NCSX Configuration Optimization Process

Long-Poe Ku

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Presentation Outline

- Configuration optimization
  - Why needed? Why of interest.
- NCSX-- LI383 plasma and M45 coils
  - What are involved in optimization—parameters and performance.
- NCSX Configuration optimization process -- how it is done.
  - Plasma optimization.
  - Coil geometry/current optimization.
- Compact stellarator reactor configuration optimization – moving forward.
  - NCSX as a base for a reactor?
  - Critical issues in reactor optimization.

Optimization -- Motivation and Necessity

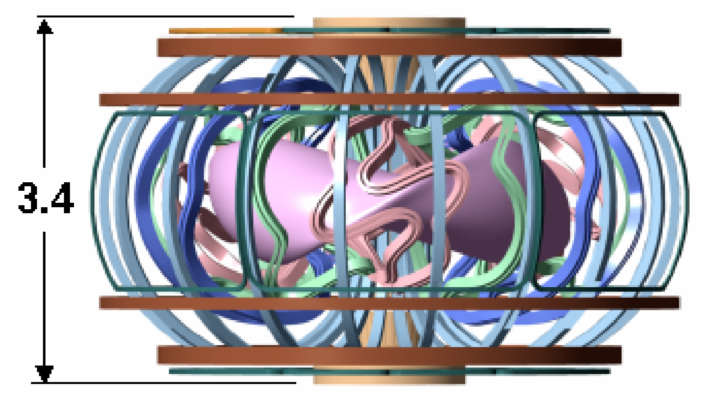
- Configuration space is vast and expansive; landscape is full of local extrema.
  - In 3-D magnetic field topology, particle drift trajectories depend only on the strength of the magnetic field, not on the shape of the magnetic flux surface.
  - QA can not be attained simultaneously on all surfaces, but can be maximized together with other desirable properties (e.g. MHD stability).
  - Not all components in magnetic spectrum have equal effects; effective optimization depends on effective targeting.
  - NCSX is good QA configuration, but may not be the best configuration.

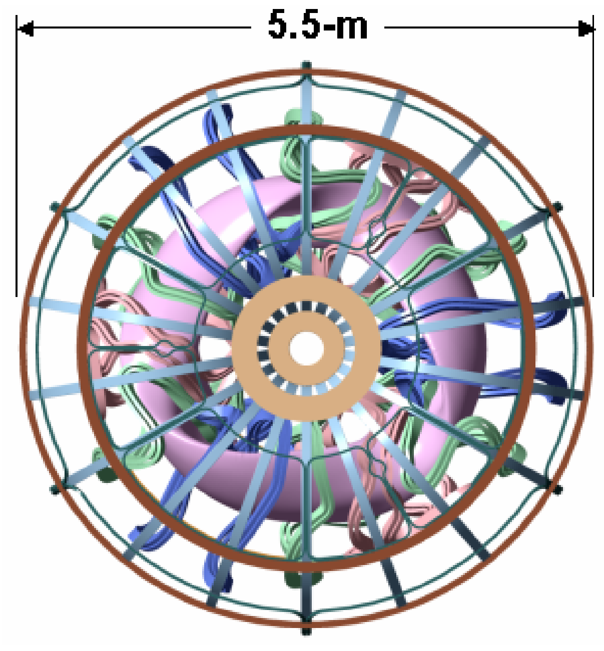
- Large number of variables and constraints are involved.
  - >30 for plasma shape optimization
  - >200 for coil geometry optimization
- Optimization process developed is not yet perfect. Better optimization techniques and goodness measures still need development and improvement.
  - Have built highly efficient algorithms and a large repertoire of physics/engineering target functions.
  - Reactor relevant measures, however, have yet to be implemented.
    - COE, coil build-ability and complexity
  - Need more effective target function evaluation.
    - Fast ion losses, surface quality, profile optimization

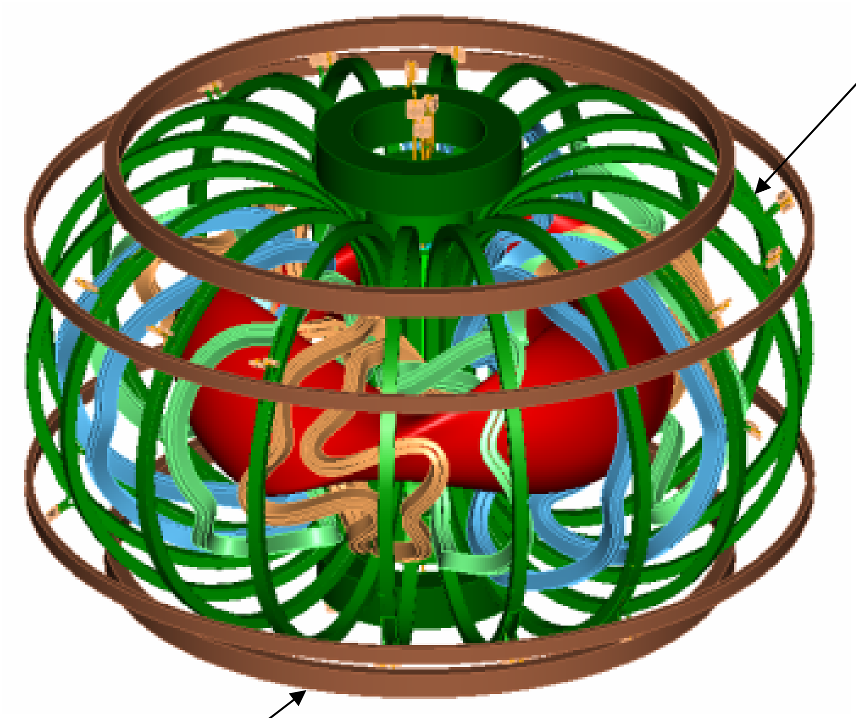
NCSX – LI383 plasma and M45 coils

1) LI383 is optimized to achieve MHD stable plasmas at 4% beta with good confinement characteristics.

2) M45 coils are optimized to provide plasma performance consistent with LI383 and to ensure good flux surface quality, good engineering characteristics, and large accessible operating space.







TF coils:

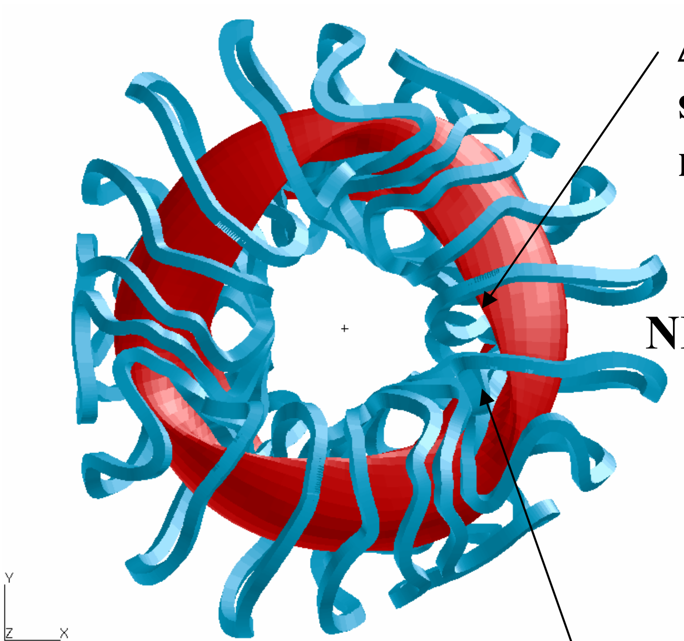
1) Current is optimized at the reference state to ease the peak current density in modular coils and to assist in their geometry optimization.

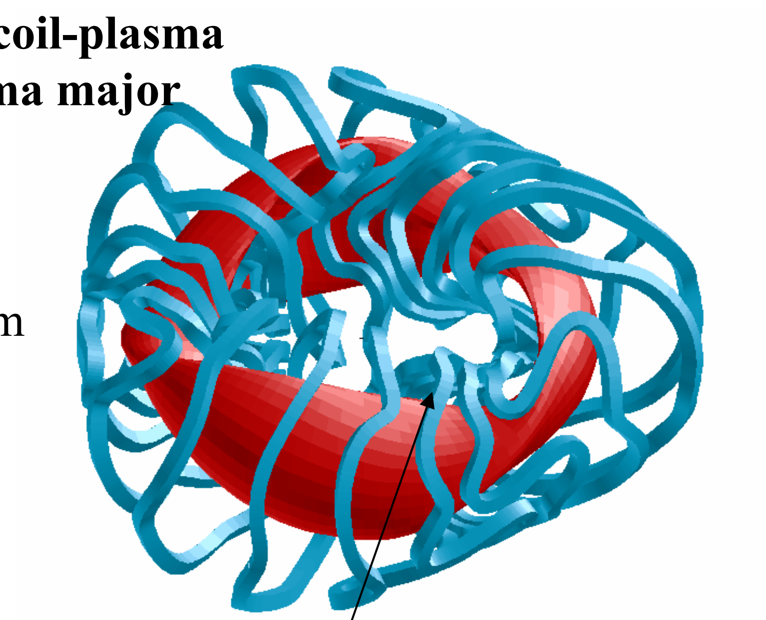
2) Optimized “dial-in” currents allow access to large operating space.

PF coils: optimized “dial-in” currents allow access to large operating space.

Modular Coils are optimized to provide:

1) **good MHD stability and particle transport at the reference state,**
2) **coil build-ability,**
3) **room for first wall, vacuum vessel, and other internal components,**
4) **good flux surface quality (island size <10% plasma volume),**
5) **wide accessible operating region.**





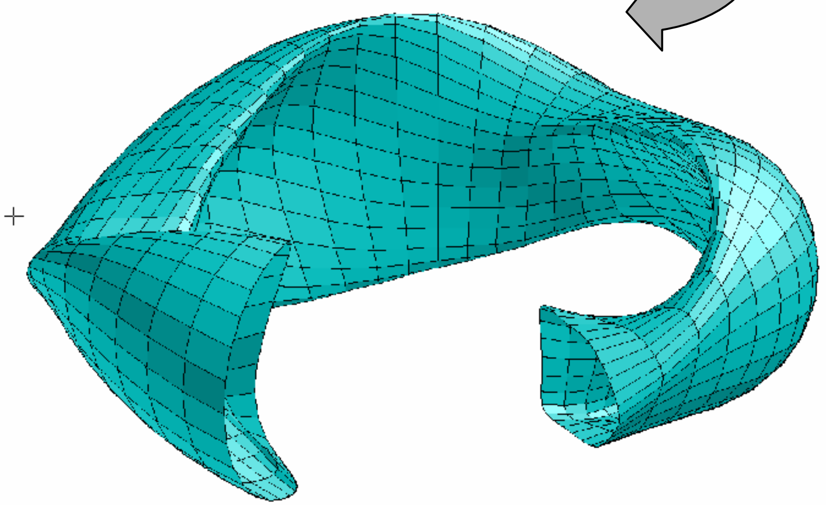
The last closed flux surface of LI383 is optimized to provide fundamental properties of the device: MHD stable at 4% β (no conducting walls), I(ext)/I(total)~70%, dι/ds>0 through most of the plasma radius, low residual non-axisymmetric components in magnetic spectrum at A<4.5.

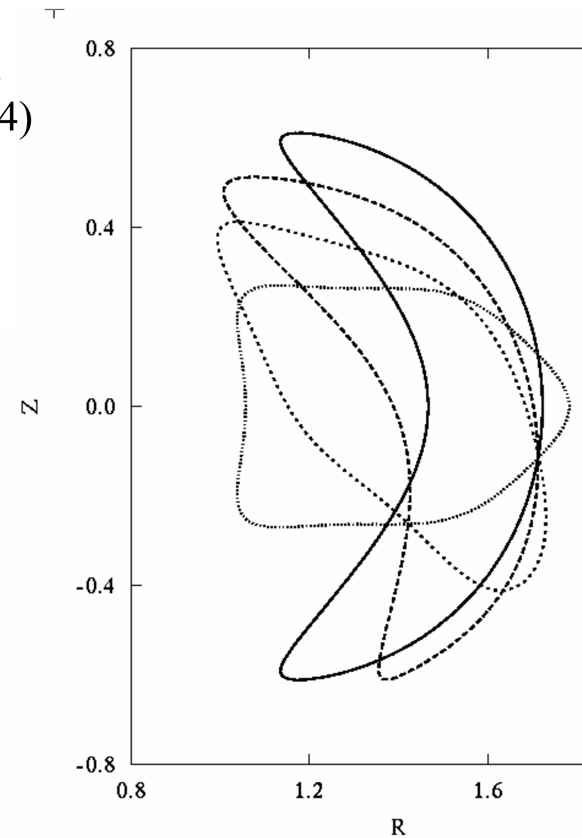
$$R = \sum_{m,n} R_{m,n} \cos(mu - nv)$$

$$Z = \sum_{m,n} Z_{m,n} \sin(mu - nv)$$

$$u = \frac{\Theta}{2\pi}, \quad v = \frac{N_p \Phi}{2\pi}$$

Boundary representation (m=0,6; n=-4,4)





3 field periods

A=4.37

R=1.42 m

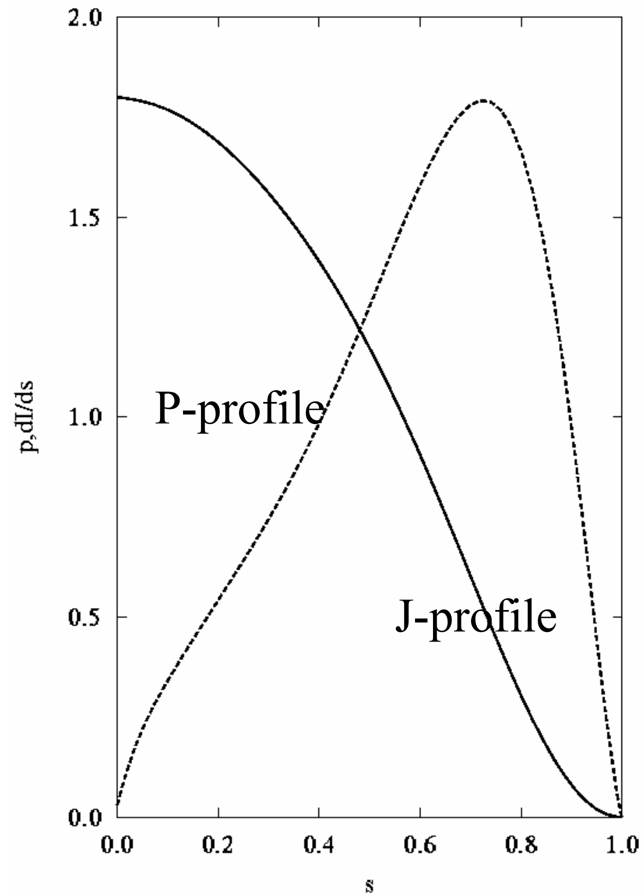
<a>=0.33 m

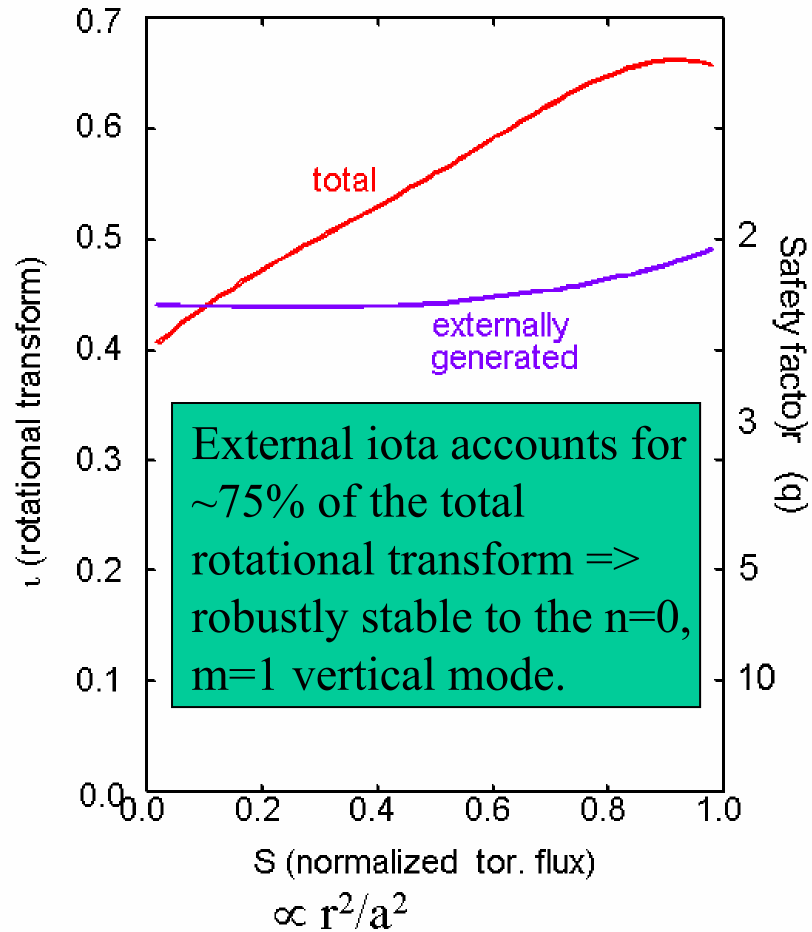
a_{min}=0.26 m

<κ>=1.72

<δ>=0.7

Positive shear promotes neoclassical stabilization of tearing modes and helps reducing equilibrium islands.

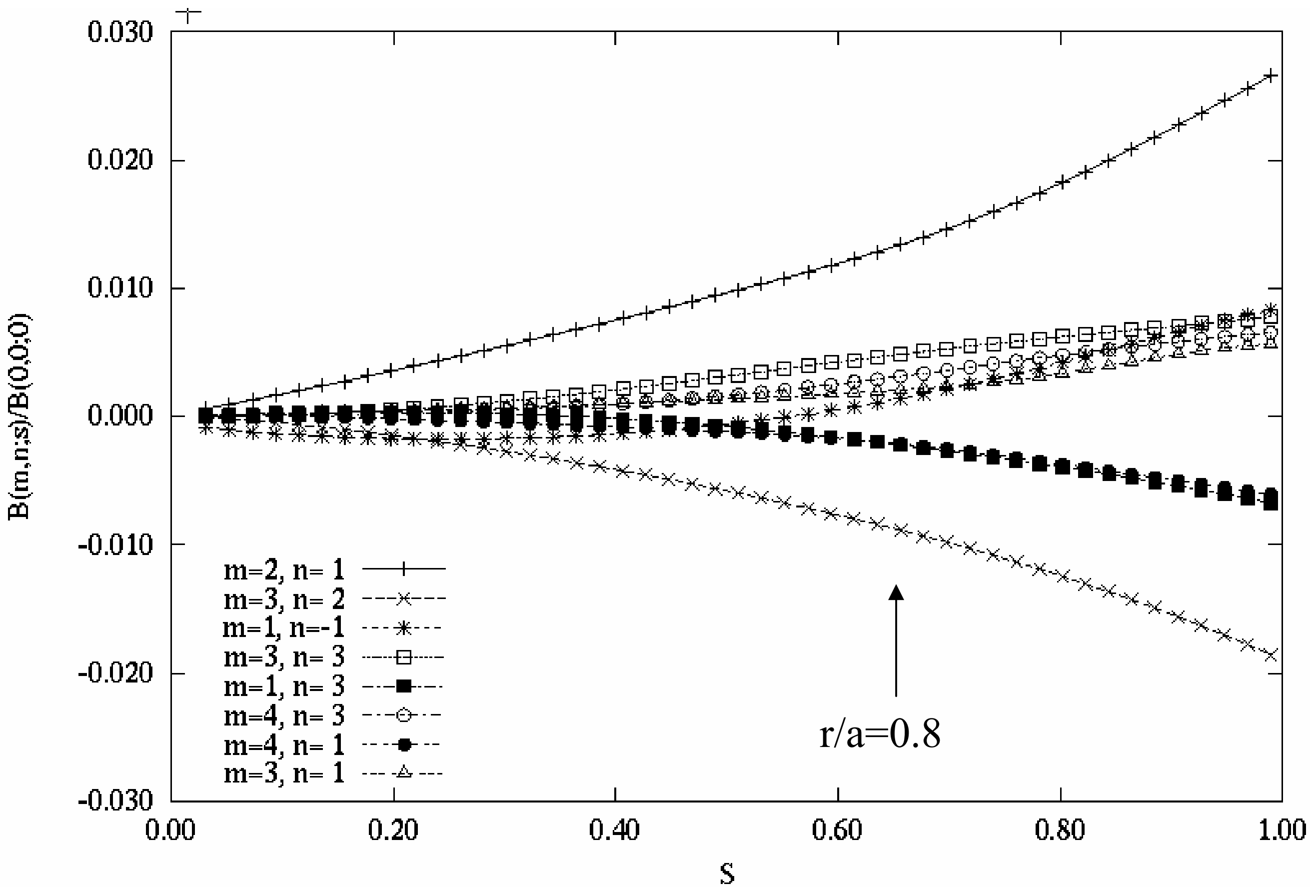




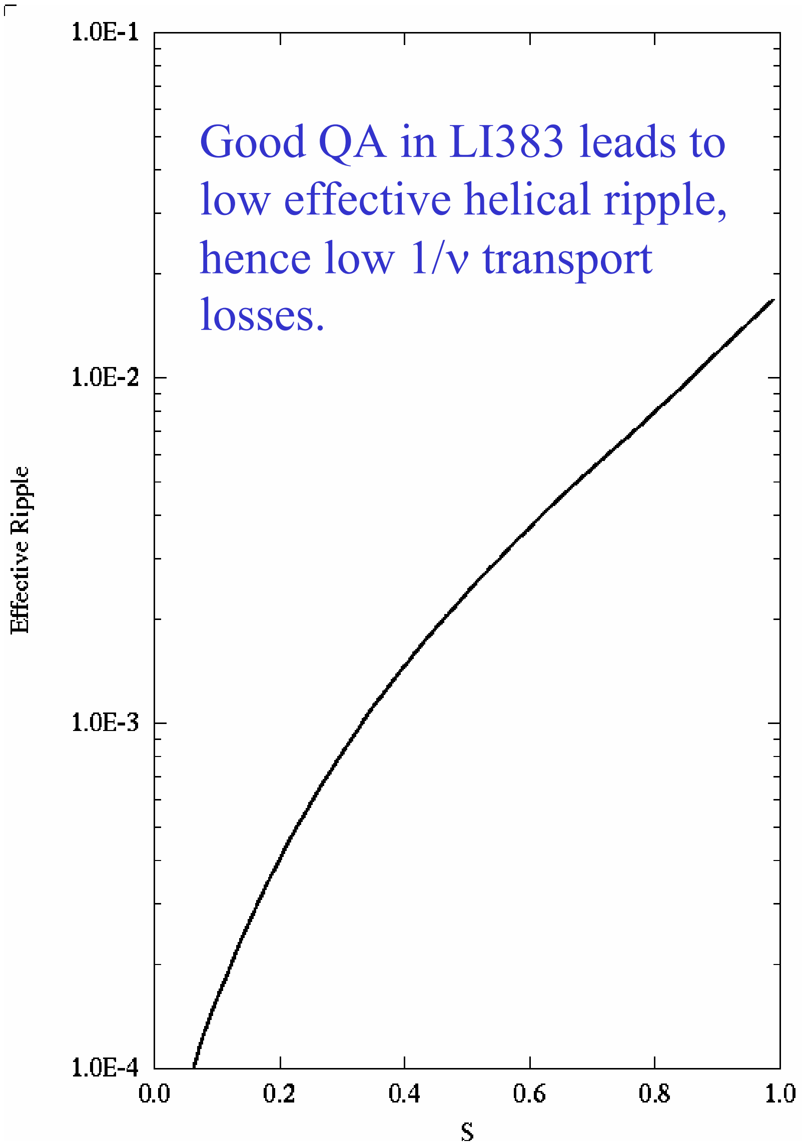
External iota accounts for ~75% of the total rotational transform => robustly stable to the n=0, m=1 vertical mode.

Self-consistent pressure and bootstrap current profiles are used in optimization, but profiles are not part of the optimization.

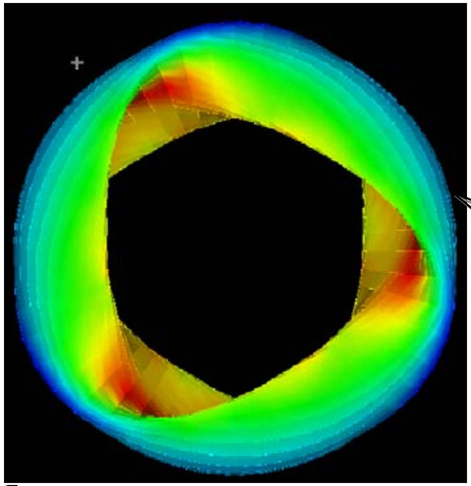
Non-axisymmetric components in magnetic spectrum are minimized, leading to good thermal ion confinement, low helical ripples, and acceptable beam ion losses.



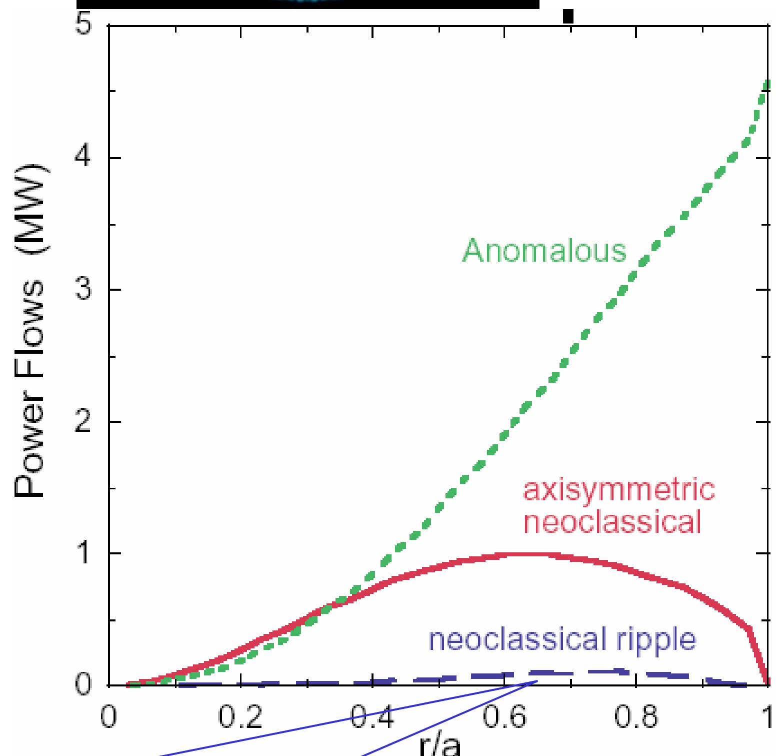
B(3,2), B(2,1) resulting from shaping the plasma to produce shear and sufficient rotational transform are the only two >1% for r/a>0.8



Good QA in LI383 leads to low effective helical ripple, hence low 1/ν transport losses.

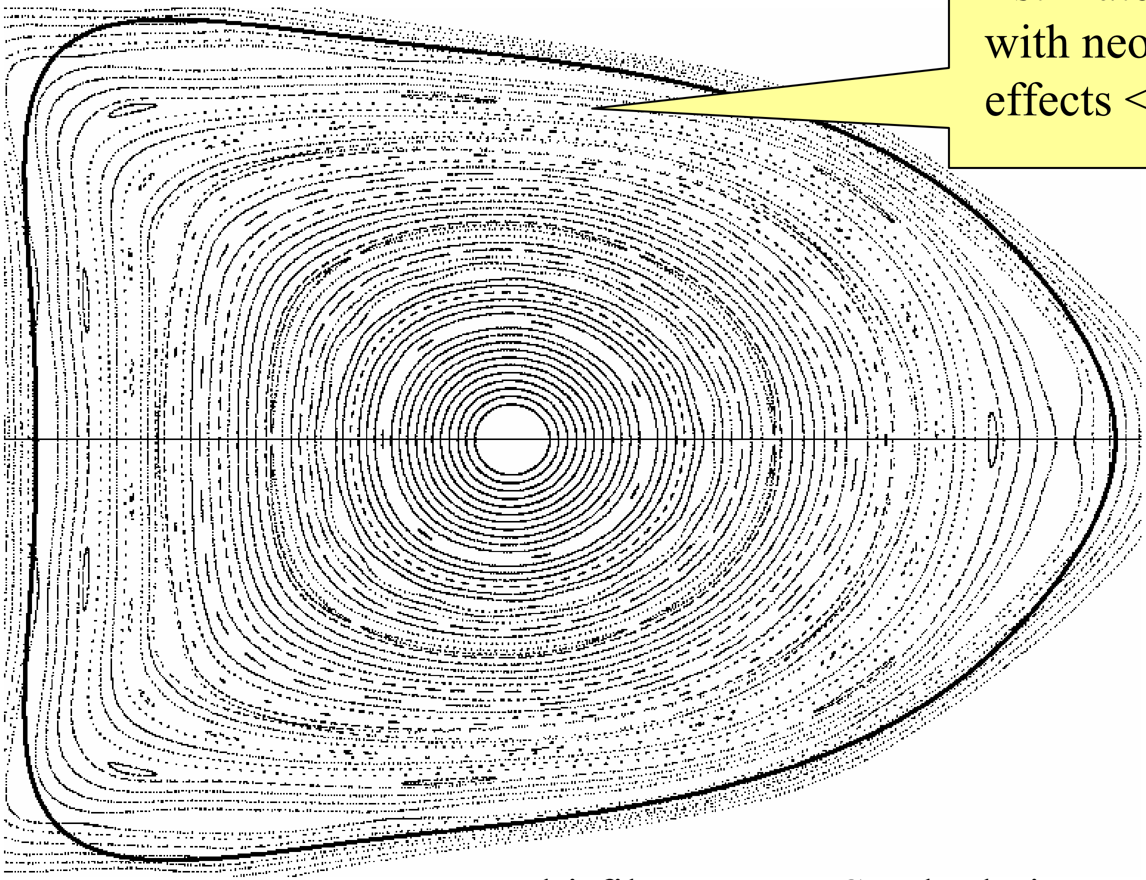


|B| contours are nearly axi-symmetric



Neoclassical ripple transport is insignificant

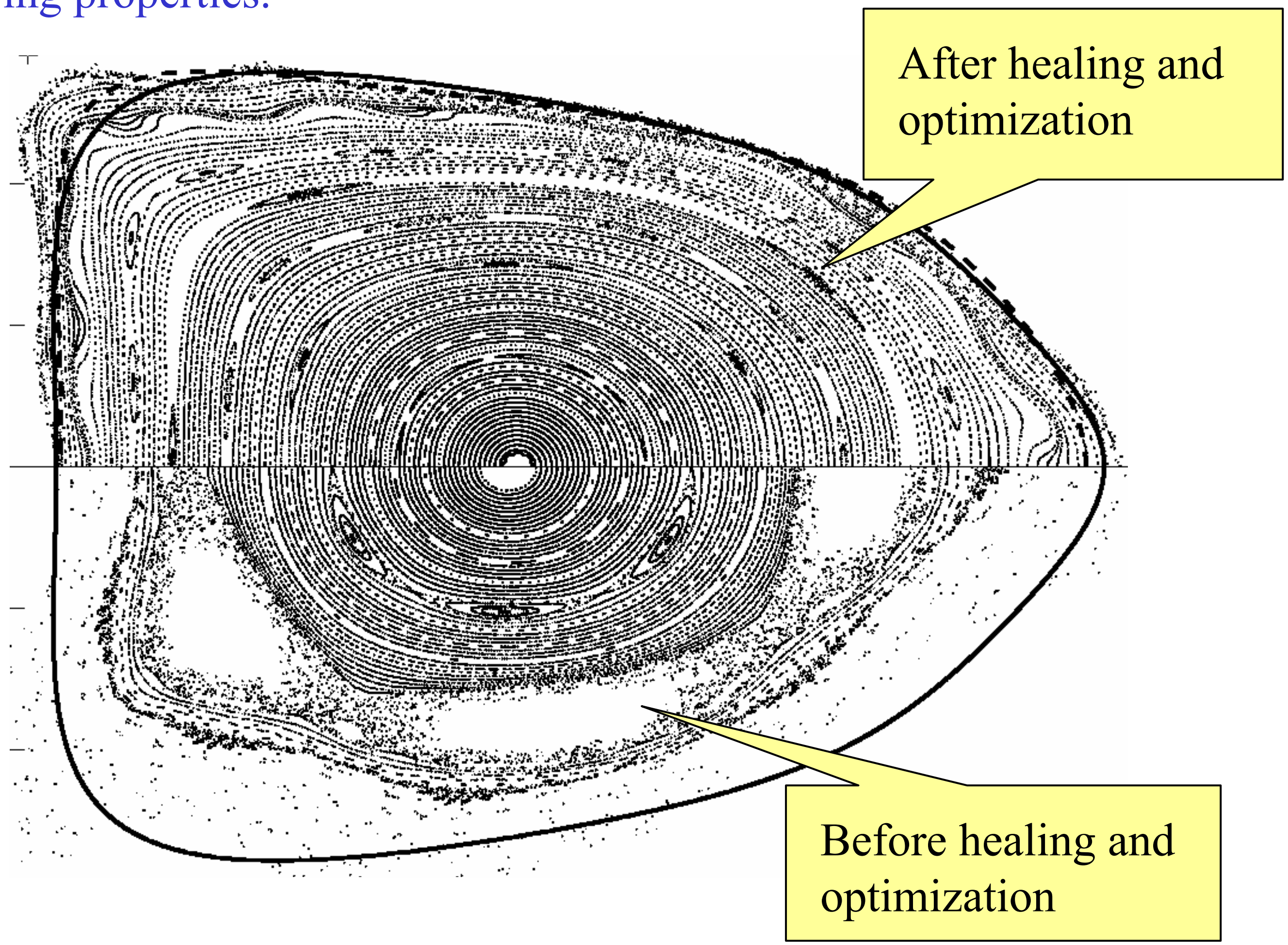
Coil and plasma optimization targeting island healing results in overall good flux surface quality at the reference full beta, full current state.



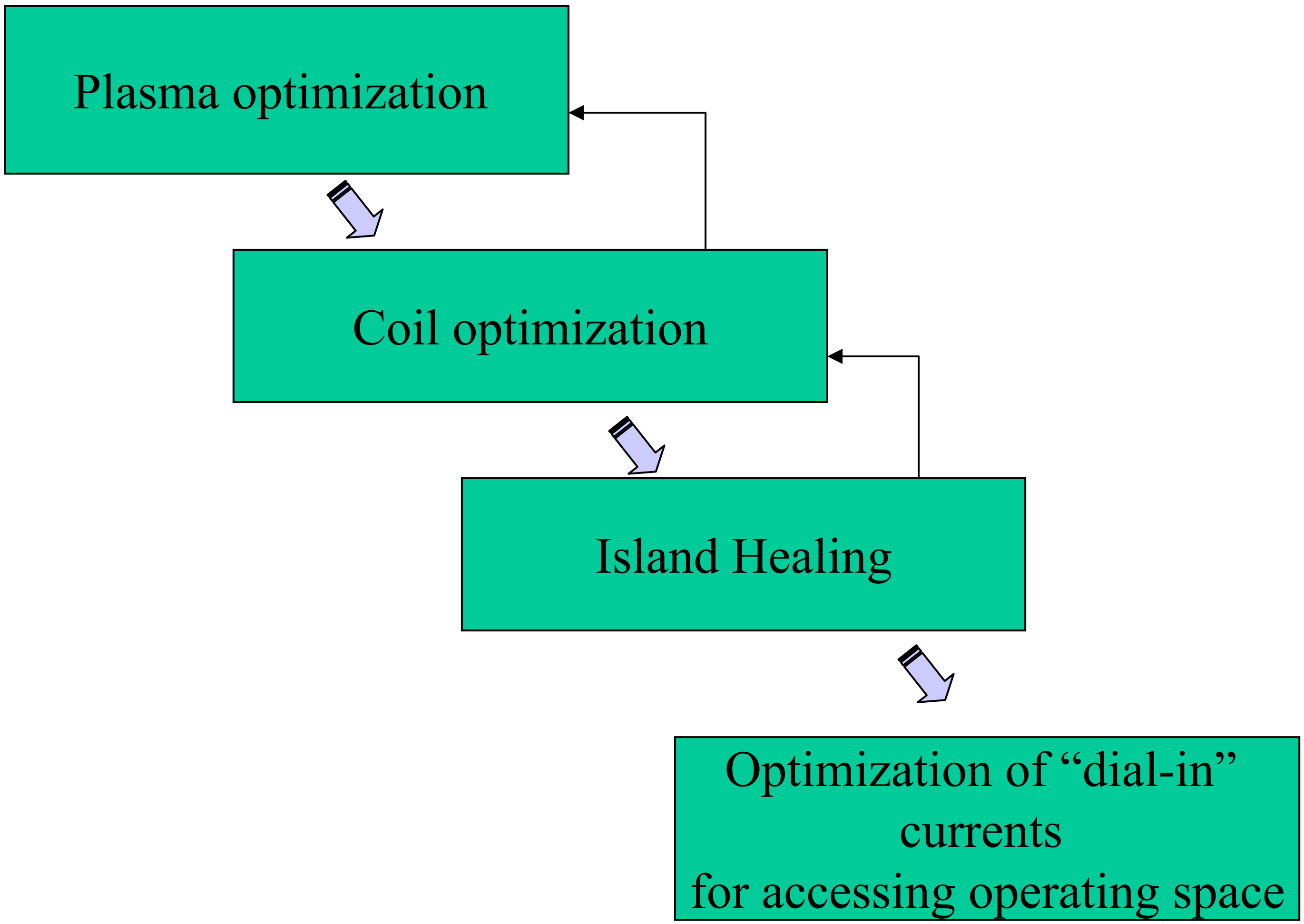
Estimated island size with neoclassical effects < 1%.

Multi-filament PIES calculation

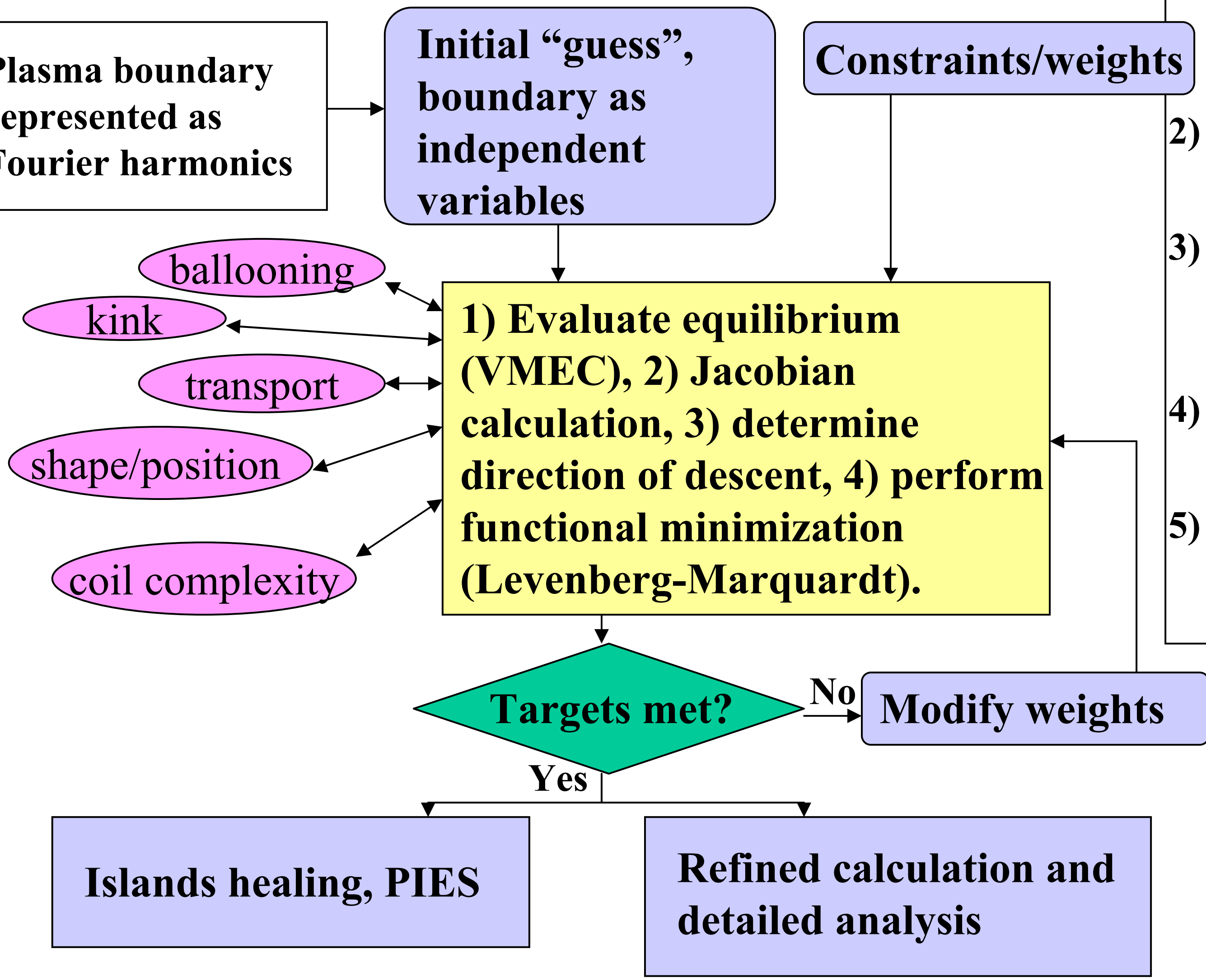
Good flux surfaces are not a given in stellarators. Imposing MHD stability and engineering constraints generally increase resonance perturbation if not controlled. PIES healing algorithm developed for NCSX has proven effective to provide good surface quality while preserving MHD and engineering properties.



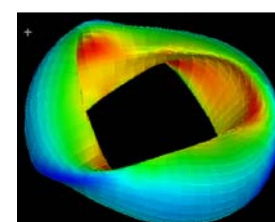
Configuration Optimization Process



Plasma optimization



1) Select p, J profiles, β (4%), B (1.4 T), F.P (3)
2) Iota target (0.4-0.65)
3) MHD stability target (Mercier, ballooning, kink)
4) Transport target (QA)
5) Coil target (complexity, current density)

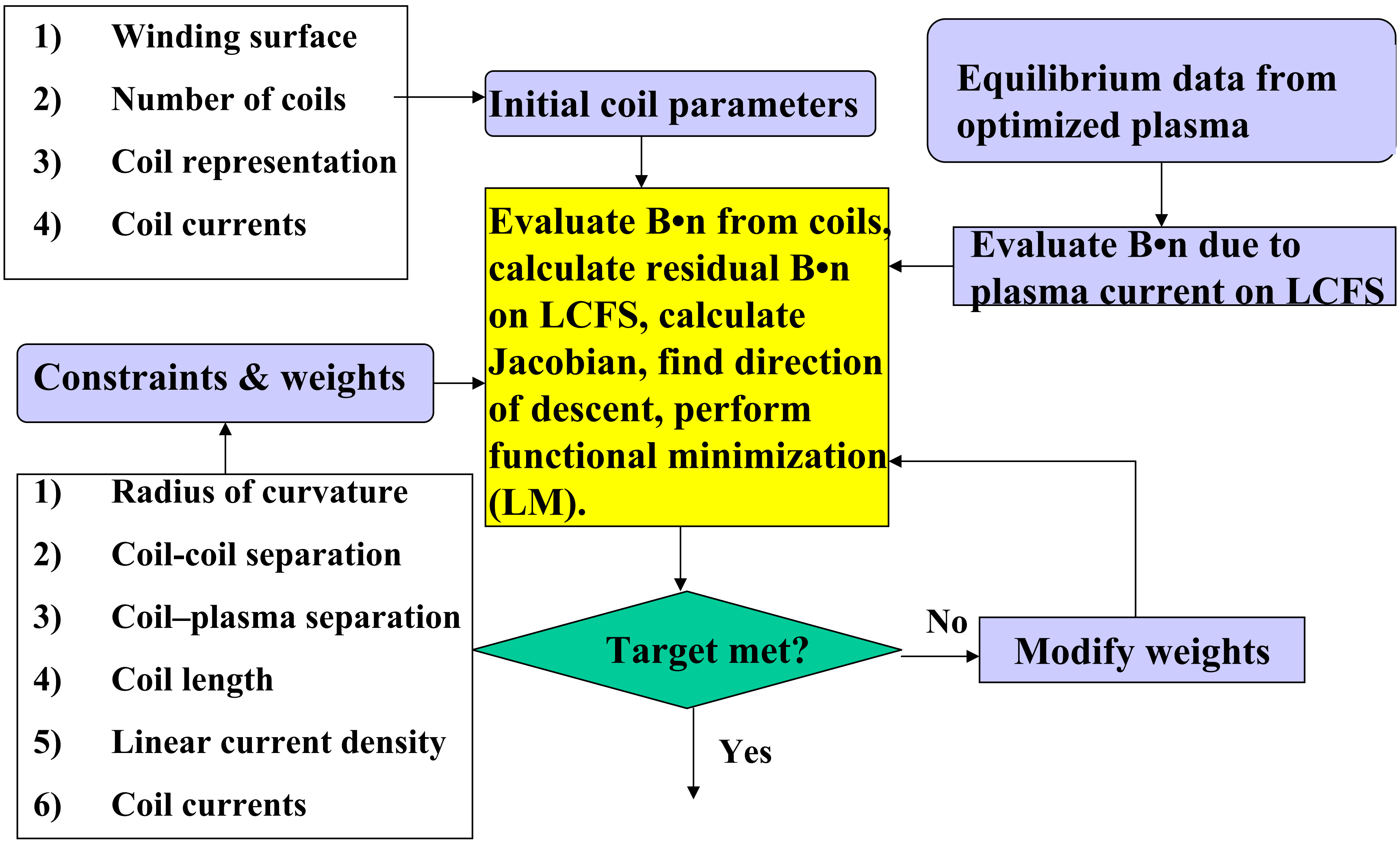


Some comments:

- Genetic algorithm and differential evolution optimization add additional capability for global search.

- Repertoire for target function evaluation greatly expanded:
  - Resonance Jacobian
  - Effective ripple (NEO)
  - Direct evaluation of fast ion loss (ORBIT)
  - Pseudosymmetry
  - Second adiabatic invariant confinement
  - Plasma position and shape control

Coil Optimization



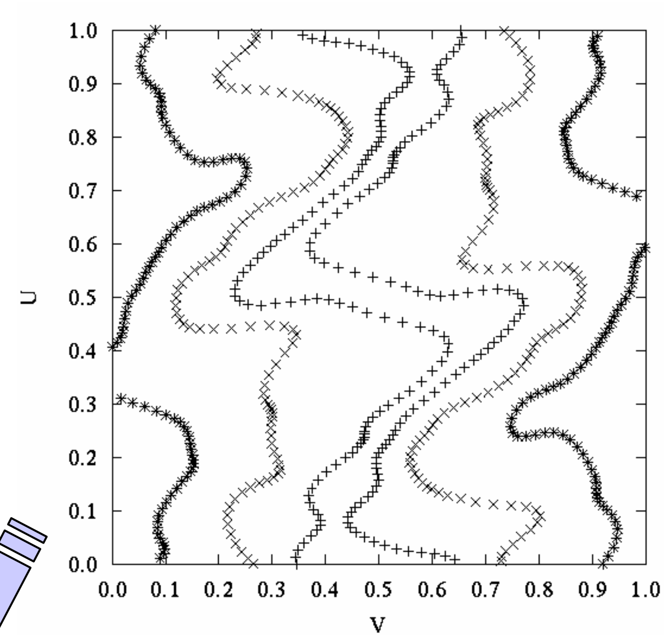
The coil geometry in cylindrical coordinates is defined as follows:

a) Coils are parameterized in (u,v) space on winding surface:

$$u(s) = s + \sum_{k=0}^{mk} a_k^u \cos(2\pi ks) + \sum_{k=0}^{mk} b_k^u \sin(2\pi ks)$$

$$v(s) = \sum_{k=0}^{nk} a_k^v \cos(2\pi ks) + \sum_{k=0}^{nk} b_k^v \sin(2\pi ks)$$

$$mk = nk = 20$$

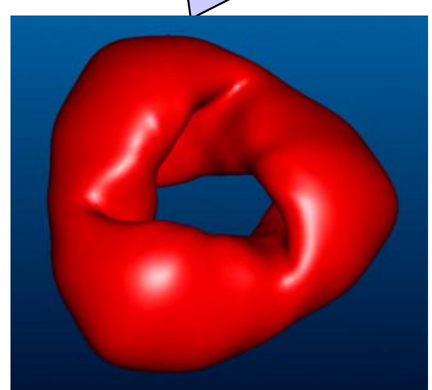


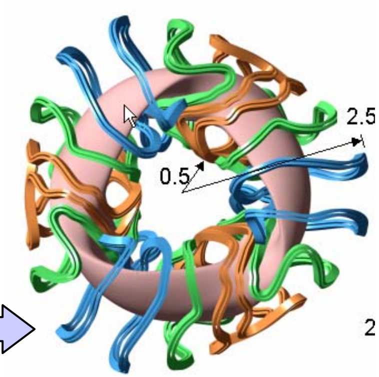
b) Coordinates are constructed on winding surface:

$$R = \sum_{m,n} R_{m,n} \cdot \cos(2\pi mu + 2\pi nv)$$

$$Z = \sum_{m,n} Z_{m,n} \cdot \sin(2\pi mu + 2\pi nv)$$

$$\Phi = \frac{2\pi v}{N_p}$$





Evaluate “free boundary” equilibrium, MHD stability and transport

1) Winding surface represented as Fourier harmonics
2) # of coils (18)
3) Coil on winding surface represented as Fourier harmonics (m=20,n=20)
4) Coil currents

Initial condition, coil parameters as independent variables

Constraints/weights

1) Iota target (0.4-0.65)
2) MHD stability target (Mercier, ballooning, kink)
3) Transport target (QA)
4) Coil target (κ, Δ’s)
5) First wall target

1) Evaluate equilibrium (VMEC), 2) calculate Jacobian, 3) determine direction of descent, 4) perform functional minimization (LM).

eff. ripple

kink

ballooning

dist. to 1st wall

Targets met?

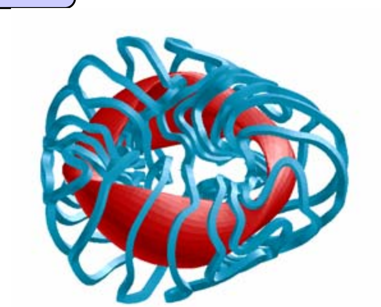
No

Modify weights

Yes

Islands healing, PIES

Discharge & flexibility (operating space) optimization



Coil Optimization and Island Healing for Good Flux Surface Quality

Initial Coil Geometry Description

Initial equilibrium

Initial Constraints and Weights

PIES equilibrium solver

$$B^n = B_p^n + B_c(\xi^n)$$

$$J^{n+1} \times B^n = \nabla p$$

$$\nabla \times B_p^{n+1} = J^{n+1}$$

Island healing (adjust coil geometry to cancel resonance fields)

$$\nabla B_c \cdot \delta \xi^n = -B_n$$

$$\xi^{n+1} = \xi^n + \delta \xi^n$$

kink

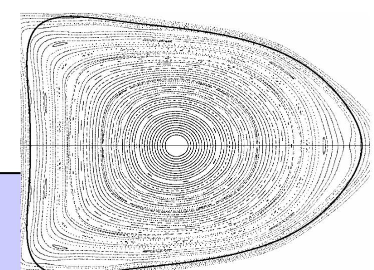
κ, Δ(c-c)

ballooning

Healed?

No → **Modify geometry/weights**

Yes → **Convergence Test**; **Flexibility, Operating Space and Discharge Optimization**



Optimization Towards a Compact Stellarator Reactor

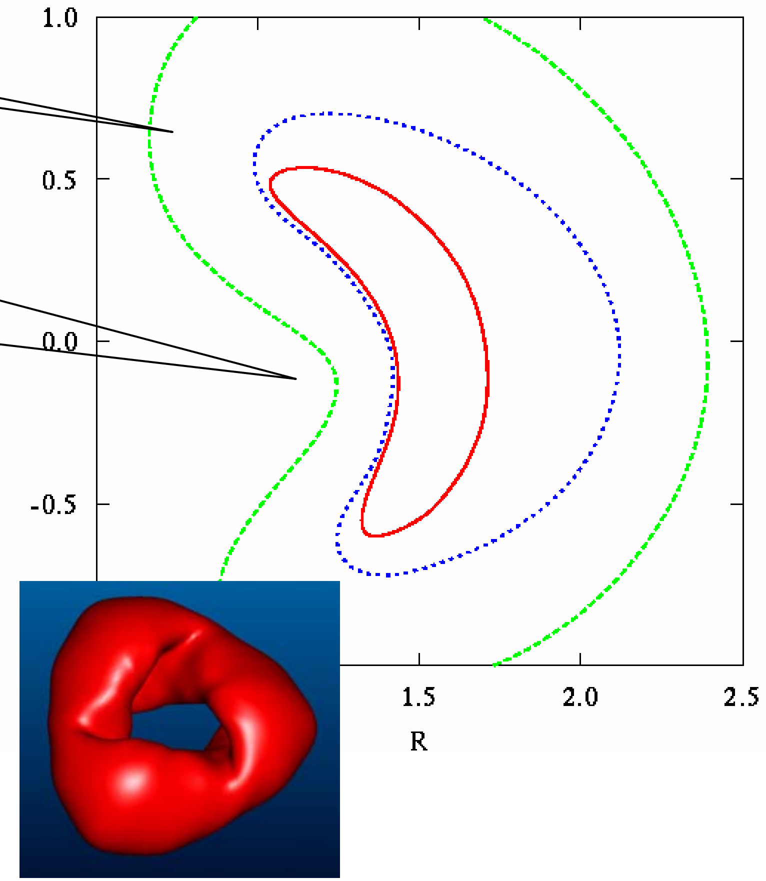
- Initial assessment of the potential of NCSX as a reactor.
  - Coil-plasma separation (Δ) and size scaling
  - Beta and MHD stability
  - Fast ion confinement and alpha energy loss

Δ is one of the most important parameters determining the "compactness" of a stellarator reactor. Together with the minimum coil-plasma separation (d), they determine the major radius of a device. NCSX coil design is a good start.

Space varies both poloidally and toroidally

Δ>13.5%. >17% has recently been shown feasible.

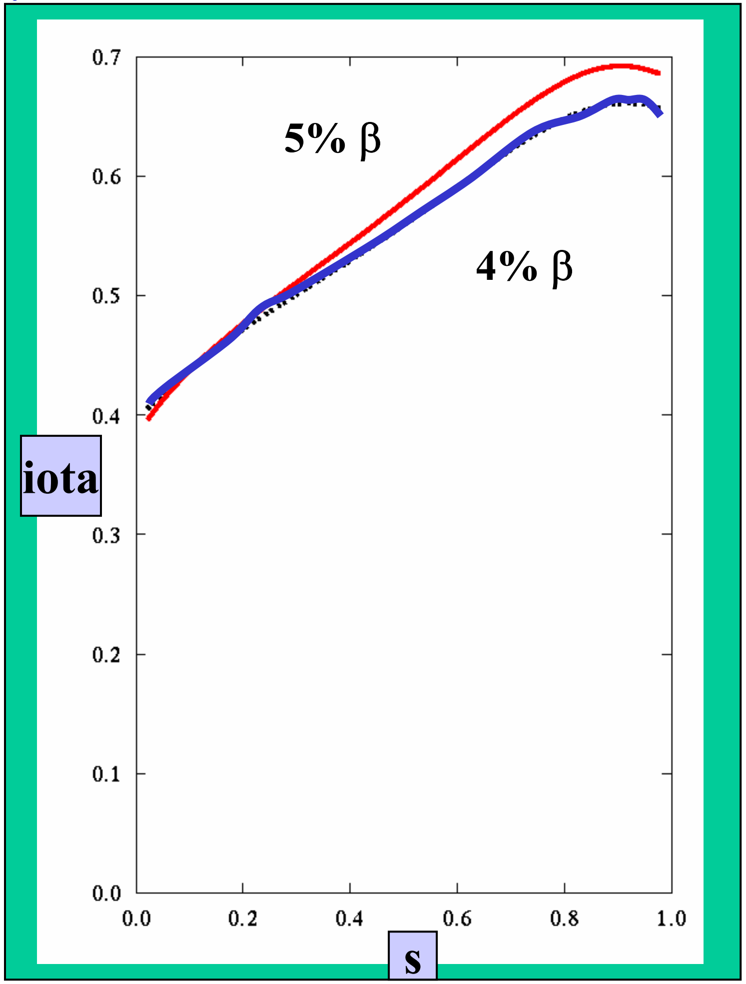
For Δmin=17%
d=1.5 m, R=9 m
d=1.2 m, R=7 m



NCSX separation is designed to accommodate beam lines, first wall, vacuum vessel, etc., but not blanket and thermal and radiation shield.

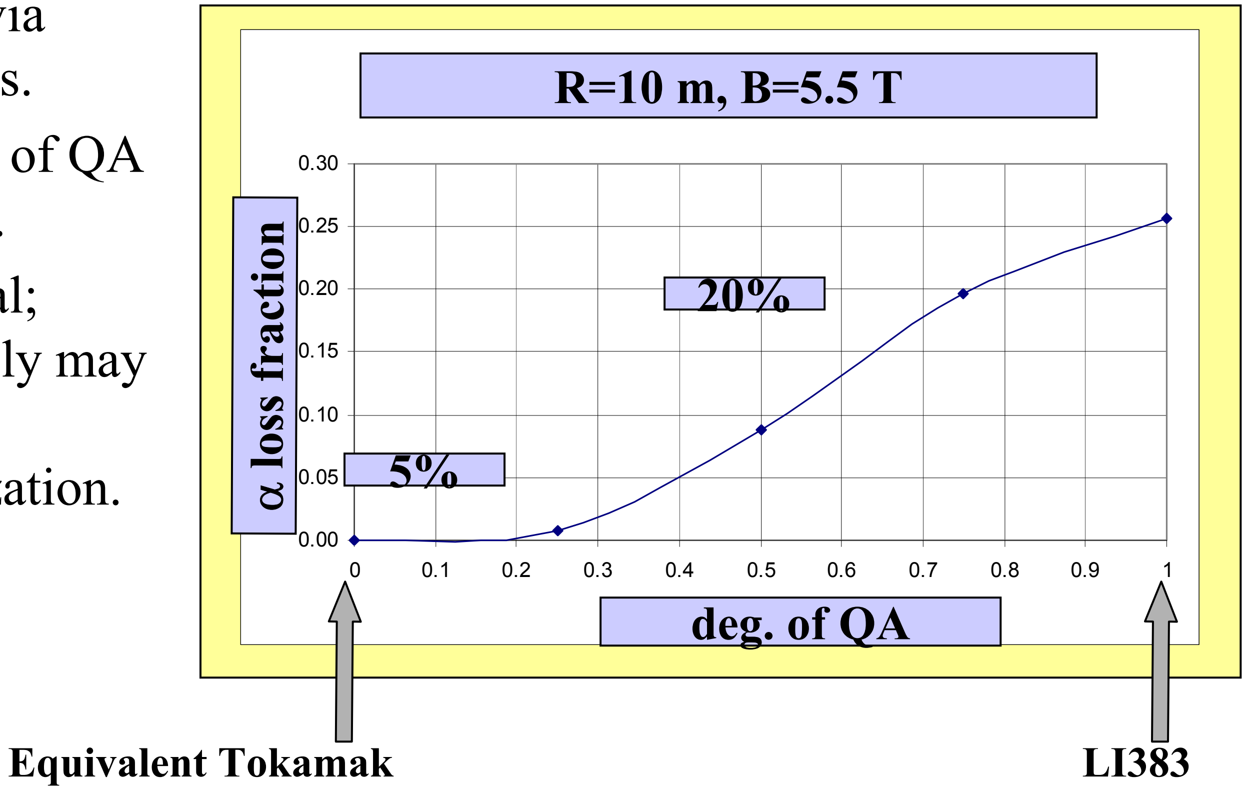
The 4% β designed for NCSX is limited by the available heating power. Increasing β leads to unstable plasma, hence re-optimization will be needed.

- Raising β increases bootstrap current.
  - $Ip \sim \beta/\iota$, $\iota \sim \iota_{ext} + \iota_p$, $\iota_p \sim Ip$
- Both increased pressure and current provide extra driving force for instability.
- Increased pressure and altered iota profile also affect the flux surface integrity.



NCSX has good QA and very low effective helical ripple, but minimizing fast ion losses was not part of the optimization strategy and the α confinement turns out to be not adequate.

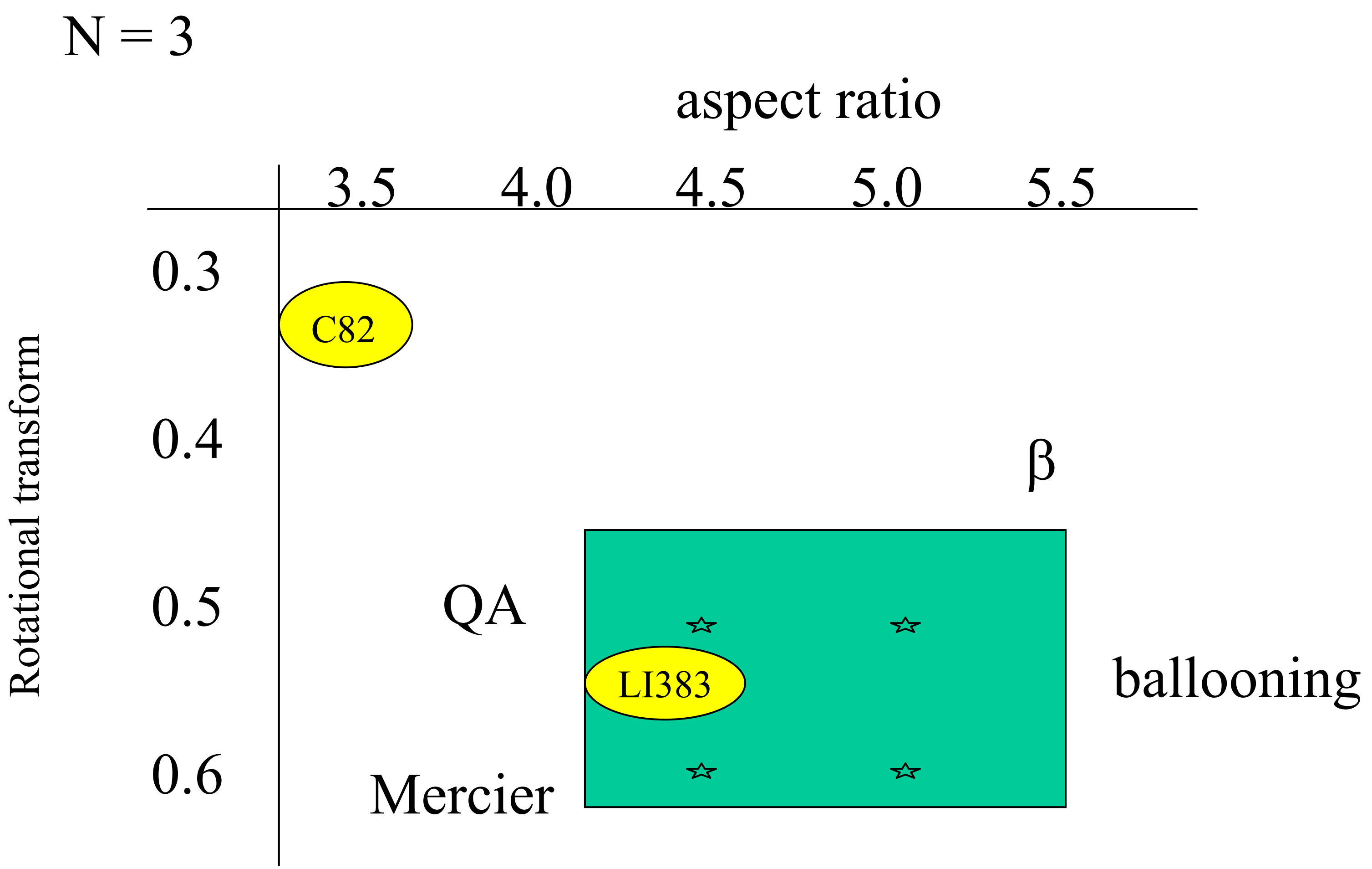
- Most alphas are lost via collisionless processes.
- Overall improvement of QA by x3 may be needed.
- Not all Bm,n are equal; target more specifically may be more effective in configuration optimization.



Reactor Configuration Optimization-- Preparation Essentials

- Minimum Δ, consistent with tritium breeding, heat removal, and radiation damage.
- Figure-of-merit for COE.
- Effective figure-of-merit for alpha confinement.
- Figure-of-merit for flux surface quality.
- Explore A-iota space and field periods for attractive reactor regimes
  - Compactness, quasi-symmetry, low alpha losses, MHD stability, simpler coils.

Initial configuration space explored for NCSX



Revisit the space with reactor aspects in mind should be useful.

Acknowledgments

- The development of stellarator optimization codes is a joint effort between PPPL and ORNL.
- NCSX is a national project with participation from and in collaboration with many institutions both inside the US and abroad.
  - USCD, Columbia, ORNL, LLNL, Auburn, NYU, SNL, Wisconsin, Taxes-Austin
  - Australia, Austria, Germany, Japan, Russia, Spain, Switzerland, Ukraine.