Reconstruction of DIII-D 3-D equilibria with helical cores

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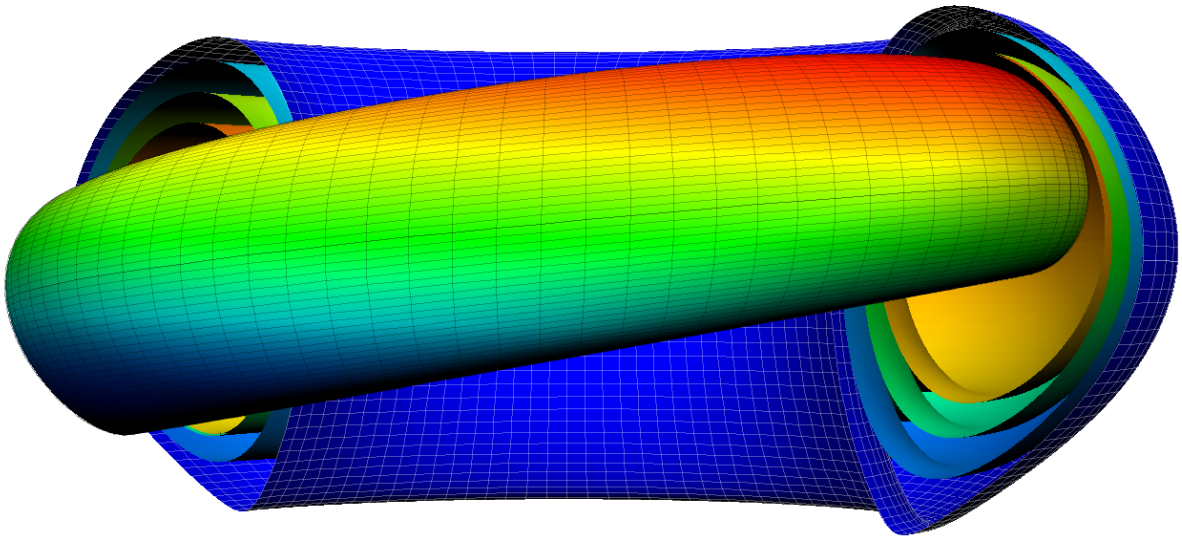
ORNL Seminar
Jan 21. 2016

LDRD Project 7395:
Workflow Optimization and Processing of Complex Datasets for Off-site Fusion Energy Research



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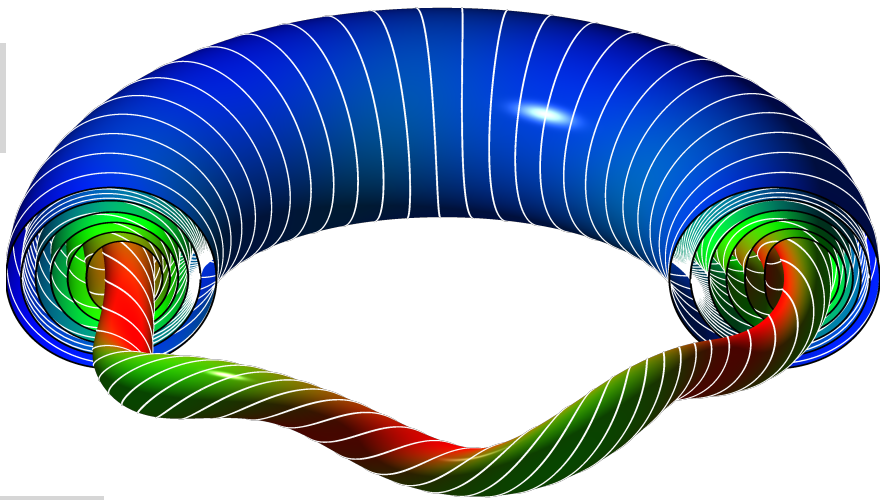
Helical core state is a saturated internal kink instability that is related to off-axis current density

- **VMEC has previously been used to model internal helical states in RFP plasmas & JET**

D. Terranova *et al.*, NF **53**, 113014 (2013)
W.A. Cooper *at al.*, NF **51**, 072002 (2011)



- **Experiments in hybrid plasmas show "magnetic flux pumping"**
  - Dynamo, conversion of kinetic to magnetic energy
  - current is "pumped" from core outwards

C.C. Petty *et al.*, PRL (2009)

- **Experiments at ASDEX-Upgrade observed helical variation in diagnostic measurements**
  - n = 1 internal kink mode forms a helical core

P. Piovesan, EPS (2015)

- **Modeling of internal helical states**
  - resolve internal magnetic structure for new DIII-D hybrid plasma experiments → Dec. 2015, Jan 2016, March 2016

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Outline

- **Operating space for helical core state**
  - using ad-hoc profiles, but realistic plasma shape
- **Modeling of realistic hybrid plasma discharge**
  - adding off-axis ECCD enables helical core
  - diagnostic response
- **First reconstruction results**
  - discharge 164661 from December flux pumping experiment
- **Summary**

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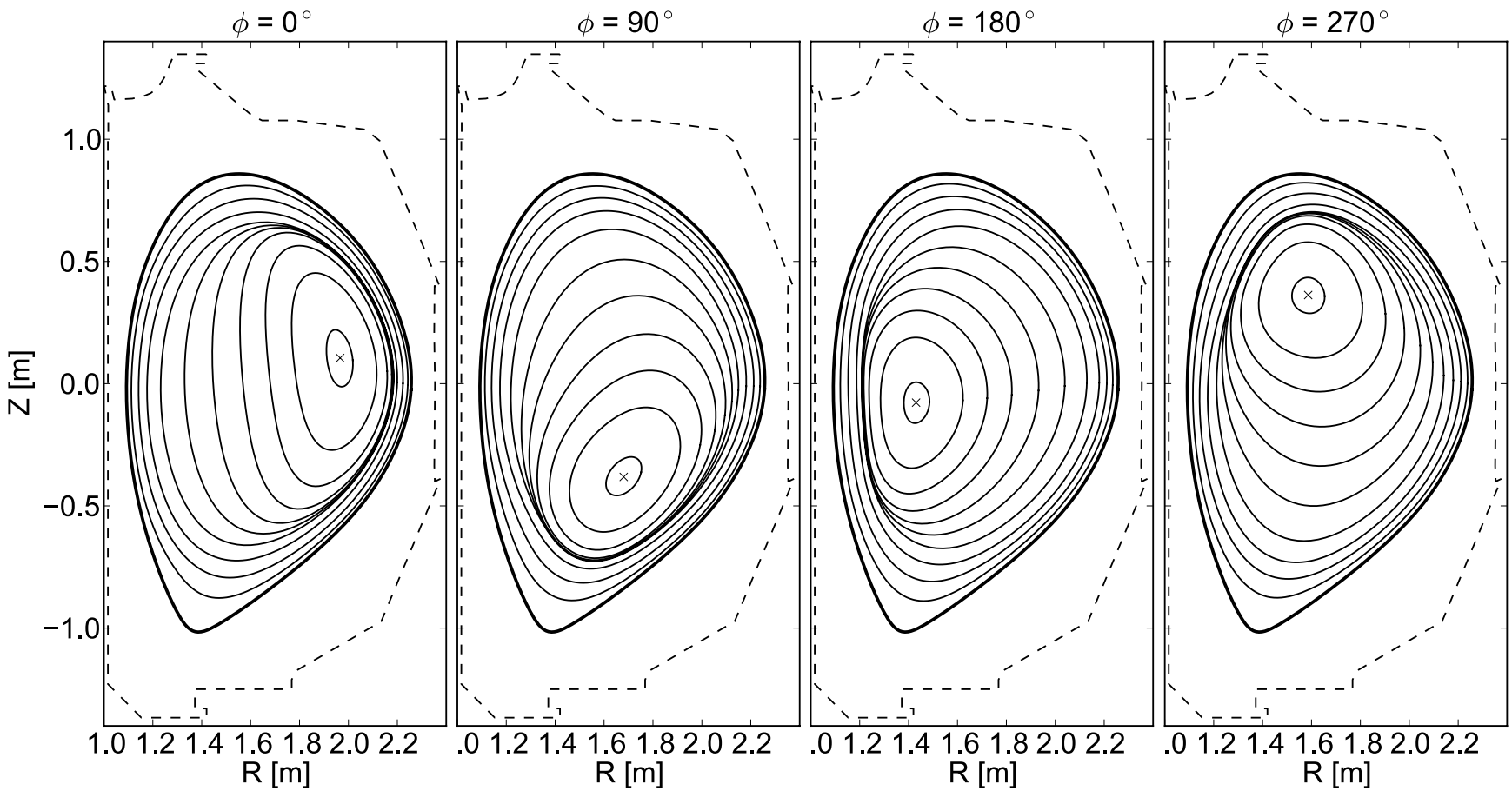
Within narrow parameter regime, VMEC shows a helical core state in DIII-D



- **fixed boundary, ns = 97, ftol = 1e-14**
- **3D perturbation required**
  - bifurcation from axisymmetric state

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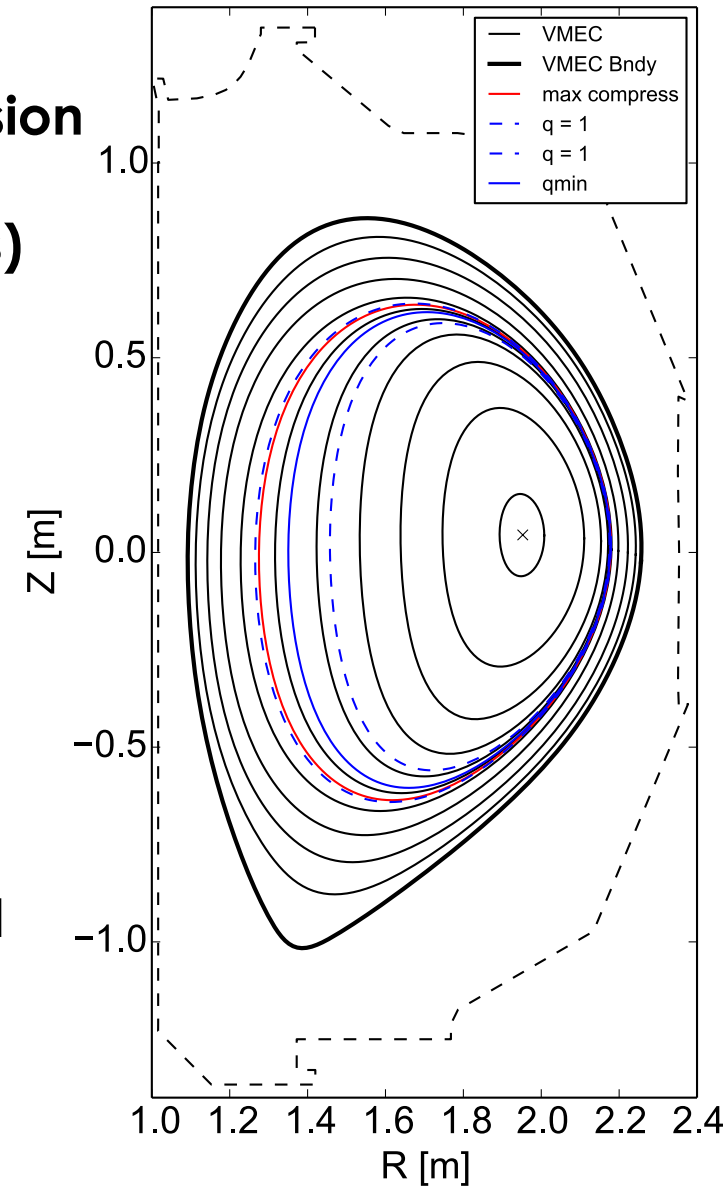
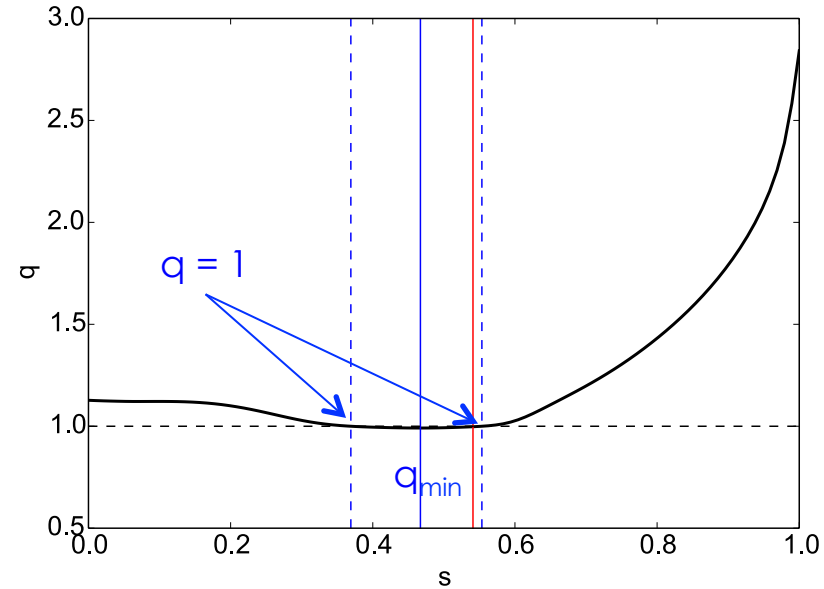
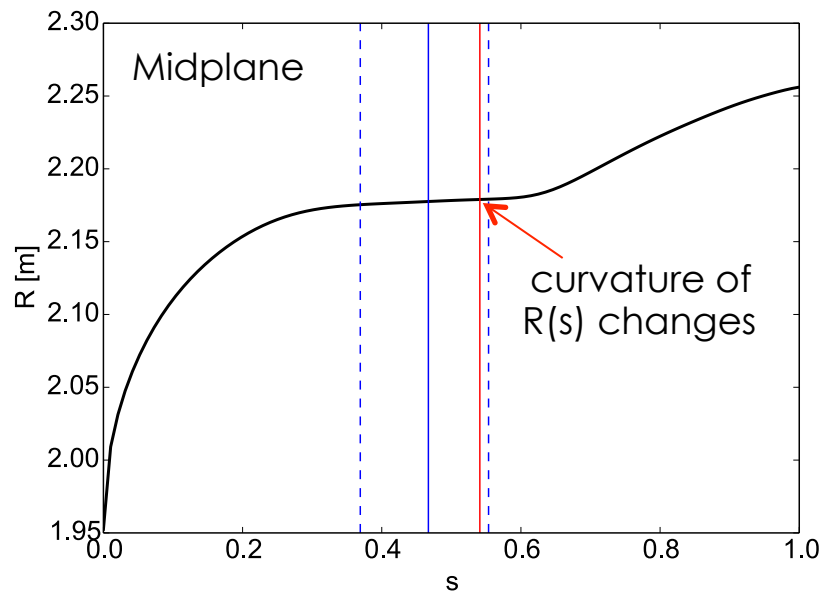
Helical core requires a reversed shear q-profile; radial range of flux compression is given by q ~ 1

- **Flux compression largest where R(s) changes curvature**
- **off-axis peak in current density creates reversed shear in q**







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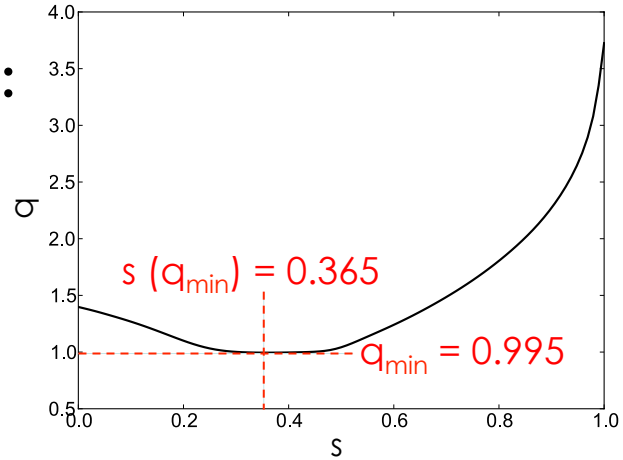
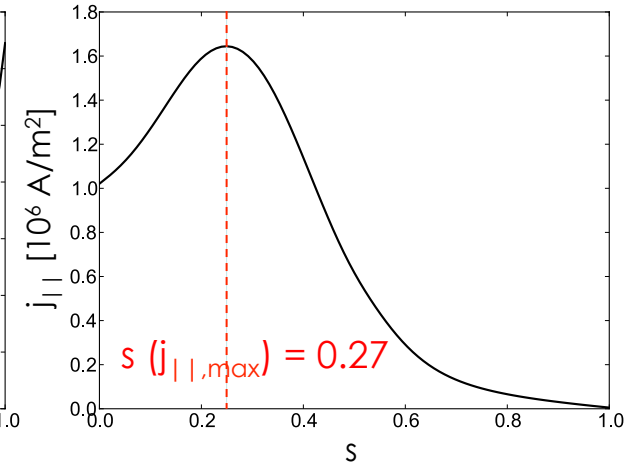
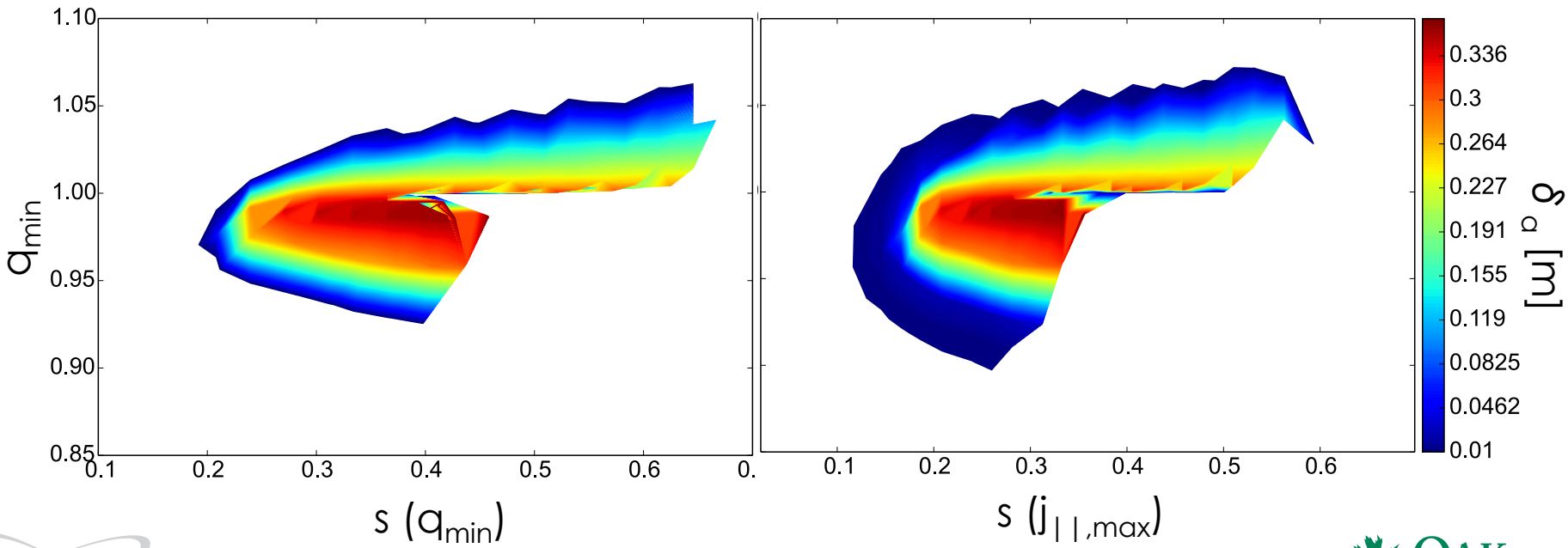
Operating space of q_{min} vs. q_{min} location or current density peak location

- **Helical state requires:**
  - reversed shear q
  - q_{min} just below 1 or off-axis current density peak

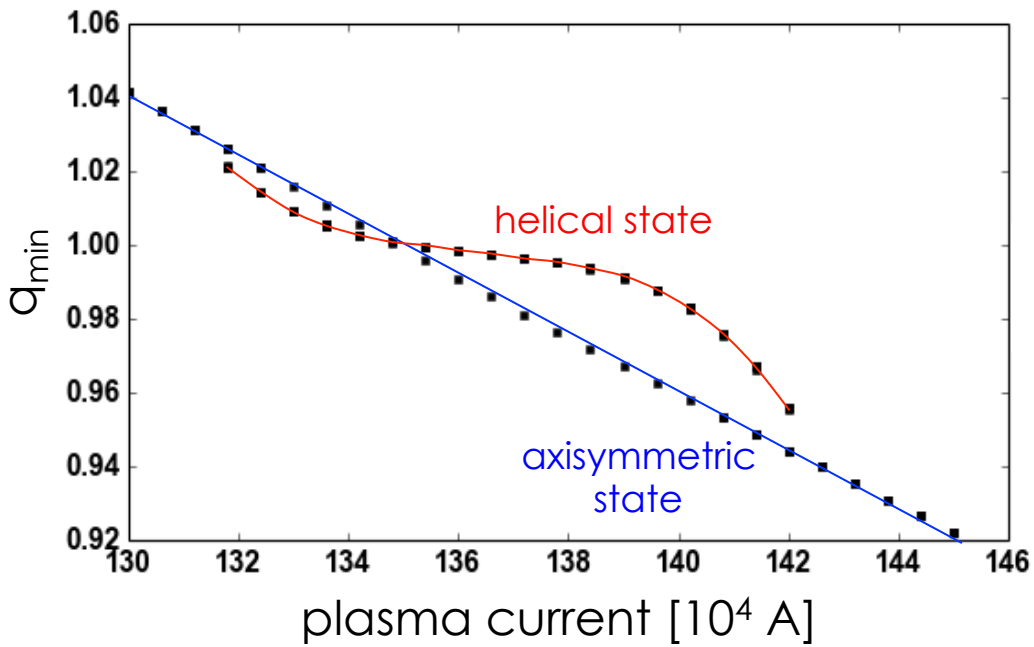


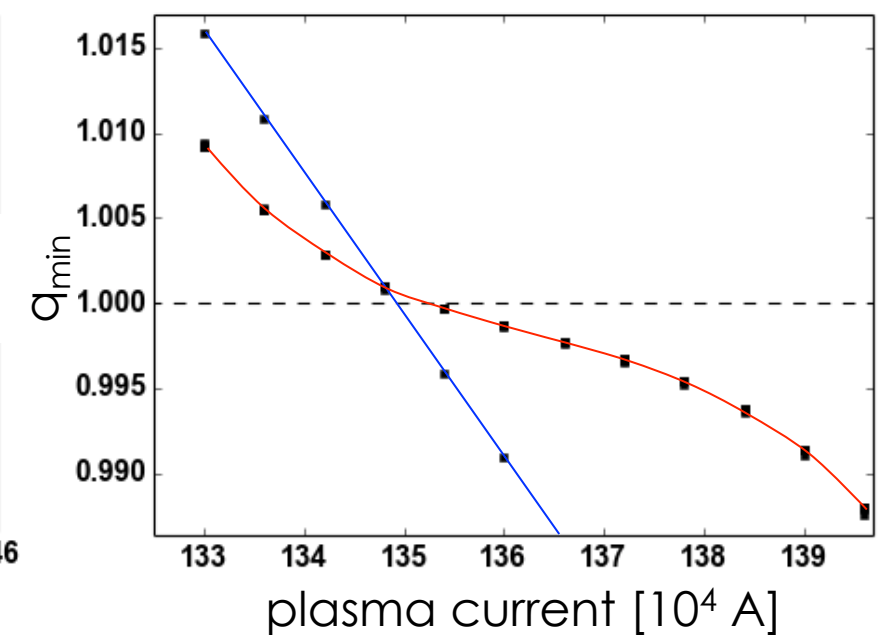




q_{min} has nonlinear relationship with total plasma current, when helical core exists

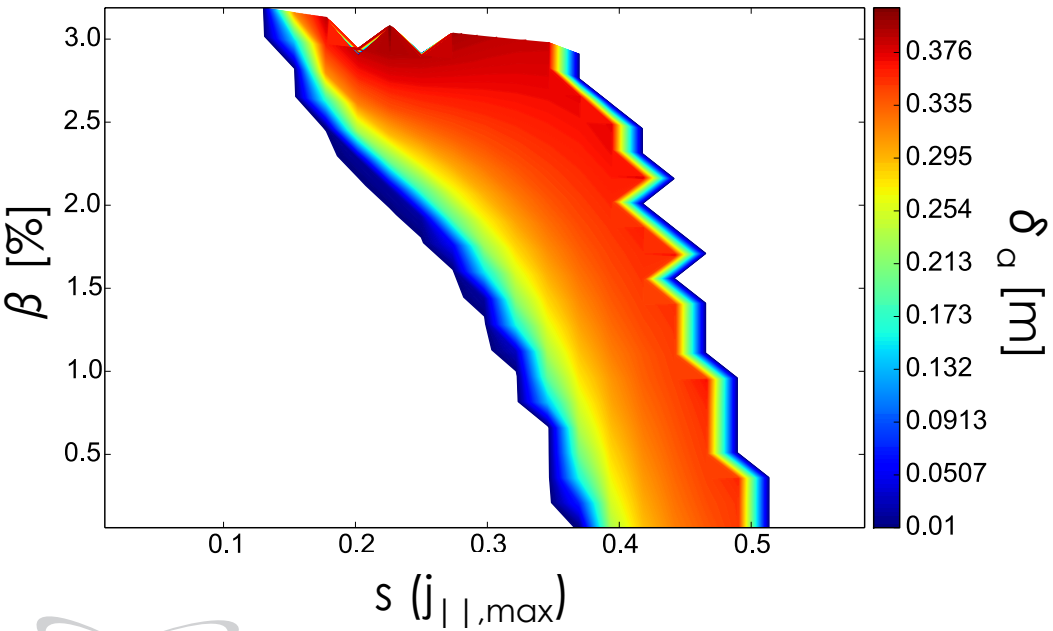
- **q_{min} is linear with total current for axisymmetric state**
  - use axisymmetric state to scan, when changing current profile, for faster result
- **q_{min} "wants to" hang out near 1**

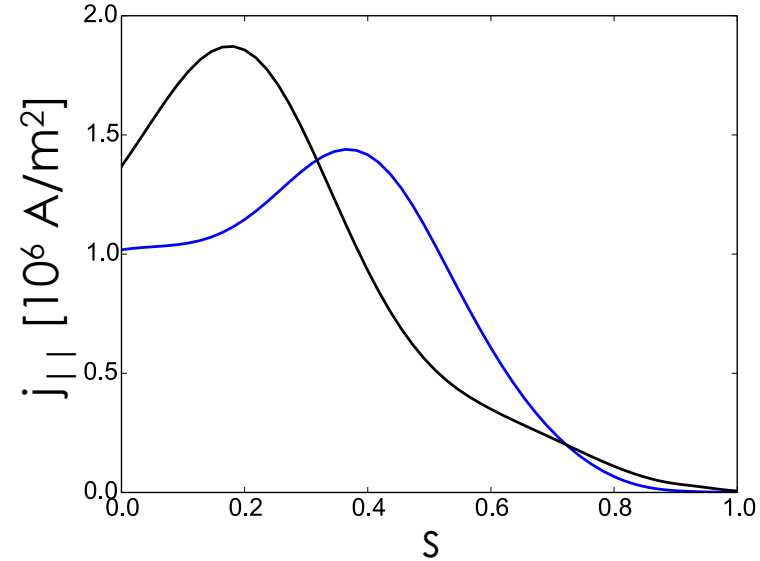


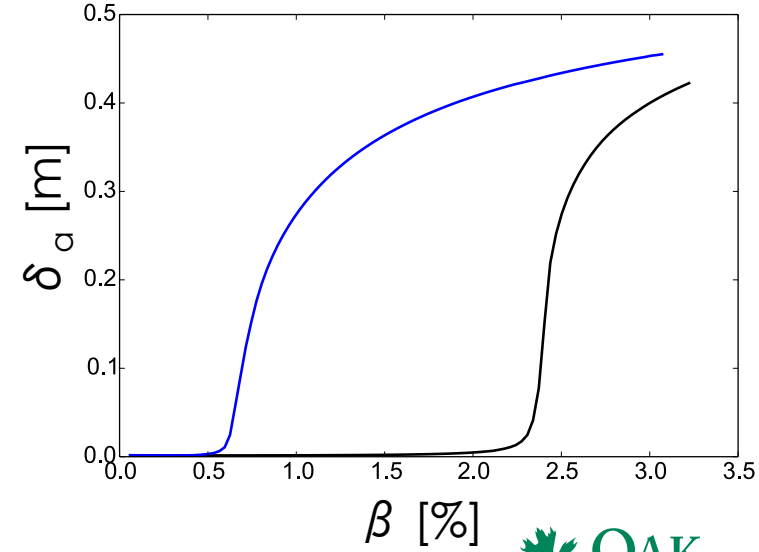


Operating space of β vs. current peak location at fixed q_{min}

- **Different current density peak locations have different β thresholds for onset of helical state**
  - total plasma current (curtor) scaled to keep q_{min} fixed







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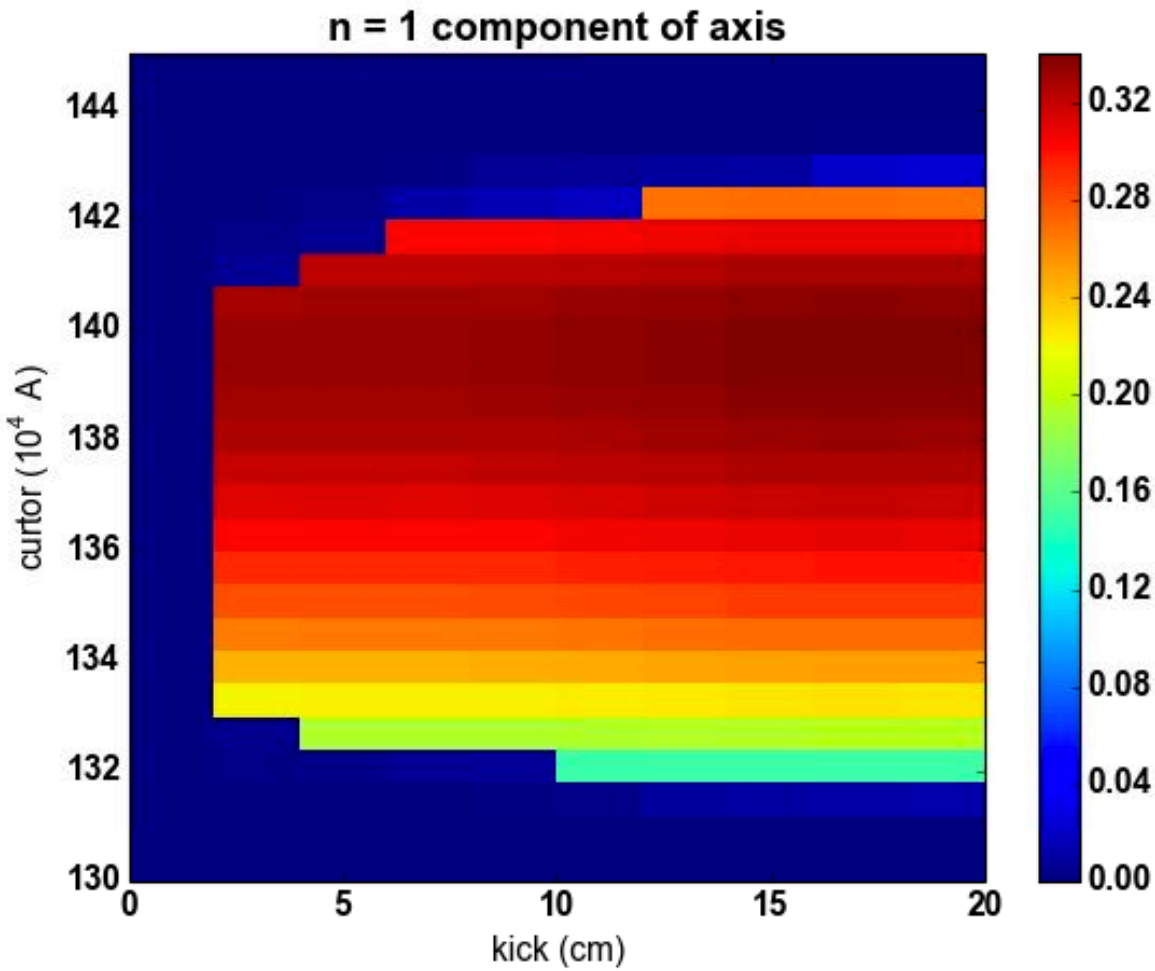
Helical state solution is relatively insensitive to initial core perturbation, even with axisymmetric LCFS

- **No kick results in axisymmetric solution**
  - axisym. LCFS
- **Helical solution only changes slightly with kick size**
  - same phase
  - if q_{min} not near 1, larger kick is needed
- **3D perturbation to LCFS only is sufficient to allow helical core to form**
  - HC phase locks to edge perturbation



Outline

- **Operating space for helical core state**
  - using ad-hoc profiles, but realistic plasma shape
- **Modeling of realistic hybrid plasma discharge**
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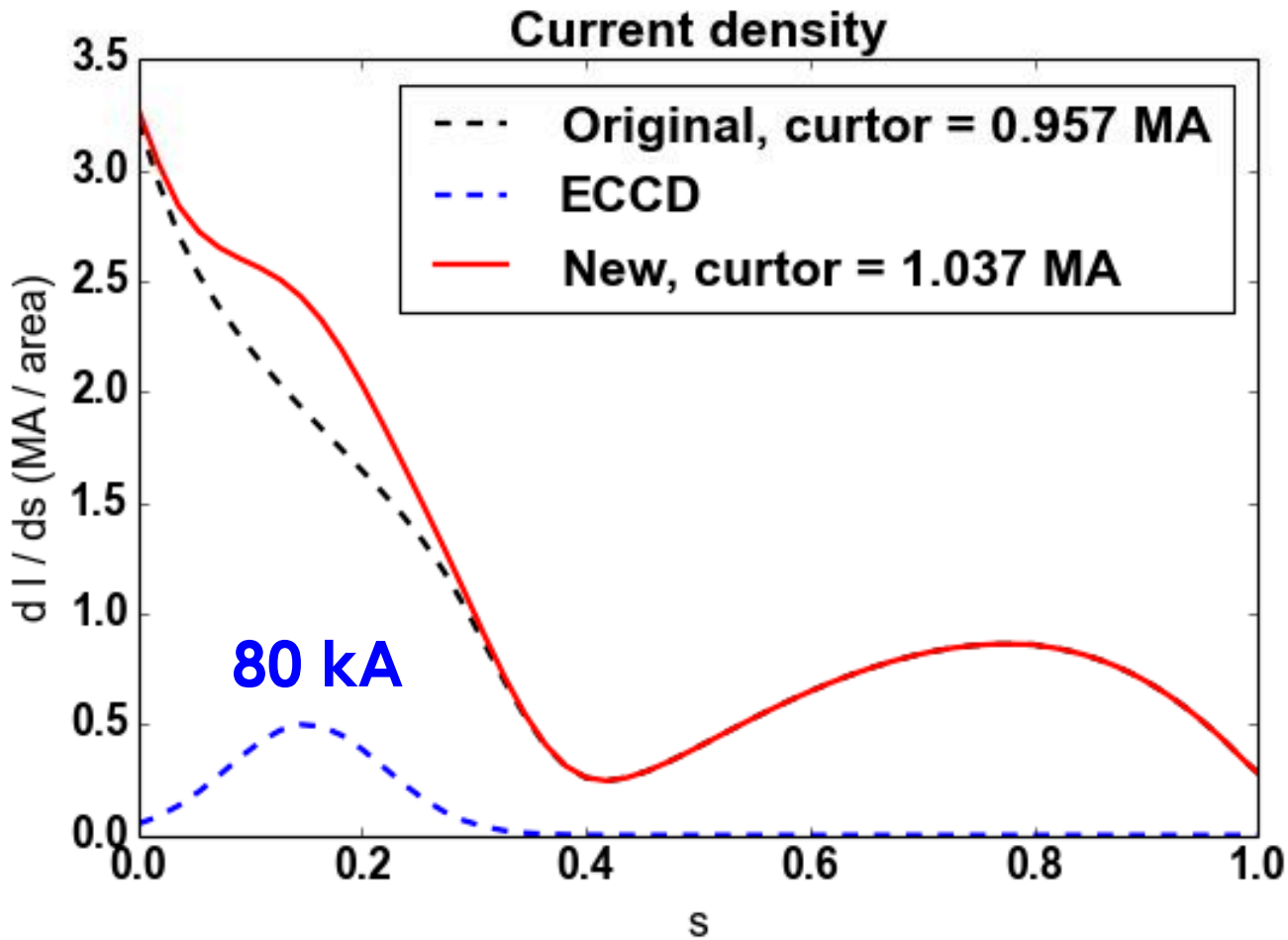
  - diagnostic response
- **First reconstruction results**
  - discharge 164661 from December flux pumping experiment
- **Summary**

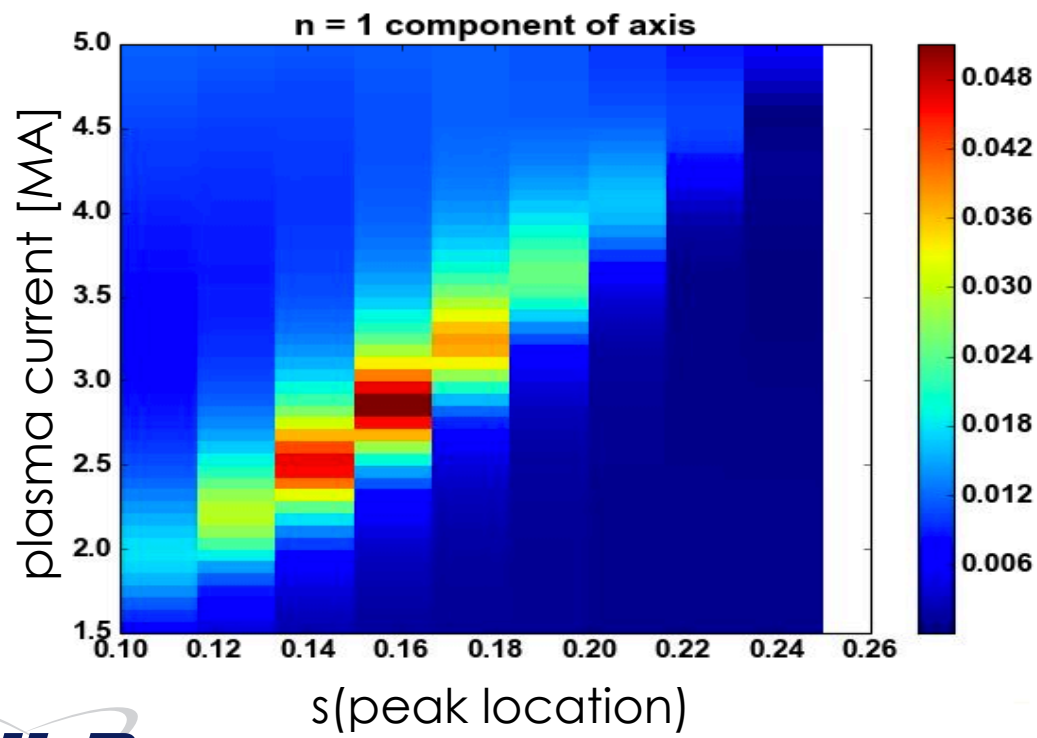
Adding ECCD to 155543 @ 2505 ms current density profile (EFIT) to get a helical core in VMEC

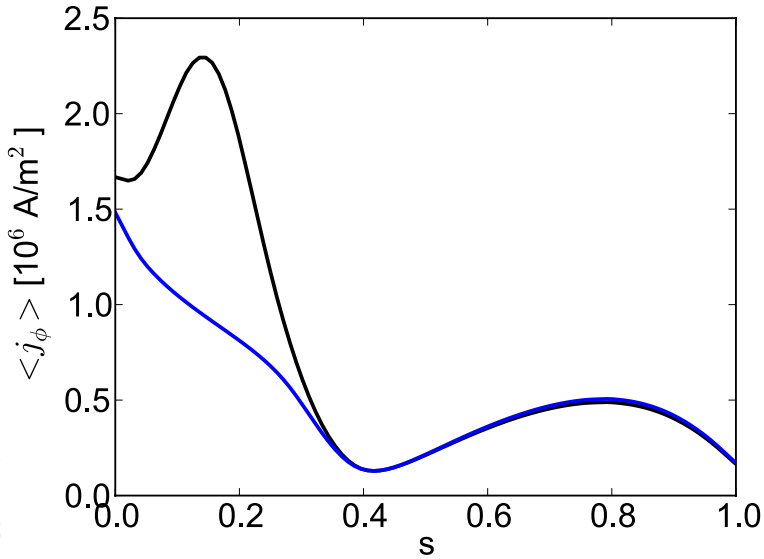
- **Change the total plasma current consistently**
  - keep pressure and plasma shape fixed
  - add Gaussian with fixed width

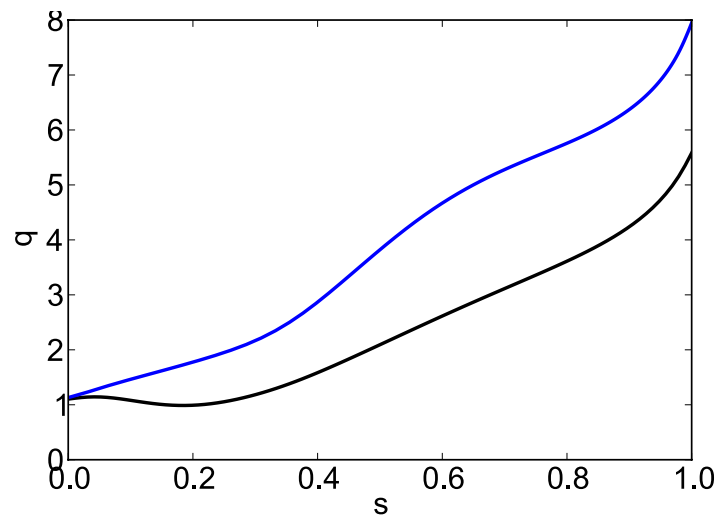


Scan the location and amplitude of additional current density

- **Only a narrow window of currents evolve to helical cores**
  - all have q_{min}~1 off axis
  - example: 3 cm helical displacement with 400 kA of off-axis current drive

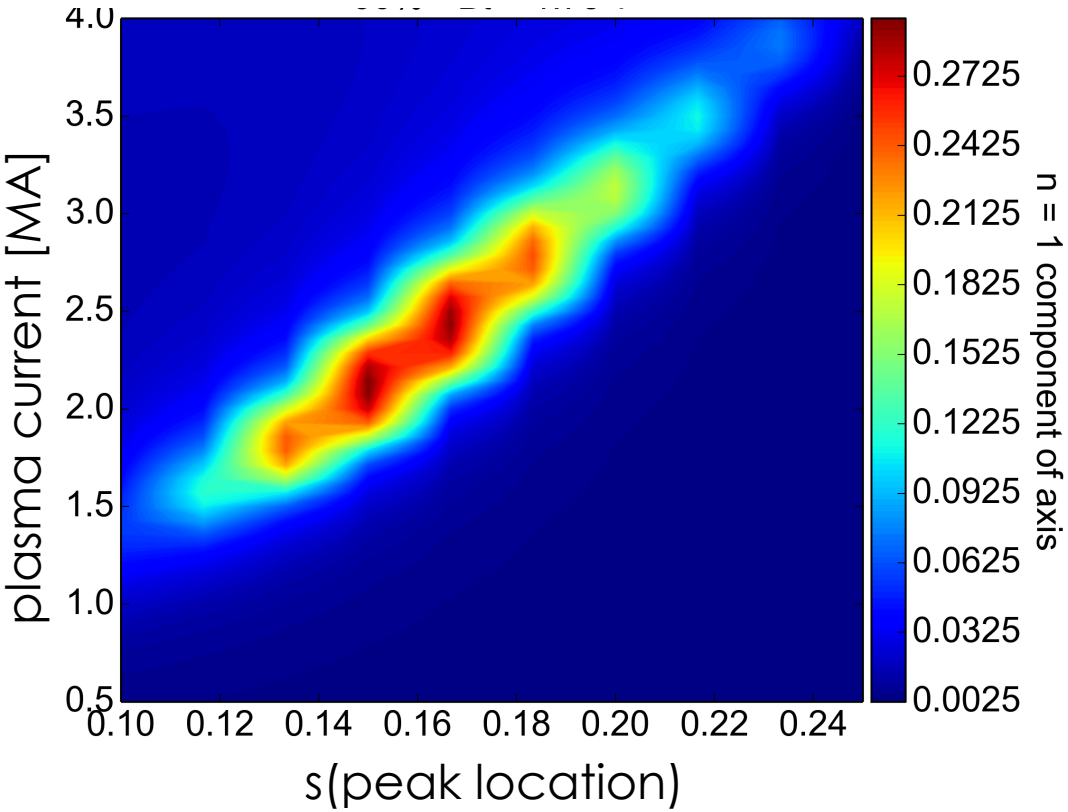


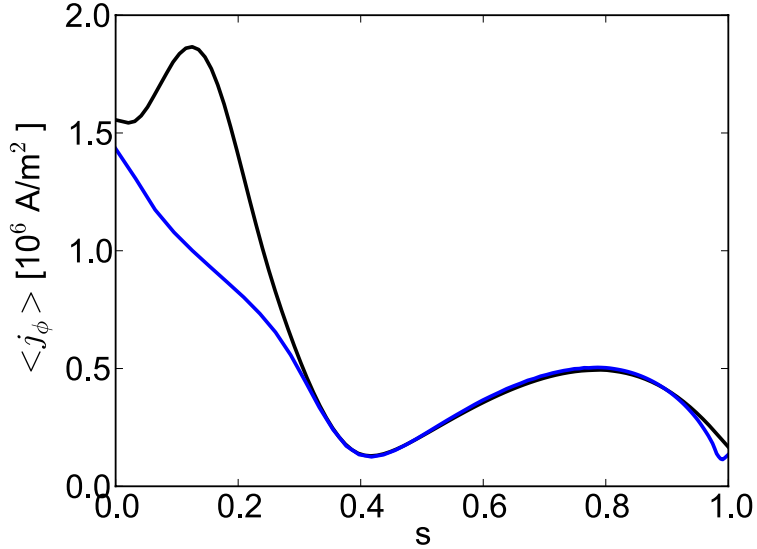


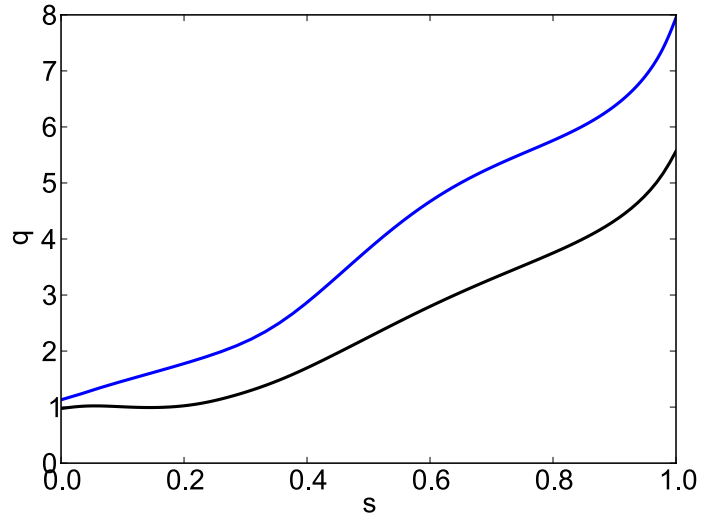


Reducing B_t allows helical core to set in at lower ECCD current

- **B_t reduced to 1.6 with pressure fixed**
  - β = 2.98%
- **250 kA additional current**

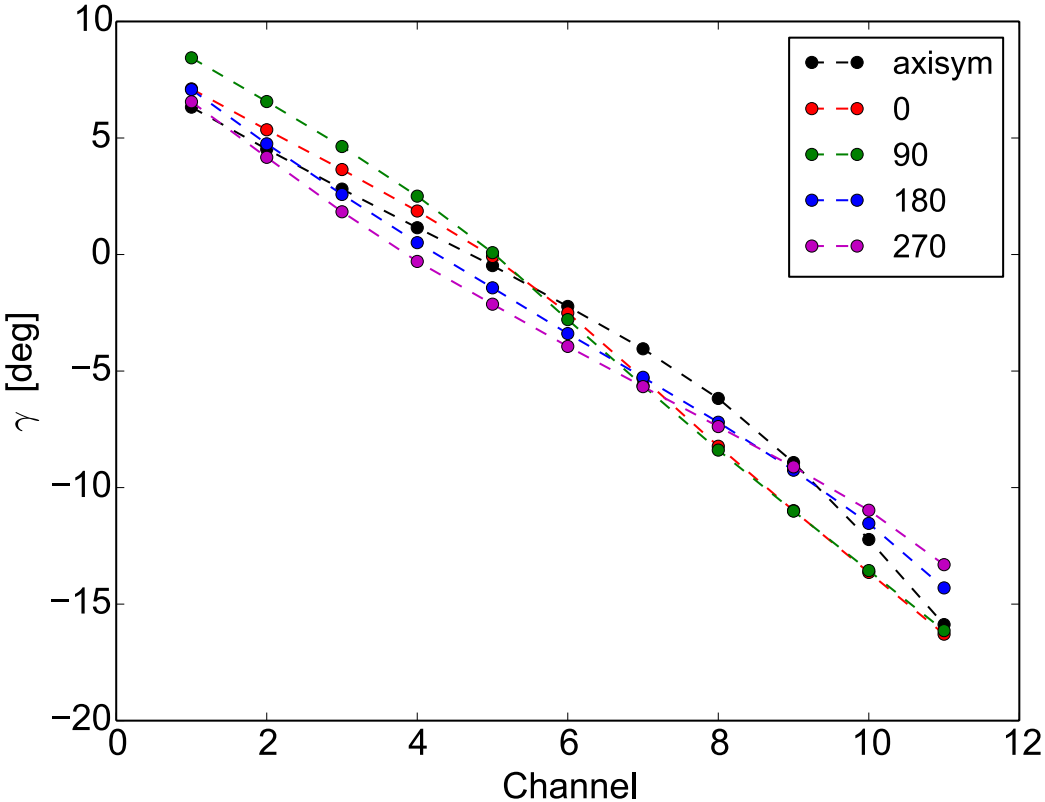


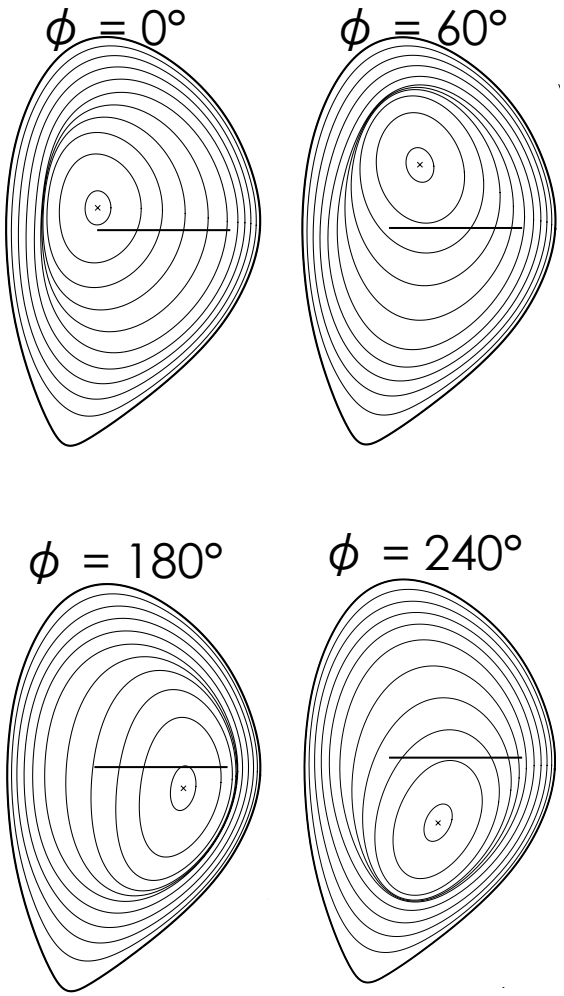




MSE diagnostic shows some variation, when helical core is rotating by

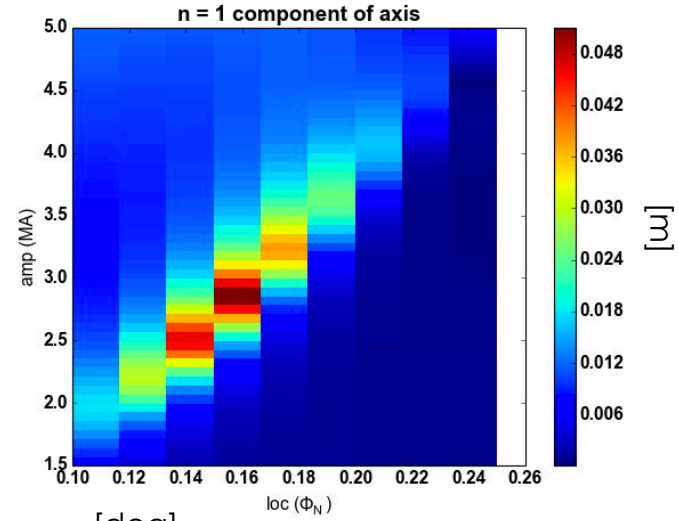
- **Variations are within the resolution of the MSE diagnostic**
  - 2° - 3° variation vs. 0.1° resolution

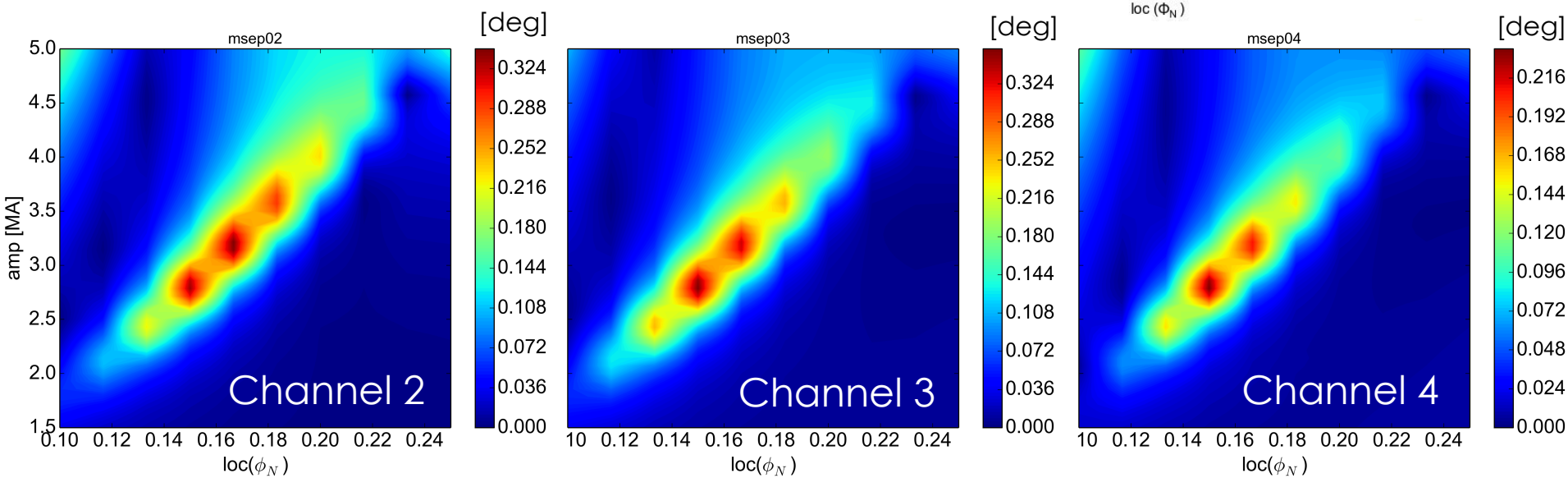




Several synthetic MSE channels see measurable n = 1 modulation for the modeled helical cores

- **MSE uncertainty = 0.1 degrees**
- **helical displacements > 1 cm can be detectable**





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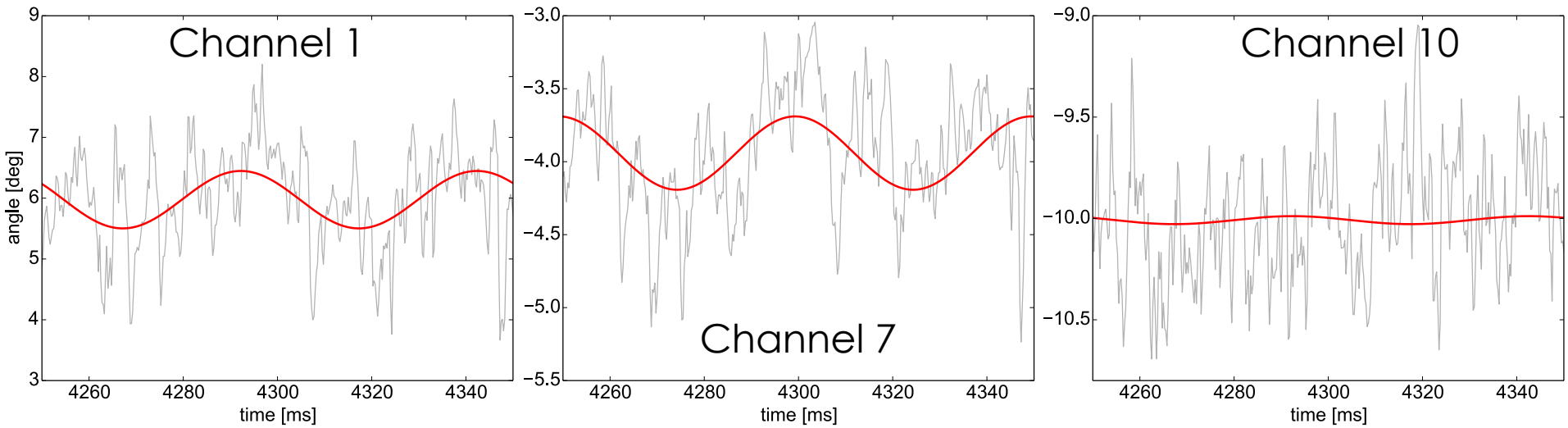
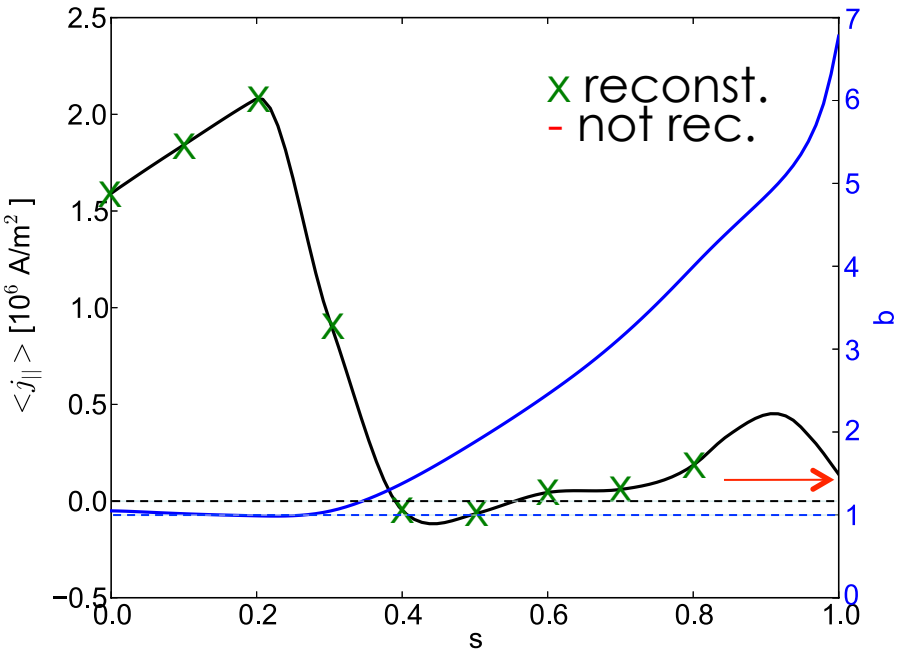
Several MSE channels observe an oscillation with the applied RMP rotation frequency, but not all

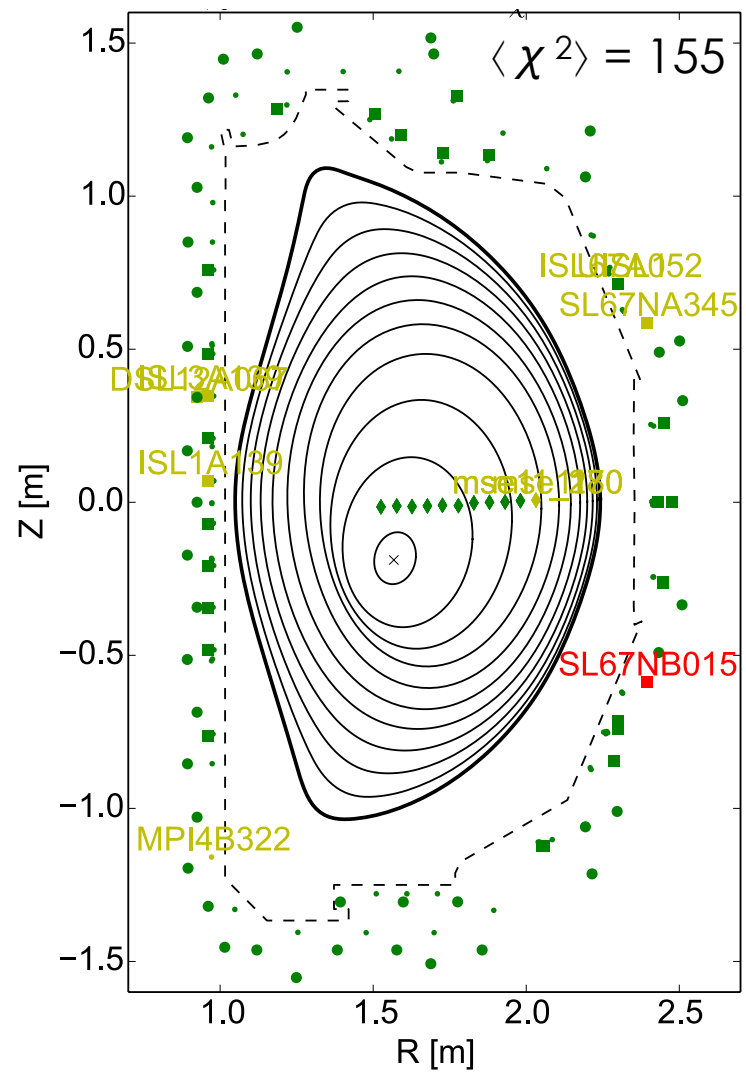
- **RMP fields are rotating toroidally at 20 Hz**
  - a helical core would lock onto that and rotate as well
  - if the entire plasma wobbles, all MSE channes would oscillate
- **Clear 20 Hz signal in some of the inner channes, but not in outer**
  - largest mode in Channels 1, 4, 7, 8, 9
  - not contributing to Channels 2, 3, >10



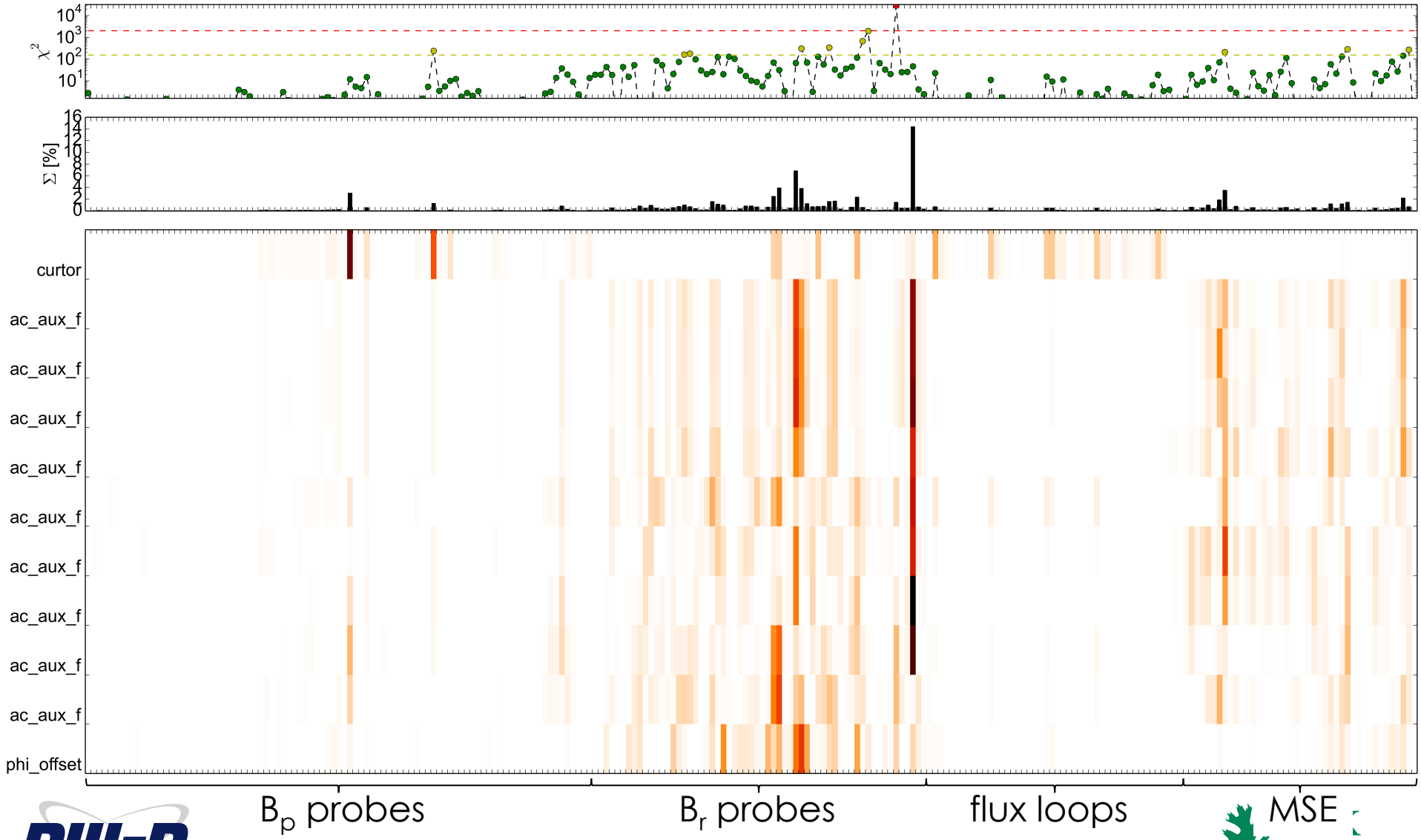
First reconstruction of 164661 @ 4300 ms shows a strong helical core, but still large χ^2

- **11 reconstruction parameter**
  - curtor, j (s <= 0.8), phi_offset
- **diagnostic set gives χ^2 = 3.7 x 10^4**
  - all single magnetic probes
  - MSE channels 1-11, χ^2_{MSE} = 1678
  - rotated MSE channels at 90,180 & 270



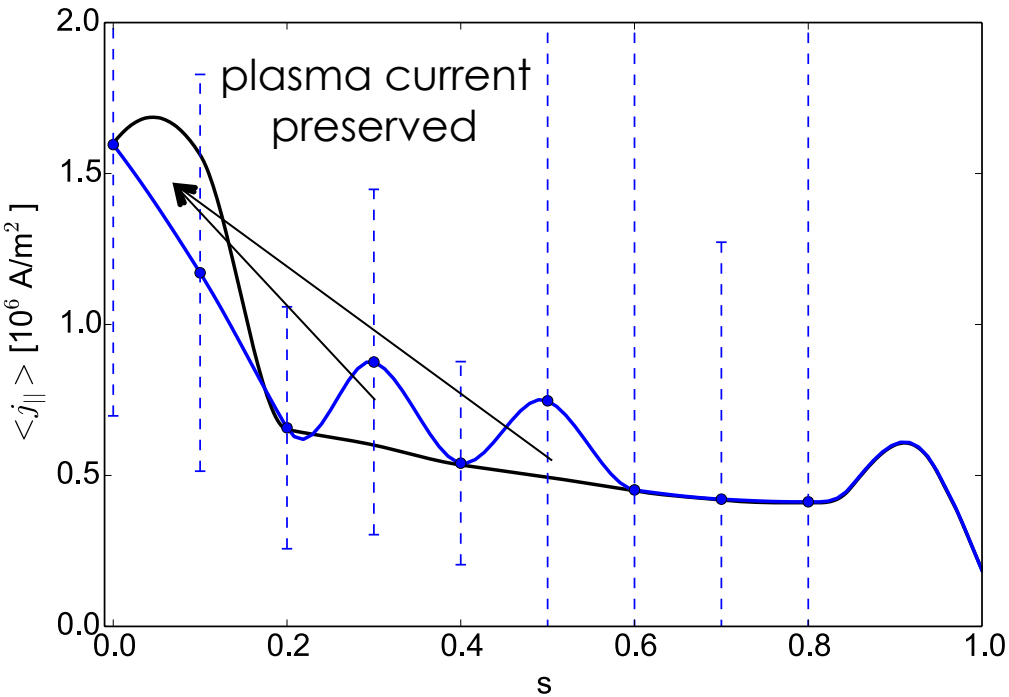


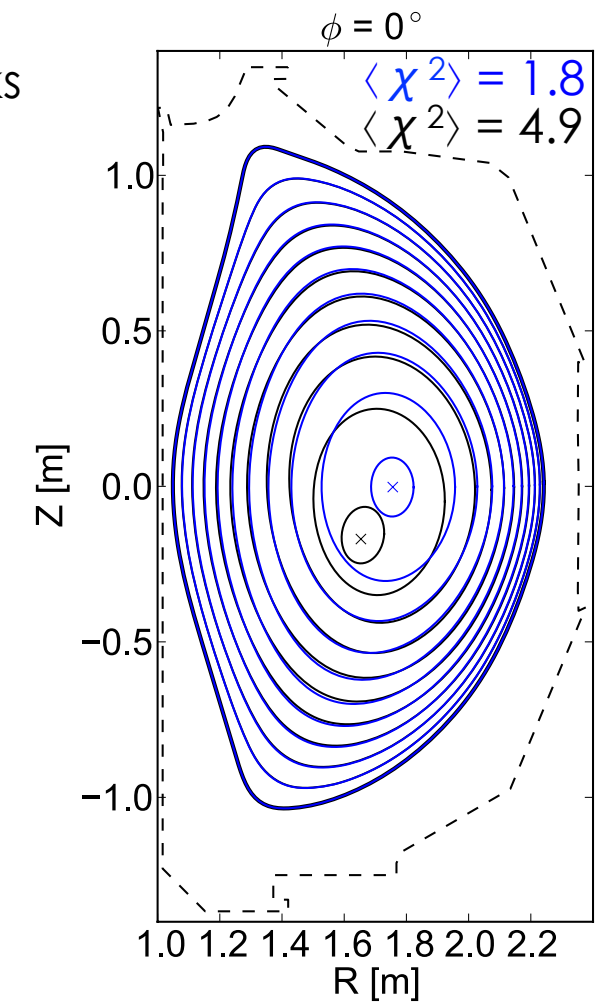
Effectiveness matrix shows: several B_r probes are badly reconstructed + one large outlier



Use magnetics subset that goes into EFIT only & MSE channels 1-11 + 41-43

- **Reconstruction**
  - axisymmetric
  - current peaks at 0.3 & 0.5 unrealistic
  - large uncertainty
  - $\chi^2_{Mag} = 201$
  - $\chi^2_{MSE} = 16$
- **Adjustment**
  - move current peaks to s = 0.1
  - within errorbars
  - helical core
  - $\chi^2_{Mag} = 168$
  - $\chi^2_{MSE} = 134$





Summary, Conclusions & Outlook

- **Reversed-shear q-profile is required**
  - the further off-axis q_{min} is, the better
- **q_{min} needs to be within a narrow range around q = 1**
  - best is $q_{min} \approx 0.98$, might be Mercier unstable though
- **The higher β, the better**
  - the closer q_{min} is to the axis, the higher β needs to be
- **MSE diagnostic sensitive to helical core**
  - rotate helical core by the diagnostic, by rotating the perturbation
    - helical core locks to applied perturbation
- **Reconstruction of recent hybrid discharge shows possible helical core**
  - axisymmetric and helical states are very close together
  - further analysis is needed
- **Next DIII-D runday in March gives opportunity to optimize helical core discharge**

We peaked the interest of the DIII-D group

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