TRI ALPHA ENERGY
THE POWER OF INGENUITY

Overview of C-2U Field-Reversed Configuration Experiments

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Exploratory Plasma and Fusion Science Research Workshop - EPR2016
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Outline

- **Introduction:**
  - Field-reversed configurations (FRCs); Concept; Project goals
- **C-2U Overview and Key Accomplishments:**
  - C-2U device, 10+ MW neutral beams, diagnostic suite
  - Key elements to high-performance beam-driven FRCs:
    - Formation; Wall conditioning; Boundary control; NB injection
  - Fast-particle effects
  - Confinement
  - Sustainment
- **Next Step – C-2W Project**
- **Summary**

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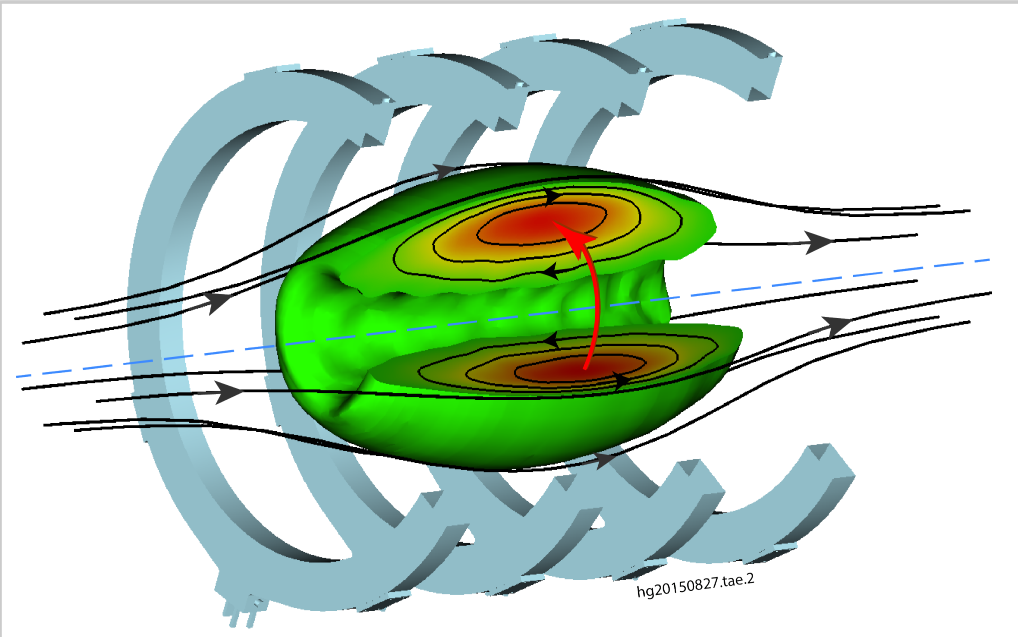
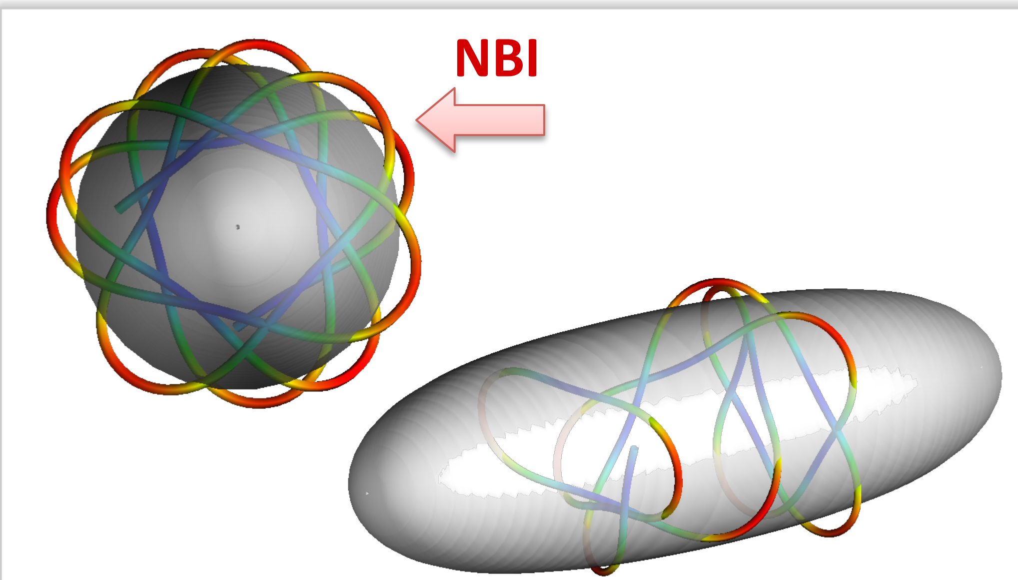
FRCs and Tri Alpha Energy's (TAE) Concept





- **High plasma β~1**
  - compact and high power density
  - aneutronic fuel capability
  - indigenous kinetic particles
- **Simple geometry**
  - only diamagnetic currents
  - easier design & maintenance
- **Linear unrestricted divertor**
  - facilitates impurity, ash and power removal
- **Tangential neutral beam injection**
  - large orbit ion population
  - improve stability and transport
- **Fast ions**
  - decoupled from micro turbulence
  - slow down at near classical rates

TAE's Present Goals – Focus of Efforts to Now

- Test for failure early and at reduced cost while reducing most critical risks
- Establish beam-driven high-β, large orbit FRC physics test bed to
  - provide fast learning cycles and large experimental dataset (~50,000 shots)
  - demonstrate sustainment via neutral beam injection (NBI) for >5 ms (longer than critical timescales) with high repeatability
  - study tangential NBI and fast particle effects on stability and transport
  - measure scaling and study fluctuations and transport
- Provide opportunity to
  - tightly integrate theory/modeling with experimentation
  - develop engineering knowhow and integration
- Invite collaboration to accelerate progress
  - Budker Institute, PPPL, UCI, UCLA, LLNL, Univ. of Pisa, Univ. of Wisconsin, Nihon Univ., Univ. of Washington, Industrial partners

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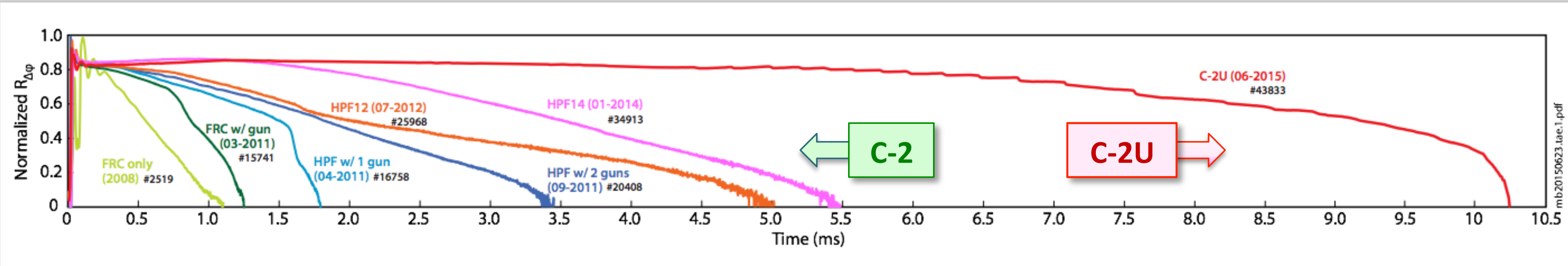
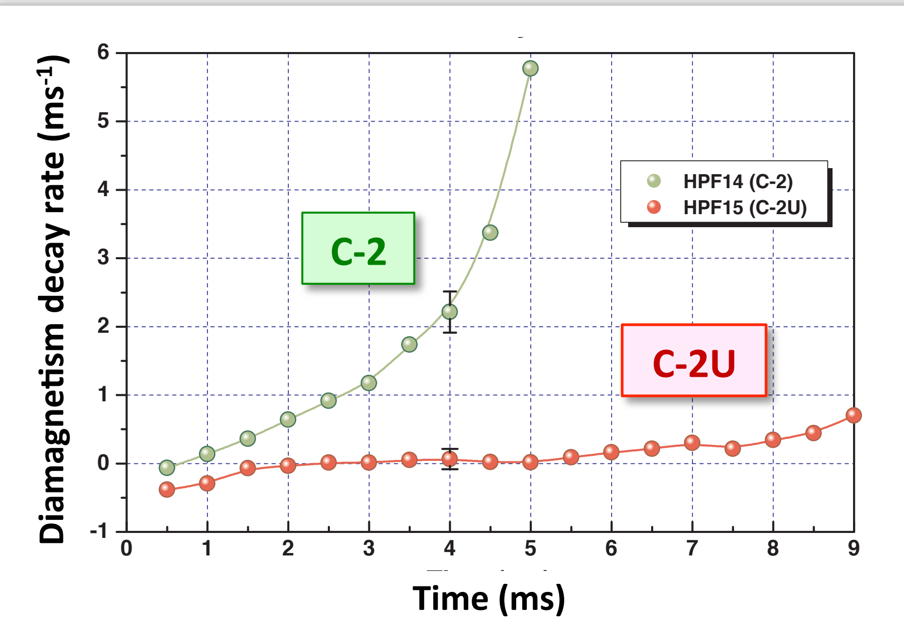
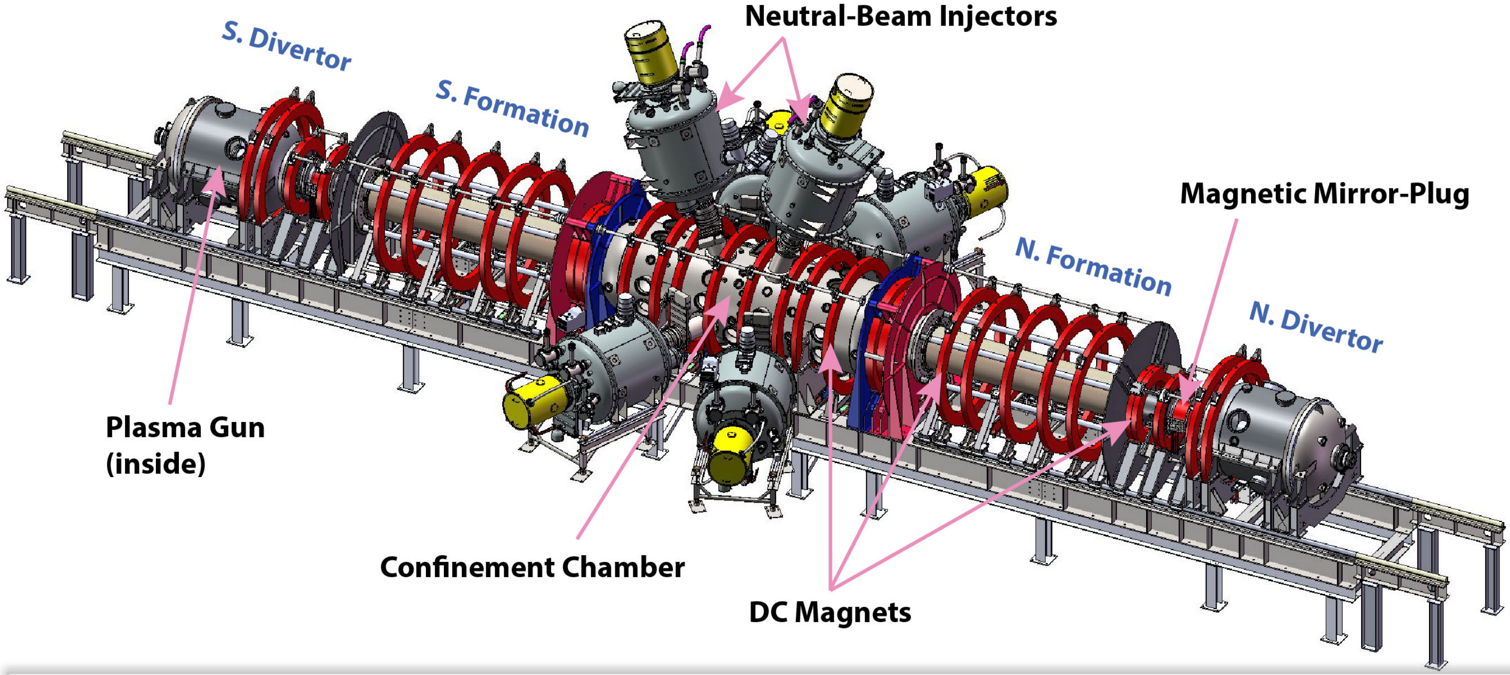
C-2U Key Accomplishments – Great Progress from C-2 and Achieved Plasma Sustainment for 5+ ms





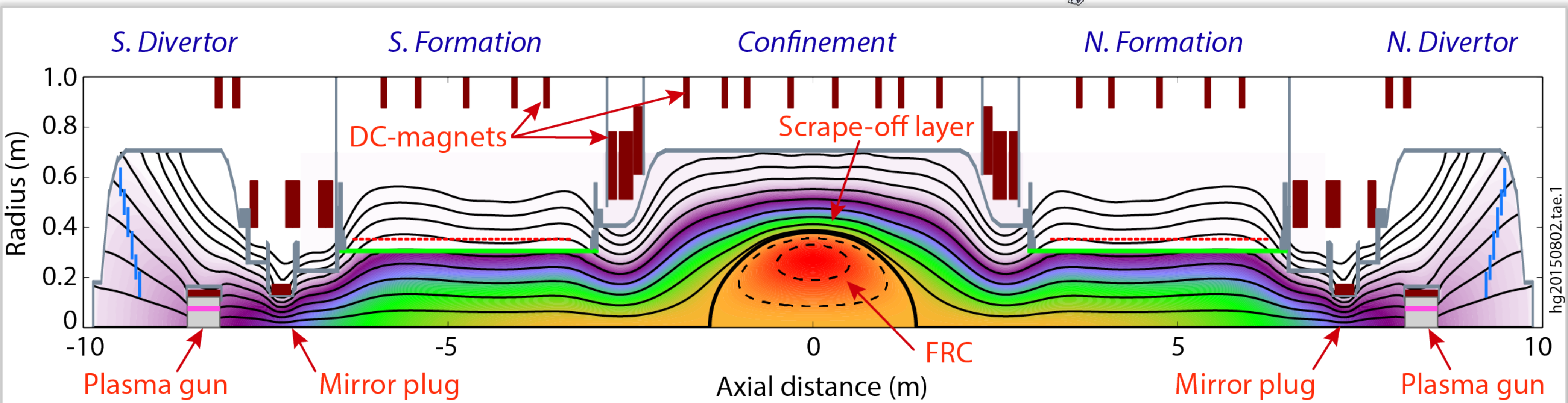
- C-2U produces **advanced beam-driven FRCs** via NBI, in which **plasma sustained for 5+ ms** and achieved ~11 ms lifetime
- **Diamagnetism maintained:**
  - showcases ability to drive current by beams
  - leaked flux not accounted for (wall time ~5 ms, while FRC lives longer)
- Other parameters (e.g. temperatures, density, energy, etc) also maintained

C-2U Research Facility to Study Sustainment of Advanced Beam-Driven FRC's

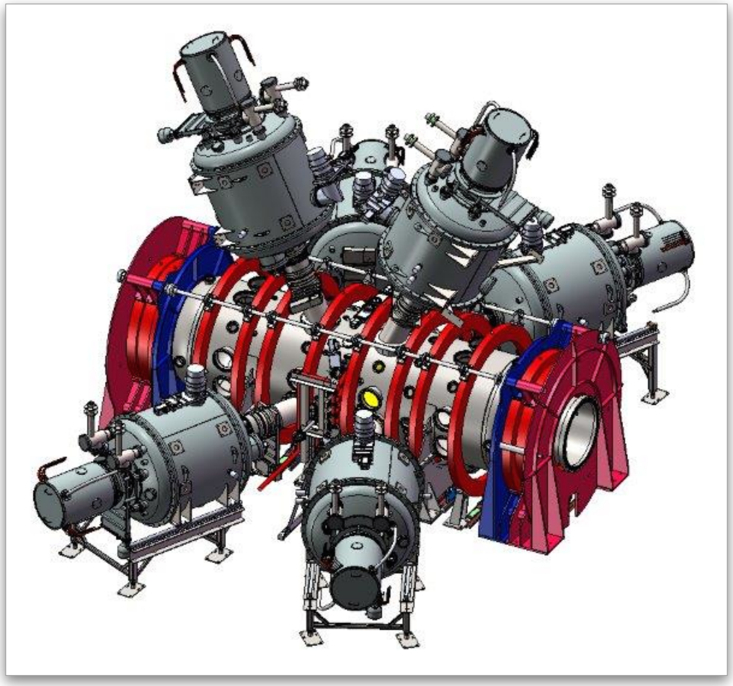


Typical Parameters

Parameter	Value
B_{ext}, kG	~1
r_s, cm	~35
L_s, m	2 – 3
n_e, m^{-3}	~3×10^{19}
T_i, eV	500 – 800
T_e, eV	100 – 150



C-2U Neutral-Beam System – Performance Makers

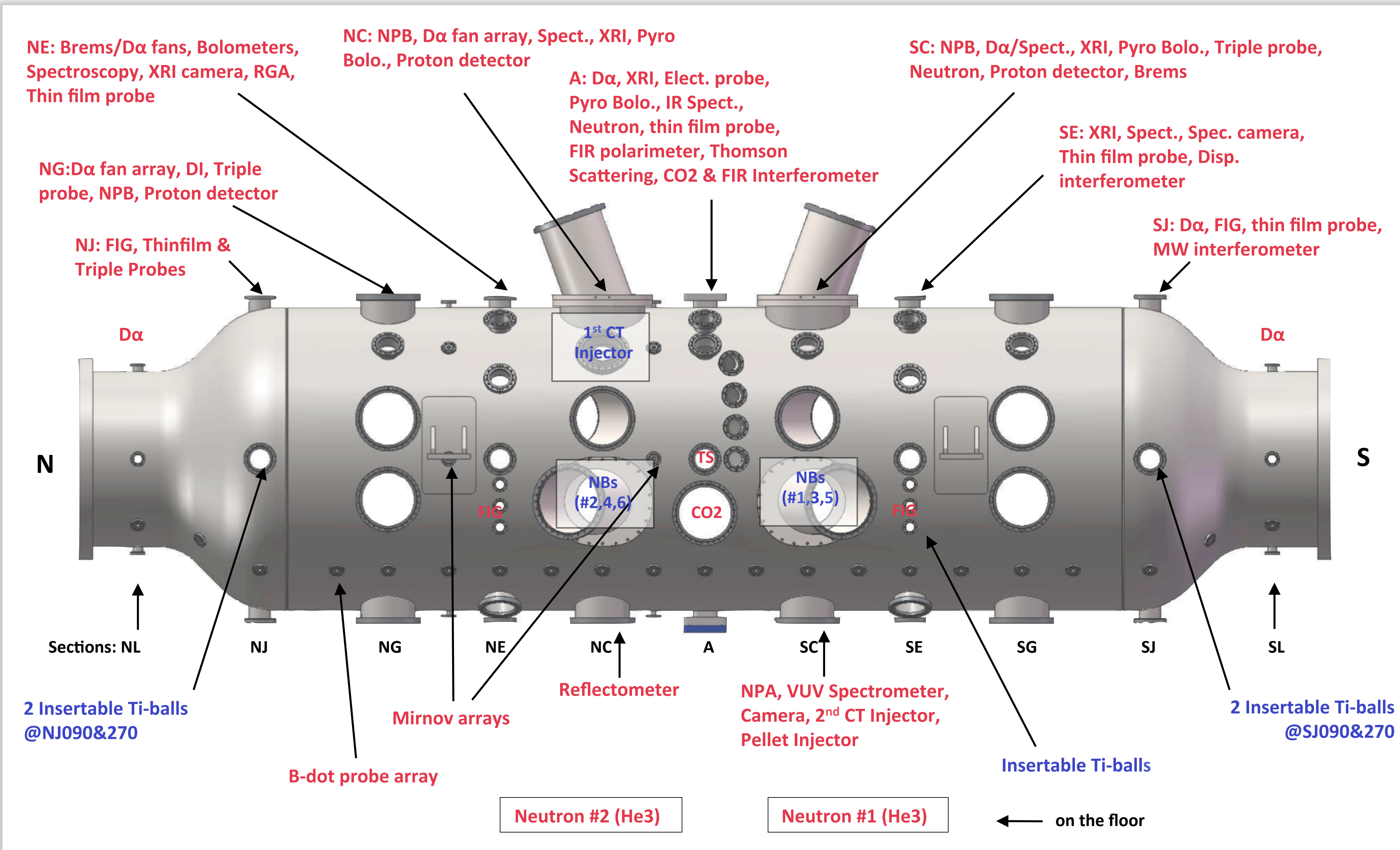


Neutral Beam System Specification

Parameter	Value
Beam energy	15 keV
Total power in neutrals	10+ MW
# of injectors	6
Pulse duration	8 ms flat top
Beam radial e-fold. size	< 10 cm
Beam divergence	< 28 mrad
Ion current per source	145 A

- **Centered, angled and tangential neutral-beam injection (NBI)**
  - **Beams aimed at mid-plane to reduce plasma shape impact**
  - **Simulations suggest optimized injection angle in range of 15°–25°**
  - **Injection in ion-diamagnetic direction to drive current**
- **High current at low beam energy**
  - **Reduces peripheral fast-ion losses**
  - **Increases core heating**
  - **Rapidly establishes dominant fast-ion pressure**

C-2U Diagnostics – Well Diagnosed Experiment



- 60+ diagnostics w/ over 1000 channels acquired on every shot (1+ GB/shot)

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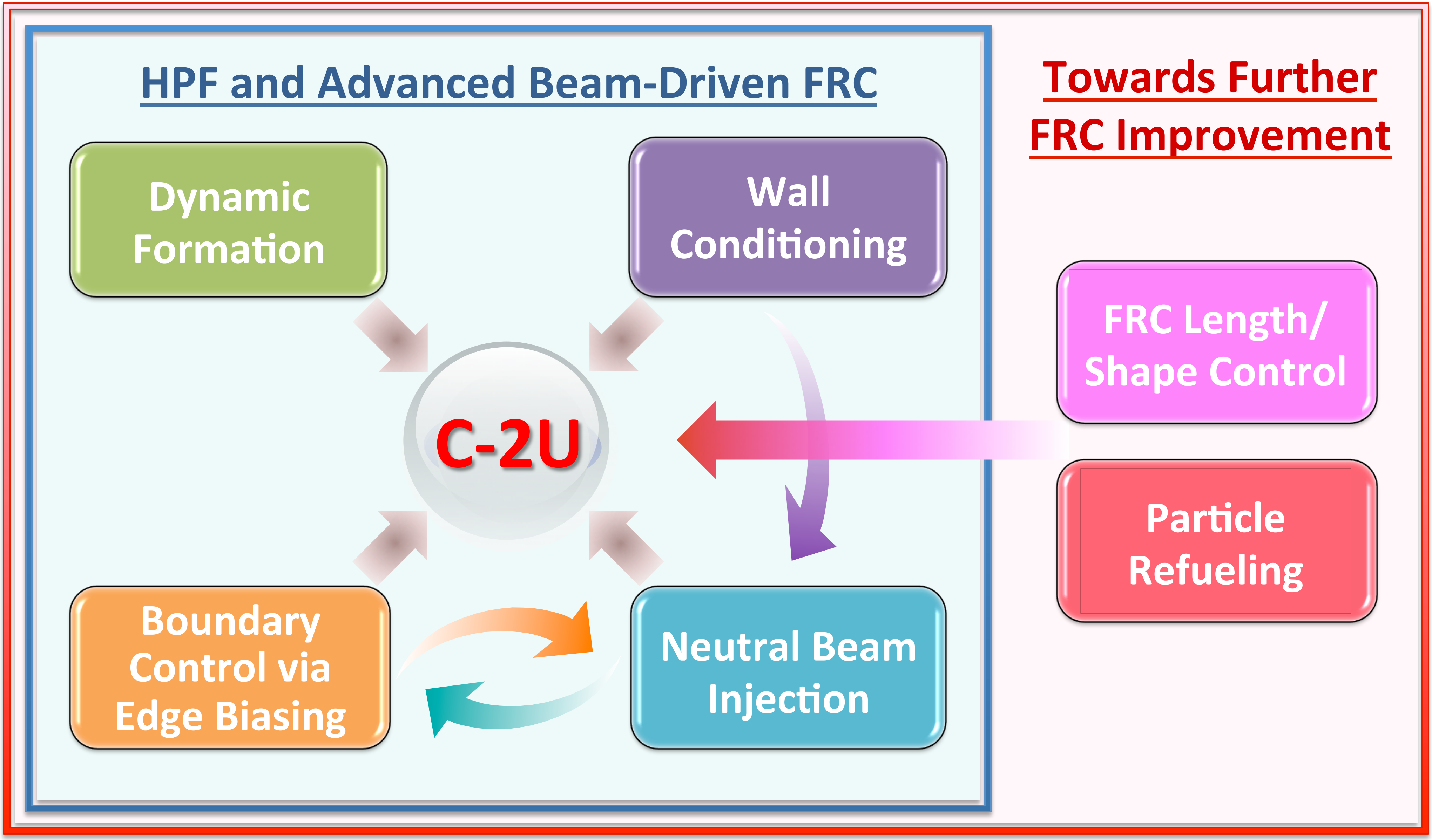
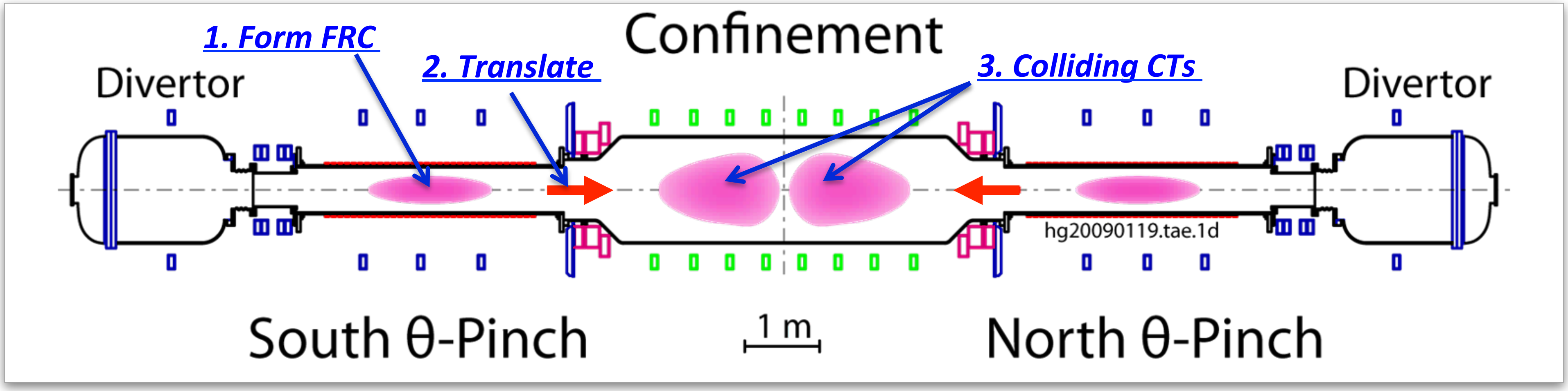
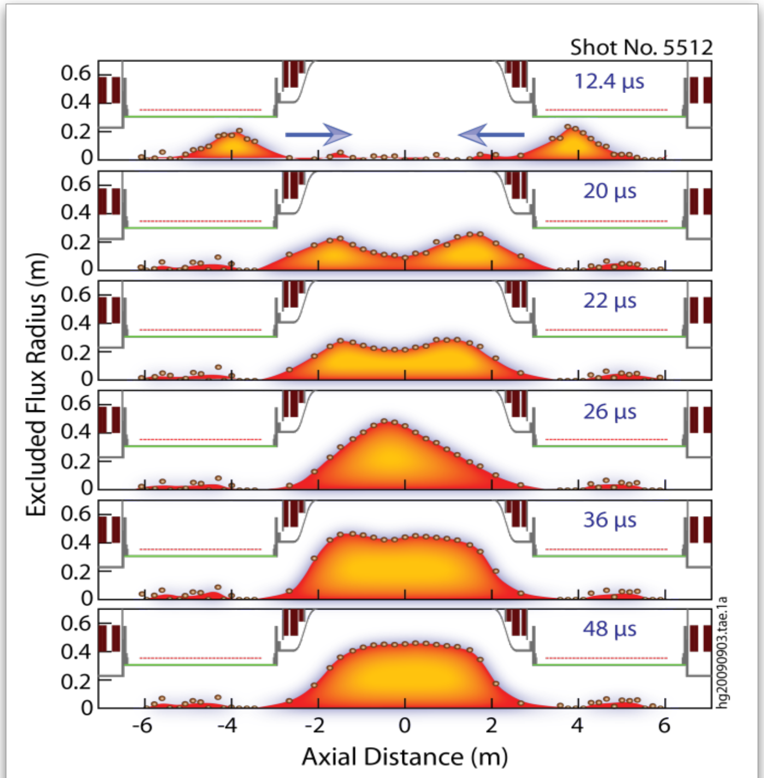
Key Approaches to C-2/C-2U: Synergetic Effects



*HPF – High Performance FRC (initially obtained in C-2)

C-2/C-2U Dynamic FRC Formation and Merging

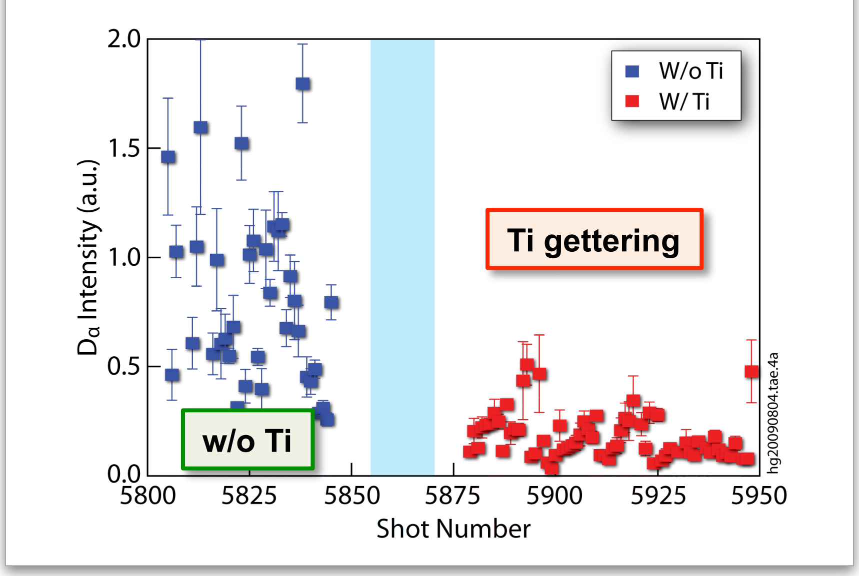




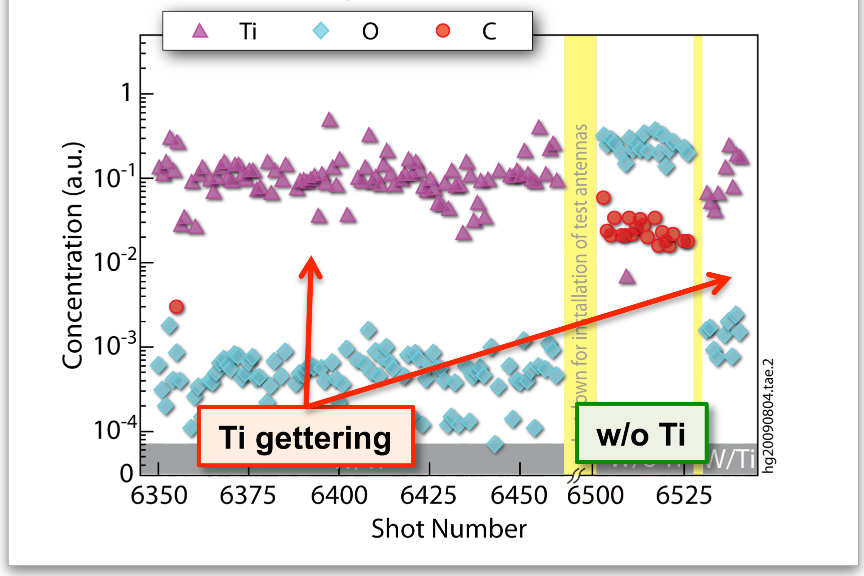
- **Compact toroids (CTs) are formed & accelerated by field-reversed θ-pinches on each side**
- **CTs survive dynamic formation and translation at supersonic speeds (>250 km/s)**
- **After collision (~100 µs) CTs merge into single FRC with characteristic profiles**
- **Axial kinetic energy (~20 kJ) – thermalizes via shock heating (retains ~7 kJ) → $T_i + T_e \sim 1$ keV**
- **Some toroidal field may persist**

C-2/C-2U Wall Conditioning – Titanium Gettering

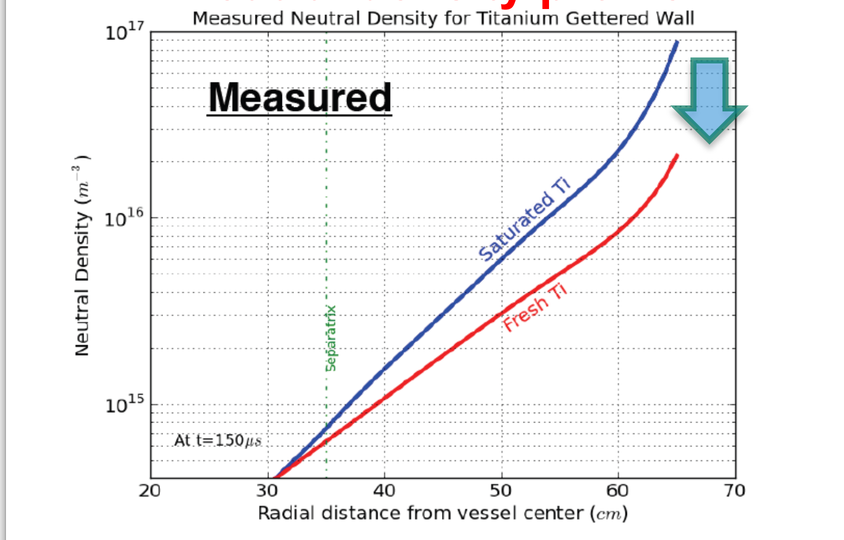
Dα emission



Impurity line emissions

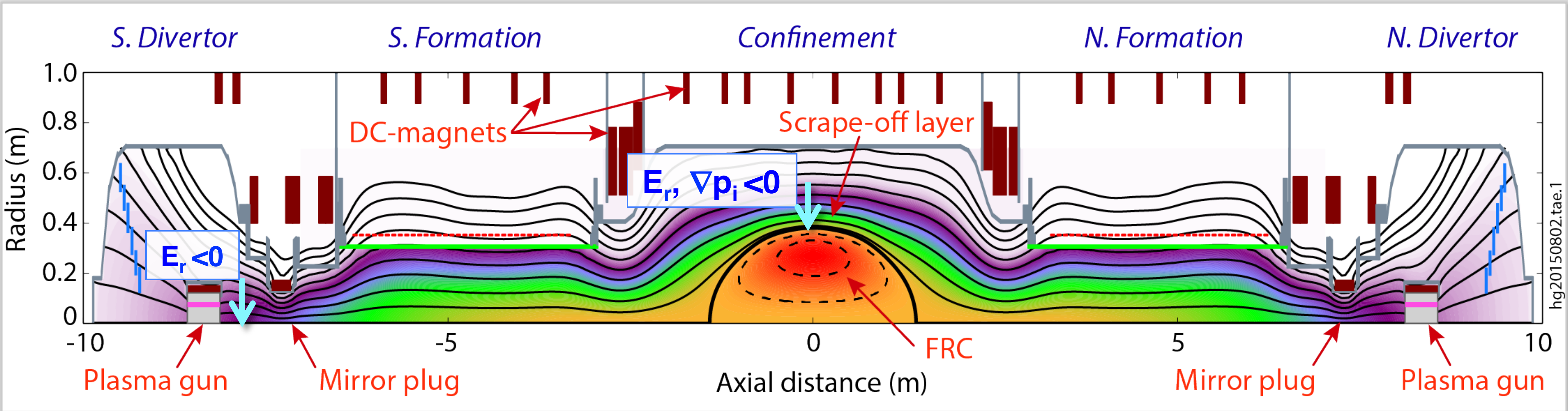


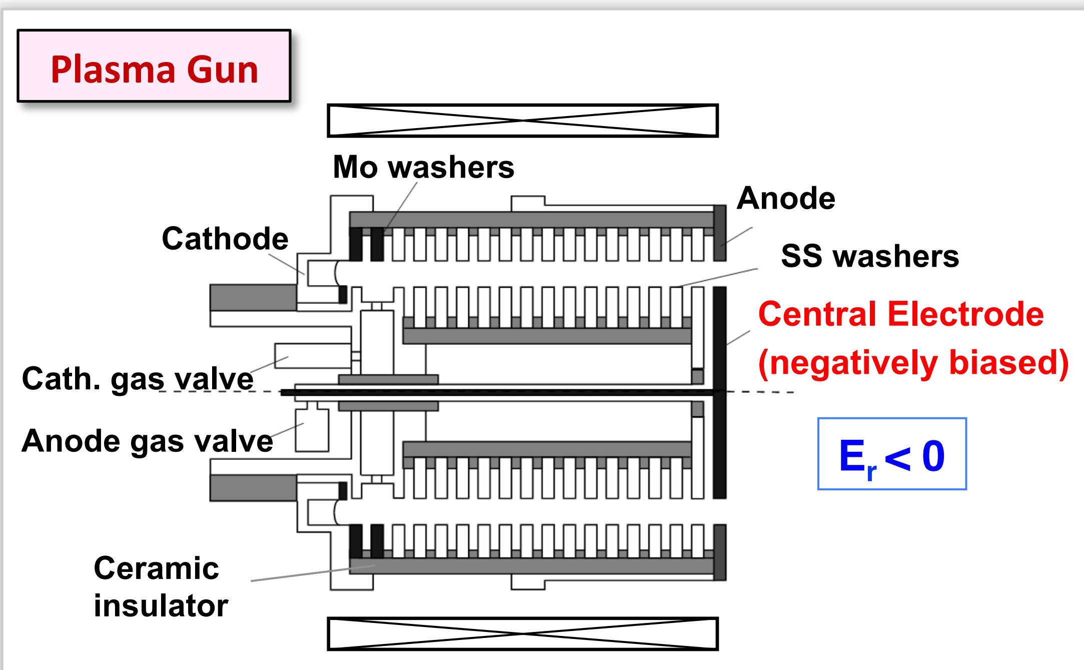
Neutral density profile



- Wall conditioning: Ti or Li gettering
- On C-2U, Ti-gettering system is routinely used in the confinement/divertor vessels
- Ti gettering reduces impurities and deuterium recycling on the wall, which leads to a reduction of neutrals in SOL and improve for NBI

C-2/C-2U Boundary Control via Edge Biasing



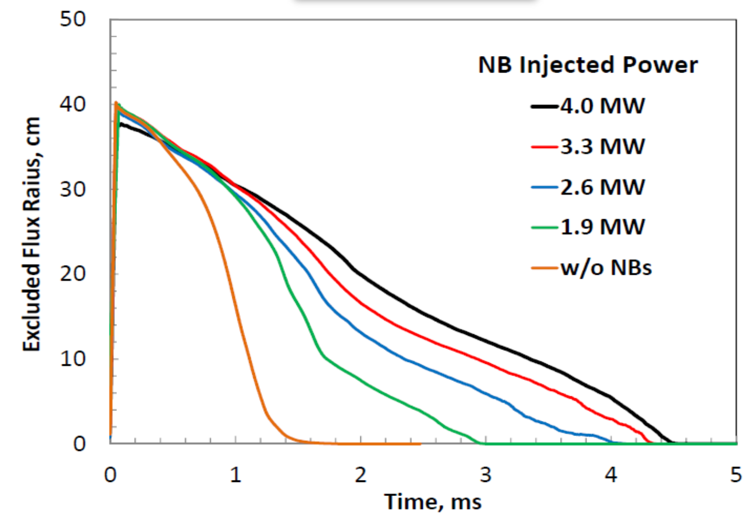


- Plasma guns "communicate" with FRC separatrix via edge layer
- PG generates inward E_r that counters usual FRC spin-up (ion diamagnetic direction): stabilize n = 2 mode
- Line-tying to PG electrode can stabilize plasma motion: n = 1 wobble

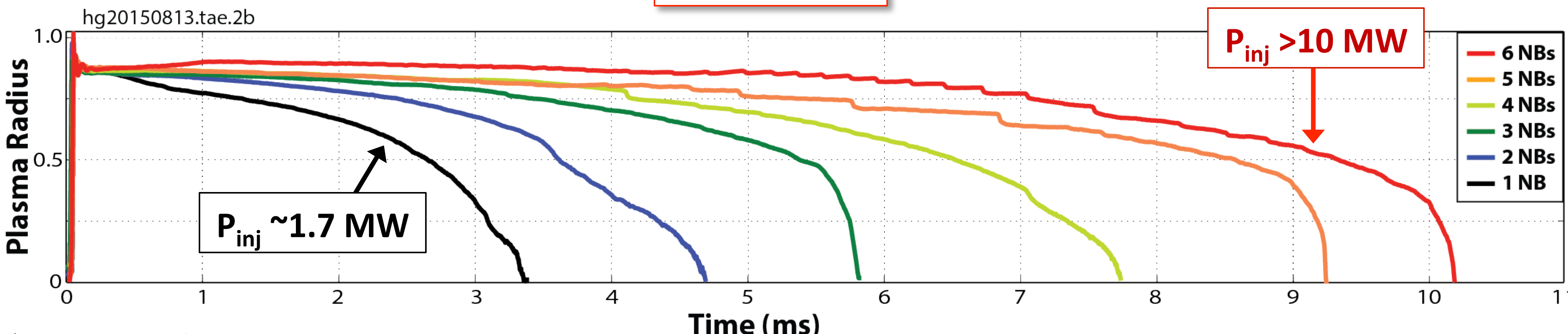
C-2/C-2U NB Injection – Performance Improvement

- Plasma longevity increases with injected-beam power (P_{inj})
  - C-2 demonstrated this relation, but C-2U NBI effect is far better than C-2 as expected
- This improvement indicates:
  - Current drive by NBI
  - Fast particle accumulation in FRC

C-2 Data



C-2U Data



*Radius normalized

Note: P_{inj} ~1.7 MW per beam line (15 keV hydrogen)

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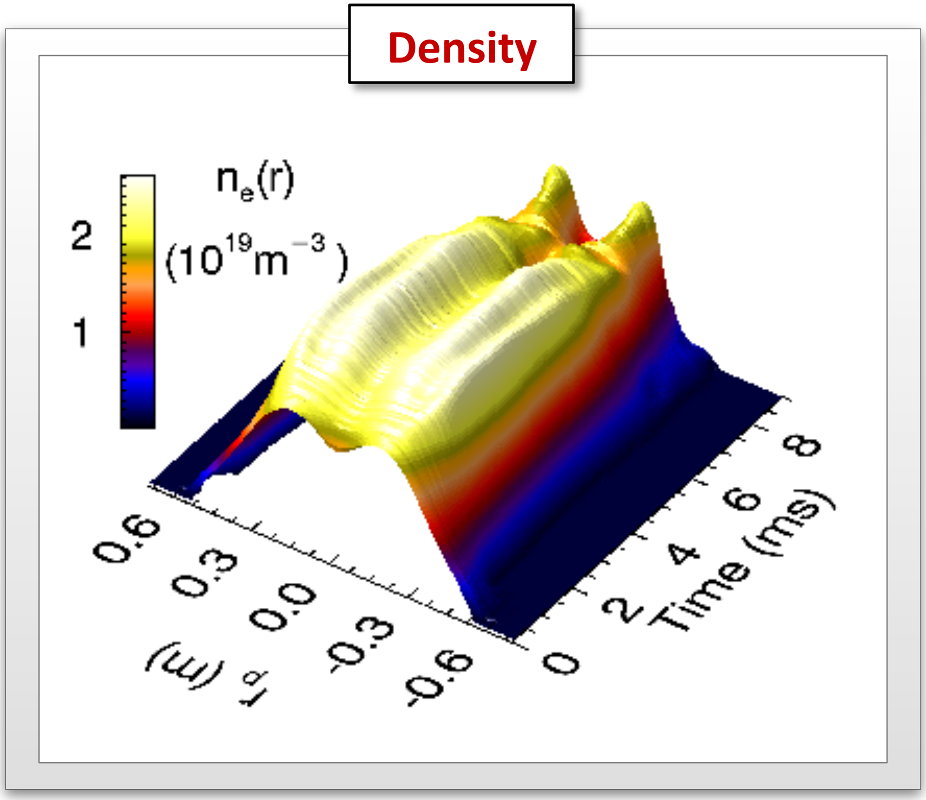
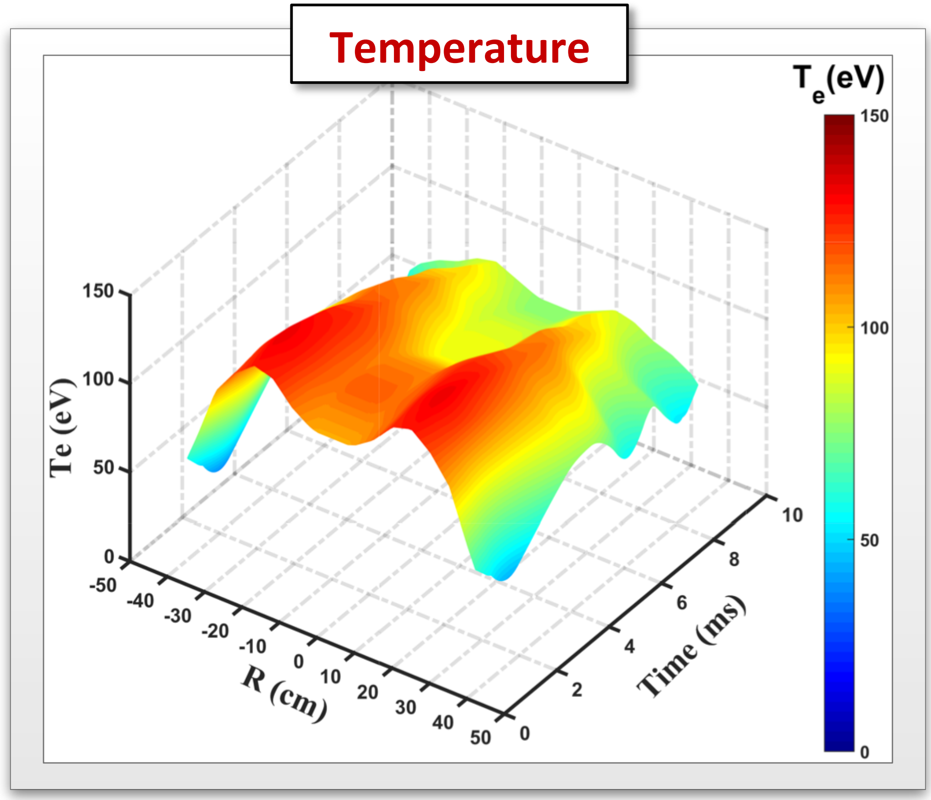
C-2U Fast-Particle Effects – Equilibrium Profiles

Signatures of advanced beam-driven FRC state



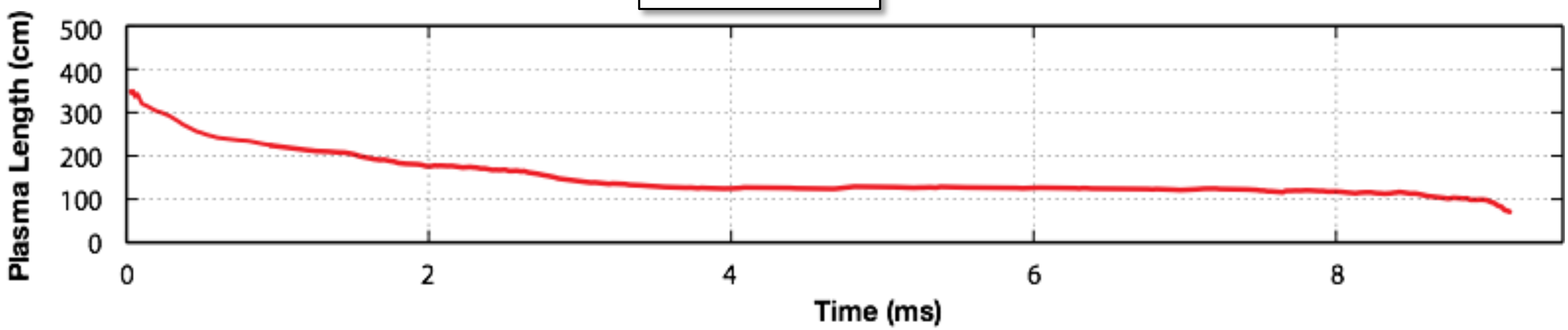


- "Double-humped" electron density and temperature profiles, indicative of substantial fast ion pressure
- Hollow center and steep separatrix gradients consistent with past FRC data and numerical simulations

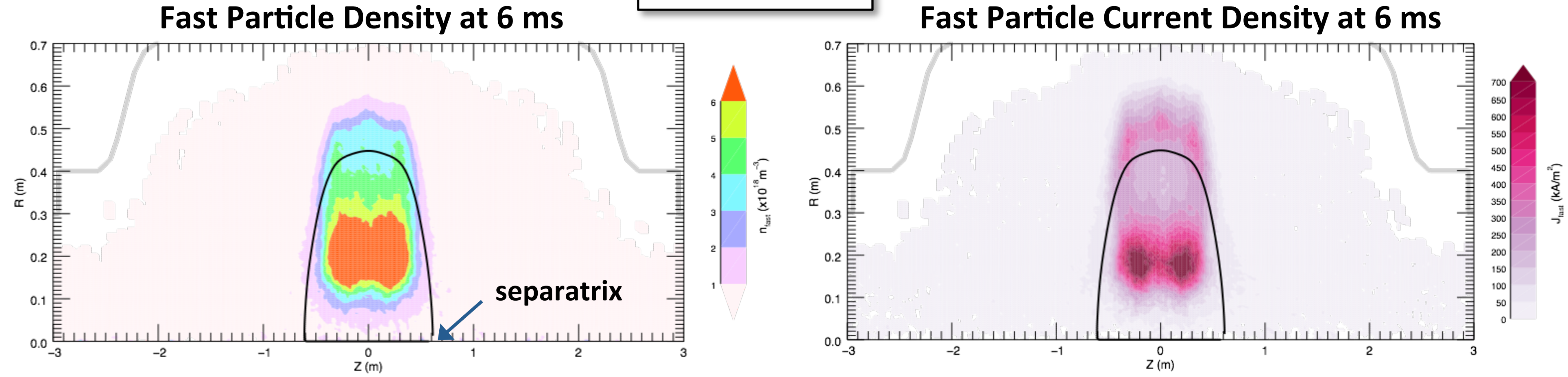
C-2U Fast-Particle Effects – Define FRC Dimensions

- Plasma length contracts to fast particle footprint, as predicted/verified by simulation
- Axial length of separatrix maintained by fast ions (post transient contraction)

Experiment

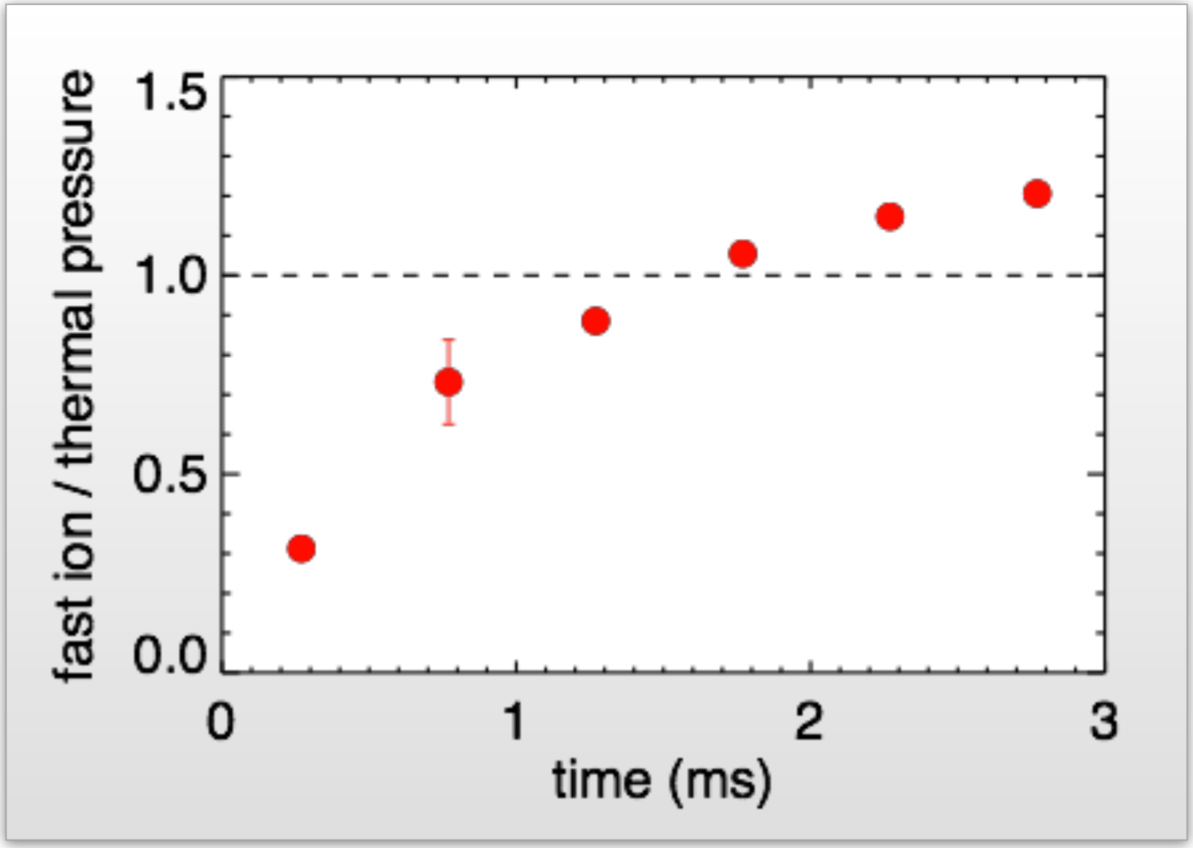


Simulation



C-2U Fast-Particle Effects – Fast Ion / Thermal Pressure

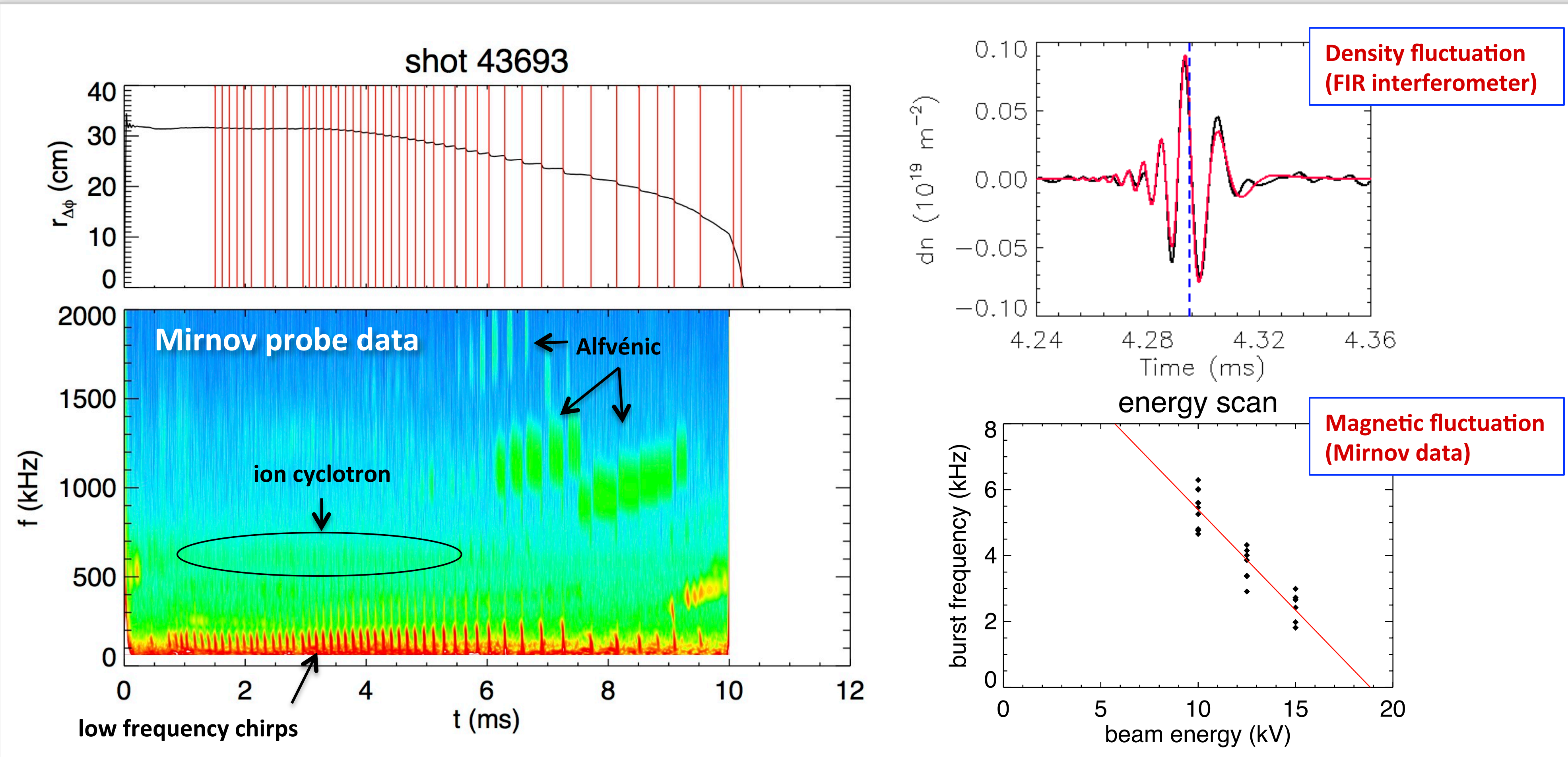
Signatures of advanced beam-driven FRC state



- **Dominant fast ion pressure term**
  - **total pressure is maintained**
  - **ultimately ~50–60% of thermal pressure replaced by fast particle pressure**

C-2U Fast-Particle Effects – Beam-Driven Micro Bursts

- Non-disruptive fast-ion driven micro bursts (staircase)
- Burst frequency varies with beam energy and external B field
- Micro bursts can be suppressed by external field profile and ExB shearing



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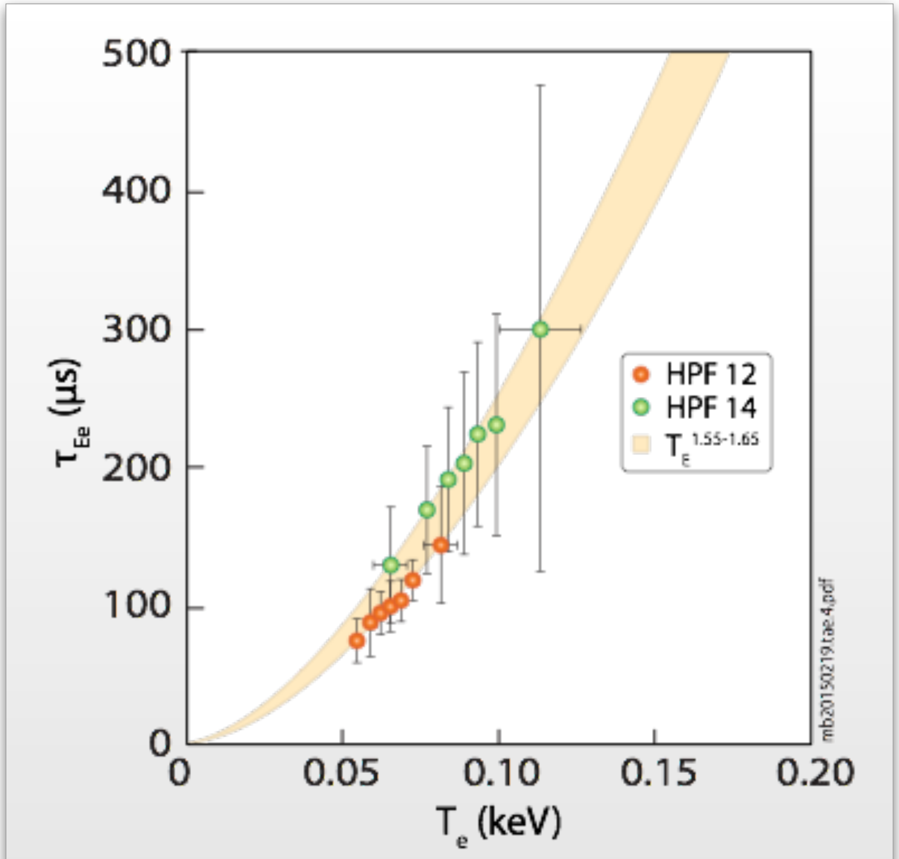
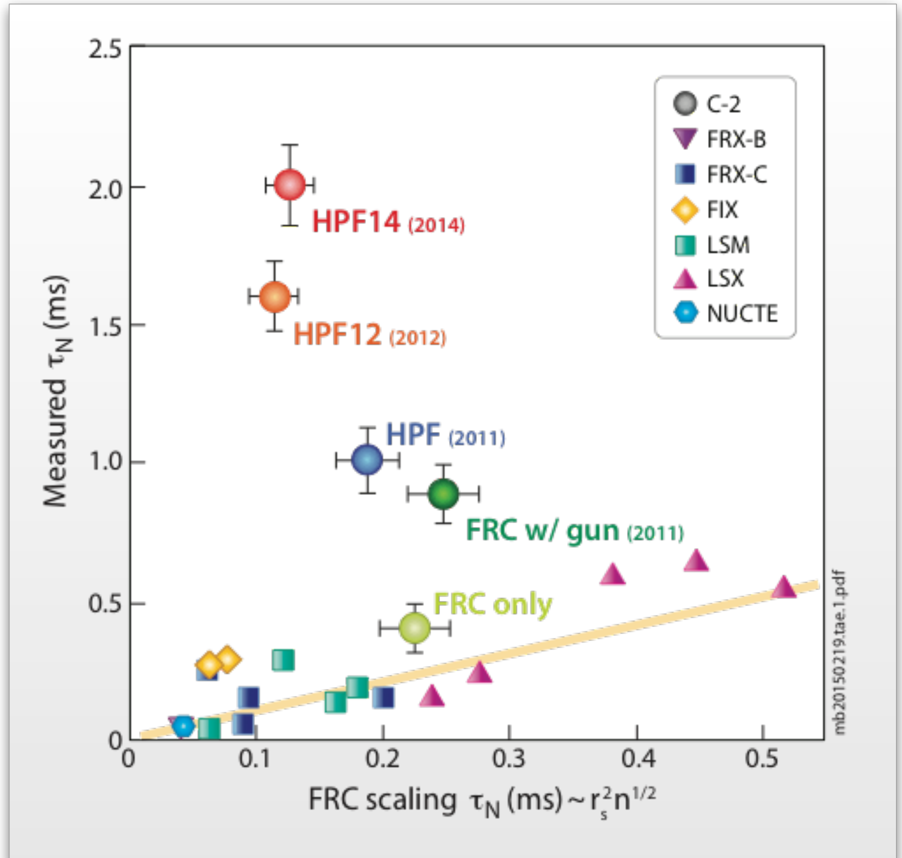
Confinement Scaling

Dramatic improvement in recent regime

Ref.: M.W. Binderbauer *et al.*, Phys. Plasmas **22**, 056110 (2015).



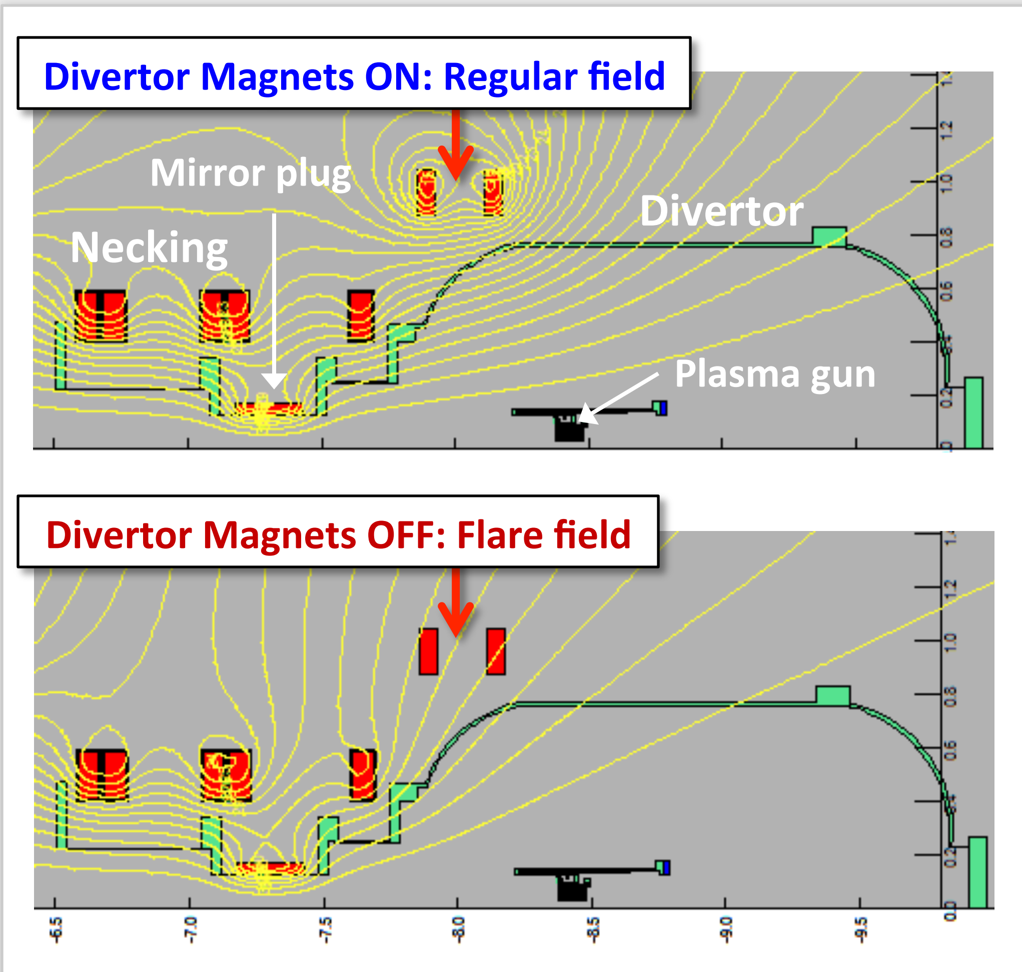


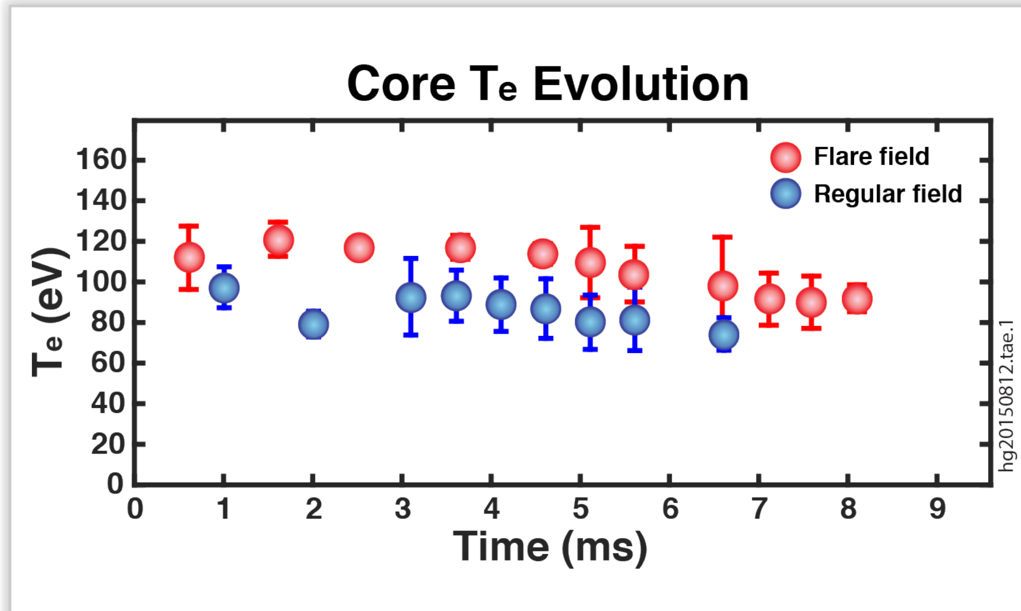
- **Strong positive correlation between T_e and τ_{Ee}**
- **Good fit:** $\tau_{Ee} \propto T_e^{1.6}$

- **Confinement dramatically better than conventional FRC scaling prediction**
- **~10× improved particle confinement**

Coupled Core-SOL Confinement

- Improving open-field-line plasmas – key for better core FRC confinement
- 20–30% higher Core T_e with flaring divertor magnetic field
- Enhanced ExB shearing – improve confinement and additional heating





*T_e measured by Thomson scattering system (C-2U midplane)

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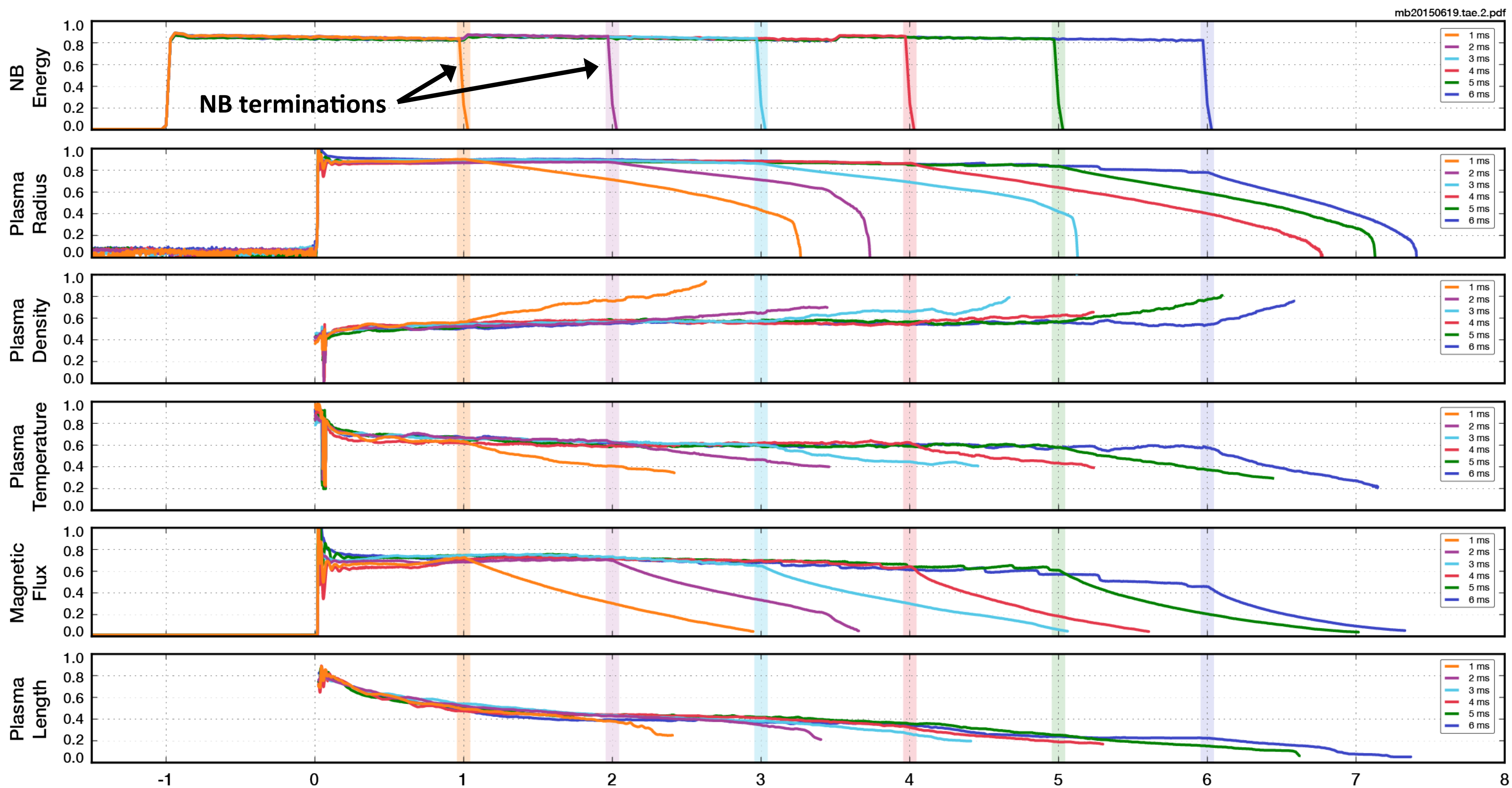
Plasma Sustainment – Correlates with NB-duration

- Key plasma parameters maintained until end of NB pulse-duration
- Diamagnetism persists ~1.5–2.5 ms after NB termination (by accumulated fast-ions)



* all quantities normalized

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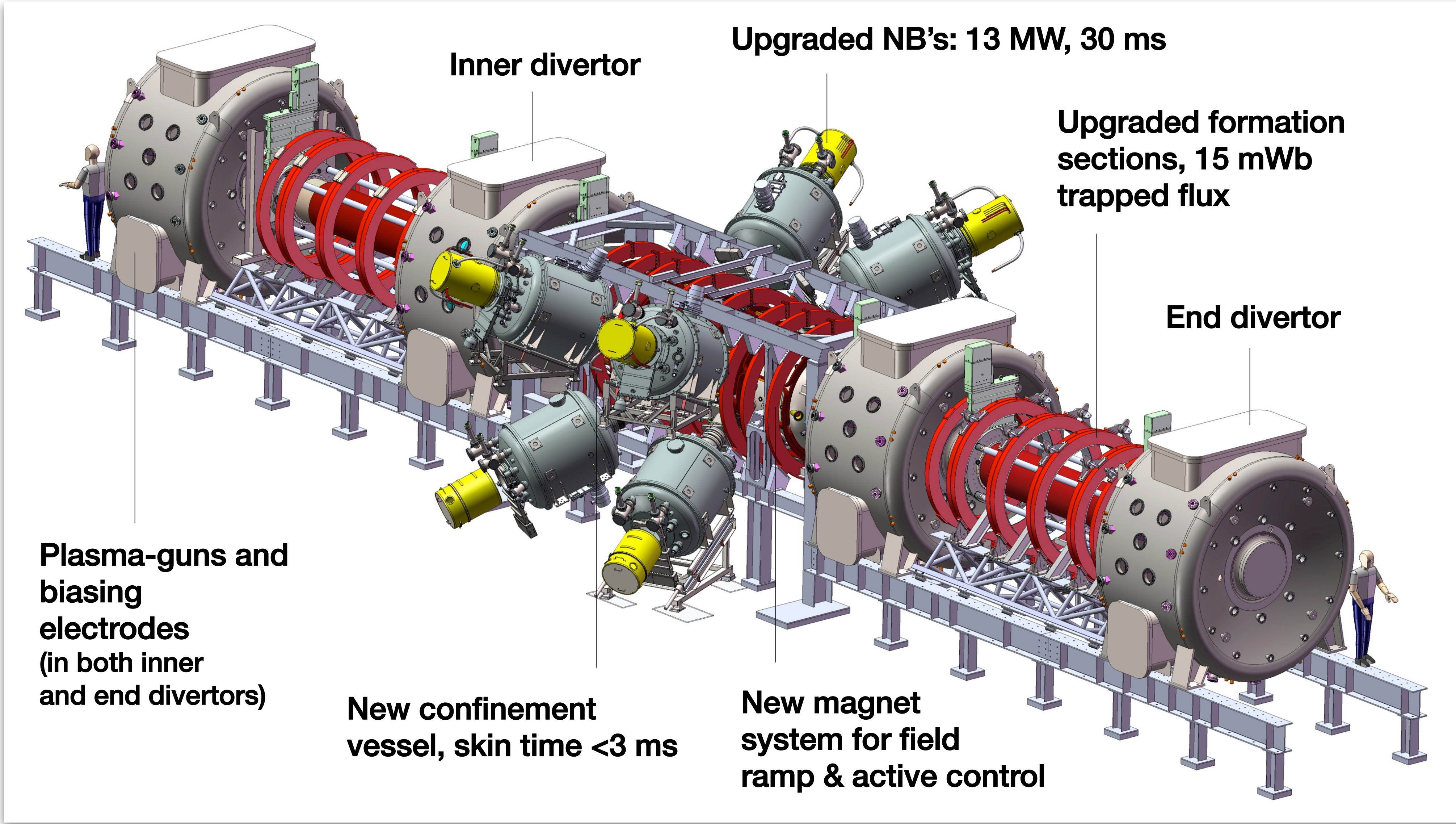
C-2W: Next Device at 10x Stored Energy at TAE



Summary – Essential C-2/C-2U Accomplishments

- **Successfully operated and studied advanced beam-driven FRCs**
  - dynamic formation and fast-ion pressure dominated equilibria
  - achieved engineering integration of major system components
- **High-Performance FRC (HPF) regime demonstrated**
  - edge biasing, neutral beams and gettering (low Z_{eff}~1.28 in core) produce HPF regime with excellent shot-to-shot reproducibility
  - improved FRC stability and confinement
  - record FRC lifetimes (~11 ms), limited only by transport
  - beneficial emerging confinement scaling and coupled core-SOL transport
- **Advanced beam-driven FRC sustainment breakthrough**
  - current drive and plasma sustainment in excess of characteristic system and plasma time scales, correlated w/ NB pulse – 5+ ms
  - Performance limited by hardware and stored energy constraints
- **Compelling foundation for success with C-2W**

Announcement

2016 US-Japan Compact Torus (CT) Workshop

Equilibrium studies and novel applications of compact toroids based on innovative confinement techniques: The future of Compact Tori

August 22–24, 2016
At the Hotel Irvine, CA

Responsible person: Toshi Tajima, UC Irvine

Workshop Organizers:
US: Toshi Tajima, University of California, Irvine
ttajima@uci.edu

Japan: Tomohiko Asai, Nihon University
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