Sawtooth Cycle Time Evolution of Measured Energy and Particle Transport in the MST Reversed-Field Pinch

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The "sawtooth cycle" is a slowly changing, but very significant aspect of the plasma equilibrium. Observations show that the character of the sawtooth event in the MST changes dramatically when the q=0 surface is removed from the plasma. Time evolved measurements of thermodynamic profiles have been obtained in both reversed (F<0) and non-reversed (F=0) plasmas, leading to the first measurement of radially resolved, time evolving heat transport in the MST. In both cases, the heat flux is predominantly conductive over the majority of the plasma volume, though convective heat transport becomes significant in the edge. The observed heat and particle fluxes cannot be described by a diagonal transport matrix. However, including cross-terms, such as those consistent with Rechester-Rosenbluth and Harvey, can account for the observed fluxes. The value of magnetic field stochasticity expected by this analysis agrees very well with predictions from DEBS modeling.

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Outline

- Motivation: To measure the coefficients for electron particle and energy transport with sufficient accuracy to make valid comparisons to theoretical models.
  - Measurements of particle and energy source terms and gradients.
- Experimental Conditions: time dependant transport study of
  - "Standard" plasma: ~385 kA, 1.1×10^{19} m^{-3}, F ~ -0.24, in deuterium.
  - "Non-Reversed" plasma: ~385 kA, 1.1×10^{19} m^{-3}, F = 0, in deuterium.
- Determination of Particle Flux (in flux surface geometry)
  - $n_e(\rho,t)$, $S_p(\rho,t)$, dn_e/dt $\Rightarrow$ $\Gamma(\rho,t)$
- Determination of Heat Flux
  - $T_e(\rho,t)$, $n_e(\rho,t)$, $\eta j^2(\rho,t)$ $\Rightarrow$ $Q(\rho,t)$
- Diffusive transport coefficients: D and χ
- The Harvey model of stochastic transport: D_{st}

Motivation

- The plasma "sawtooth cycle" is a slowly changing, but very significant aspect of the plasma equilibrium. Examining transport quantities wrt/ the sawtooth cycle phase can shed light on important plasma dynamics.
- To accurately study the movement of energy and particles in a MST plasma it is necessary to have detailed, accurate measurements of basic plasma parameters: T_e, n_e, n_D, T_i, j, etc.
- Some of these quantities can be directly measured:
  - $n_e(r,t)$ from Far Infrared Interferometry
  - $n_D(r,t)$ from n_e and a collinear D_α array
  - $T_e(r,t)$ from Thomson Scattering
  - $T_i(\sim 0,t)$ from Rutherford Scattering
- Others (in particular j) can be found from modeling (MSTFIT)

Particle and Heat Transport Equations

- Including possible sources and sinks of energy and particles, the equations of continuity and energy balance are:

$$\frac{\partial n}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma) + S_p \qquad \frac{\partial}{\partial t}(\frac{3}{2}nT) = -\frac{1}{r}\frac{\partial}{\partial r}(rQ) + S_E$$

- Solving for the particle and heat fluxes:

$$\boxed{\Gamma_e = \frac{1}{r}\int r(S_{p,e} - \frac{\partial n_e}{\partial t})\partial r} \qquad \boxed{Q = \frac{1}{r}\int r\left(S_E - \frac{\partial}{\partial t}(\frac{3}{2}nT)\right)\partial r}$$

- For electrons in a 3 component plasma (e^-, np^+, impurity Z), we can write:

$$S_{p,e} = n_e n_H \langle \sigma_i v \rangle \qquad S_{E,e} = P_e - P_{ei} - P_{ez} - P_{rad}$$

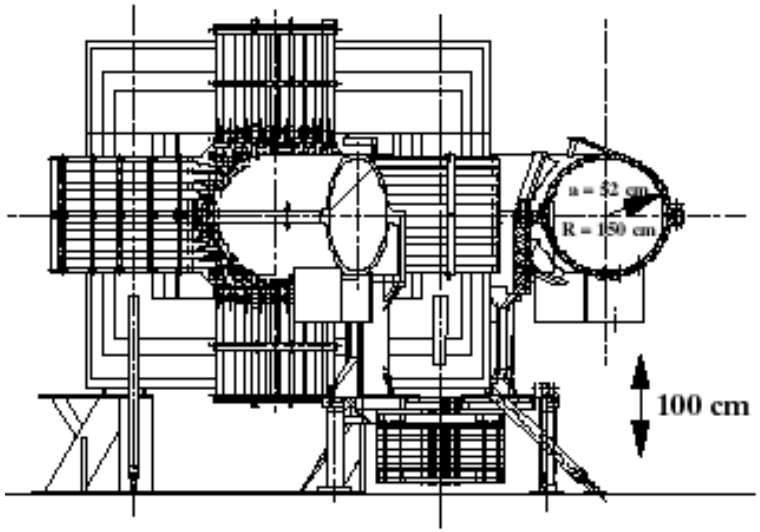
$$P_e = \eta j^2$$

$$P_{ei} = \frac{m_e}{m_i} n_i n_e e^4 \frac{\ln(\Lambda)}{4\varepsilon_0}(T_e - T_i)\sqrt{2/\pi^3 m_e T_e^3}$$

$$P_{ez} = \frac{m_e}{m_z} n_z n_e Z^2 e^4 \frac{\ln(\Lambda)}{4\varepsilon_0}(T_e - T_z)\sqrt{2/\pi^3 m_e T_e^3}$$

$$P_{rad} = C_{rad}(r/a)^8 P_e$$

The Madison Symmetric Torus Reversed Field Pinch



minor radius	0.52 m
major radius	1.5 m
plasma current	< 0.6 MA
loop voltage	~ 10 V
toroidal volt-sec	< 2 V-s
pulse length	< 80 ms
electron temperature	< 1000 eV
ion temperature	< 500 eV
electron density	< 2×10^{13} cm^{-3}
beta	~ 5 - 15%
energy confinement time	< 10 ms

Magnetic diagnostics:

Radial field:

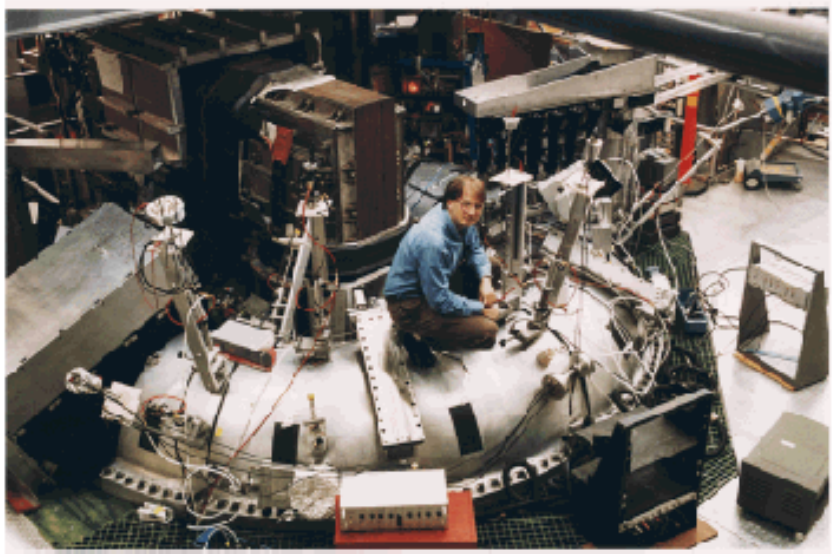
32 coils around the poloidal gap

Mode spectra:

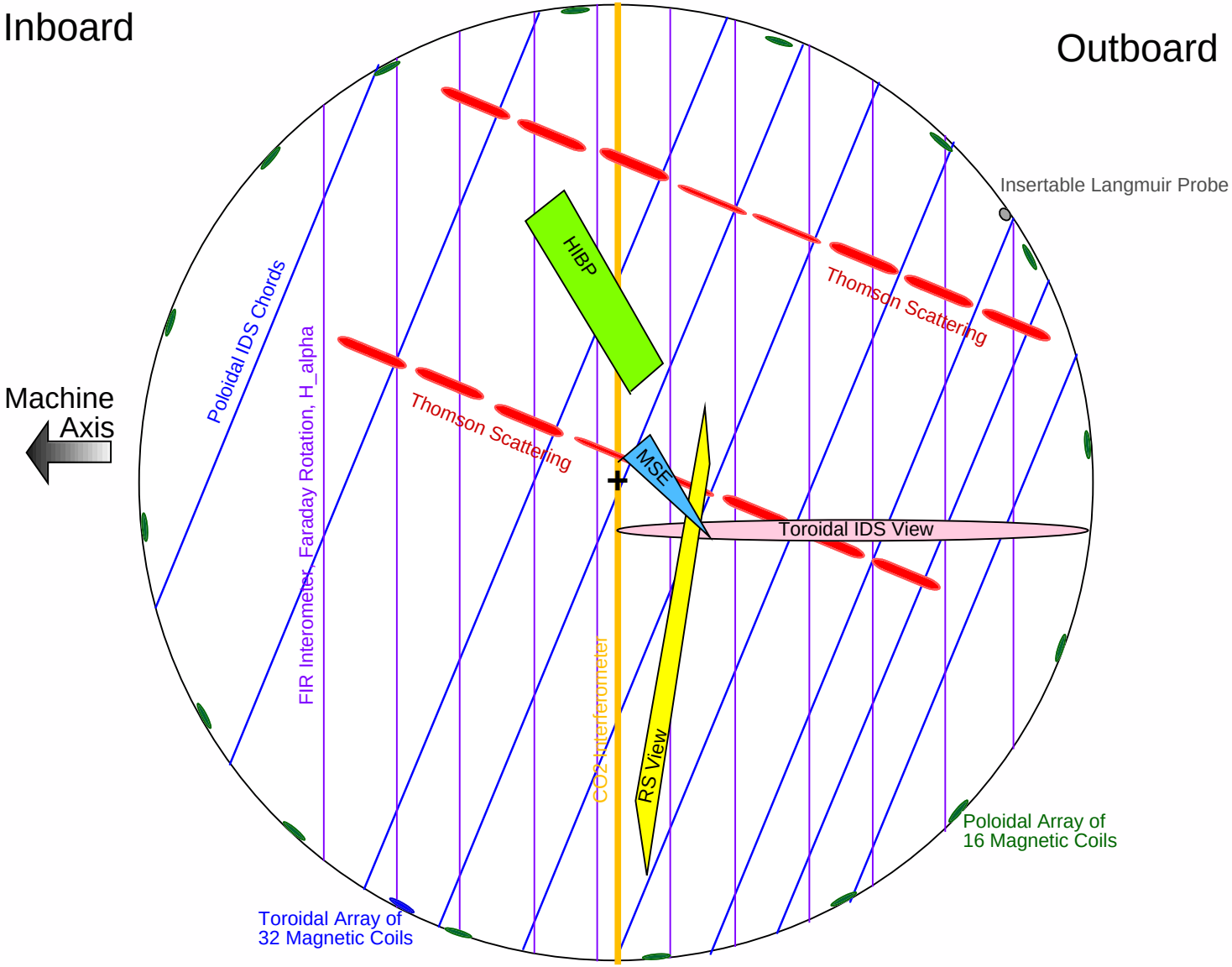
64 sets of 3 orthogonal coils toroidally distributed

16 sets of 3 orthogonal coils poloidally distributed

8 sets of 3 orthogonal coils poloidally distributed

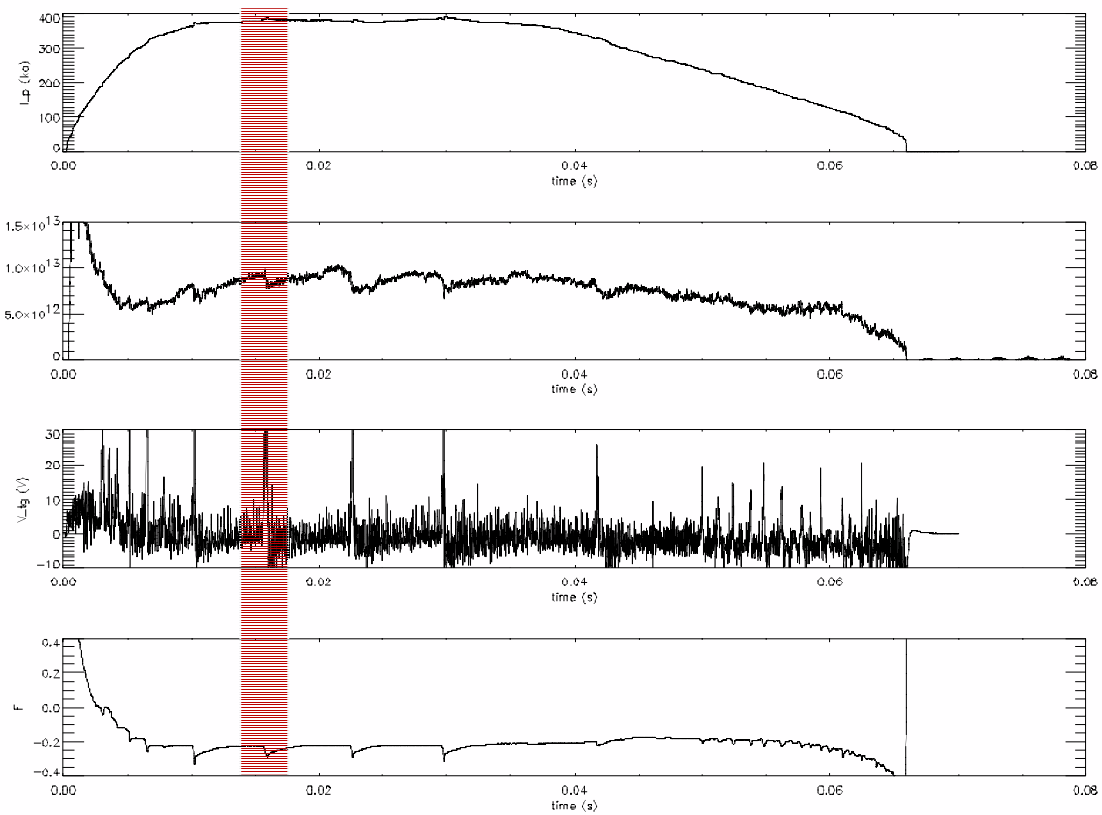


Poloidal Projection of Diagnostic Locations



Introduction to the Experiment: F~-0.2

13-nov-2000 Shot 69

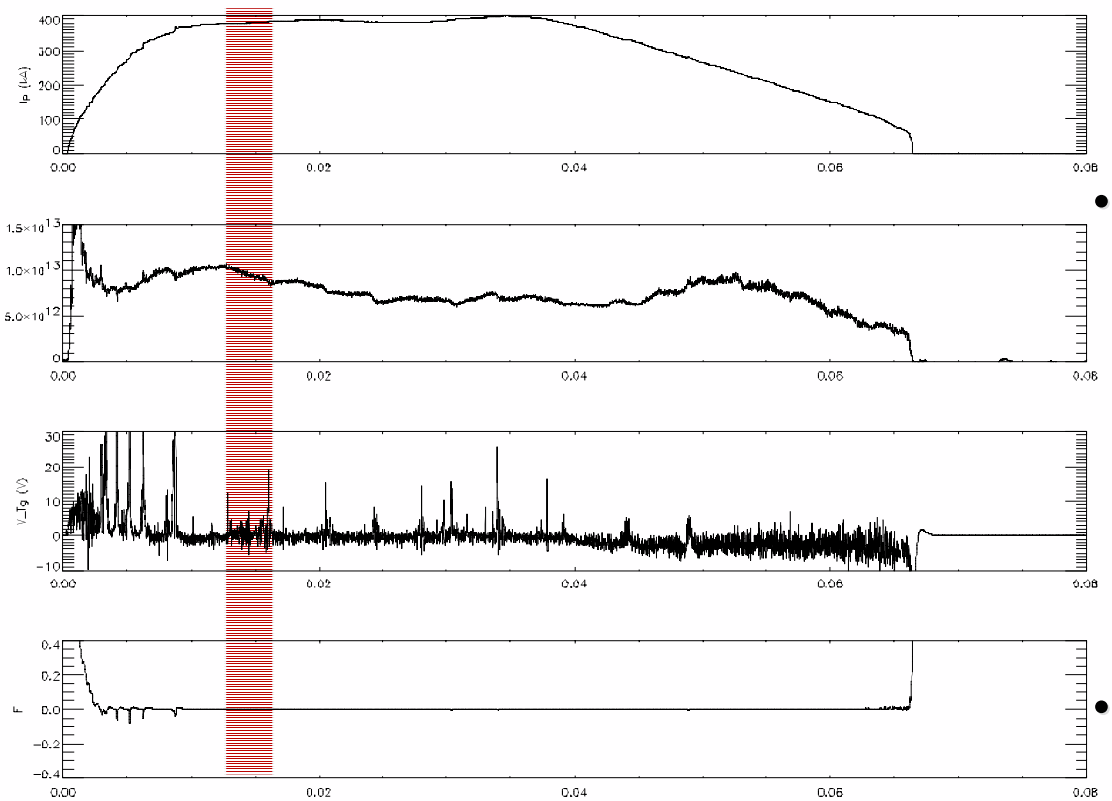


Motivation: To study the dynamics of a fully diagnosed MST plasma over a sawtooth cycle.

- Typical plasma parameters:
  - "Standard" w/ full PFN
  - I_p ~ 385 kA
  - F ~ -0.24
  - n_e ~ 1.1×10^{13} cm^{-3}
  - Deuterium
- Sawtooth period ~ 5.5 ms
- Time of interest: ~ 15 ms, i.e. early in the discharge but during plasma "flattop"

Introduction to the Experiment: F=0

30-mar-2001 Shot 80

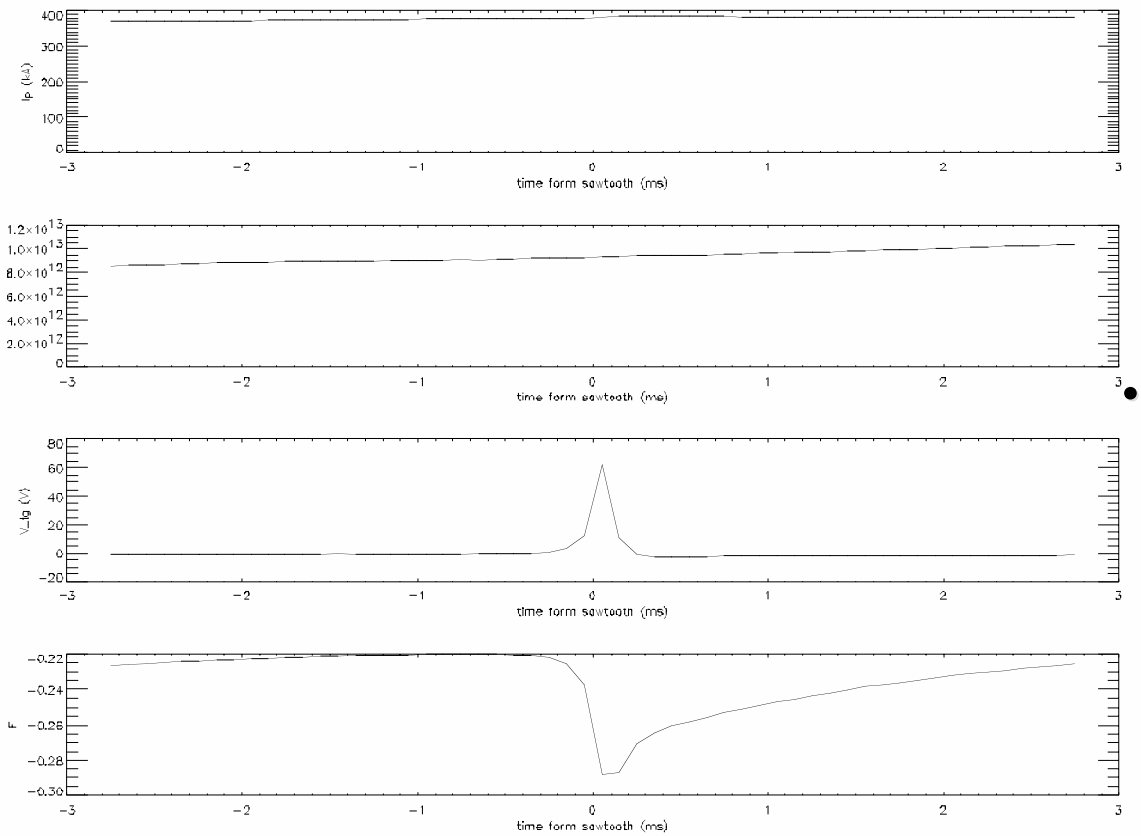


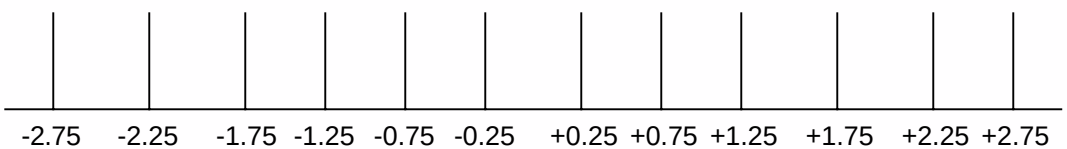
Motivation: To study the effect of removing the reversal surface from the plasma.

- Typical plasma parameters:
  - "Non-reversed" w/ full PFN
  - I_p ~ 385 kA
  - F ~ 0
  - n_e ~ 1.1×10^{13} cm^{-3}
  - Deuterium
- Sawtooth period ~ 5.5 ms
- Time of interest: ~ 15 ms, i.e. early in the discharge but during plasma "flattop"

Shots are Ensembled wrt. The Sawtooth Crash

nov-2000 ensemble of ~400 shots

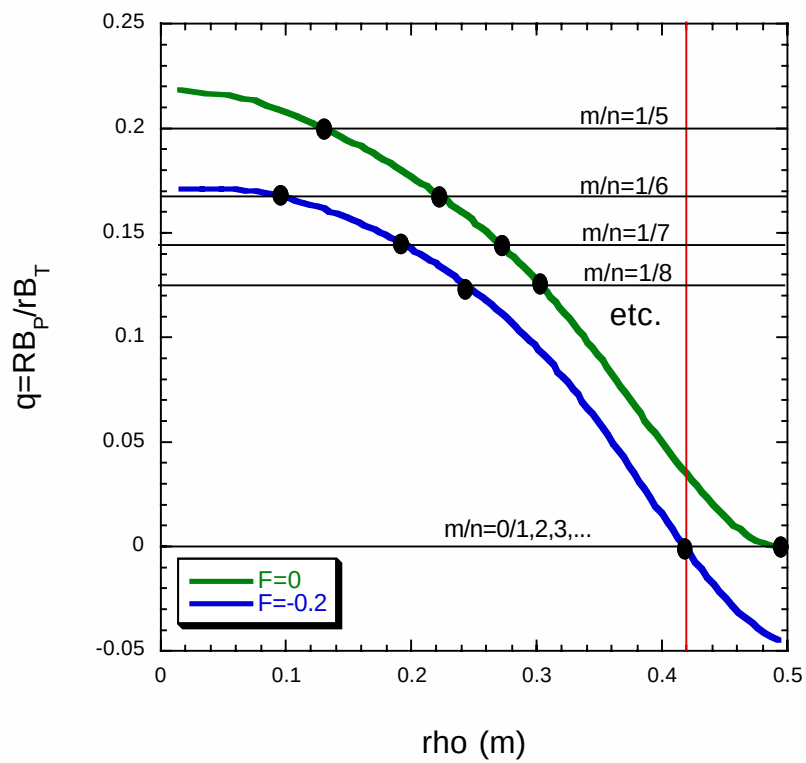




- Plasma shots are ensembled for 2 reasons:
  - Want an "average" measure of quantities, i.e. smooth out the fluctuations
  - Need ~400 shots to get $T_e(r,t)$ from Thomson sct.
- This 6 ms time window about the crash is sub-divided into 12 time slices, every 0.5 ms.
  - High time resolution signals (e.g. FIR) are computed as 0.1 ms ensembles.
  - Raw TS data is ensembled in 0.5 ms bins.

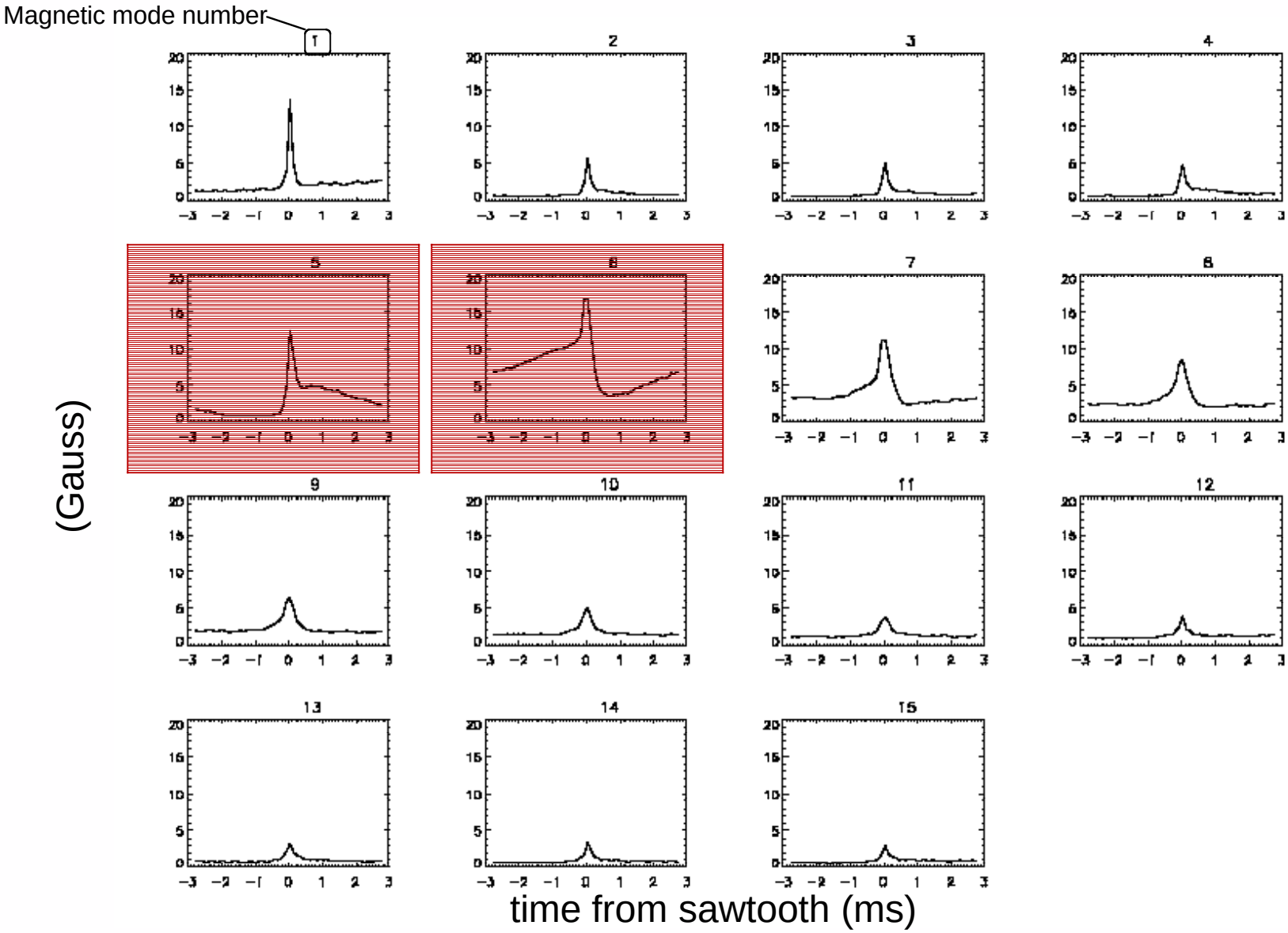
The q=0 surface is excluded in F=0 plasmas

The "Safety Factor" profile -1.75 ms away from the nearest sawtooth crash.

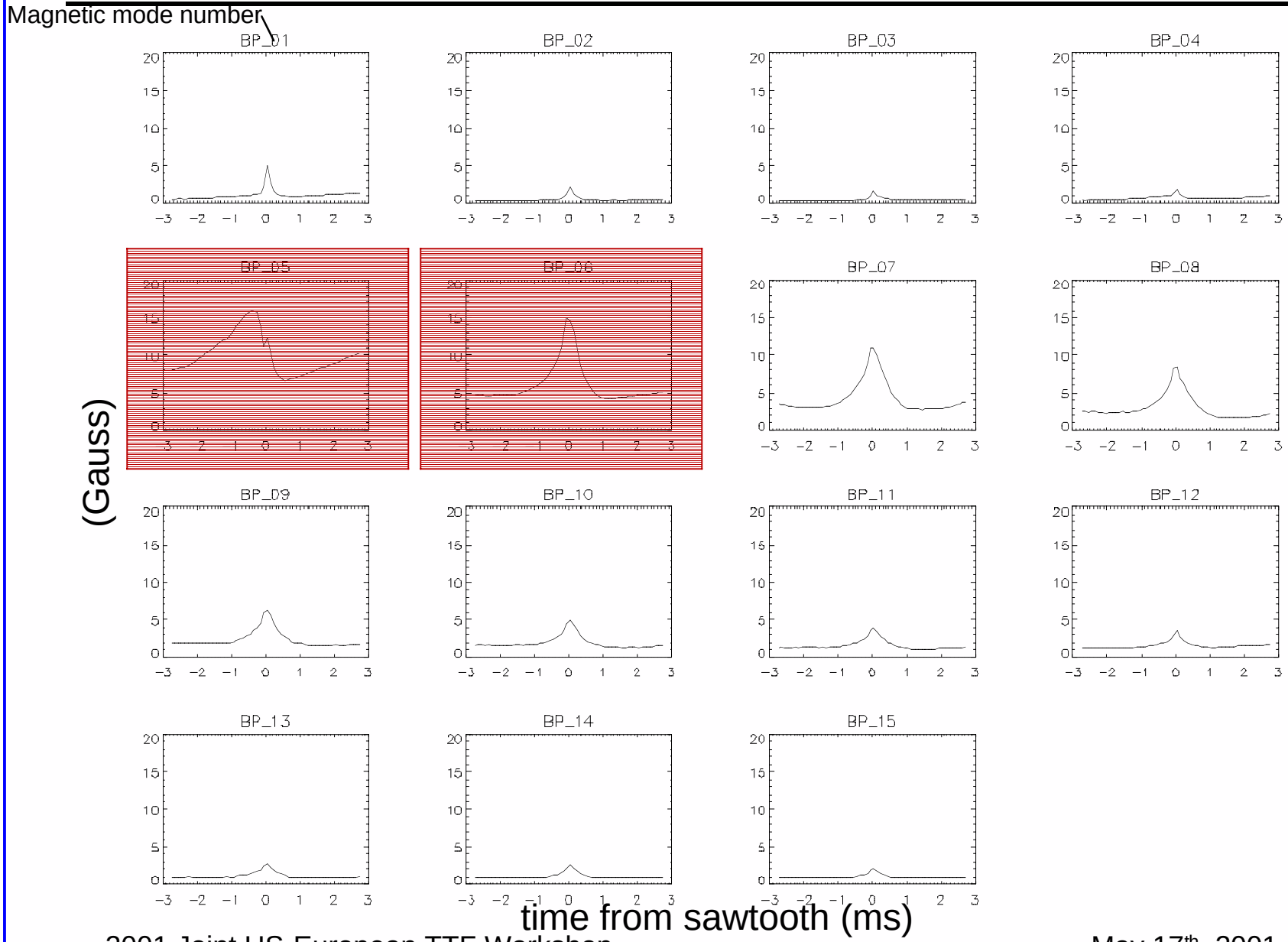


- In MST plasmas $B_T \sim B_P$ and R/a~3, resulting in q<1 everywhere.
- Core modes are dominantly m=1 and n=5,6,7
- Edge modes are dominantly m=0 (at the reversal surface) and n=1,2,3,…
- In F=0 plasmas, the q=0 surface is removed to the extreme edge, eliminating the m=0 rational surface, and presumably reducing the overal level of magnetic fluctuations.

B_P array signals constrain $q_0(t)>1/6$ for F~-0.24

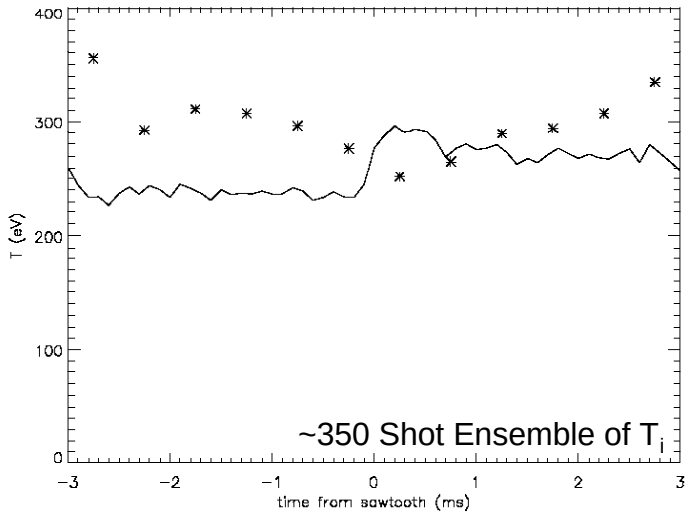


B_P array signals constrain $q_0(t)>1/5$ for F=0

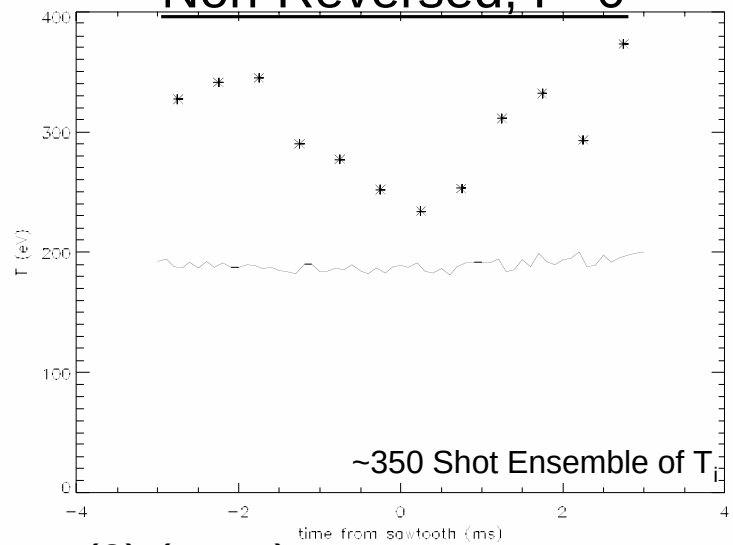


$T_i(0,t)$ from Rutherford Scattering shows ion heating

Standard, F~-0.24



Non-Reversed, F=0

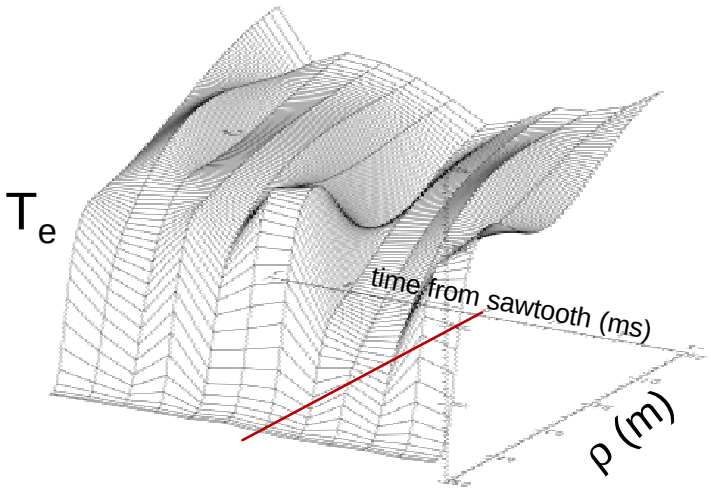


RS T_i (solid), MSTFIT $T_e(0)$ (stars)

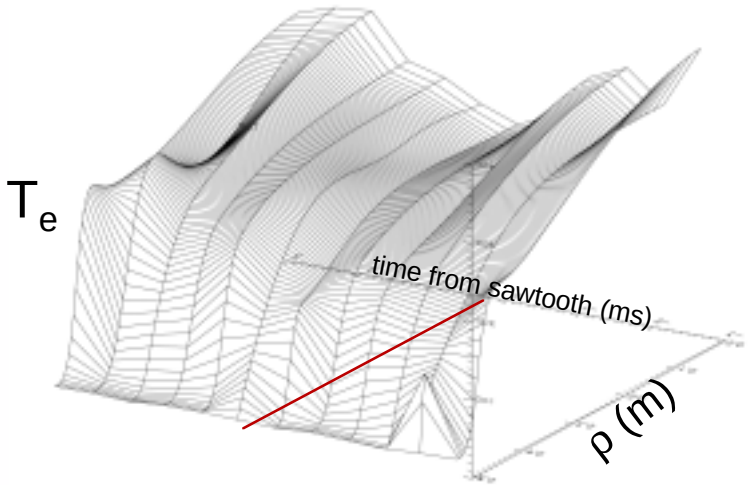
- Rutherford Scattering measures the temperature of the majority ion species, showing evidence of ion heating at the sawtooth crash to temperatures hotter than the central electron temperature for F~-0.24.
- Impurity ion (C_V) temperatures, measured via an Ion Dynamics Spectrometer, have confirmed this heating in the past. Data Pending.
- There is no evidence of this ion heating in F=0 plasmas.

Temperature Profile Evolution

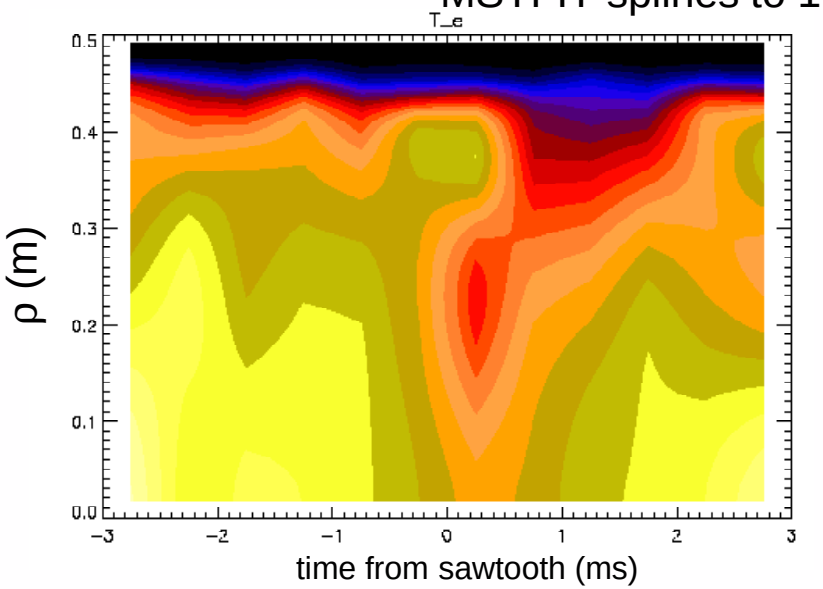
Standard, F~-0.24

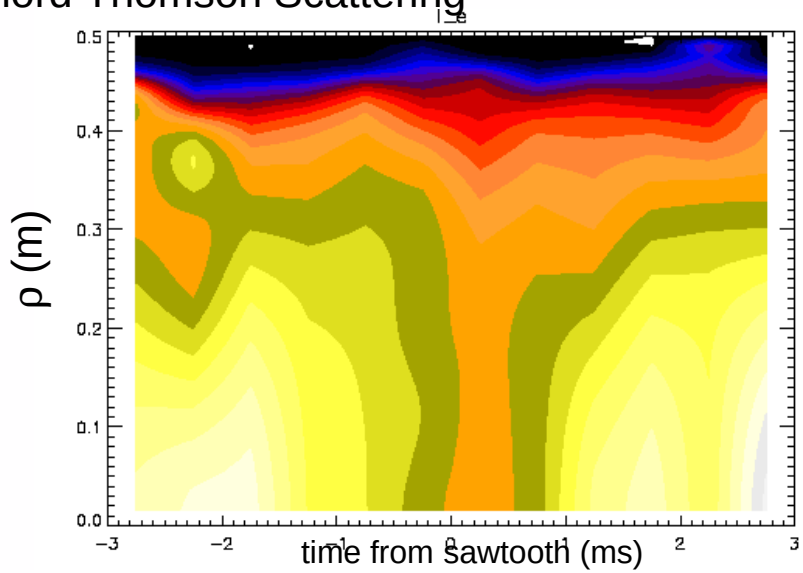


Non-Reversed, F=0



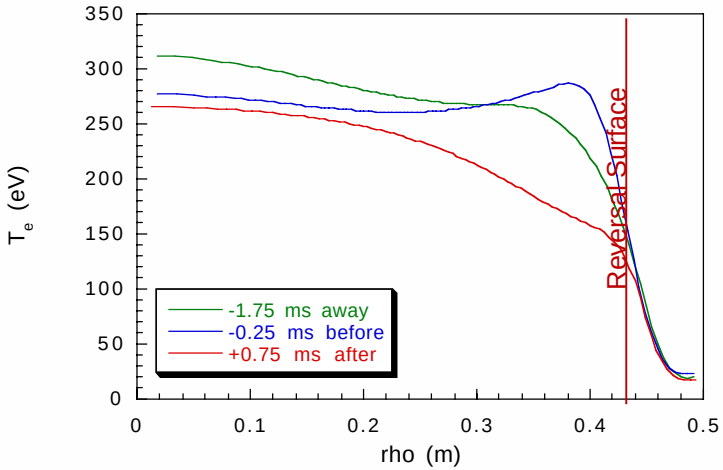
MSTFIT splines to 16 chord Thomson Scattering



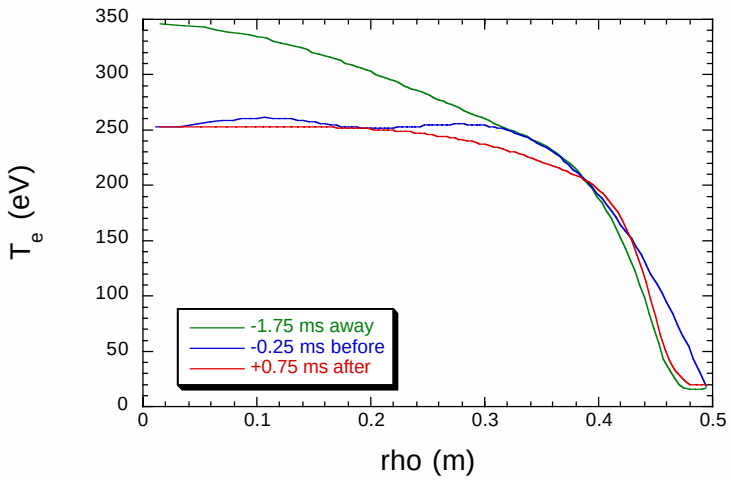


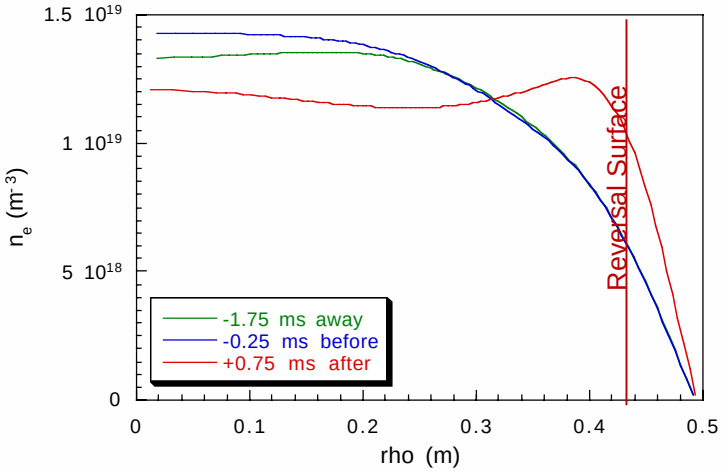
Eliminating the Reversal Surface Results in Higher T_e

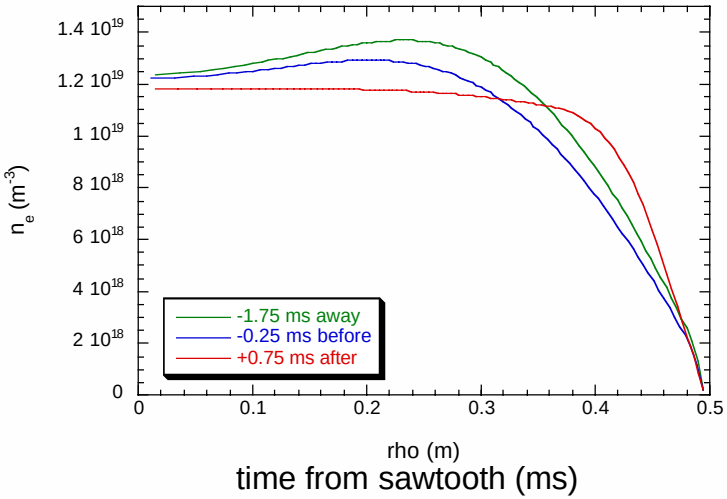
Standard, F~-0.24



Non-Reversed, F=0

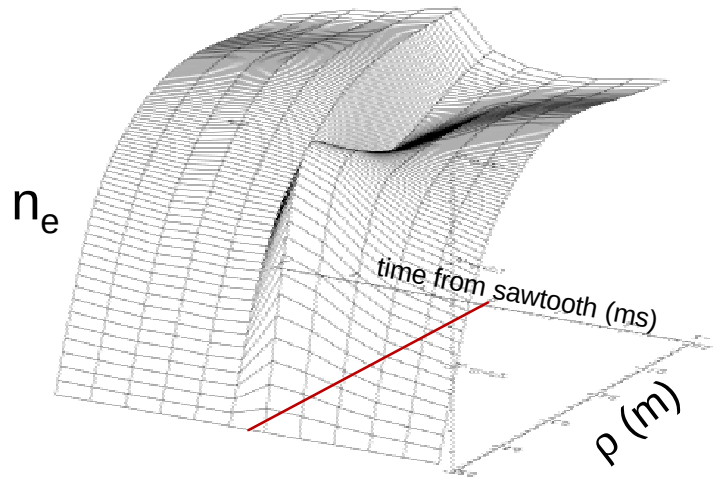




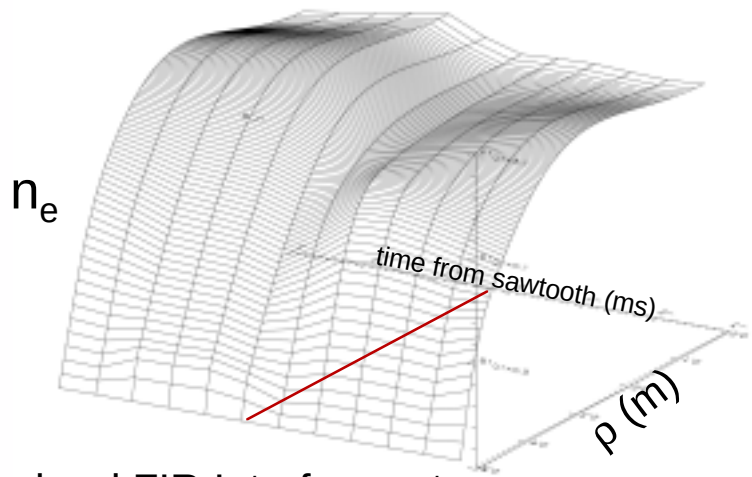


Density Profile Evolution

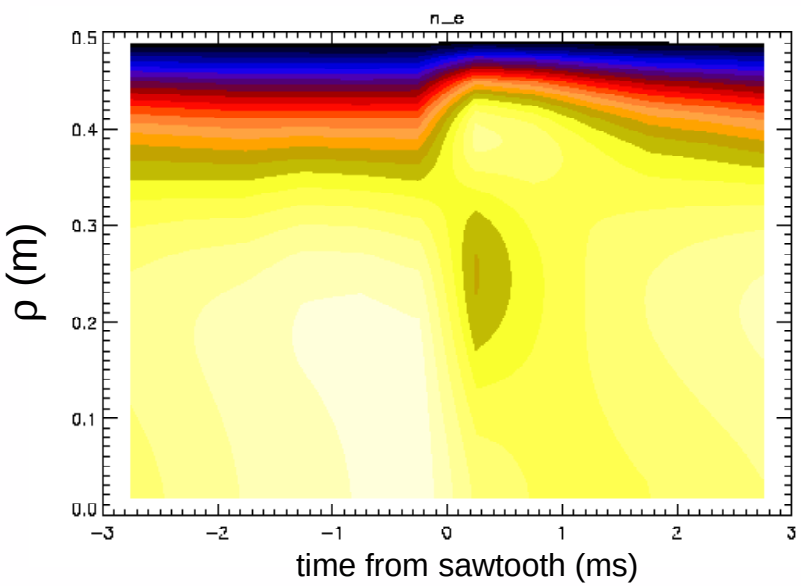
Standard, F~-0.24

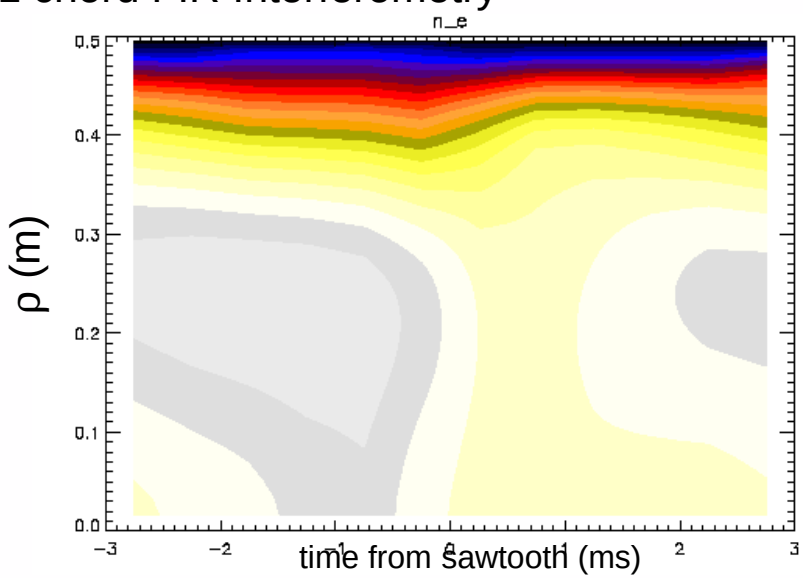


Non-Reversed, F=0



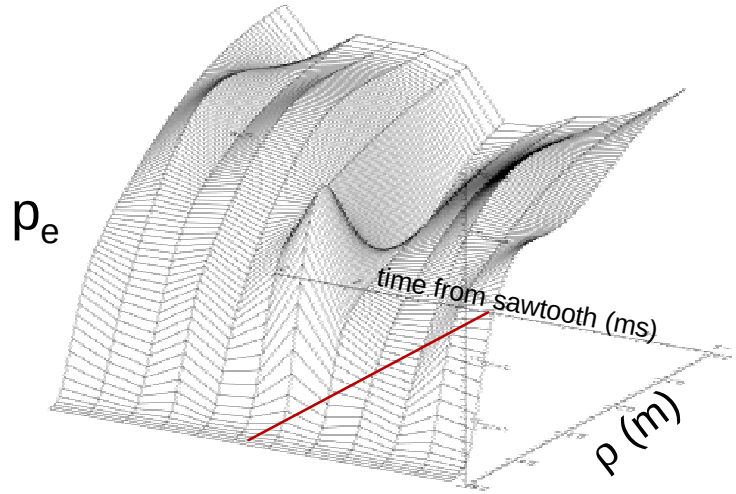
MSTFIT Abel inverted 11 chord FIR Interferometry

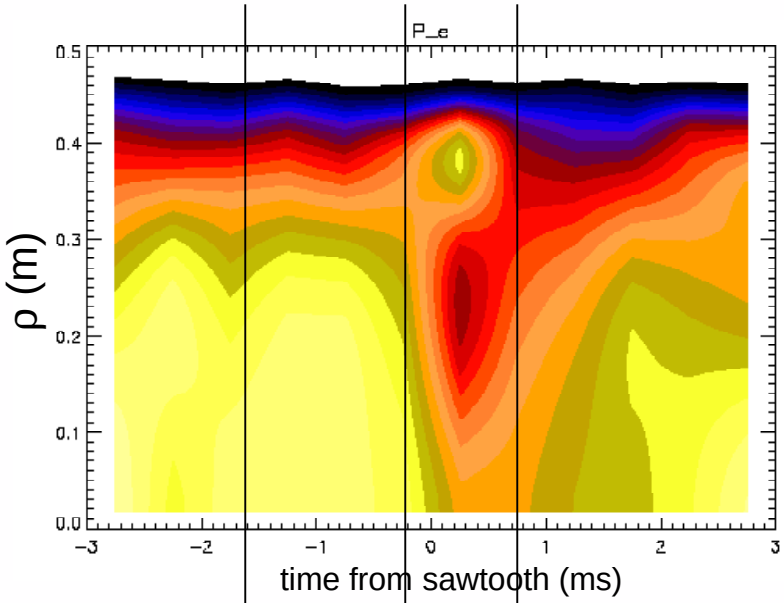




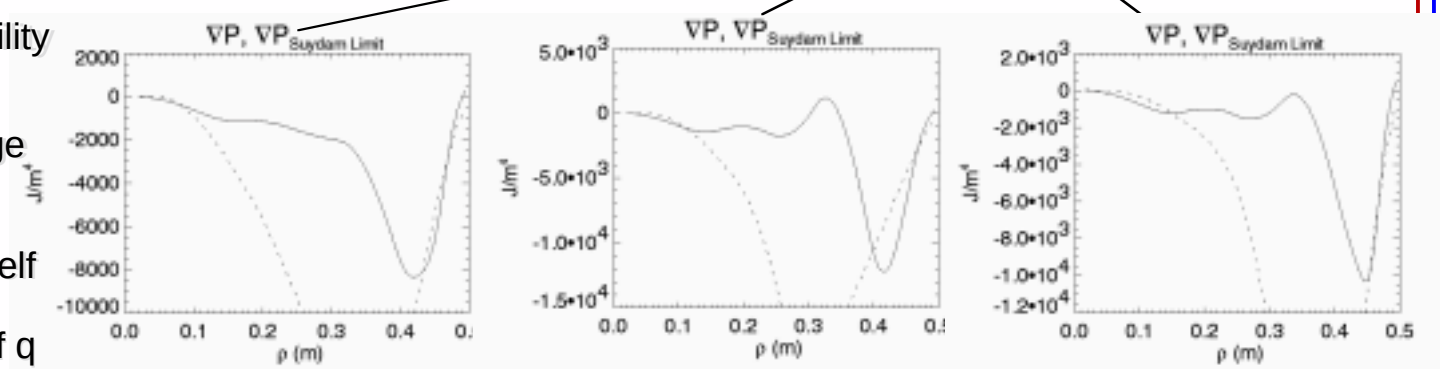
Pressure Profile Evolution: F~-0.24

Electron pressure evolution from n_e*T_e



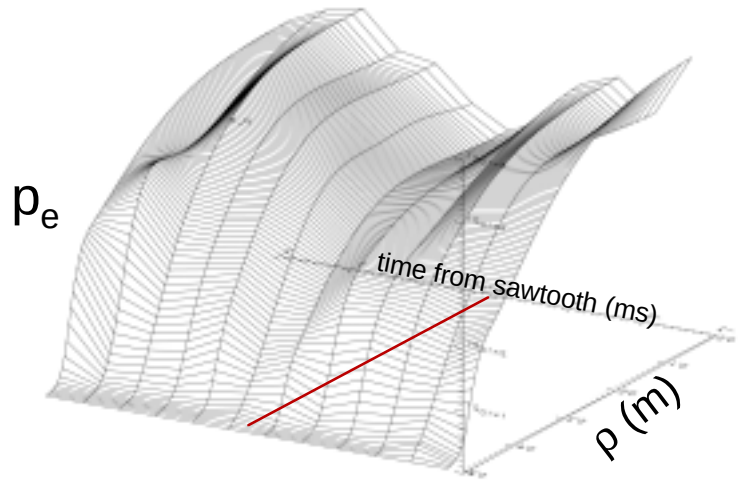


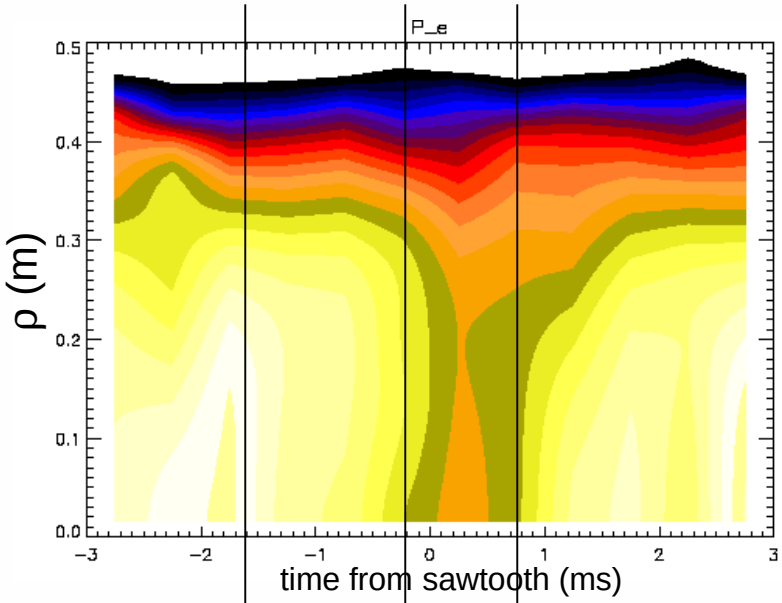
- Before the sawtooth crash the edge pressure gradient crosses the Suydam interchange mode stability limit.
- After the crash, the edge pressure gradient has relaxed away from the Suydam limit, which itself has softened due to an increase in the shear of q (ie. q'/q).



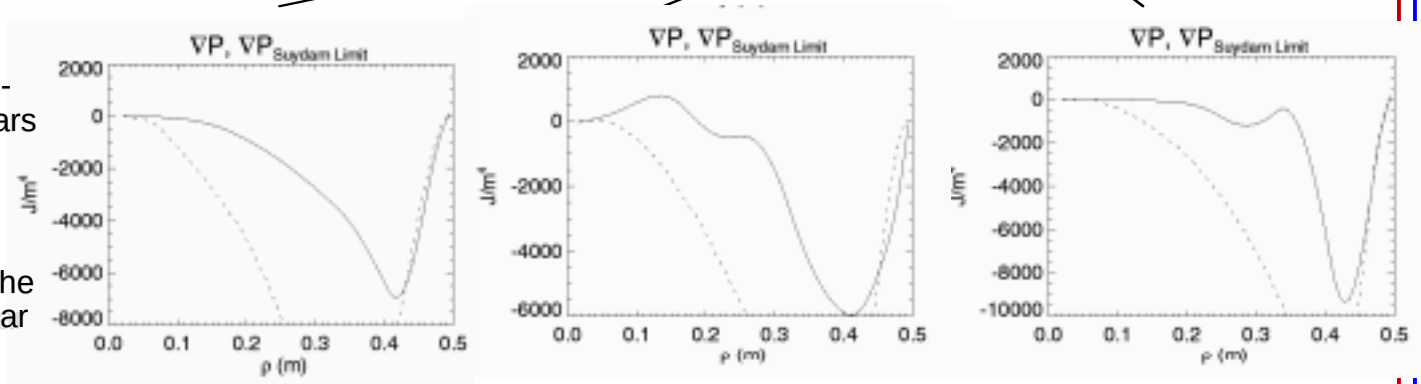
Pressure Profile Evolution: F=0

Electron pressure evolution from n_e*T_e





- Similarly, before the sawtooth crash the edge pressure gradient crosses the Suydam interchange mode stability limit.
- In both "Standard" and "Non-Reversed" plasmas, it appears that the pressure profile begins to flatten prior to the actual sawtooth crash.
- Even away from the crash, the pressure gradient is very near to the stability limit.

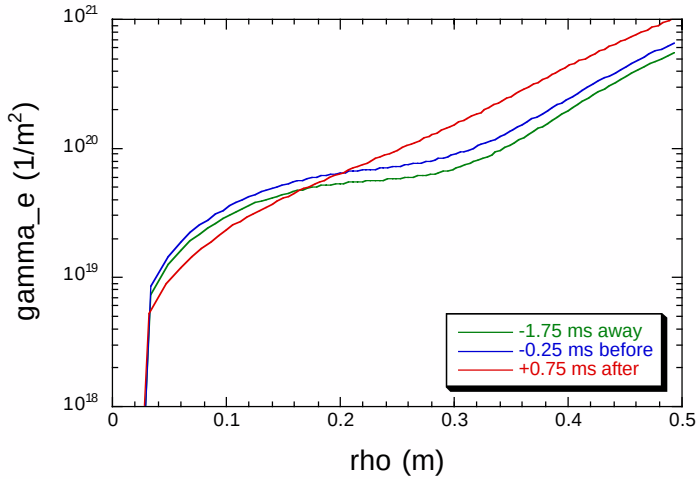


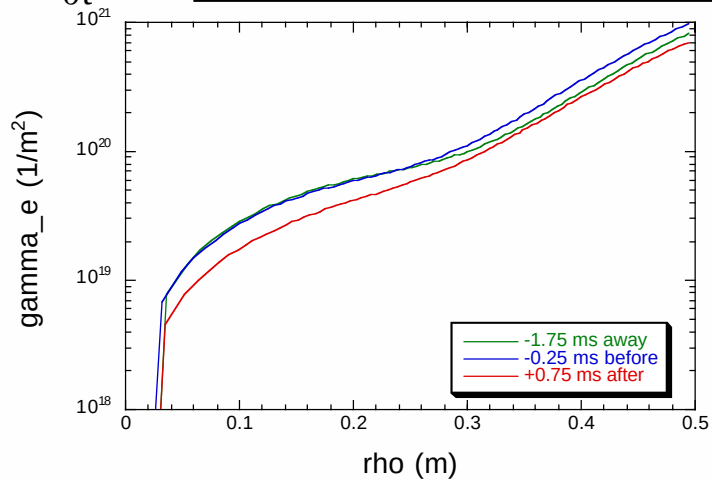
Particle and Heat Flux

Standard, F~-0.24

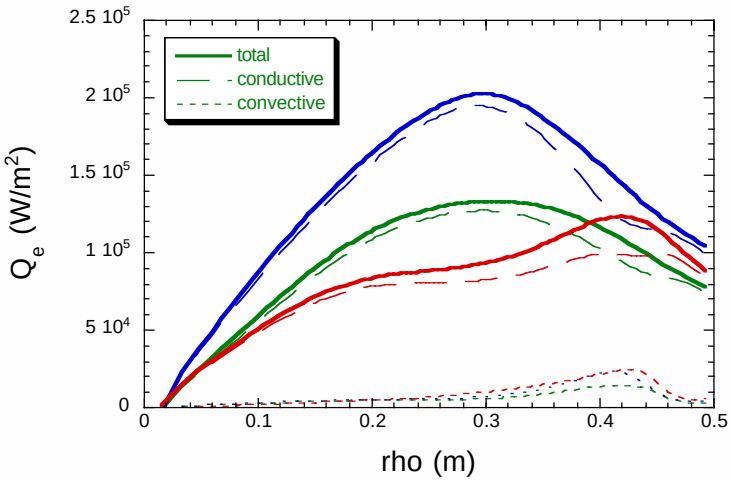
$$\Gamma_e = \frac{1}{r}\int r\left(S_{p,e} - \frac{\partial n_e}{\partial t}\right)\partial r$$

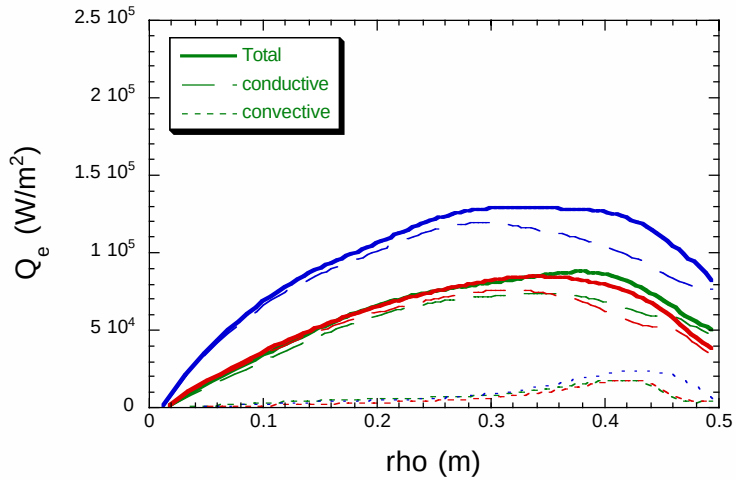
Non-Reversed, F=0





$$Q = \frac{1}{r}\int r\left(S_E - \frac{\partial}{\partial t}\left(\frac{3}{2}nT\right)\right)\partial r$$



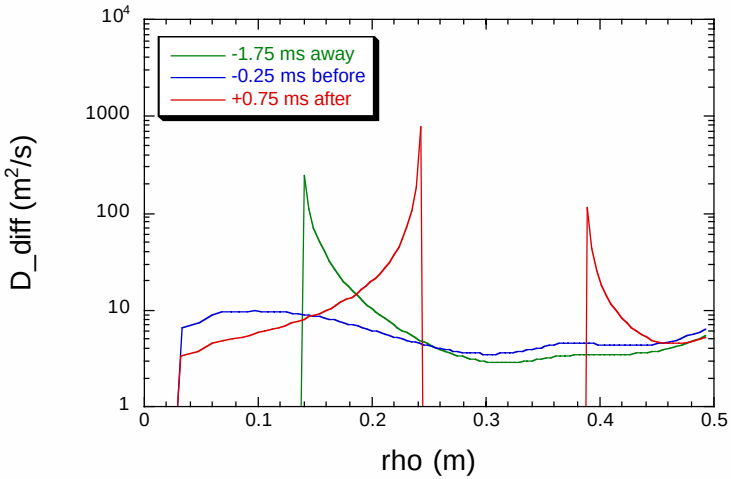


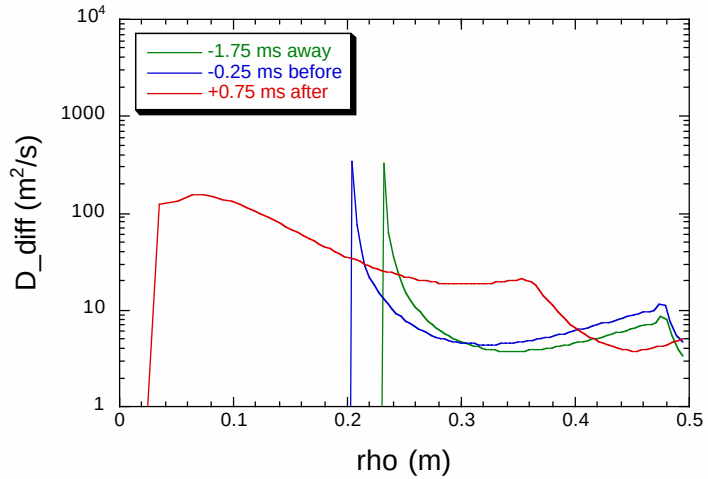
Particle and Heat transport coefficients: D, χ

Standard, F~-0.24

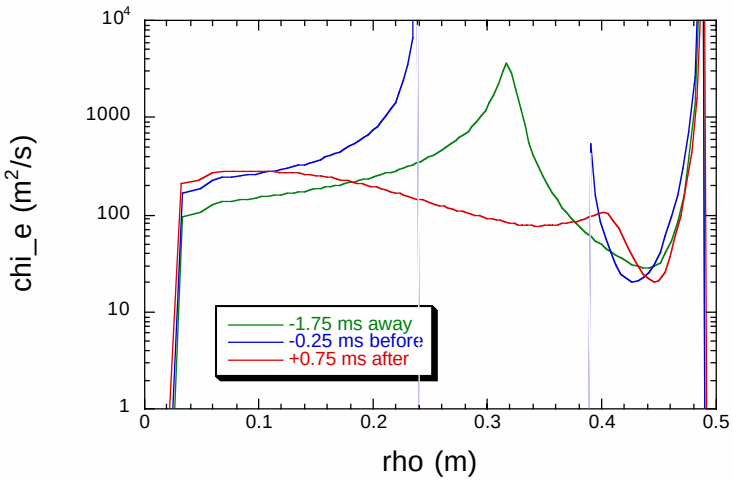
Non-Reversed, F=0

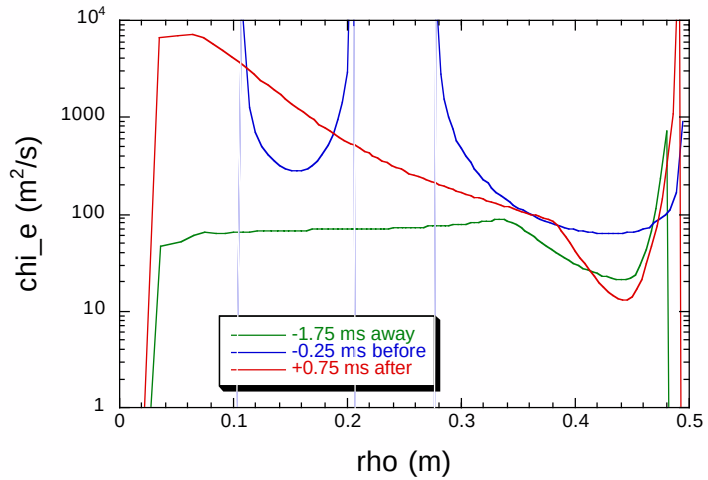
$$\Gamma = -D\nabla n$$





$$Q = \tfrac{5}{2}\Gamma T - \chi n \nabla T$$





Transport Equations (Harvey)

- The kinetically derived Fokker-Plank Equation for a plasma, including an ambipolar, radial electric field is:

$$\left(\frac{\partial f}{\partial t}\right)_m = \frac{|v_{par}|}{r}\left(\frac{\partial(rD_m)}{\partial r} + \frac{qE_a}{mv_{par}}\frac{\partial(rD_m)}{\partial v_{par}}\right)\left(\frac{\partial f}{\partial r} + \frac{qE_a}{mv_{par}}\frac{\partial f}{\partial v_{par}}\right)$$

- Taking the first two moments of this equation and comparing to the source free continuity ($\frac{\partial n}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma)$) and energy balance ($\frac{\partial}{\partial t}(\frac{3}{2}nT) = qE_a\Gamma - \frac{1}{r}\frac{\partial}{\partial r}(rQ)$) equations leads again to expressions for the particle and heat flux:

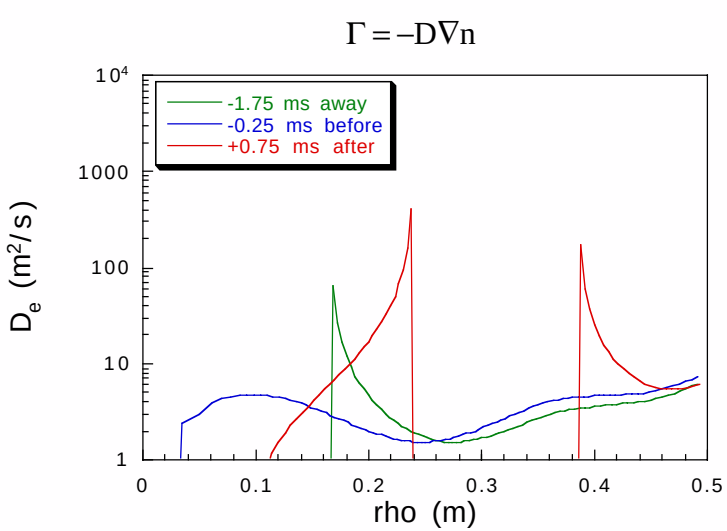
$$\boxed{\Gamma = -Dn\left(\frac{1}{n}\frac{\partial n}{\partial r} + \frac{1}{2T}\frac{\partial T}{\partial r} - \frac{qE_a}{T}\right)} \qquad \boxed{Q = -2DnT\left(\frac{1}{n}\frac{\partial n}{\partial r} + \frac{3}{2}\frac{1}{T}\frac{\partial T}{\partial r} - \frac{qE_a}{T}\right)}$$

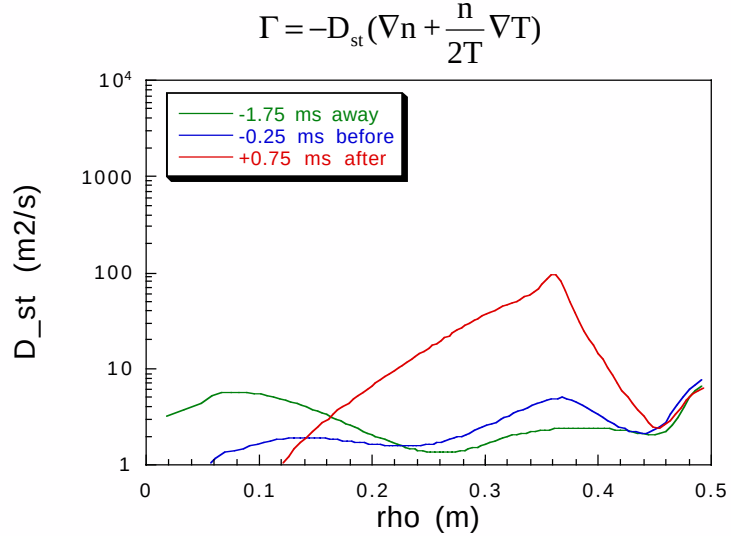
- By making the identification ($\chi = \frac{2}{\sqrt{\pi}}v_t D_m = 2D$), these expressions can be combined to yield a relation for the convective and conductive parts of the heat flux:

$$Q = 2\Gamma T - \chi n\frac{\partial T}{\partial r} = Q^{conv} + Q^{cond}$$

- Assume for the moment that the ambipolar terms are small by comparison in each expression. In this assumption a stochastic diffusion coefficient can easily be calculated.

In F~-0.24 plasmas stochastic diffusion can account for hollow T_e, n_e profiles





- In the approximation that the E_a terms are small, the derived stochastic diffusion coefficients are well behaved across the plasma volume.
- Note that in this formalism there is the identity that $\chi = 2D_{st}$.
- Including the E_a terms effectively leads to $D_{st}=\chi_{MSTFIT}/2$, since Γ is relatively small compared to Q (i.e. conductive heat flux is very much larger that convective flux) over the majority of the plasma volume.

Conclusions

- This represents the first measurement of time resolved T_e profiles in the MST.
- In both Standard and Non-Reversed plasmas, the pressure gradient appears to cross the critical Suydam limit to interchange instability prior to the sawtooth crash.
- Energy loss is primarily conductive, not convective.
- Confinement is somewhat improved in Non-Reversed plasmas over Standard plasmas by excluding the q=0 surface.
- A reduced Harvey model for transport in a stochastic magnetic field could account for observed T_e, n_e profile characteristics in Standard plasmas, especially where a simple diffusive model fails.

Future Work

- The inclusion of HIBP data is underway.
  - An additional constraint on the current profile.
  - An avenue of direct comparison between “independent” calculations of E_a and phi.
- IDS data yet to be examined.
  - minority temperature profile, $T_z(r,t)$
  - flow velocity profiles for an ion momentum balance est. of E_a
  - Possible confirmation of ion heating at the sawtooth
- Repeat the analysis for a F>0 plasma experiment.
- Repeat the analysis for a high confinement, “PPCD” experiment.

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