Progress and Next Steps at TAE

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Historical and future program overview

Continual progress towards advanced beam-driven FRC fusion

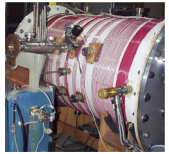
Major development platforms integrate then best design

- incremental bases for rapid innovation

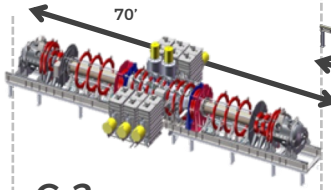
Copernicus entering phased sequence of reactor performance experiments

TAE's current machine

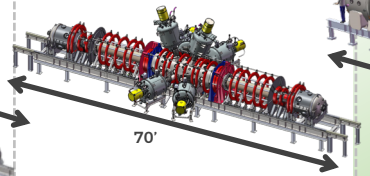
- First plasma July 2017
- One year construction
- On time, on budget
- Scaling studies ongoing



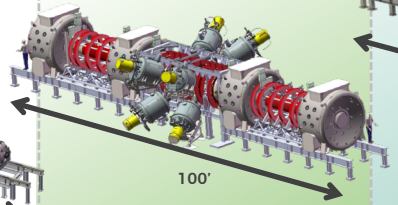
A, B, C-1
Early development
1998 – 2000s



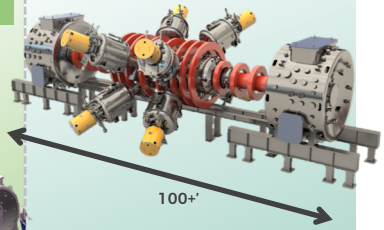
C-2
First full-scale machine
2009-2012



C-2U
Plasma Sustainment
2013-2015



Norman (C-2W)
Collisionless Confinement Scaling
2016-2019



Copernicus
Reactor Plasma Performance operating on hydrogen plasma
2020+

Norman Program Update

Norman Goals

Explore beam driven FRCs in fully collisionless regime

- 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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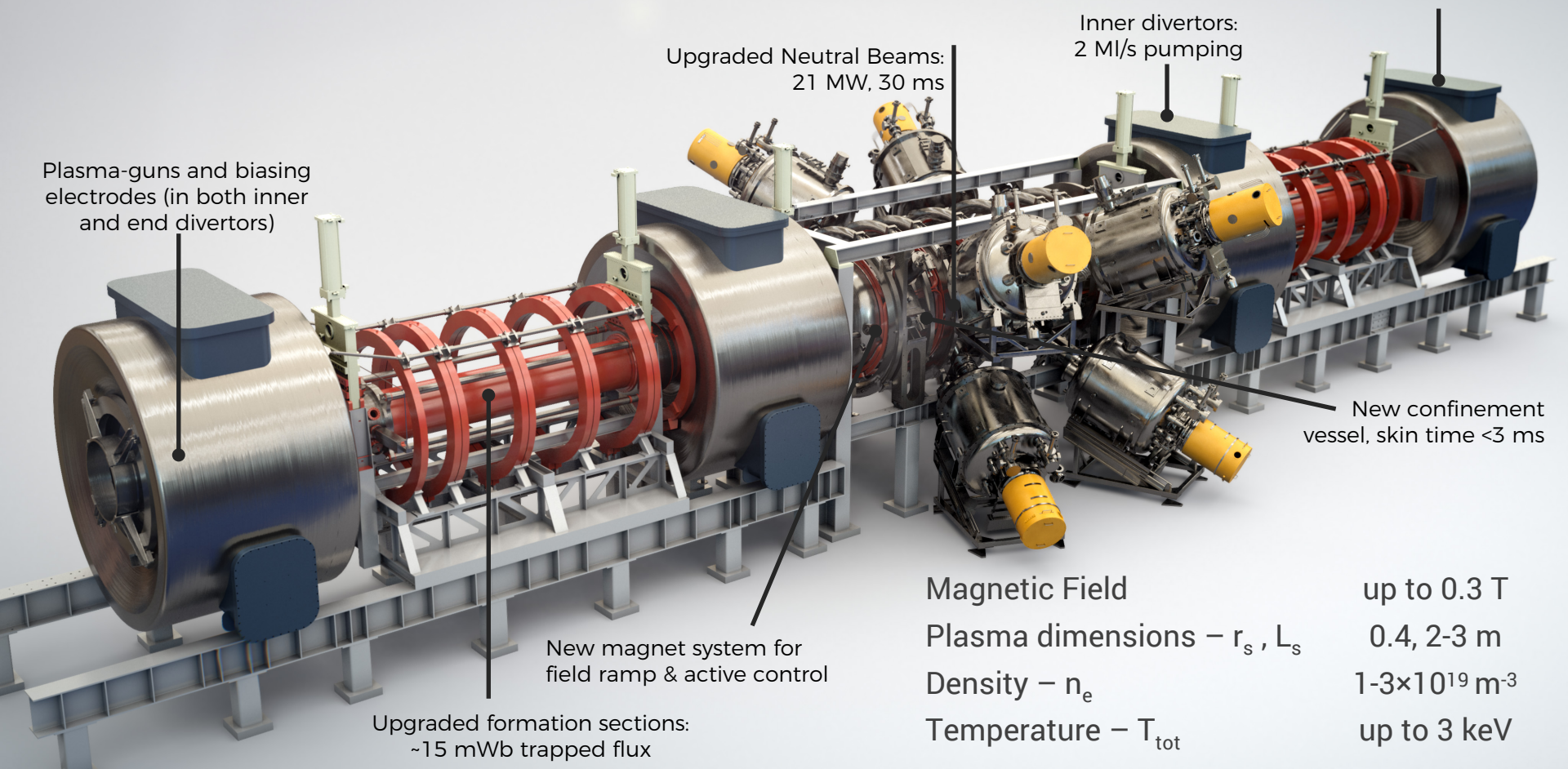
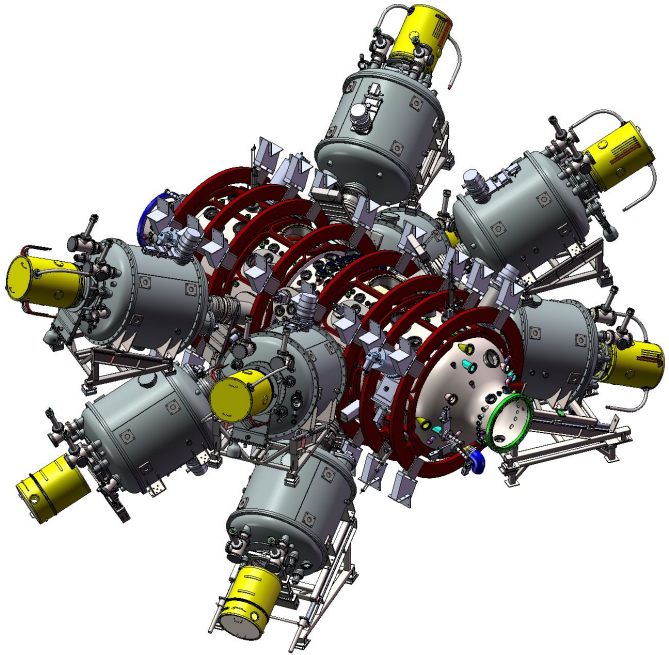
NORMAN (C-2W) — TAE's 5th generation



Magnetic Field	up to 0.3 T
Plasma dimensions – r_s , L_s	0.4, 2-3 m
Density – n_e	$1\text{-}3\times10^{19}\ m^{-3}$
Temperature – T_{tot}	up to 3 keV

Norman – Neutral Beam System



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

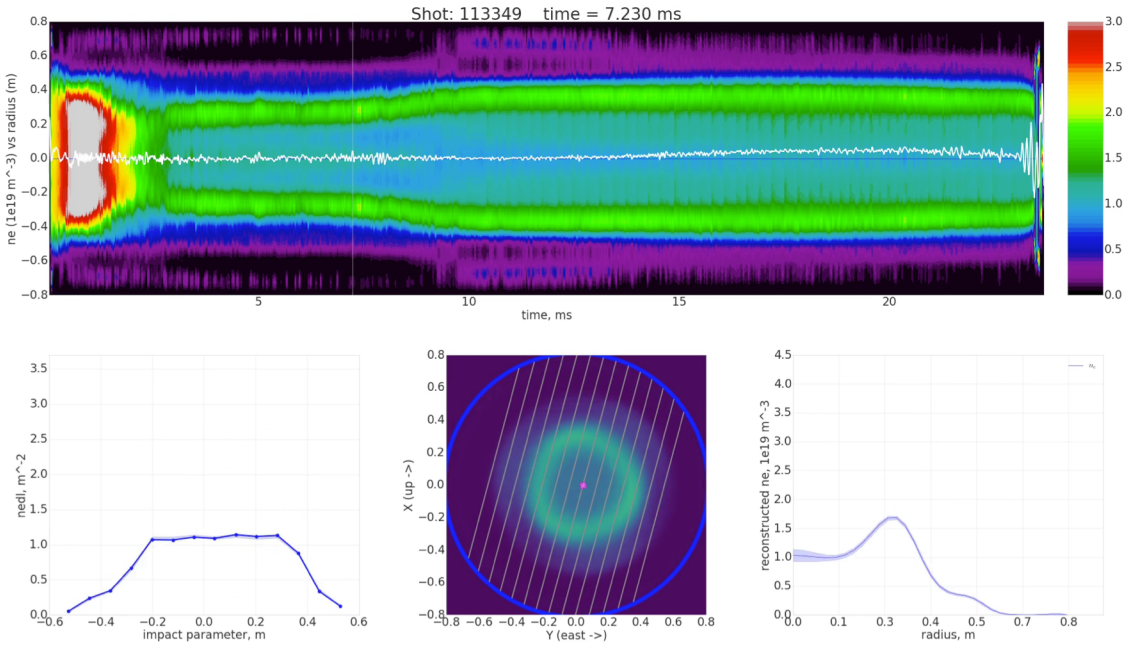
- Centered/angled/tangential neutral-beam injection
  - angle adjustable in range of 15°–25°
  - injection in ion-diamagnetic (co-current) direction
- High current with low/tunable beam energy
  - reduces peripheral fast-ion losses
  - increases core heating / effective current drive
  - rapidly establishes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

Google collaboration on diagnostics post processing

Offers unique insights into internal plasma perturbations

tae + Google

- High fidelity holistic 3-D plasma reconstruction
- Internal dynamics of plasma perturbations now visible
- Work underway to exploit insights for further feedback optimizations



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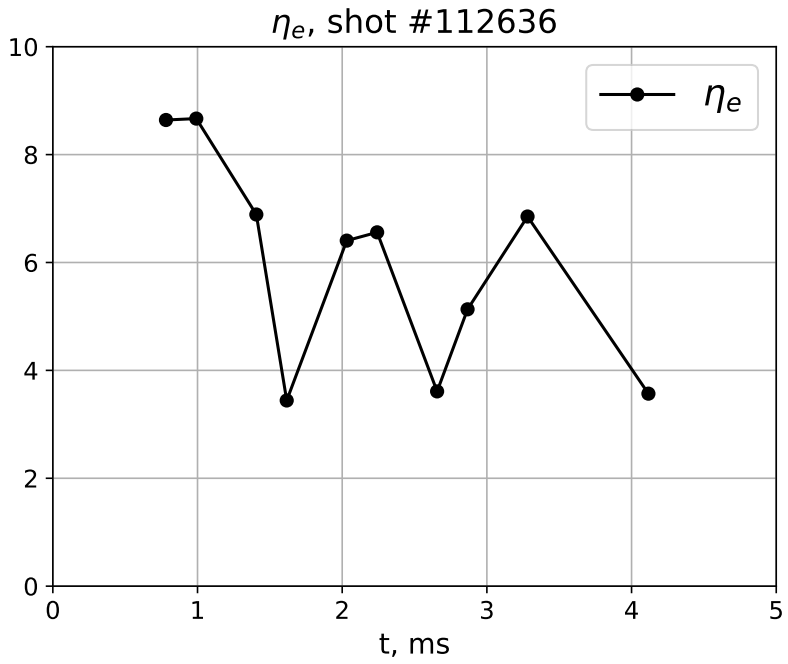
Norman divertors provide excellent edge insulation

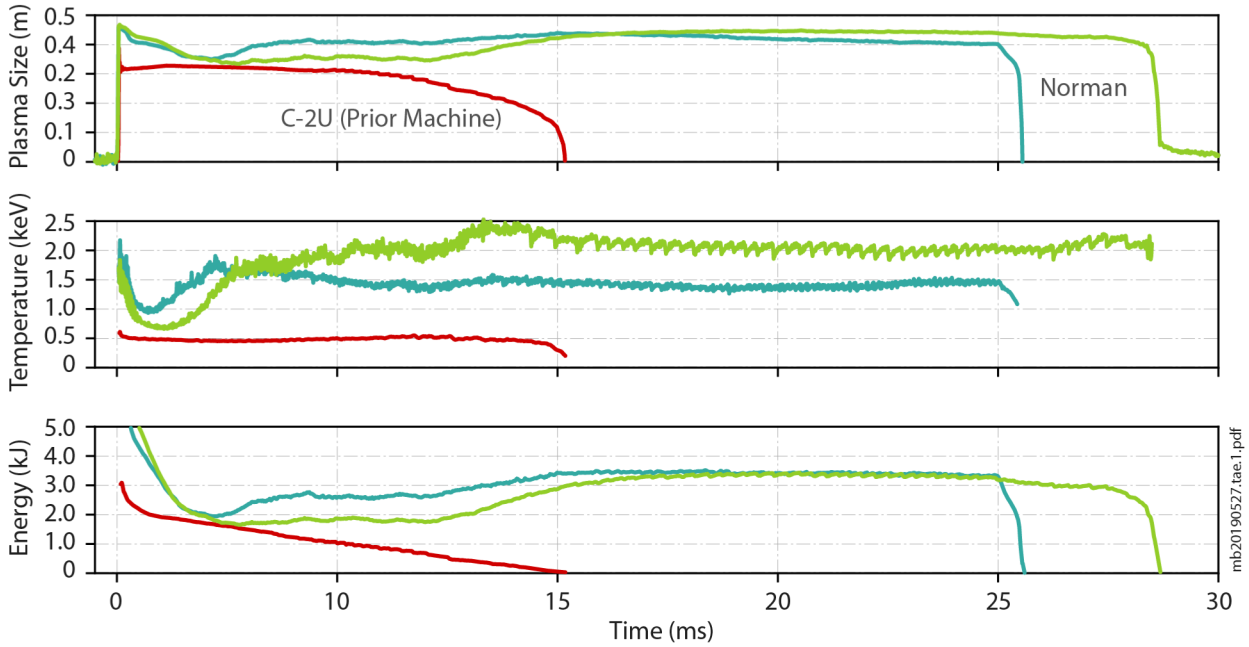
Energy loss per electron/ion pair near theoretical minimum



- Flaring magnetic fields
  - limit debye sheath voltage at the material boundary
  - minimize cold electron back streaming
- Extensive vacuum pumping
  - evacuates cold gas
  - minimizes cold ion population from ionization
- Bias electrodes improve stability and transport
- Electron energy loss per ion near ideal level
  - measured by energy analyzers in outer divertors
  - 4-8 T_e in Norman (compared to ~30 for C-2U)

Towards longer pulse operation 1/2

Continuous optimization of FRC lifetime and ramping studies



- Exciting performance
- Compared to C-2U device
  - 3x longer plasma life
  - 4-5x higher temperature
  - 4x higher plasma energy
- Robust macro-stability
- Confinement scaling consistent with prior data and modeling

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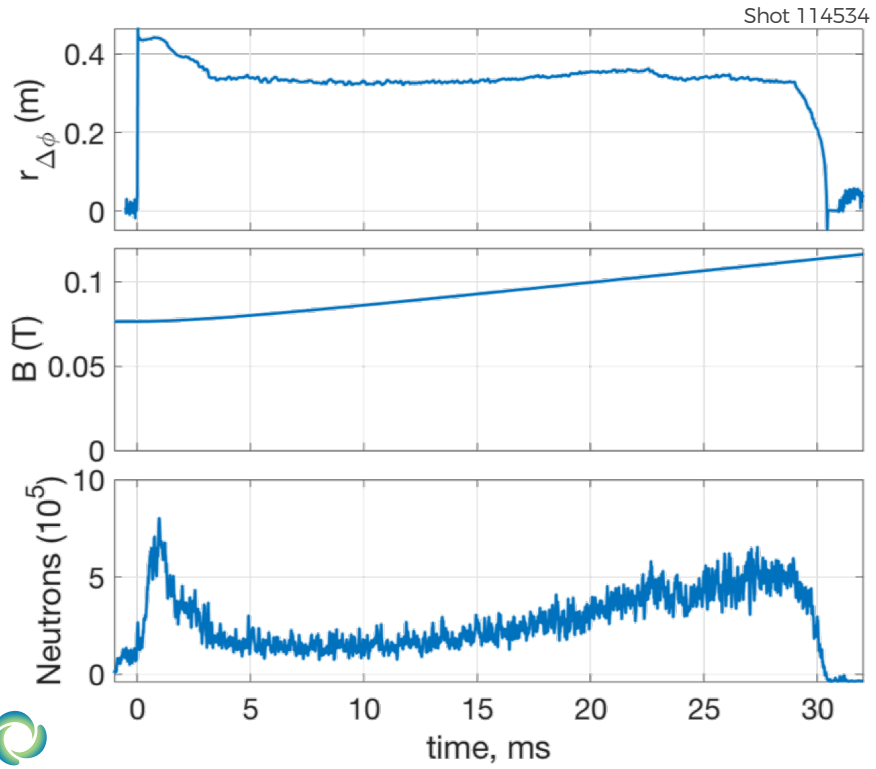
Towards longer pulse operation 2/2

Continuous optimization of FRC lifetime and ramping studies

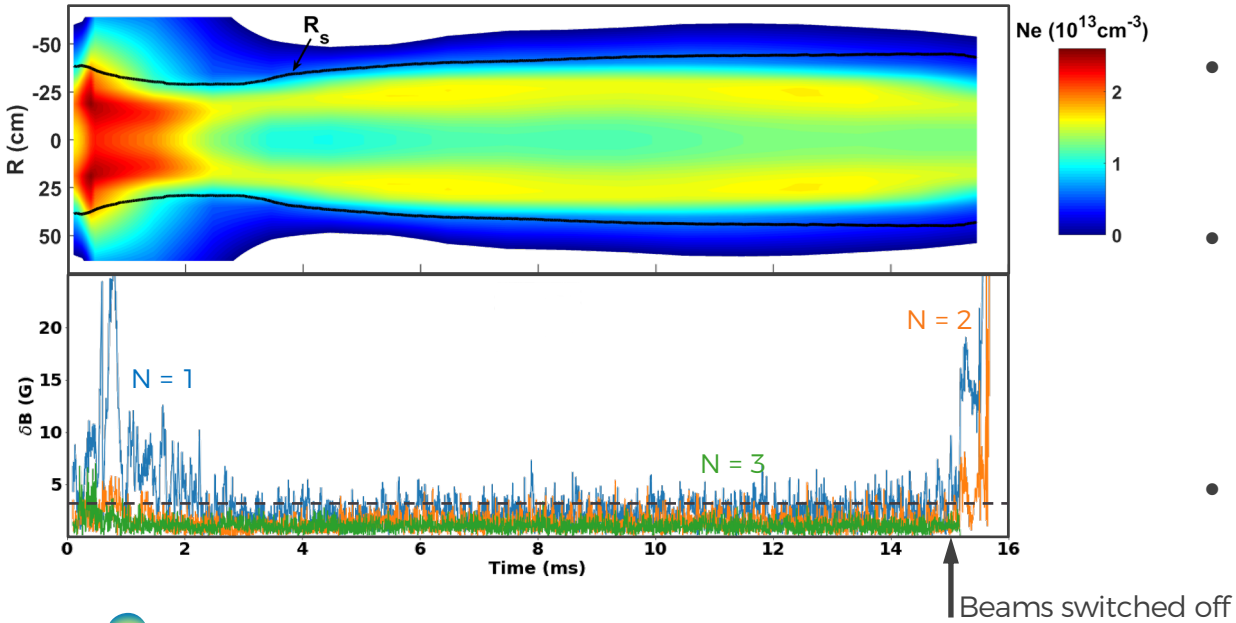


- Externally ramped magnetic pressure balanced by internally growing fast ion pressure
- Magnetic energy increases by 2-3x over the 30 ms shot
- Neutron signal good proxy for fast ion accumulation: $D_f + D_i \rightarrow {}^3He + n$
- Further optimization underway, including active magnetic control

Sustained plasma is stable and robust

Global modes are suppressed throughout the discharge

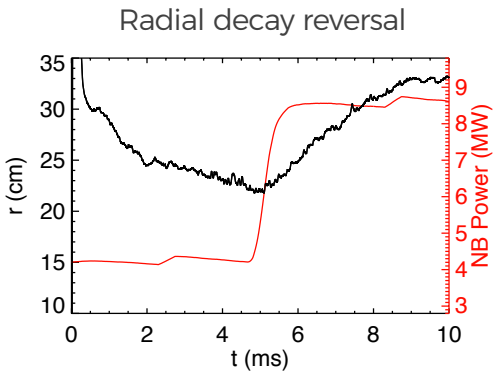
Shot 13301 – beams switched off at 15 ms

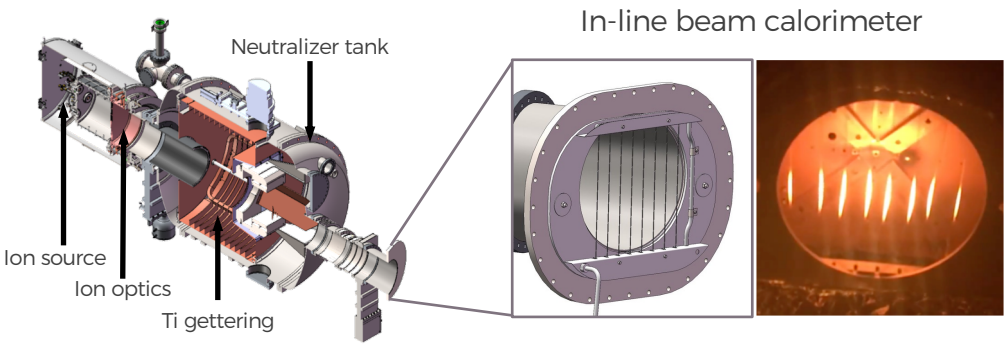


- Mode amplitude > 10 G at wall becomes destructive
- Mode amplitude < 3 G
  - experimentally benign
  - consistent with theory
- Magnetic probe noise ~ 1 G

Tunable beam ramp-up experiments

Operation with intra-shot variable beam power

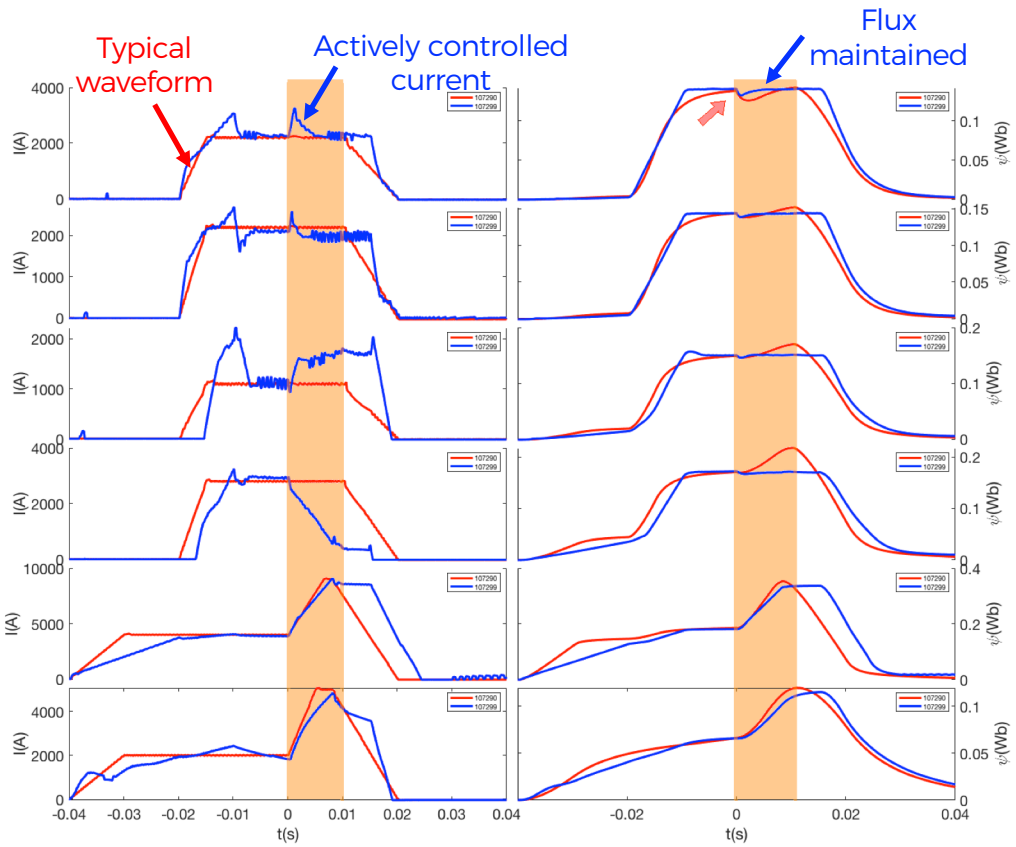




- Reversal of plasma radial decay within shot now possible by increasing beam power
- Optimized beam-plasma coupling efficiency
- Beam performance adjustable by feedback control system

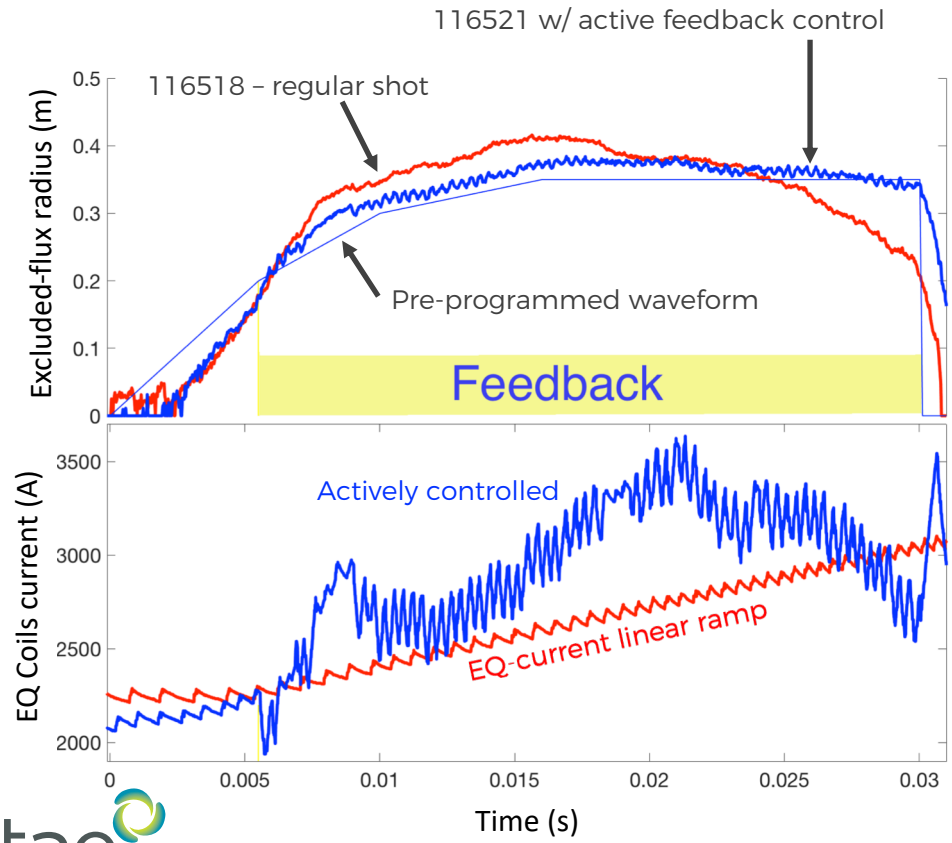
Active feedback control – flux conservation

- Active feedback via
  - tunable beams
  - electromagnetic shearing near plasma edge
  - magnetic shape and position controls
- Flux-conserver emulation studies
- Active current control of equilibrium and mirror coils
- Further control flexibility with trim coils to come soon



Currents of EQ/Mirror coils Magnetic flux measurements

Active feedback control – plasma shape



- Plasma shape actively controlled via current modulation of equilibrium and mirror coils
  - for example – plasma radius maintained at ~0.35 m
- Plasma position control via saddle and trim coils
- Active feedback control of NBs and electrodes in process

Next Steps

Summary of Progress on Norman

Basic proof of scientific feasibility established, meaning

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

Overall system integration principles and control established

Copernicus

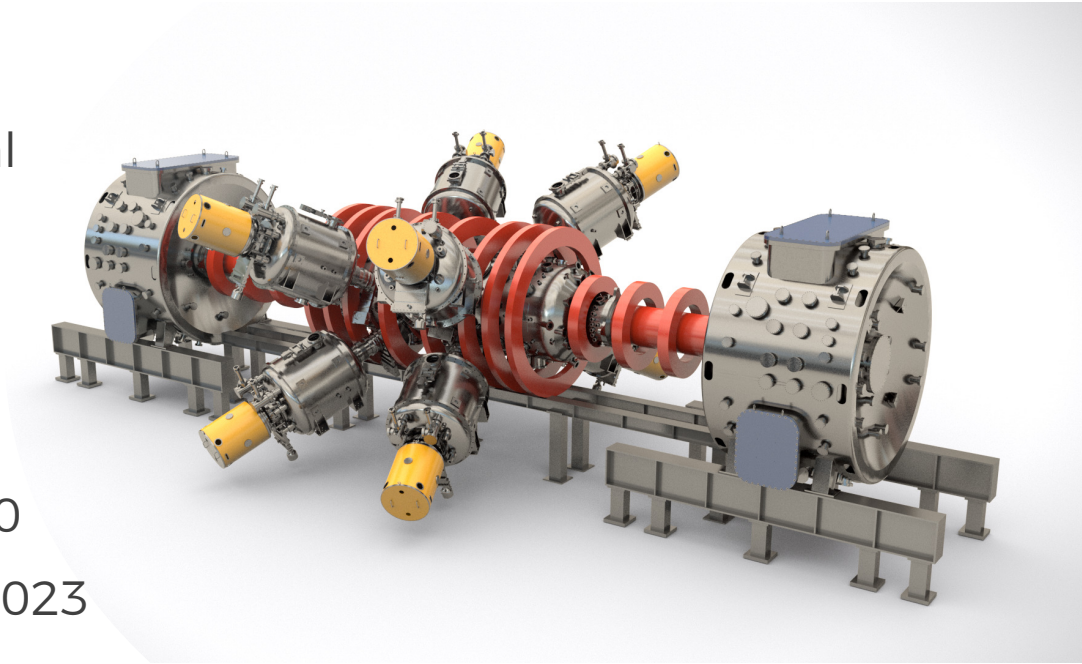
Reactor scale plasma performance platform

Design development ongoing

- 10+ keV ion temperature goal
- Hydrogen only operation

Budget and timing

- < $250 MM cap-ex estimate
- Construction to begin in 2020
- Commissioning and ops by 2023



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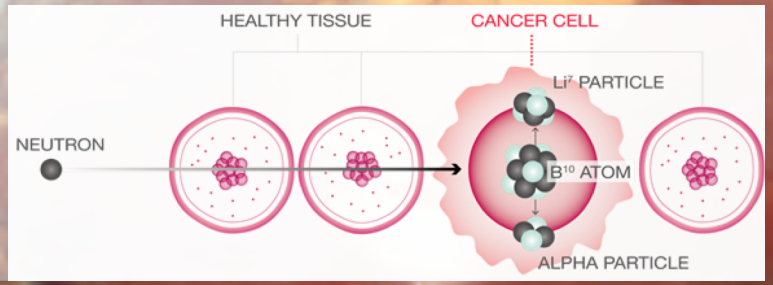
Beyond Fusion

Spin-off technologies

Boron Neutron Capture Therapy (BNCT)

Beam technology adapted to compact epithermal neutron sources

- Existing cancer treatment, but only available at research sites with a nuclear reactor
- 3x efficacy of x-ray and proton treatments
- Requires only one 30 min treatment
- IV-based vector drug delivers Boron-10 to tumor cell
- Effective in treating head and neck cancers ($30 BN market)



TAE Life Sciences

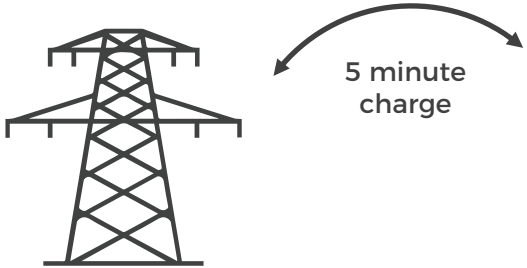
Creating a paradigm shift in radiation oncology

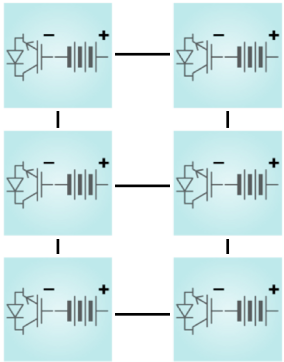
- TAE beam technology revolutionizes BNCT
  - enables cost-effective installations
- TAE majority owned company
- Provides complete solution – drugs to beams
- First clinical system in delivery – first patient treatment in Q1/2020
- Growing order book in Asia, EU, US

Power management opportunity

Derived from Norman power supply development

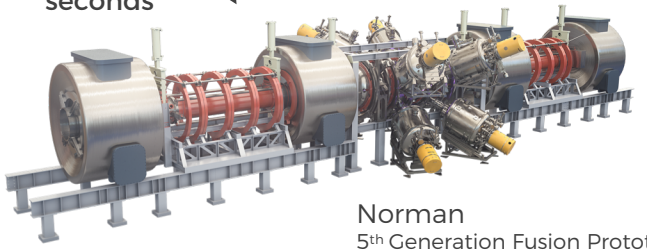
Modular distributed energy topology with advanced control algorithm





550 MW (500 kA, 1+ kV)

few milli-seconds



Norman
5th Generation Fusion Prototype

Integrated Module:

Storage, Control and Converter – autonomous module for distributed energy & control network

- High energy storage
- High power demand
- Flexible load matching
- Excellent energy efficiency & utilization
- Critical reliability & uptime capability

Power Management Technology Market

Power Management

Mobility

- Electric Cars
  - Sports e-Cars
  - Luxury e-Cars
  - Mid-Market e-Cars
  - Mass Market (48V) e-Cars
- Electric Buses
- Electric Trucks
- Electric Construction/ Mining/ Industrial equipment
- Autonomous & Ride-share Vehicles
- Flying Vehicles & Drones
- Electric Ferries
- Military Use

Energy Storage

- Residential Energy Storage
- Industrial Energy Storage
- Data Backup Solutions
- Grid Connected Battery Storage
- Mini & Micro-Grids
- Charging Stations

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TAE global power technology vision

Automotive & Grid Stabilization	Grid	Residential, Charging, Storage & Grid Stabilization
tae Power Technology for **TRANSPORTATION** Energy Storage Motor	tae Power Technology for **CLEAN FUSION**	tae Power Technology for **GRID AND STORAGE** Solar Thermal Residential Energy Storage


Thank You