Boundary control issues for the new RMF sustained steady-state FRCs

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US-Japan Workshop on
High Heat Flux Components and
Plasma Surface Interactions
for Next Fusion Devices &
Fusion High Power Density
Devices and Design

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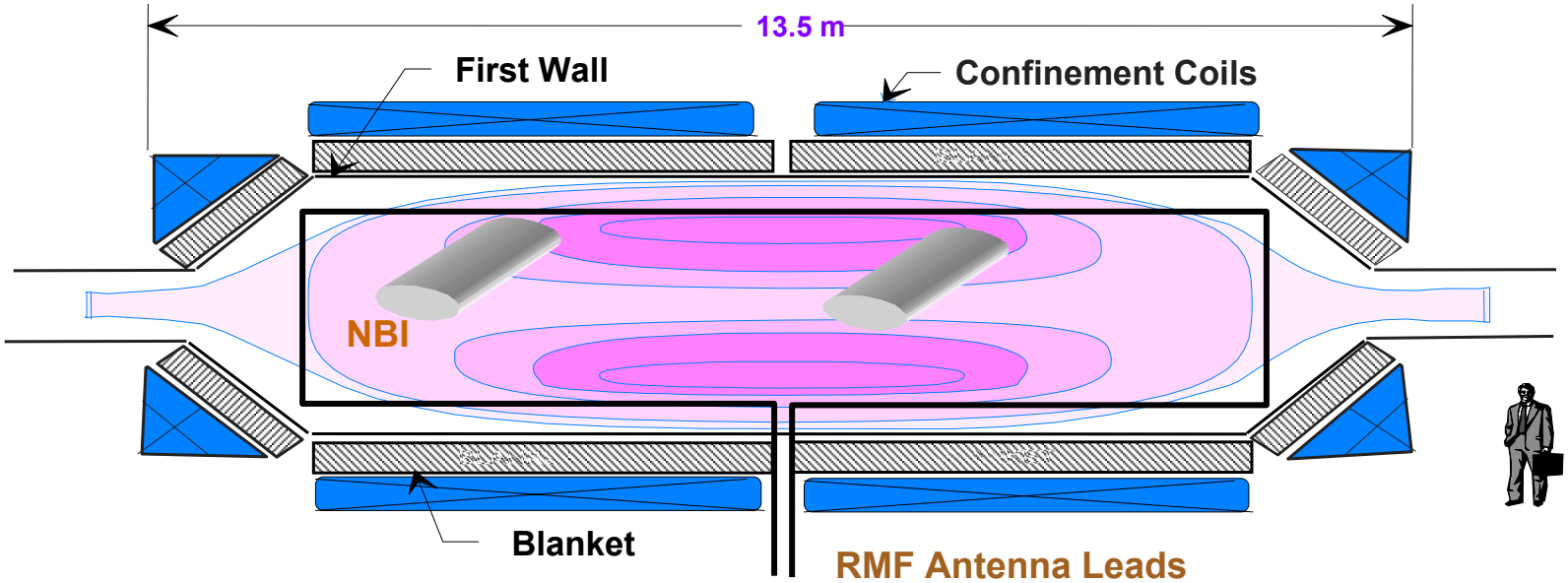
Workshop Agenda

Outline

- Field Reversed Configuration (FRC)
  - an attractive approach to confined fusion
- Current drive and steady-state maintenance using Rotating Magnetic Fields (RMF)
- Flow requirements for sustained operation
- Fuelling and impurity ingestion
- New design of TCS/mod
- Summary and conclusions

FRC Potential Advantages

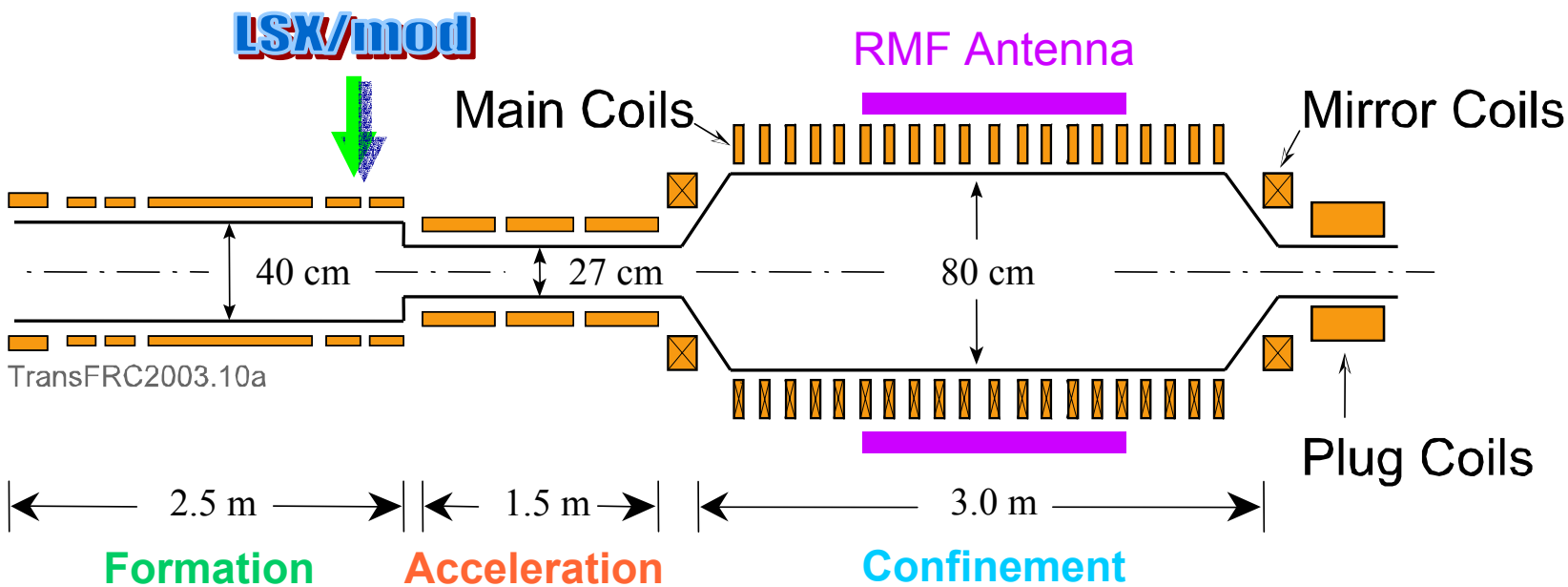


- **FRC is a compact toroid with no or little toroidal field, extremely high beta, simple linear geometry, and natural divertor.**
- **It is a very attractive candidate for a economic fusion reactor**
  - **Small reactor core, low B**
  - **Simple ash removal**
  - **Cost effective development path.**

Two Major Approaches

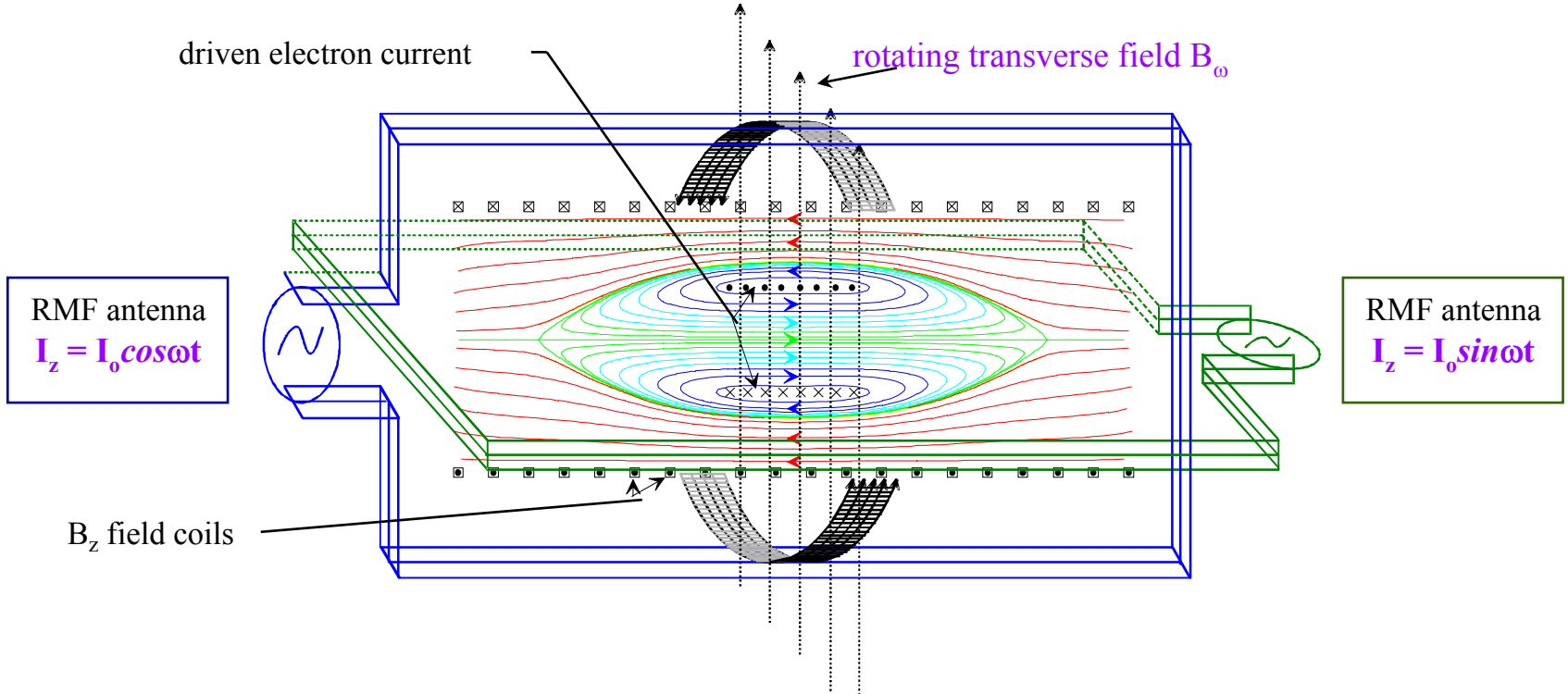
- **Pulsed - High Density**
  - Most historical research – theta pinch formation yields **high temperatures and densities**, with empirical scaling: $\tau \propto r_s^2\sqrt{n}$
  - Range of reactor scenarios
    - **Adiabatic compressor** – moving rings (oldest reactor design approach)
    - **RACE type accelerator** – use TRAP type moving wave FRC acceleration
    - **Liner compression** – Magnetized Target Fusion (MTF), LANL
- **Steady State - ~10^{20} m^{-3} Density**
  - Formation technologies: translation, merging spheromaks, ion beams, RMF
  - Current drive and flux sustainment
    - **Neutral beam driven** – first design: ARTEMES D-^{3}He reactor
    - **Rotating Magnetic Field (RMF) driven** – adapted from rotamak research
  - **FIX program: utilizing NB**, but mostly axial injection due to low flux
  - **TCS program: using RMF to form, build up flux, and sustain current**
  - ➢ ***Ultimate program: combine RMF to form and drive edge to enhance particle confinement, NB to drive center. Torques balanced.***

TCS Facility



- **Study physics of RMF driven FRCs**
- **Flux sustainment of hot FRCs in steady state by the RMF**

RMF Current Drive



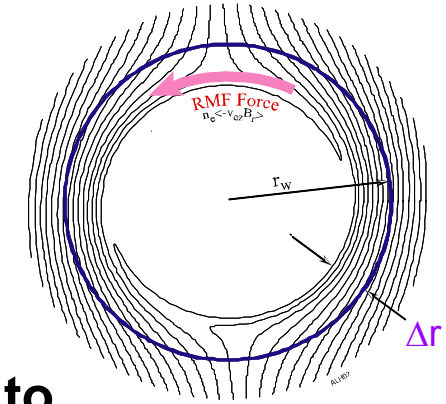
- **'Drag' Electrons Along With Rotating Radial Field**
  - Must have $\omega_{ci} < \omega << \omega_{ce}$ for electrons, but not ions, to follow rotation
- **Electrons Magnetized on Rotating Field Lines** **($\omega_{ce}\tau >> 1$)**
  - Necessary for efficient current drive
  - Absolutely necessary for rotating field penetration

Standard Model of RMF Current Drive in FRCs

- **Poloidal flux will increase** as long as the RMF torque on the electrons exceeds the torque due to electron-ion drag (resistivity)

$$T_{RMF} = \frac{2\pi B_\omega^2 r_s^2}{\mu_o} \ell_{ant} \left(\frac{\Delta r}{r_s} \right) \qquad T_\eta = 0.5\pi\eta_\perp \langle n_e^2 e^2 \omega_e \rangle r_s^4 \ell_s$$

$$\frac{d\phi_p}{dt} = 2\pi R E_\theta(R) = \frac{2}{n_e e r_s^2 \ell_s} \left(T_{RMF} - T_\eta \right)$$



- **In equilibrium** $T_{RMF} = T_\eta \Rightarrow n_e \propto B_\omega/(\eta_\perp \omega r_s^2)^{1/2}$

  RMF penetrates just far enough, $\Delta r \sim (B_e/\mu_o)/n_e e \omega r_s$ to maintain the diamagnetic current throughout the FRC

- **Plasma flow in RMF driven FRCs**

$$E_\theta = \eta_\perp j_\theta + \langle -\tilde{v}_{ez} \tilde{B}_r \rangle + V_r B_z - V_z B_r$$

Under Antenna

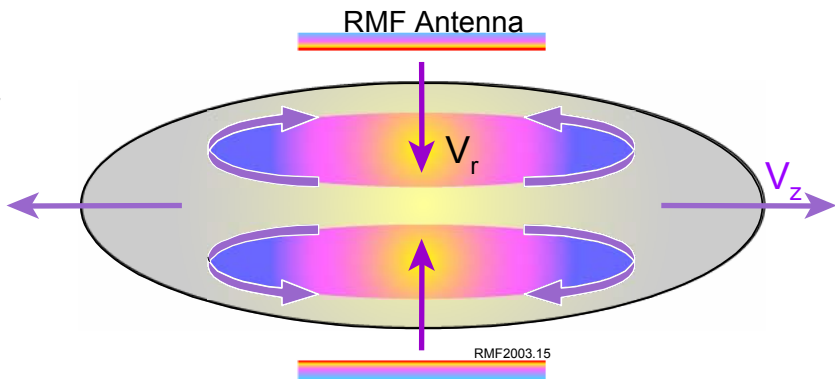
Outer: − + −

Inner: − +

FRC Ends

Outer: − +

Inner: − +



Basic RMF Scaling

- n_e given by RMF parameter
- Total temperature set by power balance
- External field $B_e = \sqrt{2\mu_o n_{em} k T_t}$

  - RMF penetration automatically adjusts to provide B_e

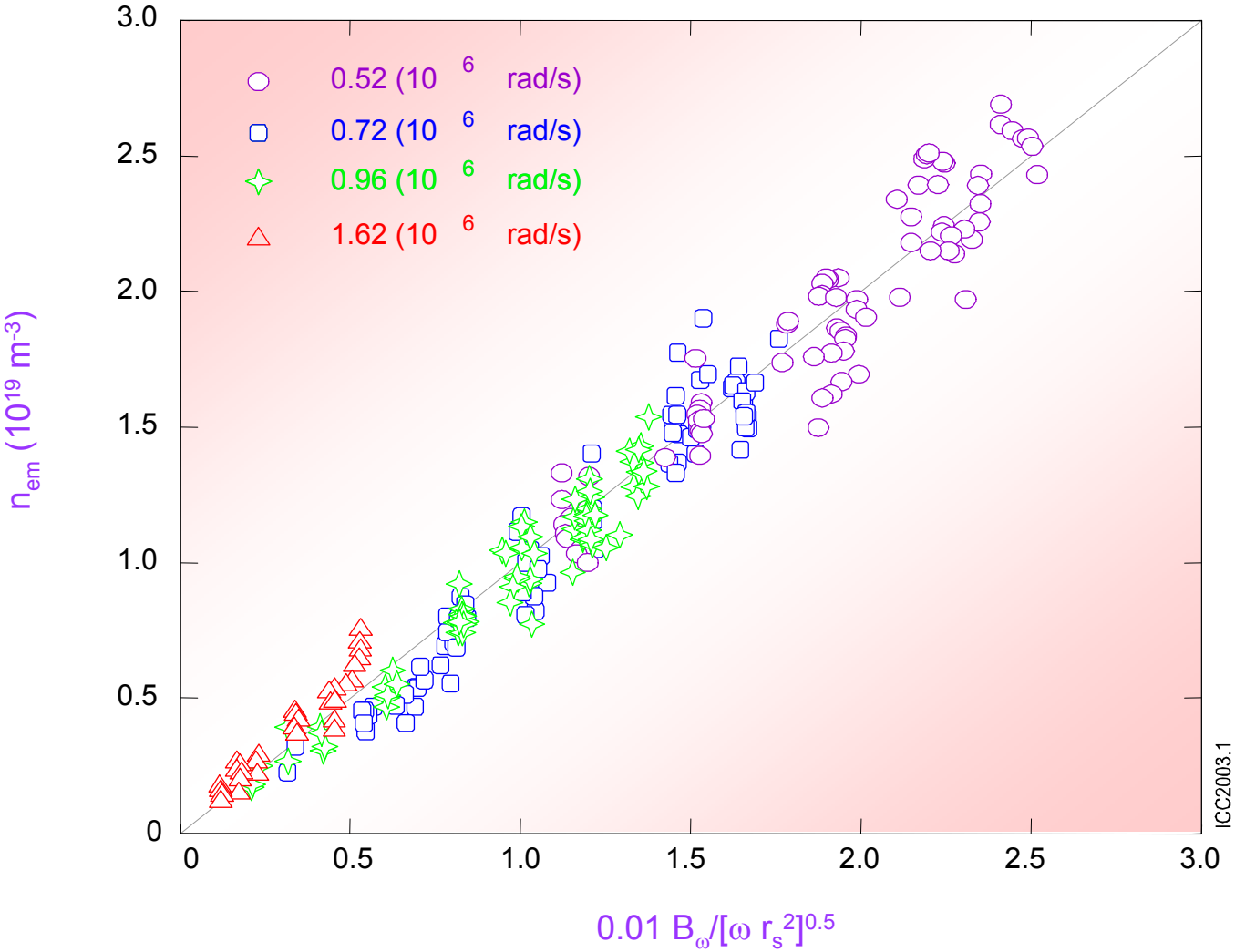
  - Limited by maximum possible $\frac{2B_e}{\mu_o} = \frac{1}{2}\langle n_e \rangle e\omega r_s^{\,2}$

$\Rightarrow$

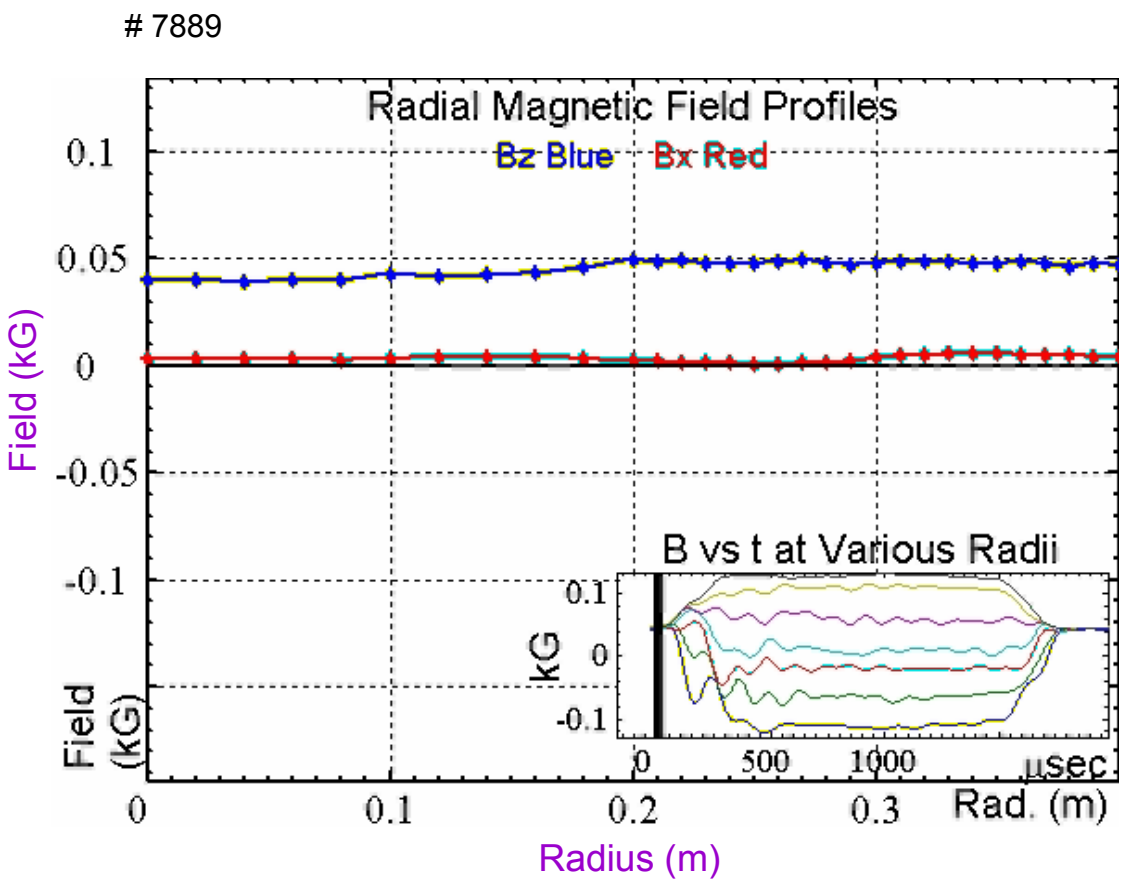
$$T_t(eV) = \frac{5\times 10^3 B_\omega[G]\langle\beta\rangle^2\left(\omega[10^6\ rad/s](r_s[m])^2\right)^{3/2}}{\left(\eta_\perp[\mu\Omega - m]\right)^{1/2}}\zeta^2 \qquad (\gamma/\lambda = 1)$$

Where $\zeta = \langle\omega_e\rangle/\omega$ so that there is maximum possible value when all electrons rotating synchronously.

Density Set by RMF Parameters

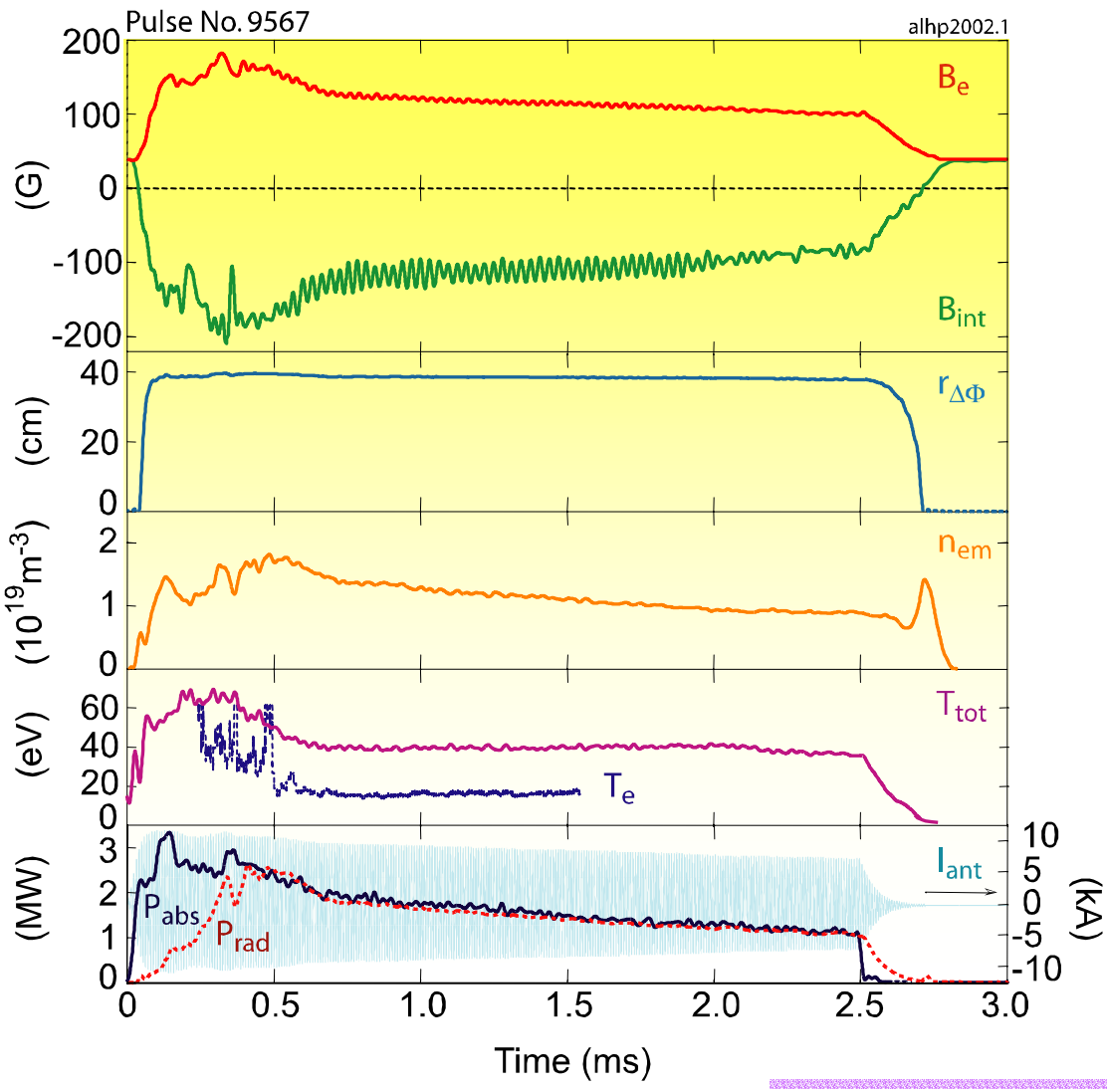


Internal Field Profiles



- **RMF just reaches field null.**
- **Full field reversal is maintained on inner field lines, presumably, by the inward flow.**
- **Separatrix pressure is very low, in contrast to non-sustained FRCs**

Steady-State Current Drive by RMF



- **Up to 60 kA of current is driven by RMF, maintained in steady state for the entire duration of RMF.**
- **Operating space:**

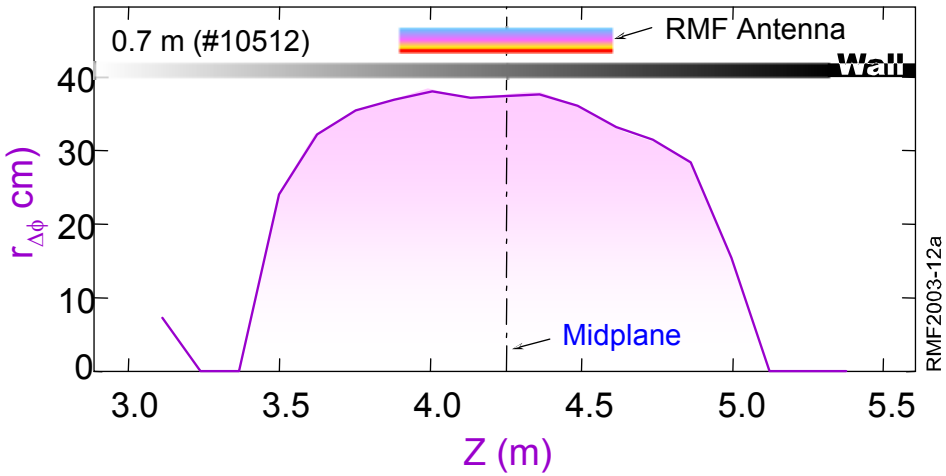
  T_{tot}: 20 ~ 120 eV

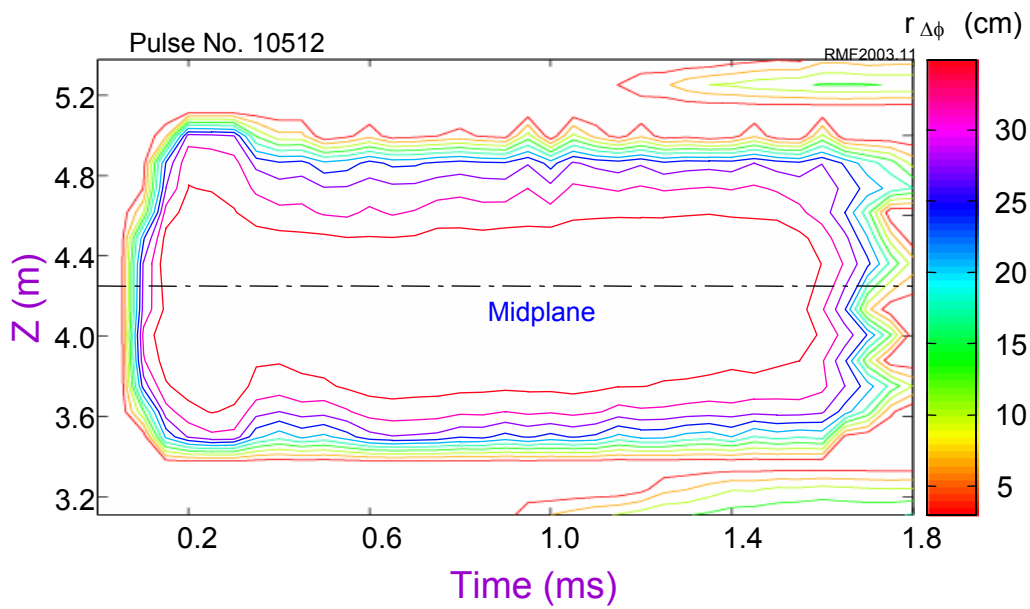
  n_e: 0.5 ~ 3.5 $\times 10^{19}$ m^{-3}

  B_e: 4 ~ 20 mT

  B_ω: 1 ~ 7 mT

Evidence of Axial Outflow





- **FRCs can be sustained with axial lengths well beyond the RMF antenna ($\ell_s \sim 2\ell_a$), presumably by induced axial outflow, as can be seen by Ohm's law:**

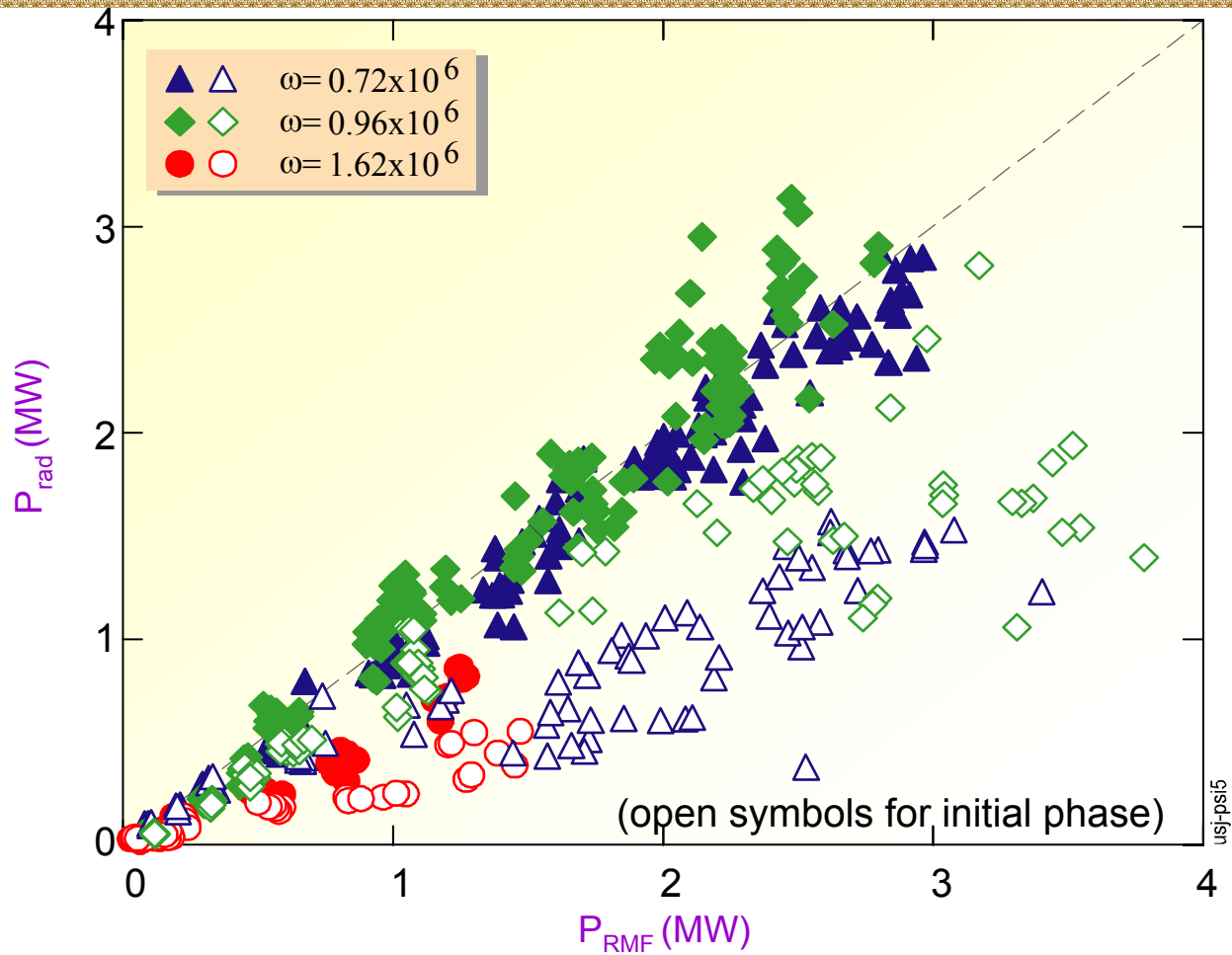
$$E_\theta = \eta_\perp j_\theta - v_z B_r$$

In steady-state, $E_\theta \equiv 0$

$$\Rightarrow \quad j_\theta = v_{ez} B_r / \eta_\perp$$

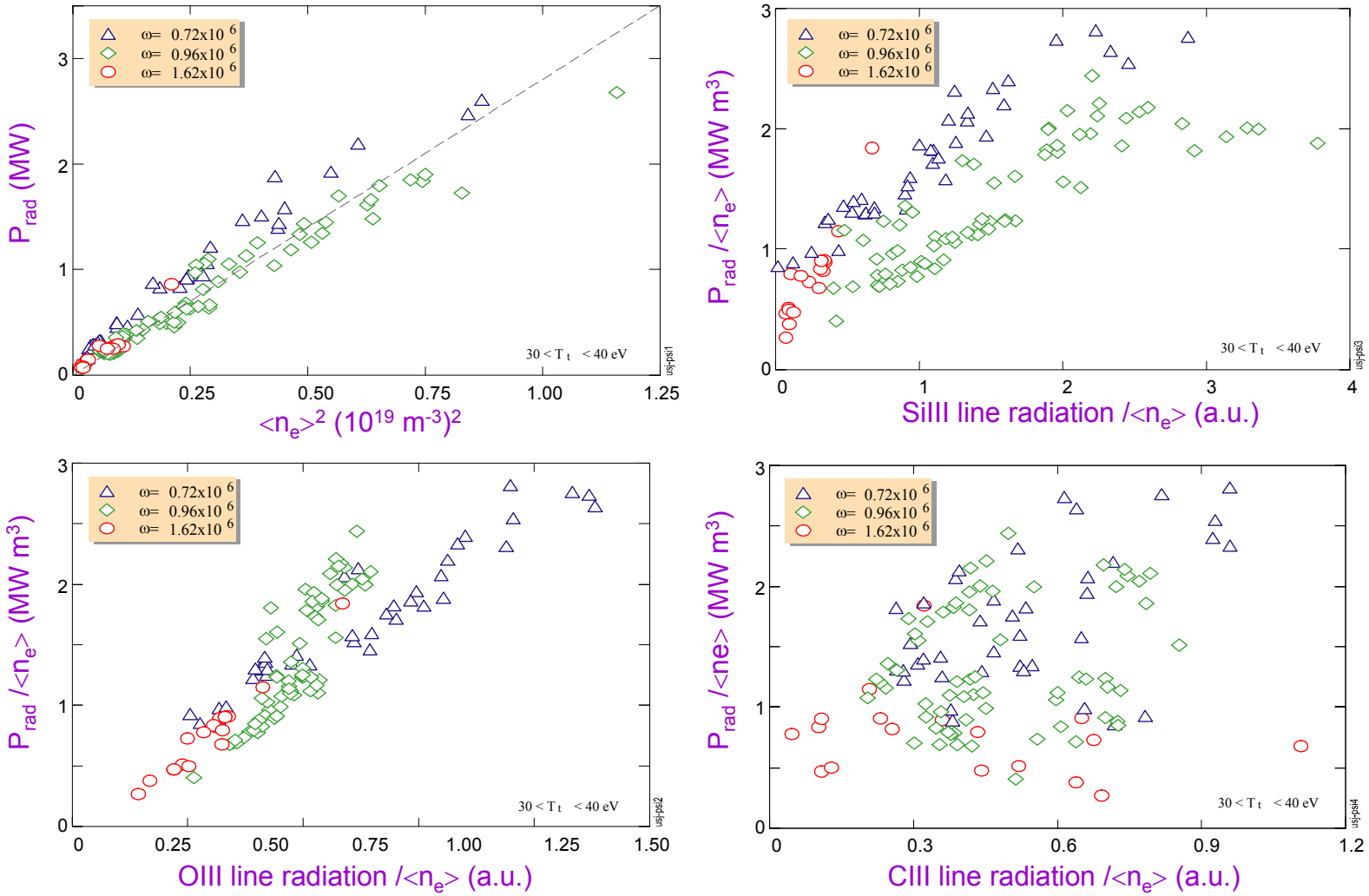
- **Operation with long antenna ($\ell_s < \ell_a$) leads to non steady behavior with decreasing ℓ_s most likely due to inhibition of swirling flow around ends, thus, degrading particle confinement time.**

RMF Heating and Power Losses



- **Losses are dominated by radiation in the presently unbaked, non-wall conditioned TCS with quartz wall except initial start-up phase.**

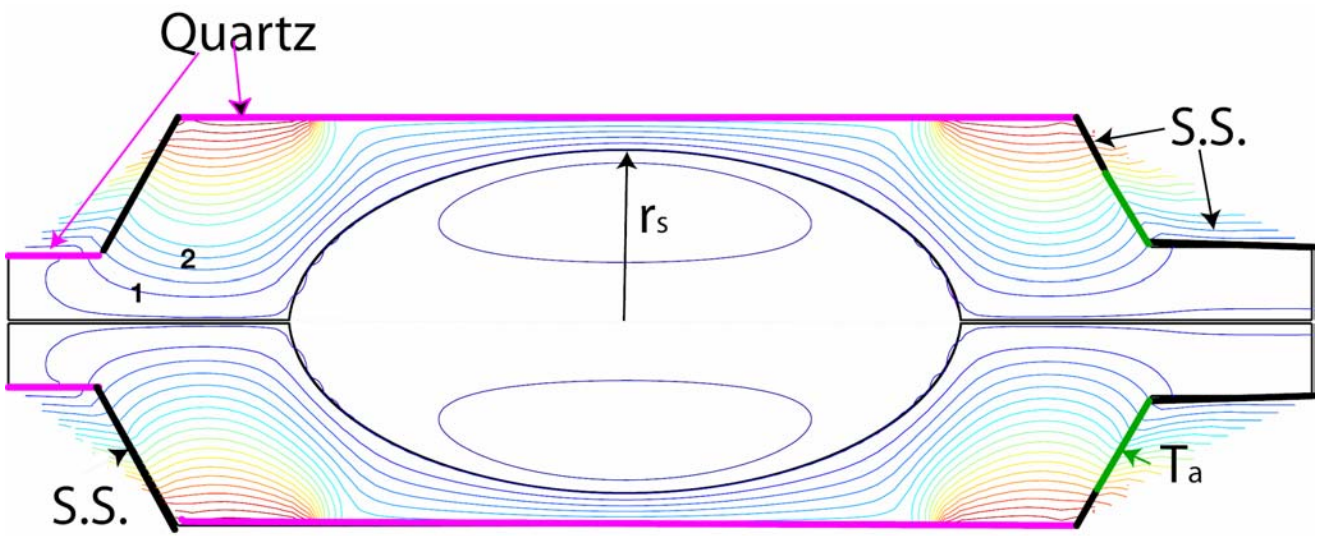
Impurity Radiation



- **P_{rad} is best correlated with OIII; no obvious correlation with CIII.**

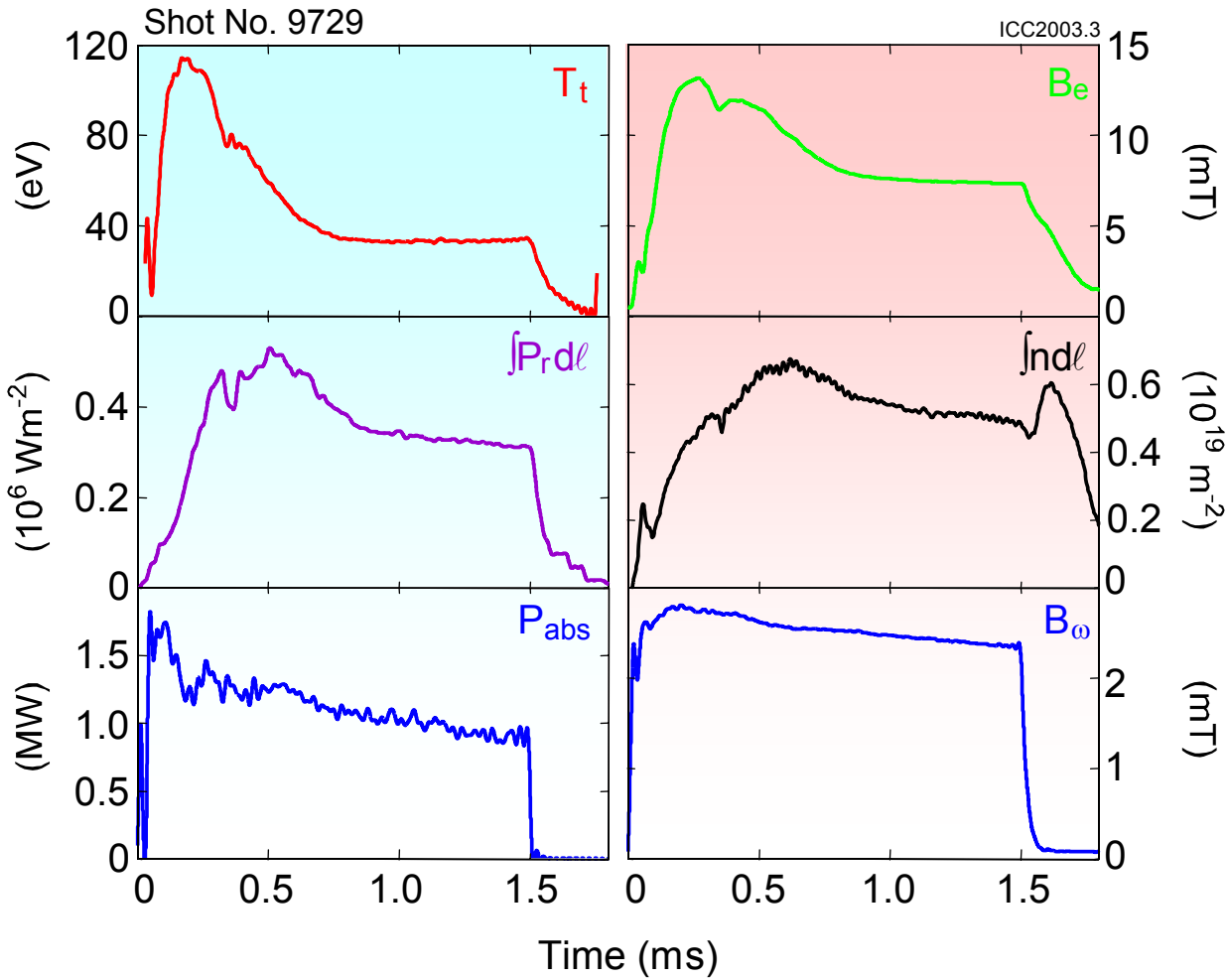
Impurity Sources

TCS Confinement Chamber



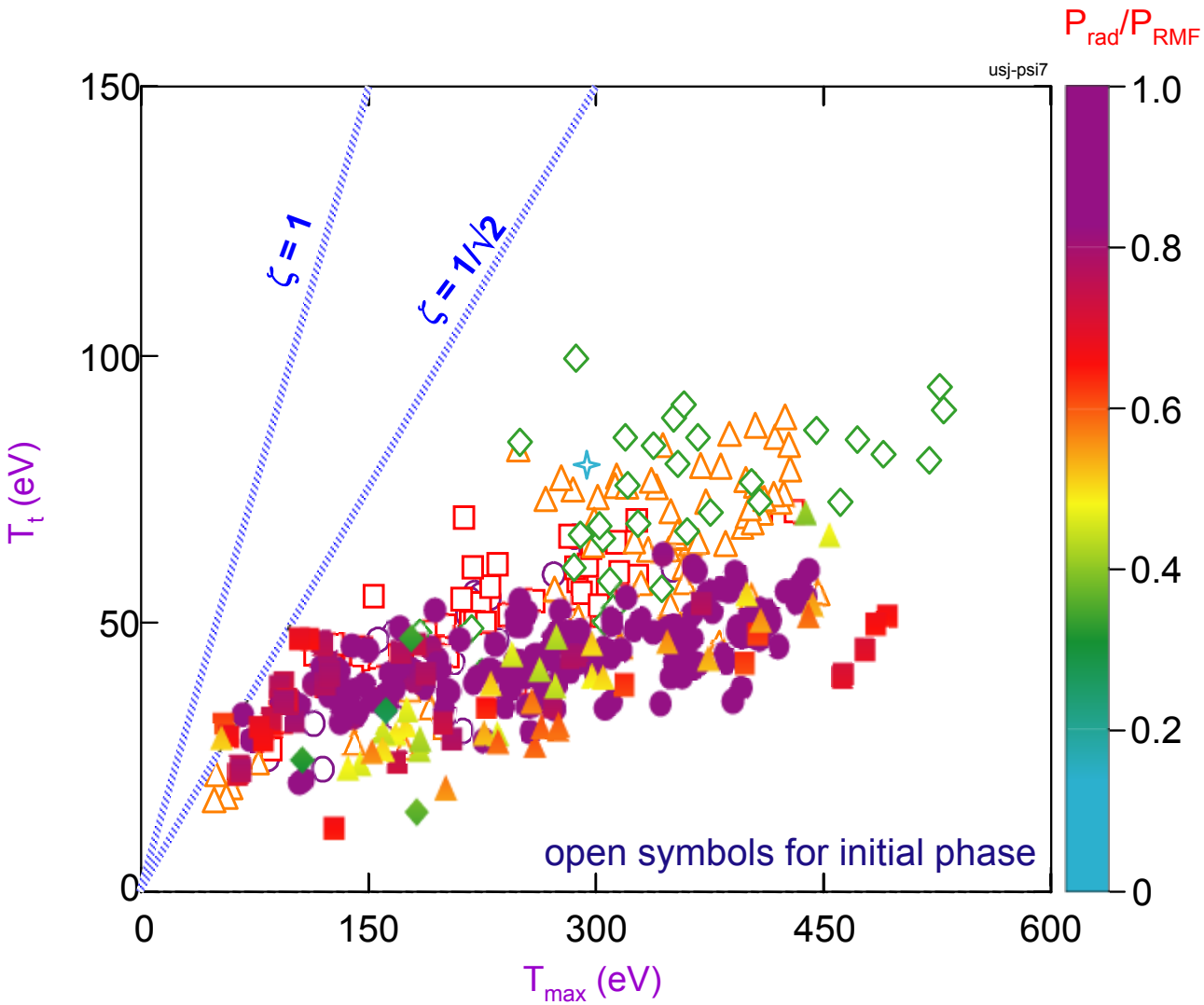
- Carbon concentration only ~ 0.5% based on CD_4 doping results.
- Dominant impurity appears to be oxygen, which may come from end metal cones, especially if the axial flow out the FRC ends is strong.
- Silicon is originated from direct interaction of the plasma with the quartz walls. Inward flow induced by the RMF would further reduce the screening efficiency for the wall source.

Illustration of Temperature Independence on RMF Parameters



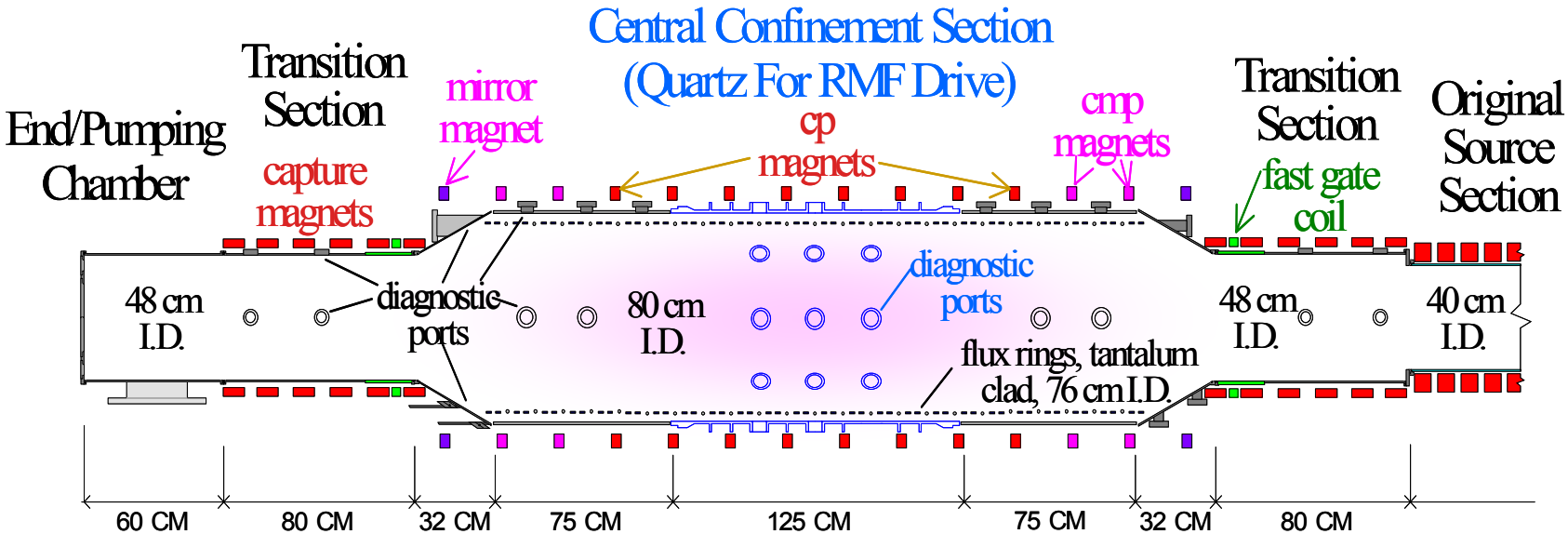
- **Initial temperature rises rapidly over 100 eV.**
- **But quickly decays as radiation increases, thus reducing B_e.**
- **Absorbed power doesn't vary much, suggesting lower resistivity for initial high temperature plasma.**

Operational Space



- **Maximum Temperature which is set by ζ=1 (full penetration) is well above the presently achieved temperatures.**
- **Operational space can accommodate higher temperature if power losses can be reduced.**

Modifications Underway on TCS to Reduce Impurity Influx



- **Larger, metal input section to avoid translated FRC contact with quartz.**
- **Protective tantalum covered flux rings under quartz RMF drive section.**
- **Elimination of "O-rings" to allow bakeout & discharge cleaning.**
- **Combination of Ti-gettering and boronization wall conditioning.**

Summary

- **FRCs have been formed and sustained in steady-state by the Rotating Magnetic Fields (RMF) in TCS.**
- **RMF just penetrates to the field null, yet full field reversal is achieved at the inner field lines. RMF drive force present in the edge must be strong enough to drive an inward flow to sustain the current on the inner field lines.**
- **FRCs can be sustained with axial lengths well beyond the RMF antenna, presumably due to induced axial outflow.**
- **TCS formed FRCs presently have temperatures limited by impurity radiation. Changes are being made to the present 'O-ring' sealed quartz chambered TCS to provide bakable metal walls and active wall conditioning (T_i gettering and boronization) to increase the temperature and further improve FRC performance.**