On the Path to Aneutronic Fusion

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From Wakefields to Astrophysics and Fusion – UC Irvine, January 25-26, 2018

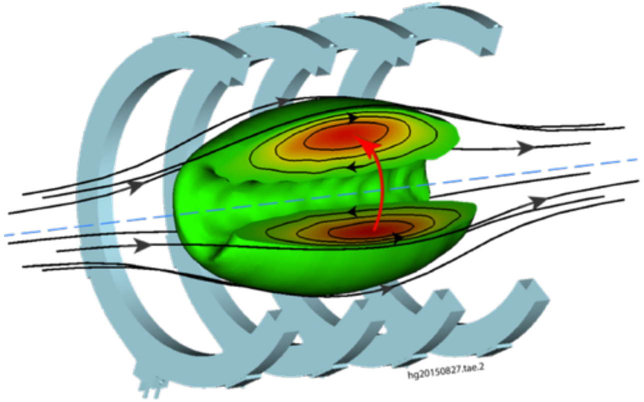
Congratulations Toshi

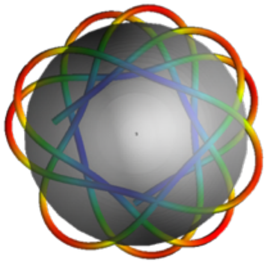
Agenda

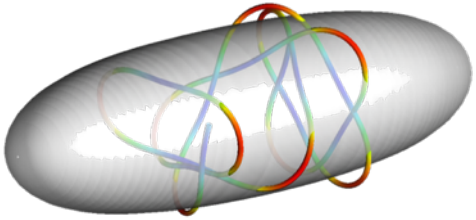
- Concept and History
- C-2W Program Overview and Initial Results
  - Program goals
  - Norman (aka C-2W) – design, subsystems and performance
  - FRC formation/translation studies
  - Initial FRC collisional-merging experiments
- Technology Spin-offs

TAE Concept

Advanced beam driven FRC







- High plasma β~1
  - compact and high power density
  - aneutronic fuel capability
  - indigenous kinetic particles
- Tangential high-energy beam injection
  - large orbit ion population decouples from micro-turbulence
  - improved stability and transport
- Simple geometry
  - only diamagnetic currents
  - easier design and maintenance
- Linear unrestricted divertor
  - facilitates impurity, ash and power removal

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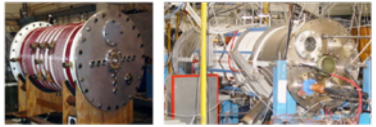
Past TAE Program Evolution



A & B – Basic FRC core

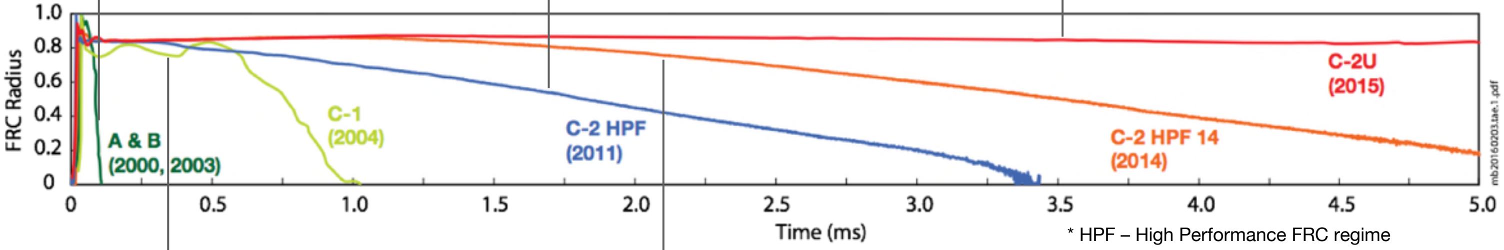
- 100-800 G, 5-10 eV
- ion beams, W_b ~0.1 kJ

C-2 – HPF* w/ 2 guns, Ti getter

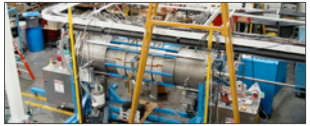
- 1 kG, 1 keV
- neutral beams, W_b ~12 kJ

C-2U – Sustainment 5+ ms

- 1 kG, 1 keV
- neutral beams, W_b ~100 kJ



* HPF – High Performance FRC regime



C-1 – Enhanced lifetime

- 400 G, 10 eV
- ion beams, W_b ~1 kJ

C-2 – HPF* w/ 2 guns, Li getter

- 1 kG, 1 keV
- neutral beams, W_b ~20 kJ

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C-2W Program Overview

Phase C-2W Goals

Explore beam driven FRCs at 10x stored energy

- Principal physics focus on
    - scrape off layer and divertor behavior
    - ramp-up characteristics
    - transport regimes

- Specific programmatic goals
    - demonstrate ramp-up and sustainment for times well in excess of characteristic confinement and wall times
    - explore energy confinement scaling over broad range of plasma parameters
        - core and edge confinement scaling and coupling
        - consolidated picture between theory, simulation and experiment
    - develop and demonstrate first order active plasma control

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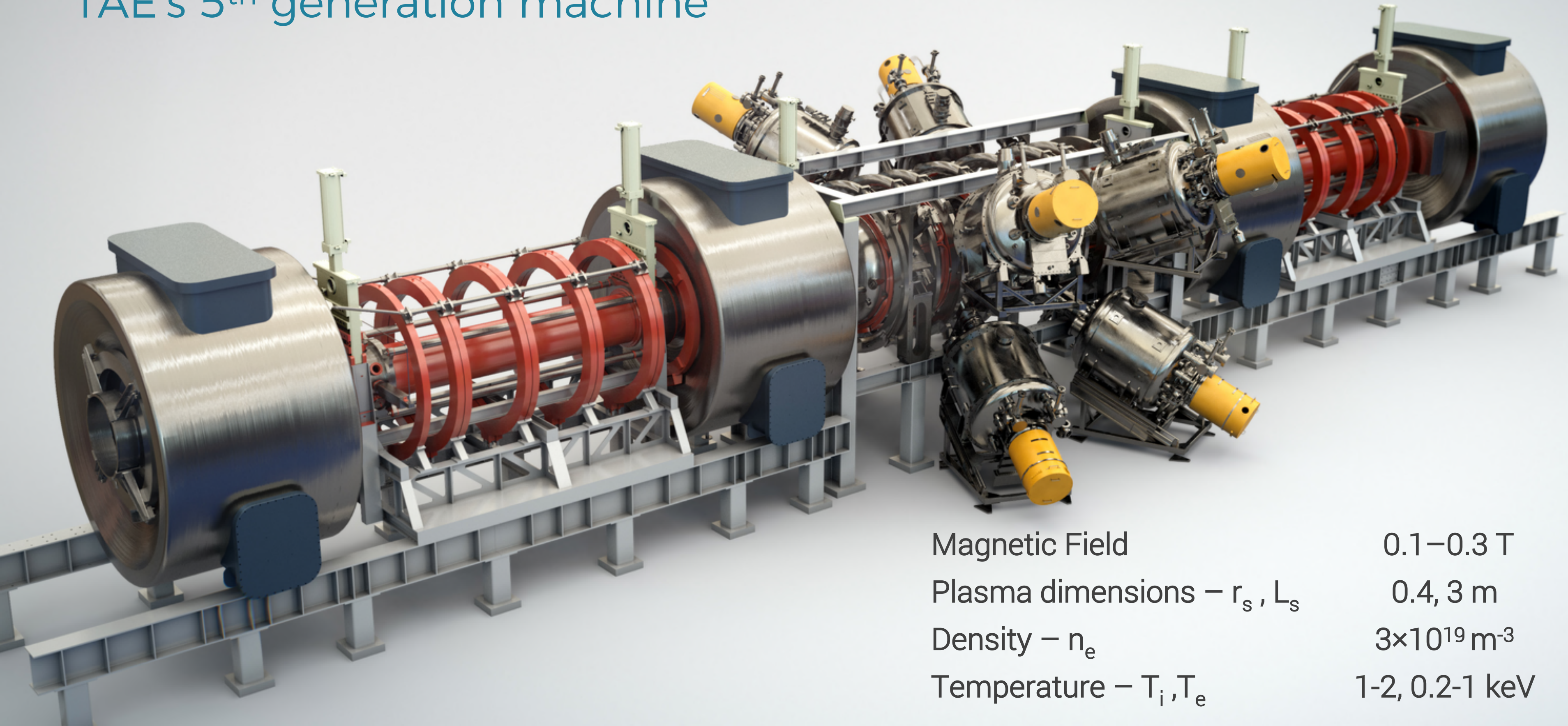
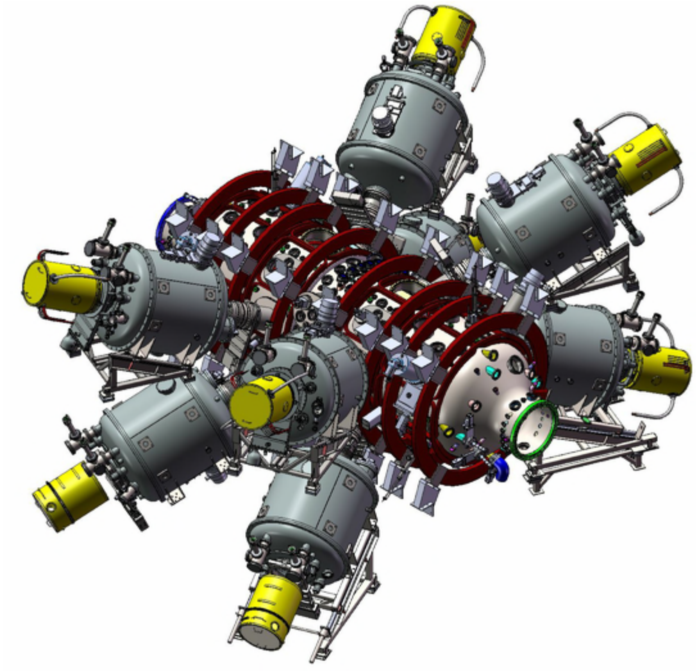
Norman (aka C-2W)

TAE's 5th generation machine



Magnetic Field	0.1–0.3 T
Plasma dimensions – r_s , L_s	0.4, 3 m
Density – n_e	3×10^{19} m^{-3}
Temperature – T_i ,T_e	1-2, 0.2-1 keV

Norman – Neutral Beam System



	C-2U	Norman Phase 1	Norman Phase 2
Beam Energy, keV	15	15	15/15-40
Total Power	10	13	21
# of Injectors	6	8	4/4
Pulse, ms	8	30	30
Ion current per source, A	130	130	130

- Centered, angled and tangential beam injection
  - angle adjustable in range of 15°–25°
  - injection in ion-diamagnetic (co-current) direction
- High current with low/tunable beam energy
  - reduces peripheral fast-ion losses
  - increases core heating / effective current drive
  - rapidly establishes dominant fast-ion pressure for ramp-up

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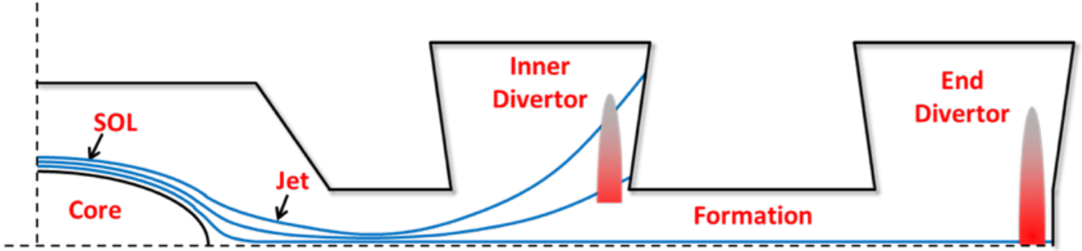
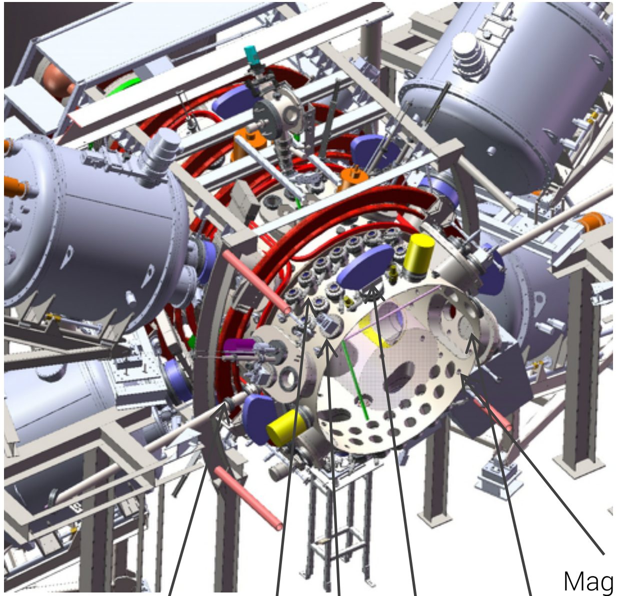
Norman – Diagnostics

Comprehensive diagnostics suite



- 4 main zones with 40+ diagnostics
  - Core plasma inside the FRC separatrix
  - mirror-confined scrape-off layer and jet
  - rapidly expanding plasma in the inner divertors and/or end divertors
  - FRC formation sections

Midplane Cross Section



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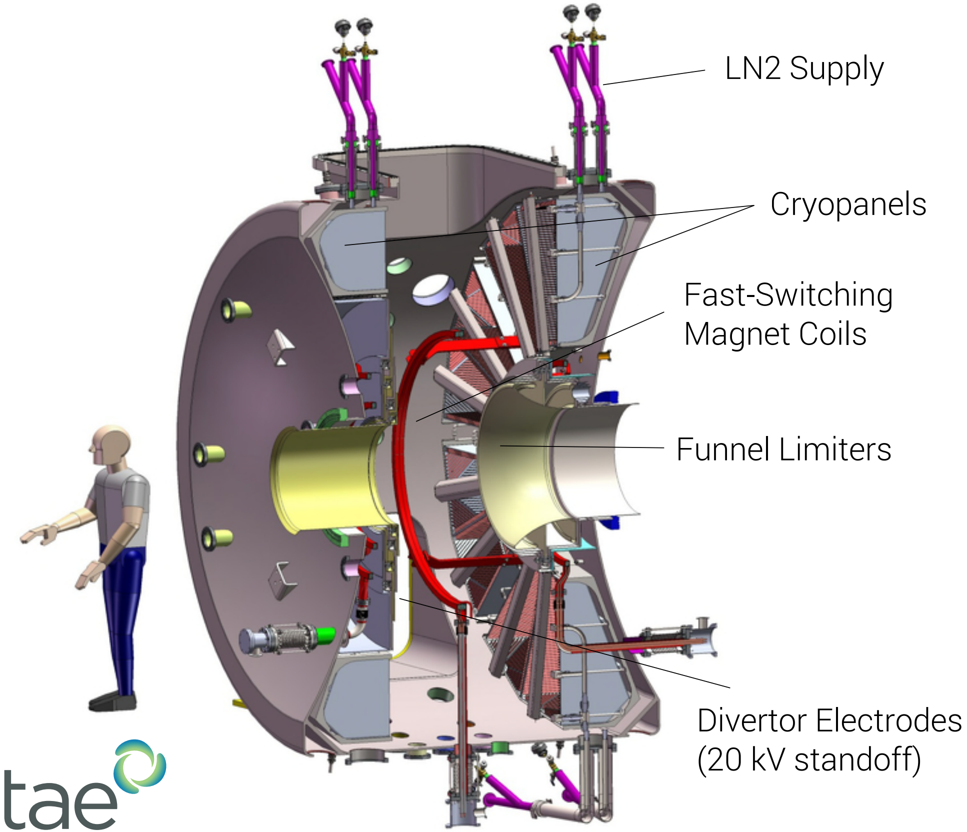
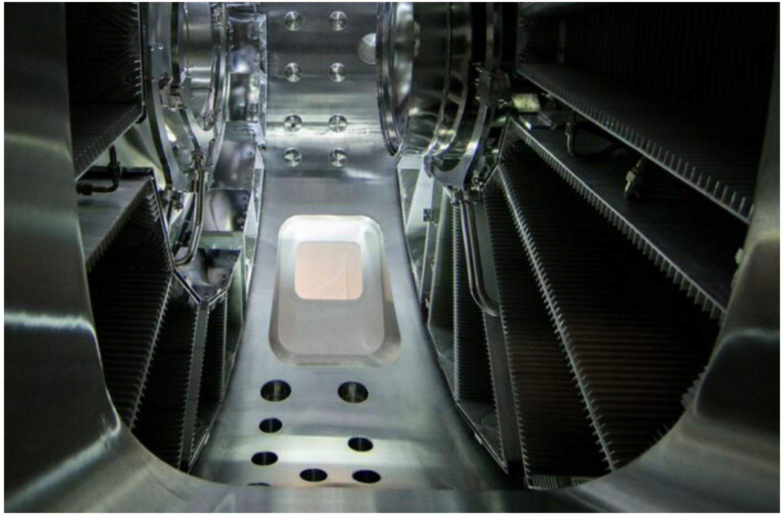
Norman – Divertors

Critical for edge control



- 2×10^6 L/s pumping to reduce recycling
- field expanders to minimize e^- cooling
- electrodes for stability control
- fast switching coils to translate FRCs



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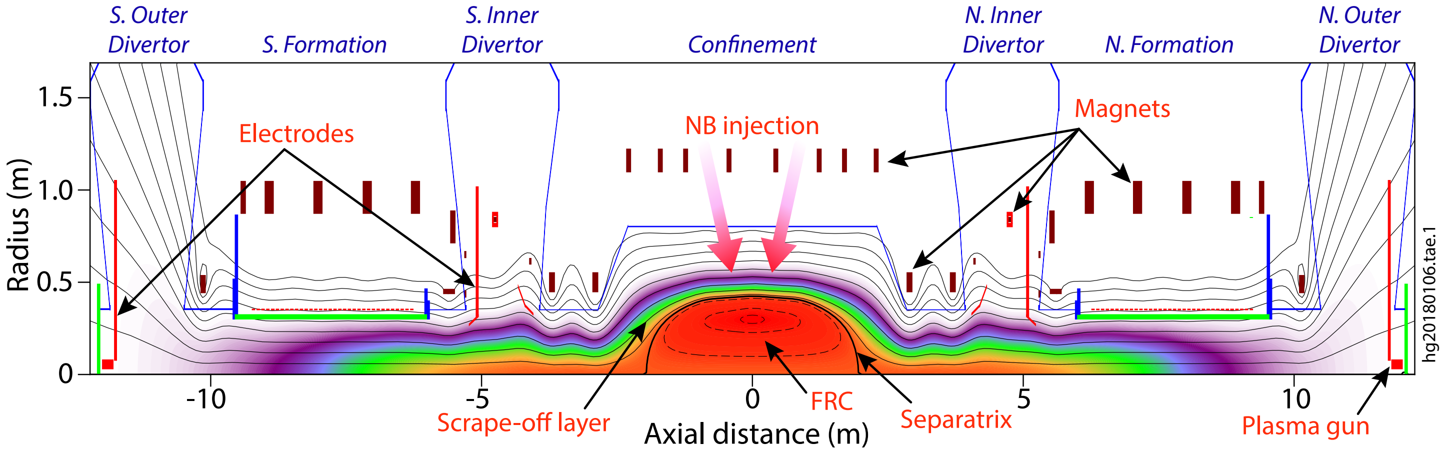
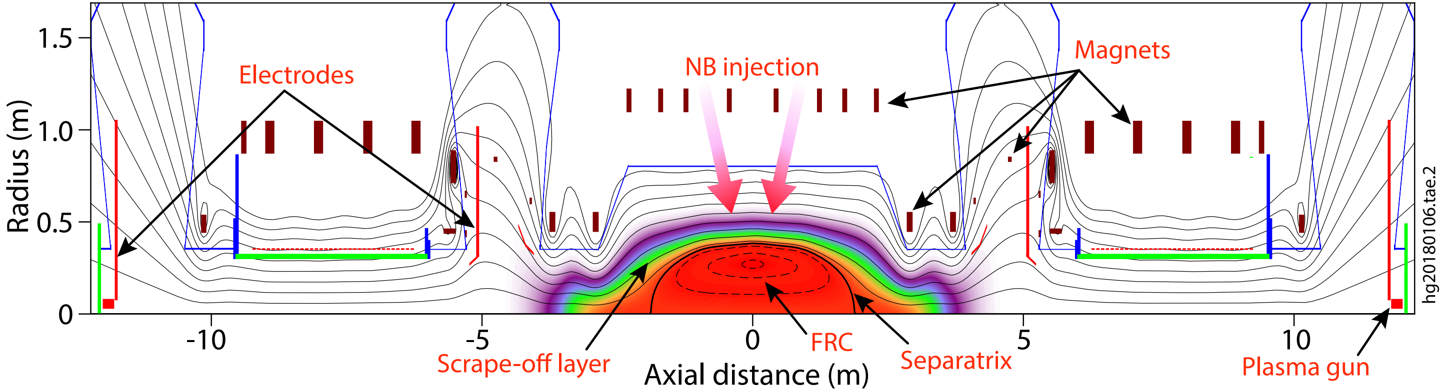
Norman – Divertor Operating Modes

Flared magnetic fields, edge biasing & outer/inner divertor switching

(1) Biasing from **Outer Divertors**



(2) Biasing from **Inner Divertors**



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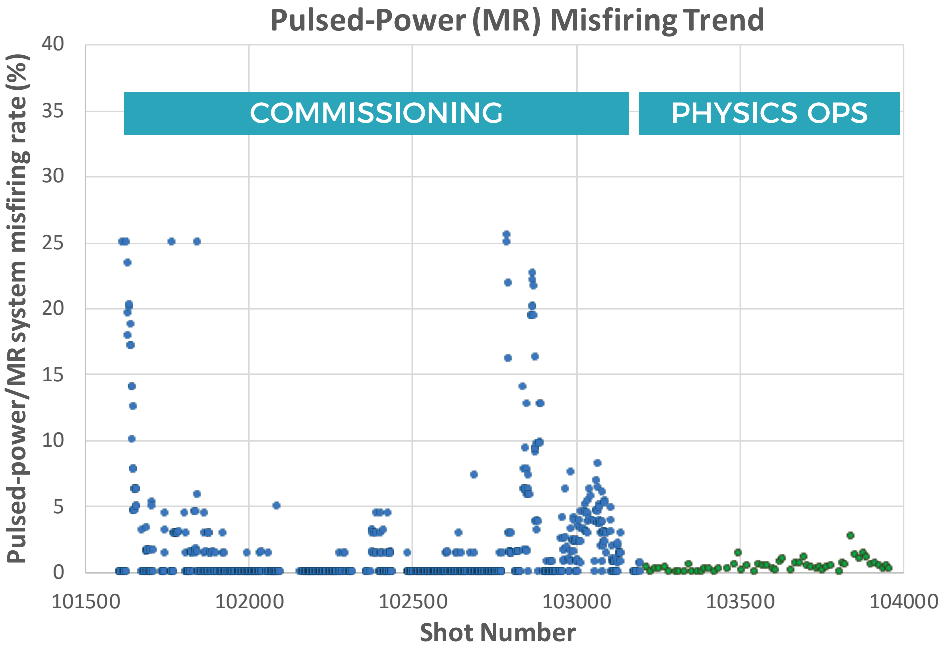
C-2W Initial Results

Norman Formation Systems Work Flawlessly

Greatly improved experimental efficiency



Formation systems fully optimized

~450 GW deployed to form plasmoids

- 400+ switched power units
- all systems fully monitored
- maximum switch jitter under 10 ns

Excellent consistency and shot-to-shot reproducibility

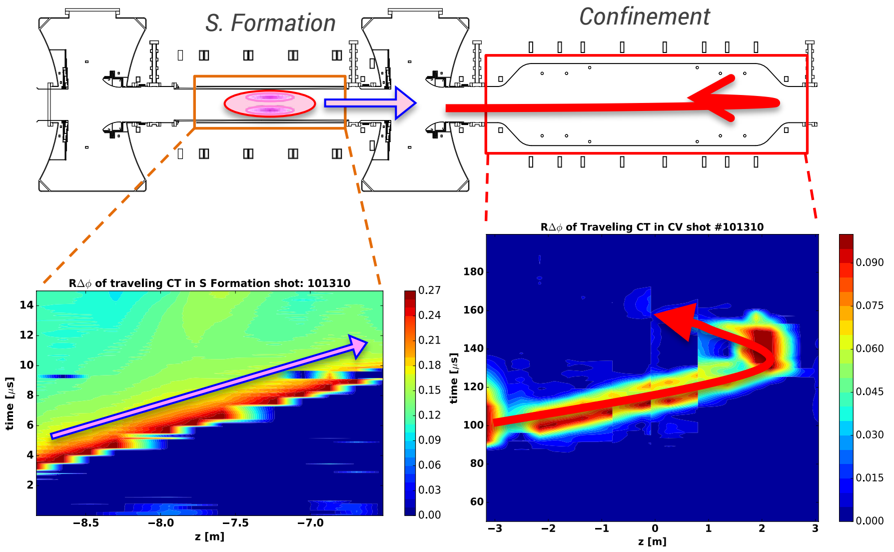
Superior operational efficiency

- less than 2% system misfires

Initial FRC Translation Studies (single-sided)

Successful translation through inner divertor achieved

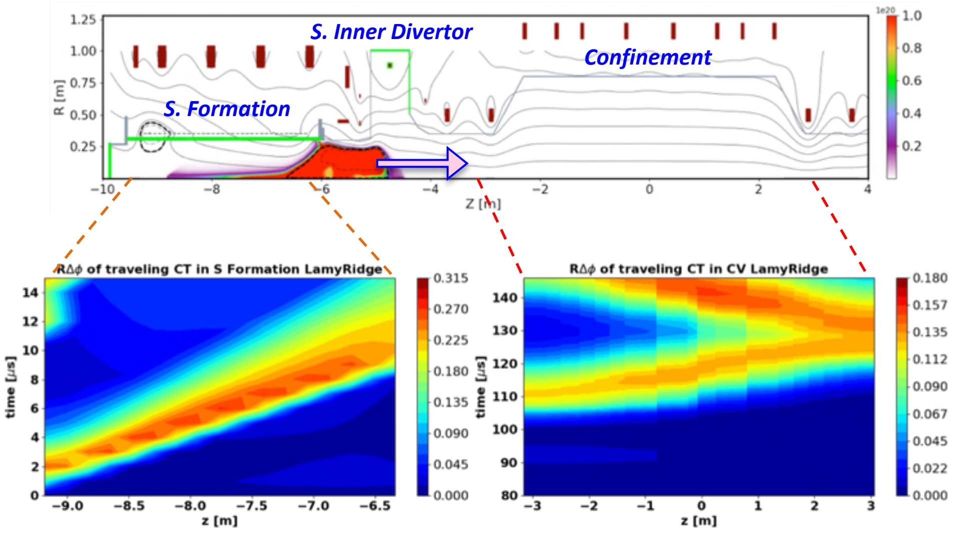
Experiment



Experimental time evolution of excluded flux radius during formation and translation

Simulation

2D MHD simulation by LamyRidge code



Simulated time evolution of excluded flux radius during formation and translation

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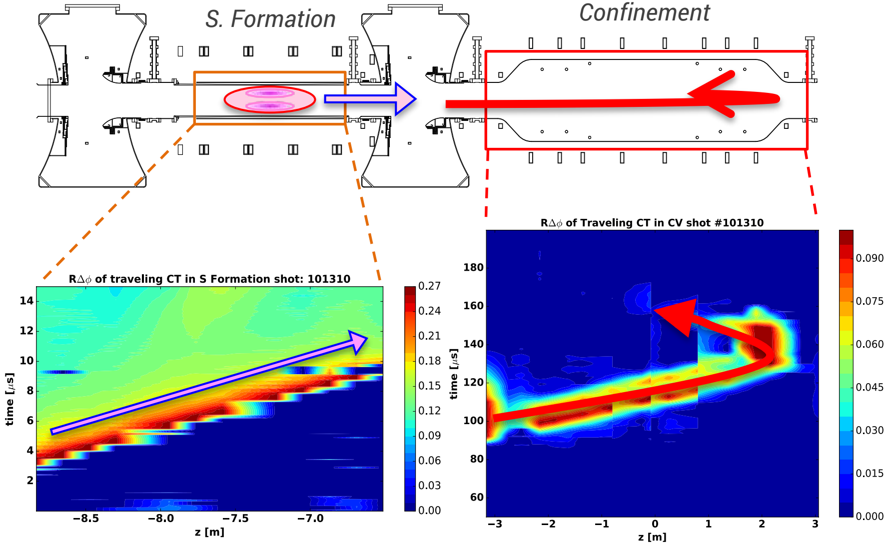
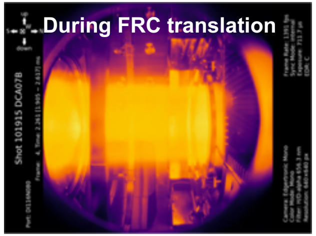


Experimental time evolution of excluded flux radius during formation and translation

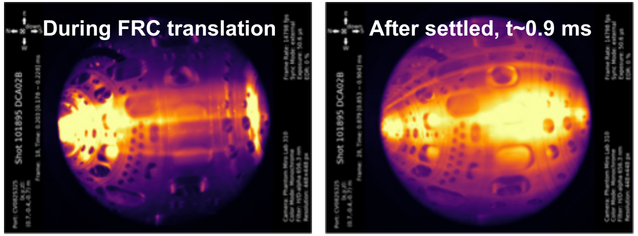
Fast-Framing Camera Images

in inner divertor



Inner divertor camera observes clean FRC translation

in confinement



Confinement vessel camera observes FRC reflections as plasma bounces back and forth in CV

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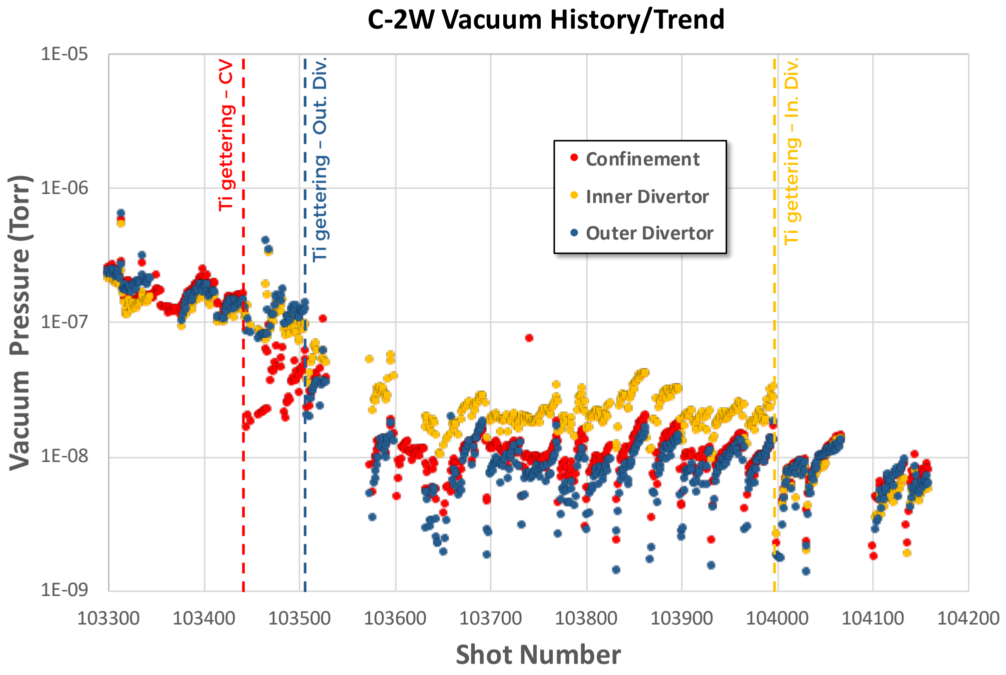
Norman Vacuum Performance Trends

Surface conditioning and patience are critical



Great improvement from Ti gettering

- correlated base pressure drops
- Significant reduction in dominant impurities (C, O, etc)

Vacuum conditions still improving

- increased gettering over time
- plasma cleaning of surfaces

Increasing FRC performance over time

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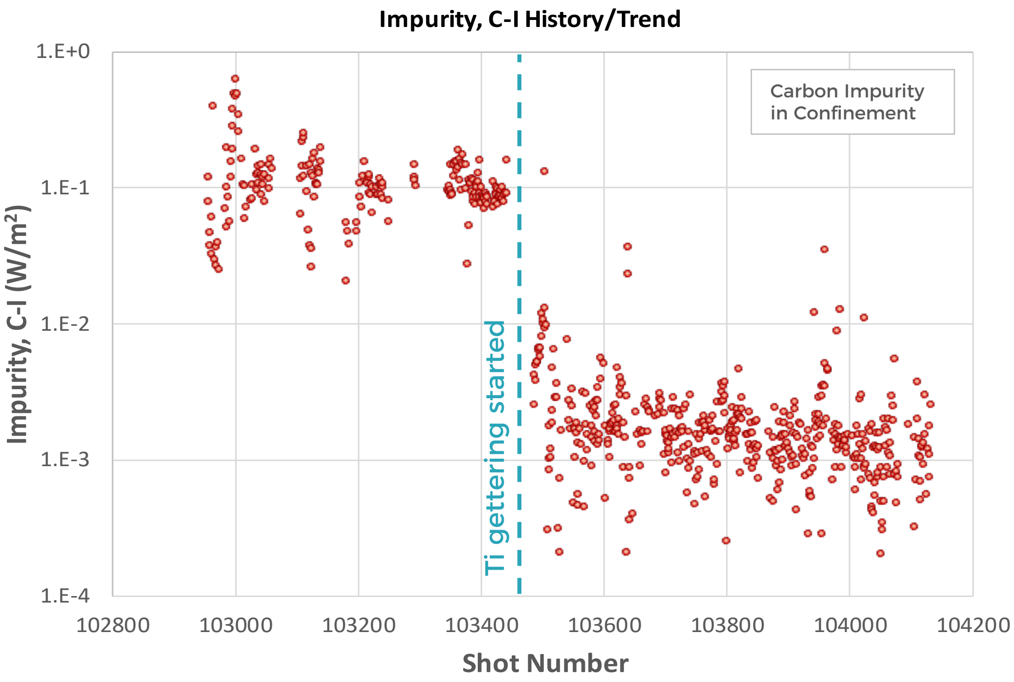

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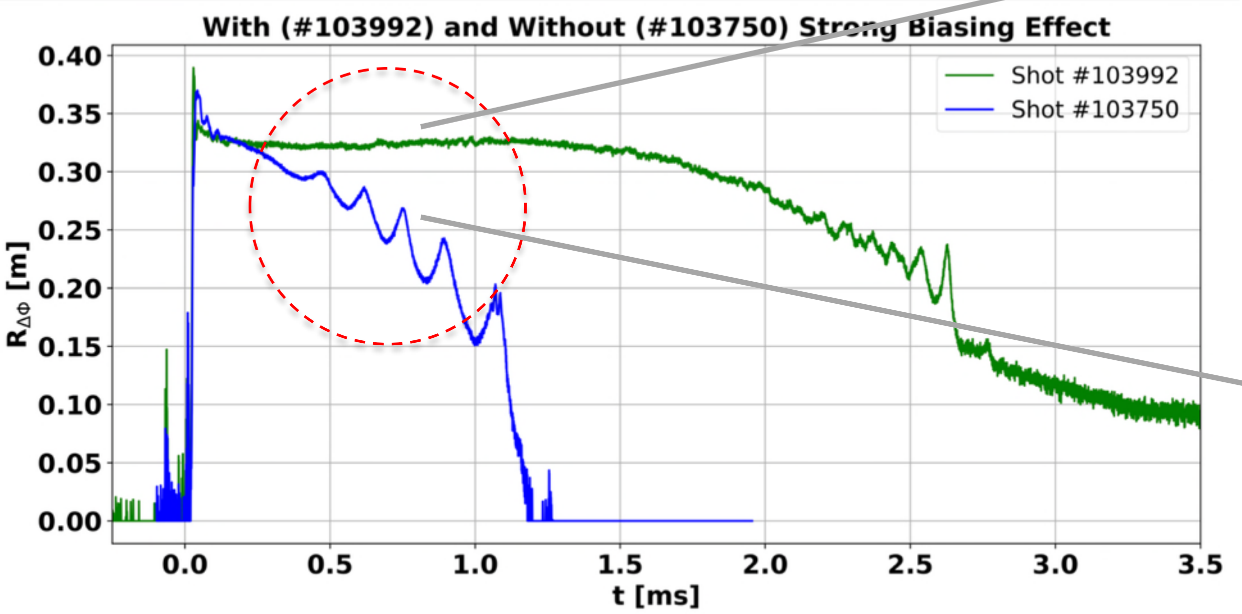
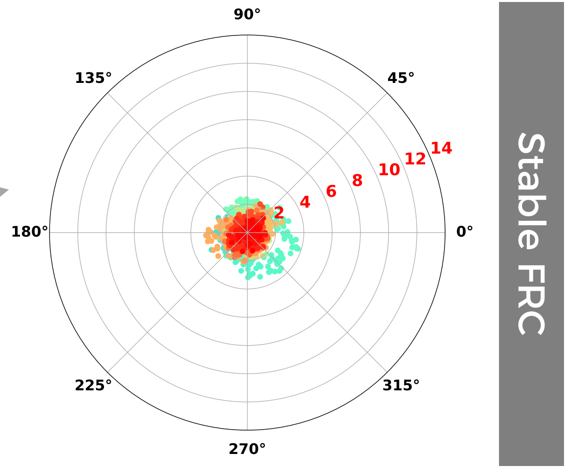
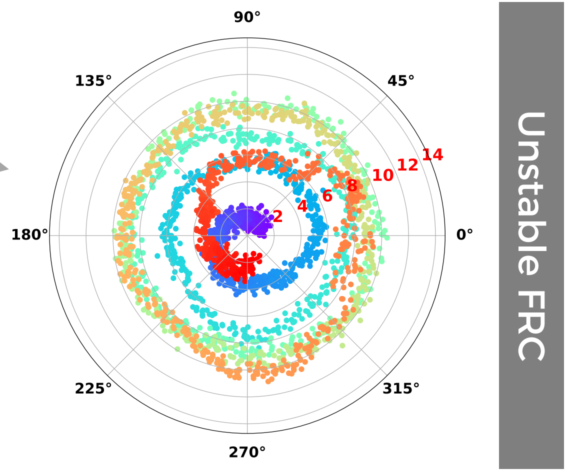
Edge-Biasing Impact

Successful instability control







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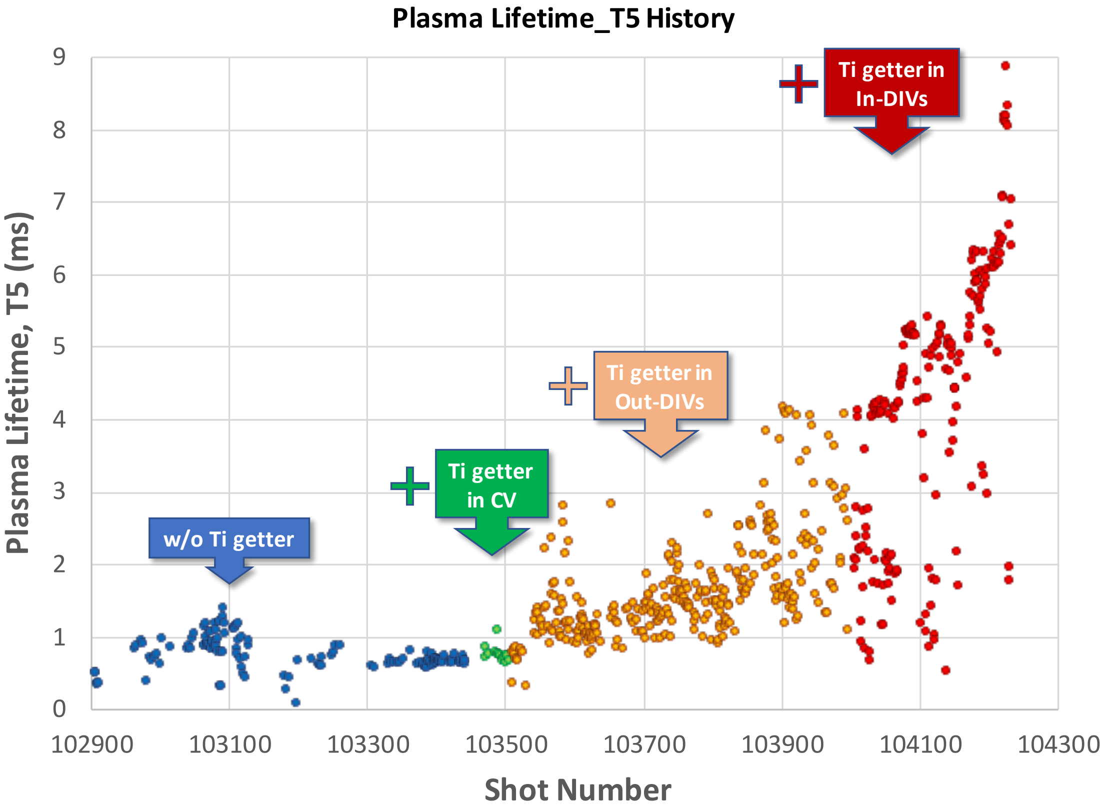
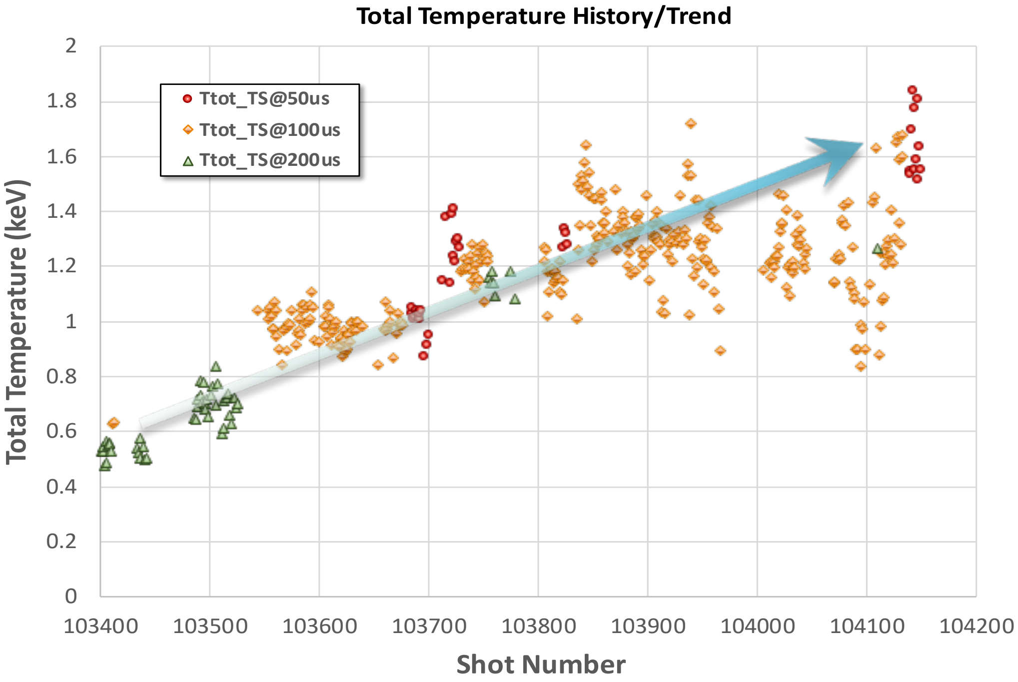
Norman Plasma Lifetime Trends

Continuous performance increase throughout past few weeks



Norman Plasma Temperature Trends

Continuous improvement in total temperature



Total temperature (ion+electron) consistently increasing

- lower impurity radiation losses
- more efficient beam coupling
- better confinement

Early temperature moving to 2 keV

- higher energy formation section
- better pre-ionization

Increasing FRC performance over time

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Norman (C-2W) Summary

- Engineering accomplishments
  - All major subsystems constructed and operational in less than 12 months build cycle
  - Highly upgraded formation pulsed power, vacuum system, neutral beams, magnets, edge-biasing systems and divertors
- Initial experimental results
  - FRCs successfully formed and translated through inner divertors
  - ~ 400 km/s translation speeds observed (250 km/s in C-2U)
  - FRC collision/merging experiments already producing 8+ ms plasma lifetime

Technology Spin-offs

TAE Life Sciences

- Spin-off based on TAE neutral beam injector technology
- TAE majority owned, but independent capital and management team
- Will offer full full treatment solution to hospitals, not just neutron beam
- First clinical system sold in October 2017, to deploy in 2019

Neutron Beam Development

- Design of first clinical beam underway
- Conceptual design review completed
- Early procurement and supply chain development under way (aids fusion beam development)
- Pre-clinical prototype under assembly, to undergo testing by summer 2018


Happy Birthday Toshi!