Progress at TAE
38th FPA Annual Meeting 2017

Michl Binderbauer | President & CTO | TAE Technologies
2017 at TAE Technologies

Key accomplishments

• Finished construction of Norman (formerly C-2W) – first plasma in June
• Regular science operation on Norman – 3,000 shots since July
  • Successful plasma formation from both ends
  • Efficient translation through inner divertors and plasma merging achieved
  • Sustained operation at 1 keV temperatures under way
• Substantial progress on turbulence simulations
• Successful launch of TAE Lifesciences
  • Spin-off to commercialize beam technology in oncology space
Agenda

• Concept Introduction and History

• C-2W Program Overview and Initial Results
  • Program goals
  • Norman – design, subsystems and performance
  • FRC formation/translation studies
  • Initial FRC collisional-merging experiments

• Technology Spin-offs
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
Past TAE Program Evolution

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

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

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

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

**C-2 – HPF* w/ 2 guns, Li getter**
- 1 kG, 1 keV
- neutral beams, $W_b \approx 20$ kJ
C-2W Program Overview
Phase C-2W Goals
Explore beam driven FRCs at 10x stored energy

• 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 plasma 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 machine

Magnetic Field 0.1–0.3 T
Plasma dimensions – $r_s, L_s$ 0.4, 3 m
Density – $n_e$ $3 \times 10^{19} \text{ m}^{-3}$
Temperature – $T_i, T_e$ 1-2, 0.2-1 keV
Norman – Neutral Beam System

**Beam Energy, keV**
- C-2U: 15
- Norman Phase 1: 15
- Norman Phase 2: 15/15-40

**Total Power**
- C-2U: 10
- Norman Phase 1: 13
- Norman Phase 2: 21

**# of Injectors**
- C-2U: 6
- Norman Phase 1: 8
- Norman Phase 2: 4/4

**Pulse, ms**
- C-2U: 8
- Norman Phase 1: 30
- Norman Phase 2: 30

**Ion current per source, A**
- C-2U: 130
- Norman Phase 1: 130
- Norman Phase 2: 130

- Centered, angled and 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 plasma ramp-up
Norman – Diagnostics
Comprehensive diagnostics suite

- 4 main zones with 40+ diagnostics
  - Core plasma inside the FRC separatrix
  - mirror-confined scrape-off layer (SOL) and jet
  - rapidly expanding plasma in the inner divertors and/or end divertors
  - FRC formation sections
Norman – Divertors
Critical for edge control

- $2 \times 10^6$ L/s pumping to reduce recycling
- field expanders to minimize e$^-$ cooling
- electrodes for stability control
- fast switching coils to translate FRCs
Density Contours

- S. Outer Divertor
- S. Formation
- S. Inner Divertor
- Confinement
- N. Inner Divertor
- N. Formation
- N. Outer Divertor

Magnetic Field Contours

- Strong field
- Weak field (thus expanded)

Norman – Divertor Operation Modes

Edge biasing & outer/inner divertor switching

- Edge biasing (Out-Div.)
- Edge biasing (In-Div.)

w/ Straight Field (at inner divertor)

w/ Field Expansion (at inner divertor)
C-2W Initial Results
Initial FRC Translation Studies (single-sided)
Successful translation through inner divertor achieved

Experimental time evolution of excluded flux radius during formation and translation

Simulated time evolution of excluded flux radius during formation and translation
Initial FRC Translation Studies (single-sided)
Successful translation through inner divertor achieved

Experimental time evolution of excluded flux radius during formation and translation

Fast-Framing Camera Images

Inner divertor camera observes clean FRC translation

Confinement vessel camera observes FRC reflections as plasma bounces back and forth in CV
First FRC Collision/Merging Data (double-sided)

- FRCs collide near midplane and live up to ~1 ms
- no beams or plasma-gun biasing
- first Thomson scattering based electron temperature/density profiles

Excluded-Flux Radius Time Evolution

Thomson Scattering Initial Data
C-2W Summary

• Engineering accomplishments
  • All major subsystems constructed and double-sided configuration operational in 12 month build cycle
  • Considerably upgraded formation pulsed power, vacuum system, neutral beams, magnets, edge-biasing systems and divertors

• Initial experimental results
  • FRCs successfully formed and translated through inner divertors
  • record translation speeds of ~400 km/s observed (250 km/s in C-2U)
  • FRC collision/merging experiments under way, already producing 1+ ms plasma lifetime even without NBs, edge biasing or wall conditioning
Technology Spin-offs
TAE Life Sciences Update

• TAE Lifesciences established
• Spin-off based on TAE neutral beam injector technology
• TAE majority owned, but independent capital and management team
• Will offer full treatment solution to hospitals, not just neutron beam
• First clinical system sold in October 2017, to deploy in 2019
Neutron Beam Development

- Design of first clinical beam underway
- Conceptual design review completed
- Early procurement and supply chain development under way (aids fusion beam development)
- Pre-clinical prototype under assembly, to undergo testing by summer 2018