Aneutronic Fusion
as a Driver for
Technology Innovation

Artem Smirnov | CTO
TAE Technologies, Inc.

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

- **Power Management for**
  - TRANSPORTATION AND ENERGY STORAGE
  - Energy Storage
  - Residential
  - Electric Vehicles

- **Fusion**
  - Power Technology for CLEAN FUSION

- **Cancer Treatment**
  - CELLULAR RADIATION THERAPY
  - 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

- High plasma $\beta \sim 1$ (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

- \(p + ^{11}\text{B} \rightarrow ^4\text{He} + ^4\text{He} + ^4\text{He}\)

- 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-\(\beta\) 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
TAE experimental device evolution

Major development platforms integrate then best design
- Incremental steps for rapid innovation

Copernicus entering phased sequence of reactor performance experiments

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

C-2
- First full-scale machine
- 2009-2012

C-2U
- Plasma Sustainment
- 2013-2015

TAE's current machine
- First plasma July 2017
- One year construction
- On time, on budget
- Scaling studies ongoing

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

Copernicus
- Reactor Plasma Performance operating on hydrogen plasma
- 2022+
NORMAN (C-2W) – current device

Plasma-guns and biasing electrodes (in both inner and end divertors)

Upgraded formation sections: ~15 mWb trapped flux

Upgraded Neutral Beams: 10 MW, 30 ms

Inner divertors: 2 ML/s pumping

New magnet system for field ramp & active control

Magnetic Field
Plasma dimensions – $r_s, L_s$
Density – $n_e$
Temperature – $T_{tot}$

New confinement vessel, skin time <3 ms

End divertor

- Magnetic Field: up to 0.3 T
- Plasma dimensions: 0.4, 2-3 m
- Density: $1-3 \times 10^{19} \text{ m}^{-3}$
- Temperature: 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 $\chi_i \sim (1-2) \chi_{icl}$
- 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

Global modes suppressed by edge biasing

- Axisymmetric stabilization via SOL biasing from end divertors

Fluctuation suppression via $E \times B$ sheared flow

- Strong $E \times B$ shearing rate due to plasma gun biasing

- Sheared $E \times B$ flow upshifts critical gradient and reduces turbulence via eddy shearing/decorrelation

- Radial transport barrier at/outside the separatrix

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
TAE PNBI system is highly modular and flexible

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Short pulse</th>
<th>Long pulse</th>
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<tbody>
<tr>
<td>Plasma Source</td>
<td>Arc</td>
<td>RF</td>
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<td>Pulse duration, s</td>
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<td>Beam energy, keV</td>
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<td>Ion current, A</td>
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<td>45</td>
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<td>NB power, MW</td>
<td>1.6 - 3</td>
<td>1</td>
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<td>Proton fraction</td>
<td>0.85</td>
<td>0.65</td>
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<td>Beam half-size, cm</td>
<td>4 x 16</td>
<td>8 x 8</td>
</tr>
<tr>
<td>Ion current density, mA/cm²</td>
<td>300</td>
<td>260</td>
</tr>
</tbody>
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**Mathematical Equation:**

\[
I_{NB} \sim \frac{j_0 E_{NB}^{3/2} A}{(d + t + r)^2} K(r) \eta_n(E_{NB})
\]
Reactor NNBI system tests and validation underway

- 1 A / 400 keV / 12 s achieved
- Plasma neutralizer ~ 80% efficiency
- Photon neutralizer ~ 95% efficiency
- Recuperator tests staring
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: $^7\text{Li} + p \to n + ^7\text{Be}$
- 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

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

Modular distributed energy topology with advanced control algorithm

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

5 minute charge

few milliseconds

550 MW (500 kA, 1+ kV)
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