Suppression of High-Energy Electrons Generated in Both Steady and Disrupting MST Tokamak Plasmas

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Theory and Simulation of Disruptions Workshop, PPPL, Princeton, NJ, July 17-19 2017

Motivation

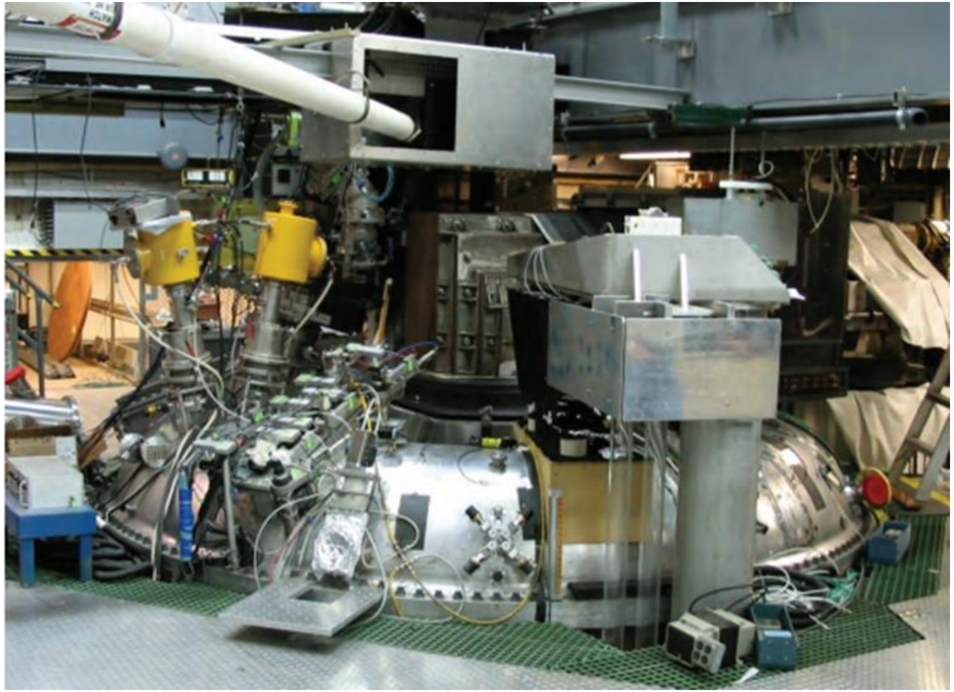
- MST rapidly growing its contributions to tokamak physics with initial focus on disruption-related topics
- Contribute, e.g., to understanding runaway generation and suppression
- Apply resonant magnetic perturbations (RMP) with non-standard configuration (applied thru narrow cut in conducting shell)
- Trigger reproducible disruptions in non-standard manner (other than use of massive gas injection)

Outline

- MST and operation as a tokamak
- RMP suppression of runaway electrons (RE) in sustained plasmas
  - Application of RMP with poloidal periodicities m = 1 and m = 3
  - NIMROD simulations of MST tokamak plasmas with RMP
- Generation of disruptions and high-energy, short-lived electrons
- Summary and future work

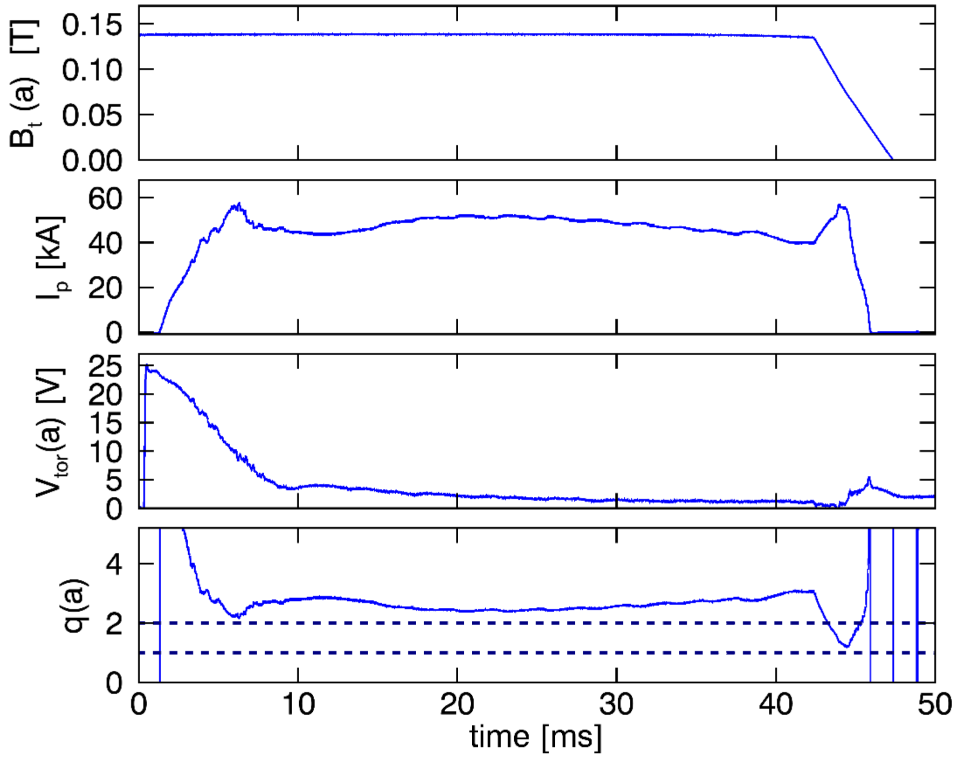
MST and tokamak operation

Madison Symmetric Torus



- MST operated as RFP for most of its life, recently added tokamak plasmas to its repertoire
- Thick symmetric Al shell acts as a single turn toroidal field winding
  - Lower inductance allows Bt manipulation on a short time-scale
- R_o = 1.5 m, a = 0.5 m

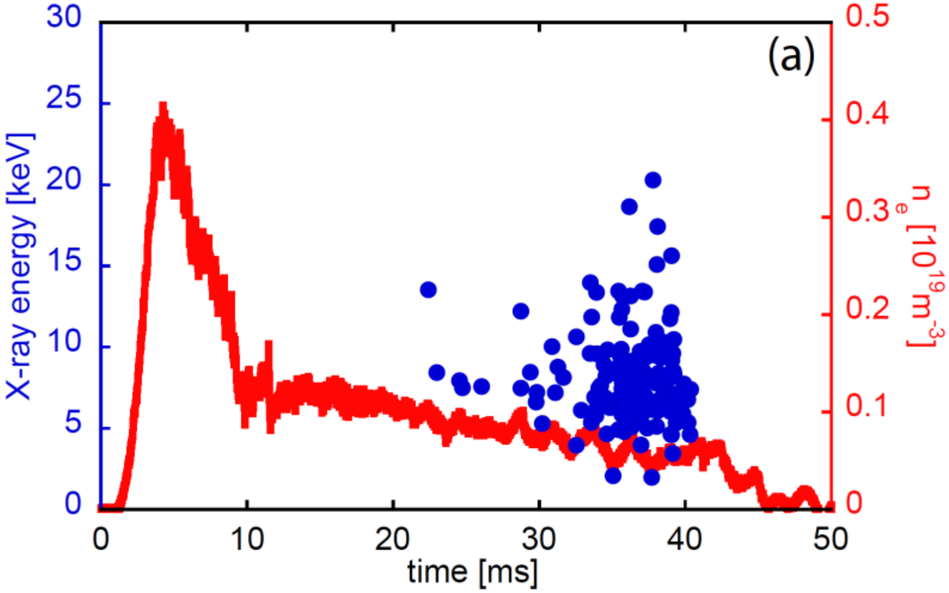
MST tokamak waveforms



- Well controlled B_t waveform
- Ip waveform not as well controlled
- B_t (a) < 0.15 T
- I_p = 40 – 60 kA
- q(a) = 2 – 3
- n_e < 0.5 – 0.6 x 10^{19} m^{-3}
- T_e < 120 eV

RMP suppression of REs in sustained plasmas

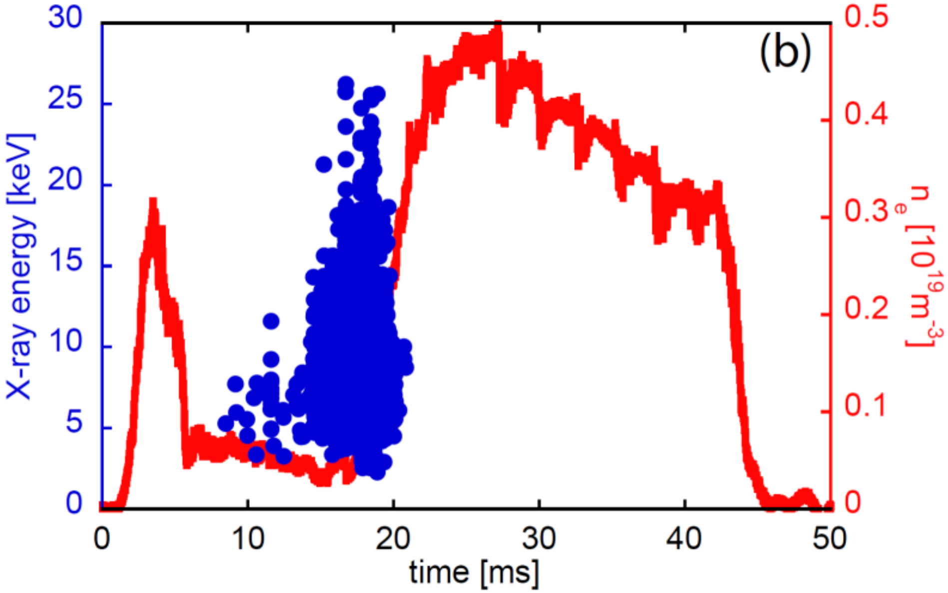
Runaway electrons observed at low density



- REEs observed for $n_e < 0.1x10^{19}$ m^{-3}
- Diagnostic: x-ray emission measured with fast-time-response detector (20 ns FWHM pulse), E > 3 keV

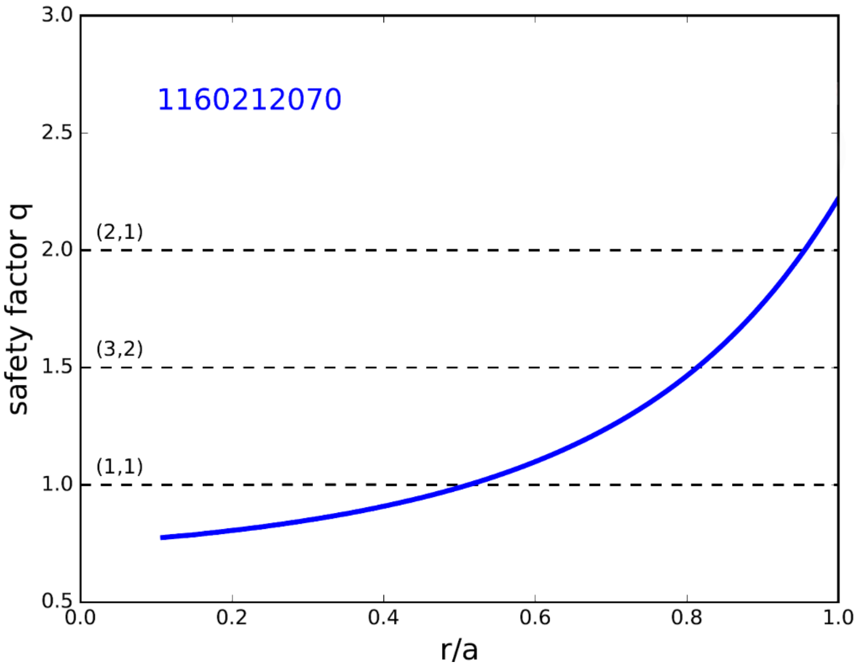
A.M. DuBois *et al.*, RSI, **86**, 073512 (2015)

Runaway suppressed for increased density



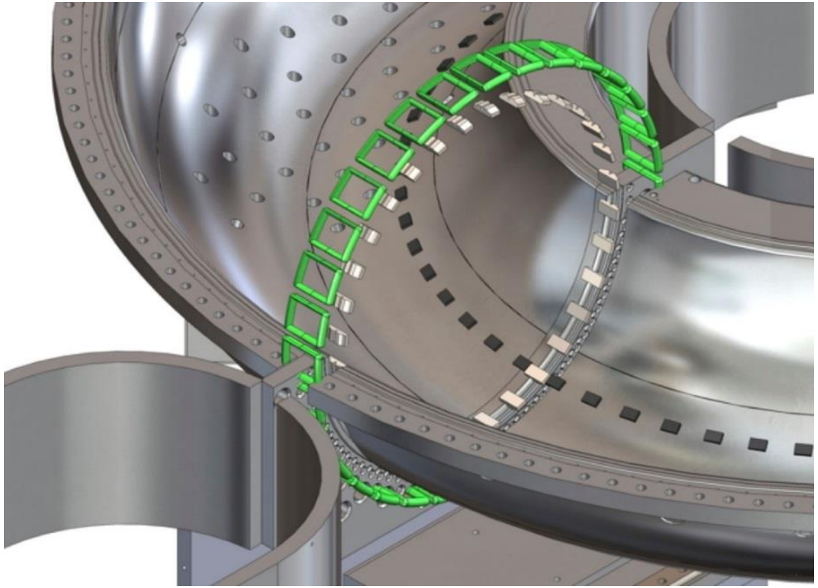
- REEs suppressed for $n_e > 0.3 \times 10^{19}$ m^{-3}
- Previous contribution to ITPA study : electric field needed for RE generation is almost two orders of magnitude than the critical field for runaway generation
- Manuscript in preparation: S. Munaretto *et al.*, PoP

m = 3 and m = 1 RMP applied have resonances in plasma

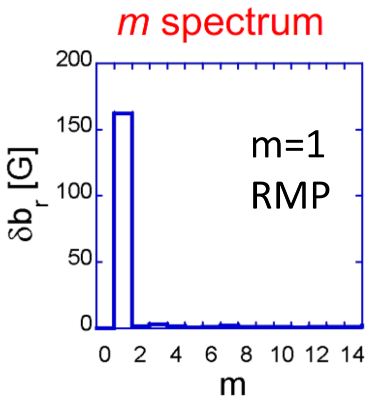


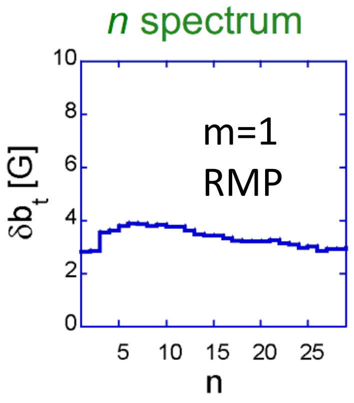
- q-profiles reconstructed w/ MSTFIT
- Using edge magnetic diagnostics, and constraints on core Te.
- q(0) < 1 , q(a) ~ 2.2
- Poloidal harmonics m = 1, m = 2, and m = 3 resonant within the plasma
- Focus of this talk: RMP with m=3 and m=1.

RMPs with various poloidal harmonics can be applied

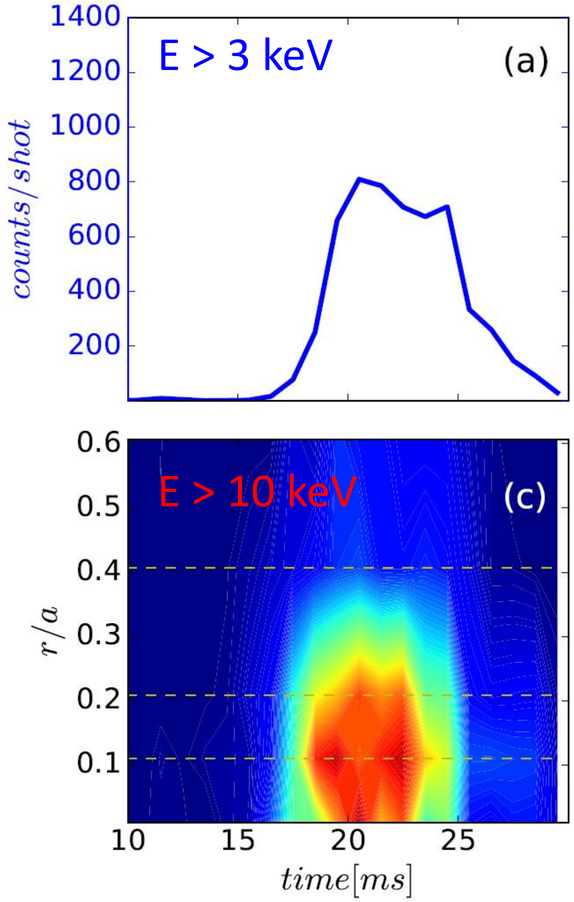


- MST has error field correction system which can be used to apply resonant magnetic perturbations (RMPs)
- RMP-drive coils (green) are adjusted to provide a prescribed poloidal harmonic at sensors (white)
  - Broad toroidal spectrum
  - This talk: m=1 and m=3



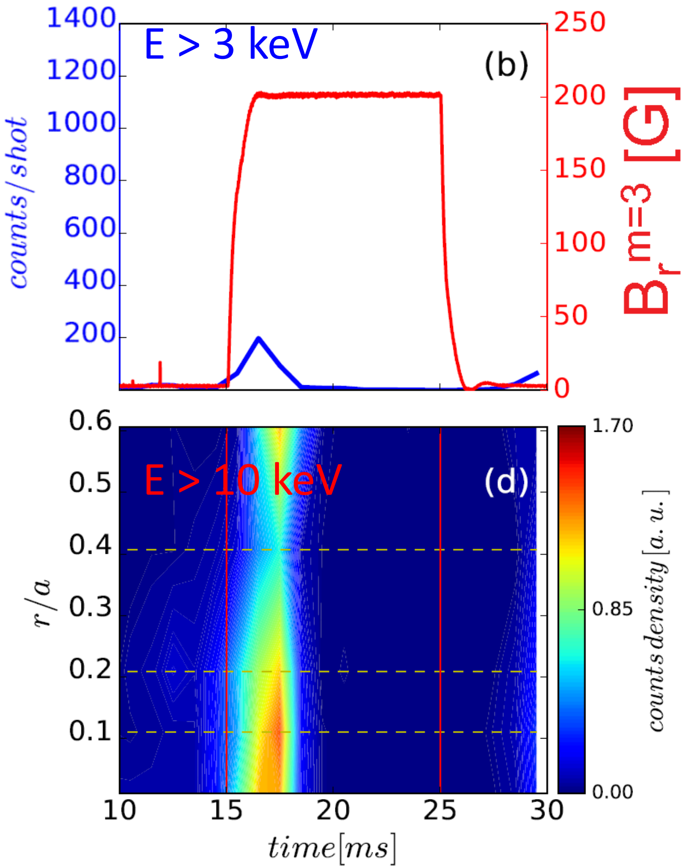


Bremsstrahlung from RE measured with multiple x-ray detectors



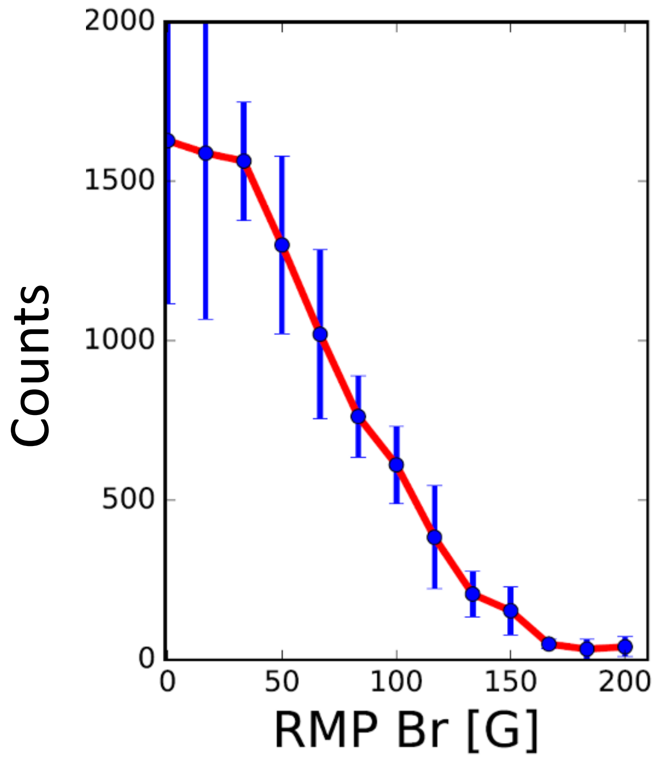
- Dataset having low densities, large runaway
  - Emission observed from t = 15-25 ms
  - X-ray detectors with fast-response for E > 3 keV
  - Array of x-ray detectors with slower response (1.2 μs FWHM) used, E > 10 keV
- X-rays generated near plasma core
- Data verified to ensure measured x rays not due to target emission

RE suppressed with application of m=3 RMP



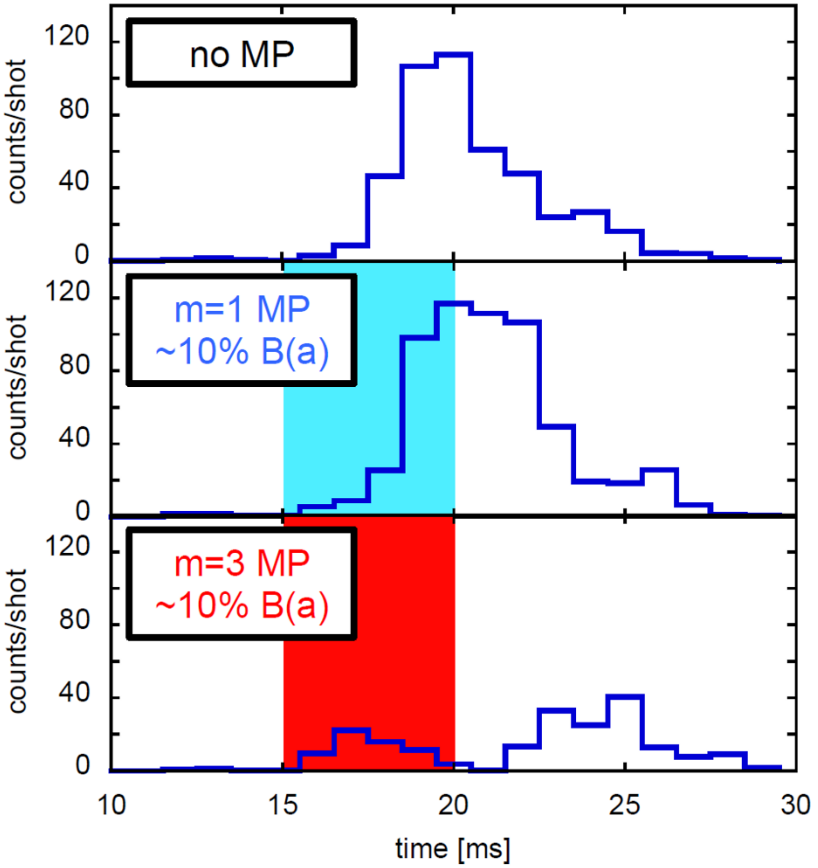
- m =3 RMP applied from 15 - 25 ms
  - 200 G, Br(a)/B(a) ~ 14 %
  - Each *n* has amplitude of about 4 G
- X rays > 10 keV absent after 2 ms
- Increased edge emission indicating loss of high energy electrons
- Increased suppression as RMP amplitude increased (next slide)

Most RE suppressed with m=3 RMP > 150 G

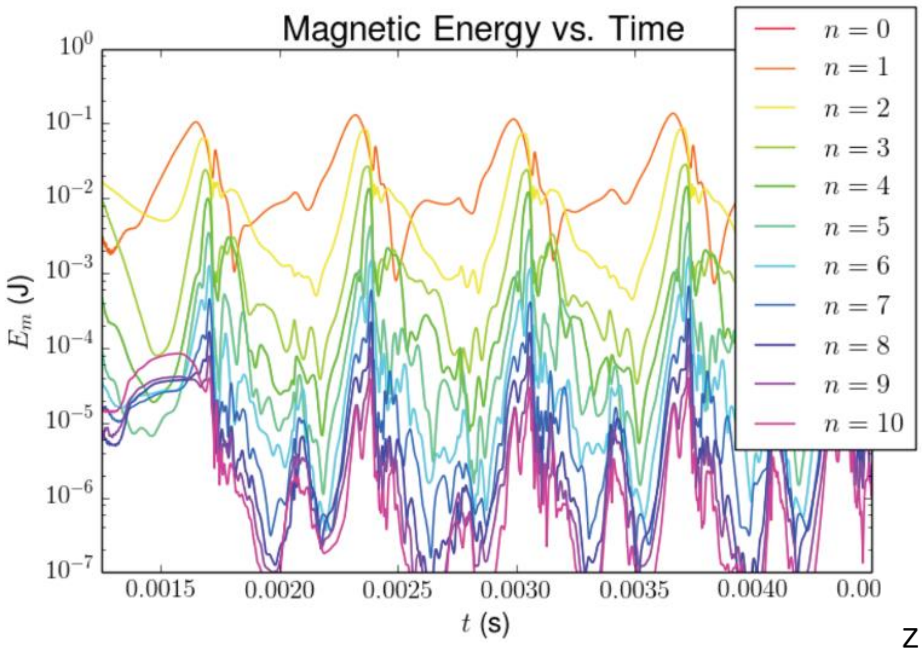


- RMP amplitude scan performed for *m* = 3 perturbation

No RE suppression observed with m=1 RMP

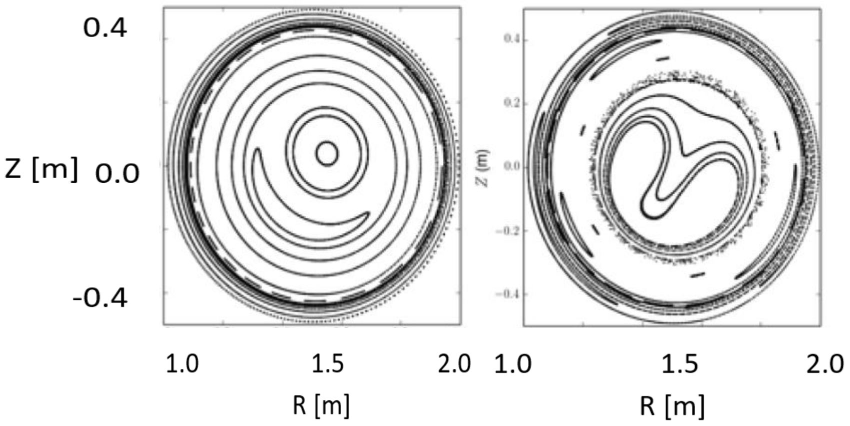


NIMROD employed to simulate MST tokamak plasmas



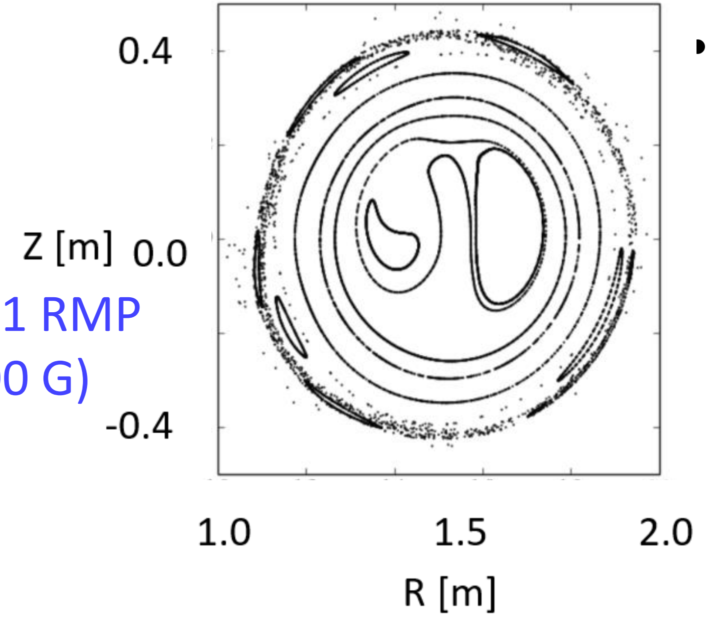
- Nonlinear computations solve resistive-MHD without RE effects.
  - Low-β conditions modeled with $p = 0$.
  - $S = 10^5$; Pm = 1
- q(a) ~ 2.2 for these simulations
- Magnetic fluctuation energy shows sawtoothing with period similar to MST

Low E_m High E_m



No RMP applied

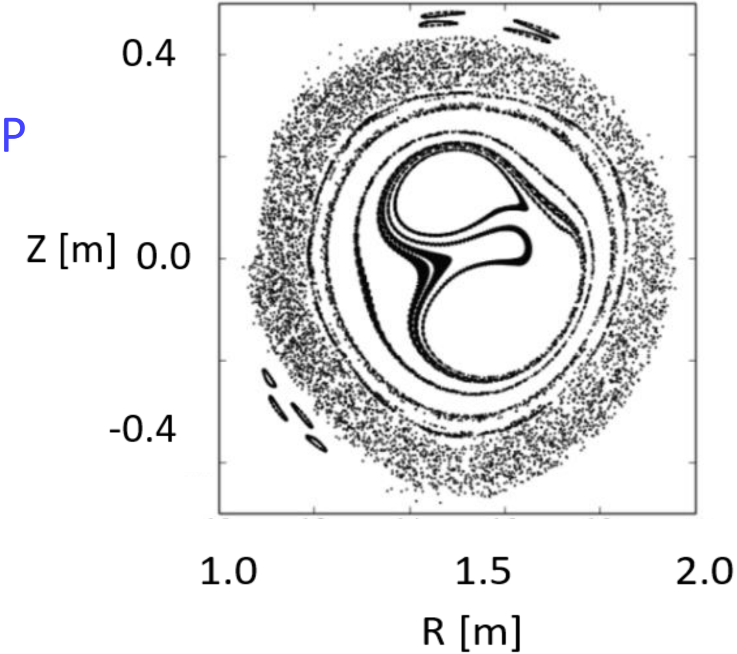
Chaotic edge region with m = 3 RMP but not with m = 1 RMP, consistent with data



m=1 RMP
(200 G)

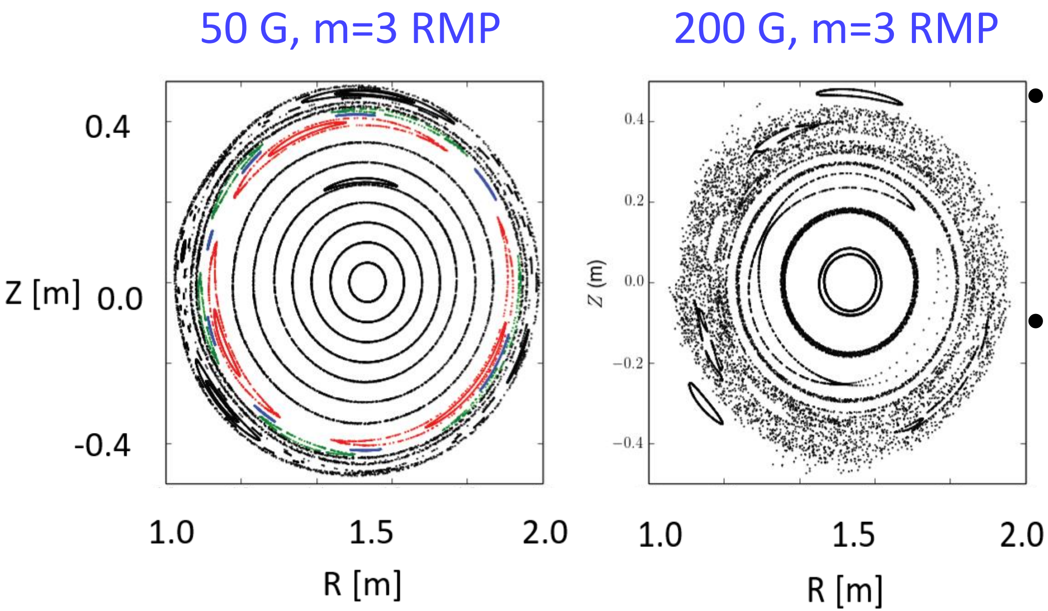
- RMP vacuum field imposed on fitted equilibrium as the initial condition
  - Applied perturbation amplitude based on data

m=3 RMP
(200 G)



•Flux surfaces intact with m = 1 perturbatior
•Edge flux surfaces highly stochastic with m = 3 perturbation

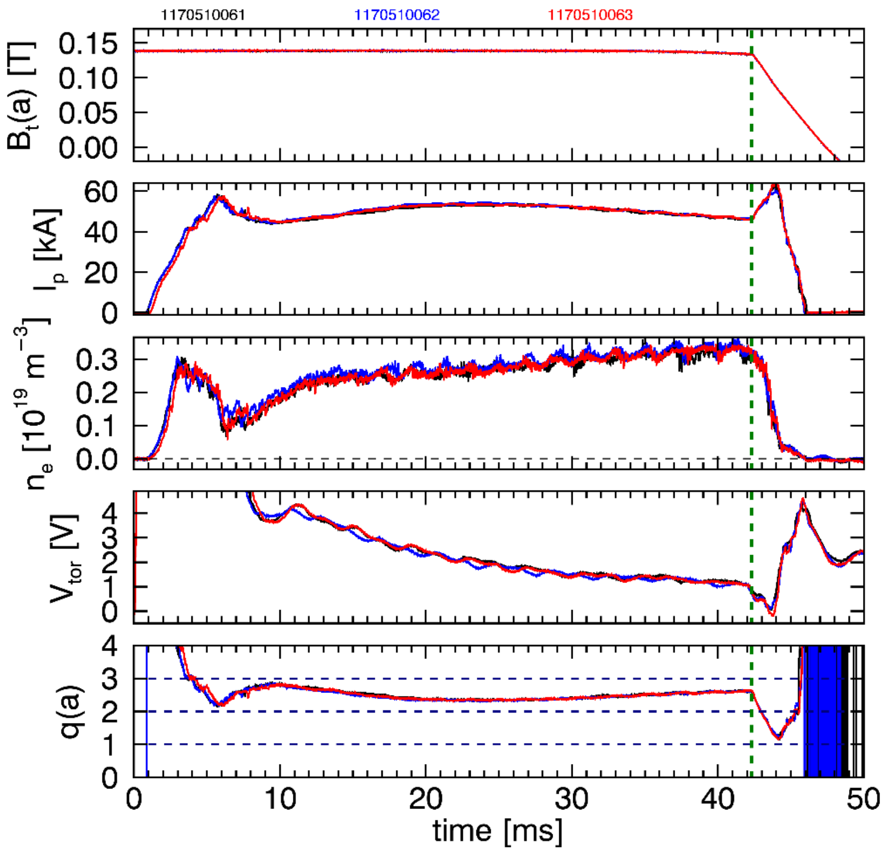
Increased stochasticity with larger m = 3 RMP might explain observed reduction of RE flux



- Data shows RE flux reduces with m = 3 RMP amplitude
- Low amplitude RMP case shows (3,3), (3,2), (8,5), (5,3), and (4,2) island chains
- With larger RMP amplitude the island chains overlap yielding highly stochastic region around core

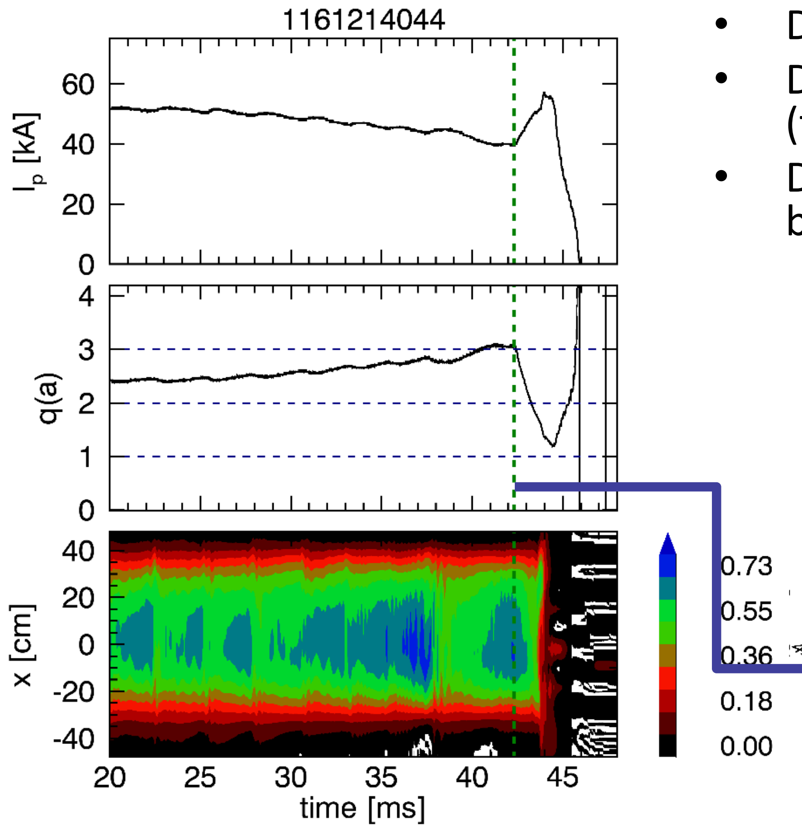
Generation of disruptions and short-lived high-energy electrons

Disruptions generated by toroidal field ramp-down

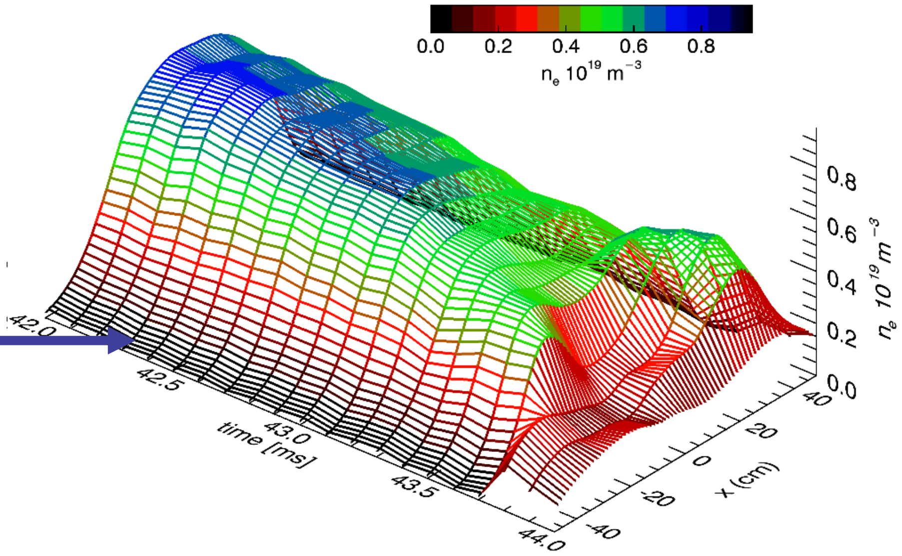


- Well controlled Bt ramp-down
- Leads to current quench
- Ip not actively controlled
- Reproducible

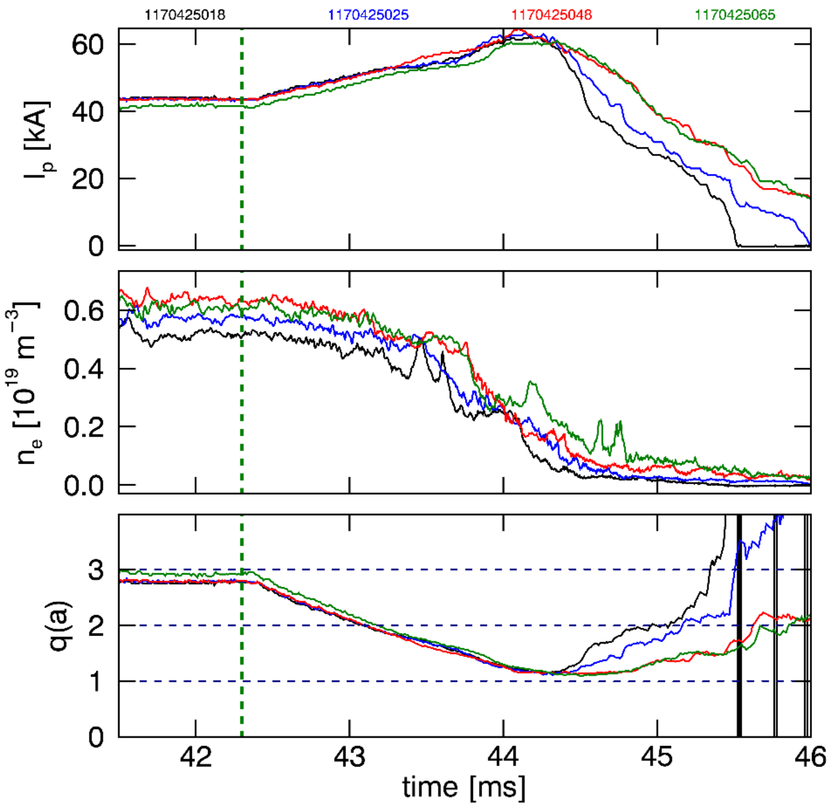
Central density and profile collapse preceding the current quench



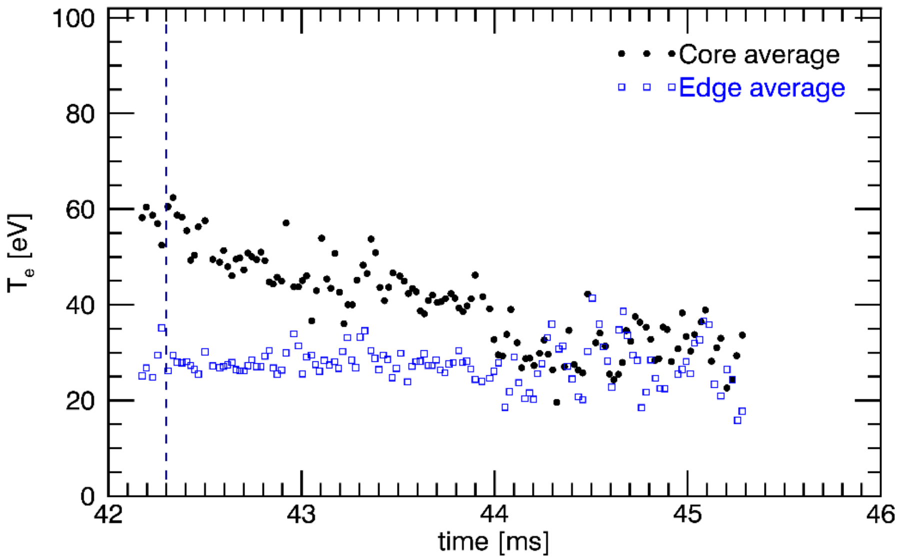
- Density measured with 11 chord interferometer
- Density profile relaxes with sawtooth-like oscillations (t = 20 – 35 ms)
- Density profile flattens after Bt rampdown starts before eventual collapse



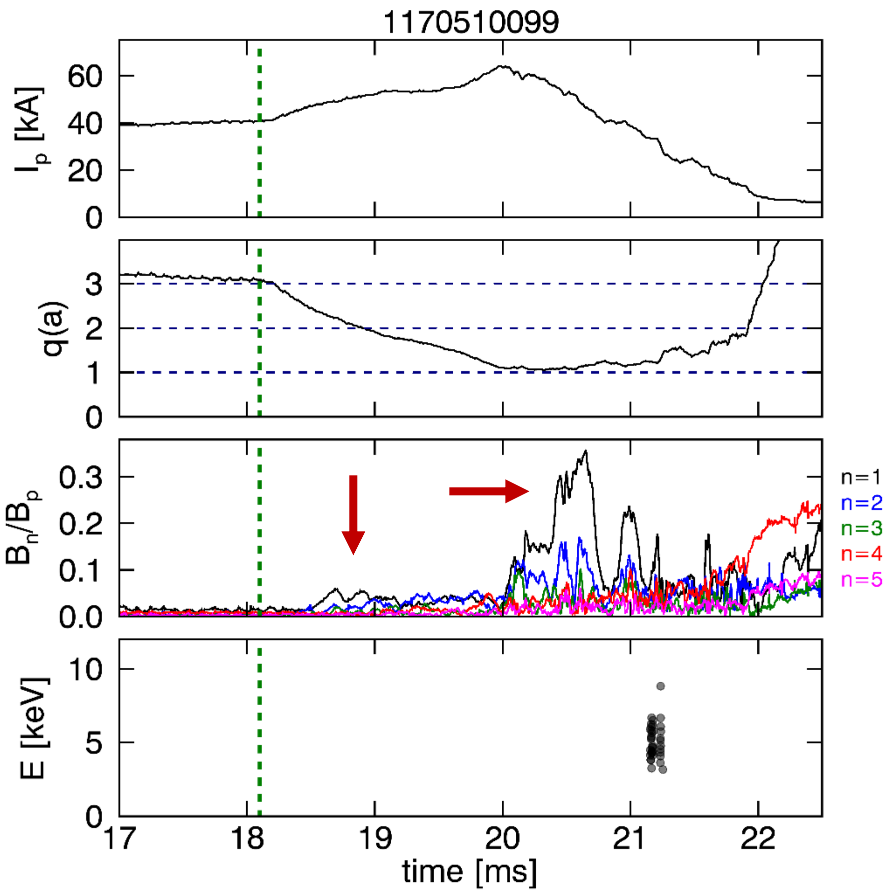
Core temperature drops and profile flattens preceding current quench



- Te measured with 21 chord TS diagnostic
  - 25 kHz, averaged over repeatable discharges
  - Core average is over 3 central channels (r/a = -0.02 to 0.05)
  - Edge average is over 2 edge channels (r/a = 0.65, 0.67)
- Core average Te drops from 60 eV to 25 eV at Ip max
- Edge Te remains fairly constant



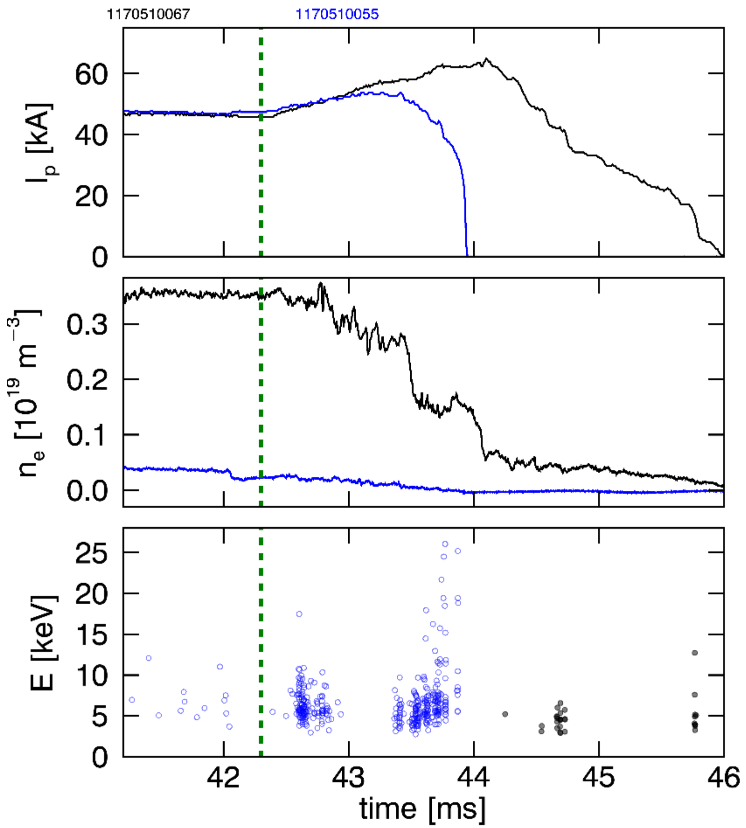
n=1 amplitude becomes larger prior to current quench

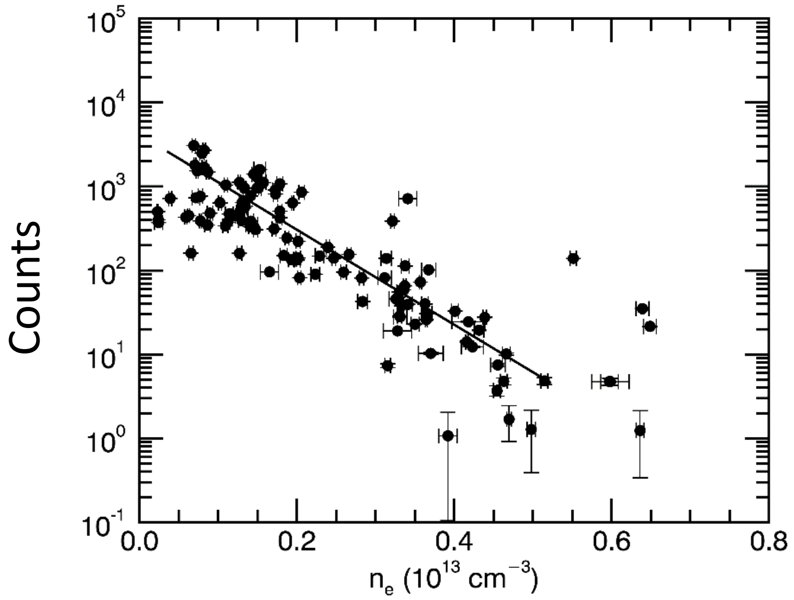


- Disruption produced earlier in time
- Toroidal mode data computed from toroidal array of poloidal field sensors
- Sudden growth of n=1 mode to ~ 40% of the equilibrium poloidal field
- High-energy (>3keV), short-lived electrons are observed during the current quench
- Non-classical energization during magnetic reconnection observed in MST RFP plasmas [A.M. DuBois et al., PRL (2017)]

Larger x-ray emission observed at low densities

- X-rays with E > 3 keV observed in short bursts with fast-time-repsonse detector
- Higher count rate at lower (pre-Bt-rampdown) densities





Summary

- m = 3 RMP with large enough amplitude suppresses RE; NIMROD computations show increased stochasticity in the edge for such RMP amplitudes
- No suppression is achieved with m =1 RMP; NIMROD computations indicate intact flux surfaces at edge
- Recently, work has begun to diagnose disruptions caused by ramping down of Bt
- Current quench is preceded by characteristic temperature and density collapse
- Short-lived, high-energy electrons with pre-termination density dependence observed during current quench

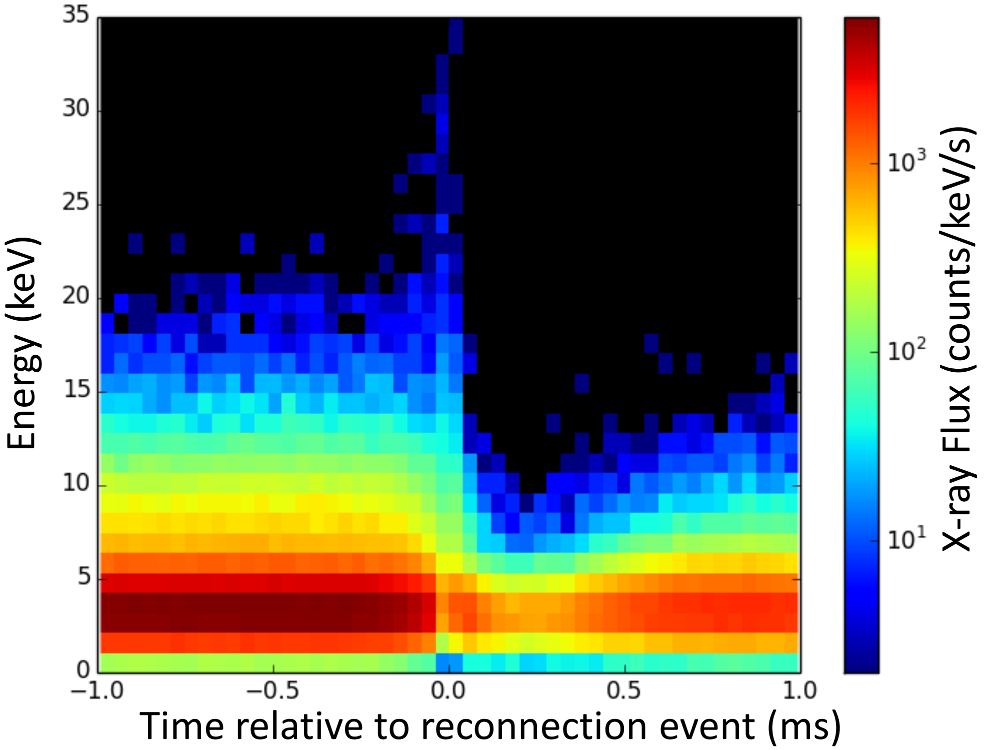
Open questions, and future disruption-related work

- What causes the slow rise in Ip as Bt ramps down?
- What causes initial “modest” increase in MHD activity?
- What causes the sudden MHD spike to very large amplitude?
- What are the roles of MHD activity in thermal quench, electron transport?

- Improving Ip waveform control with new Bp programmable power supply
- Applying massive gas injection, shattered pellets

Thank you!

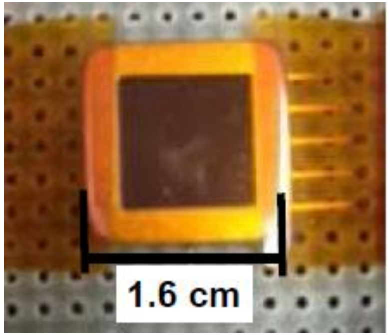
Non-classical energization during magnetic reconnection observed in MST RFP plasmas

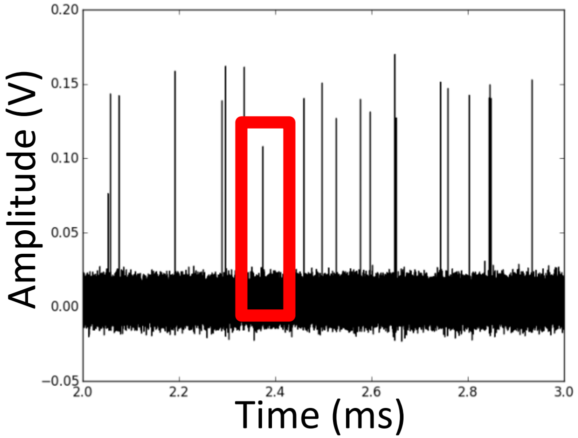


A.M. DuBois *et al.*, PRL, **118**, 075001 (2017)

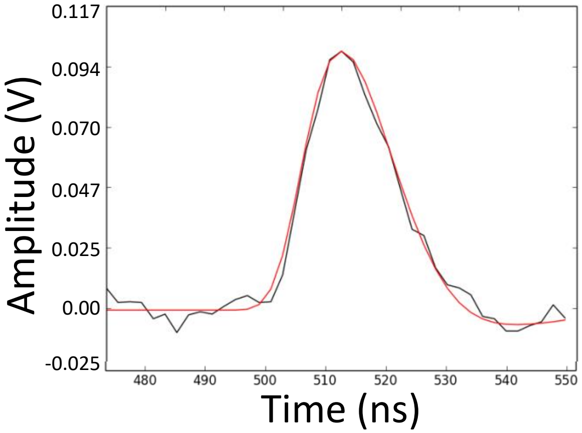
The 20 ns response time enables dynamics of energetic electron generation and losses during reconnection events to be uncovered

- High time resolution soft x-ray detector
  - Avalanche photodiode
  - 20 ns Gaussian shaping amp
  - 500 MHz digitization
  - 14 bit sampling resolution
  - 3 – 25 keV optimal sensitivity





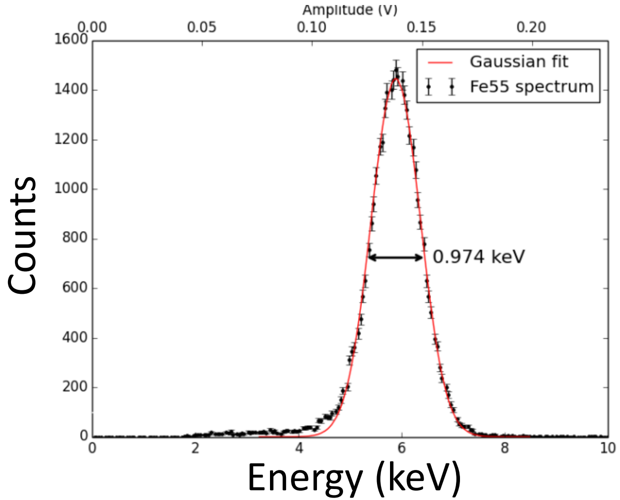
- Fe55 source (E = 5.89 keV) used for calibration
  - V → E scaling factor
  - Detector energy resolution
- **Photon pulses** fit with **characteristic pulse**



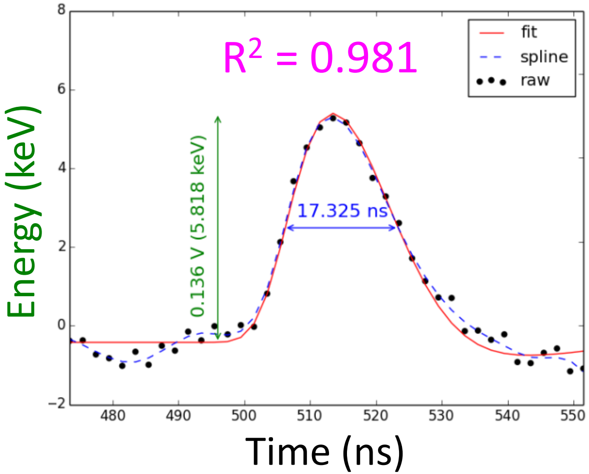
A.M. DuBois et al, RSI **86**, 073512 (2015)

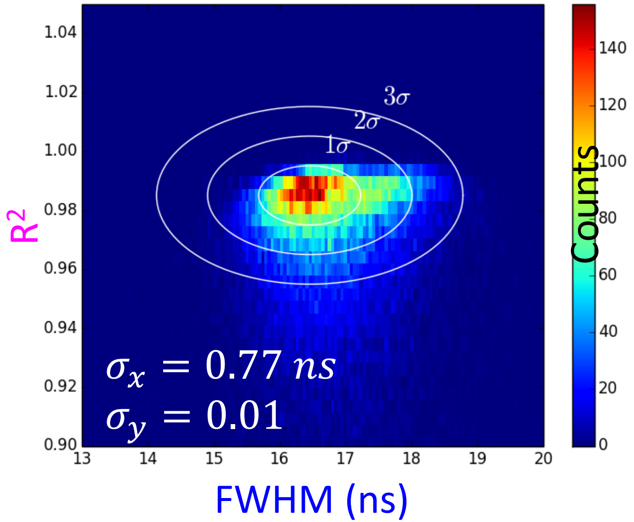
More FXR details

Fit with Gaussian to calculate scaling factor to convert voltage to **energy**



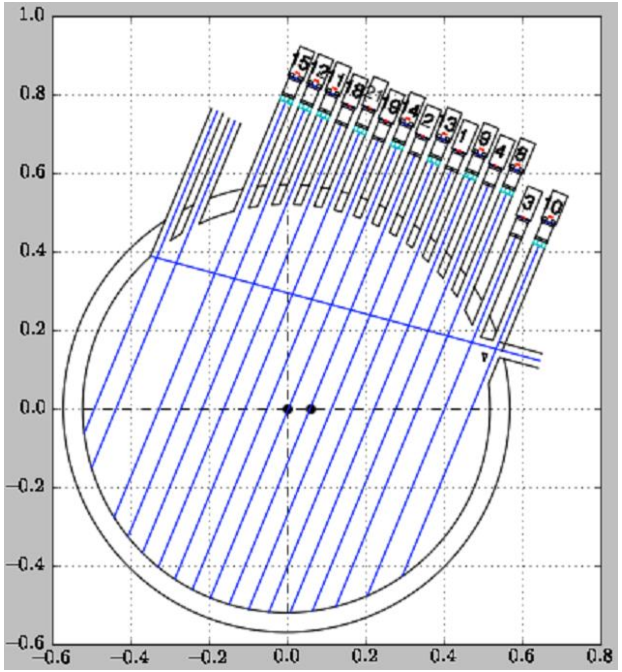
$$E = 42.64\ keV/V \times volt$$





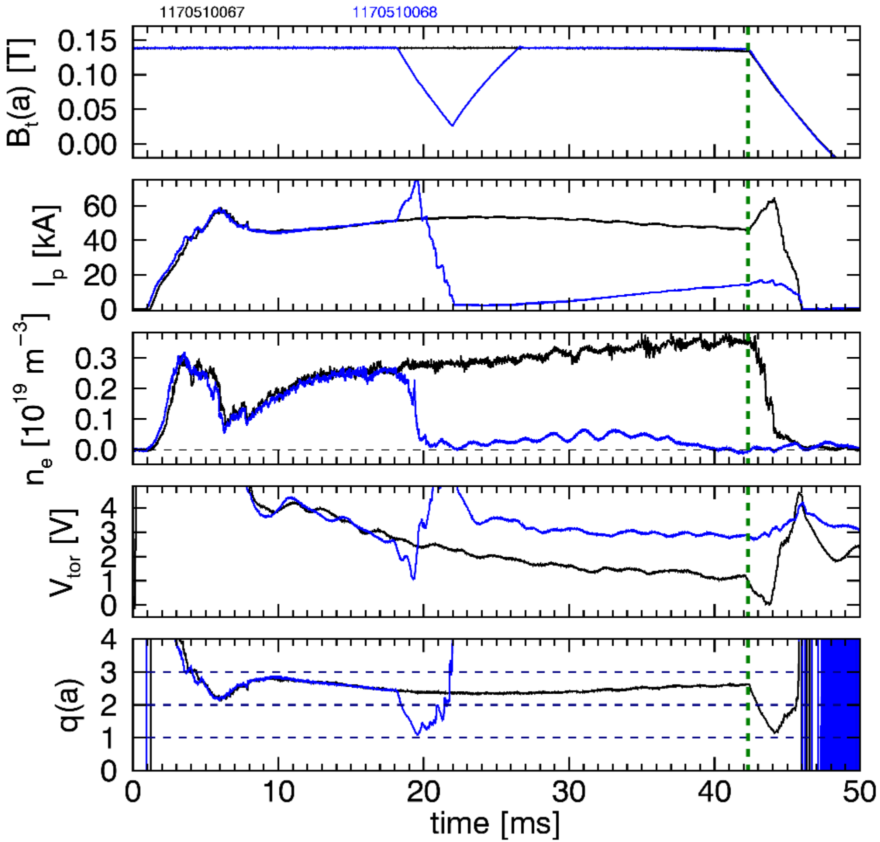
- **R^2** is calculated between **photon pulse** and **characteristic pulse**
- **FWHM** calculated from **spline fit** to **photon pulse**

Other x-ray detectors on MST



- 16 CdZnTe eV Products HXR detectors:
  - 2 keV energy resolution
  - 10 – 150 keV optimal sensitivity
  - **1200 ns shaping time**
  - **60 MHz digitization rate**
- Planned upgrades:
  - 240 MHz digitizer system
  - Improving take data scripts
  - Faster Gaussian shaping chips

Early Bt rampdown shows similar plasma termination



q(a)>> 1 at termination, faster Ip quench