NSTX

*Supported by* U.S. DEPARTMENT OF ENERGY | Office of Science

# Recent results from the National Spherical Torus Experiment

## Eric Fredrickson

***For the NSTX Team***

ICPP-LAWPP
Santiago, Chile, Aug. 8-13, 2010

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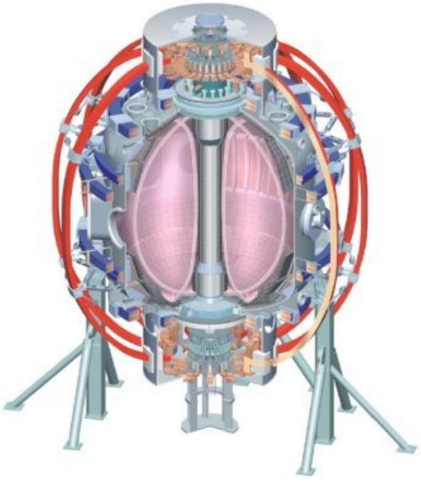

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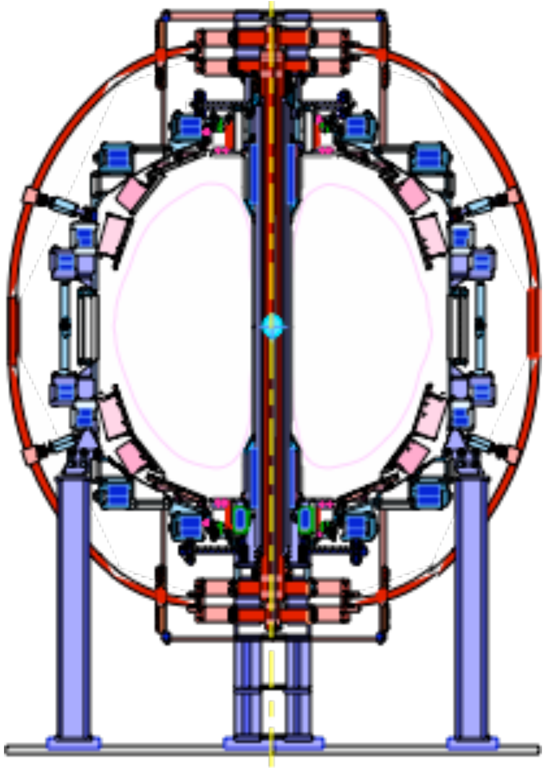
# NSTX is a midsize Magnetic Confinement Fusion Device, a Spherical Tokamak (ST)



$R_0 = 0.86\ m$

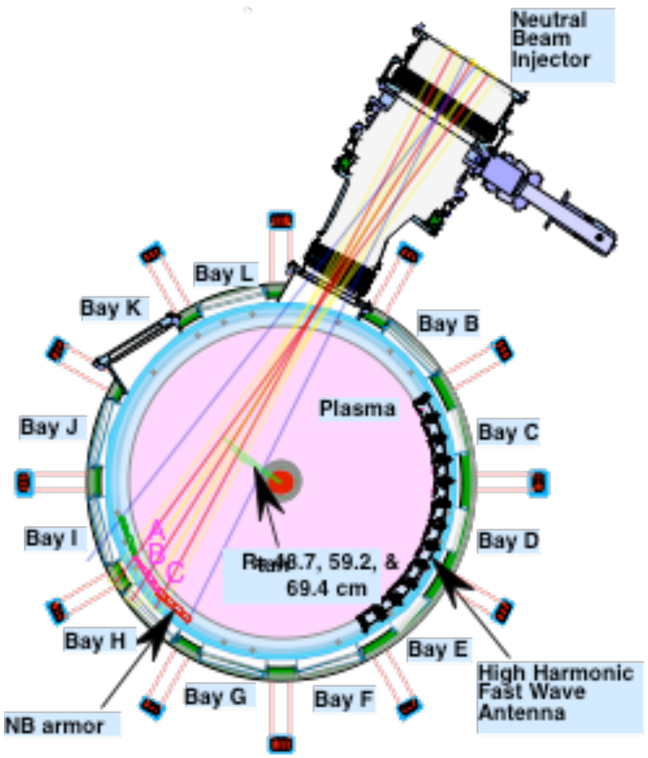
$a \quad = 0.68\ m$

$B_0 = 0.3\text{-}0.55\ T$

$I_p \quad \leq 1.2\ MA$

$\beta_{tor} \leq 40\%$

$n_e \leq 1 \times 10^{20}/m^3$



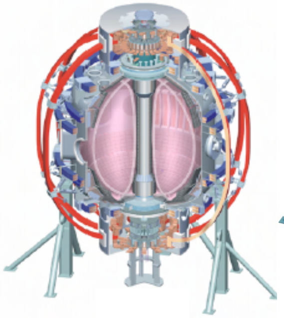
- **Tokamaks confine plasma with toroidal magnetic field and poloidal field generated by the toroidal current in the plasma.**
  - **Higher ratio of plasma pressure to magnetic pressure comes with low A.**
  - **Low aspect ratio ($A=a/R_0$) reduces toroidal field required for a given plasma current, but also leaves little room for the solonoid, shielding of TF conductors.**

# Talk Outline

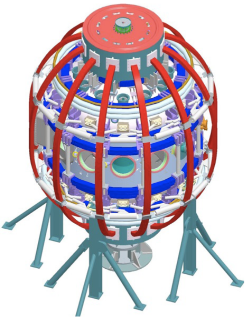
- NSTX place in fusion research
- New capability & goals of 2010 campaign
- Research Program on NSTX supports wide range of Fusion research needs.
  - Energy/particle confinement
  - Energetic Particle physics
  - Macro-stability
  - Boundary physics
  - RF heating
  - Solonoid-free start-up
  - Advanced Scenario & Control
- Summary

# STs offer cost-effective, attractive approach to address fusion program needs

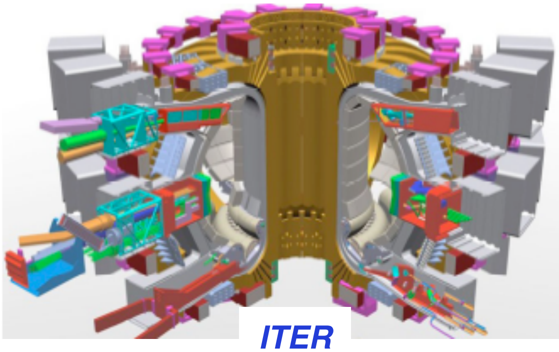
- **STs extend physics regimes of laboratory plasmas**
  - Low A, high $\beta$, high $v_{fast}$ / $v_A$ challenge theory models
  - High power density challenges power handling
  - Longer term NSTX → NSTX Upgrade goals:
    - Study high beta plasmas at reduced collisionality
    - Develop non-inductive start-up, sustainment
    - Study reactor-level heat & particle flux solutions
- **Physics parameters support ITER-relevant research**
  - High $v_{fast}$ / $v_A$, high $\beta_{fast}$ reach reactor relevant levels
- **NSTX research will form basis for designing next step Spherical Tokamak devices**
  - Understand and utilize ST for addressing key gaps between ITER and FNSF / DEMO
  - Advance ST as fusion power source



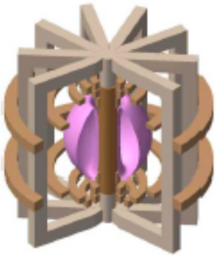
*NSTX*



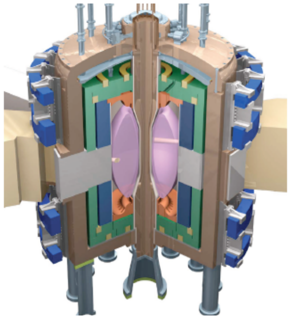
*NSTX-U*



*ITER*



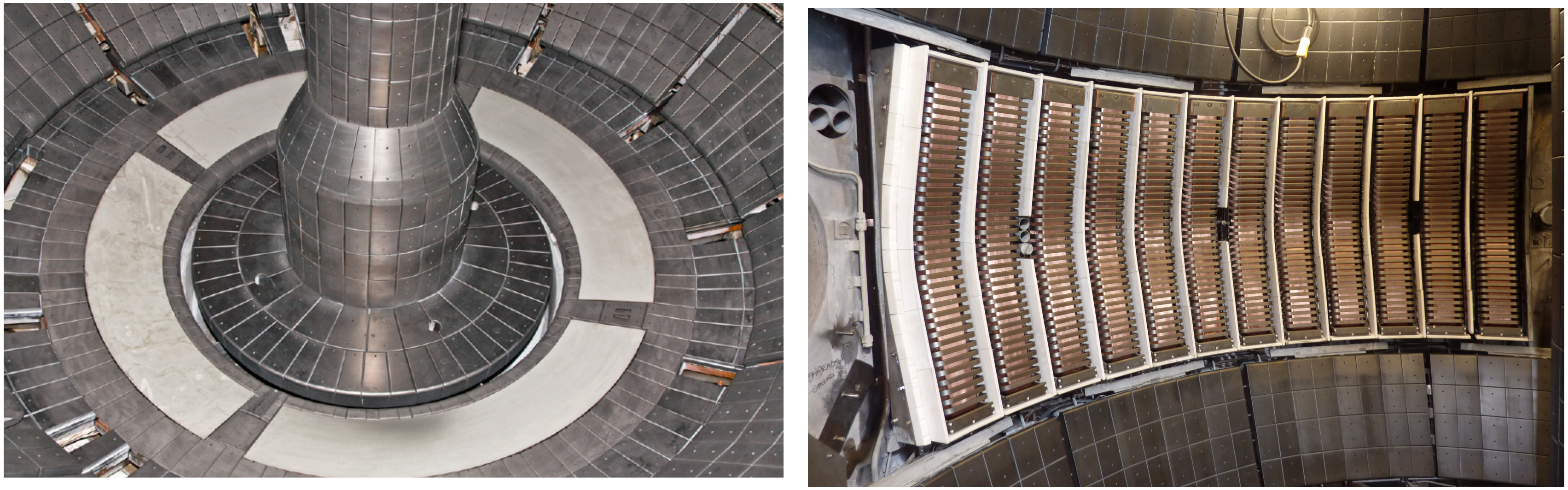
*ST-based Plasma Material Interface (PMI) Science Facility*



*ST-based Fusion Nuclear Science (FNS) Facility*

# Novel Liquid Lithium pump added for 2010, HHFW antenna upgraded for higher power

- **Porous molybdenum holds film of liquid lithium on heated plates**
  - **Liquid lithium pumps deuterium, controlling recycling & plasma density**
  - **Recycling control is proven method to improve plasma energy confinement**
  - **Liquid lithium might provide rugged, heat tolerant plasma facing material**



- **Antenna upgraded to double-ended feed to improve power handling**
  - **Multi-strap antenna launches Alfvén waves to heat, drive current**
  - **Waves well above ion cyclotron frequency, damp on electrons**
  - **Multi-strap antenna allows directional wave launching**

# NSTX research goals support ITER and fusion program needs

- Improve understanding of the heat transport in the SOL plasma in support of projecting divertor conditions in ITER
  - Measure divertor heat flux profiles, plasma characteristics in the SOL
- Assess H-mode pedestal, ELM stability vs. n*, Li conditioning
  - Determine how Li from LiTER and LLD affects ELM stability, pedestal
  - Assess L-to-H threshold, pedestal height/width/stability
- Characterize HHFW heating, current drive, and current ramp
  - Sustain 100% non-inductive plasma
  - Develop bootstrap current over-drive ramp-up
  - Enhance NBI-CD with higher electron temperatures
- Assess sustainable $\beta$ and disruptivity near/above ideal no-wall limit
  - Assess impact of improved mode detection and control algorithms
  - Characterize degree to which other instabilities (2/1 NTM) impact disruptivity

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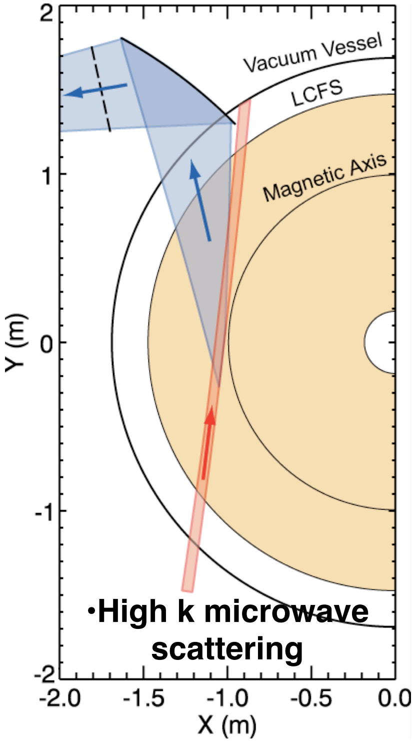
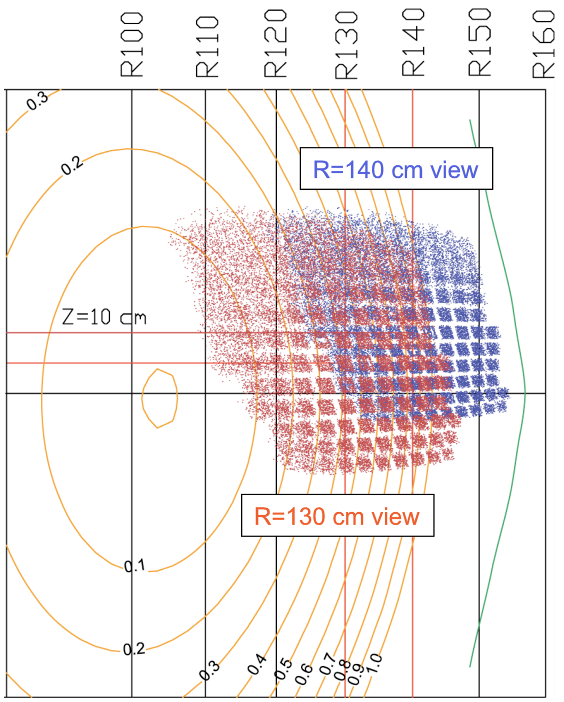
# Predictive model of thermal transport is a top priority for both ST and tokamak programs

- STs operating regime allows unique measurements of turbulence
  - high-k scattering diagnostic to measure electron gyro-scale fluctuations
  - Beam Emission Spectroscopy (BES) measures ion gyro-scale fluctuations
- NSTX can achieve neoclassical ion transport due to strong rotational flow shear, but electron transport is anomalous and high
  - high $\beta$, strong E×B flow shear, large $\rho_e$



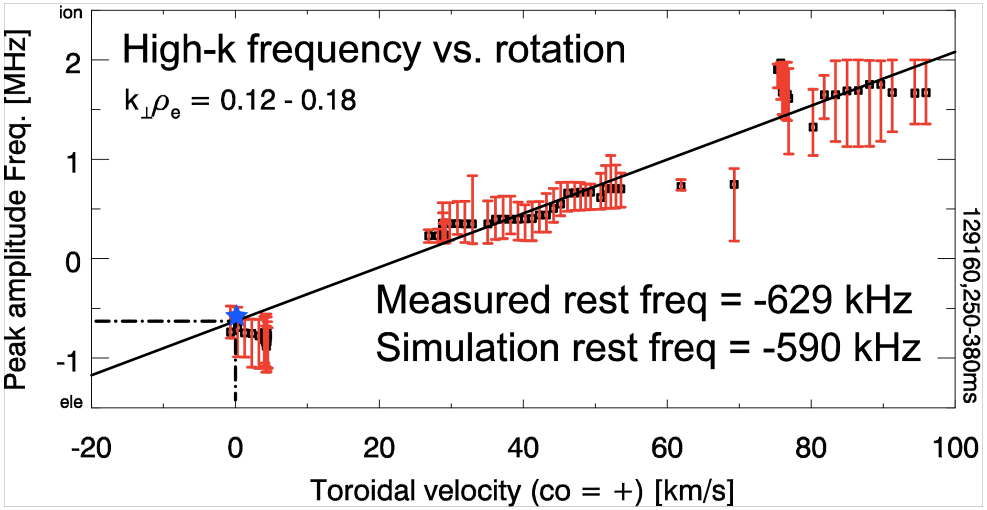
•High k microwave scattering

- **Small-angle scattering of microwave beam measures short wavelength density fluctuations**
- **BES imaging of $D_\alpha$ emission from neutral beam atoms measures local density fluctuations.**
- **Wavelength resolution limited by spatial imaging resolution**

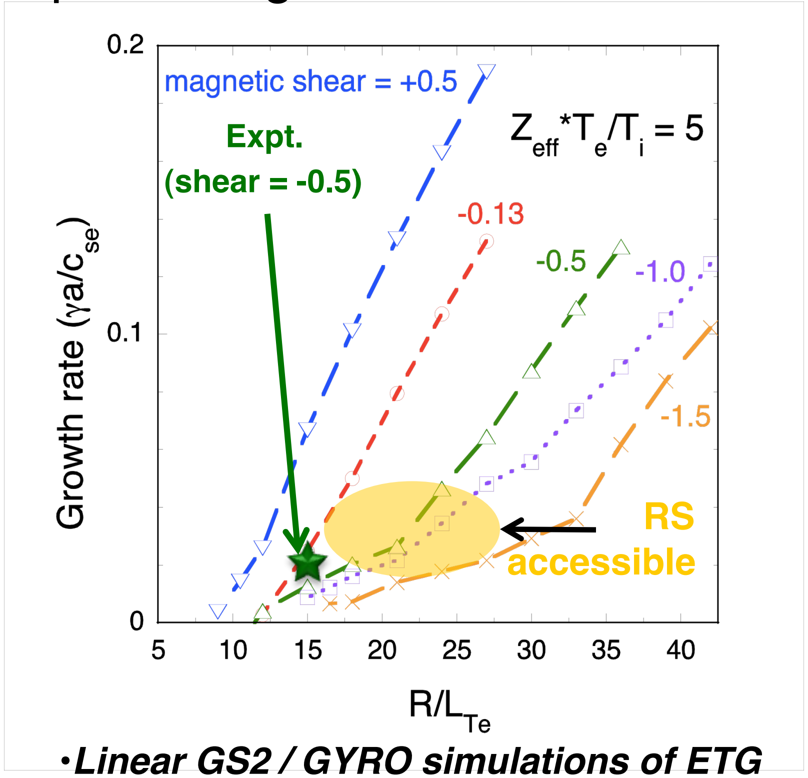


# ETG suspected of driving electron transport

- ETG mode has been identified by comparing linear growth rate and rest frequency of measured fluctuations to linear GS2/GYRO calculations
- ETG in e-ITB found to be suppressed by reversed magnetic shear, allows access to supercritical electron temperature gradients

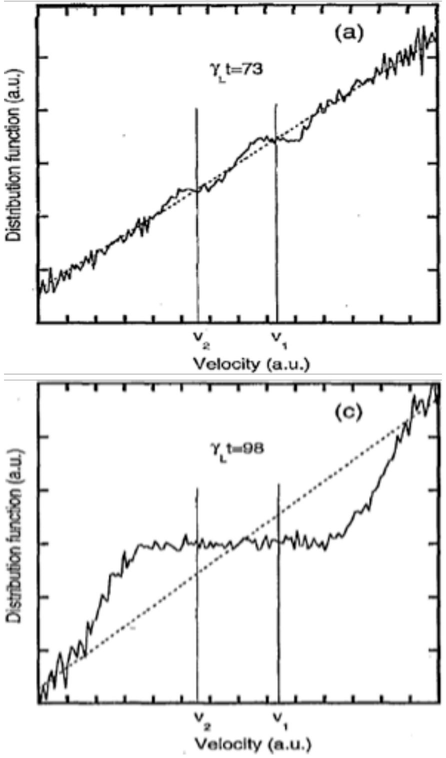


*•Rest frequency of peak amplitude mode measured by subtraction of Doppler shift due to plasma rotation*



*•Linear GS2 / GYRO simulations of ETG mode growth rates are consistent with high-k measurements*

# NSTX operates with high $\beta_{fast}$ and $V_{fast}/V_{Alfvén} \leq 4$; broad spectrum of Alfvénic modes present

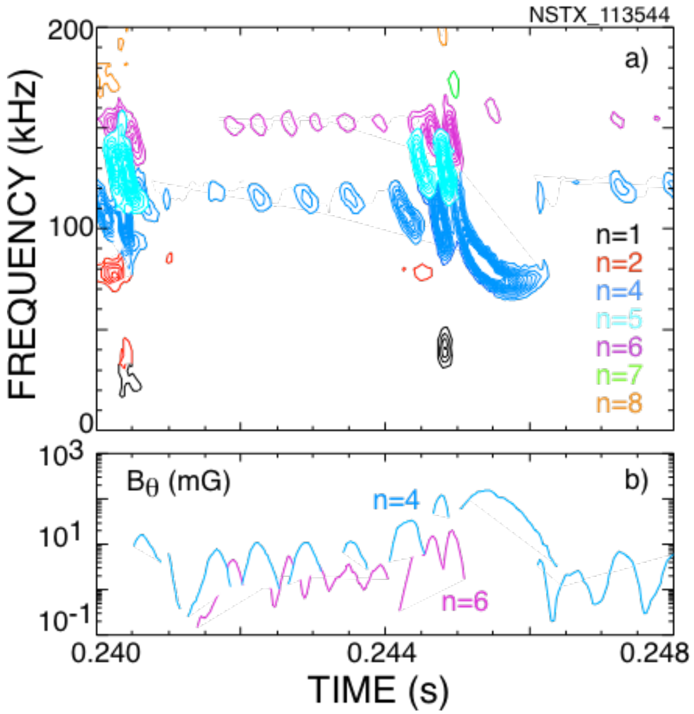


Berk, *et al.*, Phys. Plas. **2** (1995) 3007

- Large amplitude modes overlap in fast-ion phase-space.
- Interaction results in new modes, stronger drive.

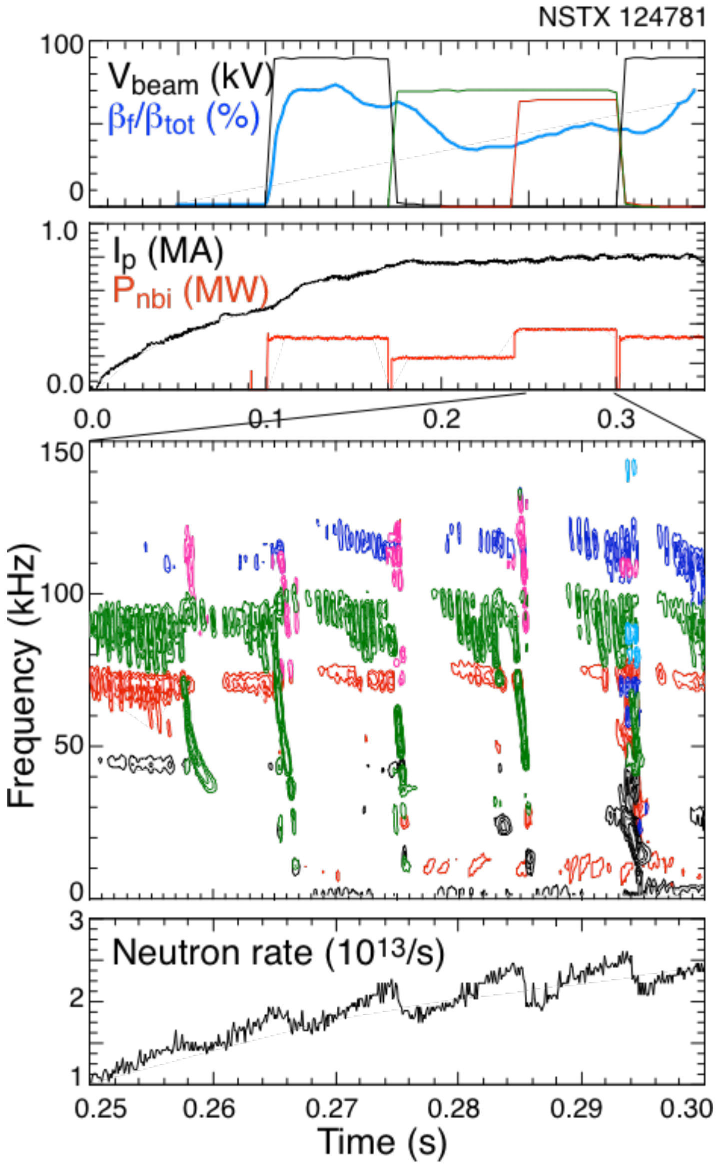
- More free energy accessed, more transport
- TAE have multiple resonances, more complex physics.

- Overlap of EPM/TAE/GAE/CAE can also lead to avalanching.



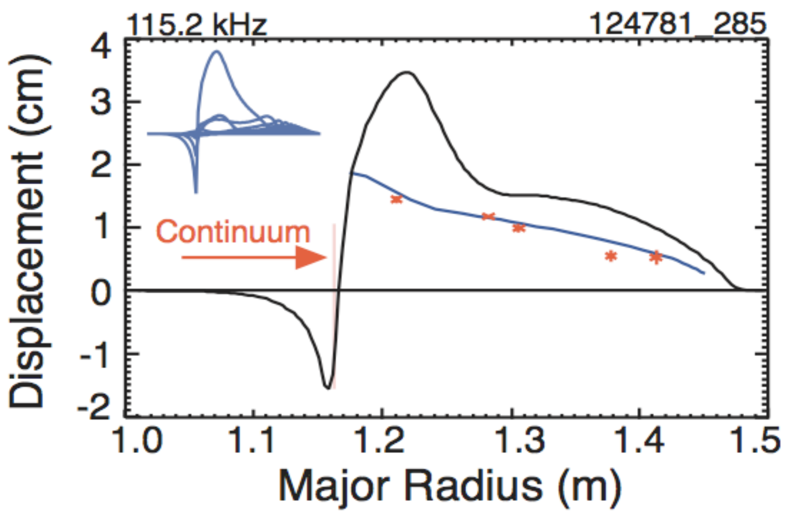
# Interaction of multiple Toroidal Alfvén Eignmodes seen to greatly enhance fast ion transport

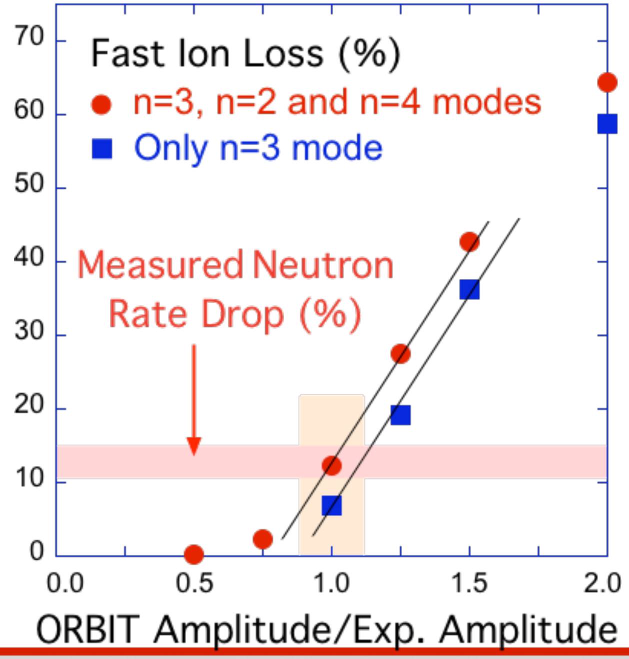
- Fast ion losses of 10% to 20% inferred from neutron drops, Da spikes, FIDA, NPA
  - Correlated with spike in TAE amplitude and presence of multiple modes
  - Mode numbers measured with Mirnov array
  - Experimental studies carried out in L-mode plasmas (peaked density profile)
    - Reflectometer array used to measure density fluctuation profiles of TAE
- Unperturbed fast ion distribution calculated with TRANSP
  - Calculation not self consistent; neglects redistribution from previous avalanches
- Mode frequencies, amplitudes and spatial structure used to simulate losses.
  - *Linear*; *not self-consistent*; mode amplitude/ frequency in ORBIT adjusted to mimic data



# Modeling TAE avalanches with linear codes (ORBIT, NOVA-K) reproduced measured fast ion losses

- Procedure:
  - Calculate linear eigenmodes with NOVA-K
  - Match and select “observed” modes based on measured mode structure (reflectometer)
  - Rescale amplitude according to measured displacement
    - Use experimental frequency evolution – NOVA doesn’t model frequency chirp
- Simulated losses agree with experiment
  - Threshold for onset of losses consistent with avalanche model
    - Presence of multiple modes lowers stochastic threshold
    - Single TAE have multiple resonances; single mode could show avalanche behavior
- Main limitations:
  - *Linear*; *not self-consistent*; mode amplitude/ frequency in ORBIT adjusted to mimic data

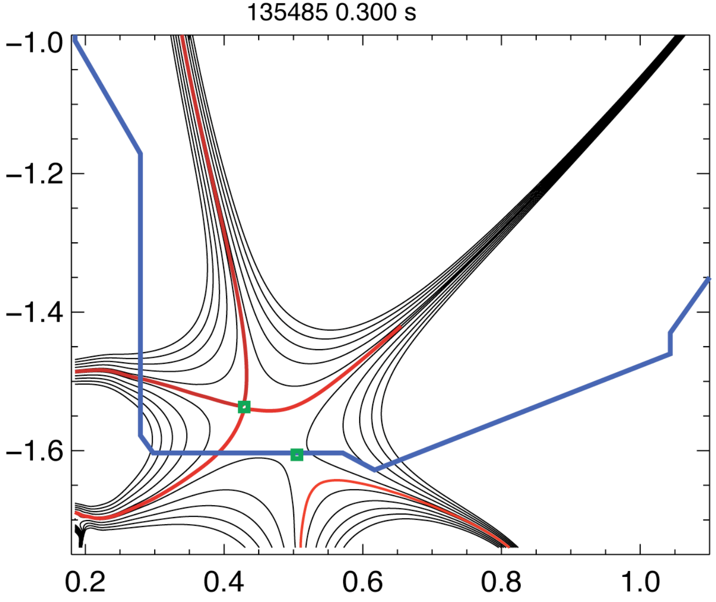


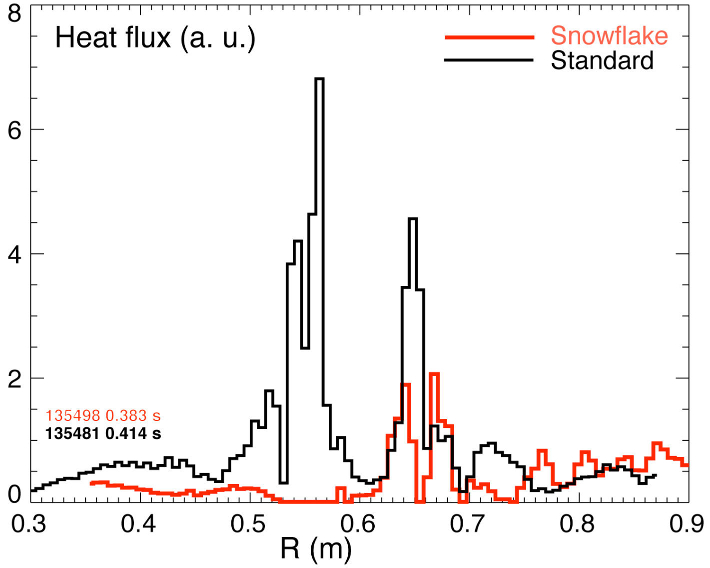


Phys. Plasmas **16**, 122505 (2009)

# NSTX contributes to critical research areas in the plasma boundary for ITER/tokamaks and STs

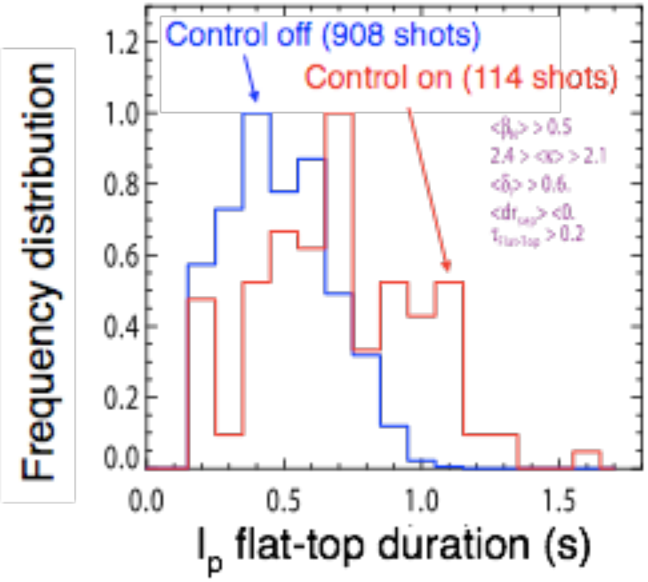
- NSTX experiments have seen reductions in peak heat flux with “snowflake” divertors
  - Improved control techniques being developed for more stable “snowflake” configurations
  - NSTX has $q_{||}$ up to 300 MW/$m^2$, $q_{peak}$ up to 15 MW/$m^2$, low $l_{||}$~5-12 m, in/out power split ~1:3
- 3D fields trigger ELMs for impurity control
  - Lithium films suppress ELMs on NSTX
- Characterize ST H-mode pedestal structure and transport
  - Improve understanding of physics of pedestal
  - SOL stability/transport vs. 3D field
- Dust is issue for ITER and future tokamaks
  - Dust diagnostics and cleaning techniques are being developed on NSTX.

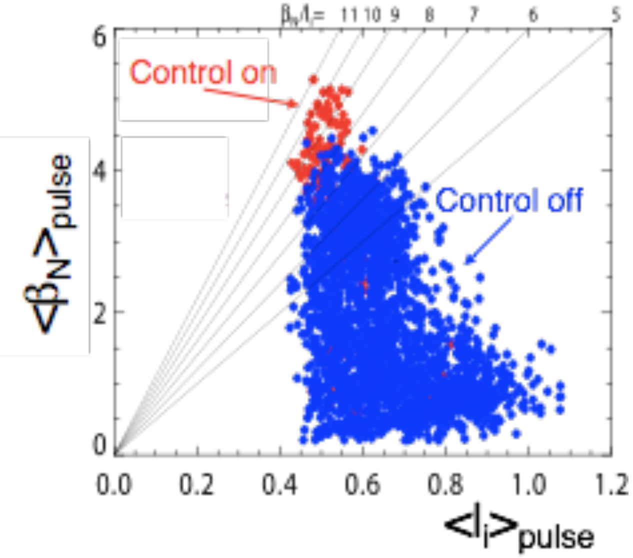




# NSTX is investigating Active Feedback Control of External Kinks to Extend Operating Space

- Hardware, feedback algorithms to actively correct error fields and feedback stabilize external kink instabilities being developed
  - External kinks stabilized by plasma rotation, close-fitting conducting wall
    - active feedback extends operating space
  - Error fields slow plasma rotation, can be amplified by plasma
    - error fields originate from mis-aligned coils, eddy currents in vacuum vessel, currents in scrape-off layer, ...
- Many aspects of disruptions need explication
  - NSTX studies contribute to understanding of disruption halo currents

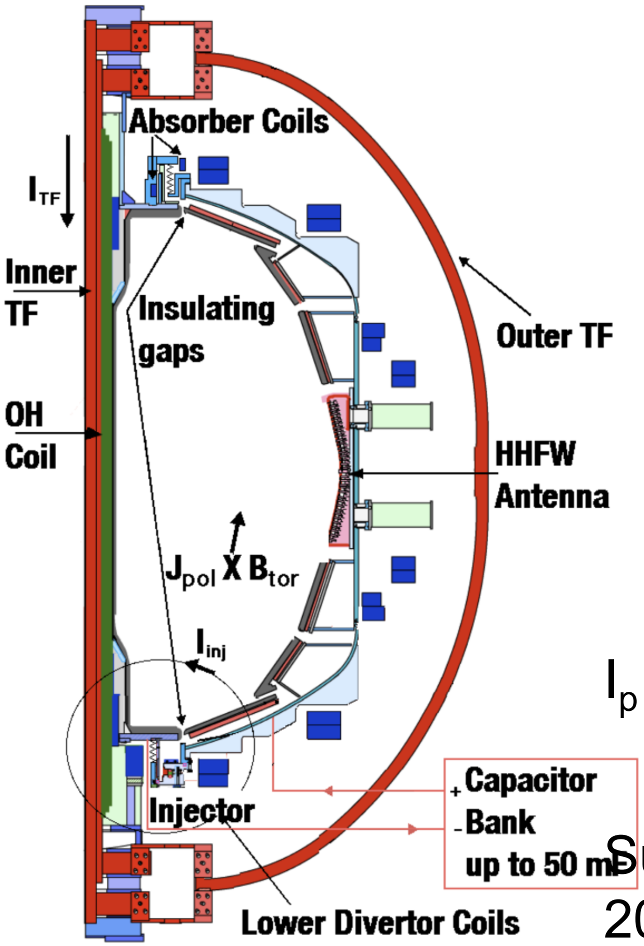


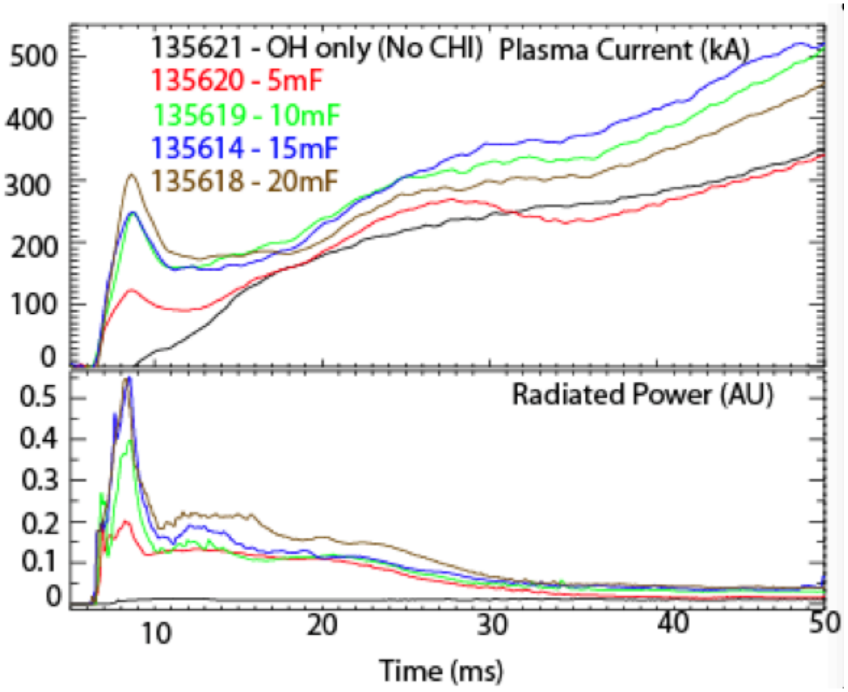


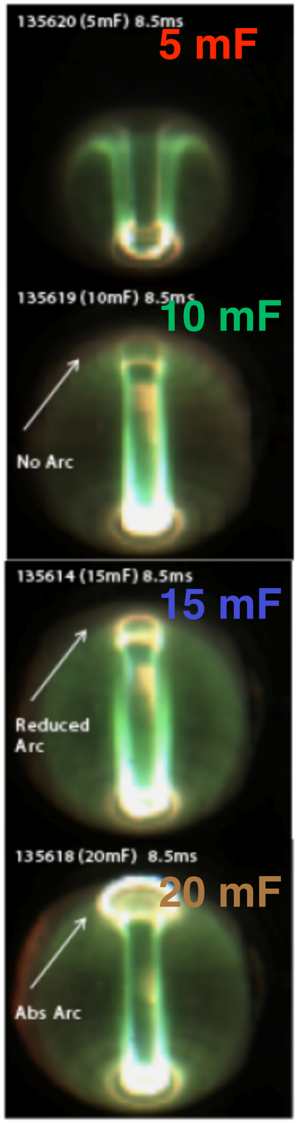
# NSTX is a leader in developing start-up and ramp-up techniques for STs

- **Transient CHI now a proven method to generate closed flux**
  - Startup & inductive coupling at 200kA demonstrated on NSTX
  - CHI initiated and inductively ramped current reached 700kA in H-mode plasmas reaching 800eV
  - Used absorber coils to reduce absorber arcs
  - Used Li to reduce impurities during CHI
  - Will investigate use of HHFW in CHI phase
  - Will test CHI performance implications of metal electrodes (from LLD)
- **HHFW Heating and Current Drive for Ramp-up**
- **Outer PF start-up was demonstrated on DIII-D and NSTX**
  - DIII-D experiment with high power ECH and NB current drive
- **Plasma Gun start-up being investigated on Pegasus**
  - Design/install on NSTX as progress on PEGASUS warrants, FY2012 or later

# Ip increases with CHI energy until absorber arc occurs





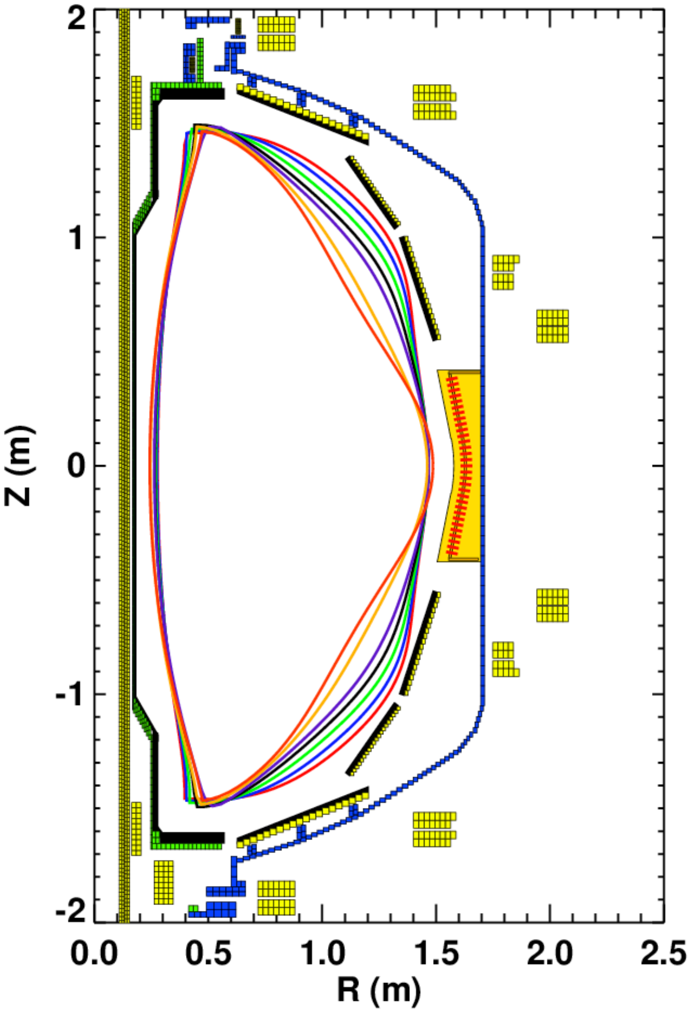


- $I_p$ ~ 200 kA greater than ohmic only
  - Best in 2008 was ~ 50 kA, 4-fold improvement
- Successful coupling to induction using 20 mF (goal is 50 mF)
  - Ignoring impurity effects, expect current to scale with capacitor energy

# Goals for the Advanced Scenarios and Control TSG

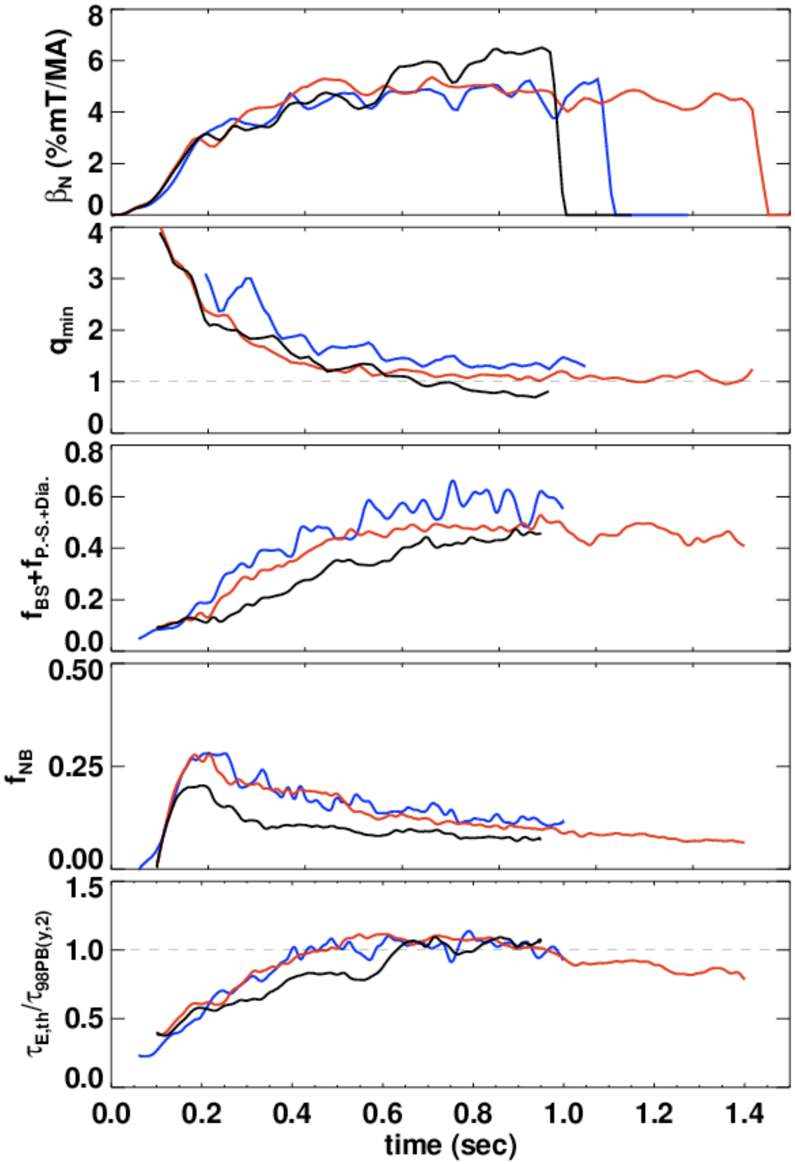
- *High non-inductive current fraction plasmas with high-$\beta$.*
- *Long-pulse density control for increased NBCD using improved fueling and lithium conditioning.*
- *Core electron heating, impurity reduction, and current drive with High-Harmonic Fast Waves.*
- *Improved plasma control for advanced operating scenarios.*
- *Extend range of achievable plasma shapes.*

***Extend the Range of Achievable Plasma Shapes***

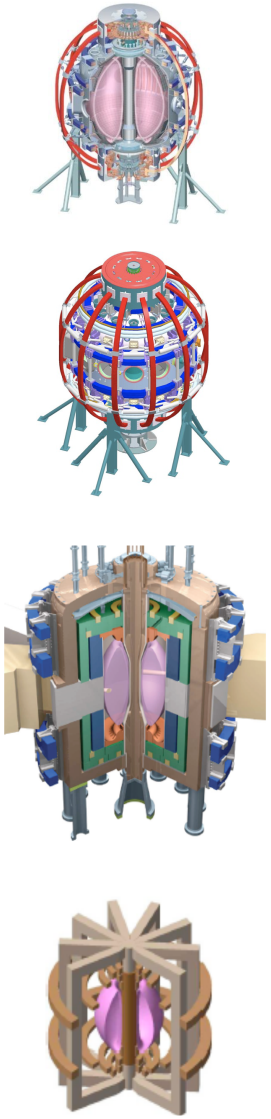


# Large Non-Inductive Fraction and Good Confinement Achieved Over a Range of q at High-κ

- *$\beta_N \geq 4.5$ for all scenarios.*
- *Matches ST-CTF design point.*
- *$f_{BS}$ approaching 50%.*
- *Matches ST-CTF design point.*
- *Early $f_{NB} > 25\%$, decreases as density rises.*
- *Loss in $f_{NBCD}$ partially made up for with $f_{BS}$.*
- *$H_{98}$~1 in all cases.*
- *Further confinement improvements are desirable.*



# NSTX Upgrade will contribute strongly to toroidal plasma science and preparation for a fusion nuclear science (FNS) program



- NSTX:
  - Providing foundation for understanding ST physics, performance
- NSTX Upgrade:
  - Study high beta plasmas at reduced collisionality
    - Vital for understanding confinement, stability, start-up, sustainment
  - Assess full non-inductive current drive operation
    - Needed for steady-state operating scenarios in ITER and FNS facility
  - Prototype solutions for mitigating high heat, particle exhaust
    - Can access world-leading combination of P/R and P/S
    - Needed for testing integration of high-performance fusion core and edge
- NSTX Upgrade contributes strongly to possible next-step STs:
  - ST Fusion Nuclear Science Facility
    - Develop fusion nuclear science, test nuclear components for Demo
    - Sustain $W_{neutron} \sim 0.2\text{-}0.4 \rightarrow 1\text{-}2 MW/m^2$, $\tau_{pulse} = 10^3 \rightarrow 10^6 s$
  - ST Plasma Material Interface Facility
    - Develop long-pulse PMI solutions for FNSF / Demo (low-A and high-A)
    - Further advance start-up, confinement, sustainment for ST
    - High $P_{heat}/S \sim 1MW/m^2$, high $T_{wall}$, $\tau_{pulse} \sim 10^3 s$

# Diagnostic Systems Operational with Strong Collaboration Contributions

*Collaboration contributions*

## MHD/Magnetics/Reconstruction

Magnetics for *equilibrium reconstruction*
Diamagnetic flux measurement
Halo current detectors
High-n and high-frequency Mirnov arrays
Locked-mode detectors
RWM sensors (n = 1, 2, and 3)

## Profile Diagnostics

Multi-pulse Thomson scattering (30 ch, 60 Hz)
T-CHERS: $T_i(R)$ and $V_f(r)$ (51 ch)
P-CHERS: $V_\theta(r)$ (71 ch)
*MSE-CIF (15 ch)*
*FIReTIP interferometer (119mm, 6 ch)*
Midplane tangential bolometer array (16 ch)

## Turbulence/Modes Diagnostics

*Tangential microwave high-k scattering*
*Microwave reflectometers*
*Ultra-soft x-ray arrays – tomography (4 arrays)*
*Fast X-ray tangential camera (2ms)*
*Beam Emission Spectroscopy*

## Energetic Particle Diagnostics

Neutal particle analyzer (2D scanning)
SSNPA
Fast lost-ion probe (energy/pitch angle resolving)
Neutron measurements
*Fast Ion $D_\alpha$ profile measurement*

## Edge Divertor Physics

*Reciprocating Edge Probe*
*Gas-puff Imaging (2ms)*
*Fixed Langmuir probes*
Edge Rotation Diagnostics ($T_i$, $V_f$, $V_{pol}$)
*1-D CCD $H_\alpha$ cameras (divertor, midplane)*
*2-D divertor fast visible camera*
Divertor bolometer (20ch)
*IR cameras (30Hz) (3)*
*Fast IR camera*
Tile temperature thermocouple array
Dust detector
Edge Deposition Monitors
*Scrape-off layer reflectometer*
*Edge neutral pressure gauges*
*Edge Sample Probe*

## Plasma Monitoring

*Fast visible cameras*
Visible bremsstrahlung radiometer
Visible survey spectrometer
UV survey spectrometer
*VUV transmission grating spectrometer*
*Visible filterscopes*
*Wall coupon analysis*
*X-ray crystal spectrometer (astrophysics)*