Reconstructing the Equilibrium of W7-AS

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Stellarator Theory & General Atomics

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IPP

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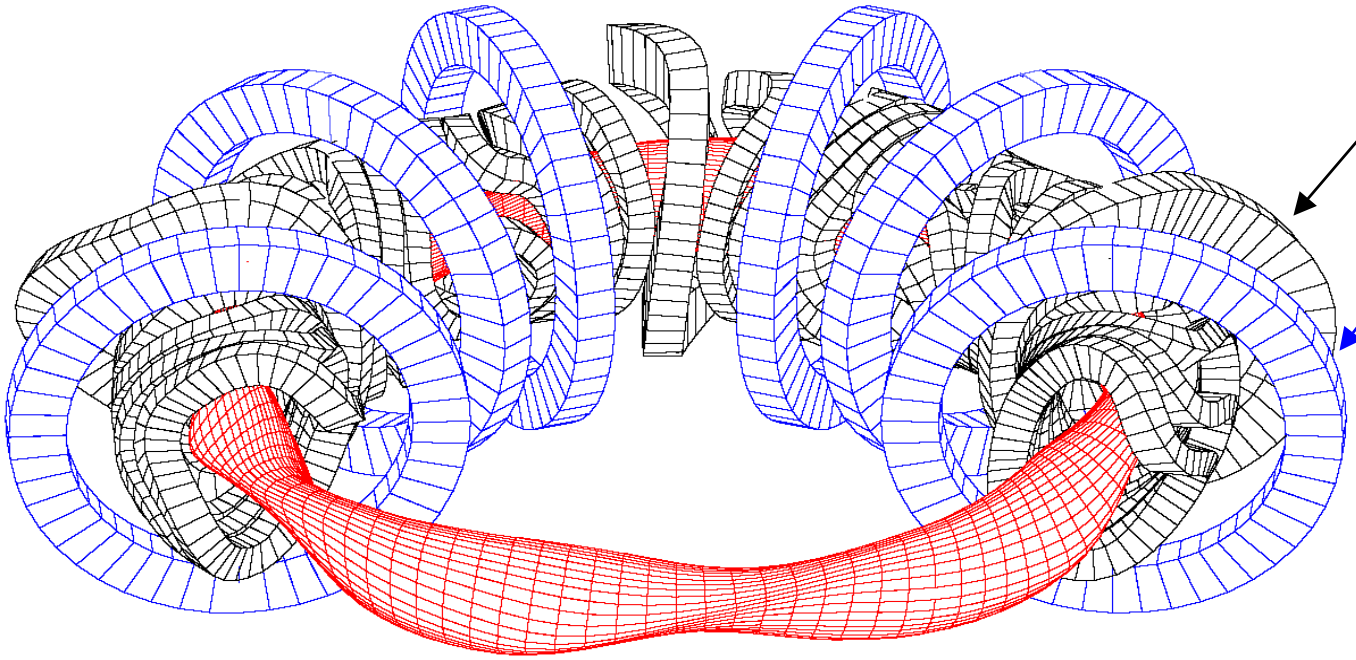
Outline

- Goals and motivation
- Available Data
- Codes
- Results
- Summary

W7-AS – a flexible experiment

5 field periods, R = 2 m, minor radius a ≤ 0.16 m, B ≤ 2.5 T,
vacuum rotational transform $0.25 \leq \iota_{ext} \leq 0.6$



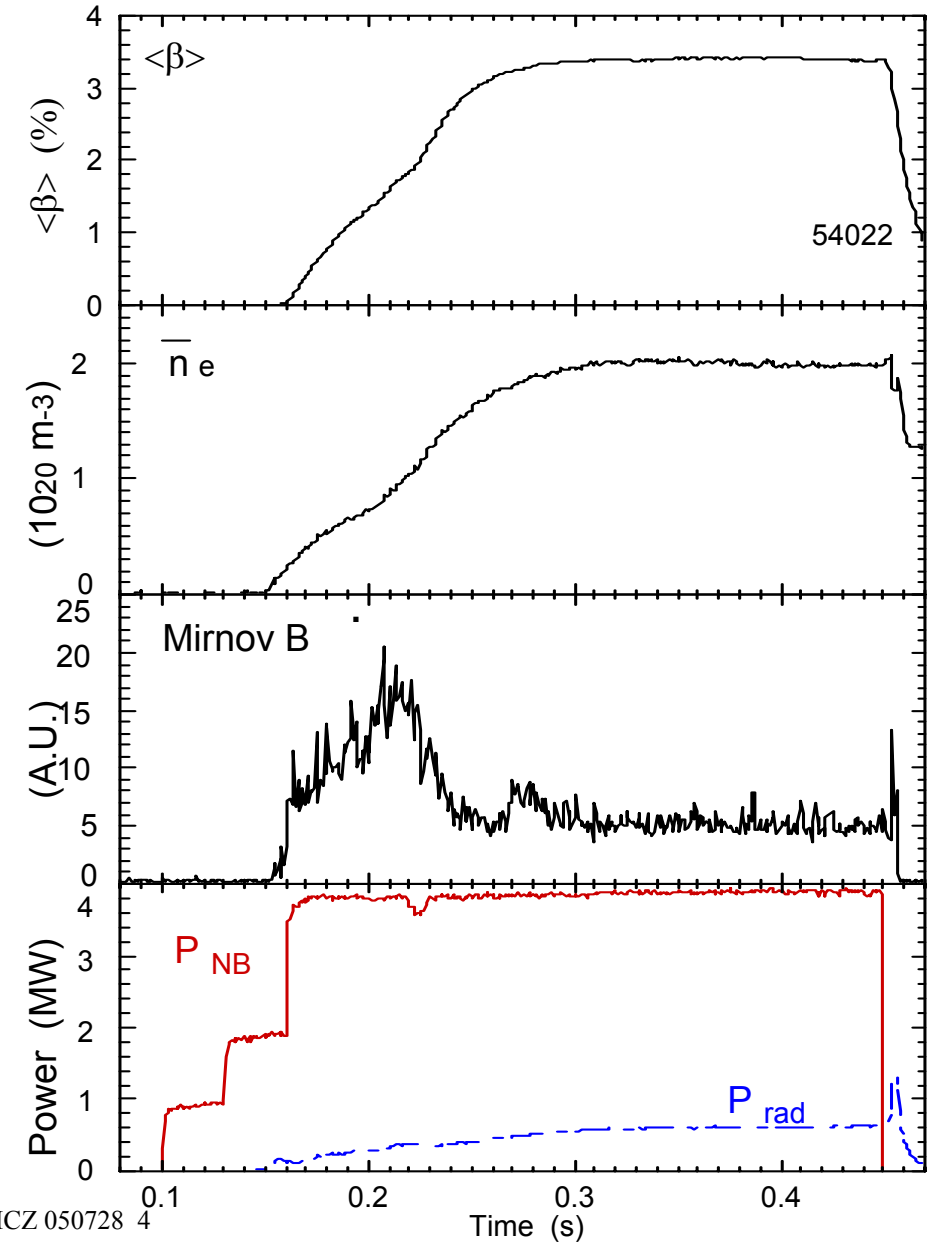
Flexible coilset:

- Modular coils produce helical field
- TF coils, to control rotational transform ι
- Not shown:
  - –divertor control coils
  - –OH Transformer
  - –Vertical field coils

W7-AS

Completed operation in 2002

High β experiments need better equilibrium treatment in stellarators



- $\langle\beta\rangle \approx 3.4$ % : Quiescent
- At low $\beta << 1\%$, vacuum flux plot is reasonable approximation
- for $\beta \geq 1\%$, discrepancies in diagnostic mapping, power flow, Location of divertor islands...

Issues:

- What is the plasma volume? and thus beta?
- What is the pressure profile? How to map diagnostics?
- What is the iota profile? and other equilibrium properties

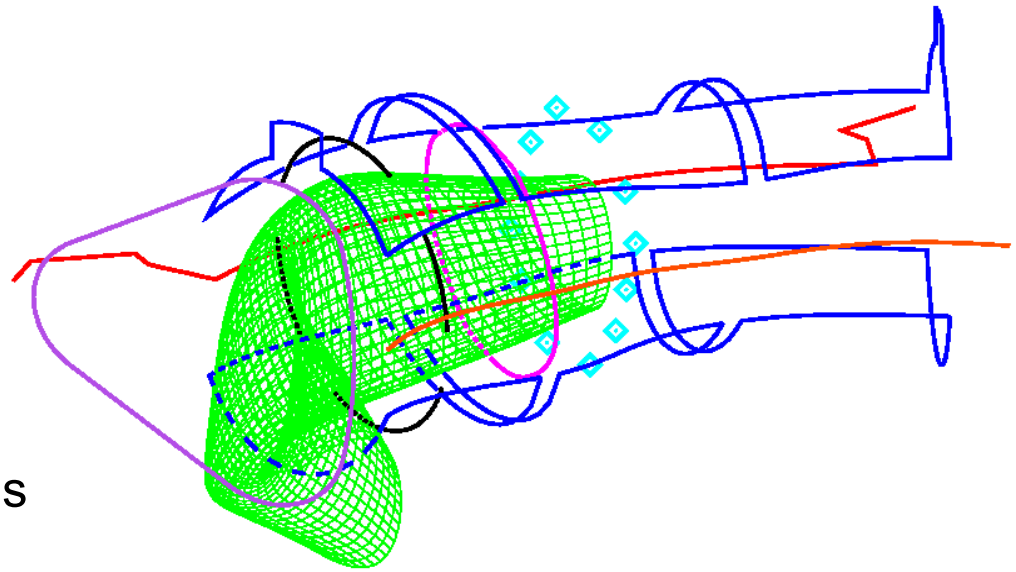
-- How to get a self-consistent equilibrium??

Data for Equilibrium Reconstruction

- Available data:
  - –19 magnetic measurements, including: segmented Rogowski, flux loops, diamagnetic loops

  - – straight forward interpretations of magnetics: I_P, W_{dia}

  - – 45 point single-time Thompson scattering system
    assume $p_i = p_e$, due to very high density $\Rightarrow$ short equilibration time

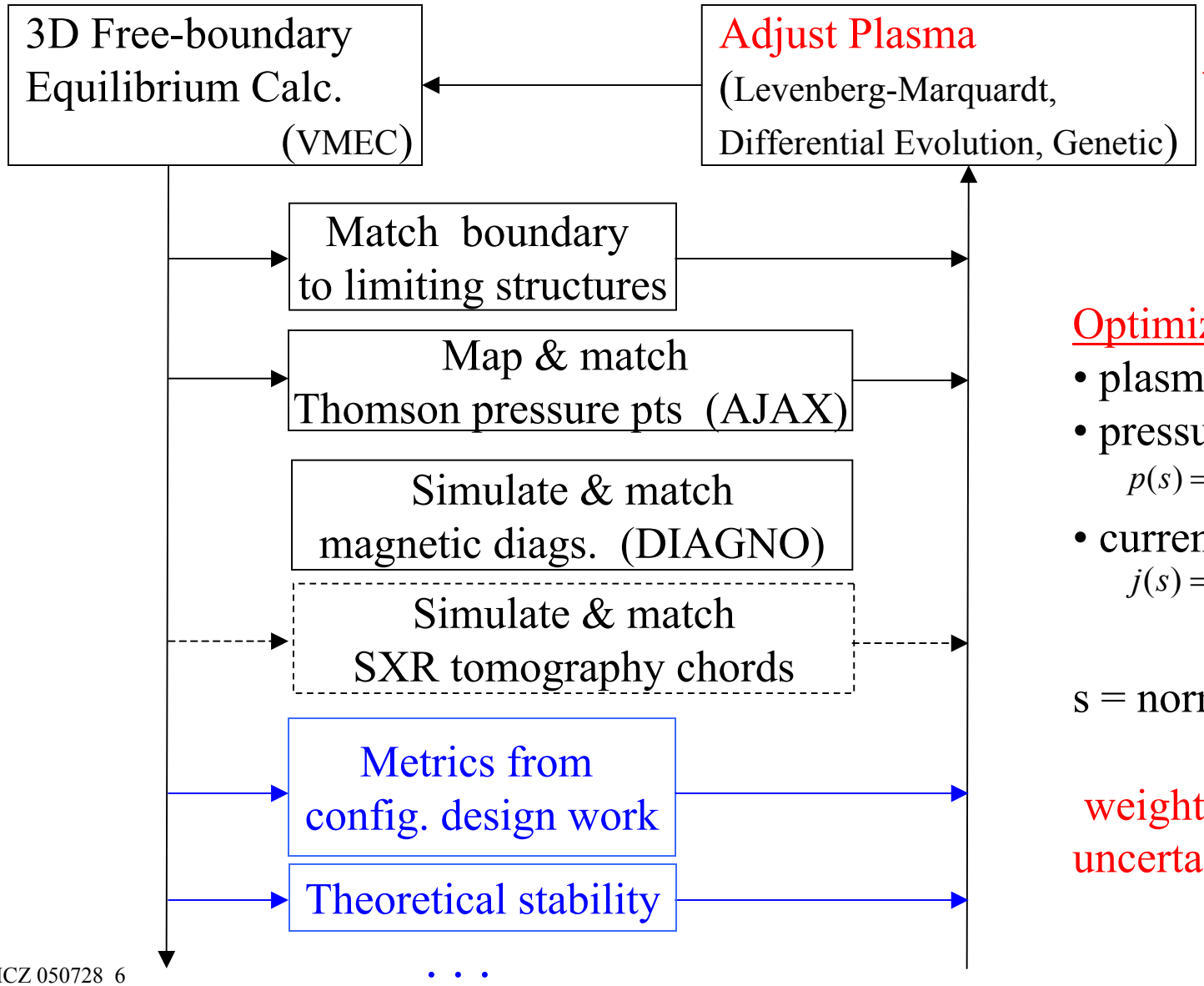


- Magnetics integrators trigger after start of field-coil flattop. Signals compensated for coil-current noise coupling.

- From SVD analysis: magnetic measurements sensitive to 3 moments of pressure profile and 2 moments of current profile.

STELLOPT: Equilibrium Reconstruction

Originally developed for the design of NCSX & QPS



Optimization Variables

- plasma size
- pressure profile

$$p(s) = \sum p_i s^i$$

- current profile

$$j(s) = \sum j_i s^i$$

s = norm. toroidal flux

weights are 1-σ uncertainties

STELLOPT Equilibrium Reconstruction

+ Code & structure exists. Easy to modify, can incorporate almost any feedback. Lots of experience using it for design.
+ Already parallelized, using either MPI or multi-processor nodes (shared mem)

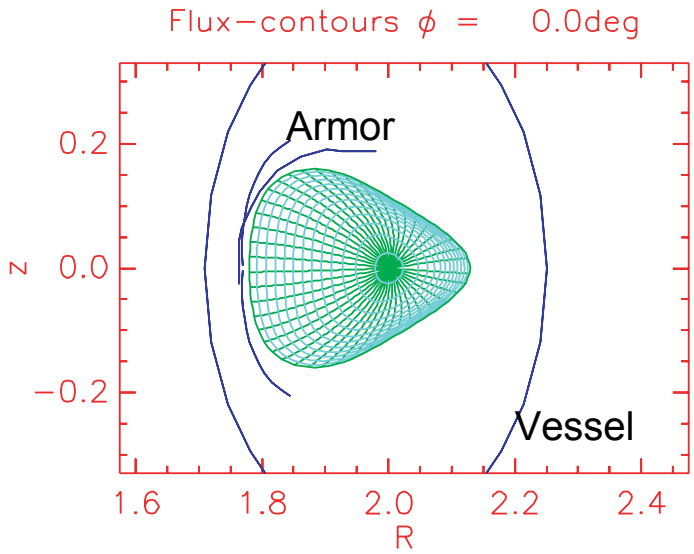
• free-boundary VMEC based. Reasonably fast, but can only represent simply-connected nested closed flux surfaces

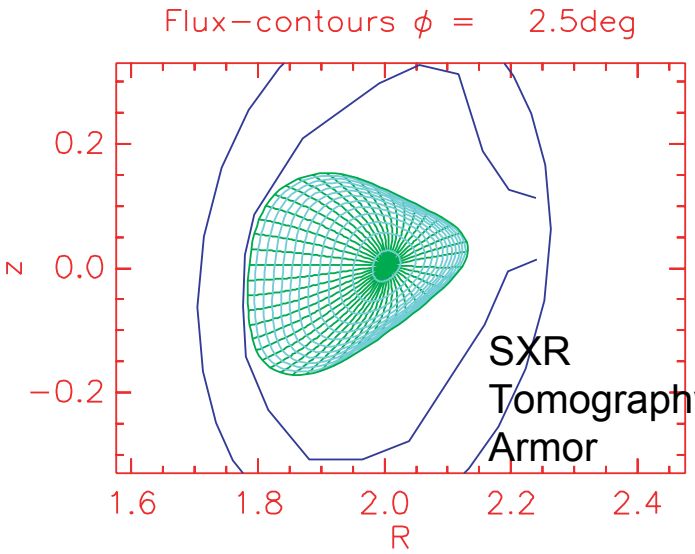
– Each iteration is a fully converged equilibrium => slow

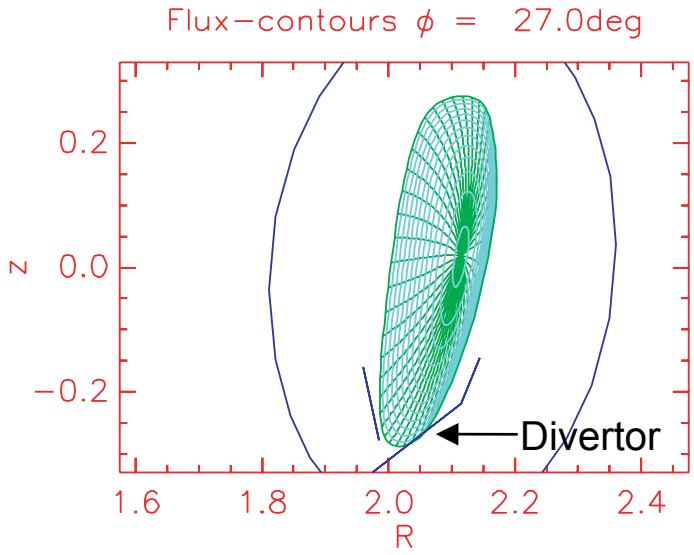
Examples:

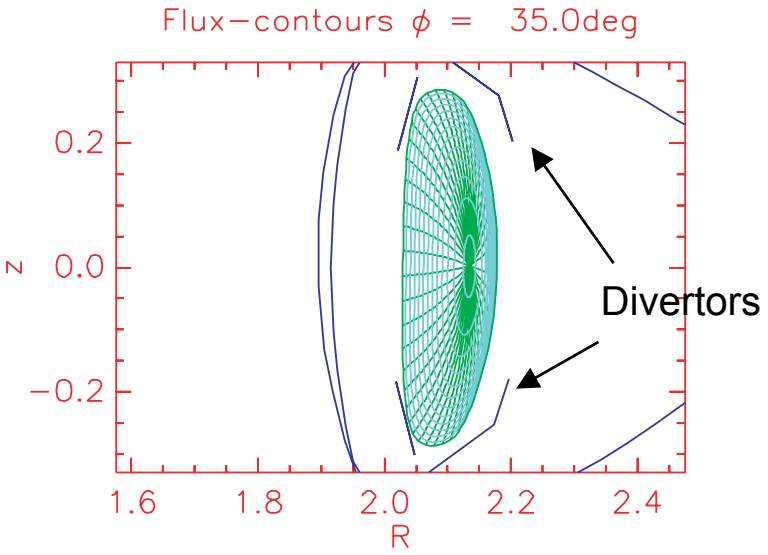
	free vbls.	iterations	wall-clock
Size and W_{dia}	2	<15	~0.5 hr
Thomson Only	12	~200	~2 hr
Magnetics+Thomson	15	~300	~3 hr

3D Limiting Structures are Complicated



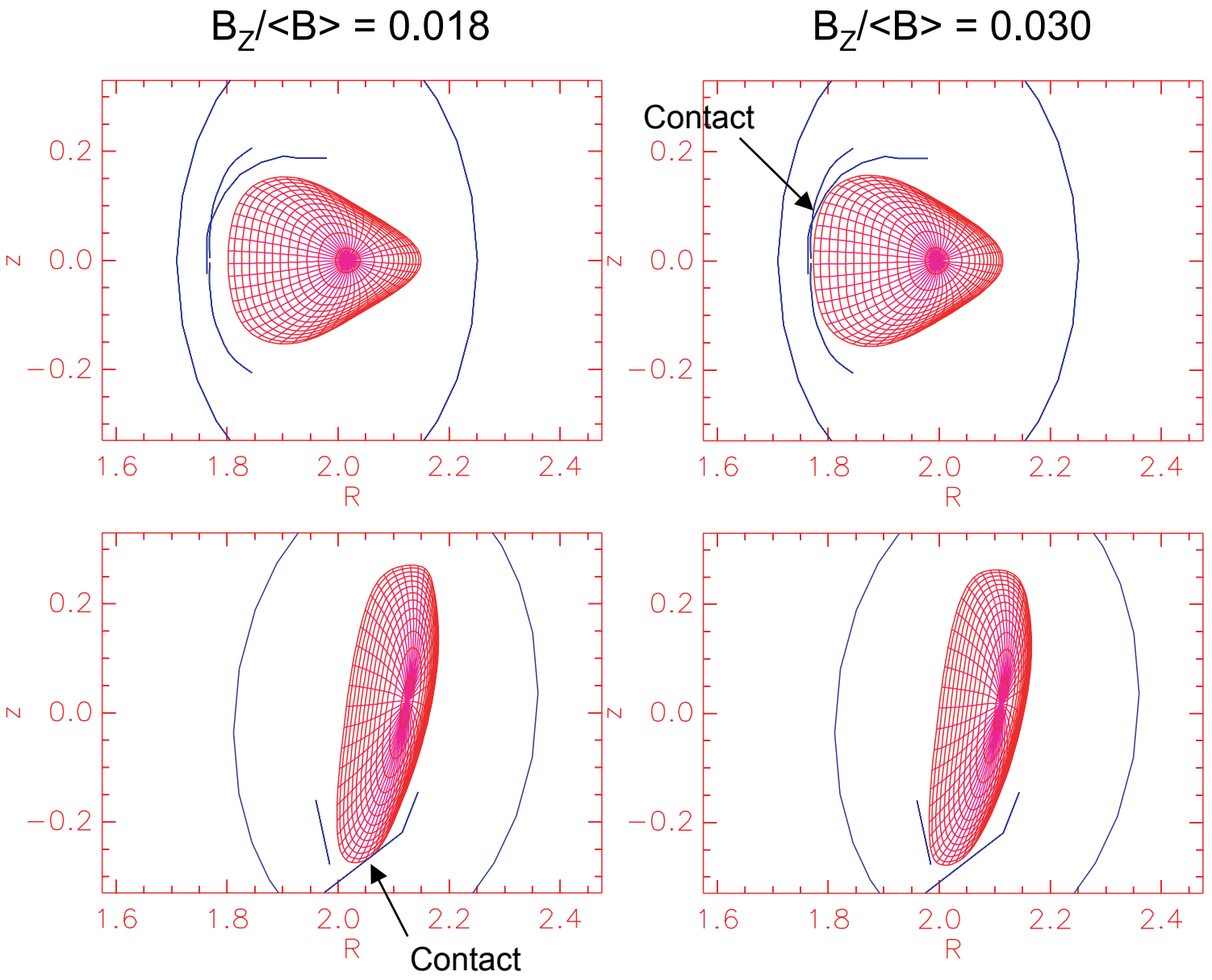




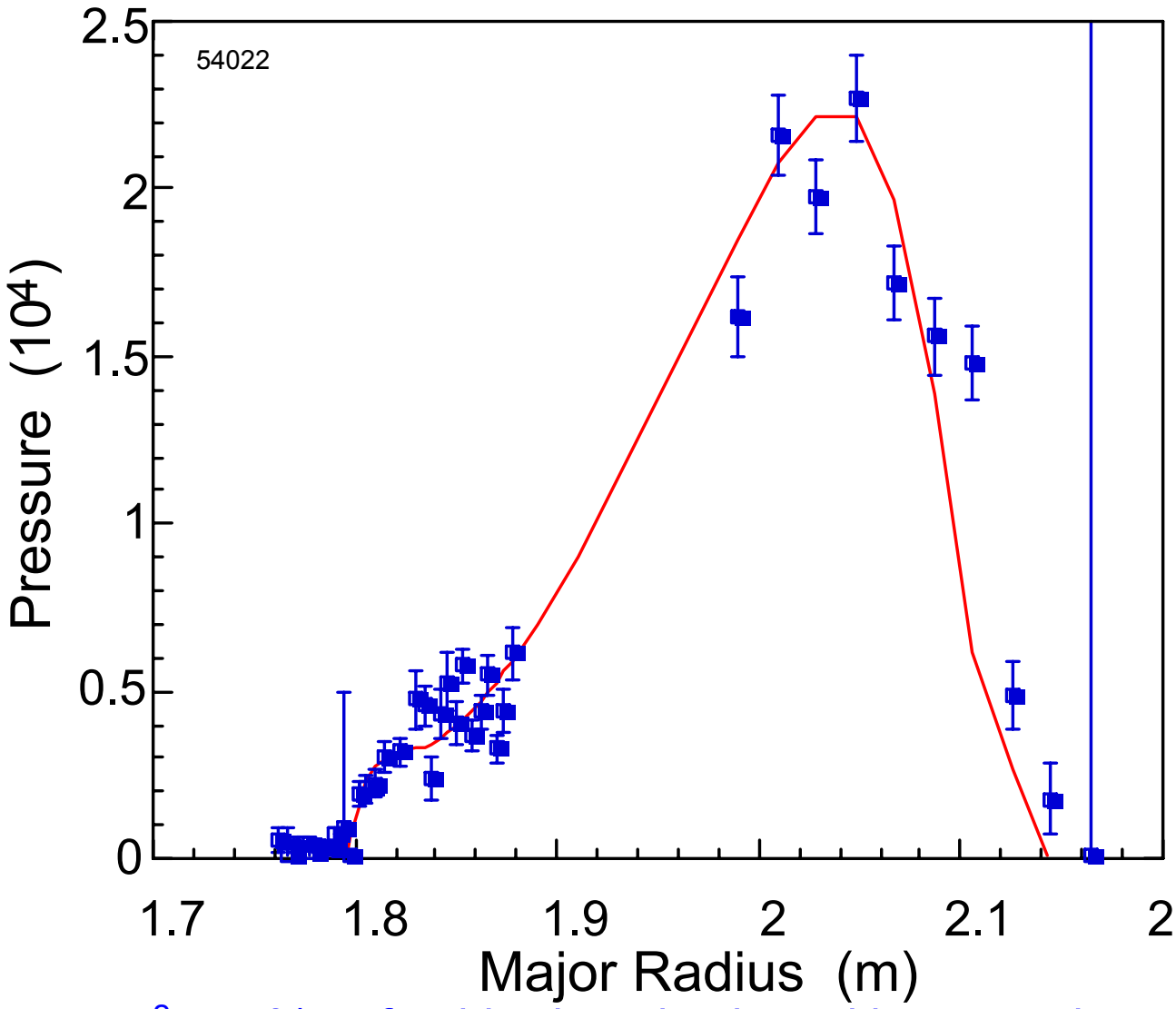


- Vessel specified by Vmec-like Fourier series (R, Z)
- Other limiters specified as piece-wise-linear sequence at discrete ϕ values

3D Limiting Structures are Complicated



Pressure profile reconstructed with Thomson Scattering



$$p(s) = \sum p_i s^i$$

can also use representation with $\sqrt{s}$ term

Data = 2 p_e

Fit includes magnitude, but it agrees within 2% with Thomson calibration.

- χ^2_{TS} ~ 3/pt. for this shot, dominated by one point at R=2.11
- χ^2_{TS} as low as 1.5/pt on other shots
- χ^2_{TS} lower if include current profile in fit, due to matching axis Shafranov shift

Information in Magnetics Data

Database of magnetic diagnostic simulations created for

- varying profiles & W_{pl}
- fixed coil currents
- $I_P = 0$

Use SVD analysis to find number of distinguishable 'eigenvectors'

- If analyze whole data base, fraction of variance due to each eigenvector is

  99.9% 4.622e-2% 1.079e-2%

  First eigenvector identifiable as W_{pl}

- If analyze database subset at fixed energy, p-profile variations only, j=0

  92.7% 7.22% 5.946e-2%

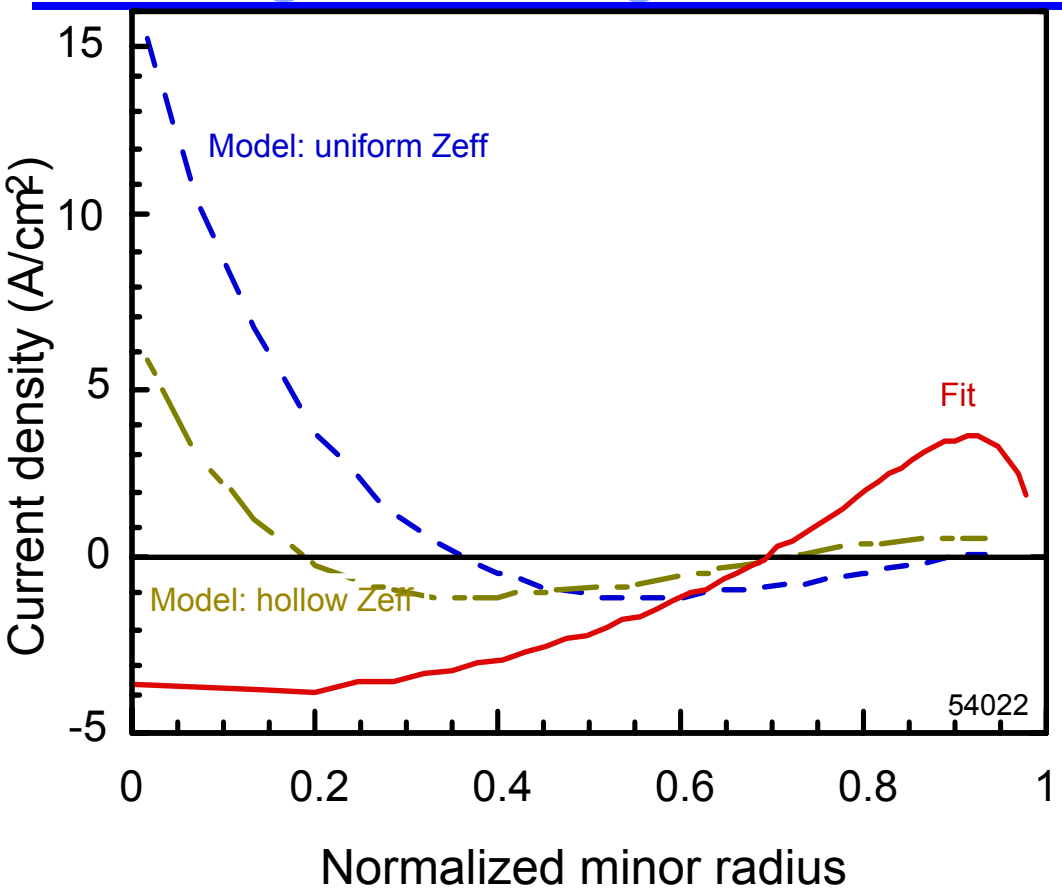
- If analyze database subset at fixed energy, j-profile variations only, p parabolic

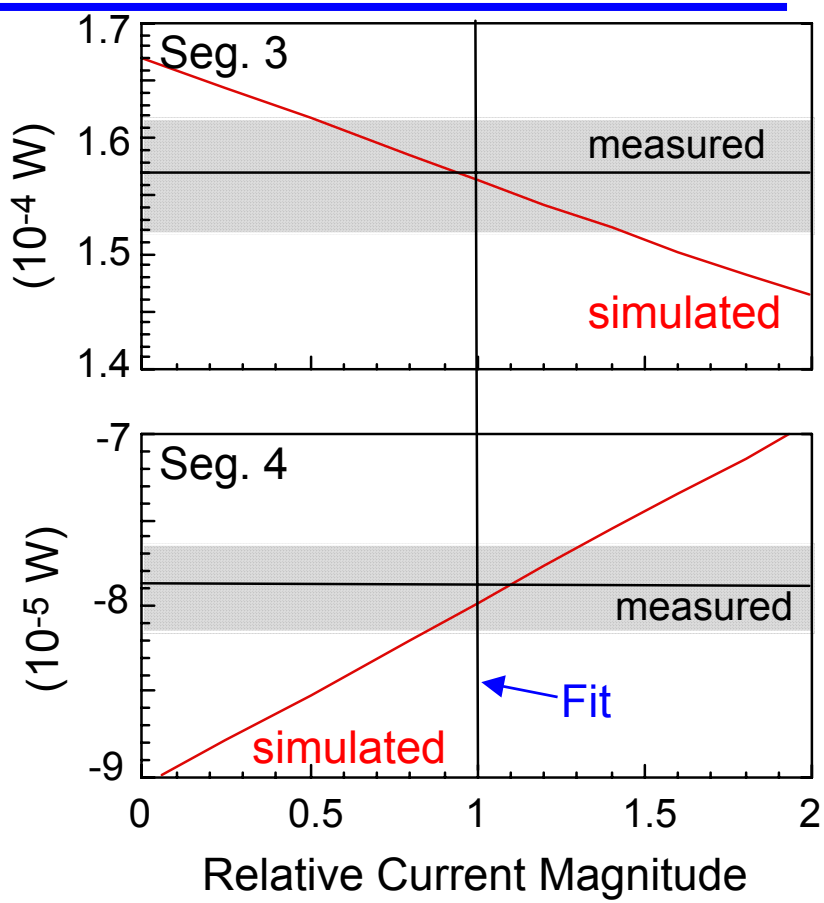
  100% 1.635e-2% 7.47e-3%

- If analyze for different fixed W_{pl}, get similar answers, but eigenvectors change

=> At most, magnetic sensitive to 2 moments of current, 3 moments of pressure

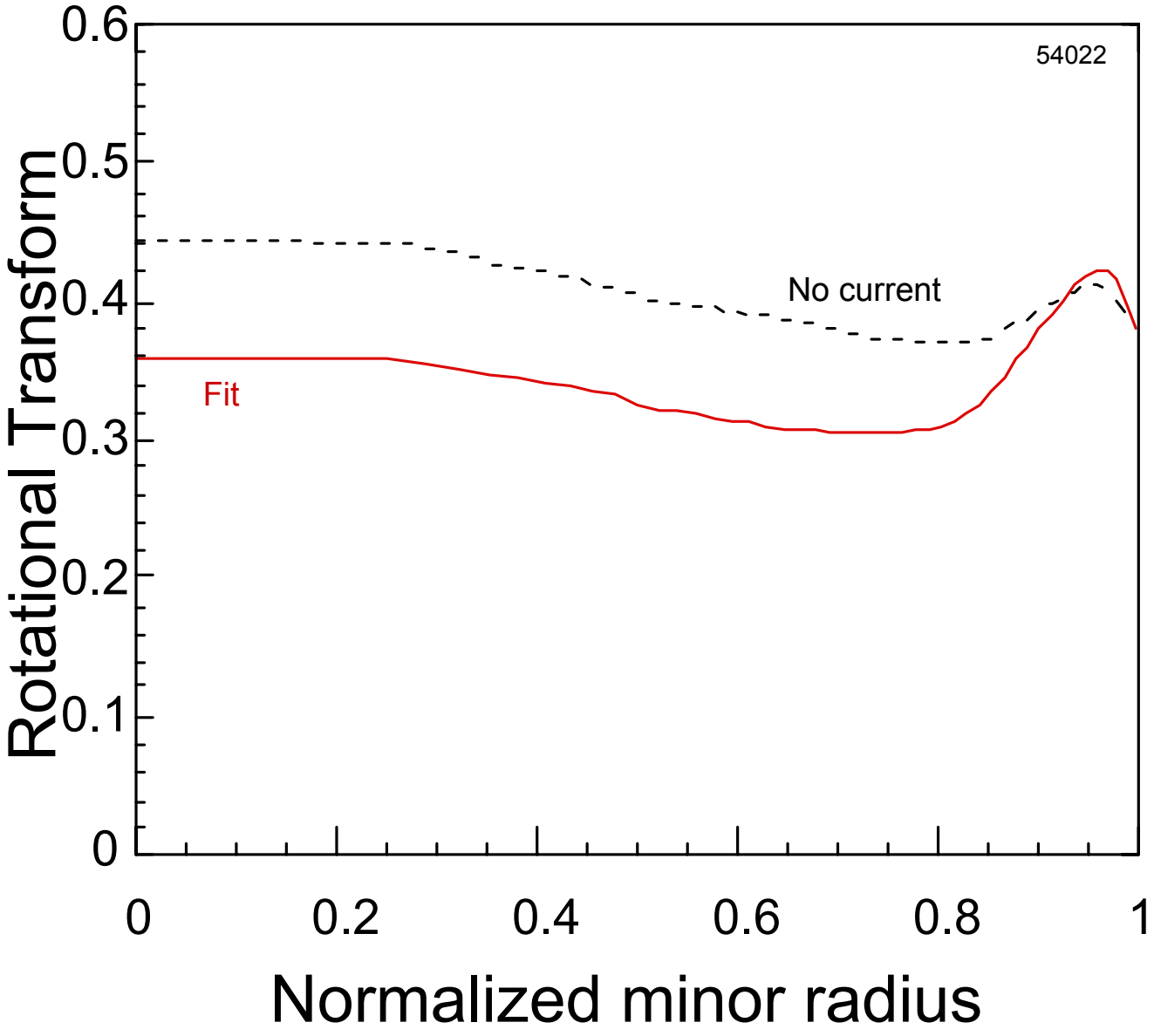
Magnetic Diagnostics are Sensitive to Current





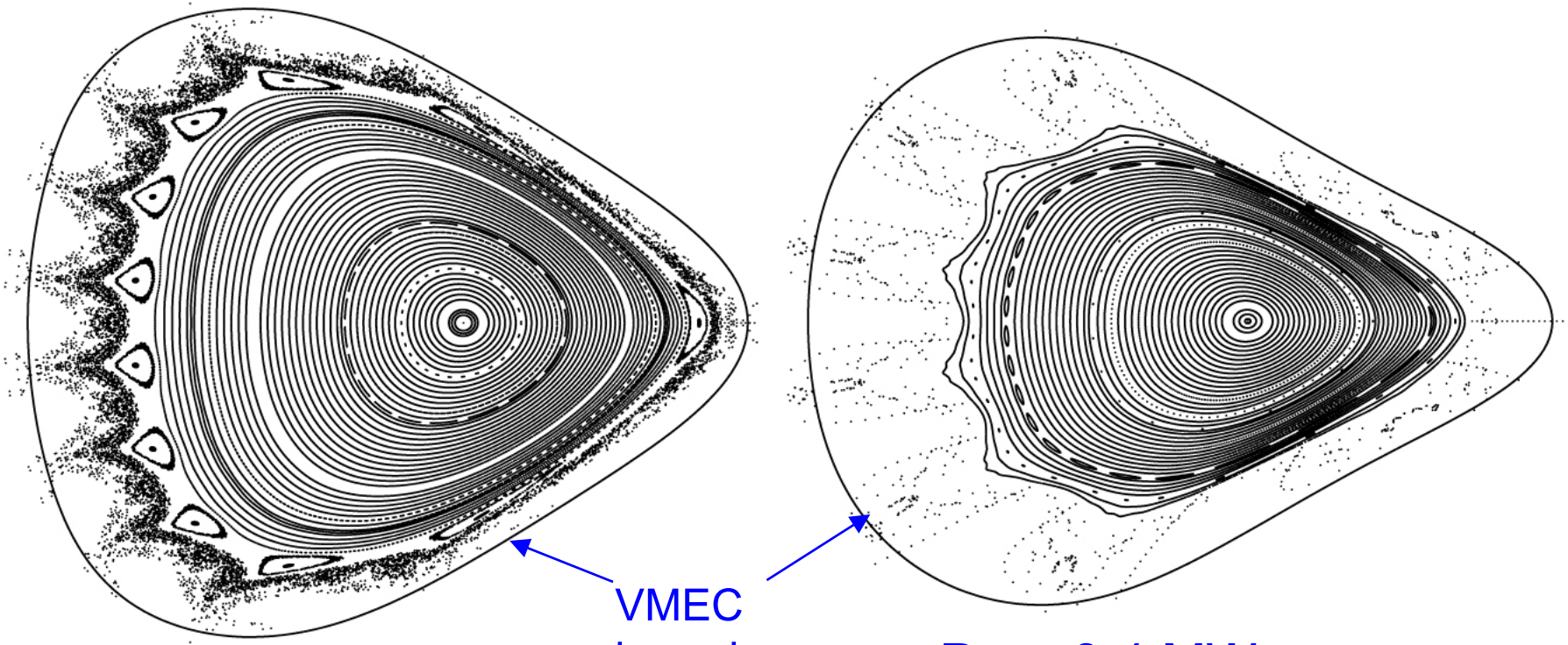
- Small, but significant current inferred from equilibrium fit.
  Estimated uncertainty of magnitude approx. ± 20% from Rogowski segments
- Three moments used to fit current profile,
  higher order moments used to force j(a)=0
- χ^2_{mag} ~ 0.83 /diag.
- Imposing calculated currents gives χ^2_{mag} ~ 2 / diag.
  inconsistent with magnetic measurements.

Reconstruction: Lower core iota



- Lower central iota, flatter profile
- Central β=8.0%

Magnetic Configuration Changes Calculated Flux Surface Topology



P_{inj} = 1.3 MW
β = 1.9%
ι_{vac} = 0.445

P_{inj} = 3.4 MW
β = 2.1%
ι_{vac} = 0.575

- PIES equilibria, starting from STELLOPT reconstructions
- See experimental differences in divertor imaging data

Summary

- A practical, initial stellarator equilibrium reconstruction code has been created, using STELLOPT / VMEC / DIAGNO / AJAX …
  - As with tokamaks, it greatly helps to have internal profile information
  - Already had a big impact in our understanding of W7-AS experiments

- W7-AS magnetics diagnostics show sensitivity to internal profiles
  - two moments of J (including total I_P)
  - Three moments of p (including W_{PL})

- PIES indicates flux surface topology changing
  - not in VMEC treatment
  - But PIES can't handle realistic limiters, can't simulate diagnostics

- W7-AS analysis uses available magnetic diagnostics
  - Not clear how much information would be available in a larger magnetic diagnostic set designed for reconstruction