Transition to helical RFP state and associated change in magnetic stochasticity in a low-aspect-ratio RFP

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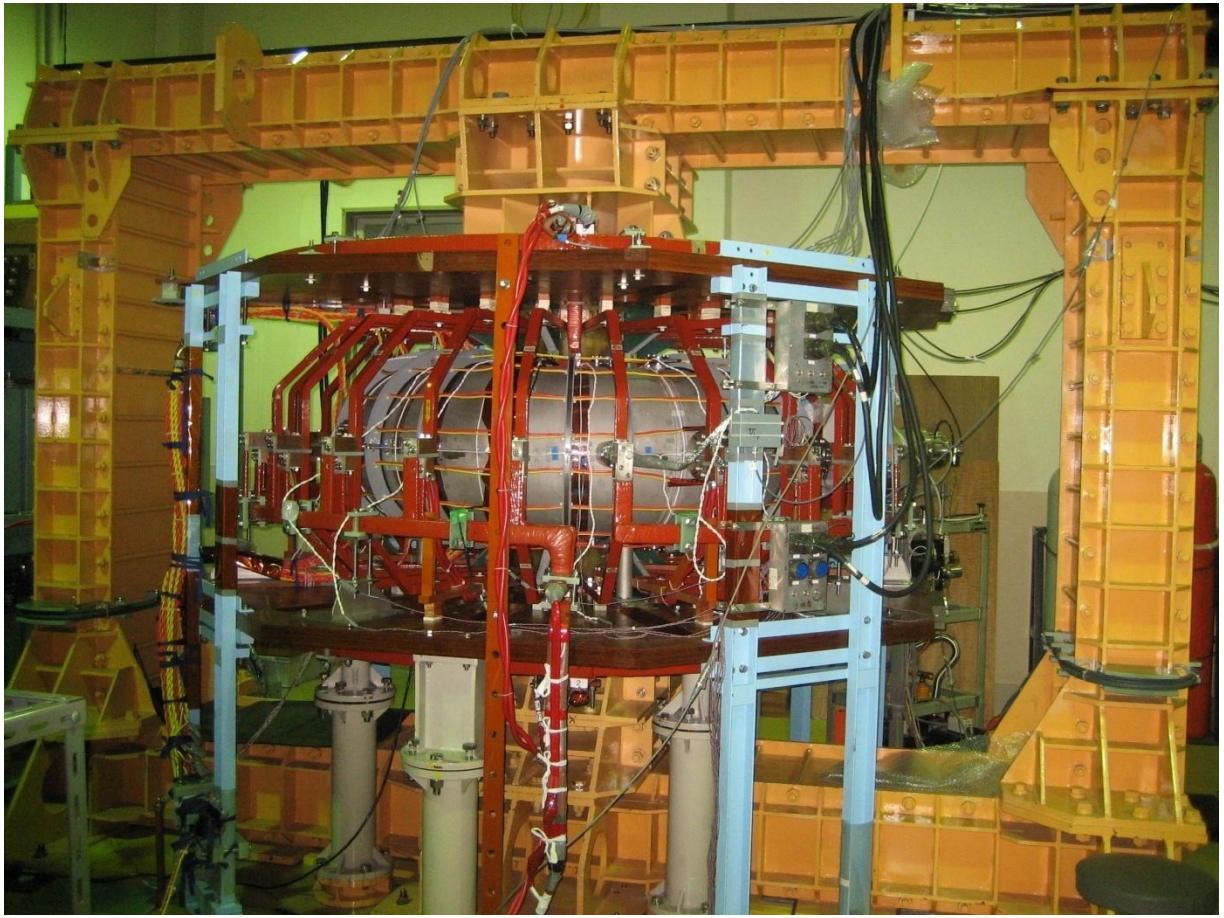
REversed field pinch of Low-Aspect-ratio eXperiment



- $R/a = A = 2$ (51 cm/25 cm)
- Optimization in progress

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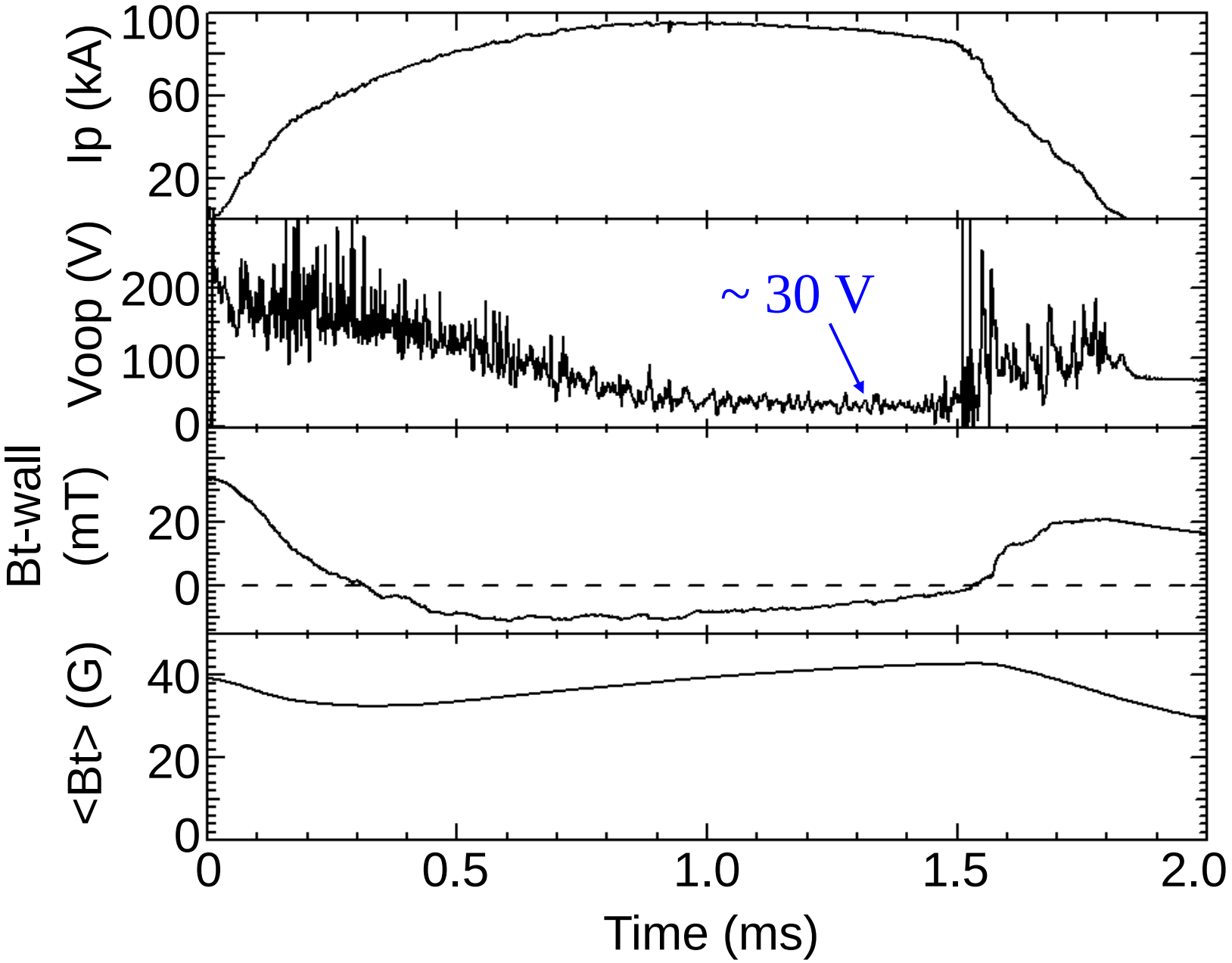
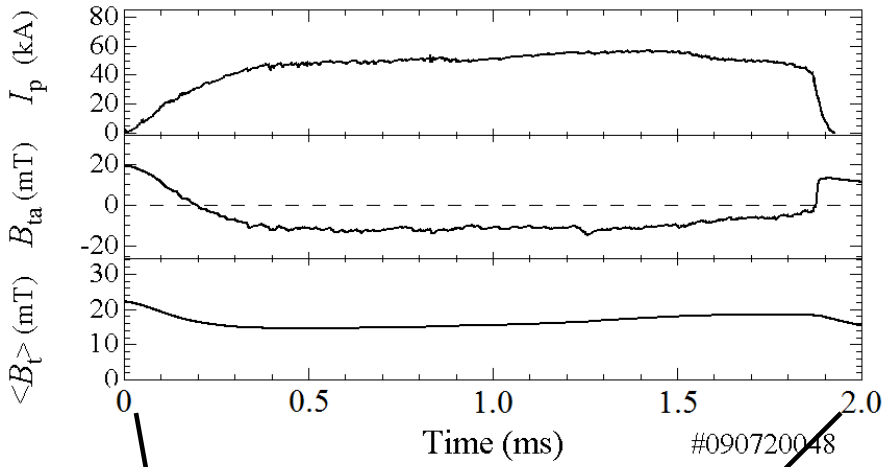
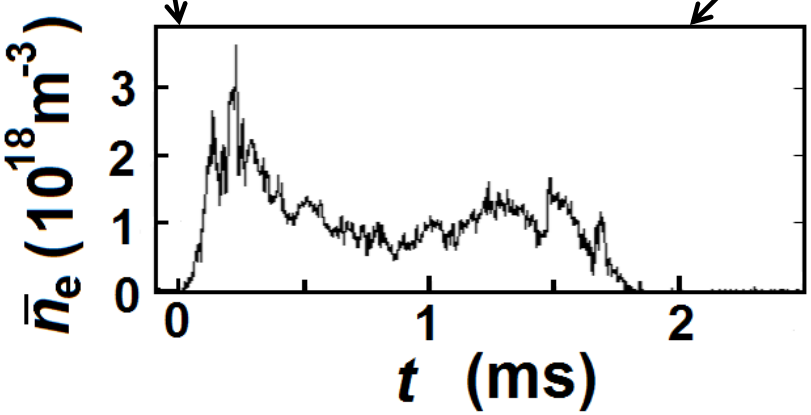
Normal RFP discharges established



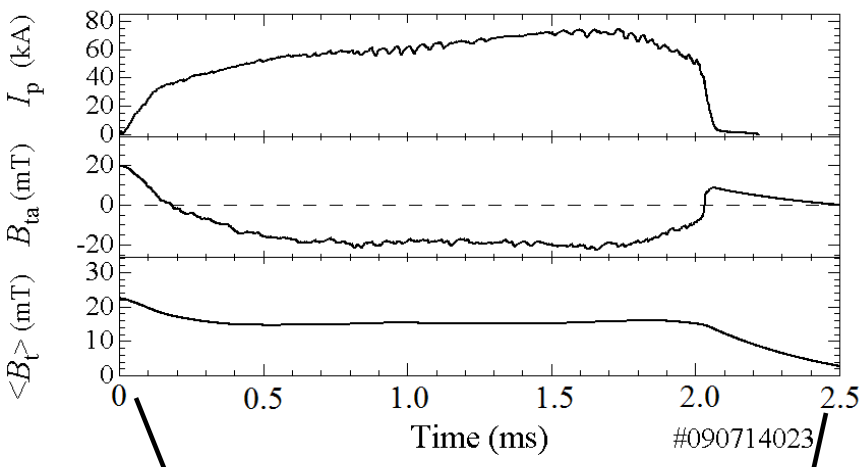
Density measurement with μ-wave interferometer

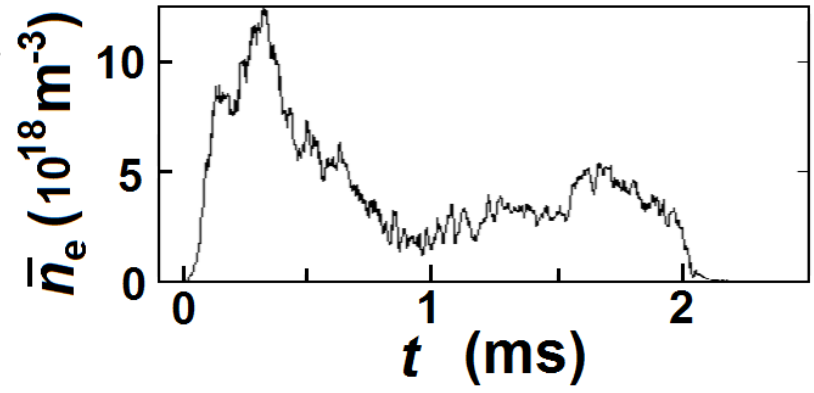
Density regime at flat-topped I_p phase : $1 - 10 \times 10^{18} m^{-3}$





low-n_e discharge



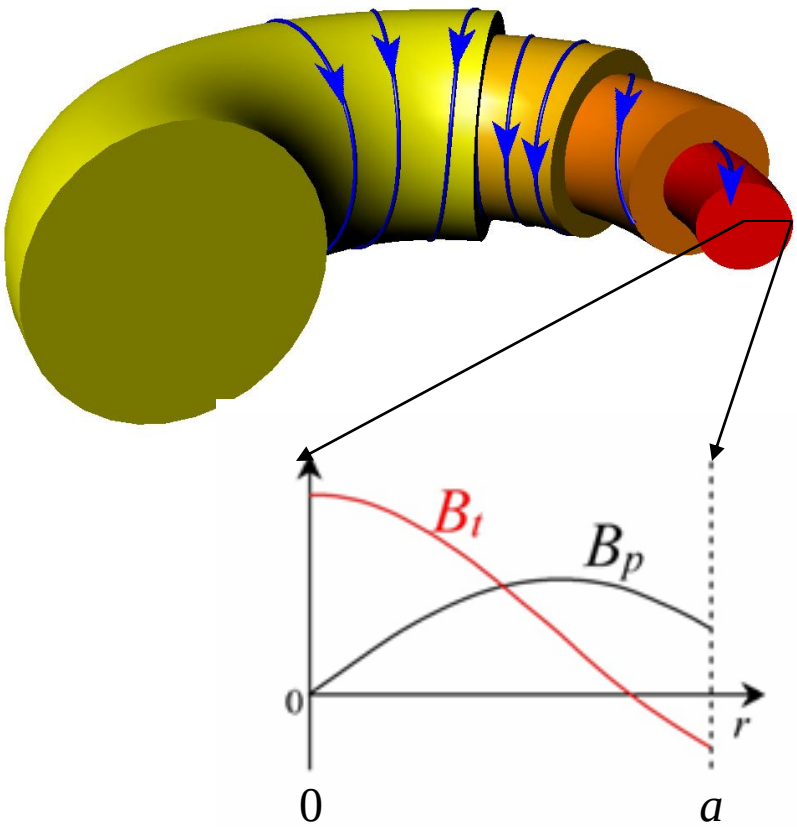


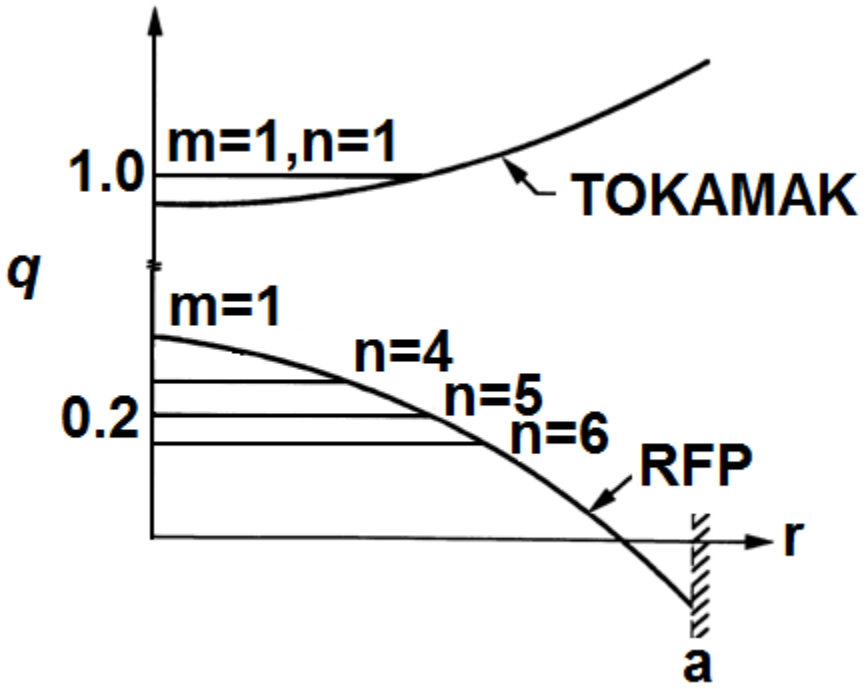
medium-n_e discharge

Outline

- Motivation to lowering *A* in the RFP
- Characterization of magnetic fluctuations in RELAX
- Helical structure in RELAX
- Magnetic structure and SXR emissivity in Helical Ohmic state
- Field line trace for RELAX plasmas
- Summary and future work

RFP configuration and its characteristics





$$B_{\text{toroidal}} \approx B_{\text{poloidal}}$$

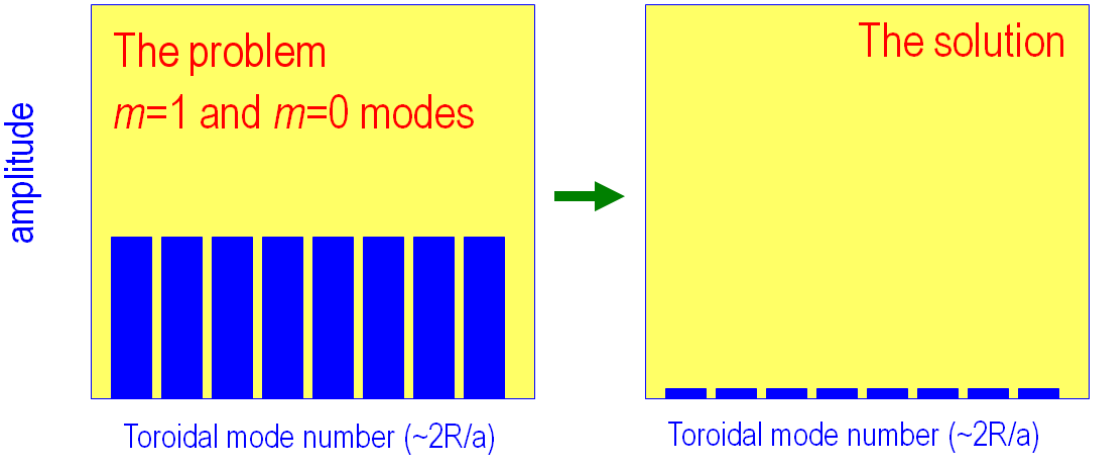
$$q << 1$$

Peaked current profile
→ tearing mode unstable

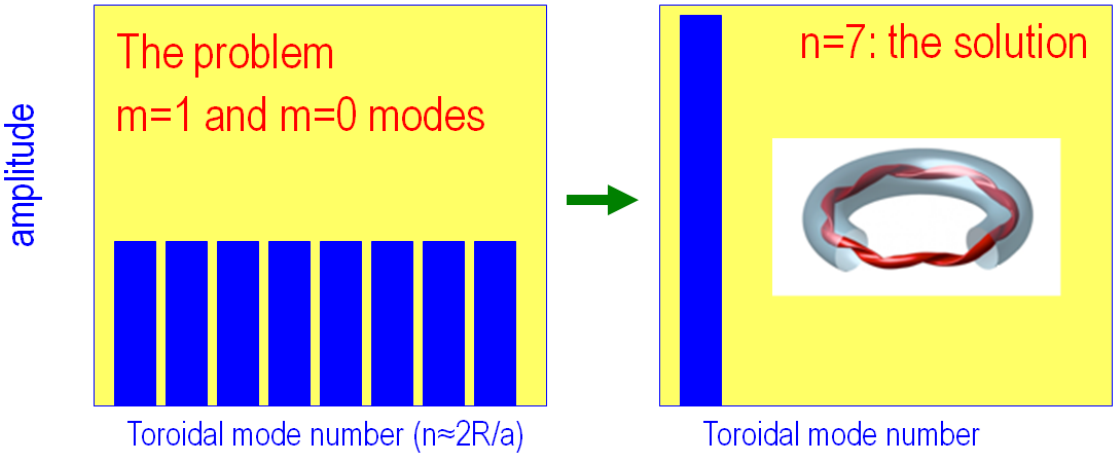
Densely spaced mode rational surfaces
→ importance of nonlinear coupling

Two solutions to avoid magnetic chaos

(courtesy of P. Martin)

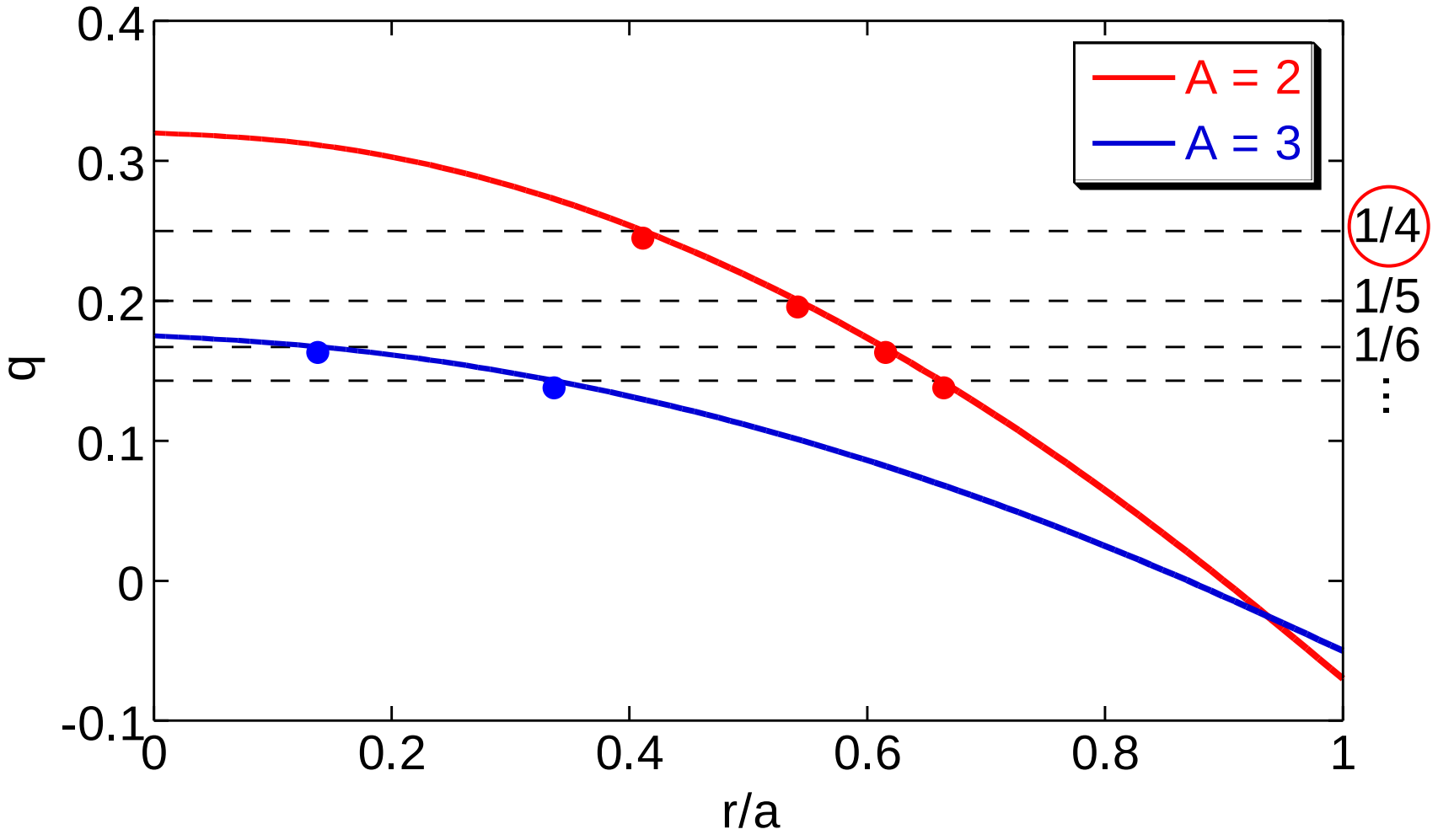


Suppression of all modes
=> PPCD in MST, etc



Concentration to single mode
=> QSH or SHAx in RFX, etc.

Lower *A* changes *q* profile - lower n of dominant m=1 modes



Goal of RELAX experiment

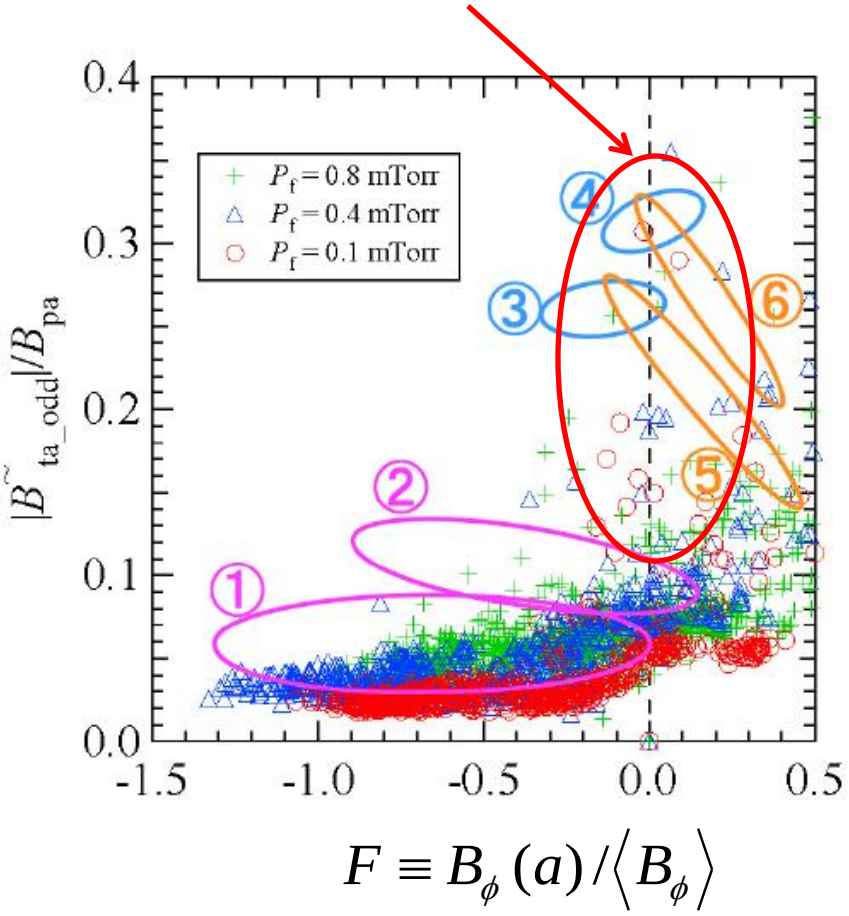
- Experimental study on advantages of low-*A* RFP configuration
  - Improved confinement with QSH for achieving high beta
  - Experimental identification of bootstrap current

  (targer parameters:

  T_e~300eV, n_e~4×10^{19}m^{-3} at I_p~100kA)

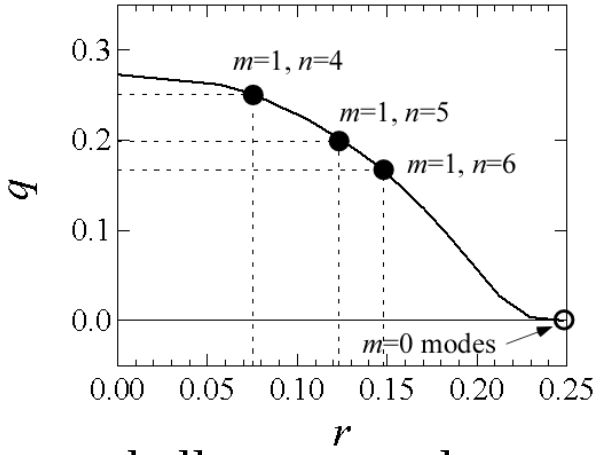
Magnetic fluctuation level depends on toroidal field reversal with transition to Helical Ohmic state at very shallow reversal

Transition to Helical state

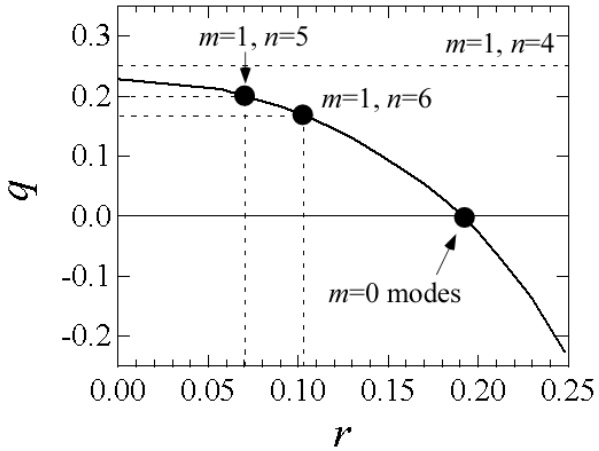


Fluctuation level of odd components

Comparison of *q* profiles

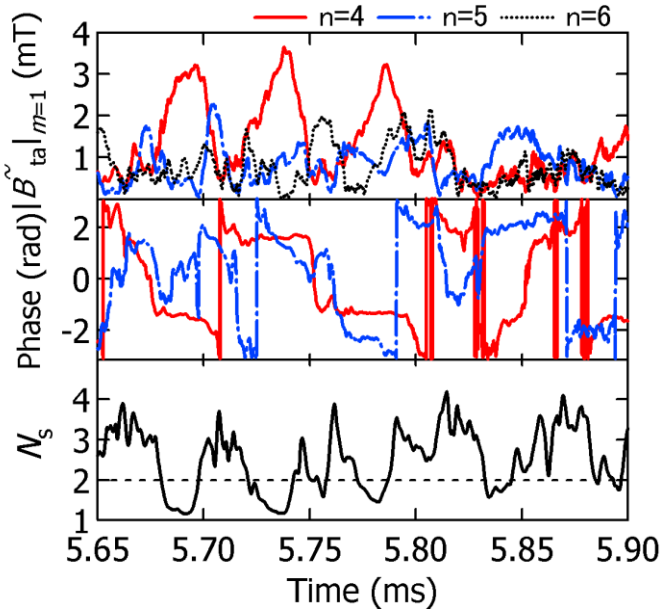


shallow reversal case



deep reversal case

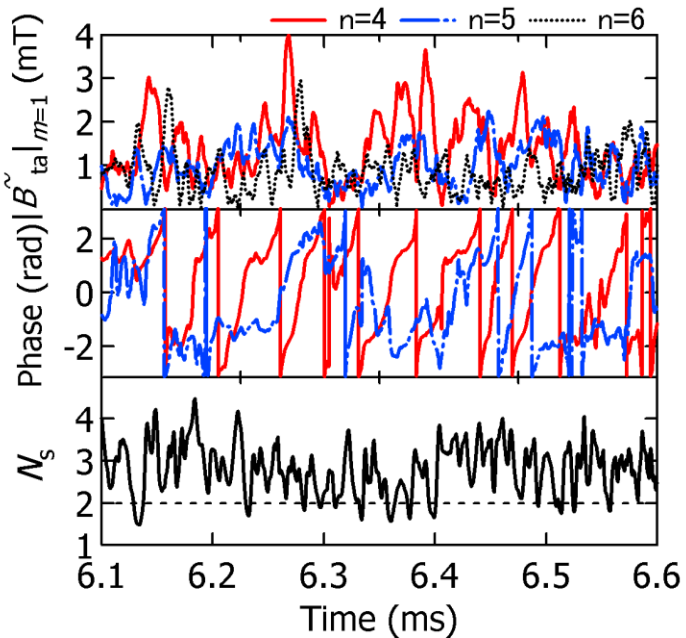
Growth of dominant modes is related to mode rotation

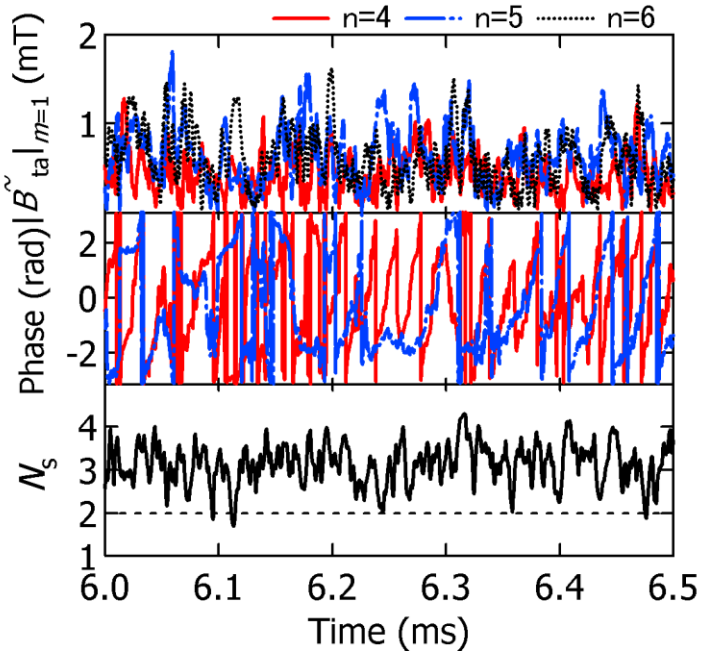


m=1/n=4 mode behavior:

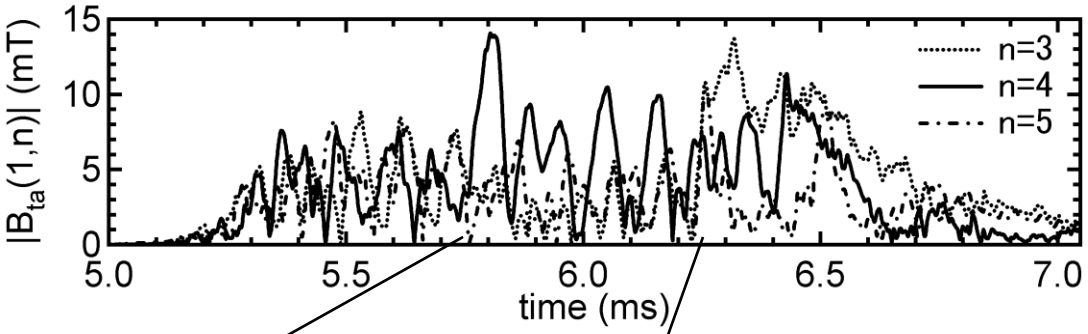
- Longer QSH period for slower rotation
- Shorter QSH period with higher spectral index N_s for faster rotation

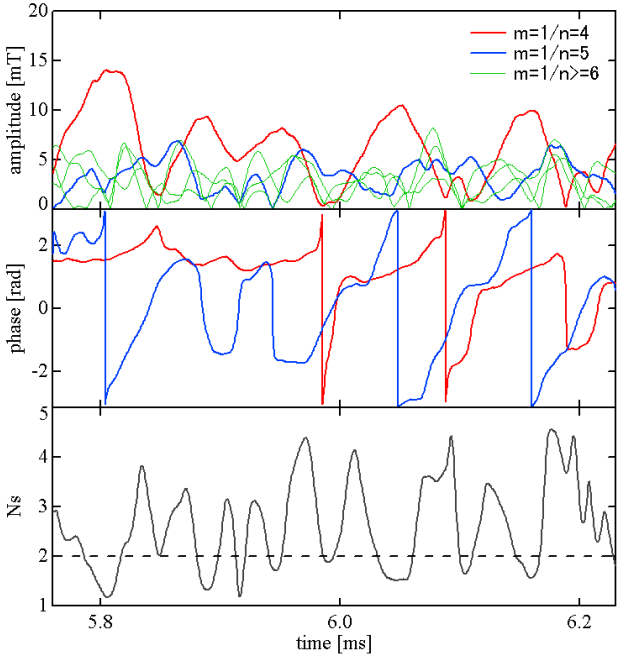
Spectral index: $$N_s = \left[\sum_{n=n_{min}}^{n_{max}} \left(\frac{b^2_{1,n}}{\sum_n b^2_{1,n}} \right)^2 \right]^{-1}$$





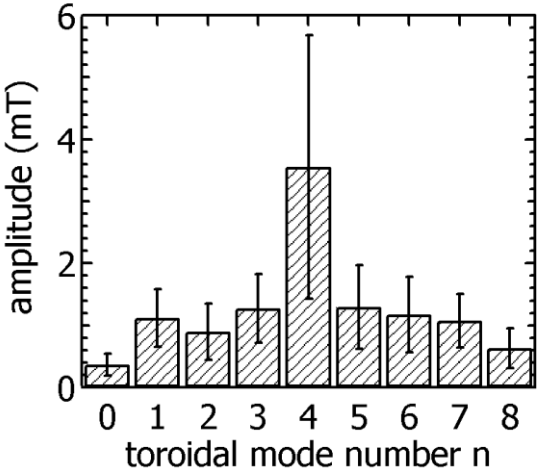
Quasi-periodic growth of a single dominant helical mode (m=1/n=4)





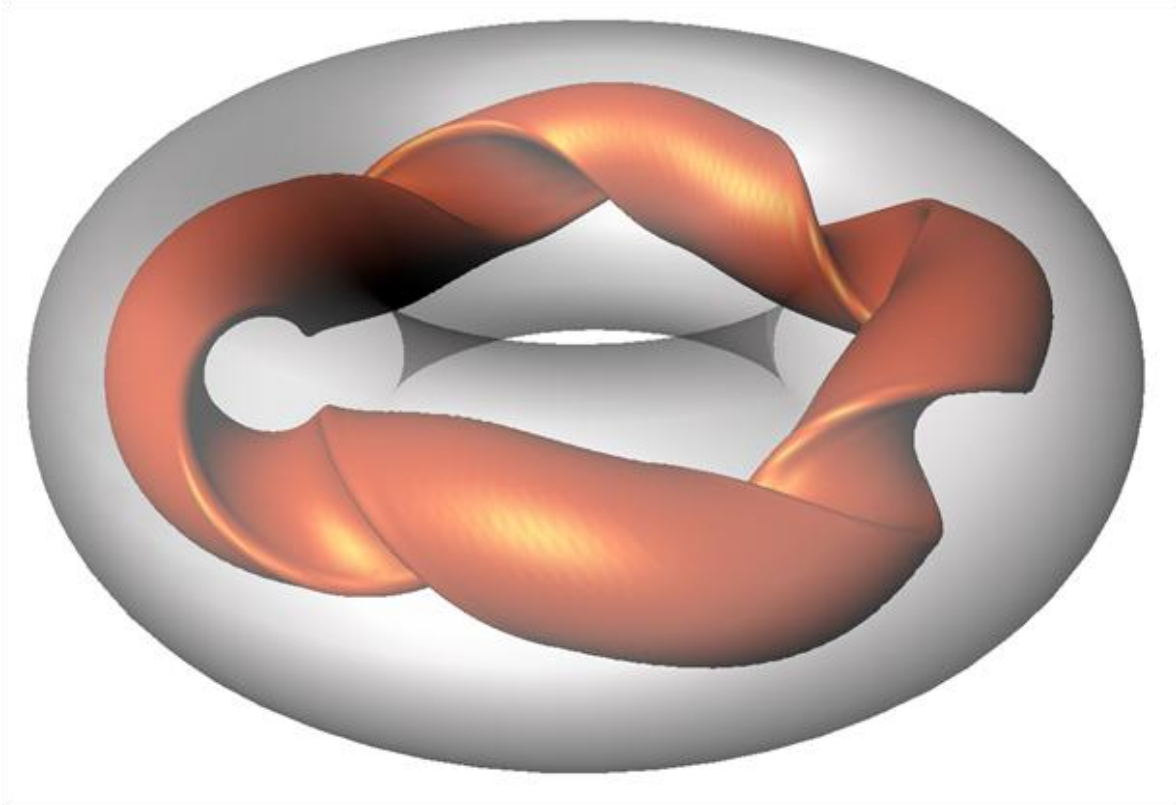
Spectral index N_s

$$N_s = \left[\sum_{n=n_{min}}^{n_{max}} \left(\frac{b^2_{1,n}}{\sum_n b^2_{1,n}} \right)^2 \right]^{-1}$$

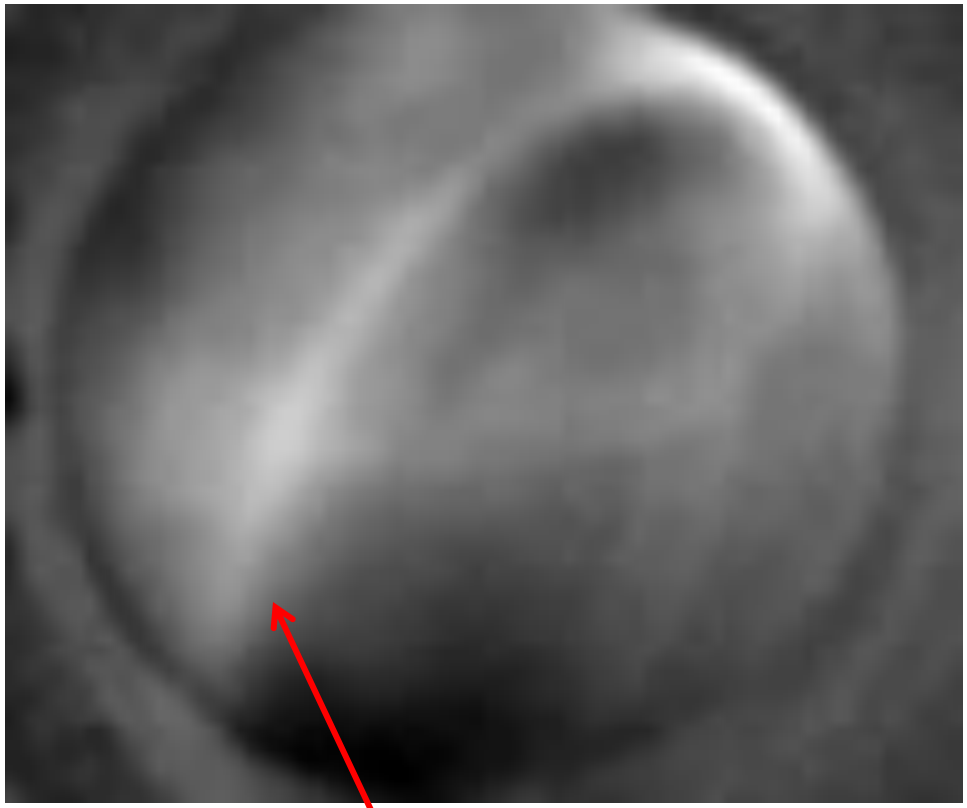


Characteristic of the QSH RFP state: lower dominant mode number (mostly n = 4) and higher amplitudes than in other RFPs.

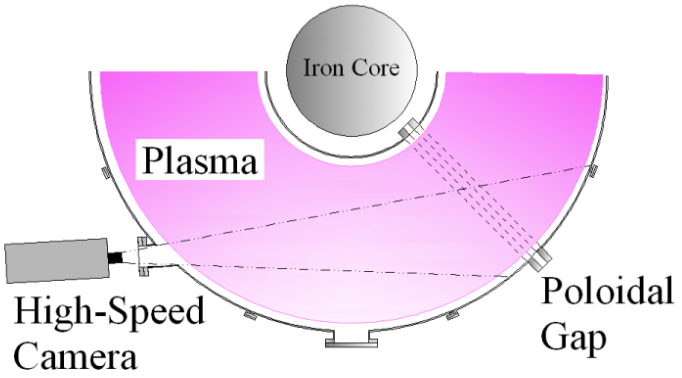
Magnetic island structure of QSH with m=1/n=-4



Rotating helical structure observed with high-speed camera - movie -



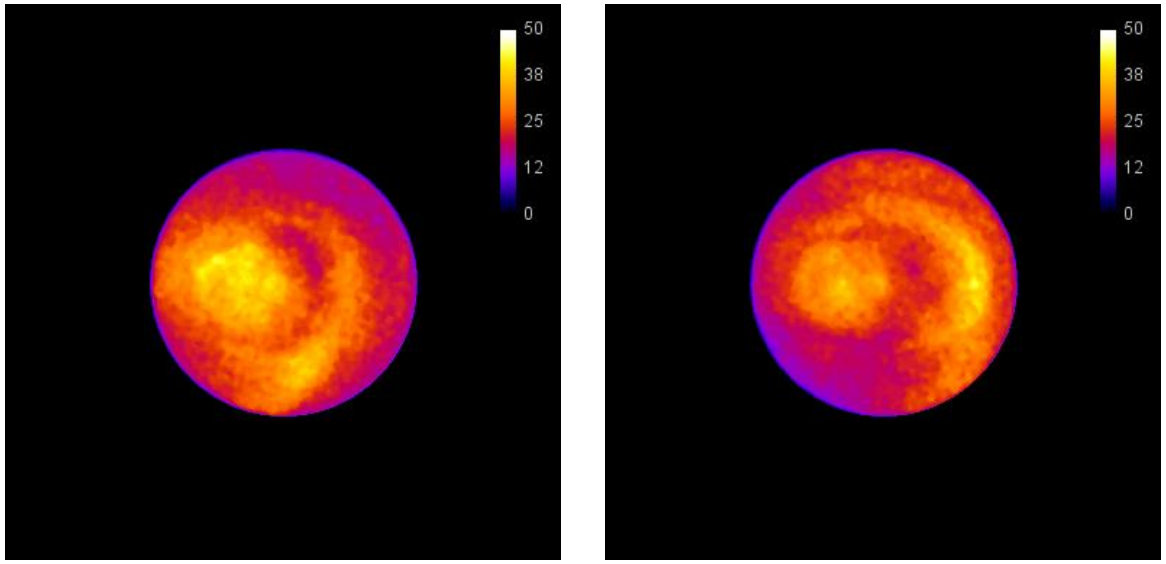
m=1/n=-4 helix



Tangential image:

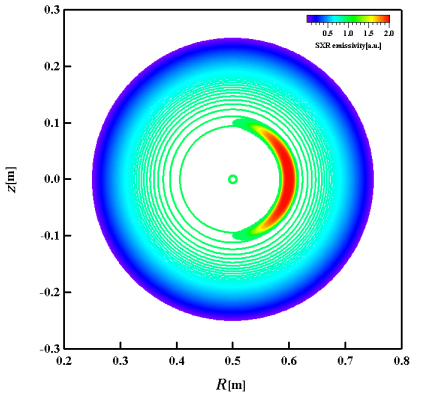
Following the initial bright phase, some structure starts to rotate, converging to a simple helix with m/n=1/-4.

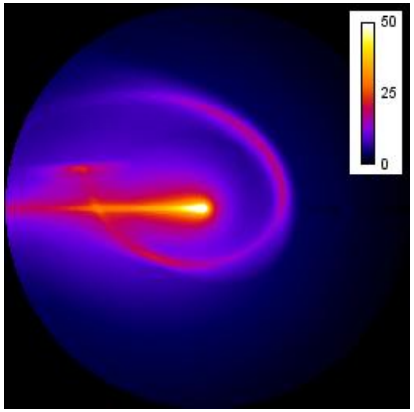
Helical structure observed also in SXR pin-hole camera image



Pin-hole images with different phase

Exposure: 5μs

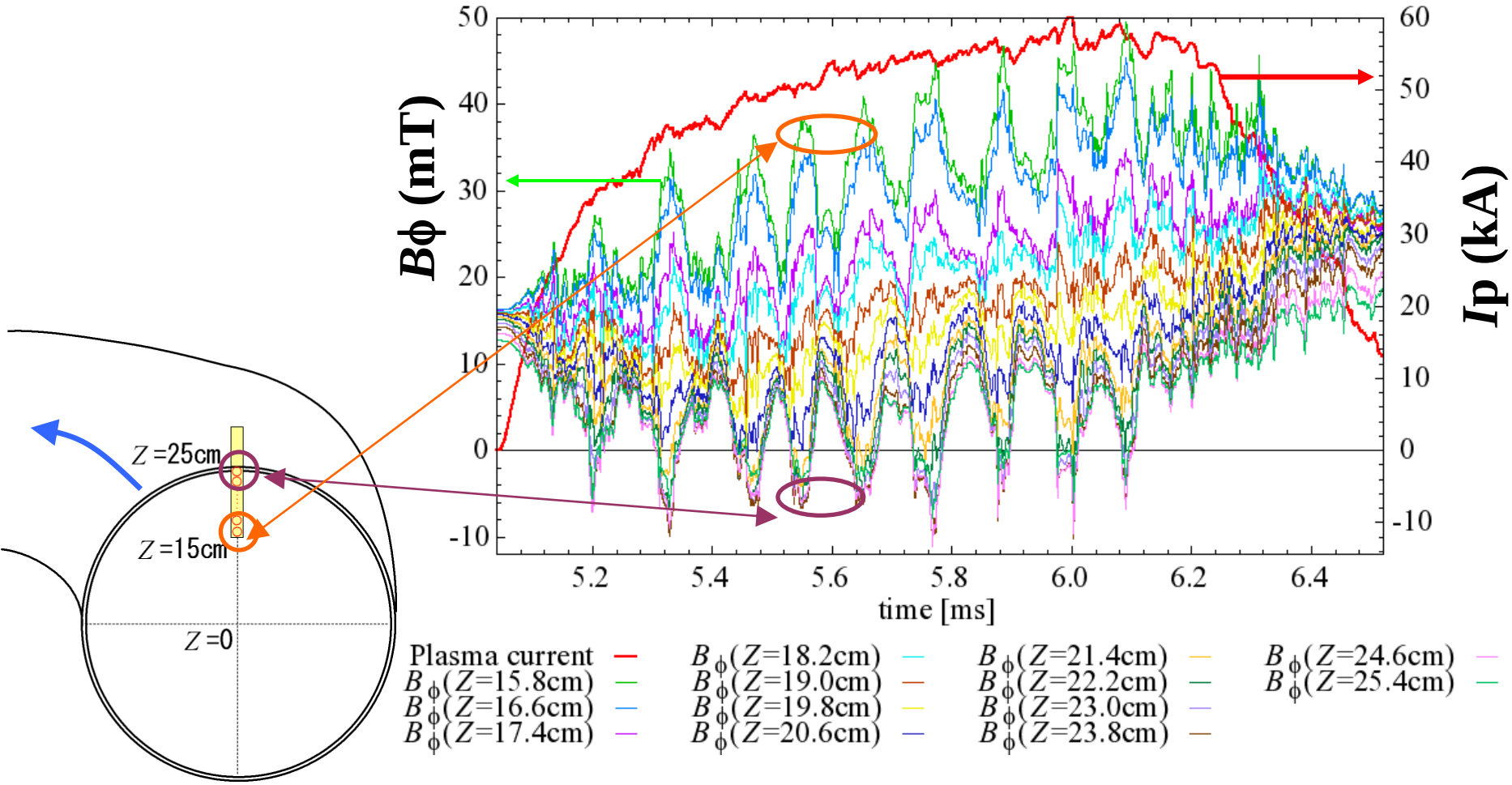




Simulated image with single island

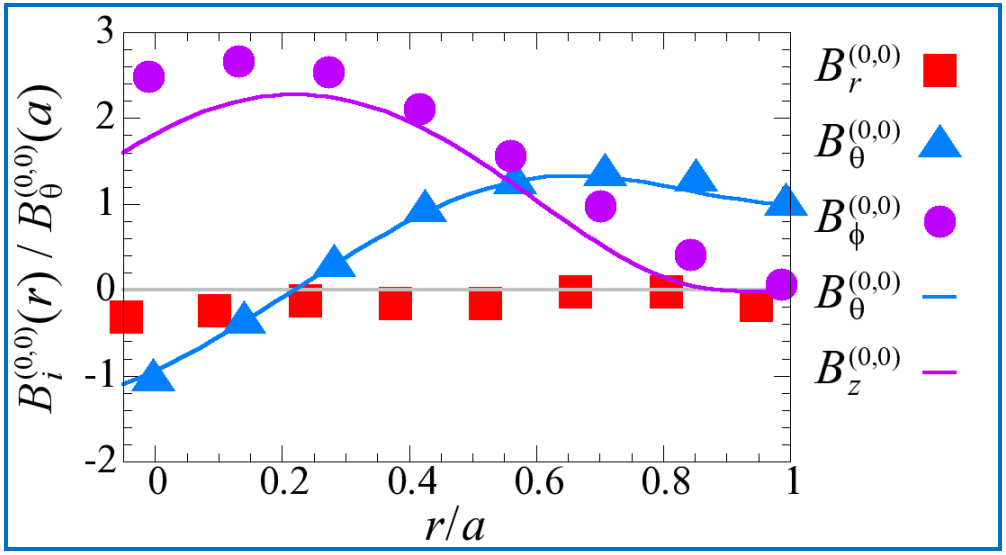
Rotating Helical Ohmic Equilibrium state indicated
- A large-scale magnetic field profile change -

- **Quasi-periodic oscillation between reversed and non-reversed profiles at a fixed point**
- **Similar large-scale oscillatory behavior in B_r and B_θ**

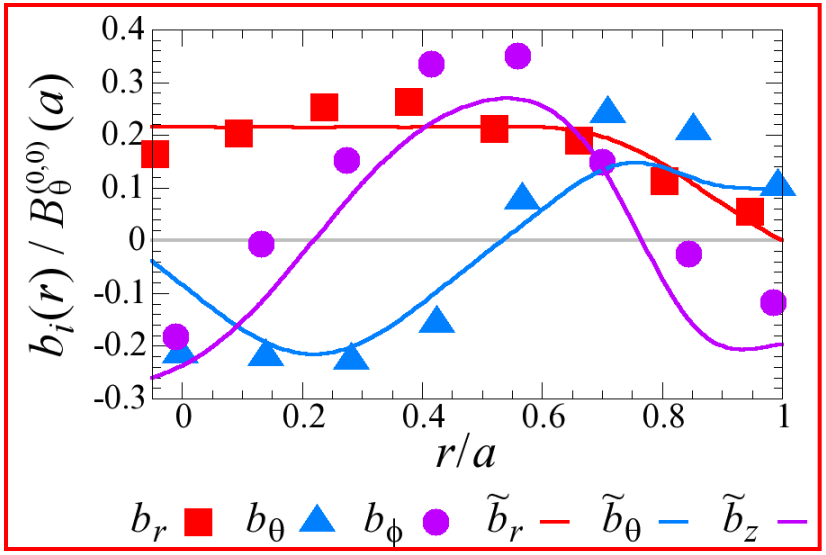


Evidence of Helical Ohmic Equilibrium state

- **Symbols**: measured profiles with radial array of magnetic probes.
- **Solid lines**: Helical Ohmic equilibrium solution (Paccagnella (2000))
- Shafranov shift $\Delta/a \sim 0.2$.
- The helical structure rotates at a frequency of ~10 kHz.

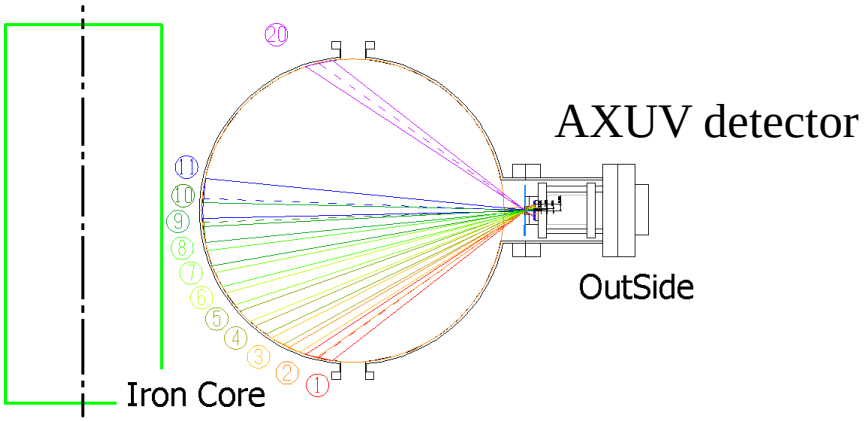


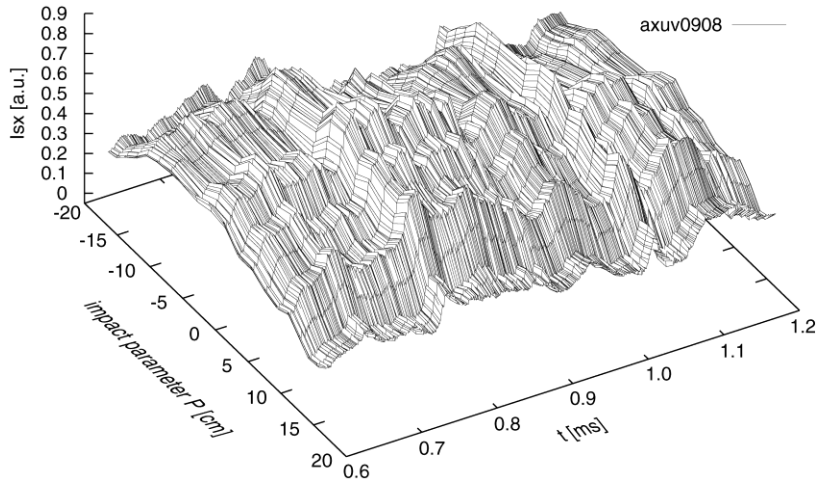
Axisymmetric components

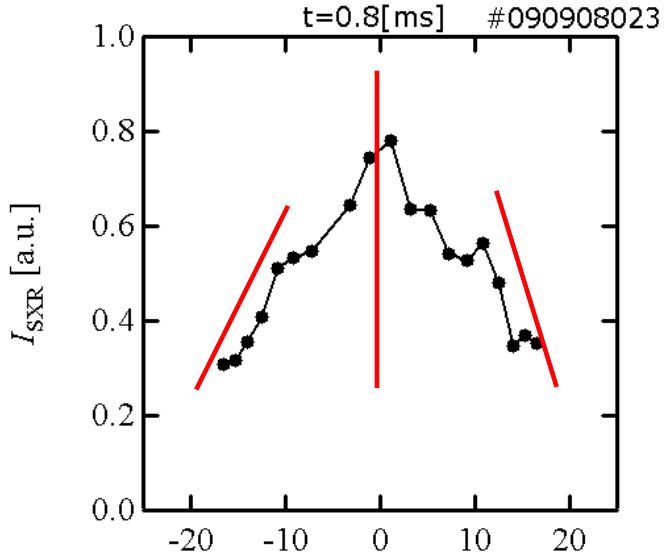


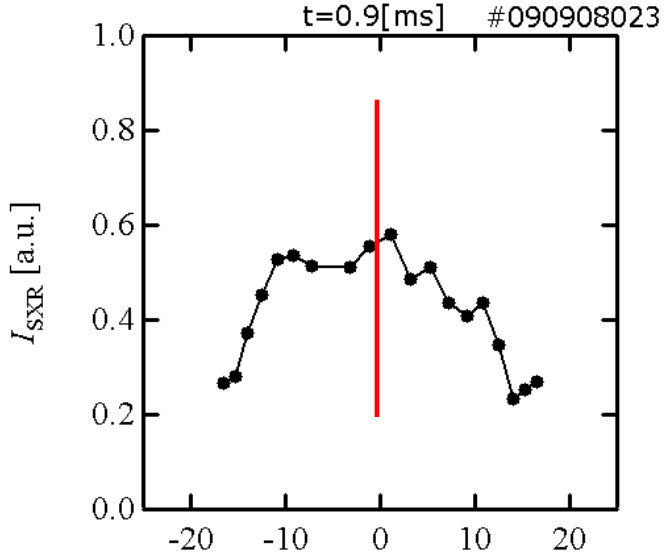
m=1 helical components

Evolution of asymmetric SXR emissivity profile



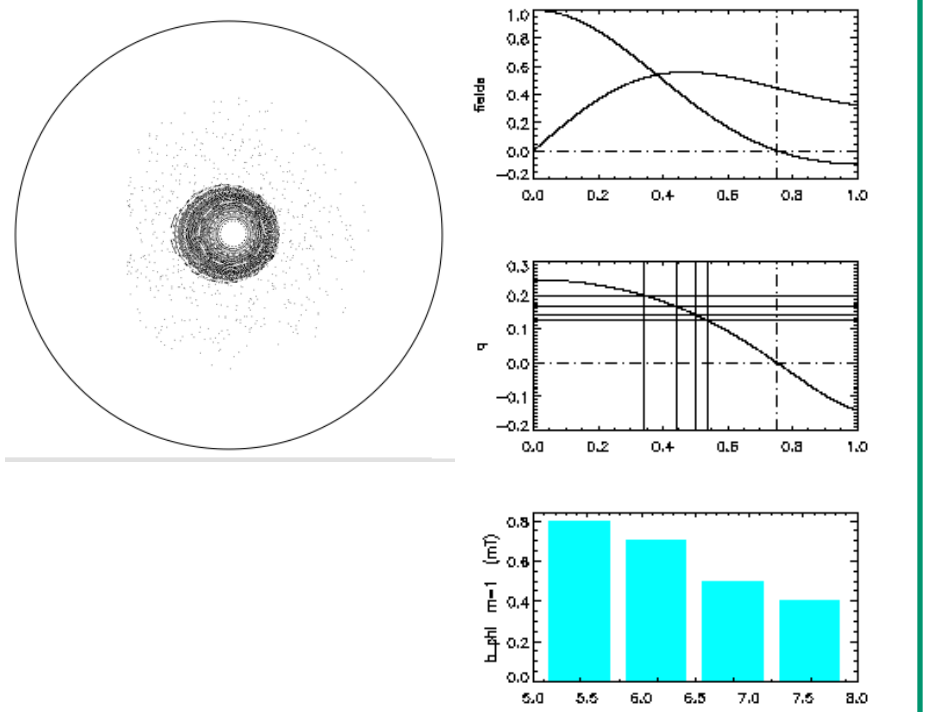




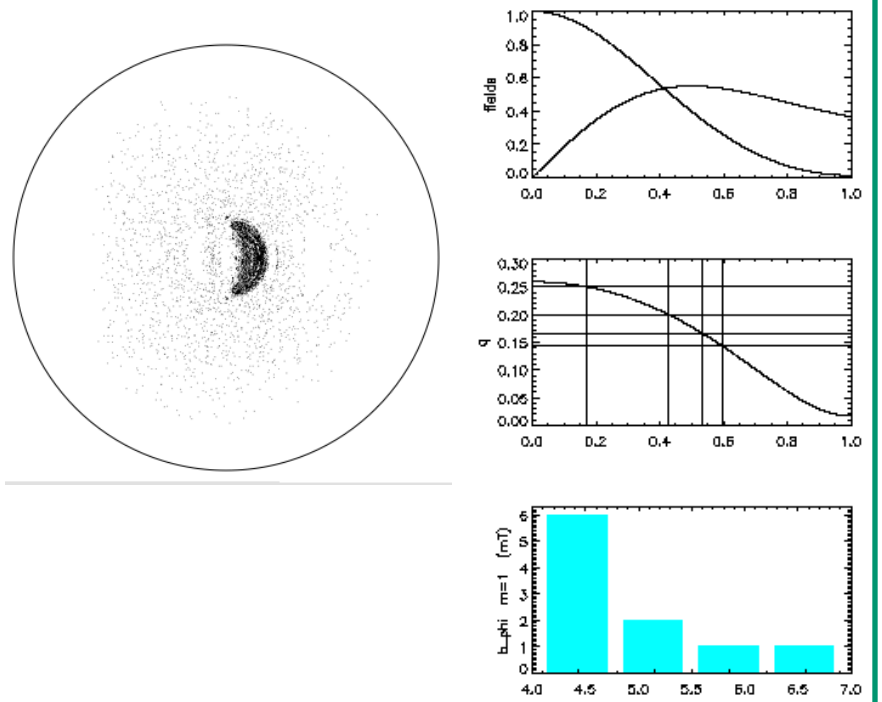


impact parameter (cm)

Field line trace with ORBIT code shows larger area of less stochastic region in deep-reversal case



Deep reversal, low fluctuation level



Helical Ohmic state

1-D equilibrium , linear eigenfunction in cylindrical geometry in ORBIT

3-D equilibrium and 3-D eigenfunctions are needed

Summary

- RFP plasma with MHD properties characteristic to low-*A* configuration attained in RELAX
- Simple rotating helical structure observed
- Helical Ohmic Equilibrium state demonstrated
- 3-D equilibrium and stability analysis needed for further studies on magnetic structure of Helical Ohmic Equilibrium state

Future work

- Discharge performance improvement:

  - Ip~100kA, τ: ~3ms => 5ms (within present capability)

  - Static helical perturbation and feedback control

Further improvement of Helical Ohmic state will require improved magnetic boundary:

  - feedback control system

Another means for confinement improvement (current profile control, e.g.) may be necessary

Helical Ohmic Equilibrium Solution

Grad-Shafranov equation with helical symmetry

$$\Delta_{\mathrm{h}}\chi = \frac{1}{f}\frac{\partial}{\partial r}\left(f\,\frac{\partial \chi}{\partial r}\right) + \frac{1}{rf}\frac{\partial^2 \chi}{\partial u^2} = \left(c - \frac{\mathrm{d}g}{\mathrm{d}\chi}\right) g(\chi) - \frac{\mathrm{d}p}{\mathrm{d}\chi}(m^2 + k^2 r^2),$$

$$f = \frac{r}{m^2 + k^2 r^2}, \quad g = \frac{-2mk}{m^2 + k^2 r^2}$$

$$\lambda(r) = \frac{\boldsymbol{j}\cdot\boldsymbol{B}}{B^2} = \frac{\mathrm{d}g}{\mathrm{d}\chi} + \frac{g}{B^2}\frac{\mathrm{d}p}{\mathrm{d}\chi}$$

Ohm's law with helical symmetry

$$(\ \boldsymbol{E} + \boldsymbol{u}\times\boldsymbol{B} = \eta\,\boldsymbol{j}\ )$$

$$E_0 \left\langle B_z \right\rangle_\chi = \eta(\chi)\left(\tilde{\lambda}(\chi)\left\langle B^2 \right\rangle_\chi + g\,\frac{\mathrm{d}p}{\mathrm{d}\chi}\right),$$

$$\hat{\lambda} = \frac{\mathrm{d}g}{\mathrm{d}\chi} = \frac{\boldsymbol{j}\cdot\boldsymbol{B}}{B^2} - \frac{g}{B^2}\frac{\mathrm{d}p}{\mathrm{d}\chi}$$

Contours of helical flux function

Theta=1.78, F=-0.06, beta=0.1