Crossroad of Fusion and Accelerator

Toshiki Tajima

Norman Rostoker Chair Professor, UC Irvine
Chief Science Officer, Tri Alpha Energy

Acknowledgements: M. Binderbauer, A. Necas, R. Magee, M. Cappello, D. Niculae, D. Silverman
Content

- Prof. Norman Rostoker’s legacy
- Basic philosophy
- Basic technical approach
- TAE’s Field Reversed Configuration
- Norman’s conjecture “Large orbits stabilize plasma” (bicycle tire=importance of accelerator)
- Confinement improved with energy
- Beam enhances fusion
- Marriage of Accelerator and FRC plasma
Dedicated to …

Norman Rostoker (1925-2014)
Irvine: 1972-2014
TAE: 1998-
Mentor, Friend, Scientific Genius, Visionary

Student of Prof. Norman Rostoker
T.Tajima: Irvine 1973-1975, PhD
Several books on fusion, plasma
Norman Rostoker Professor: UC Irvine (2013- )
Chief Science Officer: TAE (2011- )
Basic Philosophy

See home page: trialphaenergy.com/entrepreneurial-spirit-fusion-research/

Issues: Fusion research takes long time (since 1950’s-). So far federal funds. Academic research ↔ Entrepreneurial research

• The end in mind: avoid neutronic fuel
• Fail fast: try riskiest steps early to find best base camp
• Time is money: half century to 10yrs to a few?
• Low-lying fruits: immediate applications (s.a. medical)
• “Social impact” investment: climate changes, etc.
Basic technical approach

- **Aneutronic** fuel in fusion → **extreme high energy**
- **Inject** high-energy beams, rather than heat to high temp – role of **accelerator**
- **Magnetic “soft shell”** configuration, rather than low beta “hard shell” = easy to inject beam; higher energy efficiency (high β plasma = Field Reversed Configuration [FRC])
- **Vulnerability at birth** → stable operation of **“bicycle tire”**, made of beam
- **Beam** = backbone of stability and good confinement
- The more energetic, the stronger ←**Norman’s Conjecture**
- **Steering** the “tire”
Apple tree strategy

• The top golden apple
  = fusion, takes grit
• Take lowlying apples:
  validate early,
  “eat ‘em” to climb
• Faster and more fruitful path
Steering tire strategy: Fundamental importance neural net control

Learned levers:
- increase kineticness
- increase injected NB power;
  → confinement improvement:
    increase $T$

Steering-controlled (feedbacked) and more driven (powered) plasma
Neural Net Prediction of disruption possible:

(a step before steering)


FIG. 6. With the single frequency input organization, the multi-time-scale prediction of (b) shot 133 655 is compared with (a) the experimental data. The predictive result is scaled here to the range $[-1, 1]$ for the sake of numerical stability. It is shown that both major disruptions and minor disruptions are identified, though there is a small time shift between the experimental data and the predictive one ($\Delta t \sim 0.3$ ms).
TAE’s Plasma Electric Generator (PEG)
Changing the fusion paradigm ...

PEG

- Successful merger of accelerator and plasma physics
- Achieves stability and minimal plasma loss through large orbit particles
- Result: Viable candidate toward compact aneutronic fusion

Fast particles are more robust

- Utilize successful physics of accelerators (e.g. Tevatron)
- Fast particles with large orbits ride over the turbulence
- Result: Better confinement

Rotation provides sturdy plasma structure

- Accelerator-injected beams maintains plasma rotation
- Result: Better stability
FRCs and Tri Alpha Energy’s (TAE) Concept

Advanced beam driven FRCs

- High plasma $\beta \sim 1$
  - compact and high power density
  - aneutronic fuel capability
  - indigenous kinetic particles

- Tangential beam injection
  - large orbit ion population
  - increased stability and transport

- Simple geometry
  - only diamagnetic currents
  - easier design & maintenance

- Linear unrestricted divertor
  - facilitates impurity, ash and power removal
TAE’s Present Goals
Focus of efforts to now

- Test for failure early and at reduced cost while reducing most critical risks
- Establish beam driven high-β, large orbit FRC physics test bed to
  - provide fast learning cycles and large experimental dataset (~50,000 shots)
  - demonstrate sustainment via neutral beam injection (NBI) for >5 ms (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
- 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, Industrial partners
**C-2U Neutral Beam System**

**Performance Markers and Design Philosophy**

- **Centered, angled and tangential neutral beam injection (NBI)**
  - Beams aimed at mid-plane to reduce plasma shape impact
  - Simulations suggest optimized injection angle in range of 15°-25°
  - Injection in ion-diamagnet direction to drive current

- **High current at low beam energy**
  - Reduces peripheral fast ion losses
  - Increases core heating
  - Rapidly establishes dominant fast ion pressure

---

### Neutral Beam System Specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>15 keV</td>
</tr>
<tr>
<td>Total power in neutrals</td>
<td>10+ MW</td>
</tr>
<tr>
<td># of injectors</td>
<td>6</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>8 ms flat top</td>
</tr>
<tr>
<td>Beam radial e-fold. size</td>
<td>&lt; 10 cm</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>&lt; 28 mrad</td>
</tr>
<tr>
<td>Ion current per source</td>
<td>145 A</td>
</tr>
</tbody>
</table>
Celebrating 50th Anniversary of the FLR paper ’62
The RKR Theory

Genesis of
Norman’s Conjecture

N. Rostoker
N. Krall
M. Rosenbluth
Norman’s Conjecture: physics of large orbit particles

= *quiescence* in FRC core

---

**magnetic confinement**

* (tokamak etc.)

---

**Particles accelerators:**

- **C-2**: $\rho_i \sim 5$–20cm
- **Betatron**: $\rho_i \sim 20$cm
- **LHC**: $\rho_i \sim 4.5$km

---

C-2 FRC scales

- Orbit size (~10cm)
- Wave size (~3 cm)
E \left( \frac{L}{2r_s} \right)

\text{(consistent with RKR theory)}

(Tuszewski)

\text{MHD-like/unstable}

\text{Finite Larmor Radius-stabilized}
C-2/C-2U Fast Particle Effects
Improvements coupled to NBI

- Positive impact on lifetime, confinement and stability
C-2/C-2U Stability
Tilt control via NBI and plasma density

- Tilt mostly disturbs internal field
- Conventional FRC tilt stable when
  \[
  \frac{S^*}{E} = \frac{r_s/(c/\omega_{pi})}{l_s/2r_s} \sim n^{1/2} < 3-3.5
  \]
- C-2/C-2U typically operate in stable regime by controlling density, C-2U also via large fast ion pressure
**FRC fluctuations: Noisy exterior vs. Quiet interior**

Why quiet inside FRC? ⇐ Large orbits inside [Norman’s Conjecture]
Why quieter outside in HPF? ⇐ Shear flows tear islands (shear length $L_s$)

(Schmitz et al., APS)

![Graphs showing n/n vs. r for no gun and with gun conditions](image)

$\Delta r \sim 3$-8 cm

$y = 638.72x^{-1.384}$

$y = 669.96x^{-1.429}$
Sample results – Confinement law emerged

Clear path to PEG: Rostoker’s Vision

- New core transport paradigm emerges in 2012/2014 – both experimental and theoretical
- Corroborated by multiple independent observations and simulations
- Suggests very favorable scaling towards reactor – consistent with p-B^{11} burn requirements
C-2/C-2U HPF Regime Density Fluctuations
Quiescent core, turbulence located outside

- **Absolute fluctuation levels** peak just outbound of separatrix
- **Relative fluctuation amplitude** increases with radius outside the separatrix
- HPF plasmas have **very low fluctuation levels** in the FRC core
C-2U Fluctuation Suppression in HPF regime

Substantial localized shear near separatrix

Density Fluctuations during Discharge

ExB Shear Rate

Bias off (#19896)

Bias on (#20957)

$\tilde{n} (\omega, \omega_{\text{E} \times \text{B}})$ & $r_{\Delta \phi}$

High fluctuations

Low fluctuations

Time (ms)

$0.45 \text{ ms}$

$0.2$  $0.3$  $0.4$  $0.5$  $r (m)$

$0.0$  $2.0$  $4.0$  $6.0$  $8.0$  $10.0$  $\omega_{\text{E} \times \text{B}}, \Delta \omega_{\text{D}}$
Confinement Scaling

Dramatic improvement in current regime

- Strong positive correlation between $T_e$ and $\tau_{Ee}$
- Good fit: $\tau_{Ee} \propto T_e^{1.6}$
- Confinement dramatically better than conventional FRC scaling prediction
- ~10× improved particle confinement
C-2 Breakthrough Achieved by:

- Effective boundary control using Plasma Gun (PG).
- Fast particle injection using Neutral Beams (NB).

C-2 confinement quality is far beyond the prediction from conventional $\theta$-pinch FRC scaling.
C-2W
Next device at 10× stored energy

- Plasma-guns and biasing electrodes (in both inner and end divertors)
- Inner divertor
- Upgraded NB’s: 13 MW, 30 ms
- Upgraded formation sections, 15 mWb trapped flux
- End divertor
- New confinement vessel, skin time <3 ms
- New magnet system for field ramp & active control
Enhanced fusion reactivity found search for beam-driven micro-instabilities

Hydrogen beam injection enhances D-D fusion rate.

~ 10 times increase in neutron

Courtesy: Richard Magee
Thermal deuteron plasma

Injected proton beam

Distributor function

Velocity

Hypothesis

Presence of proton beam is source of “free energy”

Transfer energy from beam to deuteron

Energetic super-thermal tail in the thermal deuteron plasma

Accelerated deuterons collide with thermal (or super-thermal) deuterons

Enhanced increase in neutron production

Testing the hypothesis

Use a 1D PIC code (EPOCH)
Magnetic fluctuations peak at ion orbit frequency

- Broadband fluctuations decrease with NB power.
- Resonant peak in spectrum increases with NB power.
- Plasma lifetime and fast ion losses are unaffected.

(Courtesy: M. Thompson)
Burst of protruded fingers in beam

- Beam ions are accelerated due to collective effects
- Could result in rapture of beam component – longest fingers
- Rise several cyclotron periods
- Rapture – radially extended as beam particles

Violations of local pressure equilibrium

Field line rupture

Loss of beam particles

Neutral particle analyzer

Thermal plasma

Beams

Beam injection velocity

Volts

2.07e6 m/s

Time [ms]
Thermal deuteron plasma Injected proton beam

DistribuEon	funcEon

Velocity

Hypothesis

Presence of proton beam is source of “free energy”

Transfer energy from beam to deuteron

Energetic super-thermal tail in the thermal deuteron plasma

Accelerated deuterons collide with thermal (or super-thermal) deuterons

Enhanced increase in neutron production

Testing the hypothesis

Use a 1D PIC code (EPOCH)
Test our Hypothesis

![Graph showing energy distribution for beam protons and thermal deuterons with initial and final states marked.](image_url)
Klimontovich Reactivity for ES Case

\[ \langle \sigma v \rangle = \sum_{i \neq j} \sum_j \sigma(\|v_i - v_j\|) \|v_i - v_j\| \]

Enormous increase in reactivity due to the beam driven collective effects
Beam Orbit Samples FRC Volume

- Study each onion layer separately
- Moving radially inward, increases beta

\[
\beta = \frac{8\pi nT}{B^2} = \frac{\text{Plasma pressure}}{\text{Magnetic pressure}}
\]

Onion Skin Model

- Beta=10%
- Beta=30%
- Beta=70%
Proton (Beam) Energy Spectrum

Experimental observation and simulation show scattering of beam proton to higher than injected energy.

Courtesy: Ryan Clary
Deuteron (Thermal) Energy Spectrum

Experimental observation and simulation show energetic tail in the deuteron distribution

Courtesy: Ryan Clary
Fusion enhancement confirmed

- Introduced hypothesis for enhanced neutron observed experimentally
- Studied three different regimes => each generating enhanced neutrons
- ~10 times increase in neutron yield compares well to experiment
- Despite the presence of possible robust micro-instabilities, FRC plasma remains robust and undestroyed.

→ Importance of the beam dynamics in fusion reactivity
conclusions

• Generated new philosophy to do fusion
• avoid neutronic fuel, assisted by accelerator
• Accelerator helps usher in new plasma behavior
  stable plasma,
  confinement increases as energy goes up
  “bicycle tire” to be controlled
• half century to 10yrs to a few?
  Low-lying fruits help
  e.g. Accelerator applied to medical treatment
  isotope generation for medicine
  spent fuel to be transmuted
  New solutions sought to shorten our timeline
Once we ascend the foggy paths, all of a sudden the view of the mountain is in front of us above the clouds.

Come join us in the ascend.

Thank you!