NTM Avoidance and Suppression with Real-Time Gyrotron Steering at DIII-D (+ Snowflake Divertor Development, BetaN Dependent EFC)

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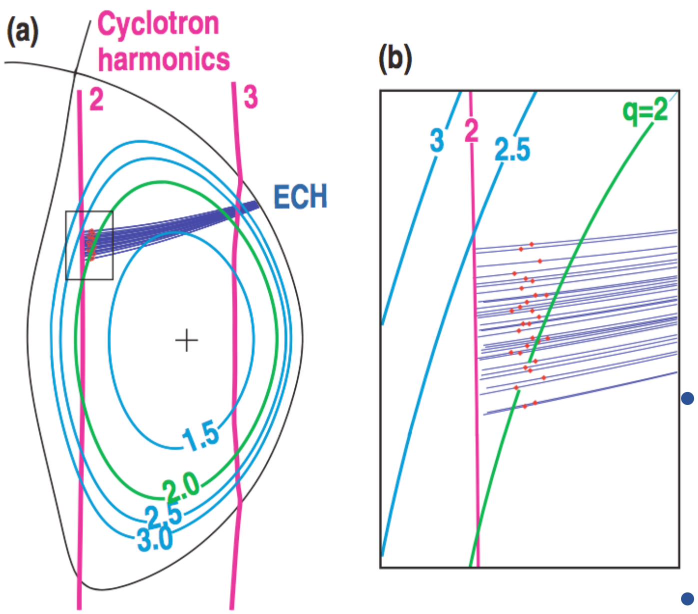
DIII-D NATIONAL FUSION FACILITY

PPPL PRINCETON PLASMA PHYSICS LABORATORY

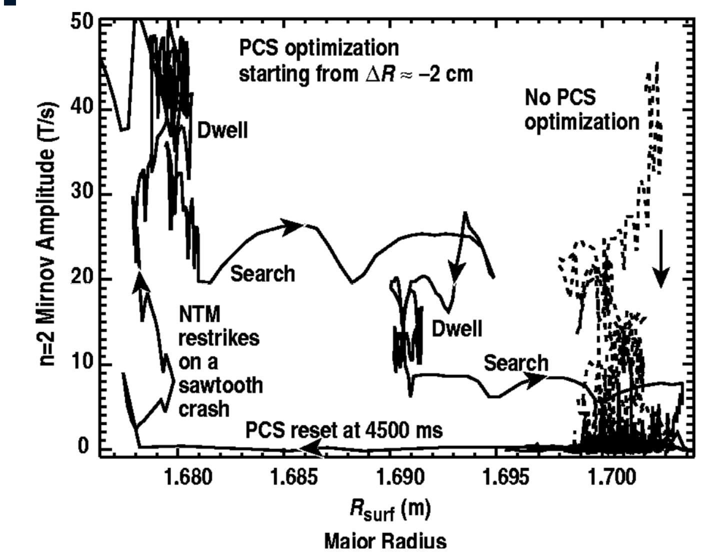
NTM Avoidance and Suppression: PHYSICS

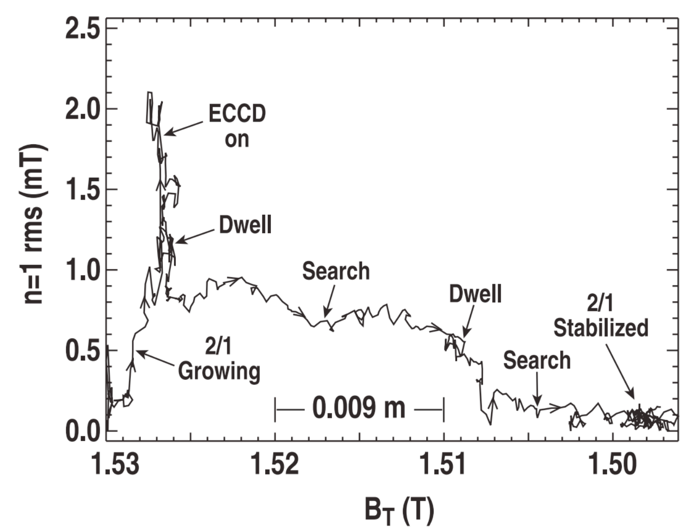
Electron Cyclotron Heating Basics



- **Electrons gyrate around magnetic field lines as they travel in the toroidal direction.**
- **A microwave beam at the electron cyclotron resonant frequency will deposit energy into the electrons.**
  - Heating [perpendicular injection] (ECH) or current drive [tangential] (ECCD)
  - Localized deposition
- **Microwave beam is generated at a gyrotron, passed through ~100m of waveguide, then directed by the ECH launcher.**
- **General Atomics 6 gyrotrons ~4MW for 5-10sec, KSTAR 1 beam * 1MW for 5-10 sec.**
- **Previous studies show: 2/1, 3/2 islands can be suppressed and avoided by depositing the ECCD at or close to the island location.**

Case for Real-time Steerable Mirror





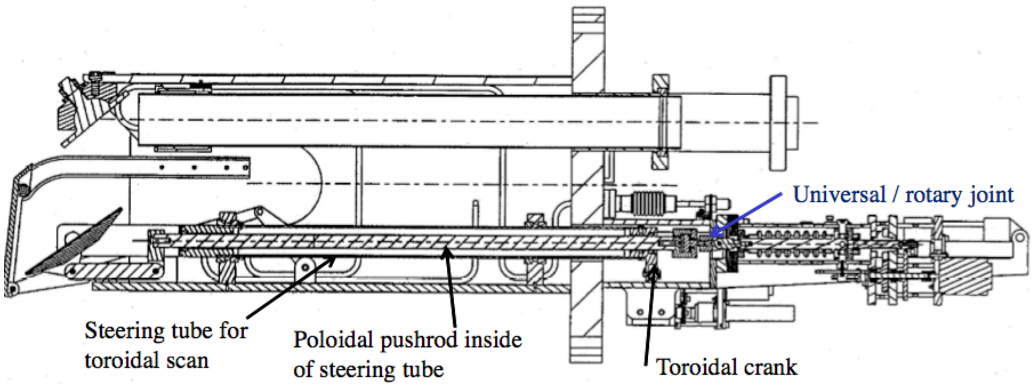
- **Previously: Intersection of the 2fce surface with q-surface was changed by:**
  - Moving the plasma radially to change the q-surface that intersects 2fce surface.
  - Change BT to move 2fce surface
- **These methods are slow and change the plasma equilibrium. Never used in physics XPs due to these limitations.**

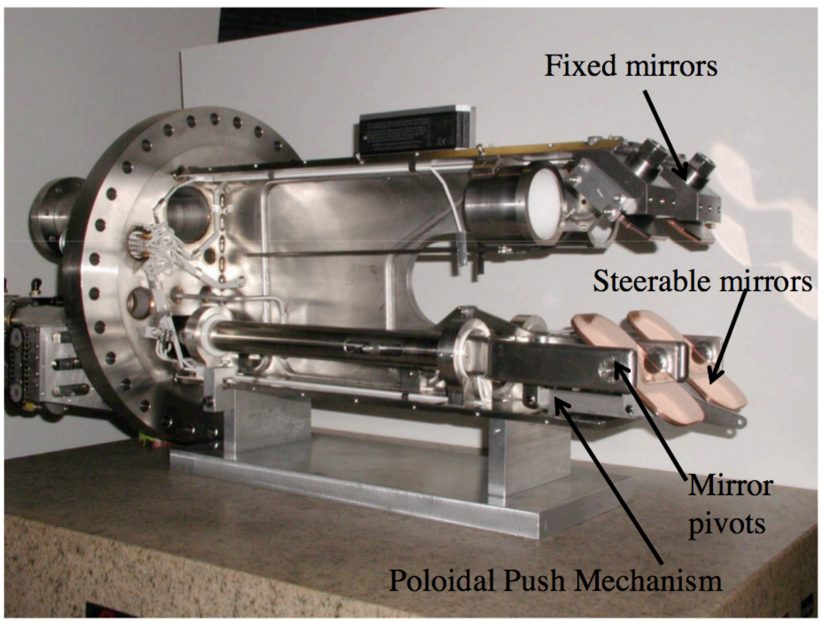
➔ **Real-time steerable mirror control of the EC deposition location**

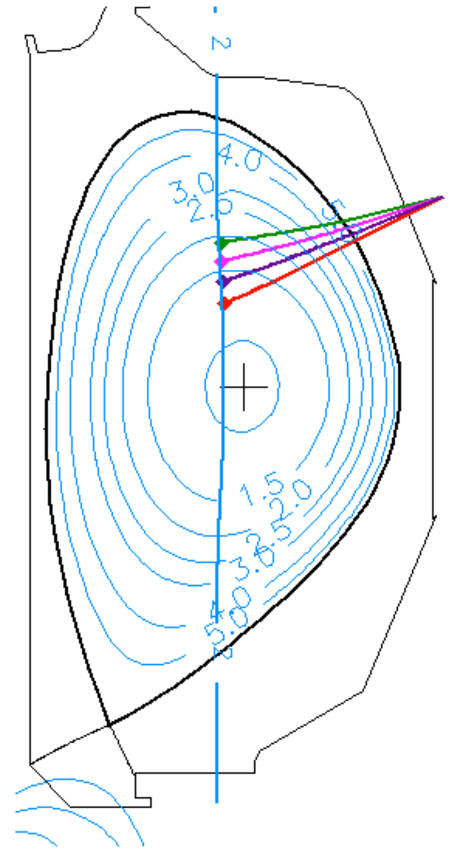
- Faster NTM suppression
- Capability to run experiments consistently in high beta.
- Possibility to control NTMs with lower EC power.
- Suppress multiple islands at the same time

NTM Avoidance and Suppression: HARDWARE

Real-Time Steerable Mirrors to Control EC Deposition





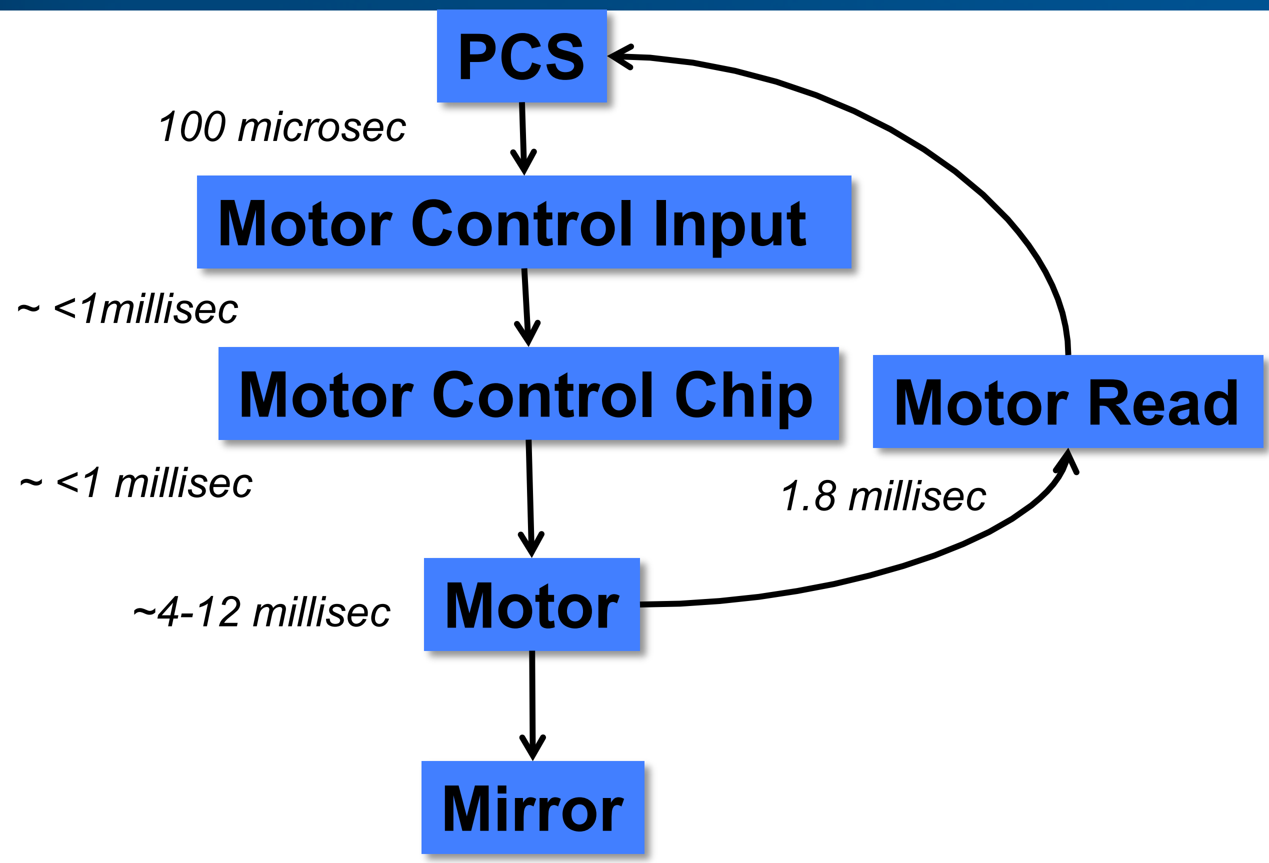


Designed by Robert Ellis of PPPL

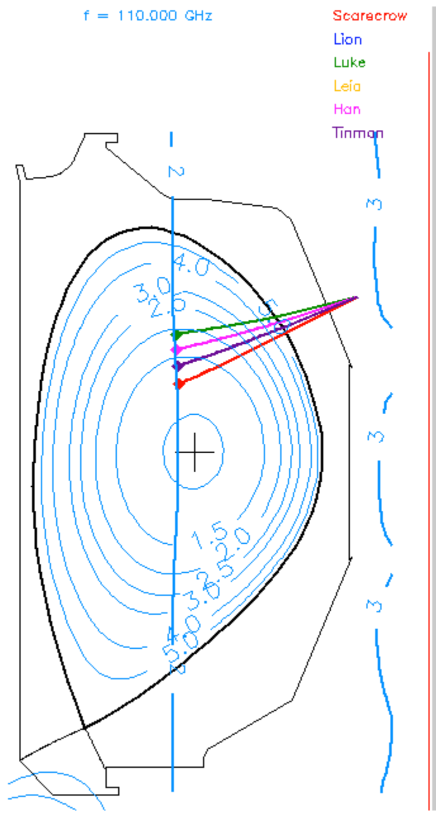
Electronics and Software: Motor Controllers, ECH Communication Computer, Mirror Net and PCS

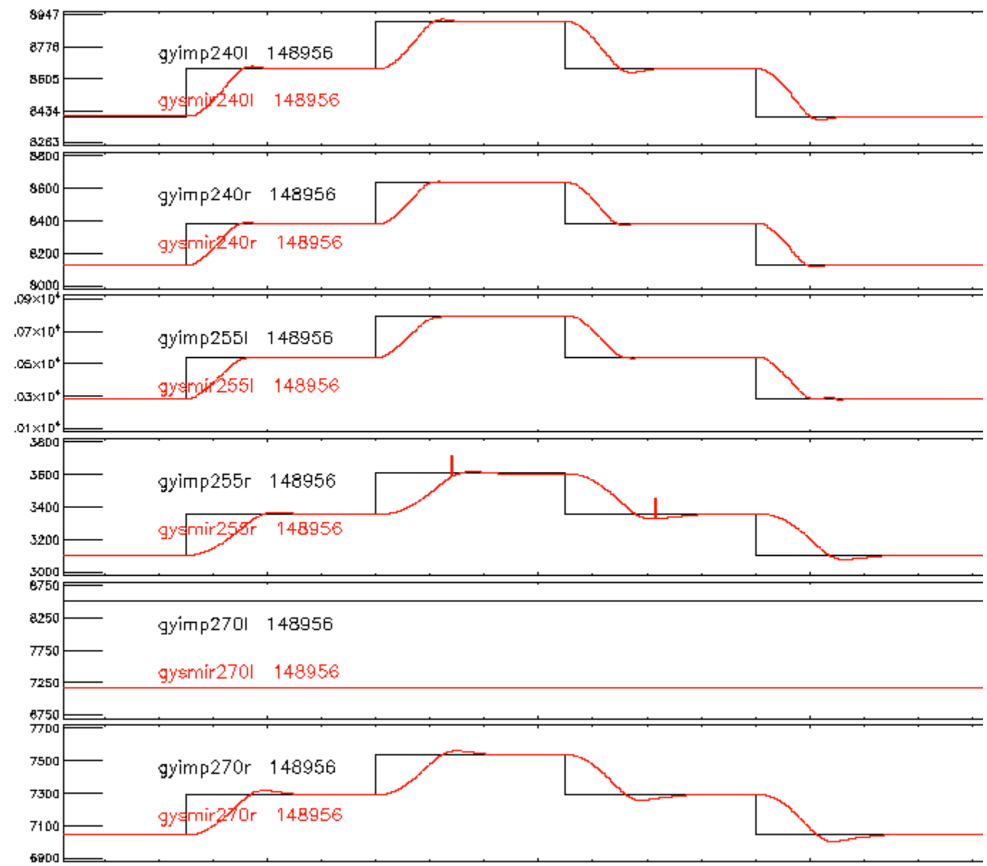
- **Upgraded and installed new motor control hardware (chips etc.) for the six mirrors.**
- **Upgraded the encoder reading hardware in order to reduce noise.**
- **Wrote new embedded control algorithms for faster processing, faster and more accurate position read out, increased robustness and hardware protection.**
- **Designed new optimal controls for the mirrors that can accomplish close to the maximum mechanically possible speed with smooth operation and with a few millimeter accuracy of alignment of the ECCD in the plasma.**
- **Designed a new architecture that enable real-time control of the mirrors form the PCS.**
- **Wrote a new PCS and embedded algorithm to reduce the latency between the PCS and the mirrors.**

Latencies of the System (6-14 ms delay)



Feed-forward EC Mirror Control

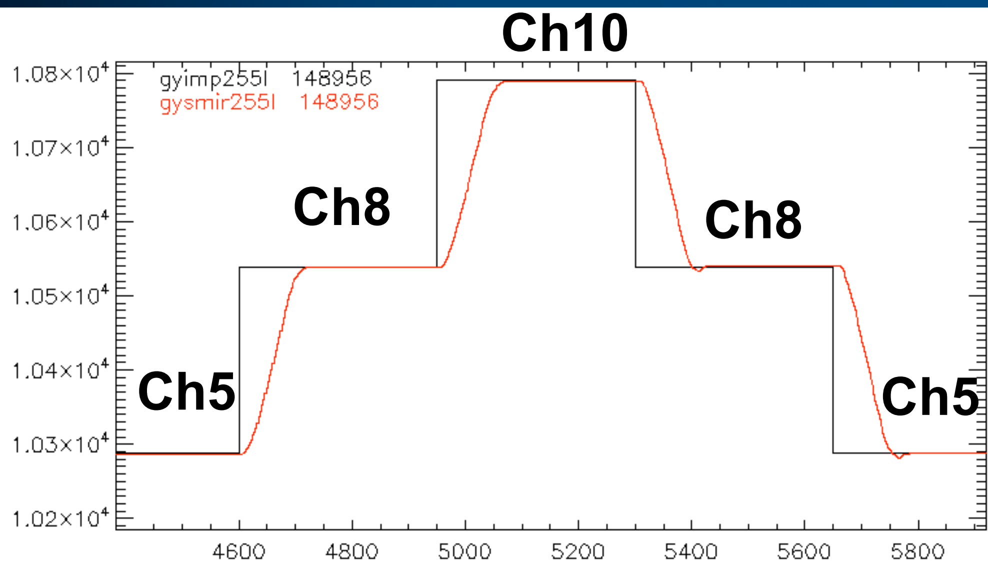




- Successful real time motion of all six mirrors.
- Control speed (~2m/s) is close to the maximum mechanically possible with smooth operation.
- Accuracy << 1 cm in Z direction (0.0-0.3 cm)

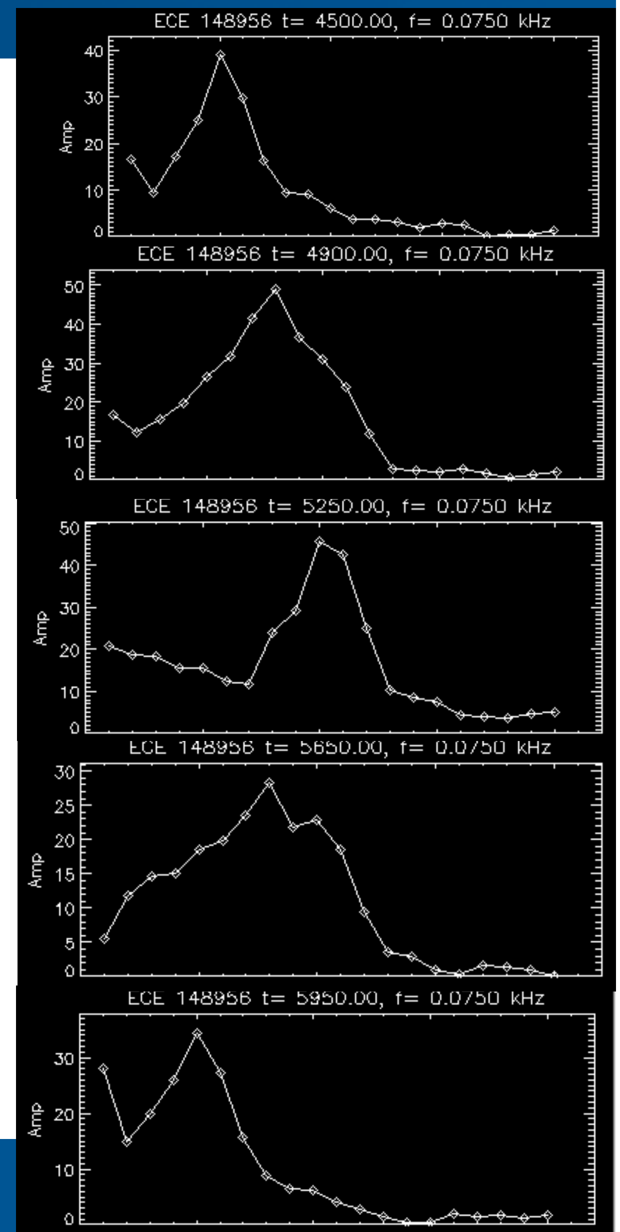
NTM Avoidance and Suppression: DIAGNOSTICS

ECE Based ECCD Deposition Calculations

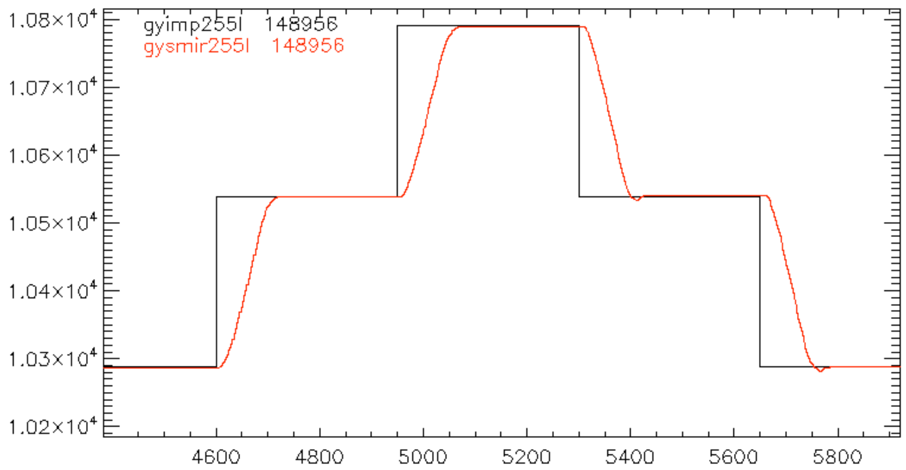


ECE Channel corresponding to peak deposition vs. Mirror Position

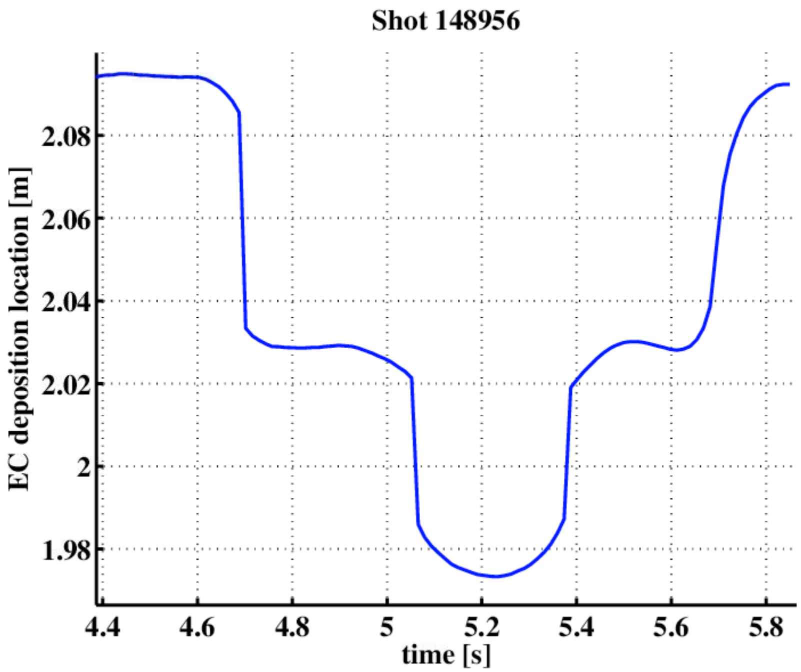
- Module EC at 70/100Hz to locate the deposition location with ECE/ECEI (>80 duty cycle is OK).
- Calculate for the amplitude of the EC modulation frequency in ECE channels.
- Interpolate to find the peak amplitude location which corresponds to the EC deposition location



ECE Based ECCD Deposition Calculations

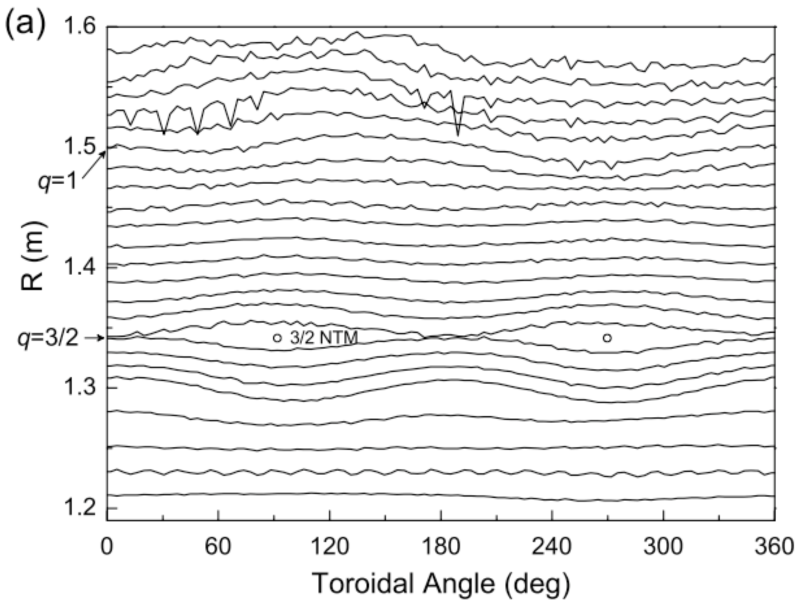


ECE based EC deposition location calculation



- Module EC at 75/100Hz to locate the deposition location with ECE/ECEI.
- Look for the amplitude of the EC modulation frequency in ECE channels
- Interpolate to find the peak amplitude location which corresponds to the EC deposition location

ECE Based NTM Location Calculation



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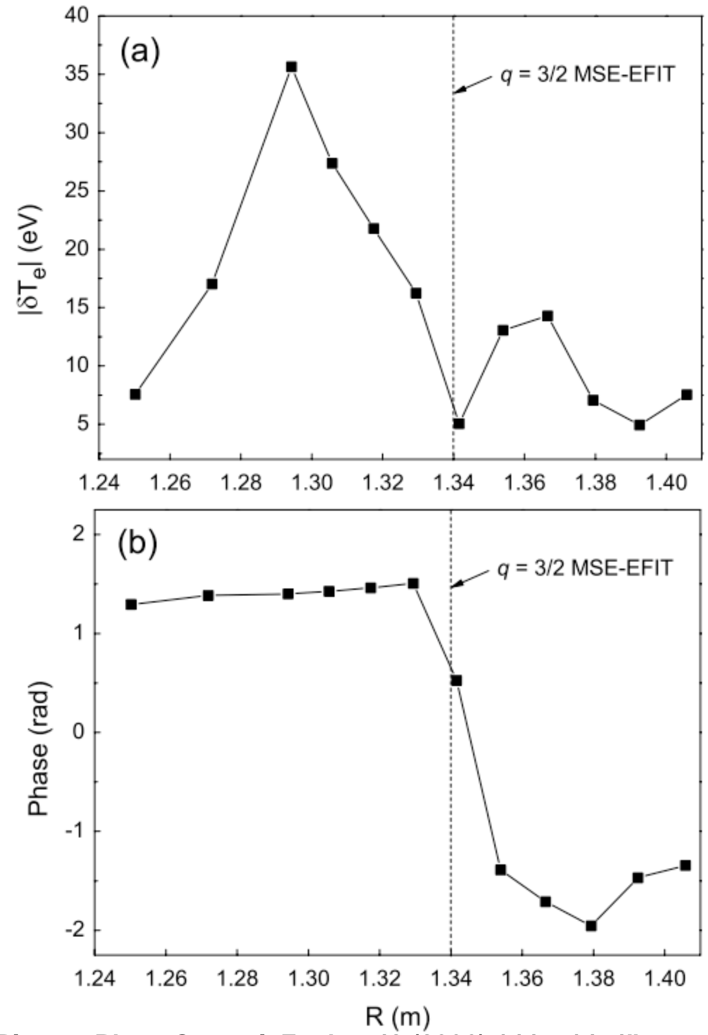


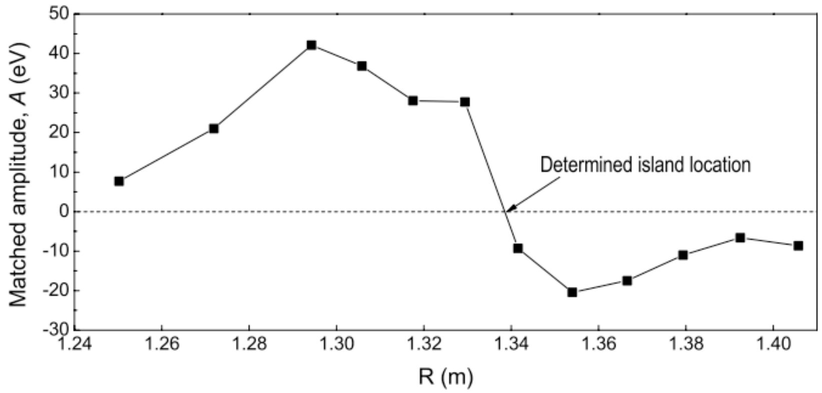
Y. S. Park, "Plasma Phys. Control. Fusion 48 (2006) 1447–1454"

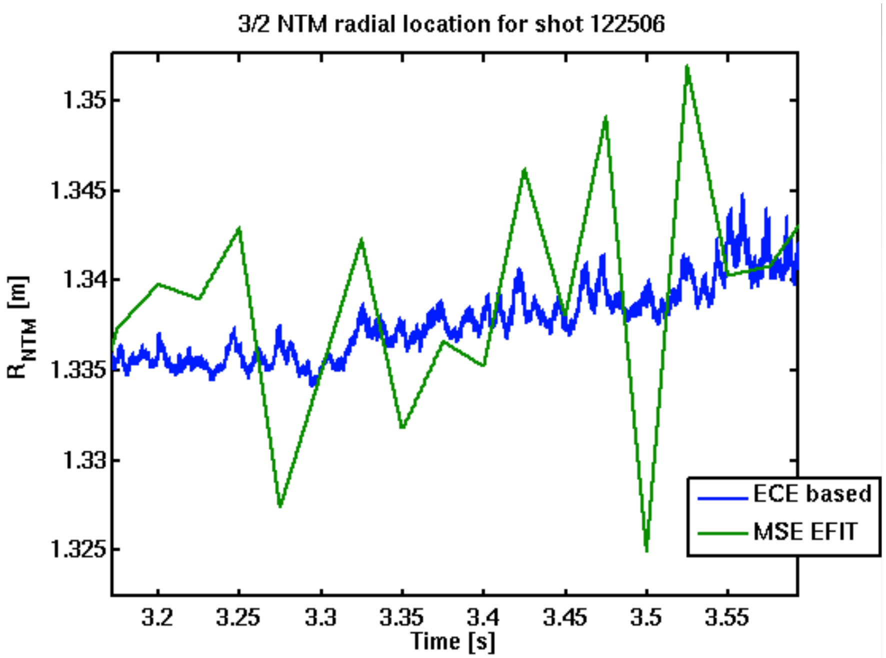
- NTM displaces the flux surfaces
- This leads to 180 degree phase shift

in the ECE data across the island.

- Use this condition to find the island location
- Get the NTM frequency from Mirnov

ECE Based NTM Location Calculation





- Find the frequency of the NTM from Mirnov.

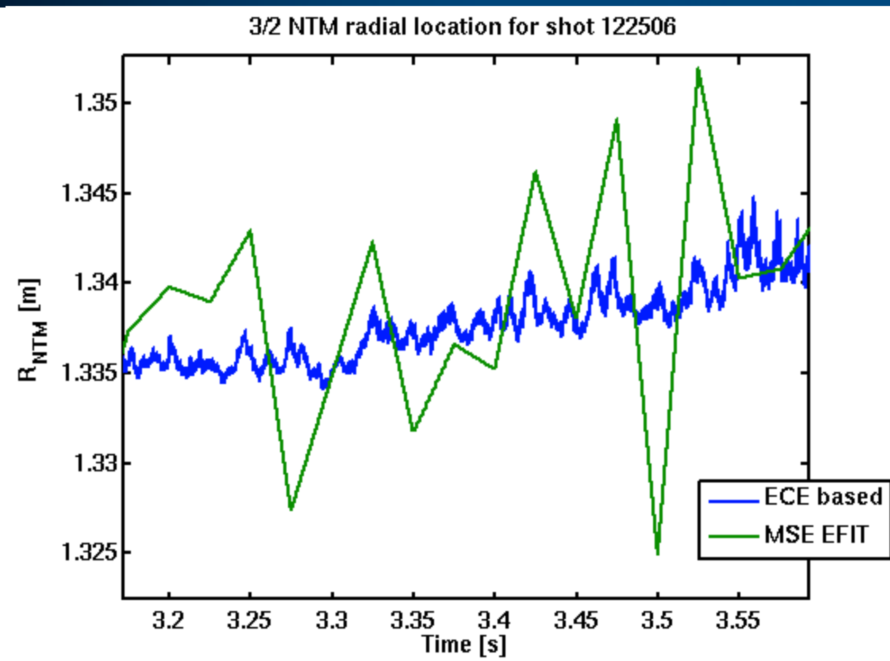
$$\delta T_e = A\cos(\Omega)$$

- Find the amplitude and phase of this frequency from ECE channel.

$$A(t) = \sum_{t-T_{smo}}^{t} (T_e - \bar{T}_e)\cos\Omega \Big/ \sum_{t-T_{smo}}^{t} \cos^2\Omega$$

- Better accuracy than MSE.
- Also, avoid the offset in MSE due to misalignment of the rational q-surface and NTM.

Current Development: Align the EC Deposition and NTM Location Using ECE



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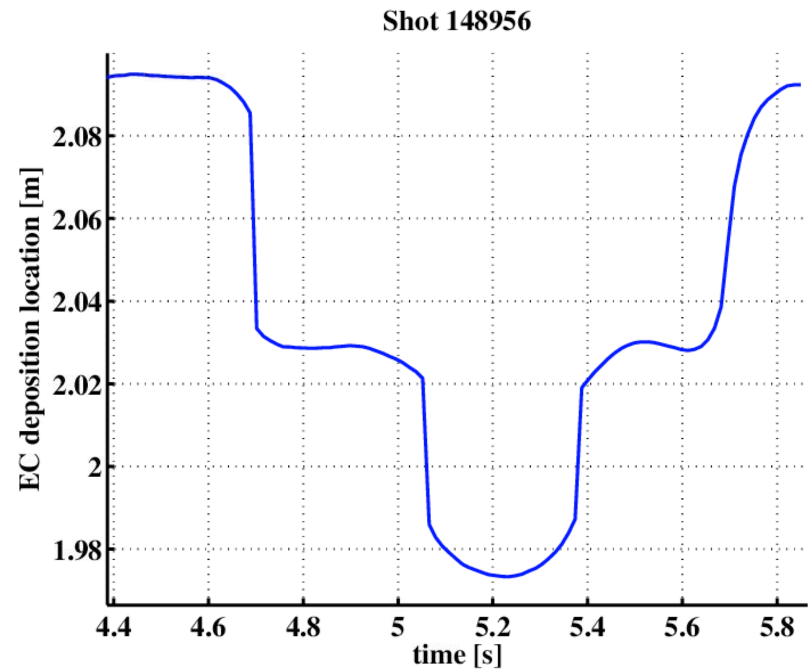
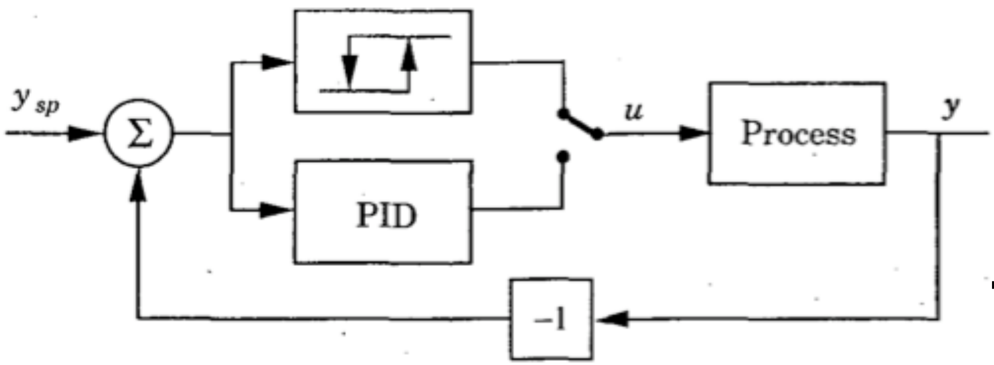


- **Great for ITER NTM control!**
  - Using the same diagnostic for target and current position (no cross calibration)
  - No need Ray Tracing! This is very hard due to not good/available density measurements and calibration problems.
  - High accuracy and self consistent data.
  - Easy to control: Just take the difference and feed to the mirror control!

CONTROL

Experimental PID Tuning: Closed Loop Auto-tune with Relay Feedback



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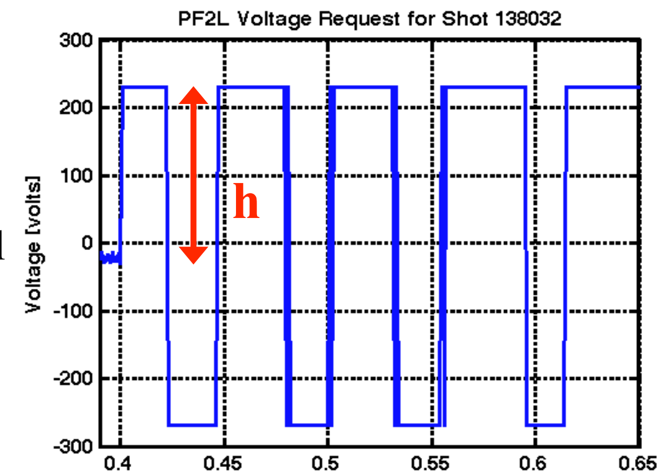
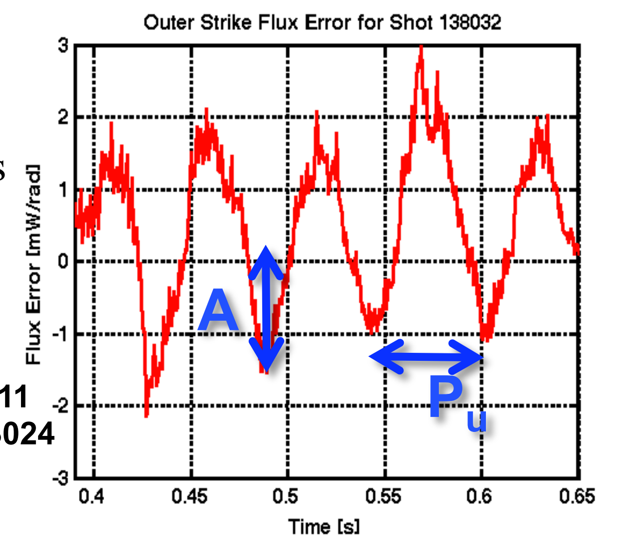
Control Output



Process Output



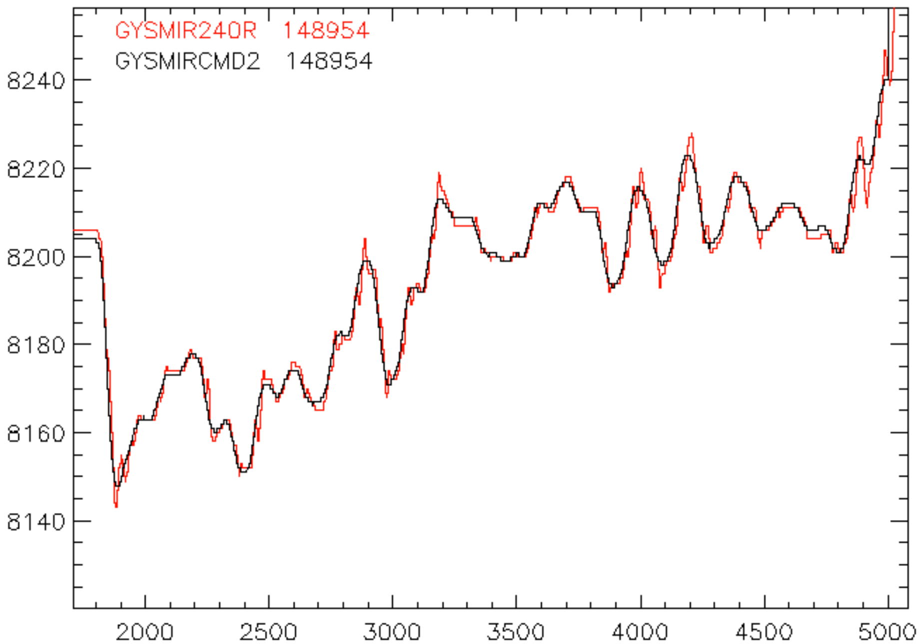
E. Kolemen *et al* 2011
***Nucl. Fusion* 51 113024**

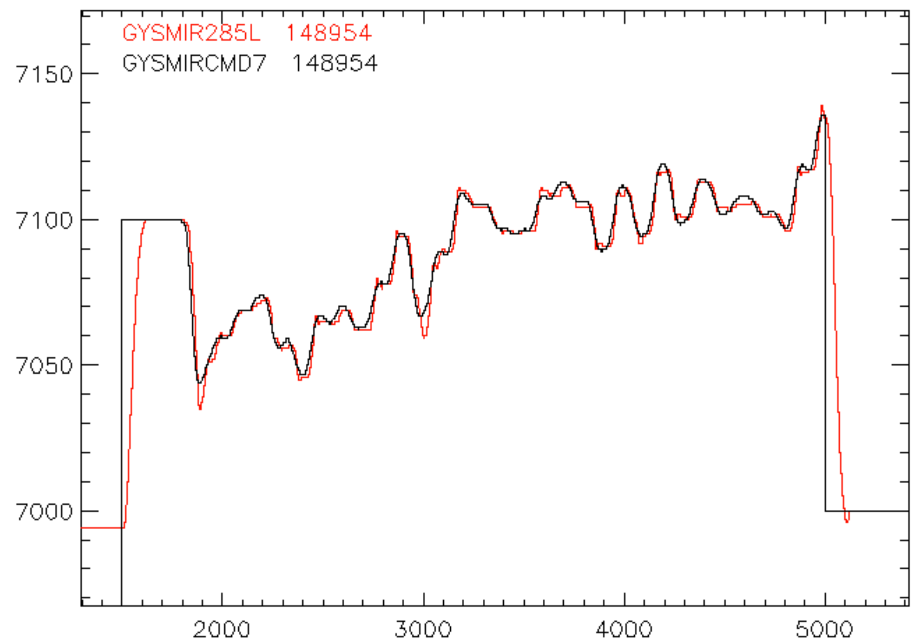
- The closed-loop plant response period (P_u) & amplitude (A) give (for example):

  $[P,I,D]=4h/(\pi A)*[0.6,\ 2/P_u,\ P_u/8]$

- Advantages:
– Only a single experiment is needed to tune many different regimes.
– Closed loop:
  1. More stable
  2. Enable tuning for actuator that can't be open loop (e.g.: Vertical Ctrl, EFC). Methods exist to join with the existing control

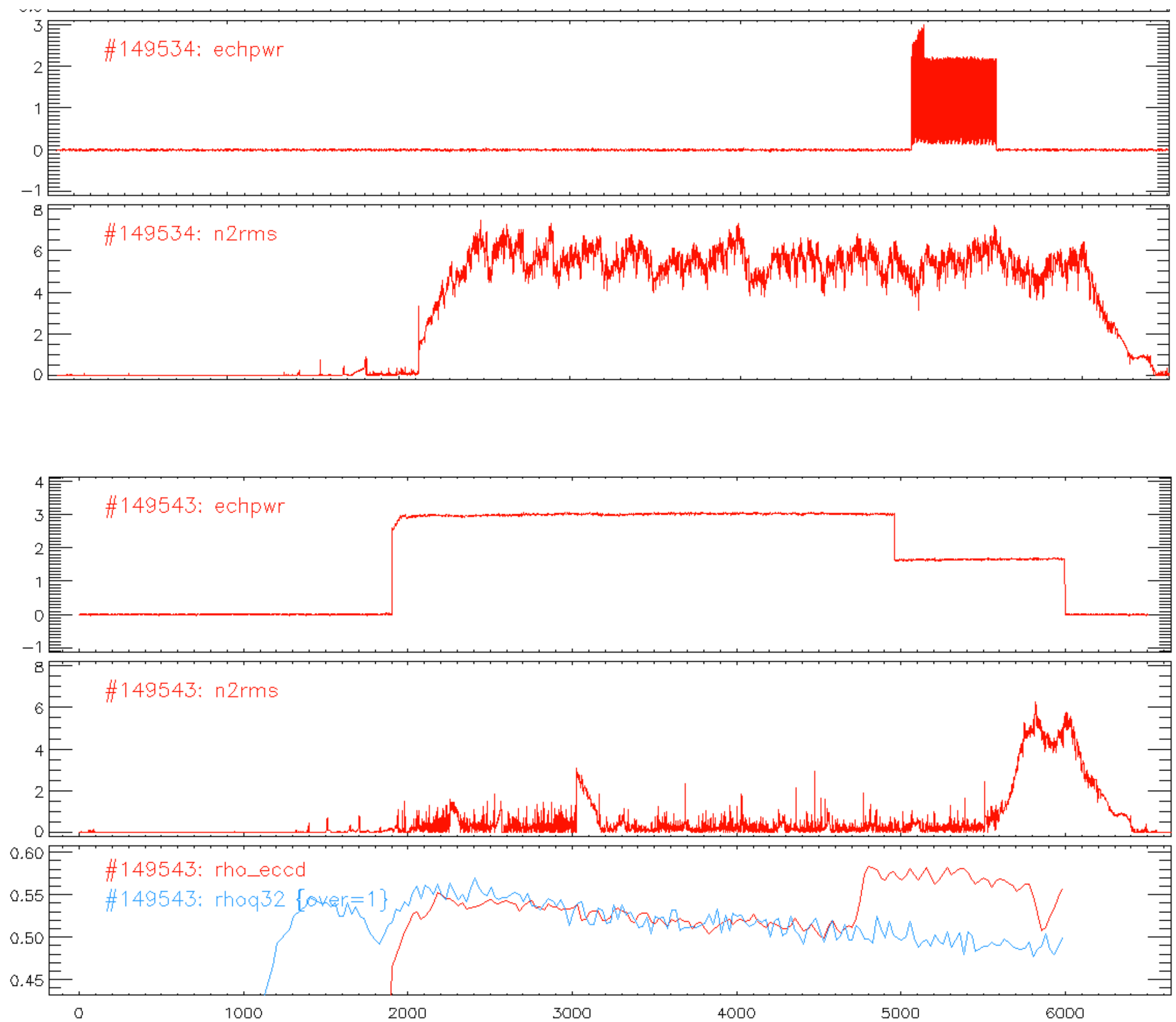
NTM Avoidance: Feed-back q-surface Following





- **Calculate the q-surface location corresponding the NTM mode (3/2, 2/1).**
- **Request the mirror to move to follow the angle that correspond to intersection of the q-surface with the 2fce using Ray tracing.**
- **Control designed for tracking performance using Relay-Feedback.**
- **Great performance with <<1 cm error.**

NTM Avoidance: Feed-back q-surface Following

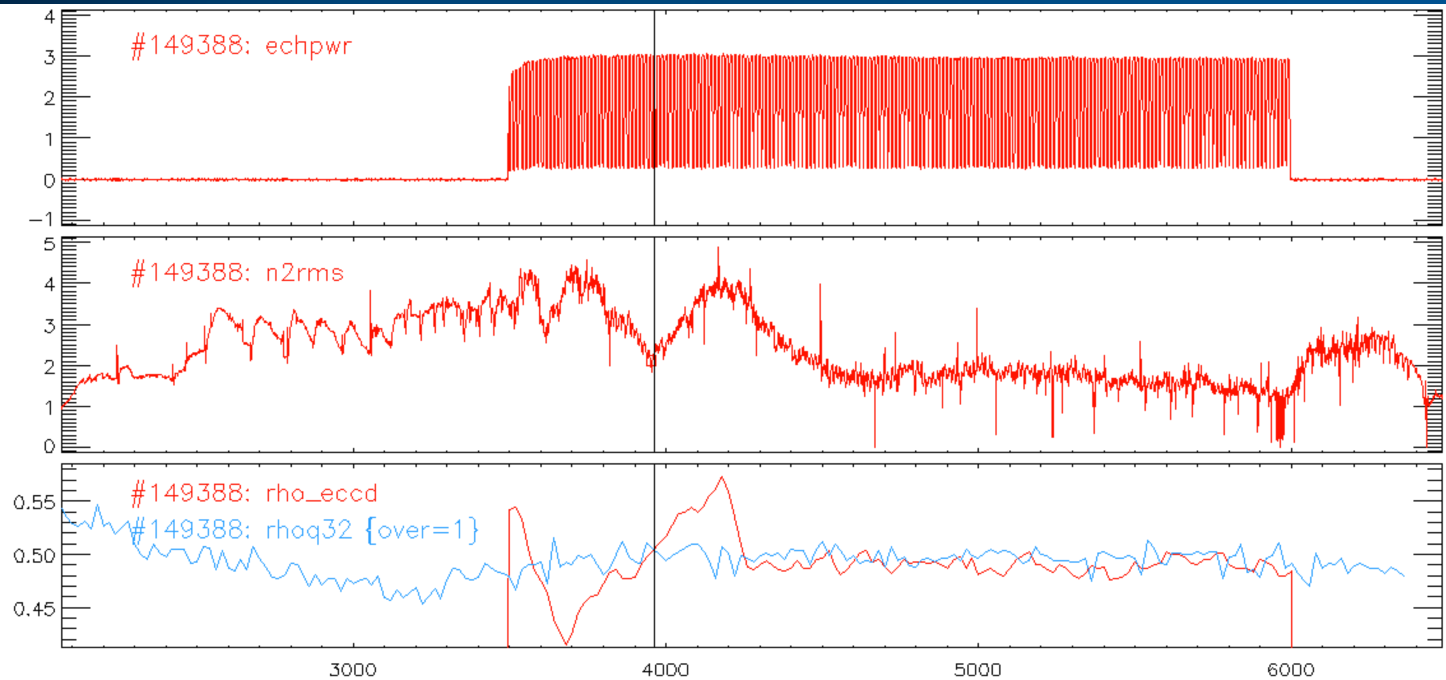


Shot with 3/2 NTM
(Almost no ECCD)

NTM Avoidance with ECCD

NTM Suppression: Feed-back q-surface Following

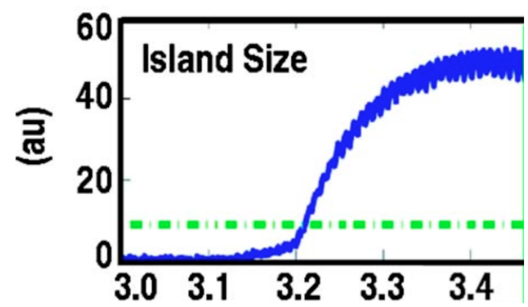
NTM Suppression: Mirnov Magnitude Based Control



- **Mirnov based Feedback Control**
  - Sweep around the NTM, look at the Mirnov amplitude to find the sweet spot.
  - Go to the sweet spot and stay there.
- **Example Shot where partial suppression is achieved is shown above.**

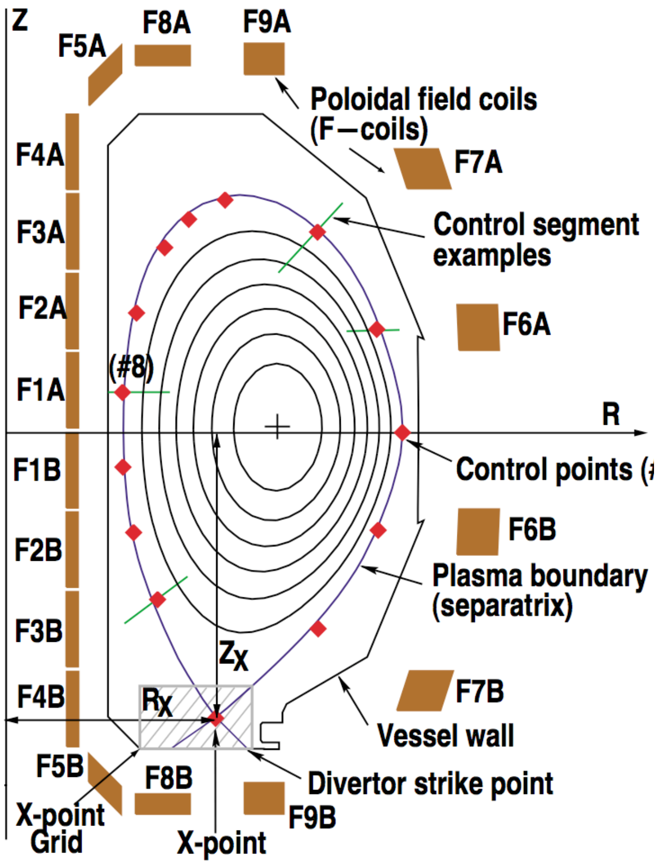
Catch and Subdue (In Development): NTM Suppression Before Mode Saturation

- **Aim: Suppress the NTM before it saturates**
  - Less power, more stable
- **Detect that island is forming**
  - This is done with Mirnov ~ 20-40 ms.
- **Find the location of the island**
  - Use ECE for target (NTM location) and current (EC deposition) position.
- **Move the EC mirror to the island location**
  - ~1-2 cm motion in plasma to hit the island (~30-50 ms)
- **Catch the island before it saturates**
  - Island saturation is a variable but for 3/2 mode ~150-200 ms can be taken as guiding conservative value
  - We need to hit the island as soon as possible but definitely before it saturates
  - Spec for time from the detection to start of ECCD @ island <~50 ms.



Snowflake Divertor for DIII-D

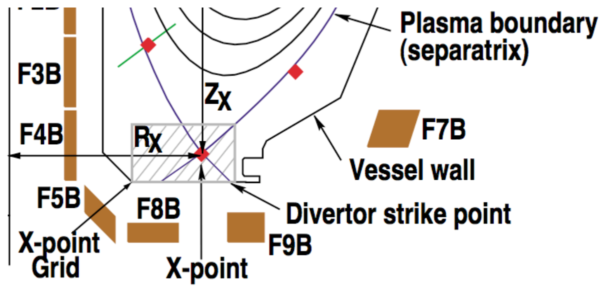
DIII-D Scenarios with Snowflake Variants



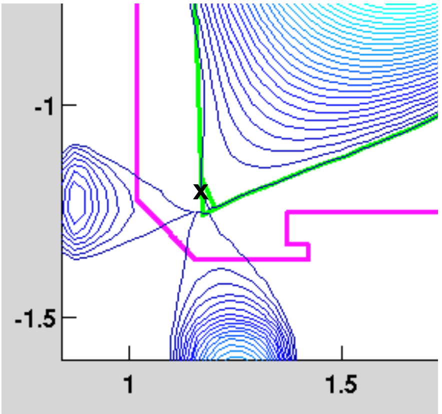
- **Engineering constraint: F9B had to be kept at negative current to avoid strike point getting in the cyro-pump gap.**
- **Due to the complicated PS at DIII-D.**
  - Need a new patch panel configuration
  - Need configurations that satisfy VFI constraints.
- **Progress to achieve the configurations:**
  - Obtained desired current levels for the coils.
  - Studied different variations around these configs.
  - Best option is to use the F4B and F8B to control the strike point locations.
  - Scan the F5B in steps to see the various snowflake configurations achieved.
- **Full control of the feedback control of snowflake to follow.**

Constrained DIII-D Scenarios with Snowflake Variants

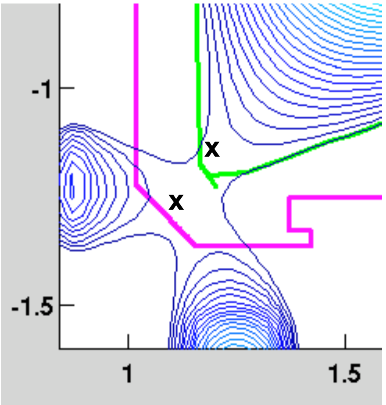
- **Perfect snowflake and snowflake flake -/+ are possible at DIII-D with various engineering and power supply constrains of the system.**



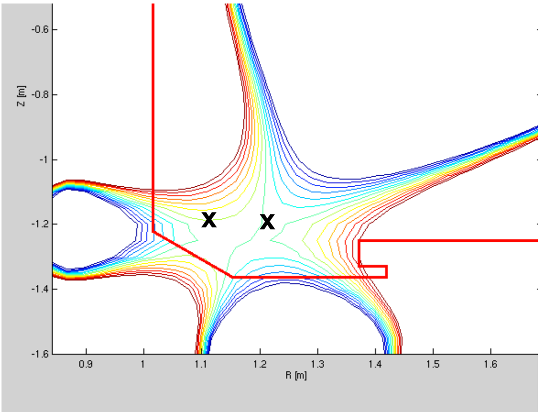
DIII-D Coil Configuration



DIII-D Perfect Snowflake

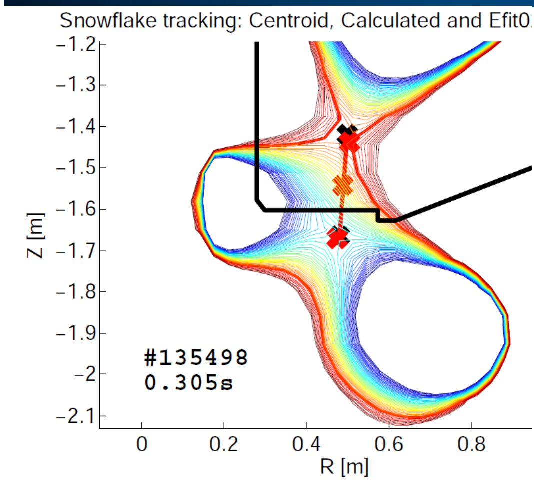


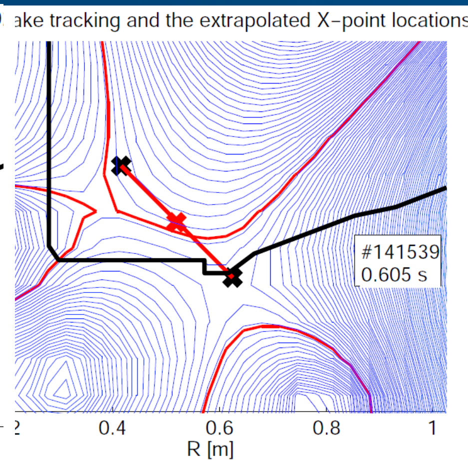
DIII-D Snowflake +



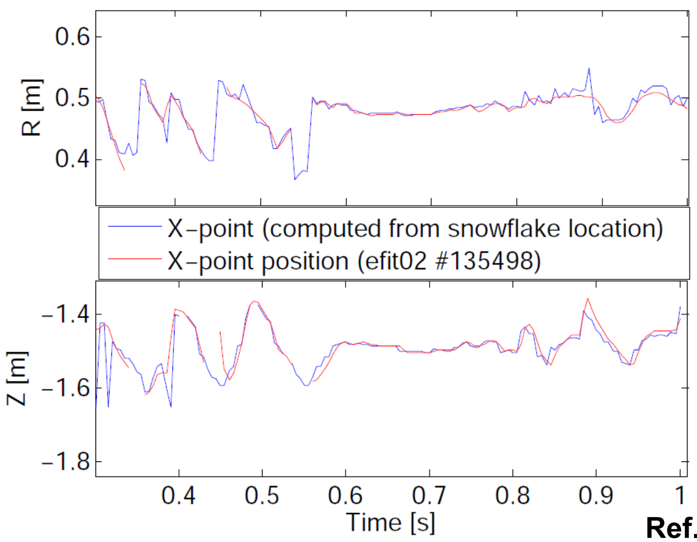
DIII-D Snowflake -

Feedback: Tracking and Control for Snowflake -/+





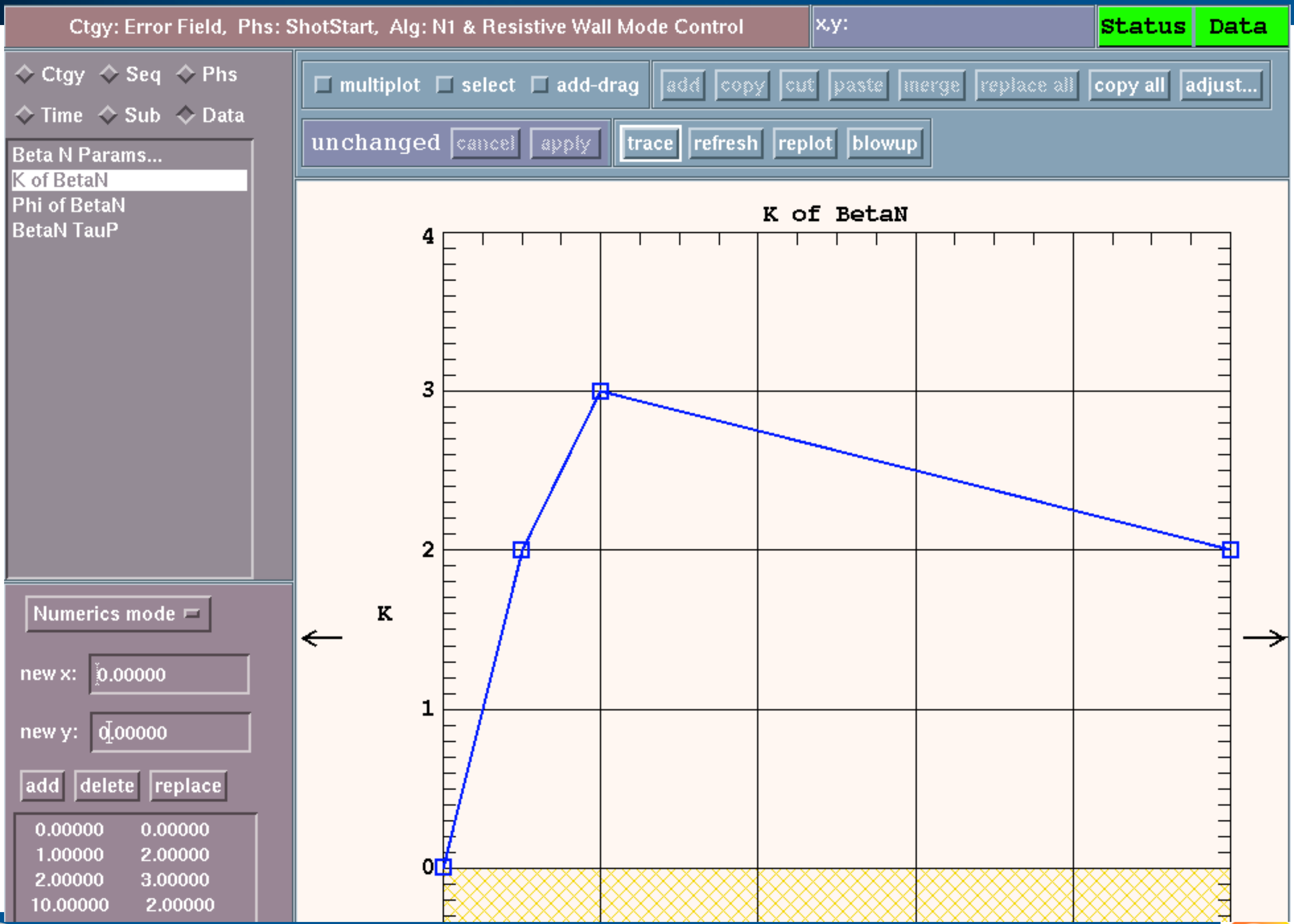
- We are running this Thursday and depending on the results, we will be given more days. We can easily do snowflake control if we are given time.
- Above: Snowflake tracking for NSTX:
    - Red cross is the tracked snowflake centroid
    - Black crosses are the calculated X-points locations by the snowflake tracking algorithm
- Below: X-point position computed from the radius and angle obtained from the snowflake tracking and position of the 2nd X-point.
- Use these methods control and asses the snowflake at DIII-D.
- PCS upgrade needed (minimal).



Ref. M.A. Makowski & D. Ryutov, “X-Point Tracking Algorithm for the Snowflake Divertor”
M.V. Umansky et al.. “Analysis of geometric variations in high-power tokamak divertors.”

BetaN Dependent Error Field Correction

BetaN Dependent Error Field Correction

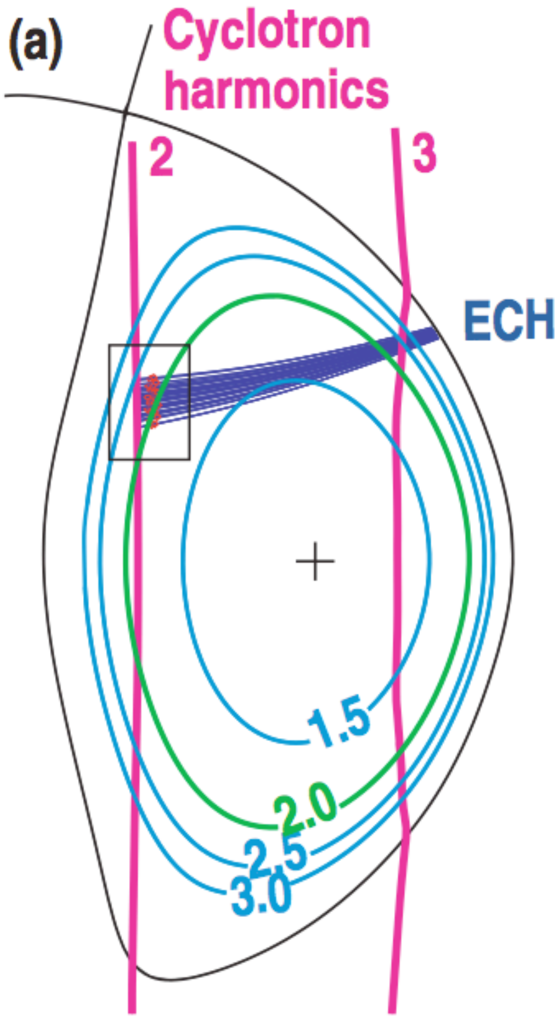


BetaN Dependent Error Field Correction

- **There is a BetaN dependence of the EFC control parameters. This is in addition to the general increase in current as the plasma evolves leading to increased Error Field in say F7B.**
- **Previous way of operation: Multiplying the control by random constants at higher BetaN.**
- **We added EFC algorithm with BetaN dependence.**
- **The algorithm is test in experiments.**
- **I hope to study the optimal EFC for BetaN and improve performance of the H-mode marginally stable shots. Does 3D coils penetration in the plasma or interaction with the plasma reduces as BetaN increases?**

Thank You!

Present ECCD Deposition Calculations: Ray Tracing



- Ray tracing: using the density profile find the diffraction and path of the ECCD
- Using EFIT and MSE find the intersection of the 2 fce and the ECCD path.
- Problem: Too many diagnostic errors add up (MSE+EFIT+Density). Density profile is not really know that well.