Status of World Spherical Torus Research

Martin Peng
NSTX Program Director
ORNL@PPPL

Fusion Power Associates Annual Meeting and Symposium:
Fusion and Energy Policy

October 11-12, 2005, Washington, DC
World Spherical Torus Research Is Expanding – 22
“Concept Exploration” and “Proof of Principle” Experiments
World Spherical Torus Research Is Addressing Important Issues in Fusion

- Active collaboration
- “Concept Exploration” STs
- “Proof of Principle” STs
- Contributions in world fusion programs
World Spherical Torus Research Has a Tradition of Strong Collaboration

- Active bilateral exchanges
  - UK-US on NSTX and MAST – START collaboration in 1997
  - Japan-US on STs – active exchanges since 2000; contributed to formation of All-Japan ST Program in 2004
  - RF-US on NSTX and Globus-M – since 1997
  - Brazil-US on initiation of ETE – collaboration since 2000
- Annual International ST Workshop since 1994; IAEA TM on ST since 1999
- Special international journal issues on progress of ST research
  - IEEJ journal issue to appear in November
  - NF issue under preparation
- Progressing toward more coordination in research
CDX-U Have Carried out Liquid Lithium Tray Limiter Experiments

- 34 cm major radius, 10 cm wide, 0.64 cm deep
- Two halves with toroidal break
- Heaters for $T_{\text{max}} \approx 500^\circ \text{C}$

- Argon glow discharge cleaning and tray heating removed surface coatings
- Lithium remains in tray with currents to ground $\approx 100 \text{A}$ at $B_p \approx 0.1 \text{T}$ for $\approx 10 \text{ms}$

Liquid lithium in tray after $\sim 40$ discharges.
**Impurity Control with Liquid Lithium Indicated by Reduction of Oxygen Emission**

Many conditioning shots required without Li to achieve currents $\approx 60\text{kA}$

No conditioning shots required with Li to achieve currents $> 60\text{kA}$
Pegasus is an Innovative ST to Explore Plasma Limits as $A \to 1$

**Original Goals:**

- Stability and confinement at high $l_p/l_{tf}$
  - Extension of tokamak studies

- Limits on $\beta_t$ and $l_p/l_{tf}$ (kink) as $A \to 1$
  - Overlap between the tokamak and the spheromak

**Future Emphases:**

- Support ST program movement to next stages
  - EBW tests for heating & CD (w/PPPL)
  - Noninductive startup & CD tests
  - Diagnostic development
  - High-pressure gas puff for deep fueling

$\frac{l_p}{l_{tf}}$ = figure of merit for access to low-A physics

Garstka
3rd IAEA TCM & 2005 ST Workshop
October 5, 2005
Pegasus Is Exploring Innovative Startup via Electron Beam Injection

• Nature of produced plasma changes as bias increased:
  - Low bias voltage:
    \[ I_{\text{toroidal}} = (I_{\text{gun}}) \times (\text{geometric windup}) \]
    \[ = \text{plasma appears as separate streams} \]
  - High bias voltage:
    \[ I_{\text{toroidal}} = (I_{\text{gun}}) \times (\text{geometric windup}) \times (\text{additional multiplication}) \]
    \[ = \text{streams merge into uniform-appearing plasma} \]

• No evidence yet of closed flux surfaces

• Two guns found to add to \( I_{\text{toroidal}} \) linearly

50 V bias: plasma streams remain separate

400 V bias: plasma streams appear to reconnect

\( 1 \text{ ms per frame} \)
Spontaneous formation of closed field equilibrium via rapid current rise under steady \( B_v \) field

Rapid current rise

\[ B_t = 720 \ G \]
\[ B_v = 85 \ G \]

FPA Meeting, 10/11-12/05
After spontaneous formation, $I_p$ can be ramped-up by a slow ramp of $B_v$ for equilibrium at larger plasma current (2.45GHz Experiment).

- $I_p = 8.1$ kA
- $n_e \sim 2 \times 10^{11}$ cm$^{-3}$
- $R_0 = 20$ cm
- $a = 14$ cm
- $b = 24$ cm
- $\omega / 2\Omega_e = 27.4$ cm
- $\bar{n}_e \sim 2 \times 10^{11}$ cm$^{-3}$
- 3 times of cutoff density
- 2nd ECH by EBW

$t = 2.37$ s
$R_j = 26.5$ cm
$Z_j = 0$ cm
$A \sim 1.4$
$\kappa \sim 1.7$
QUEST: Q-shu University Experiment on Steady State Spherical Tokamak

Advanced Fusion Research Center

FPA Meeting, 10/11-12/05
Status of World ST Research
U. Tokyo UTST-(TS&TST) Experiment for High-β ST Startup and RF Sustainment
Strategy of the All-Japan ST Research Program  
(Prof. Yuichi Takase, June 2005)

Broad research utilizing **all resources**  
(existing ST, new ST at Kyushu, diagnostics,  
theory/modelling, reactor design, etc.)

- Higher $\beta$, Higher $f_{BS}$, More compact
- UTST
- TS-3/TS-4
- HIST, TST-2, LATE
- CS-less op.

- Longer pulse, **steady state**
- Very high $\beta$ & steady state Comm. reactor
- NSTX
- MAST
- QUEST

Develop broader options for economical fusion reactor

RF current drive

FPA Meeting, 10/11-12/05
New Capabilities in NSTX

- Novel $j(r)$ diagnostics for Advanced physics
- Direct Measurement of Electron Turbulence
- EF/RWM coils to extend $\beta$ limits
- New PF1A coil for advanced shaping
Enhanced CXRS ($\Delta R \sim \rho_{Li}$) in MAST

- Spectrometer coupled to 224 chords
- 64 toroidal chords on each NBI
- 32 passive toroidal chords
- 64 poloidal chords (32 32 on/off-beam) being commissioned
H-mode Transport Coefficients Can Be Close to Ion Neoclassical

$\chi_e \sim \chi_i$ around mid-radius & close to $\chi_i^{Z-CH}$ [Chang & Hinton]

**Graphs and Diagrams:**
- Plots showing temperature profiles $T_e$ and $T_i$.
- TRANSP modelling.
- ELMs + poor gradient resolution.
STs Are Studying Super-Alfvénic Ion Heating for ITER and CTF

- NSTX has Super-Alfvénic ions (NBI), as in ITER (fusion $\alpha$’s)
- Measured instabilities driven by such fast ions & coincidental fast ion losses
- Interactions driven by small $\rho_{fast}^*$ (ITER), copious fast ions (both), and Doppler shifted resonance with Alfvén instabilities (both)
- Will fusion $\alpha$’s in ITER & CTF suffer similar losses?
Start-up Schemes – Double-Null Merging

- compatible with future ST design
- Double-null merging (DNM) involves breakdown at a quadrupole null between pairs of poloidal coils in upper and lower divertor
- Modelling predicts merging of plasma rings as current in coils ramped to zero

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>Current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>150</td>
</tr>
<tr>
<td>21</td>
<td>250</td>
</tr>
<tr>
<td>45</td>
<td>450</td>
</tr>
<tr>
<td>75</td>
<td>600</td>
</tr>
<tr>
<td>60</td>
<td>600</td>
</tr>
</tbody>
</table>
After some optimisation, plasma current up to 340kA formed and plasma sustained for 0.3sec with zero current in central solenoid

- \( T_e \approx 0.5\text{keV} \) and \( n_e \approx 9 \times 10^{19}\text{m}^{-3} \)
In HIT-II, nearly all Transient CHI produced closed flux current couples to the subsequent inductive drive.

Both discharges have identical loop voltage programming.
NSTX Produced Sustained ST Plasmas via Coaxial Helicity Injection (Introduced by HIT-II)

- Rapid turn-off of injector current → closure of plasma surface → 60 kA, ~2 m² volume
- First demonstrated on HIT-II (U Wash)
- Important progress for attractive ST and Tokamak fusion systems

Univ. of Hiroshima camera: N. Nishino; R. Kaita

- Injector
- Closed Plasma Surface

Plasma Current (kA/10)
Injector Current (kA)
Injector Voltage (kV*10)
Filaments are consistent with the structures expected from the theory of the non-linear evolution of ballooning modes [Wilson and Cowley]
Unique ST Properties and Approaches Advance Boundary Physics

**ITER-relevant heat fluxes** (10 MW/m²).
Shaping & flux expansion

Turbulence imaging: large $\rho_i$ slow dynamics enable good resolution

Heat, particle fluxes: Detached regimes, lithium coatings & liquid targets

Pedestal stability: strong shaping, low A: magnetic geometry pedestal stability & SOL transport
NSTX Accesses High $\beta$, High Bootstrap Plasmas

Fusion Requires High Beta Steady State

NSTX
⇒ Toroidal Physics (ITER)
⇒ Component Test Facility (CTF)
⇒ Power Plant

FPA Meeting, 10/11-12/05
Substantially Expanded the Spherical Torus Operating Space to Clarify Future ST Options

- Improved divertor coils
- Extended plasma to stronger shapes
- High triangularity at high elongation leads to quiescent core and edge conditions

![Diagram showing improved divertor coils and extended plasma shapes]

![Graph showing normalized performance versus energy replacement times]

FPA Meeting, 10/11-12/05

Status of World ST Research
MAST Upgrades: Proposed NBI Systems

- Investigating bold options for NBI current profile control
- Flexible system 4 PINIs, up to 10 MW (1 counter- and 3 co-current)
- Off-axis NBCD optimised with 2 off-axis co- and 2 on-axis co-counter PINIs

On-axis, counter-PINi

Double box: 2× co-PINIs on- and off-axis

Jackable on/off-axis co-PINi
BUTTRESSES ⇒ Reduce Risk/Acceleration
(Sir. Chris Llewellyn Smith, FPA meeting 2005)

- **Multi-beam** material test facility - study damage from irradiation with heavy ions to material samples with implanted Helium (+ hydrogen?)
- **Satellite tokamak** - to be operated in parallel with ITER, as part of ITER programme, to test new modes of operation, plasma technologies,...

**Component Test Facility (CTF)** - to test engineering structures (joints, ...) in neutron fluences typical of fusion power stations

We assume that a ‘fast track CTF’ (possibly a small spherical tokamak that would not need to breed tritium?) **could be operating with D-T in 2026**

Assuming successful development, it would speed up the advent of fusion power significantly **and** reduce risks (note that in ‘Pillars only’ model DEMO phase 1 is effectively a very expensive and large CTF)
ST Research Contributes to Major Components of Office of Science 20-Year Strategic Plan for Fusion

---

**Strategic Timeline—Fusion Energy Sciences**

|------|------|------|------|------|------|------|------|------|------|------|------|

**The Science**

**Burning Plasma Demonstration**
- Initiate experiments on the National Ignition Facility (NIF) to study ignition and beam propagation in ITER-relevant fuel pellets (2012)
- Complete ITER experiments to determine plasma confinement in parameter regime required for an energy-producing plasma (2017)
- Achieve high fusion power for long durations on ITER to define engineering requirements for fusion power plants (2025)

**Fundamentals of Plasma Behavior**
- Achieve a fundamental understanding of tokamak transport and stability in pre-ITER plasma experiments (2009)
- Achieve long-duration, high-pressure, well-confined plasma in a spherical regime sufficient to design and build fusion-particle-producing Next-Step Spherical Torus (2023)
- Demonstrate use of active plasma control and self-organized plasma current to achieve high-performance sustained steady-state operation for ITER (2020)
- Evaluate the physics limits that constrain the potential power production of a reactor design (2023)
- Deliver a complete integrated simulation of a power-producing plasma, validated with ITER results, that enables the design of fusion power plants (2020)

**ITER Performance Enhancement**
- Major aspects relevant to burning plasma behavior observed in experiments prior to full operation of ITER are predicted with high accuracy and are understood (2015)
- Determine the potential of one or more of the promising plasma configurations (for example a spherical torus) for use as a component test facility or a fusion power source (2020)

**Plasma Confinement**
- Evaluate the ability of the compact reactor configuration to confine high-density plasma (2010)
- Determine the potential of one or more of the promising plasma configurations (for example a spherical torus) for use as a component test facility or a fusion power source (2020)
- Evaluate the feasibility and attractiveness of potential drivers, including heavy ion beams, dense plasma beams, and laser for fusion approaches involving high-energy density (2009)

**Performance Extension Test**
- Deliver to ITER for testing the blanket test modules needed to demonstrate the feasibility of extracting high-temperature heat from burning plasmas and for a self-sustaining fuel cycle (2015)
- Complete first phase of testing in ITER of blanket technology needed to power-producing blanket that can provide high-temperature heat from burning plasma and have a shutdown margin (2024)
- Complete first phase of testing in component test facility to validate the performance of inertial confinement fusion energy resource (2025)

**Materials, Components, and Technologies**
- Start production of superconducting wire needed for ITER magnets (2006)
- Complete first phase of testing in ITER of blanket technologies needed to power-producing blanket capable of extracting high-temperature heat from burning plasma and having a shutdown margin (2024)

**Future Facilities**
- ITER: ITER is an international collaboration to build the first fusion energy reactor capable of producing a self-sustaining fusion reaction called a “burning plasma”
- Next-Step Spherical Torus (NSST): The NSST will be designed to test the spherical torus, an innovative concept for magnetically confining a fusion reaction
- Fusion Energy Contingency: If ITER construction and operation proceeds as planned, additional facilities to develop and test power plant components and materials will be needed to complete the process of making fusion energy a viable commercial energy resource by mid-century

---

*These strategic milestones are illustrative and depend on funds made available through the Federal budget process.

**For more detail on these facilities and the overall prioritization process, see the companion document, Facilities for the Future of Science: A Twenty-Year Outlook."
World Spherical Torus Research Is Expanding and Addressing Important Issues in Fusion

- Growing in breadth and depth – 22 experiments in active collaboration
- “Concept Exploration” STs push the ST scientific envelope
  - Explore high leverage innovations
  - Establish basis for “Proof of Principle” testing
- “Proof of Principle” STs
  - Contribute to resolve issues important to ITER burning plasma performance
  - Establish scientific feasibility for ST “performance extension,” CTF volume neutron source, & Demo Optimization
- STs are part of plans in world fusion programs