On TAE’s Path to Fusion
A Private-Sector Perspective

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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 $\beta \sim 1$
  - 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
Goals, Issues and Initiatives for FRC Research

Long-range mission
• Develop compact (high-\(\beta\)) 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-\(\beta\), 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 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, $W_b \sim 0.1$ kJ

**C-1 – Enhanced lifetime**
- 400 G, 10 eV
- ion beams, $W_b \sim 1$ kJ

**C-2 – HPF* w/ 2 guns, Ti getter**
- 1 kG, 1 keV
- neutral beams, $W_b \sim 12$ kJ

**C-2U – Sustainment 5+ ms**
- 1 kG, 1 keV
- neutral beams, $W_b \sim 100$ kJ

**C-2 – HPF* w/ 2 guns, Li getter**
- 1 kG, 1 keV
- neutral beams, $W_b \sim 20$ kJ
Key Past Program Accomplishments
Global Stability Control via Edge Biasing

- 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)

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 $P_{fast}/P_{th} \sim 1$
- Global modes are further suppressed
- Lifetime increases with NBI

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)
Driftwave Stable Core, Unstable Scrape-off layer

Density fluctuation (experiment)*

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

$\rho_s = \sqrt{(T_i + T_e) / m_i}$

$0.82 \leq r / R_s \leq 0.87$
FRC core

$1.10 \leq r / R_s \leq 1.22$
SOL

Schmitz, et. al, Nat. Comm. 7, 13860 (2016)
Critical SOL Gradient Controls Onset of Fluctuations

Density fluctuation (experiment)*

Linear dispersion (simulation)

\[ \kappa = \frac{R_0}{L_n} \] (normalized inverse density scale-length)

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)
Dramatically Improved Confinement

- \( \sim 10 \times \) improved particle confinement

- Strong positive correlation between \( T_e \) and \( \tau_{Ee} \)

- Good fit: \( \tau_{Ee} \propto T_e^{2.3} \)
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 ($\chi_e < 20 \chi_{cl}$)
  - $\tau_{ee}$ 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 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


A, B, C-1
Early development and science

C-2
First full-scale machine

C-2U
Plasma Sustainment

Norman (aka C-2W)
Collisionless Scaling

Copernicus
Reactor plasma performance

TAE’s current machine
  • First plasma
    July 2017
  • One year construction
  • On time, on budget

• incremental bases for rapid innovation
**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
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: \( n_e \) = \( 3 \times 10^{19} \) m\(^{-3}\)
- Temperature: \( T_i, T_e \) = 1-2, 0.2-1 keV
### Norman – Neutral Beam System

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

- **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

Plasma Lifetime_T5 History

Shot Number

Plasma Lifetime, T5 (ms)

Ti getter in In-DIVs

Ti getter in Out-DIVs

Ti getter in CV

w/o Ti getter
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
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
Key reactor readiness work post Norman (1/2)

- Multi species plasmas validation involving H-B11 mix
- Ash removal validation
- First wall design and material development
- Further RF heating development
- Further fueling development
- Critical system component validation and engineering - magnets, beams, etc.
Key reactor readiness work post Norman (2/2)

- DC performance of all systems
- Heat removal systems
- Energy conversion system design - thermal, direct conversion
- Overall system engineering
- Regulatory/licensing work
- ...

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 $\leq 8 \, \cent/kWh$, overnight cost of $\leq 5,000$ 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
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
• Siting and site development
• Tax breaks and incentives
• Regulatory and licensing support
Thank You