



# 3-D Plasma Equilibrium Reconstruction at the HSX Stellarator



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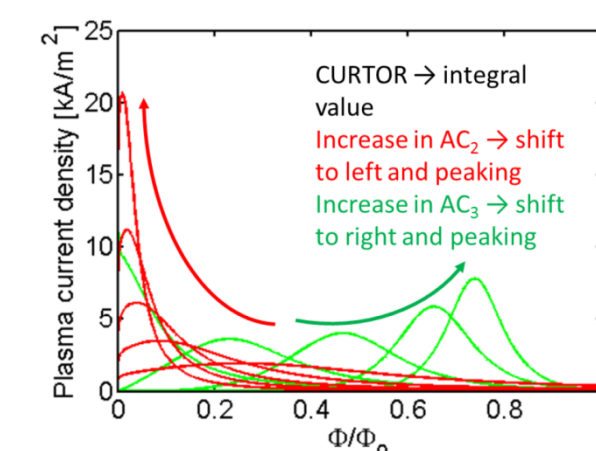
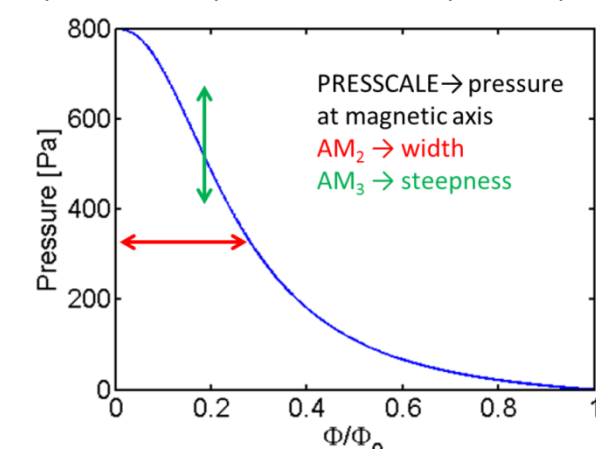
## Motivation

- Investigate MHD equilibrium properties via plasma reconstruction using the V3FIT code [1], experimental data and modeled signal responses [2]
- Three dimensional plasma reconstruction is necessary in stellarators to determine finite beta effects and in tokamaks to measure effects of non-axisymmetric coils
- HSX offers test bed for plasma reconstruction and benchmarking algorithms
- Optimized magnetic diagnostic upgrade necessary for improved reconstruction by solution reduction and increased signal-to-noise ratio
- Necessary to find most sensitive diagnostics for the plasma equilibrium currents to be measured
- Understand the limitations of plasma reconstruction performance

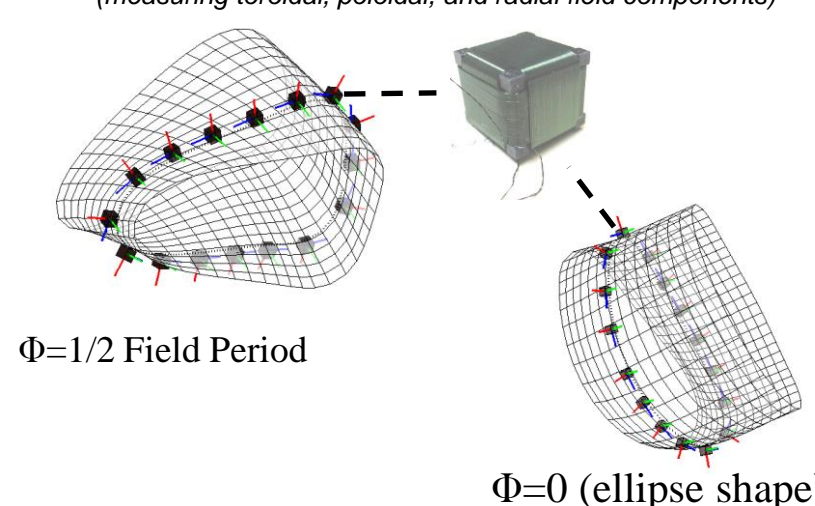
## Plasma Reconstruction

- Reconstruction is used to calculate seven free parameters, which describe plasma size, plasma current and plasma pressure profile
- $$p(s) = \text{PRESSCALE} \cdot \left[ \frac{1}{1-K} \left( \left( 1 + \left( \frac{s}{AM(2)} \right)^{AM(3)} \right)^{-1} \right) - K \right]$$
- $$K = \left( 1 + \left( \frac{s}{AM(2)} \right)^{AM(3)} \right)^{-1}$$
- $$I(s) = \text{CURTOR} \cdot \left( \frac{2}{\pi} \arctan \left( \frac{AC(2)s^{AC(3)}}{1-s} \right) \right)$$
- VMEC is used to compute the plasma equilibrium [3]
  - Plasma reconstruction is based on minimizing

Free parameters in plasma current and pressure profile



Set of two external previously installed magnetic diagnostic coils (measuring toroidal, poloidal, and radial field components)



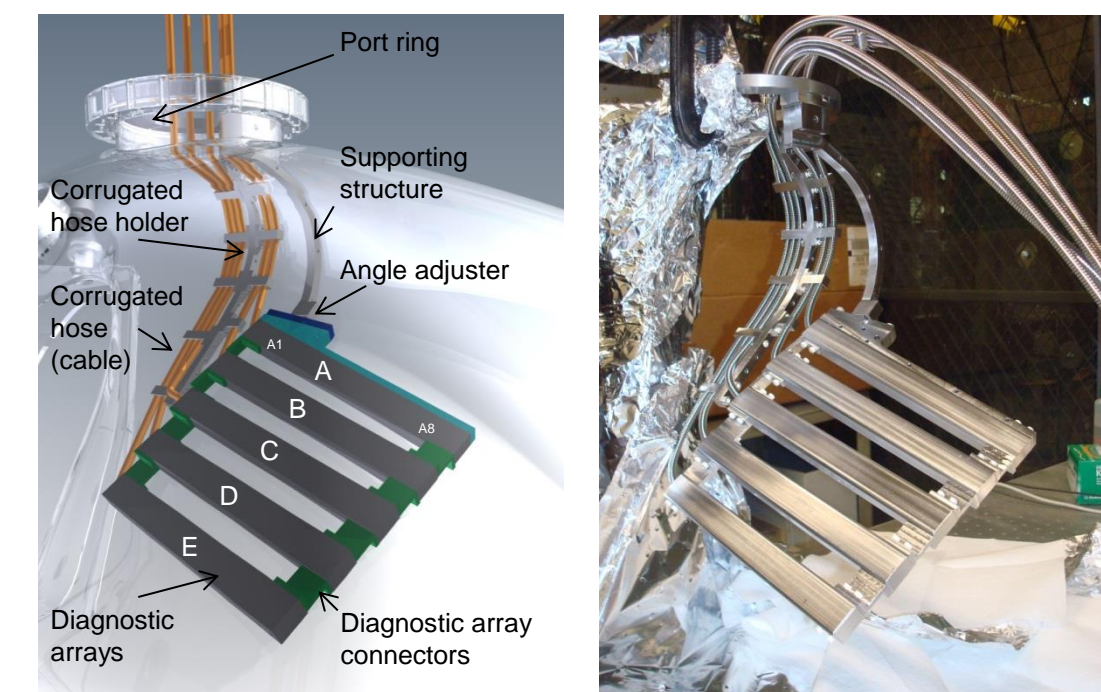
Φ=1/2 Field Period

Φ=0 (ellipse shape)

## Diagnostic Setup

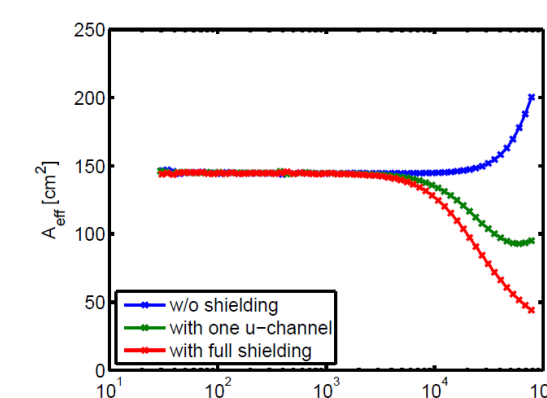
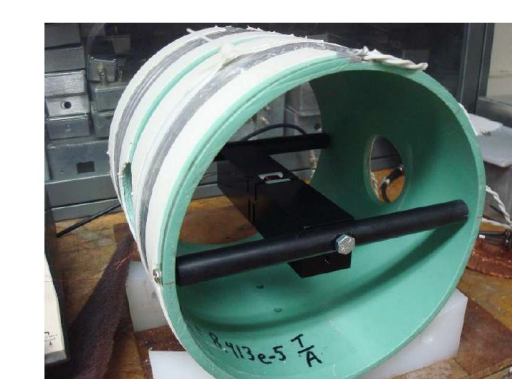
- Three different methods applied to find the location for a new set of magnetic diagnostics to improve plasma equilibrium reconstructions on HSX
- Single Value Decomposition Study [2]
    - Diagnostic set for maximizing detection of different magnetic field pattern
  - Signal Effectiveness Study (SEFFS)
    - Most effective diagnostic for minimizing the uncertainty in the reconstructed parameter
  - Single parameter dependency study (SPDS)
    - Diagnostics sensitive to change in specific reconstruction parameter

### Diagnostic Construction



- Five arrays consisting of 8 poloidal and 8 radial magnetic coils, placed inside the vacuum vessel
- Same direction vector for all pol./rad. coils in one array
- Helical field measurement not included due to low signal-noise ratio
- Fixed distance between all coils allows the determination of the position using the measured magnetic field pattern
- Flat design to lie 1cm outside the LCFS
- Ceramic used for coil body
- Stainless steel used as shielding for the coils
- Each array can be separately calibrated, replaced, and upgraded with more coils

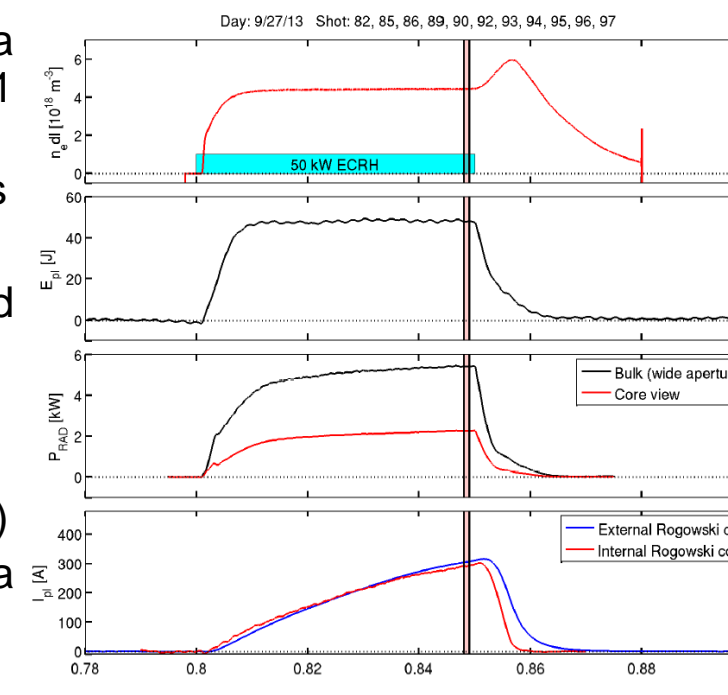
### Diagnostic calibration



- Pair of Helmholtz coils used to calibrate coils for each direction
- Metal shielding only effects frequencies above 20 kHz
- Suppression of coil self resonance

## Reconstruction Results

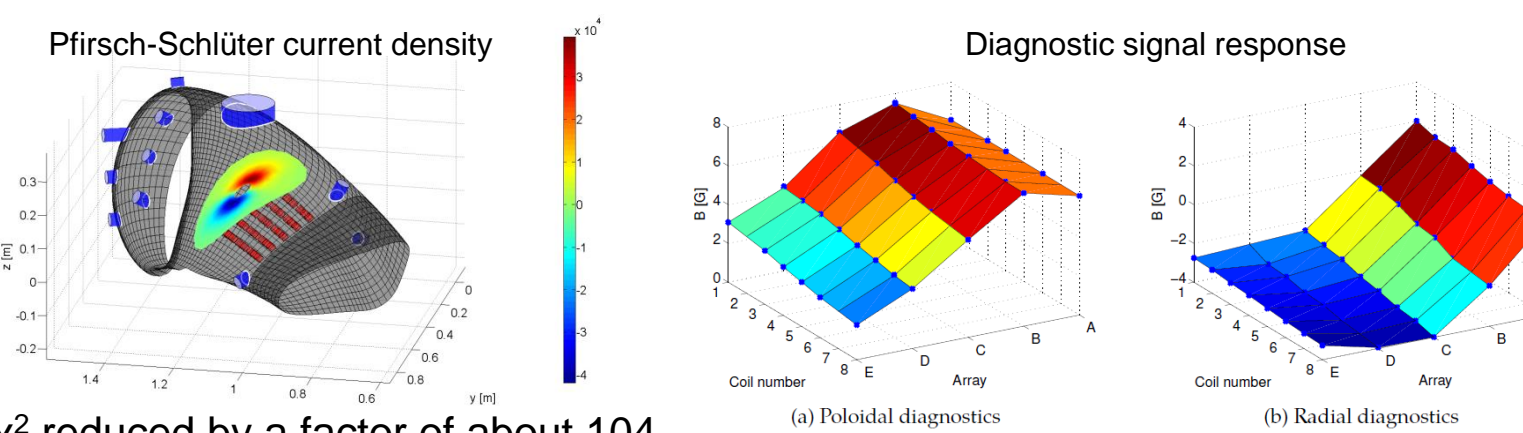
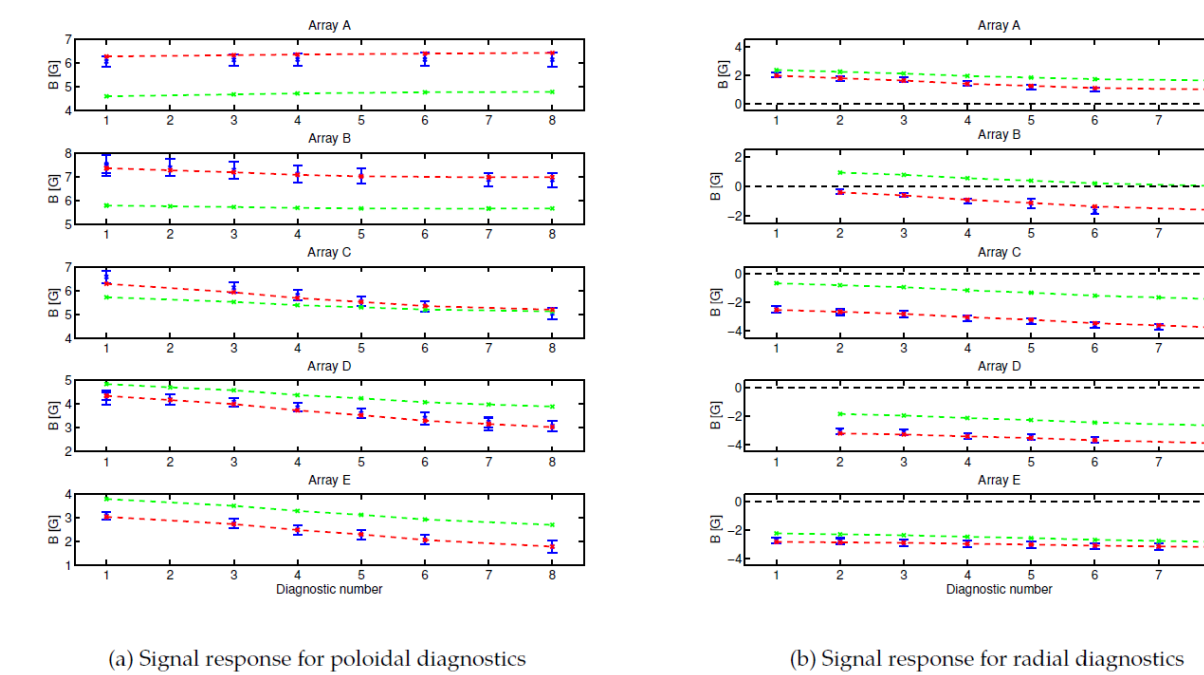
- Properties of investigated plasma discharges on right (average over 11 shots)
- Diagnostics used in reconstruction process
  - 74 Bdot coils (new array)
- Diagnostics used for initial guess and reconstruction result comparison:
  - Rogowski coil (total plasma current)
  - Diamagnetic loop (stored energy)
  - Thomson Scattering (pressure profile)
- Bootstrap current dominates plasma current evolution
- Time of reconstruction 0.848-0.849s



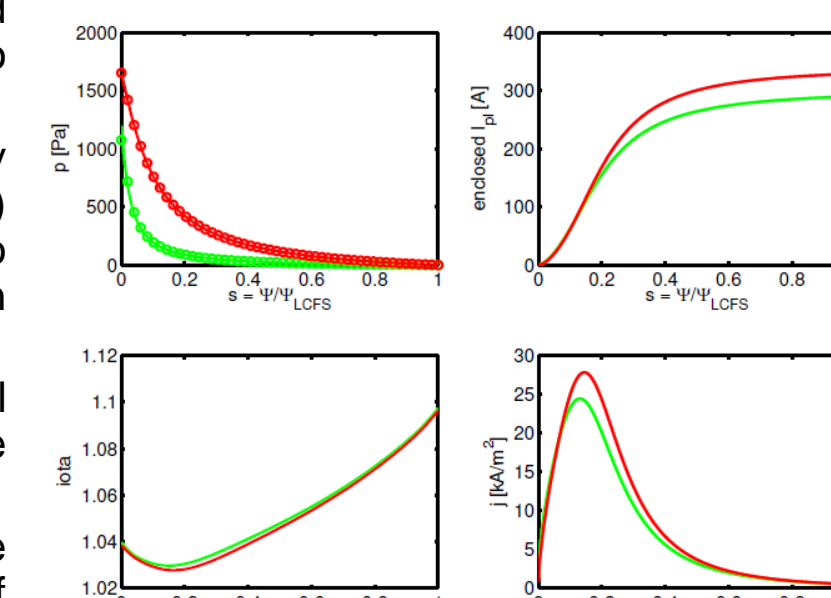
### Measurement

Modeled signals from initial guess

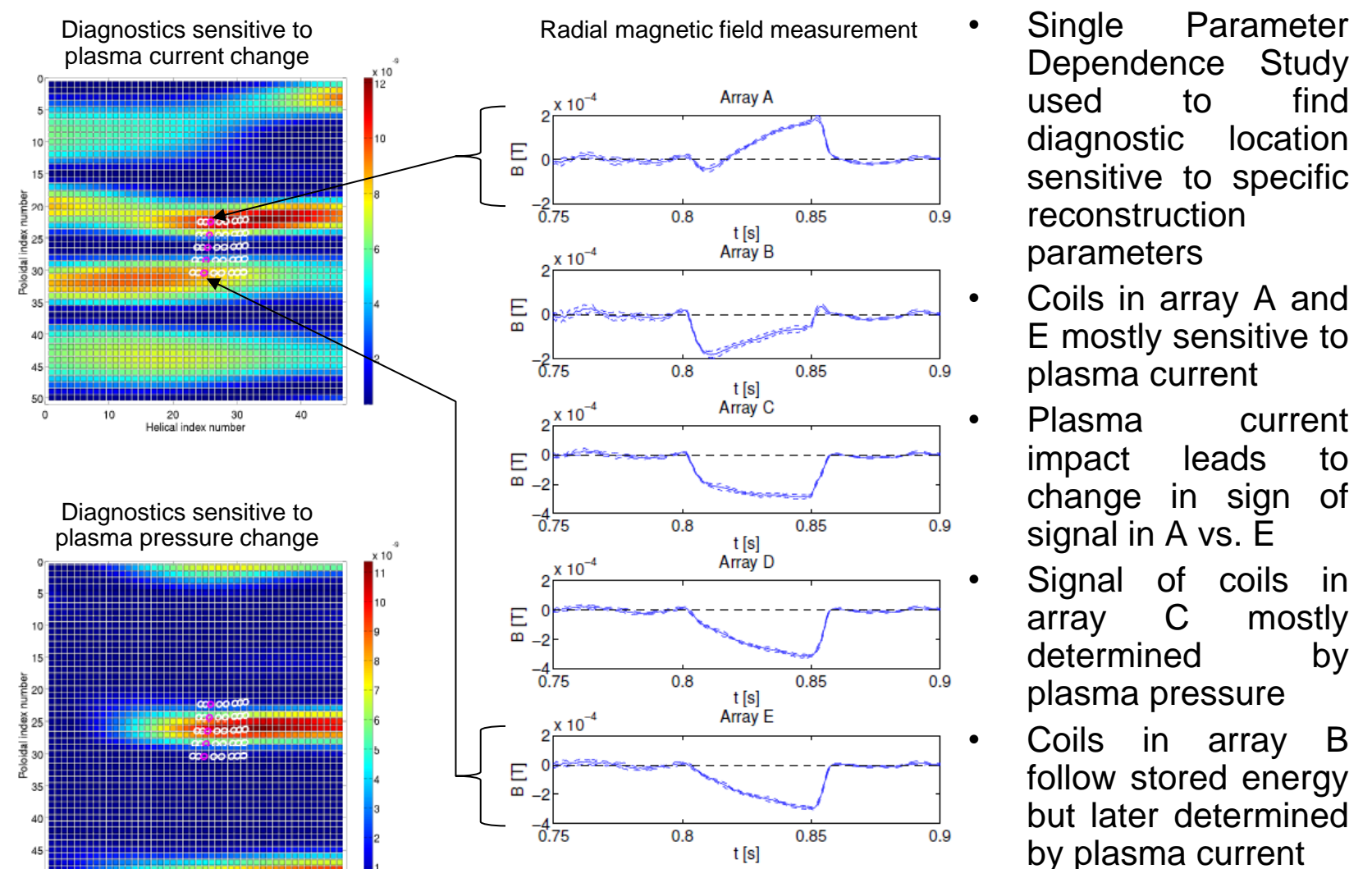
Modeled signals from reconstruction



- χ² reduced by a factor of about 104
- 13 % deviation in reconstructed plasma current compared to Rogowski coil measurement
- Reconstructed plasma energy (integral over plasma pressure) factor of 2.4 too high compared to diamagnetic loop and Thomson Scattering measurement
- Use of exclusively radial or poloidal diagnostics yield the same reconstruction results
- Different initial conditions, fits for the pressure profile, reconstruction of earlier time steps do not show a reduced discrepancy → more investigation necessary



## Diagnostic Sensitivity



- Single Parameter Dependence Study used to find diagnostic location sensitive to specific reconstruction parameters
- Coils in array A and E mostly sensitive to plasma current
- Plasma current impact leads to change in sign of signal in A vs. E
- Signal of coils in array C mostly determined by plasma pressure
- Coils in array B follow stored energy but later determined by plasma current

## Summary

- Plasma equilibrium reconstruction at HSX is based on the determination of seven free parameters describing plasma current profile, pressure profile and plasma size
- Internal diagnostic set of 80 coils built based on 3 different positioning concepts
- Helmholtz coils used to calibrate each diagnostic coil for each direction
- Possibility to design diagnostic coil set sensitive to specific MHD properties experimentally proven
- QHS plasma reconstructed solely with new array to benchmark existing diagnostics
- Relatively small discrepancy in reconstructed total plasma current
- Relatively large discrepancy in plasma pressure profile is still under investigation

## References

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- S.P. Hirshman et al. *Phys. Plas.* 11 (2004)
- S.P. Hirshman and J.C. Whitson. *Phys. Fluids*, 26 (1983)
- J.C. Schmitt Dissertation UW-Madison (2011)
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