Progress at TAE

38th FPA Annual Meeting 2017

Michl Binderbauer | President & CTO | TAE Technologies

2017 at TAE Technologies

Key accomplishments

- Finished construction of Norman (formerly C-2W) – first plasma in June
- Regular science operation on Norman – 3,000 shots since July
    - Successful plasma formation from both ends
    - Efficient translation through inner divertors and plasma merging achieved
    - Sustained operation at 1 keV temperatures under way
- Substantial progress on turbulence simulations
- Successful launch of TAE Lifesciences
    - Spin-off to commercialize beam technology in oncology space

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Agenda

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

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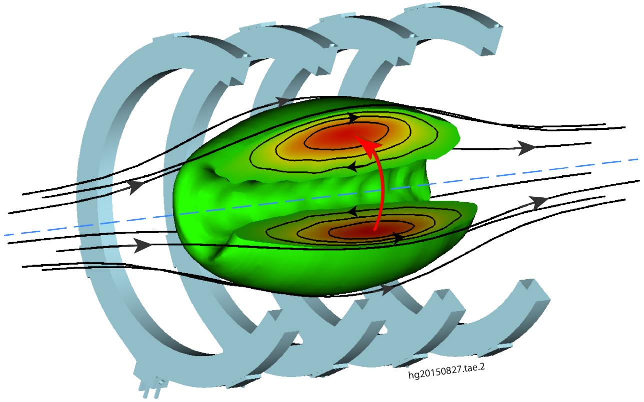
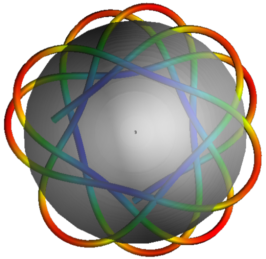
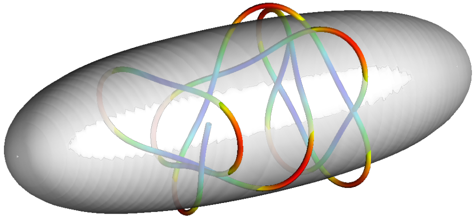
TAE Concept

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 diagmagnetic currents
  - easier design and maintenance
- Linear unrestricted divertor
  - facilitates impurity, ash and power removal

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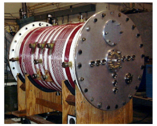
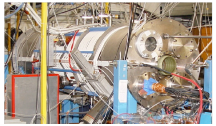
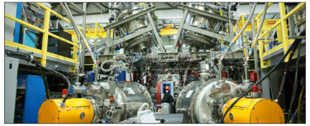
Past TAE Program Evolution

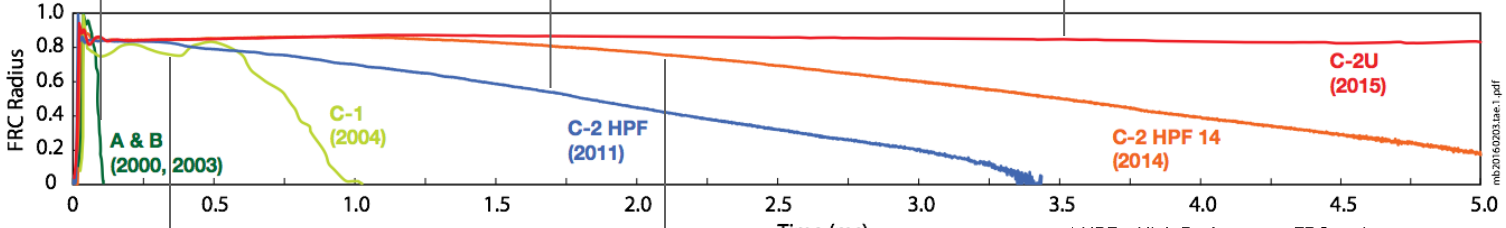



A & B – Basic FRC core
- 100-800 G, 5-10 eV
- ion beams, W_b ~0.1 kJ

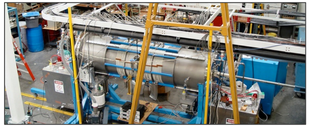
C-2 – HPF* w/ 2 guns, Ti getter
- 1 kG, 1 keV
- neutral beams, W_b ~12 kJ



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

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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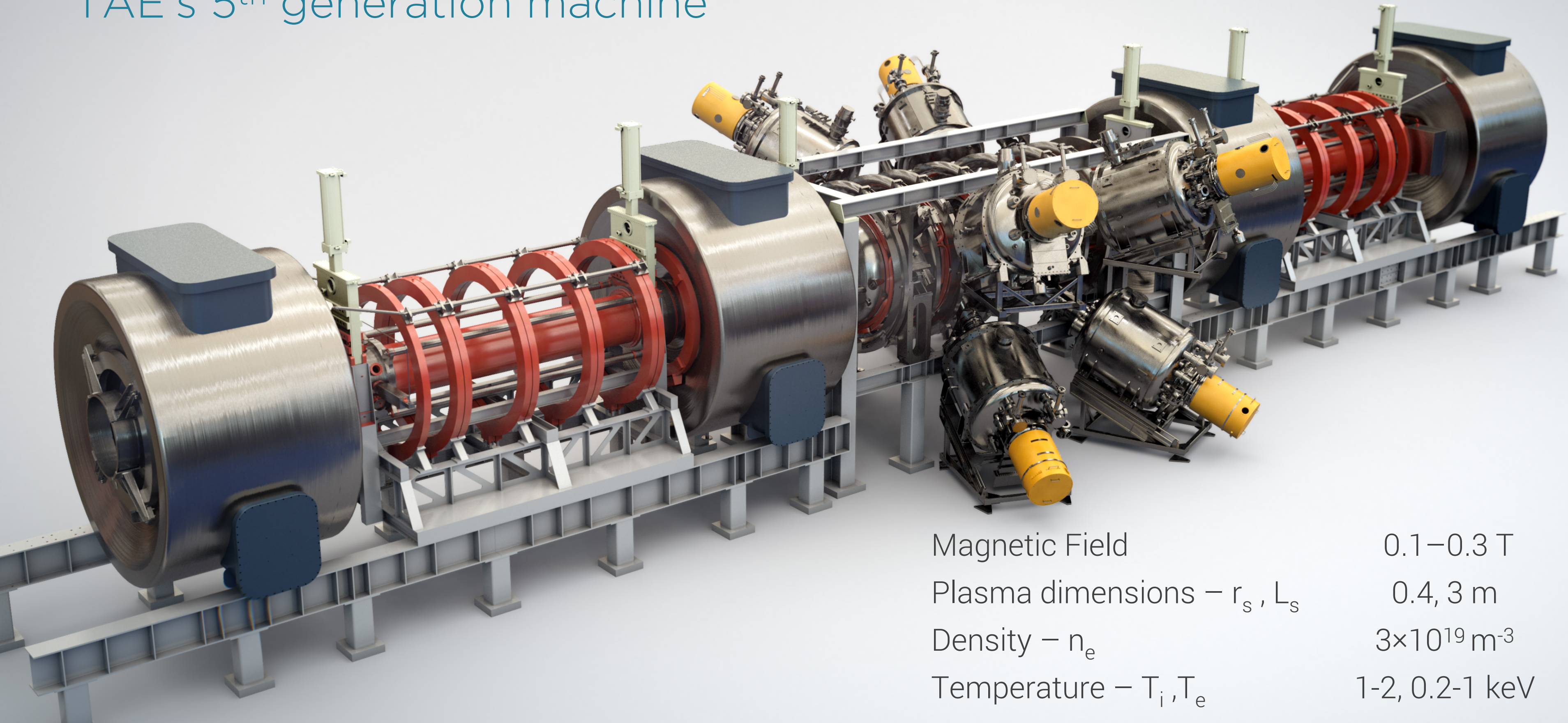
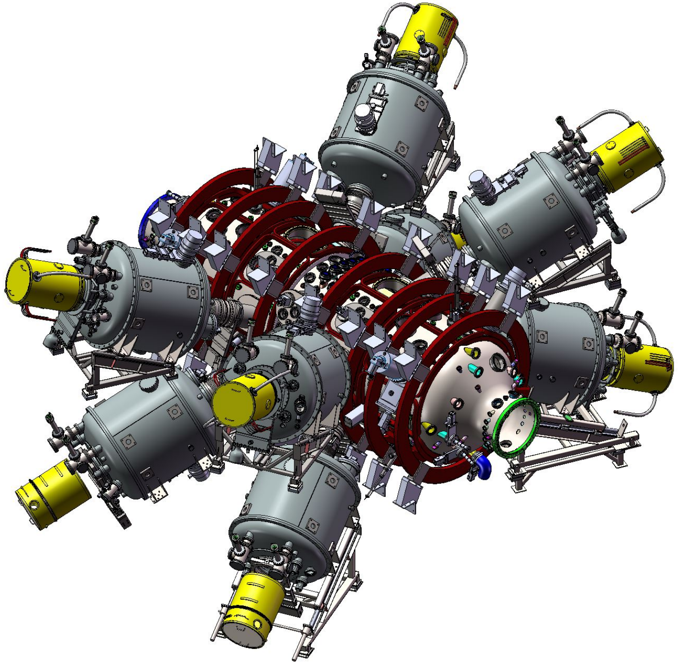
Norman

TAE's 5^{th} 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 neutral-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 plasma ramp-up

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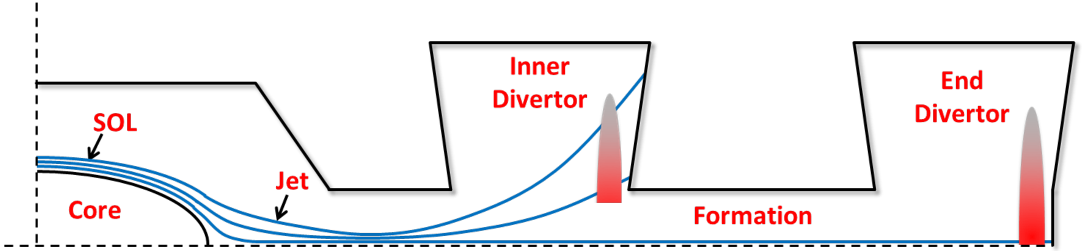
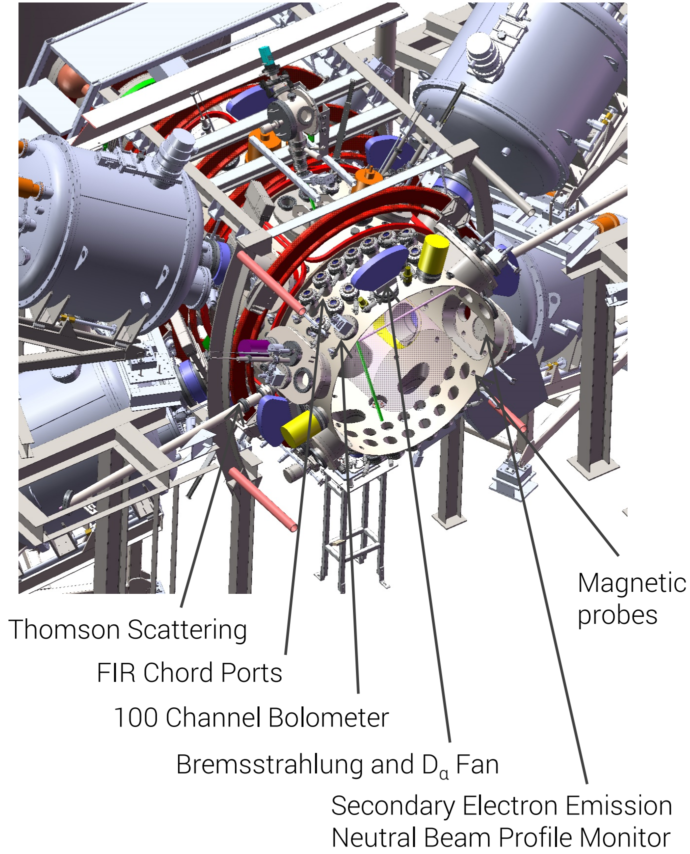
Norman – Diagnostics

Comprehensive diagnostics suite



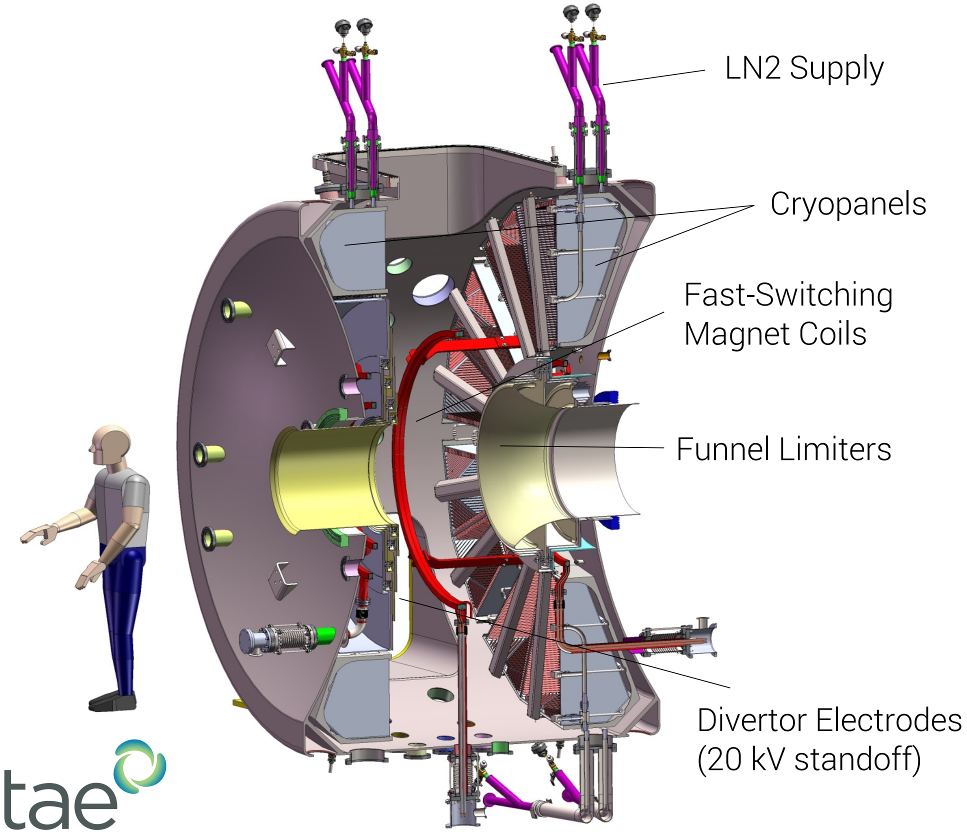
- 4 main zones with 40+ diagnostics
  - Core plasma inside the FRC separatrix
  - mirror-confined scrape-off layer (SOL) and jet
  - rapidly expanding plasma in the inner divertors and/or end divertors
  - FRC formation sections

Midplane Cross Section

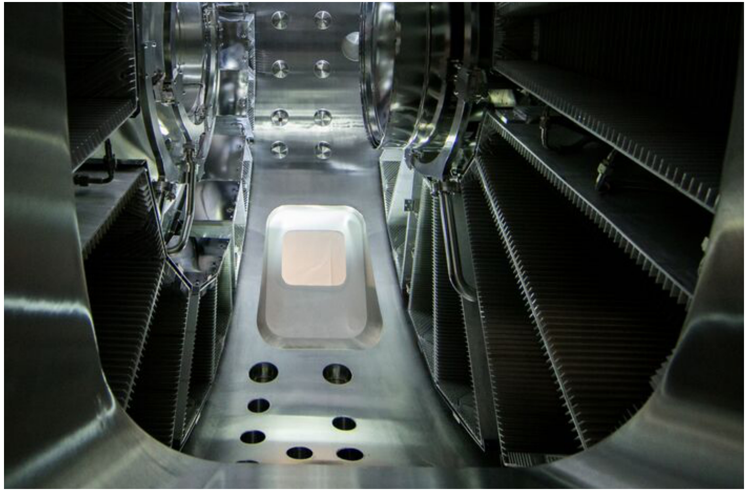


Norman – Divertors

Critical for edge control



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



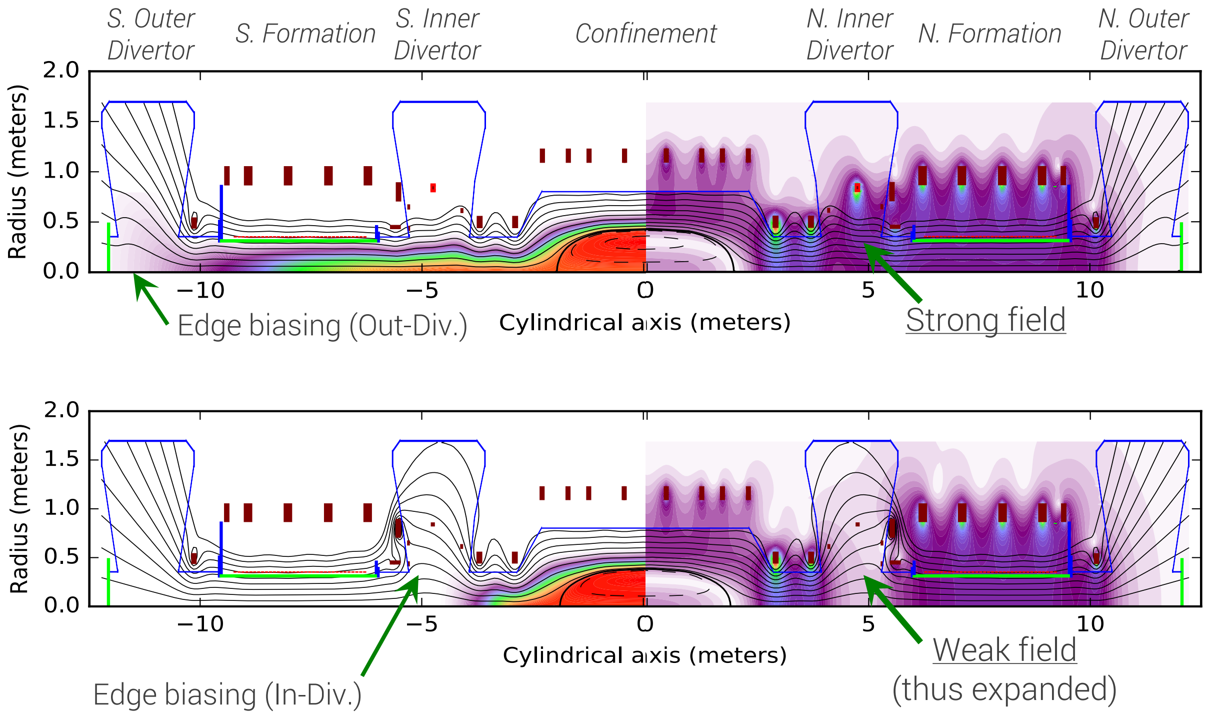
Norman – Divertor Operation Modes

Edge biasing & outer/inner divertor switching

Density Contours | Magnetic Field Contours

w/ Straight Field (at inner divertor)

w/ Field Expansion (at inner divertor)

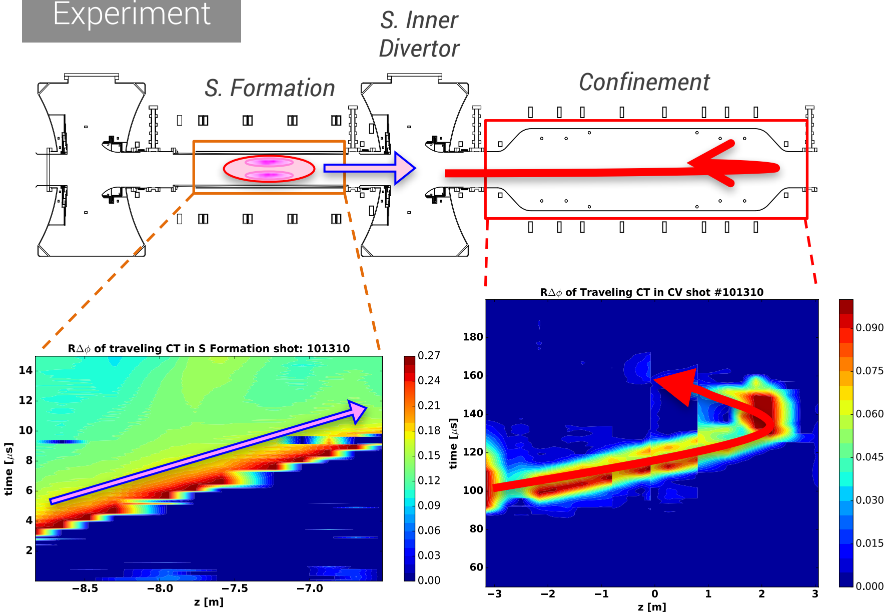


C-2W Initial Results

Initial FRC Translation Studies (single-sided)

Successful translation through inner divertor achieved

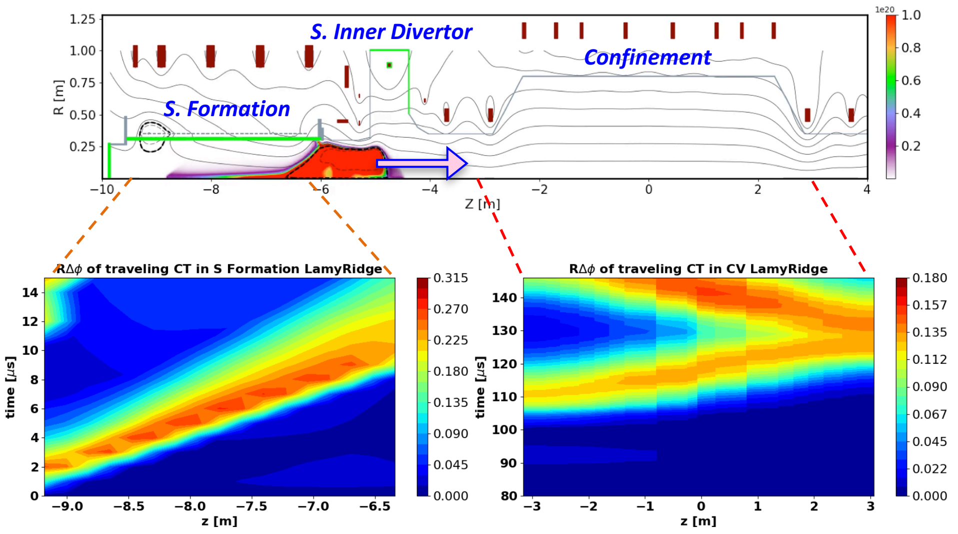
Experiment



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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Initial FRC Translation Studies (single-sided)

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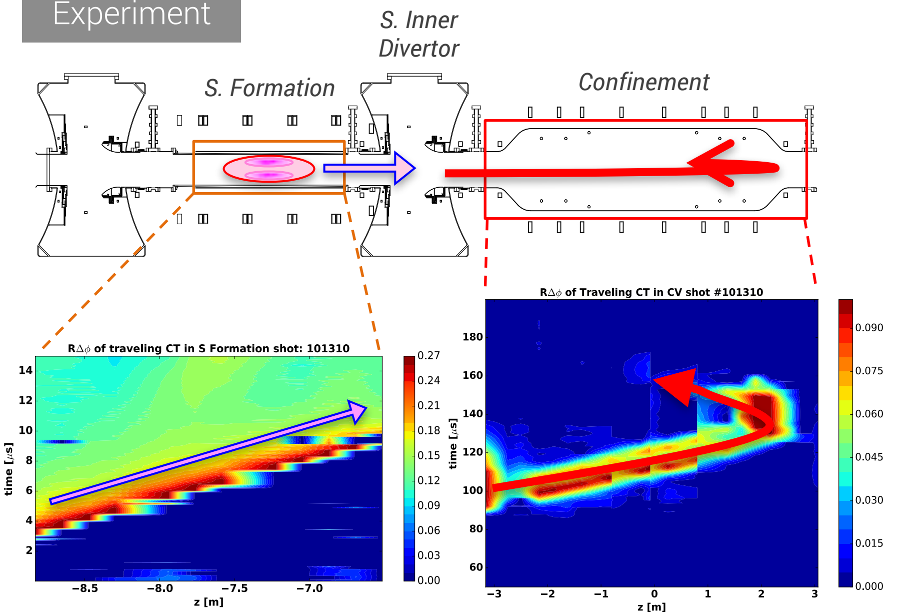
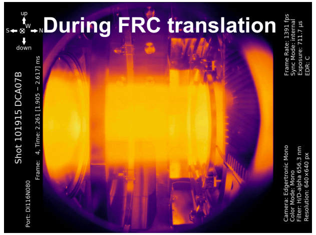


Experimental time evolution of excluded flux radius during formation and translation

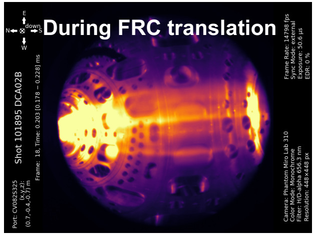
Fast-Framing Camera Images

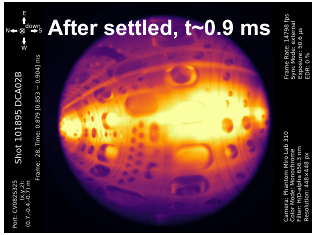
in inner divertor



Inner divertor camera observes clean FRC translation

in confinement

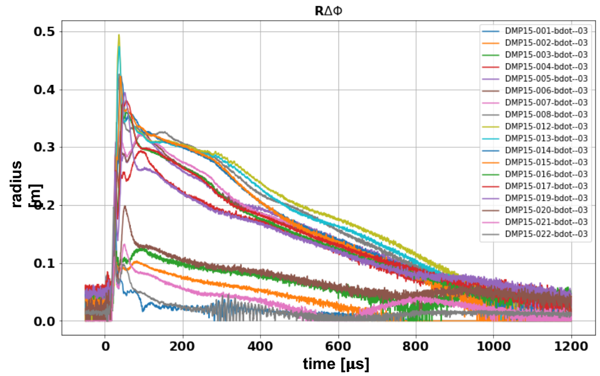


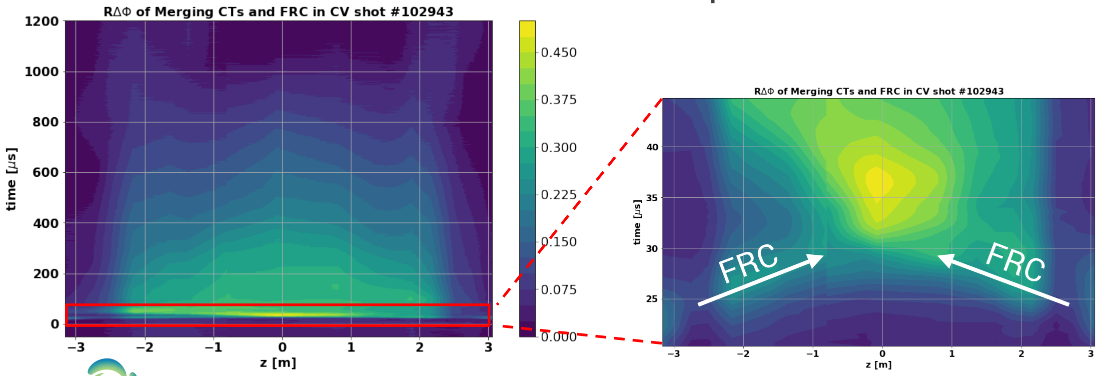


Confinement vessel camera observes FRC reflections as plasma bounces back and forth in CV

First FRC Collision/Merging Data (double-sided)

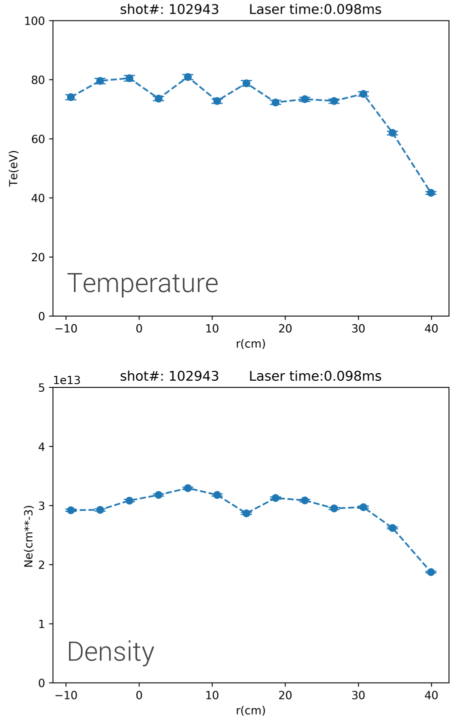
Succeful production of collided/merged state





Excluded-Flux Radius Time Evolution

- FRCs collide near midplane and live up to ~1 ms
- no beams or plasma-gun biasing
- first Thomson scattering based electron temperature/density profiles



Thomson Scattering Initial Data

C-2W Summary

- Engineering accomplishments
  - All major subsystems constructed and double-sided configuration operational in 12 month build cycle
  - Considerably 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
  - record translation speeds of ~400 km/s observed (250 km/s in C-2U)
  - FRC collision/merging experiments under way, already producing 1+ ms plasma lifetime even without NBs, edge biasing or wall conditioning

Technology Spin-offs

TAE Life Sciences Update

- TAE Lifesciences established
- 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


Thank You