Long-pulse operation of the PFRC-2 device

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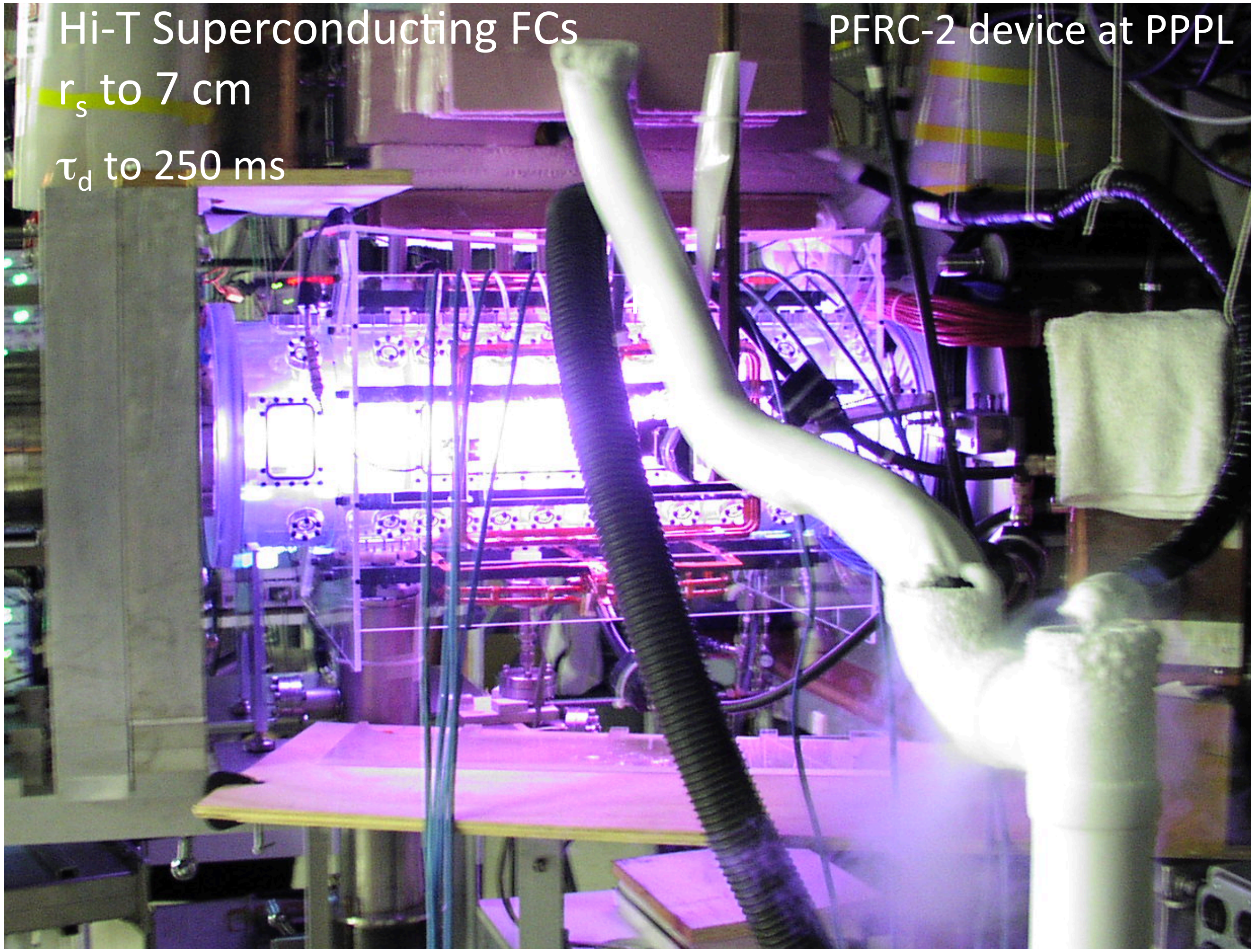

Hi-T Superconducting FCs

r_s to 7 cm

τ_d to 250 ms

PFRC-2 device at PPPL

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Take-away points

- Research aimed at small (1-10 MW), clean, fusion reactors for niche applications.

- Flux conservation is critically important.
  - Wall (PMI) interactions should be minimized.
  - Separatrix should be well away from wall.

- Fueling techniques critically important.

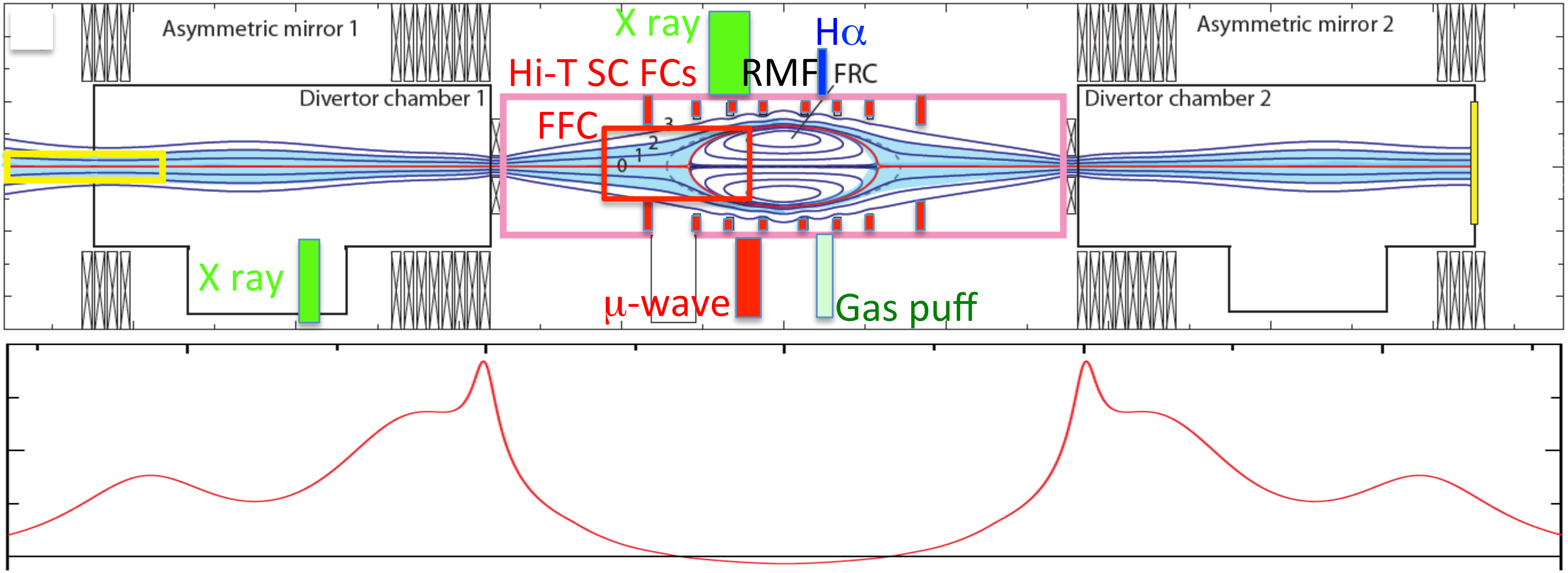
- Stable discharge durations (250 ms) exceed 10^5 τ_{Alfven}.

- Rotating interchange modes stabilized by gas puffing.

Outline

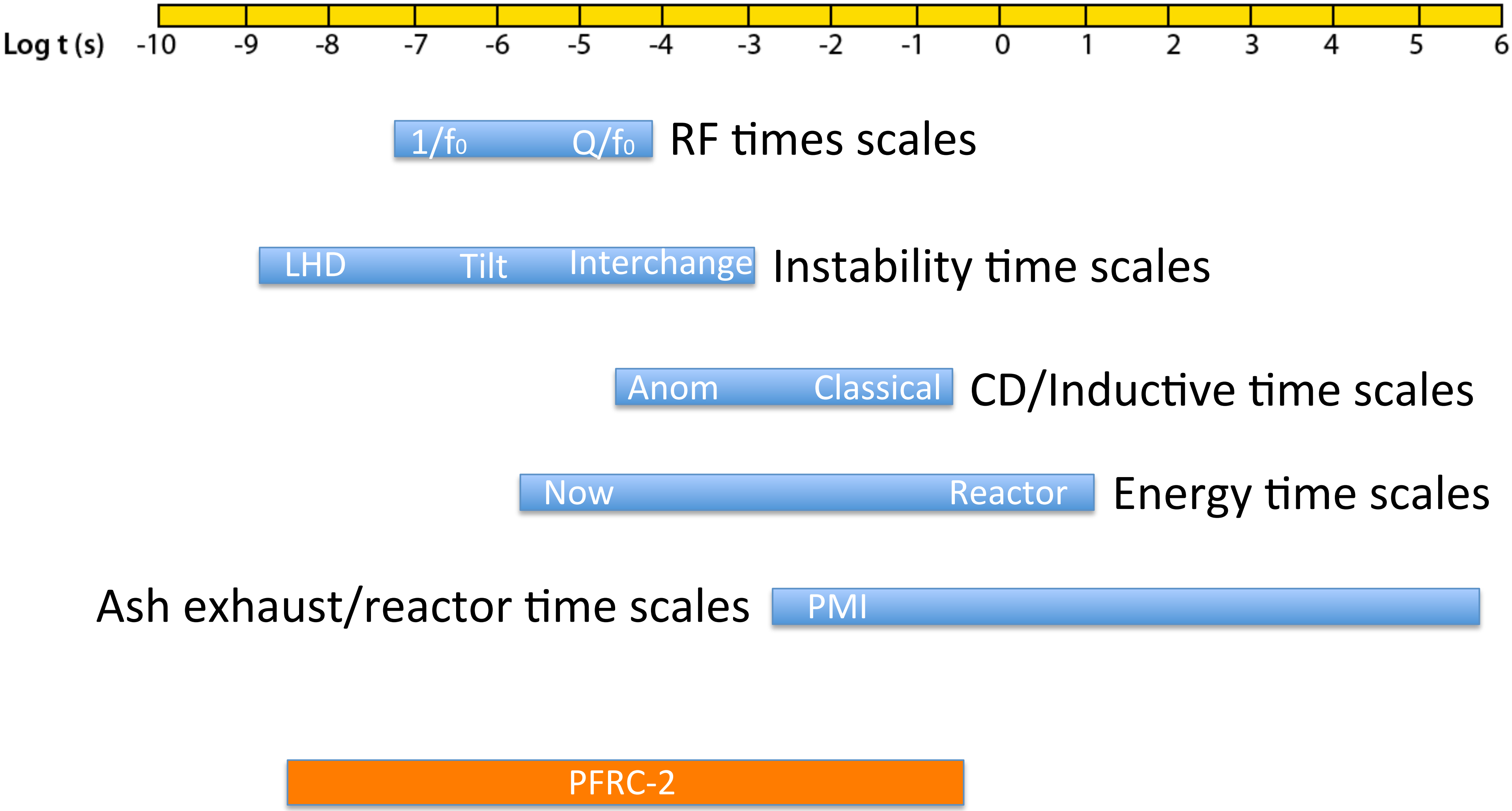
- Long pulse: to 250 ms
- Superconducting flux conservers (Hi-T SC FCs)
- RMF_o heating of the PFRC-2
- Gas puffing: refueling

The PFRC-2



An FRC embedded in an axisymmetric tandem mirror

Why long pulse – what is long pulse?



1/f0 Q/f0 RF times scales

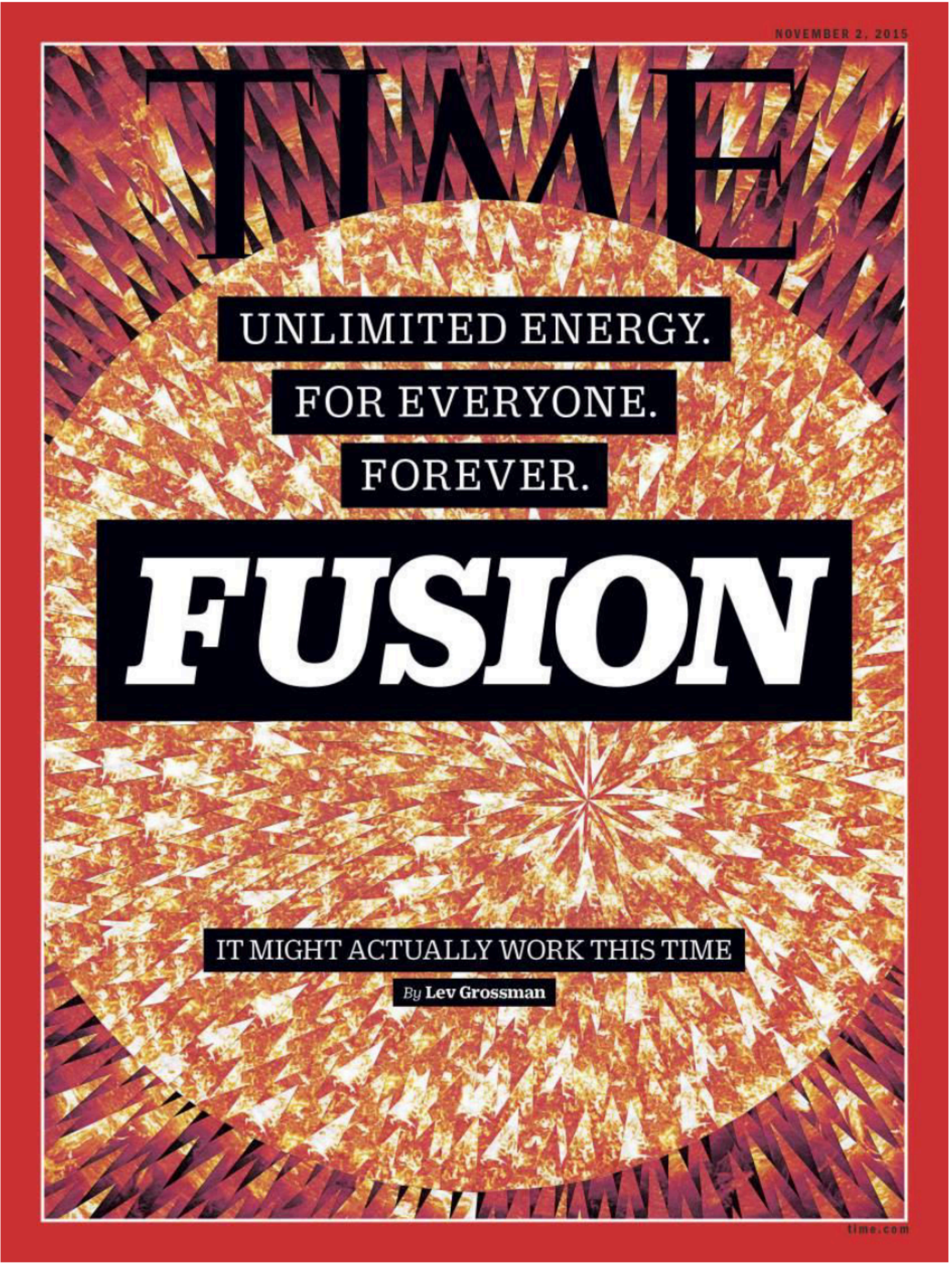
LHD Tilt Interchange Instability time scales

Anom Classical CD/Inductive time scales

Now Reactor Energy time scales

Ash exhaust/reactor time scales PMI

PFRC-2



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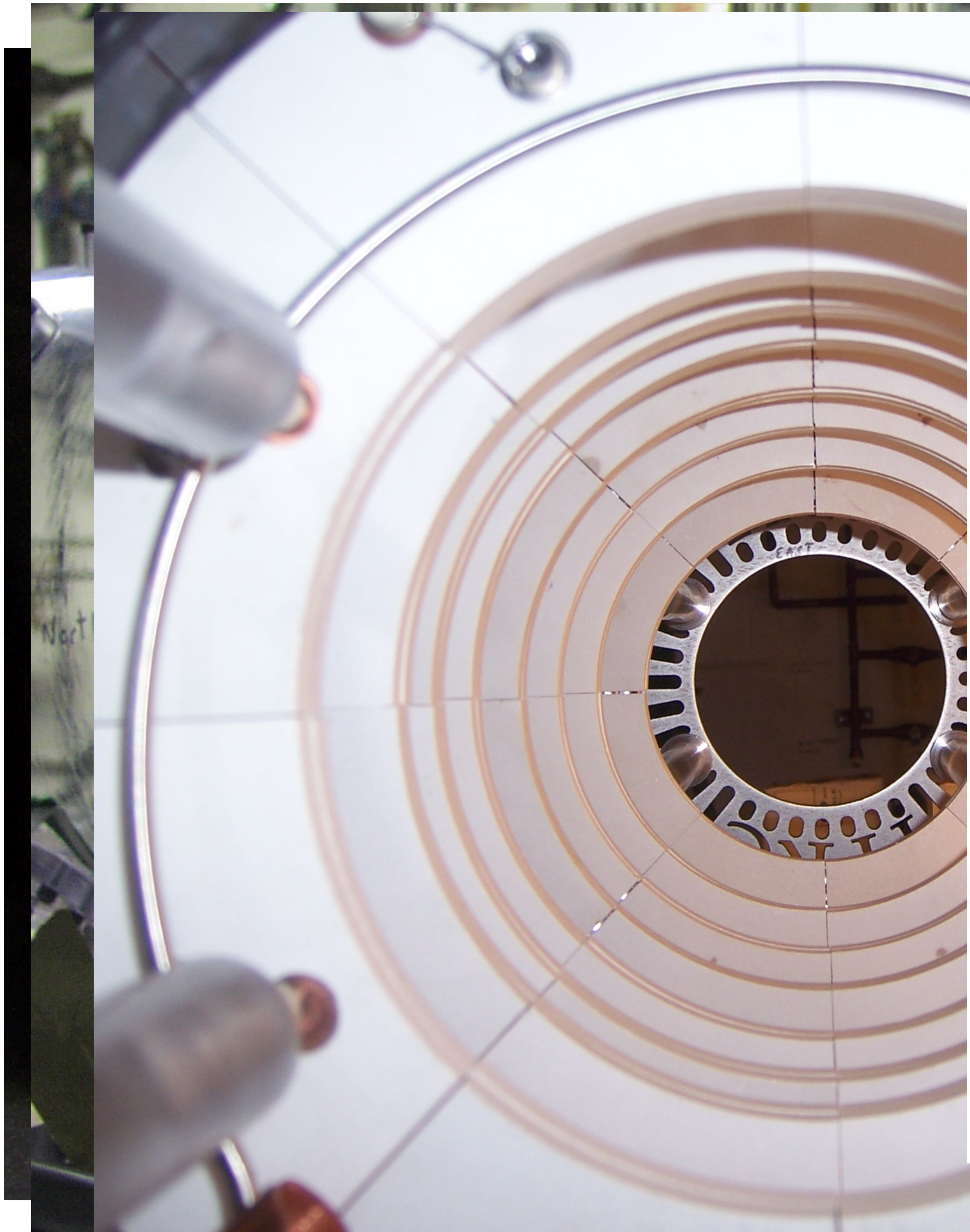
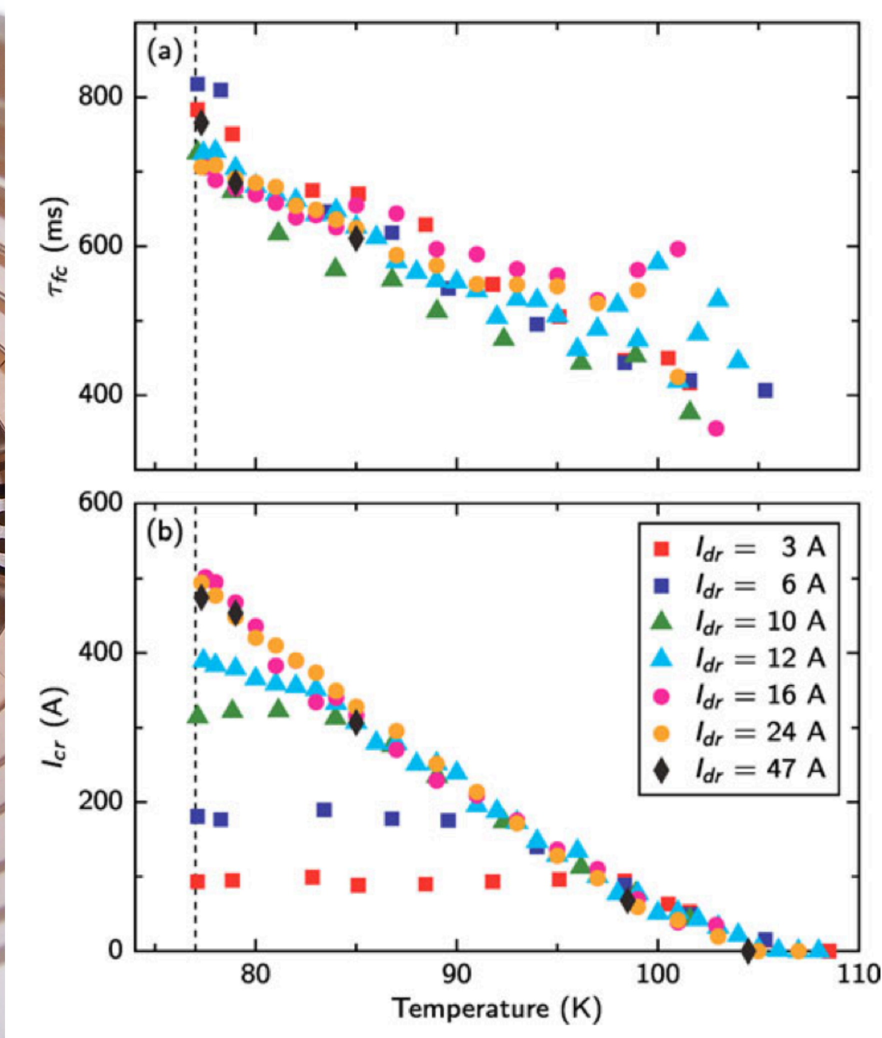
No flux conservers

High-Temperature Superconductor FCs

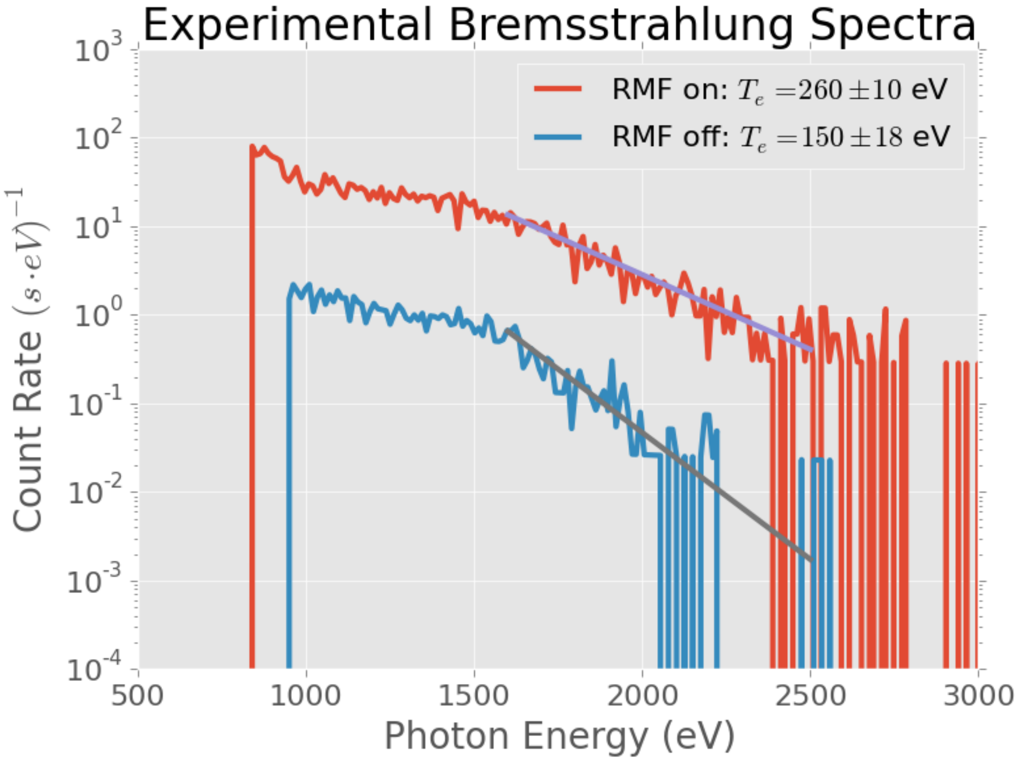




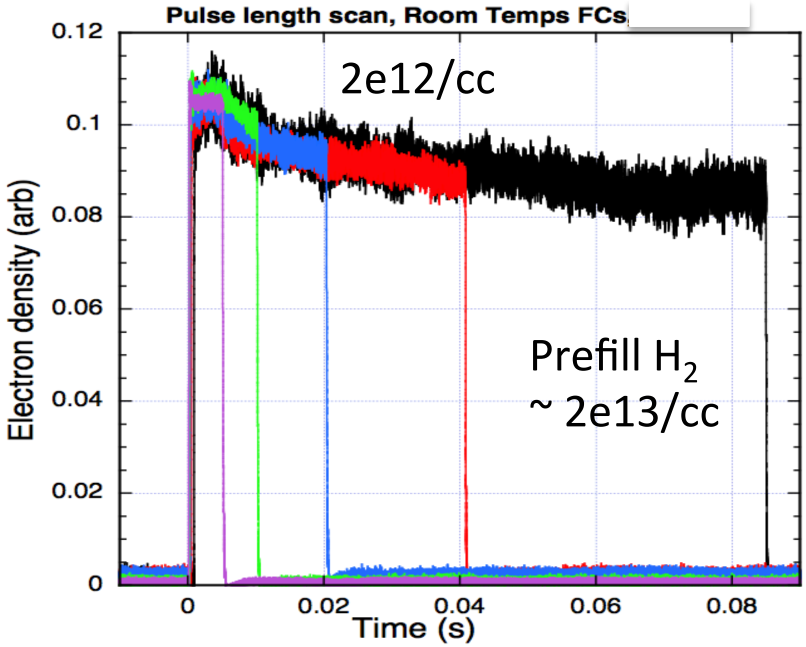
RMF$_o$ heating of the PFRC-2

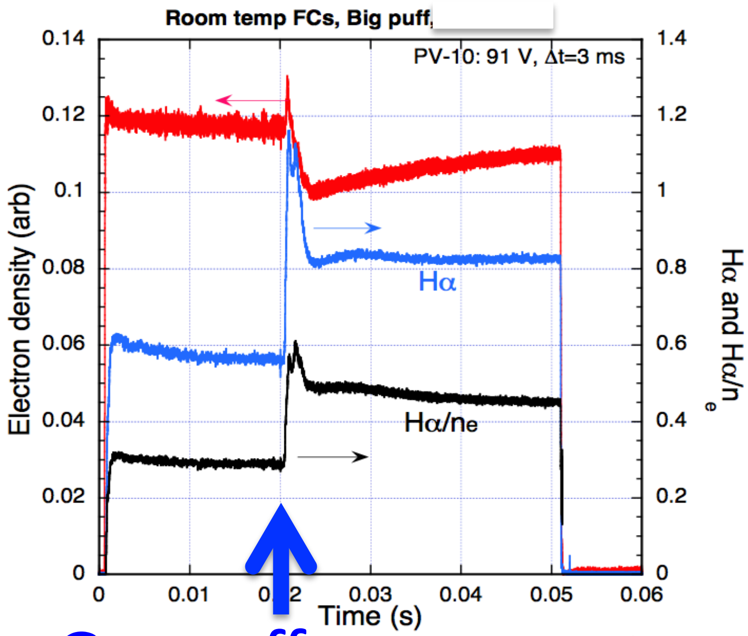
- Characteristics
  - Frequency = 8.025 MHz
  - Odd parity
  - $P_{forward}$ to 25 kW (200 kW); $P_{reflected}$ ~ ¼%
  - $P_{absorbed}$ ~ 35-75% P_f
  - Duty factor 1%
- Predicted benefits
  - Closed field lines
  - Electron heating
    - Swanson presentation
  - Ion heating (ω_{RMF}~ω_{ci})
  - Plasma stabilization

PFRC-2 count rates ~ 0.01 of PFRC-1's
PFRC-2 power density ~ 0.1 of PFRC-1's



n_e behavior with room-temperature FCs





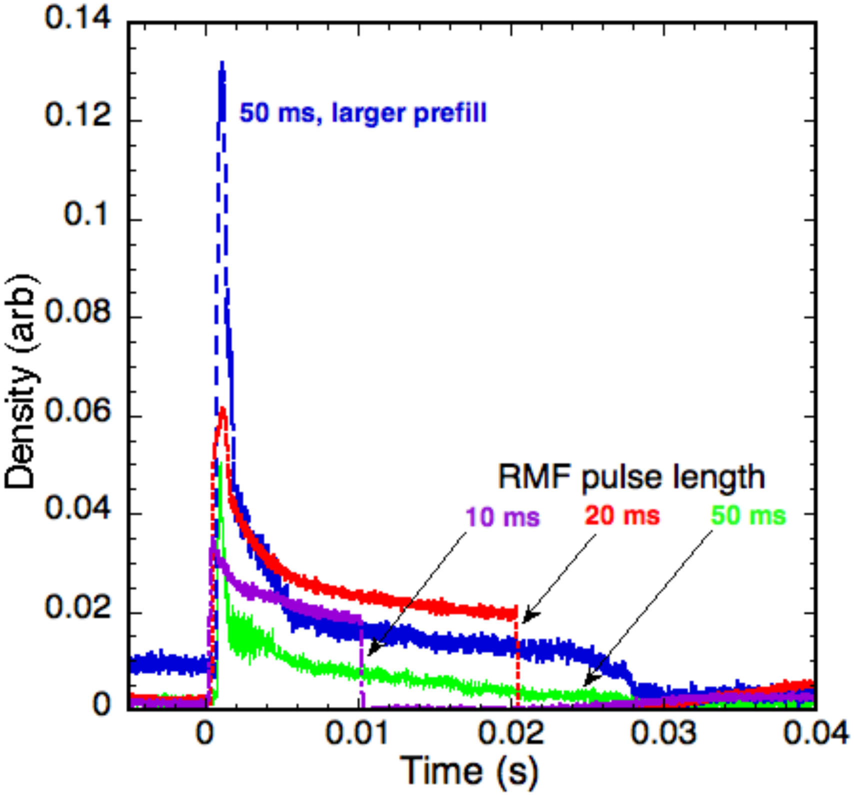
Gas puff

P_f ~ 10 kW, I_H = 100 A

- Density stays ~constant throughout pulse.
- Gas puff only increases n_e briefly.
- Temporary reduction in n_e fluctuations.
- Midplane H_α rises, stays high long after gas puff.
  - Recycling off room temperature FCs (τ_{FC}~ 3 ms @ 70F)

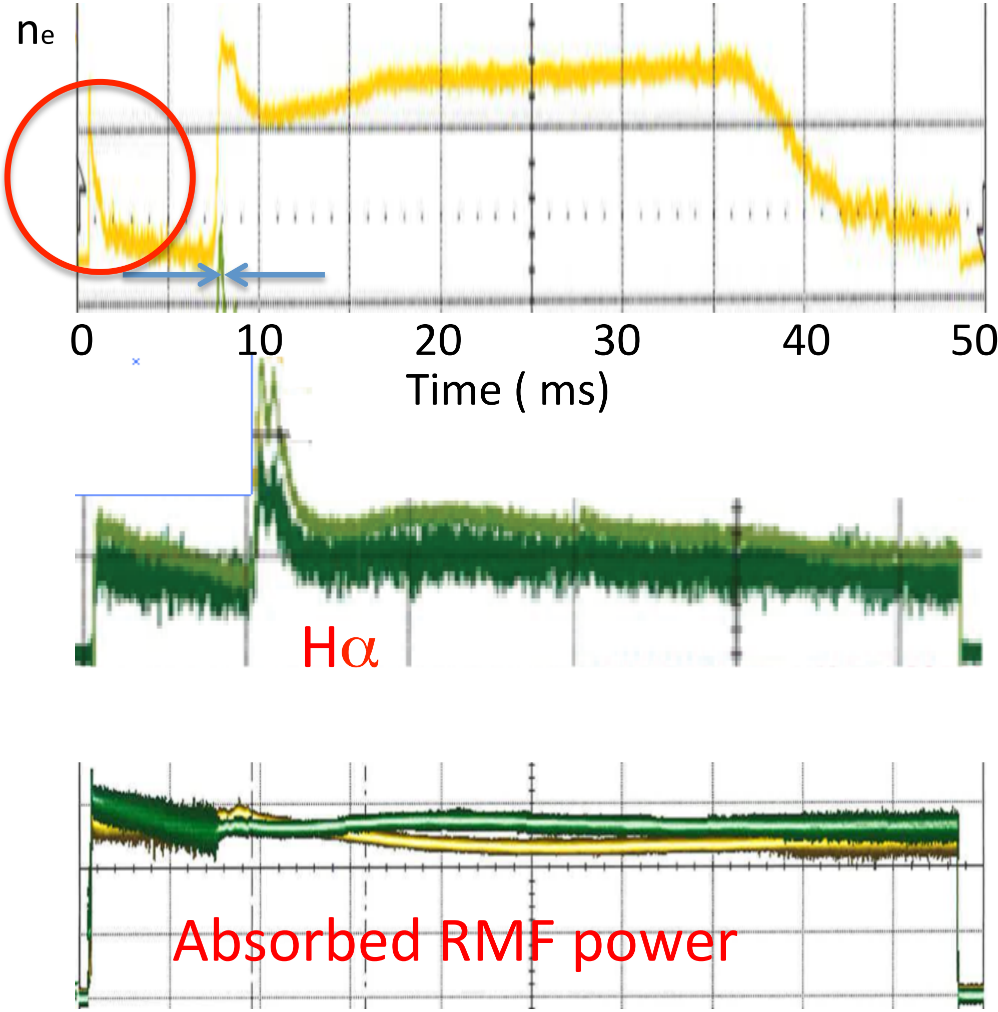
Behavior with SC FCs at LN2 temperature: (τ_{FC} = 1 s)

Pulse length scan



Density rapidly decays

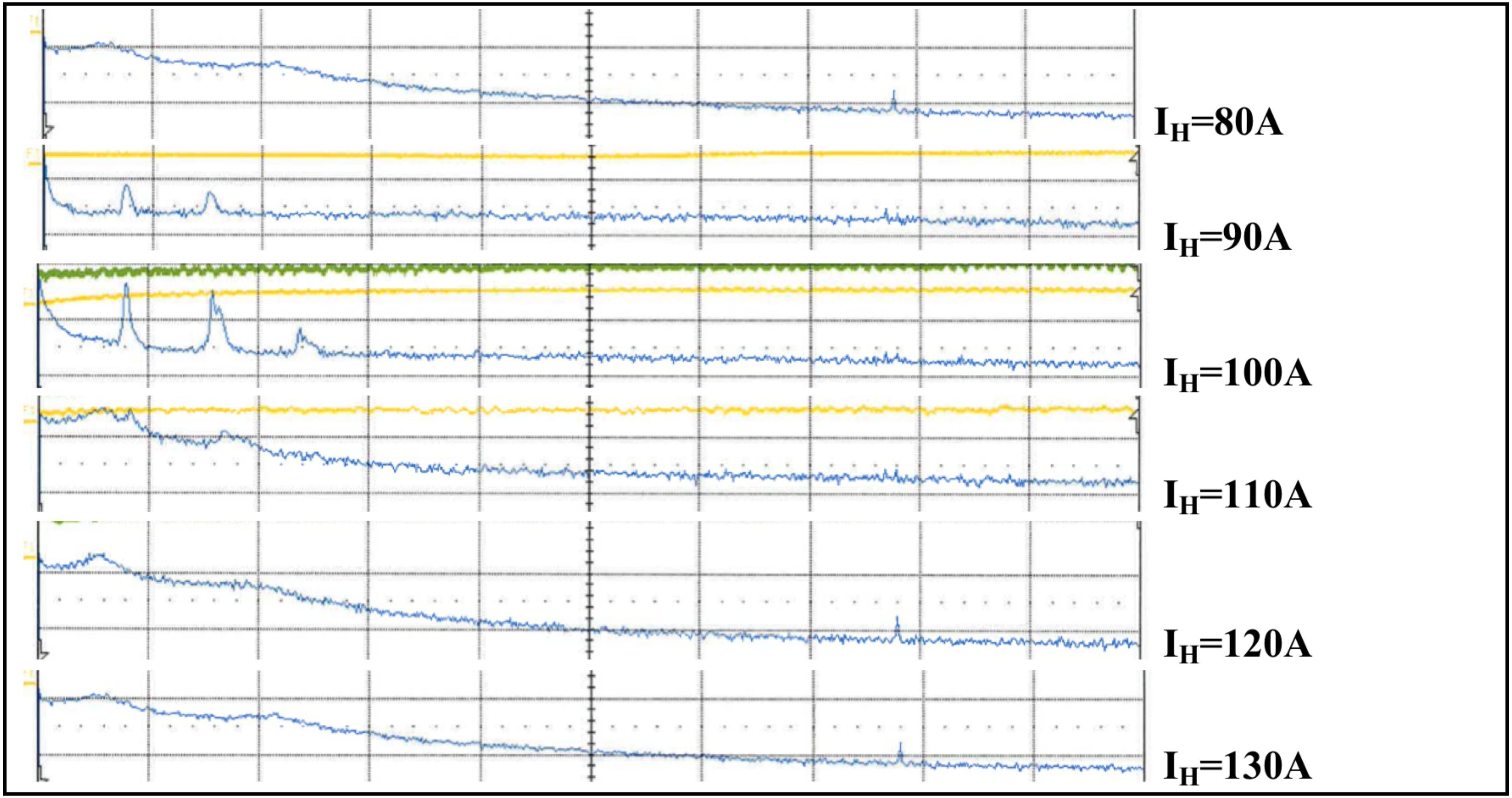
Gas puff!



Fluctuations suppressed longer

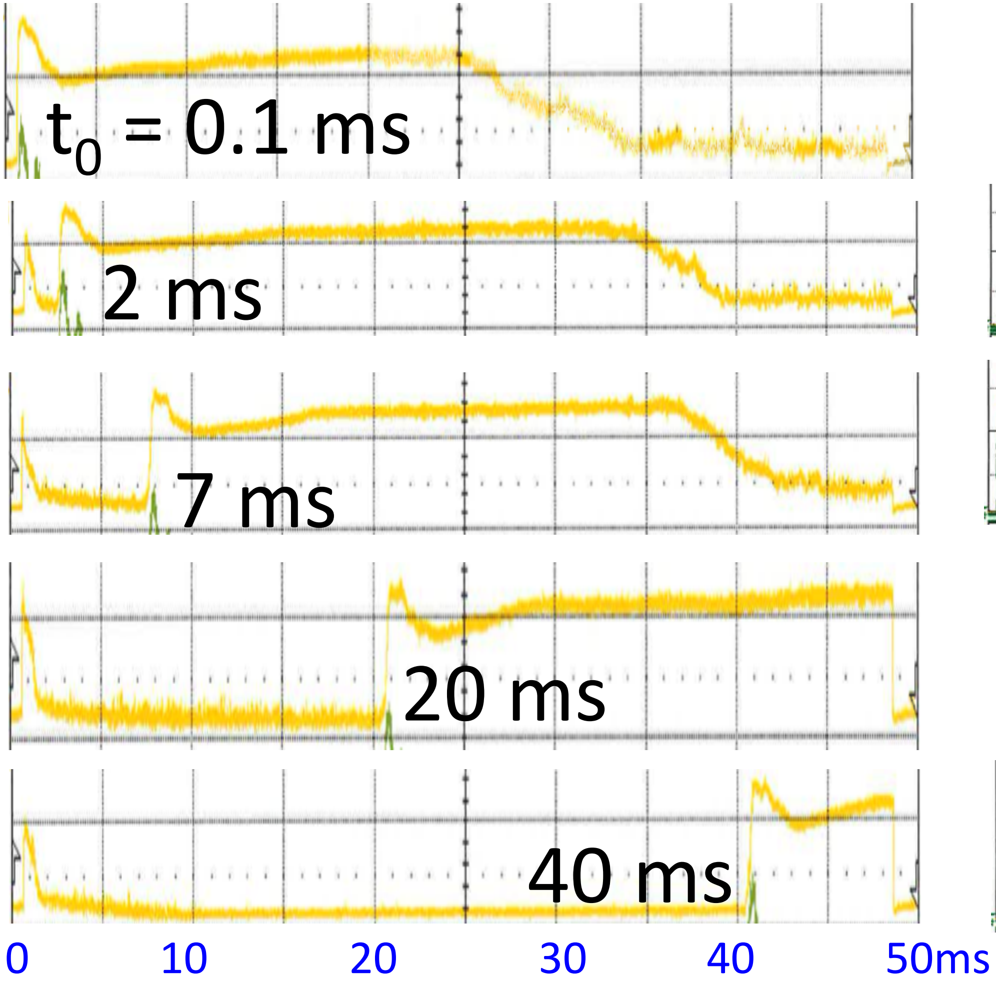
Density flattop from 2 ms gas puff persists for 10s to 100s ms

Behavior low-f n_e fluctuations with SC FCs (LN2)

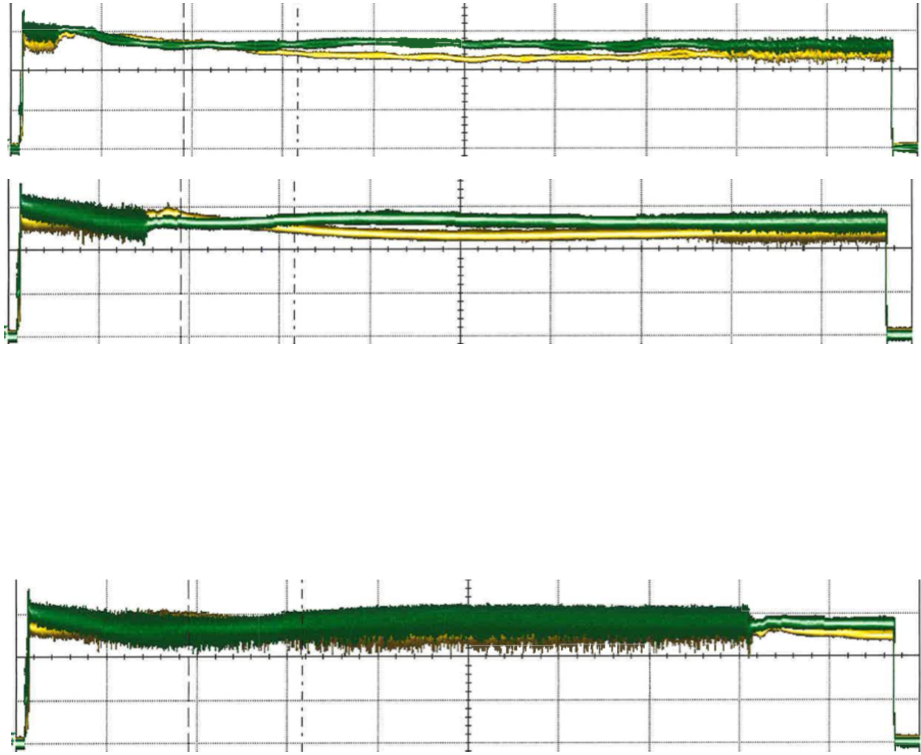


10 kHz/div, p_o = 0.66 mT, P_f =8 kW

Effect of gas-puff-time on n_e with SC FCs (LN2)



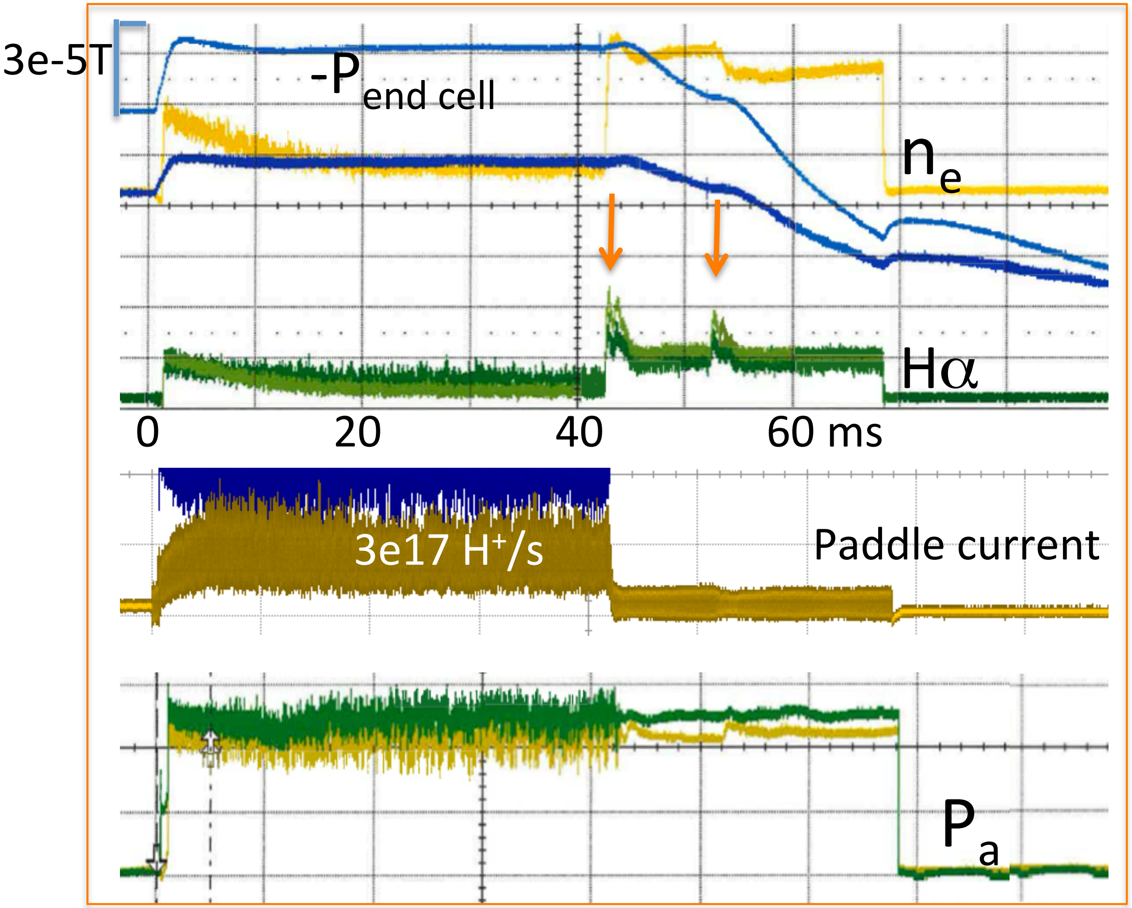
Line–average density



Absorbed RMF power

Injecting too early decreases density plateau duration

Effects of gas puffs in end cell



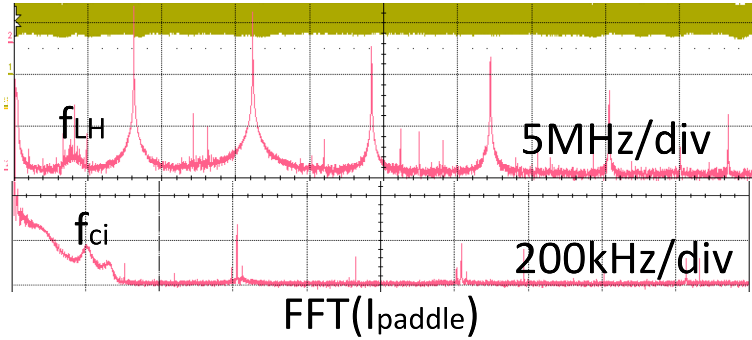
P_f = 10 kW; I_H = 130 A

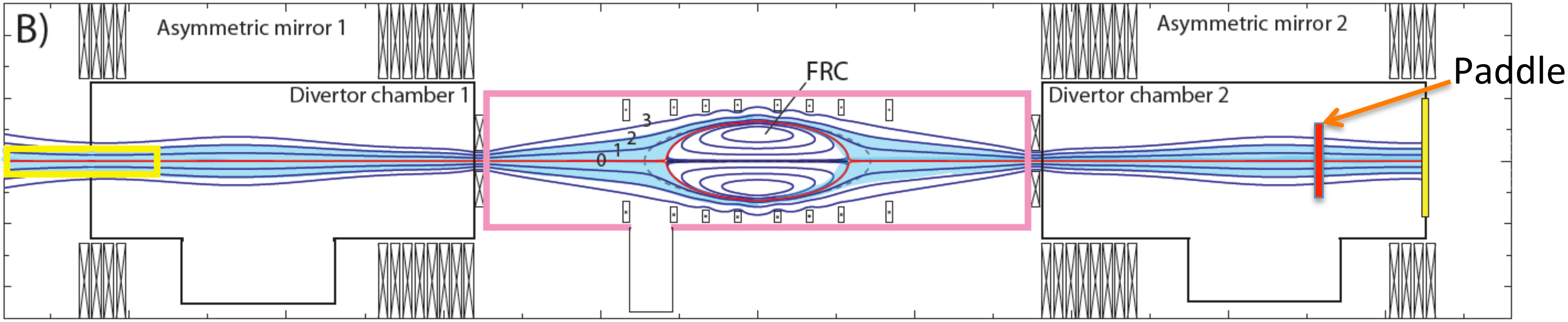
Initial pump out of end cell.

Gas puff raises pressure in end cell

For this case Hα increases.

Gas puff stifles ion flow to paddle.





Working model of density behavior

- RMF efficiently ionizes central cell gas in < 0.2 ms.
- With Hi-T SC FCs, plasma flows into end cells until density in central cell falls, increasing RMF penetration $\sim T^{5/4}/n^{1/2}$.
- Good heating occurs, promoting full RMF penetration.
- Current drive & re-distribution: FRC forms

  $L/R|_{cl} \sim 2$ ms while $L/R|_{anom} \sim 20\ \mu$s
- Confinement improved because FRC formed.
- Subsequent gas puff penetrates low-density FRC plasma, is ionized throughout, and decorates the already established FRC field pattern.
- Long pulses, *via* **SC** FCs, were necessary to see this wall-influenced behavior.

Open questions (immediate)

- Profile effects
  - Is density increase due to axial contraction or improved confinement?
  - Need full n_e, T_e, T_i profiles
  - Separatrix existence and shape
  - SOL parameters, including flows
- The role of hydrogen implantation in the walls
- Ion-electron & ion-neutral drag
- CD efficiency
- Higher field, higher power: ion heating

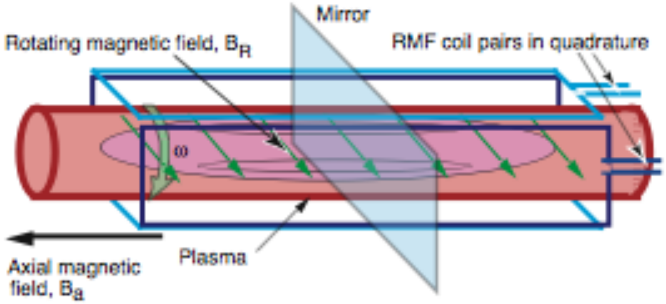
Summary: Long-pulse RC discharges

- Flux conservation is critically important.
    - Wall (PMI) interactions should be minimized.
    - Separatrix should be well away from wall.
- Gas fueling technique has been essential.
- Stable discharge durations exceed $10^5\ \tau_{\mathrm{Alfven}}$.
- Rotating interchange modes stabilized by gas puffing.
- *A posteriori*, surprising long-pulse behavior justifies our decision to built Hi-T SC FCs.
- Niche applications
    - Spacecraft propulsion (planetary defense, exploration)
    - Forward deployment
    - Distributed power grid

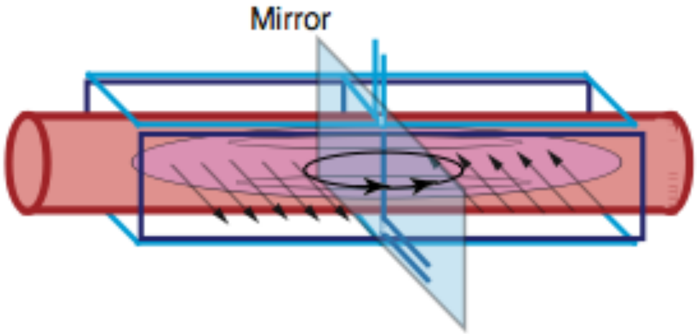
Additional slides

What is odd parity? Symmetry under mirror reflection

Even

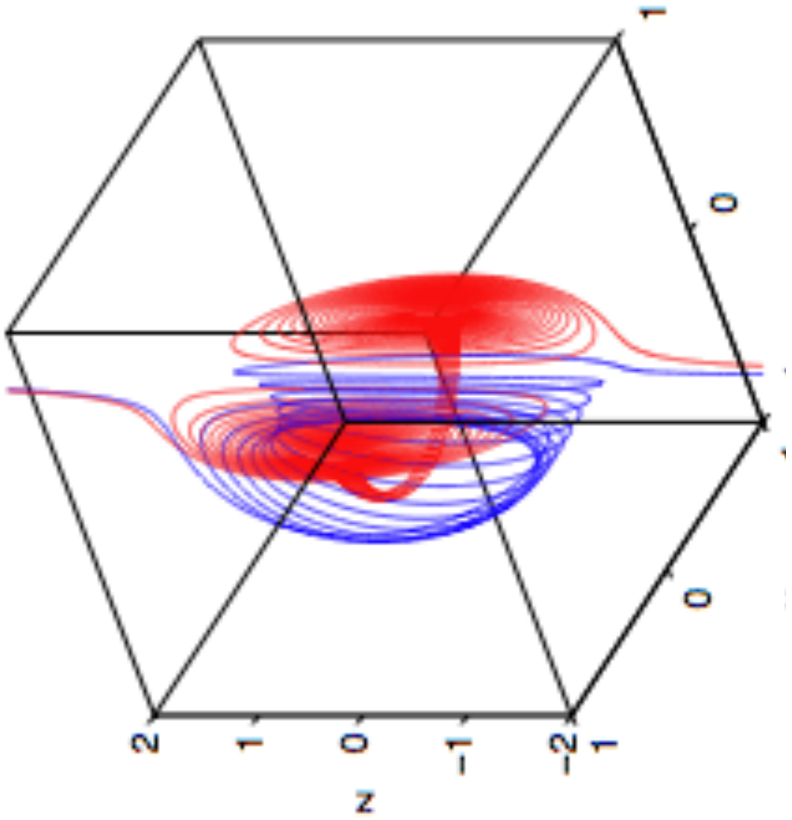


Odd

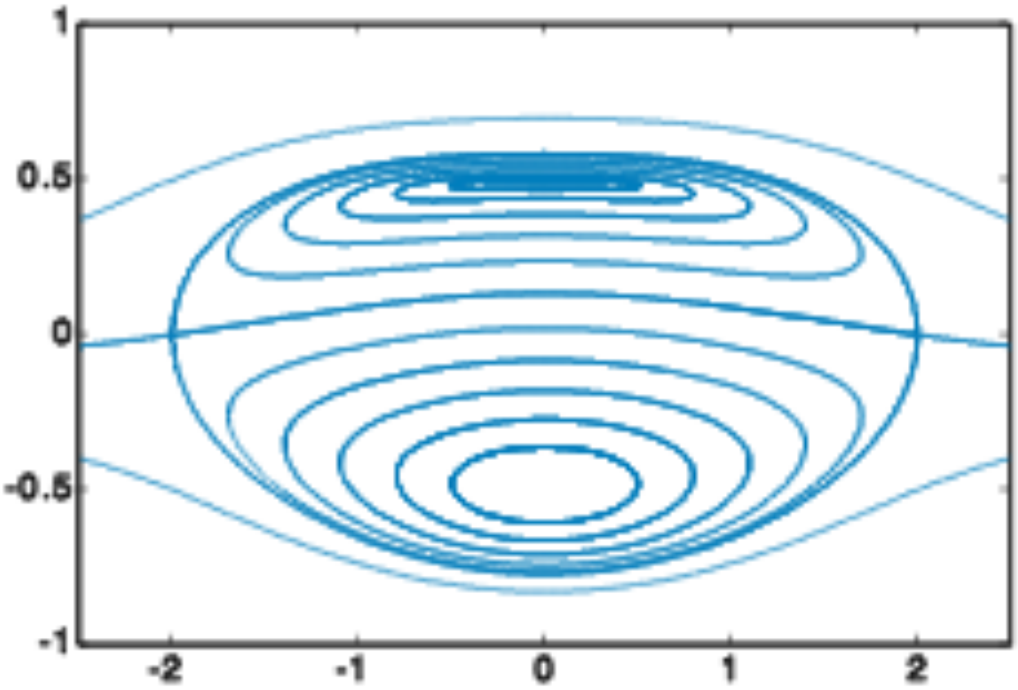


Open field lines are ones that intersect a material object or leave the device.

Closed *vs* open field lines

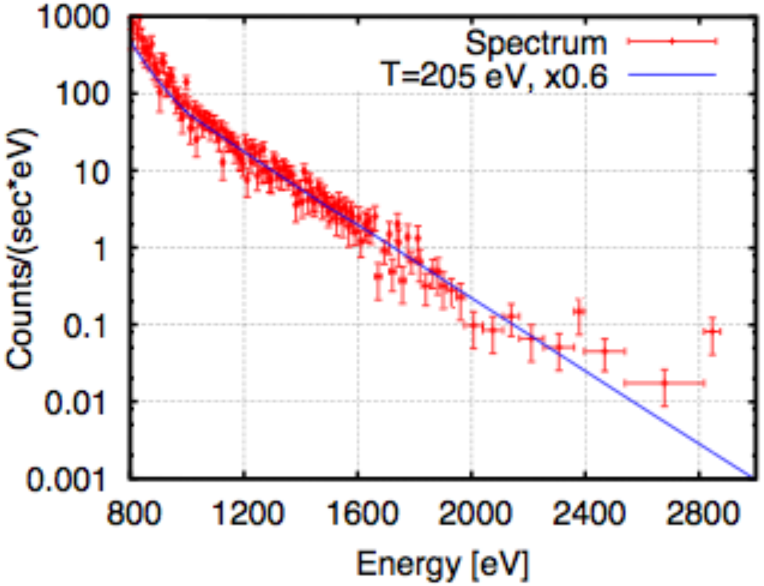


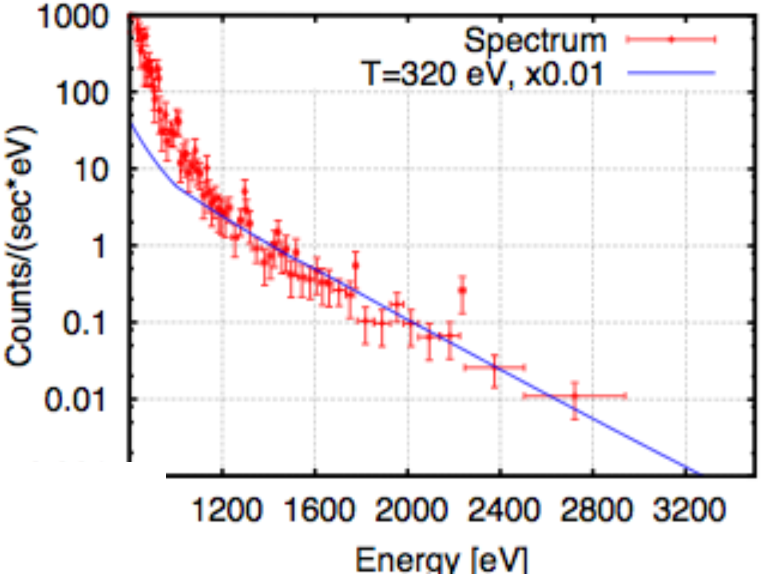
Even parity

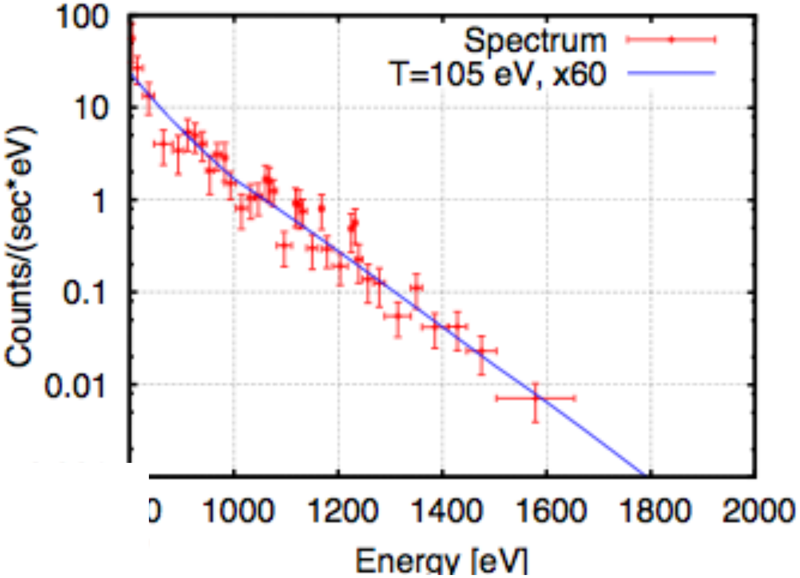


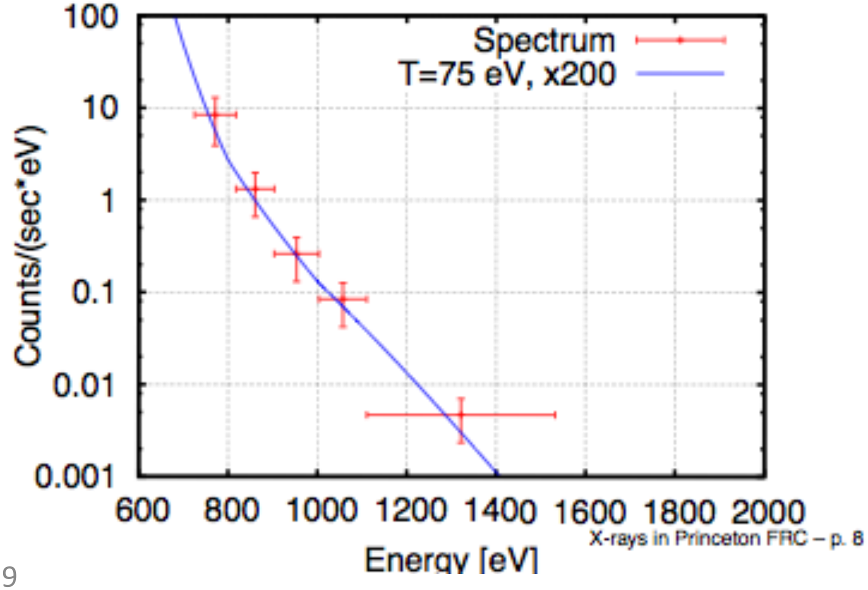
Odd parity
Better confinement

Closed field lines work – higher T_e

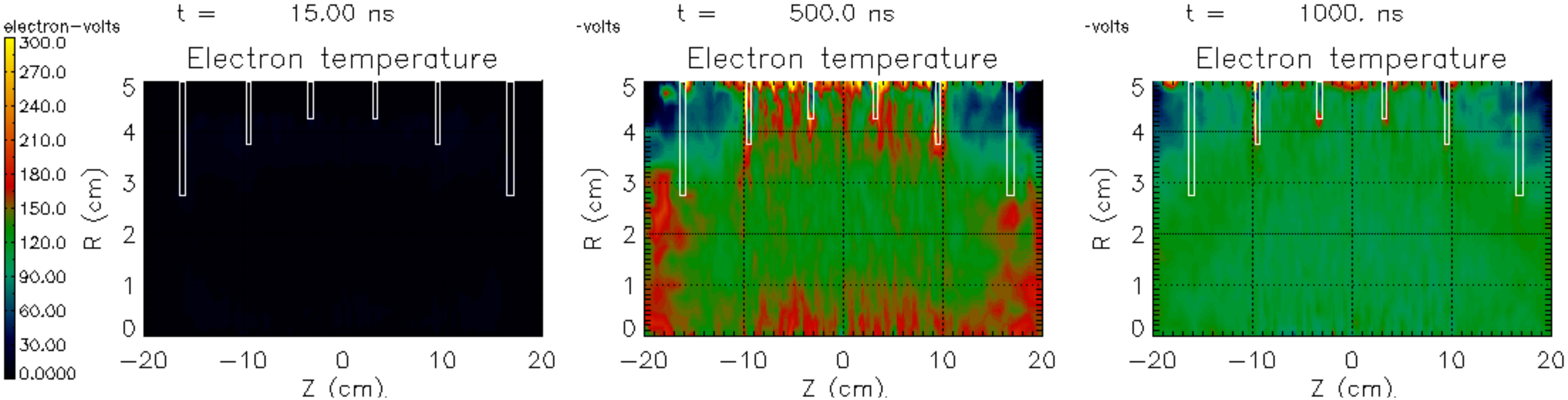






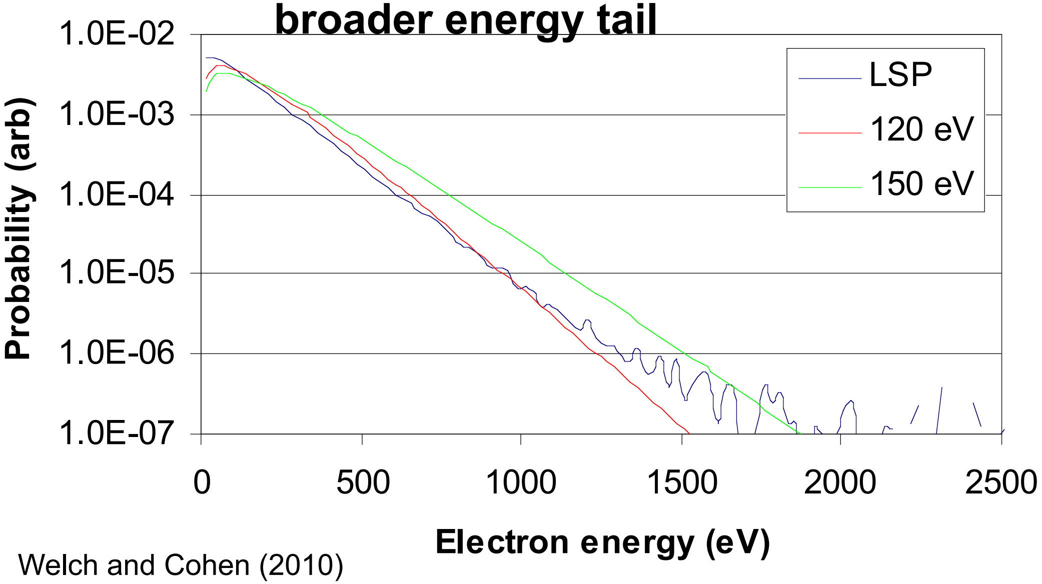


1. RMF_o electron heating- Lsp (PIC) code



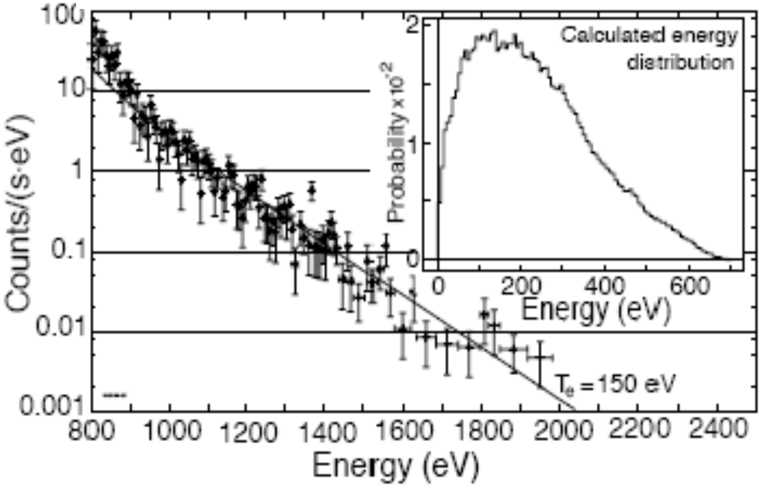
Fully self consistent, fully electromagnetic

LSP simulation between 120 and 150 eV Maxwellian, but with broader energy tail



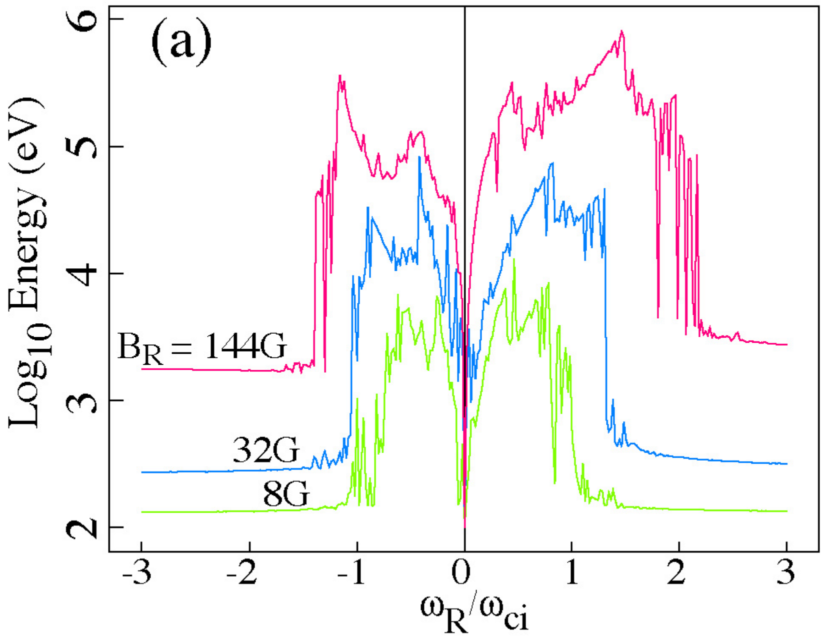
Welch and Cohen (2010)

PFRC Data showing 150-eV electron temperature



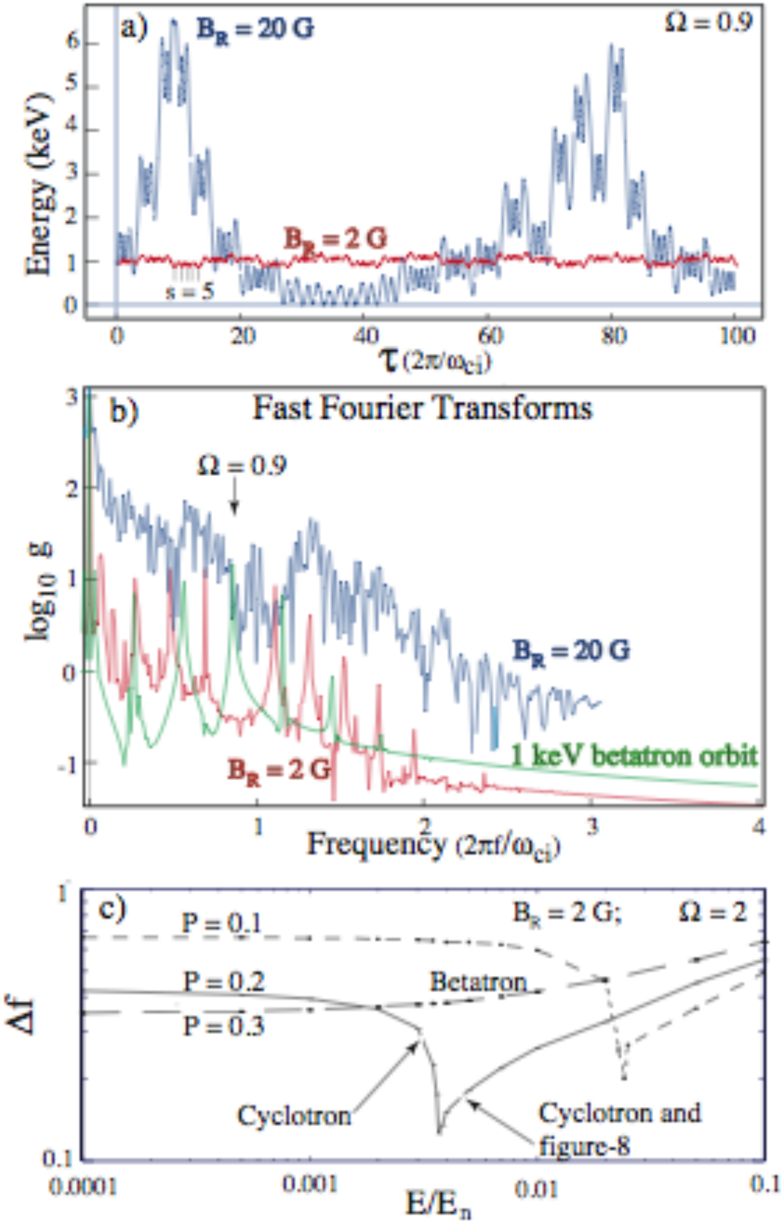
Roach and Cohen (2007)

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



$$K_{odd} \approx 8\pi s \left(\frac{1}{kR}\right)\left(\frac{B_R}{B_a}\right)\frac{d\tilde{\omega}(\tilde{E})}{d\tilde{E}}$$

$$K_{even} \approx \frac{\pi}{2} s^2 (kR) \left(\frac{B_R}{B_a}\right)\frac{d\tilde{\omega}(\tilde{E})}{d\tilde{E}}$$

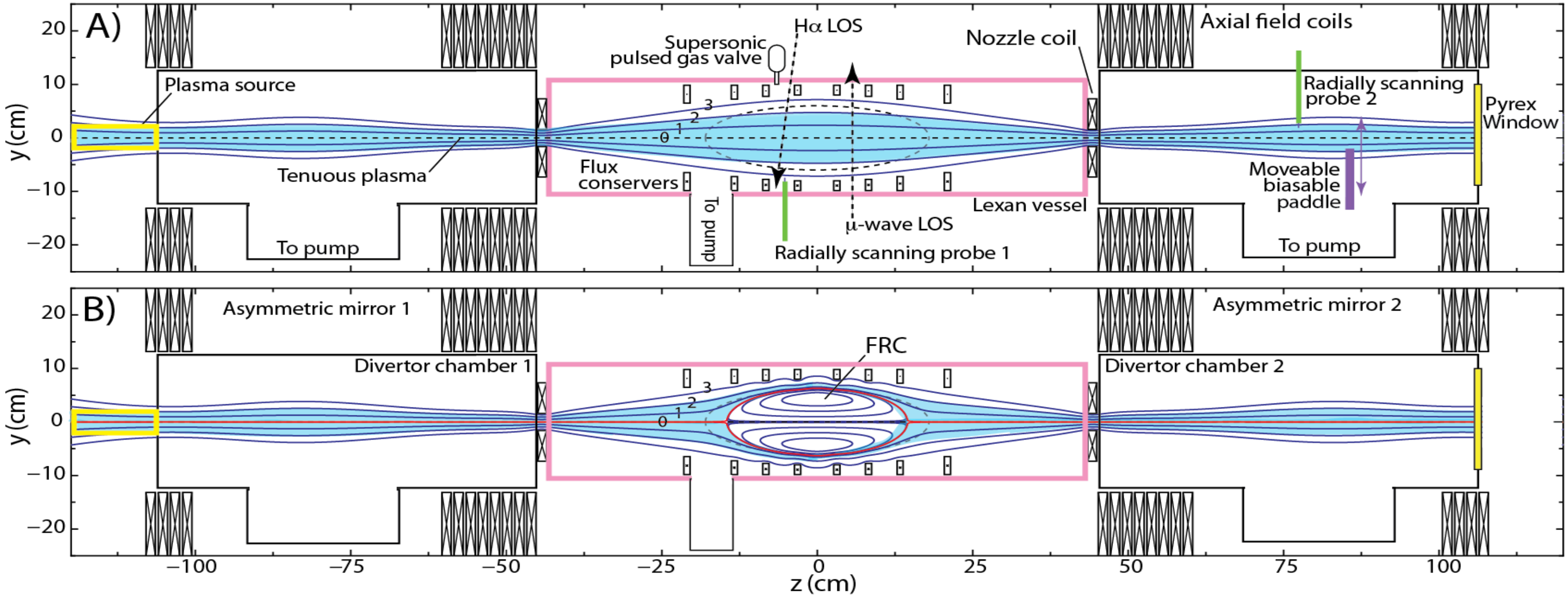


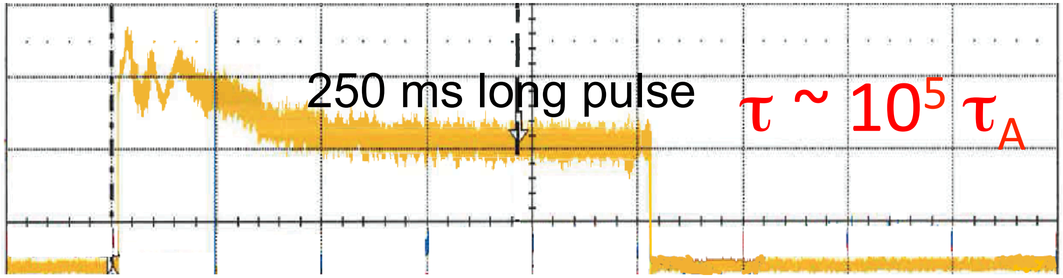
Cohen and Glasser (PRL 2000)

Cohen, Landsman, Glasser (PoP 2007)

Evidence for closed field lines

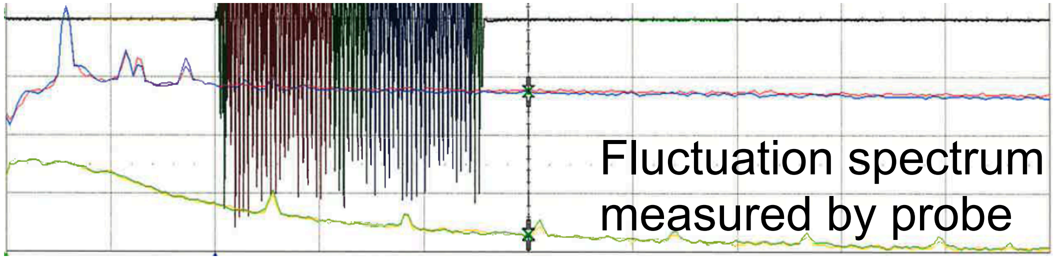
1st Goal: to close field lines, form a separatrix and improve confinement



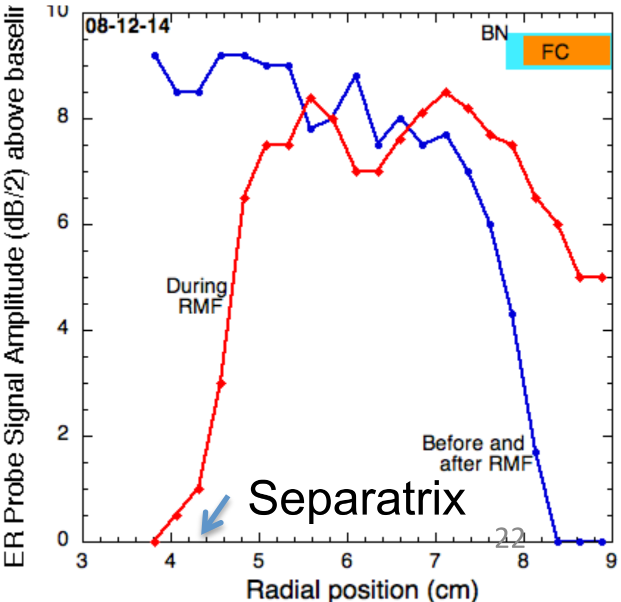


250 ms long pulse

$\tau \sim 10^5\, \tau_A$

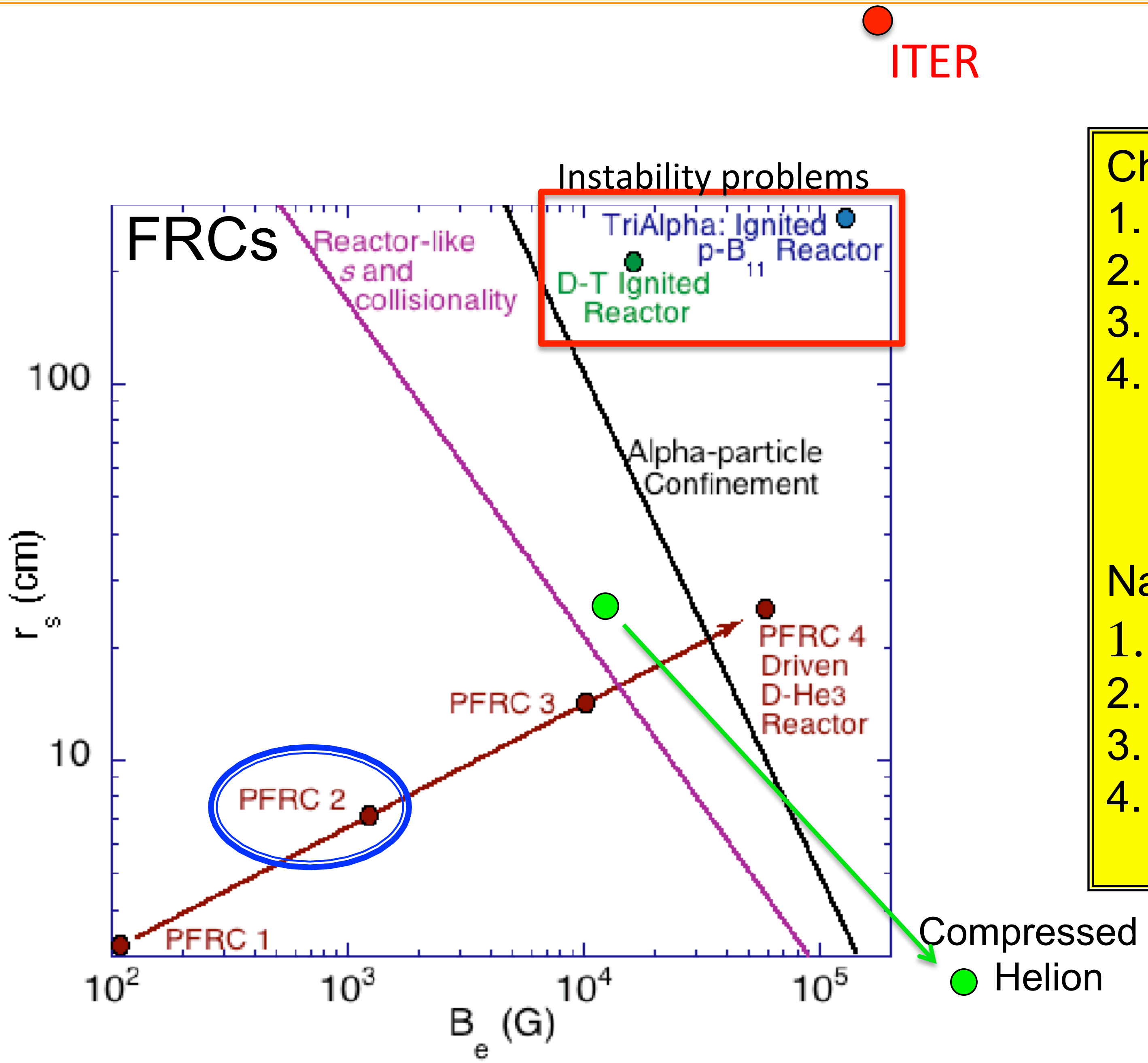


Fluctuation spectrum measured by probe



Separatrix

FRC options: The size-field plane



Choices
1. Fuel
2. Beta
3. Configuration
4. Heating method

Nature
1. τ_E
2. Size
3. Stability
4. Fusion power