NCSX Research Plans

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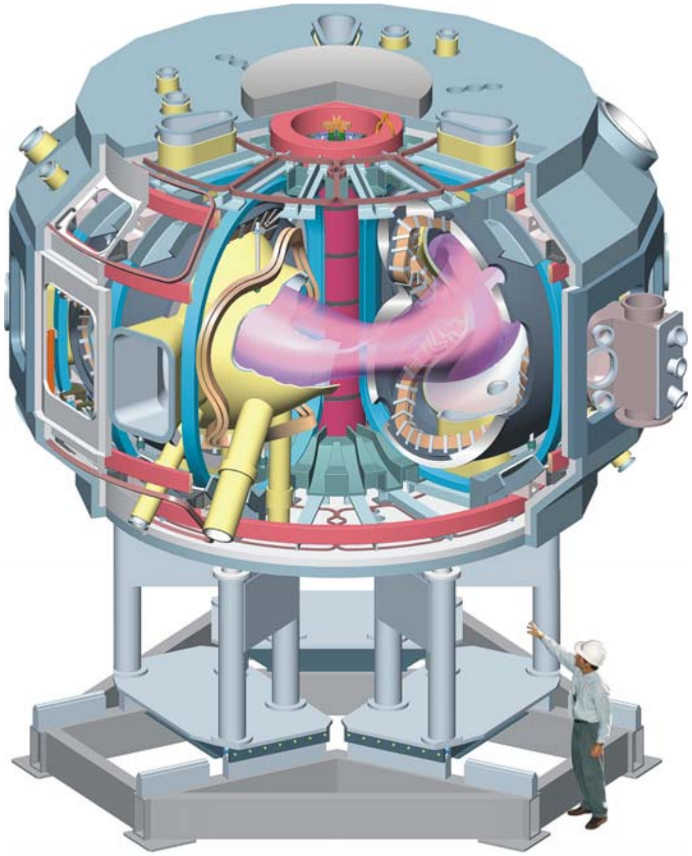
For the NCSX Team

NCSX PAC Meeting - 8

9 November 2006

Outline

- Mission and Context
- Alternate Year Operation
- Research Plans, Upgrades, Priorities
- Impact
- First Research Forum



NCSX Research Mission

Acquire the physics data needed to assess the attractiveness of compact stellarators; advance understanding of 3D fusion science.

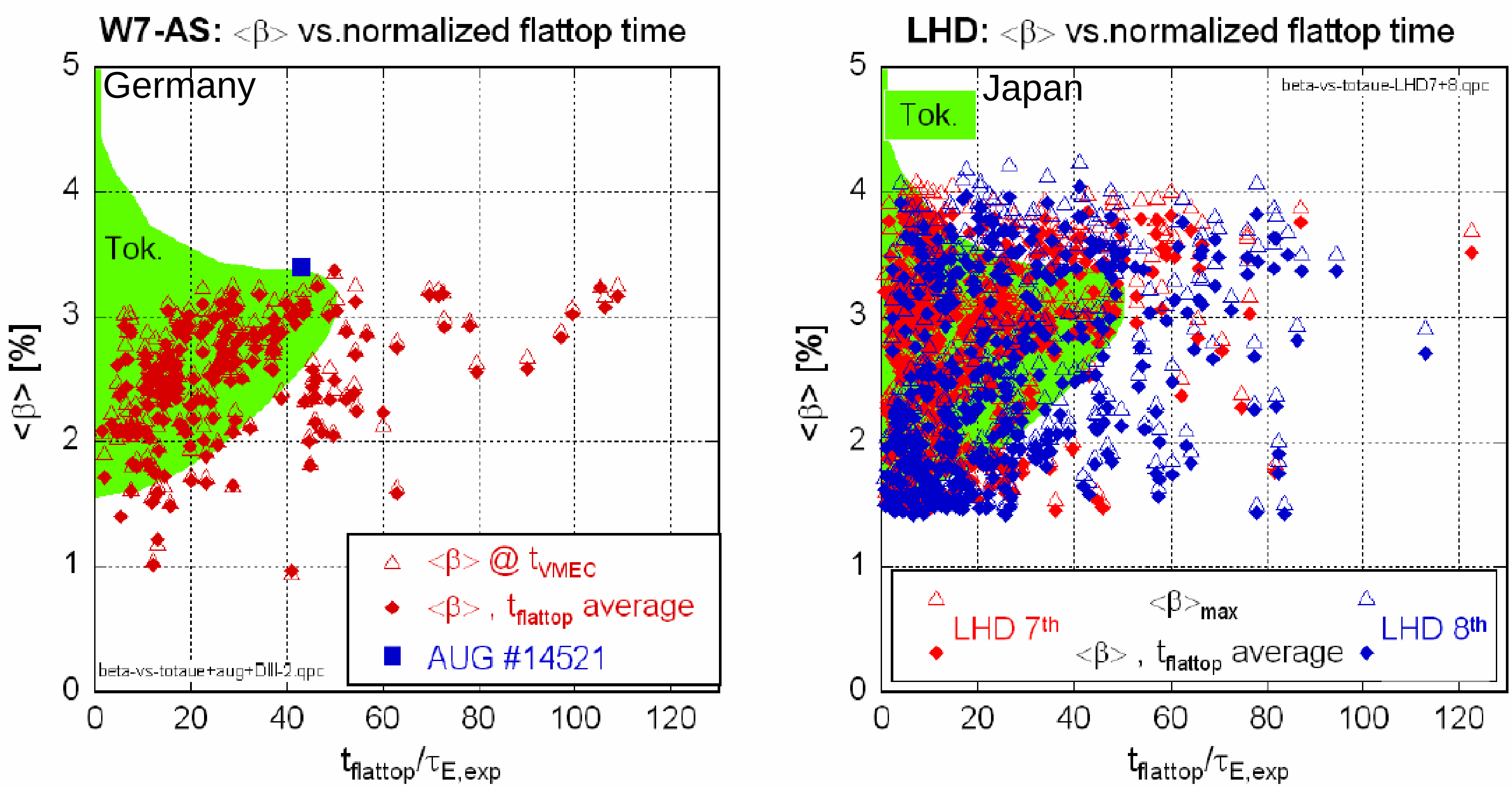
Understand…

- Pressure limits and limiting mechanisms in a low-A optimized stellarator
- Effect of 3D magnetic fields on disruptions
- Reduction of neoclassical transport by quasi-axisymmetric design.
- Confinement scaling; reduction of turbulent transport by flow shear control.
- Equilibrium islands and tearing-mode stabilization by design of magnetic shear.
- Compatibility between power and particle exhaust methods and good core performance in a compact stellarator.
- Energetic-ion stability and confinement in compact stellarators

Demonstrate…

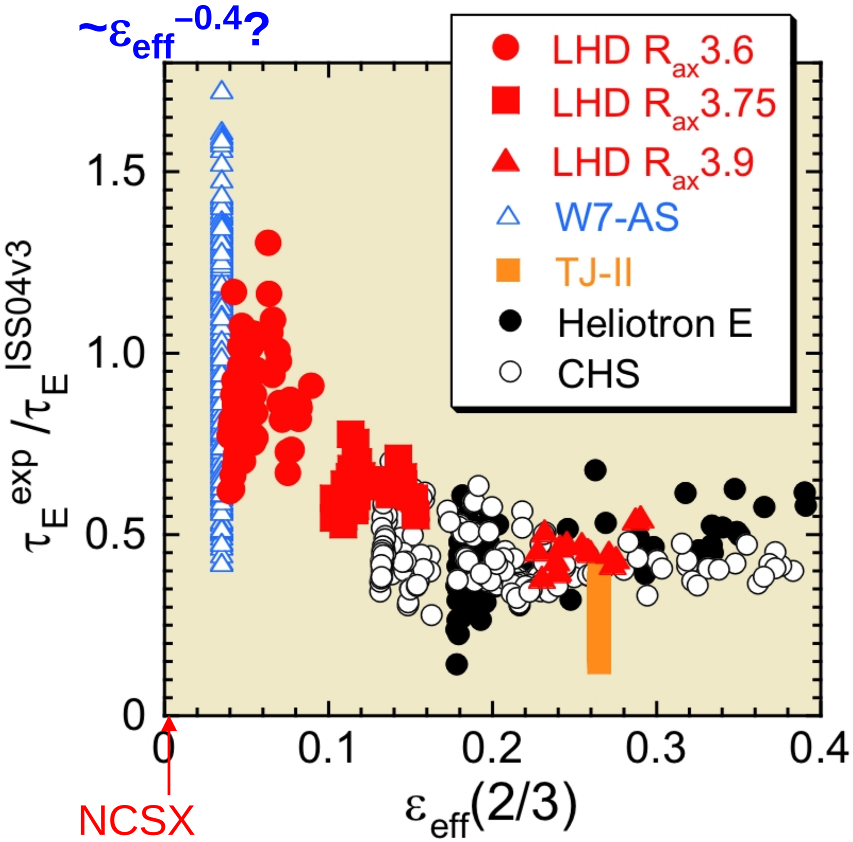
- Conditions for high β, disruption-free operation
- High pressure, good confinement, compatible with steady state

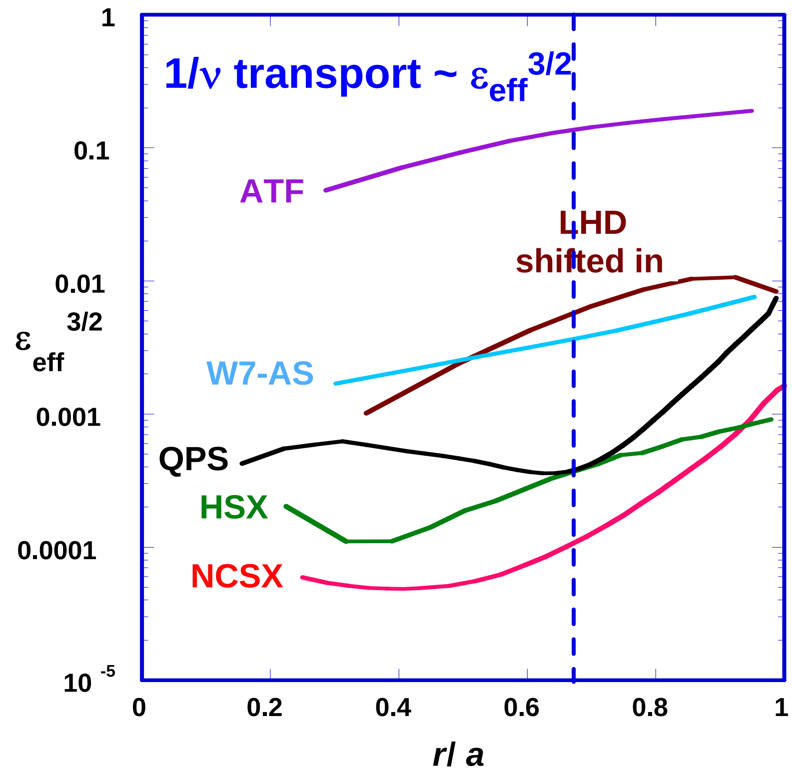
Recent W7AS and LHD Experiments: Steady High-β, Above Linear Limit



- In both cases, well above theoretical stability limit < 2%
- Not limited by MHD activity. No disruptions observed. Sustained without CD.
- Not compact. Not optimized for orbit confinement, flows, stability.

Confinement Depends on Ripple ε_{eff}





- New global confinement scaling study for stellarators (ISS04v3) found strong dependence on ripple magnitude (ε_{eff}).
- Quasi-symmetric designs have the lowest ripple of all configurations.
- HSX has demonstrated advantages of quasi-symmetry: increased confinement and decreased flow damping
- Confinement improvement is stronger than just reduction of neoclassical transport. What is the mechanism?

ARIES-CS Physics R&D Needs

For compact, quasi-symmetric, sustainable high-beta configurations:

1. Can beta ~5% be achieved and sustained at good confinement? What is the maximum useful beta?
2. Can low alpha loss be achieved? Can alpha loss due to MHD instabilities be mitigated by operation at high density?
3. Develop a workable divertor design with moderate size and power peaking, that controls impurities and enables ash pumping.
4. Demonstrate regimes of minimal power excursions onto the first wall (e.g. due to disruptions and ELMs).
5. Under what conditions can acceptable plasma purity and low ash accumulation be achieved?
6. Is the energy confinement at least 1.5 times ISS95 scaling? How does it extrapolate to larger size?
7. Characterize other operational limits (density, controllable core radiation fraction)
8. How does the density and pressure profile shape depend on configuration and plasma parameters?
9. Can the coil designs be simplified? Can physics requirements be relaxed, by
   a. Reduction of external transform
   b. Elimination of stability from optimization
   c. Reducing flux-surface quality requirements
   d. Increased helical ripple
10. What plasma control elements and diagnostics are required?

Plan: Alternating NCSX & NSTX Operation

- Expect budget constant with present NSTX (operating) + NCSX (construct.)
- Devices #1 and #2 are either NSTX or NCSX, alternating
- Cost for NSTX and NCSX operations are considered to be equivalent
- Necessitates sharing of Research and Operations staff: Joint Operation

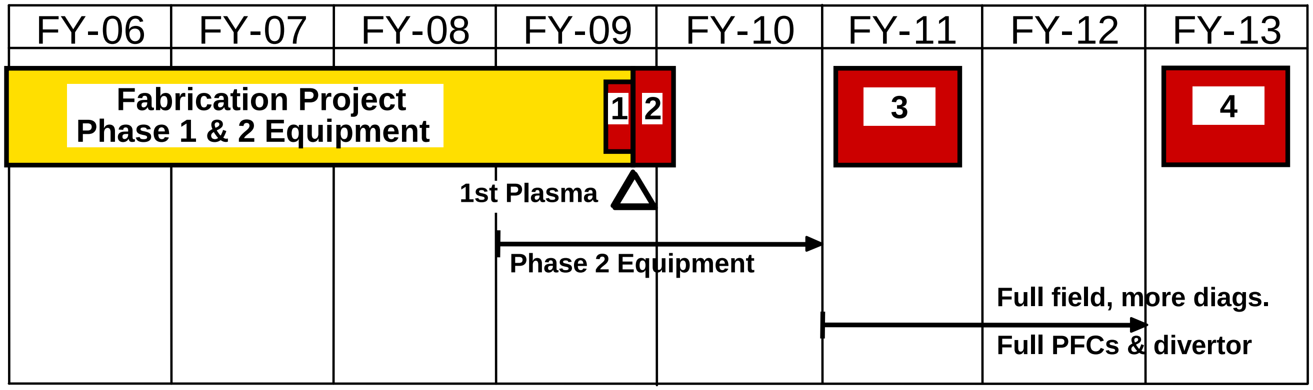
Steady state operation	FY07 $M
Run weeks	
Device #1	25
Device #2	0
Total Run Weeks / Year	25
Budget($M in FY 07)	
Device #1	
Facilty	19.3
Research	17.0
Device #1 Total	36.3
Device #2	
Facilty (incl. upgrades)	7.8
Research (incl. diag. upgr.)	7.9
Device #2 Total	15.7
National NSTX+NCSX	52.0

Fiscal Year	2007	2008	2009	2010	2011	2012	2013
NCSX run weeks			6	0	25	0	25
NSTX run weeks	12	10	12	17	0	25	0

Starting in FY10-11, NSTX and NCSX Alternate Operation

- Both NSTX & NCSX Research are national/international collaborations
  - NCSX Research led by PPPL-ORNL partnership
- Joint facility operation staff, alternating between NSTX & NCSX
- Will share equipment when sensible (some already envisioned)
- Shared research staff
  - Most will participate in both experiments, alternating
- U.S. Collaborators that participate on both NSTX & NCSX will increase efficiency, highly desirable

NCSX Experimental Campaigns



Research Phases:

1. Stellarator Acceptance Testing & First Plasma (Fabrication Proj.)
2. Magnetic configuration studies
   – electron-beam mapping studies
3. Initial Heating Experiment
   – 3MW NBI. ECH?
   – B $\geq$ 1.2T
   – Partial PFC coverage
   – Initial diagnostics, magnetics, profiles (n_e, T_e, T_i, v_ϕ, P_{rad}) & SOL
4. High beta Experiments
   – 6MW heating
   – B = 2T; divertor
   – Improved diagnostics

Magnetic Configuration Mapping Goals for FY09

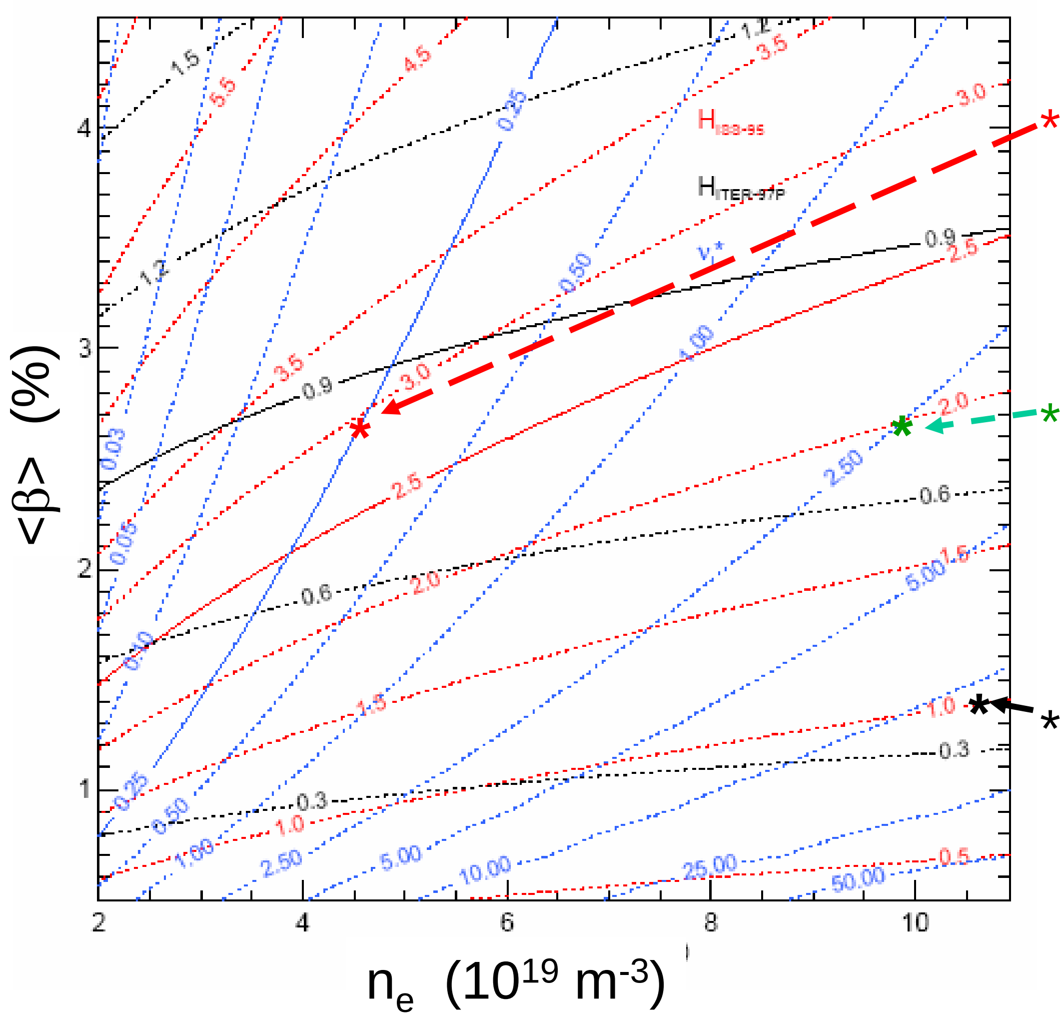
- Document vacuum flux surface characteristics
  - Particularly low-order resonant perturbations
- Document control of vacuum field characteristics using coil current
- Document and model as-built coils

See E. Fredrickson's talk for more details

Wide Range of β and ν* Accessible in FY11

Contours of H_{ISS95}, $H_{ITER-97P}$, and min ν_{*i}

<u>B = 1.2 T, 3MW</u>



β=2.7%, ν_{*i} =0.25 with
H_{ISS95}=2.9; **H_{ISS04}=1.5**
$H_{ITER-97P}$=0.8

β=2.7%, ν_{*i} =2.5 with
H_{ISS95}=2.0; **H_{ISS04}=1.0**

β=1.4%, collisional with
H_{ISS95}=1.0, ; H_{ISS04}=0.5
sufficient to test stability theory

LHD and W7-AS have achieved H_{ISS95} ~ 2.5
PBX-M obtained β = 6.8% with $H_{ITER-97P}$ = 1.7 and H_{ISS95} ~ 3.9

Initial Heating Experiments (FY11) Programmatic Goals

- Demonstrate basic real-time plasma control (I_P, n_e, R? Iota??)
- Characterize confinement and stability
  - Variation with global parameters, e.g. iota, shear, Ip, density,rotation...
  - Sensitivity to low-order resonances
  - Operating limits

- Investigate local ion, electron, and momentum transport and effects of quasi-symmetry
- Test MHD stability at moderate β, dependence on 3D shape
- Characterize SOL properties for different 3D geometries, prepare for the first divertor design.
- Explore ability to generate transport barriers and enhanced confinement regimes.

Collaboration on achieving these goals is welcome.

Details will be discussed in talks this afternoon, and at Research Forum.

Scientific Goals: FY11

What high priority results and papers should be produced?

- Effect of quasi-axisymmetry on rotation damping
- Effect of quasi-axisymmetry on plasma confinement
- Comparison of very low ripple stellarator confinement with scalings

- Equilibrium reconstruction in NCSX
- Comparison of measured and calculated linear MHD stability
- Whether pressure-driven linear MHD stability is limiting
- Whether current-driven linear MHD stability is limiting w/ reversed shear
- Occurrence of pressure driven islands vs iota and shear

- Effect of 3D equilibrium on SOL characteristics and contact footprint

FY09-10: NCSX Diagnostic Upgrades for FY11

Initial diagnostic upgrades (complete list in B.Stratton's talk)

- In-vessel magnetic diagnostics + instrument external magnetics diags.
- Thomson-scattering profile (10 core, ~5 edge channels, multipulse)
- DNB and toroidal CHERS profile (v_ϕ, T_i, n_C)
- UV spectrometer
- PFC-mounted probes
- Filtered 1D and 2D cameras. Filterscopes.
- IR camera
- SXR camera
- Bolometer array

Black: shared w/ NSTX may be more

- MSE
- SXR tomography

Probably not affordable until FY-13

Collaborations on diagnostics are welcome.

Choices and details will be discussed at NCSX Research Forum

FY09-10: Equipment Upgrades for FY11

Major elements in FY09 & FY10 :

- Data acquisition and control
  - acquisition of diagnostics, data infrastructure
  - diagnostic control; initial plasma feedback control

- Heating systems
  - 3MW NBI refurbishment and installation
  - 600 kW ECH heating possible via collaboration with MP/IPP

- Plasma facing components and NB armor
  - partial liner inside vacuum vessel (~1/3 coverage)
  - wall conditioning & boronization

- Power systems (supporting 1.2T operation)
  - Modular coils and TF powered from D-site, PF coils from C-site
  - Merged C/D-site interlocks and controls
  - Power for diagnostics

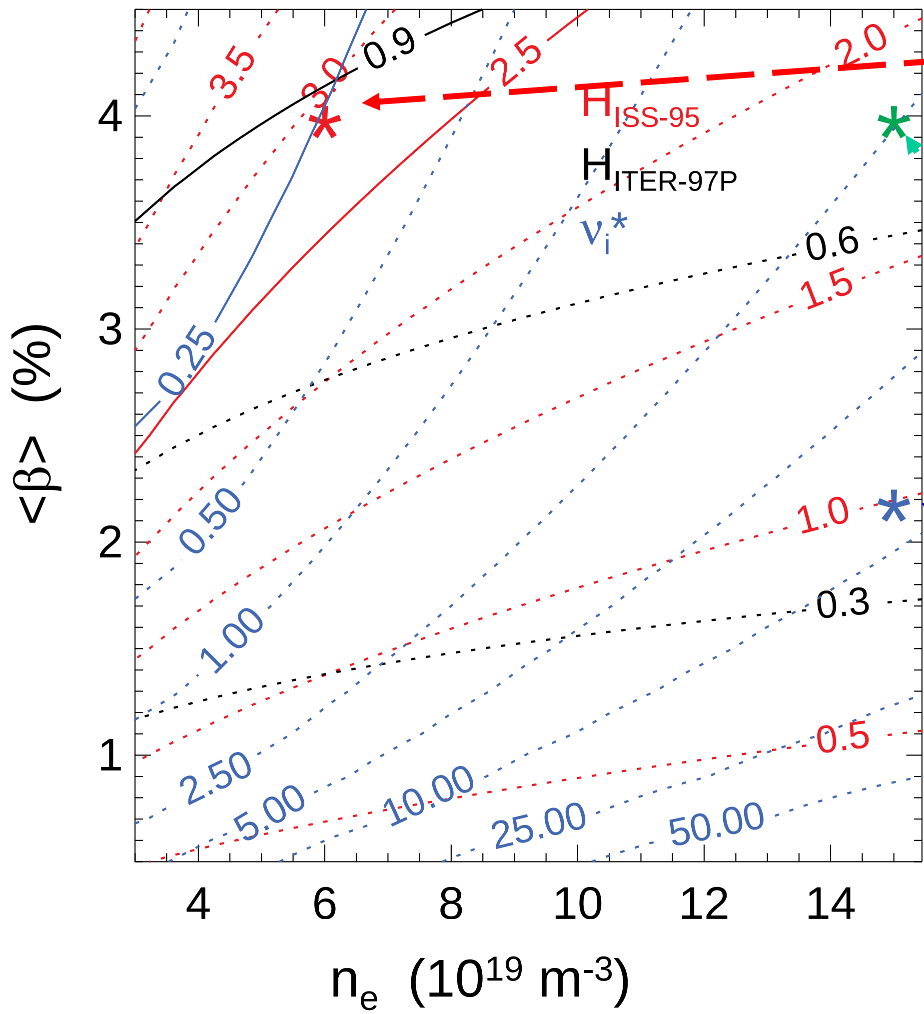
FY11: Tradeoffs & Priorities

Finite resources require choices between opportunities. In our present planning, elements near the resource boundary are (in approximate priority order) :

- Install PF3 (and full-design OH solenoid)
  - MIE project installing smaller, existing solenoid (adequate for 1.2T) (and, considering not installing any solenoid)
  - MIE also not installing PF3 shaping coil (same design as original solenoid)
  - We need to study impact on research for FY11. Current plan: install PF3 & solenoid
- 600 kW ECH Heating (IPP collaboration)
  - Heating without driven currents. Less risk of density control problems than NBI
  - Allows low collisionality & perturbative transport experiments. Separation of ion and electron channels
- 25 Weeks of runtime
  - Alternative is ~20 weeks of running
  - Need runtime to commission diagnostics; aggressive start on experiments
- Additional major diagnostic systems
  - MSE: to diagnose plasma effects on internal Bp
  - Initial SXR tomography cameras: for more MHD and flux surface shape info

High-β, low ν* Plasmas Accessible in FY13

Contours of H_{ISS95}, $H_{ITER-97P}$, and min ν_{*i}



B = 1.2 T, 6MW

* **β=4%,** ν_{*I} =0.25 requires H_{ISS95}=2.9, **H_{ISS04}=1.5** **$H_{ITER-97P}$=0.9**

* **β=4%** at Sudo 'density-limit' H_{ISS95}=1.8, **H_{ISS04}=0.9**

* **H_{ISS95}=1.0** gives **β=2.2%** at high collisionality

LHD and W7-AS have achieved H_{ISS95} ~ 2.5

PBX-M obtained β = 6.8% with $H_{ITER-97P}$ = 1.7 and H_{ISS95} ~ 3.9

Research Goals for FY13

More detailed studies, higher beta, adding:

- Search for β limits, limiting mechanisms
- Detailed comparisons of MHD stability with predictions, effect of shaping
- Alfvenic mode stability and consequences
- Safe operating area for disruptions

- Detailed measurements of local transport properties & scaling
- Fast ion confinement
- Perturbative transport studies
- Impurity confinement

- Study of initial divertor effectiveness (power handling, detachment)

NCSX Analysis & Modeling Research Goals

FY09

- eBeam mapping inversion (I.e. how to interpret errors)

FY11

– Equilibrium reconstruction analysis (ongoing V3Fit collaboration)

- Diagnostic mapping
- Heating modeling and transport analysis (~ Transp)
- SOL & divertor analysis/modeling

Longer Term Needs (via Theory and International programs)

- Improved equilibrium calculations, including neoclassical, kinetic & flow effects
- Non-linear stability, including kinetic effects
- Turbulence simulations, including self-generated flows
- Stability of Alfvenic-modes, including fast ion kinetic effects

Collaboration on this Research is essential.

Example: PPPL Theory 5-year Plan (2005)

Gyrokinetic transport (GTC)
- Stellarator neoclassical (FY07)
- Nonlinear turbulence (FY08)

Fast-ion MHD Stability (HINST)
- Modified for stellarator geometry (FY08)
- Fast ion drive in 3D (FY08)

Nonlinear Hybrid MHD Stability (M3D) (Collaboration with NYU & MIT)
- Nonlinear energetic particle driven modes (2010)
- Free-boundary studies of stellarators (2010)

MHD Equilibrium (PIES)
- Neoclassical effects on islands (FY07)
- Parallelization (FY08)
- Flow shielding (FY09)
- PIES-Lite for rapid evaluation (FY09)
- PIES-based time-dependent transport modeling (FY10)

ORNL Stellarator Theory program is also strong, making key contributions.
NCSX has urged DOE/OFES support of US-wide 3D theory efforts.

Plan Addresses All Research Mission Elements

	FY11	FY13
Pressure limits and limiting mechanisms	Moderate β	High β
Effect of 3D fields on disruptions	Look for occurance	√
Confinement scaling, rotation effects	√	√
Equilibrium islands, tearing stabilization	√	√
Compatibility of exhaust with core performance	Develop understanding	√
Energetic island stability	Look for AE modes	√
Conditions for high-β, disruption free	Survey	√
High-β, high confinement	Survey	√

Plan Addresses ARIES-CS R&D Needs

	FY11	FY13
β ~ 5%? What is maximum β?		√
Low alpha loss. Can alpha driven MHD be avoided at high density?	√	√
Workable divertor design		√
Conditions for minimal power excursion on PFCs (disruptions or ELMs)	survey	√
H(ISS95) > 1.5? Scalings?	√	√
Operating limits (density, radiation fraction)	√	√
Density, pressure profile shape & dependencies	√	√
Maximum external transform needed		√
Is MHD stability limiting?	√	√
Is calculated flux-surface quality limiting?	√	√
What is the allowed helical ripple?		√
Necessary plasma control elements	√	√

NCSX Research Forum (7-8 Dec.)

Goals:

– Discuss the NCSX Research Program, priorities and opportunities with Team and prospective collaborators

– Identify areas of expected interest and capability to participate

Agenda:

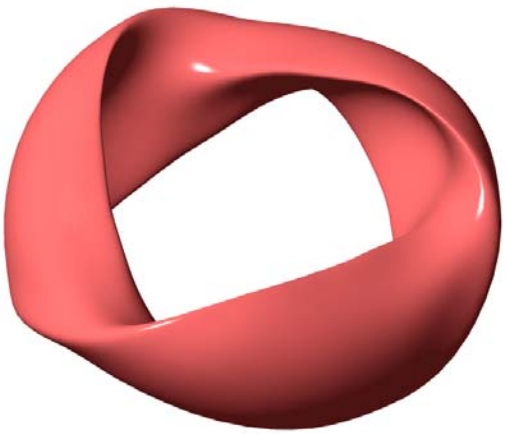
- Talks (similar to PAC agenda)
  - Status of Constructions
  - Research Plan
  - eBeam Mapping and Equilibrium Studies Plan
  - Stability Plan
  - Transport Plan
  - Edge Plan
  - Diagnostic Plan
- Topical Breakout Groups to discuss and give input
- Summary

Conclusions

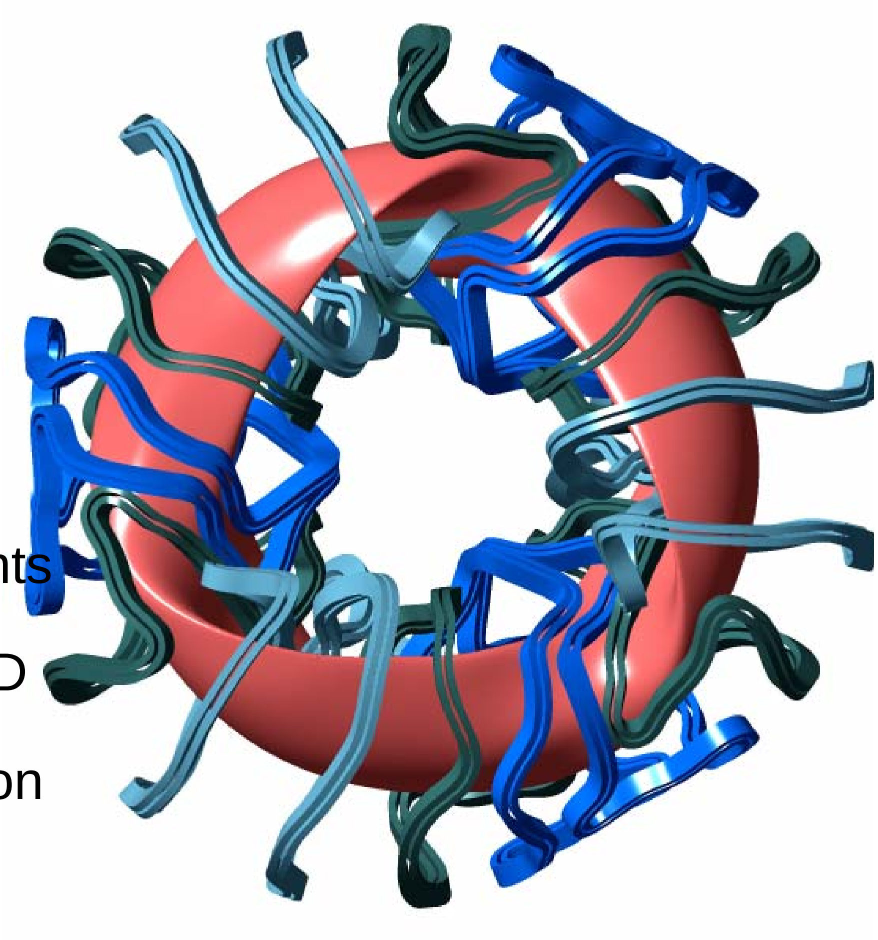
- NCSX is entering an exciting time: 2 years to first plasma

- Research Plan uses the NCSX device and available resources for unique fusion-science research, addressing both NCSX Mission and R&D needs
  - Understand effect of 3D fields on plasma confinement, stability
  - Effect of quasi-axisymmetry on transport & confinement.
  - Access to high β, high confinement using 3D shaping
  - 3D divertor solutions
  - Search for high- β in good confinement, sustainable configurations without disruptions.

- NCSX research planning underway!
  - First Research Forum 7-8 December 2006
  - Formation of the (Inter)National NCSX Research Team



NCSX Designed for Attractive Properties



- 3 periods, R/⟨a⟩=4.4, ⟨κ⟩~1.8 , ⟨δ⟩~1
- Quasi-axisymmetric
- Passively stable at β=4.1% to kink, ballooning, vertical, Mercier, neoclassical-tearing modes, …
- Stable for β > 6% by adjusting coil currents
- Steady-state compatible. No need for CD
- Natural divertor at elongated cross-section
- Passive disruption stability: equilibrium maintained even with total loss of β or I_P
- Flexible coils: by adjusting currents can control stability, transport, shape: iota, shear