TRI ALPHA ENERGY
THE POWER OF INGENUITY

Overview of Tri Alpha Energy's Experimental Program and Recent Progress on Transport Analysis

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Outline

- **Introduction:**
  - **Field-reversed configurations (FRCs); Concept; Project goals**
- **C-2U Accomplishments:**
  - **Sustained plasmas, driven by beams**
- **Confinement and Scaling**
- **C-2W Project Vision**
  - **Goals, parameters, upgrades**
- **Summary**

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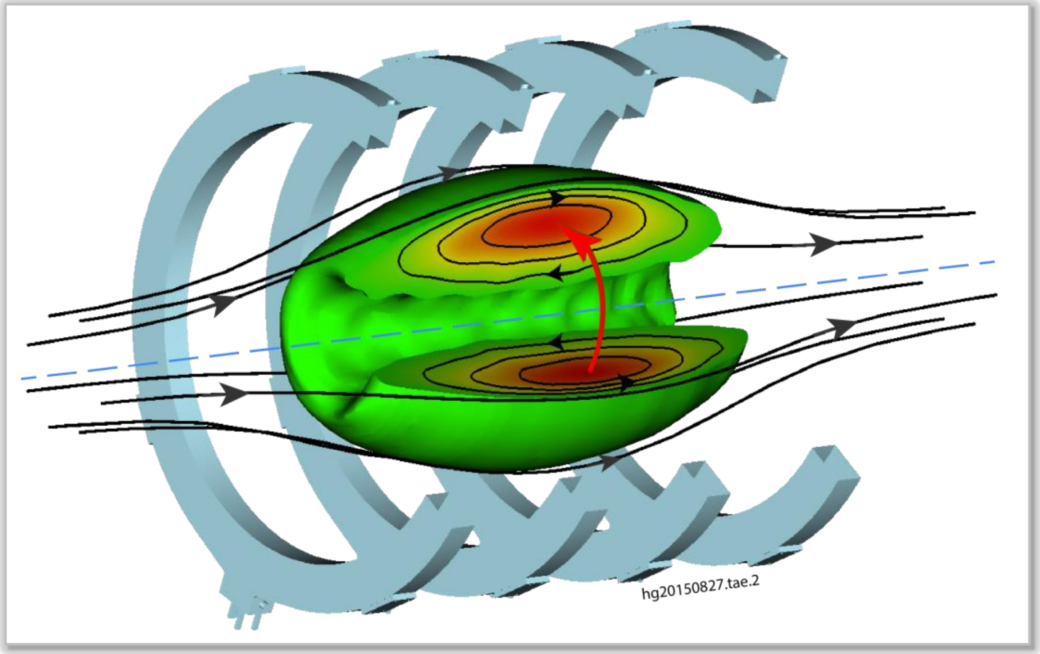
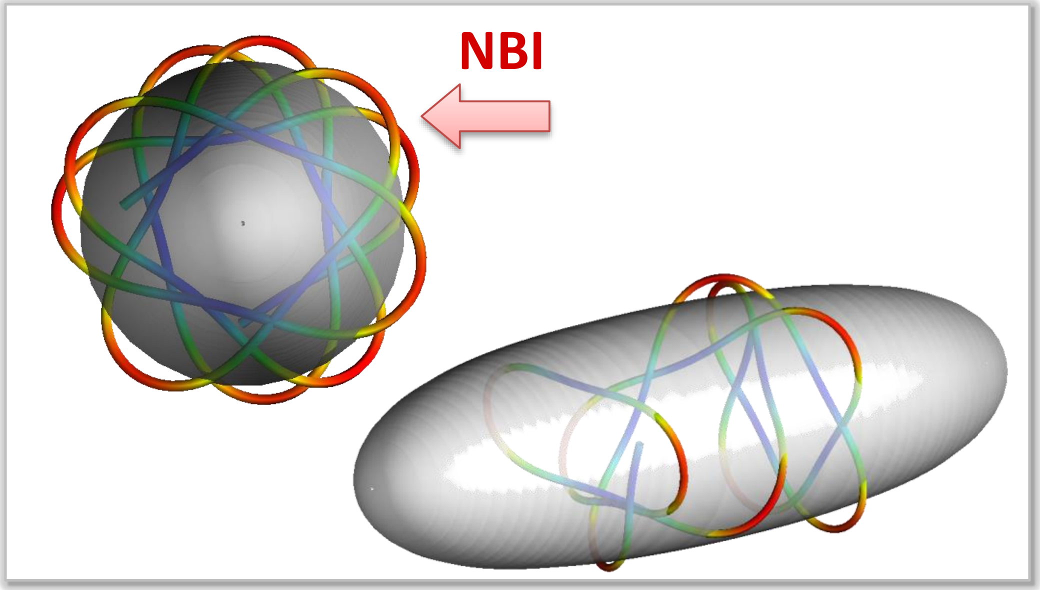
FRCs and Tri Alpha Energy's (TAE) Concept



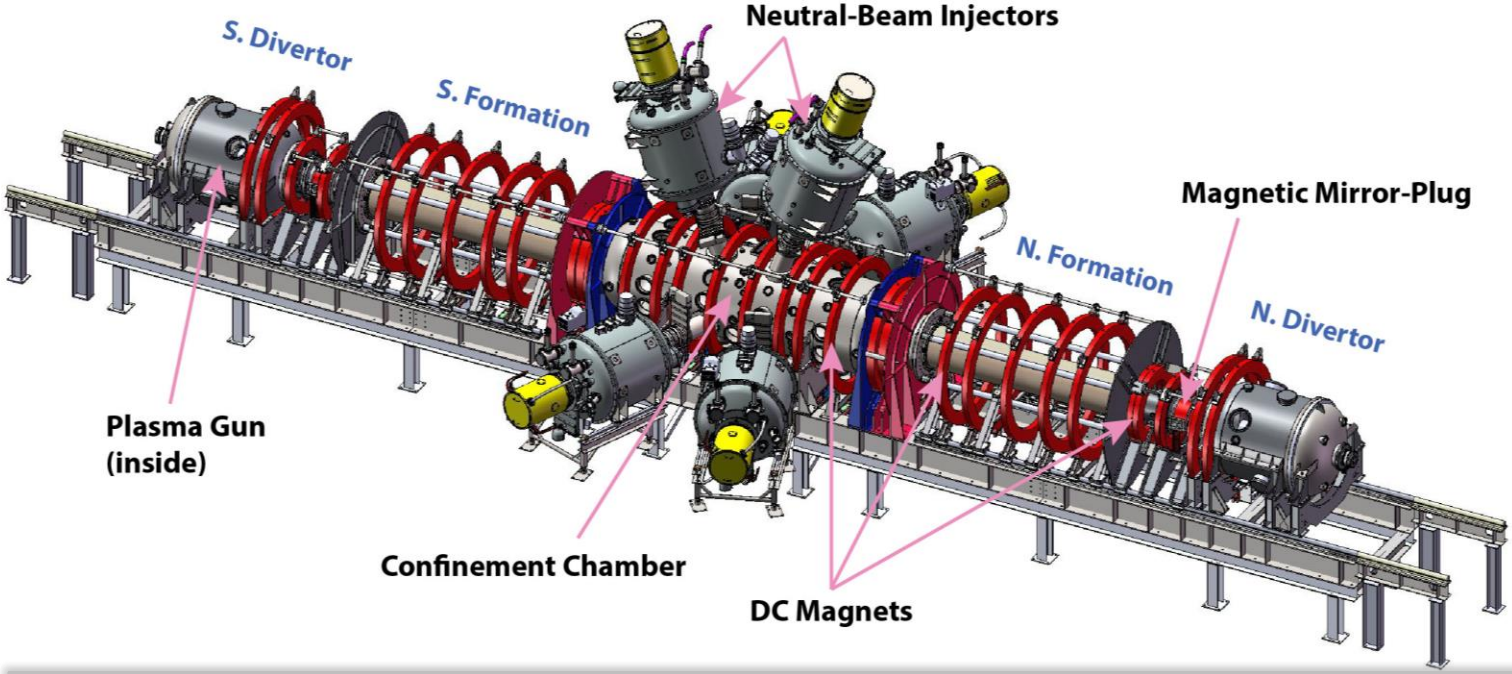


- **High plasma β ~ 1**
  - compact and high power density
  - aneutronic fuel capability
  - indigenous kinetic particles
- **Simple geometry**
  - only diamagnetic currents
  - simpler design & maintenance
- **Linear unrestricted divertor**
  - facilitates impurity, ash and power removal
- **Tangential 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 and Focus of Efforts

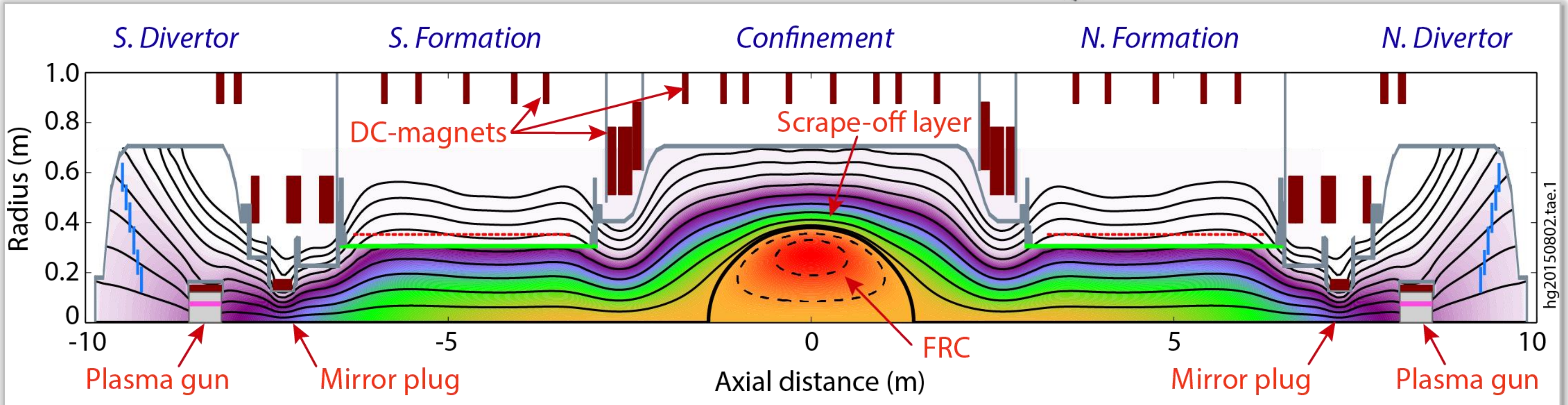
- **Establish beam-driven high-β, large orbit FRC physics test bed to:**
  - provide fast learning cycles and large experimental dataset (~51,000 shots)
  - demonstrate sustainment via neutral beam injection (NBI) for >5 ms (longer than critical timescales) with high repeatability
  - study tangential NBI and fast particle effects on stability and transport
  - measure scaling and study fluctuations and transport
- **Test for failure early and at reduced cost while reducing most critical risks**
- **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

C-2U Research Facility to Study Sustainment of Advanced Beam-Driven FRCs



Typical Parameters

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



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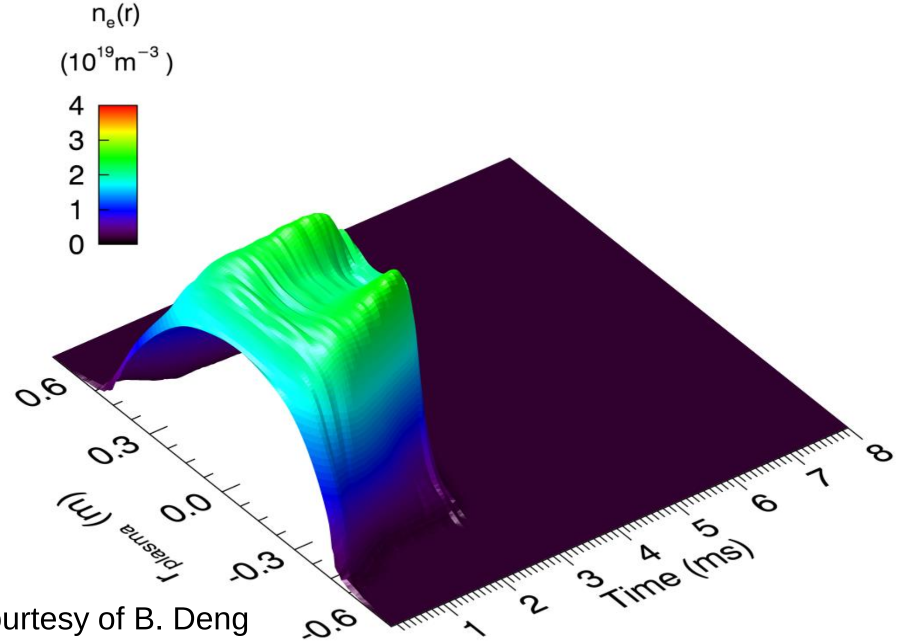
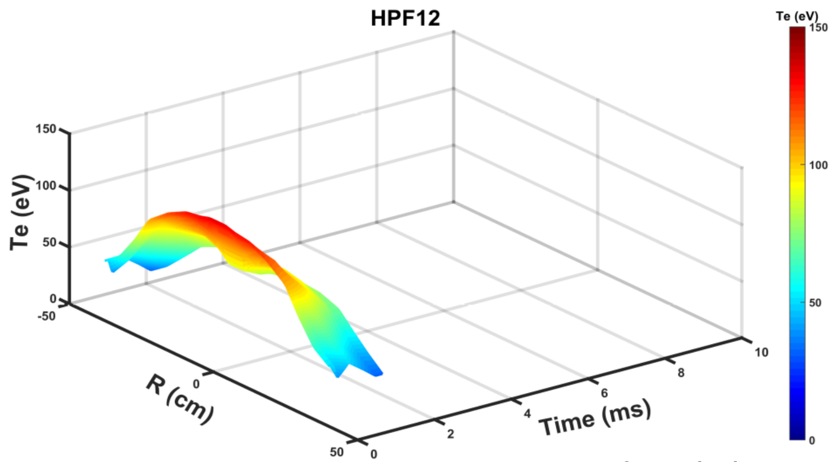
C-2 to C-2U: A Brief History

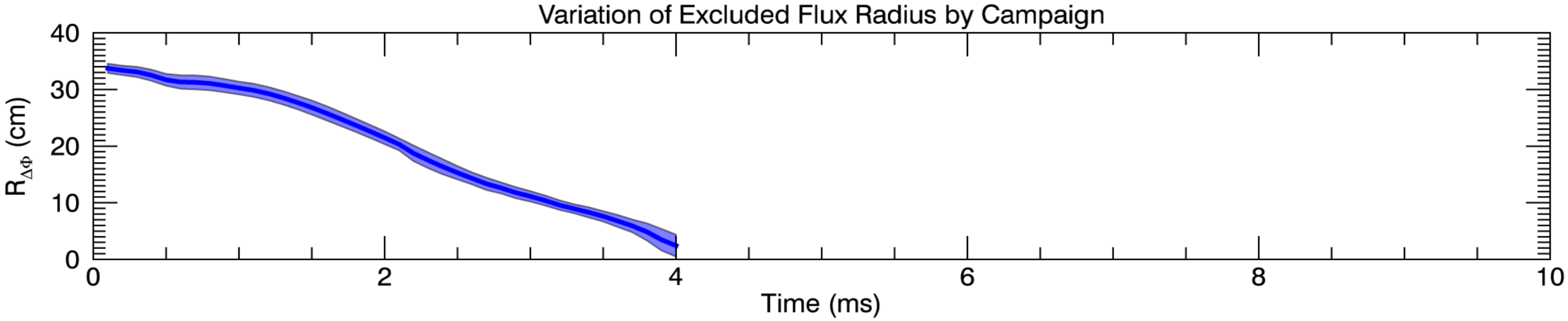
- C-2: Addition of magnetic plugs and plasma guns extend lifetimes to over 2ms in 2012



Courtesy of B. Deng
And M. Beall

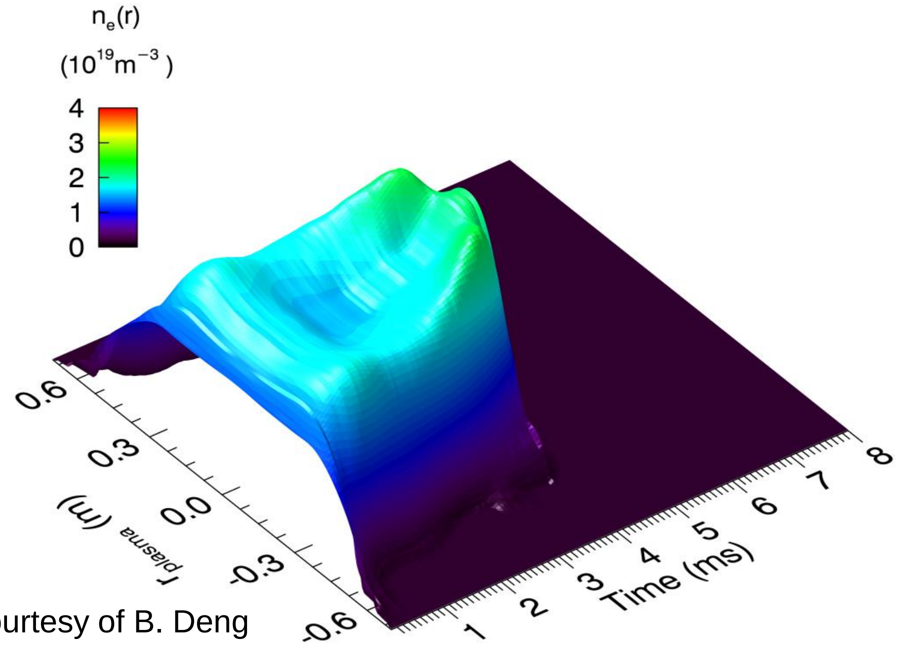


Courtesy of K. Zhai



C-2 to C-2U: A Brief History

- C-2: Lithium gettering and decreased recycling lead to pressure increases in 2014



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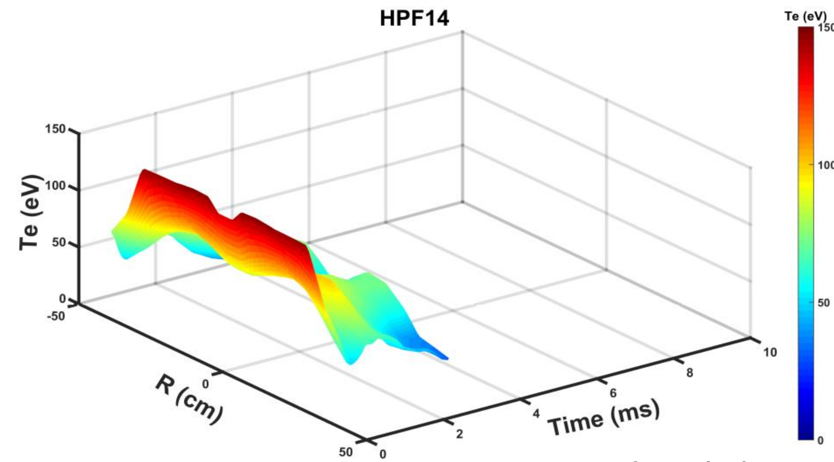

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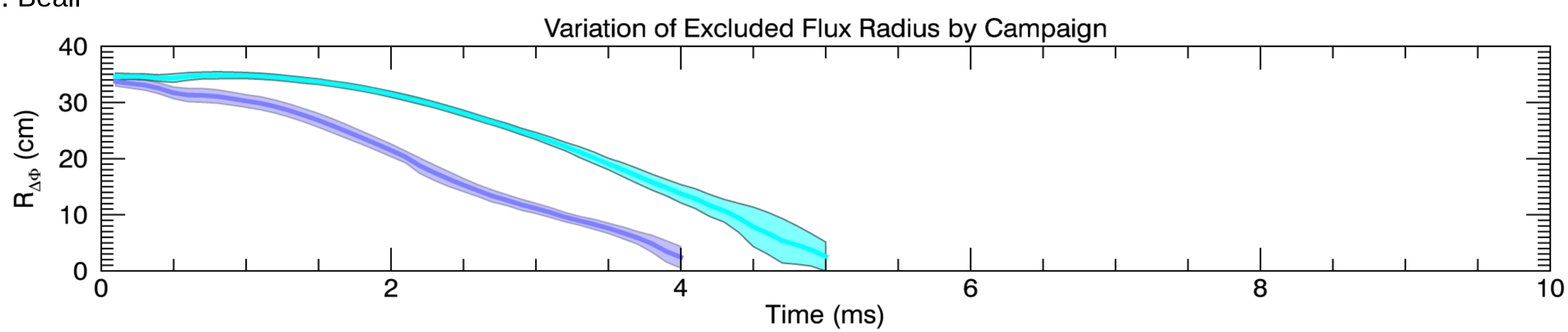
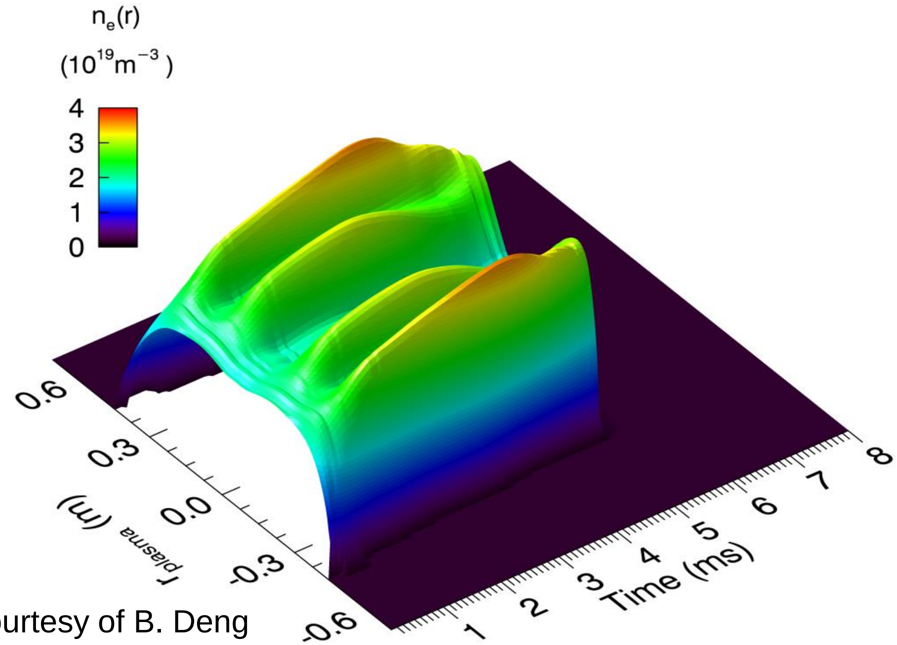


C-2 to C-2U: A Brief History

- C-2U: Lifetimes of 5+ ms achieved with higher beam power and SOL B field changes in 2015. Beam effects are evident in profiles.



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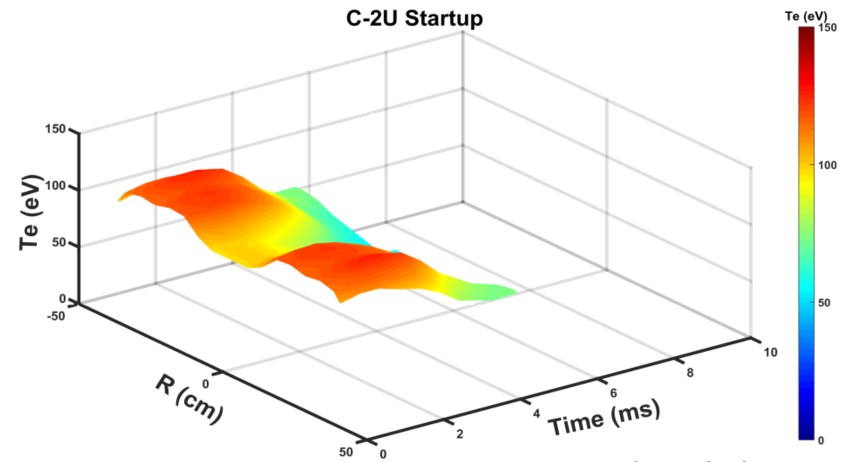

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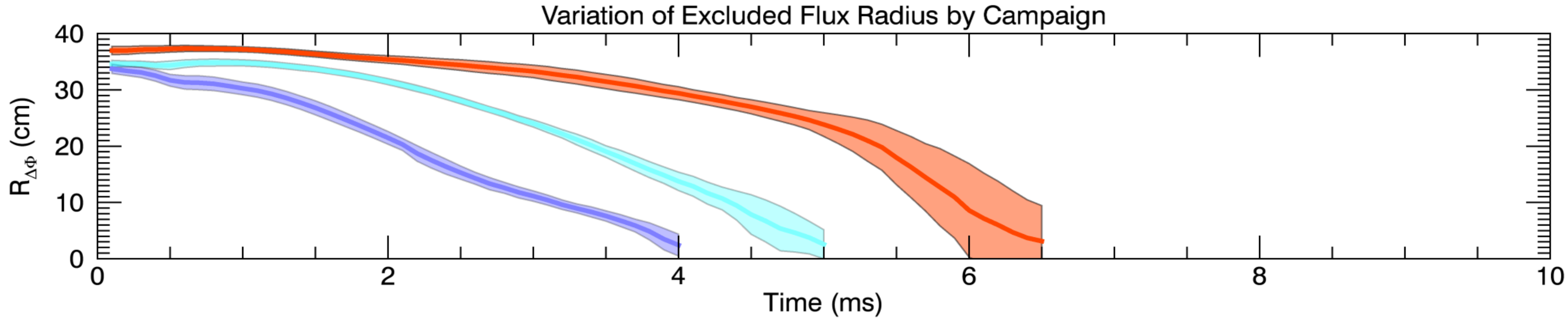
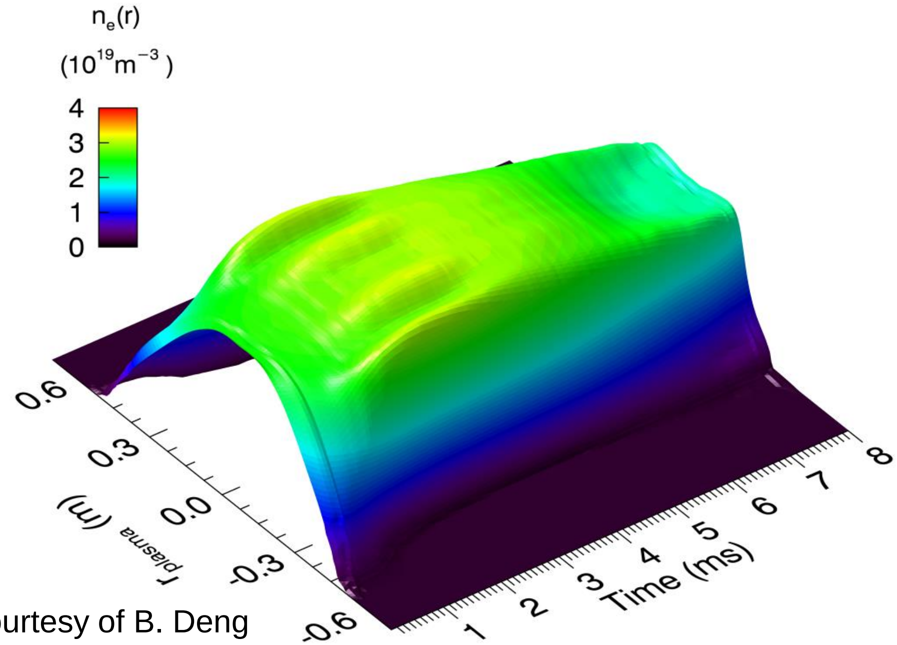


C-2 to C-2U: A Brief History

- C-2U: Sustainment achieved after only 3 months of operations!



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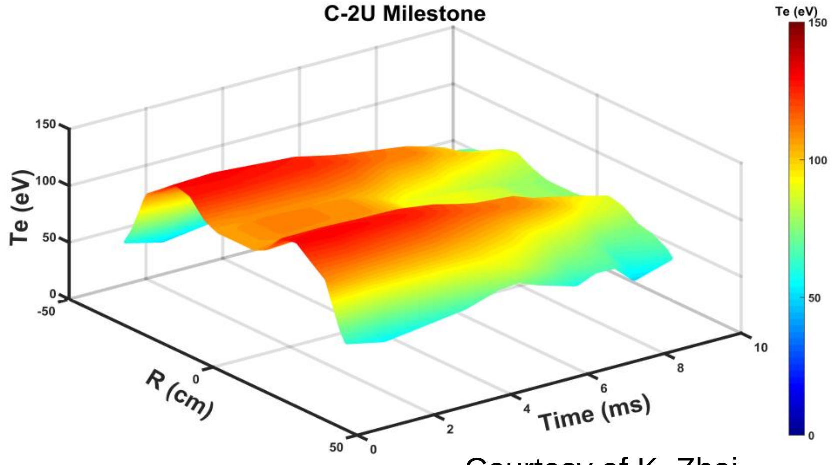

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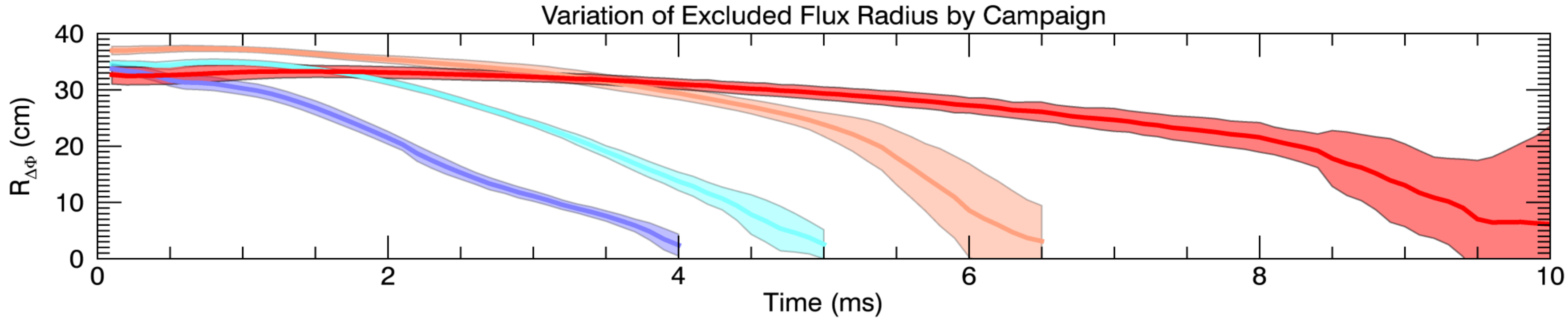
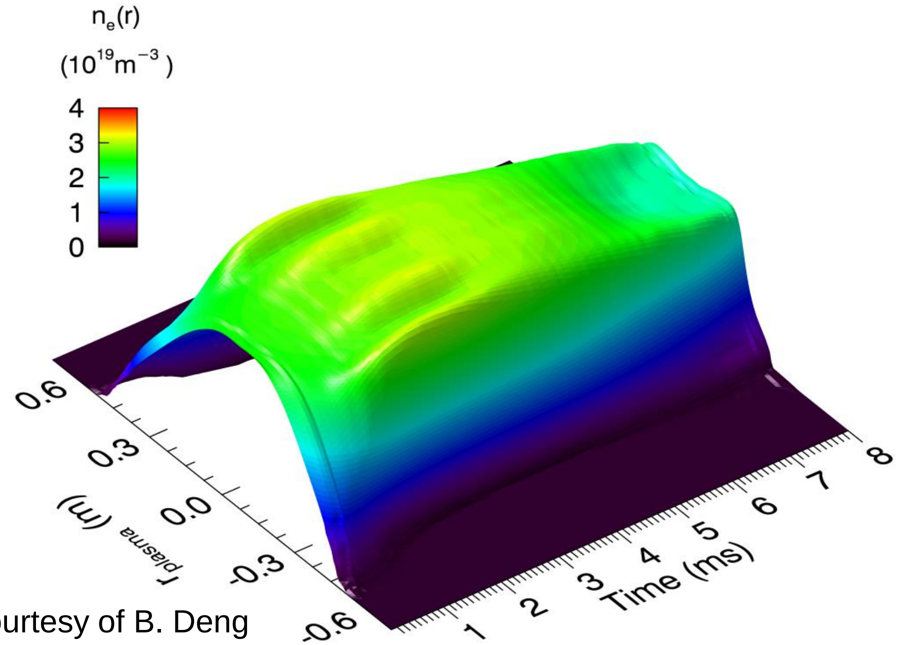


C-2 to C-2U: A Brief History

- C-2U produces **advanced beam-driven FRCs** via NBI, **sustained for 5+ ms,** with up to 11 ms lifetimes



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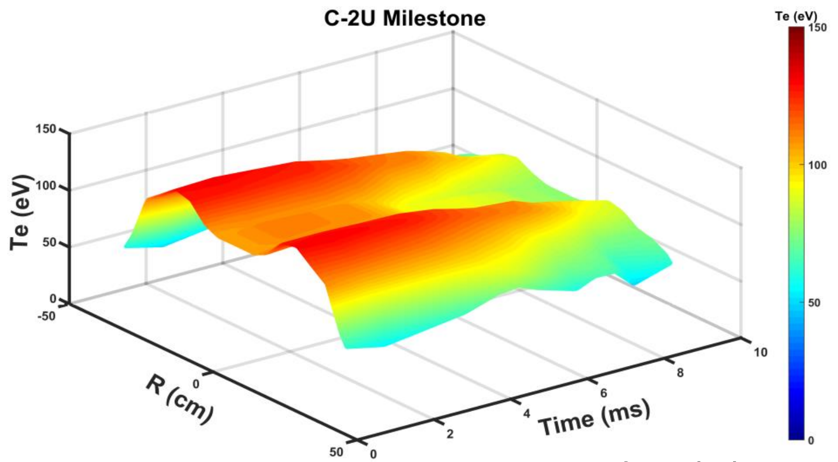

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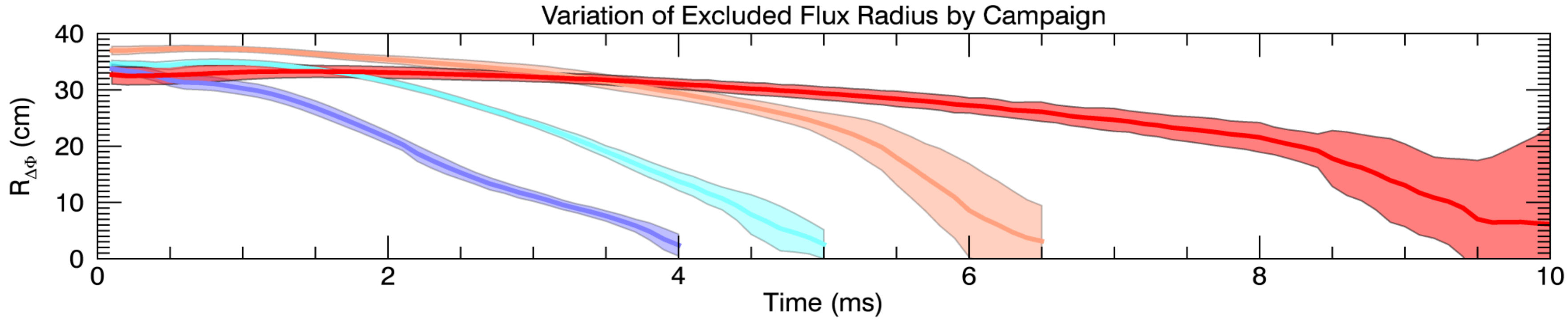
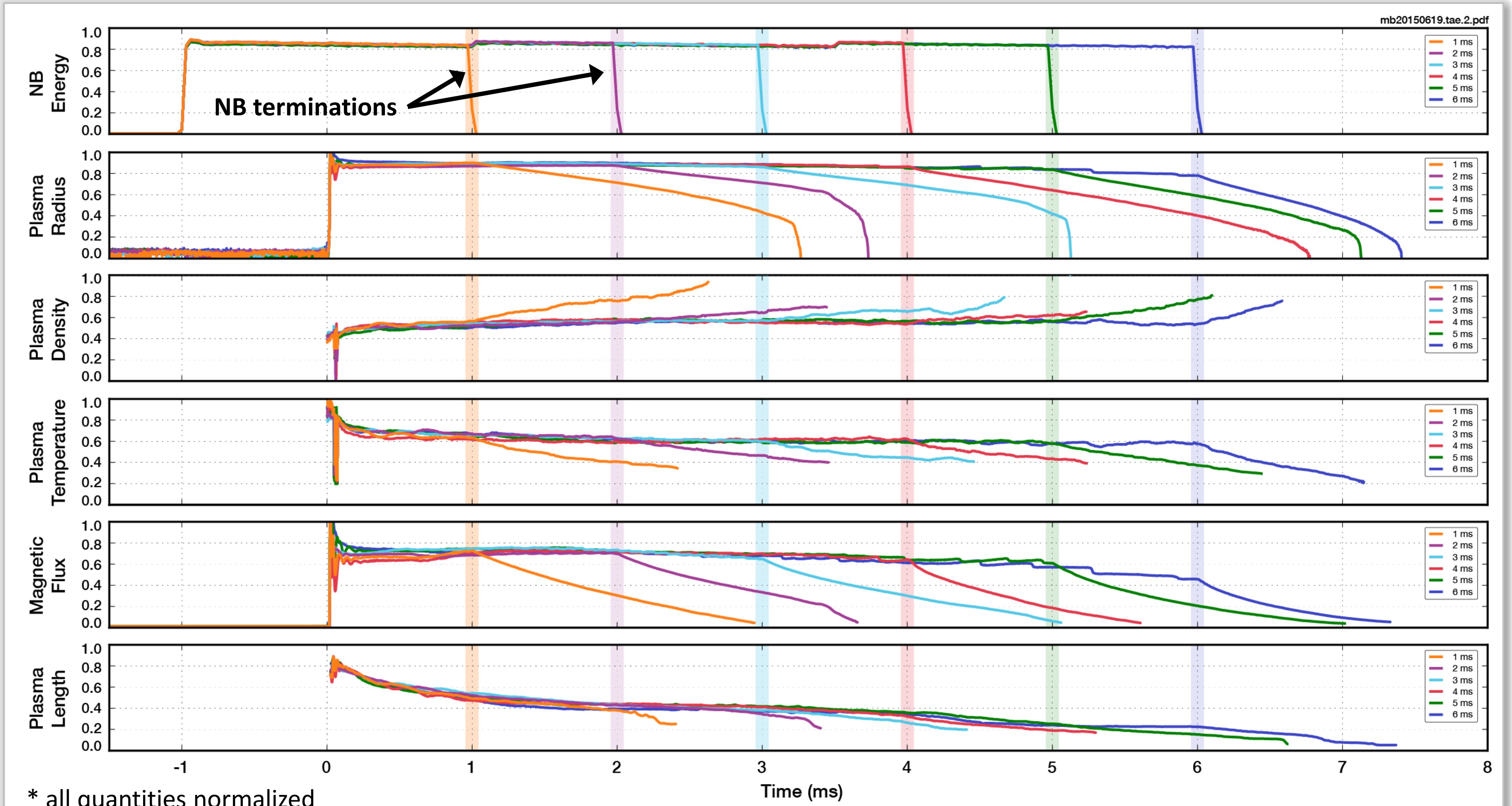


Plasma Sustainment – Correlates with NB-duration

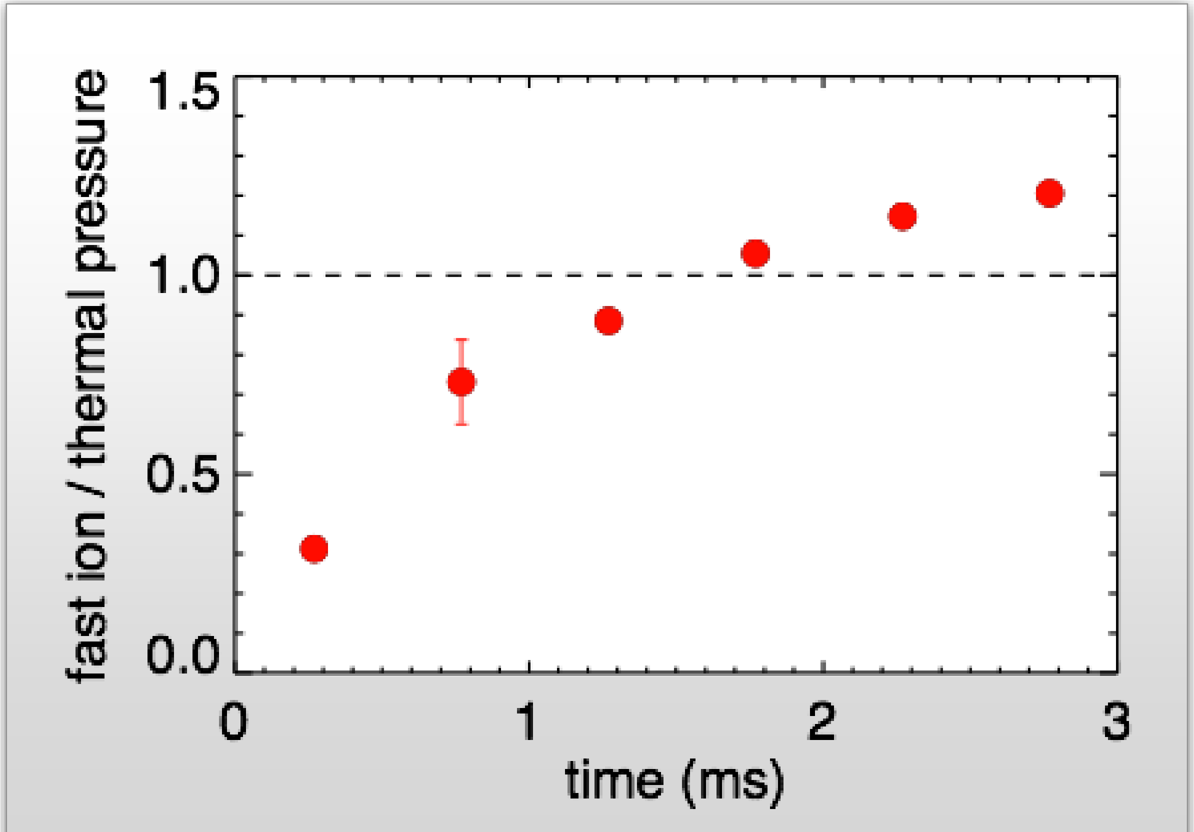
- **Key plasma parameters maintained until end of NB pulse-duration**
- **Diamagnetism persists ~1.5–2.5 ms after NB termination (by accumulated fast-ions)**



* all quantities normalized

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

Signatures of advanced beam-driven FRC state



- **Good agreement from multiple, independent diagnostics for peak value of fast-ion pressure**

Technique	Primary inputs	Peak P_{fi} (kPa)
neutrons	neutron rate, $\langle n_e(r) \rangle$	1.5
1D EFIT	B_e, $n_e(r)$	1.2
T_i (Doppler)	B_e, $n_e(r)$, T_e, $T_{i,Doppler}$	1.5
T_i (CHERS)	B_e, $\langle n_e(r) \rangle$, T_e, $T_{i,CHERS}$	1.4

- **Dominant fast ion pressure term** (See R. Magee's talk for more details)
  - **total pressure is maintained**
  - **ultimately ~50–60% of thermal pressure replaced by fast particle pressure**

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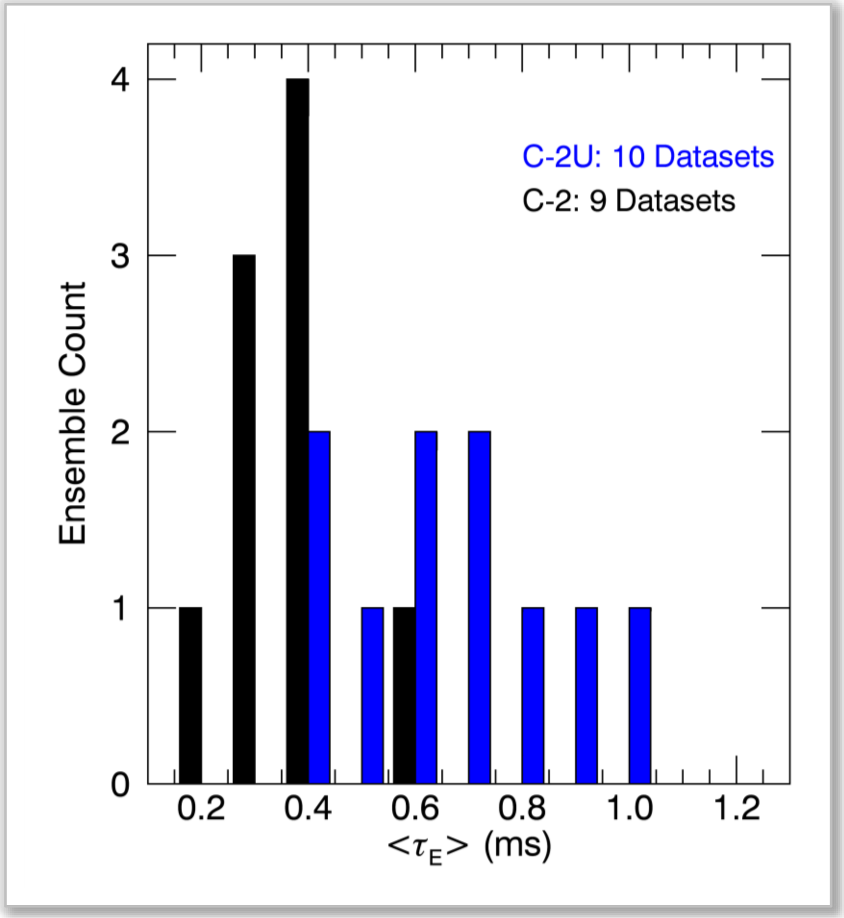
C-2 to C-2U: Energy Confinement Times Improved

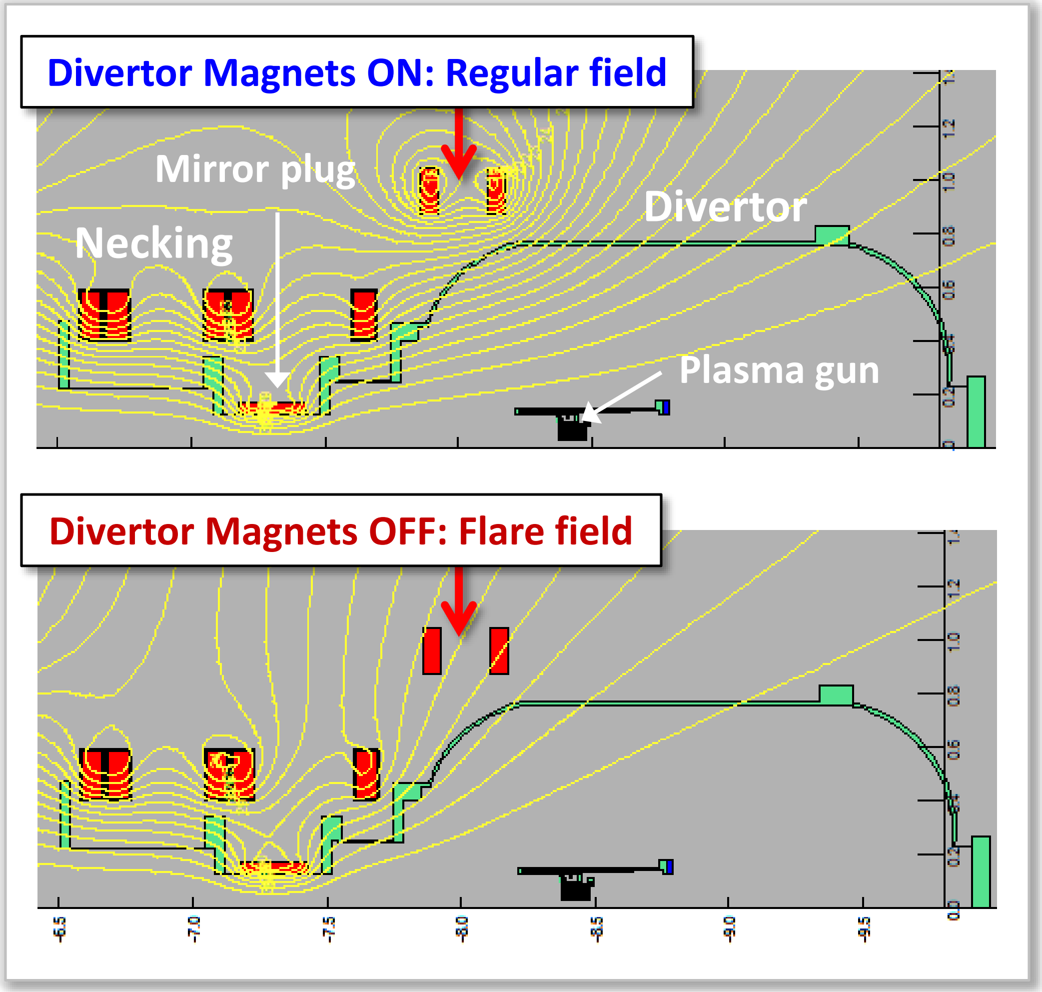
Time Window: 0.3-1.5ms	C-2 (HPF14)	C-2U Sustainment
Beam Power	4.8 MW	10.8 MW
τ_E	0.65 ms	1.15 ms
$\tau_{E,ions}$	1.1 ms	3.8 ms
$\tau_{E,electrons}$	0.14 ms	0.22 ms
$\langle T_e \rangle$	90 eV	116 eV
<Pressure>	3.3 kPa	3.9 kPa

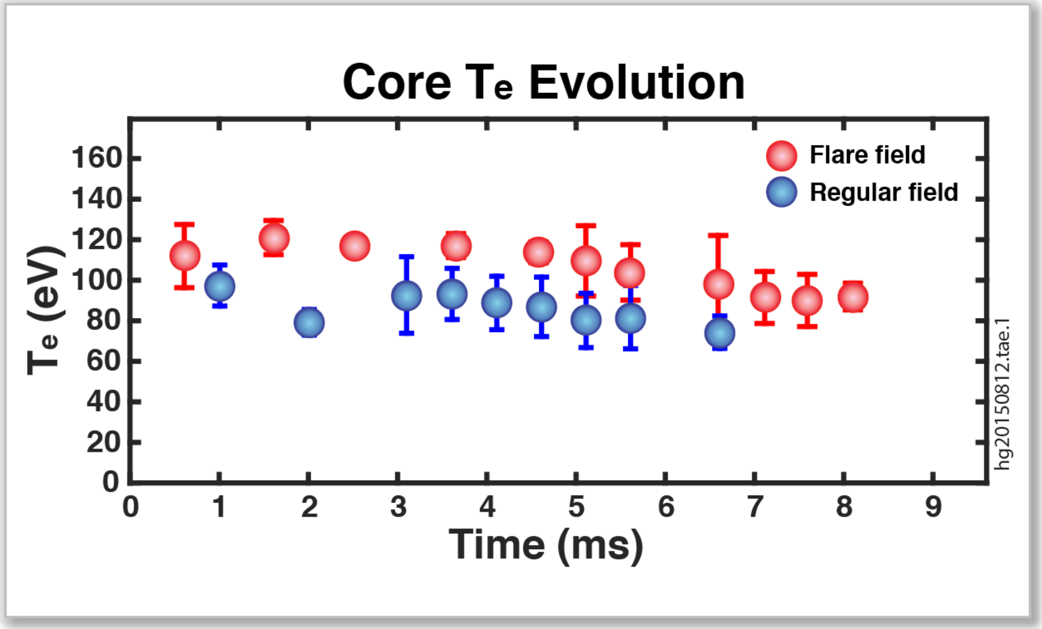


- **C-2U confinement times: ~2 x C-2**
  - **Primary improvement in particle confinement and electron conduction channel**
- **Total pressure and core T_e increased with beam power**
  - **Larger differences later in time as beams build up**
- **Pace of improvements is increasing due to many cycles of learning**

Coupled Core-SOL Confinement Effects

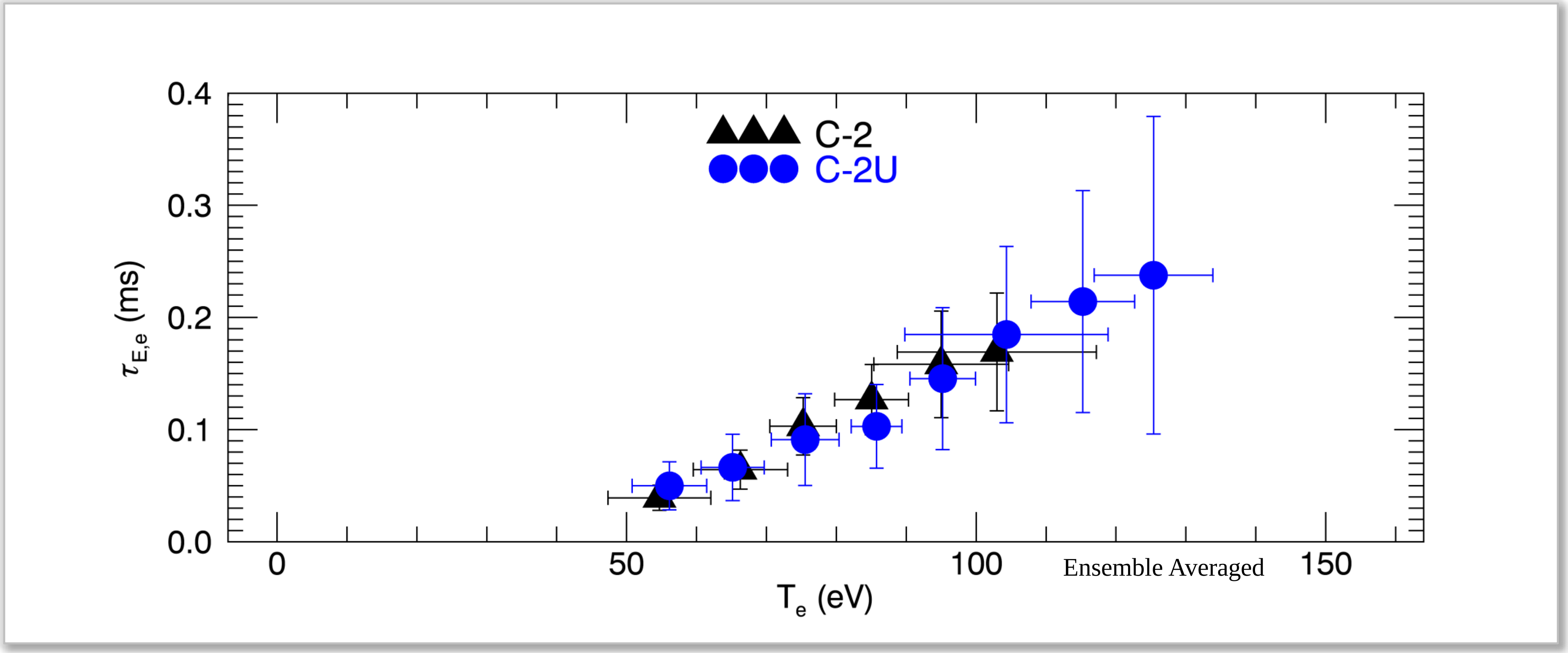
- Improving open-field-line plasmas – key for better core FRC confinement
- 20–30% higher Core T_e with flaring divertor magnetic field
- Enhanced ExB shearing – improve confinement and additional heating





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

Electron Confinement Time Is Strongly Correlated With T_e



- **C-2 and C-2U eras have good agreement**
  - **Only major change was increased beam power**

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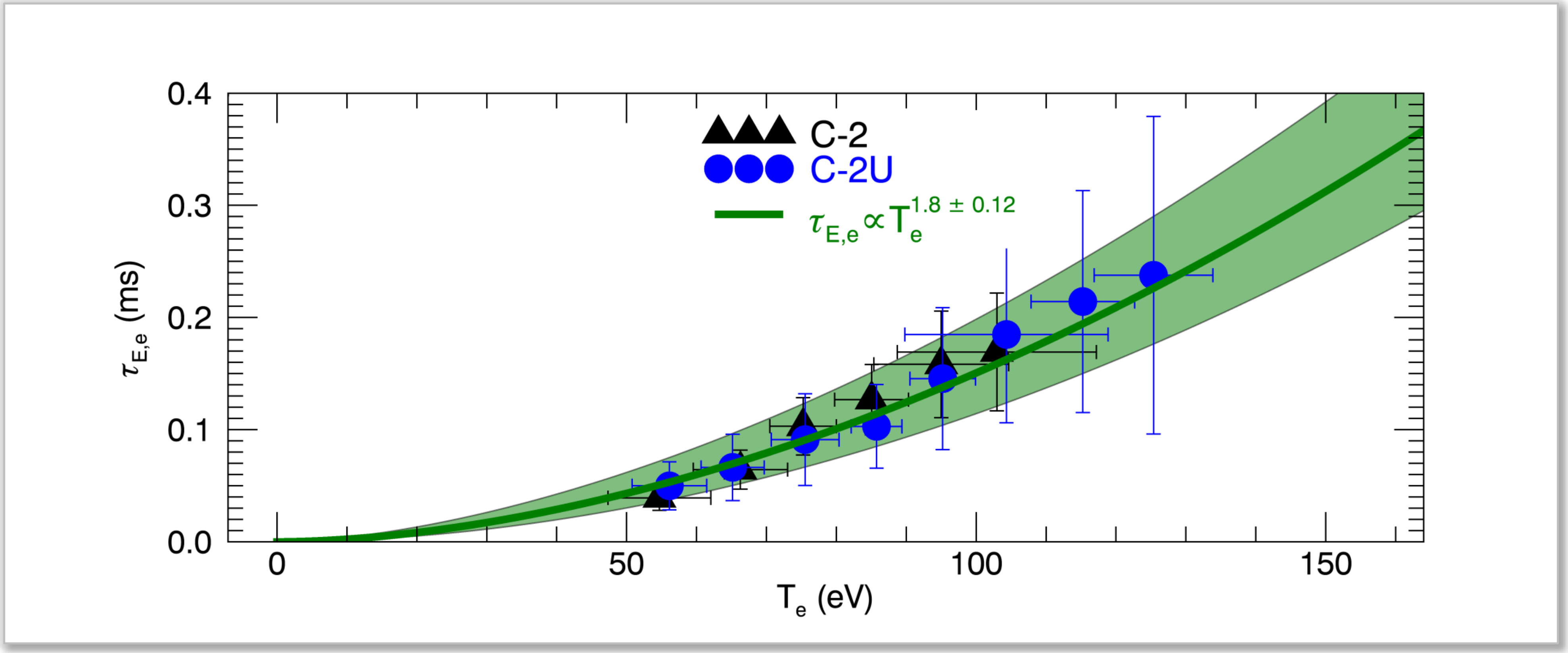

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- Regression gives temperature exponent of 1.8

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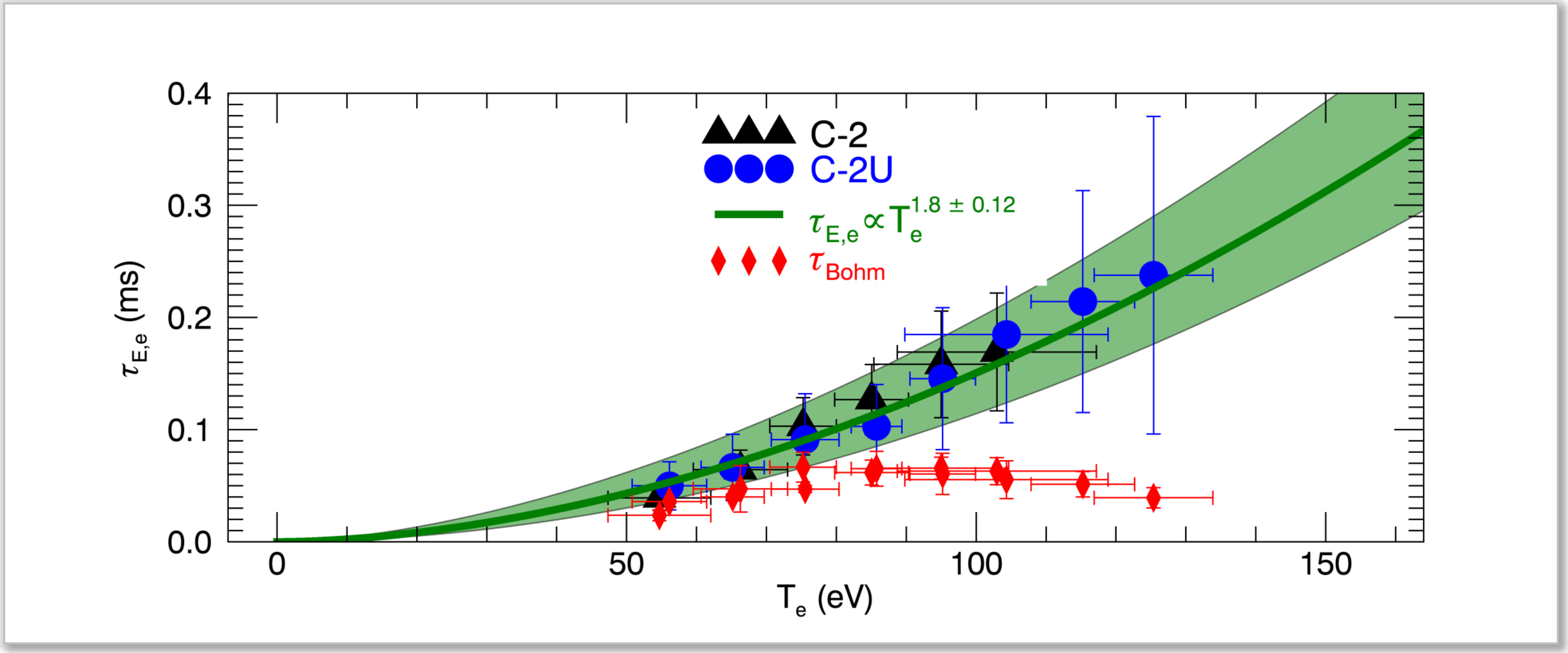
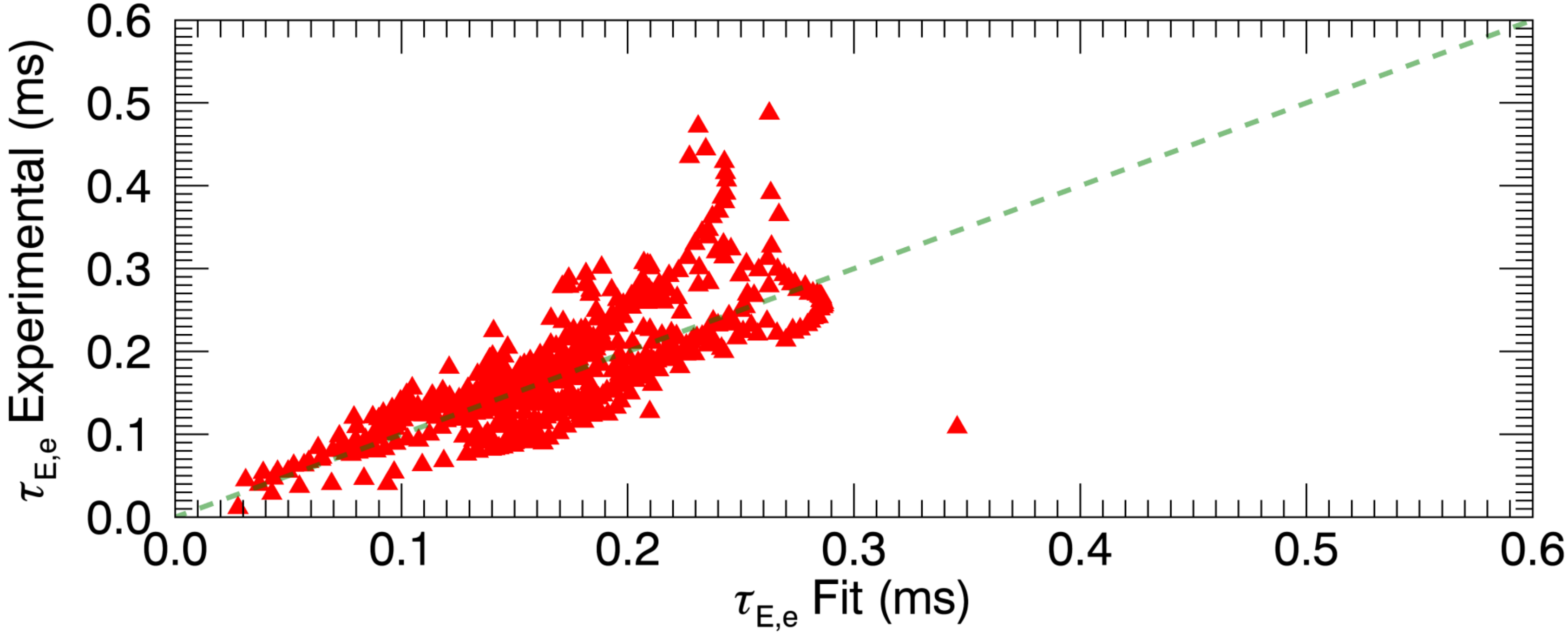


- C-2 and C-2U eras have good agreement
  - Only major change was increased beam power
- Regression gives temperature exponent of 1.8
  - Very different than Bohm-type scaling

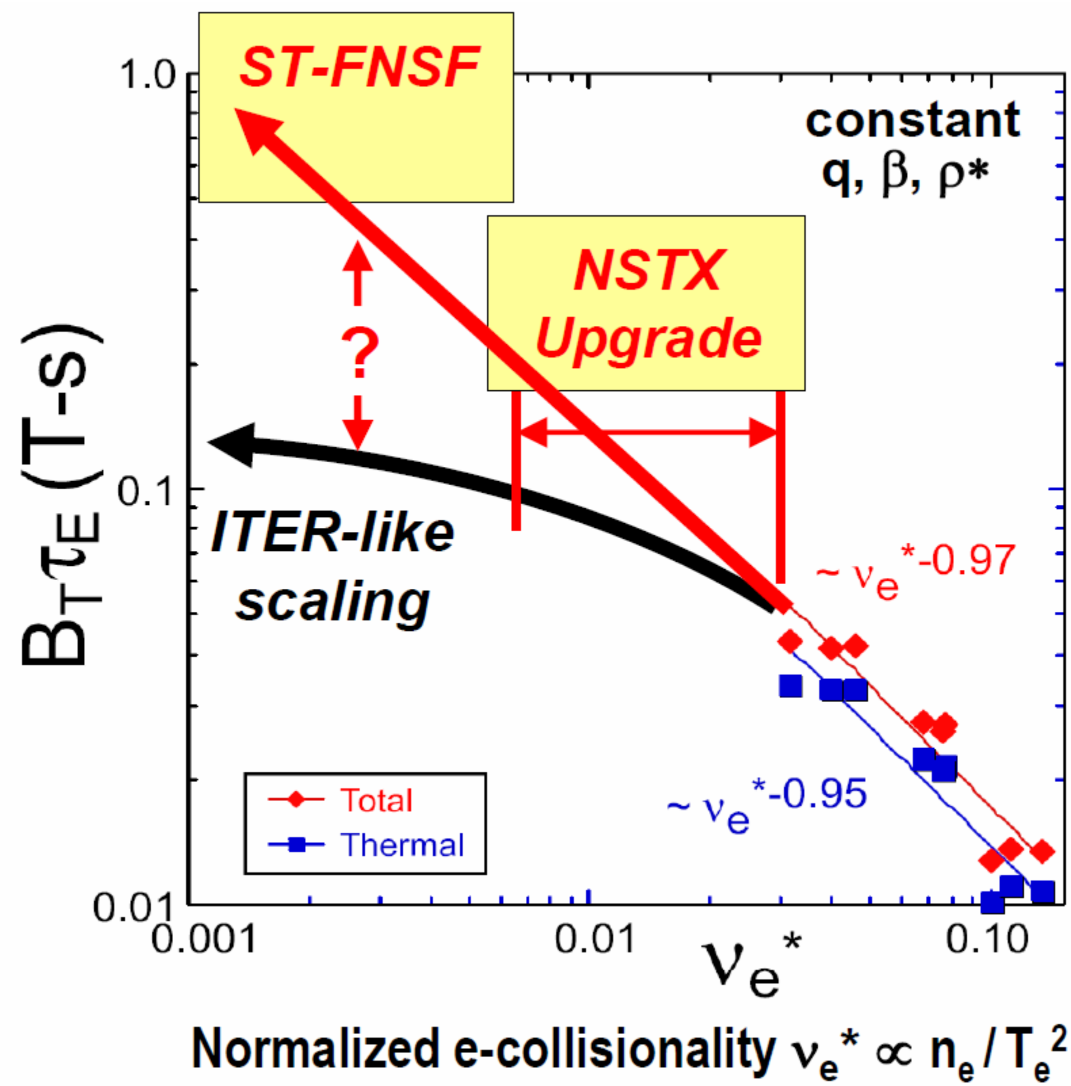
Transport Scaling Over C-2 and C-2U Datasets Has Positive Trend With Electron Temperature



Power Law:	T_e	B_e	R_s	R^2
$\tau_{E,e}$	1.8 ± 0.12	-1.3 ± 0.3	1.0 ± .15	**0.68**

- Anomalous electron losses model differs greatly from Bohm-type scaling

High-β ST And TAE Scaling Is Remarkably Similar



- **Scaling from NSTX and MAST compares well with TAE results**

$$\text{TAE: } \tau_{E,e} \approx T_e^{1.8} R_s / B^{1.3}$$

$$\text{ST: } \tau_E \sim 1/(B\upsilon^\star) \approx T_e^2 / B n_e$$

- **Common features of STs and FRCs include:**
  - **High plasma beta**
  - **Magnetic field and pressure gradients that oppose each other**

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C-2W Goals and Expected Parameters

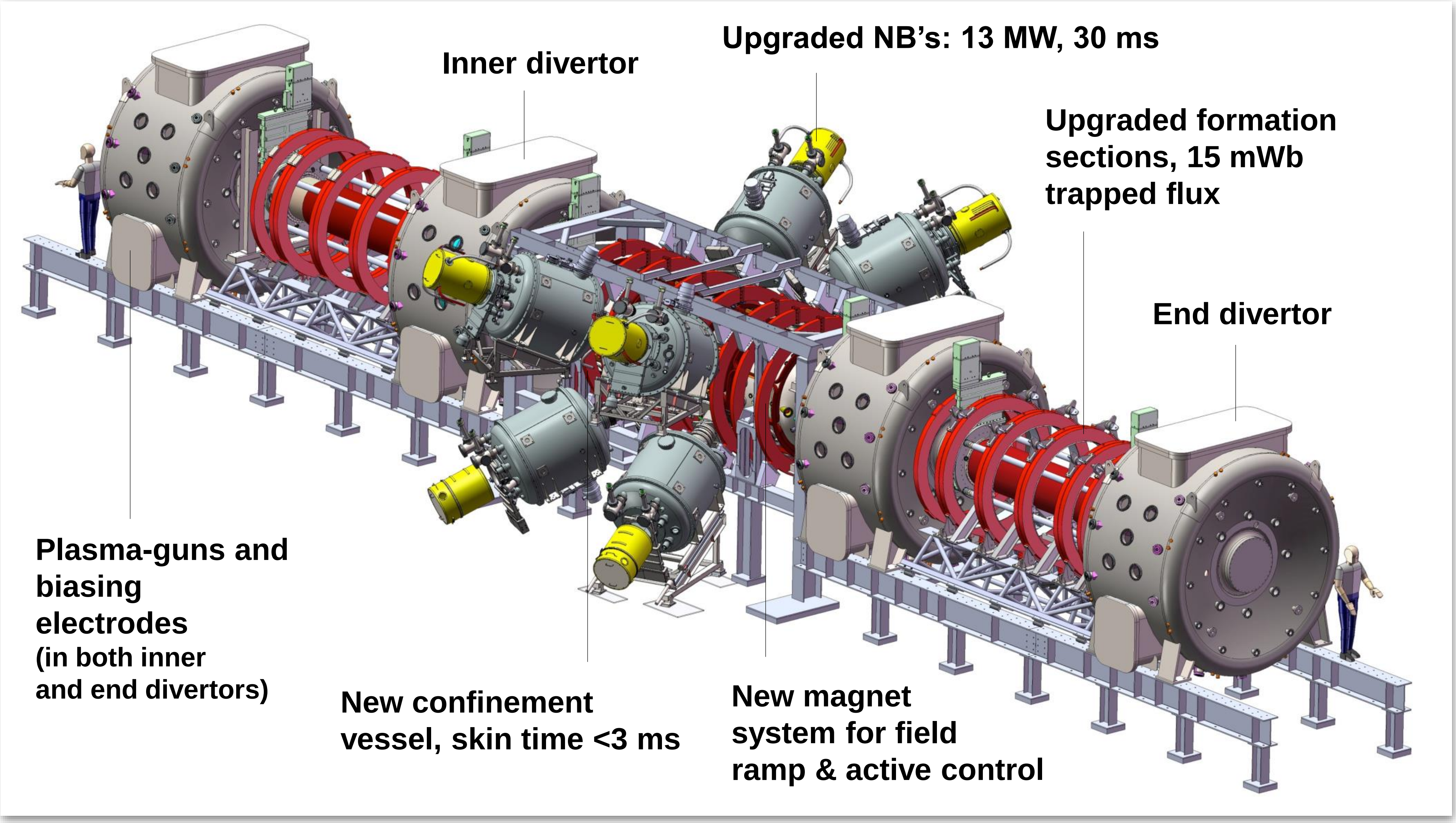
1. Improve performance of the plasma edge and divertor to achieve **high electron temperature** at the plasma edge. T_e

2. Develop plasma control on the time scale significantly longer than L/R vessel time and plasma confinement times and demonstrate **plasma controllable ramp**.

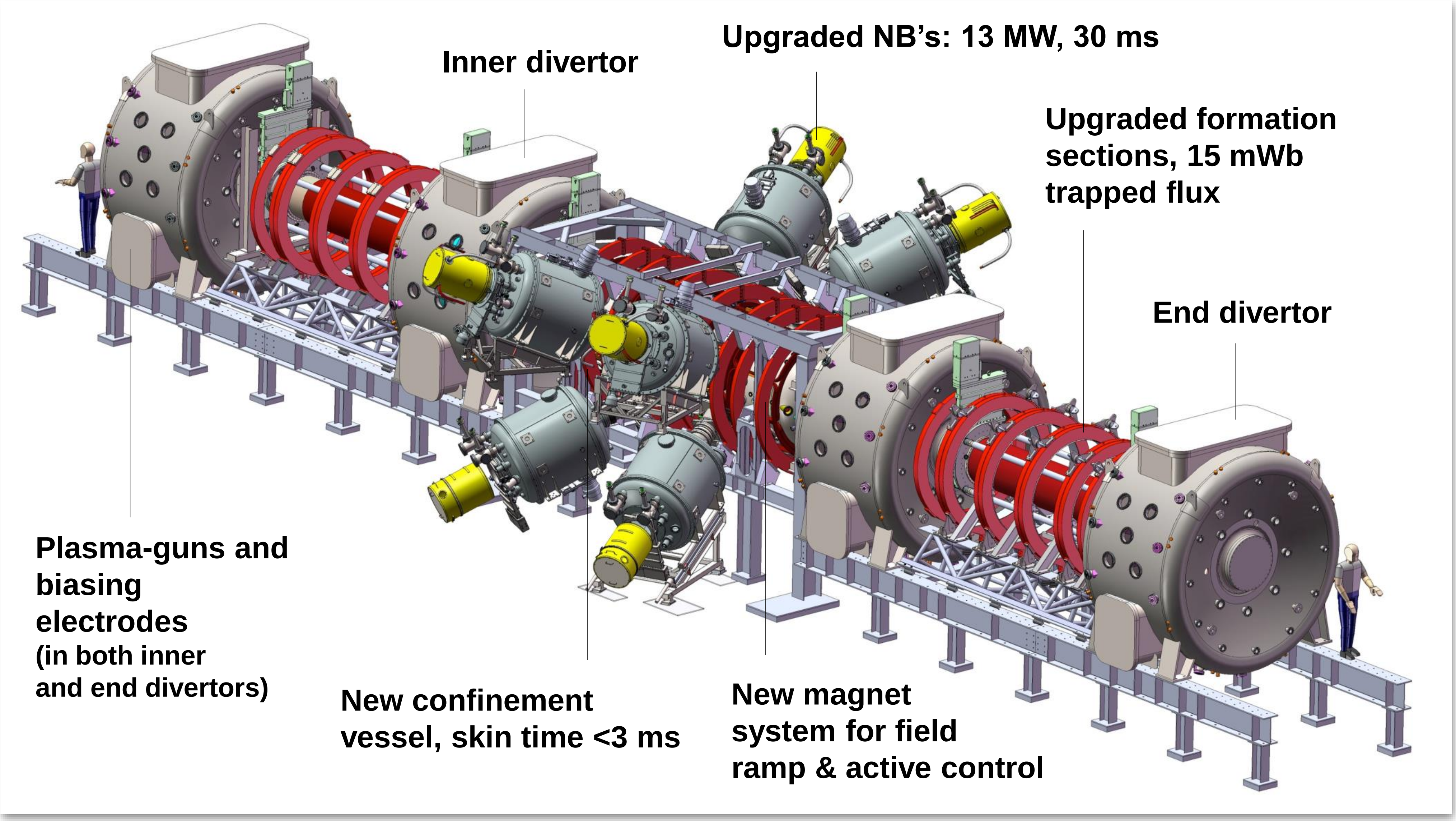
3. Explore a wide range of plasma parameters such as plasma temperature, magnetic field and plasma size to confirm TAE **energy confinement scaling**. τ_E

	(Te, Ti)	Magnetic Field	Pulse Length	Diagnostic Count
C-2U	(0.1, 0.5) keV	0.7-1.1 kG	Up to 11ms	~60 types ~1Gb / shot of data
C-2W	(1, 2) keV	1-3kG	Up to 30ms	>25 new/modified 5-10 Gb / shot

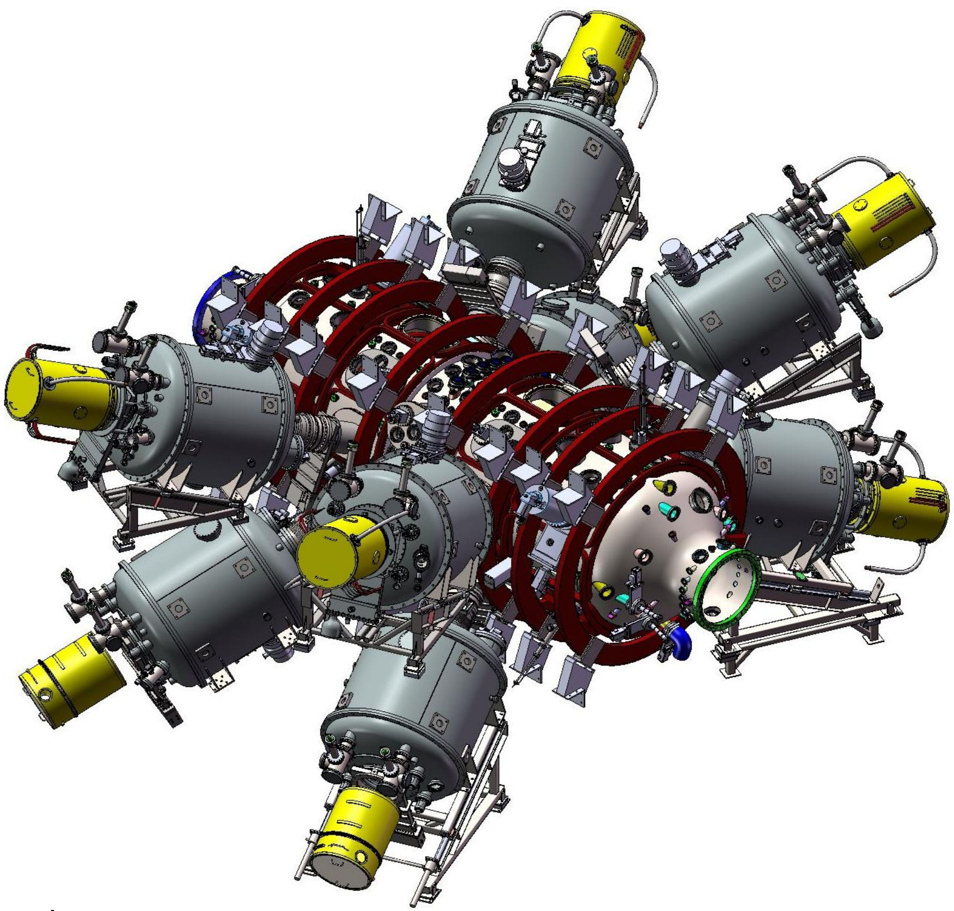
C-2W: Next Device at 10x Stored Energy at TAE

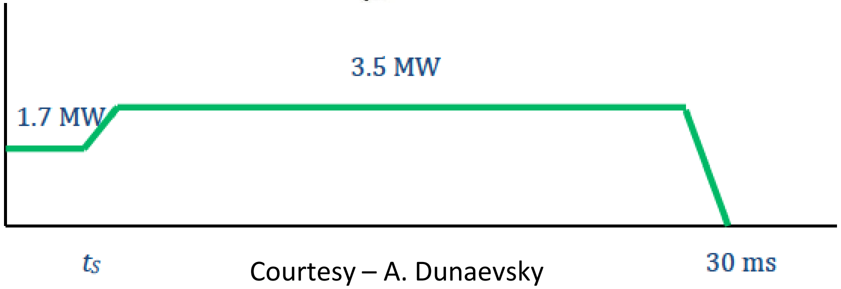


C-2W: Under Construction Now!



Upgrade Example: Switchable Beams





Courtesy – A. Dunaevsky

- **Ramp up of equilibrium magnetic field allows operation at higher beam energy**
  - **Orbits are well confined**
- **Variable energy beams maximize power into FRC core**
  - **Heating, current drive, build up of fast particle pressure**

Parameter	C-2U	C-2W phase 1	C-2W phase 2
Fixed-energy injectors	6	8	4
Switchable energy injectors	0	0	**4**
Beam energy, keV	15	15	15/**40**
Ion current per source, A	130	130	130
Pulse duration, ms	8	30	30
Power in neutrals through the port, per beamline, MW	1.7	1.7	1.7 @15keV **3.5 @ 40kV**
Total NB power, MW	~10	~13	**~21**

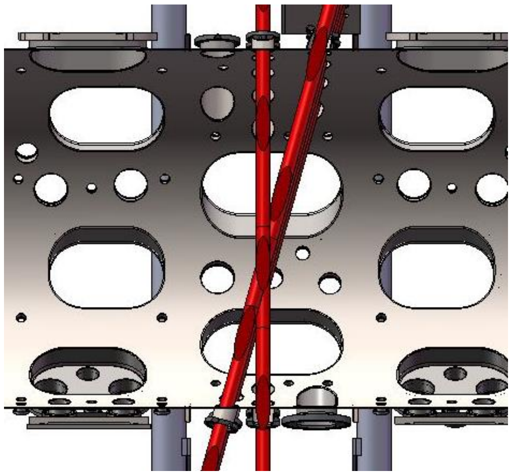
Upgrade Example: FIR Interferometry

- **C-2W Mid-Plane Laser Interferometer:**
  - **14 Chords of Far Infrared (FIR) laser at 433 μm.**

$$\text{Phase Shift}: \phi_I = 2.81\times10^{-15}\lambda\int n_e dl$$

  - **High sensitivity and full coverage into the scrape-off layer.**

- **Polarimetry Function**

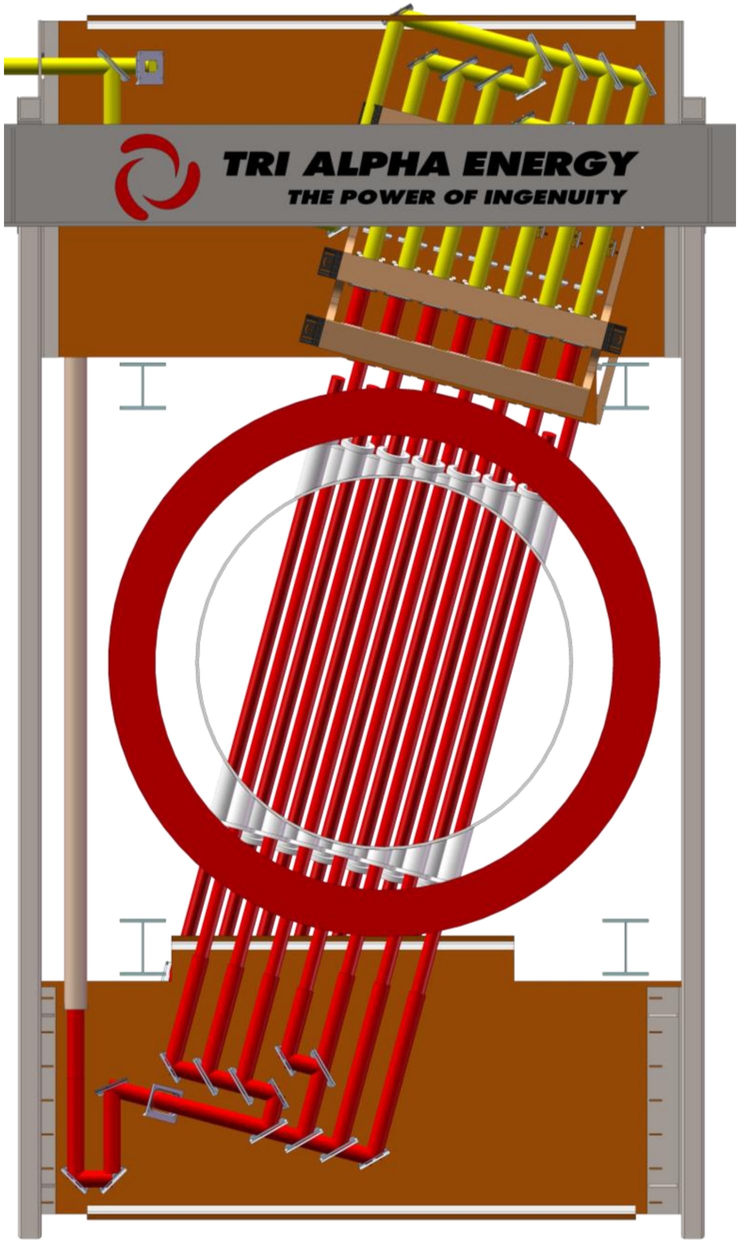


Faraday Rotation Angle:

$$\psi_F = 2.62\times10^{-13}\lambda^2\int n_e B_{//} dl$$

Excellent sensitivity to B_θ

7 tilted chords provide a chance to measure B_z via Faraday rotation



Courtesy – B. Deng and M. Beall

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

- **High-Performance FRC (HPF) regime demonstrated**
  - edge biasing, neutral beams and gettering produce HPF regime with excellent shot-to-shot reproducibility
  - record FRC lifetimes (~11 ms) are only limited by transport
  - beneficial emerging confinement scaling with 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**
  - hardware changes will improve SOL temperatures
  - diagnostic expansion will characterize equilibria and power flows
  - scaling of confinement timescales will be extended

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