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Fusion via Beam-Driven FRCs

Michl Binderbauer | TAE Technologies

USBPO Webinar on Burning Plasma Concepts
MAY 5, 2022

THANK YOU

Our sincere kudos to all that have contributed to this work over the past 20+ years — TAE staff and investors, all our partners and consultants. There are simply too many to fit here . . .

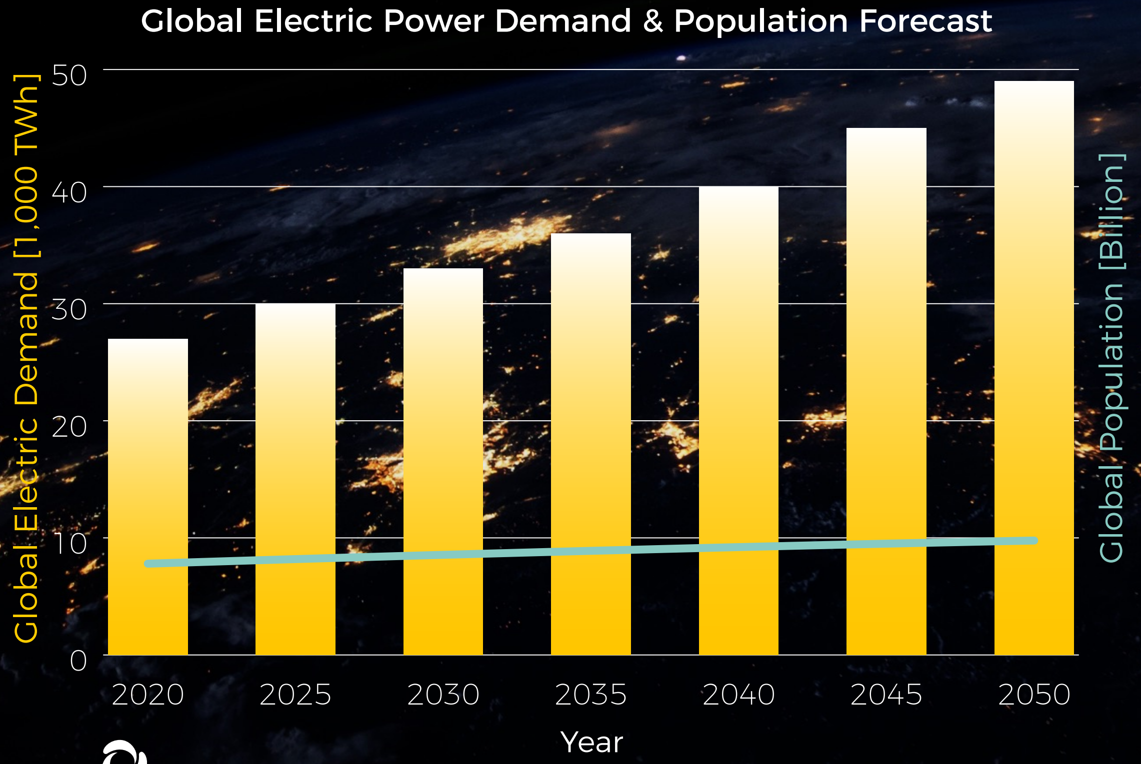
In addition, we are beneficiaries of masterful work in fusion and plasma science over many decades before us. Without standing on the shoulders of these giants this work would not have been possible.

Please accept our sincere thank you for each and all of your contributions!

"I would like to see the development of fusion power to give an unlimited supply of clean energy and a switch to electric cars.

– Stephen Hawking

Electric Energy Demand to Double



Source: McKinsey, Global Energy Perspective (2019), UN Data

- Global electric demand to double by 2050, with > 75% of increase driven by rising standards in developing world
- Total energy demand exhibits similar growth
- Transportation and industrial sectors use >70% global energy (only ~6% in form of electricity)
- Need clean energy transformation over next 2-3 decades
- Fusion and fission only way to provide utility-scale zero emissions baseload power globally

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Content

Criteria for Clean Energy

Vision and Roadmap

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Current Generation Advances

Next Step

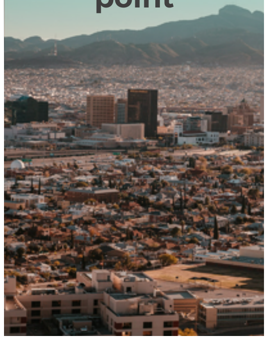
Beyond Fusion – Spin-off Technologies

Criteria for Clean Energy

Why Fusion Power is a good Solution

Criteria for a Permanently Sustainable Clean Energy Source

1.
Dispatchable baseload power produced near consumption point



2.
Smallest possible land footprint for power plant

3.
Minimized transmission lines, infrastructure footprint, and cost

4.
Carbon free

5.
No long-lived nuclear waste

6.
Must not diminish a natural resource

Vision and Roadmap

On the path to aneutronic fusion

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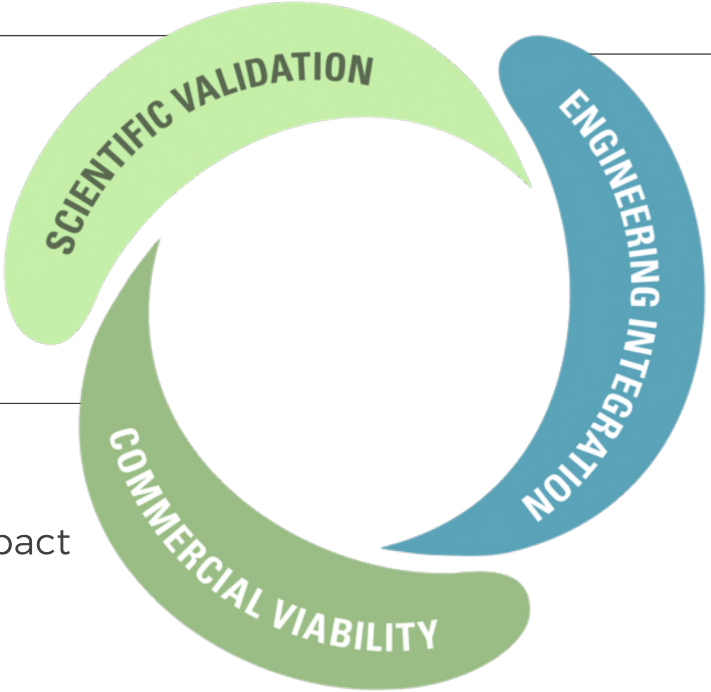
Beginning with the End in Mind
Holistic approach to fusion

Net Energy Output

- High Temperature capable
- Efficient confinement
- Good stability



Technological Readiness

- Aneutronic fuel
- Little to now radioactivity
- Low materials challenge

Cost Competitive

- Compact size
- Least environmental impact
- Ease of maintenance

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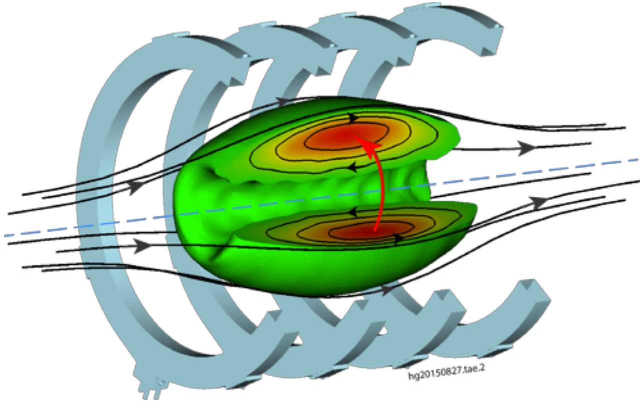
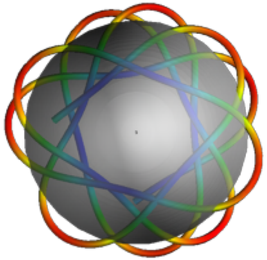
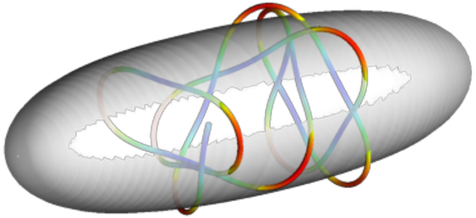
How TAE accelerates innovation

- **Build platforms with opportunities for fast cycles of learning**
- **Strategic partnerships to pool talents/resources**
    - Traditional fusion partners – universities and national labs
    - Outside of typical fusion efforts – Google, utilities/EPRI, industrial sector
- **Deploy advances in machine learning and AI**
    - Operational optimization
    - Feedback control – assessing and driving “patterns” might be good enough
- **Aim for aneutronic fuel cycle**
- **Take advantage of forcing function provided by private capital**
- **Spin-off applications – medical, EV, etc – develops early revenue, supply chain**

TAE's Reactor Concept
Advanced beam driven FRC core







- **High plasma β~1**
  - compact and high power density
  - aneutronic fuel capability
  - indigenous large orbit particles
- **Tangential neutral 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 power, ash and impurity removal

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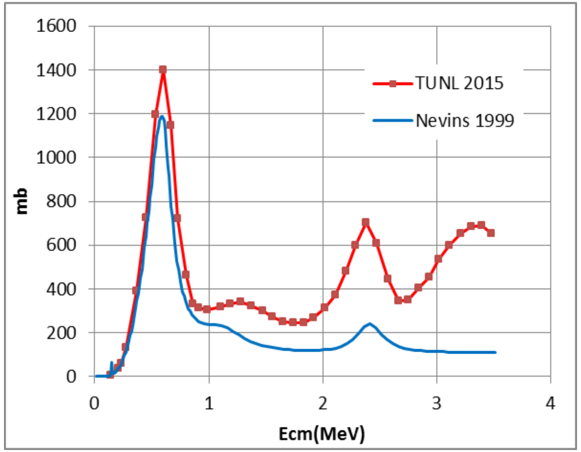
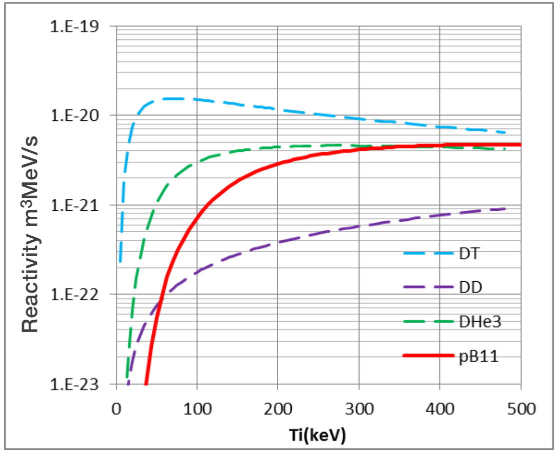
TAE's ultimate goal – p-^{11}B fusion





- Engineering Advantages
  - (almost) no neutrons
  - benign, readily available fuel
  - little radioactive waste
  - viable economics

- Physics Challenges
  - requires **stable plasma**
  - requires **high temperatures**
  - less margin than D-T — lower reactivity

S.V. Putvinski et al 2019 Nucl. Fusion 59 076018

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Goals, Issues and Initiatives for FRC Research
FESAC TAP report (2008) & ReNeW (2009)

Long-range mission

- Develop compact (high-β) reactor without toroidal field coils or a central solenoid

ITER era goal

- Achieve stable, long-pulse keV plasmas with favorable confinement scaling

Key issues

- Is global stability possible at large s ($a/\rho_i \geq 30$) with low collisionality?
- What governs energy transport and can it be reduced at high temperature?
- Is energy-efficient sustainment possible at large-s and with good confinement?
- Theory and simulation challenges (high-β, kinetic effects, transport)

Suggested possible initiatives

- Build larger facility with rotating magnetic fields or neutral beam injection (NBI)
- Develop comprehensive diagnostics suite (profiles, fluctuations, …)

TAE's path towards commercial fusion

Major development platforms integrate then best design

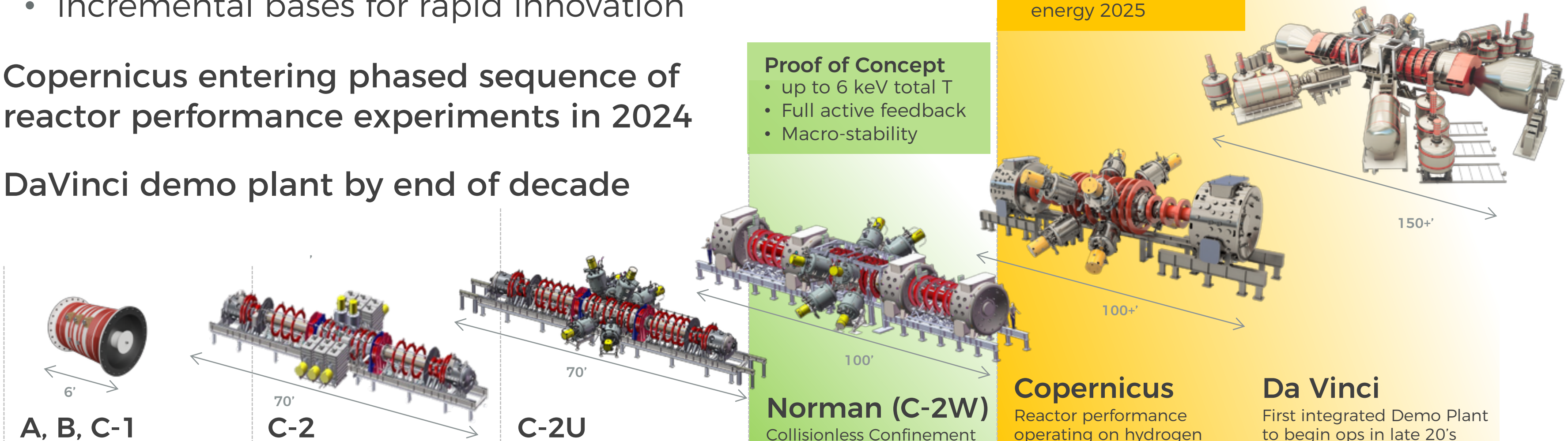
- incremental bases for rapid innovation

Copernicus entering phased sequence of reactor performance experiments in 2024

DaVinci demo plant by end of decade

TAE's next machine
- In final design
- Construction 2022+
- First ops in 2024
- Viability of net energy 2025

Proof of Concept
- up to 6 keV total T
- Full active feedback
- Macro-stability



A, B, C-1
Early development steps

1998 – 2000s

C-2
First full-scale machine

2009-2012

C-2U
Plasma sustainment

2013-2015

Norman (C-2W)
Collisionless Confinement Scaling

2016-2024

Copernicus
Reactor performance operating on hydrogen plasma

2022-2026

Da Vinci
First integrated Demo Plant to begin ops in late 20's and fueled with $H\text{-}B^{11}$

2023+ onward

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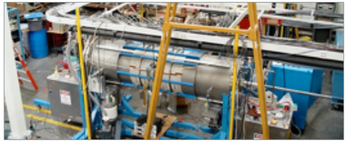
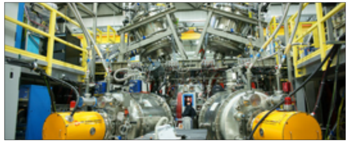
Key Past Program Accomplishments

Past TAE Program Evolution

From 2000 to 2016





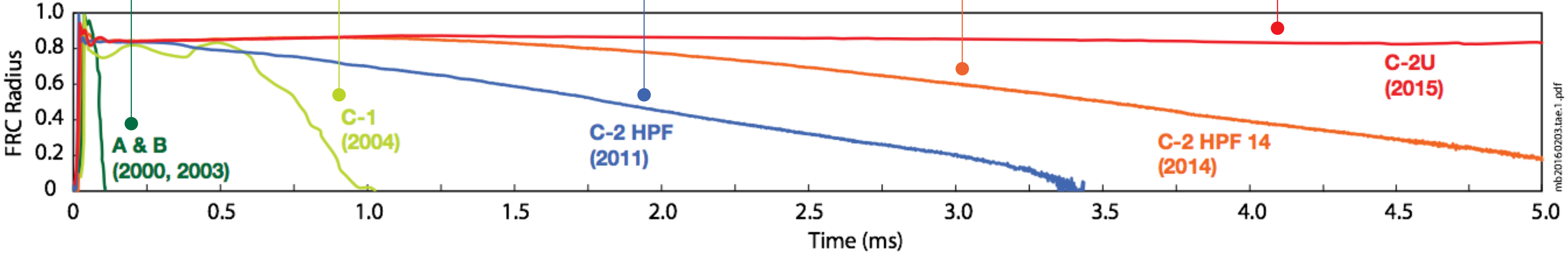
A & B – Basic FRC core
100-800 G, 5-10 eV
ion beams, W_b ~0.1 kJ

C-1 – Enhanced lifetime
400 G, 10 eV
ion beams, Wb ~1 kJ

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

C-2 – HPF* w/ 2 guns, Li
1 kG, 1 keV
neutral beams, Wb ~20 kJ

C-2U – Sustainment 5+ ms
1 kG, 1 keV
neutral beams, Wb ~100 kJ



* HPF – High Performance FRC regime

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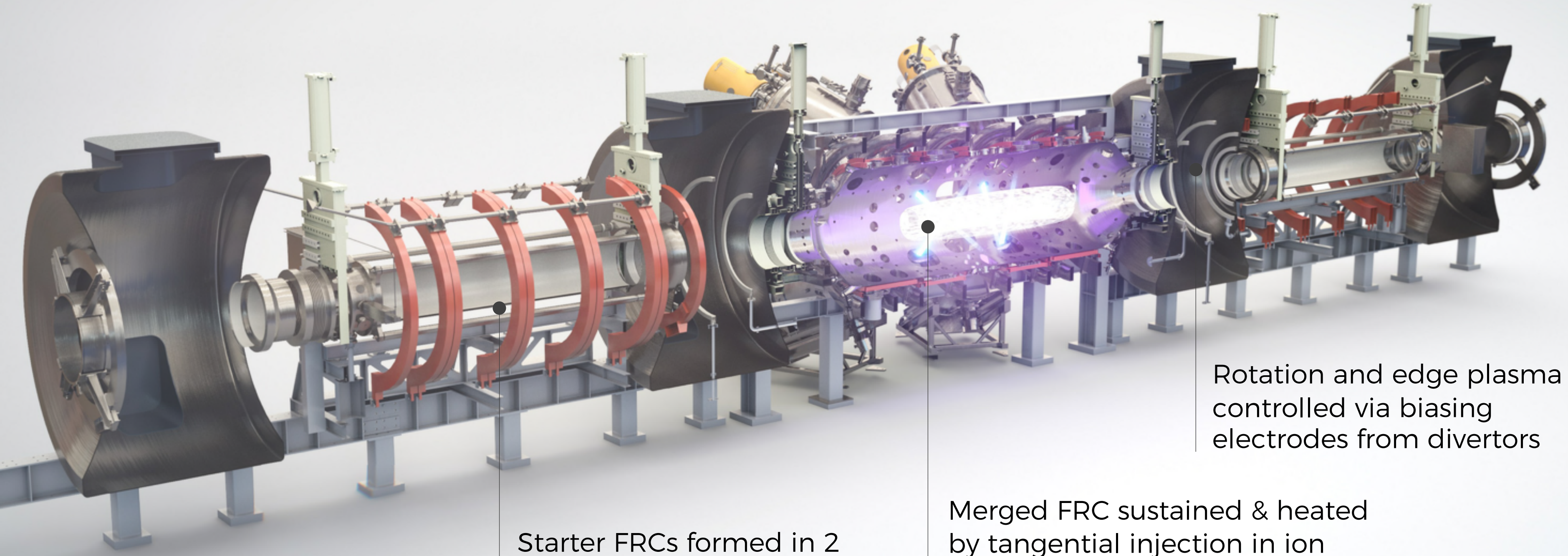
Typical experimental setup



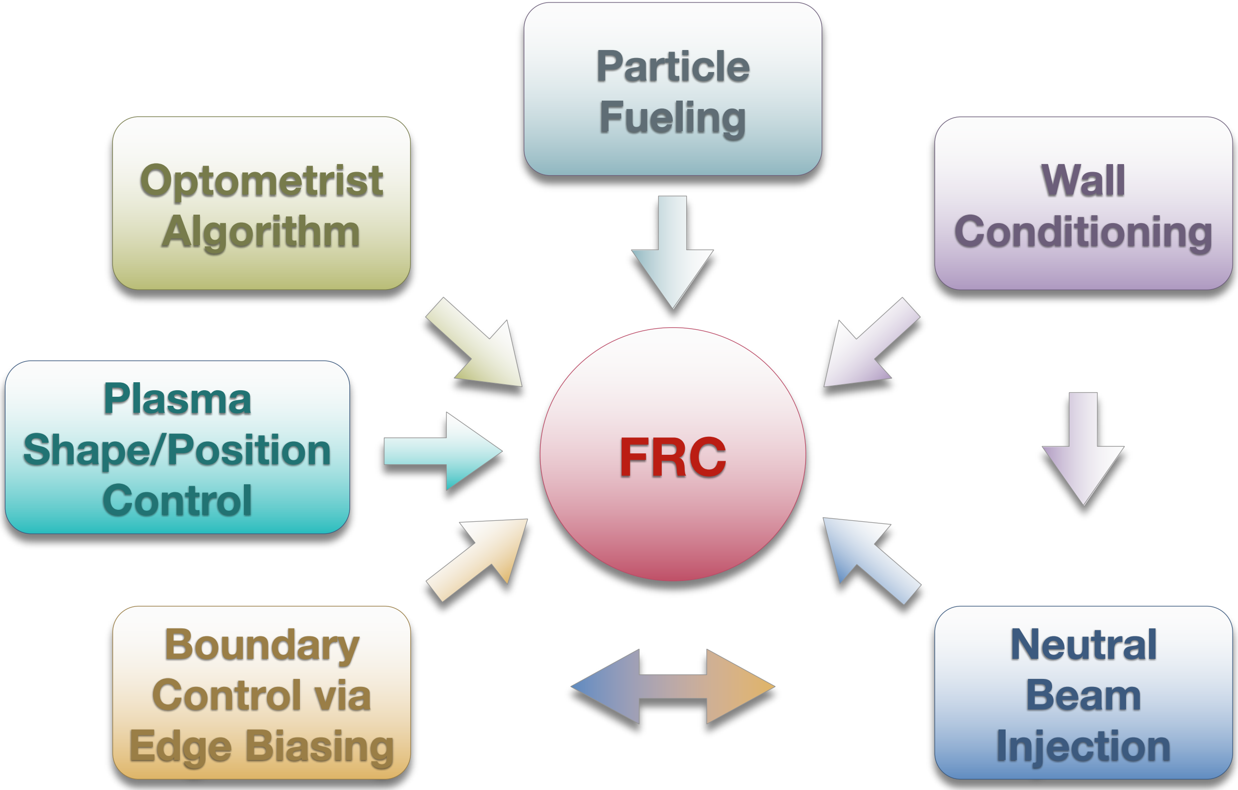
Starter FRCs formed in 2 formation sections and supersonically translated

Merged FRC sustained & heated by tangential injection in ion diamagnetic direction of neutral beams into outer core

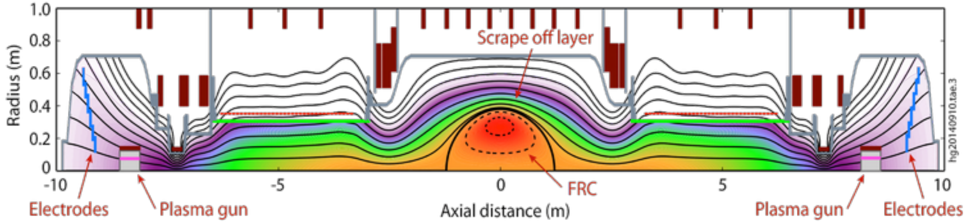
Rotation and edge plasma controlled via biasing electrodes from divertors

Key approaches to beam driven FRCs

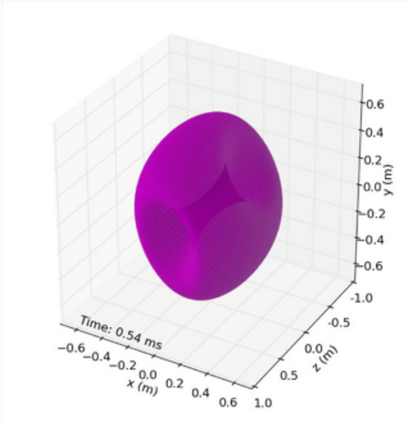
Synergetic effects



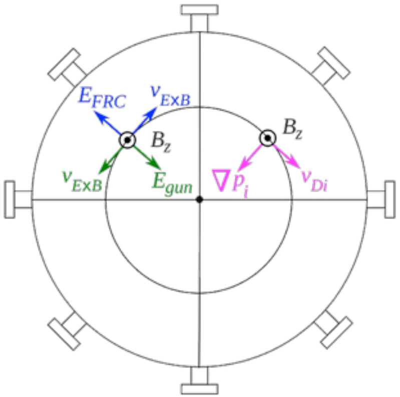
Global stability control – rotational modes



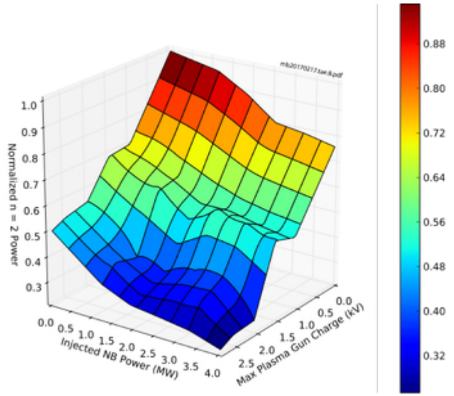
- Axisymmetric stabilization of rotational free energy via electromagnetic shear from bias electrodes



Mode Visualization



Bias: On/Off



Experimental Data

Binderbauer, et. al, Phys. Plasmas 22, 056110 (2015)

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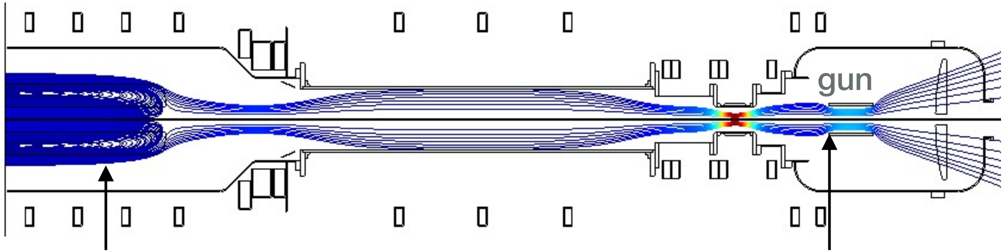
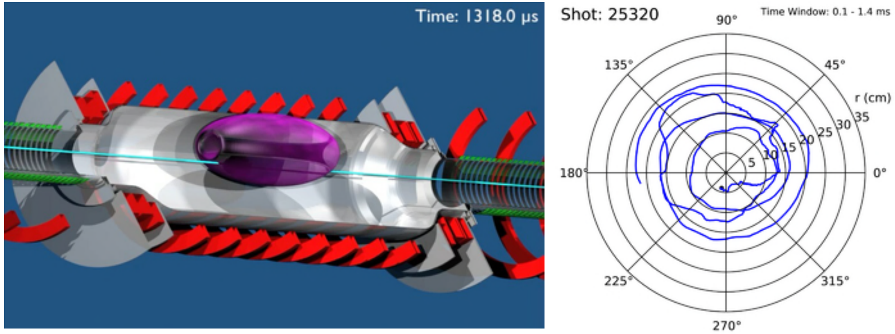
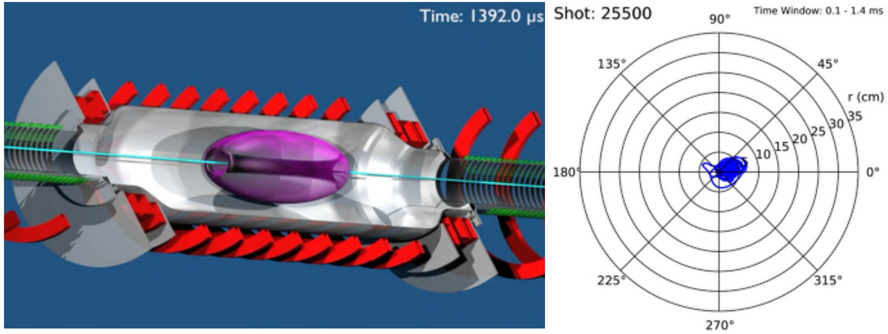
Global stability control – wobble modes



- Line-tying between FRC and plasma gun stabilizes wobble (provided sheath resistance is low)



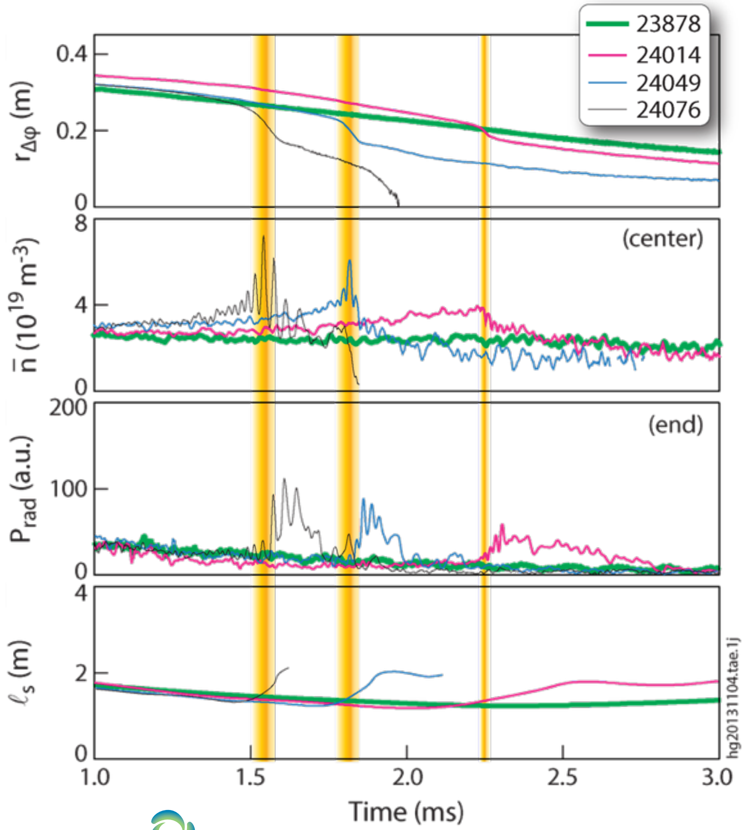
Wobble Controls Off



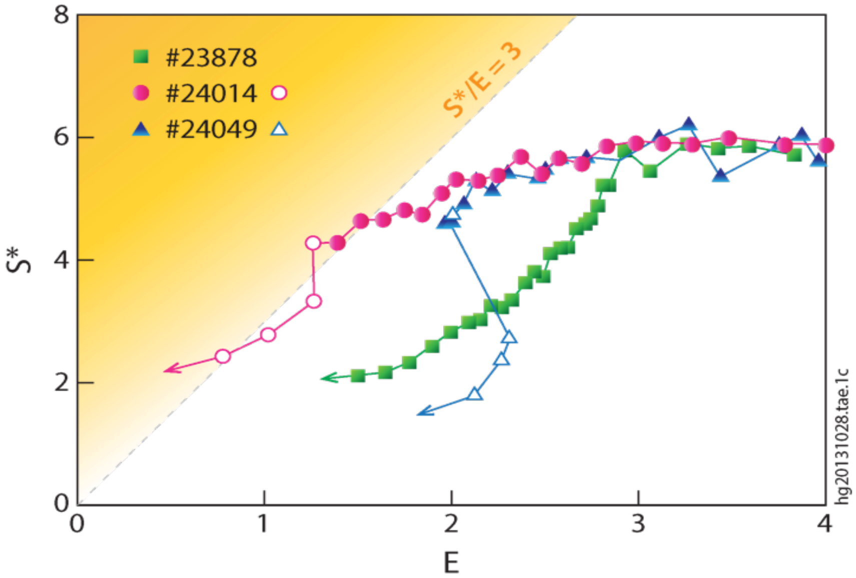
Wobble Controls On

Binderbauer, et. al, Phys. Plasmas 22, 056110 (2015)

Global stability control – tilt modes



- C-2/C-2U typically operate in stable regime by controlling density and creating large fast ion pressure



Guo, et. al, Nat. Comm. 6, 6897 (2015)

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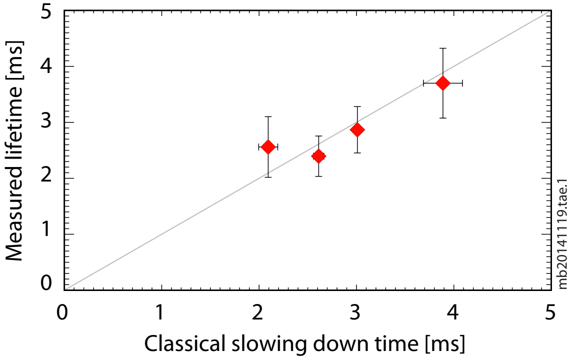
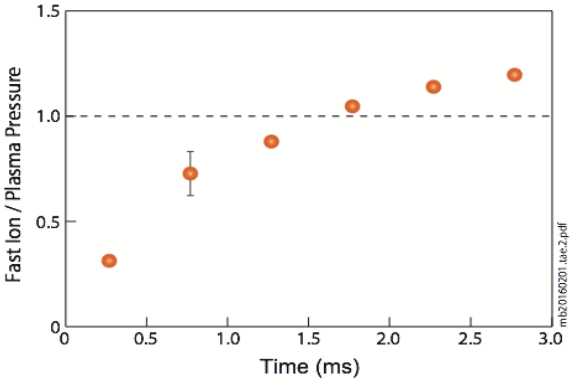
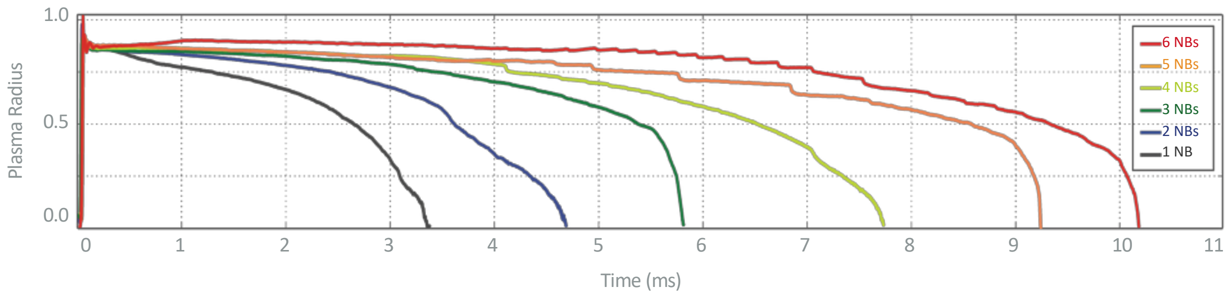
Advanced beam driven FRC enabled by fast ions



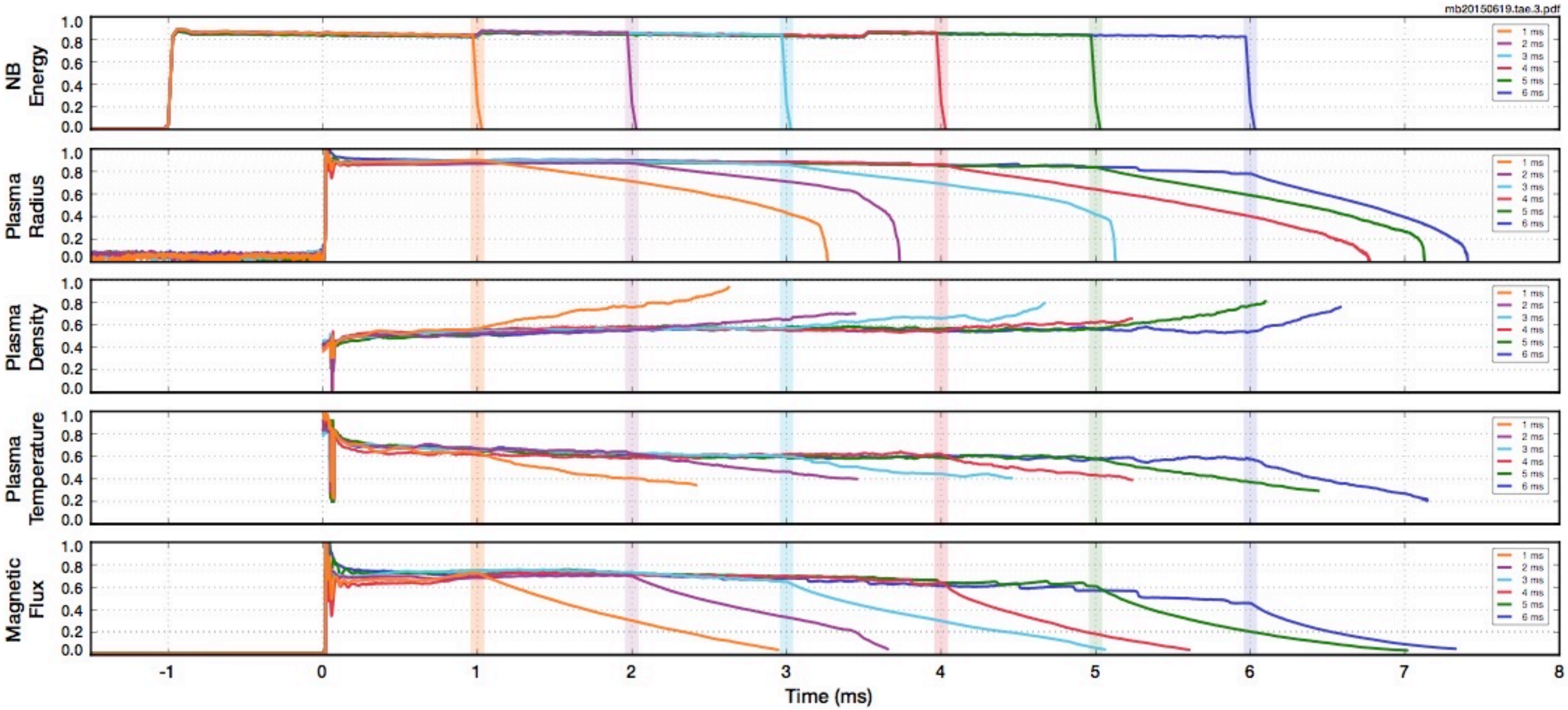


- Fast ion confinement near classical limit $\chi_i \sim (1\text{-}2)\ \chi_{icl}$
- Total pressure is maintained, while thermal pressure is replaced by fast ion pressure, up to $P_{fast}/P_{th} \sim 1$
- Global modes are further suppressed
- Lifetime increases with NBI



Binderbauer, et. al, Phys. Plasmas 22, 056110 (2015)

FRC Sustainment



- Pulse length limited by hardware and stored energy supply (biasing, beams)
- Flux maintained up to at least 5-5.5 ms – showcases ability to drive current

M. Binderbauer, et. al, AIP Conf. proceedings 1721, 030003 (2016)

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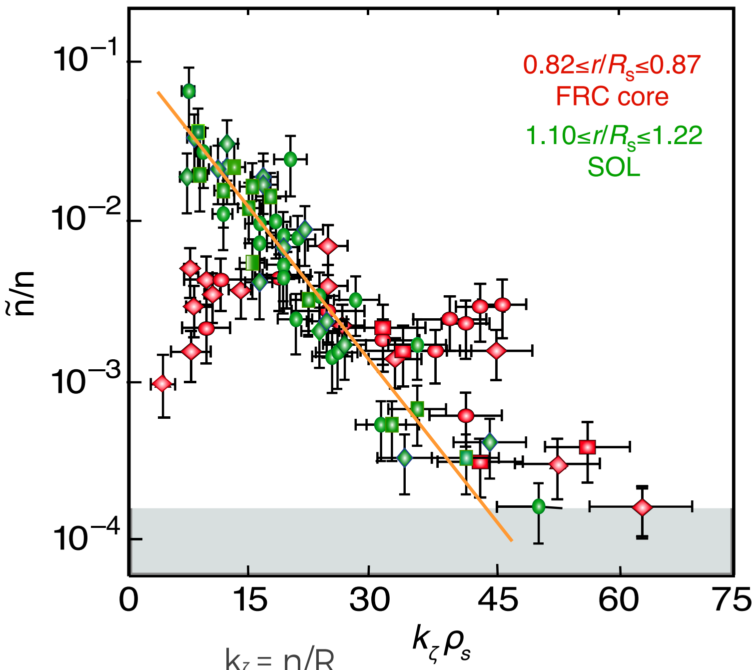
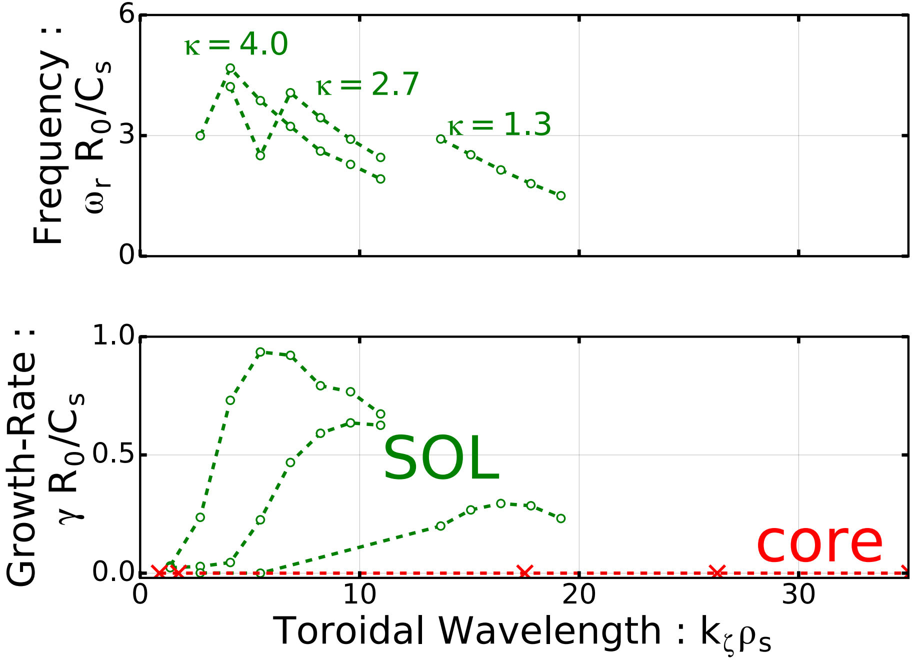
Driftwave stable core, unstable scrape-off layer

Density fluctuation (experiment)*



$k_\zeta = n/R$
$\rho_s=\sqrt{((T_i+T_e)/m_i)}$

Linear dispersion (simulation)



$\kappa=R_0/L_n$ (normalized inverse density scale-length)

Schmitz, et. al, Nat. Comm. 7, 13860 (2016)

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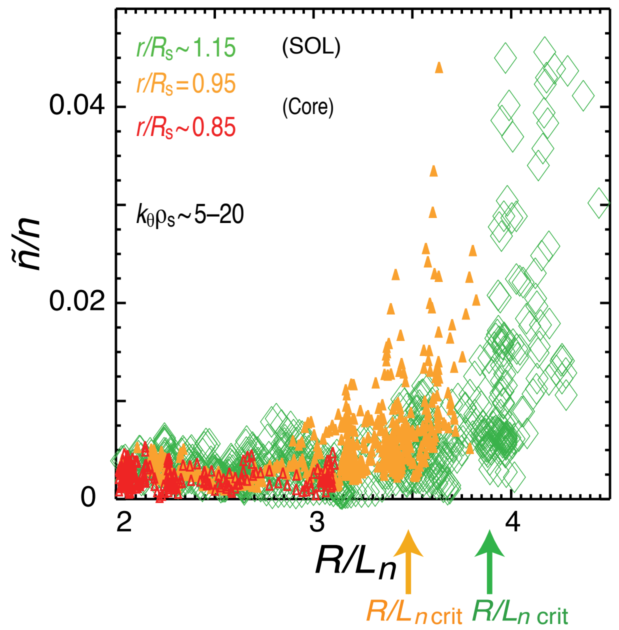
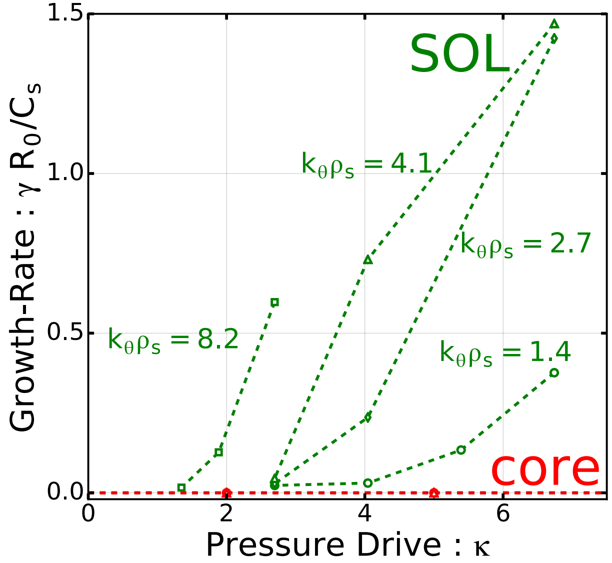
Critical SOL gradient controls onset of fluctuations

Density fluctuation (experiment)*



Linear dispersion (simulation)



(R_0/C_s = 2.5 μs)

$\kappa = R_0/L_n$ (normalized inverse density scale-length)

Lau, et. al, Phys. Plasmas 24, 082512 (2017)

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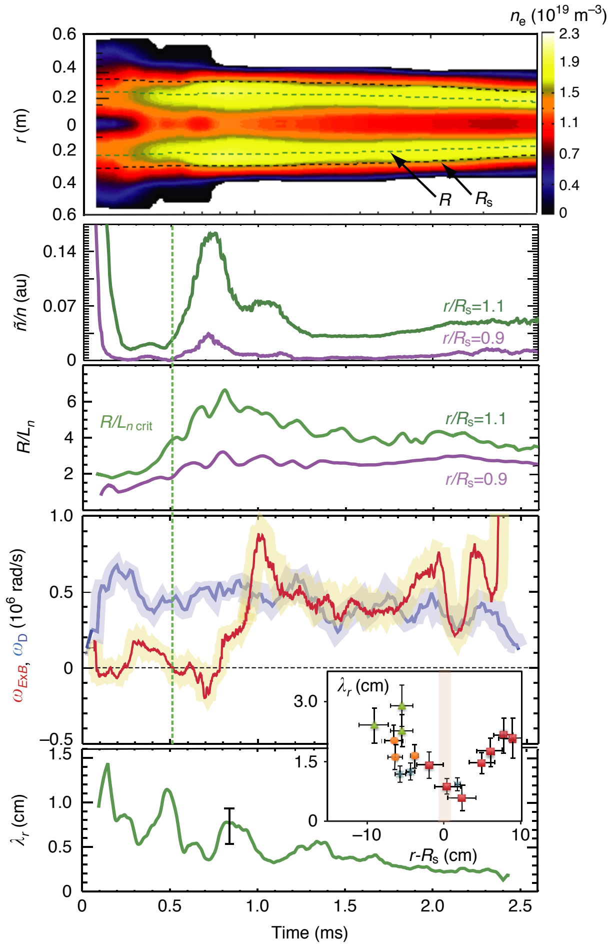
Fluctuation suppression via E×B sheared flow

- Strong E×B shearing rate due to plasma gun biasing
- Sheared E×B flow upshifts critical gradient and reduces turbulence via eddy shearing/decorrelation
- Radial transport barrier at/outside the separatrix



Schmitz, et. al, Nat. Comm. 7, 13860 (2016)

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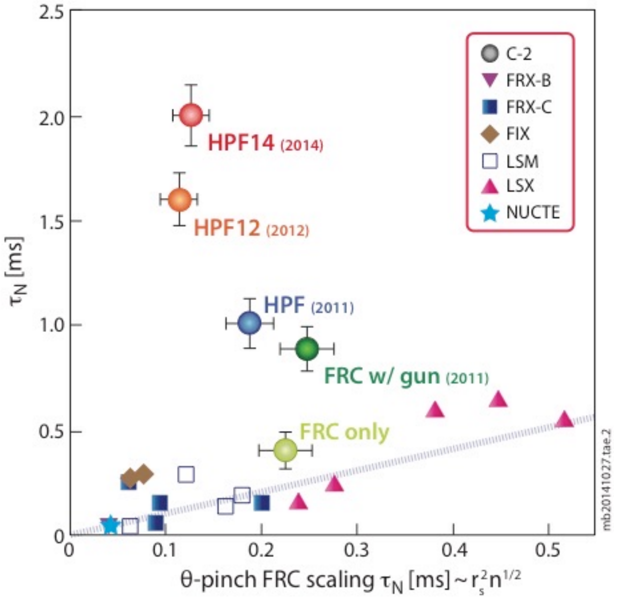
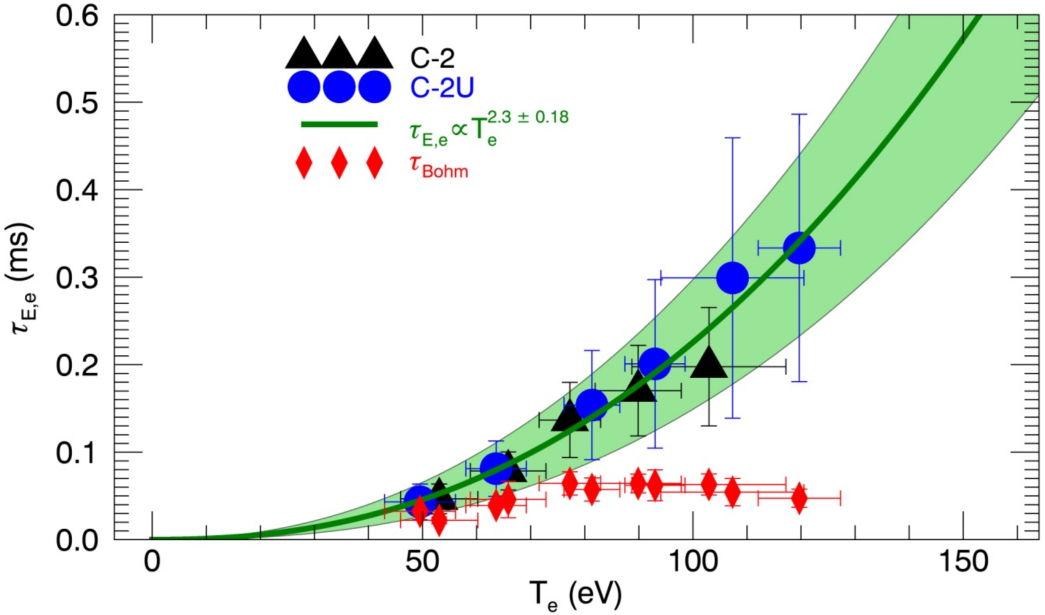
Dramatically improved Confinement

Binderbauer, et. al, Phys. Plasmas 22, 056110 (2015)



- ~10× improved particle confinement



- Strong positive correlation between Te and τEe
- Good fit – $\tau_{Ee} \propto T_e^{2.3}$

Trask, et. al, PBull. Am. Phys. Soc. 61, CP10.00064 (2016)

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Past Achievements Summary

- Fast ion confinement is close to classical
- Quiescent Core
  - Stabilized by FLR effects, magnetic well, fast electron parallel dynamics
  - Inverted wavenumber spectrum – evidence of FLR stabilization of ion modes – consistent with near-classical core thermal ion transport
  - Some electron-scale turbulence – anomalous electron transport ($\chi_e < 20\ \chi_{cl}$)
  - τ_{Ee} exhibits positive T_e power dependence
- SOL/Edge Fluctuations
  - Fluctuations peak outbound near separatrix, with radial outbound convection
  - Exponentially decaying gyro-scale turbulence up to $k_\theta \rho_s < 50$
  - Critical density gradient controls onset of density fluctuations
- Core and SOL coupling – SOL turbulence affects FRC confinement
- Evidence of localized flow shear at separatrix creating thermal barrier

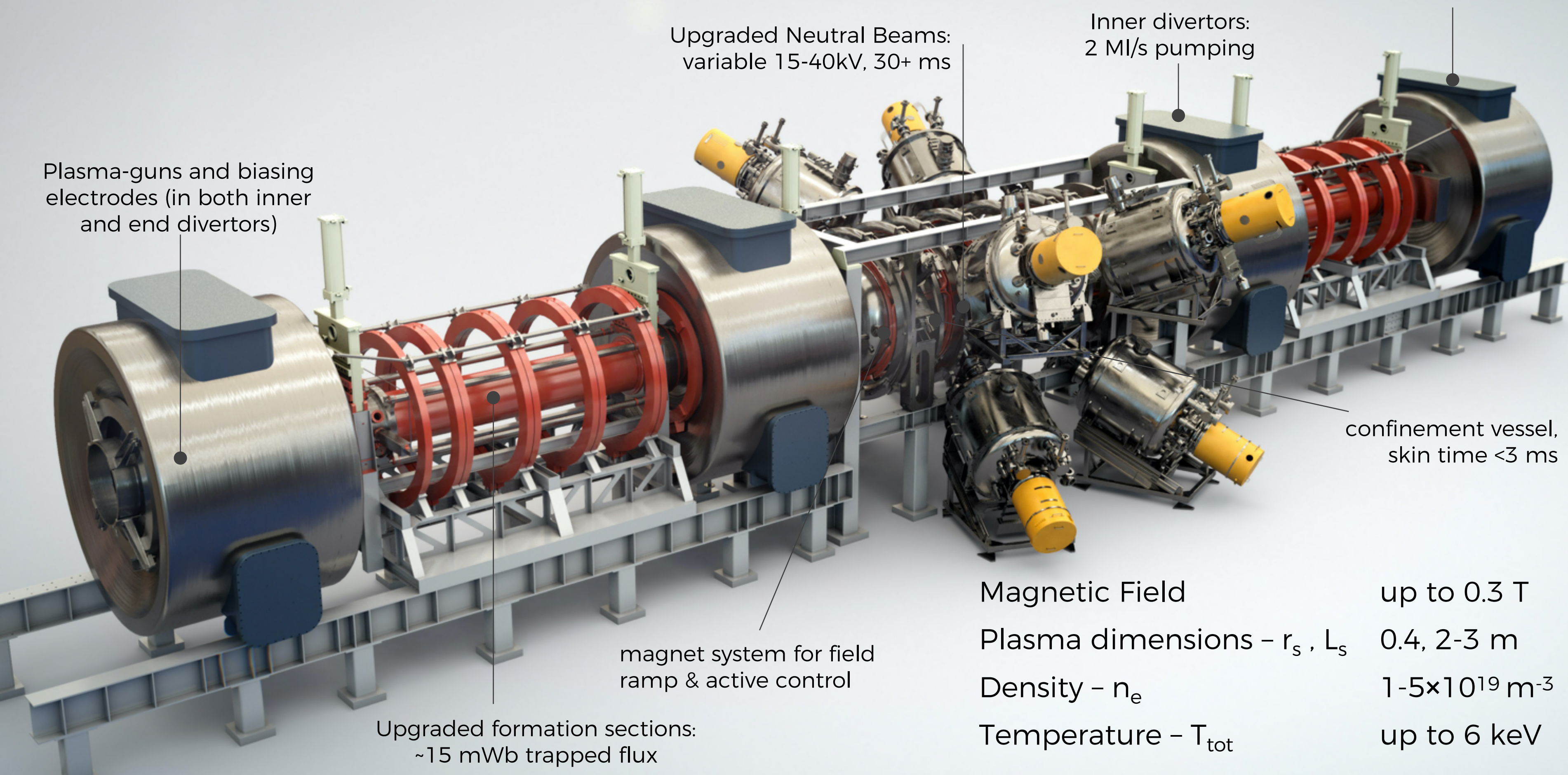
Current Generation Insights

Goals for Norman

Explore beam driven FRCs in fully collisionless regime

- 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 active plasma control

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	$1\text{-}5\times10^{19}$ m^{-3}
Temperature – T_{tot}	up to 6 keV

Extensive diagnostic suite

66 systems operational, more under way

DBL05 - Multi-Channel Pyro-Bolometer
DBL08 - 100 Channel Filtered AXUV Bolometers
DBL09 - Total Radiation Bolometer
DBL10 - CV Linear Array Bolometers (Upgraded)
DBL11 - Grazing Incidence Ion Bolometers
DBL12 - Enhanced View Pyro-Bolometer
DBL13 - LANL X-Ray Bolometer Array*
DBL14 - Multi-faced Compact Bolometer
DCA02 - Phantom Cameras
DCA07 - Edgertronic Fast Cameras
DCA10 - Infrared Cameras
DCL01 – Neutral Beam Calorimeters
DCP01 - Graphene Coupon Test
DEA03 - Divertor End Loss Analyzers
DEA04- Upgraded Divertor End Loss Analyzers
DEP01 - Single Triple Probe
DEP08 - Combination Triple / Mach Probe
DEP09 - Baffled Probe
DEP12 - Divertor Insertable Probe Platform
DEP13 - Electrostatic Fluctuation Probe Array
DEP14 - Ball Pen Probe
DFI01 - Fast Ion Gauge: Hot Cathode
DFI02 - Divertor Fast Ionization Gauge QCCG:FIG
DIN04 - Dispersion Interferometers
DIN08 - Jet Region Multi Chord Interferometer

DIN09 - Inner Divertor Interferometer
DIN10 - Off-Axis CO_2 Interferometer
DLS01 - Doppler Free Saturation Spectroscopy*
DMP14 - MI Combination Flux Loop / B-dot
DMP15 - Chip Inductor Mirnov Probes
DMP16 - Internally Mounted Mirnov Probes
DMP17 - In Vacuum Rogowski Coils
DMP19 - Formation Flux Loops
DMP20 - External Flux Loops on Coils and Vessel
DMP21 - Inner Divertor Field Verification Array
DMP23 - Hall Probe Array
DMP24 - Internal Magnetic Probe Array
DMP25 - Extended Mirnov Probe
DNB01 - Diagnostic Neutral Beam
DND03 - Neutron Detector Type 1 (radial detector)
DND04 - Neutron Detector Type 2 (axial detector)
DND05 - Helium-3 Neutron Ball
DNP03 - Electrostatic Neutral Particle Analyzer
DNP05 - Electromagnetic Neutral Particle Analyzer
DOM01 - Optical Magnetic Sensor
DOP01 - Visible Bremsstrahlung Measurement System
DOP02 - Deuterium Alpha Detector Fan Arrays
DOP05 - Near-IR Bremsstrahlung Measurement System
DOP06 - Photodiode D-Alpha Detector Array
DOP07 - Multi-Fiber Optic Mount 8CF

DOP08 - Symmetrical Optical Fan Array
DOP09 - Photodiode Monitors
DPD01 - Single View Proton Detectors
DPD02 - Multi-Chord Proton Detectors
DPL02 - Far Infrared (FIR) Interferometer and Polarimeter
DRE02 - Fluctuation Reflectometer
DRE03 - Electron Cyclotron Wave Detector
DSE04 - Secondary Electron Emission (SEE) Detectors
DSP04 - Vacuum Ultraviolet (VUV) Spectrometer
DSP05 - Avantes Survey Spectrometers
DSP08 - CV Helium Puff Line Ratio Te Measurement
DSP10 – iCHERS Spectrometer
DSP11 - Divertor Helium Puff Line Ratio Te Measurement
DSP12 - Spectrometer - (FIDA + mCHERS)
DSP13 - mCHERS
DSP14 - White SPEX 1702/04 Spectrometer
DSP16 - Jet Outflow Spectrometer
DSP17 - Prototype Spatial Heterodyne Spectrometer
DSP18 – X-Ray Spectrometer
DTC01 - Internal Thermo-optical Array
DTC02 - Electrode Thermocouples
DTC03 - Mirror Plug Thermocouples
DTS02 - Mid-Plane Thomson Scattering System
DTS03 - Jet Thomson Scattering

Coming Soon
*INFUSE

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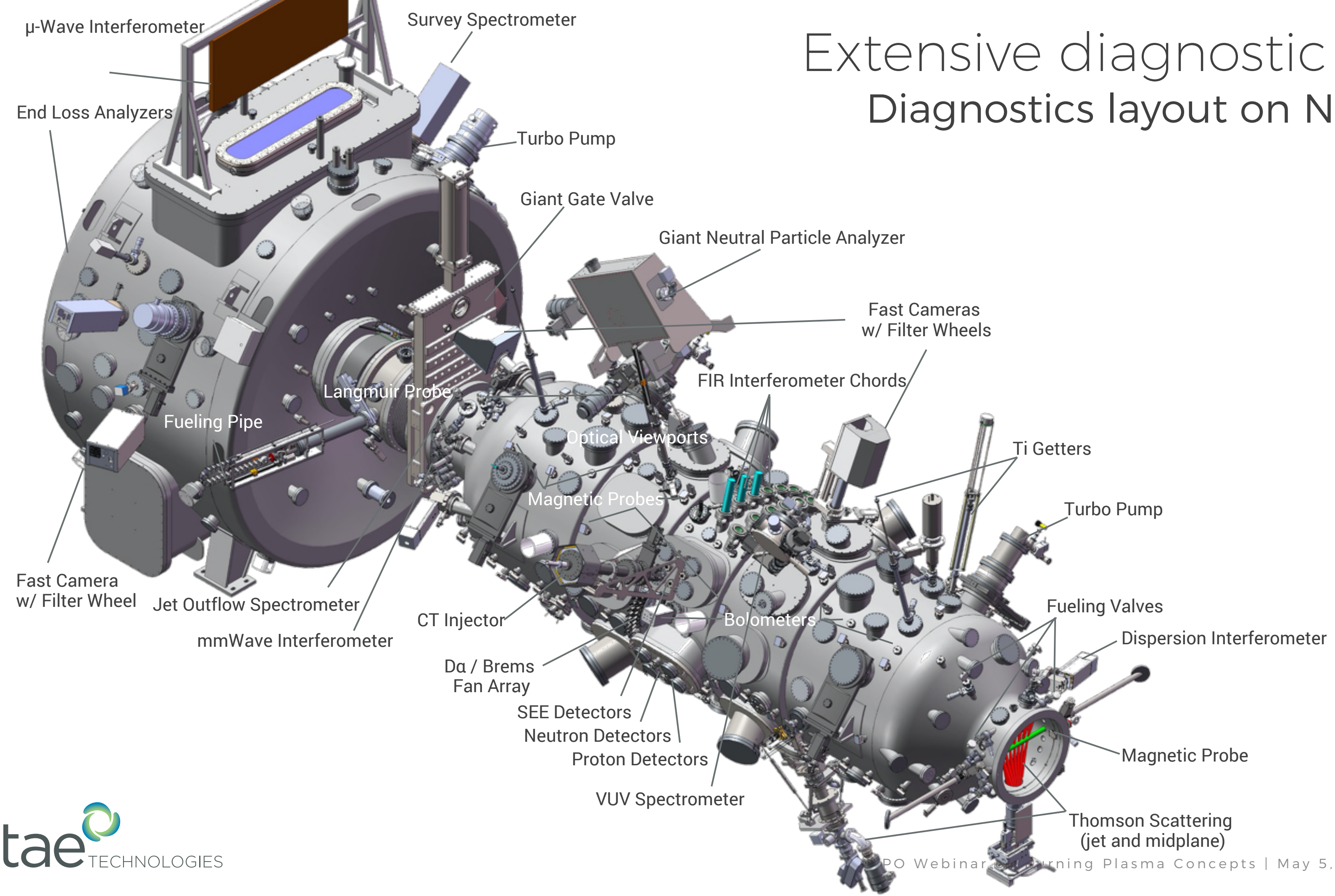
Extensive diagnostic suite
Diagnostics layout on Norman



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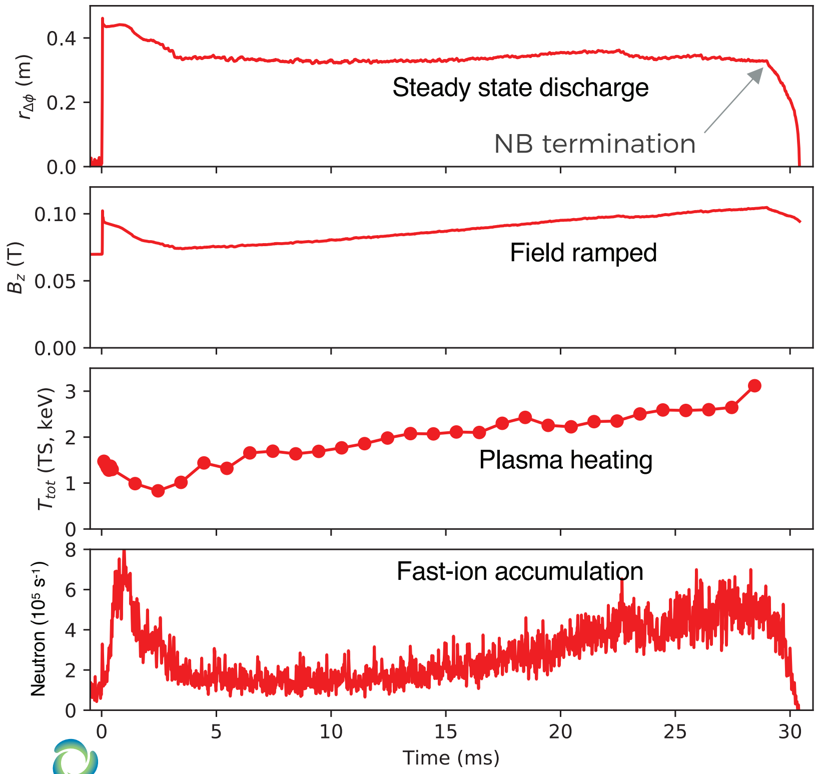
Steady-state FRC discharges

Sustainment with active feedback of beam-driven FRCs

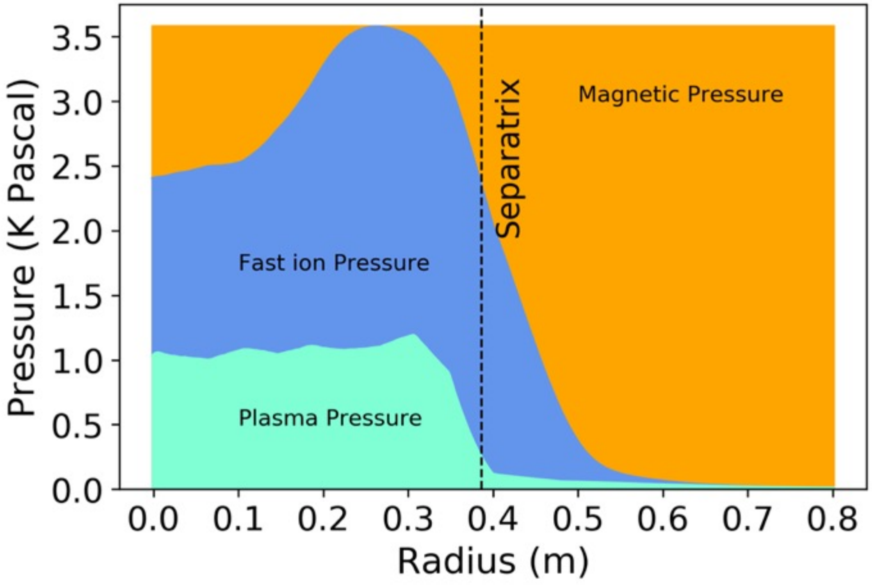


- Duration up to 30+ ms (limited by energy storage)
- Plasma heating and ramp-up clearly observed
- Macroscopically stable operation
- Neutron signal indicates fast-ion accumulation (up to and exceeding thermal pressure)
- Active external field and shape control as plasma pressure builds up

Fast ions enable stable beam-driven FRCs

Strong stabilizing impact without any deleterious consequences

Sample Norman Pressure Profile



- Dominant fast ion pressure
- Provides enhanced stability
- Expands operating regime
- No fast ion driven deleterious modes
- Large ion orbits and turning points well outside separatrix — $P_{fast} > P_{th}$

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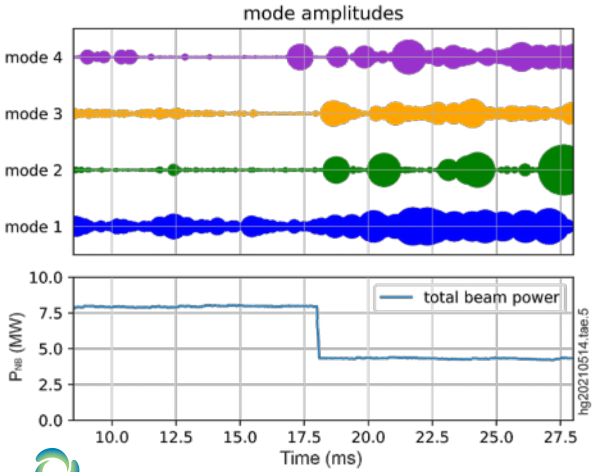
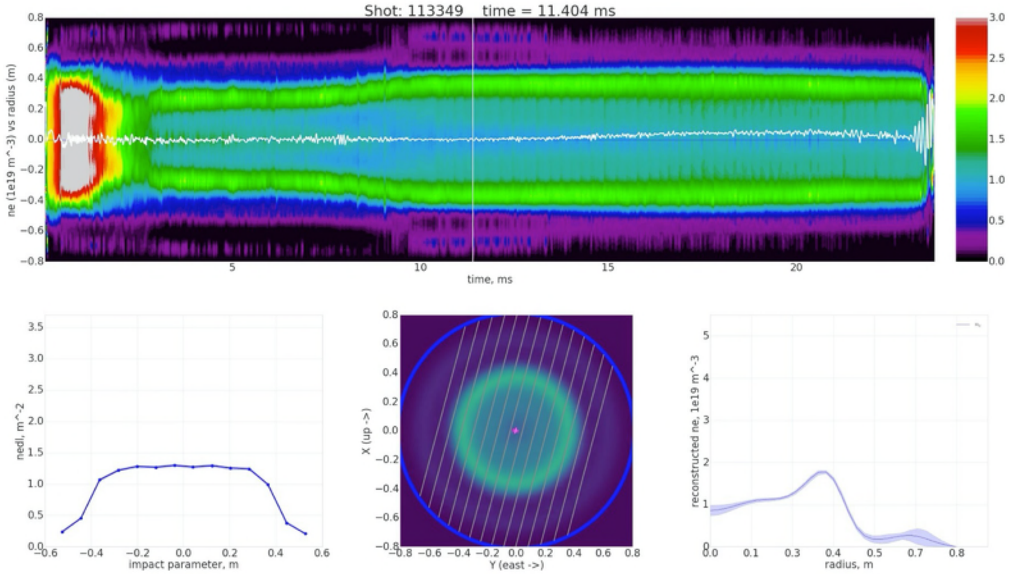
Integrated diagnostics reconstruction

Provides identification of internal plasma perturbations

- Powerful Bayesian tools developed in collaboration with Google infer core mode structures
- Further evidence for stabilization by energetic ions





M. Dikovsky, et. al., Physics of Plasmas **28**, 062503 (2021)

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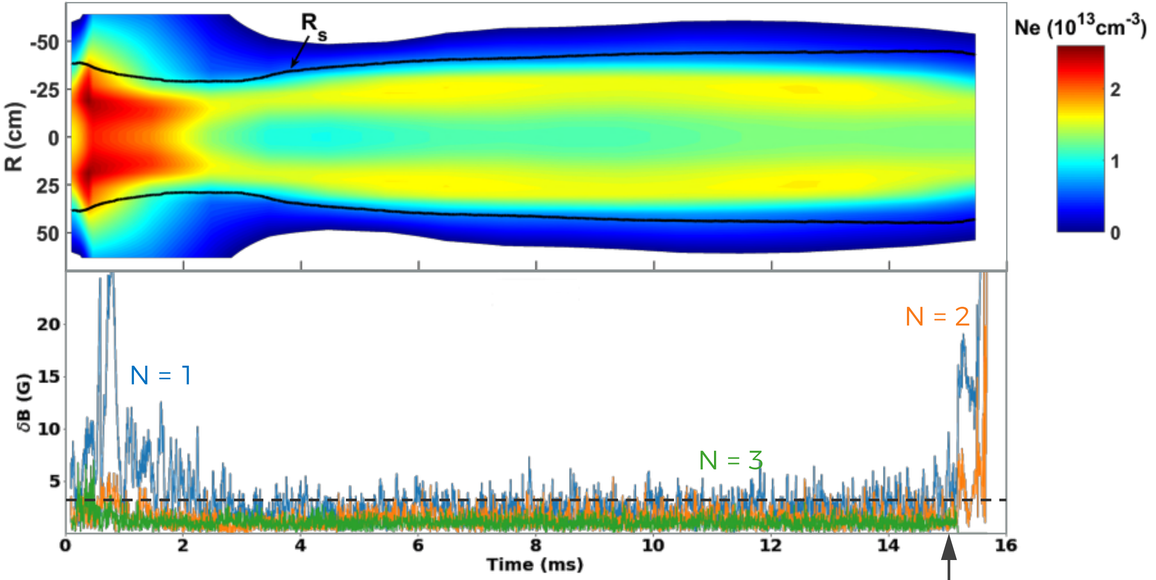
Sustained plasma is stable and robust

Global modes are suppressed throughout the discharge

Shot 13301 – beams switched off at 15 ms



Beams switched off

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

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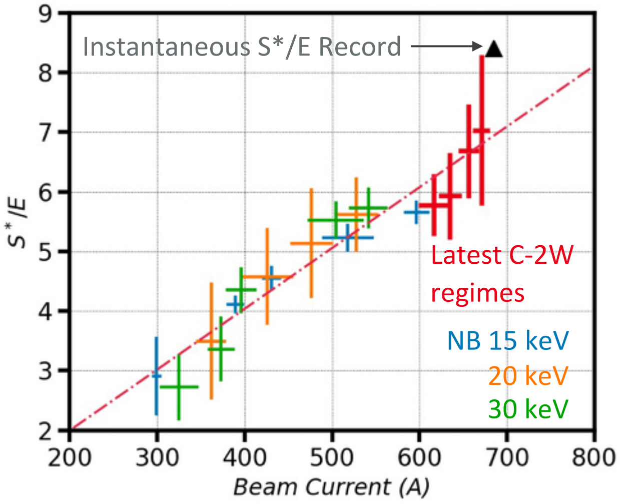
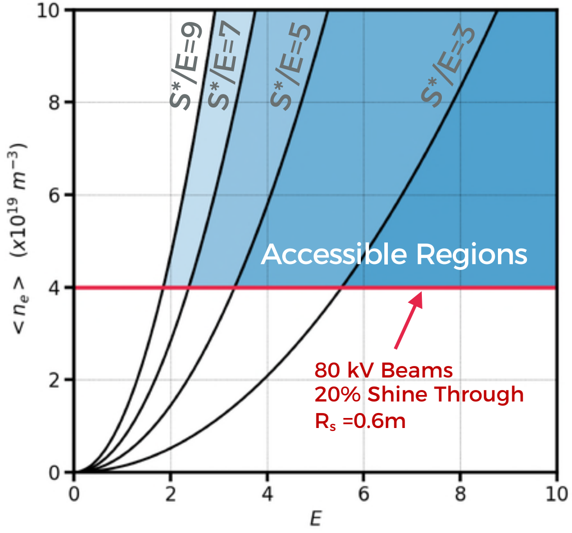
Fast ion stabilization expands operational domain

Removes any constraining density limit

$S^* = r_s/\delta_i$ and $E = L_s/2r_s$



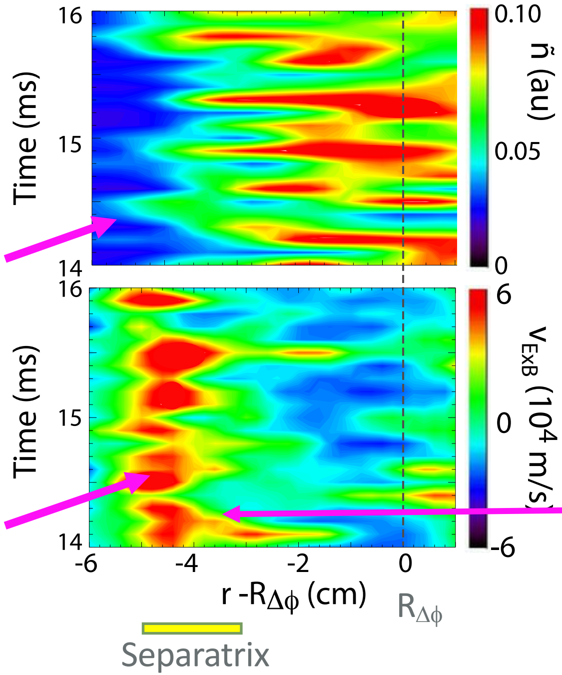


- Tilt improves with growing fast ion population well beyond historical limit of S*/E ~ 3
- Higher S*/E expands Copernicus design space and provides operating flexibility

Evidence of separatrix transport barrier

Zonal Flow (ZF) and E×B shear quenches turbulence near separatrix

Fluctuation level ñ and ExB velocity

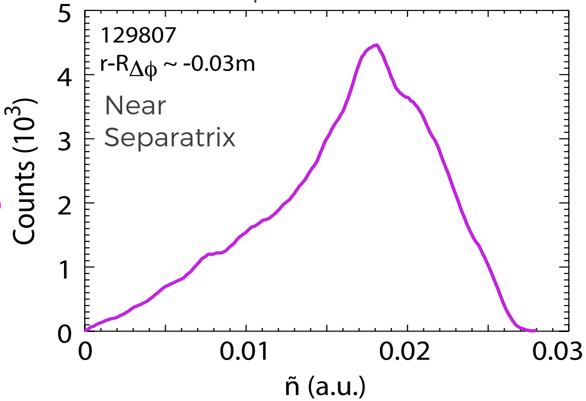


Turbulence quenched near separatrix

High ZF ExB shear forming barrier near separatrix

- Quiescent core, turbulence on open field lines
- Zonal-flow shear based transport barrier just outbound of separatrix
- Inward propagation w/ avalanche like features
- Consistent w/ 3D turbulence simulations

Negative ñ skewness near separatrix, indicative of turbulence quench and barrier formation



Small "events" dominate

Schmitz, et. al, Bull. Am. Phys. Soc. 63, GP11.00065 (2021)

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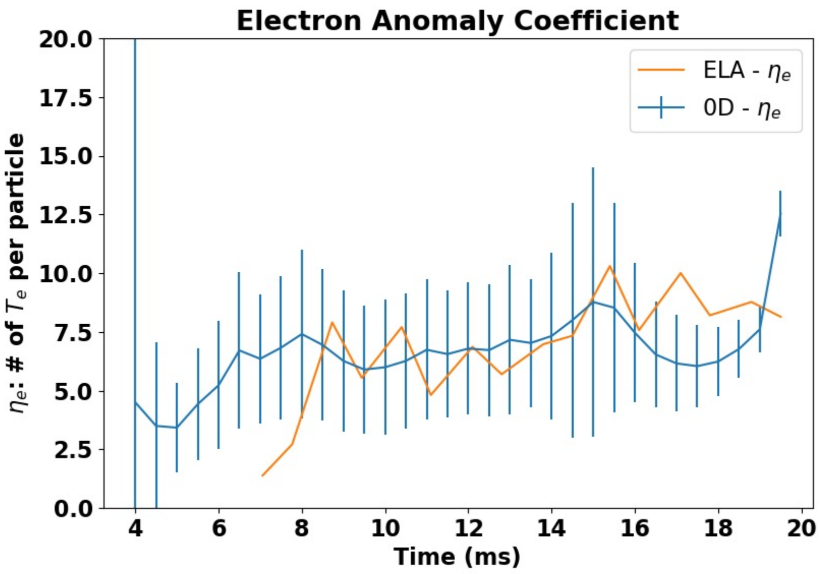
Norman divertors provide excellent edge insulation

Energy loss per electron/ion pair near theoretical minimum



see - Pastukhov V.P. 1974 Nucl. Fusion **14** 3

Flaring magnetic fields

- limit debye sheath voltage at the material boundary
- minimize cold electron back streaming

Extensive vacuum pumping

- evacuates cold gas – minimized cold ion population

Bias electrodes improve stability and transport

Electron energy loss per ion near ideal level

- measured by energy analyzers in outer divertors
- indicates parallel losses in **convective regime** $\frac{q_{\parallel}}{n} \sim T_e^{\frac{3}{2}}$
- $\boldsymbol{\eta_e \sim 6-7}$ near ideal ambipolar electron confinement η_e~5-6

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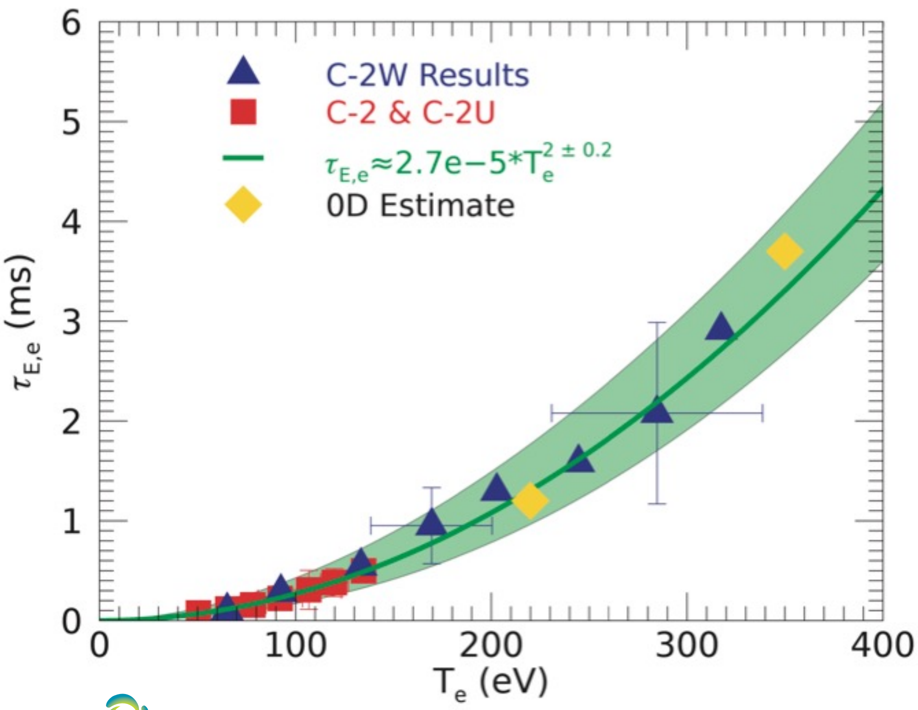
Promising energy confinement scaling extends

Norman machine shows same trend as prior experiments

Trask, et. al, Bull. Am. Phys. Soc. 61, CP10.00125 (2019)



Features of FRC plasma:

- Collisionless — $\lambda_{mfp} \sim 5 - 50\text{m} \geq L_{C-2W}$
- High-β scaling matches data best
  - Dimensionless parameters with some cross-machine resolution
  - J.W. Connor, J.B. Taylor, Nucl. Fusion 17, (1977)
- Weak scaling with ρ^*
  - Expected since <B> in core is low
  - High β makes n, T, B degenerate too
- Collisionality scaling is strong — $\tau \propto T^2$

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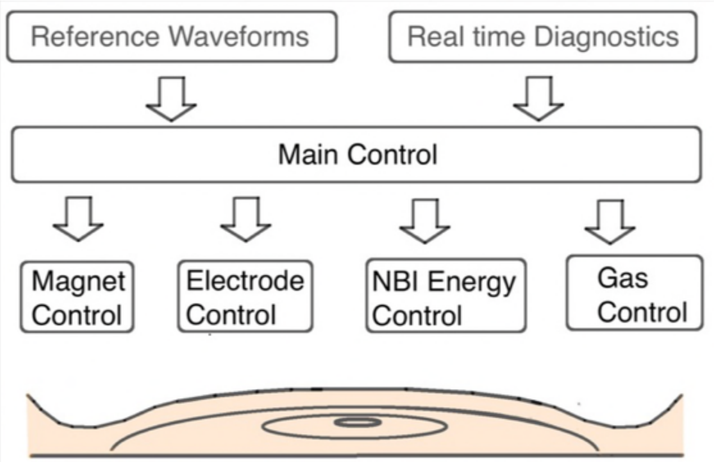
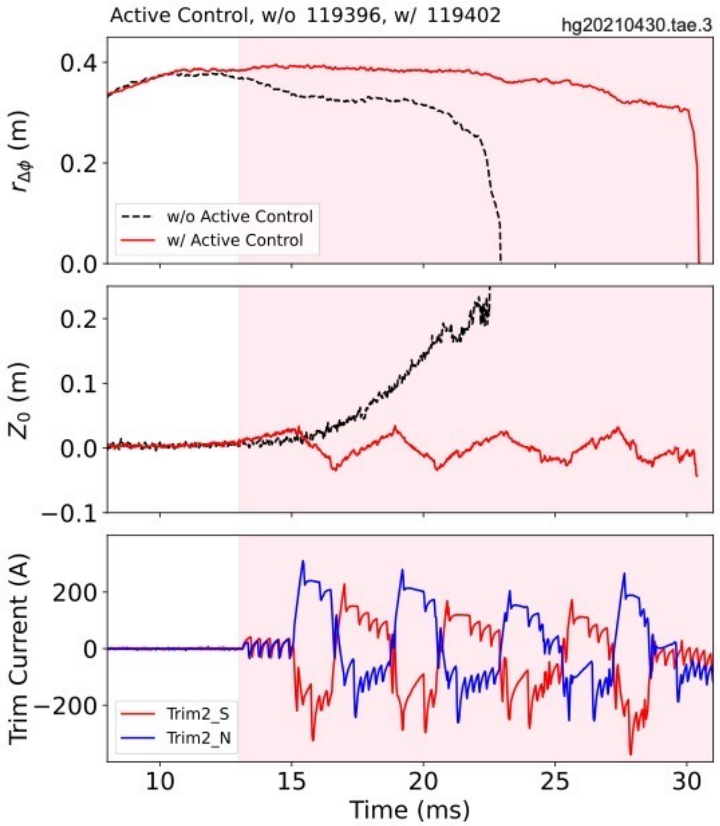
Active feedback control — plasma position

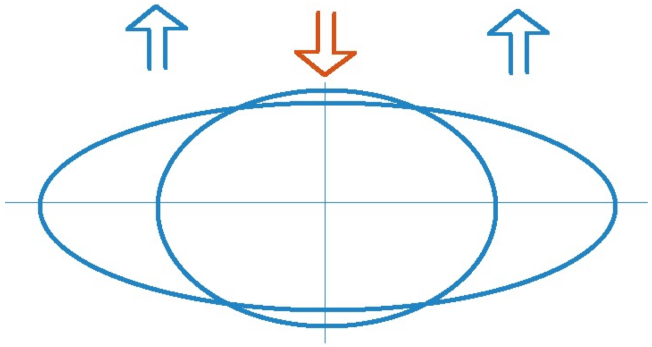
- Axial and radial/azimuthal position control with real-time feedback
- System capable of controlling several additional actuators

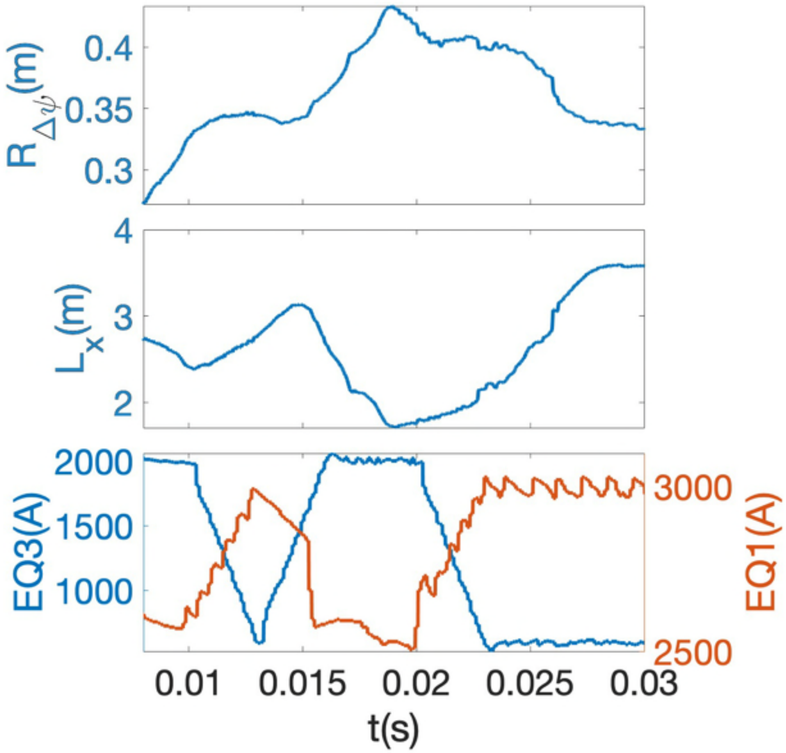




Active feedback control — plasma shape

- Length no longer determined by intrinsic processes
- Elongation responds to external fields





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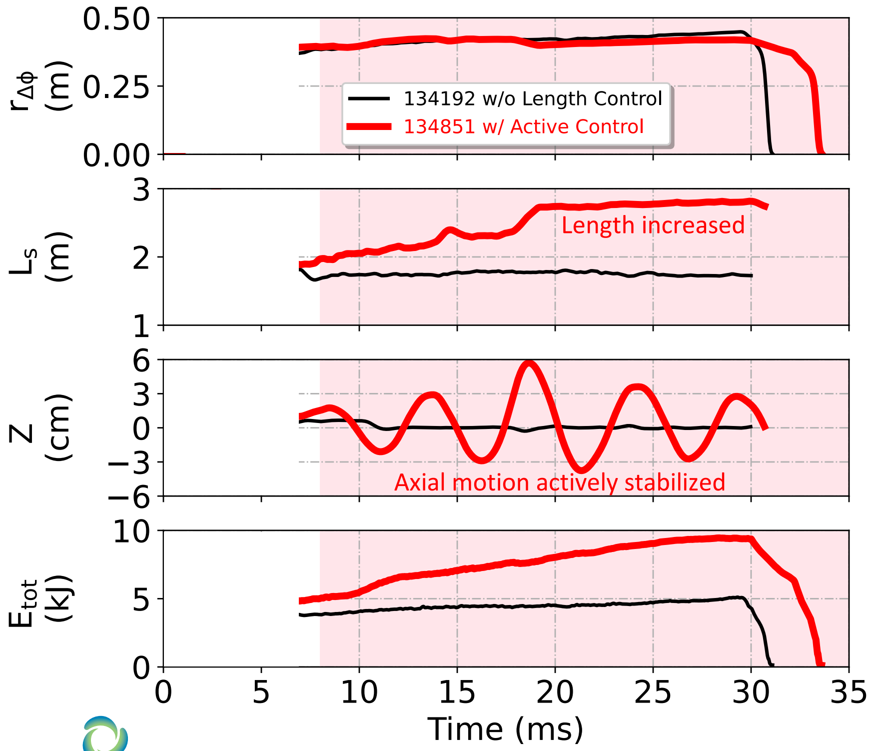
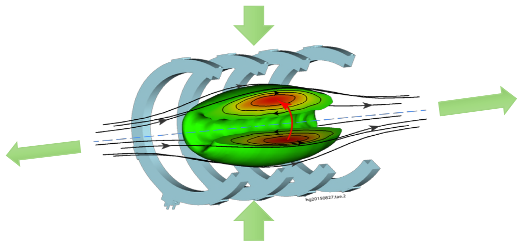
Active-feedback control of plasma length expands Copernicus design space





- Beam injection helps to break an intrinsic coupling between FRC density and length ($S^*/E < 3$)
- Active-feedback, real-time magnetic control implemented to independently control plasma length
- Improves operating flexibility and enables broader options for future machines

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Norman goals achieved

Beam driven FRCs explored in fully collisionless regime

- Physics performance goals achieved
  - Sustainment for 30+ ms, limited by stored energy
  - Total temperature over 6 keV, electron temperature up to 1 keV
  - Favorable confinement scaling extended to collisionless regime
  - Excellent edge insulation – energy loss per ion/electron pair ~6 T_e
  - Practical density limit removed – opens larger operating space
- Technology development goals demonstrated
  - Millisecond-scale ramp-up and heating
  - Real-time active feedback with
    - tunable beam system – 15-40 keV within 100s of micro-seconds
    - stability and transport control via end-biasing
    - position and shape control via trim and saddle-coils

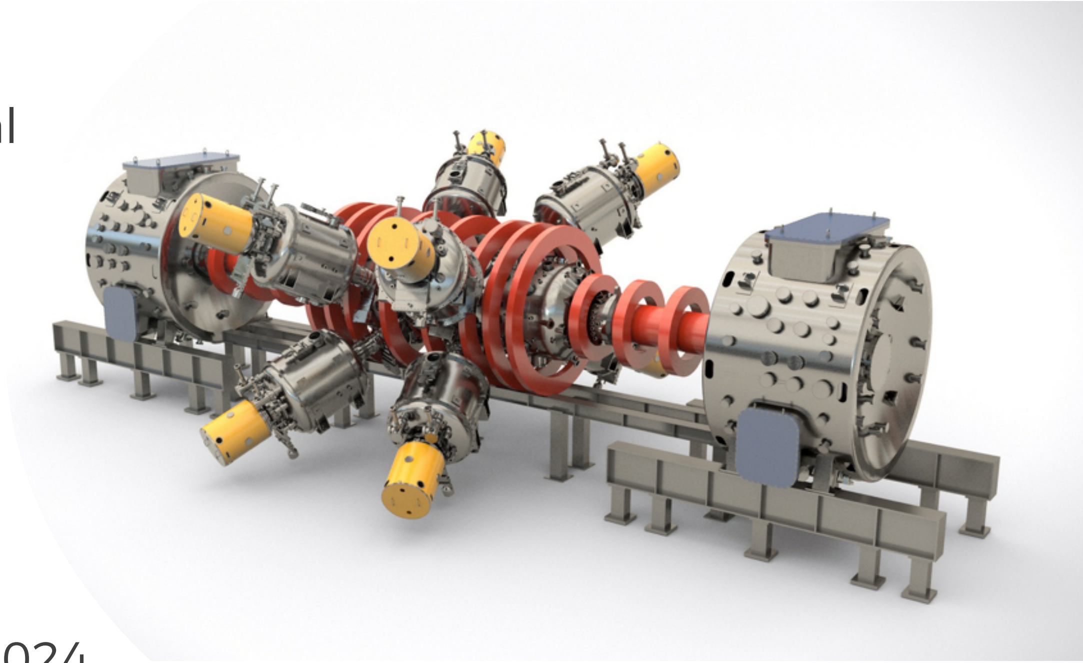
Next Step

Copernicus

Reactor scale plasma performance platform

Design established

- 10+ keV ion temperature goal
- Hydrogen only operation
- 3 sec pulse length



Budget and timing

- $250 MM cap-ex
- Fabrication under way
- Commissioning and ops by 2024

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Beyond Fusion

Spin-off technologies

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From fusion power supplies to power management

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, Charging, Storage & Grid Stabilization

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Power Technology for
GRID AND STORAGE

Solar Thermal | Residential | Energy Storage

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From fusion beams to targeted radiation oncology

Beam technology adapted to compact epithermal neutron sources

- BNCT (boron neutron capture therapy) – existing cancer treatment, but only available at research sites with a nuclear reactor
- Derivative of partnership with Budker Institute
- 3x efficacy of x-ray & proton treatments
- First clinical system delivered – first patient treatment this year
- Growing order book in Asia, EU, US

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Thank You