terrestrial use

Produces 2.45 & 14.1 MeV neutrons

http://www.helionenergy.com/

Beam-heated p-^{11}B: TAE

$$p + {}^{11}B \rightarrow 3\ {}^{4}He\ (8.7\ MeV)$$

FAR fewer technical (materials, fuel availability) problems

But

$$^{11}B + \alpha \rightarrow {}^{14}N + n + 157\ keV$$

$$^{11}B + p \rightarrow {}^{12}C + \gamma + 16\ MeV$$

and

$$^{11}B + p \rightarrow {}^{11}C + n\ \ - 2.8\ MeV$$

10^{-3} as much neutron power as D-T/unit power

For occupational doses

1 m of shielding still required due to n and γ

More scientific challenges

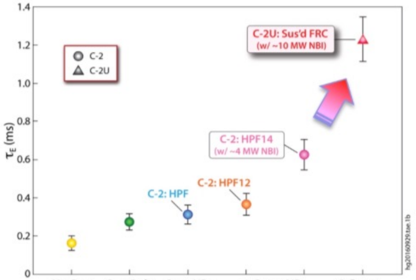
R. Feldbacher, “The AEP Barnbook DATLIB,” International Nuclear Data Committee Report INDC(AUS)-12/G, V. 1 (IAEA, Vienna, 1987)

Heindler and Kernblicher, Proc. 5th Int. Conf. on Emerging Nucl. Energy Systems, 177 (1989)

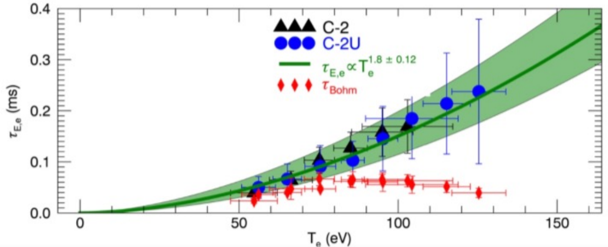
TriAlpha Energy: *Selected results through 2021*

Improvements in Confinement / Transport

- **0-D global power-balance analysis indicates substantial improvements in equilibrium and transport parameters**
- **Regression gives electron energy confinement time, $\tau_{E,e} \sim T_e^{1.8}$; more heating power, better confinement**

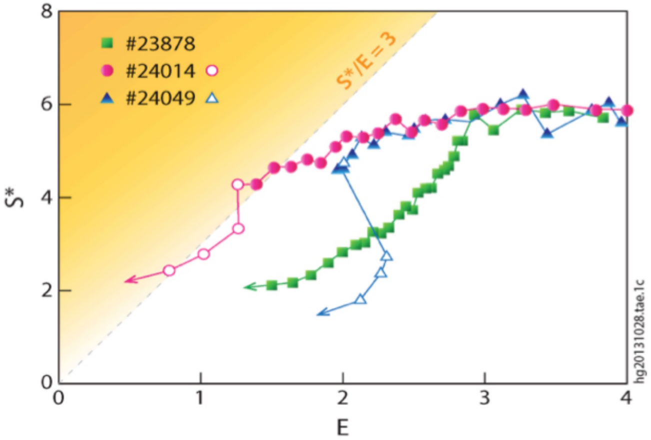


Global energy confinement time in C-2/C-2U



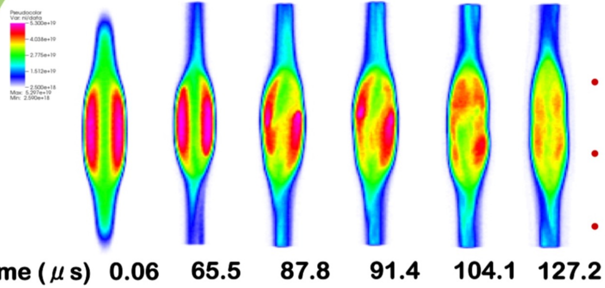
- Merged FRC as beam target
- Discharges sustained for > 10 ms ($t > 10^3\ \tau_A$)
- Stabilized by end plasma guns & biased rings
- T_e ~ 140 eV
- T_i ~ 1 keV
- $n_e \sim 4 \times 10^{13}$/cc
- $\tau_E \sim 1.2$ ms; $\tau_{Ee} \sim 0.2$ ms
- Fast ion confinement near classical
- $P_{fast\ ions}/P_{thermal} \sim 1$; Fast ions drive current

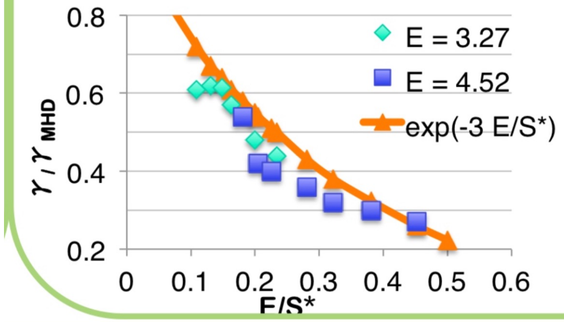
- C-2/C-2U typically operate in stable regime by controlling density and creating large fast ion pressure



Guo, et. al, Nat. Comm. 6, 6897 (2015)

Stability of Tilt Mode – FPIC Code





- **Fully kinetic ions, fluid electrons**
- **Ohm's law, no displacement current**
- **Growth rate agrees with analytic theory [4]**
- **Nonlinear saturation of tilt leading to new FRC equilibrium [5]**
- **Elongated FRCs and beam presence (Belova) stabilizes n=1 tilt mode**

S. Dettrick , F. Ceccherini and L. Galeotti

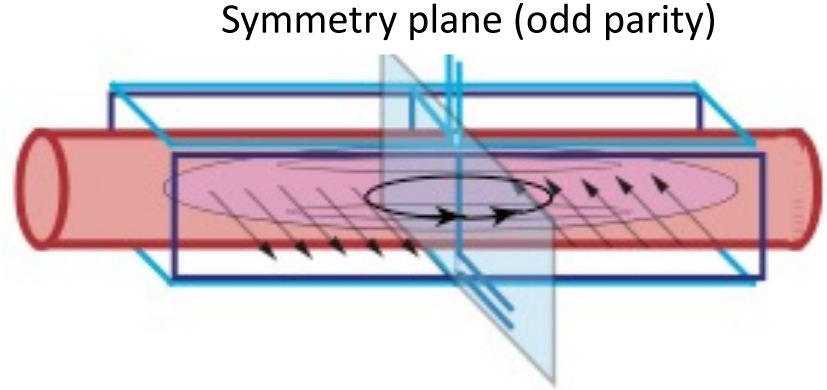
The heating method determines an FRC's physical size

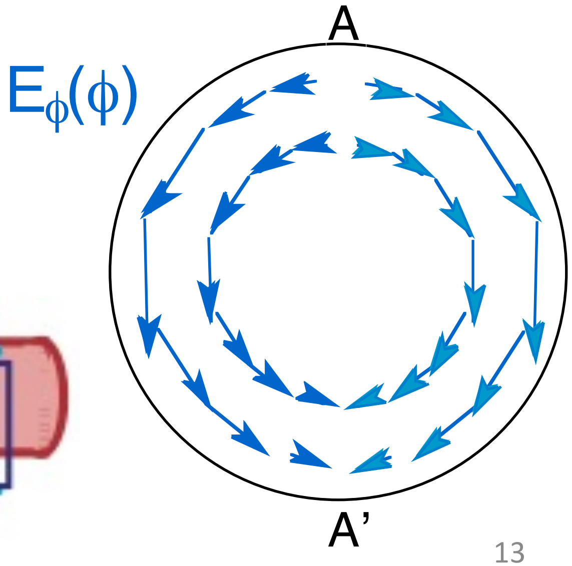
- Compressional heating requires high powers and energy proportional to the volume. **Small**
- Beam heating requires large dense plasmas to "stop the beam." **Large**
- RF heating requires machine size comparable to or exceeding the wavelength. **Medium**

The E field is what gives energy and momentum to charged particles. RMF heating provides that E.

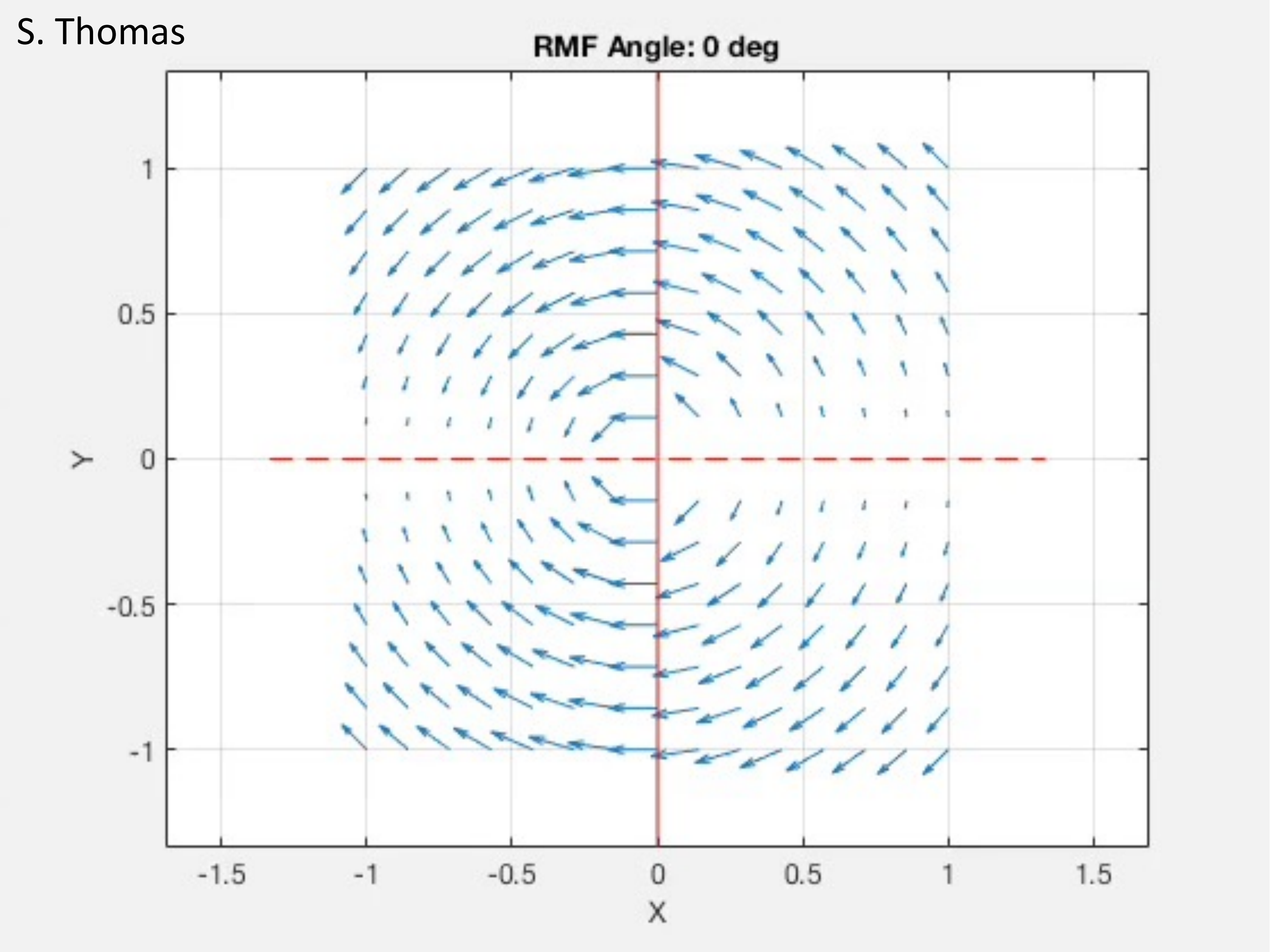
$$\nabla x E = -\partial B_{RMF}/\partial t$$

$$E \sim \omega r B_{RMF}$$





The midplane E-field *vs* time (RMF$_o$)

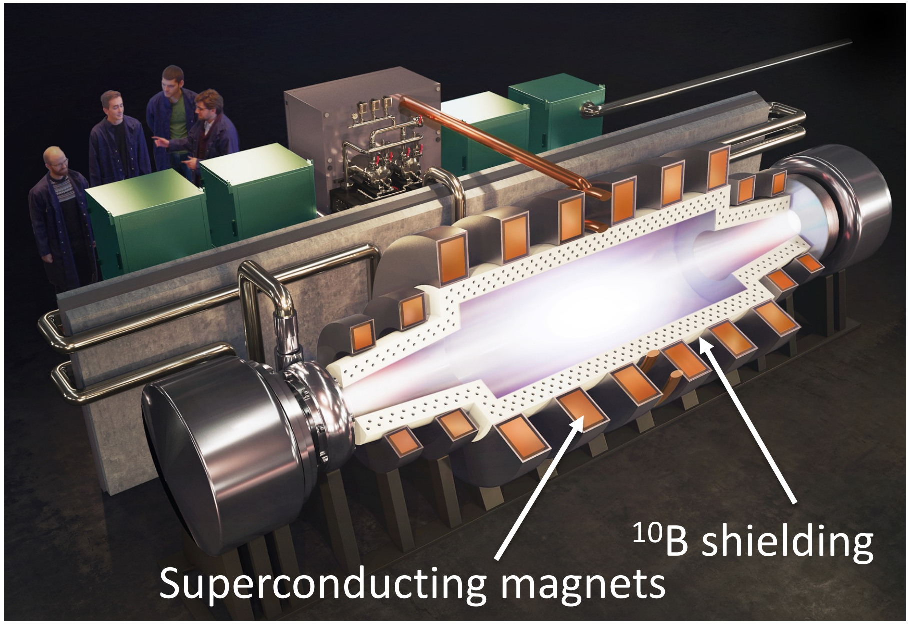


If B present: ExB drift

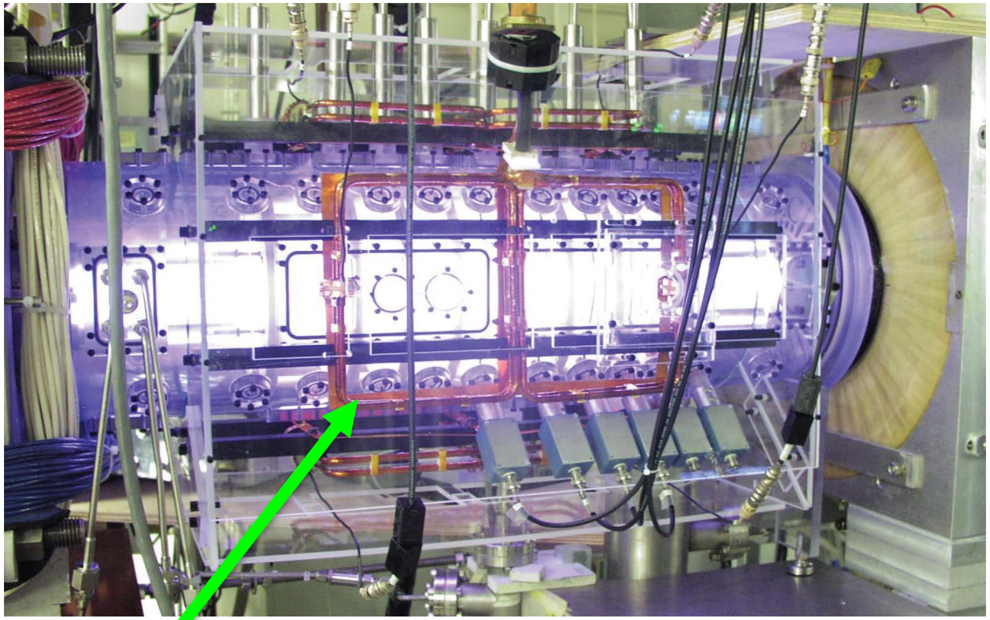
If no B: || acceleration

The Princeton Field-Reversed Configuration

RMF$_o$ heating of medium-sized D-He^3 fueled FRCs



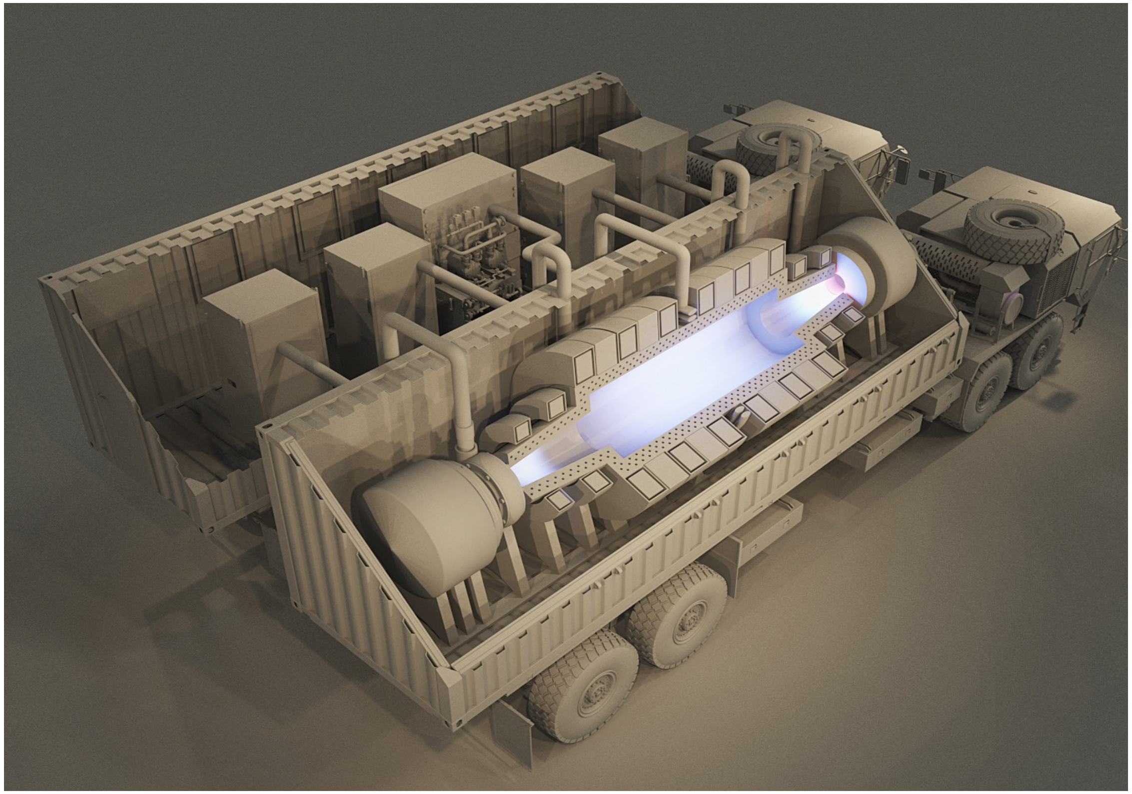
PFRC-type power plant
Conceptual design: PFRC-4



PFRC-2 in operation

Odd-parity RMF antenna

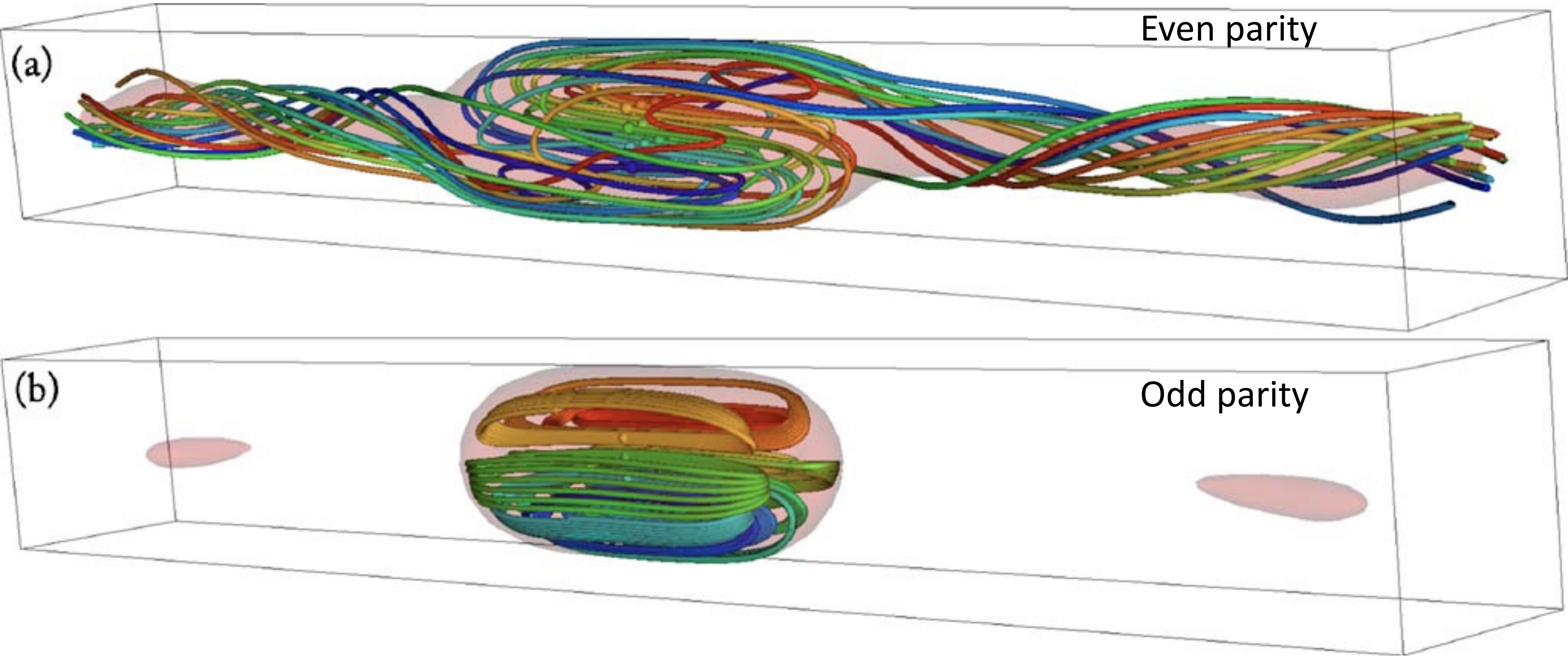
PFRC physics questions



1. Confinement
2. Electron heating
3. Current drive
4. Ion heating
5. Stability
6. Fuel sources
7. Ash (esp. T) extraction
8. FRC formation

How these determine design and applications

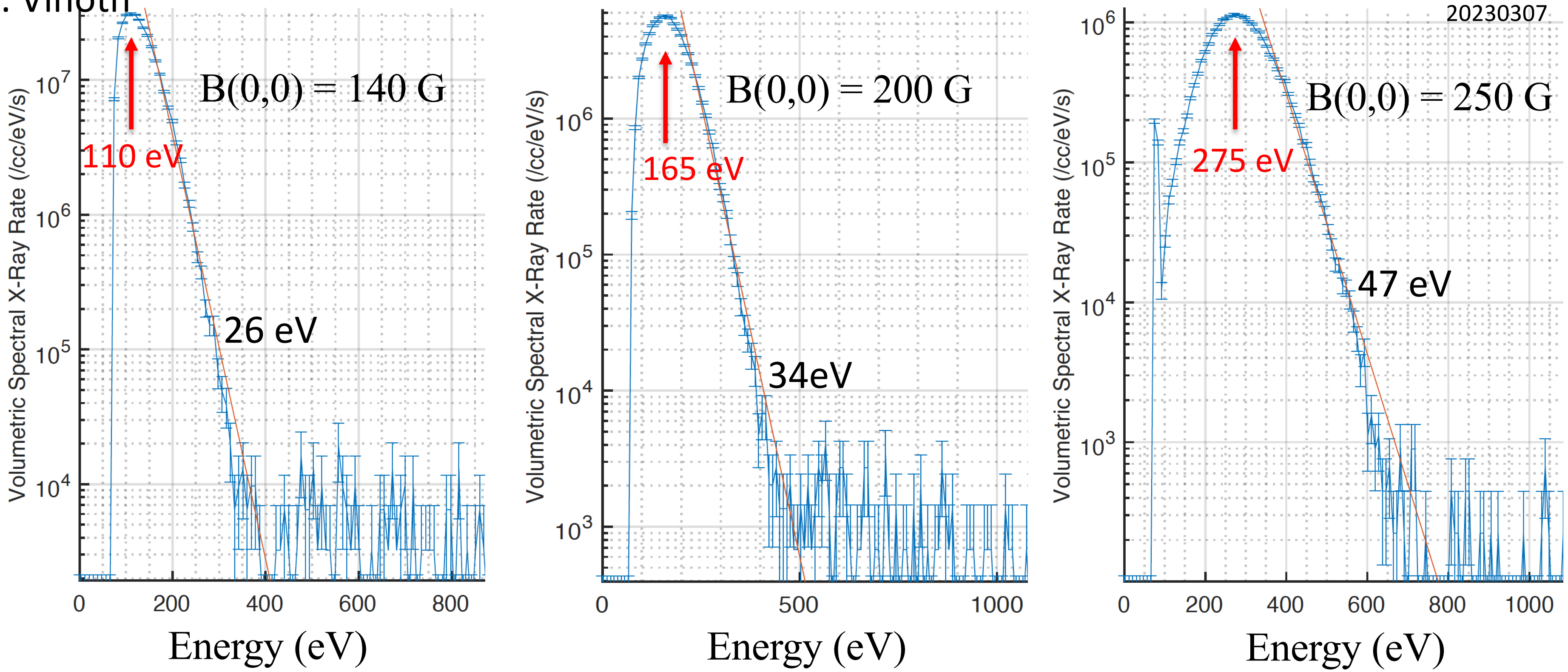
1. Confinement: MHD calculations show closed field lines only for odd parity



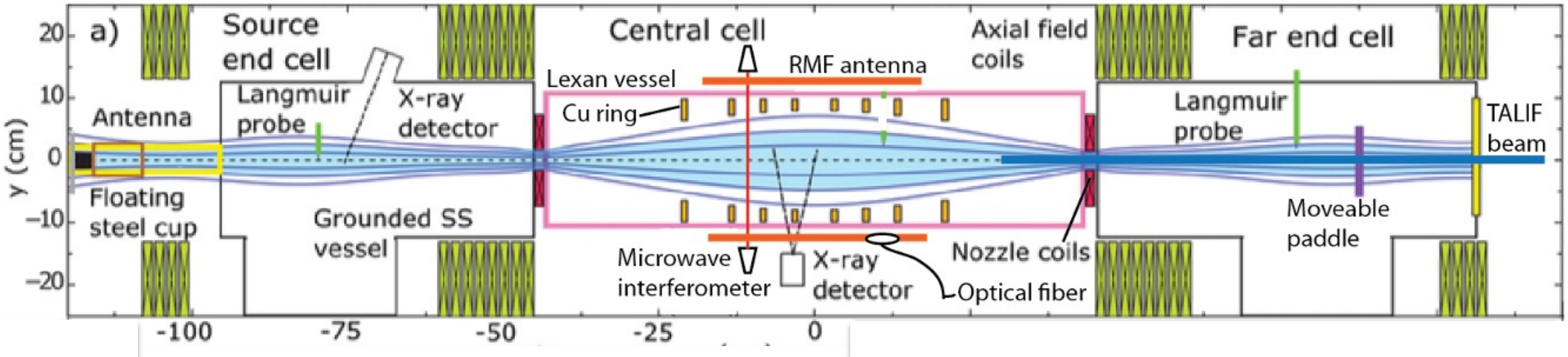
R. D. Milroy, C. C. Kim, and C. R. Sovinec, PoP 2010

Measured PFRC-2 core plasma EED$_e$

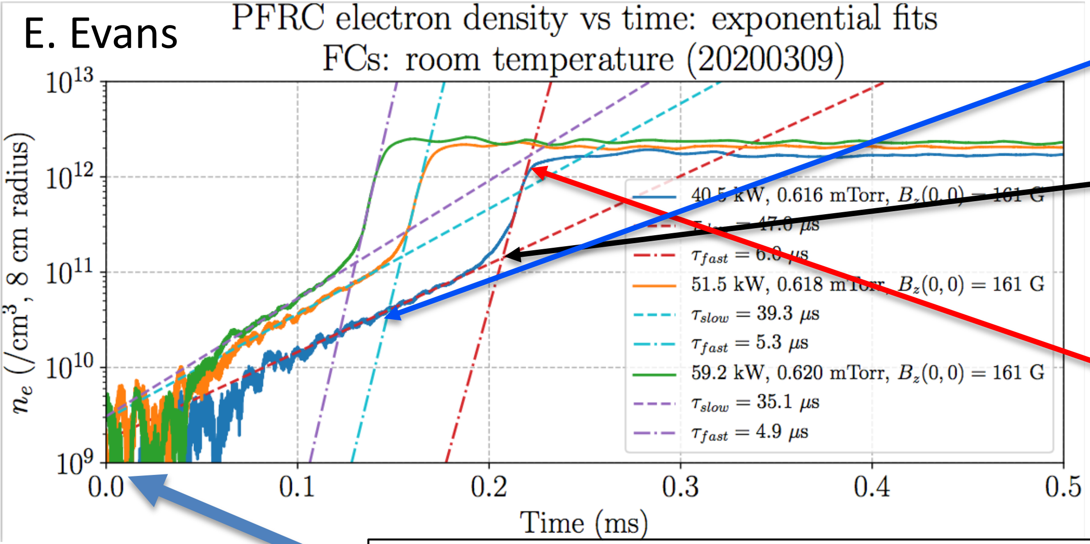
S. Vinoth



Ar fill gas, p_{cc}~ 0.25 mT, P_a~ 27 kW, 4 ms pulses, 4.3 MHz, n_e~ 7 x 10^{12} cm^{-3}



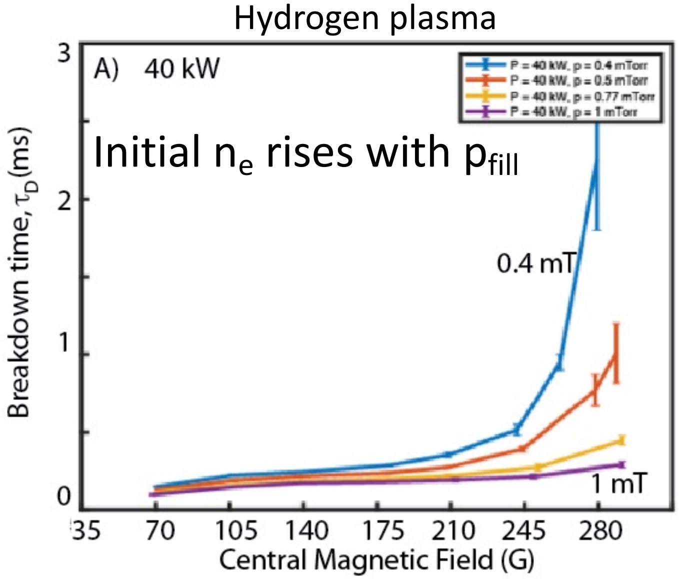
FRC formation in PFRC-2: Low T_e


E. Evans

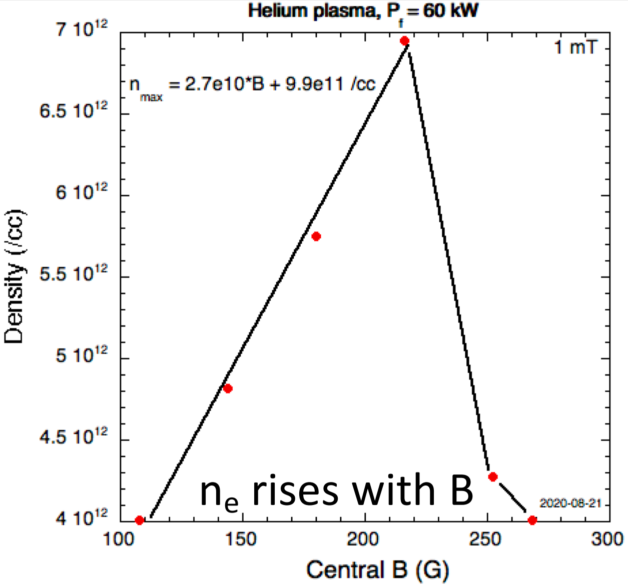
Model

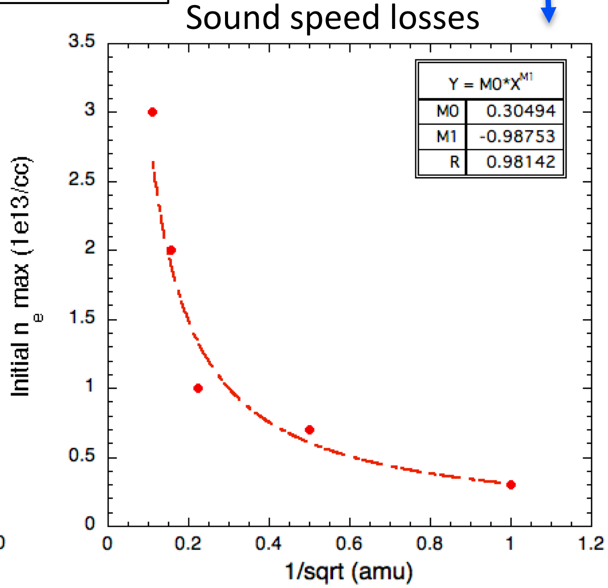
- Slow rise (τ_s) due to ionization (5-7 eV) and limited by axial losses.
- Fast rise begins (τ_D) when $\beta \sim 0.02$, heating and confinement improves.
- Fast rise (τ_f) ends at $\beta \sim 0.5$. ($T_e > 50$ eV.)

Seed plasma ~ 5e9/cc, T_e ~ 5 eV, $E_{\text{minority (0.1\%)}}$ ~ 500 eV


Hydrogen plasma

Initial n_e rises with p_{fill}


n_e rises with B


Sound speed losses

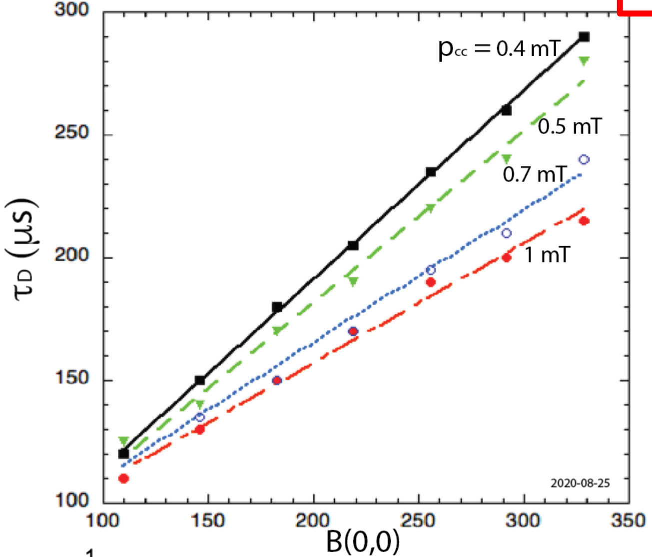
(Assumes 8 cm plasma radius & flat density profile)

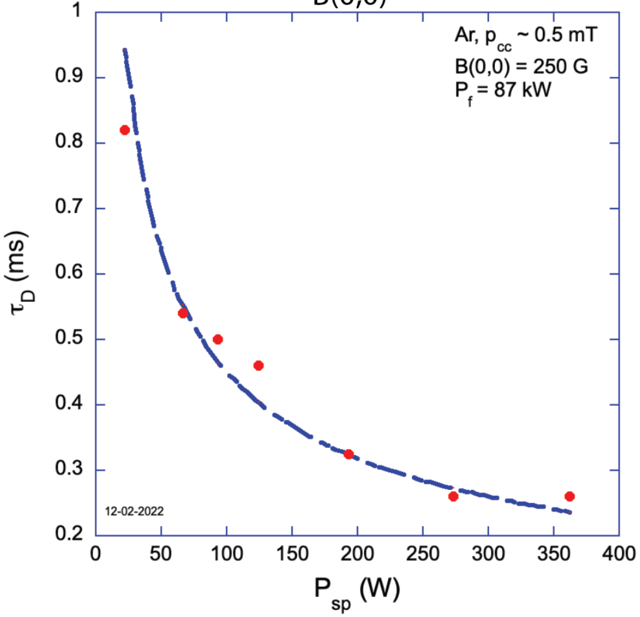
FRC formation in PFRC-2: (con't)

Is the transition

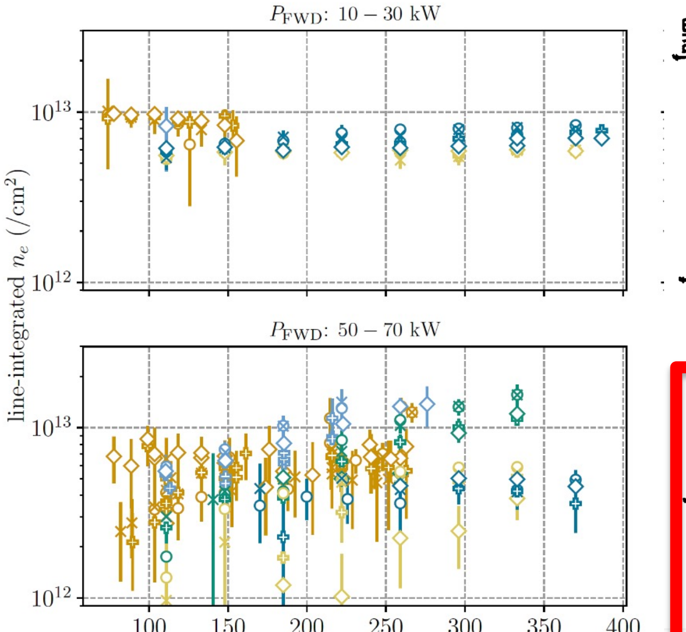
E to H mode?

It does not appear so.

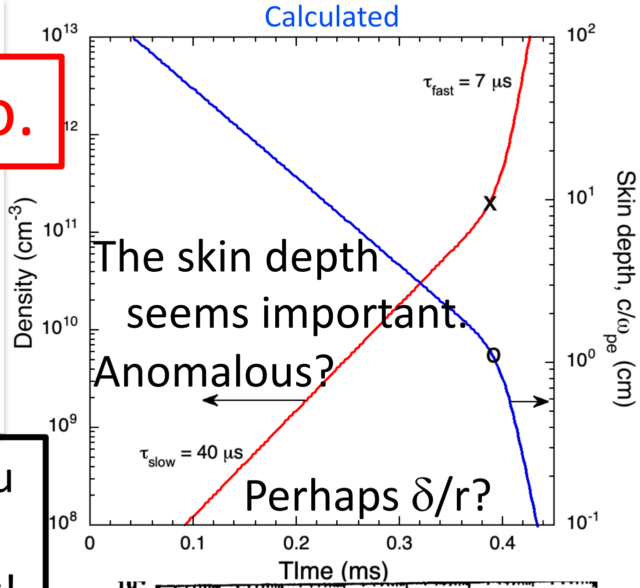




τ_D changes with P_a, B, P_{sp}, amu BUT n_{trans} does not.
The transition is not a β effect!

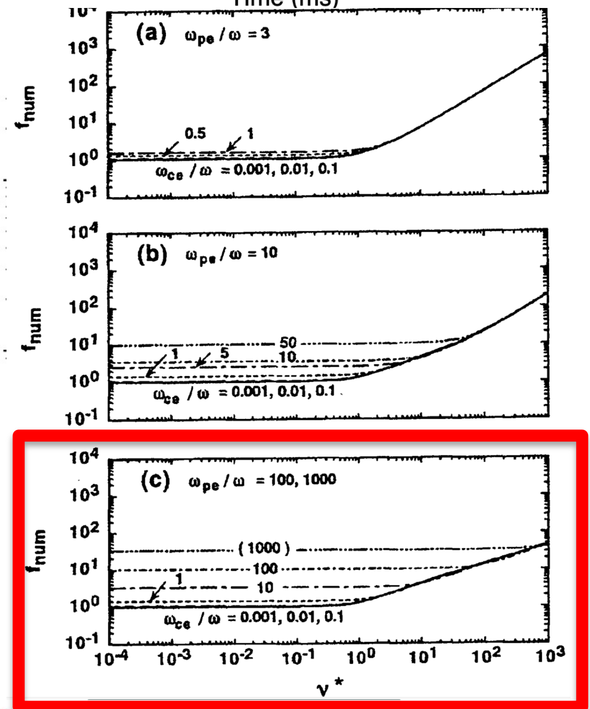


E. Evans



The skin depth seems important. Anomalous?

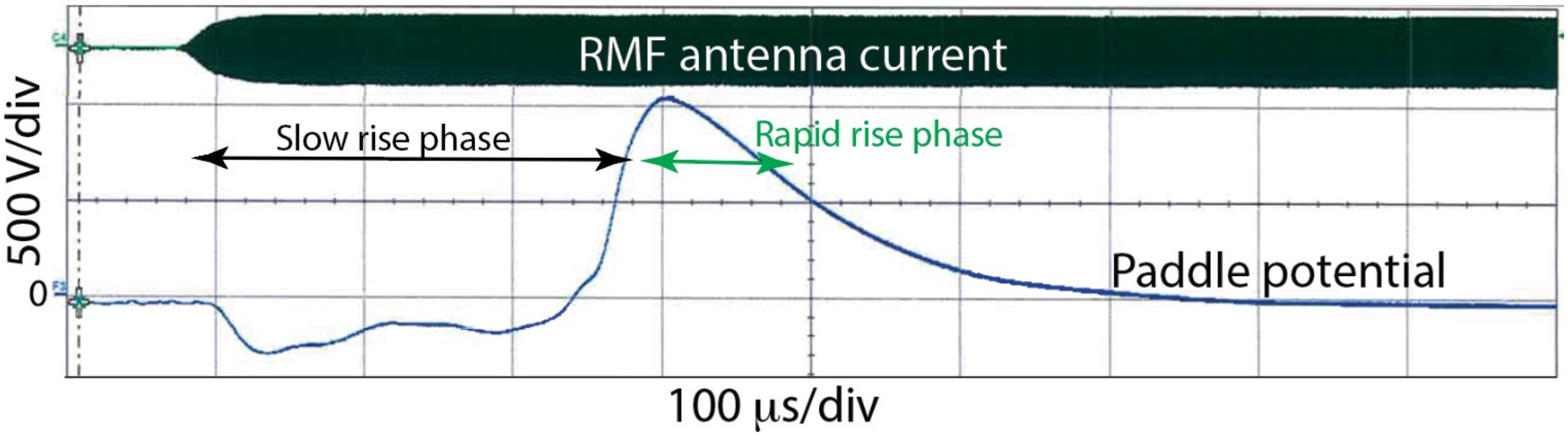
Perhaps δ/r?

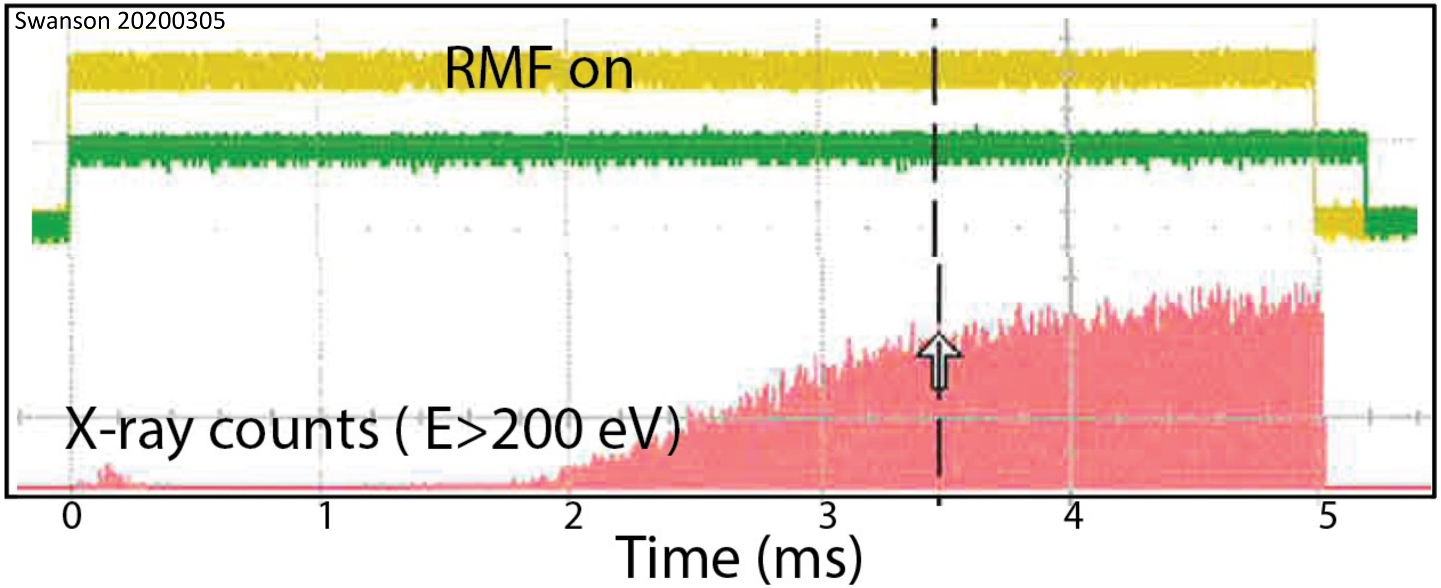


Shinohara (1996)

FRC formation in PFRC-2: (con't)

Does the fast electron population in the seed plasma play a role in densification?




Swanson 20200305

NO

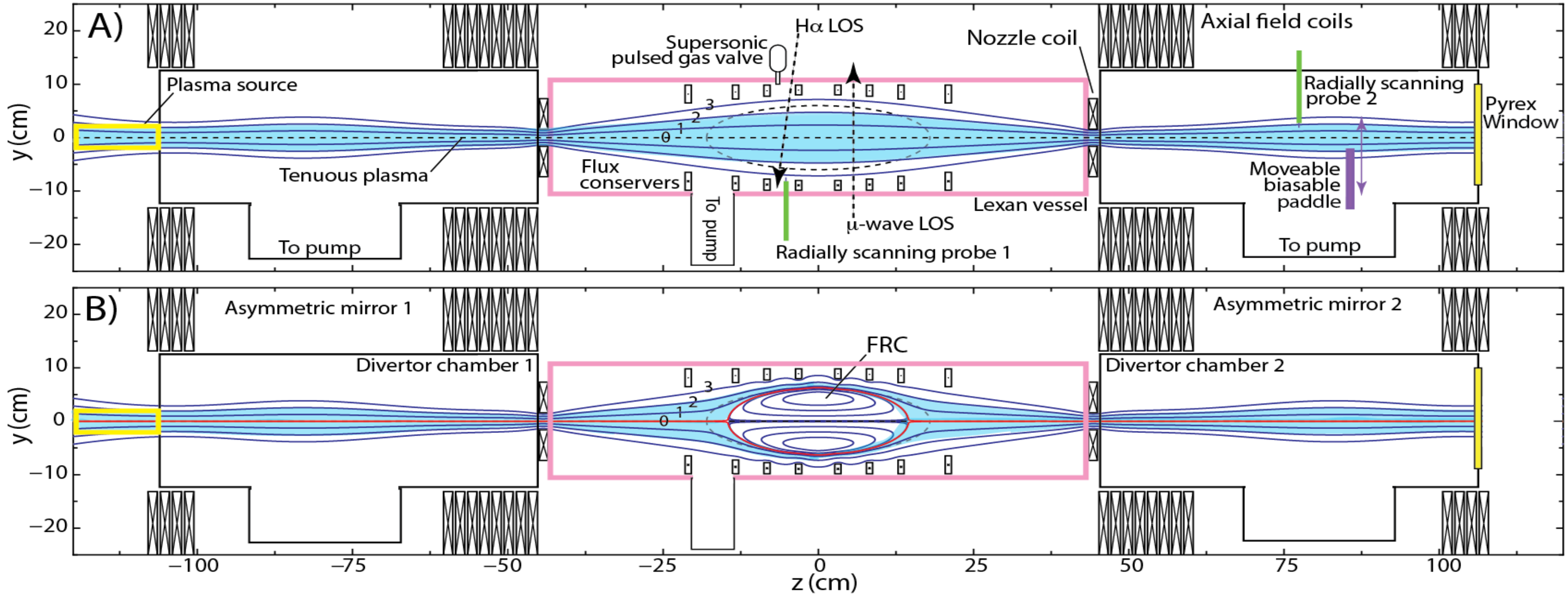
Stabilization methods for FRCs against low-frequency interchange modes

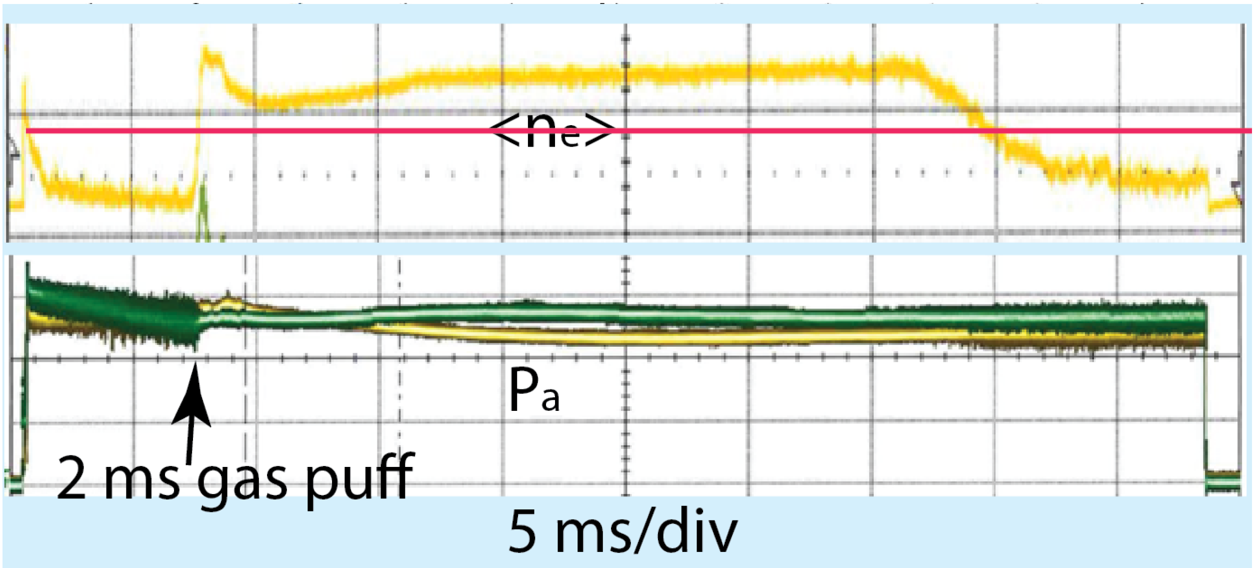
Demonstrated in experiments

1. RF: ponderomotive force
2. Biased rings/end plates: radial electric fields, E/B
3. Field-line tying & axial hole: δW
4. Kinetic: FLR, betatron orbits
5. Flows: rotation, axial flow
6. Spindle cusps in end cells: stability if $0 > \int {}^{dl}\!/_{B}$
7. Ioffe bars: min B (line cusps, central or end cell)
8. Gas puffing: momentum loss from ions?

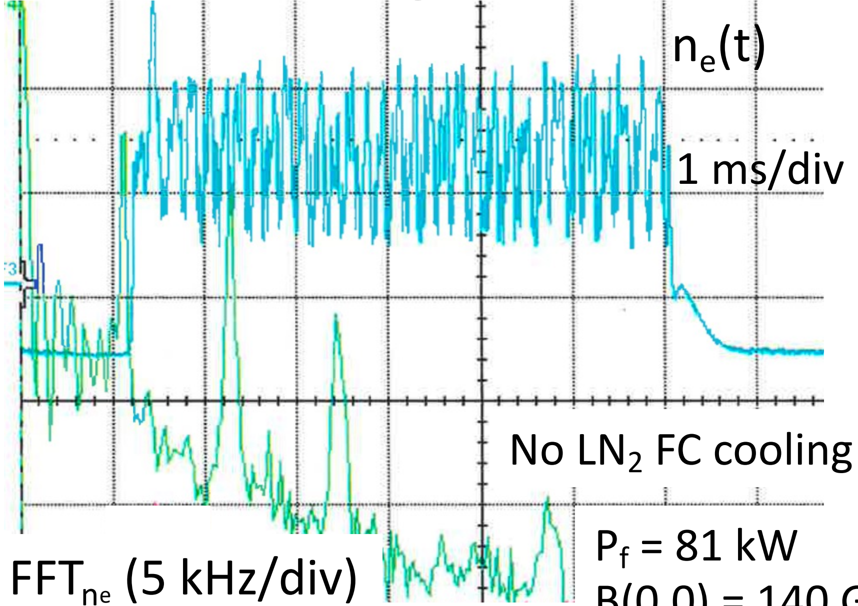
Evidence for stability (PFRC-2 device)

1st Goal: to close field lines, form a separatrix and improve confinement

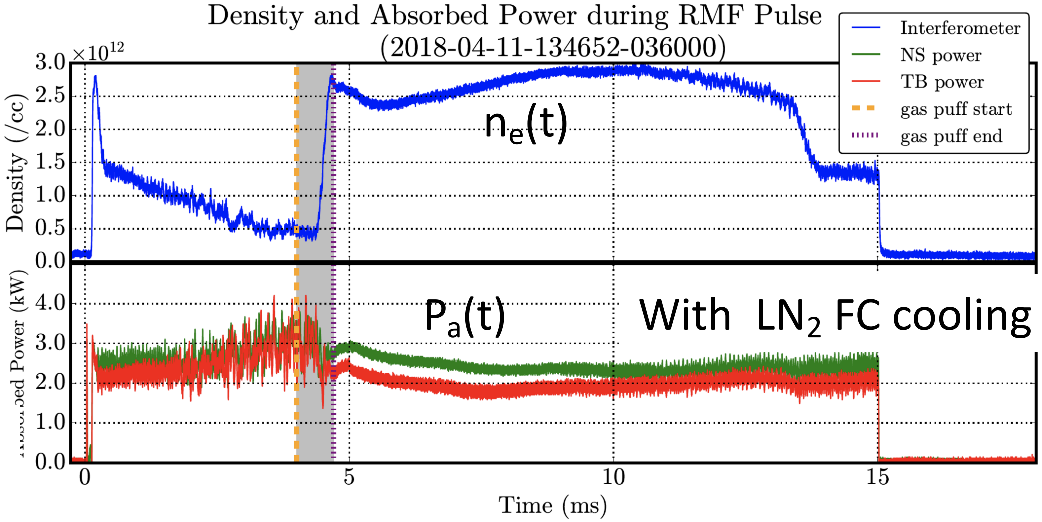




Interchange (in)stability: flutes



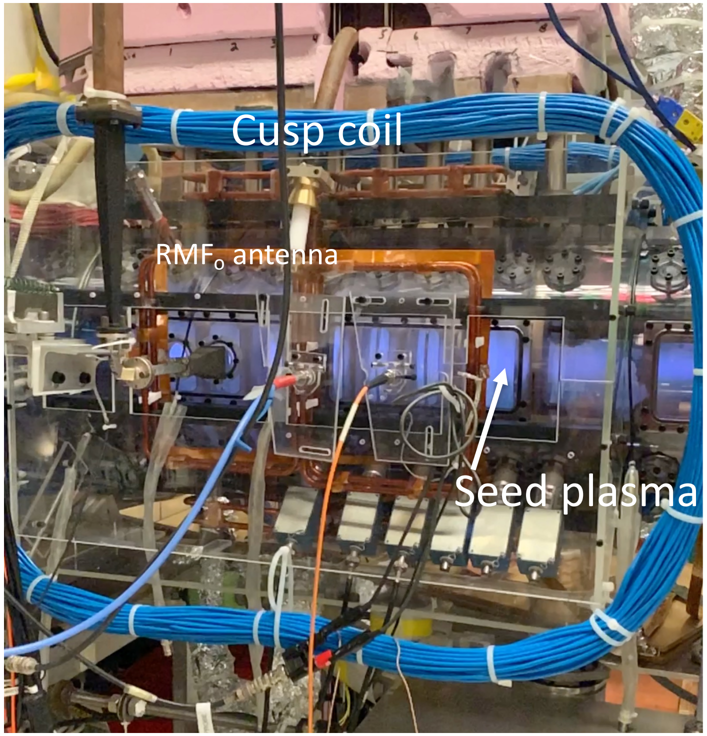
P_f = 81 kW
B(0,0) = 140 G)

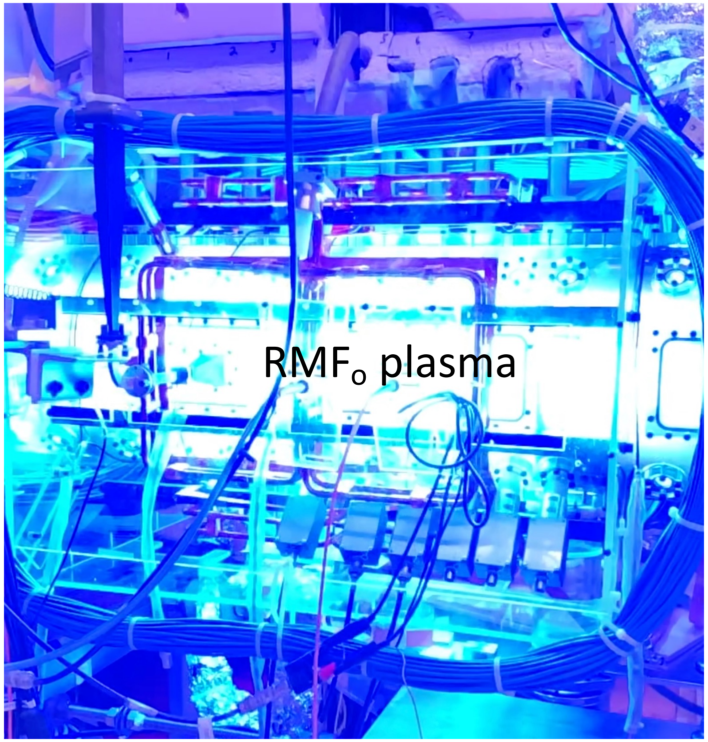


Stabilized by gas puffing

E. Ho

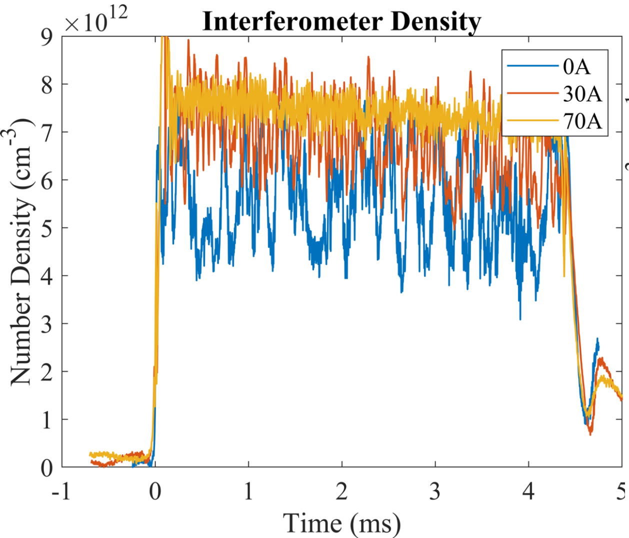
Interchange stabilization by adding cusp fields

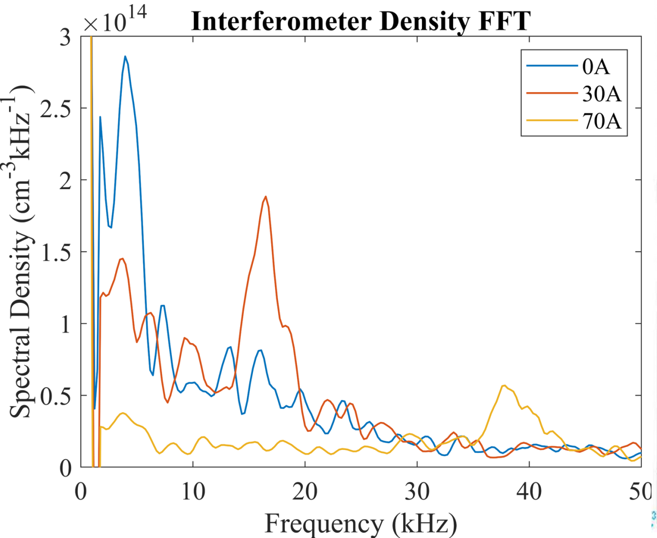


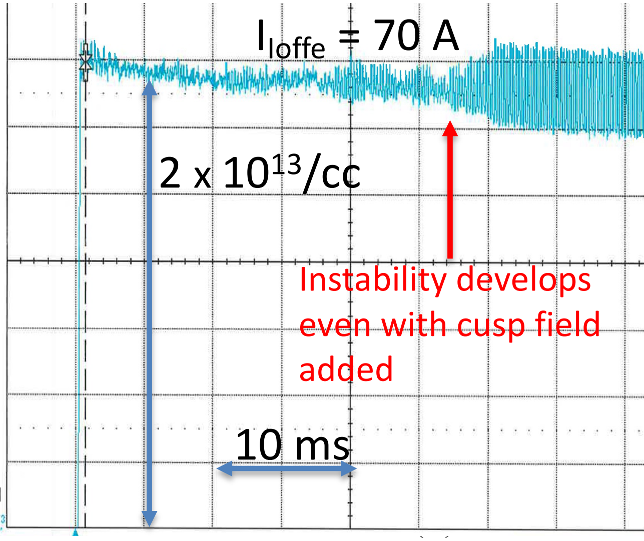


Ar plasma
4-50 ms pulses
f_{RMF} = 1.8 MHz
P_{RMF} = 92 kW
p_{cc} = 0.65 mT
B(0,0) =180 G

But in
50-ms discharges

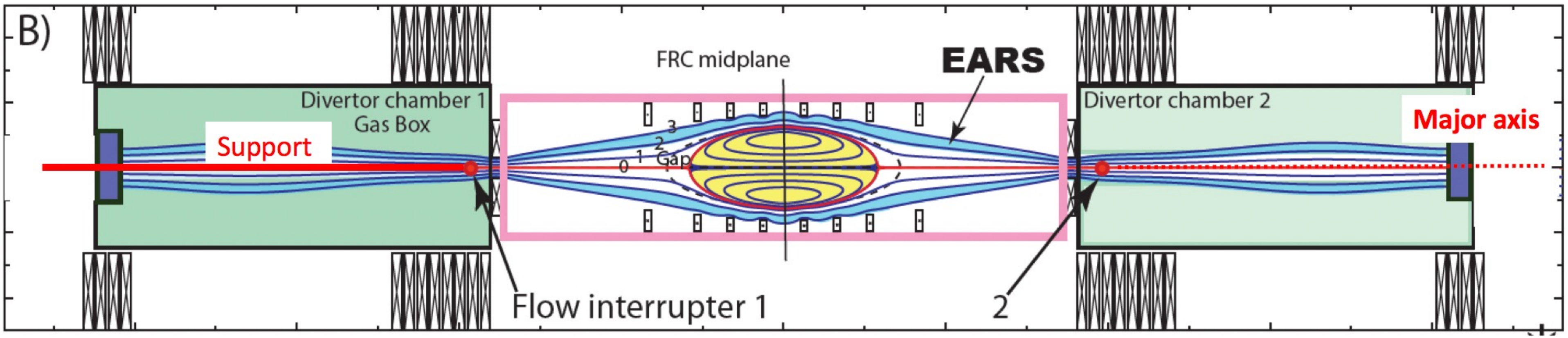


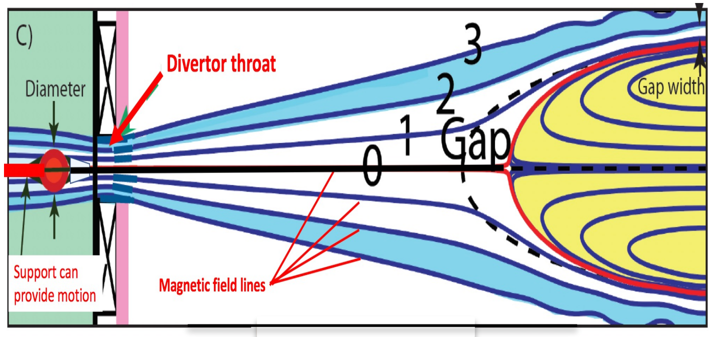


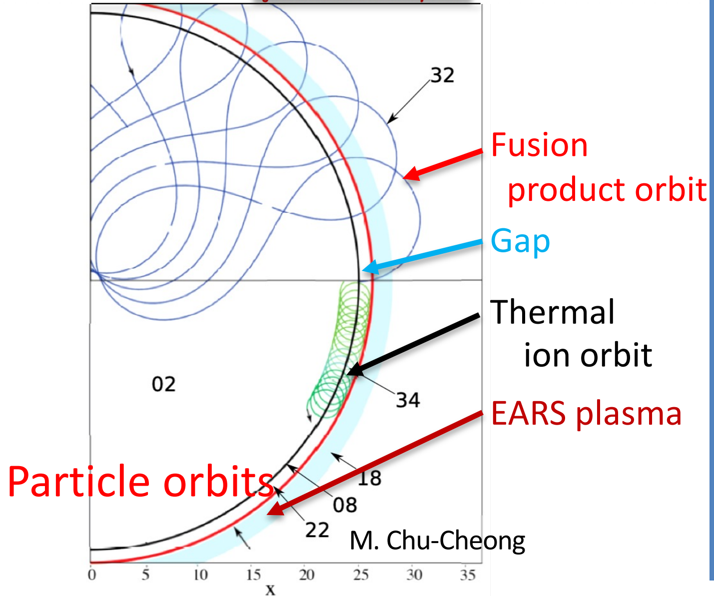


Instability develops even with cusp field added

Energy and Ash Removal Shell, Gap and *EARS*







M. Chu-Cheong

Need to reduce cross-separatrix (diffusive) heat flux.
Need to extract fusion products (ash).
Need to extract fusion energy.

Solution: energy transfer to **COLD** edge plasma, with a gap between open-field-line and closed-field-line plasmas.

The gap would be formed by “extruders” (flow interrupters) in the divertors.

Fusion ash would have large enough gyro-radii to reach the edge plasma, the EARS, but the thermal plasma would not.

Stability is a critical question.

Effect on energy confinement?

Mobile power sources

Civilian

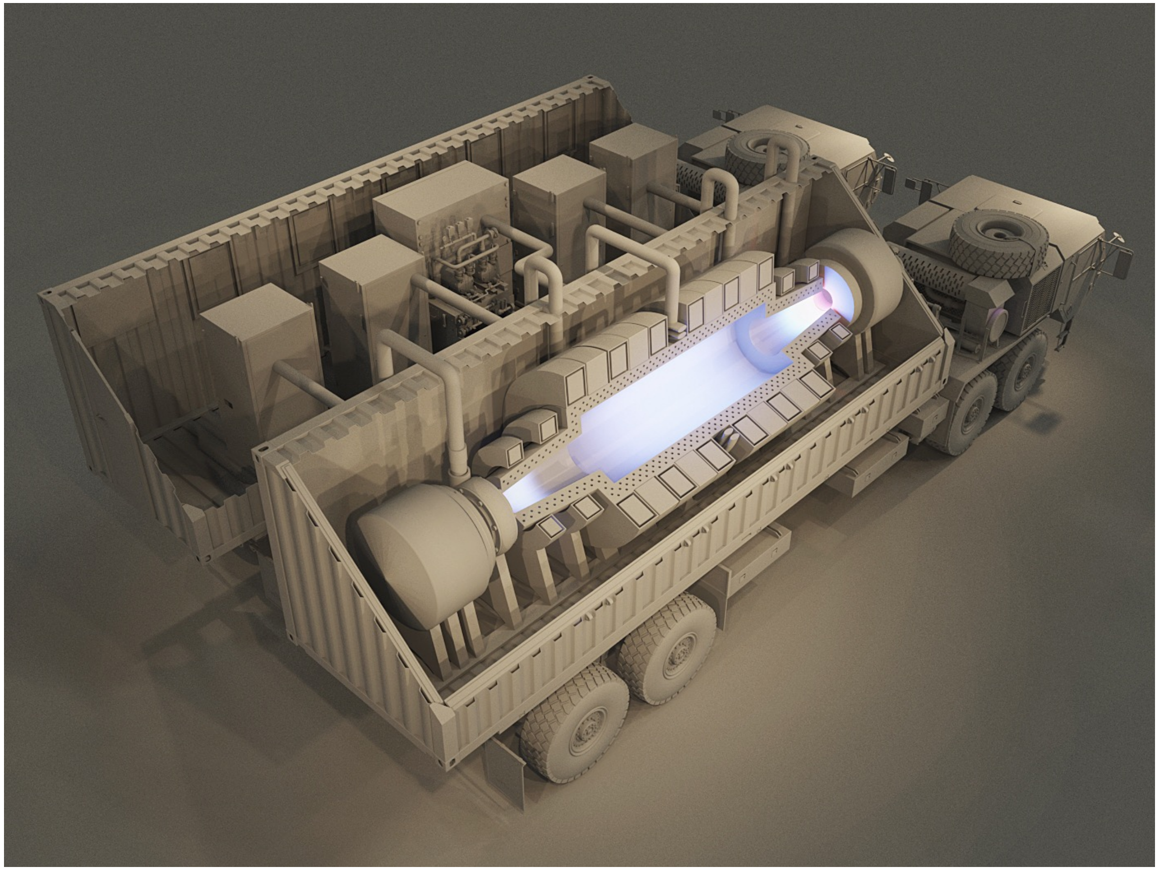
Natural disaster relief

Trains

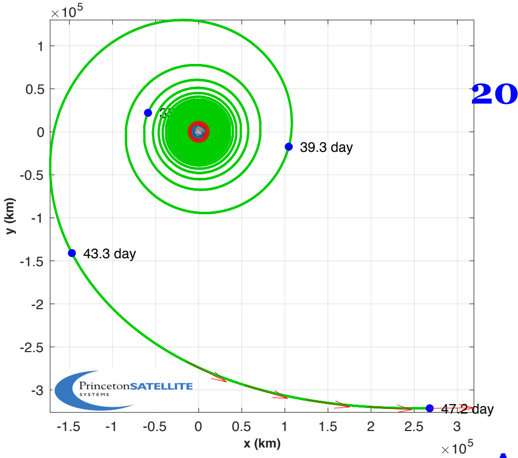
Temporary auxiliary power on slabs

Small remote communities

- Where transmission lines are not economical



Rocket propulsion & space communications



2011 – ALPHA CENTAURI MISSION

2012 – TUG FOR LARGE SPACE TELESCOPE

2013 – ASTEROID DEFLECTION

2013- JUPITER ICY MOONS

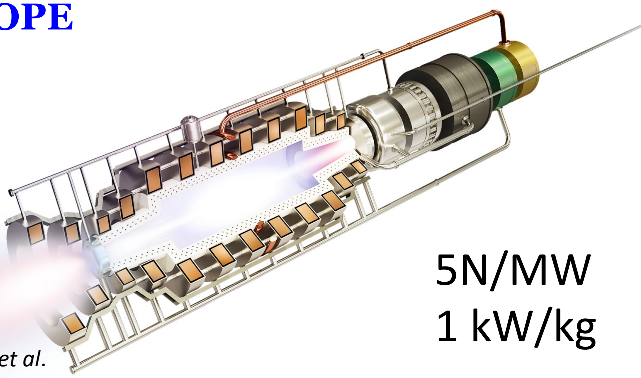
2014 – MANNED MISSION TO MARS

2015 – LUNAR SETTLEMENT

2015 – PLUTO ORBITER/LANDER

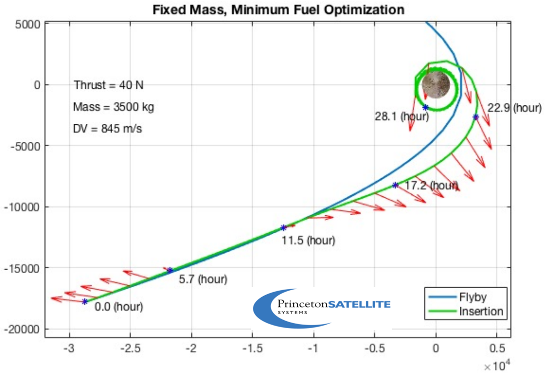
2016 – PLANETARY DEFENSE

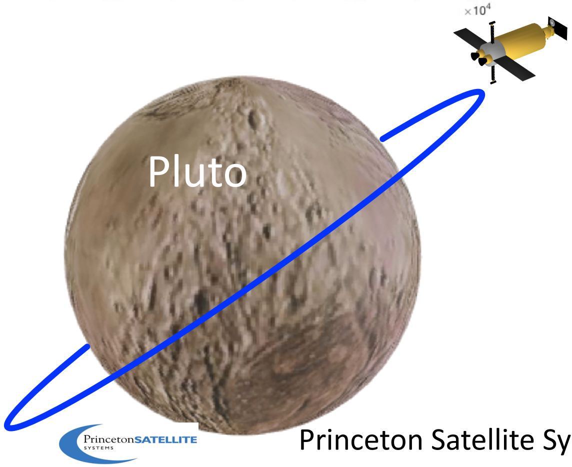
2017 – 550 AU: GRAVITATIONAL LENS STUDY OF EXOPLANETS



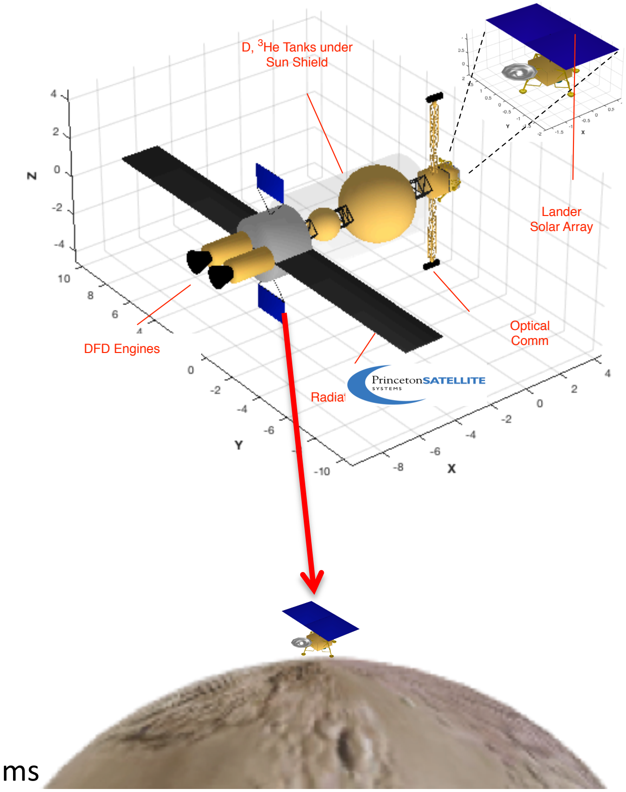
Wurden *et al.*

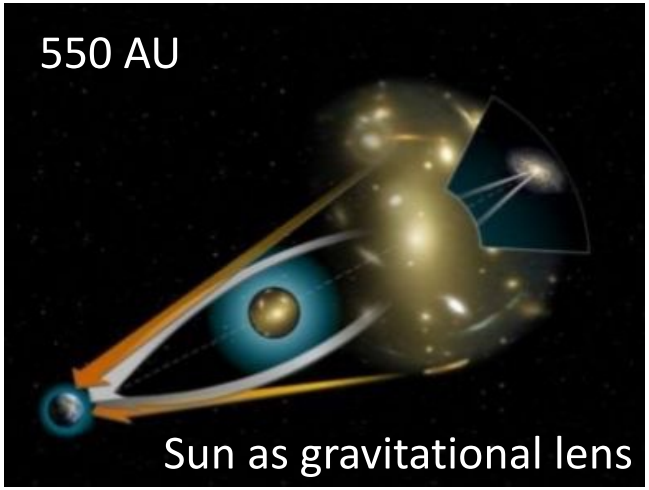
5N/MW
1 kW/kg





Princeton Satellite Systems



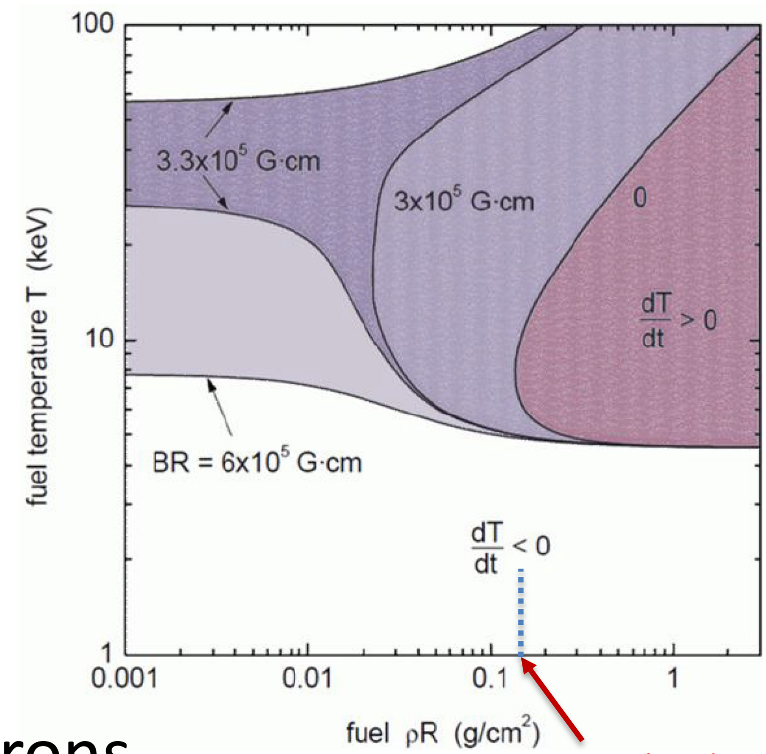


Summary

- PFRC-2: $\bar{E}_e$ to 300 eV; n_e to 5e13 /cc; duration to 300 ms
- B$-level of support comes from VCs: TAE and Helion
- Previous asserted problems are **myths** or being **addressed**.
  - Tilt instability, ^{3}He scarcity, transport, Low Q.
- FRC database: Excellent science opportunities
- Experimental data approaching fusion-relevant n and T.
- Need for fully kinetic analyses.
  - Stability, ash removal, the gap, antenna design, current drive, ……
- PFRC-type reactors would be clean, 1-10 MW, and compact.
- Applications abound.
- Source of ^{3}He is essential for wide-spread use.
- China is entering the arena in a big way.

Back-up slides

Helion Energy: Fusion driven rocket



Density liquid D_2 for R = 1 cm

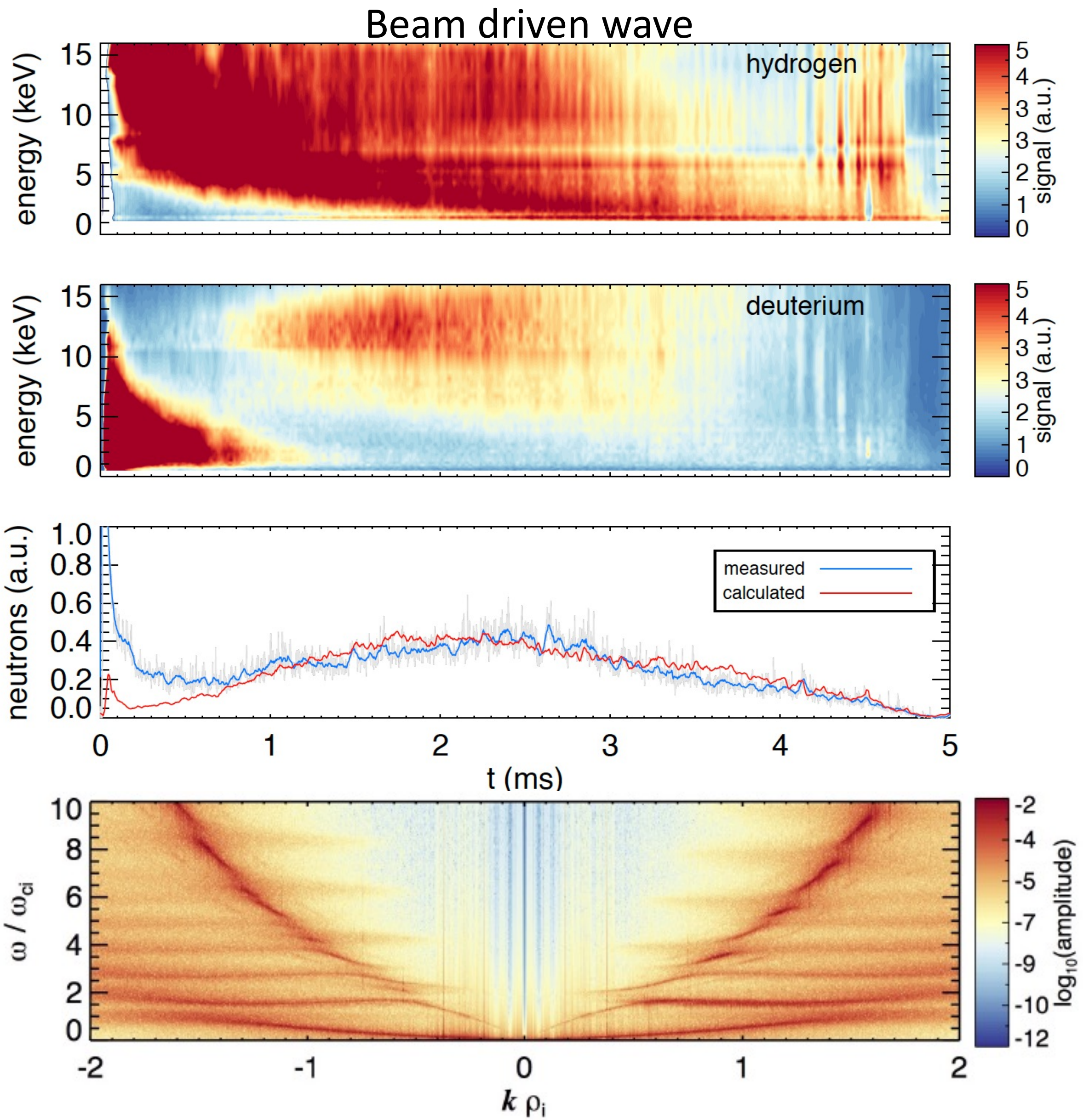
Science questions

- Fully 3-D compression/merging
- Stability (s = 200, $\tau_A < 10^{-8}$ s)
- Li liner dynamics(if used)
- Burn fraction, liner dwell time
- Q with D-D(+^{3}He+T) burning

Technical questions

- Shielding from D-T and D-D neutrons
- Rep rate, efficiency, & lifetime of pulsed driver coils
- Energy recovery efficiency of coils
- Fuel utilization efficiency

TAE: H^o beam injected into C2-U D^+ plasma



Fast particles generate waves, enhance neutron production: First experimental support for hybrid of thermonuclear fusion and beam-plasma fusion (Kolmes, Ochs & Fisch)

Confinement: transport losses

Effects of fluctuations

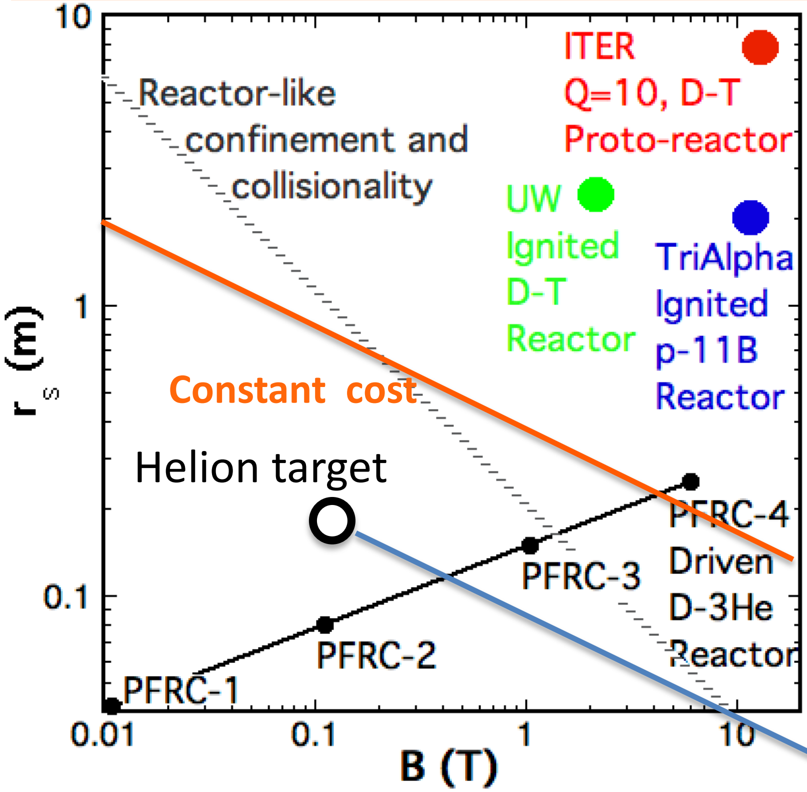
- Unimportant for $\rho_i >> L_{turb} < r_s/5$, i.e., orbits average over the electric fields of the turbulence.*
- As first seen in tokamaks, much better confinement for high energy particles which have $\rho >> L_{turb}$
- Betatron orbits feel force towards midplane; opposite for cyclotron orbits
- LHDI predicted stable when $(v_{th,i})^2/ (v_{\nabla pe}\, v_{\omega r}) > 1$ (~ 10^4 in PFRC-type reactor)

Classical *vs* neoclassical: $\tau \sim 1/(1+q^2)$

- $\tau_i \sim (r_s/\rho_i)^2/\nu_{ie}$ but maybe ρ_e!!
- $1/\nu_{ie}$ momentum transfer time
- Rostoker loss cone does not exist
- Axis-encircling loss cone does exist – but strong mirror forces
- Weighting of which particles transfer momentum ~ 1/7 of density
- Gap/EARS, electrostatic

*N. Rostoker and A. Qerushi (2003)

Path to a fusion reactor: 1. confinement



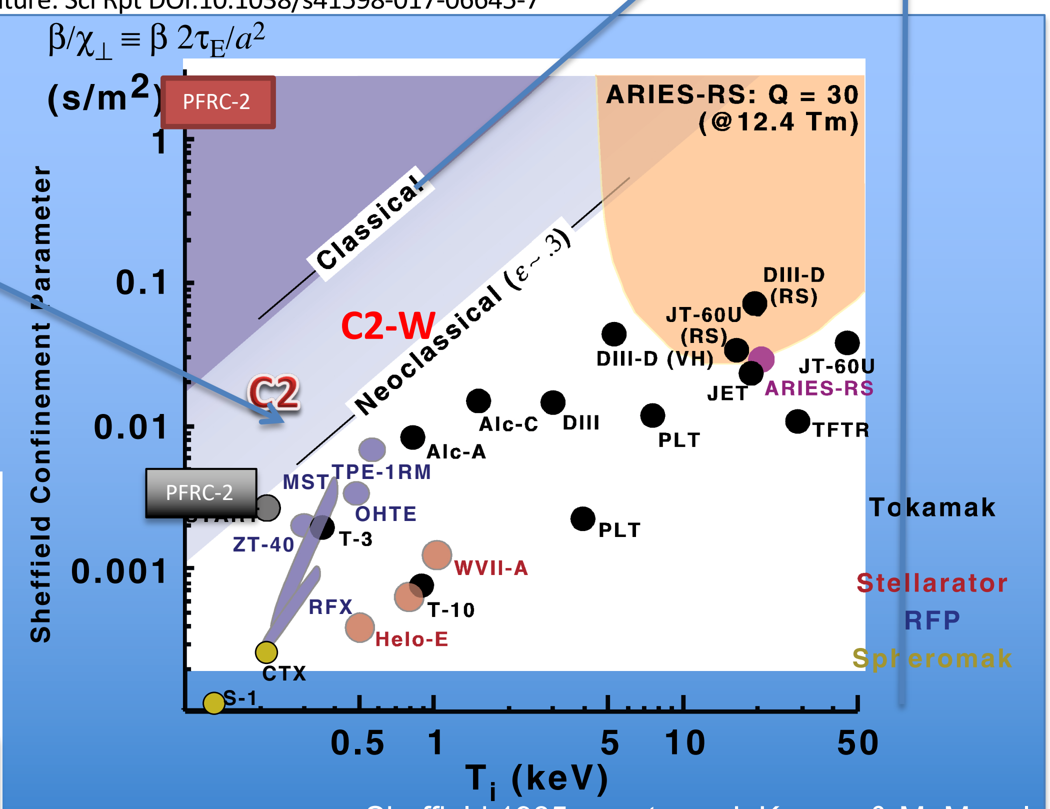
$$$$ ~ $r_s^3 \times B^2$

$\tau_{E,\text{PFRC-4}} \sim 1$ s

PFRC-4

$\tau \sim (1+q^2)^{-1}$

Nature: Sci Rpt DOI:10.1038/s41598-017-06645-7



Sheffield 1985, courtesy: J. Kesner & M. Mauel

2 CRITICAL parameters

β **and** χ

$\beta \sim 8\pi nT/B^2$

$\chi \sim$ thermal conductivity

$$nT=B^2\beta$$

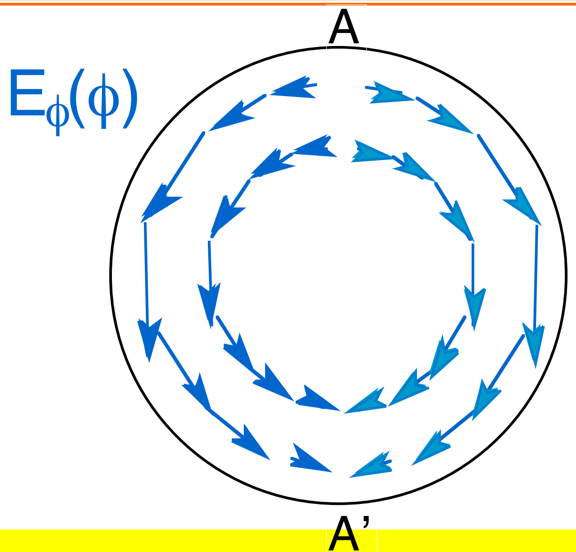
$$\tau=a^2/\chi$$

$$n\tau T=\overset{\text{Rich}}{\boxed{B^2a^2}}\overset{\text{Smart}}{\boxed{\beta/\chi}}$$

Aside: Why RMF$_o$? The basics

Predicted to

1. Improve τ_E
2. Maintain stability
3. Cause ion heating
4. Cause electron heating
5. Generate current needed to sustain the FRC
6. Provide a means for direct energy extraction
7. Smaller machine than beam heated



An odd-parity rotating *magnetic* field creates a rotating *electric* field on the midplane.

Occam's razor

The simplest solution, fewest assumptions, is usually the best one.

PFRC Program plan and philosophy

- Commercially available materials and equipment

- Safe and reliable operations

- As did the fission program: ***niche markets***

- Distributed, not central station, power
  - No transmission lines
  - Less susceptibility to rolling black outs and service interruptions

- Slow entry into civilian-power marketplace

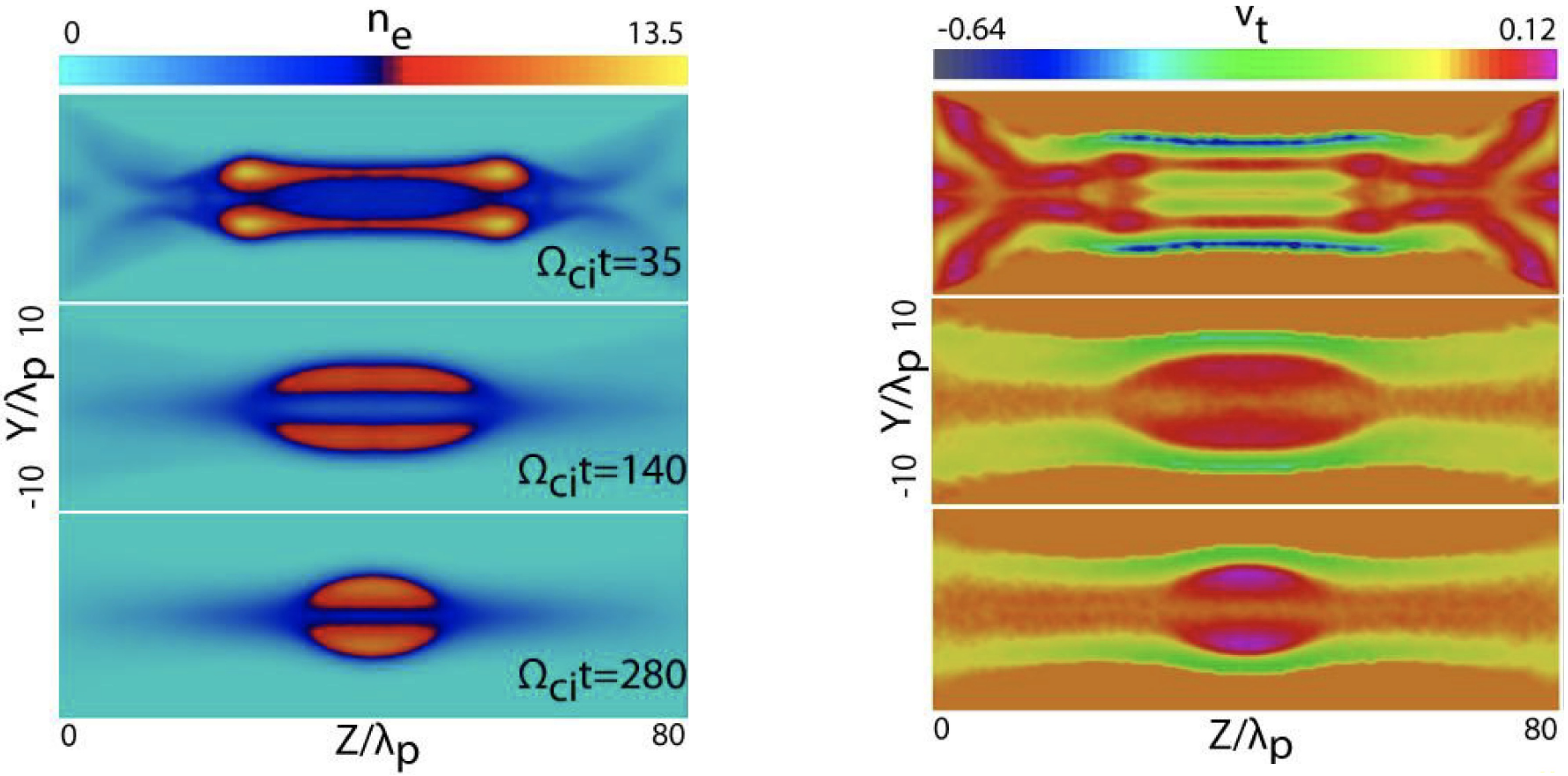
China's clean energy

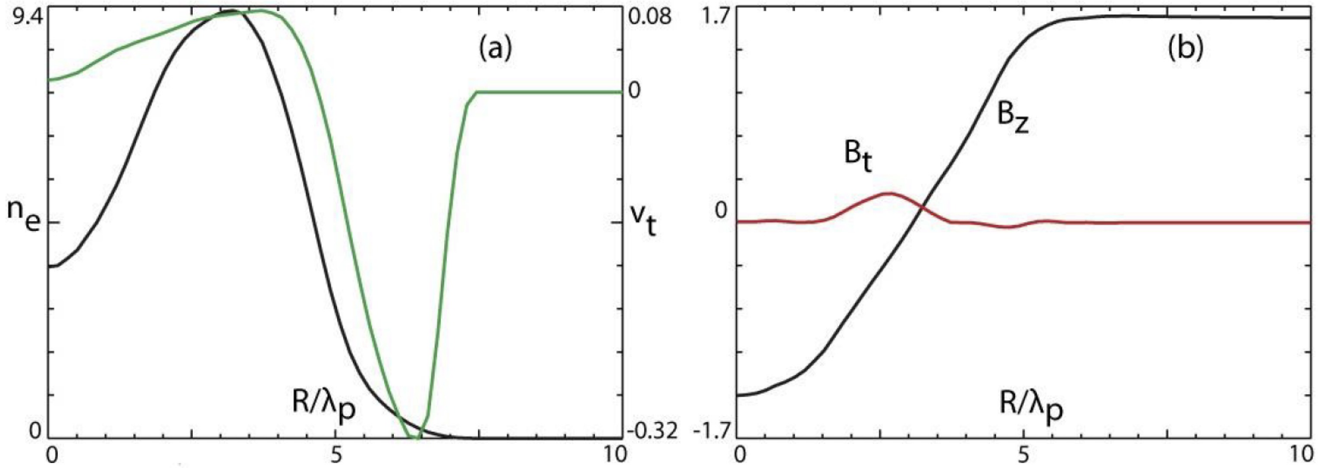
2016 Wind power: 149 GW; 240 TWh

2017 Solar power: 100 GW; 66 TWh

“Modern” FRC Theory: PIC and Hybrid codes

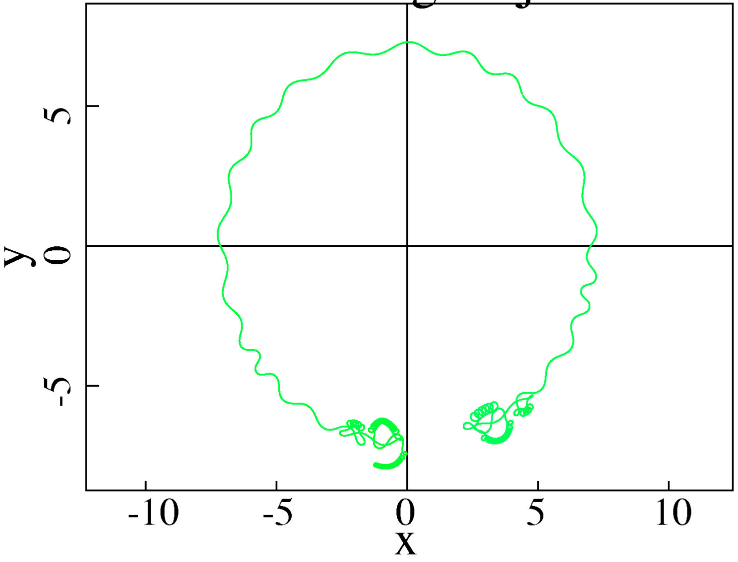
Stable FRC formation (3-D) by Θ-pinch method: Y. Omelchenko



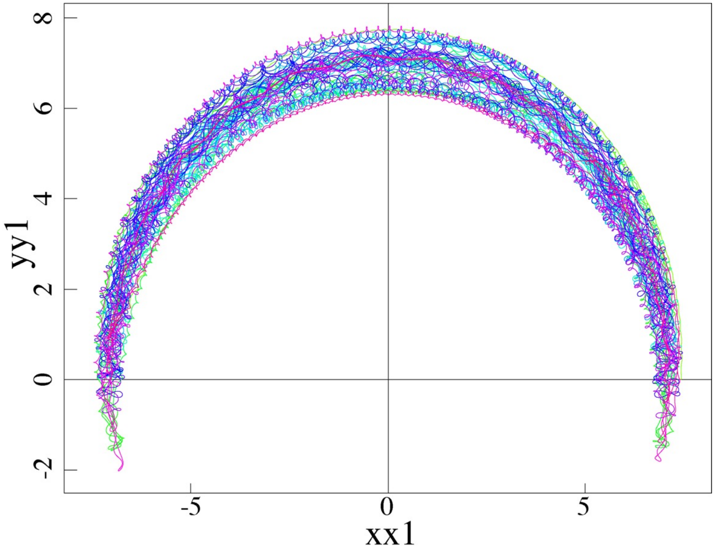


Prediction: RMF$_o$ heats electrons

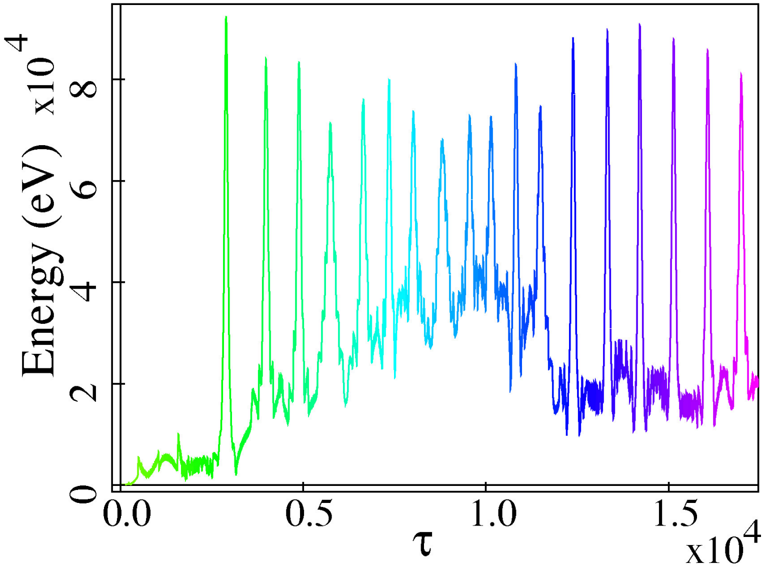
View along major axis



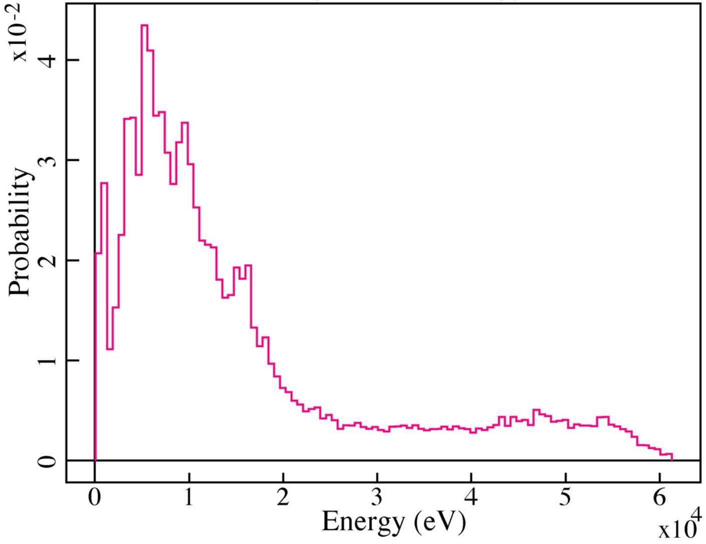
In rotating frame



$B_o = 20 kG$, $r_s = 10$ cm, $\omega_{RMF} = 0.5\ \omega_{ci}$

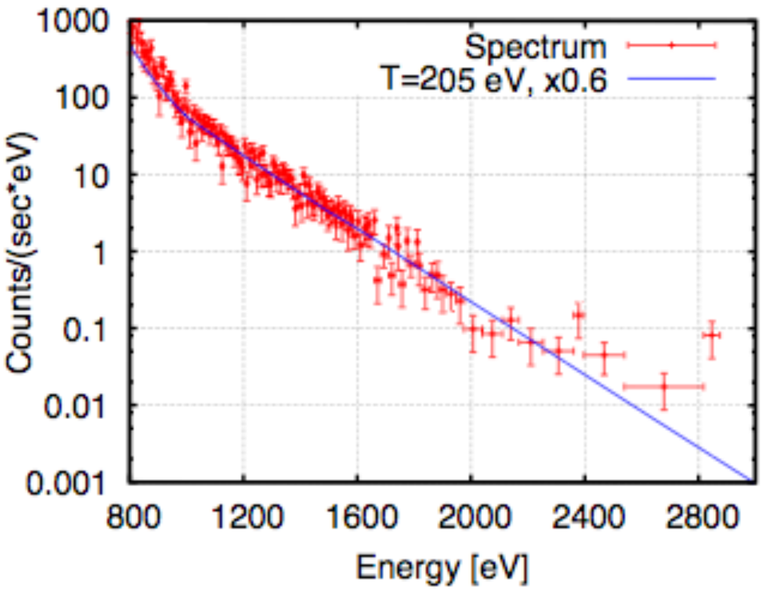


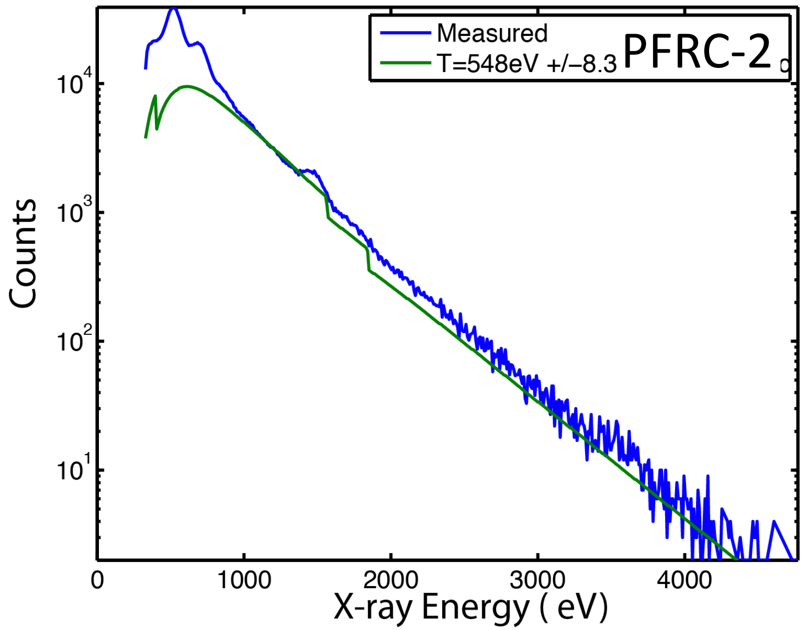
Histograms of Energy

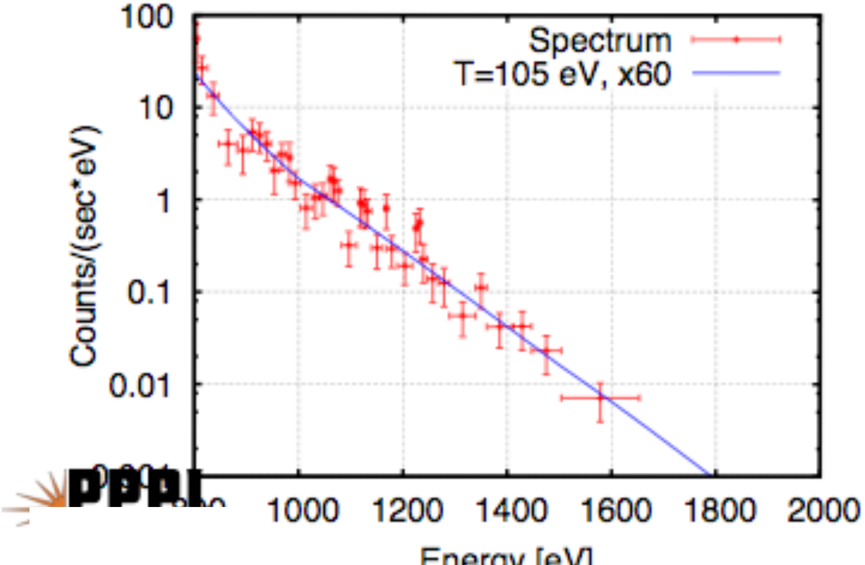


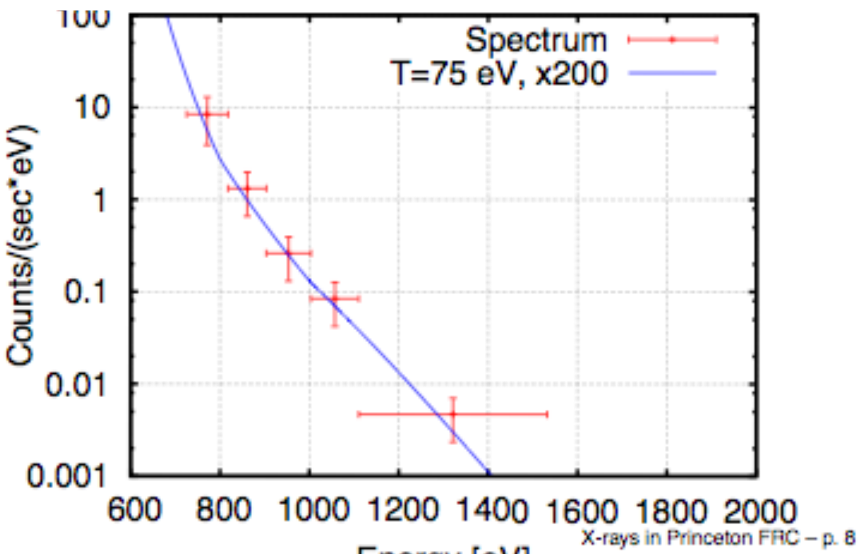
Glasser and Cohen (PoP 2001)

Experiment: higher T_e with RMF_o – PFRC-1

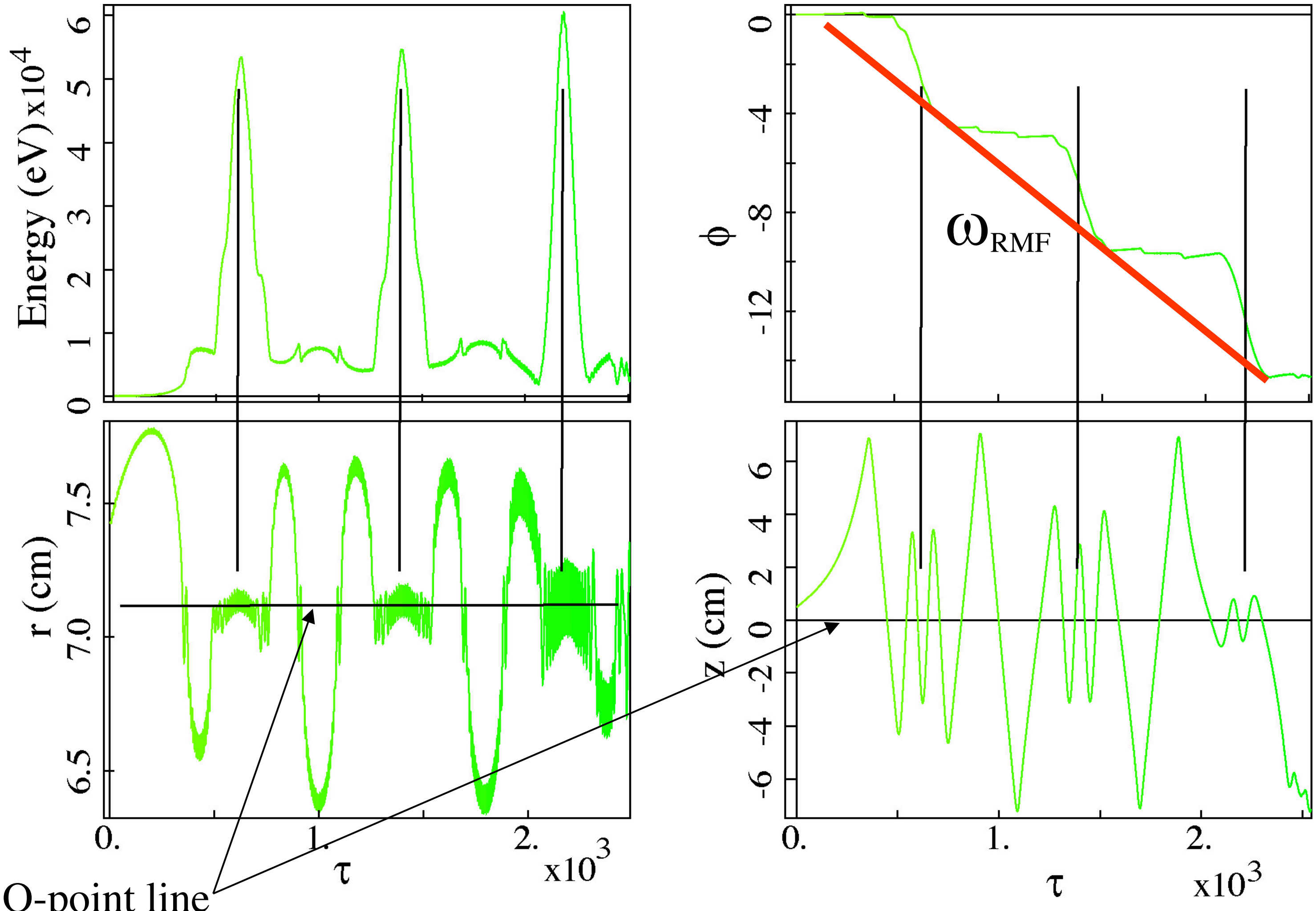








Prediction: 3. $\mathrm{RMF_o}$ drives current

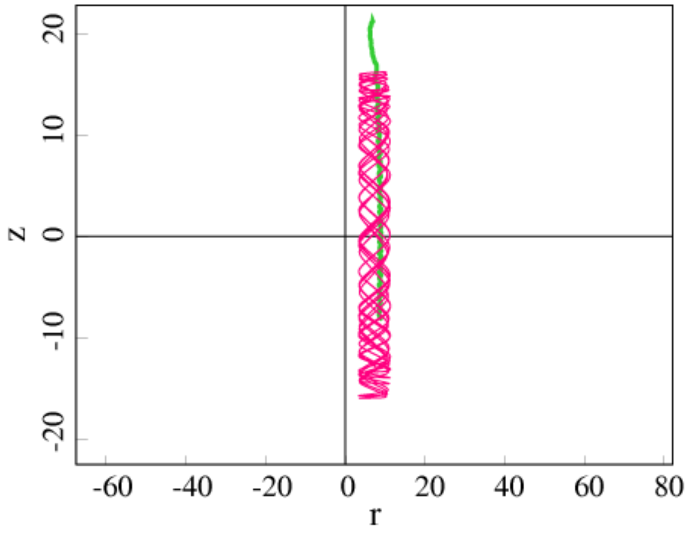


O-point line location

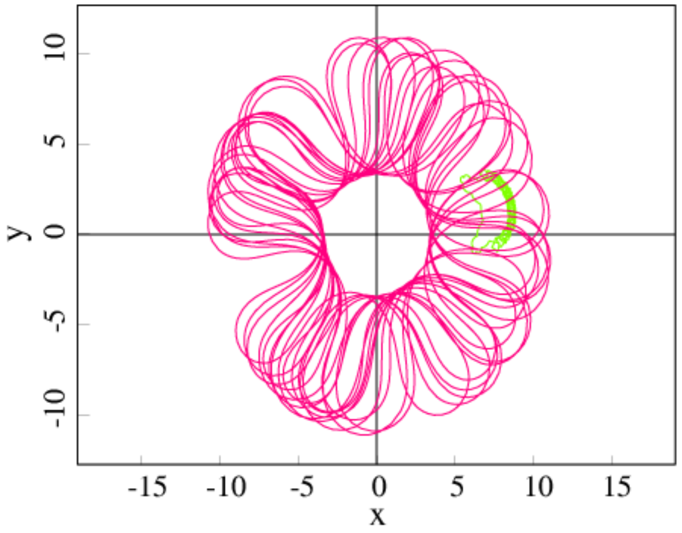
Glasser and Cohen (PoP 2002)

Prediction: 4. RMF$_o$ heats ions (experiments underway)

Orbit in Poloidal Plane



Orbit Viewed Along Z Axis



B_o = 20 kG

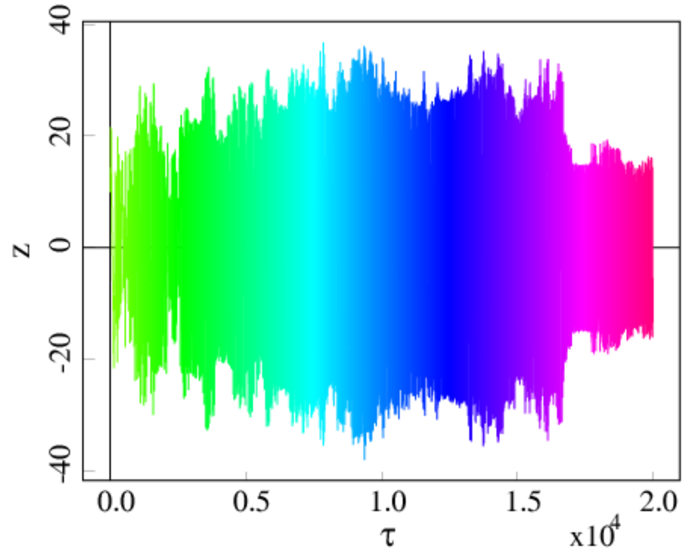
B_R = 100 G

r_s = 10 cm

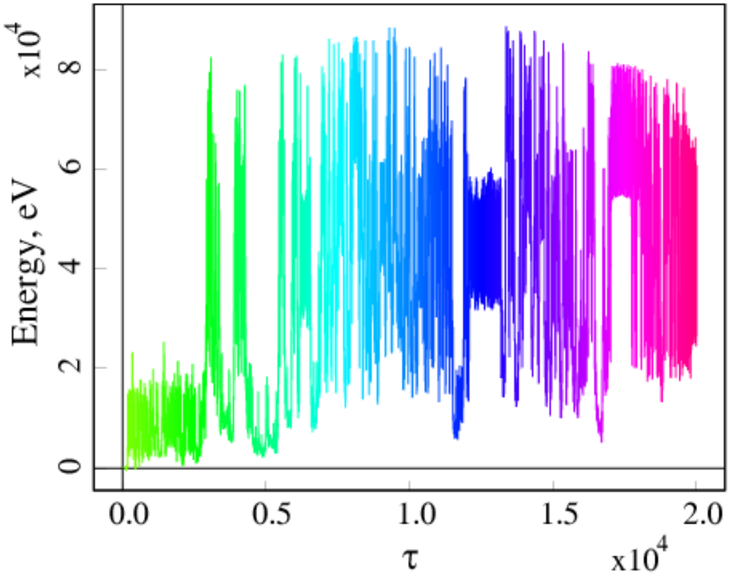
ω_{RMF}= 0.8 ω_{ci}

Ion energy reaches fusion range in 0.01 ms with no loss of confinement!

Axial Position

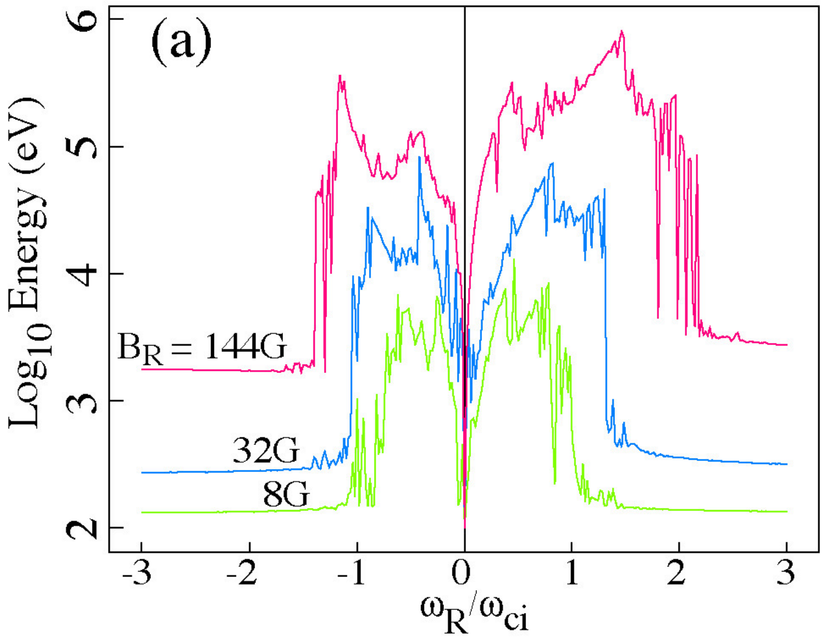


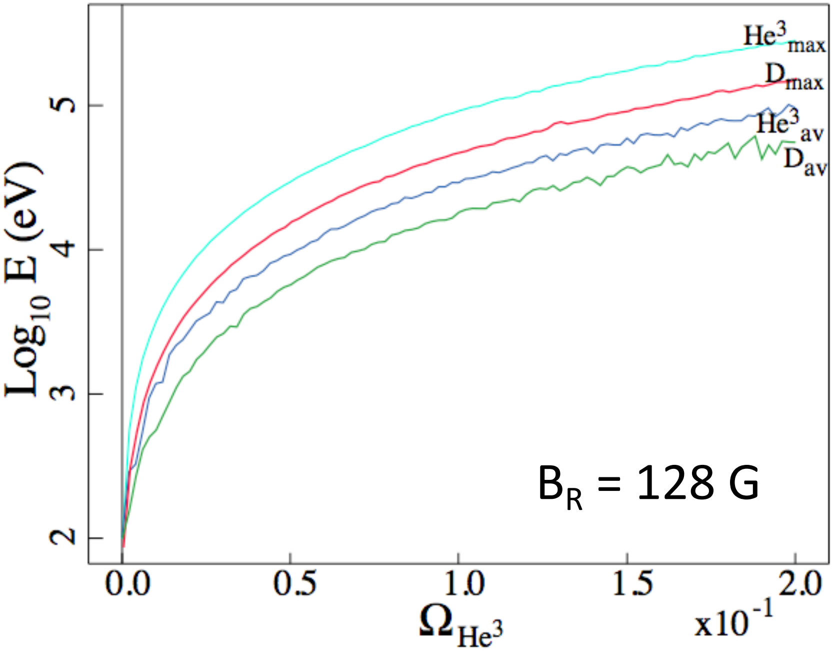
Kinetic Energy



Cohen and Glasser PRL (2000)

Predicted ion heating: r = 10 cm, κ = 5, B_a = 20 kG





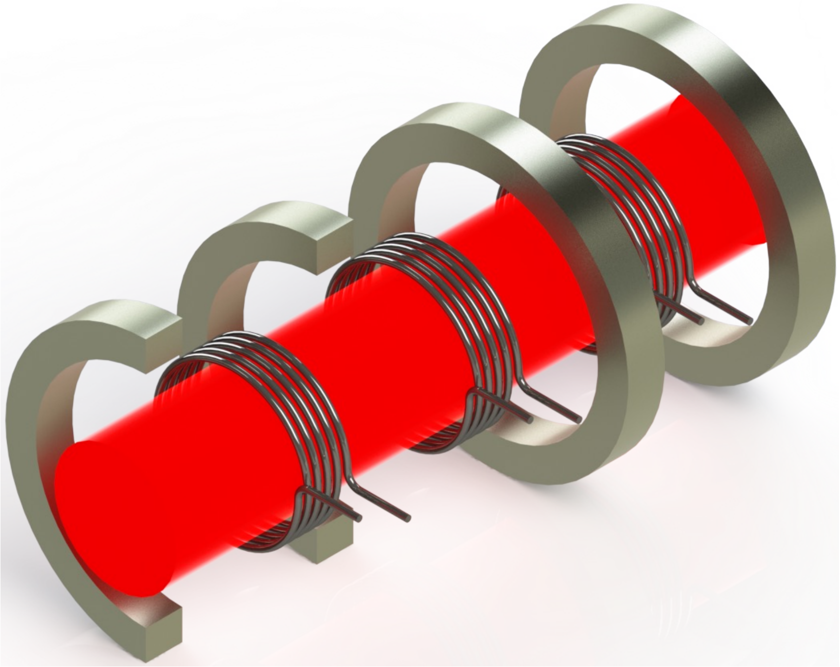
- Ion heating ($\Omega = \omega_R/\omega_{ci}$)
  - Threshold
  - Saturation
- Good heating for
  - $0.1 < |\omega_R/\omega_{ci}| < 2$
  - $B_R/B_a < 0.01$
- Gradient in heating efficiency may allow tuning for isotopes

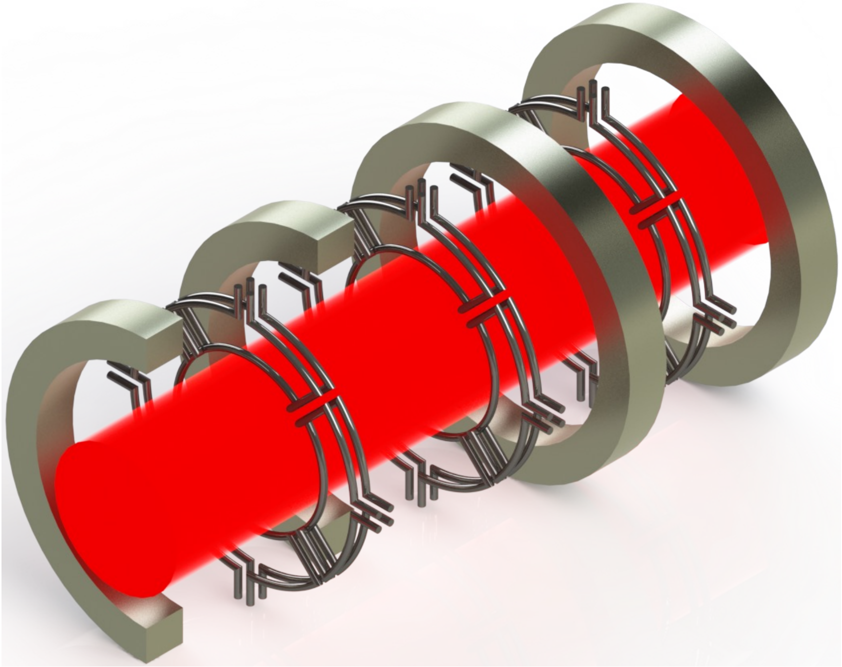
Cohen and Glasser (PRL 2000)

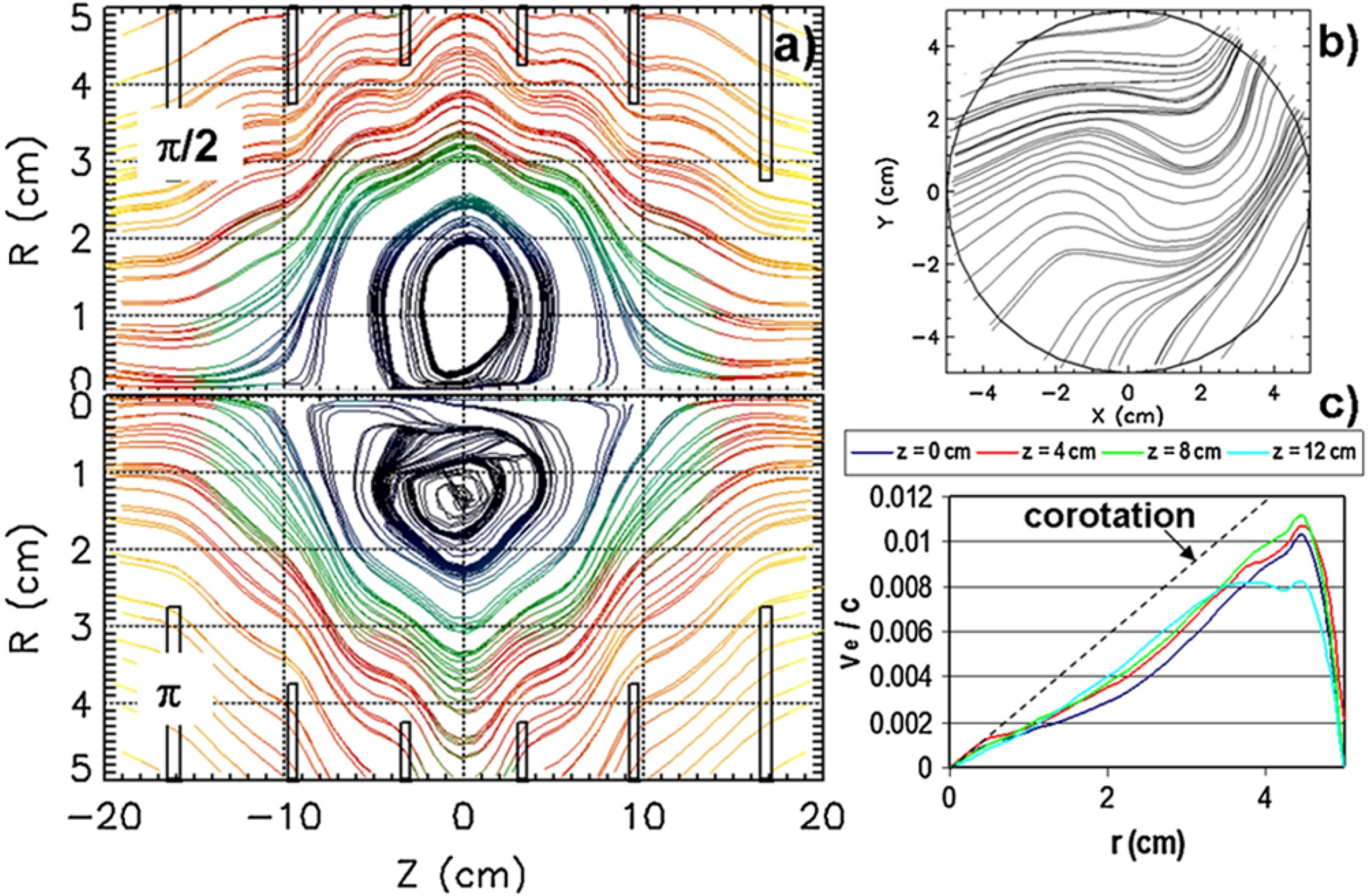
Cohen, Landsman, Glasser (PoP 2007) tbs

Alternate odd-parity antenna possibilities

Also: phase control
Linear polarization



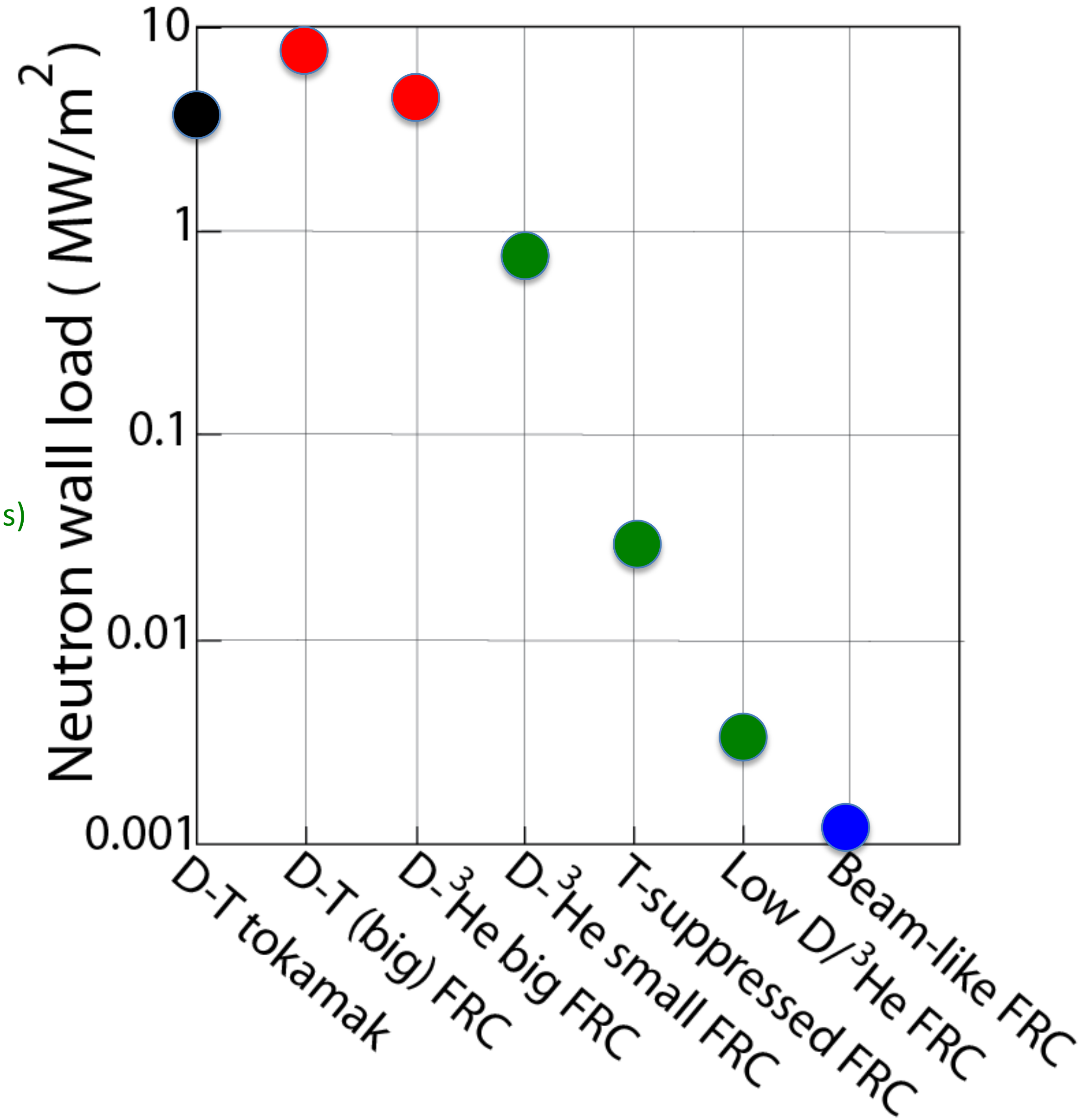



a)
π/2
π
R (cm)
R (cm)
Z (cm)
−20
−10
0
10
20
0
1
2
3
4
5
b)
Y (cm)
X (cm)
−4
−2
0
2
4
c)
z = 0 cm
z = 4 cm
z = 8 cm
z = 12 cm
corotation
v_e / c
r (cm)
0.012
0.01
0.008
0.006
0.004
0.002
0

Reducing neutron wall load: small→clean

- Big D-T tokamak
  → big FRC
- D-T → D-^{3}He
- Big FRC (14.4)
  → small FRC
- Rapid T removal
- Low D/^{3}He (1:3) (Santarius)
- Beam-like
  distributions

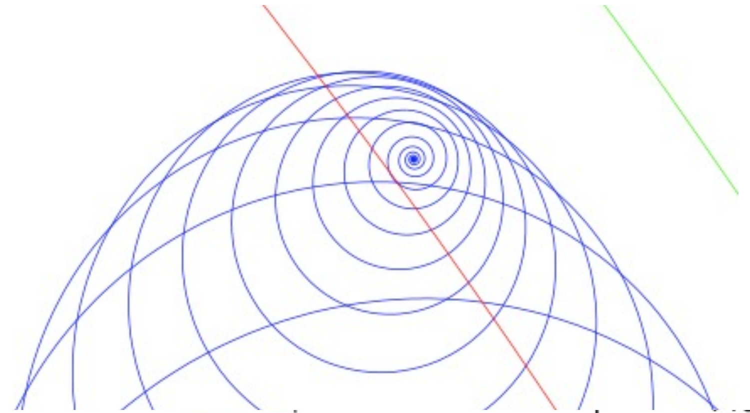
- Polarized fuel?
- Other non-thermal
  distributions?



α & p slowing down in SOL: why it matters

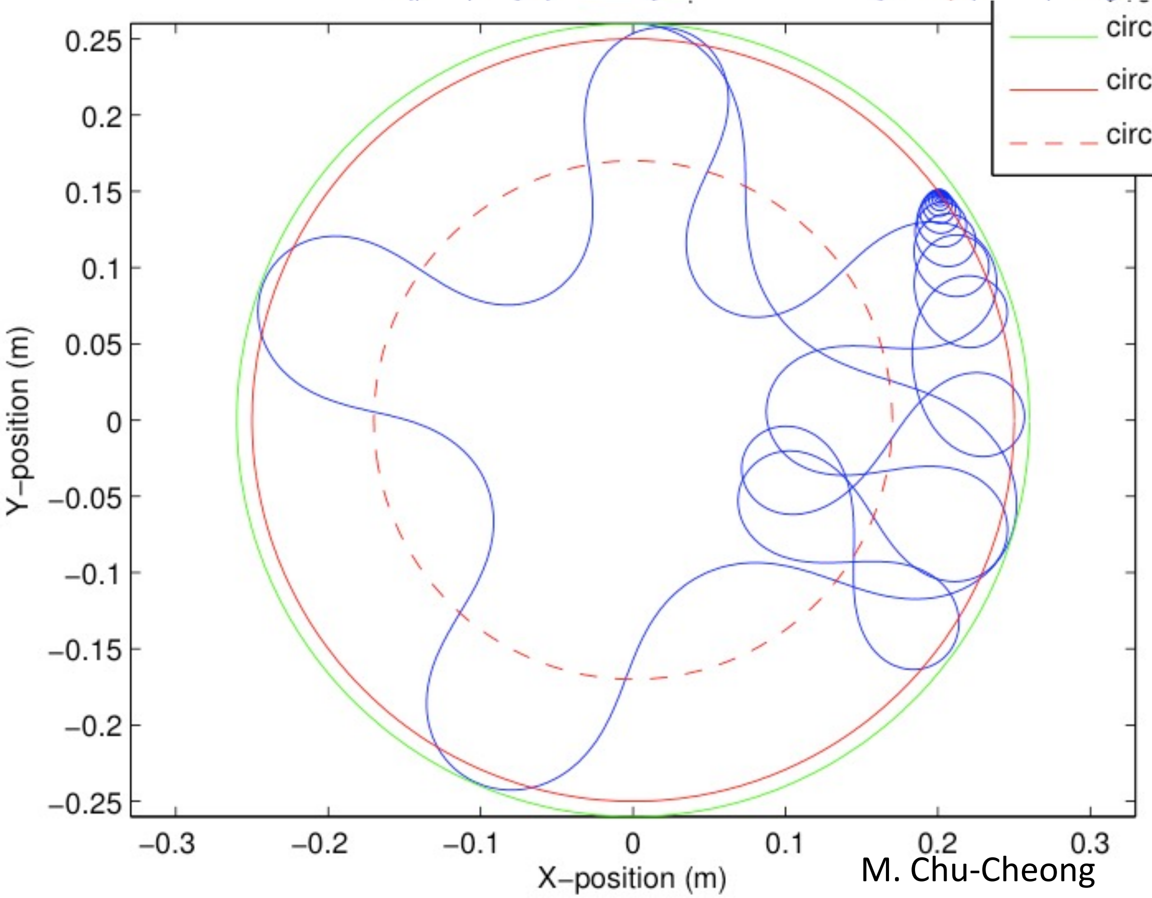
Ash and Power exhaust

In a **small** FRC, fusion products are born predominantly in betatron orbits which traverse the cold dense SOL where they slow down .



$$s = 0.3 r_s / \rho_i$$

Fusion product	s
^{3}He	8.05
T	3.65
P	3.63
^{4}He	3.38

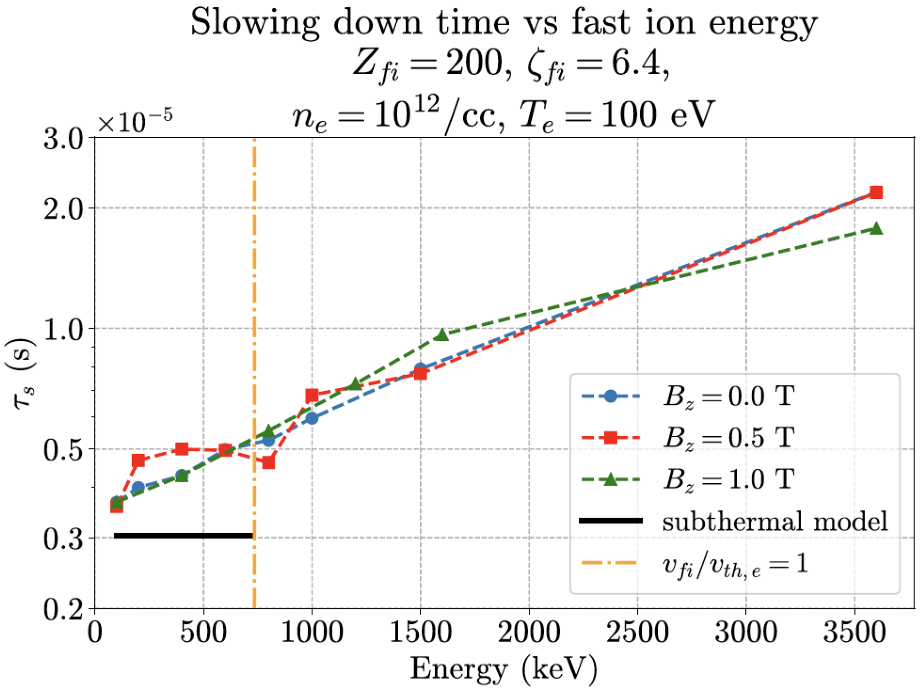


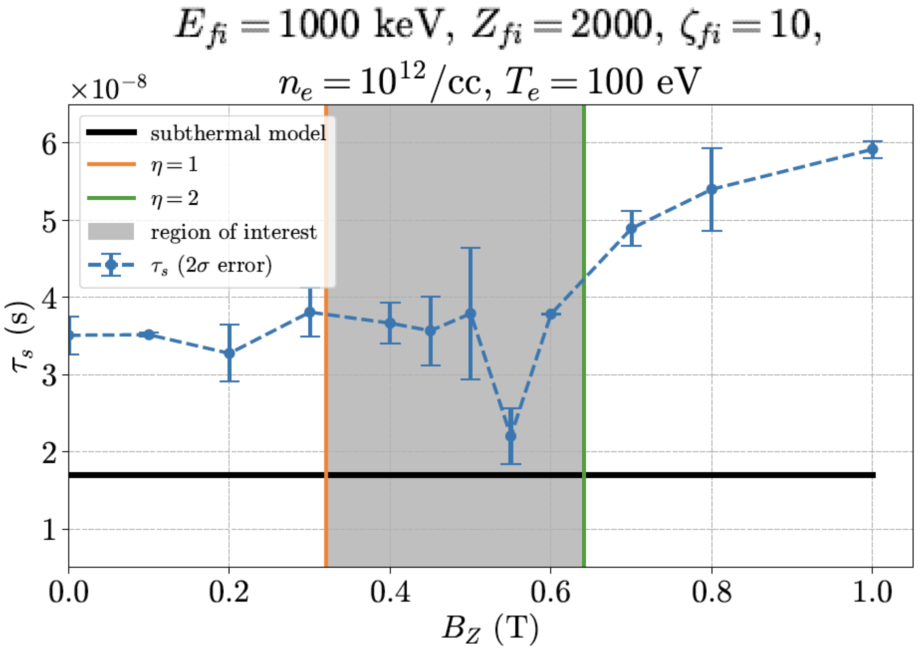
M. Chu-Cheong

PIC modeling of fast-ion slowing down

Situation in SOL: $v_{fi} > v_{th,e}$ & $\lambda_D > \rho_e$

$$\frac{1}{\tau_s} = \zeta_{fi} Z_{fi}^2 \left(\frac{n_e}{(\kappa T_e)^{3/2}}\right)\left(\frac{m_e^{1/2} e^4 \ln\left(\Lambda/\zeta_e\right)}{12\sqrt{2}\pi^{3/2}\epsilon_0^2 m_p}\right)$$


Slowing down time vs fast ion energy
$Z_{fi} = 200$, $\zeta_{fi} = 6.4$,
$n_e = 10^{12}$/cc, $T_e = 100$ eV


$E_{fi} = 1000$ keV, $Z_{fi} = 2000$, $\zeta_{fi} = 10$,
$n_e = 10^{12}$/cc, $T_e = 100$ eV

E. Evans, *et al.* (2018)

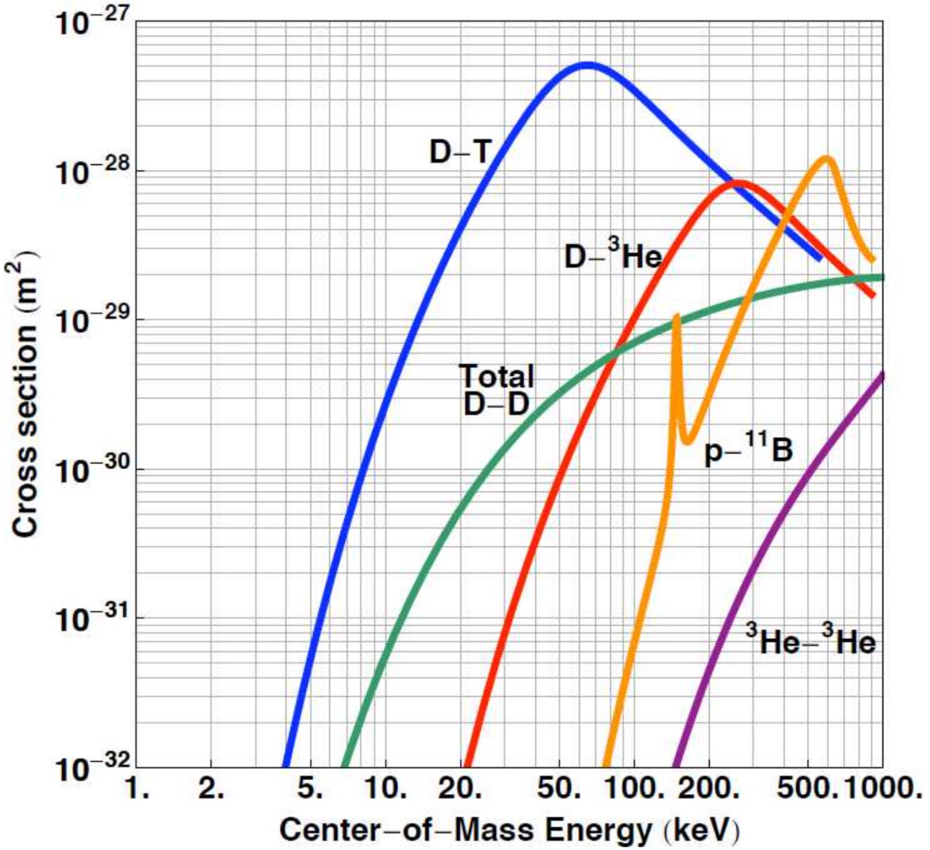
TriAlpha Energy

Science questions

- Q Maintaining non-thermal distributions: Rider *vs* Rostoker
- MHD and kinetic stability at $S^*/\kappa > 3$. (α^3 reactor $r_s/\rho_i > 30$)
- Synchrotron ($\propto B^4$) and Bremsstrahlung radiation losses
- Transport
- Ash exhaust

Technical questions

- Shielding for neutrons + γs
- Energy exhaust
- Energy recovery efficiency



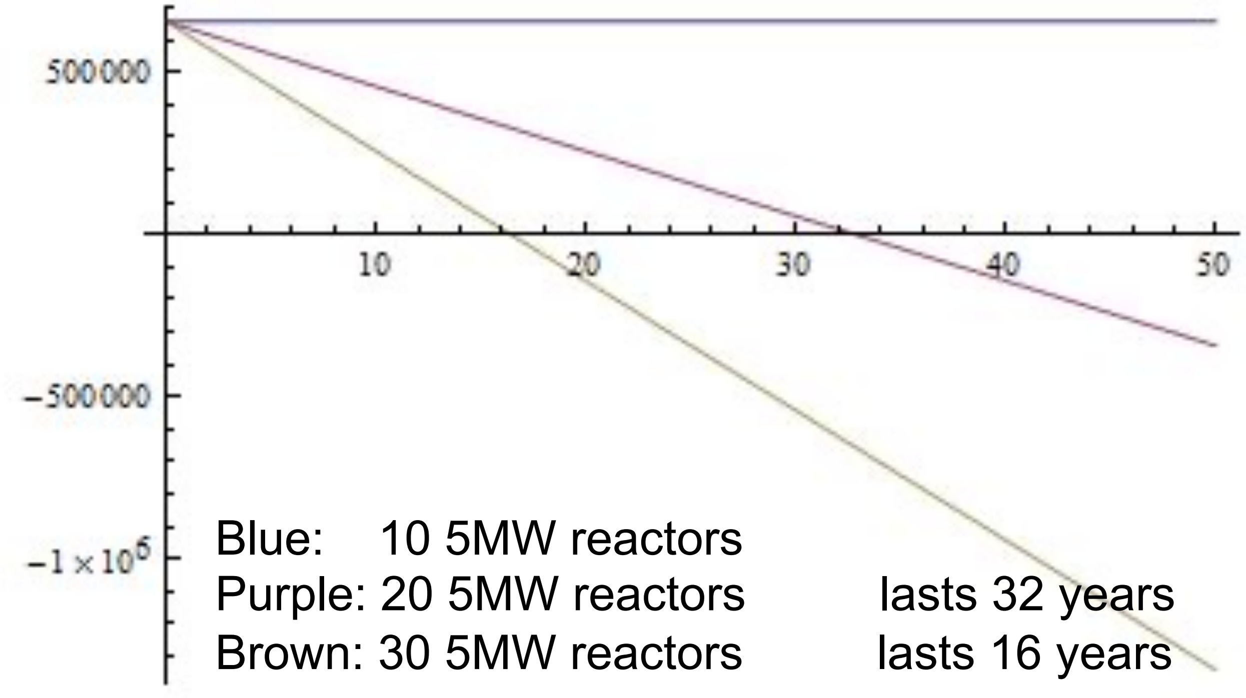
TriAlpha Energy (TAE)

Q with p-^{11}B: *research required*

- Low energy *per* fusion event
  - D-T (17.6 MeV); D-^{3}He (18.3 MeV); p-^{11}B (8.7 MeV)
- Low $<\sigma v>$ requires high T_i -> high T_e
  - D-T (5-10 keV); D-^{3}He (50-120 keV); p-^{11}B (>160 keV)
- Fuel dilution due to high nuclear charge
  - D-T ($n_e/2$); D-^{3}He ($n_e/3$); p-^{11}B ($n_e/6$)
  - $P_f \sim n_1 n_2$: D-T (1/4); D-^{3}He (1/9); p-^{11}B (1/36)
- Beam or fusion-product heating mostly goes to electrons until $E < E_{crit} \sim 15T_e \sim 500$ keV
- Large $n_e r_s$ required to “stop” beam
- Synchrotron & Bremsstrahlung radiation

Accessible ^{3}He ~ accessible ^{3}H

If we started burning existing ^{3}He reserves in 10 years, it would fuel 10-30 5-MW$_{th}$ reactors.



Blue: 10 5MW reactors
Purple: 20 5MW reactors lasts 32 years
Brown: 30 5MW reactors lasts 16 years

Small D-^{3}He fueled reactors would not have to worry about T breeding.

S. Newbury

7. Increasing terrestrial power generation

2-plant model: based on

Khvesyuk and Chirkov – He^3 self-sufficient D-D cycles

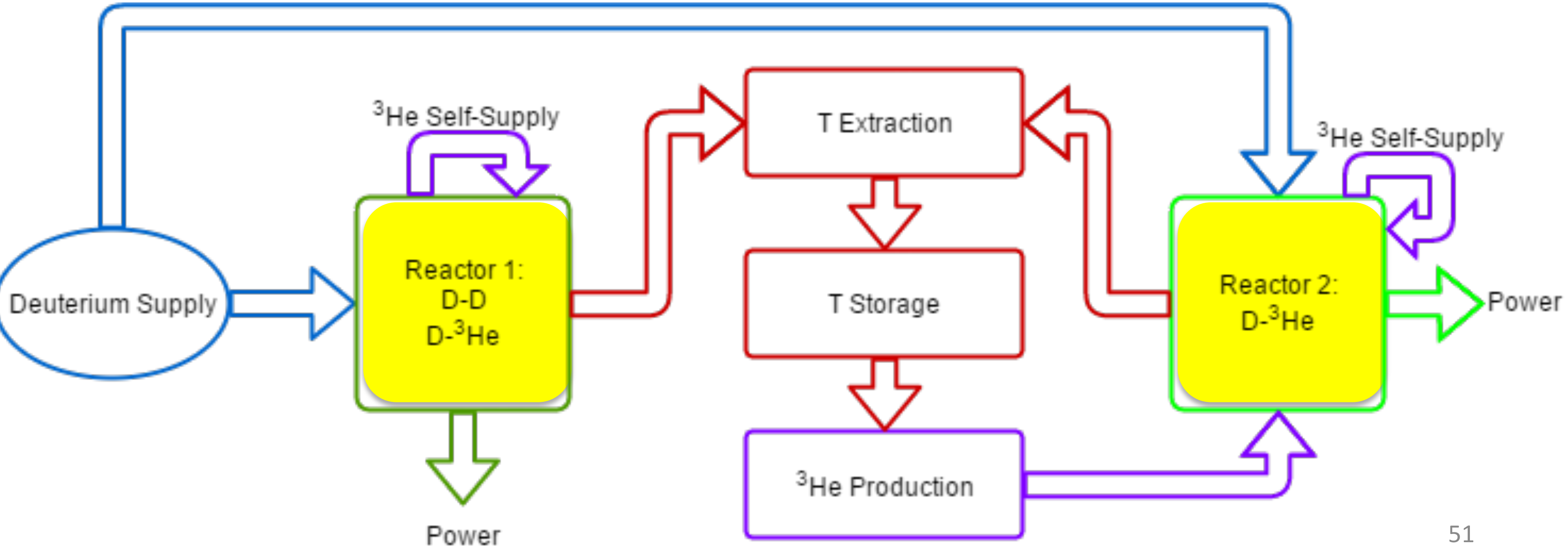
Plasma Phys. Control. Fusion 44, 253 (2002)

Sawan, Zinkle, and Sheffield - Tritium suppressed D-D

Fusion Engineering and Design **61-62**, 561 (2002)

Kesner, Garnier, *et al*.- He-catalyzed D-D

Nucl. Fusion **44**, 193 (2004)



Projection

Psychological projection is a theory in psychology in which humans defend themselves against *their own qualities* by denying their existence in themselves while *attributing them to others.*

R. H. Dicke

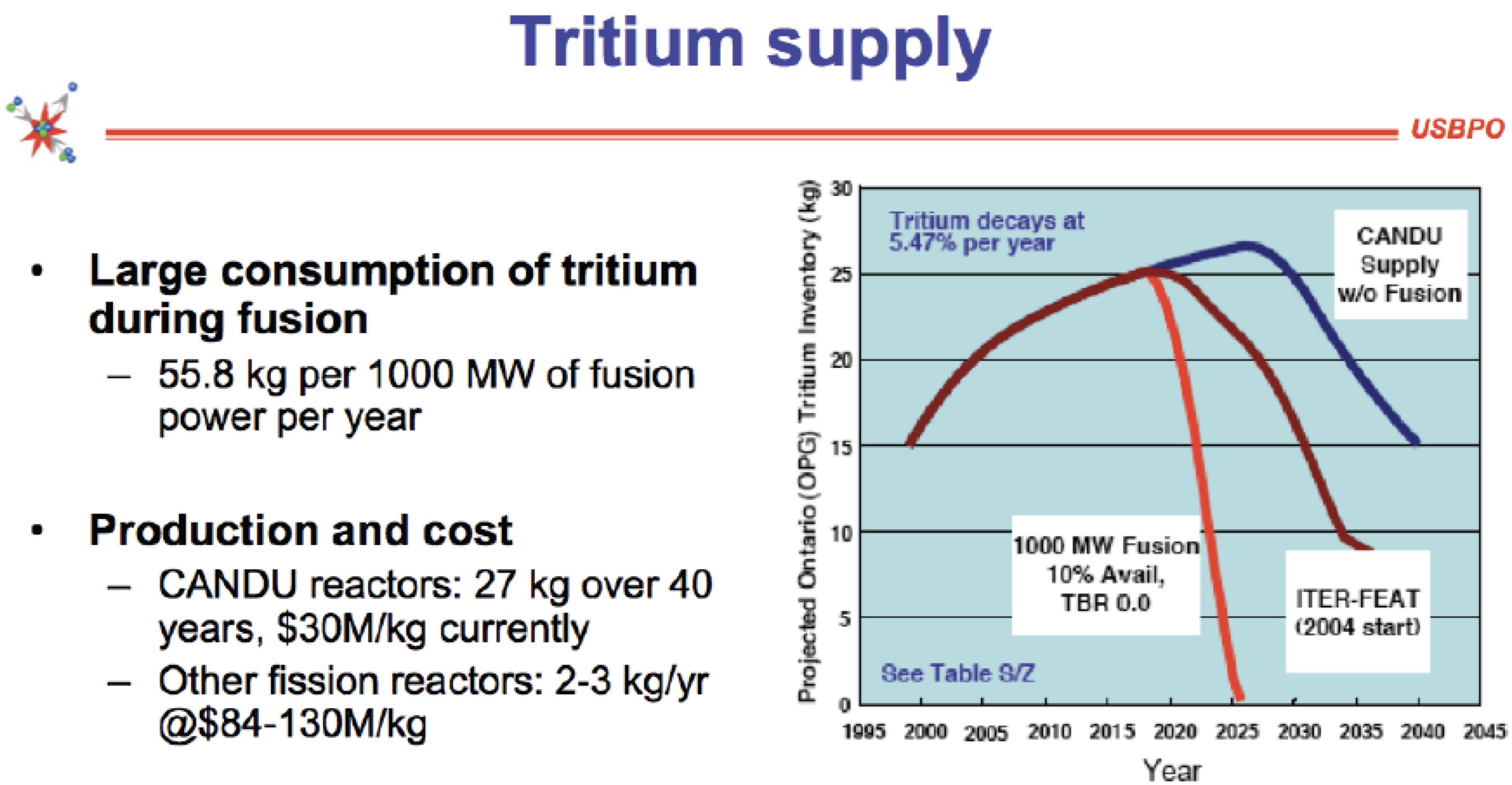
*"I have long believed that an experimentalist should not be unduly inhibited by theoretical untidiness. If he insists on having every last theoretical “**t**” crossed before he starts his research the chances are that he will never do a significant experiment. And the more significant and fundamental the experiment the more theoretical uncertainty may be tolerated.*

By contrast, the more important and difficult the experiment the more that experimental care is warranted."

Why tokamaks can't utilize ^{3}He effectively

1. Needs higher $\langle\beta\rangle$, 0.5 instead of 0.05.
2. Needs higher field magnets, > 20 T on coils.
3. Too big – would consume entire ^{3}He inventory less than one month into full power operation.
4. Steady-state heat load on divertor is x5 higher than for D-T.
5. Needs 5x shorter τ_{ash} than D-T. Active, untested ash exhaust method.
6. Higher synchrotron radiation losses are bad for τ_E.
7. Higher plasma stored energy (at higher B and β) will make heat loads from disruptions even higher.

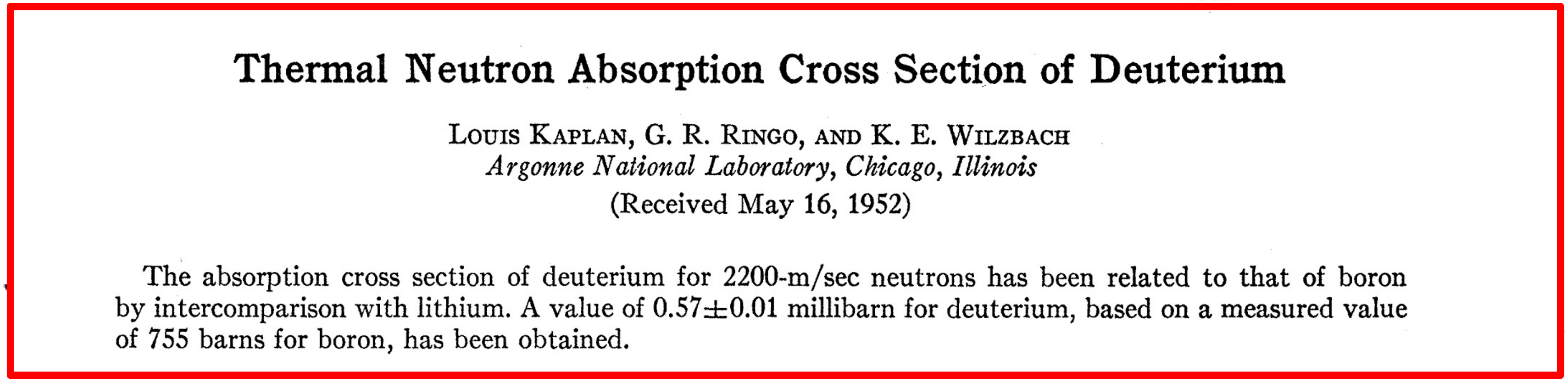
The mainline approach is to burn tritium



Tritium supply

USBPO

- **Large consumption of tritium during fusion**
  - 55.8 kg per 1000 MW of fusion power per year
- **Production and cost**
  - CANDU reactors: 27 kg over 40 years, $30M/kg currently
  - Other fission reactors: 2-3 kg/yr @$84-130M/kg



Thermal Neutron Absorption Cross Section of Deuterium

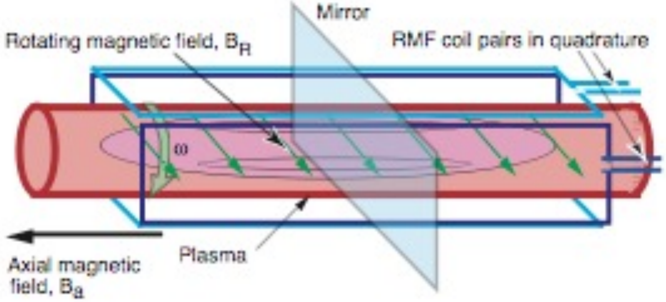
Louis Kaplan, G. R. Ringo, and K. E. Wilzbach
Argonne National Laboratory, Chicago, Illinois

(Received May 16, 1952)

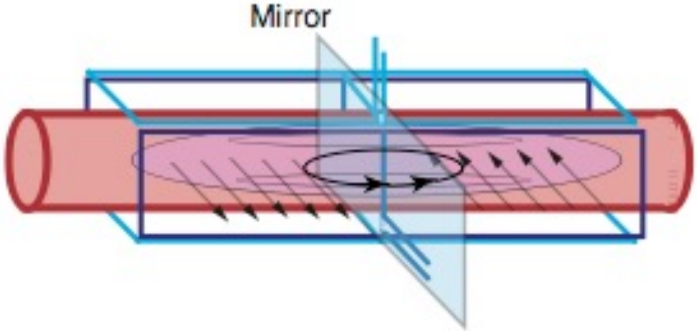
The absorption cross section of deuterium for 2200-m/sec neutrons has been related to that of boron by intercomparison with lithium. A value of 0.57±0.01 millibarn for deuterium, based on a measured value of 755 barns for boron, has been obtained.

Parity: Symmetry under mirror reflection

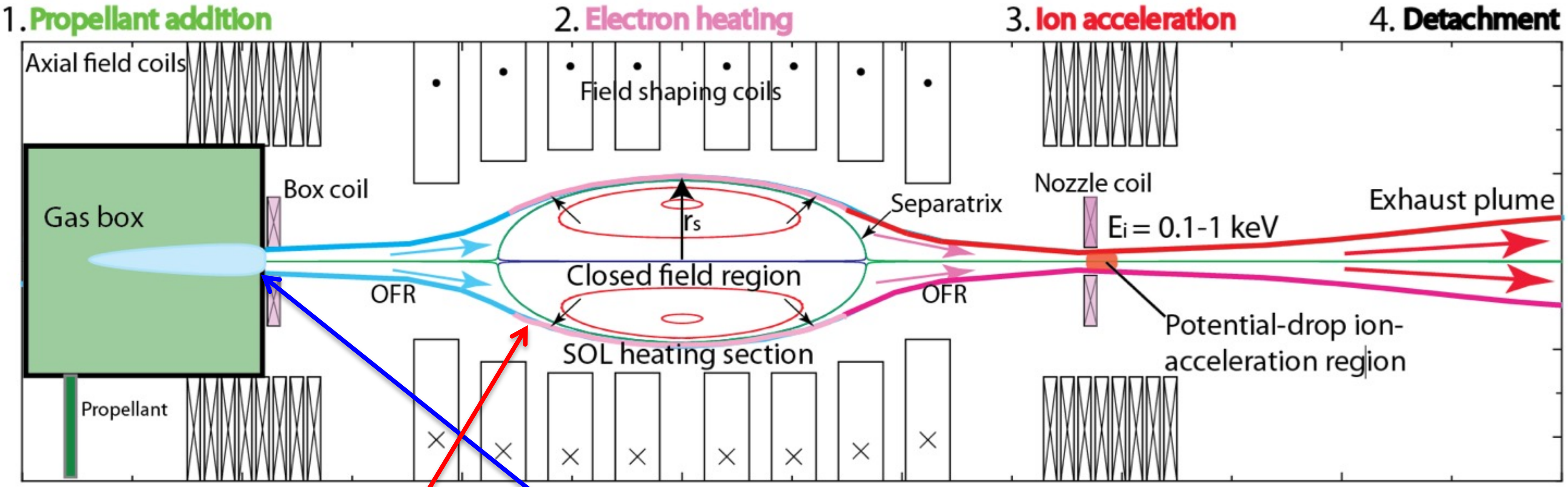
Even



Odd



Energy extraction and thrust production

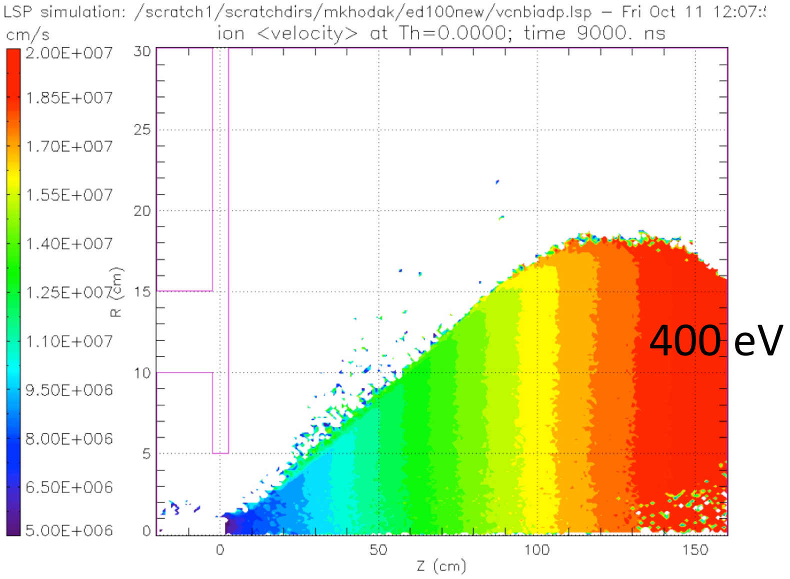


SOL width set by gas box geometry and heating by large ρ_i fusion products, NOT by diffusion across separatrix.

Gas input (propellant or coolant) ~ $3\text{x}10^4$ x fusion burn-up

A small machine promotes rapid loss of ash

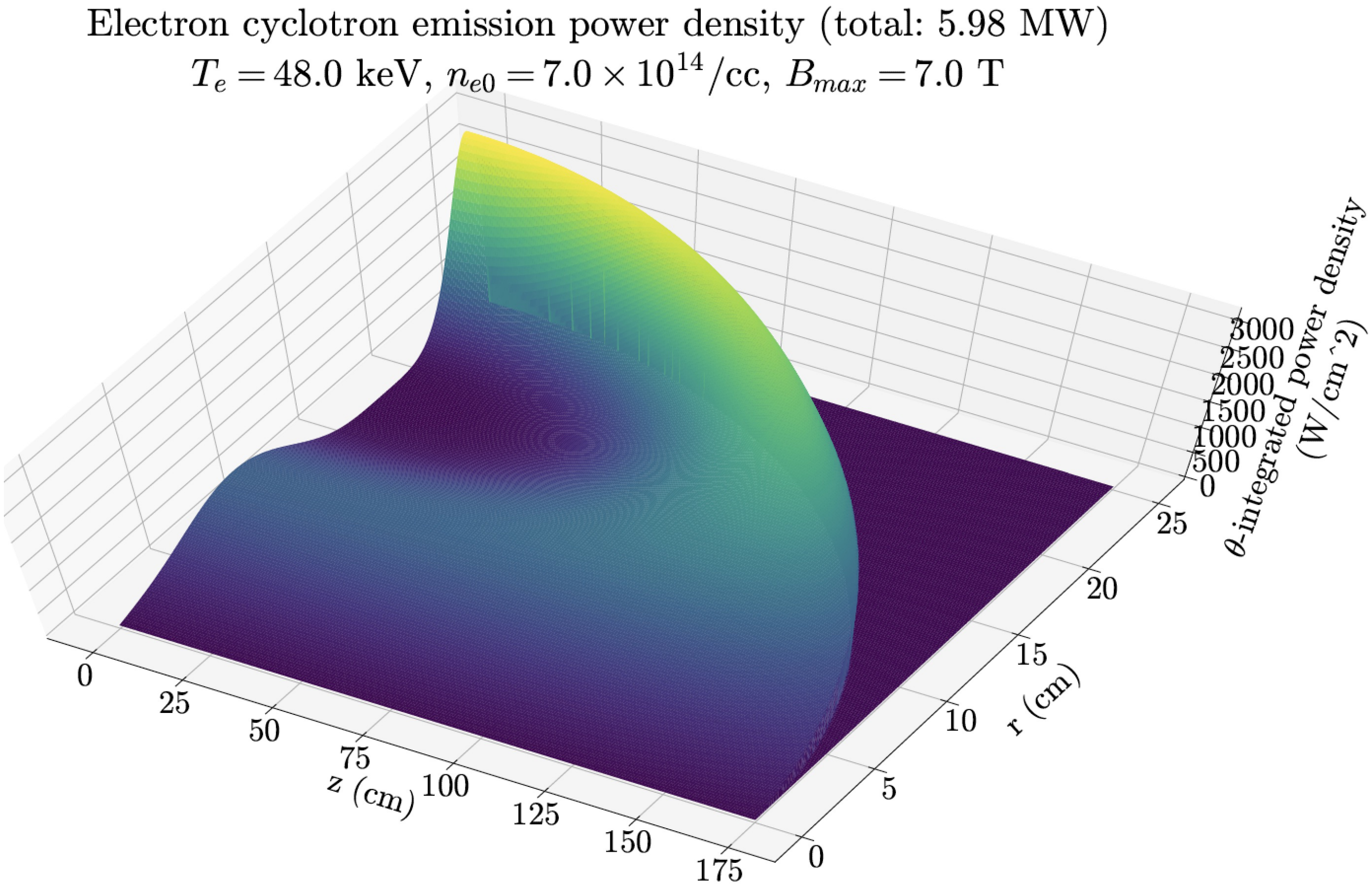
Expansion out nozzle



Khodak

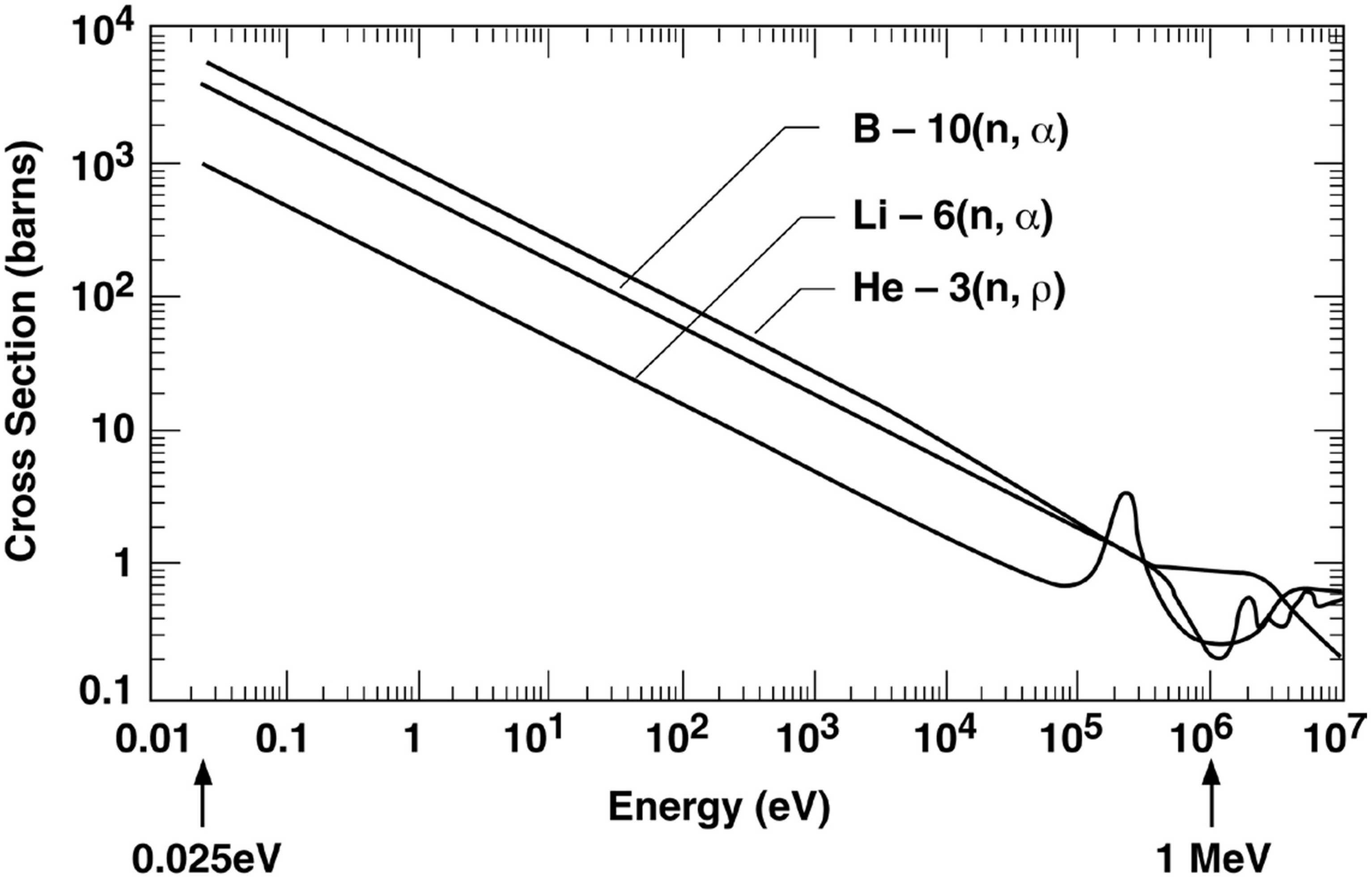
Confinement: Radiation losses

- Bremsstrahlung – well understood
  - $\sim n^2 T_e^{1/2} Z_{eff}$
    - $0.1\ P_f$
- Synchrotron radiation – poorly understood



Electron cyclotron emission power density (total: 5.98 MW)
$T_e = 48.0$ keV, $n_{e0} = 7.0 \times 10^{14}$/cc, $B_{max} = 7.0$ T

Neutron absorption cross sections



Alexander Martin Okowita