Status of Physics and Configuration Studies of ARIES-CS

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Compact Stellarators Can Improve Our Vision of Magnetic Fusion Power Plants

Stellarators can solve major problems for MFE:

- Steady state operation, with no current drive and minimal recirculating power.
- Immunity to disruptions, passively stable to troubling instabilities

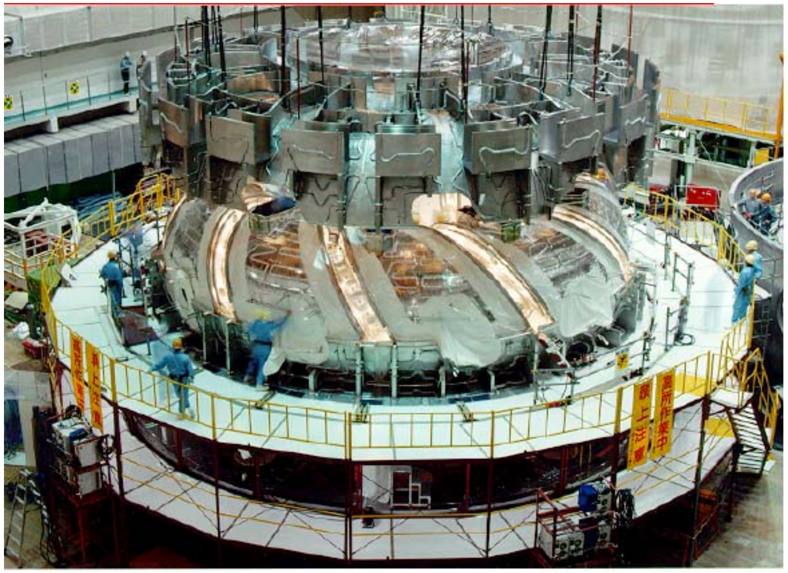
Compact stellarators can incorporate attractive advanced tokamak features to improve on previous stellarator designs :

- Compact size ← Lower aspect ratio.
- Higher power density ← Higher beta
- 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 Study is critical: Optimizing the compact stellarator as a power plant.



Recent Stellarator Physics Developments Are Promising

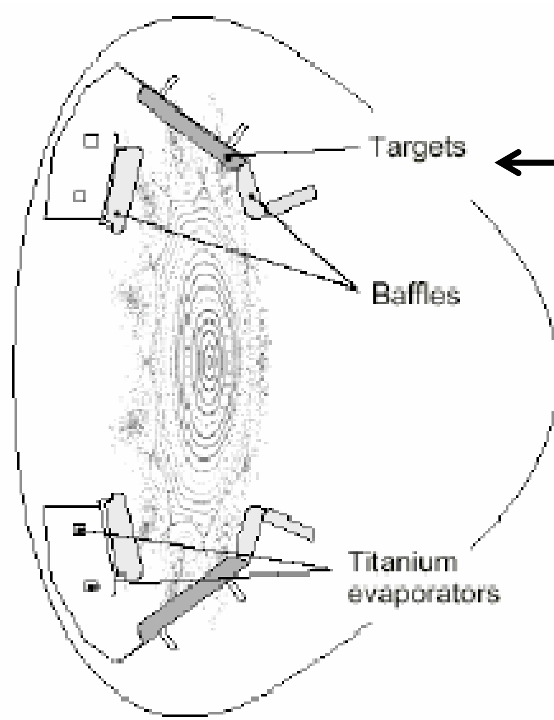
Large Helical Device (Japan)

$\beta > 3\%$.

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

enhanced confinement.

2-minute pulses.

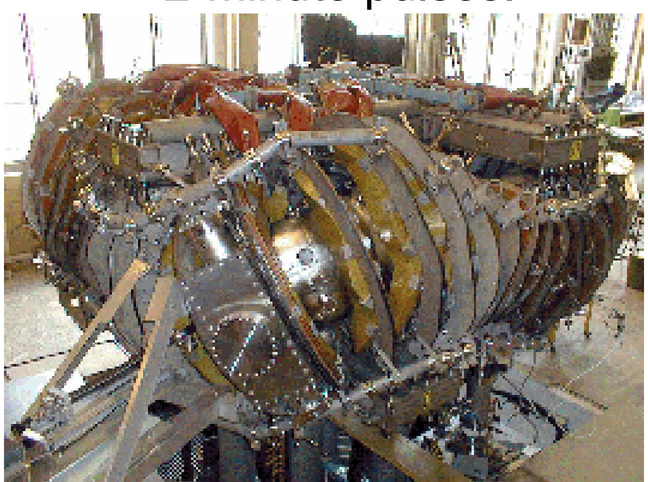


Wendelstein 7-AS (Germany)

$\beta > 3\%$.

enhanced confinement.

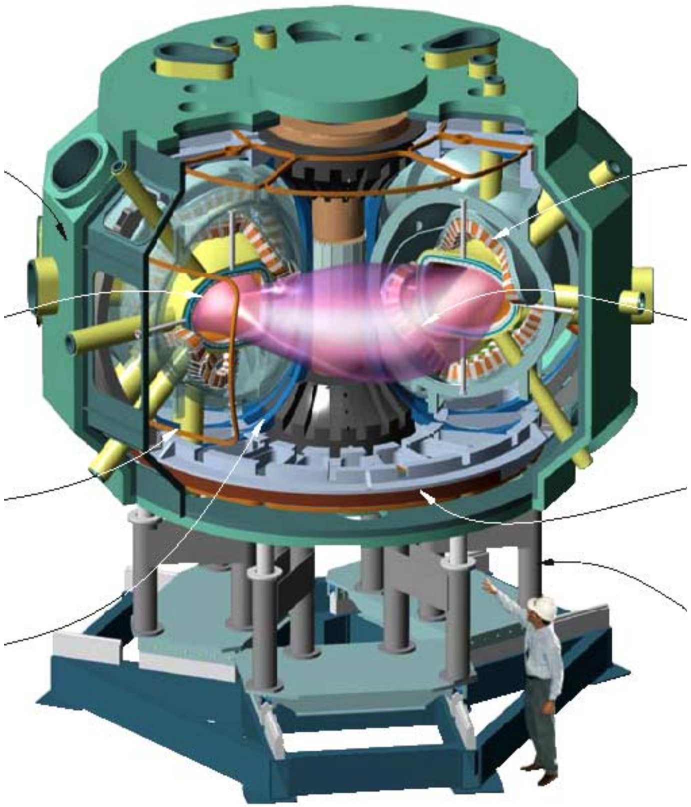
density control & enhanced performance w/island divertor.

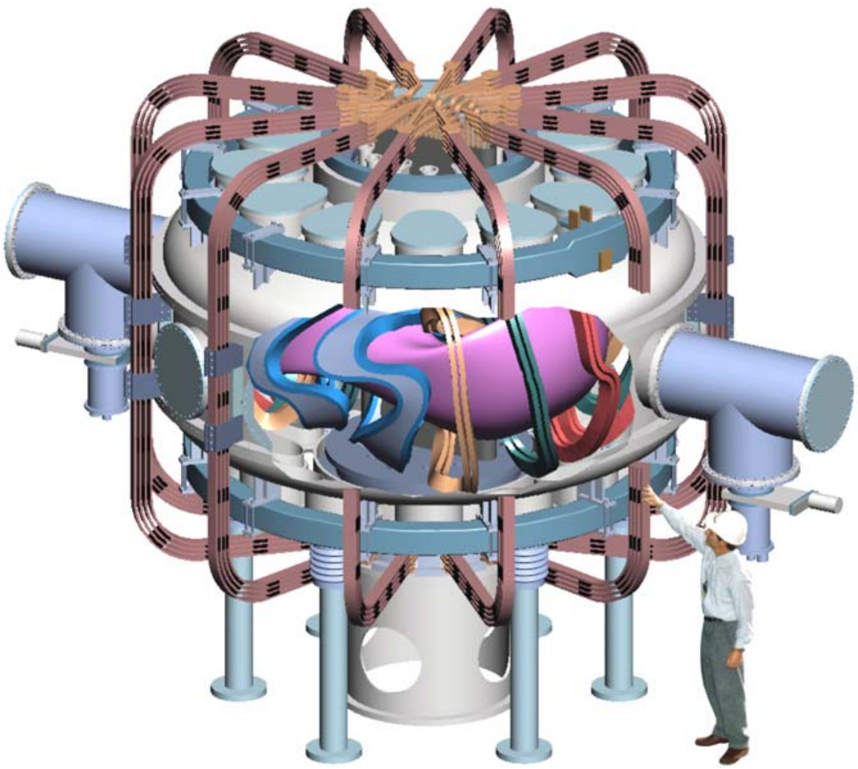


Helically Symmetric Experiment (U. Wisc.)

- Successful test of quasi-symmetry.

Compact Stellarator Experiment Designs in USA





NCSX (PPPL-ORNL)

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

Fab. project starts in FY-03

PDR just Completed

QPS (ORNL)

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

CDR completed April 03

Compact Stellarator Reactor Vision

A steady-state toroidal reactor with

- No disruptions
- No conducting structures or active feedback control of instabilities
- No current drive (⇒ 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?)

ARIES aims to develop the physics and understand reactor implications to determine optimum CS configuration and power plant design.

- **Optimum design involves tradeoffs among various features.**

Program Plan to Assess Compact Stellarators: ARIES Reactor Studies

Optimize a compact stellarator reactor configuration.

- Objectives will include:
  - Minimize alpha particle losses
  - Minimize ripple or maximize quasi-axisymmetry (sufficient to confine alphas)
  - Provide sufficient space between coil and plasma for blanket and shield
  - Identify simplest coil geometry with sufficient space between coils for simple maintenance
  - Preserve the overall size compactness

- Configuration alternatives need to be explored
  - Plasma configurations: # of periods, beta, aspect ratio, shaping.
  - Coil configurations: simple coils; alternatives to modular coils.

Identify high-leverage issues for further physics research:

- What are the cost sensitivities?

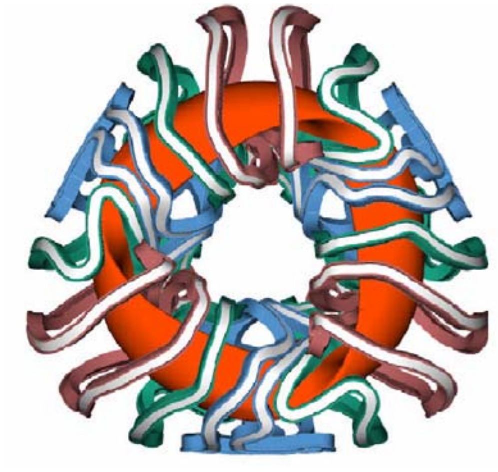
Develop an attractive design around the optimum configuration.

- Requires close interaction between physicists and engineers

Status of Physics and Configuration Studies

- We have developed two candidate CS configurations, with 2 and 3 field periods, for self-consistent evaluation and comparison.

Parameter	3-field period (NCSX)	2-field period
Δ (m)	1.4	1.4
Coil Cross Section	30 cm x 30 cm	40 cm x 40 cm
<R> (m)	9.7	7.5
<a> (m)	2.15	2.0
Aspect ratio	4.5	3.75
β (%)	4.15	4.0
V_p (m^3)	872	595
S (m^2)	1060	732
Number of coils	18	16
B_o (T)	5.65	5.0
B_{max} (T)	14.4	14.36
<j> (kA/cm2)	17.4	7.76



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Status of Physics and Configuration Studies (Continued)

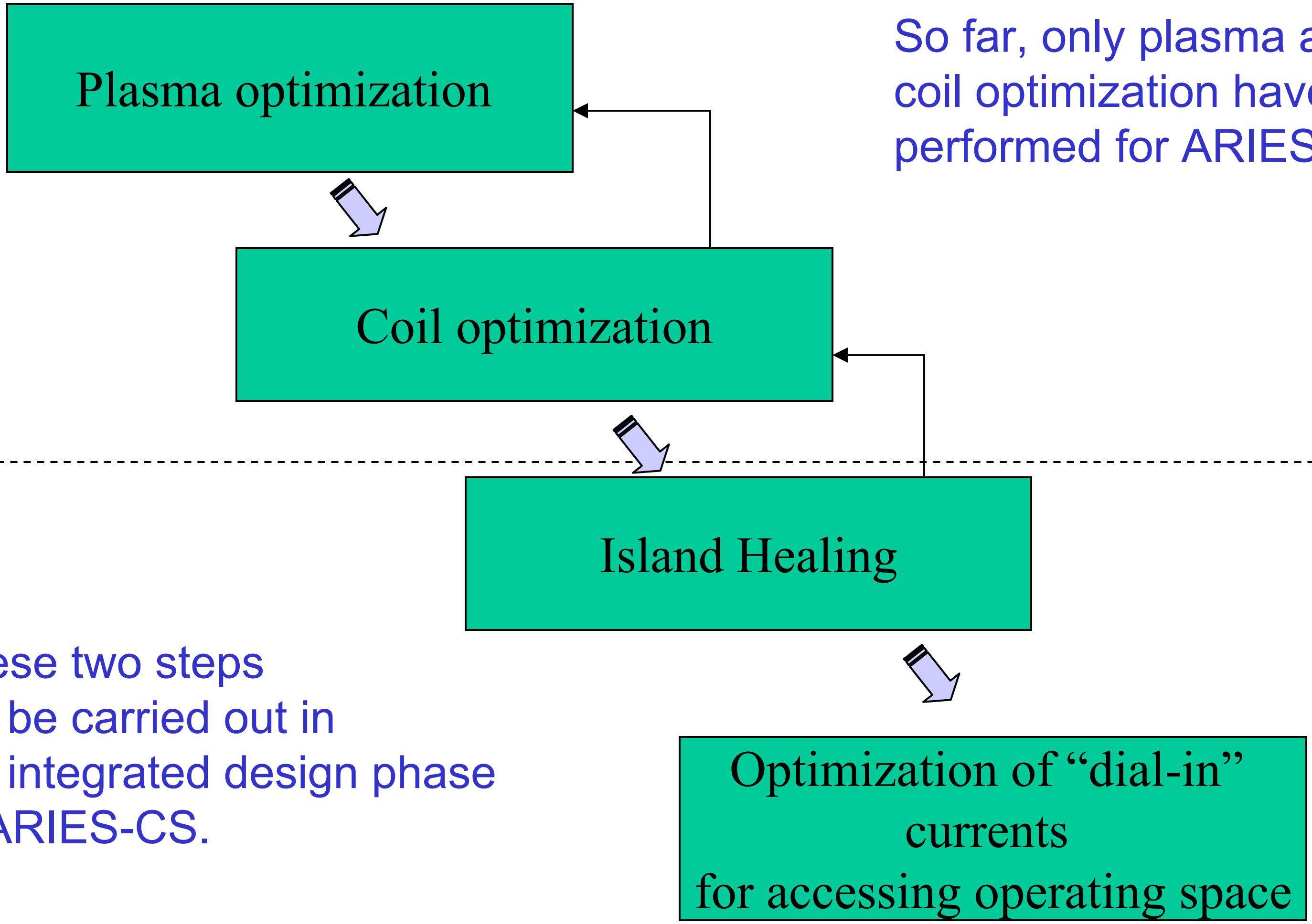
- The bulk of the analysis was on the 3-field-period case, which is modeled after NCSX and scaled by the systems code to produce 2 GW of fusion power, consistent with blanket/shield requirements.

- The 2-field-period candidate is developed with the motivation to allow for simple sector maintenance, with a smaller number of modular coils. Detailed evaluation is on-going.

The rest of the presentation will highlight results of the configuration optimization studies for the NCSX-like candidate.

POPCON and heating studies will also be briefly presented.

Configuration Optimization Process



So far, only plasma and coil optimization have been performed for ARIES-CS.

These two steps will be carried out in the integrated design phase of ARIES-CS.

Plasma Optimization Process - STELLOPT

Plasma boundary represented as Fourier harmonics → **Initial "guess", boundary as independent variables**

Constraints/weights

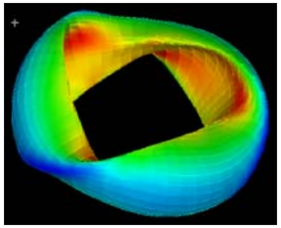
1) Select p, J profiles, β (4%), B (1.4 T), F.P (3)
2) Iota target (0.4-0.65)
3) MHD stability target (Mercier, ballooning, kink)
4) Transport target (QA)
5) Coil target (complexity, current density)

1) Evaluate equilibrium (VMEC), 2) Jacobian calculation, 3) determine direction of descent, 4) perform functional minimization (Levenberg-Marquardt).

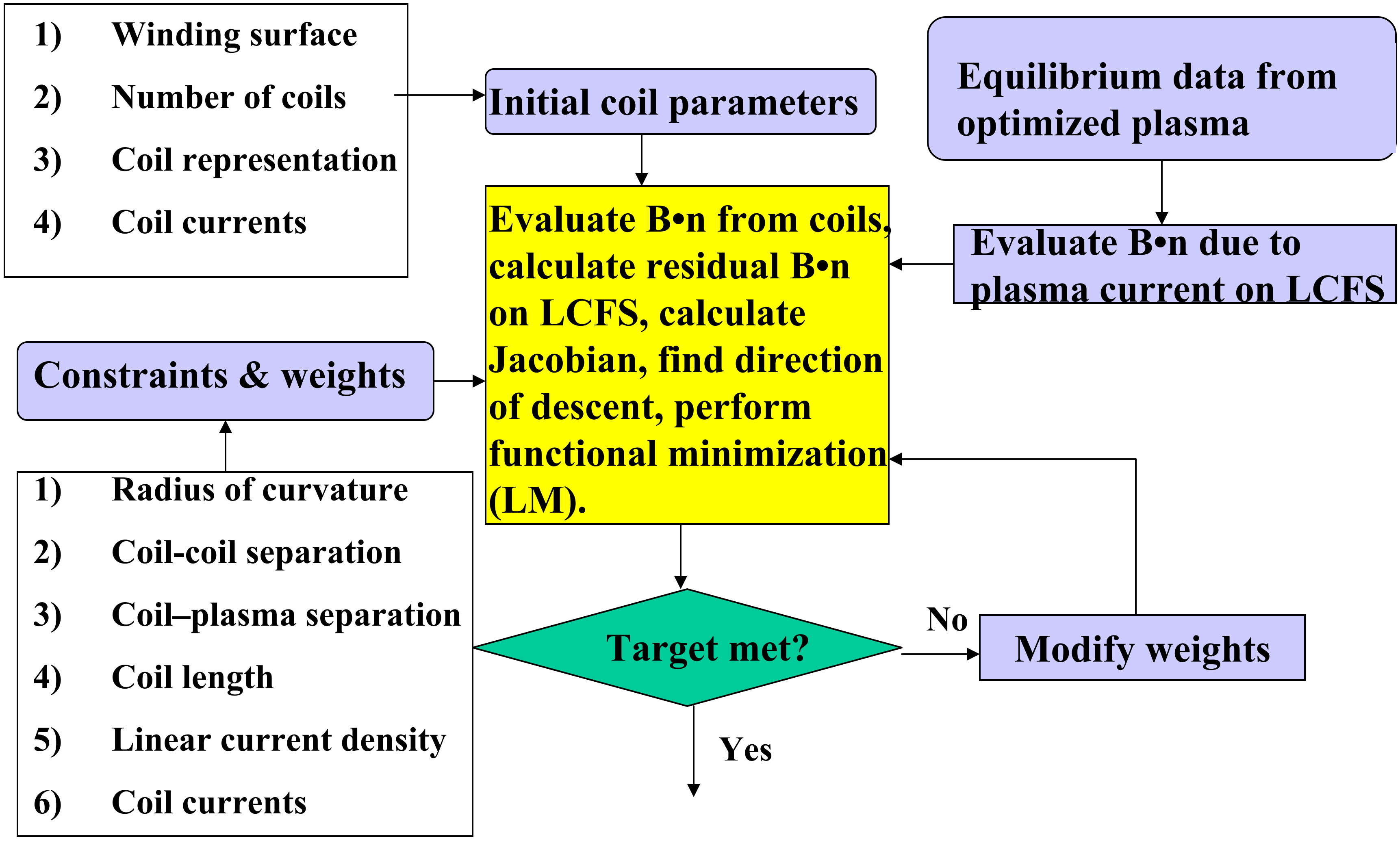
- ballooning
- kink
- transport
- shape/position
- coil complexity

Targets met?

- No → **Modify weights**
- Yes → **Islands healing, PIES**; **Refined calculation and detailed analysis**



Coil Optimization Process - COILOPT



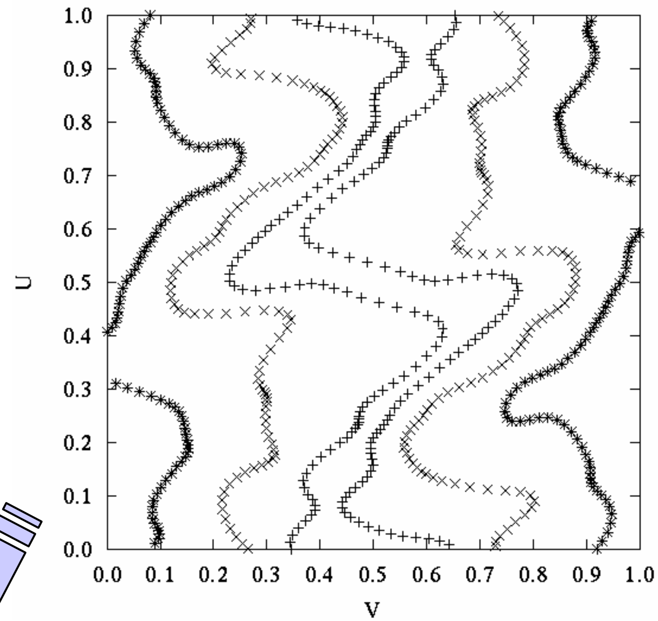
Coil Geometry in Cylindrical Coordinates - COILOPT

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

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

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

$$mk = nk = 20$$

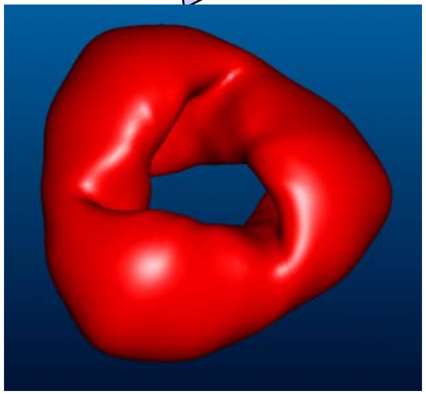


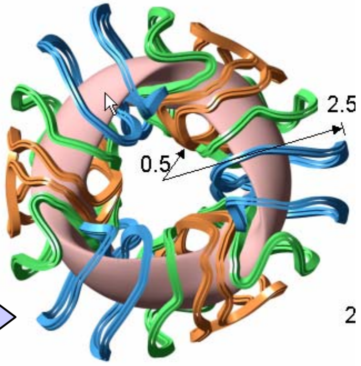
b) Coordinates are constructed on winding surface:

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

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

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

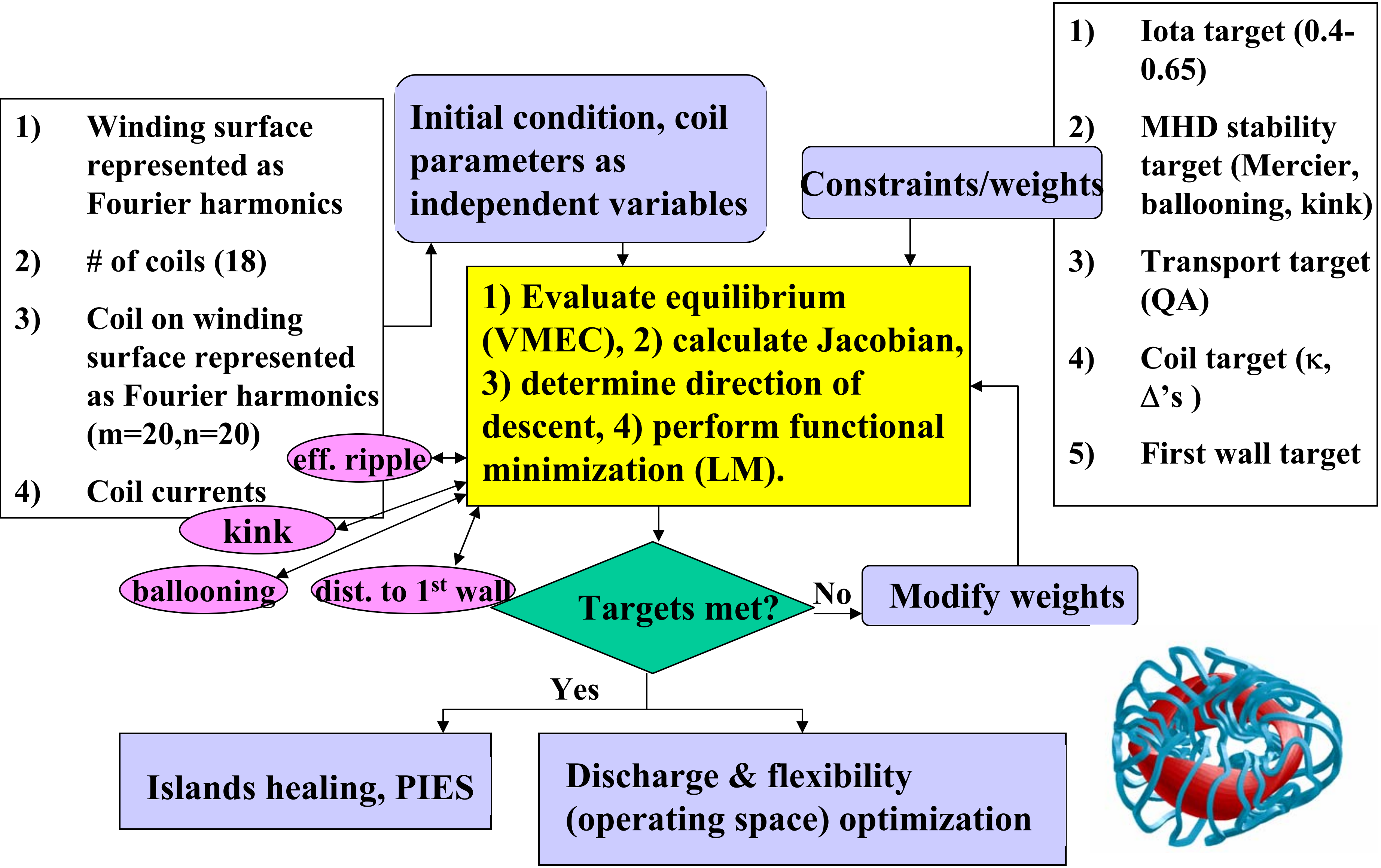




s : toroidal flux

$u = \theta/2\pi$; Φ = toroidal angle

Evaluation of “free boundary” equilibrium, MHD stability and transport



Reactor Configuration Optimization-- Critical Considerations

√ • Minimum Δ (coil-plasma separation), 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.

We Identified Methods to Develop Configurations that Minimize α Loss

- We looked at five figures of merit for α confinement to determine best procedure to search for a configuration to minimize α loss.

√ - Minimization of residuals in magnetic spectrum: weighted and un-weighted.

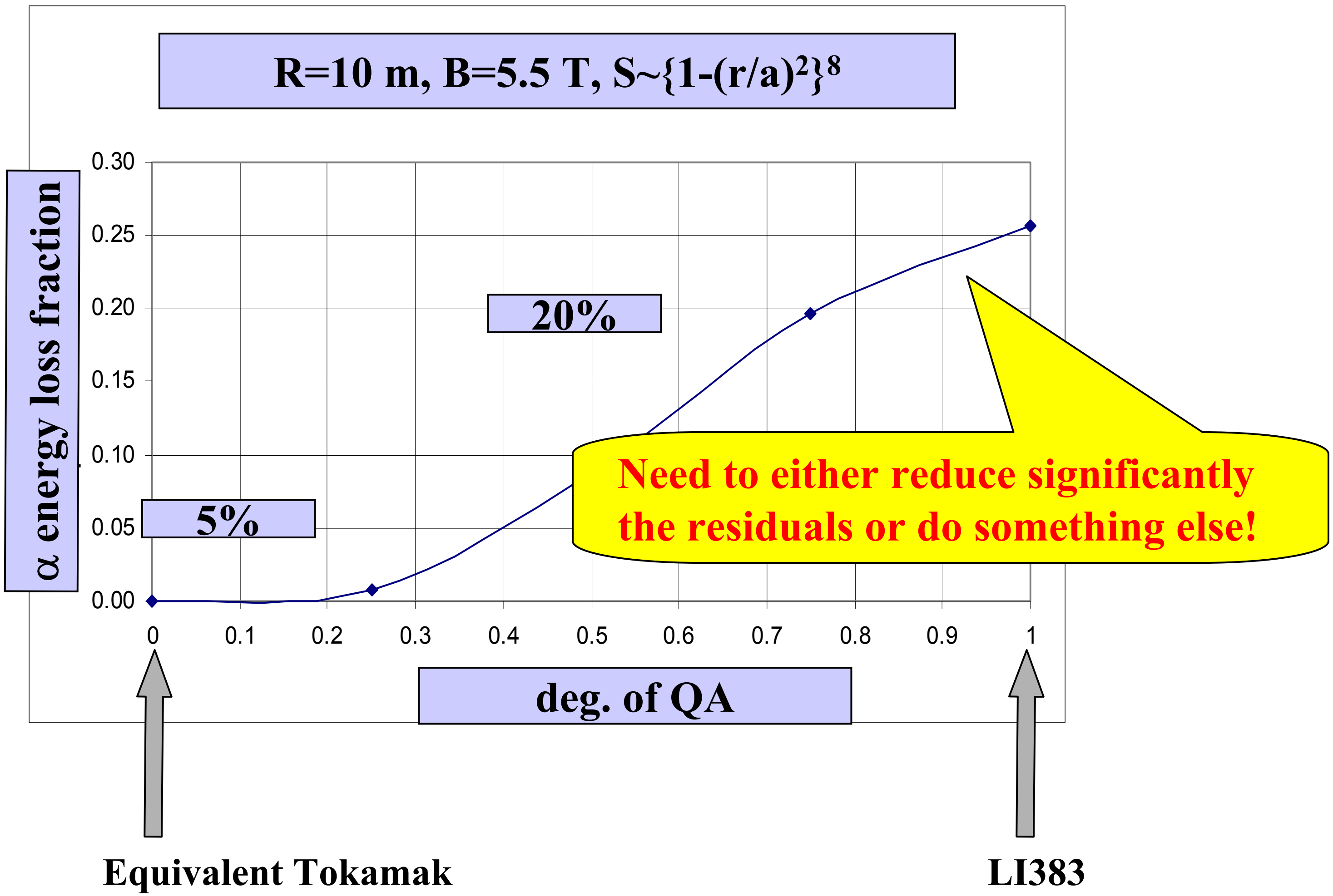
- Pseudo-symmetry (PS): minimization of ripple well areas.
- Effective ripple: equivalent effects of helical ripples in 1/n transport.
- Second adiabatic invariant, $J_{||}$: minimization of contour losses to outside flux surfaces.

√ - Reduction of initial loss of collision-less fast ion orbits.

- An extensive study indicates that to obtain an α optimized QA configuration (if no other means are found) the most effective procedure would be
  - Minimize the residual $B_{m,n}$ to reach the QA regime,
  - Minimize initial α loss (maximizing its residence time in plasma)
- The Monte Carlo particle orbit code, ORBIT, in 3D magnetic geometry is used for this analysis.

α Energy Loss Increases with B Residuals (Deg. of QA)

- Calculated for LI383 (The Baseline Configuration for NCSX)

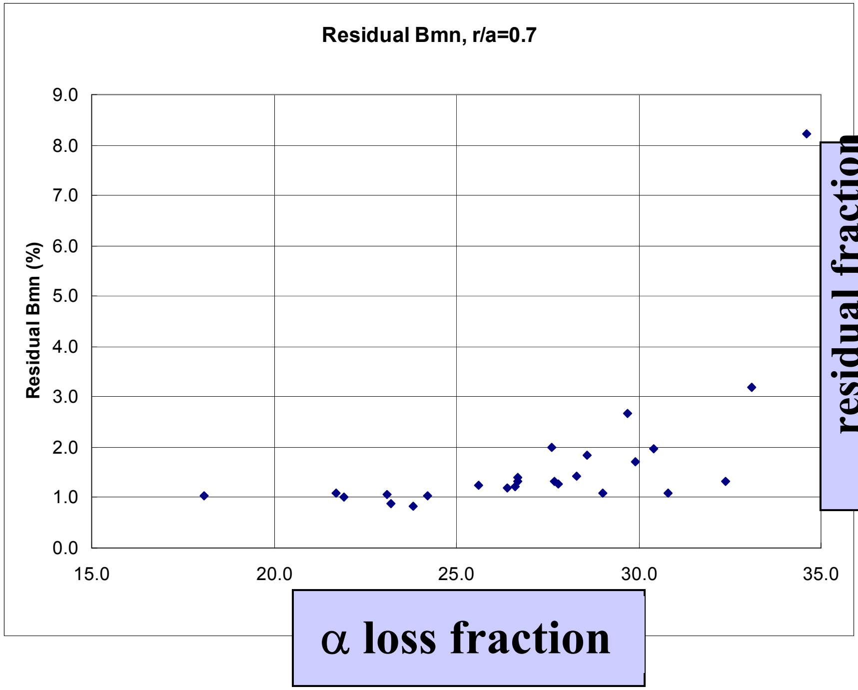


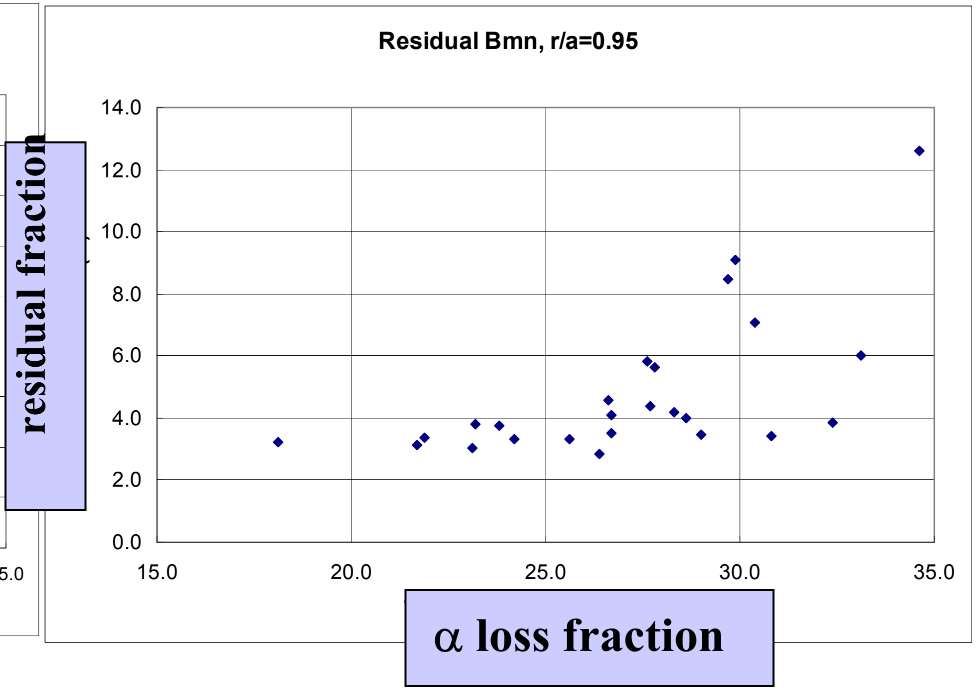
Correlation of Residual Bm,n with α Loss

As expected, the magnitude of residuals in the magnetic spectrum does not correlate well with the α loss except for the very good or very bad cases.

r/a=0.7

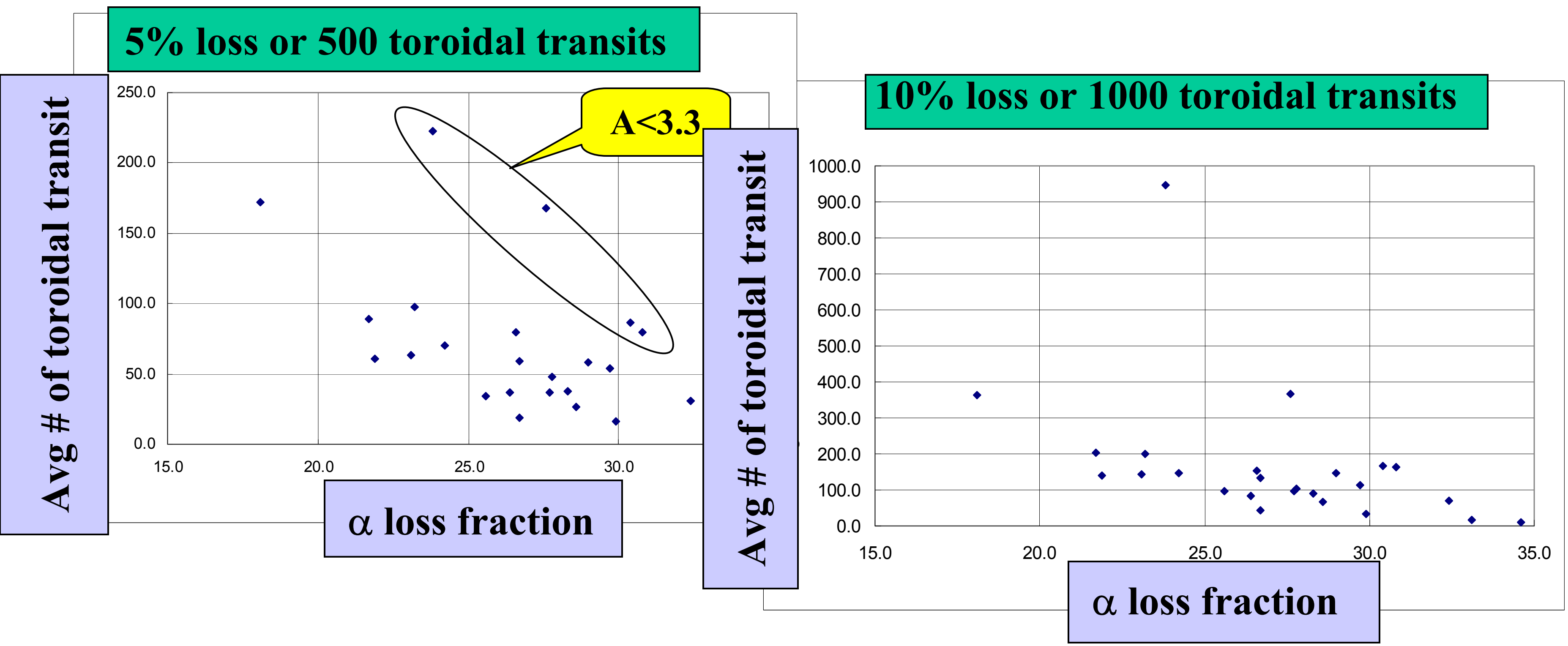
r/a=0.95





Correlation of α Residence Time with α Loss

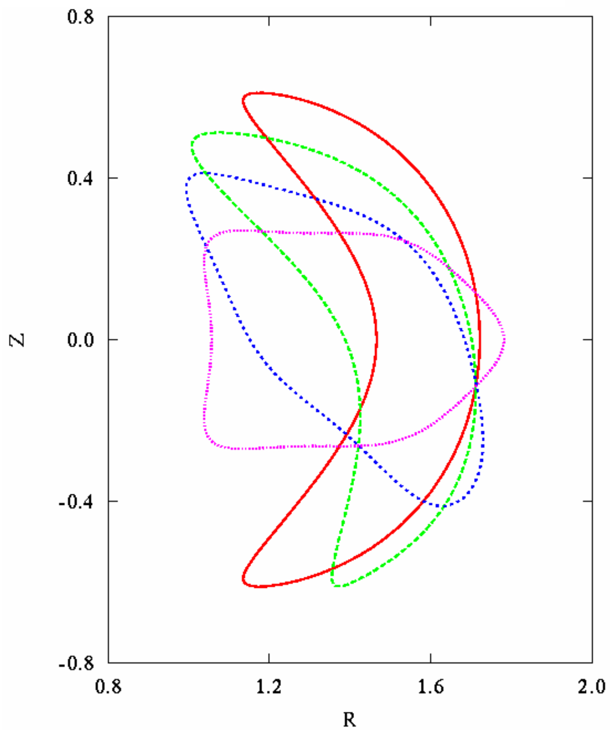
The initial loss measure shows a much better correlation, clearly separating out the aspect ratio effect on the confinement. There is still a sizable scatter; however. Toroidal transit calculations are based on R=10 m, B=5.5 T, 1024 α's born at r/a=0.5.



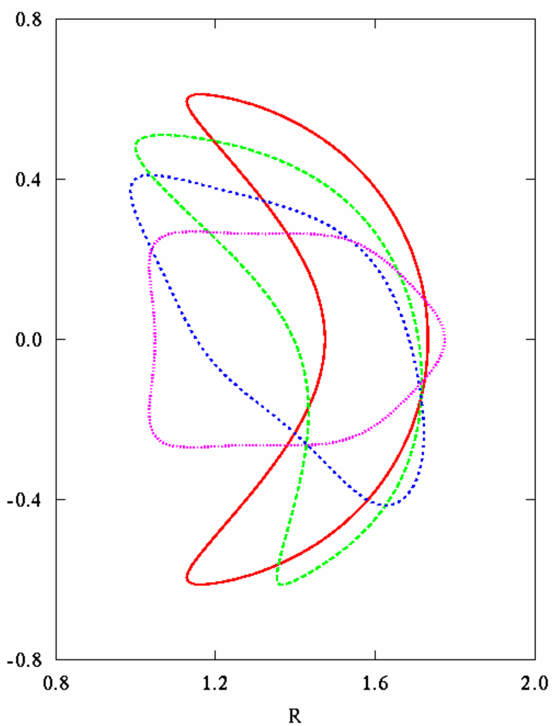
Comparison of three 3-field period, A=4.4 configurations with different α confinement characteristics.

(No MHD Constraint)

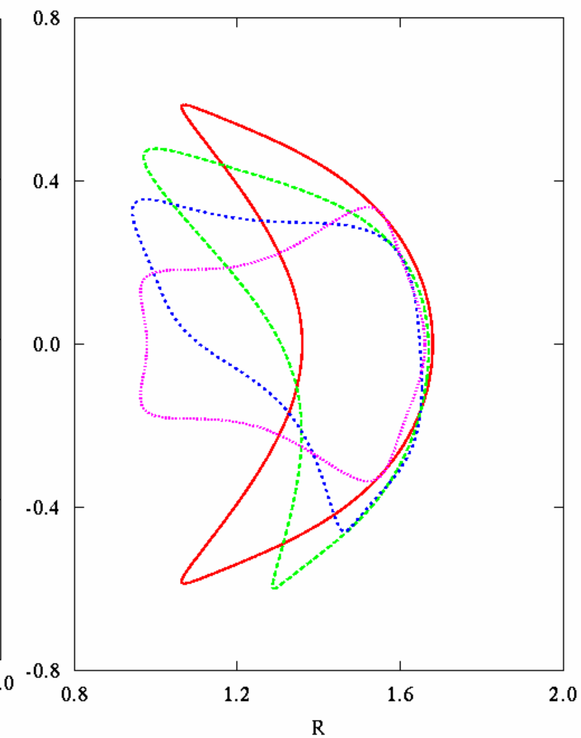
LI383
α loss=25.6%



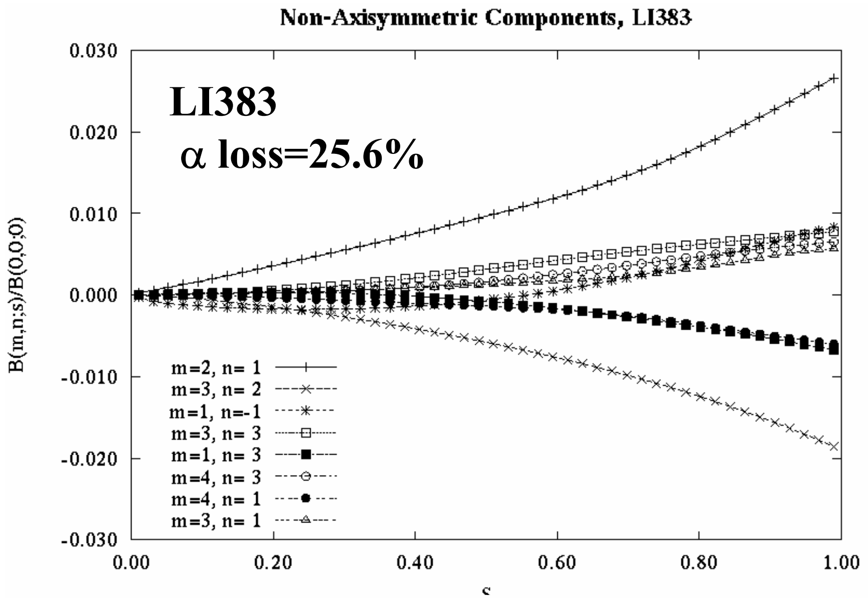
N3AEC
α loss=16%

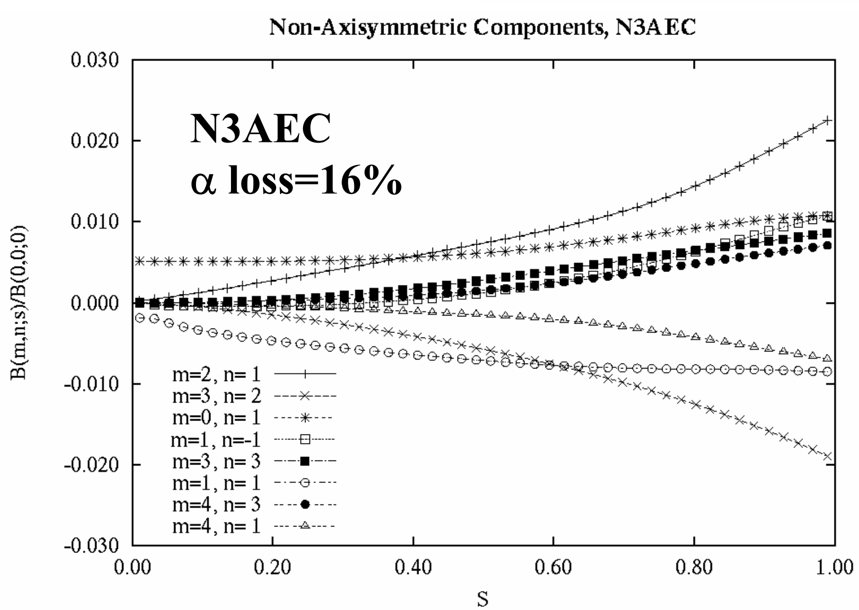


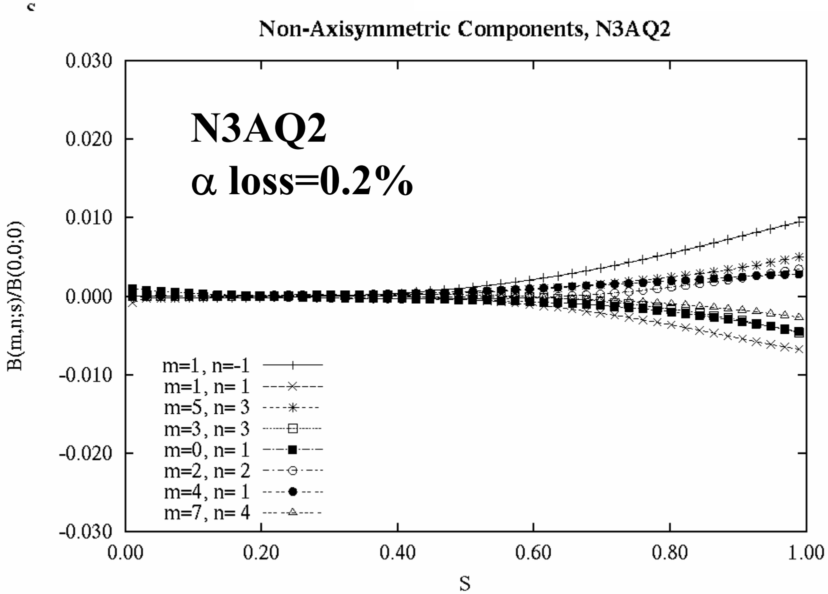
N3AQ2
α loss=0.2%



Configuration with Largest Bm,n has the Highest α Loss Fraction

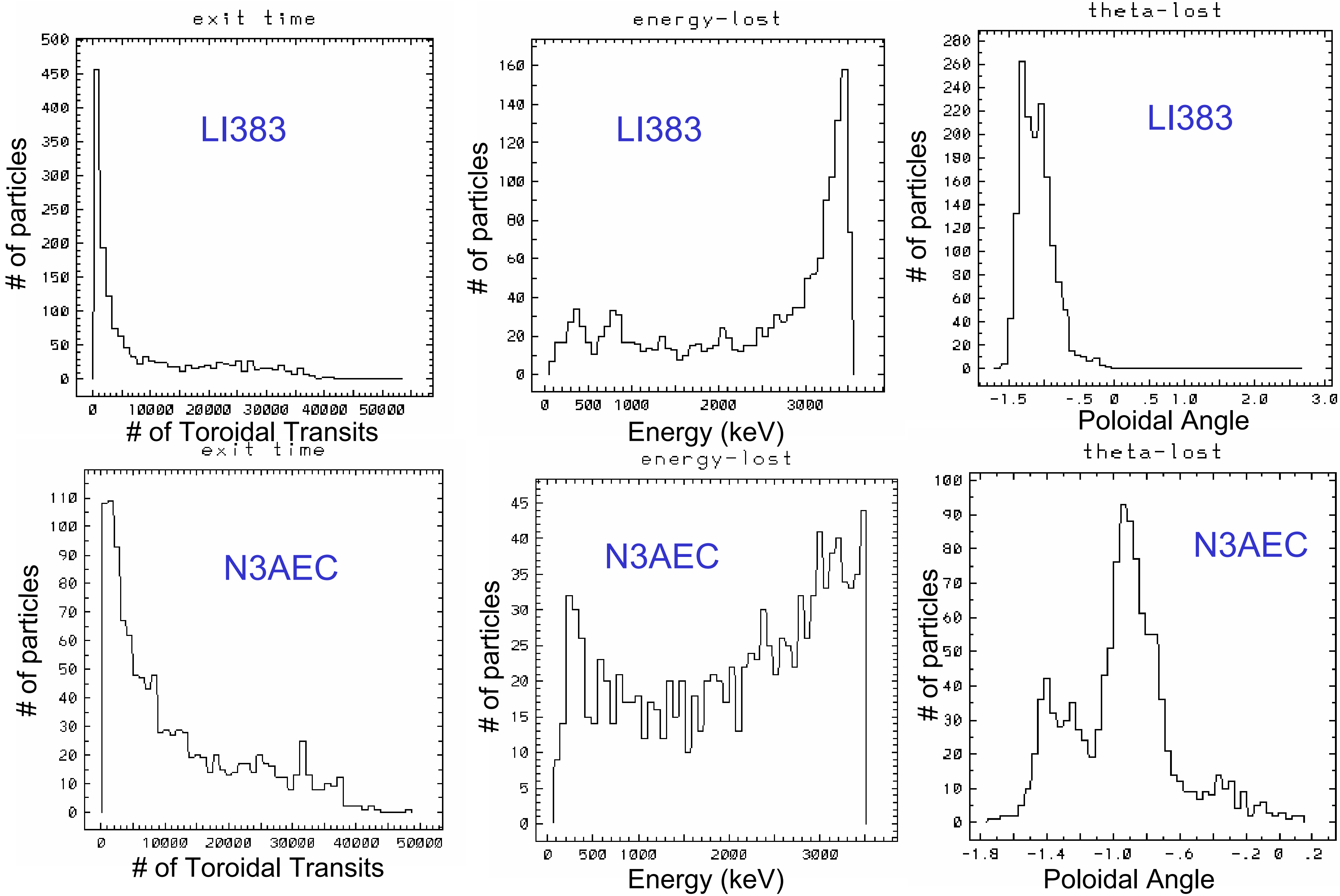






Comparison of α Loss Characteristics for two NCSX-like Configurations

Initial Loss of α's is more severe for case LI383.



General Observations from Extensive Analysis

- Almost all measures considered correlate weakly to the full α loss.
  - Configurations with good QA have all good measures, but converse is not true.
- Good α confinement at high β can be achieved in QA devices.
  - The MHD stability constraints limit how good the confinement can be.
  - There may exist an optimal aspect ratio at a given ι for QA reactors.
- Good QA is a sufficient condition for good α confinement, but is not a necessary condition. There might be intriguing roles played by the mirror, B(0,1), B(0,2), and helical, B(1,1), B(1,-1), field components.

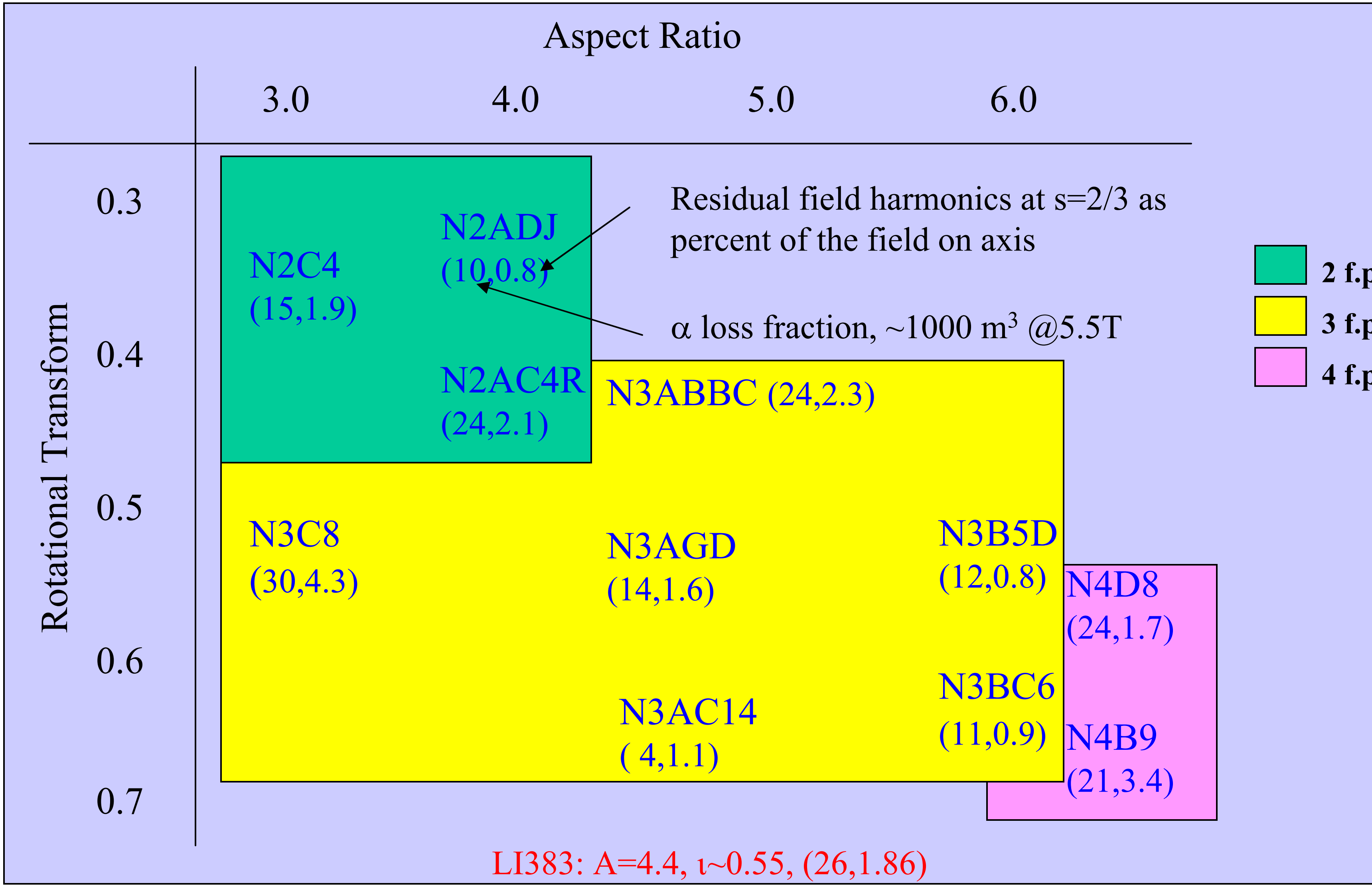
Exploration of QA Configuration Space

(aspect ratio, rotational transform, field period)

- Exploration is limited to NCSX (LI383) class configurations.
- We have explored regions with aspect ratio from 3 to 6.5, rotational transform (@s=0.5) from 0.3 to 0.75.
  - The region is bounded by the consideration:
    - higher iota →difficulty in the kink and Mercier stability and too strong shape deformation
    - higher A → no longer compact
    - lower iota → not enough poloidal flux and difficulty in vertical stability
    - lower A → too difficult to achieve acceptable QA
- Regions of "good" α loss characteristic (~10% energy loss) are found:
  - Low ι (ι-max~0.5, ι-min~0.2), A~4
  - High ι (ι-max~0.8, ι-min~0.4), A~5-6.

Significantly improved compared to ~30% loss for previous QA configurations which were not optimized for α losses.

Representative Configurations in Aspect Ratio-Iota Space



Improvement of QA and α confinement with less stringent MHD stability constraints?

- Attainment of good QA is often limited by plasma MHD stability constraints (kink, ballooning, Mercier) in the optimization calculations.
- However, recent experiments observed plasma stability optimistic compared to ideal MHD and linear stability theory predictions. Non-linear theory appears to agree better with experimental results.
- While the issue is being addressed, we still try to minimize growth rates of the external kinks and ballooning (based on ideal MHD and linear theory) while allowing some marginal instability.
- Allowing a larger eigenvalue in external kink calculations, $8.4 \cdot 10^{-5}$ in N2ADR versus $1.7 \cdot 10^{-5}$ in N2ADJ, enables us to find a solution in which α losses are reduced to 6.5% from 10.4%.

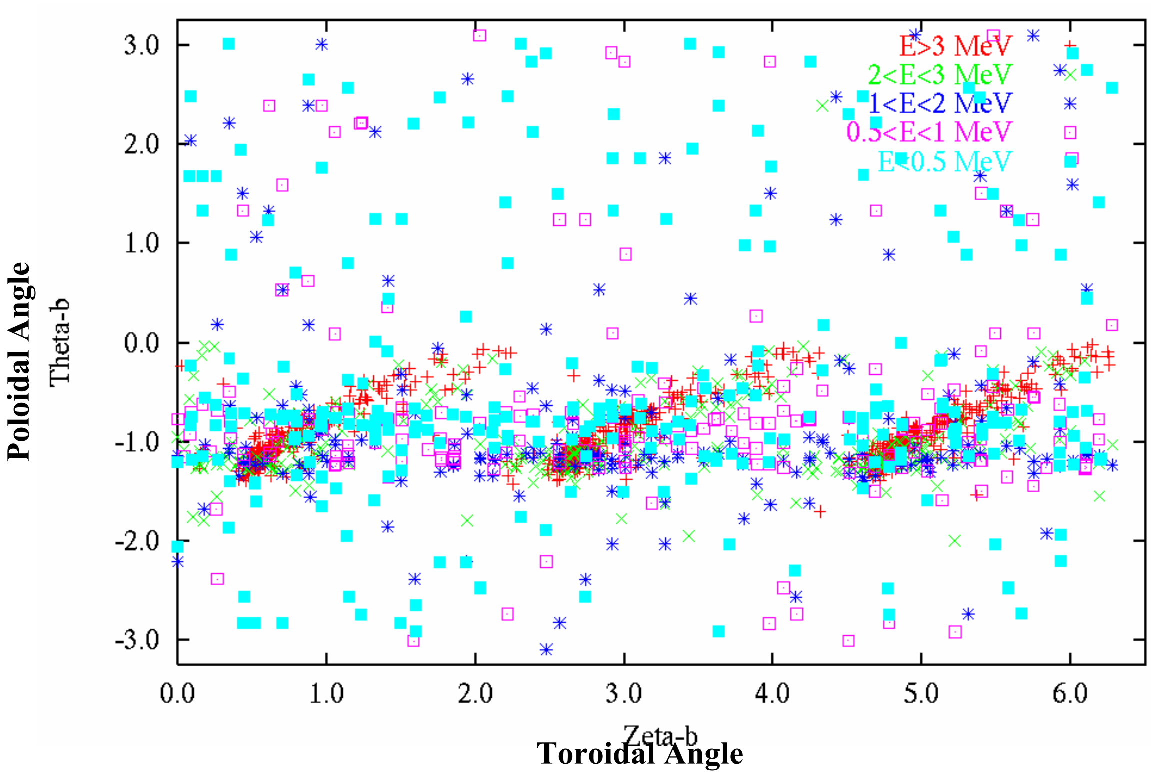
Initial Assessment of Heat Load on First Wall due to Lost α's

- We start by looking at the footprint of alphas lost from the LCMS.

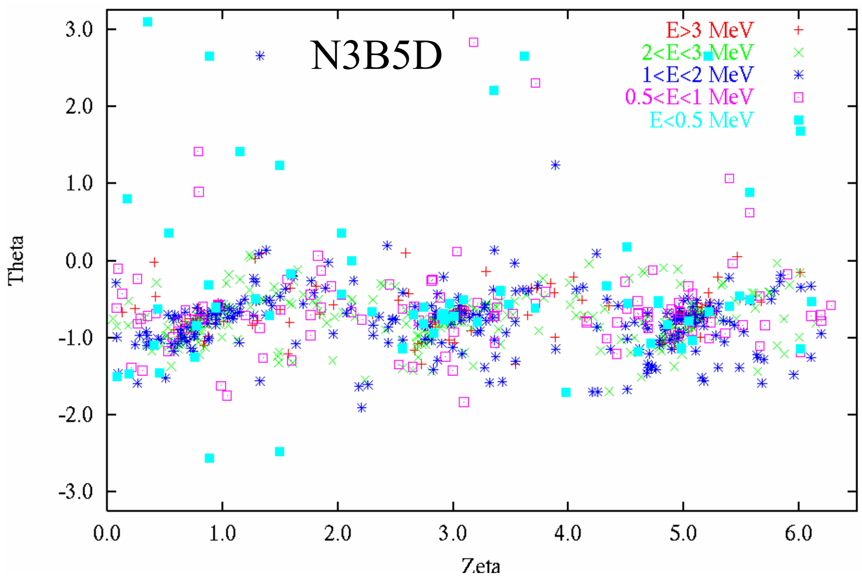
For LI383 (α un-optimized), most lost energy is concentrated in narrow helical bands centered around θ_b~-60° and ζ_b ~ 120° in each field period.

(θ_b,ζ_b) where α's leave the last closed flux surface.

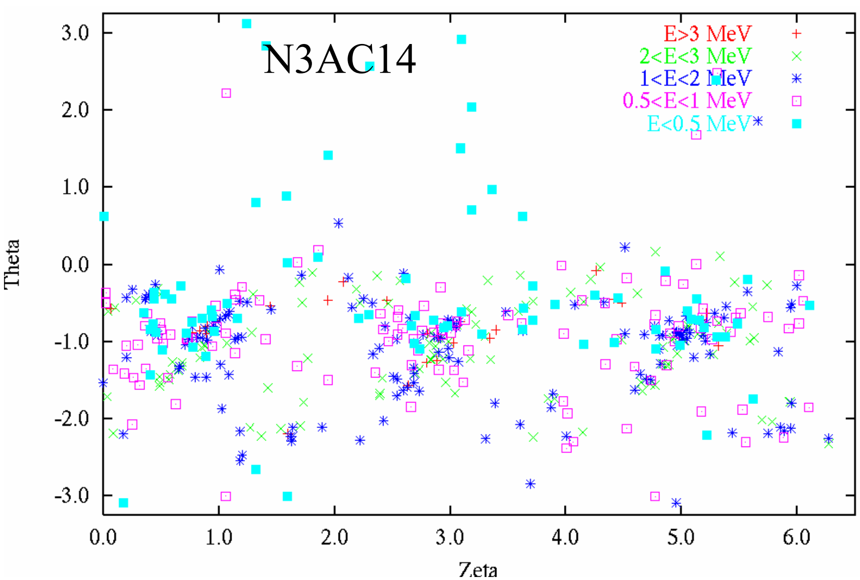
R = 8.3 m, A = 4.5, B = 5.3 T NCSX-like

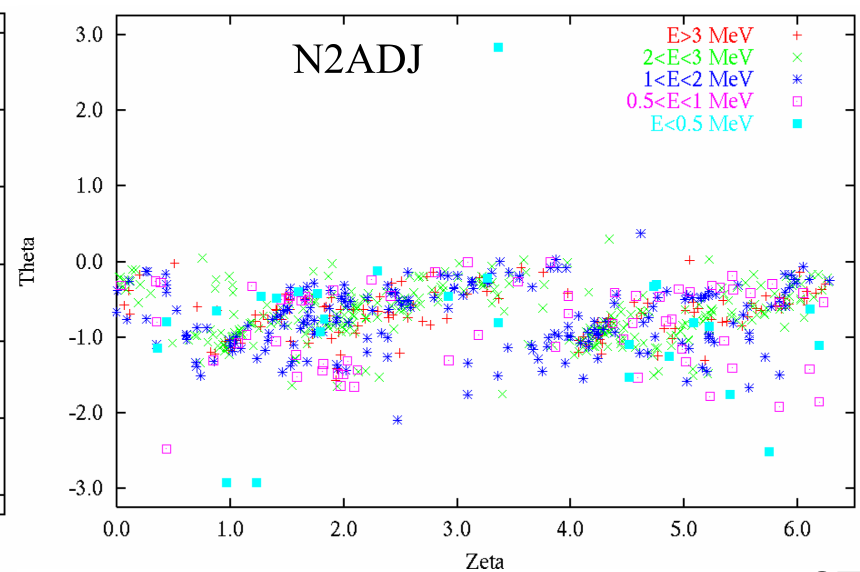


Lost α Footprint for Lower Loss Configurations



For lower loss configurations, the energy loss band tends to be broader, its average poloidal angle smaller (closer to midplane) and toroidal angle closer to half a field period. We note that (1) footprints on 1st wall may be different, (2) flux expansion for diverter may not coincide with the most intense loss zone.

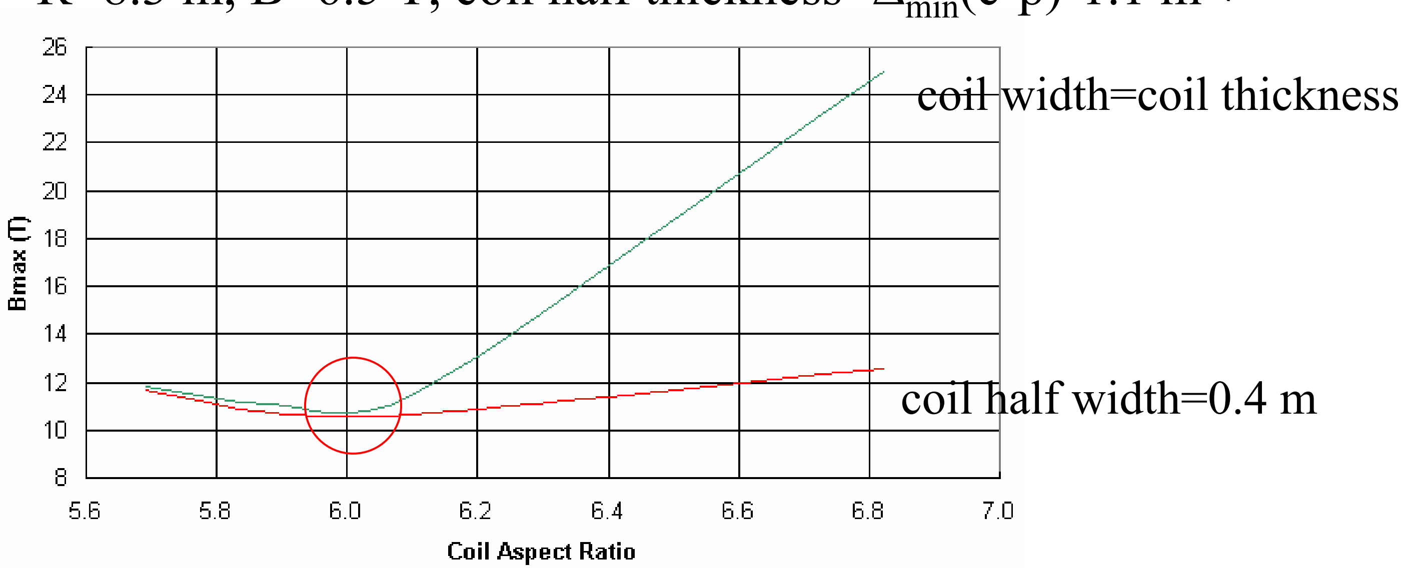




An Optimum Coil Aspect Ratio A_c

We can take advantage of the increase in Δ_{min}(c-p) as A_c is decreased to increase the coil cross section to reduce J_{max} and B_{max}, but there is a point where further decrease in A_c will no longer be paying off.

R=8.3 m, B=6.5 T, coil half thickness=Δ_{min}(c-p)-1.1 m (blanket/shield)



For A_p=4.5, NCSX-like plasmas, A_c=6 gives the minimum B_{max} for R=8.3 m and B=6.5 T.

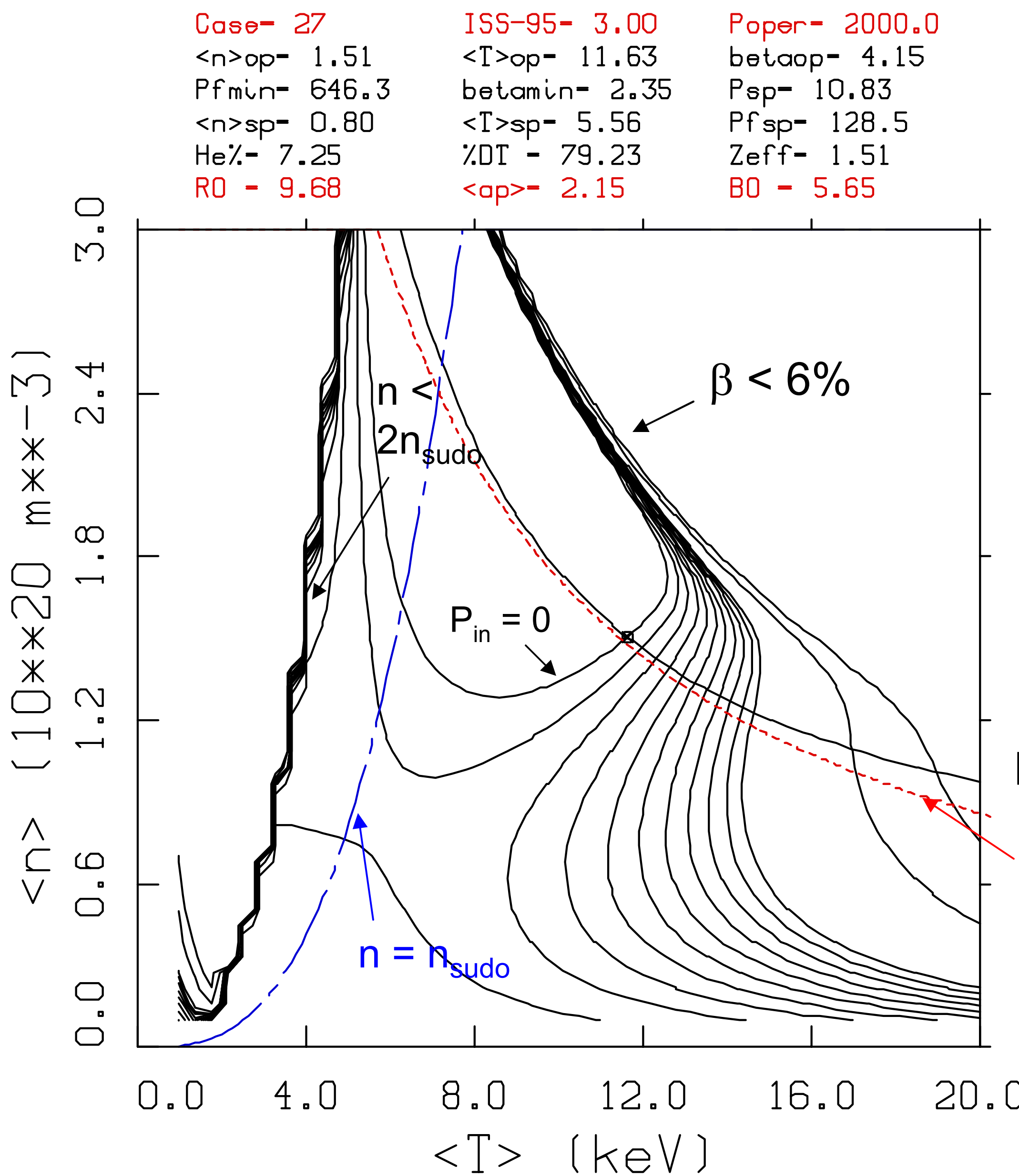
1-D POPCON Calculations

- **Input *variables***
  - magnetic configuration: $<R>, <a>$, B_0, $\iota(r/a)$,
  - plasma properties: τ_E^{ISS-95} multiplier H, τ_{He}/τ_E, α-particle loss %, $n(r/a)$ and $T(r/a)$ shapes, C and Fe %

- **Constraints**
  - fusion power P_{fop}, $n < 2n_{Sudo}$, $\beta < \beta_{limit}$,

- **Calculated quantities**
  - operating point: $<n>$, $<T>$, $<b>$, P_{fusion}, %He, %D-T, Z_{eff}
  - minimum ignited point: $<n>$, $<T>$, $<\beta>$, P_{fusion}
  - saddle point: $<n>$, $<T>$, $<\beta>$, P_{in}
  - $P_{in}(<n>,<T>)$ contours
  - $P_{rad}(<n>,<T>)$: coronal and bremsstrahlung; P_α losses

NCSX-like Candidate Configuration with *R* = 9.68 m



Heating power ~ 15 MW

P_f = 2 GW

<β> = 4.15%

ECH has been Considered for Heating in a CS Reactor

- A plasma heating system is essential for heating to ignition, plasma initiation, and pressure and current profile control for MHD stability and confinement optimization.

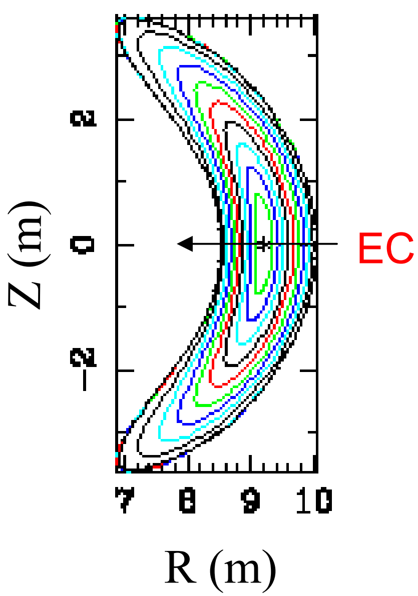
ECH is attractive for the following reasons:

- Capable of localized heating and profile control
  - control knobs are frequency, wave launch location and launch angle
- Requires relatively compact components
  - potentially compatible with complicated coil and vessel geometry
- Minimal neutron irradiation of components as only launching mirrors are in direct line of sight of plasma
- Requires no large antenna structure near first wall
- No coupling issue as the EC wave propagates in vacuum
- EC waves do not interact with ions and energetic α's

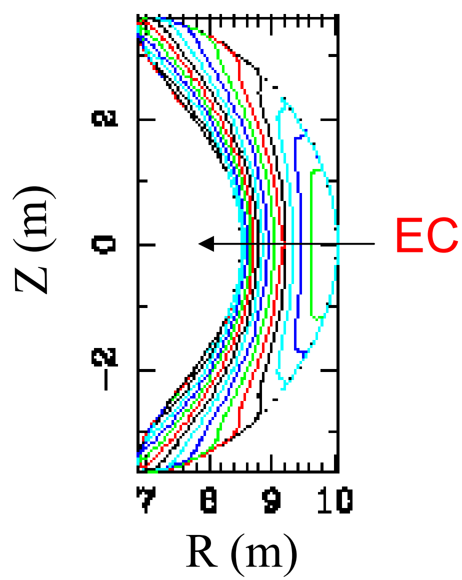
ECH Launch and Propagation Scenario at $\phi = 0^o$ Toroidal Location

- Core penetration of EC waves requires low density and high magnetic field.
- Perpendicular Launch from Outboard Side : $k_\phi = 0$, $k_Z = 0$
- Frequency = (1 - 2) × f_{ce} (on axis) = 147 - 293 GHz. @ Bo = 5.2 T.

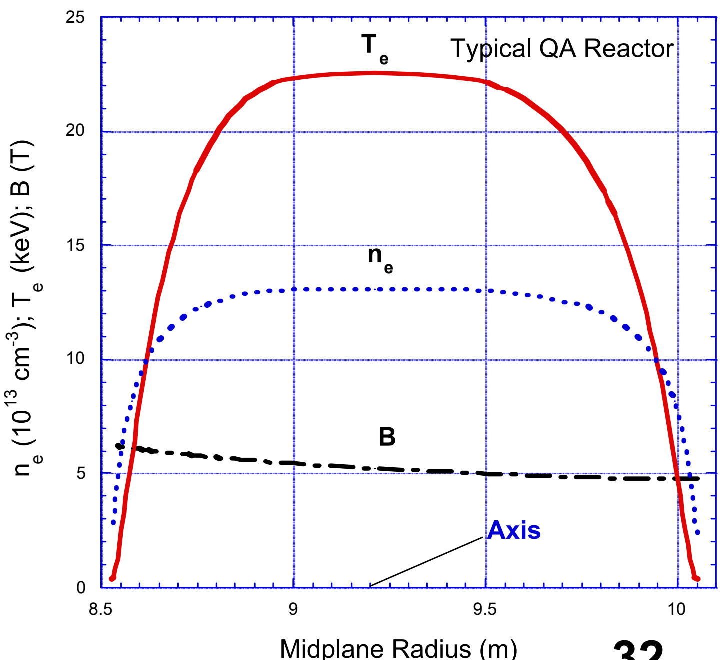
√Φ Surfaces



Mod-B Contours

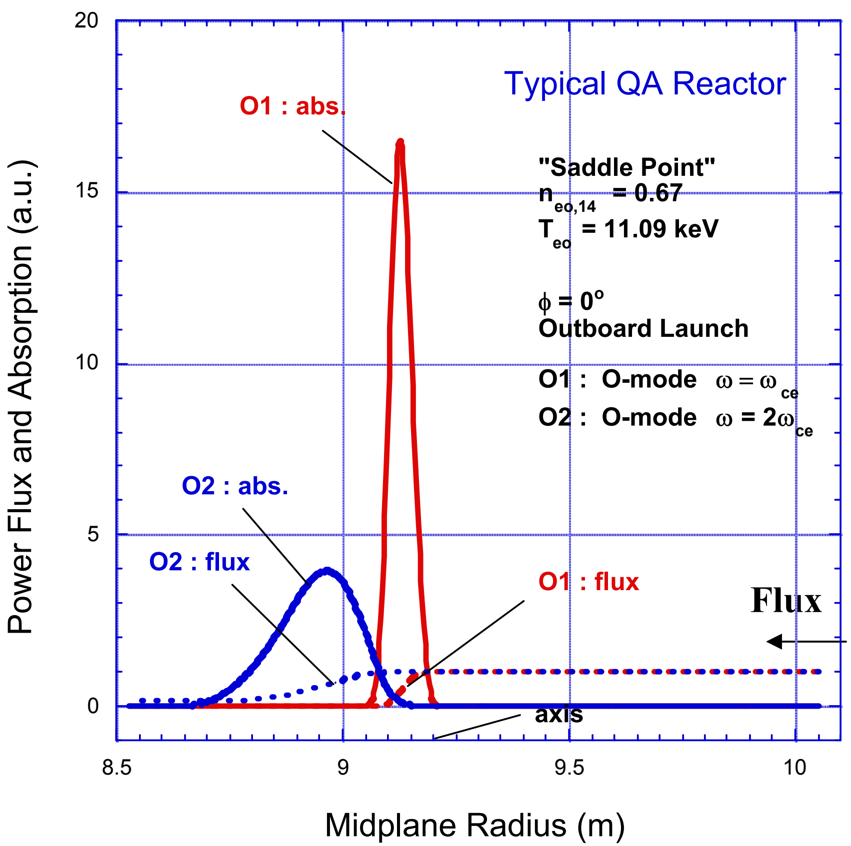


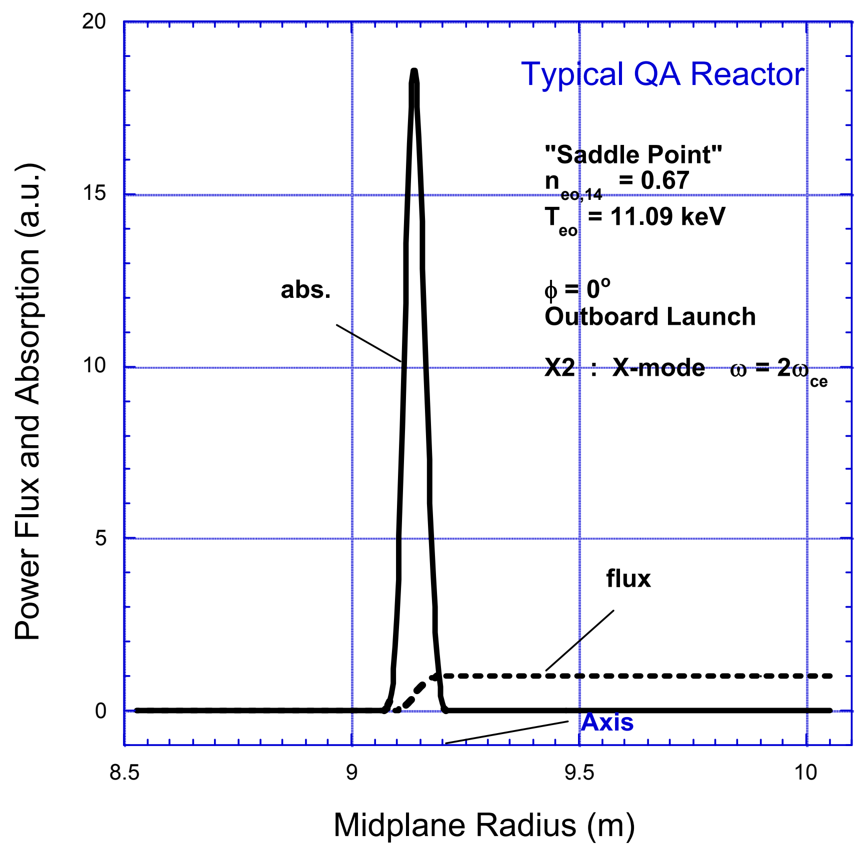
Plasma Profiles along Midplane



Strong Single-Pass Absorption for both O- and X-Mode

- O-mode at $f = f_{ceo}$ [O1] shows complete absorption in one radial pass for the saddle point.
  At $f = 2f_{ceo}$, [O2] absorption is weaker, with broader deposition profile on HFS of axis.
- Even stronger absorption is obtained with the X-mode at the 2nd harmonic.

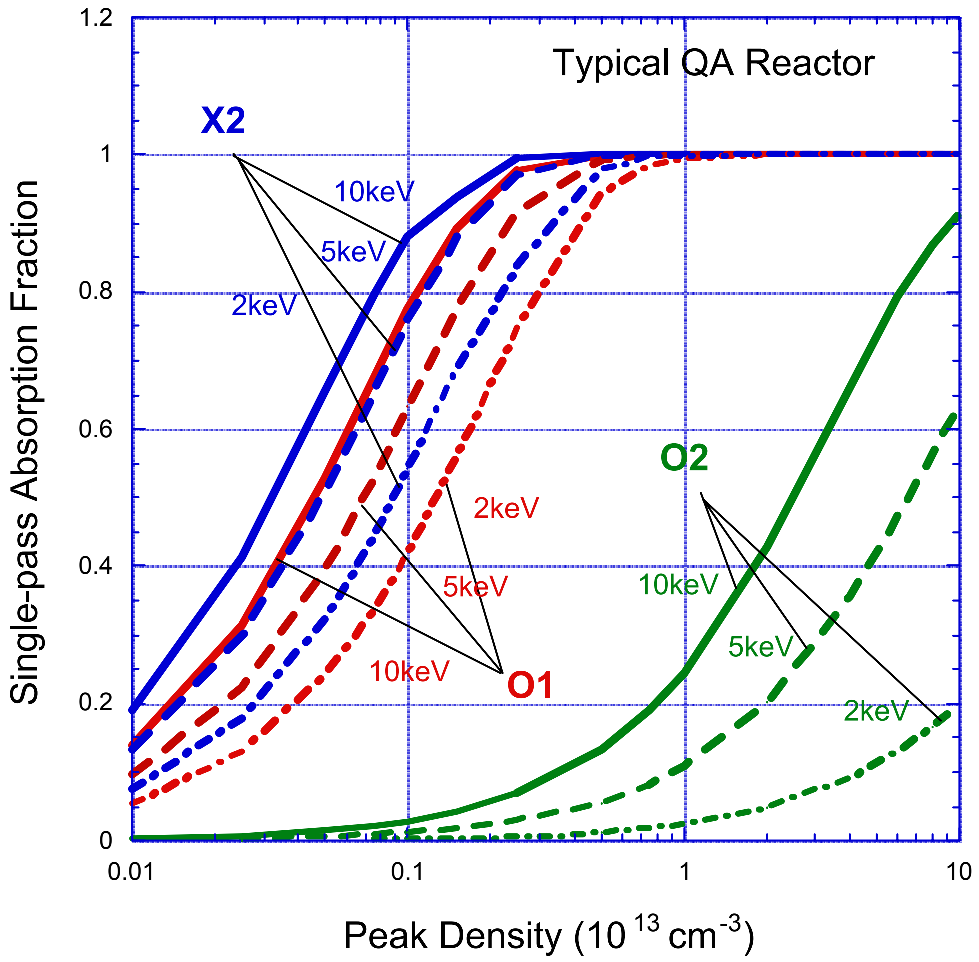




EC O-mode (n=1) is the Most Attractive for Heating

- O-1 and X-2 modes are attractive for heating purposes as they provide strong single-pass damping over the start-up range of plasma parameters.
- A drawback for the X-2 mode is the high frequency of ~293 GHz which requires substantial gyrotron development, or operation at lower B.
- Note these results are based on a restricted launch scheme.

Strength of absorption increases with n_e and T_e.



Summary and Plans

- We identified critical areas where issues relevant to reactors have not adequately been addressed during the design of NCSX.
- We identified two effective figures of merit for optimizing α confinement.
- We explored configuration space for attractive reactor regimes (compactness, good QA, low α loss, robust MHD stability at high β, simple coils).
- We investigated interplay between Δ_{min}, coil aspect ratio and B_{max} for coil design.
- We developed two CS candidates with 2 and 3 field periods for further study.
- We identified EC waves to be a viable candidate for plasma heating.
- For FY04, we will continue to explore design space for the two CS candidates and optimize the configuration/coil design.
- Towards the end of FY04, we will select one candidate for detailed design.

Path to Compact Stellarator Assessment