# Introduction to NCSX Physics and Research Plans

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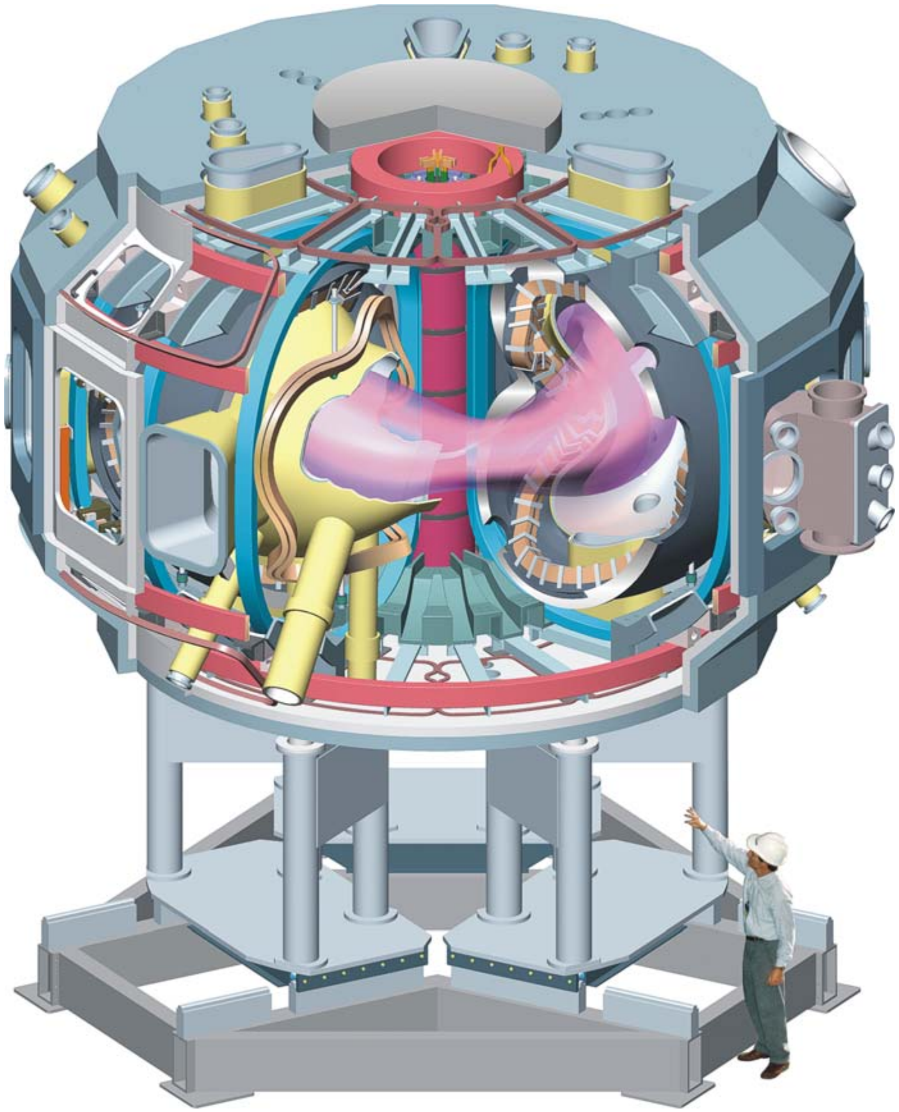
*For the NCSX Team*

**NCSX Research Forum 1**
**7 December 2006**

# Outline

- Motivation and Mission
- NCSX Physics Design
- Reactor implications and Aries-CS
- Research Plans, Upgrades, Priorities



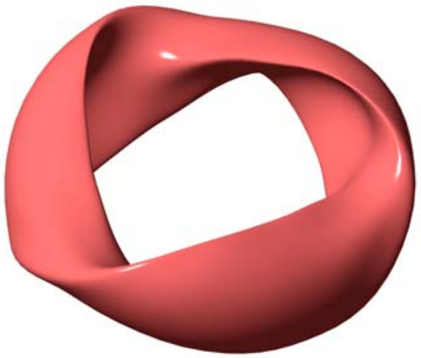
# NCSX Motivation: Build Upon and Combine Advances of Stellarators and Tokamaks

Tokamaks:

- Confirmation of ideal MHD equilibrium & stability theory;
- Importance of flows ( including self-generated) for turbulence stabilization
- 'Reversed shear' to reduce turbulence, increase stability
- Compact $\rightarrow$ cost-effective

Stellarators:

- Externally-generated helical fields
  - Plasma current not required. No current drive. Steady-state easy.
  - Robust stability. Generally, disruption-free
- Numerical design of 3D field (shape) to obtain desired physics properties, including
  - Quasi-axially symmetric
  - Increased stability



Goal: Steady-state high-$\beta$, good confinement without disruptions

# 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 and anomalous 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

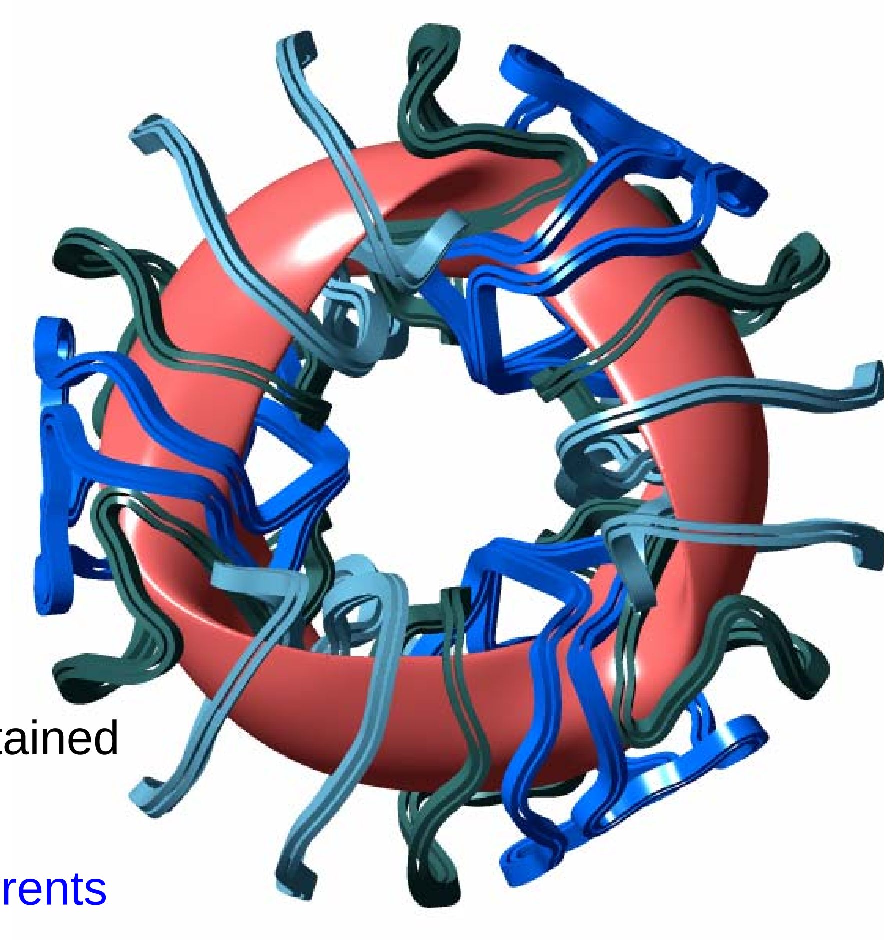
**Demonstrate…**

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

# 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, …
  (steady-state tokamak limit ~ 2.7% without feedback stabilization)
- Stable for β > 6% by adjusting coil currents
- Passive disruption stability: equilibrium maintained even with total loss of β or $I_P$
- Flexible configuration: 9 independent coil currents

by adjusting currents can control stability, transport, shape: iota, shear

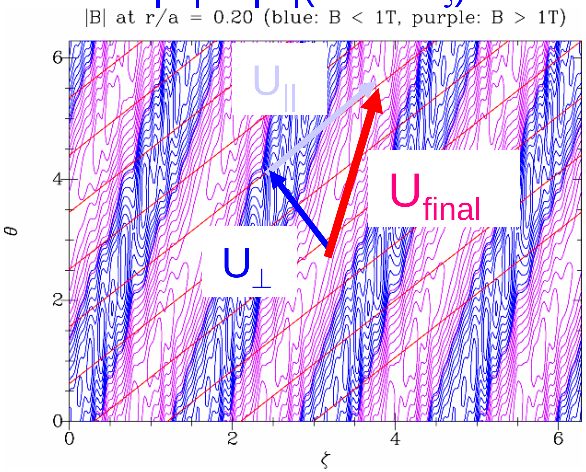


# Compact Stellarator Experiments Optimize Confinement Using Quasi-Symmetry

HSX

Quasi-helical symmetry

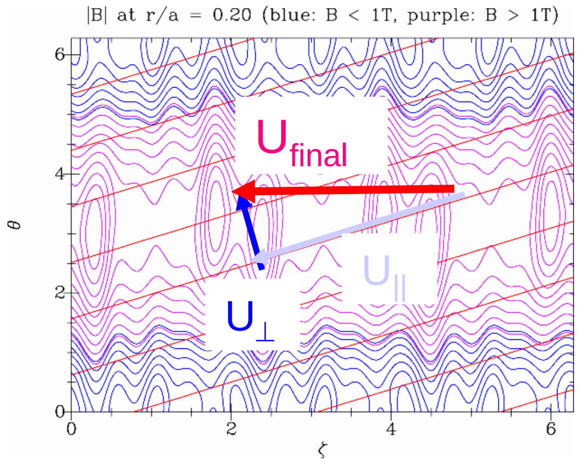
$|B| \sim |B|(m\theta - n\zeta)$




NCSX

Quasi-toroidal symmetry

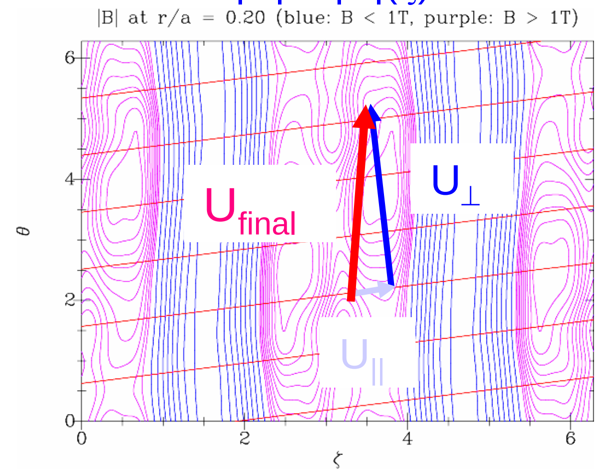
$|B| \sim |B|(\theta)$




QPS

Quasi-poloidal symmetry

$|B| \sim |B|(\zeta)$




- **Quasi-symmetry: small |B| variation and low flow damping in the symmetry direction**
- **Low effective field ripple for low neoclassical losses**
- **Allows large flow shear for turbulence stabilization**

# Quasi-Axisymmetric: Very Low effective ripple

- Very low effective magnetic ripple (deviation from perfect symmetry)

  $\varepsilon_{eff}$ ~ 1.4% at edge

  < 0.1% in core

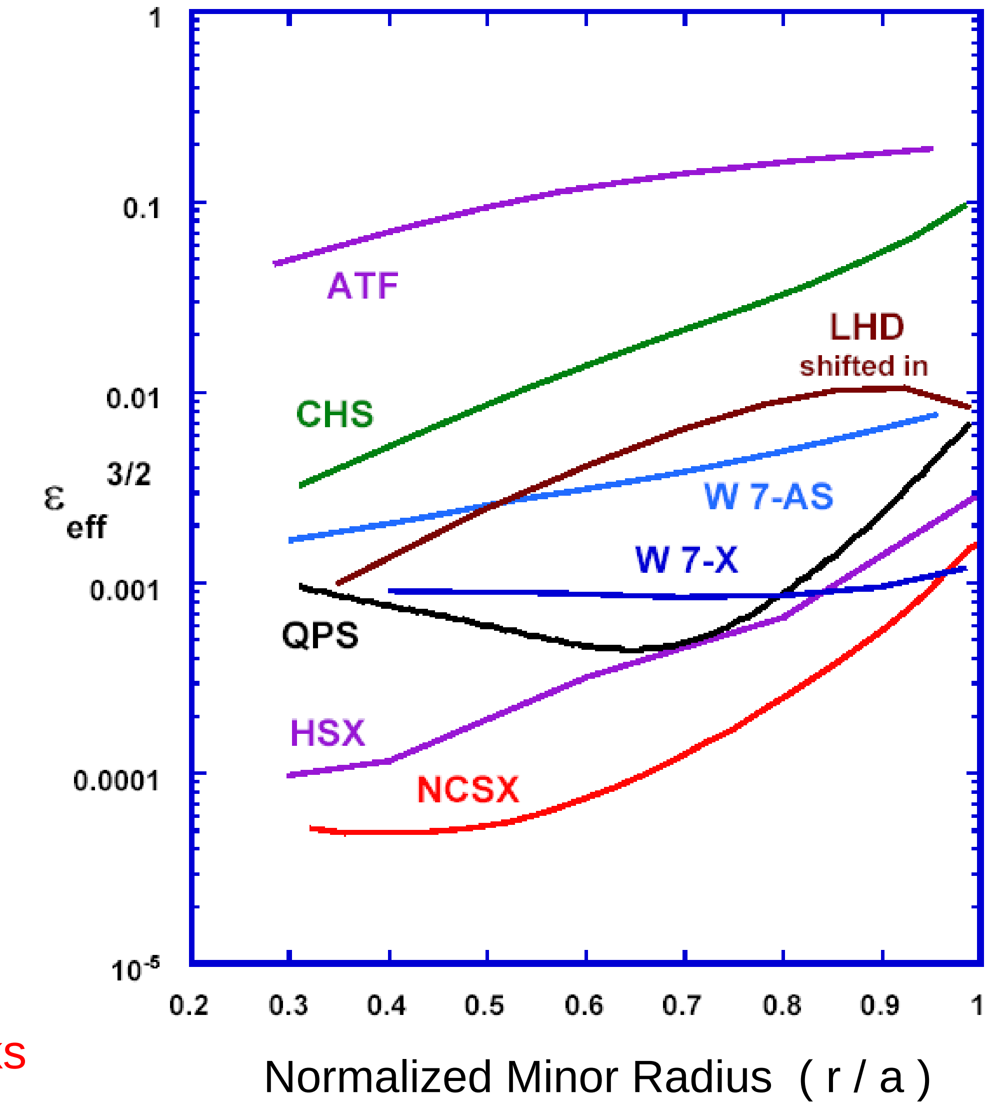
  $\varepsilon_{eff}^{3/2}$ characterizes collisionless transport

- Gives low flow-damping

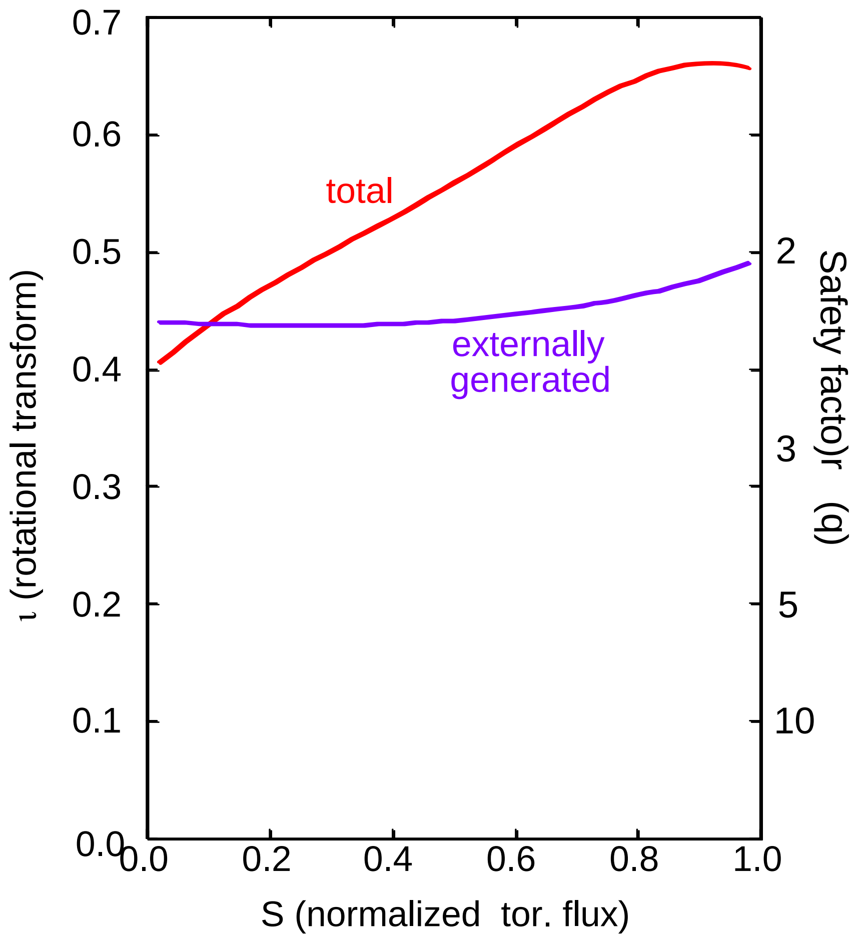
  allow manipulation of flows for flow-shear stabilization

- Can vary ripple to study:
  - Effects of flow damping
  - Interaction of 3D field with fast ion confinement

  Understand 3D effects in tokamaks



# ‘Reversed Shear’ Key to Enhanced Stability




Radial Coordinate$^2$

• Quasi-axisymmetry
⇒ tokamak like bootstrap current
(but q(a) ~ 1.5)

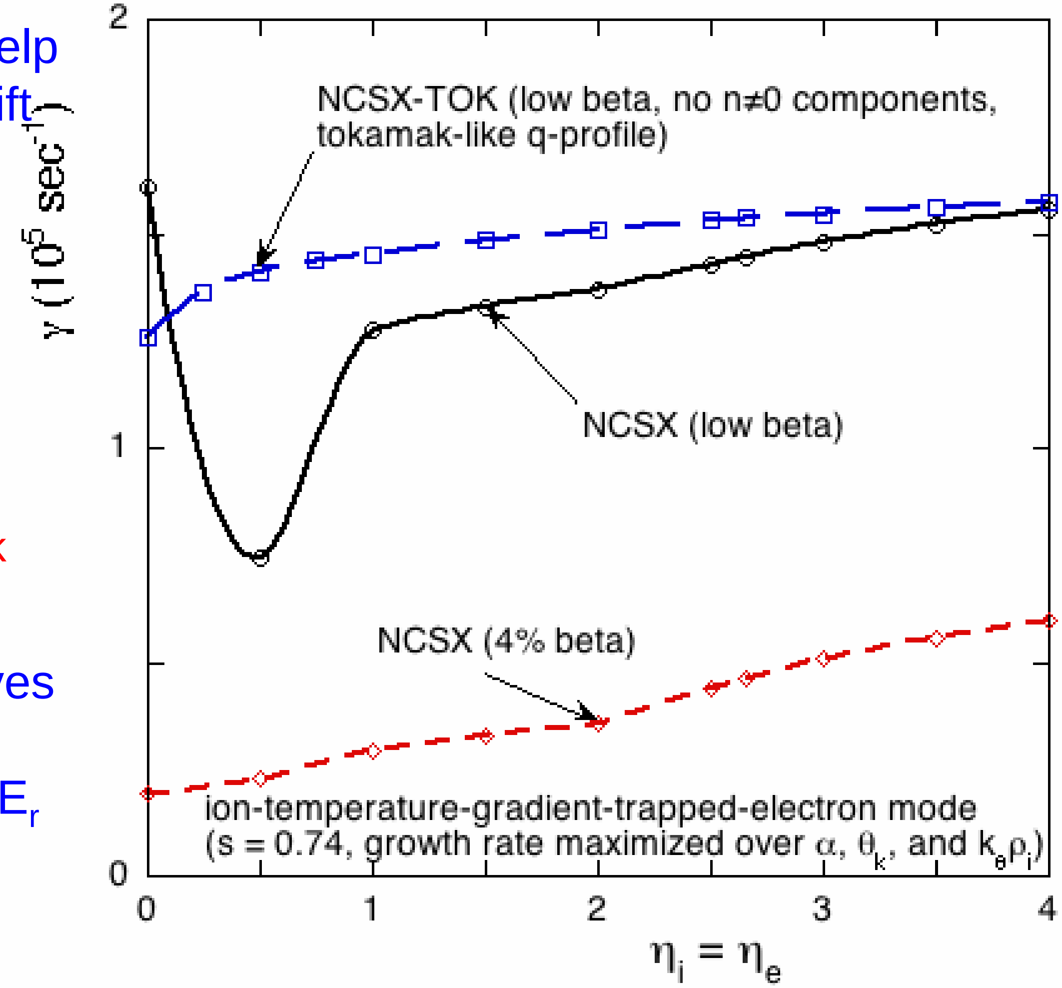
• ~3/4 of transform (poloidal-B) from external coils ⇒ externally controllable

• Rotational transform rising to edge key for stabilizing trapped particle and neoclassical tearing instabilities

Explored locally on tokamaks, but cannot be achieved across whole plasma using current.

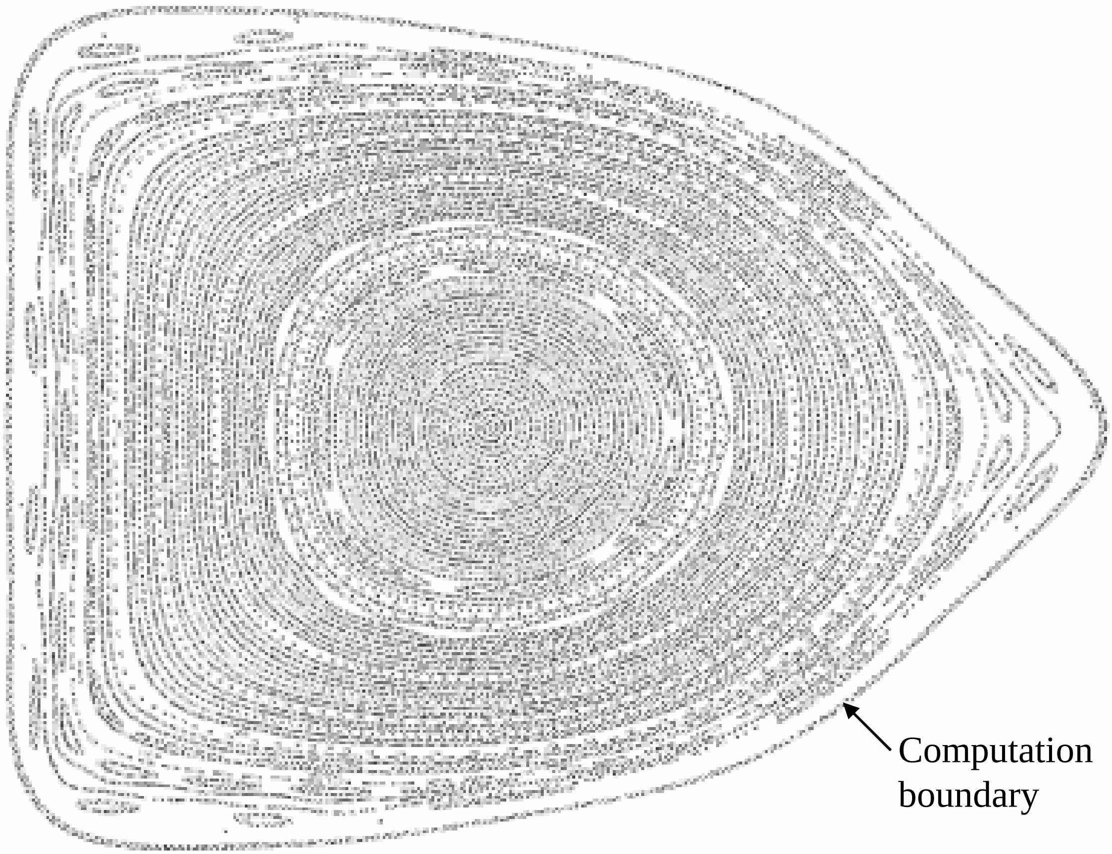
# Turbulence Growth Decreases for Higher ∇p Similar to Reversed Shear Tokamak

- Designed for 'reversed shear' to help stabilize turbulent transport, via drift-precession reversal
- Linear ITG/TEM growth rate calculated by FULL (Rewoldt):
  - TEM stabilized by reversed shear
  - ITG $\gamma$ strongly reduced with $\beta$
  - Similar to reversed shear tokamak
- Very low effective helical ripple gives low flow-damping allows efficient flow-shear stabilization, control of $E_r$
- Zonal flows should be similar or larger than equiv. tokamak (using Sugama & Watanabe, 2005) Experimentally?




G.Rewoldt

# Coils Designed to Produce Good Flux Surfaces at High-$\beta$




Poincare: PIES, free boundary without pressure flattening

< 3% flux loss, including effects of reversed shear and || vs. ⊥ transport.

S.Hudson, A. Reiman, D. Monticello

- Explicit numerical design to eliminate resonant field perturbations
- 'Reversed shear' configuration ⇒ pressure-driven plasma currents heal equilibrium islands (not included in figure)
- Robust: good flux surfaces at vacuum, intermediate and high $\beta$

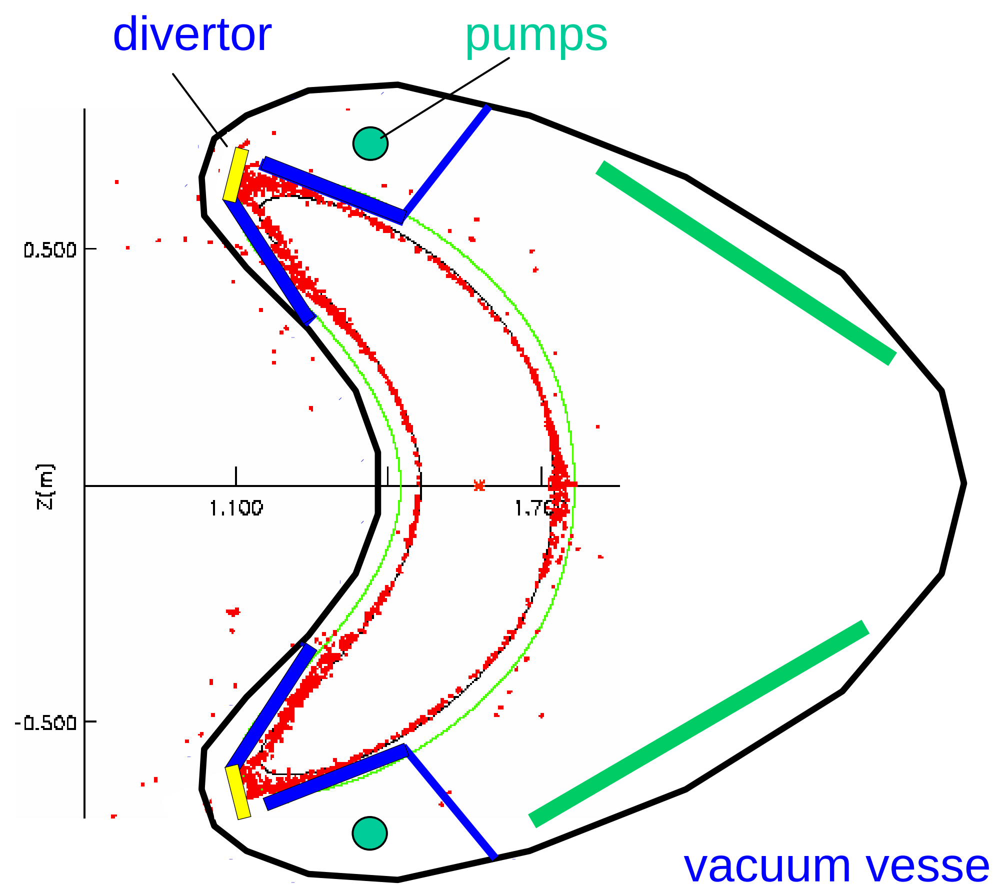
# Divertors in Bean-tips

- Strong flux-expansion always observed in bean-shaped cross-section. Allows isolation of PFC interaction.

- Similar to expanded boundary shaped-tokamak configurations

- Possible divertor plate & liner geometries being studied

- See R. Maingi's talk




Field-line tracing in SOL

# NCSX Coils Designed for Flexibility

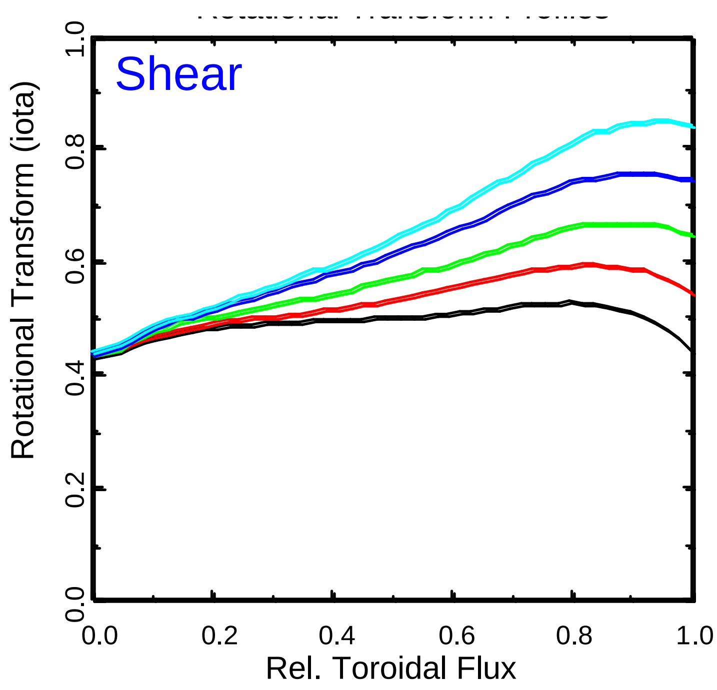
- Modular Coils + Toroidal Solenoid + Poloidal Coils for shaping control & flexibility

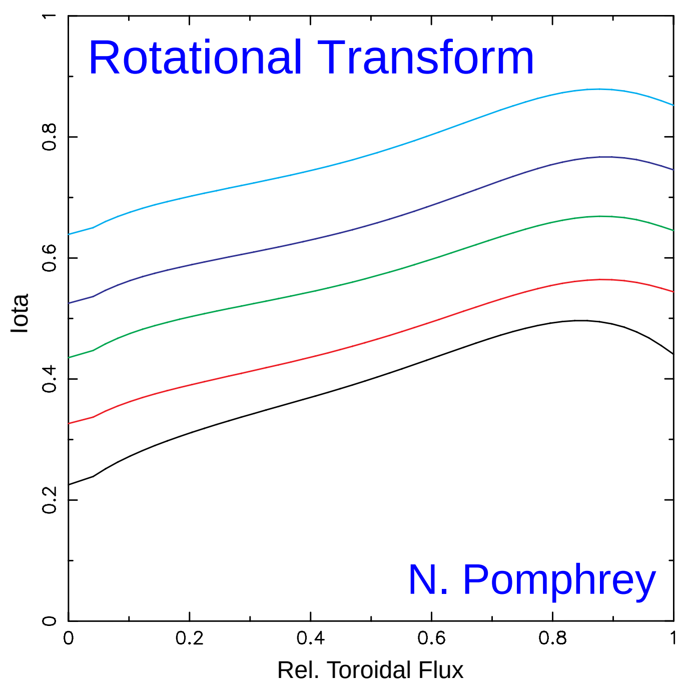
- Useful for testing understanding of 3D effects in theory & determining role of iota-profile

- E.G., can use coils to vary
  - effective ripple by factor > 10.
  - Avg. magnetic shear by factor > 5
  - Edge rotational transform by factor of 2

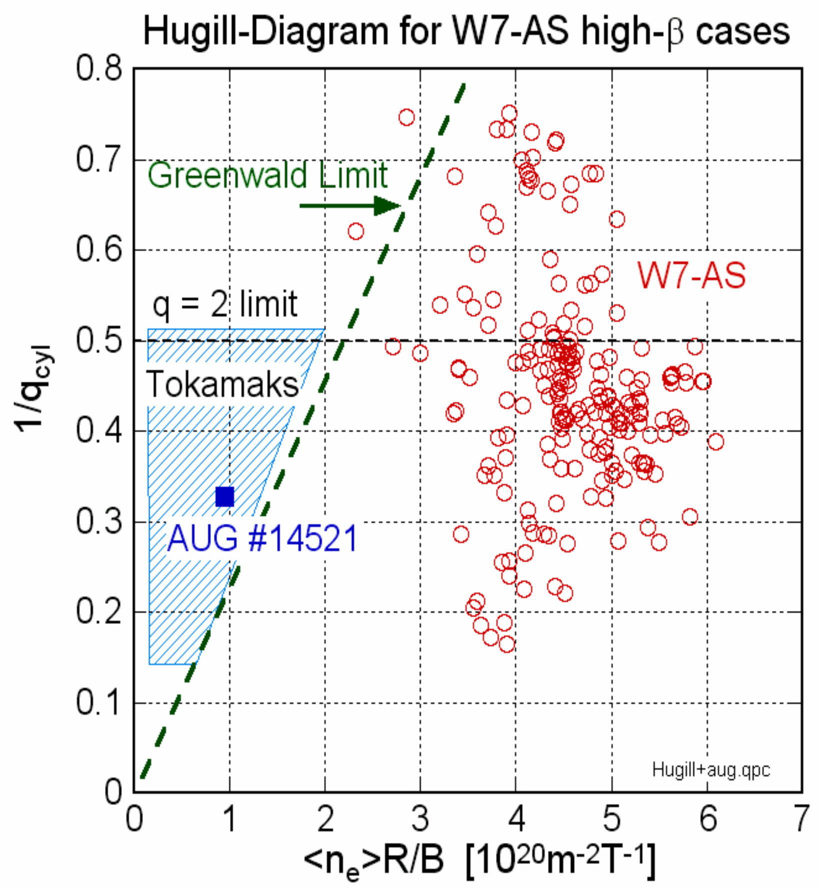
- Can control shape during plasma startup
  - Keep shape fixed (E. Lazarus)
  - Keep edge iota ~fixed

- These types of experiments will be key for developing and validating our understanding



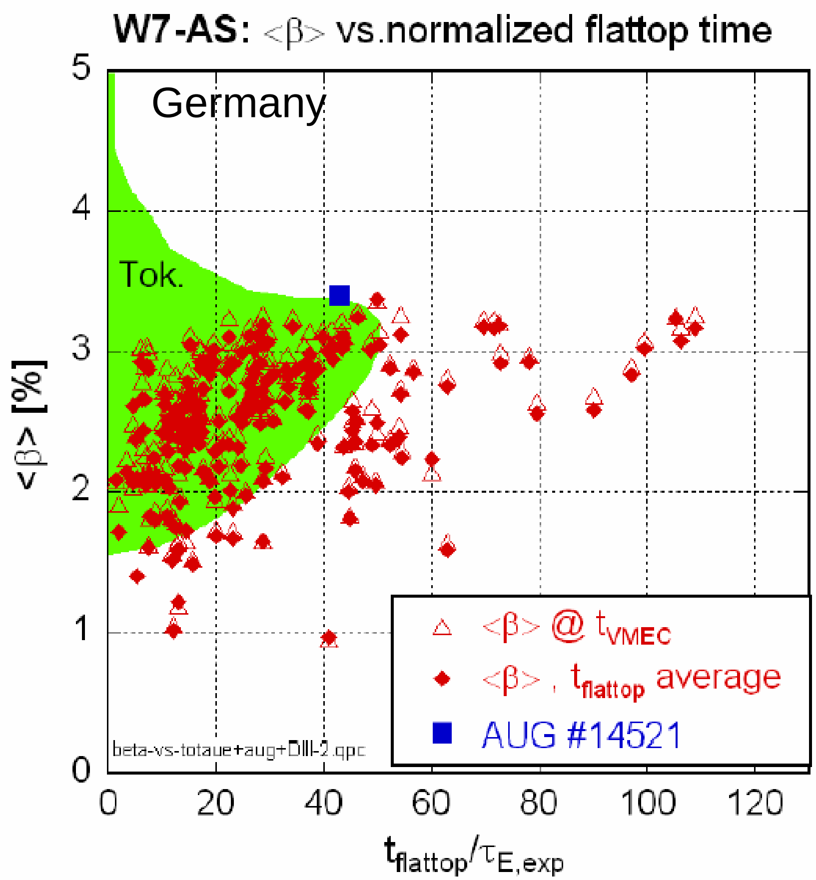



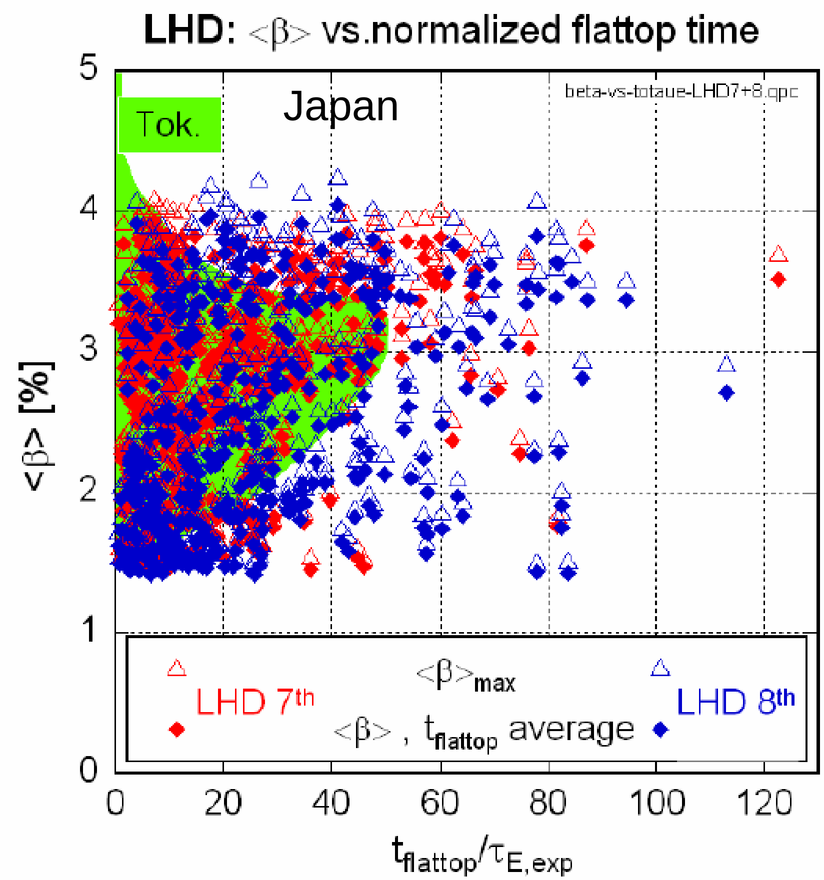
# Stellarator Operating Range much larger than Tokamaks




- Using equivalent toroidal current that produces same edge iota
- High density favorable:
  - Lower plasma edge temperature, Eases edge design
  - Reduced drive for energetic particle instabilities
- Limits are not due to MHD instabilities. No disruptions.
  - Lower peak power on PFCs

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




- In both cases, well above theoretical stability limit < 2%
- MHD activity not limiting. No disruptions observed. Sustained without CD.
- Not compact. Not optimized for orbit confinement, flows, stability.
- May be limited by degradation of flux-surface integrity at high-β

# Energy Vision: a More Attractive Fusion System

**Vision: A steady-state toroidal reactor with**

- ✓ Steady state at high-beta, without current drive ($\Rightarrow$ min. recirculating power)
- ✓ No disruptions => eases PFC choices
- ✓ High density => easier plasma solutions for divertor
  reduced fast-ion instability drive
- ✓ No need for feedback to control instabilities or nearby conducting structures
- ✓ Projects to ignition
- • High power density (similar to ARIES-RS and –AT)

✓ = already demonstrated in high-aspect ratio, non-symmetric stellarators

**Design involves tradeoffs.**
**Need experimental data to quantify, assess attractiveness.**

# ARIES-CS Reactor Core

Reference parameters for baseline:

Quasi-axisymmetric

$\langle R \rangle$ = 7.75 m

$\langle a \rangle$ = 1.72 m

$\langle n \rangle$ = 3.6 x $10^{20}$ $m^{-3}$

$\langle T \rangle$ = 5.73 keV

$\langle B \rangle_{axis}$ = 5.7 T

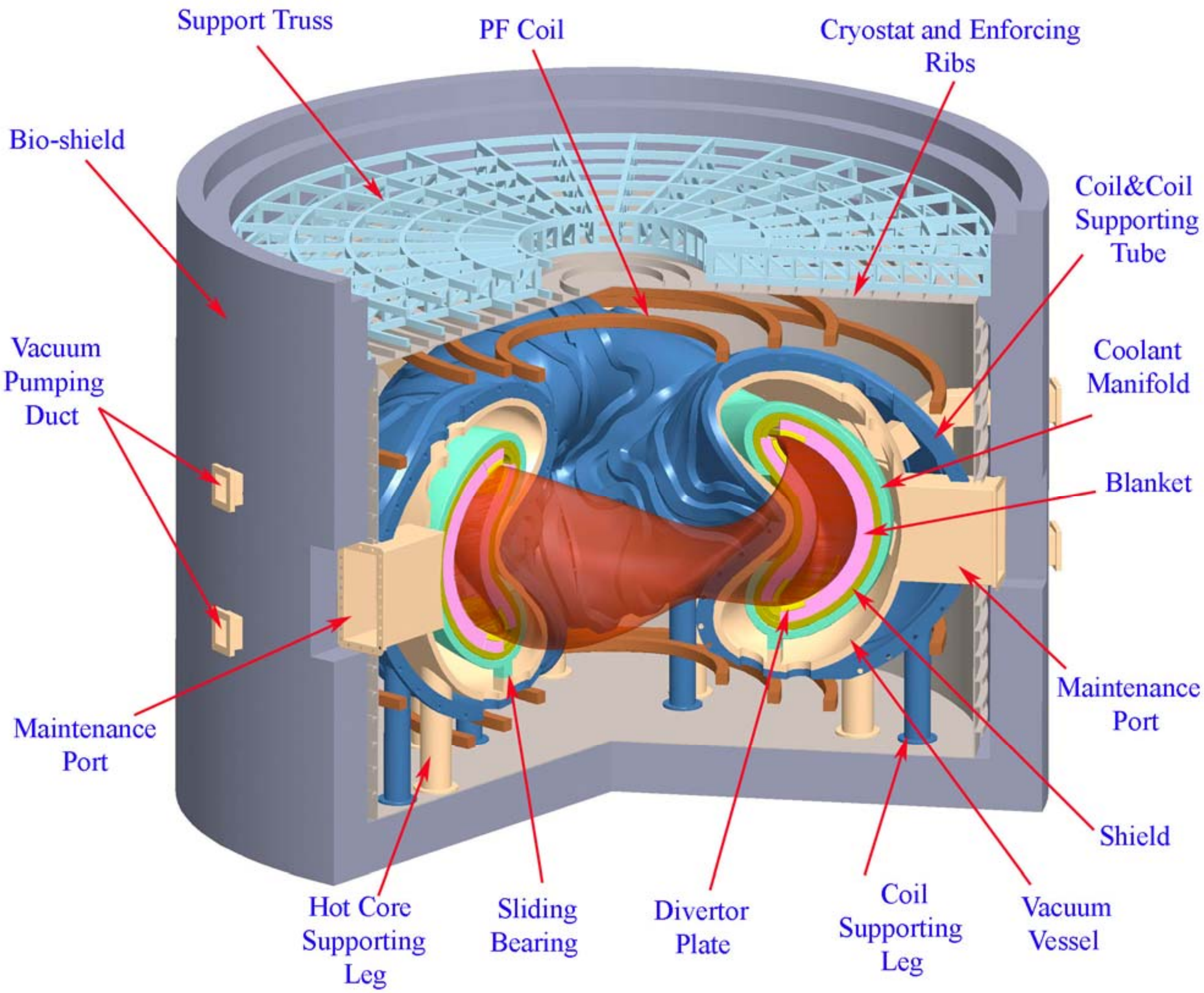
$\langle \beta \rangle$ = 5%

H(ISS95) = 1.4

$I_{plasma}$ = 3.5 MA (bootstrap)

*P*(fusion) = 2.364 GW

*P*(electric) = 1 GW



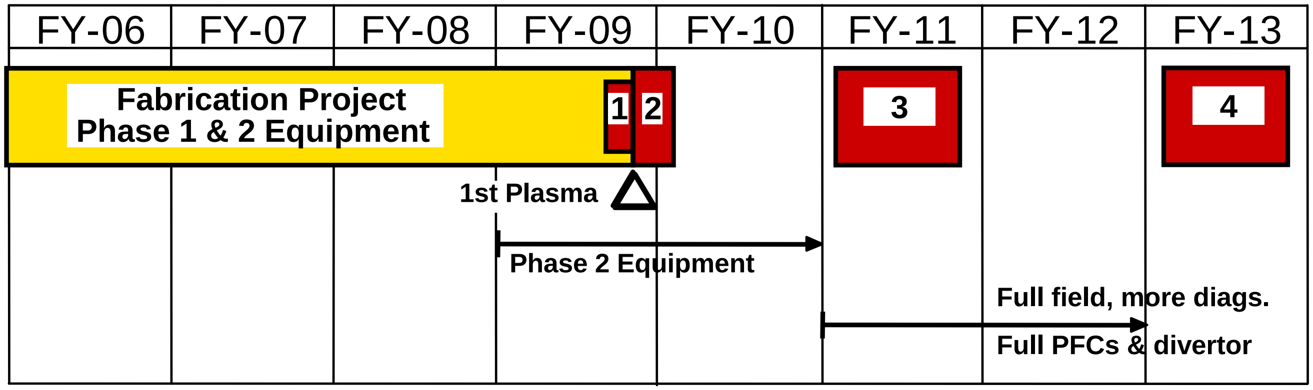

Study will complete at end of 2006.

# 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?

# 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 ($n_e$, $T_e$, $T_i$, $v_\phi$, $P_{rad}$) & SOL
4. High beta Experiments
   – 6MW heating
   – B = 2T; divertor
   – Improved diagnostics

# Magnetic Configuration Mapping Goals for FY09

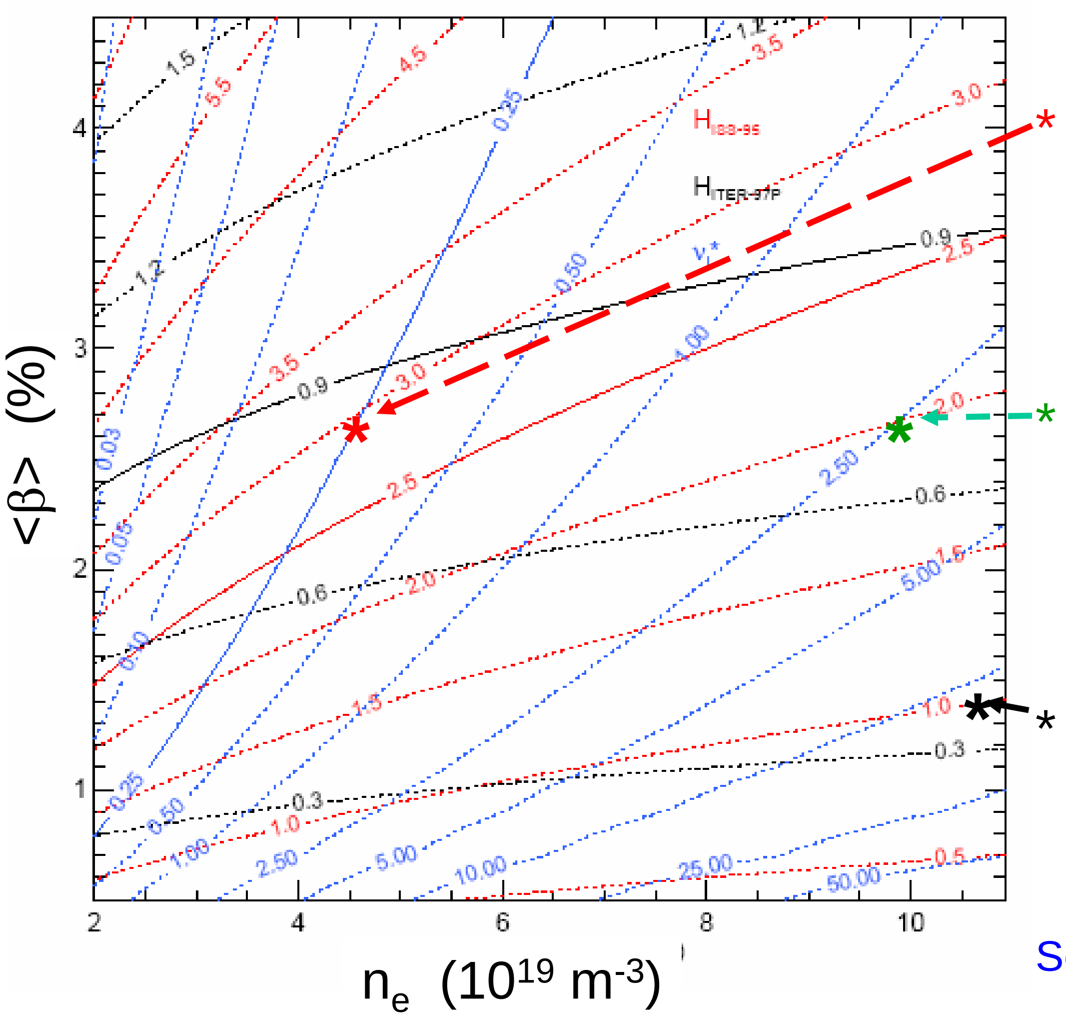
- Document vacuum flux surface characteristics
  - Particularly low-order resonant perturbations
- Document control of vacuum field characteristics using coil current
- Document and model as-built coils

See E. Fredrickson's talk for more details

# Wide Range of $\beta$ and $\nu^*$ Accessible in FY11

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

B = 1.2 T,  3MW




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

**β=2.7%,** $\nu_{*i}$ =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

See D. Mikkelsen's talk

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

# Initial Heating Experiments (FY11) Programmatic Goals

Prioritized

(1) Demonstrate basic real-time plasma control ($I_P$, $n_e$, R? Iota??)

(1) Characterize confinement and stability

- Variation with global parameters, e.g. iota, shear, Ip, density,rotation...
- Sensitivity to low-order resonances
- Operating limits

(1) Characterize SOL properties for different 3D geometries, prepare for the first divertor design.

(2) Investigate momentum transport and effects of quasi-symmetry

(2) Test MHD stability at moderate $\beta$, dependence on 3D shape

(3) Explore ability to generate transport barriers and enhanced confinement regimes.

(3) Investigate local ion, electron transport and effects of quasi-symmetry

Collaboration on achieving these goals is welcome.

Details will be discussed in topical talks.

# Scientific Goals: FY11

What high priority results and papers should be produced?

Prioritized

- (1) Effect of quasi-axisymmetry on plasma *global* confinement
- (1) Comparison of very low ripple stellarator *global* confinement with scalings
- (1) Effect of 3D equilibrium on SOL characteristics and contact footprint

- (2) Effect of quasi-axisymmetry on rotation damping
- (2) Whether pressure-driven linear MHD stability is limiting (e.g. disruptions)

- (3) Equilibrium reconstruction in NCSX
- (3) Comparison of measured and calculated linear MHD stability
- (3) Whether current-driven linear MHD stability is limiting w/ reversed shear (e.g. disruptions)
- (3) Occurrence of pressure driven islands vs iota and shear

# 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 ($v_\phi$, $T_i$, $n_C$)
- UV spectrometer
- PFC-mounted probes
- Filtered 1D and 2D cameras. Filterscopes.
- IR cameras
- SXR camera
- Bolometer array

Black: shared w/ NSTX may be more

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- MSE
- SXR tomography

Probably not affordable until FY-13

Collaborations on diagnostics are welcome.
Choices and details are for discussion

# FY09-10: Equipment Upgrades for FY11

Major elements in FY09 & FY10 :

Black: shared w/ NSTX

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

  Plan: PC-based acquisition; MDS+ organized similar to NSTX

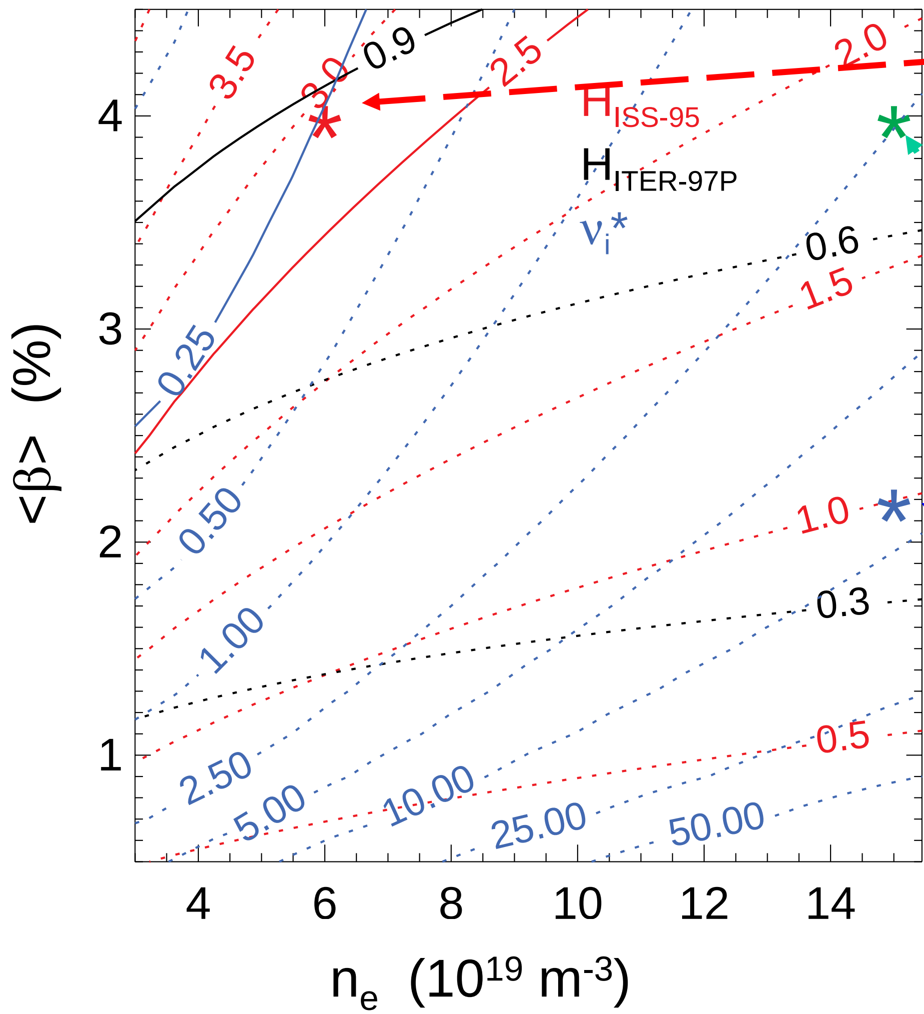
- Heating systems
  - 3MW NBI refurbishment and installation
  - 600 kW 70GHz ECH heating possible via collaboration with MP/IPP

- 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

# High-β, low ν* Plasmas Accessible in FY13

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




<u>B = 1.2 T, 6MW</u>

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

* **β=4%** at Sudo-density $H_{ISS95}$=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

(1) Goals not accomplished in FY11

More detailed studies, higher beta, adding:

(2) Search for β limits, limiting mechanisms

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

(2) Fast ion confinement

(3) Impurity confinement

(3) Safe operating area for disruptions

(3) Alfvenic mode stability and consequences

(4) Detailed comparisons of MHD stability with predictions, effect of shaping

(4) Detailed measurements of local transport properties & scaling

(4) Perturbative transport studies

# NCSX Analysis & Modeling Research Goals

FY09

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

FY11

– Equilibrium reconstruction & analysis (V3FIT, STELLOPT; PIES)

See E.Fredrickson talk

- 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.**

– See A. Reiman's talk

# Conclusions

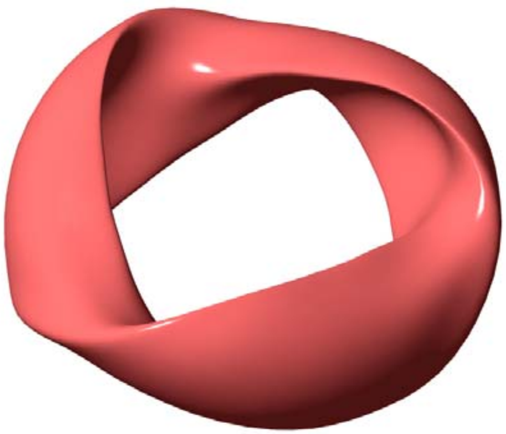
- NCSX is entering an exciting time: 2 years to first plasma

- 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!

Formation of the (Inter)National NCSX Research Team

We look forward to your participation



# Starting from FY-11, About 1/4 to 1/3 of NCSX Science Will Be Done by Collaborators

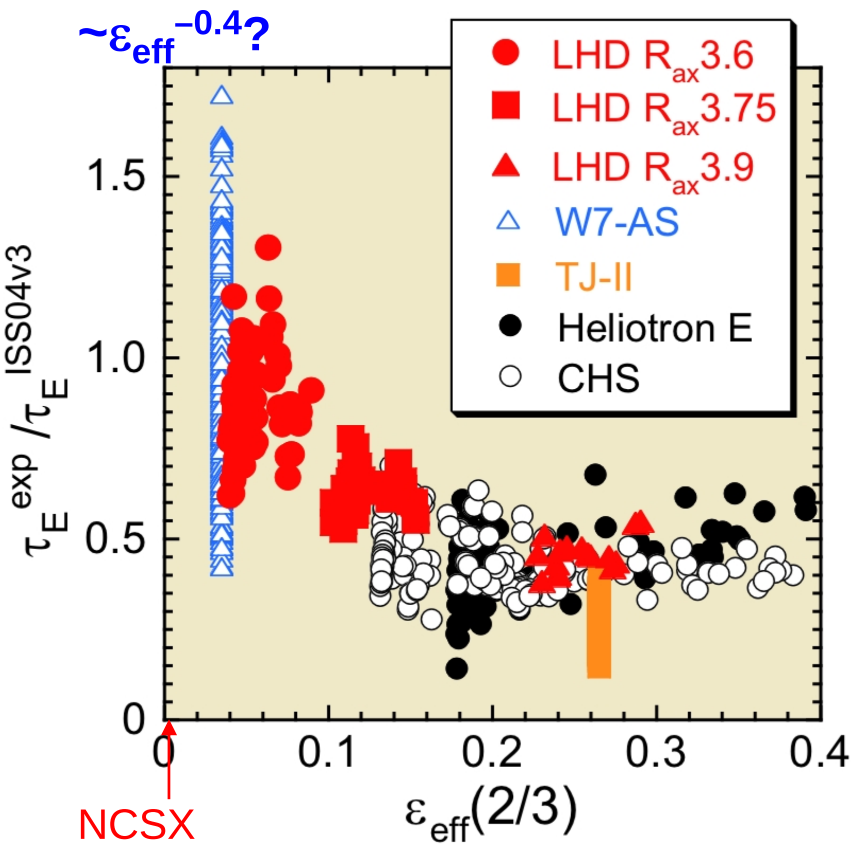
## Process will be similar to NSTX's

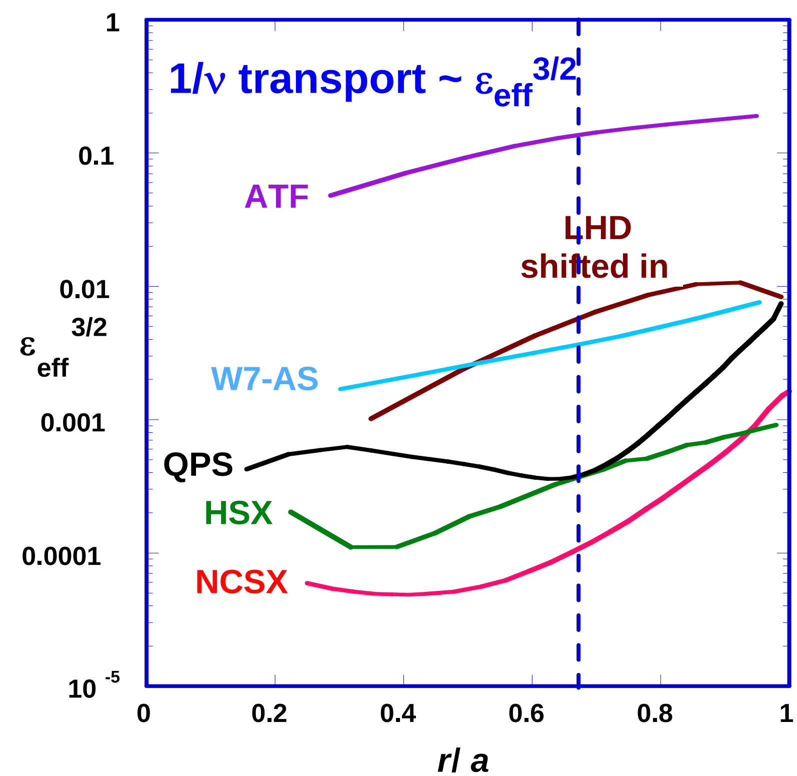
- Annual Research Forums to inform plans and identify collaborator interests.
- Project identifies collaboration needs in a "program letter" to DOE.
- Proposers & project coordinate to ensure common understanding of requirements.
- Proposals go to DOE. DOE decides and provides funding.

## Plan

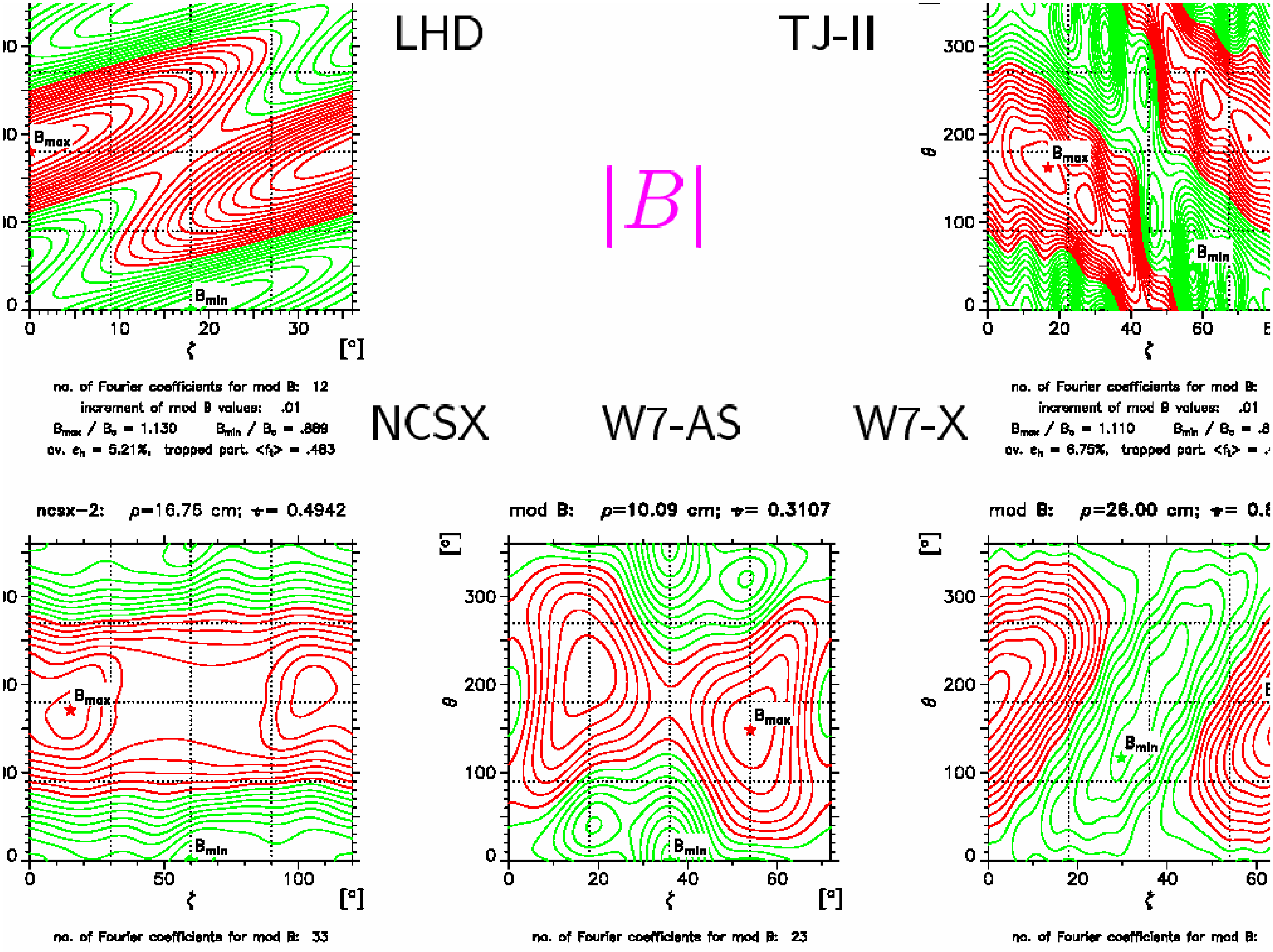
- NCSX and NSTX will issue joint program letters, encouraging collaboration on both experiments.
- First NCSX program letter and proposal call are expected in FY08 for funding in FY09–12. (Note transition to 4-year cycles.)
- Limited NCSX collaborations planned for FY09-10. Main focus is FY11 and beyond.
- At this Research Forum:
  - Project will present its current plans, including envisioned collaborator roles.
  - Input from the community is sought.
    - Feedback on the project's plans.
    - Ideas and suggestions, including collaboration interests.
    - Questions and concerns.
- First NCSX program letter will go out after next year's Research Forum.

# Confinement Depends on Ripple $\varepsilon_{eff}$




- New global confinement scaling study for stellarators (ISS04v3) found strong dependence on ripple magnitude ($\varepsilon_{eff}$).
- 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?


LHD
TJ-II
$|B|$
NCSX
W7-AS
W7-X
$B_{max}$
$B_{min}$
ζ
[°]
θ
no. of Fourier coefficients for mod B: 12
increment of mod B values: .01
$B_{max}$ / $B_0$ = 1.130 $B_{min}$ / $B_0$ = .889
av. $\epsilon_h$ = 5.21%, trapped part. <$f_t$> = .483
no. of Fourier coefficients for mod B:
increment of mod B values: .01
$B_{max}$ / $B_0$ = 1.110
av. $\epsilon_h$ = 6.75%, trapped part.
ncsx-2: ρ=16.75 cm; ι= 0.4942
mod B: ρ=10.09 cm; ι= 0.3107
mod B: ρ=26.00 cm;
no. of Fourier coefficients for mod B: 33
no. of Fourier coefficients for mod B: 23
no. of Fourier coefficients for mod B: