Progress and Next Steps at TAE

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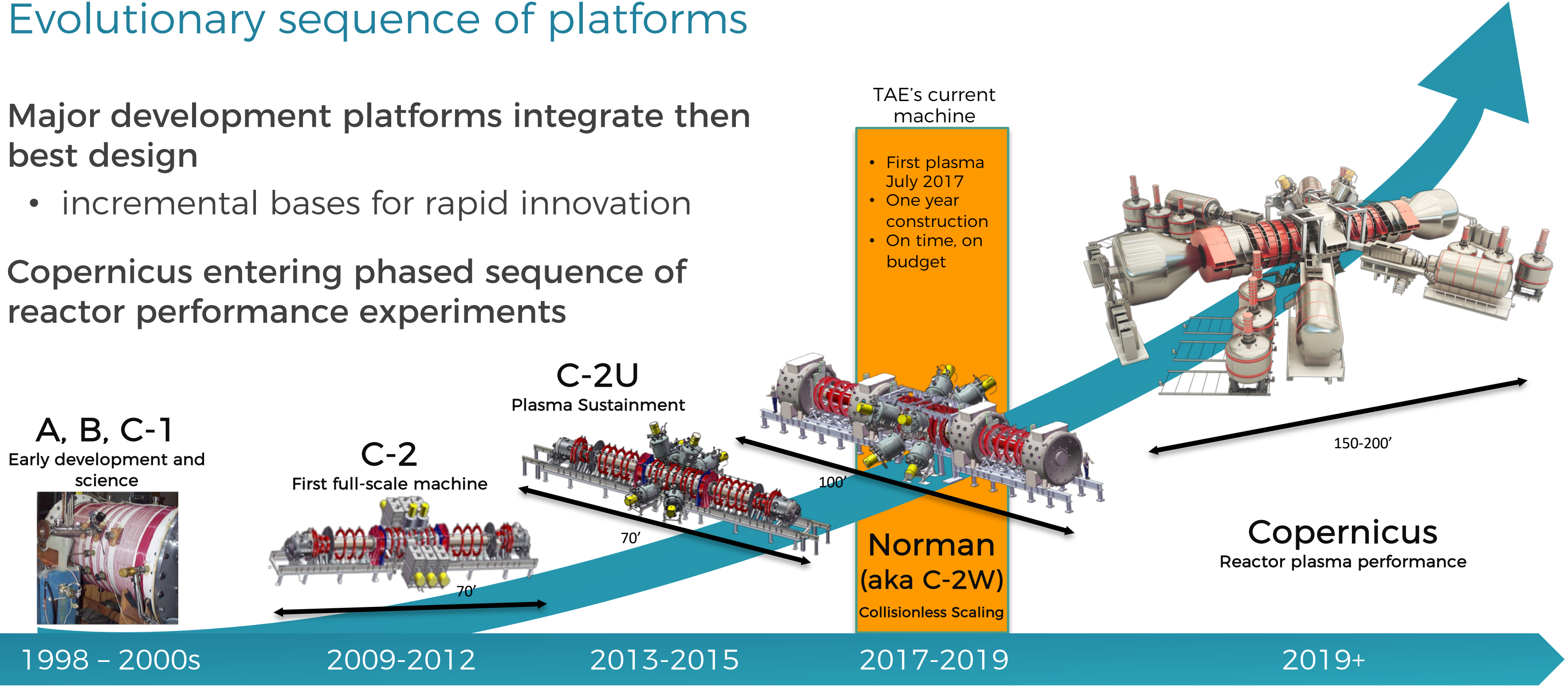
TAE Progress towards Fusion

Evolutionary sequence of platforms

Major development platforms integrate then best design

- incremental bases for rapid innovation

Copernicus entering phased sequence of reactor performance experiments



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Norman Program Overview

Norman Goals

Explore beam driven FRCs at 10x stored energy compared to C-2U

- 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 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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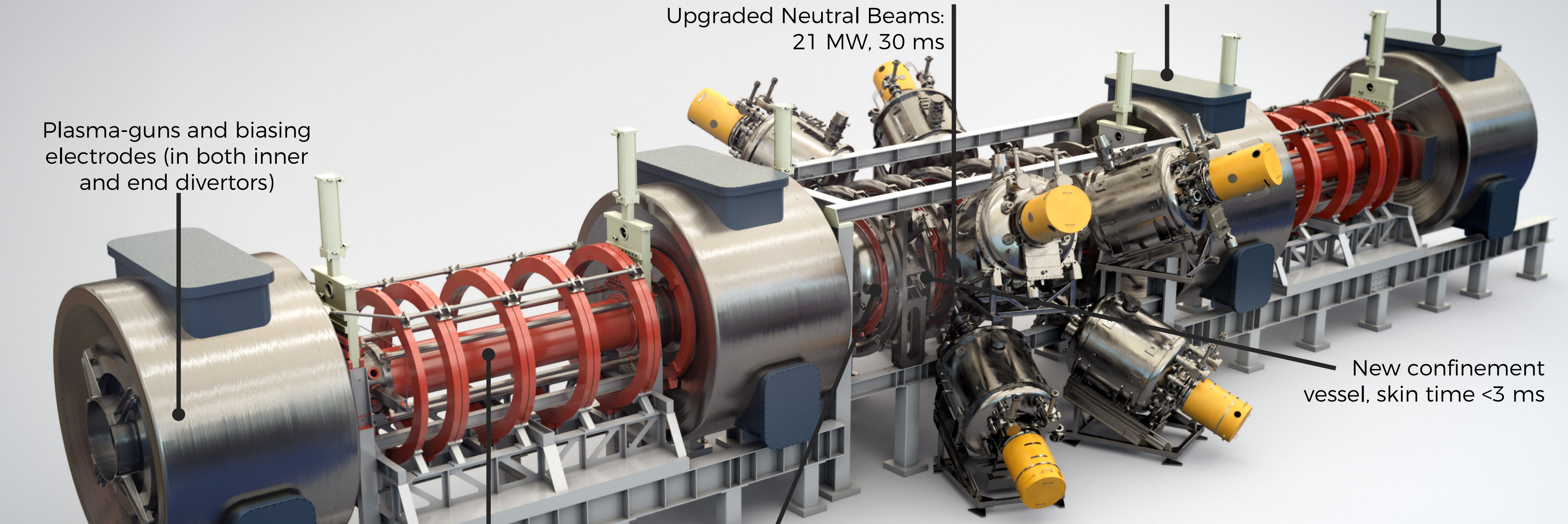
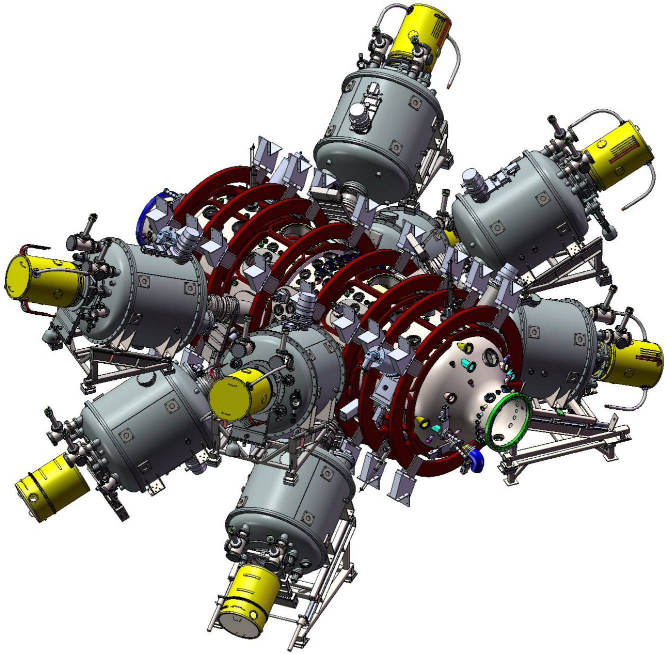
NORMAN – TAE's 5th Generation



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/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 ramp-up

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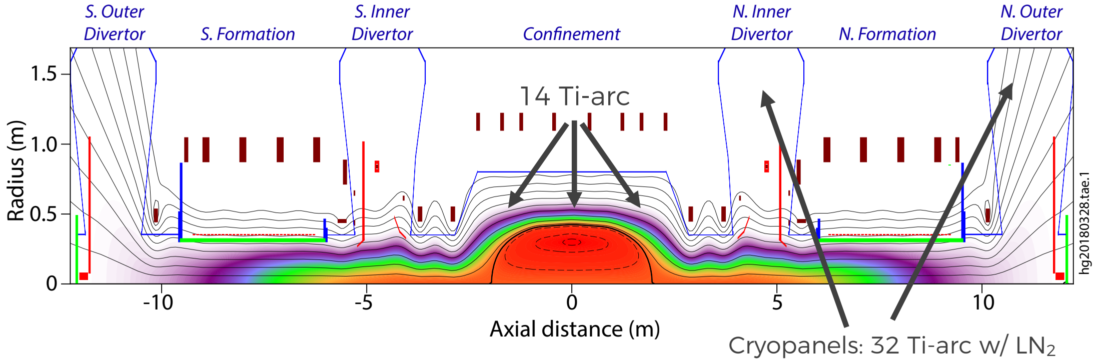
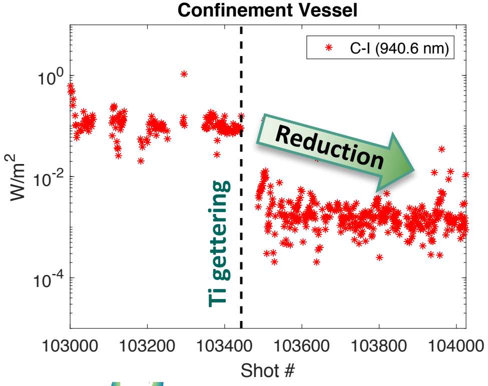
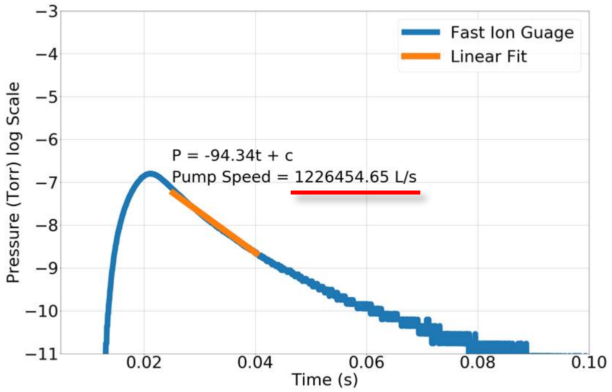
Norman Wall Conditioning/Pumping Systems



Carbon-I impurity trend



Divertor test w/ Ti-arc and LN_2 systems

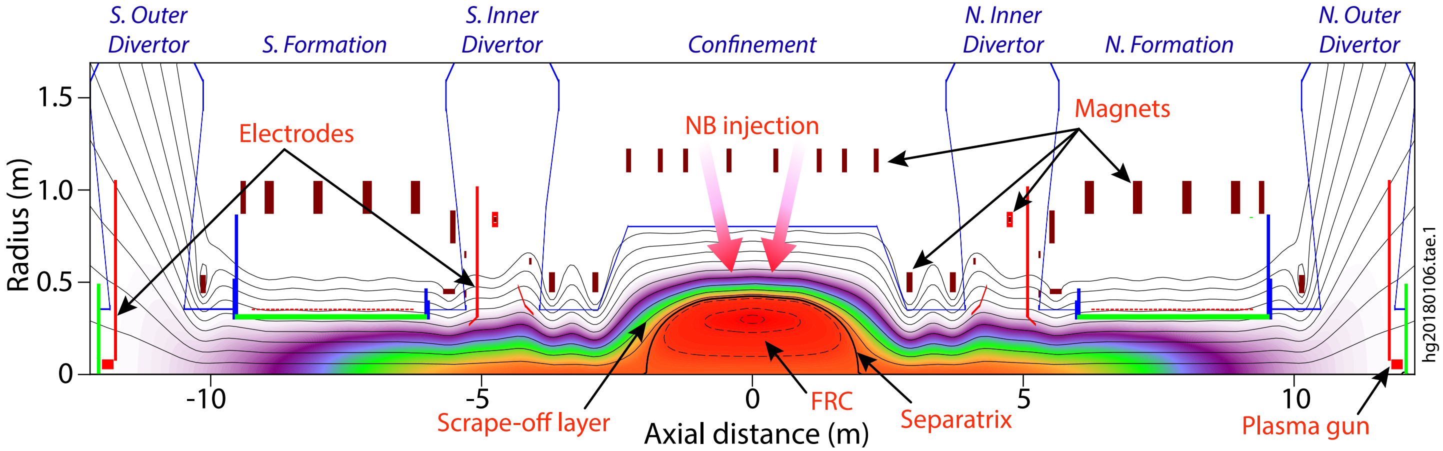


- CV gettering – 14 Ti-arc rods – 1 M L/s
- 32 Ti-arcs w/ LN_2 system per divertor – 2 M L/s
- Base pressure ~10^{-10} torr
- Improved wall condition and impurity levels – Z_{eff} ~1.3
- New glow-discharge cleaning system under development

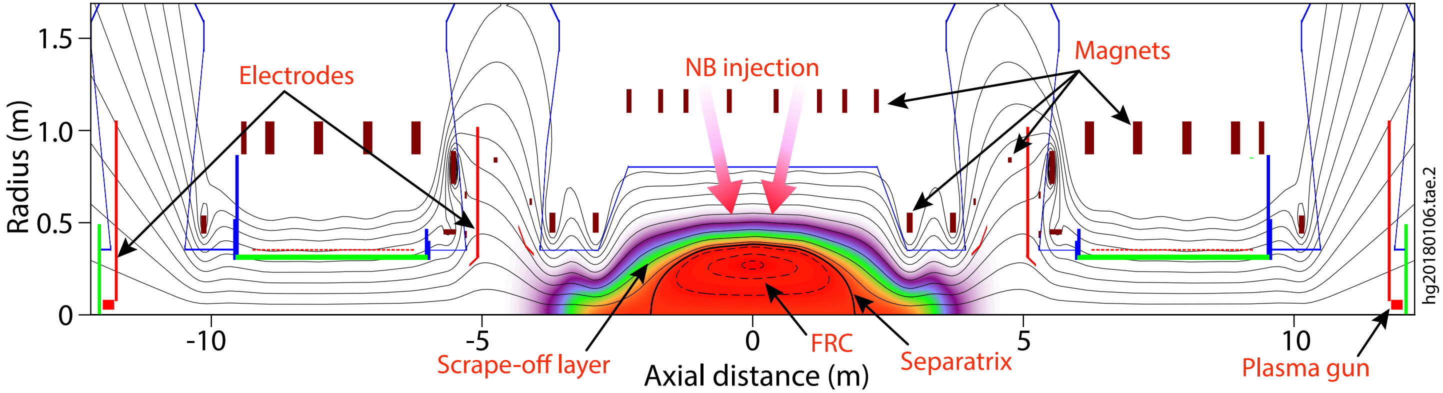
Transfer to Inner Divertor Control

Flared magnetic fields provide thermal insulation

(1) Biasing from **Outer Divertors**



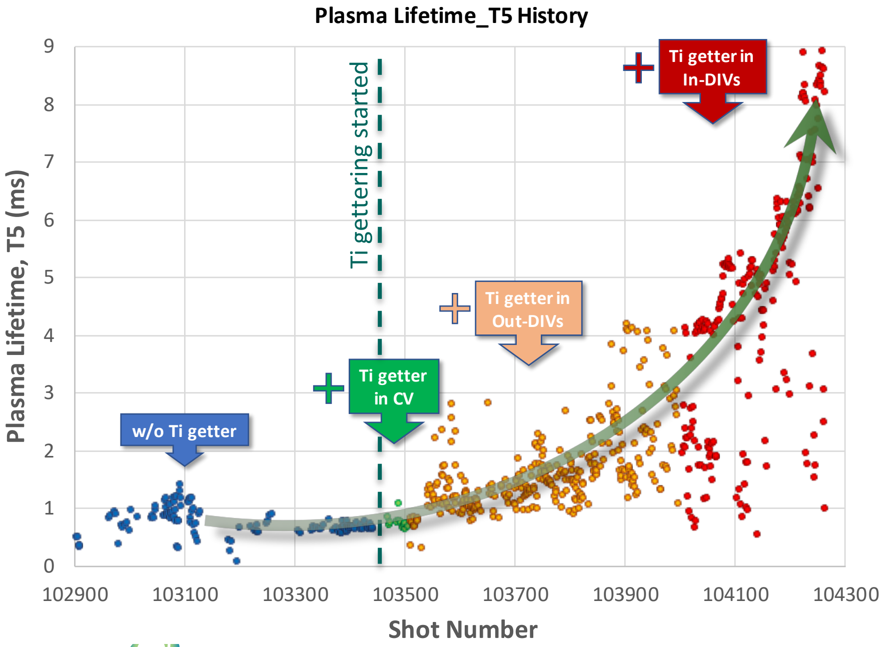
(2) Biasing from **Inner Divertors**

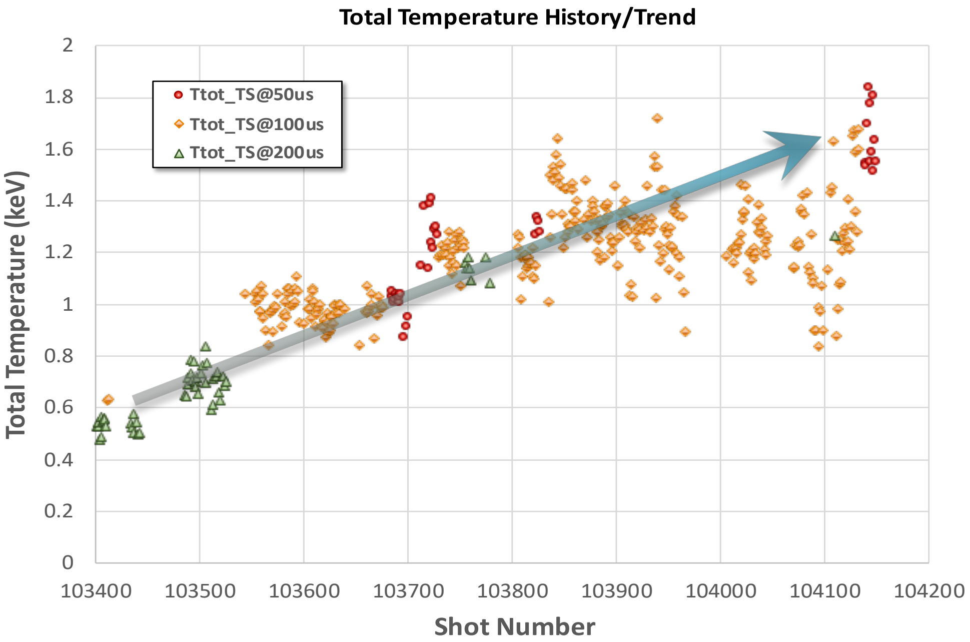


Experimental Progress in 2018

Norman Lifetime and Initial Temperature Trends

- FRC performance increase with vacuum/wall conditioning
- Total temperature (ion+electron) consistently increased – early T_{tot} up to 2 keV

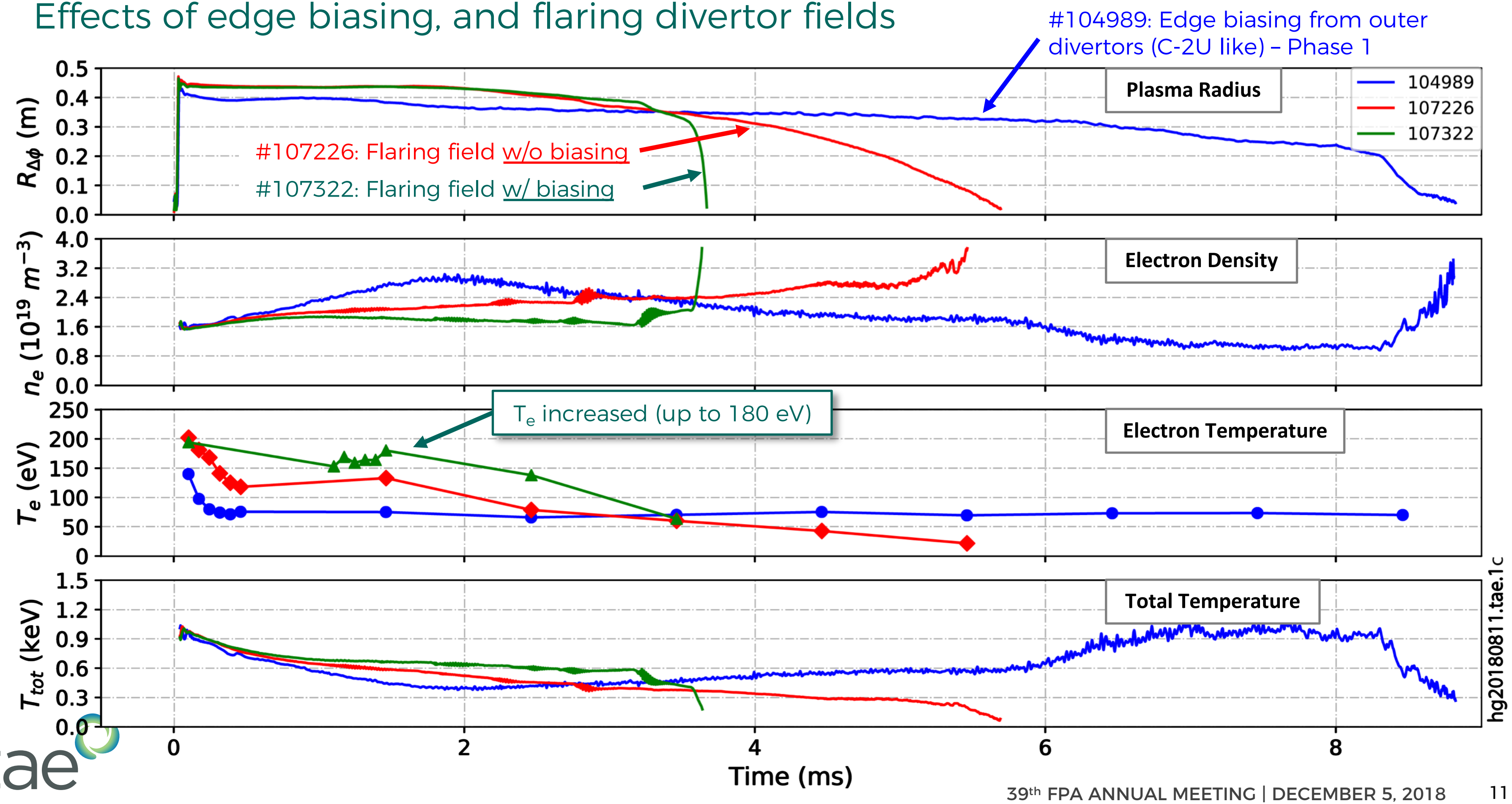




Edge biasing/control from outer divertors – C-2U like configuration

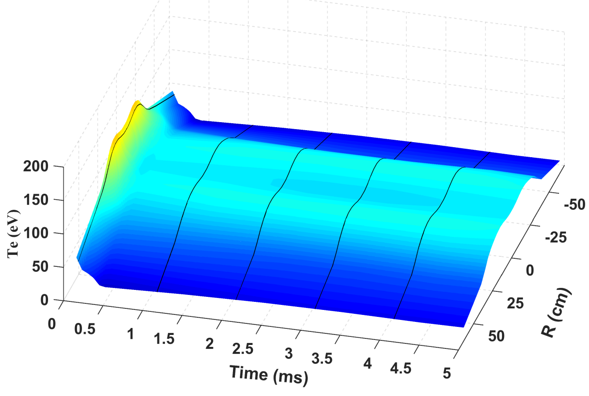
Optimization towards Inner Divertor Control (2/2)

Effects of edge biasing, and flaring divertor fields

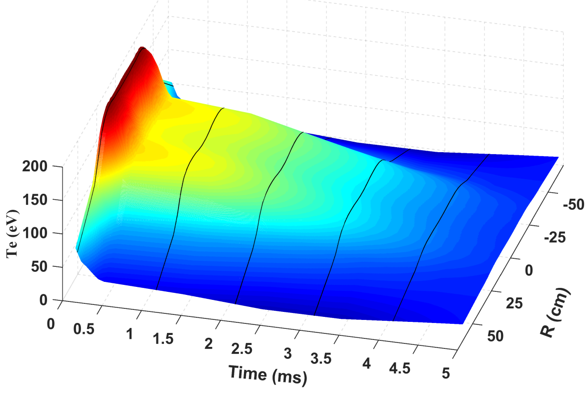


Comparison between Operating Conditions

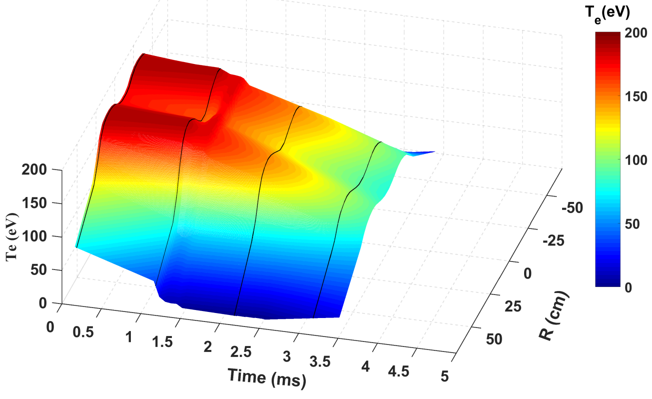
Outer divertor biasing (C-2U like)



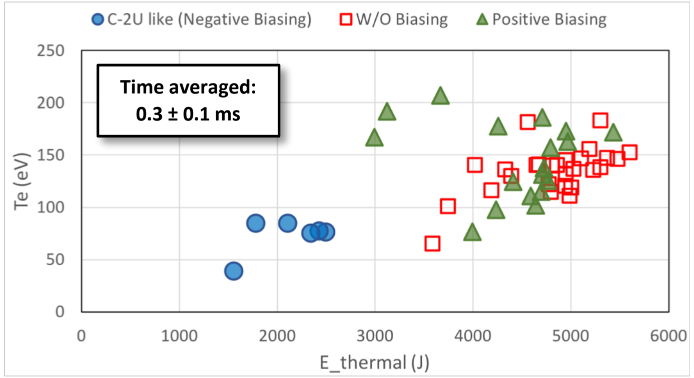
Inner divertor w/ flaring, no biasing

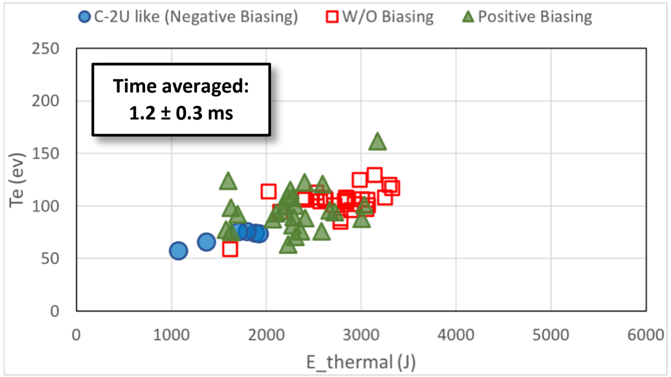


Inner divertor w/ flaring & biasing



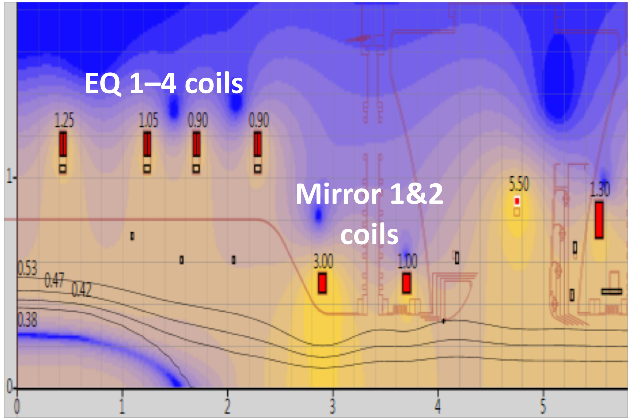
- Improved performance from optimization

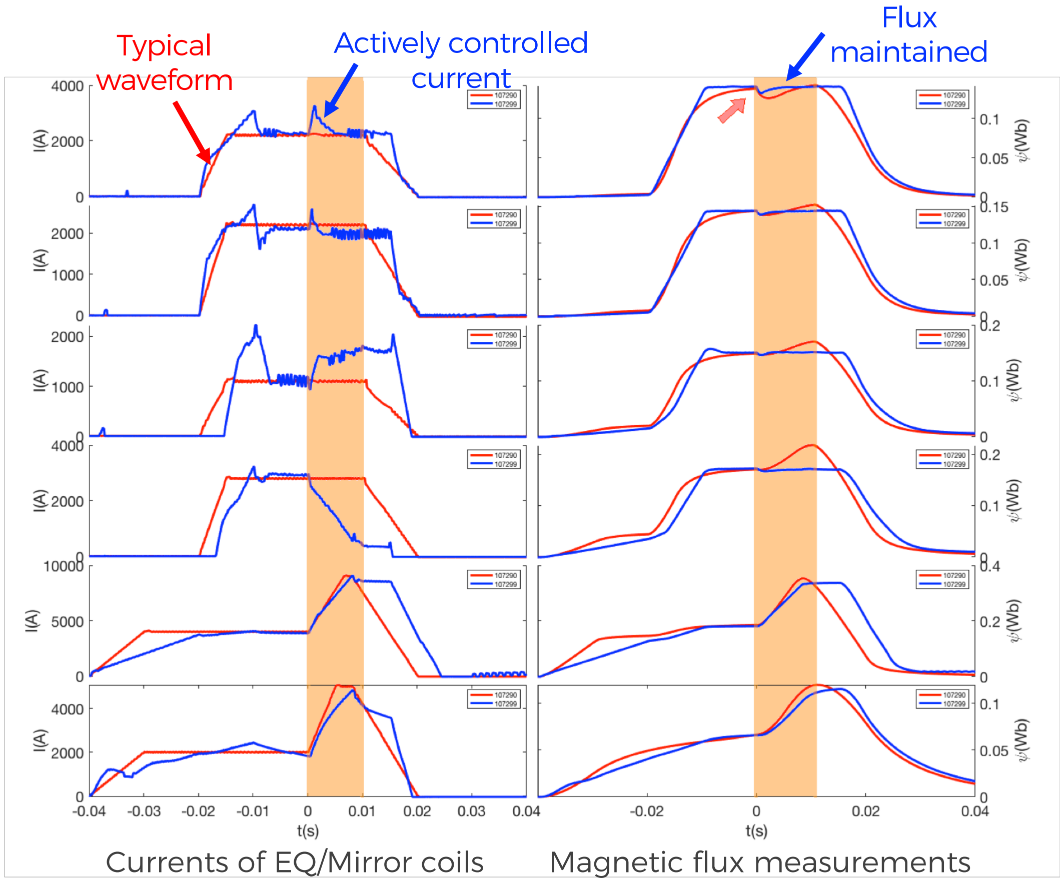




First Efforts towards Active Feedback Control

- Flux-conserver emulation studies
- Active current control of EQ and mirror coils
- Further control flexibility with trim coils to come soon





Summary of Progress on Norman

Key Engineering Accomplishments and Status

- Majority of Norman constructed in <1 year (including C-2U dismantle)
- Significantly improved system reliability and functionality – over 98% uptime
- Tunable neutral beam upgrade completed

Key Physics Accomplishments and Status

- Robust FRC formation and translation
- Much improved initial FRCs – increased size, thermal energy and temperature
- Successfully (re)produced long-lived FRCs (C-2U like)
- Improved FRC performance with flaring divertor magnetic fields
- Steady progress towards active feedback control, transitioning divertor control, beam power/tunability upgrade

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2019 Preview and Next Steps

Post Norman Milestone

Basic proof of scientific feasibility established, meaning

- Transport scaling established for collisionless regime
- Macroscopically stable operation
- Active feedback control established and demonstrated
- Heating and current drive established and demonstrated
- Open field line/SOL/divertor thermal insulation demonstrated

Overall system integration principles and control established

Norman to become user facility post milestone

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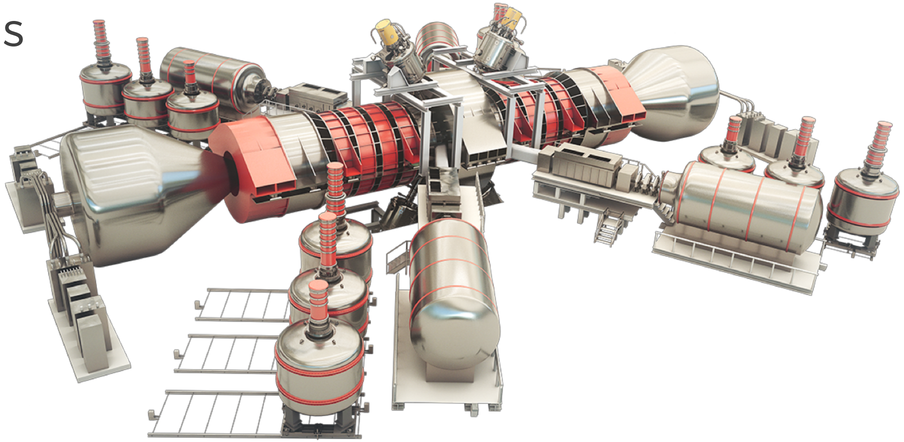
Copernicus – Reactor Plasma Platform

Design under study

- 10+ keV ion temperature goal
- Super-conducting vs resistive coils
- Hydrogen only operation

Budget and timing

- $500+ MM cap-ex estimate
- Break ground around early 2020
- Commissioning/early ops 2024



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Beyond Fusion

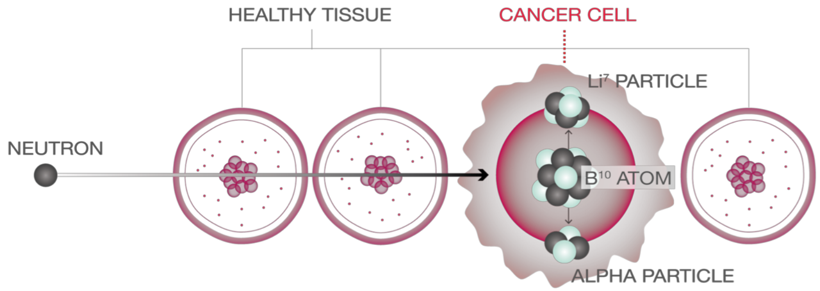
Spin-off technologies

BNCT technology

A step change in treatment of multi-centric and inoperable cancers

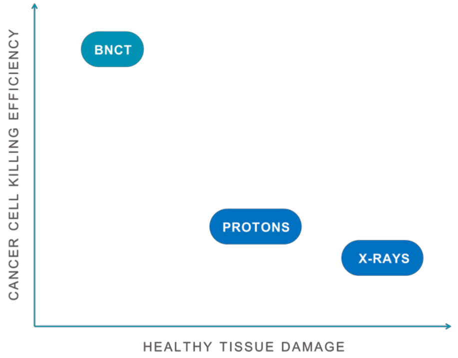
HOW BNCT WORKS

- IV-based vector drug delivers B^{10} to tumor cell
- B^{10} captures neutrons from TAE source
  - 3,000x higher neutron absorption than any other element in human body
- Reaction products only kill tumor cell while sparing neighboring healthy cells



WHY IT MATTERS

- BNCT cancer killing efficacy 3x X-ray and proton treatments
- Much less collateral tissue damage due to **biochemical** (vs. mechanical) targeting
- Fewer side effects and less toxicity
- 30-minute procedure performed once or twice
- Dramatic improvements in survival time and quality of life

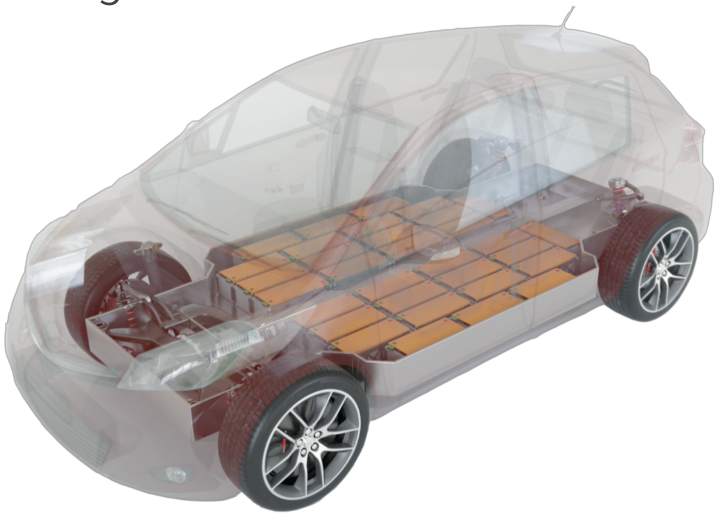


TAE Life Sciences

- Spin-off based on TAE neutral beam injector technology
- TAE majority owned, but independent capital and management team
- Will eventually offer full solution to hospitals – drugs to beams
- First clinical system sold in October 2017, to deploy in 2019
- Growing order book in Asia, US, EU

Disruptive power technology for EVs

- Technology derives from 750 MW power supply challenge of Norman
- Enables
  - higher battery safety and reliability
  - better performance and efficiency
  - next generation in-wheel motors
- Manufacturer agnostic
- Architecture scales from cars to buses/trucks
- Enables non-traditional parties to enter space – software defines vehicle characteristics
- Commercialization strategy in early execution
- Further applications to follow



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Superior performance of TAE EV drivetrain solution

Performance Parameter	Conventional	TAE**	Comments
Maximum Range Extension [%]*,**	N/A	+30 %	Until 30% state of charge of one module (FTP-72 driving cycle)
Power [Power factor of drive cycle]*	1	1.4	Power factor of the drive cycle to keep max battery temp the same
Efficiency – Reduction in Battery Losses [%]*	N/A	-7 %	Integrated over one drive cycle with low power factor
Efficiency – Reduction in Inverter Losses [%]*	N/A	-40 %	Integrated over one drive cycle with low power factor
Efficiency – Reduction in Motor Losses [%]*	N/A	-28 %	From test report at Elaphe's site (PSM in-wheel motor company)
Range in Case of Failure [%]*	No operations	>94 %	One module is taken off for 2 case scenarios: (1) testing of module and (2) module failure (FTP-72 cycle)
Thermal Management – Max Battery Temperature [°C]*	67 °C	51 °C	Max battery temperature with a high power factor drive cycle and 2 modules with higher thermal resistance

* Simulated with the same battery pack (16.2 kWh) for conventional and TAE technology
** Simulation includes TAE solution incorporating super capacitor buffering

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TAE global power technology vision

Automotive & Grid Stabilization

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Power Technology for
TRANSPORTATION

- **Energy Storage**
- **Motor**

Grid

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Power Technology for
CLEAN FUSION

Residential, EV Charging Stations & Grid Stabilization

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Power Technology for
RESIDENTIAL STORAGE

- **Solar Thermal**
- **Residential**
- **Energy Storage**


Thank You