Spherical Tokamak Plasma Science & Fusion Energy Development

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Yoshida-Honmachi, Kyoto, Japan
Spherical Tokamak (ST) Offers Rich Plasma Science Opportunities and High Fusion Energy Potential

- What is ST and why?
- Scientific opportunities of ST
  - How does shape ($\kappa$, $\delta$, $A$ ...) determine pressure?
  - How does turbulence enhance transport?
  - How do plasma particles and waves interact?
  - How do hot plasmas interact with walls?
  - How to supply magnetic flux without solenoid?
- Contributions to burning plasmas and ITER
- Cost-effective steps to fusion energy
- Collaboration
Tokamak Theory in Early 1980’s Showed Maximum Stable $\beta_T$ Increased with Lowered Aspect Ratio (A)

- A. Sykes et al. (1983); F. Troyon et al. (1984) on maximum stable toroidal beta $\beta_T$:

$$\beta_{T\text{max}} = C \frac{I_p}{a} \langle B \rangle \approx 5 C \frac{\kappa}{A q_j}; \quad \langle B \rangle \approx B_T \text{ at standard A}$$

- $C \approx$ constant ($\sim 3 \text{ } \text{m} \cdot \text{T/MA} \Rightarrow \beta_N$

- $\langle B \rangle = \text{volume average } B \Rightarrow B_T$

- $\kappa = b/a = \text{elongation}$

- $A = R_0/a = \text{aspect ratio}$

- $q_I \approx \text{average safety factor}$

- $I_p = \text{toroidal plasma current}$

- $B_T \approx \text{applied toroidal field at } R_0$

- Peng & Strickler (1986): **What would happen to tokamak as } A \rightarrow 1?**
  
  - How would $\beta_N, \kappa, q_j$, change as functions of $A$?
ST Plasma Elongates Naturally, Needs Less TF & PF Coil Currents, Increases $I_p/aB_T \Rightarrow$ Higher $\beta_{Tmax}$

- Naturally increased $\kappa \sim 2$; $I_{TF} < I_p$, $I_{PF} < I_p \Rightarrow$ higher $I_p$; lower device cost
- Increased $I_p/aB_T \sim 7$ MA/m·T $\Rightarrow \beta_{Tmax} \sim 20\%$, if $\beta_N \sim 3$
- Increased $I_p q_{edge}/aB_T \sim 20$ MA/m·T $\Rightarrow$ improved confinement?
Very Low Aspect Ratio (A) Introduces New Opportunities to Broaden Toroidal Plasma Science

**ST Plasmas Extends Toroidal Parameters**

\[ A = \frac{R}{a} \text{ can be } \geq 1.1 \]

---

**How does shape determine pressure?**
- Strong plasma shaping & self fields (vertical elongation \( \leq 3 \), \( B_p/B_t \sim 1 \))
- Very high \( \beta_T \) (\( \sim 40\% \)), \( \beta_N \) & \( f_{\text{Bootstrap}} \)

**How does turbulence enhance transport?**
- Small plasma size relative to gyro-radius (\( a/\rho_i \sim 30–50 \))
- Large plasma flow (\( M_A = V_{\text{rotation}}/V_A \leq 0.3 \))
- Large flow shearing rate (\( \gamma_{E\times B} \leq 10^6/\text{s} \))

**How do plasma particles and waves interact?**
- Supra-Alfvénic fast ions (\( V_{\text{fast}}/V_A \sim 4–5 \))
- High dielectric constant (\( \varepsilon = \omega_{pe}^2/\omega_{ce}^2 \sim 50 \))

**How do plasmas interact with walls?**
- Large mirror ratio in edge B field (\( f_T \rightarrow 1 \))
- Strong field line expansion

**How to supply mag flux without solenoid?**
- Small magnetic flux content (\( \sim \ell_i R_0 I_p \))
ST Research Is Growing Worldwide

- **Concept Exploration (~0.3 MA)**
  - HIT-II (US)
  - Pegasus (US)
  - NSTX (US)
  - CDX-U (US)
  - ETE (B)
  - SUNIST (PRC)
  - HIST (J)
  - TST-2 (J)
  - TS-4 (J)
  - TS-3 (J)
  - Globus-M (RF)

- **Proof of Principle (~MA)**
  - MAST (UK)
  - TS-3 (J)
  - TS-4 (J)
Pegasus Explores ST Regimes As Aspect Ratio → 1

- Stability and confinement at high $l_p/l_{tf}$
- Limits on $\beta_t$ and $l_p/l_{tf}$ as $A \to 1$
NSTX Exceeded Standard Scaling & Reached Higher \( I_p/aB_T \), Indicating Better Field and Size Utilization

- Verified very high beta prediction \( \Rightarrow \) new physics:
  \[
  \beta_T = 2\mu_0 \langle p \rangle / B_{T0}^2 \leq 38\%
  \]
  \[
  \beta_N = \beta_T / (I_p / aB_{T0}) \leq 6.4
  \]
  \[
  \langle \beta \rangle = 2\mu_0 \langle p \rangle / \langle B^2 \rangle \leq 20\%
  \]

- Obtained nearly sustained plasmas with neutral beam and bootstrap current alone
  - Basis for neutral beam sustained ST CTF at \( Q \sim 2 \)
  - Relevant to ITER hybrid mode optimization

- To produce and study full non-inductive sustained plasmas
  - Relevant to DEMO

CTF \( \beta \) requirement well within stability Limits, without using active control

\[
\begin{align*}
2004 (\kappa = 2.0 - 2.5) & \quad \beta_N = 6 \\
2002-2003 (\kappa = 1.8 - 2.3) & \quad \beta_N = 5
\end{align*}
\]

\( \langle \beta \rangle \) versus \( I_p / aB_{T0} \) (MA/m-T)

Field Utilization – Toroidal \( \beta_T \) (%)

(Columbia U, LANL, PPPL)
Detailed Measurements of Plasma Profiles Allows Physics Analysis and Interpretations

Plasma Flow Shearing Rate up to $\sim 10^6$/s
Strong Plasma Flow ($M_A = V_\phi / V_{Alfvén} \sim 0.3$) Has Large Effects on Equilibrium and Stability

- Internal MHD modes stop growing
- Pressure axis shifts out by ~10% of outer minor radius
- Density axis shifts by ~20%

**Equilibrium Reconstruction with Flow**

- Pressure surfaces
- Magnetic surfaces

**Plasma Current=1.2MA**

- Beam Power=7MW
- Avg. $\beta_T=35\%$
- High $\beta_T$ Sustained

**MHD Mode Spin Frequency (kHz)**

**MHD Mode Amplitude (Gauss)**

**Time (s)**: 0.10, 0.15, 0.20, 0.25, 0.30

**R (m)**: 0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4

**$n_e (m^{-3})/4\times10^{19}$**

**$T_e (keV)$**

**$Z(m)$**

**Columbia U, GA, PPPL, U Rochester**
High-Resolution CHERS, SXR, and In-Vessel $B_R$ and $B_p$ Sensors Reveal Strong Mode-Rotation Interaction

CHarge-Exchange Recombination Spectroscopy (CHERS) shows $v_\phi$ collapse preceding $\beta$ collapse.

In-vessel sensors measure rotating mode as $v_\phi$ decays before mode locking.

SXR shows rotating 1/1 mode during $v_\phi$ decay.

ST2004-9/29-10/1/04 ST Science & Fusion Energy

Sabbagh, Bell, Menard, Stutman

RWM, NTM, 1/1 modes, and rotation physics of high interest to ITER
Active Control Will Enable Study of Wall Mode Interactions with Error Fields & Rotation at High $\beta_T$

Ex-Vessel Feedback Control Coils are being built

VALEN model of NSTX (cutaway view)

Resistive Wall Mode Growth Rate (s$^{-1}$)

$\Delta\beta_N = (\beta_N - \beta_{N\text{no-wall}})/(\beta_{N\text{wall}} - \beta_{N\text{no-wall}})$

Increasing $\beta$ beyond passive $\beta$

Columbia U, GA, PPPL
Global and Thermal $\tau_E$'s Compare Favorably with Higher A Database

- Compare with ITER scaling for total confinement, including fast ions
- TRANSP analysis for thermal confinement

L-modes have higher non-thermal component and comparable $\tau_E$! Why?

Bell, Kaye, PPPL
Ion Internal Transport Barrier in Beam-Heated H-Mode Contrasts Improved Electron Confinement in L-Mode

Transport Barrier region where \( \chi_i \sim \chi_i^{NC} \)
and \( \chi_e >> \chi_i \)

But L-mode plasmas show improved electron confinement! Why?
Transport Analysis of NSTX Plasmas Using TRANSP Confirms This Contrast

- $\chi_e >> \chi_i \sim \chi_{\text{NCLASS}}$ in most H-mode
- $\chi_e \sim \chi_i$ in L-mode
- Diagnostic Resolution improvements continue
Analysis Shows Stability to Modes at Ion Gyro-Scale & Strong Instability at Electron Gyro-Scale (H-Mode)

<table>
<thead>
<tr>
<th>Core Transport Physics</th>
<th>In ion confinement zone</th>
</tr>
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<tbody>
<tr>
<td>Thermal Conductivity</td>
<td>- $\chi_{\text{ion}} \sim \chi_{\text{neoclassical}}$</td>
</tr>
<tr>
<td></td>
<td>- $\chi_{\text{elec}} \gg \chi_{\text{ion}}$</td>
</tr>
<tr>
<td>Impurity Diffusivity</td>
<td>- $D_{\text{imp}} \sim D_{\text{neoclassical}}$</td>
</tr>
<tr>
<td>Micro-instability calculations</td>
<td>- Driven by T and n gradients</td>
</tr>
<tr>
<td></td>
<td>- $k_{\theta}\rho_i &lt; 1$ (ion gyro-scale) stable or suppressed by $V_\phi$ shear</td>
</tr>
<tr>
<td></td>
<td>- $k_{\theta}\rho_i \gg 1$ (electron gyro-scale) strongly unstable</td>
</tr>
</tbody>
</table>

Cadarache, JHU, PPPL, U. Maryland
A Broad Spectrum of Energetic Particle Driven Modes is Seen on NSTX

Do these Alfvén Eigenmodes (AEs) and fish-bones (f.b.s) Interact to expel energetic particles?

![Graph showing frequency vs. time with Alfvén Eigenmodes (AEs) and fish-bones (f.b.s).]
TAE’s, “Fish-Bones,” and CAE/GAE’s Can Interact to Expel Energetic Particles

(I_p = 0.65 MA, P_b = 3.6 MW, \( \beta_T = 10\% \))

Synchronous sudden activities of
- Edge D\( \alpha \) rises; D-D neutron drops
- Fish-bone modes rises
- TAE mode crashes
- Separately, asynchronous drops of f.b. and CAE modes

- So far observed for \( \beta_T \leq 10\% \) and \( I_p \leq 700 \text{ kA} \) ⇒ high-\( \beta \) effects?
- NPA measured depletion for 50-80 kV at higher \( \beta_T \) – MHD (m/n=4/2) induced?
- Nonlinear effects relevant to lower \( \beta \) burning plasmas (ITER)
NSTX RF Research Explores High Dielectric ($\varepsilon \sim 100$) Effects for Efficient Heating & Current Drive

M. Ono (1995): High Harmonic Fast Wave (HHFW) decay (absorption) rate:

$$k_{\perp \text{im}} \sim \frac{n_e}{B^3} \sim \frac{\varepsilon}{B},$$

$$\varepsilon = \frac{\omega_{pe}^2}{\omega_{ce}^2} \sim 10^2$$

HHFW: Heat Electrons and Trigger H-Modes, Relevant to Slowly Rotating ITER Plasmas

- Antenna operated in $6\times(0-\pi)$ phasing for slow wave: $k_T \approx 14\text{m}^{-1}$
Electron Bernstein Wave: Oblique "O-X-B" Launch Is Resilient to Changes in Edge Density Gradient

Efficient conversion between ECW and EBW predicted.

- Optimum $n_{/\parallel} = 0.55$; toroidal angle $\sim 34^\circ$ from normal to $\mathbf{B}$
- > 75% coupling for O-X-B antenna with $\pm 5$ degree beam spread
EBW Emission Shows Near-Circular Polarization and $T_{\text{rad}}/T_e \sim 70\%$, Consistent with Modeling

- Thomson Scattering $T_e$ (keV)
- Magnetic Field Pitch 35-40 Degrees
- Approx. Antenna Acceptance Angle
  - Average Coupling ~ 70%
- Frequency = 16.5 GHz

- Time (s)
- Field Pitch (Deg.)
- Total EBW $T_{\text{rad}}$ (keV)
  - (Including Window/Lens Loss)
- Ratio of Radiometer Signals
- OPTIPOL/GLOSI
- Poloidal Angle (deg.)
- Toroidal Angle (deg.)

ST Science & Fusion Energy
Modeling Predicts that 28 GHz EBW Can Drive Efficient Off-Axis Current at Plasma $\beta \sim 40\%$

- EBW ray tracing, deposition and CD efficiency being studied with GENRAY & CQL3D for frequencies between 14 to 28 GHz

- $B_t = 3.75$ kG
- $b = 42\%$

Frequency = 28 GHz
EBW Power = 3 MW
Total Driven Current = 135 kA
Strong Diffusion Near Trapped-Passing Boundary Enables Efficient Ohkawa Current Drive

NSTX, $\beta_T = 42\%$

$U_{\text{norm}} = 30$ keV

$U_{\text{perp}}/U_{\text{norm}}$

$U_{\text{parallel}}/U_{\text{norm}}$

$p = 0.7$
ST Plasma Edge Possesses Large Mirror Ratio & Geometric Expansion of Scrape-Off Layer (SOL)

Scrape-Off Layer Geometry of Inboard Limited ST Plasma

- **Divertor**
- **Limiter**
- **Plasma Flux to Limiter**

\[ R(m) \]

\[ Z(m) \]

\[ |B| (T) \]

Distance Along SOL Field Line (m)

Larger Mirror Ratio (\( M_R \))
- More Instabilities
- Larger \( \perp \) Loss
- Thicker SOL

Area Expansion Ratio

B: Plasma Flux To Divertor

SOL Flux Surface

Plasma Edge

A: Plasma Flux to Limiter
Increased SOL Mirror Ratio ($M_R$) $\Rightarrow$ Increased Footprint & Decreased Peak of Divertor Heat Flux

Factor of $\sim 2$ in $R_{\text{div}}$ and $M_R$
$\Downarrow$
Factor of $\sim 3$ in $\Delta_{\text{div}}$

Why?

**High & Low $\delta$ Divertor Bolometer Measurements**

<table>
<thead>
<tr>
<th>$R_{\text{div}}$ (m)</th>
<th>0.36</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOL $M_R$</td>
<td>$\sim$ 3</td>
<td>$\sim$ 1.5</td>
</tr>
<tr>
<td>$\Delta_{\text{div}}$ (m)</td>
<td>$\sim$ 0.3</td>
<td>$\sim$ 0.12</td>
</tr>
</tbody>
</table>

SOL $M_R \approx 3$

3.3 MW DND ($\delta_L \sim 0.73$)

SOL $M_R \approx 1.5$

4.1 MW LSN ($\delta_L \sim 0.40$)
Plasma Edge Studies Reveal Turbulence and “Blobs” Important to Divertor Flux Scaling Studies

Broadly Based Study:
- Gas Puff Imaging views along field lines (PPPL, LANL)
- Very fast camera, 10^5/s (PSI)
- Reflectometers and edge (UCLA, ORNL)
- Reciprocating probe (UCSD)
- Divertor fast camera (Hiroshima U)
- IR Cameras (ORNL), Filterscope (PPPL)
- Modeling (PPPL, UCSD, LLNL, Lodestar)
CDX-U Is Testing Innovative Lithium Plasma Facing Component Effects, to Control Recycling

- First successful test of toroidal liquid lithium tray limiter
- Dramatic reduction in plasma edge fuel recycling, lowering impurity influx and loop voltage
- NSTX tests of lithium pellets and lithium wall coating in 2004
Solenoid Free Start-Up via Coaxial Helicity Injection & Outer Poloidal Field Coil Are Being Tested

Coaxial Helicity Injection Tests
New absorber insulator installed

Three Outer Poloidal Field Startup Scenarios, e.g.:
Outboard Field Null

Capacitor bank to be installed

Flux contours

HIT-II Experiment
CHI + OH
OH only

Shot 23918
Shot 23919
Shot 23920

Culham, KAIST, Kyushu-Tokai U, PPPL, U Tokyo, U Washington
JT-60U Tests on Solenoid-Free Start-Up via RF and NBI Offers Additional Exciting Opportunities

- **JT-60U**: from 200 kA to 700 kA with LHW + NBI (2002)
- **PLT**: 100 kA with LHW (1980s)
- **CDX-U, TST-2**: up to 4 kA with ECH
- **MAST**: 1-MW ECH
- **NSTX**: to develop and test up to 4-MW EBW in 5 years
- Utilize outer PF coil induction with simple ramp

U. Tokyo, JT-60U – JAERI
Nearly Sustained Plasmas with Broader Values of $\kappa$, $\ell_i$, $I_p$, and $\beta_T$ Can Contribute to ITER Hybrid Scenario

Co-NBI plasmas:
- Improved vertical control $\Rightarrow$ higher $\kappa$
- $\beta_p \geq 1$ and $I_{BS}/I_p \leq 0.5$
- $\beta_N \sim 6$ and $\beta_T > 20\%$
- Reduced $V_L$
- Help developing ITER hybrid scenario
- Driven steady state ST plasmas (CTF).
- Need to reduce ELM size
NSTX Made Large Progress in Producing and Studying the Science of Attractive Sustained Plasmas

Fraction of Self-Driven Current

\[ f_{BS} \sim 0.5 \times \varepsilon^{1/2} \beta_P \]

\[ \beta_T (\%) \]

- EFIT02
- Peak \( \beta_T \)
- All shapes

NSTX Potential

FY01-03

FY04
Long-Pulse H-Mode Plasmas Made Large Progress in Physics Basis for Next-Term ST Science Facilities

Well positioned to address the science of sustained high-performance plasmas.
Research Topics to Achieve Long-Pulse, High Performance Plasmas Are Identified

- Enhanced shaping improves ballooning stability
- Mode, rotation, and error field control ensures high beta
- NBI and bootstrap sustain most of current
- HHFW heating may contribute to bootstrap
- EBW provides off-axis current & stabilizes tearing modes
- Particle and wall control maintains proper density
Answering the Plasma Science Questions Also Enable Cost-Effective Steps toward Fusion Energy

<table>
<thead>
<tr>
<th>Plasma Science Questions in Extended ST Parameter Space</th>
<th>⇒</th>
<th>Optimize Fusion DEMO &amp; Development Steps</th>
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<tbody>
<tr>
<td>How does shape determine pressure?</td>
<td>⇒</td>
<td>Lowered magnetic field and device costs</td>
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<tr>
<td>How does turbulence enhance transport?</td>
<td>⇒</td>
<td>Smaller unit size for sustained fusion burn</td>
</tr>
<tr>
<td>How does plasma particles and waves interact?</td>
<td>⇒</td>
<td>Efficient fusion $\alpha$ particle, neutral beam, &amp; RF heating</td>
</tr>
<tr>
<td>How do hot plasmas interact with wall?</td>
<td>⇒</td>
<td>Survivable plasma facing components</td>
</tr>
<tr>
<td>How to supply magnetic flux without solenoid?</td>
<td>⇒</td>
<td>Simplified smaller design, reduced operating cost</td>
</tr>
</tbody>
</table>
Future ST Steps Are Estimated to Require Moderate Sizes to Make Key Advances toward DEMO

<table>
<thead>
<tr>
<th>Device</th>
<th>NSTX</th>
<th>NSST</th>
<th>CTF</th>
<th>DEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission</td>
<td>Proof of Principle</td>
<td>Performance Extension</td>
<td>Energy Development, Component Testing</td>
<td>Practicality of Fusion Electricity</td>
</tr>
<tr>
<td>R (m)</td>
<td>0.85</td>
<td>~1.5</td>
<td>~1.2</td>
<td>~3</td>
</tr>
<tr>
<td>a (m)</td>
<td>0.65</td>
<td>~0.9</td>
<td>~0.8</td>
<td>~2</td>
</tr>
<tr>
<td>κ, δ</td>
<td>2.5, 0.8</td>
<td>~2.7, ~0.7</td>
<td>~3, ~0.5</td>
<td>~3.2, ~0.5</td>
</tr>
<tr>
<td>I_p (MA)</td>
<td>1.5</td>
<td>1</td>
<td>~5</td>
<td>~9</td>
</tr>
<tr>
<td>B_T (T)</td>
<td>0.6</td>
<td>0.3</td>
<td>~1.1</td>
<td>~2.1</td>
</tr>
<tr>
<td>Pulse (s)</td>
<td>1</td>
<td>5</td>
<td>~50</td>
<td>~77</td>
</tr>
<tr>
<td>P_{fusion} (MW)</td>
<td>~50</td>
<td>Steady state</td>
<td>~300</td>
<td>~3100</td>
</tr>
<tr>
<td>W_L (MW/m²)</td>
<td>~1</td>
<td>~4</td>
<td>~4</td>
<td></td>
</tr>
<tr>
<td>Duty factor (%)</td>
<td>~0.01</td>
<td>~0.01</td>
<td>~15</td>
<td>30</td>
</tr>
<tr>
<td>TFC; Solenoid</td>
<td>Multi-turn; Solenoid</td>
<td>Multi-turn; Solenoid</td>
<td>Single-turn; No-solen.</td>
<td>Single-turn; No-solen.</td>
</tr>
</tbody>
</table>
ST Research Has Broad and Growing Opportunities for Collaborations

- **Exploratory ST’s in Japan**
  - **TST-2**: ECW-EBW initiation
  - **TS-3,4**: FRC-like $\beta\sim 1$ ST plasmas
  - **HIST**: helicity injection physics
  - **LATE**: solenoid-free physics

- **Active participation in ITPA (ITER)**
  - $A$ and $\beta$ effects on confinement, ITB, ELM’s, pedestal, SOL, RWM, and NTM; scenarios, window coating, etc.

- **ST Database with MAST, U.K.**
  - NBI H-mode, transport, $\tau_E$
  - EBW H&CD (1 MW, 60 GHz), FY03
  - Divertor heat flux studies, FY03-04
  - NTM, ELM characterization

- **DIII-D & C-Mod collaboration**
  - Joint experiments: RWM, Fast ion MHD, pedestal, confinement, edge turbulence, X-ray crystal spectrometer

- **MST**: electromagnetic turbulence, EBW
Spherical Tokamak (ST) Offers Rich Plasma Science Opportunities and High Fusion Energy Potential

- Early MHD theory suggested ST could permit high $\beta$, confirmed recently by experiments
- Recent research identified new opportunities for addressing key plasma science issues using ST
  - Results have been very encouraging in many scientific topical areas
- ST research contributes to burning plasma physics optimization for ITER
- ST enables cost-effective steps toward practical fusion energy
- ST research is highly collaborative worldwide
Backup VUs
Minimizing Tokamak Aspect Ratio Maximizes Field Line Length in Good Curvature $\Rightarrow$ High $\beta$ Stability

Small-$R$ close to Tokamak & large-$R$ close to CT.
ST Is Closest to Tokamak; Operates with High Safety Factor and More Comparable Self & Applied Fields

- **Spherical Tokamak** (Spherical Torus) - (NSTX, MAST, TST-2, TS-3,4, HIST, LATE, etc.)
- **Tokamak & Advanced Tokamak** - (DIII-D, C-Mod, K-Star, JT60-U, etc.)
- **Stellarators** - (QPS) In Design
- **Example** Fusion Configurations
  - Spherical Tokamak (Spherical Torus)
  - Tokamak & Advanced Tokamak
  - Stellarators
- **Improved Plasma Stability at High β**
- **Average Safety factor, q_avg**
- **Field Reversed Configuration** - (LDX, etc.)
- **Reversed Field Pinch** - (MST, etc.)
- **Dipole** - (LDX, etc.)
- **LHD**

(SSPX, etc.) Spheromak

0.5 \( \frac{\text{(Applied Field)}}{\text{(Applied + Plasma-Produced Field)}} \) → 1

(Self-Organized) Increase Controllability → (Externally Controlled)
In MAST, However, Counter NBI Reduces Electron Energy Loss

High flow shear scenario on MAST (Co- & Counter-NBI)

- Counter-NBI produces stronger $\omega_{SE} \sim 10^6\ s^{-1}$ and strong local reduction in $\chi_e$ at broader radius
- Pressure gradient contribution to $E_r$ reinforces that due to $V_\phi$ with ctr-NBI
- Strong ExB flow shear and weak magnetic shear $s \sim 0$ produced by NBI heating during current ramp
- With co-NBI ion thermal transport reduced to N.C. level $\chi_i \sim \chi_{i, NC}$ with weaker reduction in $\chi_e$
- Strong ExB flow shear $\omega_{SE} > \gamma_{m, ITG}$ and $s \sim 0$ at minimum of $\chi_{i,e}$
Detailed Diagnosis and Gyrokinetic Analysis of $\beta \sim 1$ Turbulence Has Broad Scientific Importance

Can $k_{\perp}\rho_i \geq 1$ turbulence at $\beta \sim 1$ be understood?

Astrophysics turbulence dynamics: cascading of MHD turbulence to ion scales is of fundamental importance at $\beta > 1$

Fusion’s gyrokinetic formalism apply to astrophysical turbulence, covering shocks, solar wind, accretion disks

Laboratory ST plasmas provide validation of formulism
Optimized Device Configuration Features of ST Can Fulfill the CTF Mission Effectively

- Single-turn demountable center leg required for toroidal field coil to achieve small size and simplified design.
- Fast remote replacement of all fusion nuclear test components (blanket, FW, PFC) & center post required to permit high duty factor & neutron fluence.
- Large blanket test areas $\propto (R+a)\kappa a$.
- Adequate tritium breeding ratio & small fusion power from low A required for long term fuel sufficiency.
- High heat fluxes on PFC.
- Initial core components could use DEMO-relevant technologies (such as from ITER and long-pulse tokamaks).
- 12-MA power supply – Single-turn TF.