Progress and Next Steps at TAE

Michl Binderbauer | CEO | TAE Technologies

39th FPA ANNUAL MEETING | DECEMBER 5, 2018
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

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

1998 – 2000s
2009-2012
2013-2015
2017-2019
2019+

Copernicus
Reactor plasma performance

150-200'
Norman Program Overview
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 — TAE’s 5th Generation

- Upgraded Neutral Beams: 21 MW, 30 ms
- New confinement vessel, skin time <3 ms
- Inner divertors: 2 ML/s pumping
- Upgraded formation sections: ~15 mWb trapped flux
- New magnet system for field ramp & active control
- Plasma-guns and biasing electrodes (in both inner and end divertors)

**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

Magnetic Field
- 0.1–0.3 T
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 Wall Conditioning/Pumping Systems**

- **CV gettering** – 14 Ti-arc rods – 1 M L/s
- **32 Ti-arcs w/ LN₂ system per divertor** – 2 M L/s
- **Base pressure** ~10⁻¹⁰ torr
- **Improved wall condition and impurity levels** – Zₑffective ~1.3
- **New glow-discharge cleaning system under development**
Transfer to Inner Divertor Control

Flared magnetic fields provide thermal insulation

(1) Biasing from Outer Divertors

(2) Biasing from Inner Divertors
Experimental Progress in 2018
Norman Lifetime and Initial Temperature Trends

- FRC performance increase with vacuum/wall conditioning
- Total temperature (ion+electron) consistently increased – early $T_{tot}$ up to 2 keV

Edge biasing/control from outer divertors – C-2U like configuration
Optimization towards Inner Divertor Control (2/2)

Effects of edge biasing, and flaring divertor fields

- #104989: Edge biasing from outer divertors (C-2U like) – Phase 1
- #107226: Flaring field w/o biasing
- #107322: Flaring field w/ biasing

- Electron Temperature: $T_e$ increased (up to 180 eV)
Comparison between Operating Conditions

Outer divertor biasing (C-2U like)  Inner divertor w/ flaring, no biasing  Inner divertor w/ flaring & biasing

- Improved performance from optimization

Time averaged: 0.3 ± 0.1 ms

Time averaged: 1.2 ± 0.3 ms
First Efforts towards Active Feedback Control

- Flux-conserver emulation studies
- Active current control of EQ and mirror coils
- Further control flexibility with trim coils to come soon

Typical waveform
Actively controlled current
Flux maintained
Summary of Progress on Norman

Key Engineering Accomplishments and Status

• Majority of Norman constructed in <1 year (including C-2U dismantle)
• Significantly improved system reliability and functionality – over 98% uptime
• Tunable neutral beam upgrade completed

Key Physics Accomplishments and Status

• Robust FRC formation and translation
• Much improved initial FRCs – increased size, thermal energy and temperature
• Successfully (re)produced long-lived FRCs (C-2U like)
• Improved FRC performance with flaring divertor magnetic fields
• Steady progress towards active feedback control, transitioning divertor control, beam power/tunability upgrade
2019 Preview and Next Steps
Post Norman Milestone

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 established

Norman to become user facility post milestone
Copernicus – Reactor Plasma Platform

Design under study

• 10+ keV ion temperature goal
• Super-conducting vs resistive coils
• Hydrogen only operation

Budget and timing

• $500+ MM cap-ex estimate
• Break ground around early 2020
• Commissioning/early ops 2024
Beyond Fusion
Spin-off technologies
BNCT technology
A step change in treatment of multi-centric and inoperable cancers

HOW BNCT WORKS

• IV-based vector drug delivers B\textsuperscript{10} to tumor cell
• B\textsuperscript{10} captures neutrons from TAE source
  • 3,000x higher neutron absorption than any other element in human body
• Reaction products only kill tumor cell while sparing neighboring healthy cells

WHY IT MATTERS

• BNCT cancer killing efficacy 3x X-ray and proton treatments
• Much less collateral tissue damage due to biochemical (vs. mechanical) targeting
• Fewer side effects and less toxicity
• 30-minute procedure performed once or twice
• Dramatic improvements in survival time and quality of life
TAE Life Sciences

- Spin-off based on TAE neutral beam injector technology
- TAE majority owned, but independent capital and management team
- Will eventually offer full solution to hospitals – drugs to beams
- First clinical system sold in October 2017, to deploy in 2019
- Growing order book in Asia, US, EU
Disruptive power technology for EVs

- Technology derives from 750 MW power supply challenge of Norman
- Enables
  - higher battery safety and reliability
  - better performance and efficiency
  - next generation in-wheel motors
- Manufacturer agnostic
- Architecture scales from cars to buses/trucks
- Enables non-traditional parties to enter space – software defines vehicle characteristics
- Commercialization strategy in early execution
- Further applications to follow
# Superior performance of TAE EV drivetrain solution

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Conventional</th>
<th>TAE**</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Range Extension [% ]***</td>
<td>N/A</td>
<td>+30 %</td>
<td>Until 30% state of charge of one module (FTP-72 driving cycle)</td>
</tr>
<tr>
<td>Power [Power factor of drive cycle]*</td>
<td>1</td>
<td>1.4</td>
<td>Power factor of the drive cycle to keep max battery temp the same</td>
</tr>
<tr>
<td>Efficiency – Reduction in Battery Losses [%]*</td>
<td>N/A</td>
<td>-7 %</td>
<td>Integrated over one drive cycle with low power factor</td>
</tr>
<tr>
<td>Efficiency – Reduction in Inverter Losses [%]*</td>
<td>N/A</td>
<td>-40 %</td>
<td>Integrated over one drive cycle with low power factor</td>
</tr>
<tr>
<td>Efficiency – Reduction in Motor Losses [%]*</td>
<td>N/A</td>
<td>-28 %</td>
<td>From test report at Elaphe’s site (PSM in-wheel motor company)</td>
</tr>
<tr>
<td>Range in Case of Failure [%]*</td>
<td>No operations</td>
<td>&gt;94 %</td>
<td>One module is taken off for 2 case scenarios: (1) testing of module and (2) module failure (FTP-72 cycle)</td>
</tr>
<tr>
<td>Thermal Management – Max Battery Temperature [°C]*</td>
<td>67 °C</td>
<td>51 °C</td>
<td>Max battery temperature with a high power factor drive cycle and 2 modules with higher thermal resistance</td>
</tr>
</tbody>
</table>

* Simulated with the same battery pack (16.2 kWh) for conventional and TAE technology
** Simulation includes TAE solution incorporating super capacitor buffering
TAE global power technology vision

Automotive & Grid Stabilization

Grid

Residential, EV Charging Stations & Grid Stabilization

Power Technology for TRANSPORTATION

Power Technology for CLEAN FUSION

Power Technology for RESIDENTIAL STORAGE

Energy Storage

Motor

Solar Thermal

Residential

Energy Storage