NCSX Flux Surfaces

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for the NCSX Magnetic Surface Group

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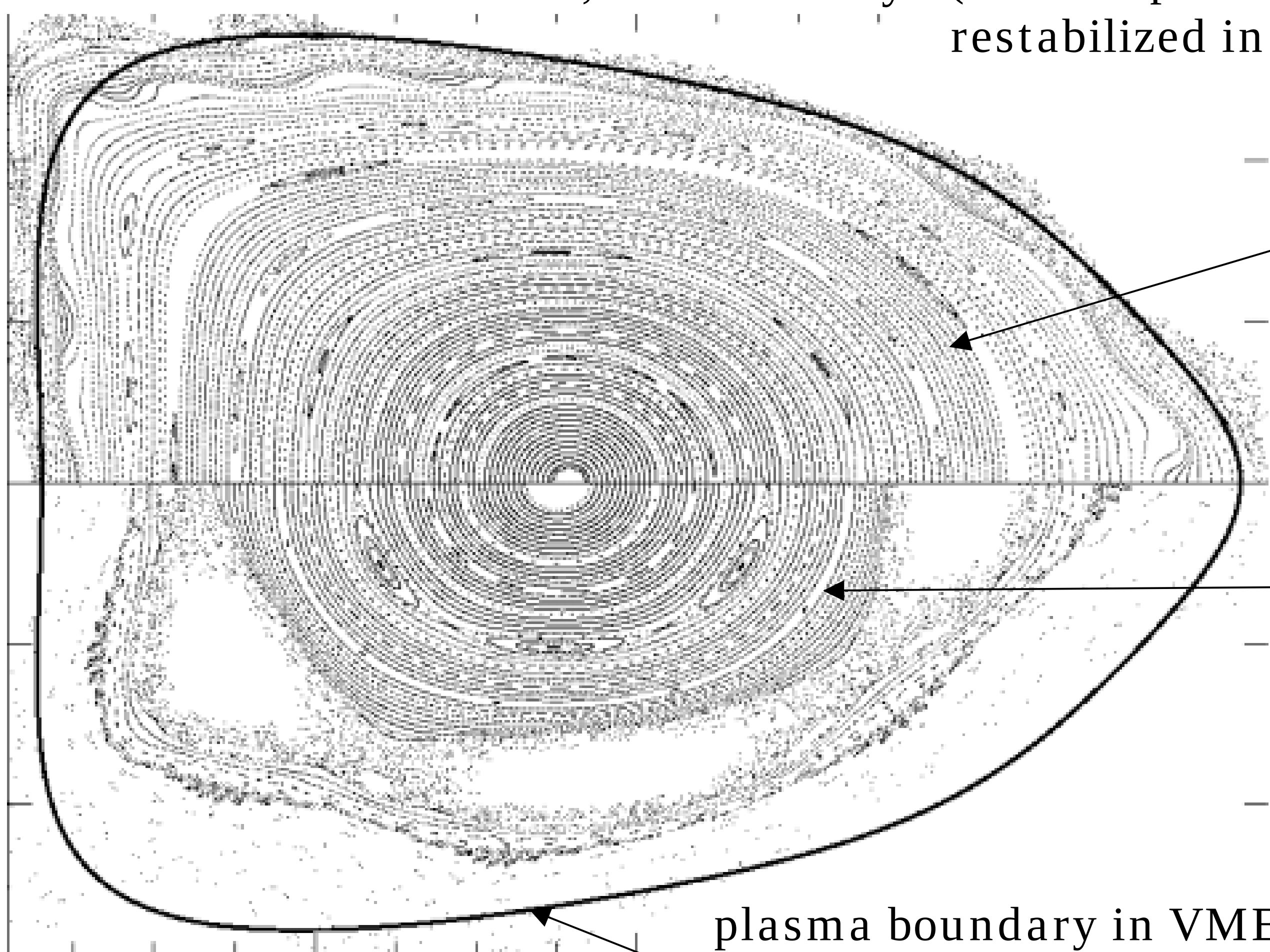
NCSX is Designed to Have Good Flux Surfaces

- NCSX coils designed to produce good flux surfaces. (PIES code)
- NCSX designed so that neoclassical effects reduce island widths.
- Have verified that coils give acceptable surfaces for range of configurations.
  - Equilibrium calculations with PIES code. (Do not include neoclassical effects.)
  - Estimate neoclassical effect and effect of finite $\chi_{\perp} / \chi_{//}$ in assessing effective total surface loss.
- External and internal trim coils designed to extend range of configurations with good surfaces.
- Strong ambipolar flow predicted to shield out resonant perturbations.

Coil Design Has Been Modified to Produce Good Surfaces

- "Dynamic healing" algorithm modifies coils in each PIES iteration to suppress targeted islands.
- Preserves engineering and physics constraints on coil curvature, minimum distance between coils, kink stability. (Stable up to n=45. Ballooning restabilized in startup scenario.)



Converged, free-boundary PIES calculation with healed coils. Sum of effective island widths < 1%.

PIES calculation with original coils. Continues to deteriorate as iteration proceeds.

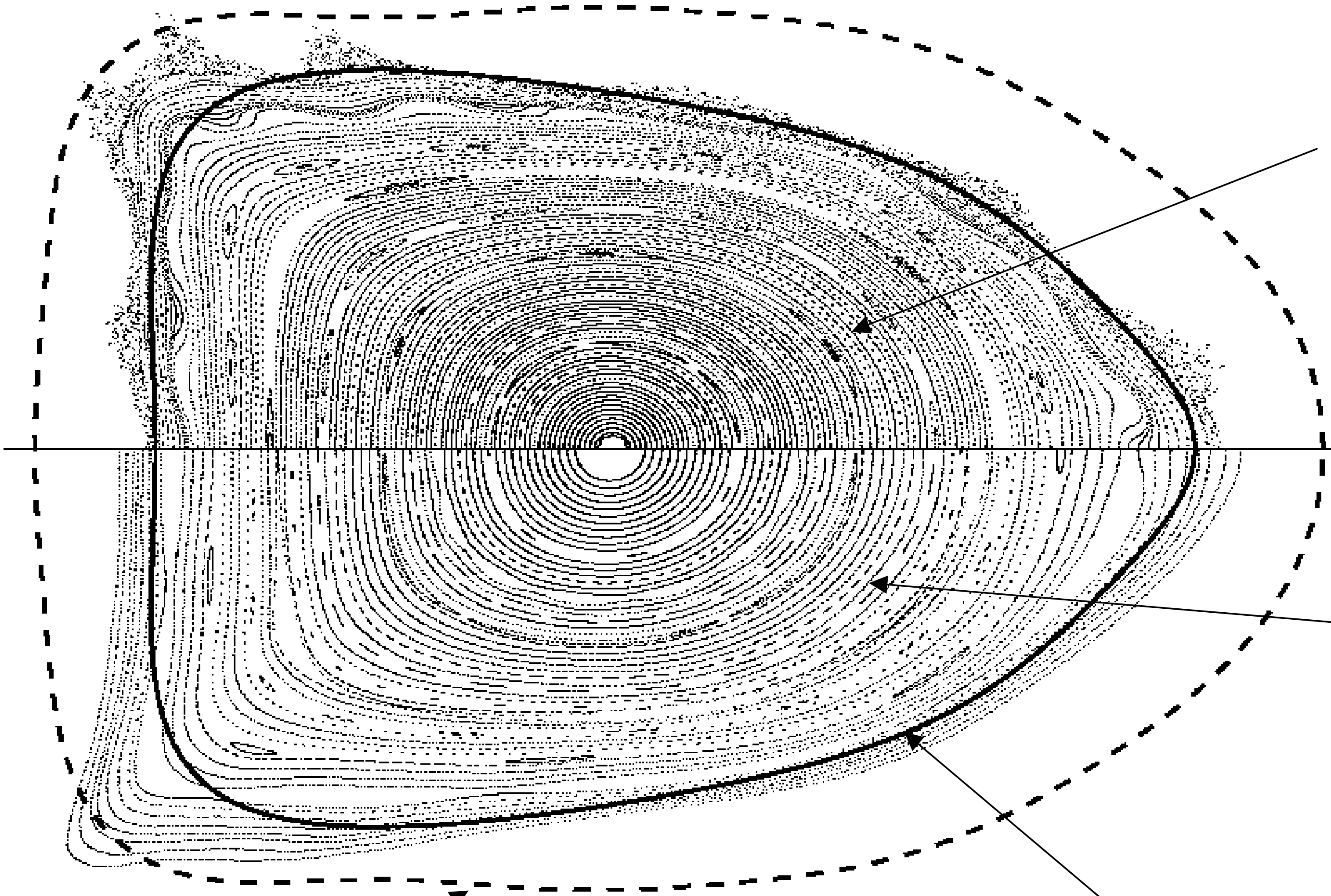
plasma boundary in VMEC calculation with unhealed coils.

Small Islands Have Little Effect on Transport

- Large islands short-circuit confinement by allowing heat to flow along separatrix.

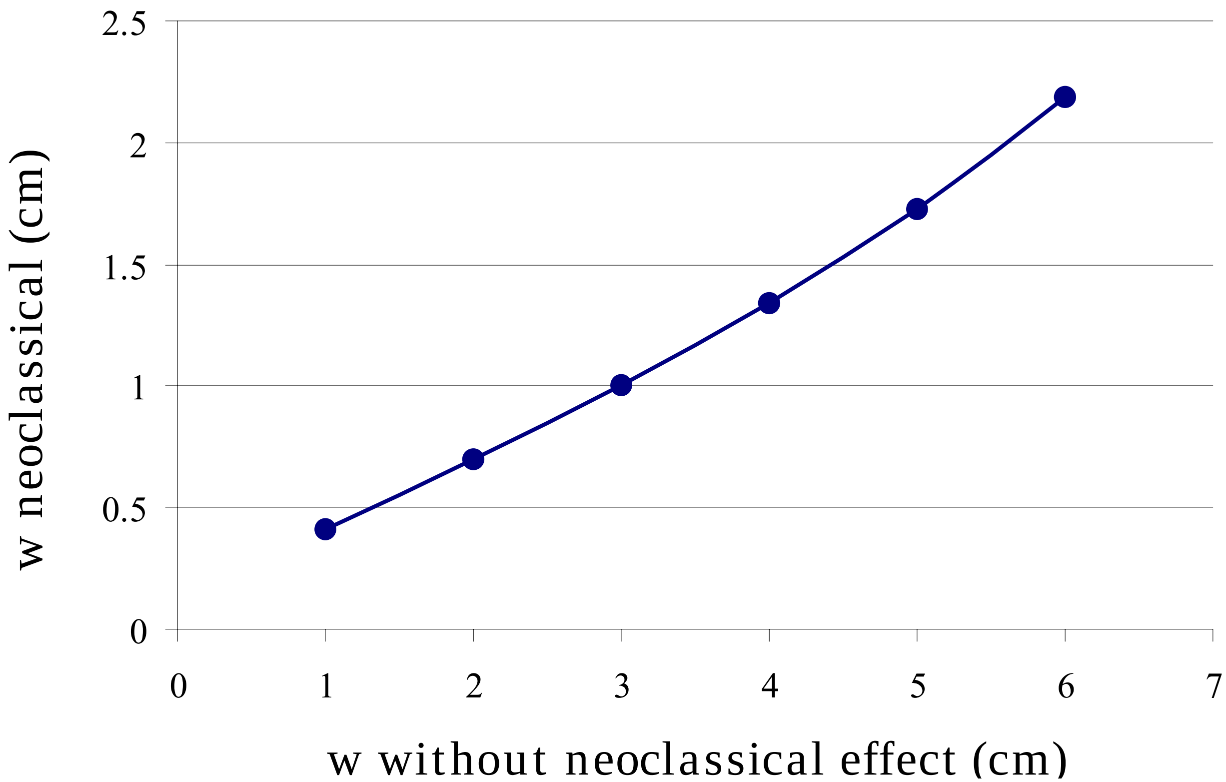
- For narrow islands, path length along field line long, and parallel conductivity prevents short-circuiting of confinement.
- Critical island width at which transport due to island is comparable to cross-field transport: $w_0 \approx 5 (\chi_\perp / \chi_{//})^{0.25} (RL_\iota / m\iota)^{0.5}$, where L_ι is shear scale length.
- Estimate $w_0/a \approx 3.5\%$ for m=5 island in NCSX. (At $\beta = 4.2\%$, B = 1.2 T, $\langle n_e \rangle = 5.8 \times 10^{19}\ m^{-3}$)
- In calculating flux surface loss, use effective island width $w/(1+(w_0/w)^4)$. (Effective diffusivity across island $\chi \approx \chi_\perp(1+(w/w_0)^4)$).

Multi-Filament Model Improves Flux Surfaces



Neoclassical Effect Reduces Island Widths in NCSX

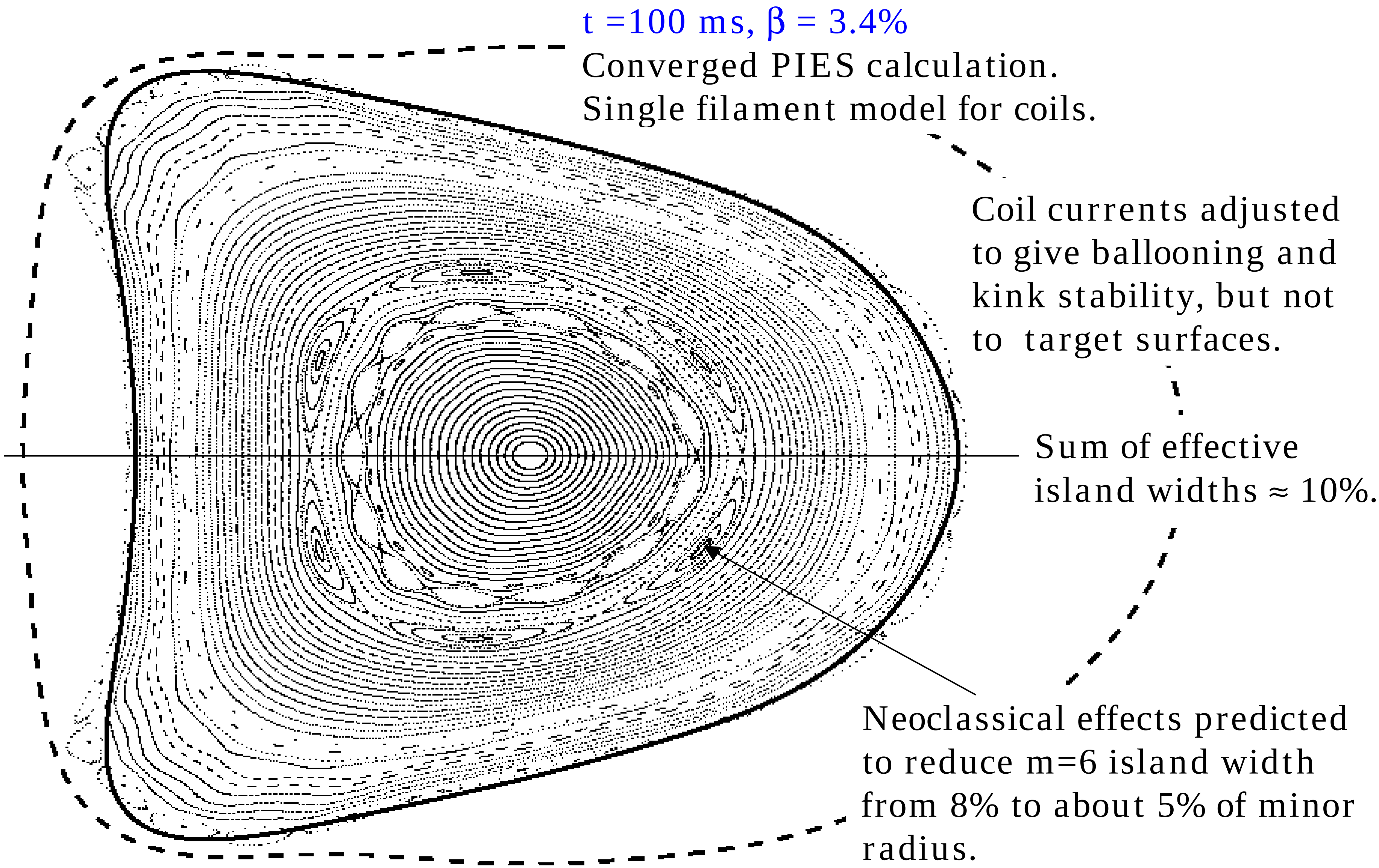
- Gives neoclassical tearing mode in tokamaks ($\iota' < 0$).
- For $\iota' > 0$, effect predicted to reduce NCSX island widths.



Effect estimated for island at $\iota = 0.6$ surface. Analytic calculation in cylinder. Estimate $\Delta' = -2\ m / r$. Take $\beta = 4.2\%$, $B = 1.2$ T, $\langle n_e \rangle = 5.8 \times 10^{19}\ m^{-3}$.

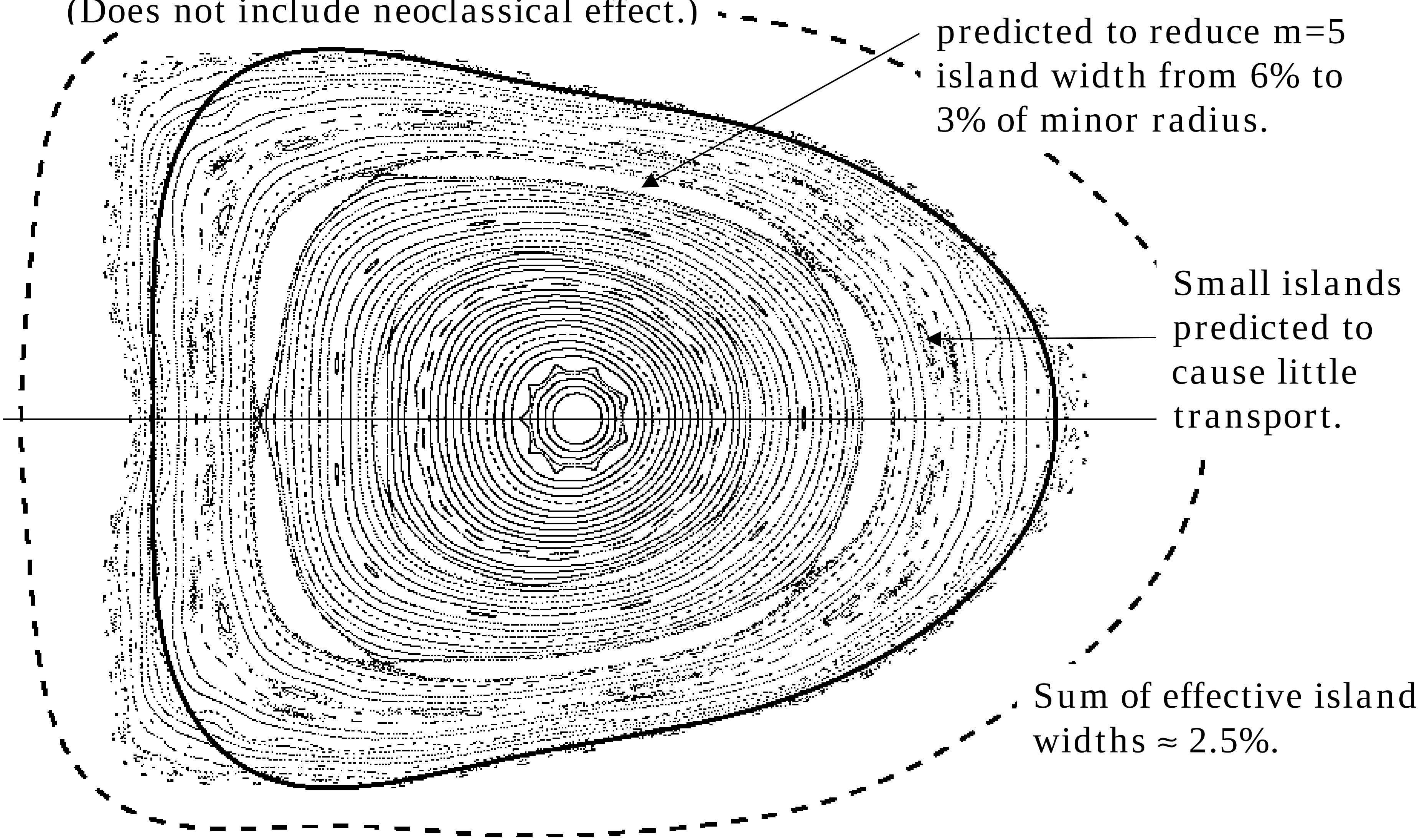
- Evaluation of effective island widths takes into account finite $\chi_\perp / \chi_{//}$ effect, as well as neoclassical effect.

Flux Surfaces Evaluated for Five Snapshots in Startup Scenario are Acceptable



Good Flux Surfaces at β Values Exceeding Design Value, with Transport Determined Profiles

t = 303 ms, β = 4.6%. Converged PIES calculation with healed coils. (Does not include neoclassical effect.)



Summary of Effective Flux Surface Loss for PIES Calculations

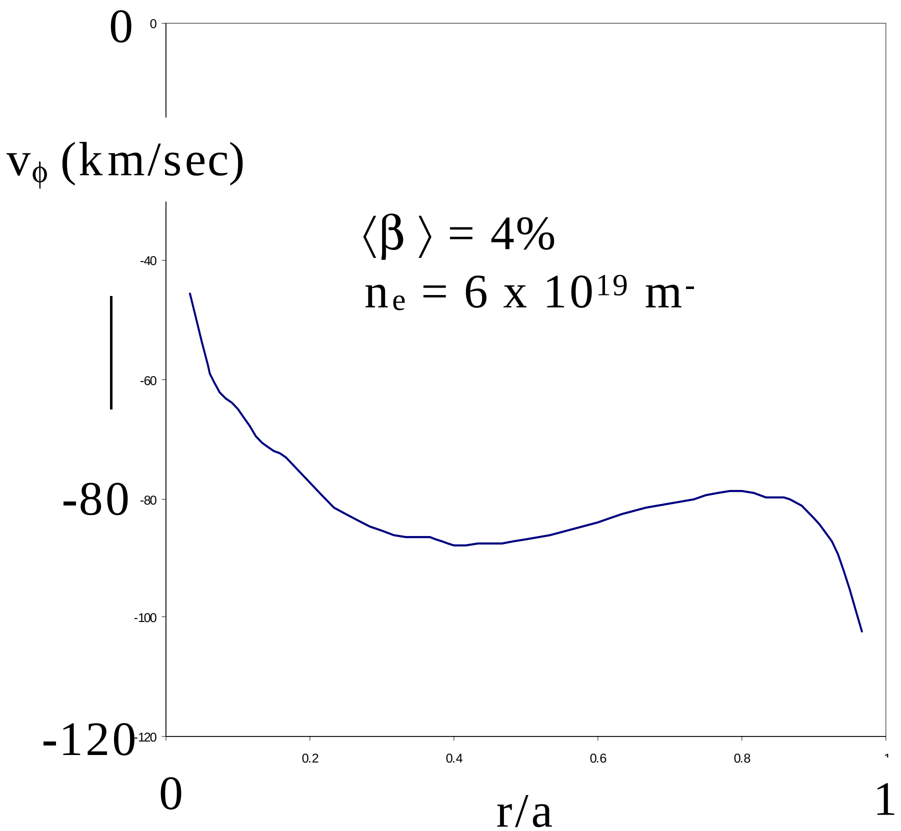
(Details in Physics Design Document)

	case	β (%)	Loss of surfaces at edge (%)	Sum of effective island widths (%)	Total effective flux surface loss (%)
Reference case	S3	4.1	0	<1	<1
Vacuum cases	vac1	0	3.1	<1	3.1
	vac2	0	10.4	<1	10.4
	vac3	0	5.2	<1	5.2
	vac4	0	<1	<1	<1
	vac5	0	2	<1	2.0
Startup snapshots	t=50	1.2	6.2	3.8	10.0
	t=100	3.4	0	10.1	10.1
	t=116	3.7	0	5.5	5.5
	t=139	3.9	11.4	1.2	12.6
	t=303	4.6	0	2.5	2.5

- Expect further improvements using trim coils.

An Additional Effect: Plasma Flow Shields out Resonant Perturbations at Rational Surfaces

- Plays major role in reducing vulnerability of present day tokamaks to field errors.
- Tokamaks most vulnerable just before neutral beams turned on, when flow diamagnetic.



Predicted NCSX rotation frequency ≈ DIII-D cases where penetration threshold studied with neutral beams turned on.

Strong flow driven by ambipolar E_r even in absence of external momentum input.

Predicted resonant magnetic perturbation penetration threshold ≈ measured DIII-D threshold with beams turned on.

$(B_{rnm}/B \approx 6\text{x}10^{-4}$ for $n \approx 6\text{x}10^{19} m^{-3})$

Conclusions

- A new coil design code has been built around PIES and applied to NCSX. Coil design modified to heal flux surfaces, while preserving engineering and physics constraints.
- More accurate modeling of coil pack (using multiple filaments) improves calculated flux surfaces.
- Calculations for five different vacuum states and five snapshots during startup scenario find acceptable flux surfaces loss.
- Trim coils will provide additional flexibility.
- Strong ambipolar flow additionally predicted to shield out resonant perturbations.