On TAE's Path to Fusion

A Private-Sector Perspective

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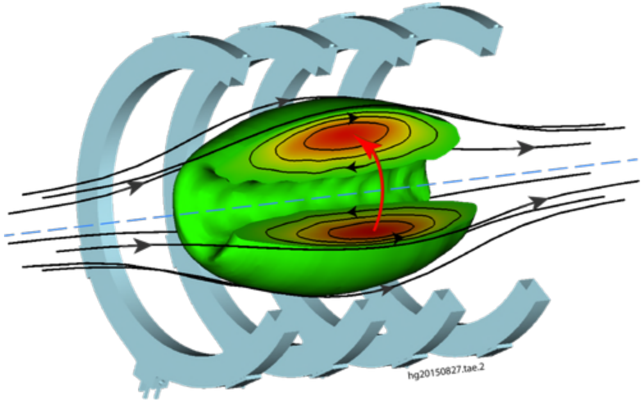
Committee on a Strategic Plan for US Burning Plasma Research, General Atomic, Feb 26-28, 2018

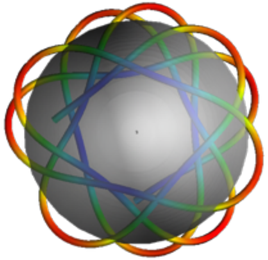
Agenda

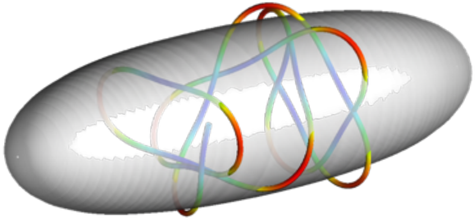
- Concept, Motivation and History
- Key Past Program Accomplishments
- Current Status and Next Steps
- Overall Perspective Forward – Public-Private Partnership

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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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, …)

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TAE's Goals to Now

Test for failure early and at lower cost while reducing most critical risks

Establish beam driven high-β FRC physics test beds to

- provide fast learning cycles and large experimental dataset (close to 60,000 shots)
- demonstrate sustainment via Neutral Beam Injection (NBI) for >5 ms discharges (longer than critical timescales) with high repeatability
- study tangential NBI and fast particle effects on stability and transport
- measure scaling and study fluctuations and transport
- assess potential for current drive, power balance and its implications

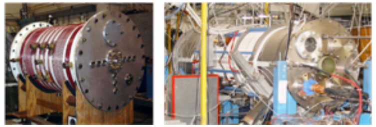
Provide opportunity to

- tightly integrate theory/modeling with experimentation
- develop engineering knowhow and integration

Invite collaboration to accelerate progress

- Budker Institute, PPPL, UCI, UCLA, LLNL, Univ. of Pisa, Univ. of Wisconsin, Nihon Univ., Univ. of Washington, Google, Industrial partners

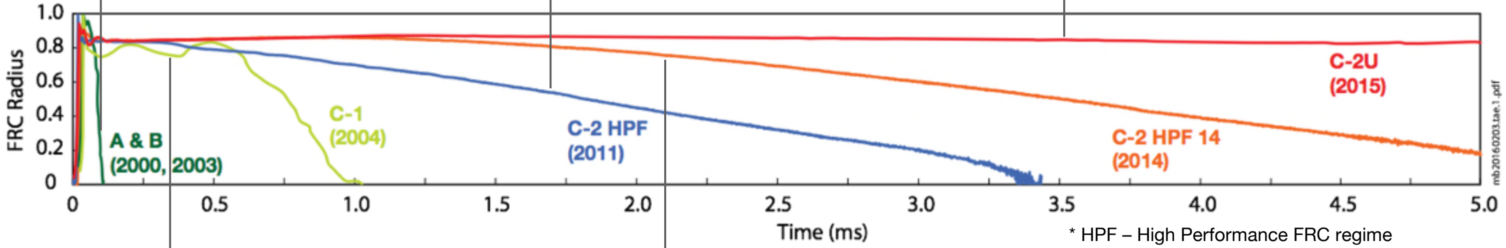
Past TAE Program Evolution



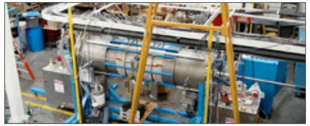
A & B – Basic FRC core
- 100-800 G, 5-10 eV
- ion beams, W_b ~0.1 kJ

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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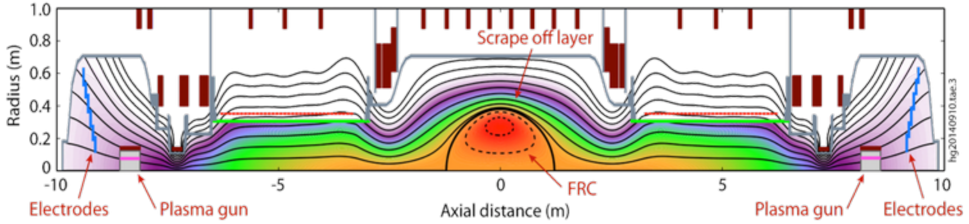
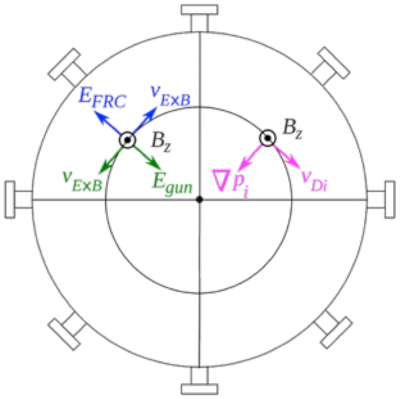
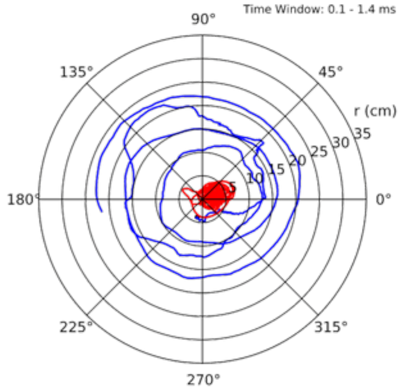
Key Past Program Accomplishments

Global Stability Control via Edge Biasing





Bias: On/Off

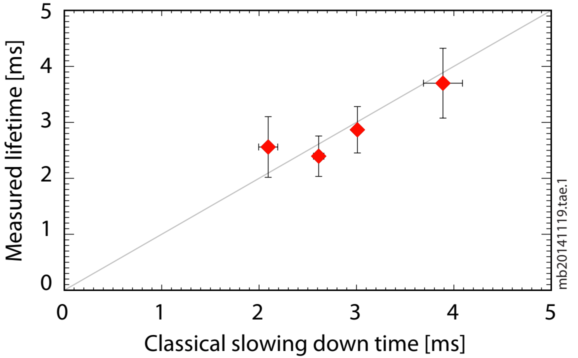


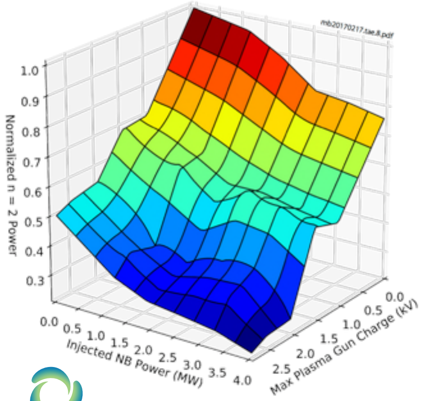
Plasma Gun: On/Off

- Active and passive bias electrodes “communicate” with FRC separatrix via scrape-off layer
- Generate inward E_r to counter FRC spin-up, and stabilize rotational modes (e.g. n=2) in axisymmetric way
- Line-tying between FRC and plasma gun stabilizes wobble (provided that sheath resistance is low)

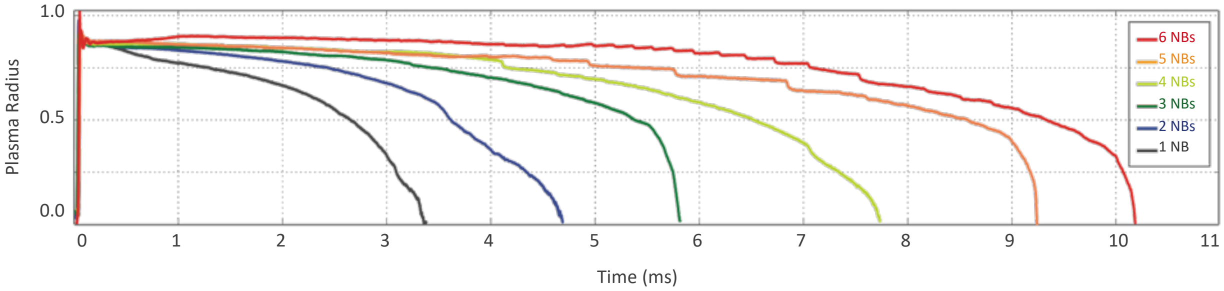
Binderbauer, et. al, Phys. Plasmas 22, 056110 (2015)

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



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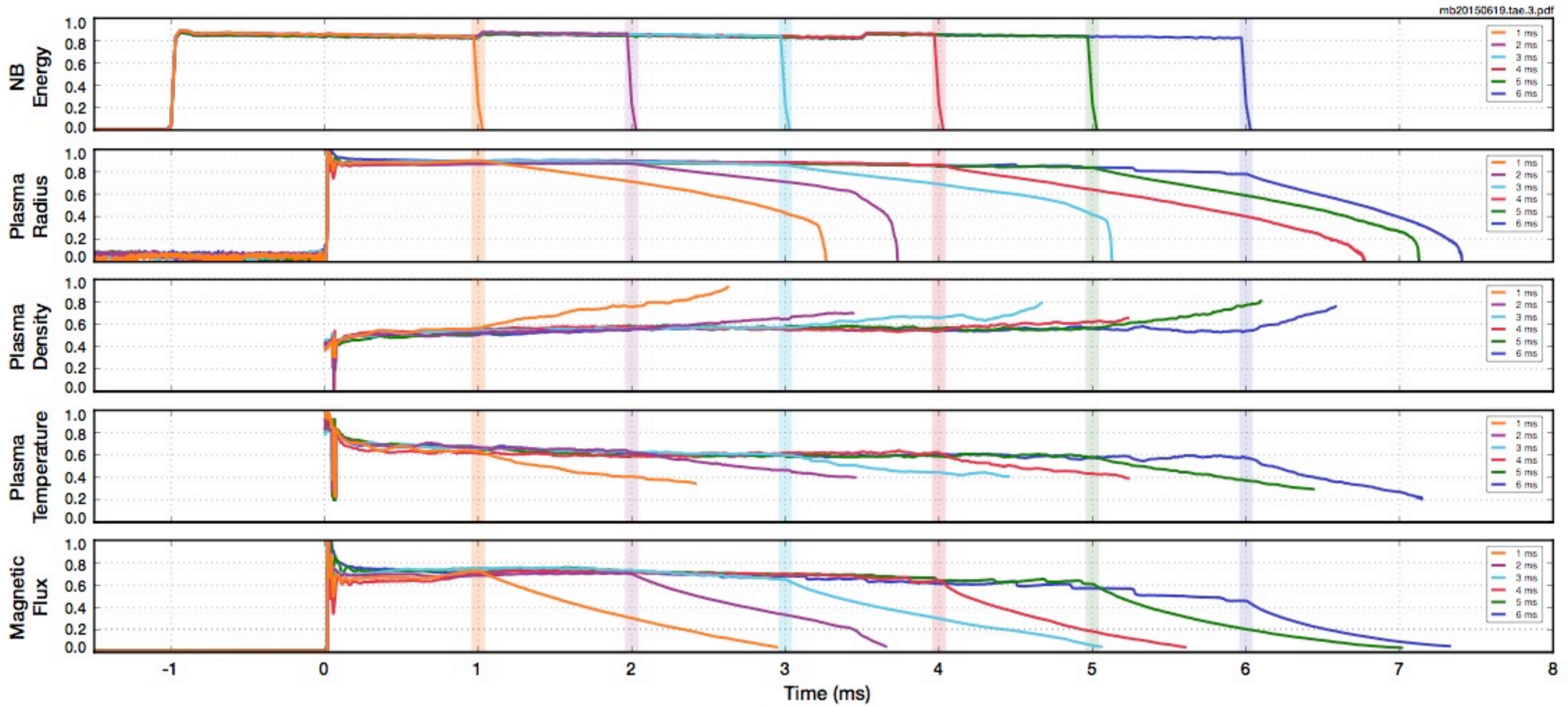
FRC Sustainment Correlates with NBI



- 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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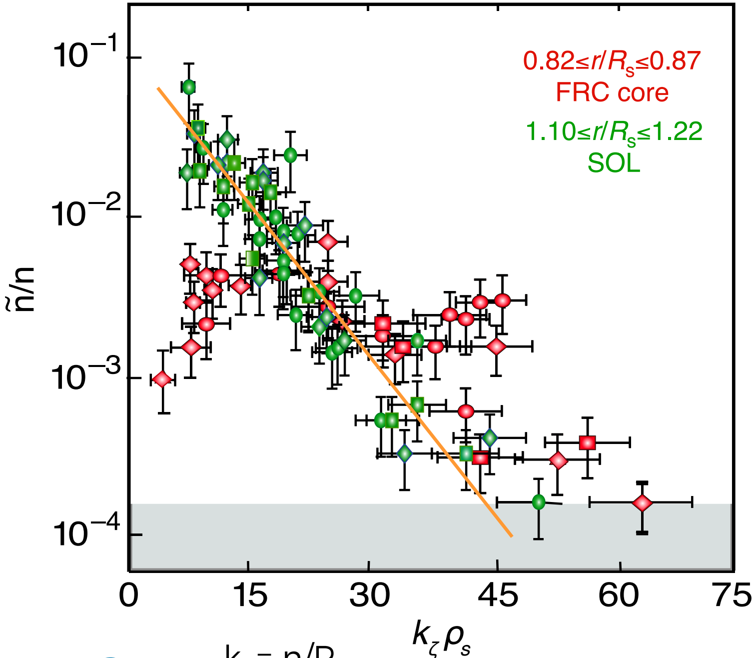
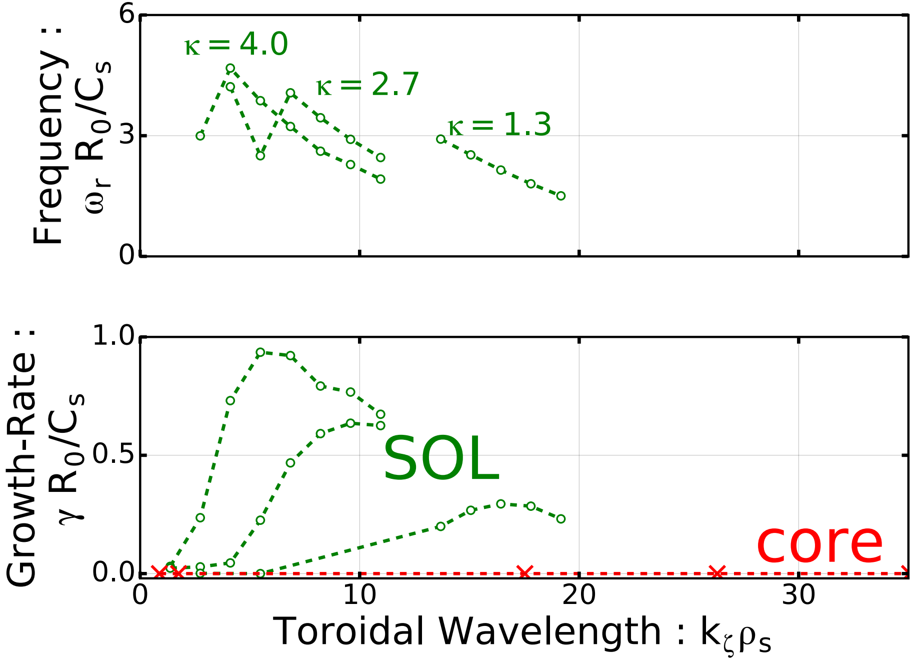
Driftwave Stable Core, Unstable Scrape-off layer

Density fluctuation
(experiment)*



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

Linear dispersion
(simulation)

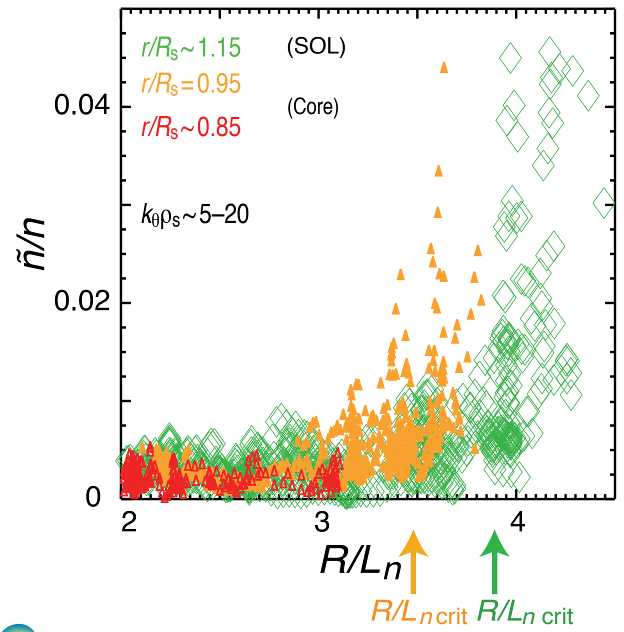


$\kappa = R_0/L_n$ (normalized inverse density scale-length)

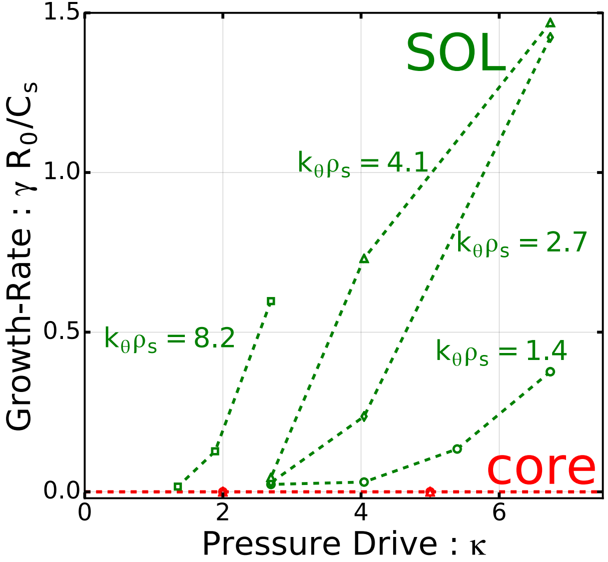
Schmitz, et. al, Nat. Comm. 7, 13860 (2016)

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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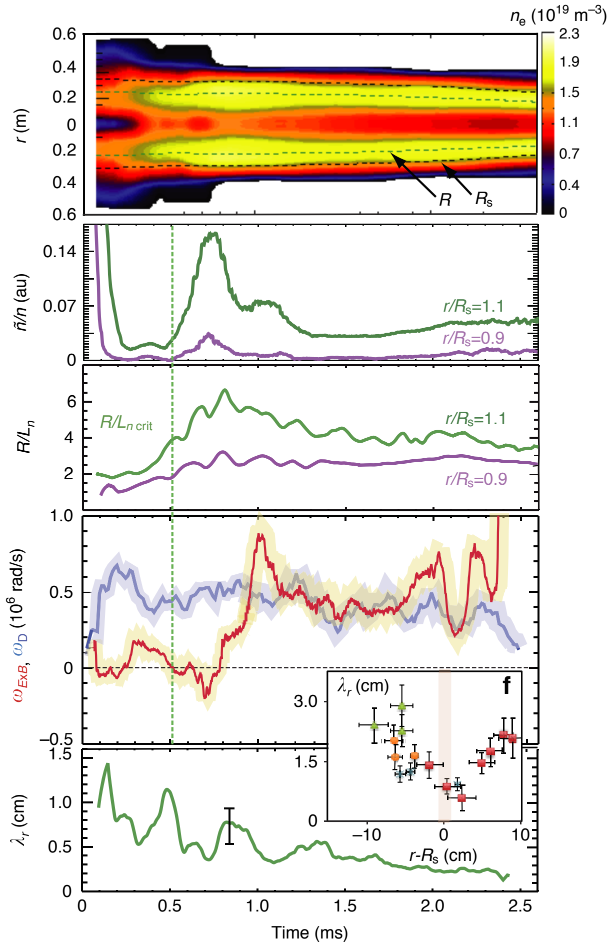
Fluctuation Suppression via **E×B** Sheared Flow

- 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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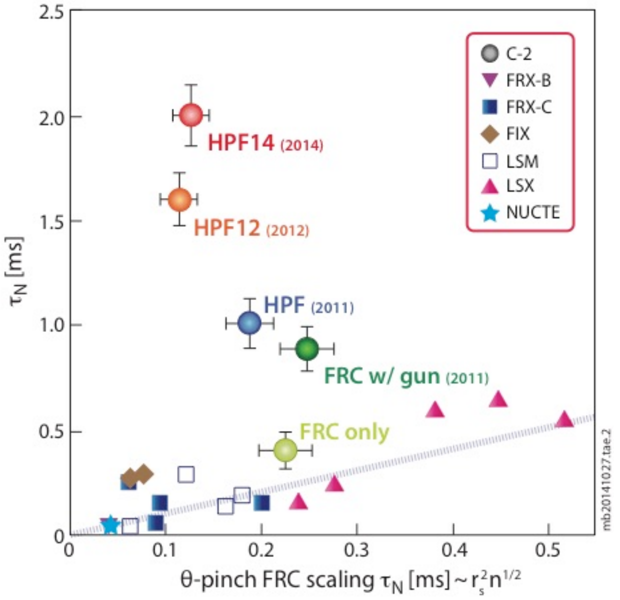
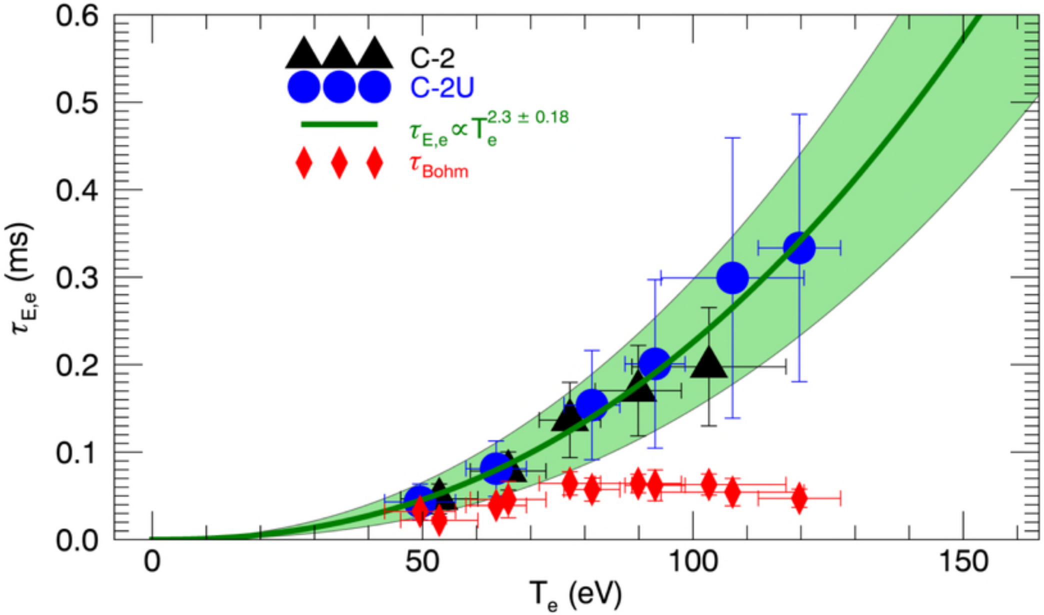
Dramatically Improved Confinement

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



- ~10× improved particle confinement



- Strong positive correlation between T_e and τ_{Ee}
- 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 TAE Program Evolution

- 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 controlls onset of density fluctuations
- Core and SOL coupling – SOL turbulence affects FRC confinement
- Evidence of localized flow shear at separatrix creating thermal barrier

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Current Status and Next Steps

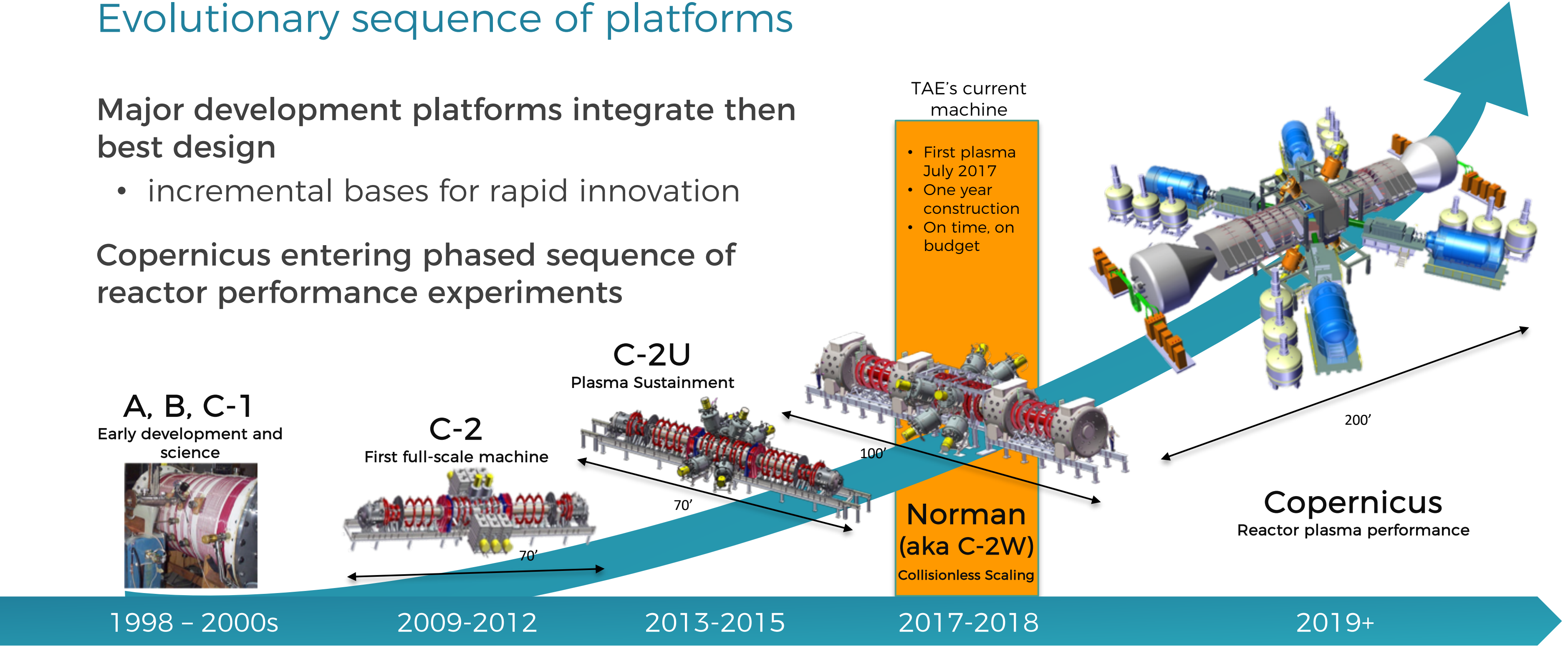
TAE progress towards fusion

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 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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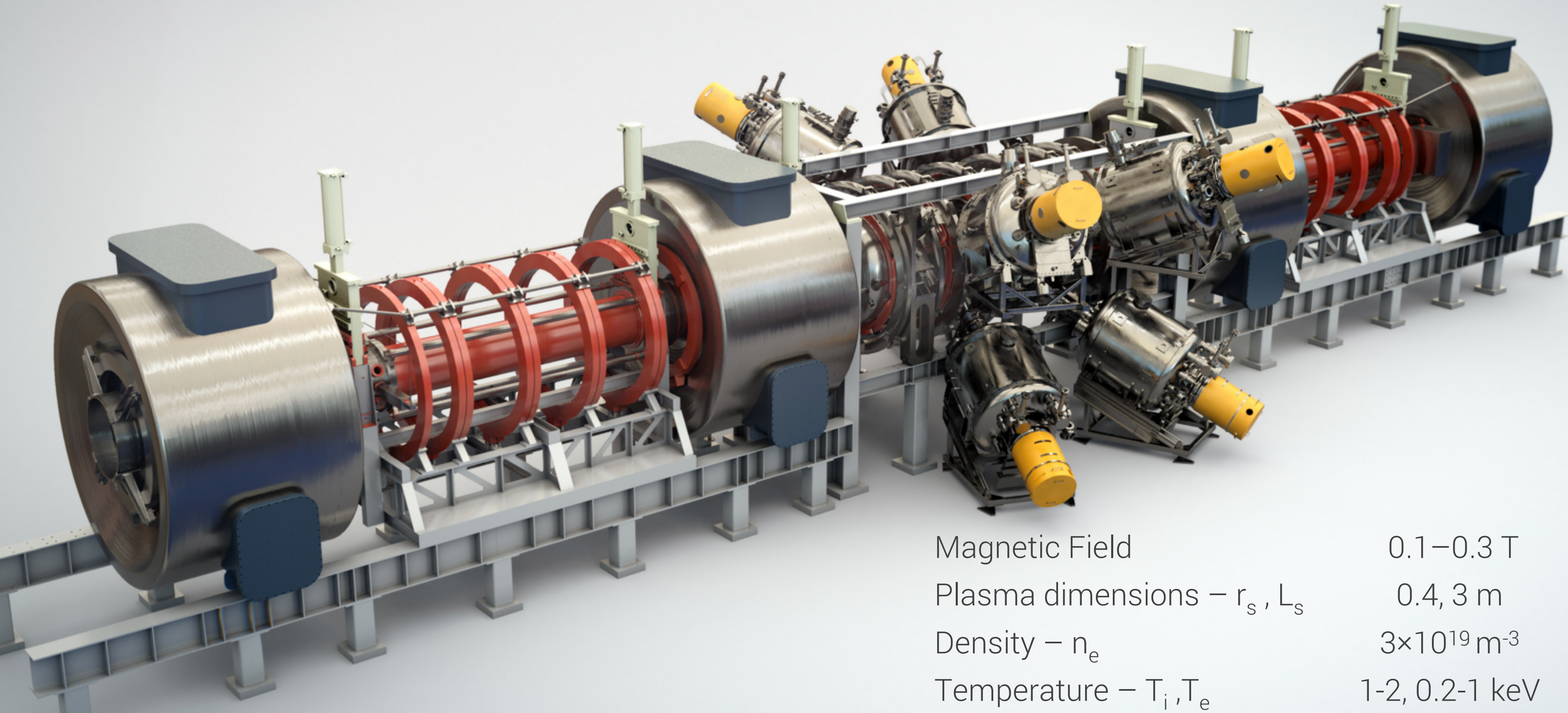
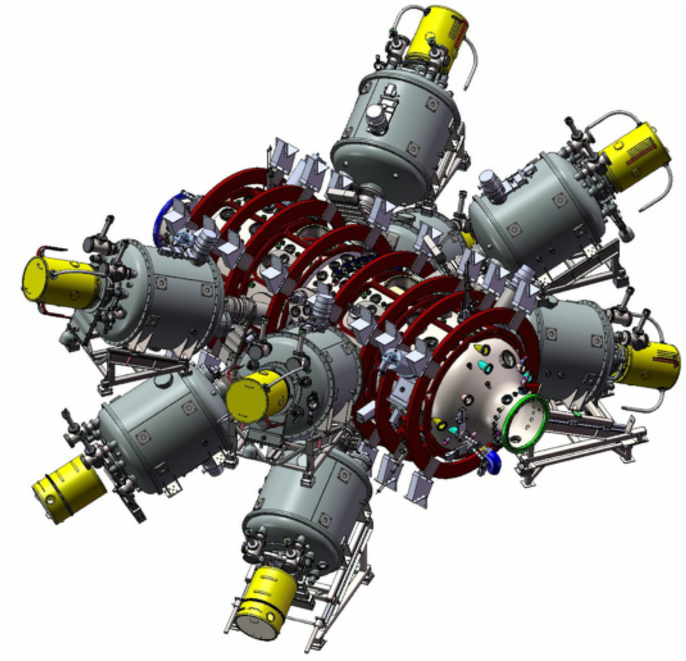
Norman (aka C-2W)

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

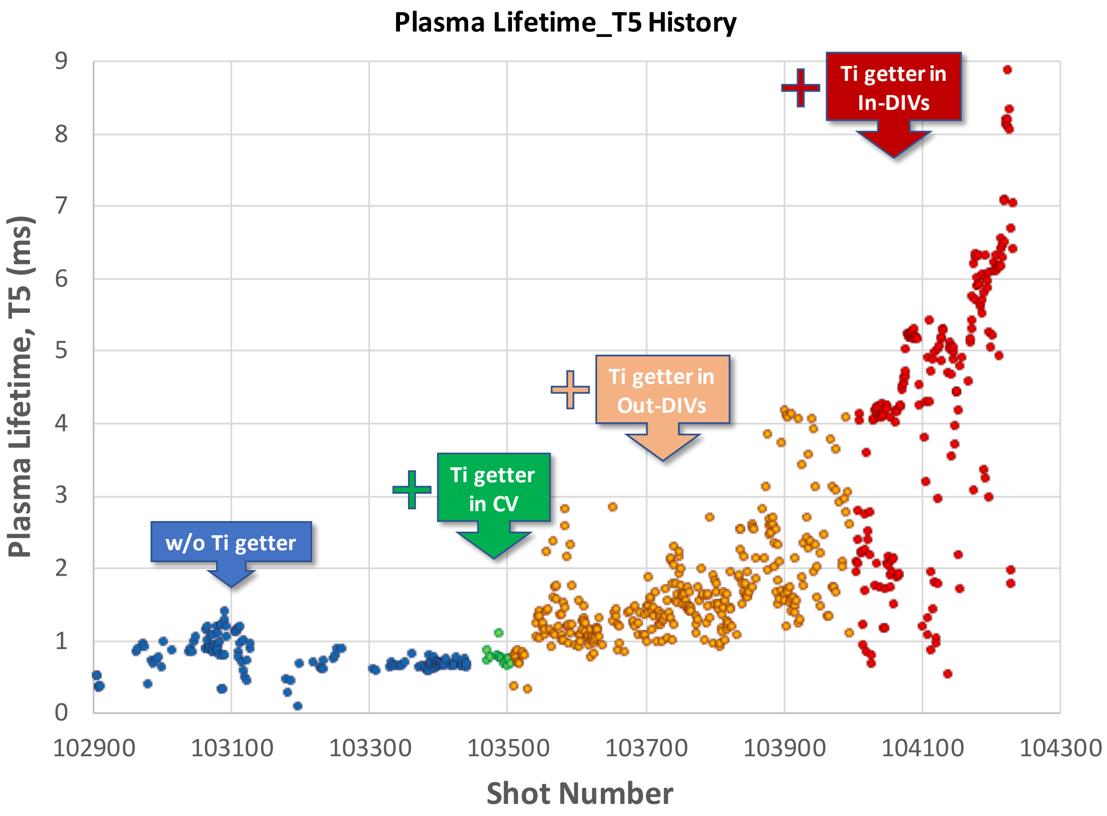


	C-2U	Norman Phase 1	Norman Phase 2
Beam Energy, keV	15	15	15/15-40
Total Power	10	13	21
# of Injectors	6	8	4/4
Pulse, ms	8	30	30
Ion current per source, A	130	130	130

- Centered/angled/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

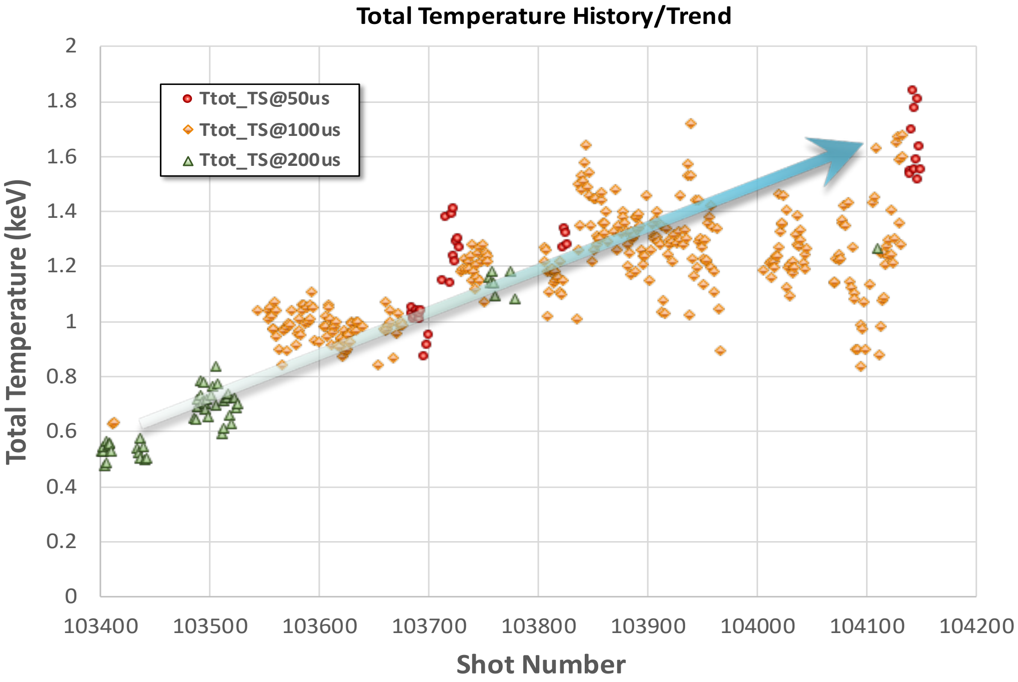
Norman Plasma Lifetime Trends

Expected increase commensurate with vacuum performance



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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Where will TAE be post Norman

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 system know-how established

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Overall Perspective Forward

Fusion Goals and Opportunity

- Start with End in Mind – applied product
- Clean and safe power generation asset
- Competitive with present energy sources
  - LCoE of $\lesssim$ 8 ¢/kWh, overnight cost of $\lesssim$ \$5,000 per kW
- Minimized regulatory burden
- Clear market opportunity now (even vis-a-vis renewables + storage)

How do we get there (1/2)

- Sense of urgency
- Broad target approach
    - Take advantage of advances in one concept to bootstrap others
- Look at (parallel) technology evolutions that tilt equation in our favor
- Re-evaluate scale needed now and at full power plant
    - Smaller devices are cheaper, faster to built, easier to rebuild, etc
- Pool with stakeholders that may only have partial overlap with fusion
    - Attract more funding by building larger community
    - Critical mass to move public policy

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How do we get there (2/2)

- Innovate fast
    - Don't be afraid of failure – learn by breaking things
    - Iterating is essential to fast progress
    - Generate volume of data necessary to apply AI and machine learning
- Public-private partnership
    - Involve industrial and private sector early
    - Helps to recalibrate goals
    - Introduces private sector thinking and customer needs

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

What TAE needs help with (1/2)

Overall

- Collaborate with community to minimize re-learning

Particular areas of support

- First wall Materials and design
- Divertor design and engineering
- RF heating - overdense plasma (high-beta)
- Computational support – codes and computing time

What TAE needs help with (2/2)

Particular areas of support (cont.)

- Diagnostics and sensor development for burning plasma regime
- Magnet system design and possible HTS use
- Overall system engineering support
- Remote handling
- Siting and site development
- Tax breaks and incentives
- Regulatory and licensing support

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Thank You