Aneutronic Fusion as a Driver for Technology Innovation

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TAE Technologies, Inc.

OLTP Seminar | July 27, 2021

tae TECHNOLOGIES

Who we are

- Founded in 1998
- Span out of UC Irvine
- Funded by visionary investors
- 200+ scientists and engineers
- National lab-scale fusion device
- Technology spin-offs
- tae.com/research-library/

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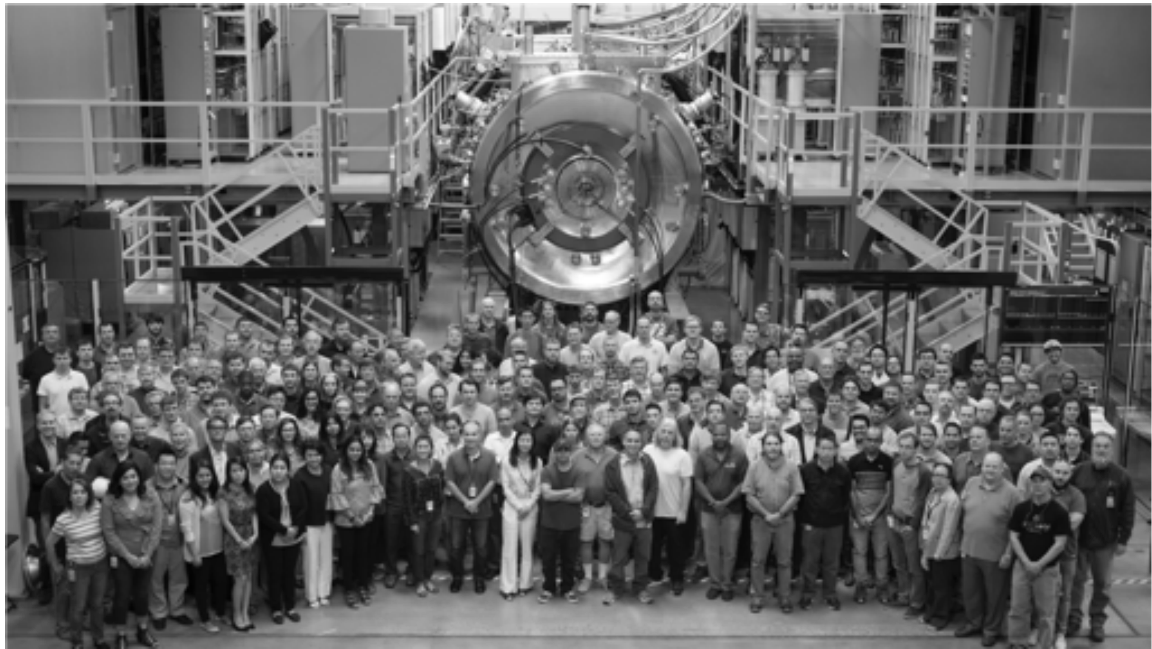


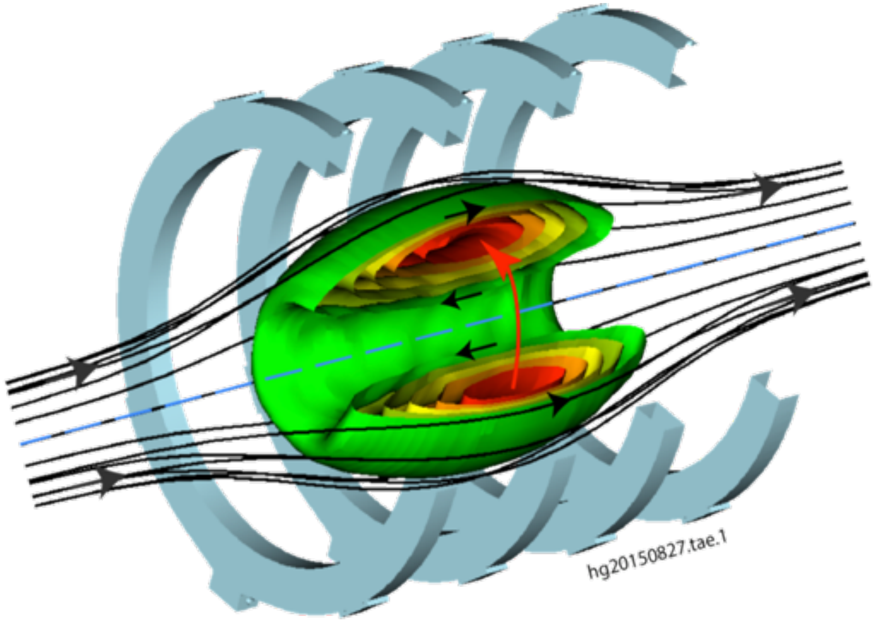
As with the Space Race, Fusion is the genesis of numerous pillars of technological innovation

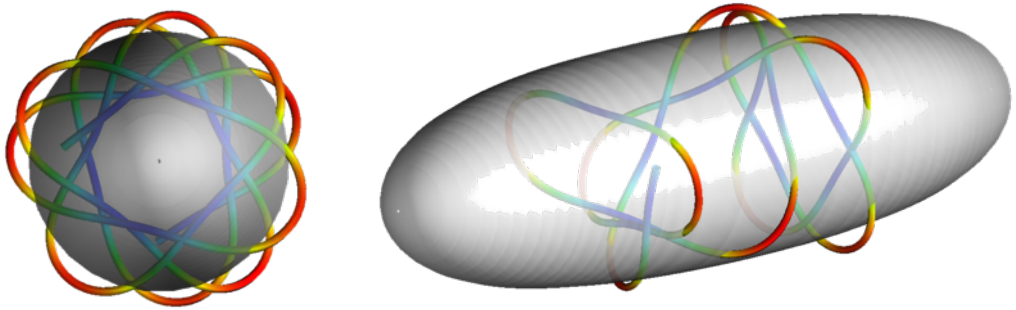
POWER MANAGEMENT	FUSION	CANCER TREATMENT
Power Management for **TRANSPORTATION AND ENERGY STORAGE**	tae Power Technology for **CLEAN FUSION**	tae LIFE SCIENCES **CELLULAR RADIATION THERAPY**
Energy Storage · Residential · Electric Vehicles		Particle Accelerators · Vector Drugs

Agenda

- TAE Fusion Concept, Motivation and History
- Key Program Accomplishments
- Technology spin-offs

TAE's concept –beam-driven Field Reversed Configuration

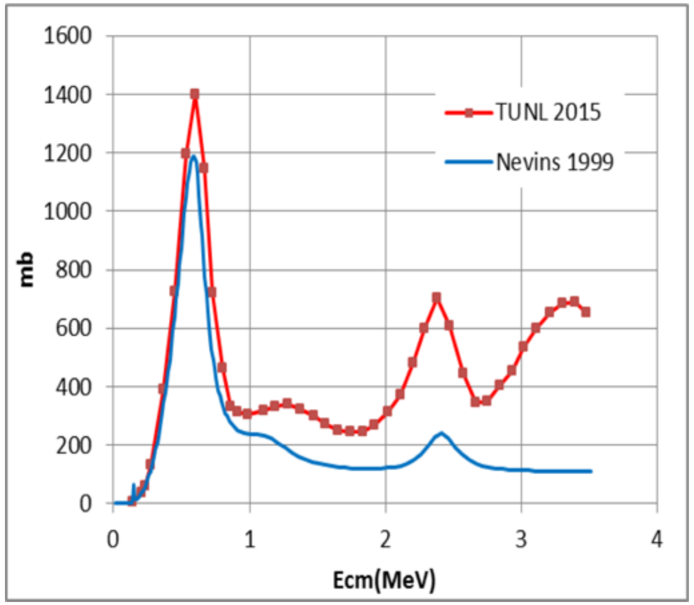


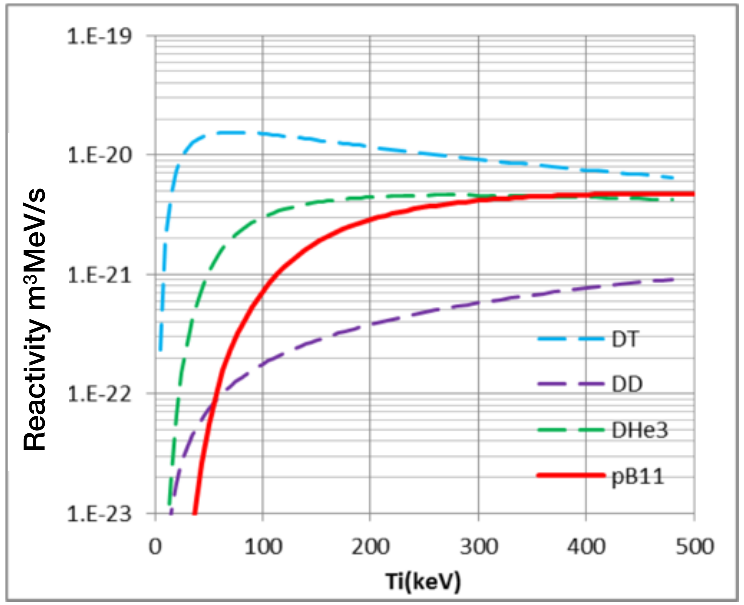


Large orbit ions via Neutral Beam injection

- High plasma β ~ 1 (plasma pressure / B^2)
  - Compact and high power density
  - Aneutronic fuel capability
  - Indigenous large orbit particles
- Tangential Neutral Beam Injection
  - Large orbit ion population
  - Increased stability and reduced transport
- Significant engineering advantages that translate to viable reactor economics

TAE's ultimate goal – p-^{11}B fusion





- p + ^{11}B → ^{4}He + ^{4}He + ^{4}He
- Cross section larger than previously believed

- Advantages
  - (Almost) no neutrons
  - Benign, readily available fuel
  - Little radioactive waste
  - Viable economics

Key accomplishments

- Established beam-driven high-β FRC physics test bed with unmatched operating flexibility
- Demonstrated high-temperature FRC sustainment via Neutral Beam Injection and edge biasing up to 30 ms (limited by the energy storage on-site)
  - Edge biasing provides plasma MHD stabilization and sheared-flow suppression of turbulence
  - Favorable transport scaling observed
- Developed engineering knowhow to facilitate reactor design
- Established collaboration with academia and industry to accelerate progress
  - PPPL, UCI, UCLA, LLNL, ORNL, Univ. of Pisa, Univ. of Wisconsin, Nihon Univ., Univ. of Washington, Budker Institute, Google, industrial partners

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TAE experimental device evolution

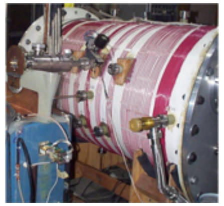
Major development platforms integrate then best design

- Incremental steps for rapid innovation

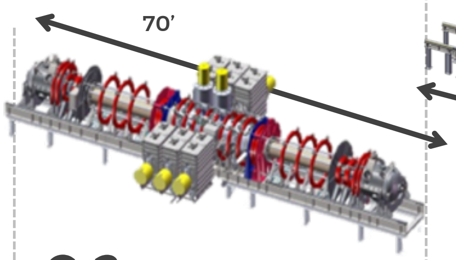
Copernicus entering phased sequence of reactor performance experiments

TAE's current machine

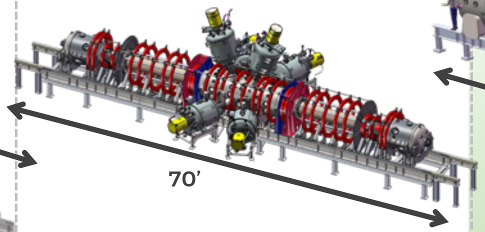
- First plasma July 2017
- One year construction
- On time, on budget
- Scaling studies ongoing



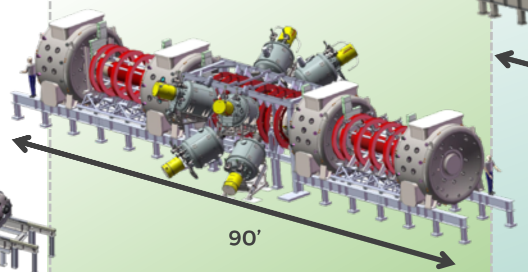
A, B, C-1
Early development
1998 – 2000s



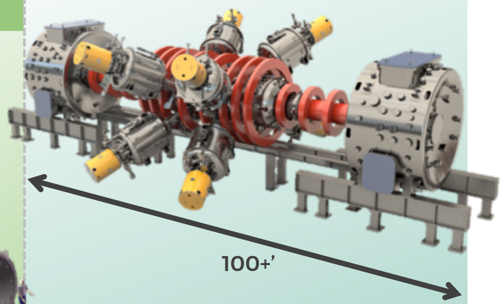
C-2
First full-scale machine
2009-2012



C-2U
Plasma Sustainment
2013-2015



Norman (C-2W)
Collisionless Confinement Scaling
2016-2021



Copernicus
Reactor Plasma Performance operating on hydrogen plasma
2022+

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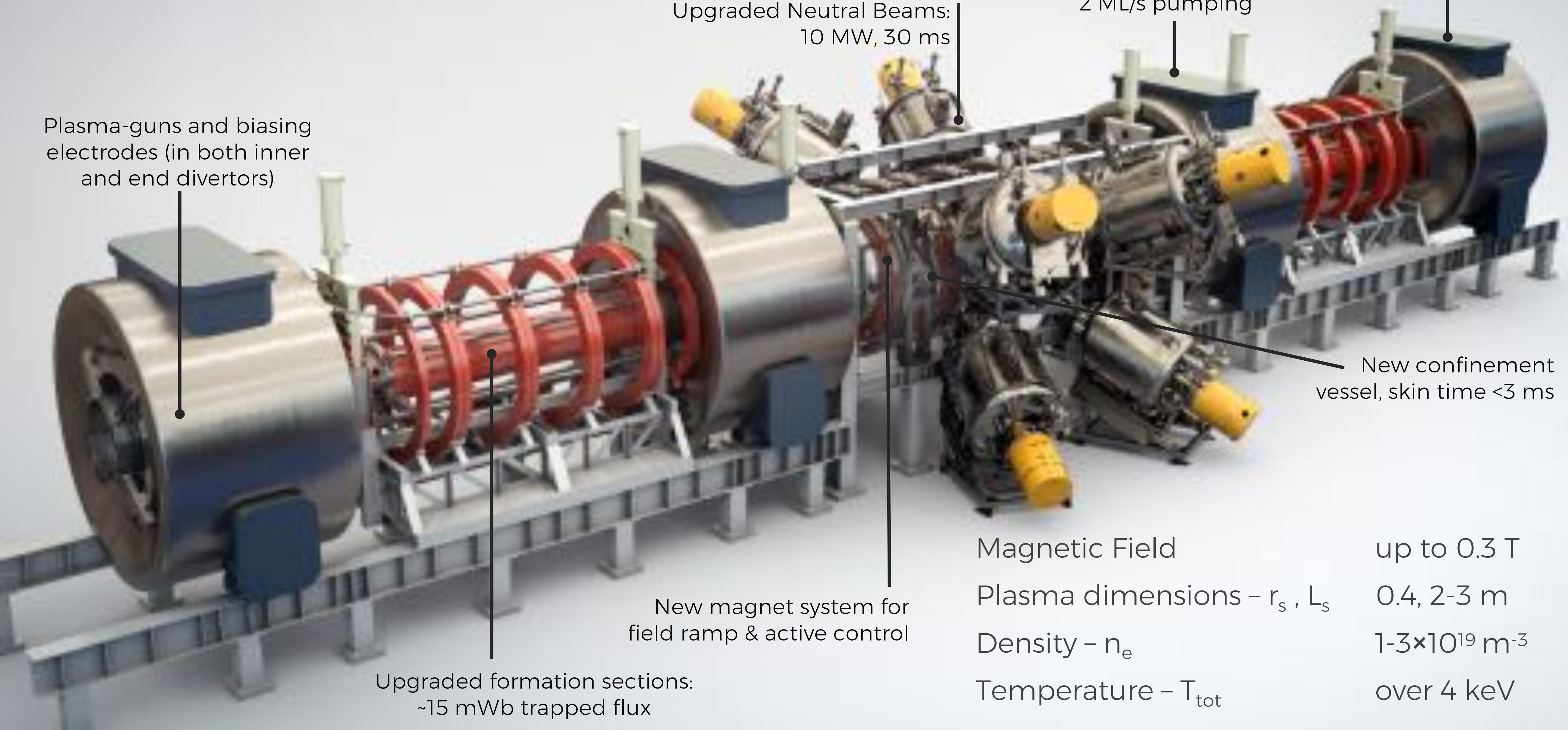
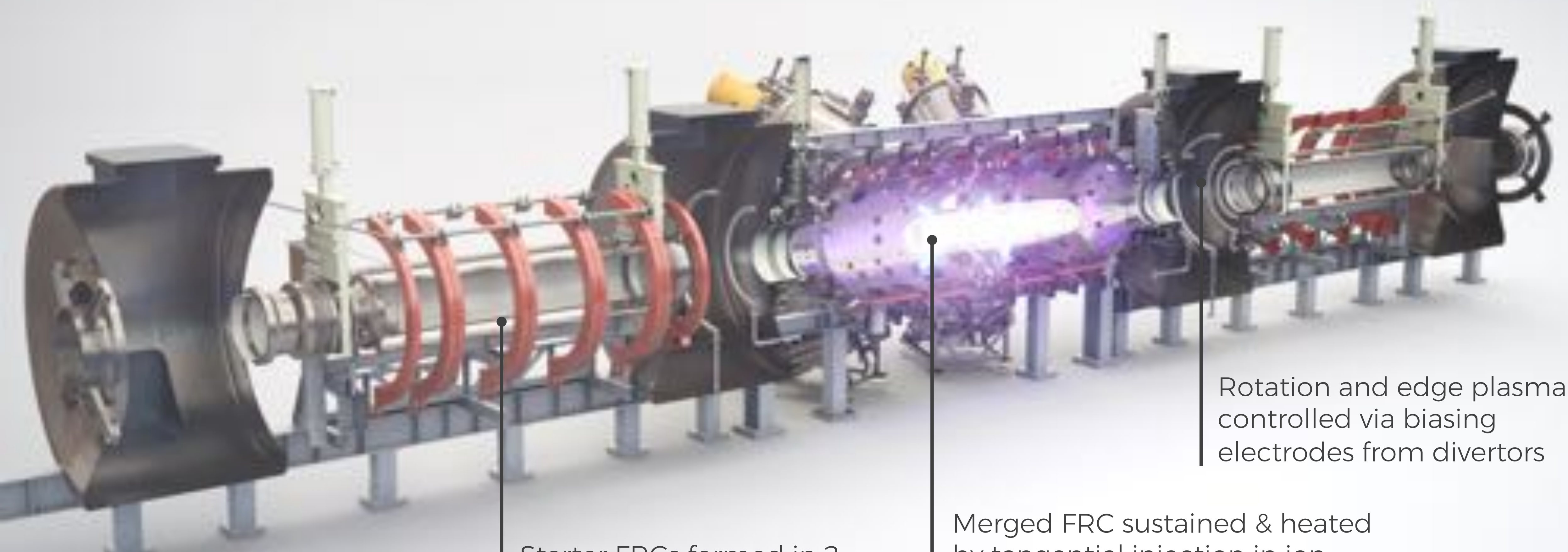
NORMAN (C-2W) — current device



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}	over 4 keV

Typical experimental setup

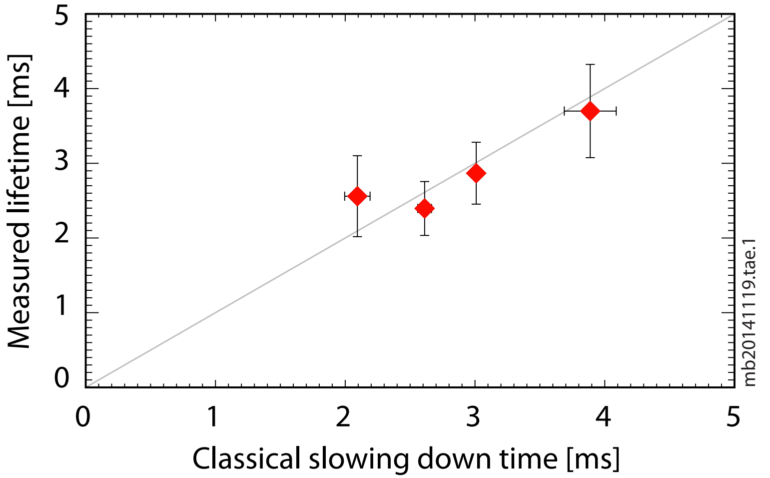


Starter FRCs formed in 2 formation sections and supersonically translated

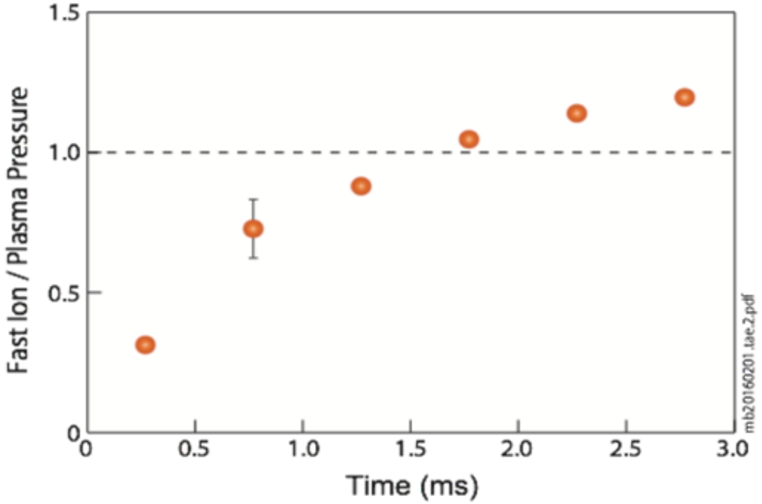
Merged FRC sustained & heated by tangential injection in ion diamagnetic direction of neutral beams into outer core

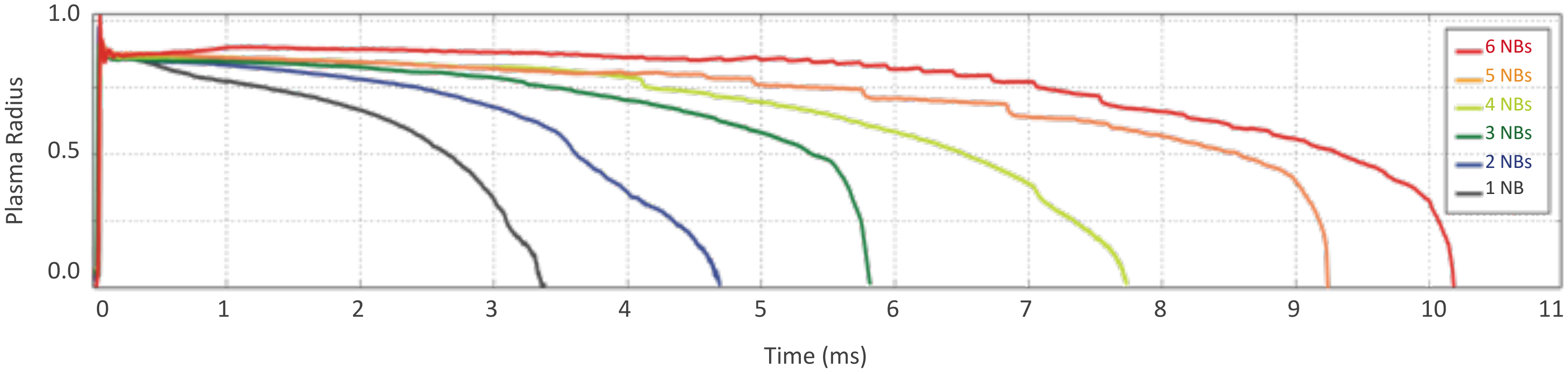
Rotation and edge plasma controlled via biasing electrodes from divertors

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 $P_{fast}/P_{th} \sim 1$
- Lifetime increases with NBI





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

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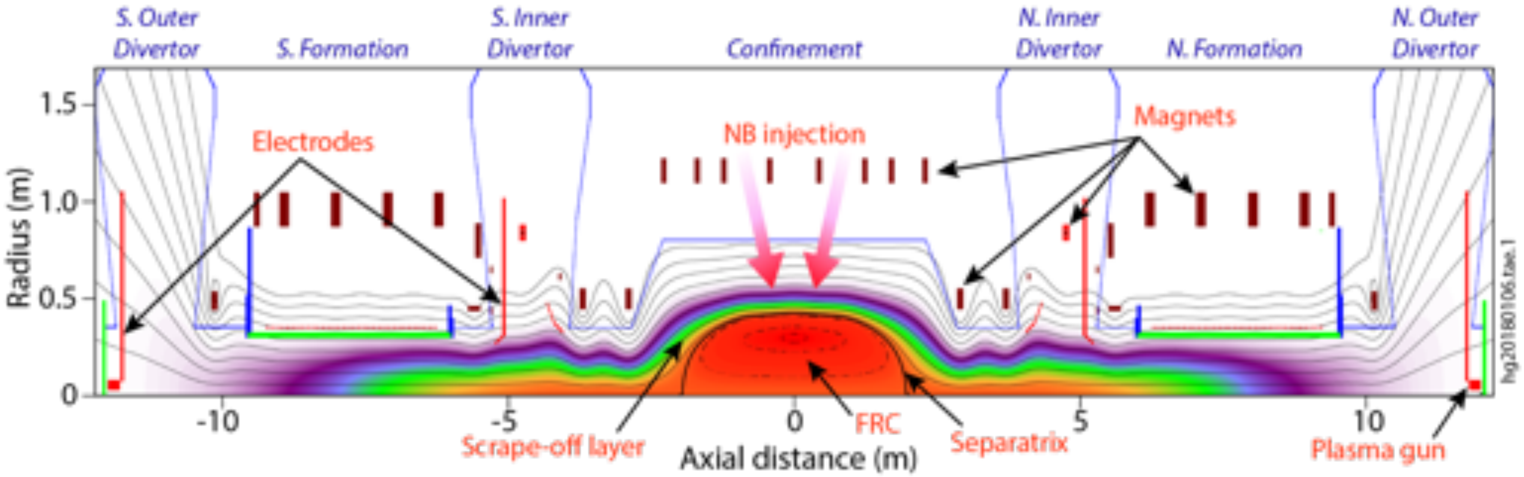
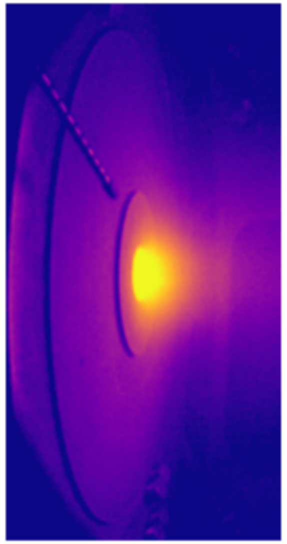
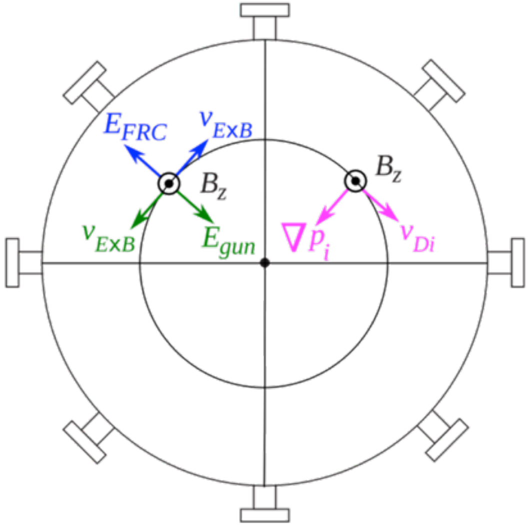
Global modes suppressed by edge biasing





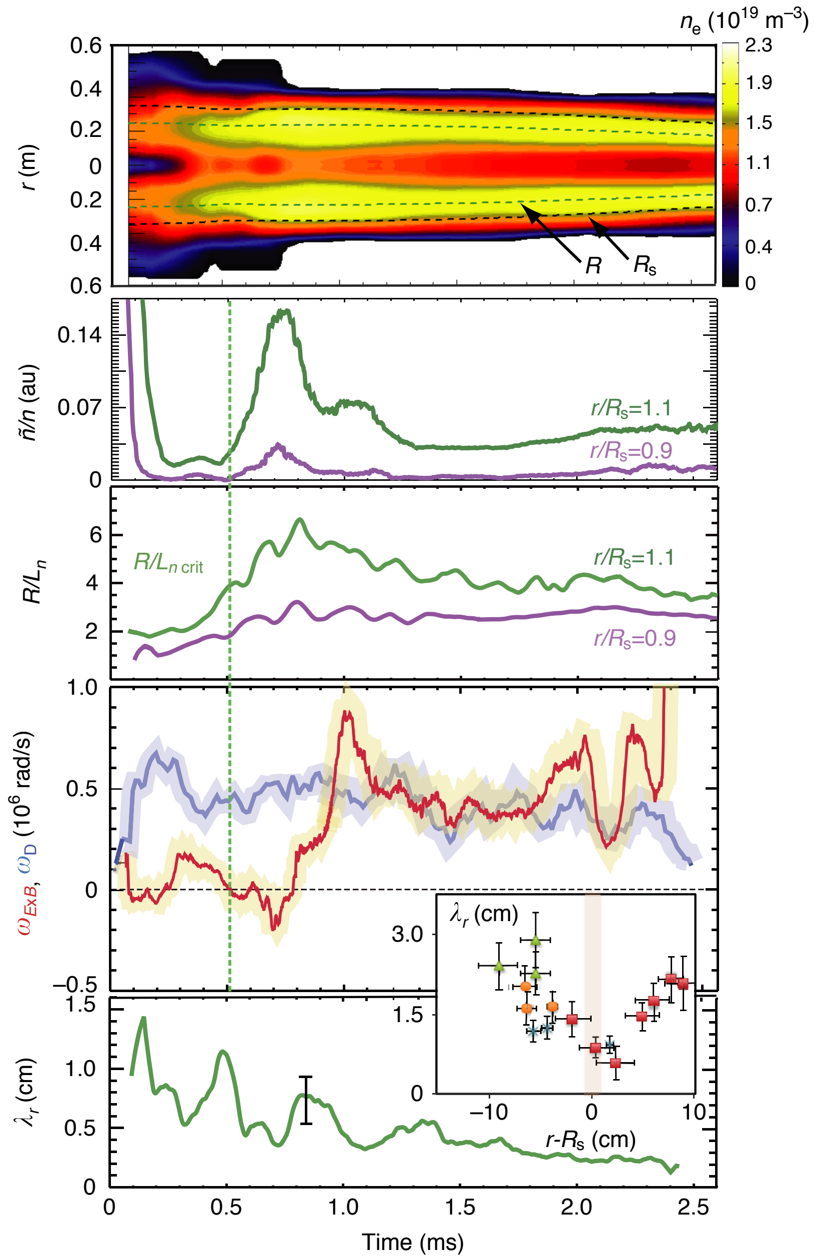


Bias: On/Off

- Axisymmetric stabilization via SOL biasing from end divertors

Fluctuation suppression via E×B sheared flow

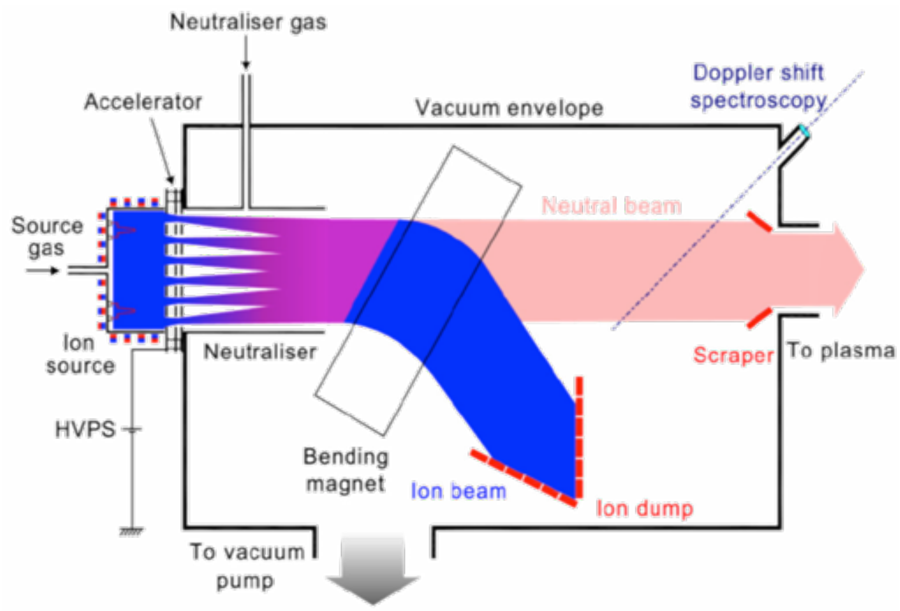
- Strong E×B shearing rate due to plasma gun biasing
- Sheared E×B flow upshifts critical gradient and reduces turbulence via eddy shearing/decorrelation
- Radial transport barrier at/outside the separatrix

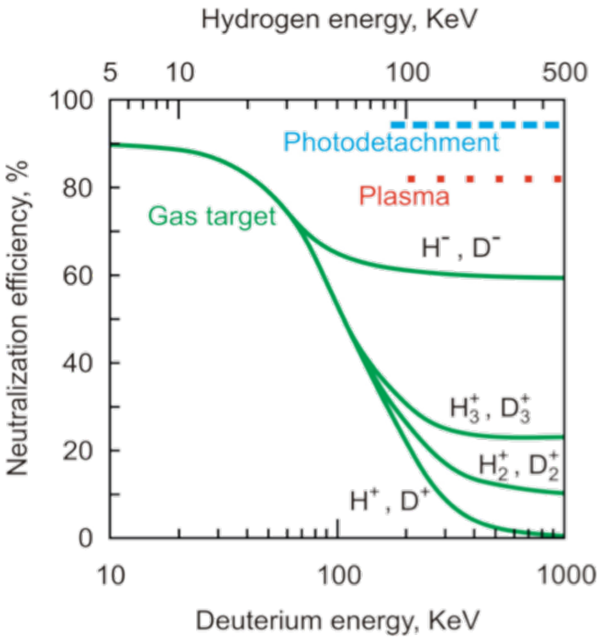


Schmitz, et. al, Nat. Comm. 7, 13860 (2016)

Accelerator Technology

Positive and negative-ion-based neutral beams for fusion





- Low-energy beams (< 150 keV) → Positive-ion-based (PNBI)
  - Mature technology, ~ 100 beams built mostly btw 1970-90’s
  - Presently, TAE and Budker Institute (Russia) are the only commercial suppliers
- High-energy beams (> 150 keV) → Negative-ion-based (NNBI)
  - Active R&D area; conventional design faces severe challenges
  - TAE and Budker developed and tested breakthrough solutions

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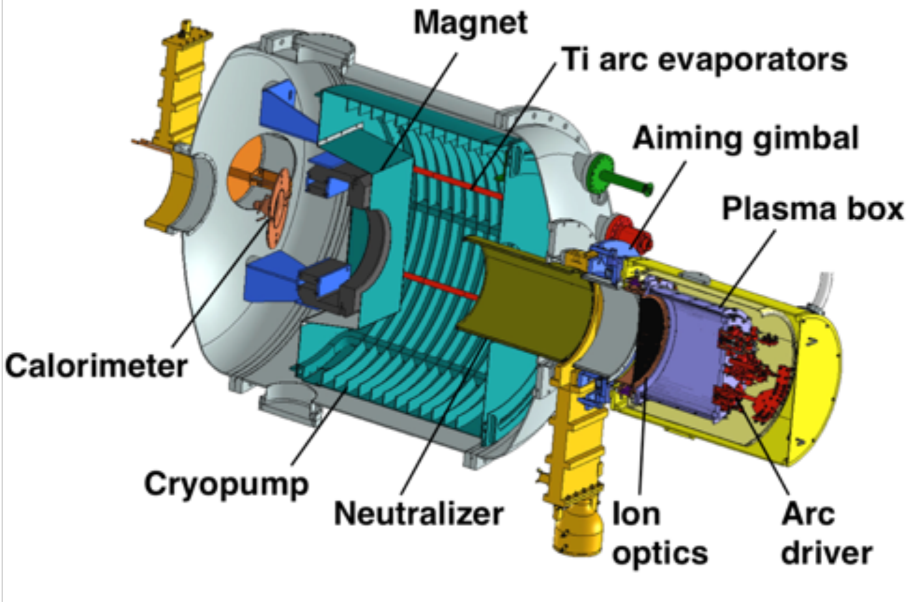
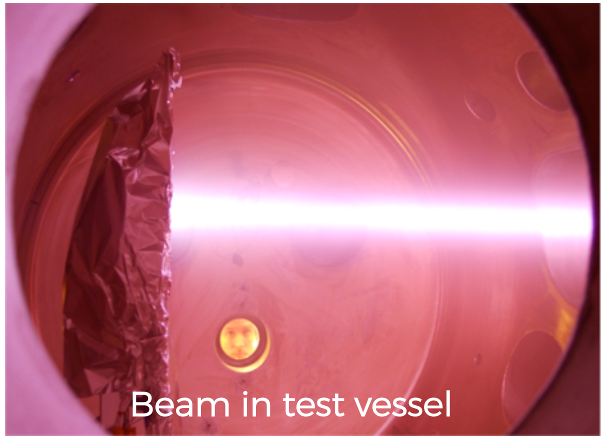
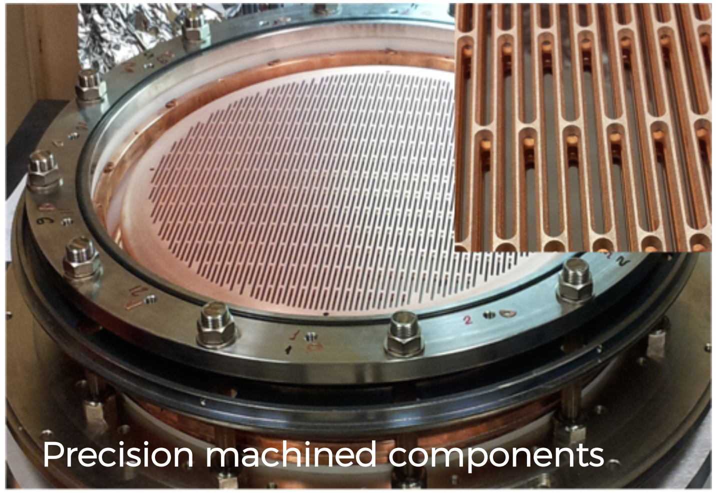
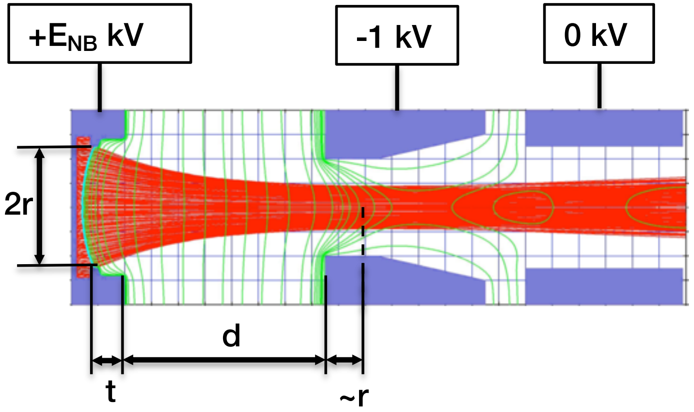
TAE PNBI system is highly modular and flexible




Beam in test vessel

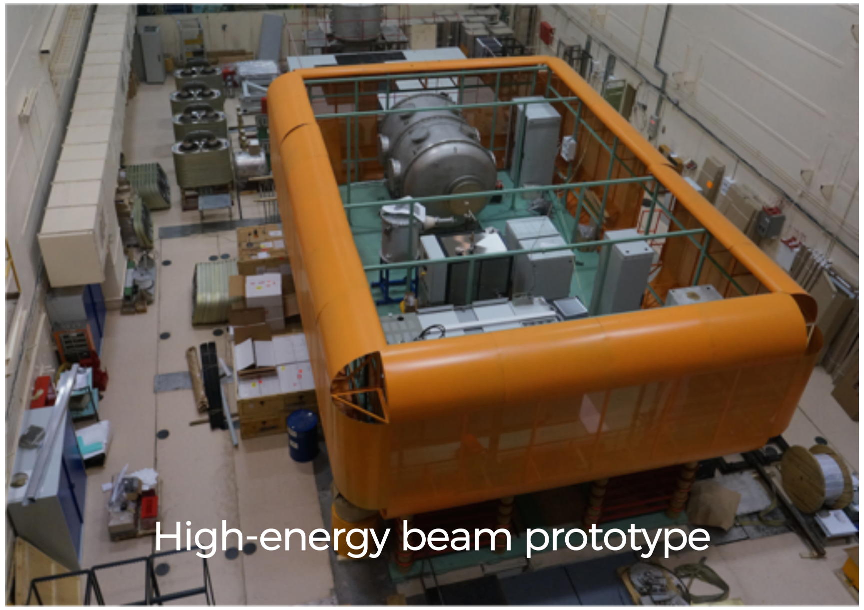
Parameter	Short pulse	Long pulse
Plasma Source	Arc	RF
Pulse duration, s	0.03	1
Beam energy, keV	15 - 40	40
Ion current, A	150	45
NB power, MW	1.6 - 3	1
Proton fraction	0.85	0.65
Beam half-size, cm	4 x 16	8 x 8
Ion current density, mA/cm^2	300	260


Precision machined components



$$I_{NB} \sim \frac{j_0 E_{NB}^{3/2} A}{(d+t+r)^2} K(r)\eta_n(E_{NB})$$

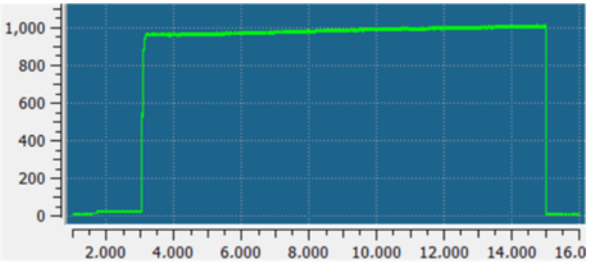
Reactor NNBI system tests and validation underway



High-energy beam prototype

H- beam test bed

Recuperator tube



- 1 A / 400 keV / 12 s achieved
- Plasma neutralizer ~ 80% efficiency
- Photon neutralizer ~ 95% efficiency
- Recuperator tests staring

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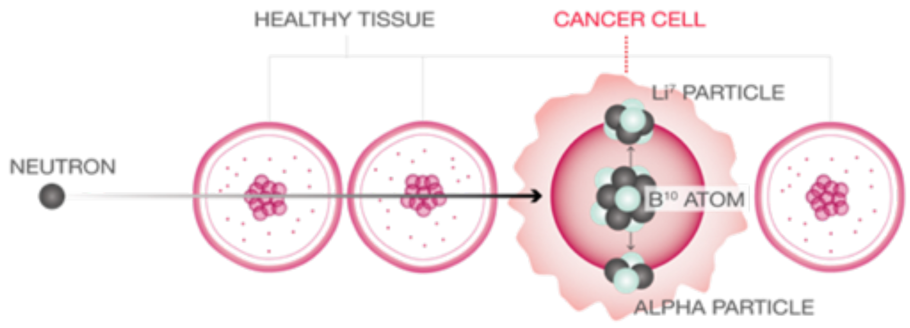
Accelerator technology for transformative cancer therapy

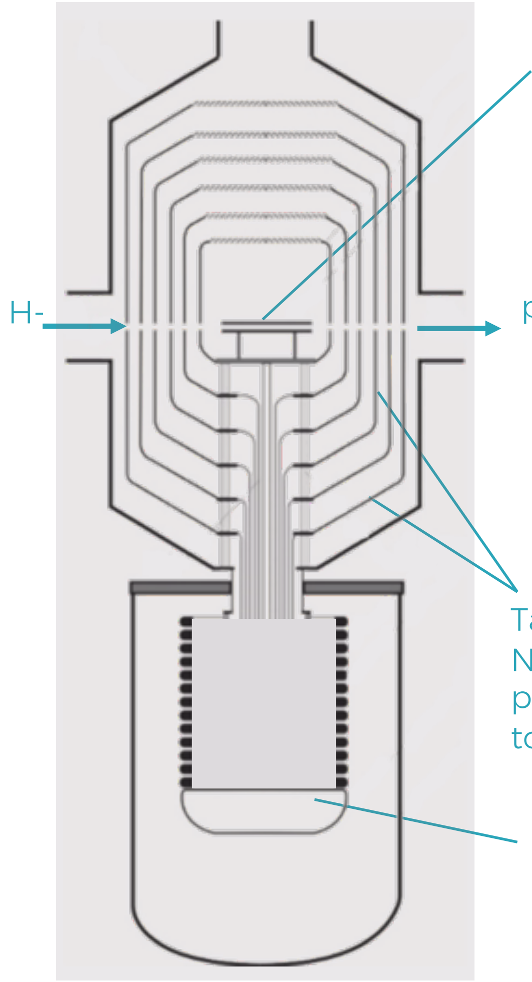
TAE Life Sciences

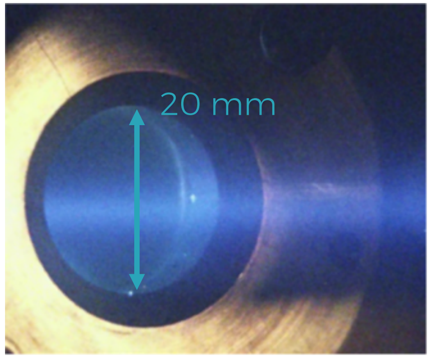
- Boron neutron capture therapy
  - TAE accelerator-based neutron source
  - Vector drug
- Can treat millions of patients with harshest cancers
- First clinical system is being commissioned
- Clinical trials to start in 2021



Electrostatic tandem accelerator is optimal for BNCT

- Tunable energy ~ 2.5 MeV at ~10 mA
- Cs-free 15 mA H- ion source
- Neutron-producing target: $^{7}Li + p \rightarrow n + {}^{7}Be$
- Neutron yield ~ 10^{13} n/s
- Offers an optimal therapeutic neutron beam
- Compact, simple, robust, and reliable
- Relatively inexpensive

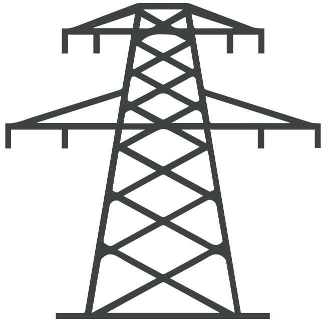




Power Management

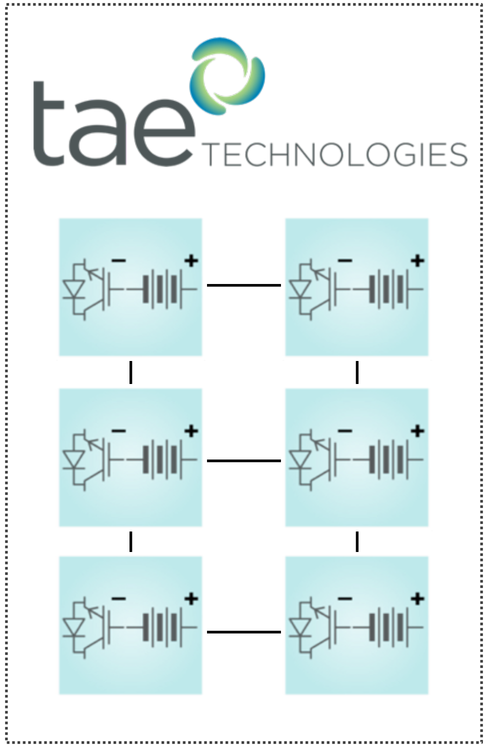
Power management technology spin-off

Derived from Norman power supply development



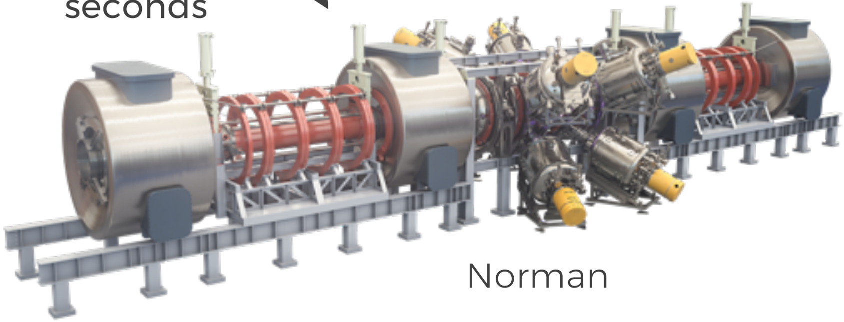
5 minute
charge

Modular distributed energy topology with advanced control algorithm



550 MW (500 kA, 1+ kV)

few milli-
seconds



Norman

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

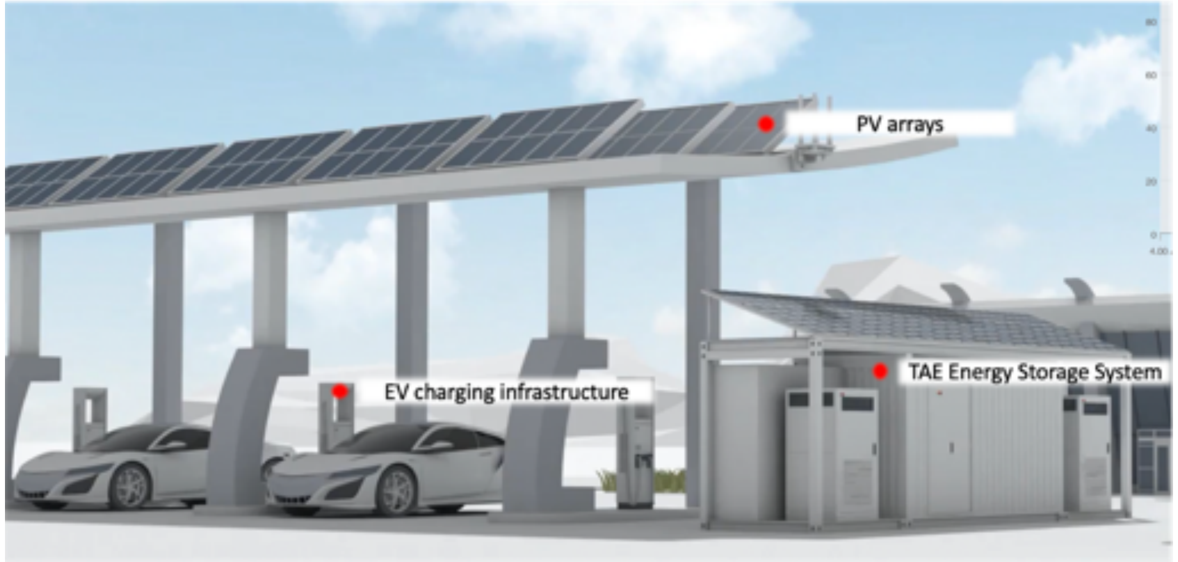
Integrated Module:

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

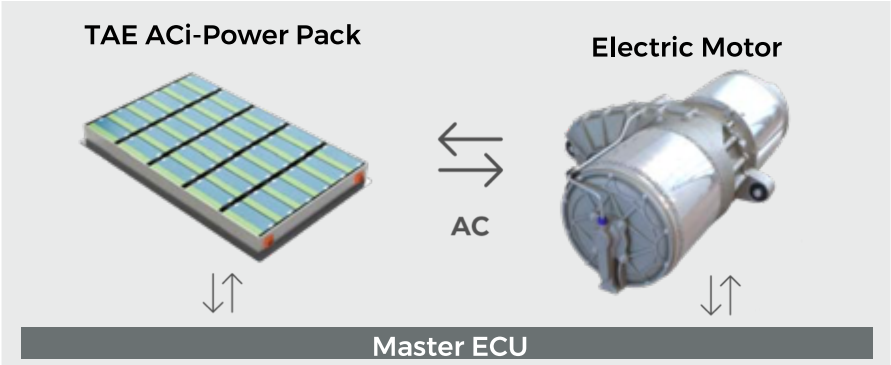
TAE power management

Efficient solutions for energy storage and electric vehicles

- Decarbonization of economy requires efficient solutions at scale for
  - Energy storage
  - Grid infrastructure
  - Electric vehicles



- TAE ACi-Power Pack consolidates the powertrain by eliminating the need for all other power electronics components used in conventional battery-electric powertrains




Thank You