# Steps Toward a Compact Stellarator Reactor

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**ARIES Team Meeting**

**October 3, 2002**

# Compact Stellarators Can Improve Our Vision of Magnetic Fusion Power Plants

**Stellarators solve major problems for MFE:**

- Steady state operation with minimal recirculating power.
- Eliminating disruptions.

**Compact stellarators can improve on previous stellarator designs:**

- Lower aspect ratio.
- Higher power density.
- Lower physics risk, shorter development path.
  - Connection to the tokamak data base via magnetic quasi-symmetry.

**The U.S. is carrying out a proof-of-principle program to further develop the compact stellarator. FESAC-approved 10-year goal:**

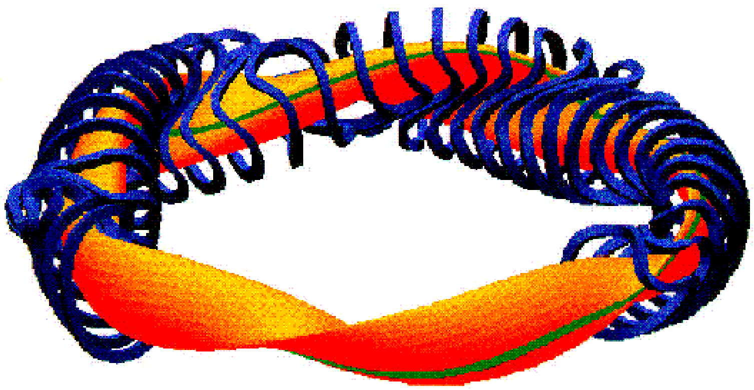
> **"Determine the attractiveness of a compact stellarator** by assessing resistance to disruption at high beta without instability feedback control or significant current drive, assessing confinement at high temperature, and investigating 3D divertor operation."

**ARIES role is critical: optimizing the compact stellarator as a power plant.**

# Stellarators Have Interesting Reactor Properties

**Stellarators are 3D toroidal configurations which can have up to 100% of the rotational transform generated by external coils.**

- Don't need current drive, rotation drive, or instability feedback control to be steady state.
- 3D plasma shaping provides extra degrees of freedom (opportunity!) which can be used to design for better properties.



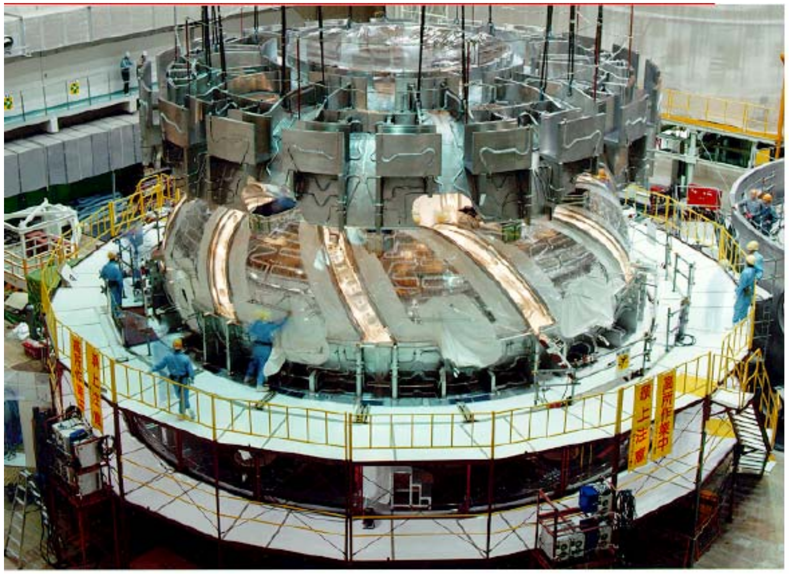
**Wendelstein 7-X (Germany)**

**Compact stellarator properties:**

- low aspect aspect ratio and high beta
- passively stable to troubling instabilities $\Rightarrow$ no disruptions, even with current.
- good magnetic surfaces.
- magnetic quasi-symmetry $\Rightarrow$ tokamak-like confinement benefits (good particle orbits, low flow damping, can use bootstrap current to generate transform).

**Advances in physics, optimization methods, and computer performance make it possible to take advantage of the opportunity.**

# Recent Stellarator Physics Developments Are Promising



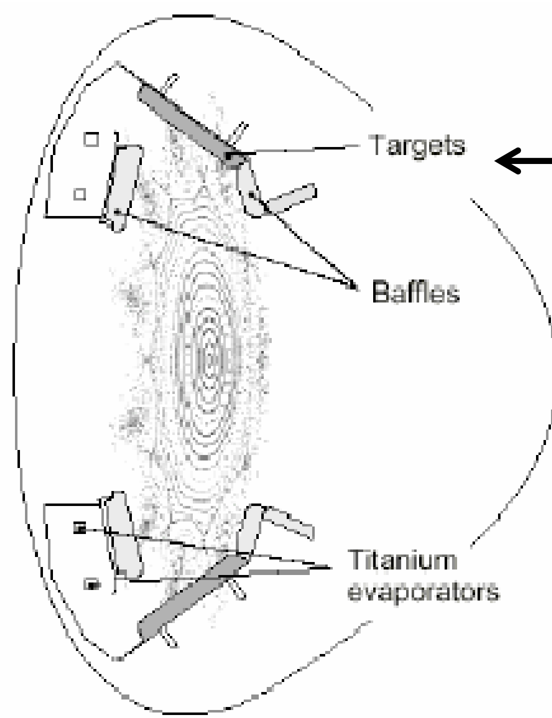
**Large Helical Device (Japan)**

β > 3%.

$T_e \approx 10$ kev, $T_i \approx 5$ keV.

enhanced confinement.

2-minute pulses.

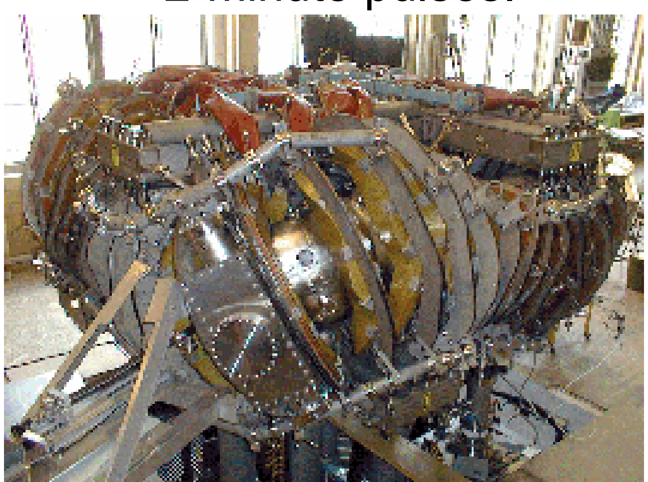



**Wendelstein 7-AS (Germany)**

β > 3%.

enhanced confinement.

density control & enhanced performance w/island divertor.



**Helically Symmetric Experiment (U. Wisc.)**

- Successful test of quasi-symmetry.

# U.S. Compact Stellarator Design Efforts (NCSX and QPS) Have Been Successful

**NCSX and QPS designs optimized as *experiments* with $R/\langle a \rangle < 4.4$ and $\langle \beta \rangle > 4\%$.**

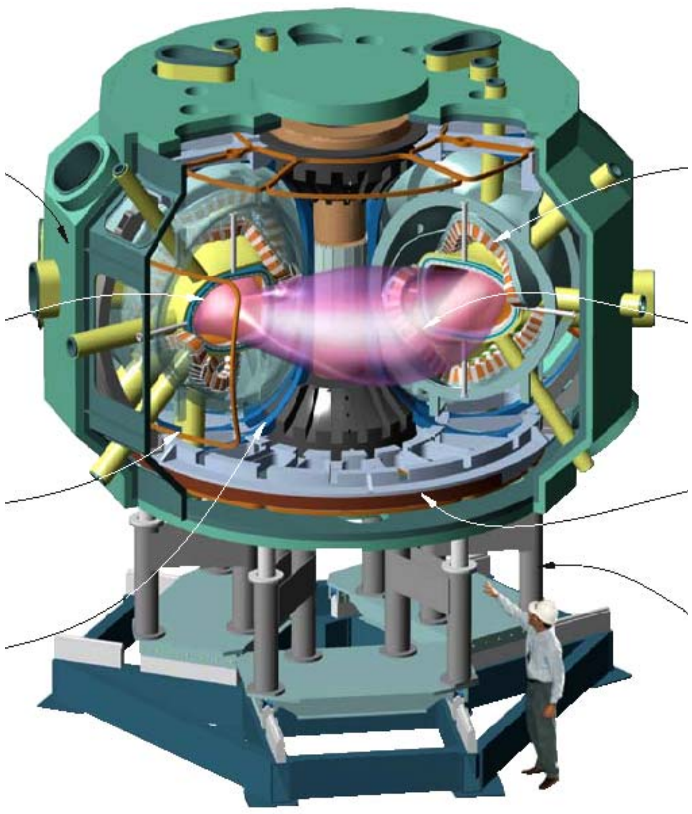
**Reviews have been successful**

- NCSX and QPS Physics Validation Reviews confirmed compact stellarator physics approach (2001).
- NCSX Conceptual Design Review demonstrated a feasible design. (2002).
- QPS conceptual design in progress; CDR next Spring.

**Designs were developed by national stellarator team using common tools. Starting point for next design task:**

**Optimizing compact stellarators as *reactors.***

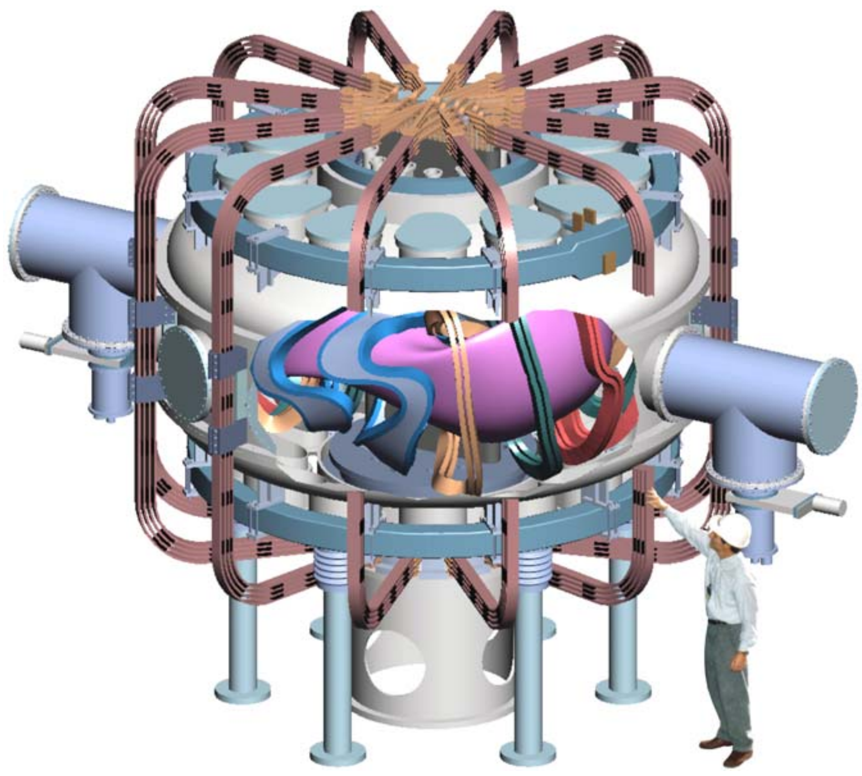
# Compact Stellarator Experiment Designs



**NCSX (PPPL-ORNL)**

PoP test of high-β, quasi-axisymmetric stellarator.

**Fab. project starts in FY-03**

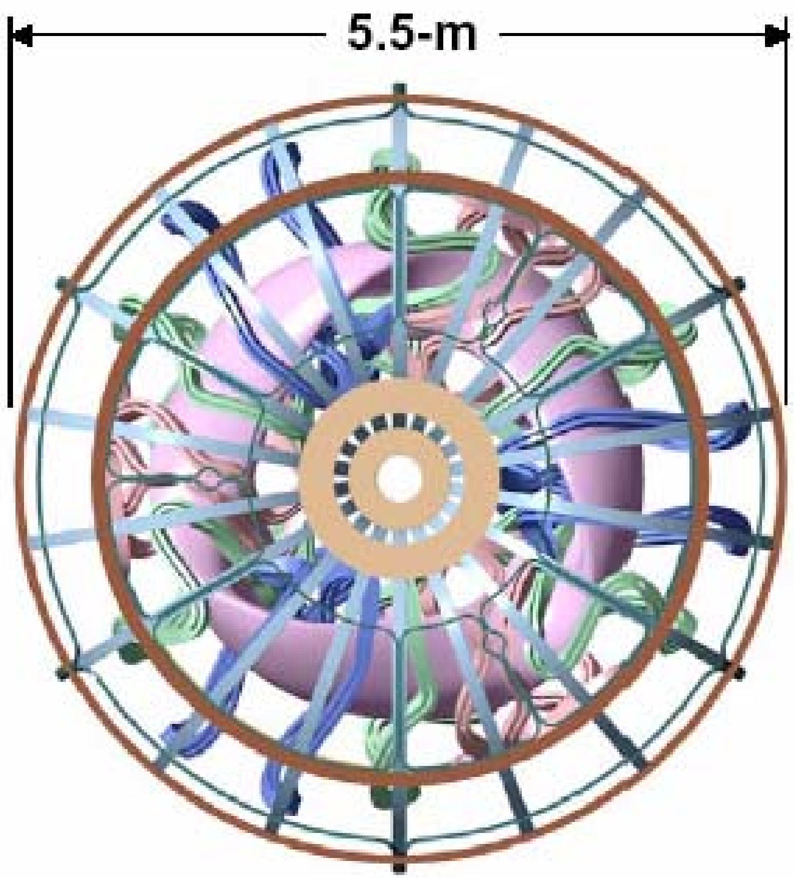


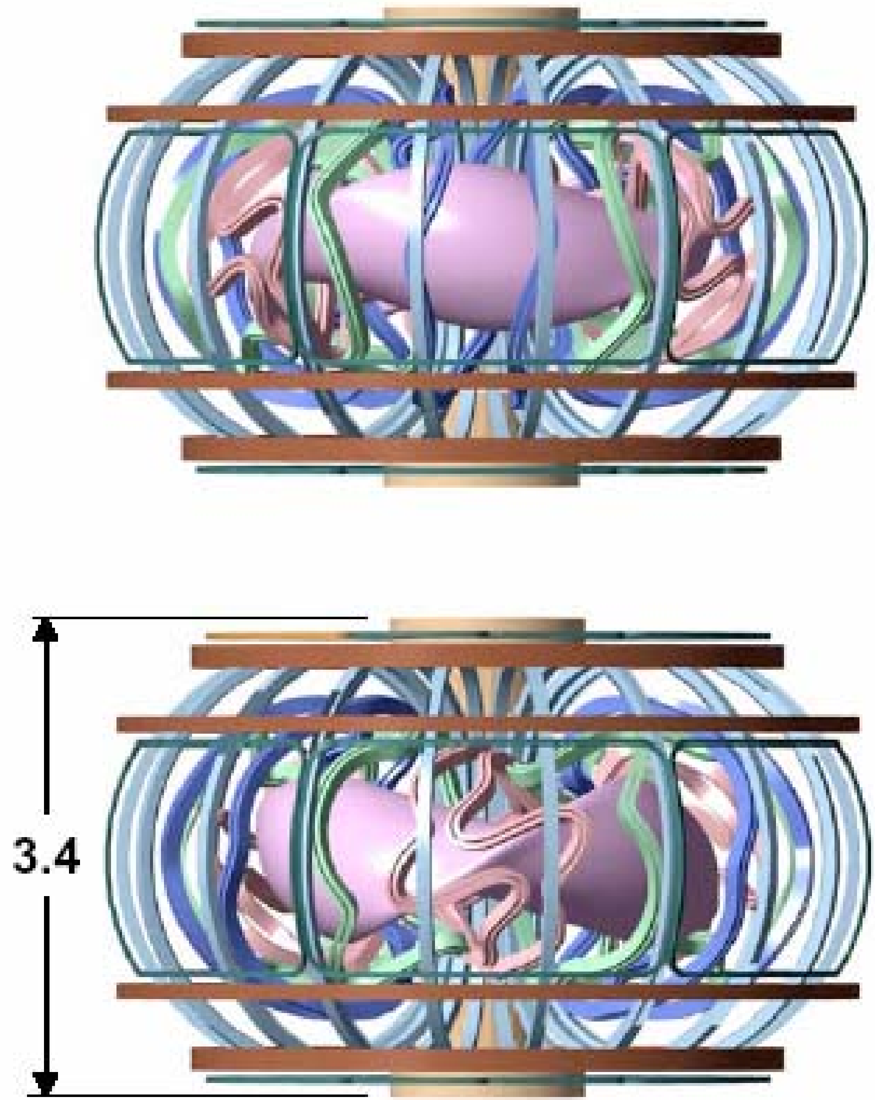
**QPS (ORNL)**

CE test of quasi-poloidal symmetry at R/a = 2.7

**CDR planned April 03**

# NCSX Magnets Optimized for Experimental Flexibility Include Modular, TF, PF, and Trim Coils




**What is needed for a reactor?**

# Compact Stellarator Reactor Vision

**A steady-state toroidal reactor with**

- No disruptions
- No conducting structures or active feedback control of instabilities
- No current drive ($\Rightarrow$ minimal recirculating power)
- High power density (~3 $MW/m^2$)

**Likely configuration features**

- Rotational transform from a combination of bootstrap and externally-generated sources. (how much of each?)
- 3D plasma shaping to stabilize limiting instabilities. (how strong?)
- Quasi-symmetric to reduce helical ripple transport, alpha losses, flow damping. (how low must ripple be?)
- Power and particle exhaust via a divertor. (what magnetic topology?)
- $R/\langle a \rangle \leq 4.4$ (how low?) and $\beta \geq 4\%$ (how high?)

**Optimum design involves tradeoffs among features. Need to develop the physics and understand reactor implications to determine optimum power plant design, assess attractiveness.**

# Program Plan to Assess Compact Stellarators: Physics

## Stellarator Theory and Experiments (HSX, CTH, LHD, other non-U.S.)

- Fundamental understanding.
- Validated physics models.
- Benchmarked tools for physics analysis and design.

## New Compact Stellarator Experiments (NCSX, QPS)

- Test compact stellarator physics models and design drivers.
  - What sets the beta limits?
  - How low can the aspect ratio be?
  - How low must the ripple be?
  - What is the best enhanced confinement strategy?
  - What does the divertor look like?
- Determine the conditions for high-beta, disruption-free operation.

# Program Plan to Assess Compact Stellarators: ARIES Reactor Studies

**Optimize a compact stellarator reactor configuration.**

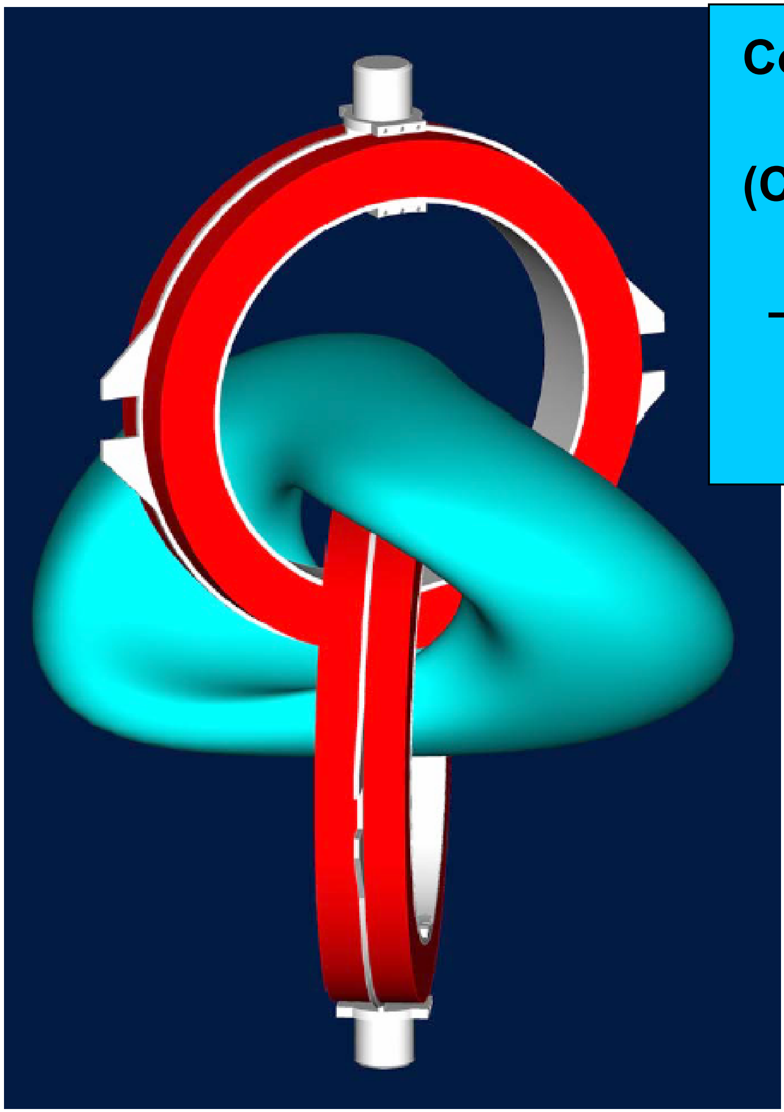
- Optimization objectives will differ from those used in experiment design. Possible examples:
  - More emphasis on alpha confinement, blanket & shield space.
  - Less emphasis on minimizing ripple (sufficient to confine alphas).
  - Less emphasis on flexibility (sufficient to have a start-up path)
  - Less reliance on coils for island reduction (take more credit for physics effects)
  - Engineering criteria appropriate for reactors (guidance from ARIES experts and NCSX/QPS engineers.)
- Configuration alternatives need to be explored
  - Plasma configurations: # of periods, beta, aspect ratio, shaping.
  - Coil configurations: alternatives to modular coils.

**Identify high-leverage issues for further physics research:**

- What are the cost sensitivities?

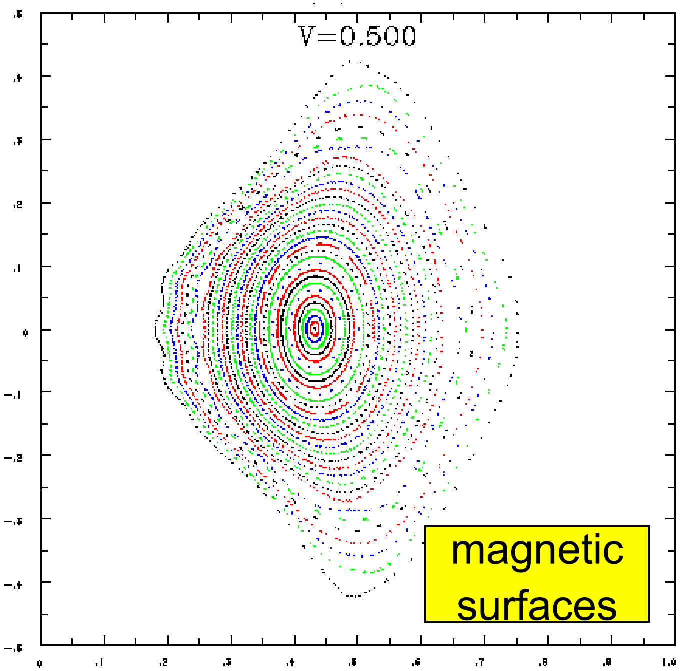
**Develop an attractive design around the optimum configuration.**

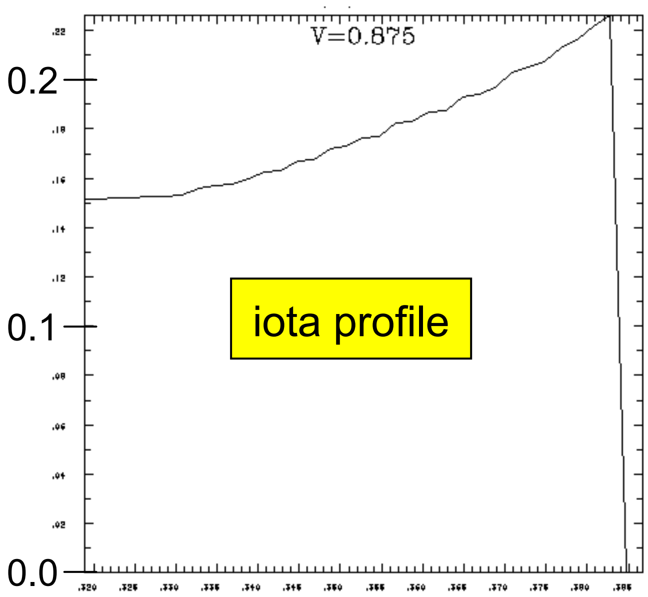
# Stellarator Configurations Can Be Made with Surprisingly Simple Coils



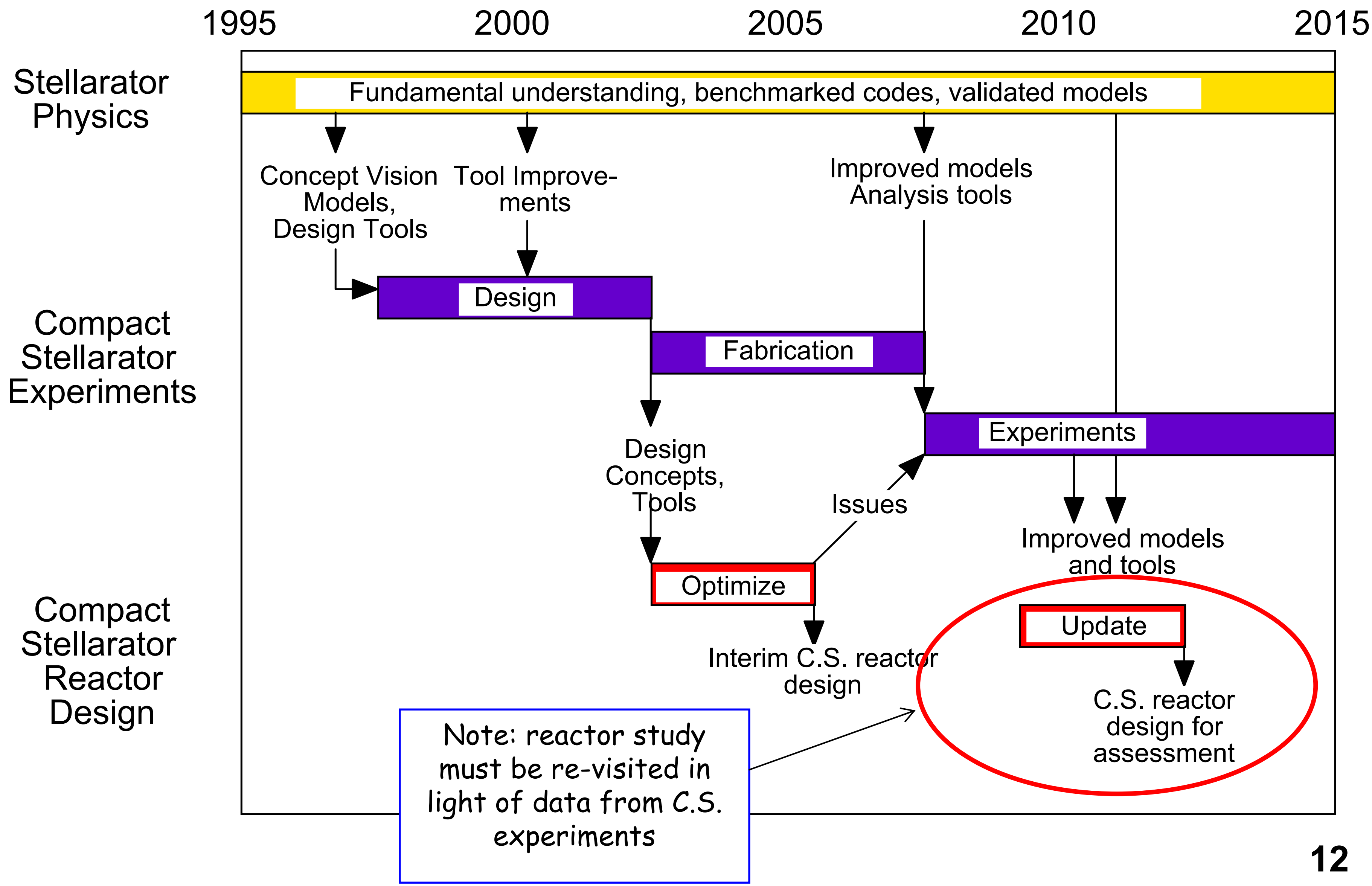
**Concept for CNT Experiment (Columbia Univ.)**

**– proposed by W. Reiersen, PPPL**



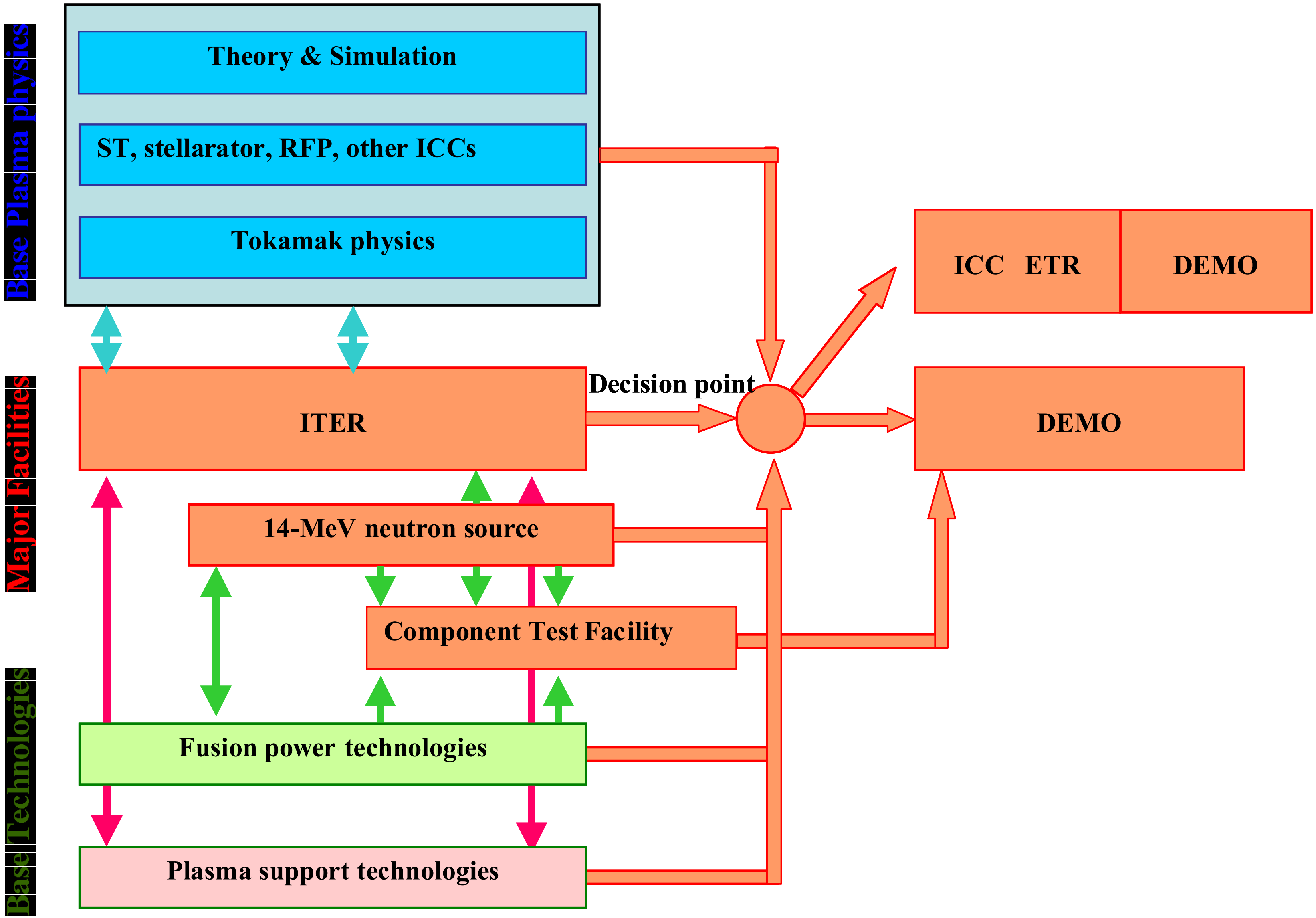
# Path to Compact Stellarator Assessment



# With a Well-Integrated Program, a Stellarator DEMO Could Be the Next Step After a Tokamak BPX.

- By 2025, there will be a substantial knowledge base on stellarator physics and long-pulse integration from 2-3 PE-class stellarators (LHD, W7-X, and a possible "CS-PE").
- The BPX will produce a knowledge base on toroidal physics in the regime of alpha-dominated, large-size plasmas.
  - Compact stellarators have a physics link to tokamaks (via quasi-symmetry) that can facilitate knowledge transfer from tokamaks to stellarators.
  - Compact stellarators can use the tokamak data base. Reduced development time.
- Predictive capability for toroidal systems will be improved by virtue of expanded data base from large machines, theory advances, exploitation of advanced computation, and commitment to cross-portfolio integration.
- The BPX can provide a knowledge base on the operation of fusion-relevant technologies in a burning-plasma environment, readily applicable to stellarators.

# Snowmass MFE Development Path



# Summary

- Stellarators solve important problems for MFE.
- Compact stellarators offer further improvements, but the optimum reactor configuration needs to be developed before its potential can be adequately evaluated.
  - Physics models and tools.
  - Reactor criteria.
  - Design tradeoffs and optimization.
- ARIES role is critical in understanding the reactor implications and identifying issues for R&D.
  - Developing a reactor-optimized compact stellarator configuration is the first step.