Stellarator Program Update

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NCSX PAC Meeting **Dec. 2, 1998**

Topics

- US developments since last our PAC meeting that affect the NCSX program
- Update on the proposed US stellarator Proof-of-Principle program
- Developments in the international stellarator program affecting NCSX
- Other areas for NCSX program development

- **Impressive progress has occurred in stellarator research this year that impacts the NCSX program**
- **There is increasing recognition that a clear opportunity and niche has opened up for the U.S. with a compact stellarator PoP program**

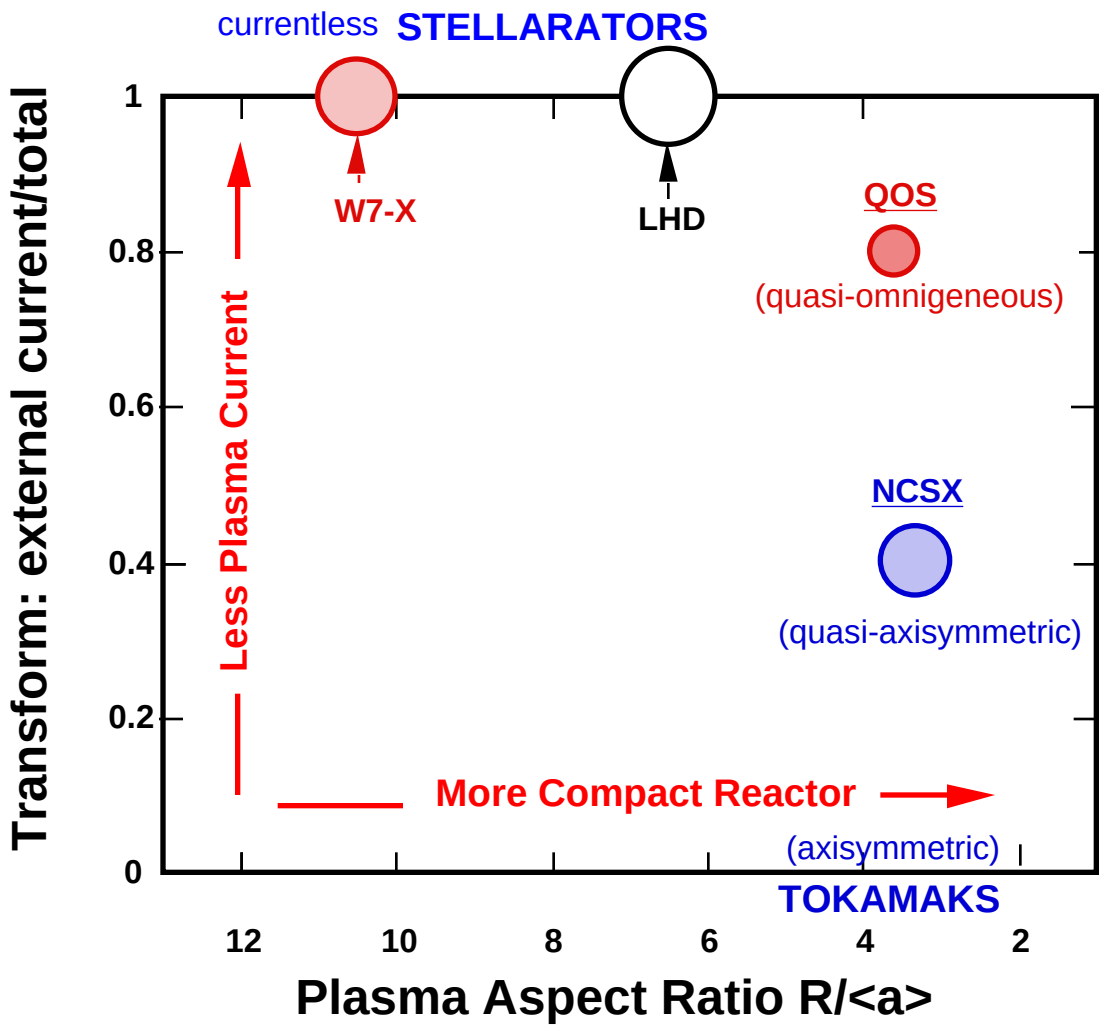
Events in the US Program since our last PAC Meeting

- Choice of QA for the NCSX facility and QO for a concept exploration experiment
- Proposal for a Compact Stellarator PoP program with NCSX as the main element
  - FWP meeting, ICC workshop, White Paper
  - favorable review by DOE PoP review panel
  - Interactions with FESAC: discussion of PoP programs and 2-pagers for later program review
- Presentation of QA and QO progress at Sherwood meeting, EPS, IAEA, APS, etc.
- Partnerships:NCSX at PPPL, QOS at ORNL

Community Response Favorable to the Proposed PoP Program and NCSX

- **DOE Review Panel: endorsed program readiness for PoP step, and a lead experiment based on QA, "a concept based on a new direction rather than a refinement of more standard directions."**
- **FESAC Review: favorable toward all PoP programs, recommended "maintain momentum", broader program review in 1999**
- **World stellarator community is contributing to US compact stellarator development**
  - **bootstrap current, MHD stability, coil design**

NCSX and QOS Are Complementary Stellarator-Tokamak Hybrid Devices



- **Low aspect ratio of tokamaks**
- **Disruption immunity of stellarators**

HSX Construction Is Nearing Completion

- ***R*** **=1.2 m, <*a*> = 15 cm, *B* = 1.35 T, *P* = 0.2 MW (ECH)**
- **Coil module assembly is complete**
- **Half-period vacuum vessel sections are assembled**
- **Main support structure is complete**
- **Main field and auxiliary bus parts complete, one quadrant installed**
- **Motor/generator tested for B = 0.5 T**
- **ECH system nearing completion**
- **First operation is expected in January**

HSX Will Test an Exciting Concept and Complement the NCSX Program

- **The first experimental test of new stellarators designed to reduce neoclassical transport to low levels**
  - **flexibility to determine how far to reduce NC transport without compromising other desired features**
- **HSX has a high "effective" rotational transform: $|N - m\iota| \sim 3$**
  - **small equilibrium (Pfirsch-Schlüter) currents**
  - **small banana widths of high-energy trapped particles**
  - **lower neoclassical and anomalous transport**
- **Span the range between a large plasma flow in the direction of symmetry contributing to the radial electric field to a non-intrinsically ambipolar field with broken symmetry for quenching anomalous transport**
- **The first test of quasi-symmetry (QHS): very low toroidal curvature, low parallel viscosity in the symmetry direction**

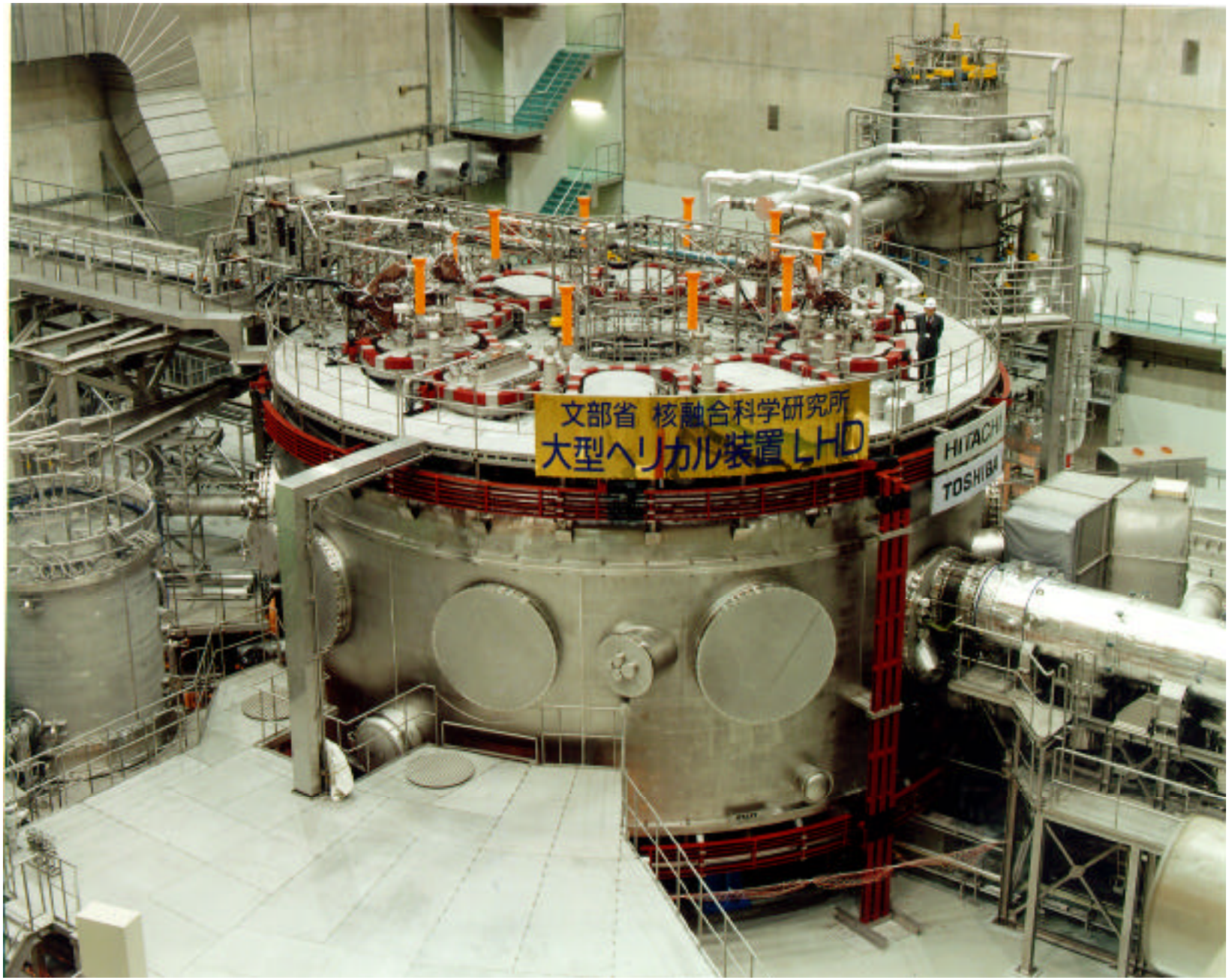
Compact Auburn Torsatron Upgrade Underway

- **CAT has R = 0.53 m, <a> = 11 cm, B = 0.1 T**
  - **can vary edge transform from 0.15 to 0.7**
  - **B = 0.1 T 0.5 T**
  - **P = 2 kW 100 kW (ICRF), 50 kW (OH)**
  - **n_e = 8 x 10^{16} m^{-3} 5 x 10^{18} m^{-3}**
  - **T_e = 5-10 eV 100-200 eV (ISS-95)**
  - **T_i = 0.25 eV <50 eV**
  - **Ip = 0 25 kA**
- **Good progress on hardware and physics plans**
  - **8 of 10 motor generators for the higher B delivered**
  - **designs underway for coil support structure upgrades, basic OH system, and RF power amplifier built for CDX-U**
  - **1-D stability studies say plasma can be unstable to both resistive and kink modes, allowing study of disruptions**

Role of Upgraded Compact Auburn Torsatron in the US Stellarator PoP Program

- **Investigate tearing instabilities, kink modes, and disruptions in current-carrying stellarator plasmas.**
  - **contribute to development of NCSX in which bootstrap current will provide ~ 50% of the rotational transform**
- **Investigate influence of controlled magnetic islands on stability of current-carrying discharges**
- **Study of non-resonant ICRF plasma production for greater flexibility in stellarator operation**
- **Investigate novel ICRF stellarator heating scenarios**
- **High field-side mode conversion electron heating**
  - **apply to electron β limit studies on HSX and QOS**

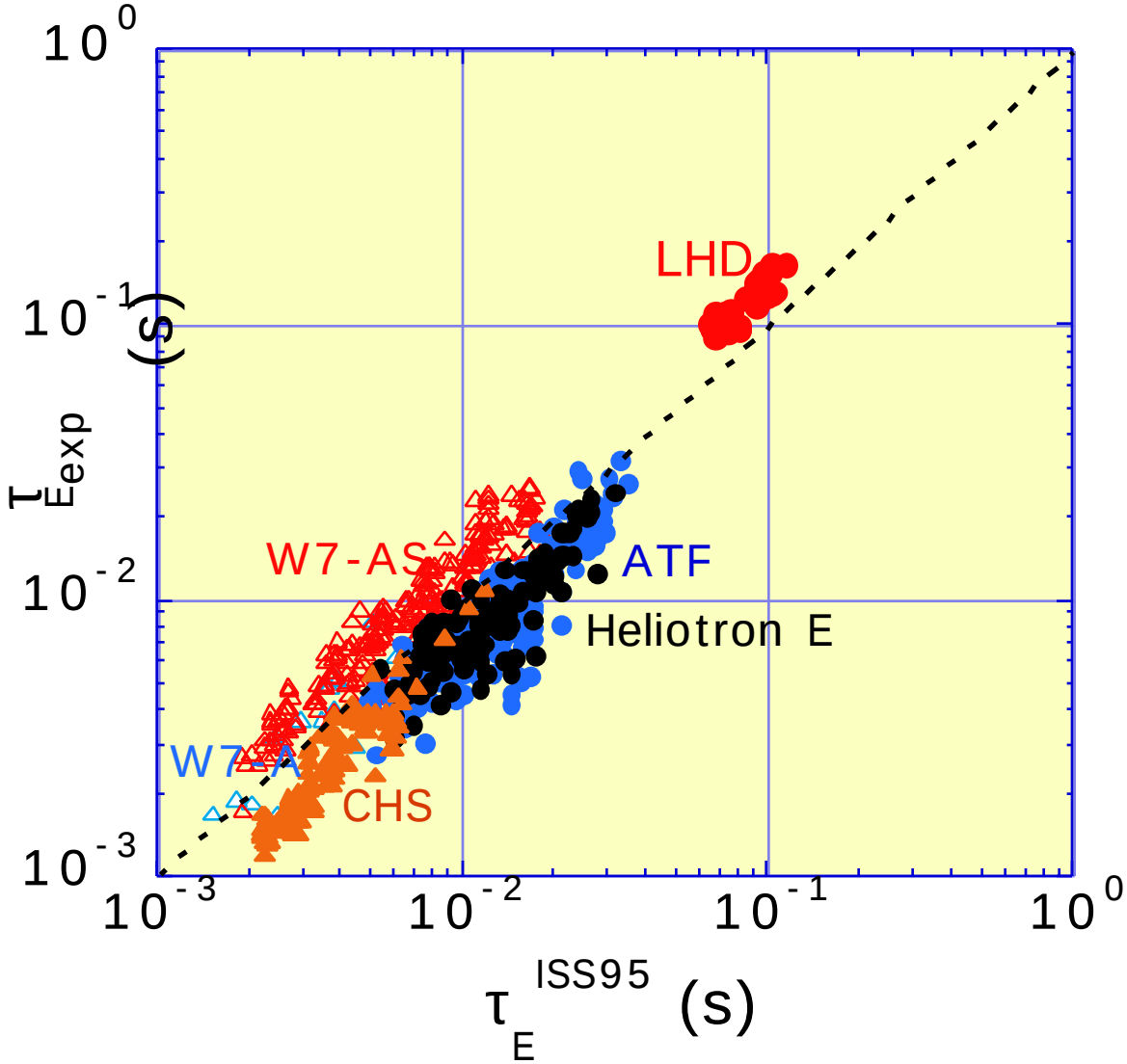
LHD Has Started Operation



Initial LHD Results at B = 1.5 T and Low Power Are Encouraging for NCSX:

- $\tau_E \approx 1.5\ \tau_E$(ISS95)
- $n_e = 1.5 \times 10^{19}\ m^{-3}$, $T_e = 1.5$ keV, $T_i = 1.1$ keV, $\tau_E = 0.11$ s, $P_{abs} = 1.3$ MW
- $n_e = 5 \times 10^{19}\ m^{-3}$, $T_e = 0.8$ keV, $\tau_E = 0.17$ s, $n\tau T = 0.9 \times 10^{19}$ keV m^{-3} s, $P_{abs} = 1.6$ MW
- $W_{plasma} = 0.22$ MJ, $\langle\beta\rangle = 0.7\%$
- 10-s operation with 1-MW NBI
- Some experiments planned for Dec. at 2.5 T
- Operation at B = 3 T and P = 10-15 MW in 1999

Initial LHD Results Already Above ISS95 Scaling



Compact Helical System Program

- **CHS (NIFS): R = 1 m, <a> = 0.2 m, B = 2 T**
  - **lowest plasma aspect ratio (R/<a> = 5)**
  - **significant physics results have been obtained**
    - **transition from L mode to high-T_i mode: peaked $n_e(r)$, T_i = 1 keV, χ_i reduced by factor 2-3**
    - **internal transport barrier in $T_e(r)$**
    - **effect of energetic ion orbit losses**
    - **toroidal rotation and parallel neoclassical viscosity**
    - **steady-state electric field pulsations (E_r bifurcation)**
    - **study of drift-orbit optimized configurations at low ν^***
    - **Mercier unstable discharges are experimentally stable**
- **Future plans**
  - **operate at Nagoya until end of March**
  - **move CHS to new building at Toki in JFY 1999**
  - **studies for replacement for CHS are underway (CHS-qa?)**

Impressive Progress in the W7-AS Program

- **Wendelstein 7-AS (*R* = 2 m, <a> ≤ 0.2 m, *B* = 2.5 T)**
  - **has obtained impressive plasma parameters**
    - T_e = 5.8 keV, T_i = 1.5 keV, n_e = 3 x 10^{20} m^{-3}, <β> = 2%, τ_E = 50 ms
  - **has obtained significant physics results**
    - MHD equilibrium agreement with theory
    - study of current-driven tearing modes due to resonances, GAE
    - confinement and the role of shear, resonances
    - neoclassical core transport, electron and ion roots
    - global confinement and improved confinement regimes
    - particle transport; edge transport and turbulence
    - ECH, EC current drive, ICRF heating
  - **installed control coils to vary size of external magnetic islands (for island divertor test)**
  - **modifications for last operational period (thru 2001)**
    - reorient all beams for co-injection to improve heating
    - install full island divertor system
    - install perpendicular NB system to modify radial electric field
  - **this information will be important for the NCSX program**

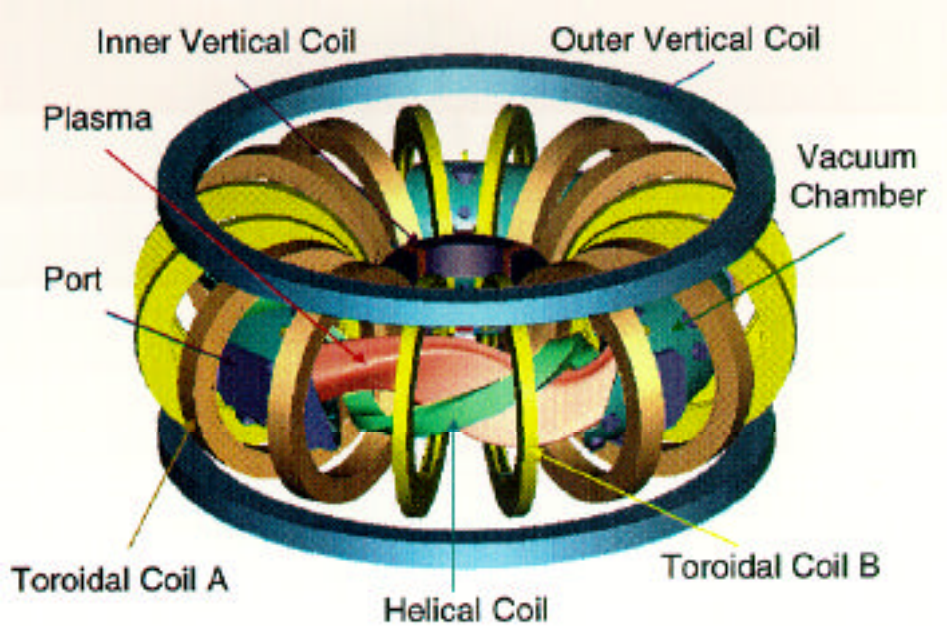
Wendelstein 7-X Project Well Underway

- **W7-X (R = 5.5 m, $\langle a \rangle$ = 0.52 m, B = 2.5 T)**
  - **will test the Helias approach to stellarator optimization**
  - **site construction at Greifswald is well underway**
  - **starting coil system procurement process with industry**
  - **completion scheduled for 2004**

Helical-Axis Stellarator Programs

- **TJ-II Heliac (Madrid):** R = 1.5 m, <a> = 0.22 m, B = 1.2 T
  - first plasma operation with 250-kW ECH
  - T_e = 0.4-0.8 keV, $n_e \leq 10^{19}$ m^{-3}, W_p = 0.2-1 kJ, $\tau_E \leq 4$ ms
- **H-1 Heliac (Canberra):** R = 1 m, <a> = 0.2 m, B = 1 T
  - confinement transitions at low p, T
  - fluctuating H modes, role of electric field
- **New Heliotron J (Kyoto University)**

Helical axis heliotron with
R = 1.2 m, <a> = 0.1-0.2 m
B = 1-1.5 T, 1% well depth
ι = 0.2-0.8 (low shear)
0.5 MW ECH
1.5 MW NBI
2.5 MW ICRF
1st plasma 1999-2000



Growth in the Theory Program Is Important for Further Development of the Stellarator Concept

- transport calculations (neoclassical and energetic particle confinement)
- improvements in ballooning, external kink instability, bootstrap current calculations
- additional features in configuration/coil optimization codes
- optimization of coil systems to produce desired magnetic configurations
- reconstruction of magnetic surfaces from coils and reducing the effects of resonant magnetic fields

Reactor/Systems Studies Are Planned

- **Reactor scoping studies will be carried out with the stellarator systems/optimization code using ARIES costing and engineering assumptions**
- **Tradeoffs and key issues will be examined**
  - **β limits , B_{max}/B_0 , $R/\langle a \rangle$, R/Δ, confinement improvement, α-particle losses, divertors**
  - **ARIES-RS thin inboard blankets and shields**
- **Some effort by the ARIES group on selected high-leverage issues for compact reactors**
- **The stellarator systems/optimization code will be used to study performance and cost tradeoffs under different physics and design assumptions for both NCSX and QOS**

Summary

- **Impressive progress has been made this year in stellarator research**
  - **LHD, CHS, W7-AS, heliac experiments**
  - **progress on HSX and CAT-U construction**
  - **refinement of the QA and QO concepts**
- **An exciting opportunity for a U.S. niche in compact stellarator research is recognized**
  - **2 optimization strategies are being developed**
  - **QA configuration in NCSX as the main element of the US compact stellarator PoP program**
  - **QO in a “concept exploration” experiment QOS**