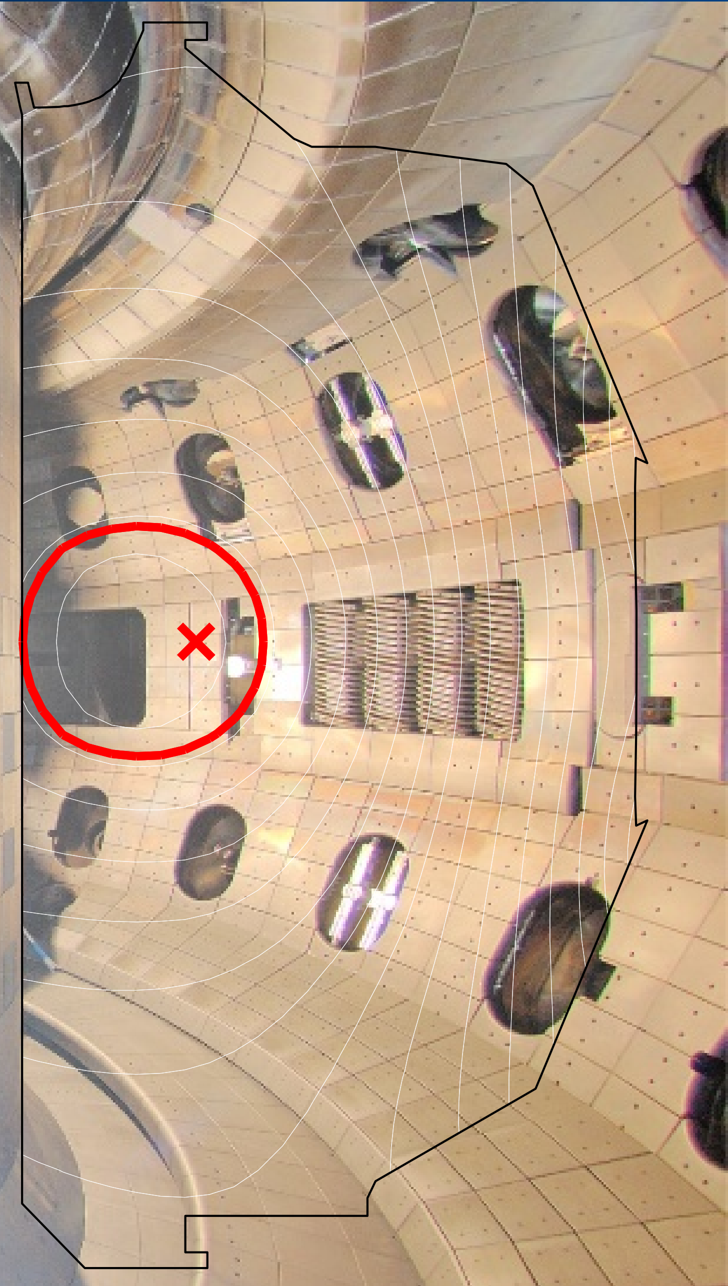
Generation and stability of runaway electrons during rapid-shutdown in DIII-D

by
Alex N. James

with
E. M. Hollmann[1], V. A. Izzo[1], G. R. Tynan[1], D. A. Humphreys[2], P. B. Parks[2], E. J. Strait[2], J. C. Wesley[2]

[1]UC San Diego
[2]General Atomics



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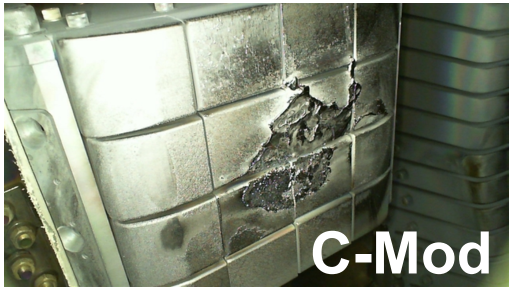
Motivation

- Disruption mitigation schemes fail to prevent runaway electron generation in present machines



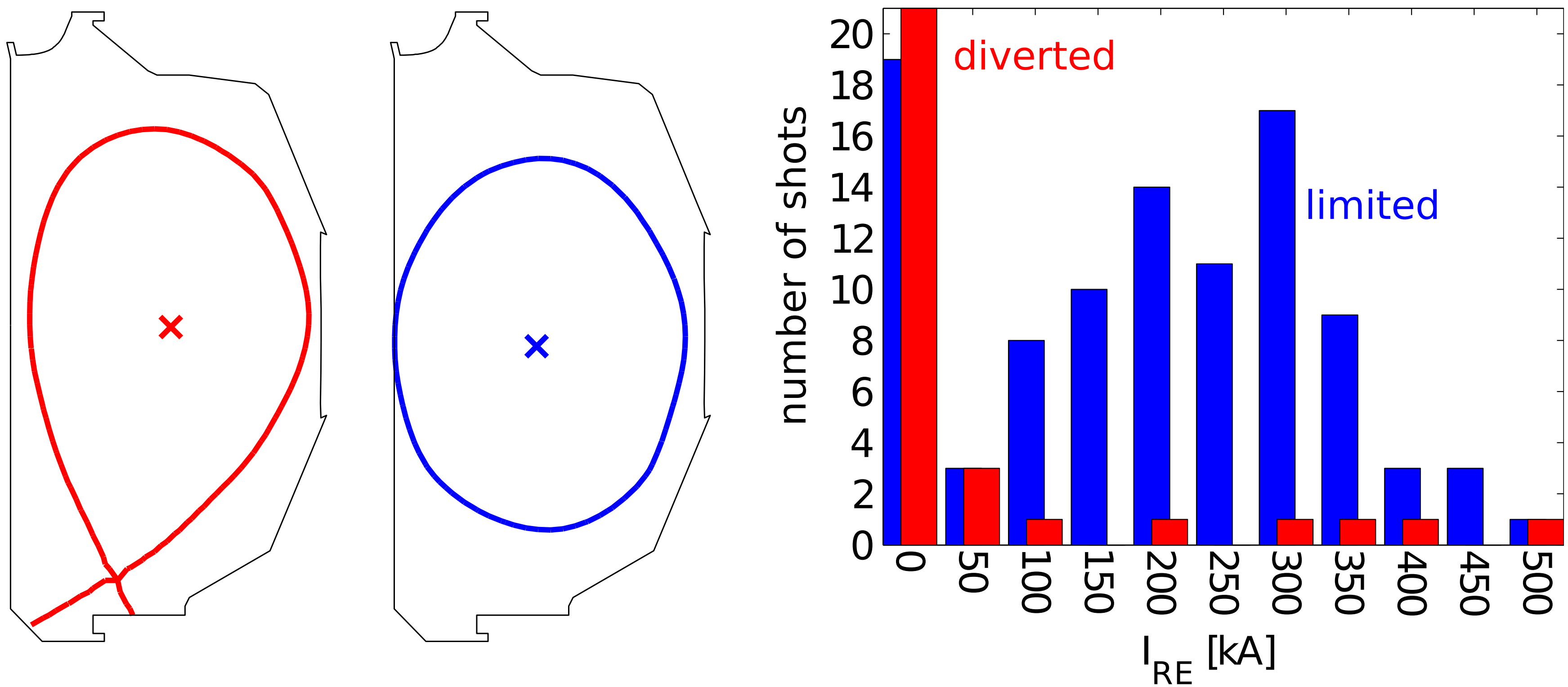
- Runaway generation is poorly understood by simplistic analysis, so more sophisticated efforts are necessary

- Thorough understanding of runaway generation and stability will lead to new solutions to these problems

Outline

- Runaway electrons are observed before current quench loop voltages
- Inclusion of the often neglected inductance drop reveals an early and large loop voltage term
- Much runaway seed impacts the vessel wall in varying quantities dependent on the plasma shape
- Runaway current eventually terminates with possible signatures of kink instability

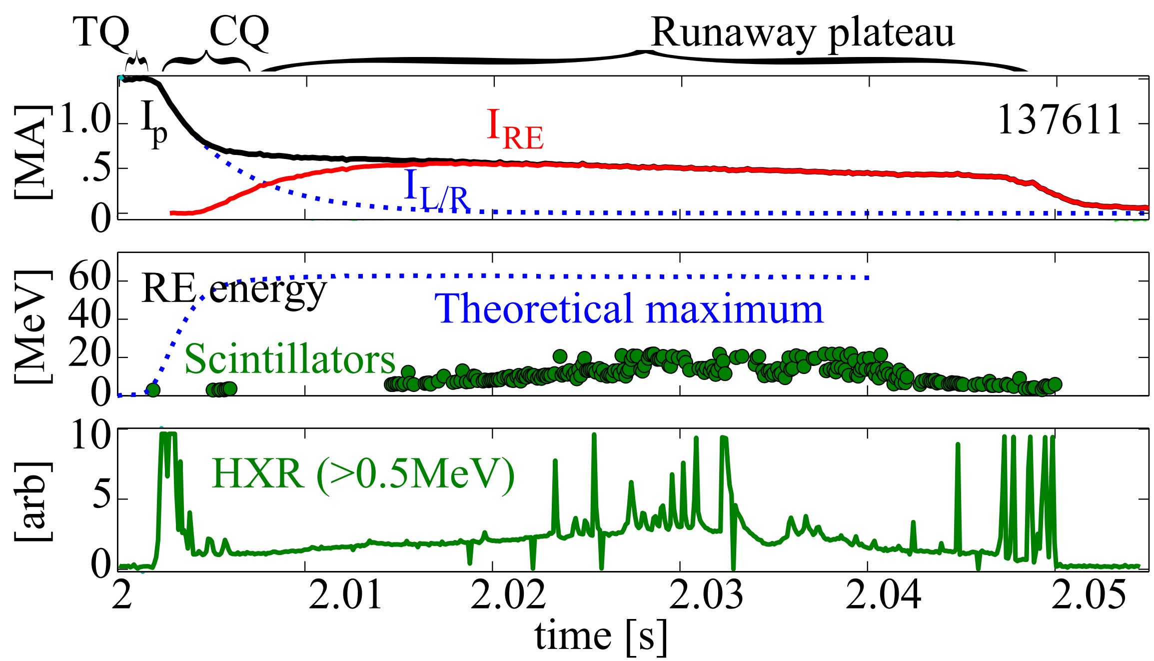
Experiments feature rapid shutdown of two different shapes using argon 'killer pellets'



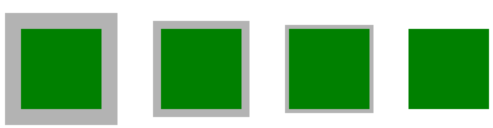
- Begin with a stable plasma
- Inject a cryogenic argon killer pellet
- Runaway generation occurs, with avalanche and plateau
- Limited shape is good for studying runaway generation, bad for reactor operation where runaways are undesirable

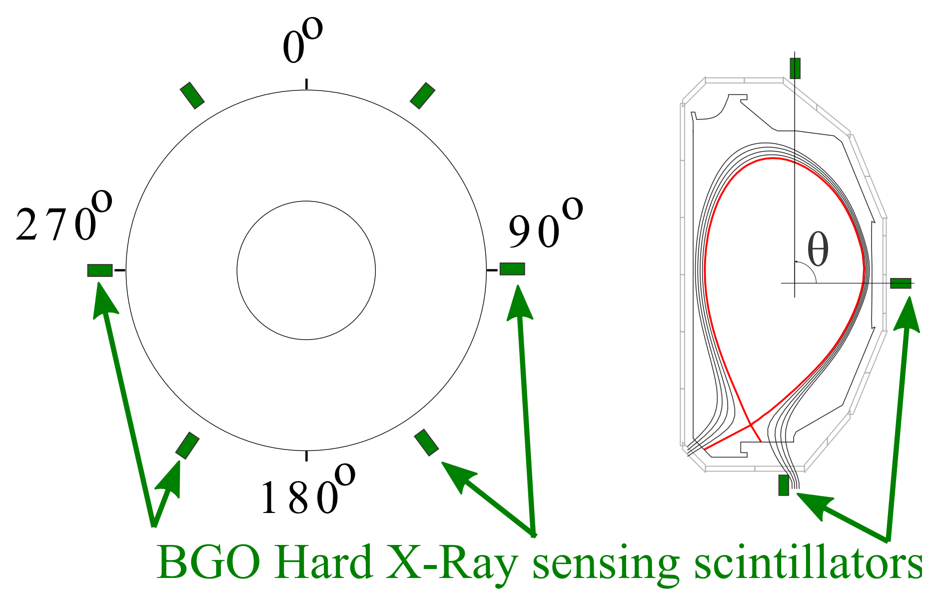
High energy runaway electrons are generated before current quench during rapid-shutdowns

- A new hard x-ray sensing scintillator array observes runaway electron emissions [James RSI 2010]
- Plasma control enables >150ms confinement! [Humphreys U04.00001]



BGO scintillators with various lead shield thickness measure average runaway energy

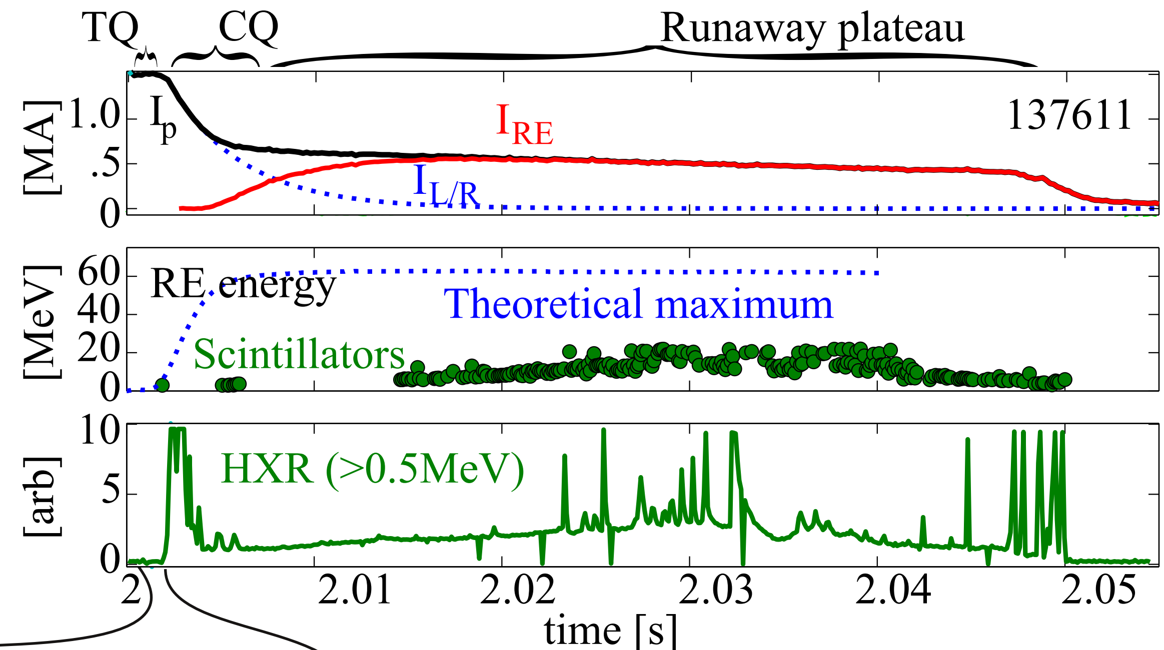


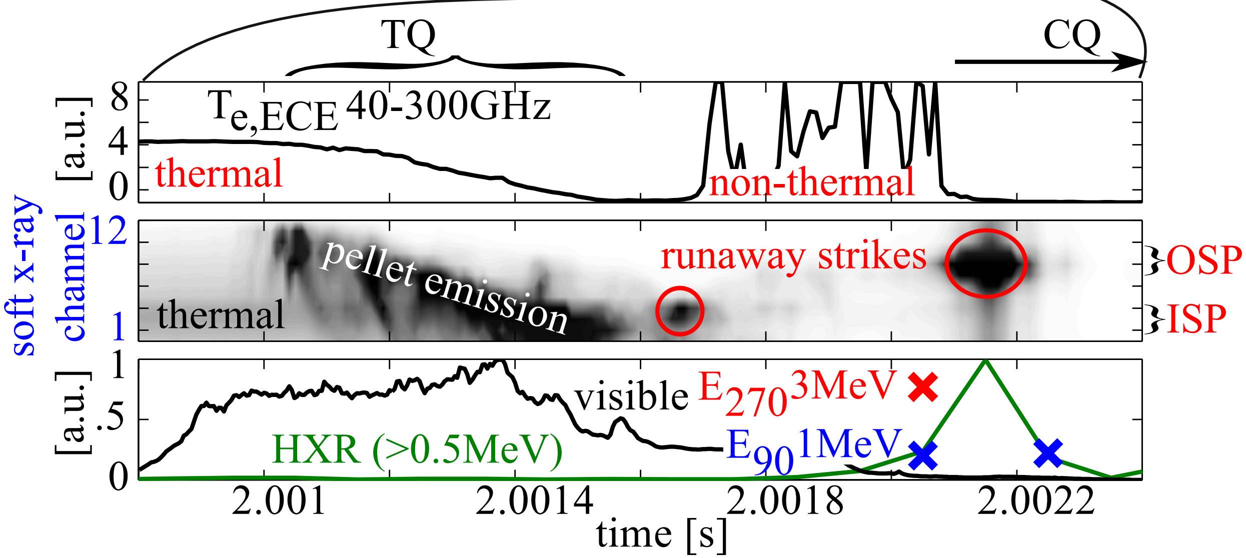


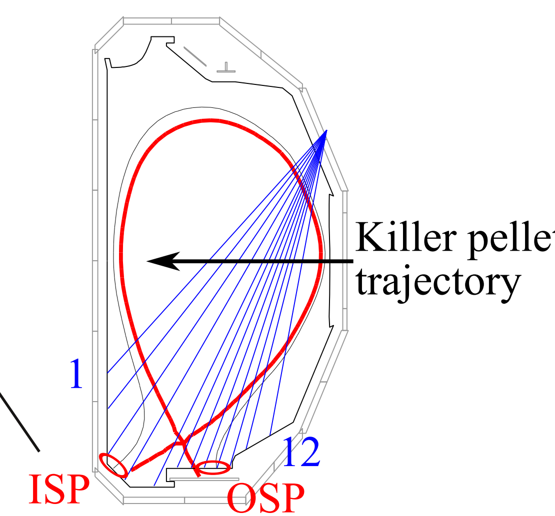
High energy runaway electrons are generated before current quench during rapid-shutdowns

- A new hard x-ray sensing scintillator array observes runaway electron emissions [James RSI 2010]

- Signatures of high energy runaways appear BEFORE current quench begins

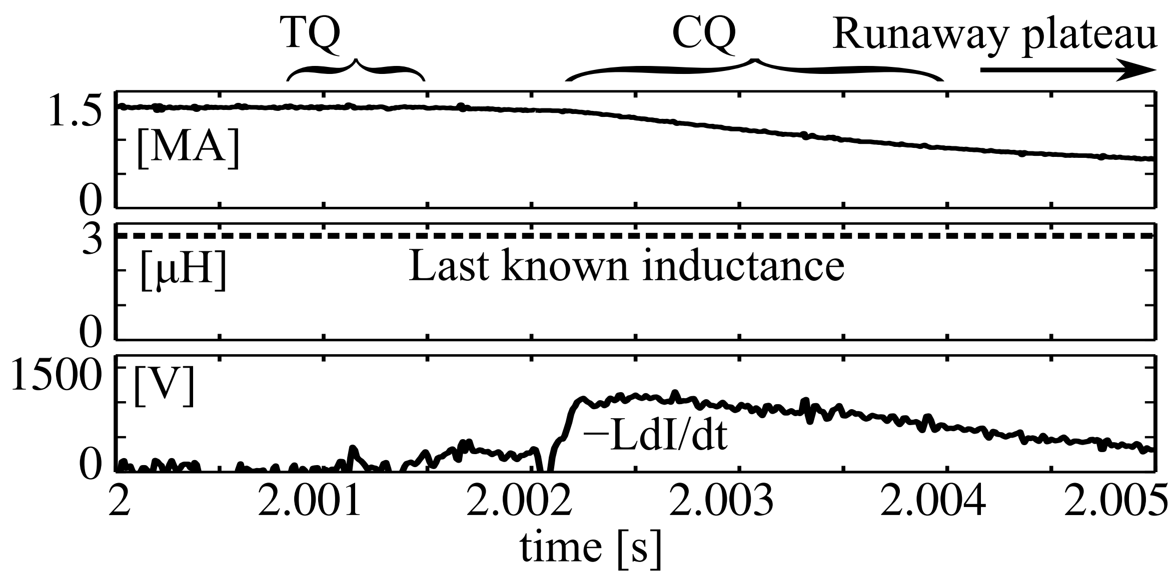






Loop voltage from current quench occurs after runaways appear

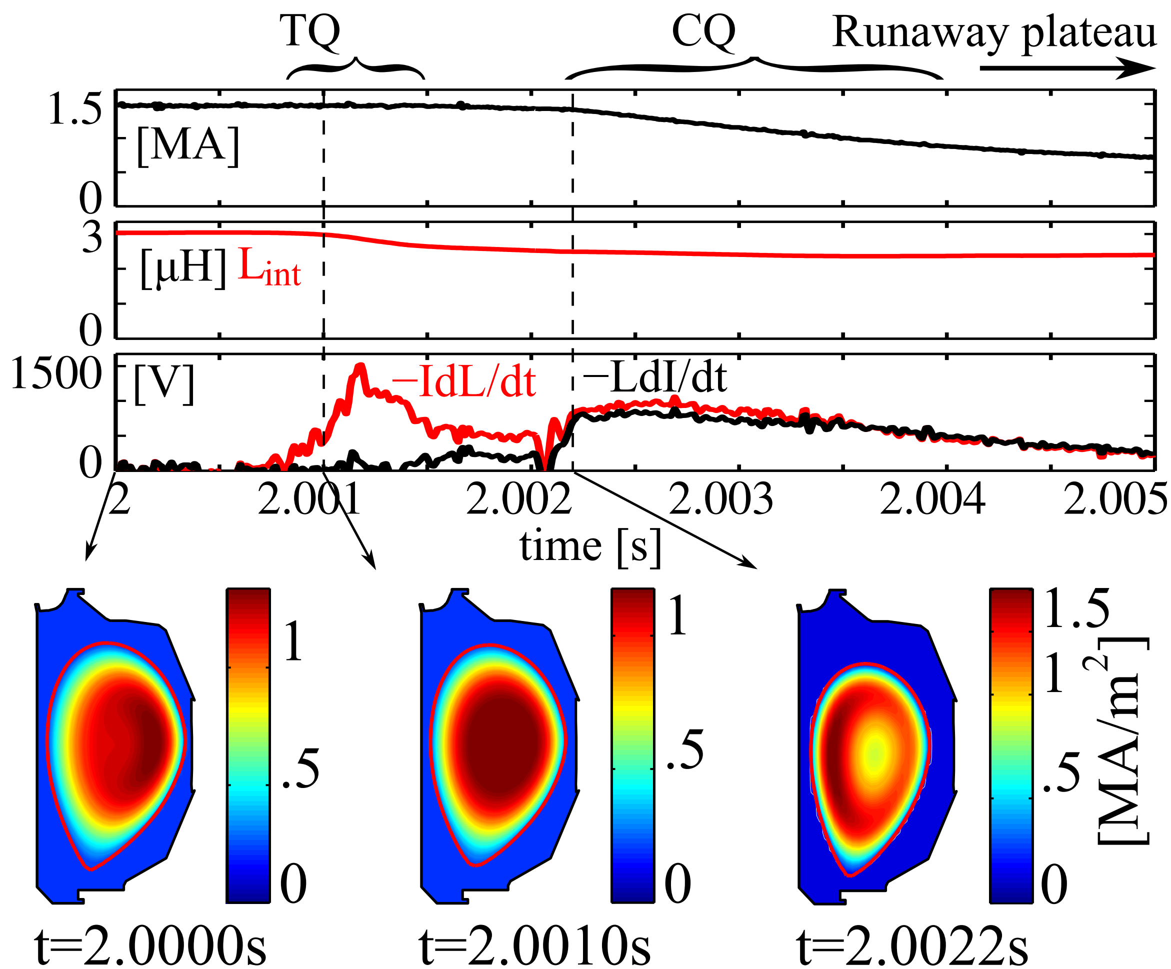
- Begin with simple estimate of loop voltage by extending the last known inductance before shutdown



$$V_{loop} = -L\frac{dI}{dt}$$

Reconstructed inductance reveals an earlier loop voltage term

- Begin with simple estimate of loop voltage by extending the last known inductance before shutdown
- Improve by calculating inductance from a reconstruction
- Inductance drop term **occurs earlier** and is larger in magnitude than current drop term



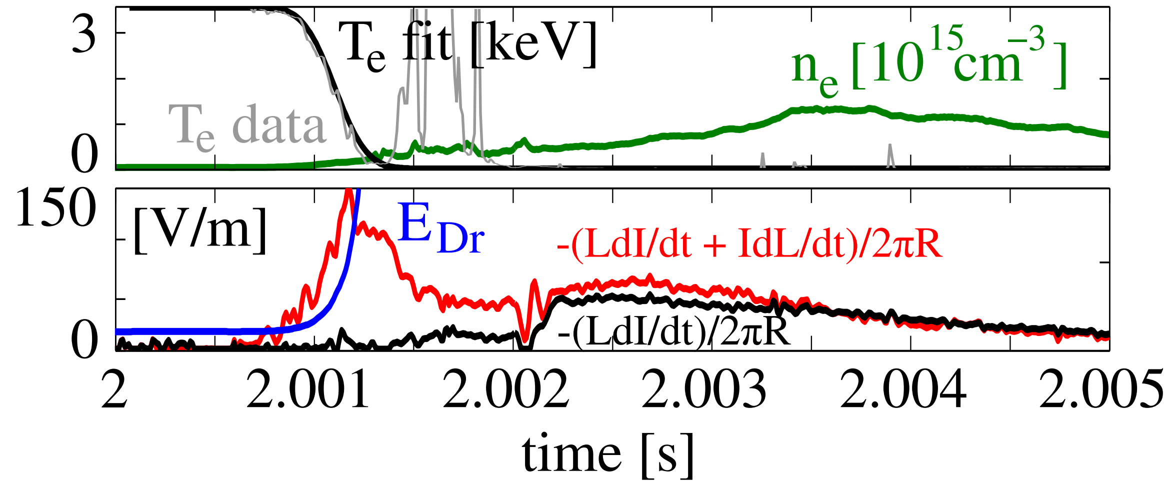
$$-\frac{d\Phi}{dt} = -\frac{d}{dt}(LI) = V_{loop} = -L\frac{dI}{dt} - I\frac{dL}{dt}, \qquad L = \frac{1}{\mu_0 I^2}\int B_p^2 dV$$

Improved disruptions diagnostics of density and temperature necessary to calculate seed current

- Dreicer described how electrons exceeding a critical velocity can runaway

$$v_{Dr} = \sqrt{\frac{ne^4 ln\Lambda}{4\pi\epsilon_0^2 m_e E}}, \quad E_{Dr} = \frac{e^3 ln\Lambda}{4\pi\epsilon_0^2}\frac{n_e}{T_e}$$

- Temperature and density are volume and line averaged 0D measurements
- Loop voltage term only revealed by invoking 2D analysis

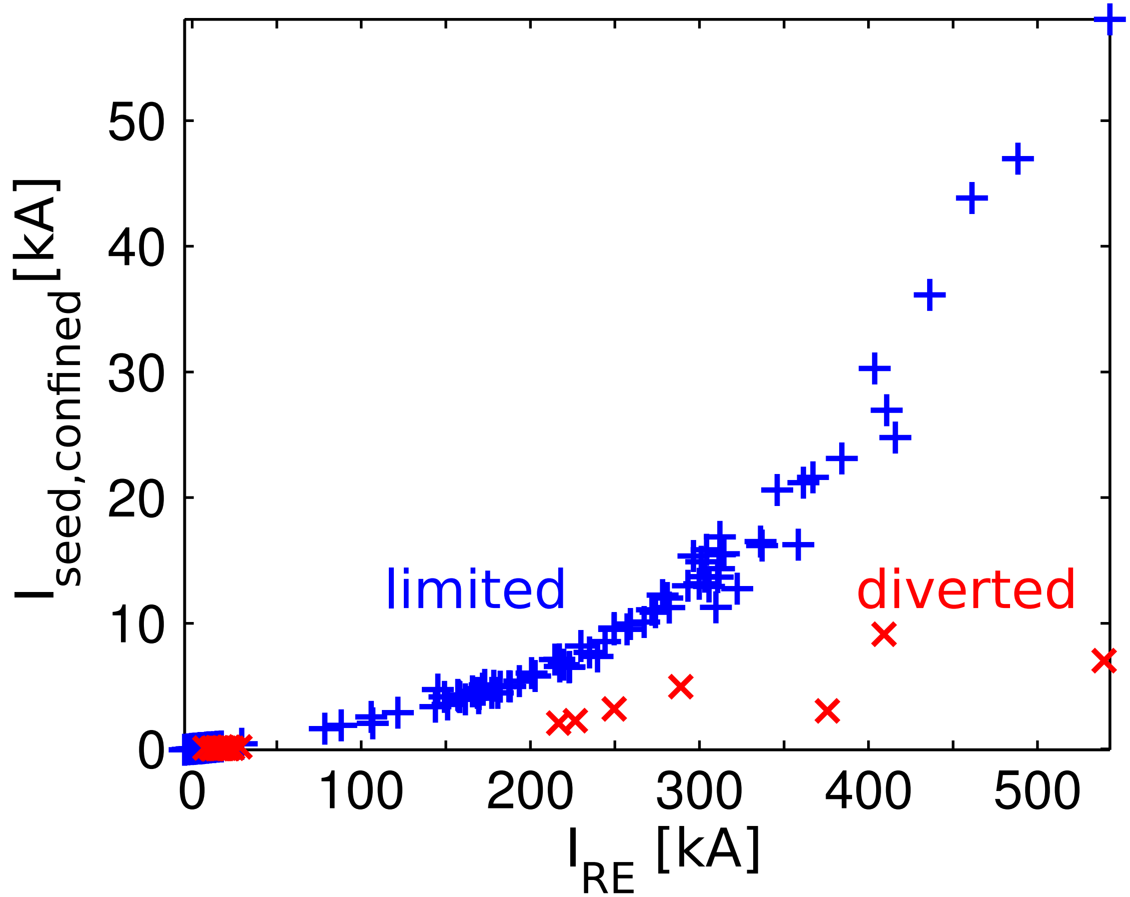


Voltage spike during thermal quench appears to exceed Dreicer field, so predicted seed current is non-physically large.

Improved measurements are necessary
for a realistic calculation of runaway seed currents!

Confined seed current is inferred from avalanche theory

- Assumed Z=1, neglected small critical field for avalanche
- Only calculates CONFINED seed current, not lost seed
- Diverted shape converts smaller seed to larger plateau compared with limited shape

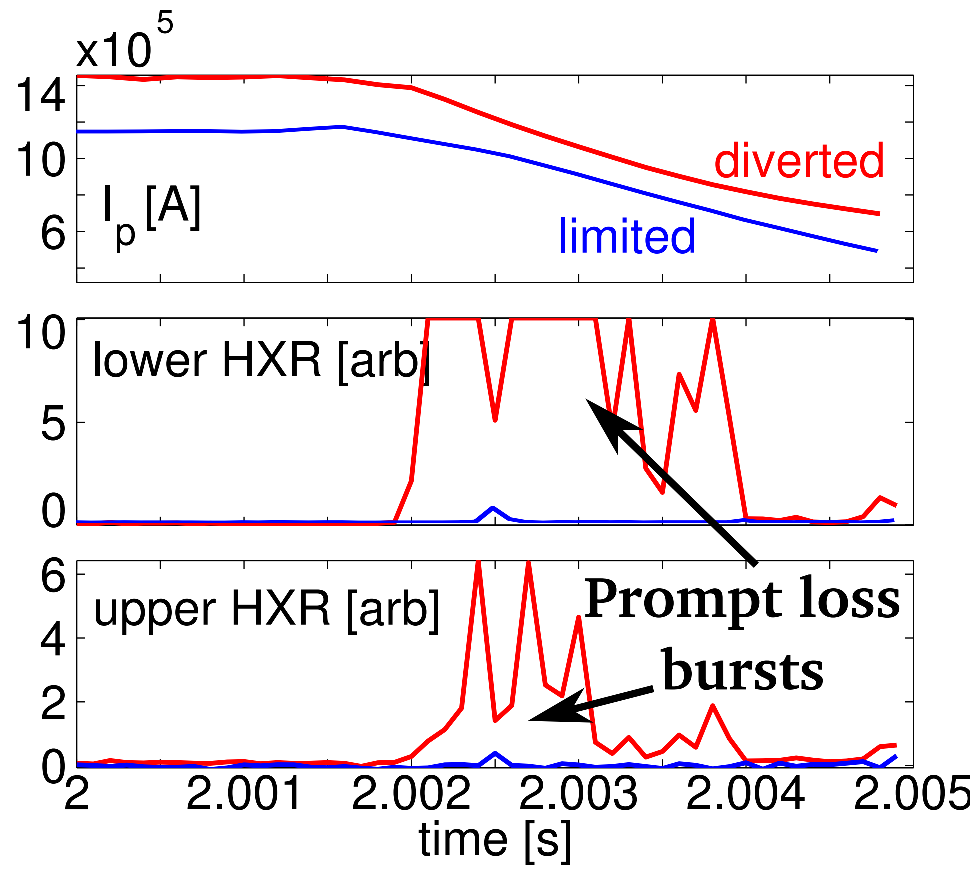


$$I_{seed} = I_{RE}\, exp\left(-\frac{e}{m_e c\bar{p}}\int_{t_0}^{t_{plateau}} E dt\right)$$

normalized momentum

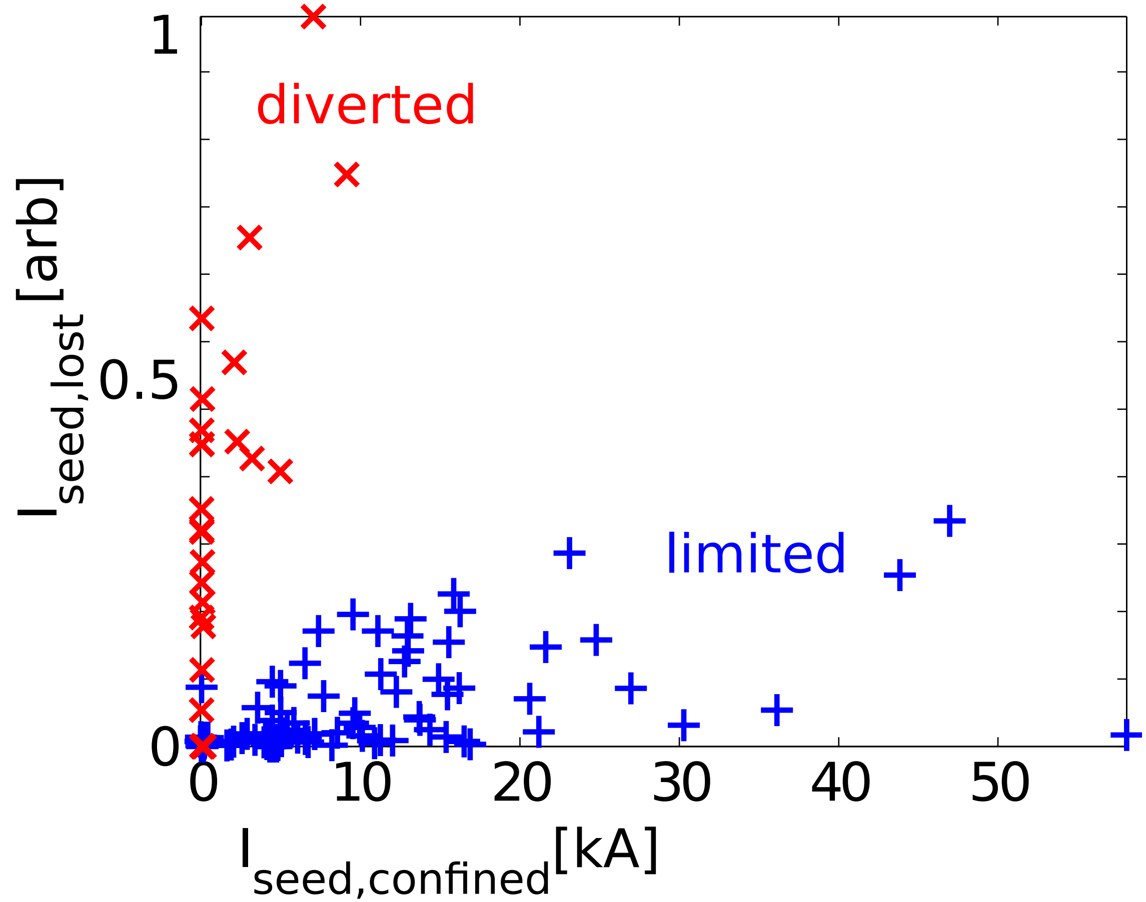
Hard x-ray measurements indicate more seed runaways escape in diverted shape

- Prompt loss hard x-ray bursts are reduced in limited shape compared with diverted shape
- Diverted shape loses a greater number of seed runaways to wall surfaces
- Limited shape has improved confinement?



Integrated scintillator signals support increased seed confinement for limited shape

- Integrated scintillator signals are proportional to lost runaway seed current
- Again, calculated seed current represents only confined runaways
- Diverted shape has greater seed loss compared to confined seed, while limited shape has greater confined seed compared to loss



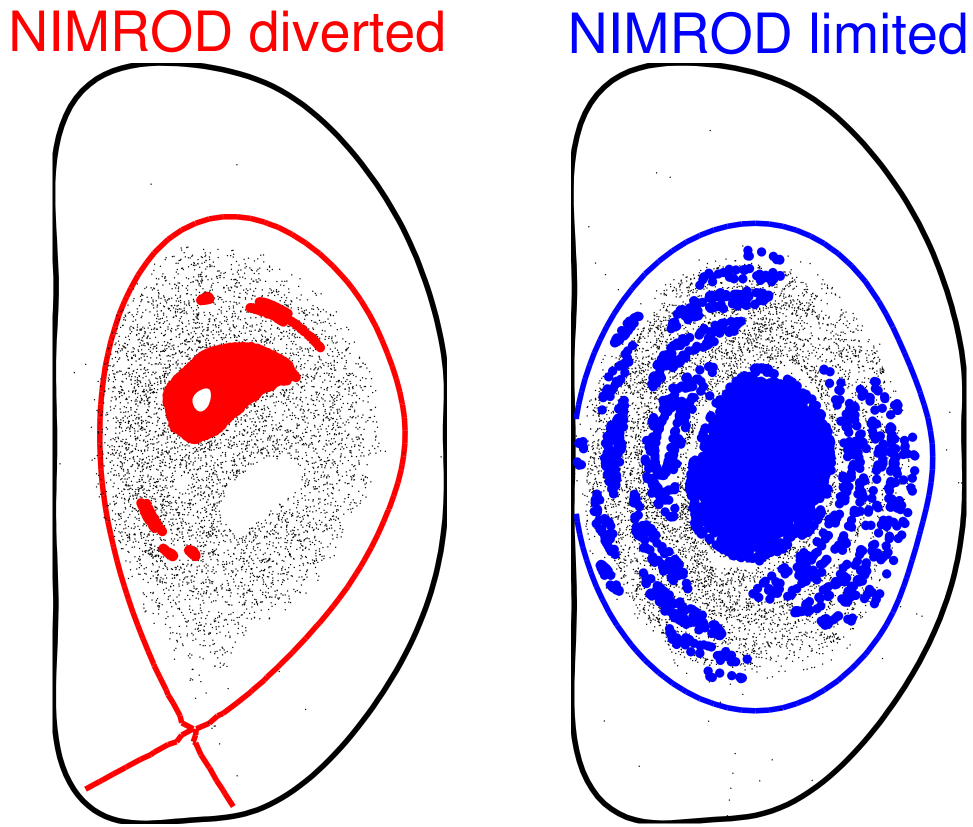
These experimental observations are supported by NIMROD simulations

- NIMROD simulations indicate decreased island overlap in limited shape compared with diverted shape reduces magnetic stochasticity

  See also [Izzo UP9.00059]

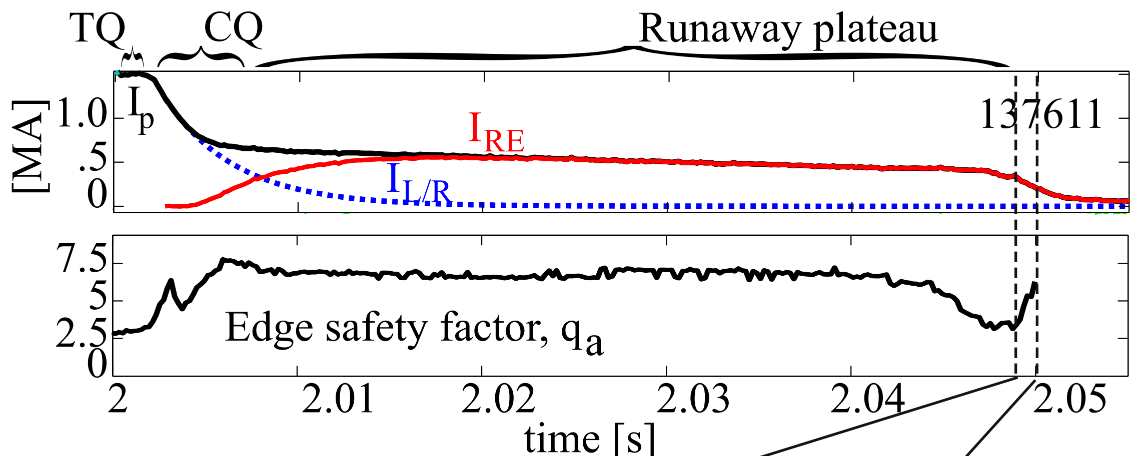
- Runaway electrons on closed surfaces (colored patches) remain confined and can avalanche

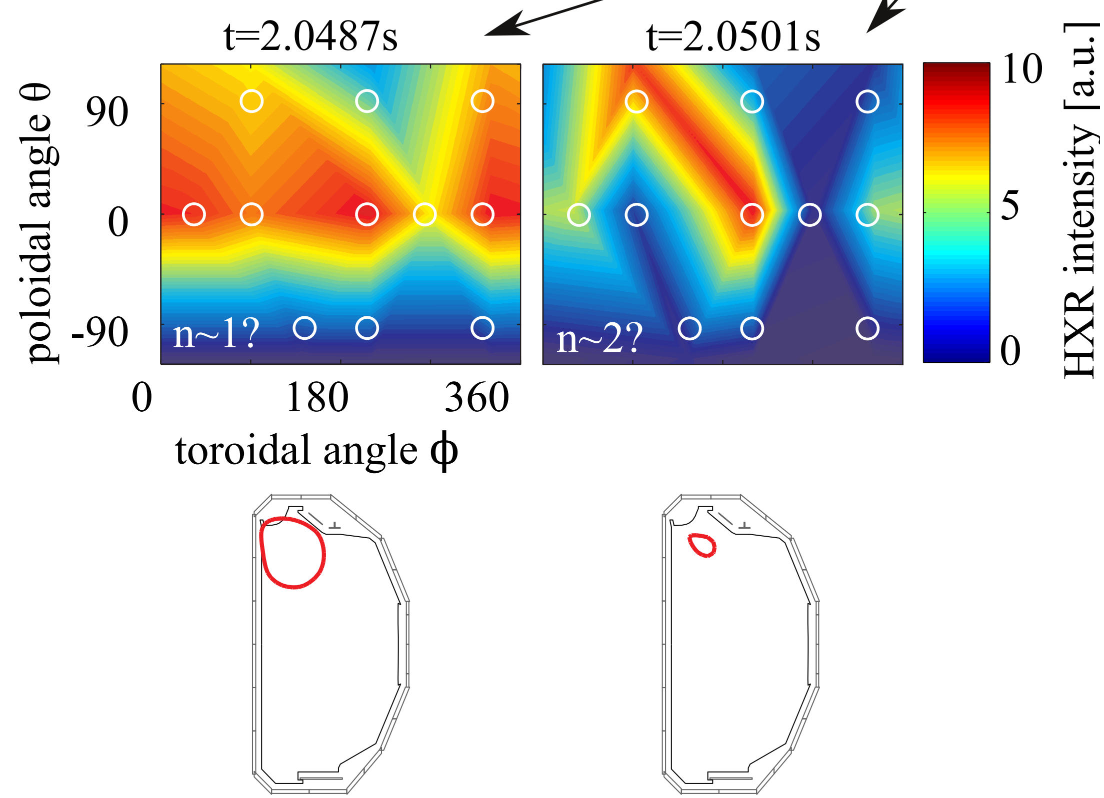
- How does the duration of this stochasticity scale to ITER?

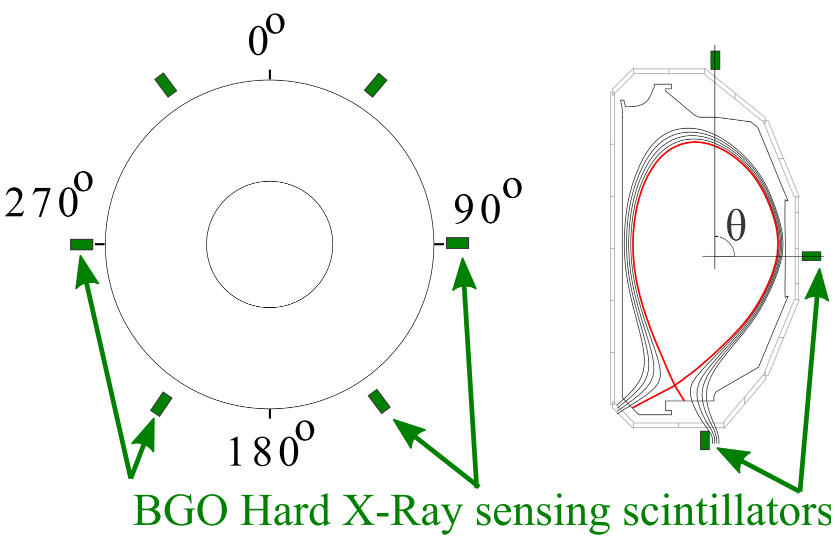


Runaway plateau eventually terminates with toroidally asymmetric hard x-ray emission

- HXR asymmetry shows apparent n=1-2 progression
- Edge safety factor drops
- Possible signatures of kink instability resulting from vertical displacement?







Summary

- Runaway electrons are observed before current quench loop voltages
- Inclusion of the often neglected inductance drop reveals an early and large loop voltage term
- Much runaway seed impacts the vessel wall in varying quantities dependent on the plasma shape
- Runaway current eventually terminates with signatures of kink instability and VDE