Disruption Mitigation Studies on DIII-D

by

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with contributions from

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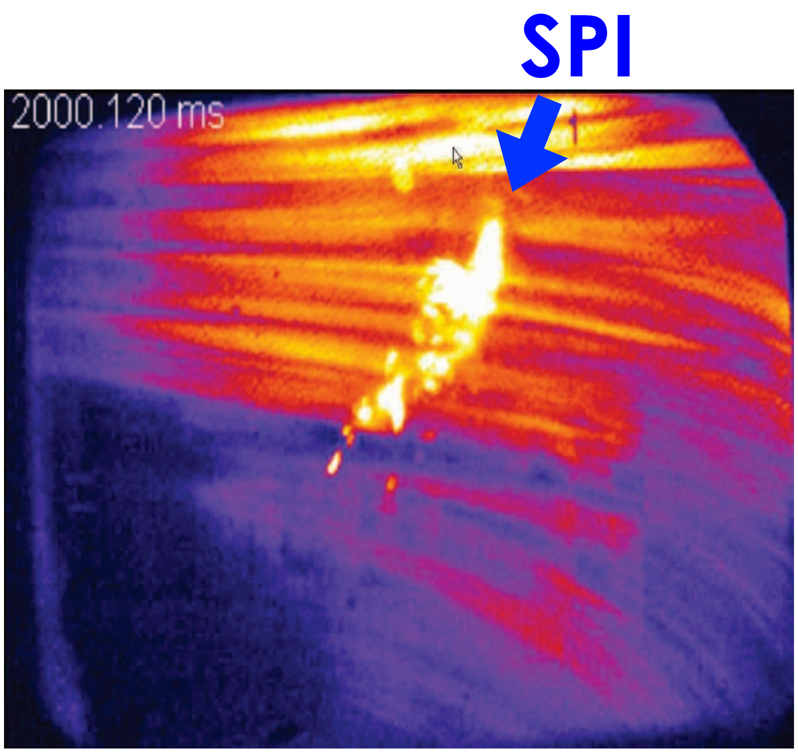
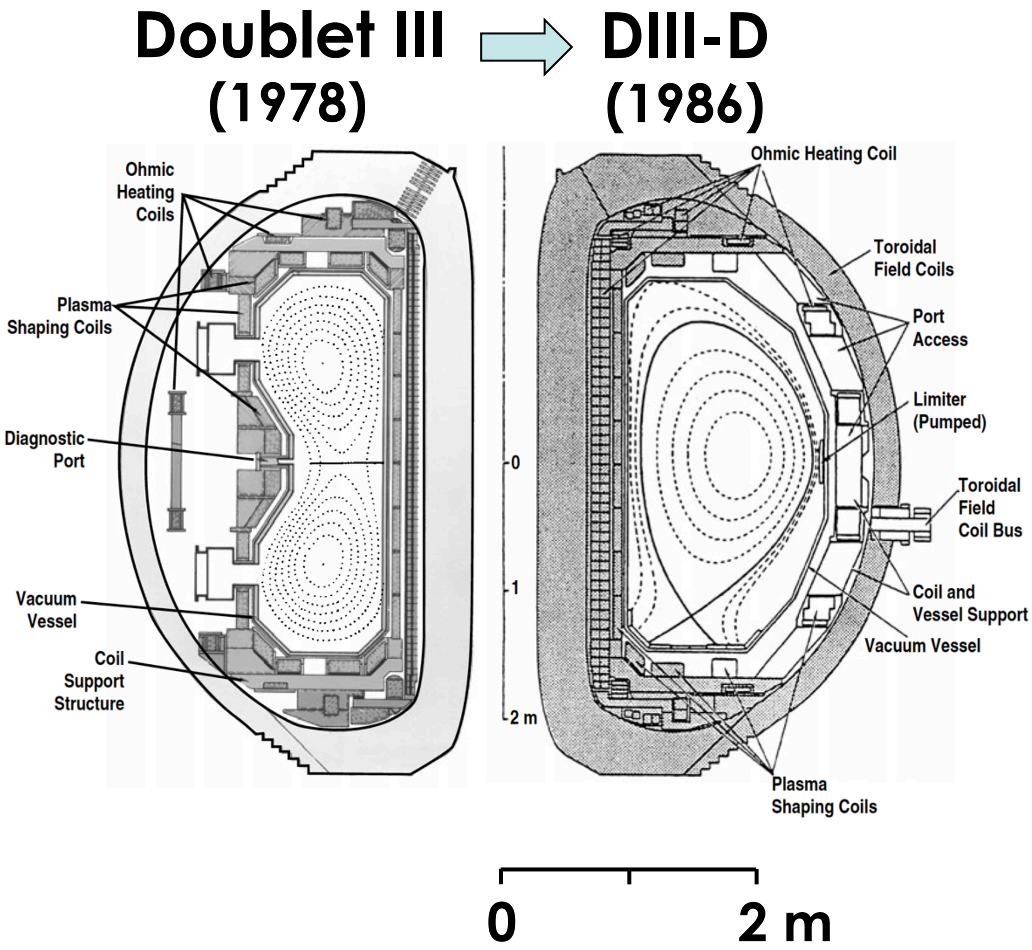
Outline

- **Introduction to DIII-D**
- **Shattered pellet injection**
  - Background
  - Comparisons with massive gas injection
  - Effect of SPI on disruption properties
- **Runaway electron physics studies**
  - Post-disruption runaway electron suppression/dissipation
  - Quiescent runaway regime
- **Summary**



DIII-D tokamak

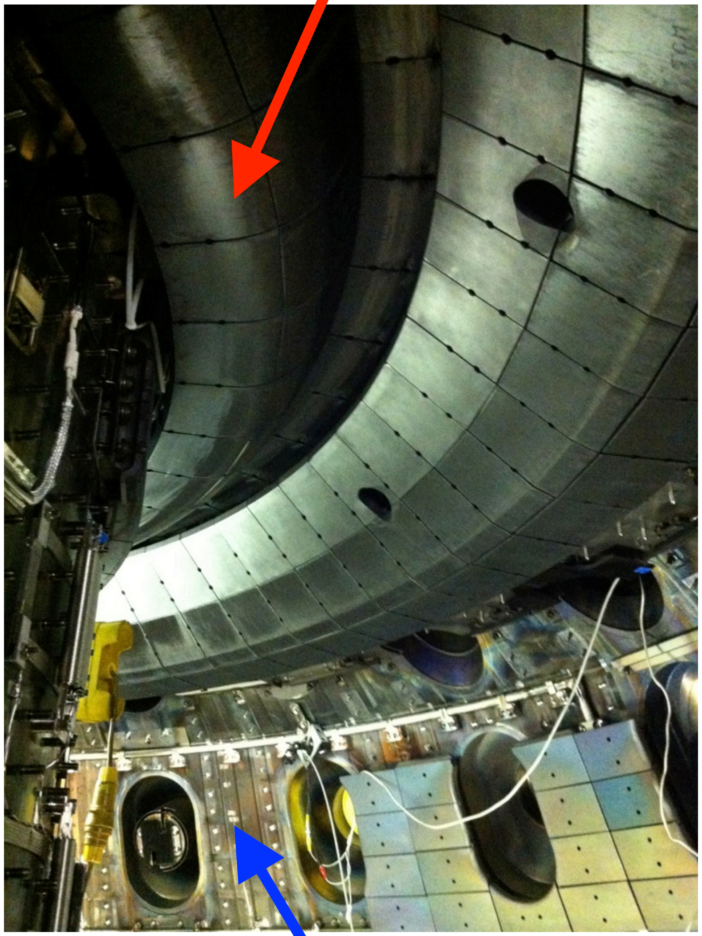


- Toroidal field = 2.2 T
- Plasma current < 3.0 MA
- Neutral beam power = 16 MW
- Pulse length < 10 s

- Unique plasma shaping and control capabilities
  - e.g. Runaway electron control

DIII-D is well suited for disruption research

- **Vacuum vessel designed to handle large disruption forces**
- **Thick all-graphite first wall can withstand high temperatures (> 2000°C)**
  - Thermal quench heat loads as well as runaway electron strikes
- **Allows disruption studies without fear of damage!**



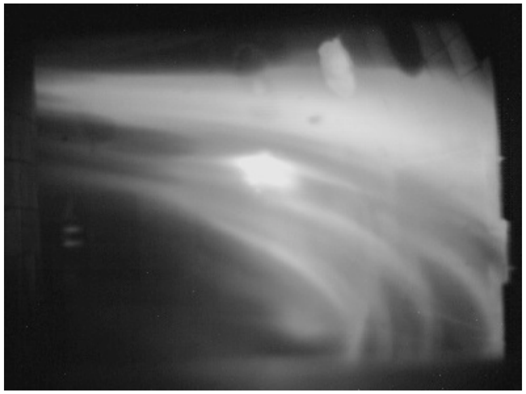
DIII-D has extensive disruption mitigation system

- **Shattered pellet injection (SPI)** - Two systems (2nd system for 2017)
  - Unique to DIII-D (Installation on JET this year)
  - ITER disruption mitigation system will be based on SPI
- **Massive gas injection (MGI)** – Two systems
  - Large, high-pressure gas pulse
- **'Killer' pellet injection**
  - Small high-Z cryogenic pellet
  - Designed as a tool for generating runaway electrons

DIII-D also has a large number of disruption diagnostics

- **Time scales, amplitudes are unique from typical flat-top measurements**
- **Strong forces/vibrations during disruptions are a challenge**

Fast camera imaging

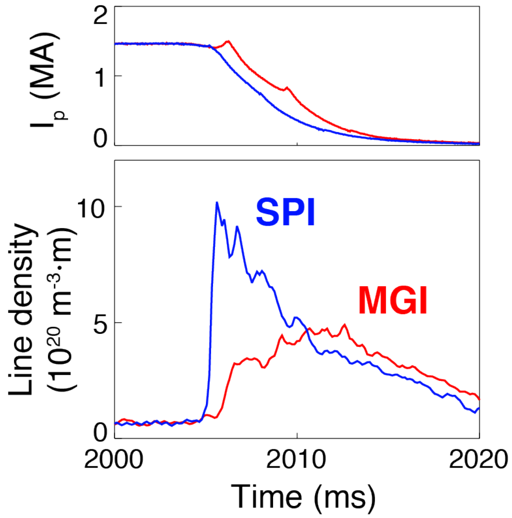


TQ radiated power

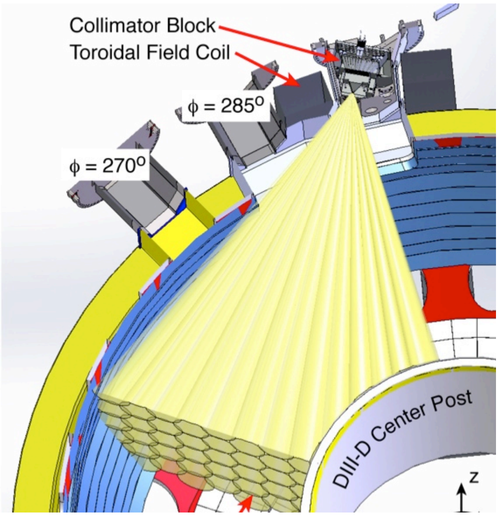
E.M. Hollmann *et al* Phys. Plasmas **22** (2015) 021802

First-wall/divertor temperature

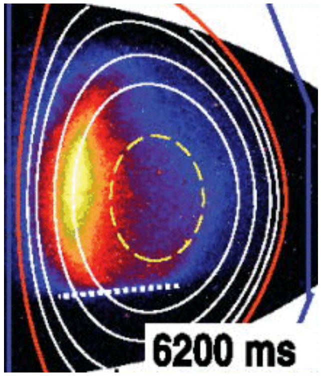
Two-color interferometry



RE gamma ray imager



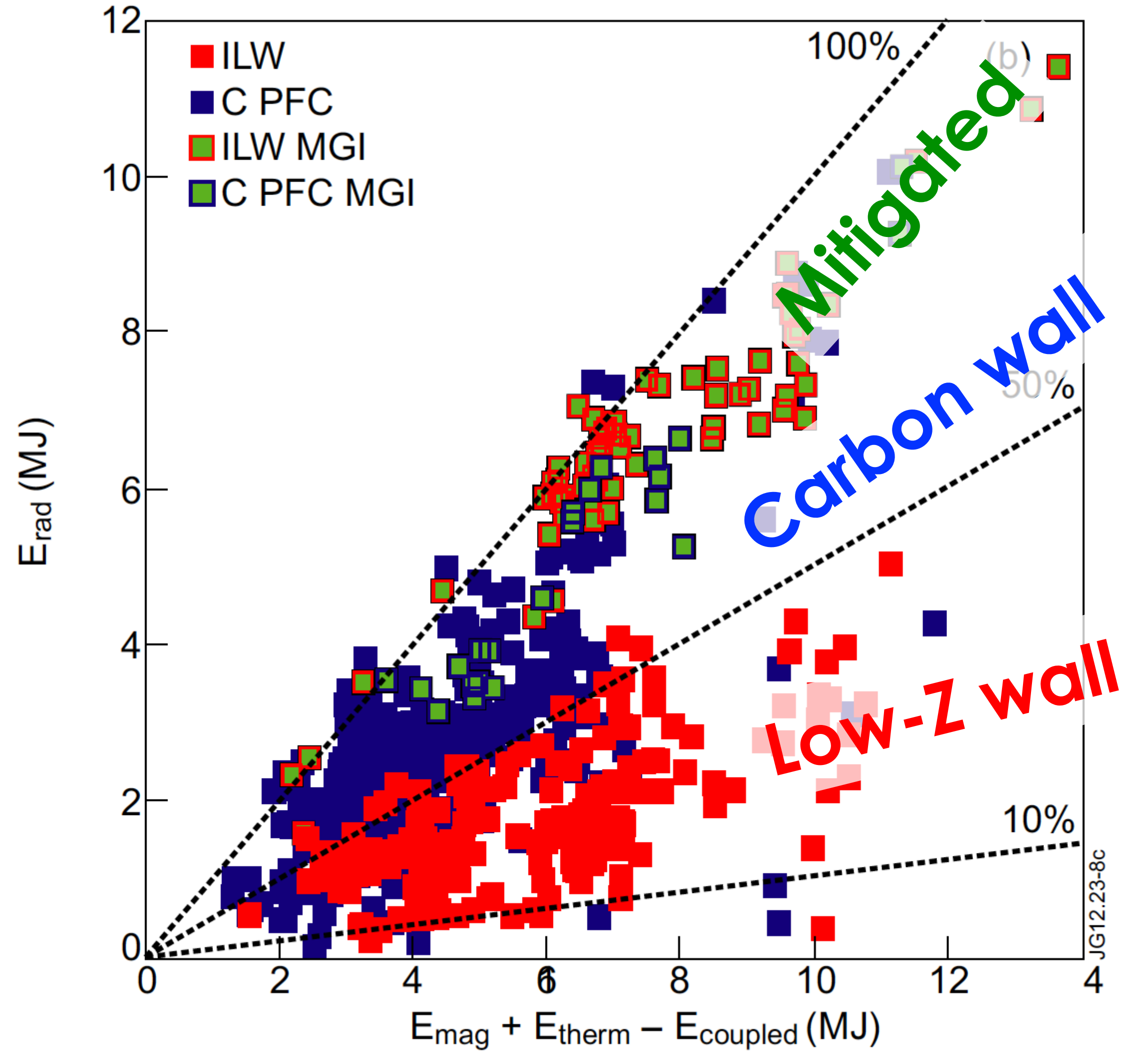
RE visible synchrotron emission



C. Paz-Soldan *et al* Phys. Plasmas **21** (2014) 022514

Carbon wall causes unmitigated disruption properties to differ from low-Z wall machines such as ITER

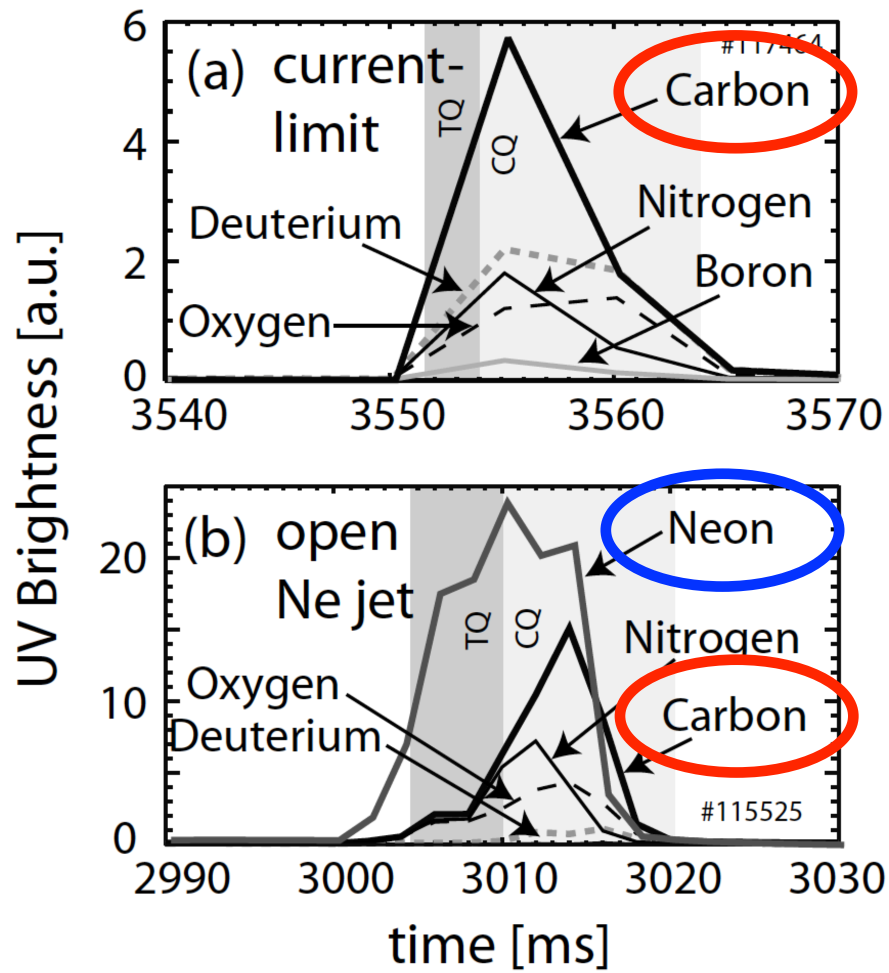
- **Well documented on JET**
- **Carbon (Z=6) is a radiating impurity**
- **Disruptions in a carbon-walled machine are partially 'self-mitigated'**



P.C. de Vries et al., PPCF 54 (2012) 124032

For mitigation by high-Z impurity injection, carbon effects can be ignored

- **UV survey spectrometer shows dominant radiating species**
- **In unmitigated disruptions, effect of carbon is significant**
- **For mitigated disruptions, high-Z injection is dominant over carbon**



E.M. Hollmann et al., NF 45 (2005) 1046

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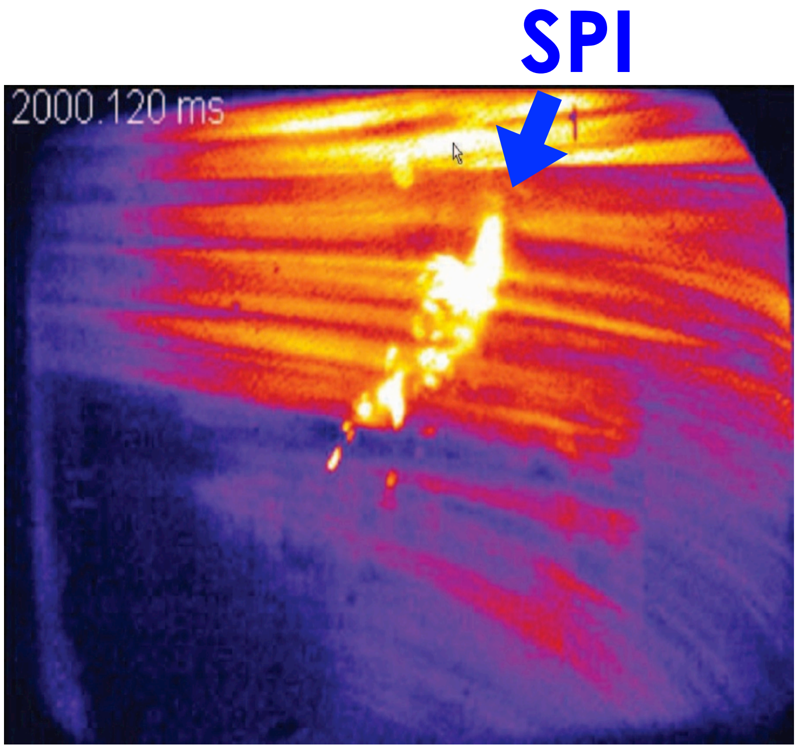
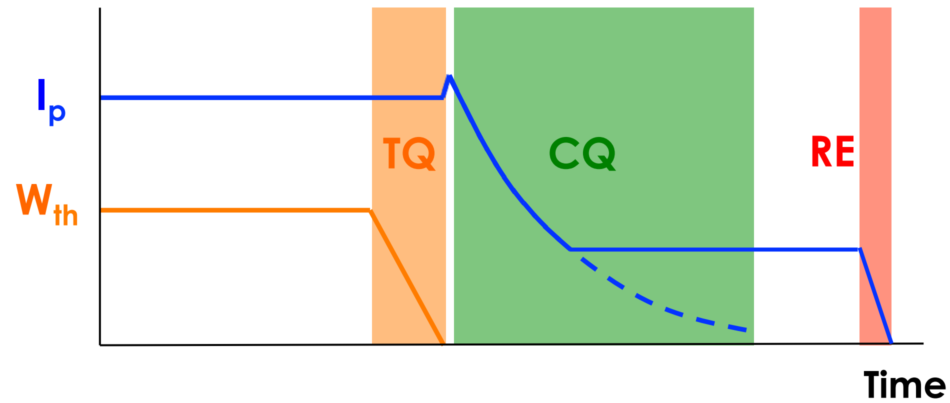


Disruption mitigation in ITER will be based on rapid, massive high-Z impurity injection

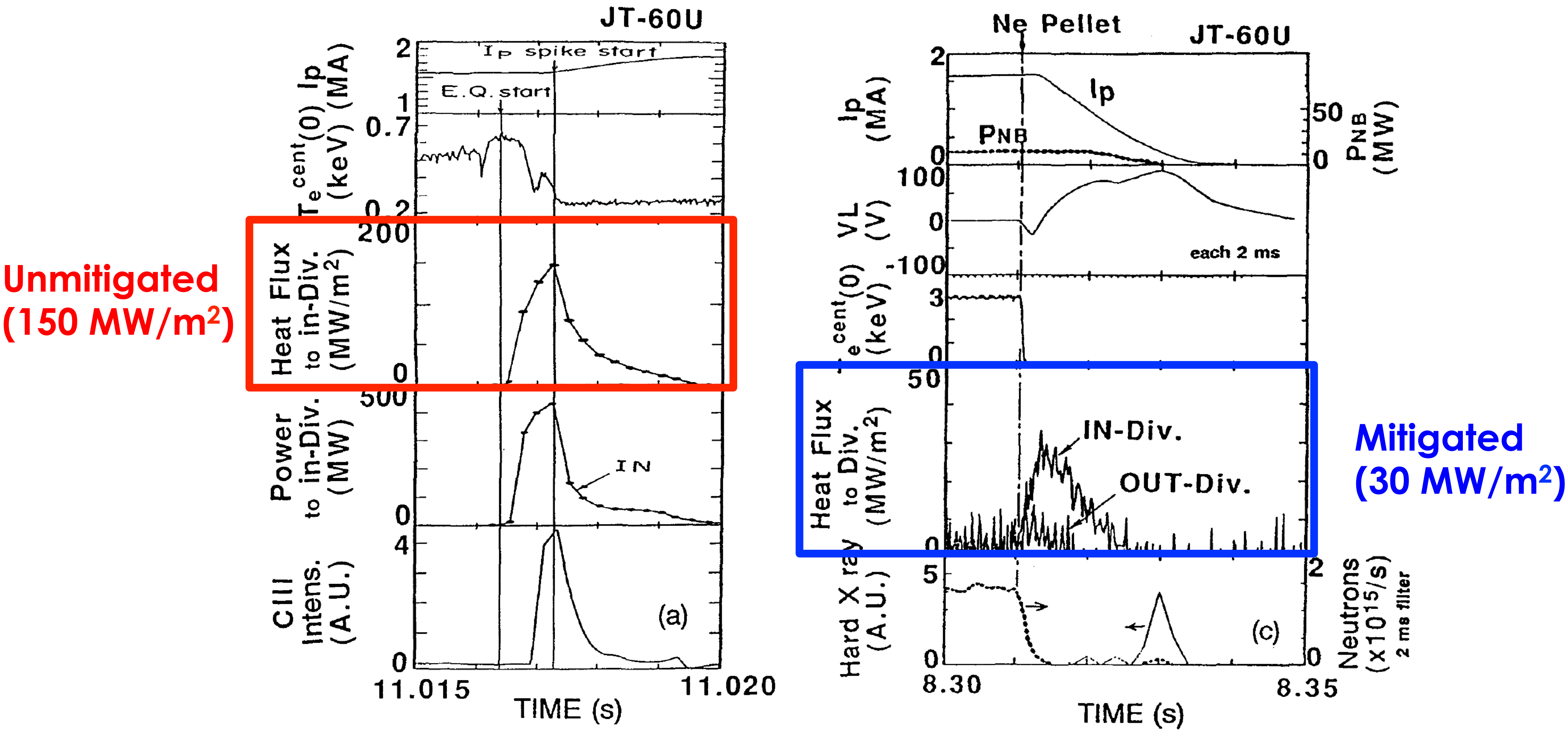
- **Must protect against all three stages of the disruption**



- Thermal quench (TQ) heat loads → Spreads thermal energy through radiation
- Current quench (CQ) electromagnetic forces → Reduces halo currents through faster current decay
- Runaway electron (RE) wall strike → Collisionally suppresses or dissipates REs

Small high-Z impurity pellets first shown to mitigate disruptions (JT-60U)

R. Yoshino et al., Plasma Phys. Control. Nucl. Fusion (1994)



One fatal flaw: tends to generate runaway electrons due to rapid cooling!

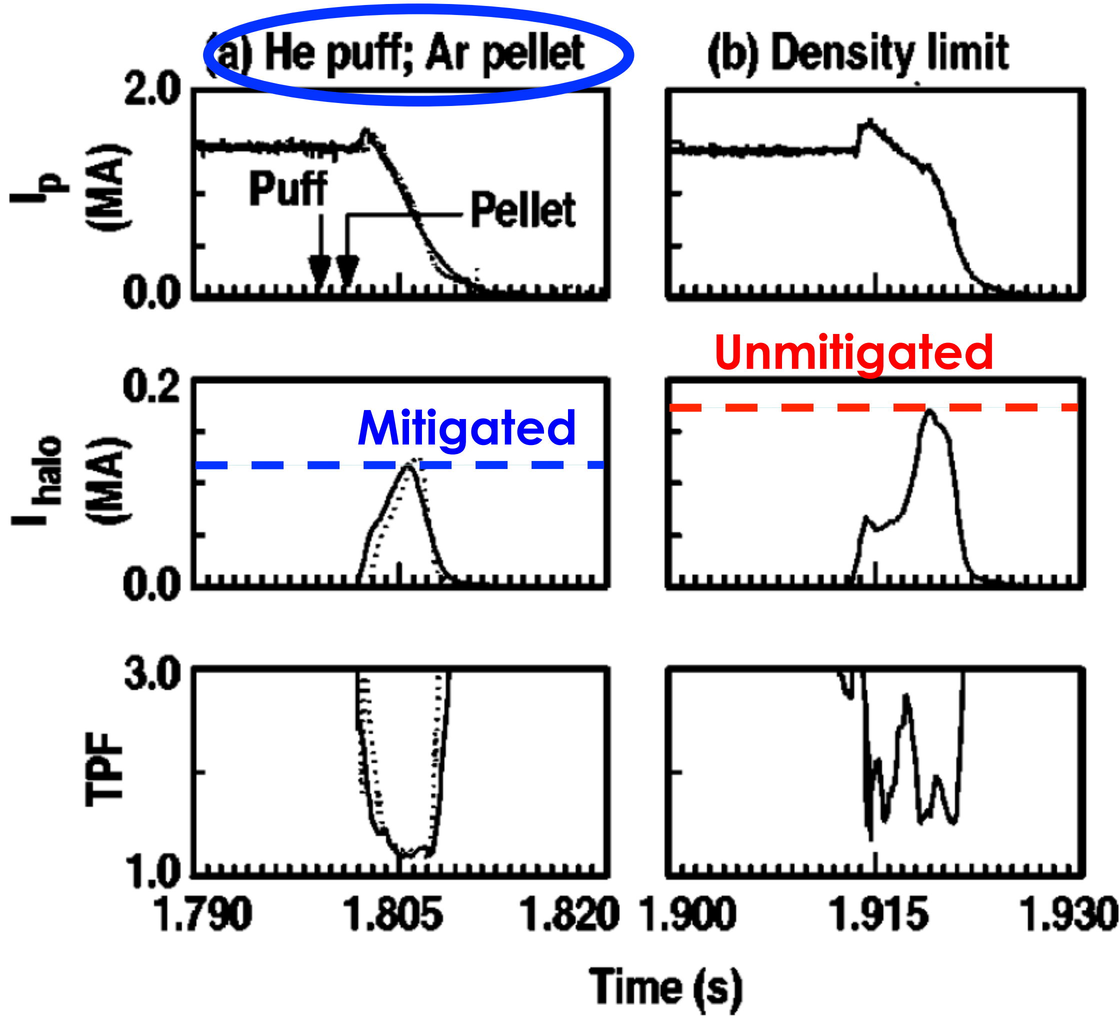
Massive gas injection achieves similar mitigation, without runaway generation

- Large gas quantities injected:

  N_{inj} ~ 10^22 atoms > N_{plasma} ~ 10^21 atoms

- Widely tested on many tokamaks

- As we'll see, there are many advantages to pellet injection over gas injection

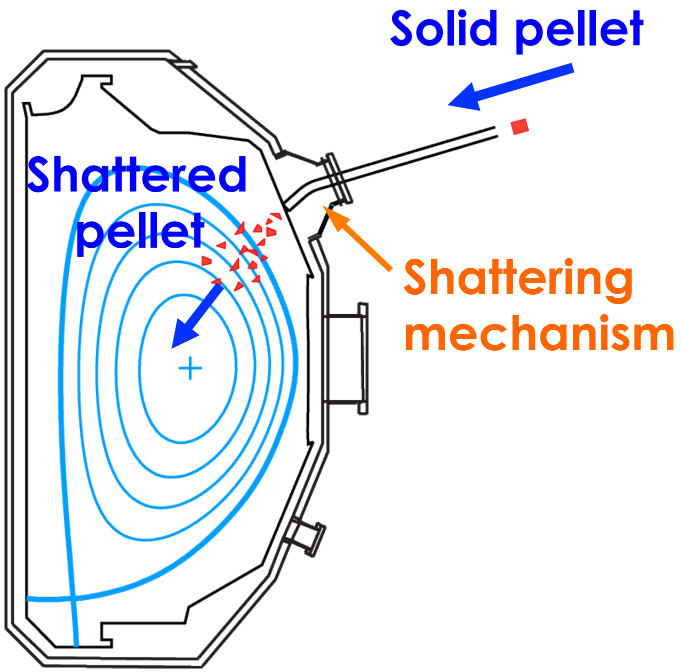


P.L. Taylor et al., Phys. Plasmas 6 (1999) 1872

Large pellets could be used, if they are "shattered"

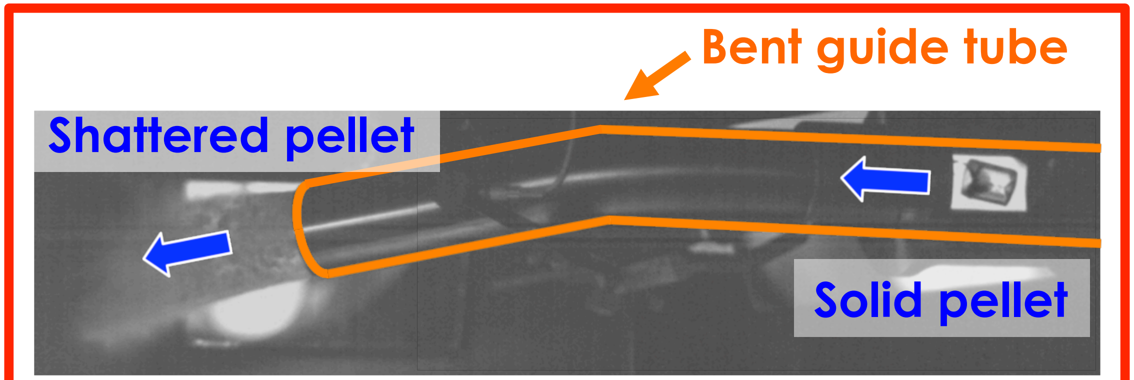
- **To get around runaway problem, must use very large pellets, which significantly raise plasma density (collisional dissipation)**
- **Two problems with using such large pellets:**
  - Can cause damage to the first wall
  - Would transit the plasma without fully ablating
- **Solution: Fire a large pellet, but shatter it just prior to entering the plasma**

ITER has selected shattered pellet injection for its disruption mitigation system

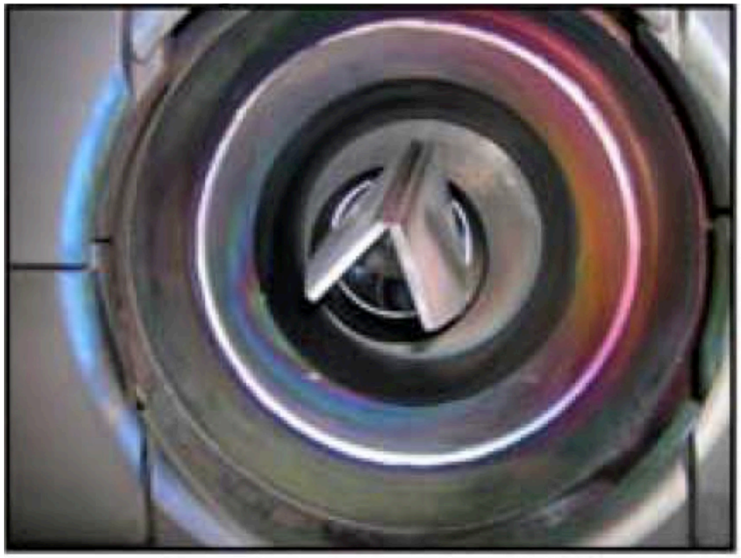


Several shattering mechanisms have been tested

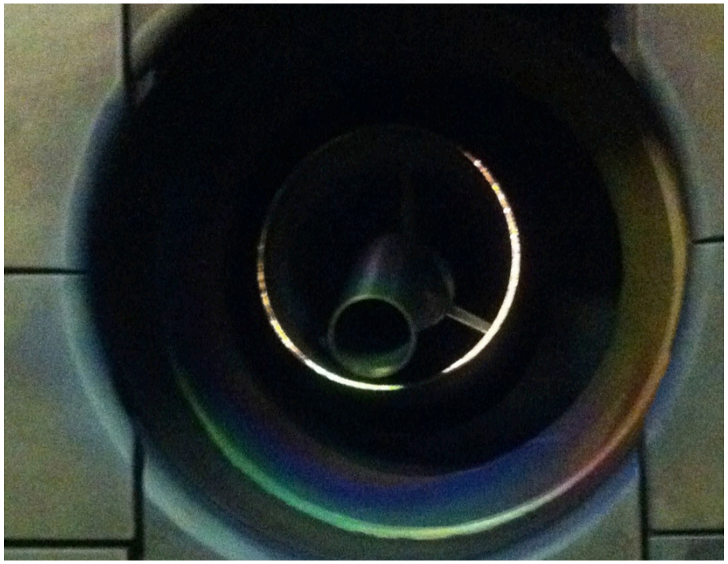
- Various designs tested: funnel, various bend angles, S-bends
- Initial design used on DIII-D: Target plate and V-groove
- Current design: 25° bend in guide tube



Composite image from ORNL laboratory tests



View from Inside DIII-D



Shattered pellet generates a stream of solid pellet fragments, along with gas

- Fragments of several millimeters exist
- Shattered pellet is a mix of solid, liquid, and gas

S.K. Combs et al, IEEE Trans. Plasma Sci. 38 (2010) 400

- After development and testing at ORNL, SPI system was installed on DIII-D in 2009

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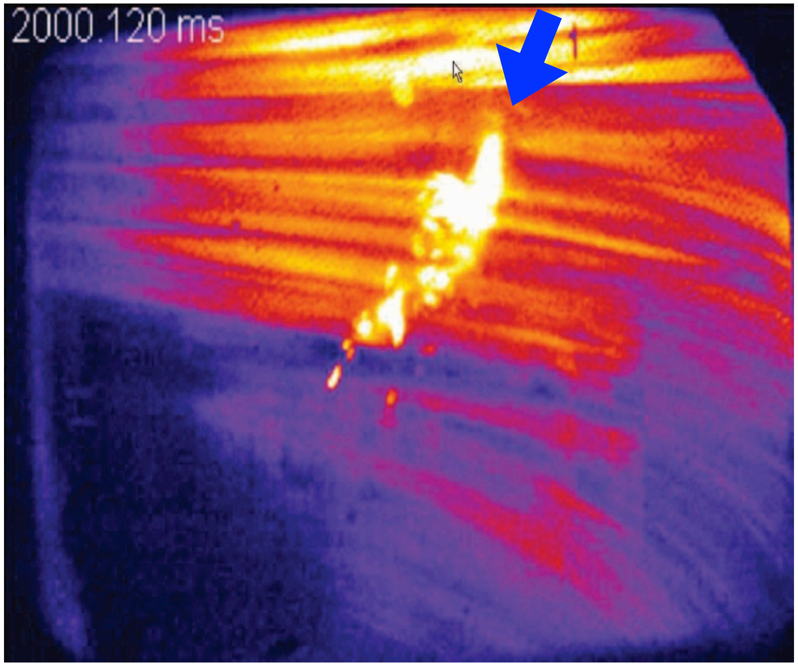
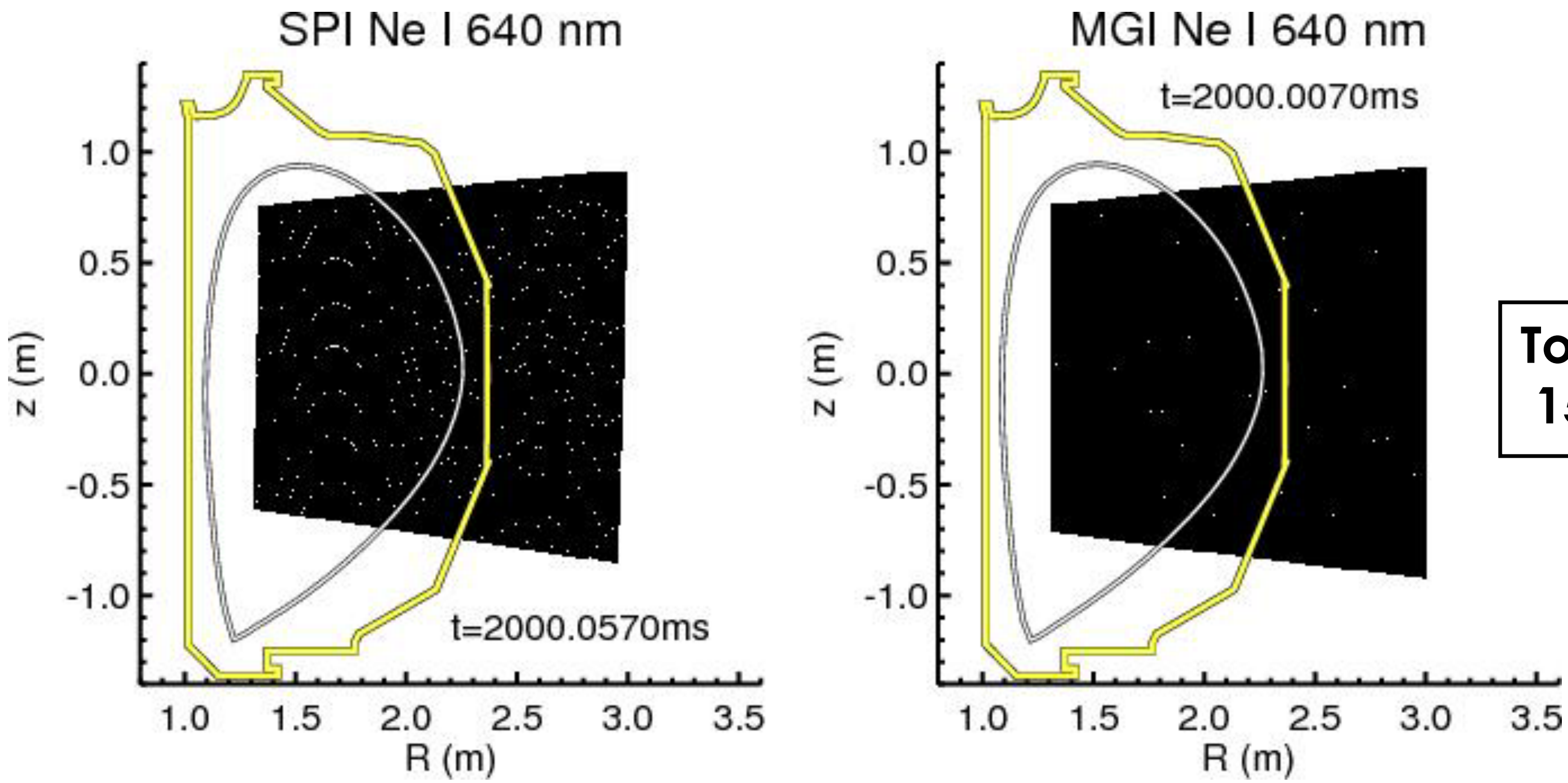
SPI



SPI delivers injected particles more abruptly than does MGI



Total time:
15 ms

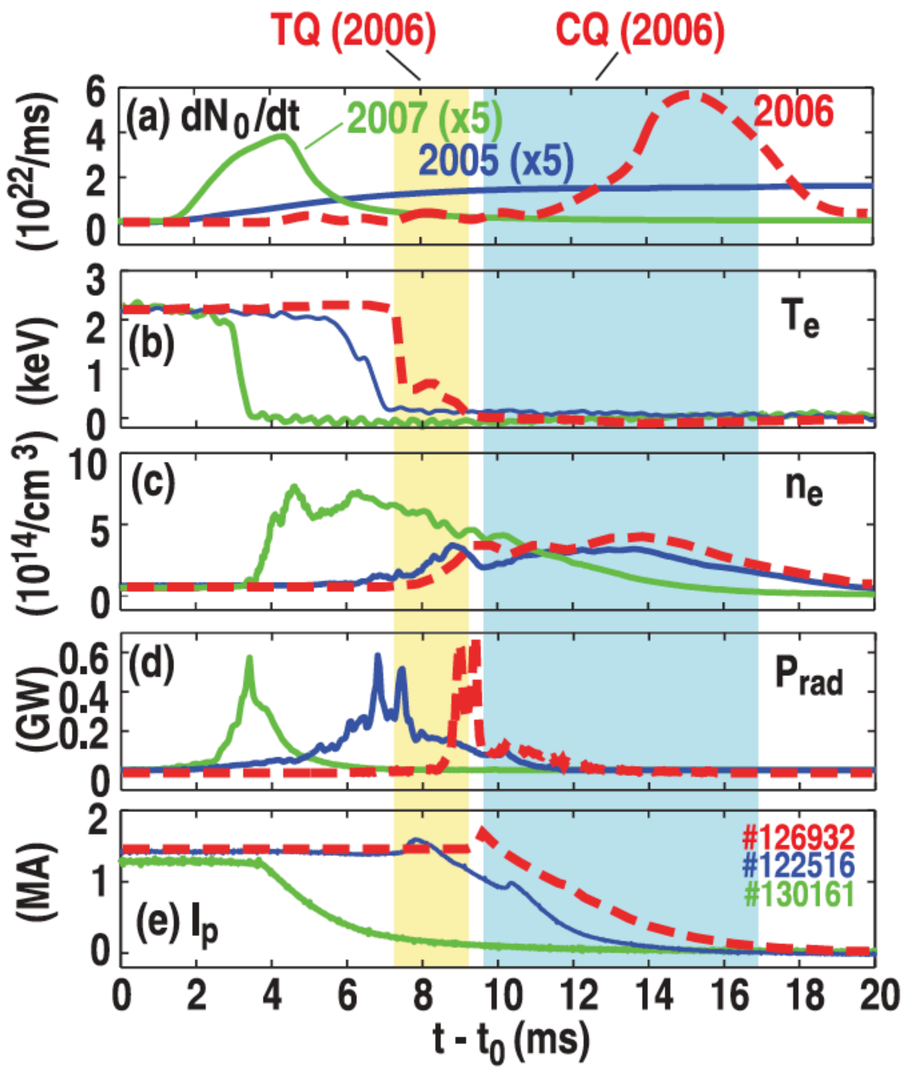
- **SPI: Particles travel to shatter tube as a solid pellet at constant velocity**
  - Particles enter plasma abruptly
- **MGI: Gas pulse spread out due to limited conductance of delivery tube**
  - Particle delivery is more gradual

MGI flow rates can be slow relative to TQ timescales

Neutral flow into vacuum vessel

E.M. Hollmann et al, NF 48 (2008) 115007

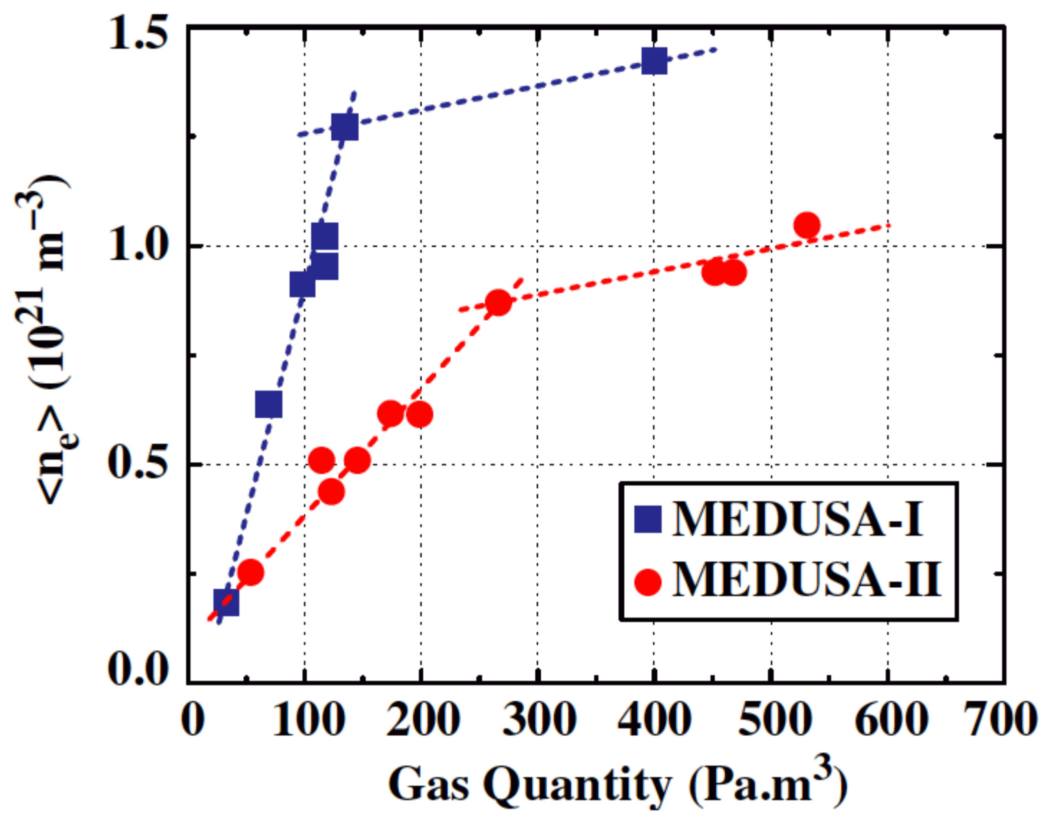
Plasma current



- Peak flow rates from MGI can occur well into the CQ

Resulting assimilation of MGI is limited by gas flow rates

- MGI particle assimilation measured by interferometer
- Two geometries compared:
  - Open duct
  - Restricted duct
- Assimilation reduced with lower gas conductance



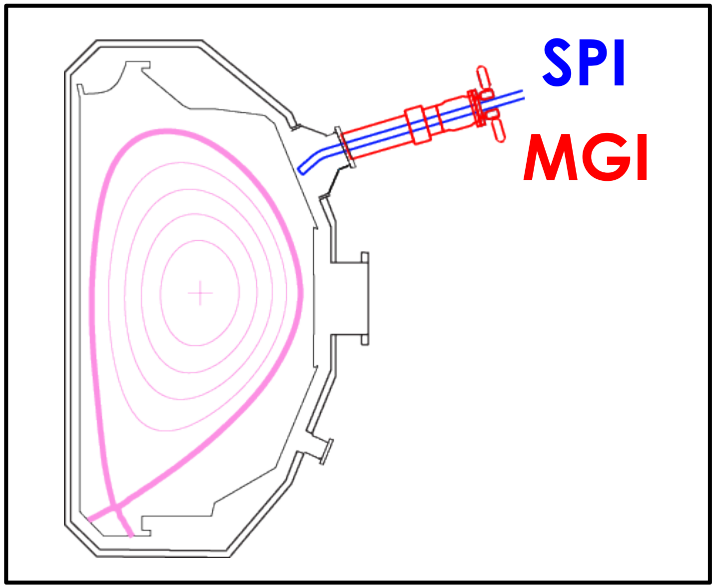
N. Commaux et al, NF 51 (2011) 103001

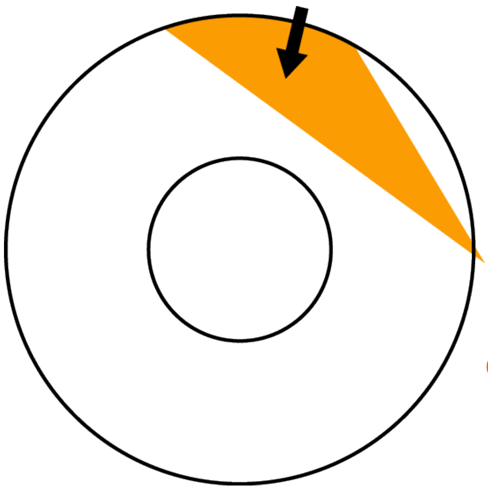
DIII-D experiments have made direct comparisons of SPI and MGI techniques

- **SPI and MGI systems installed on same upper port in DIII-D**

- **Allows direct comparison of the two injection techniques**
  - Identical injection quantities
  - Same plasma target

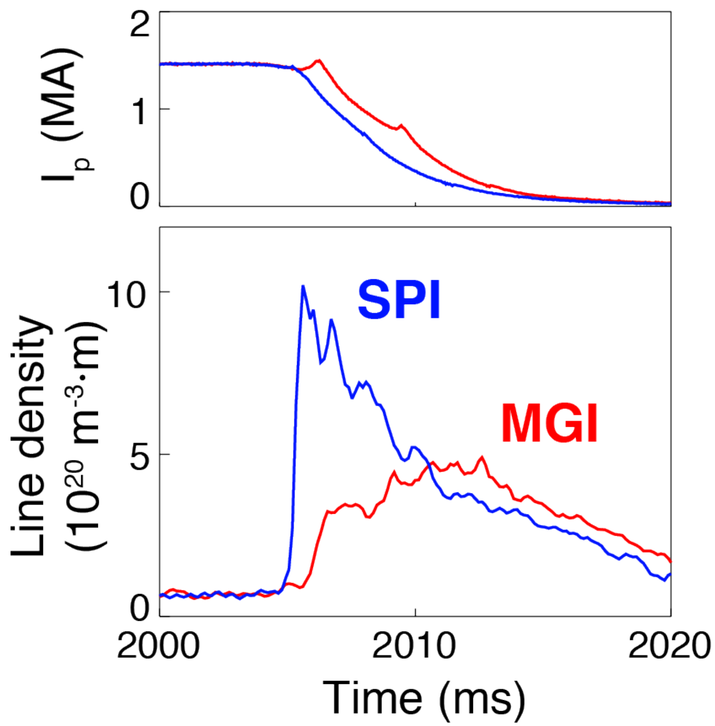
- **Identical diagnostic coverage**
  - Example: fast-framing camera

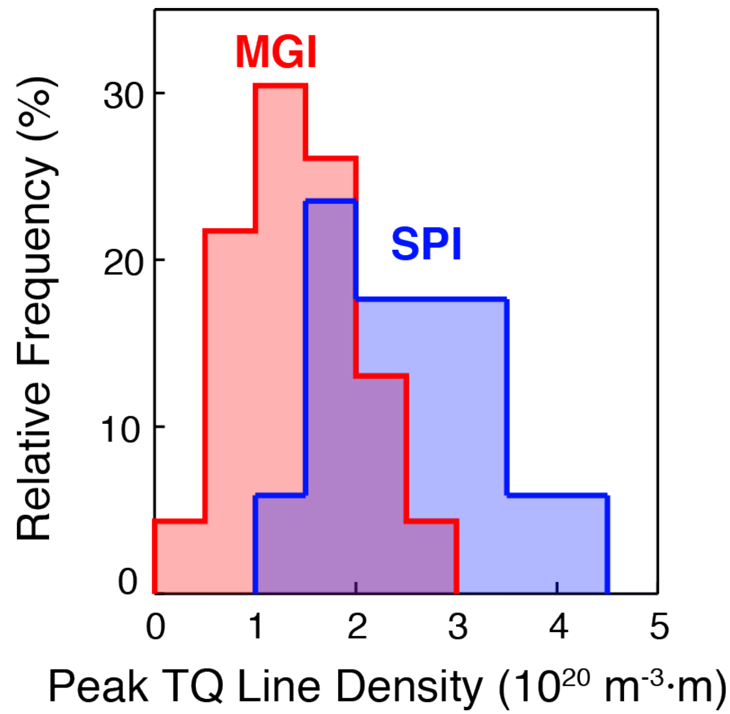




Faster particle delivery by SPI results in higher total particle assimilation than MGI

- **Measured peak density from SPI is a factor of 2 higher than from MGI**

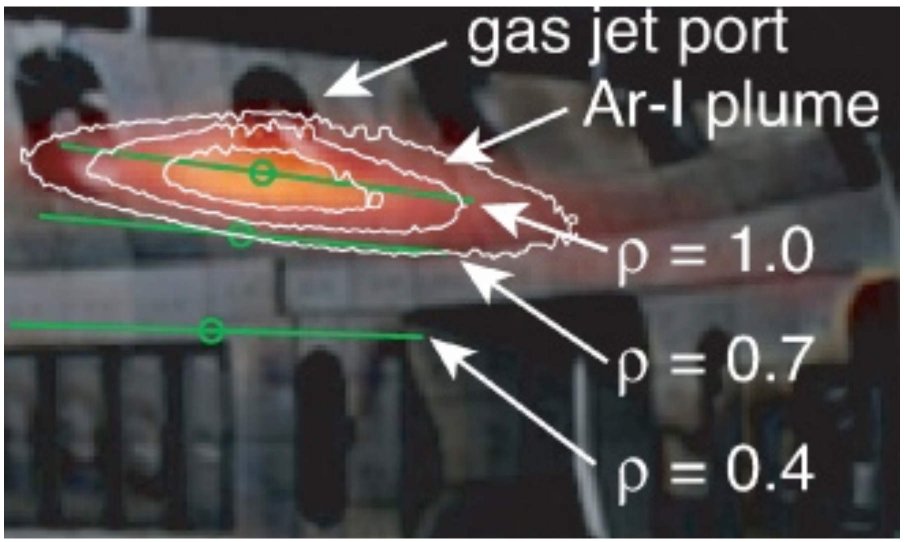


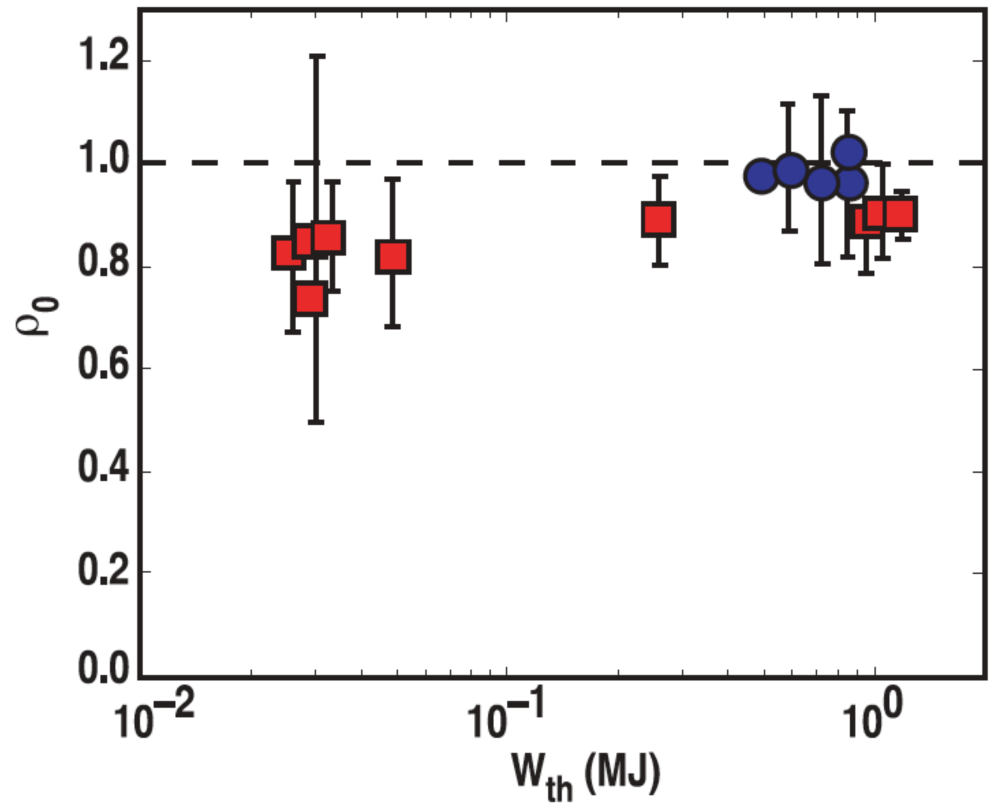


- **Peak density during SPI is reached earlier in the disruption**
  - Rapid assimilation of radiating impurities needed for TQ mitigation
  - Advantageous for collisional suppression of seed REs during early CQ

MGI neutrals are stopped near the plasma edge

- **Estimated based on field-line pitch, seen from parallel spreading**



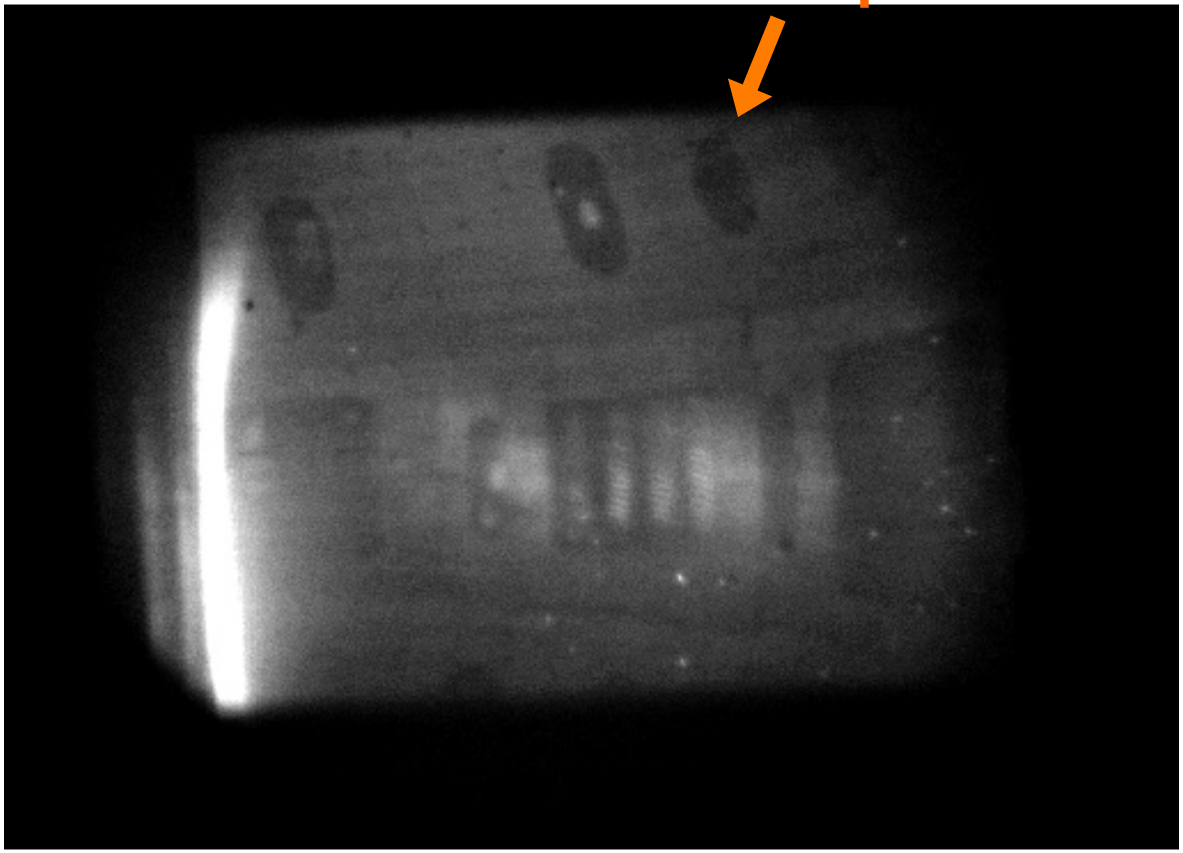


E.M. Hollmann et al, NF 48 (2008) 115007

- **Once TQ starts, enhanced radial transport due to MHD mixing**

SPI rapidly injects impurities, to shutdown plasma

Fast camera field of view



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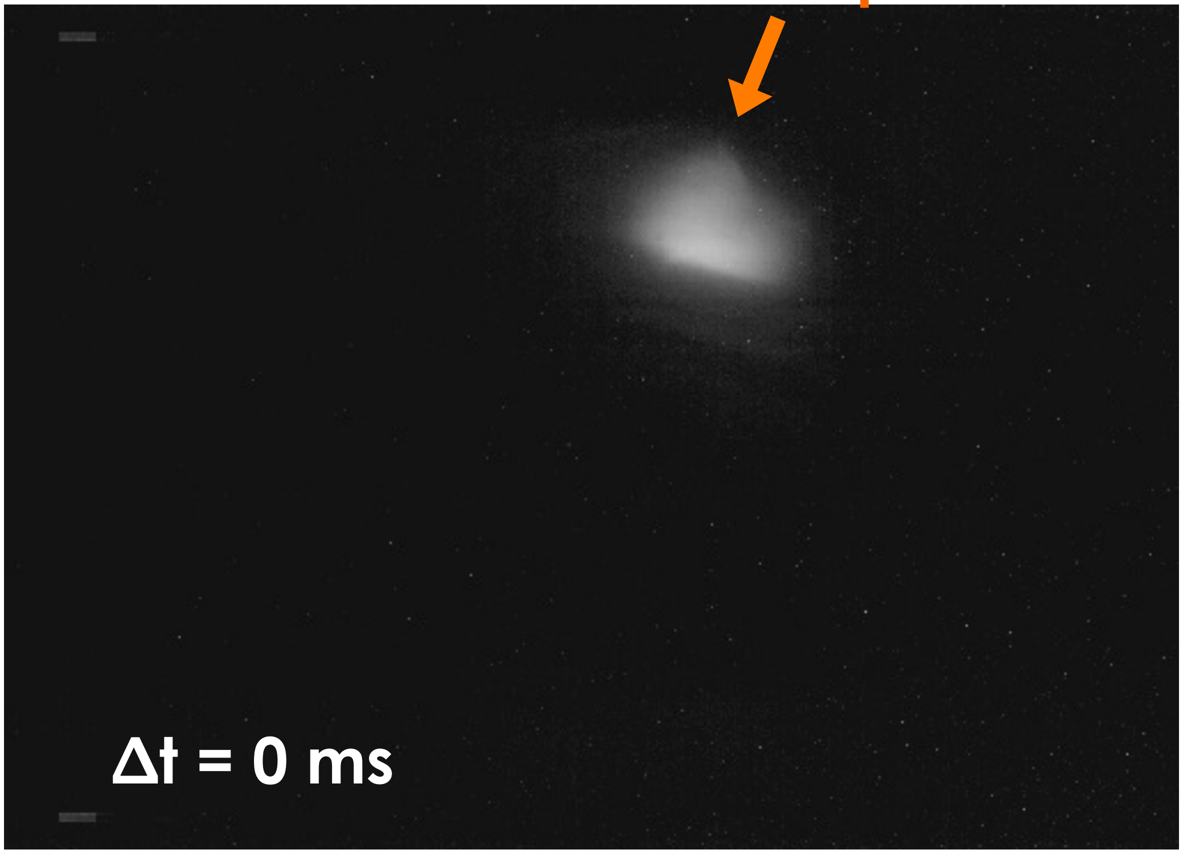
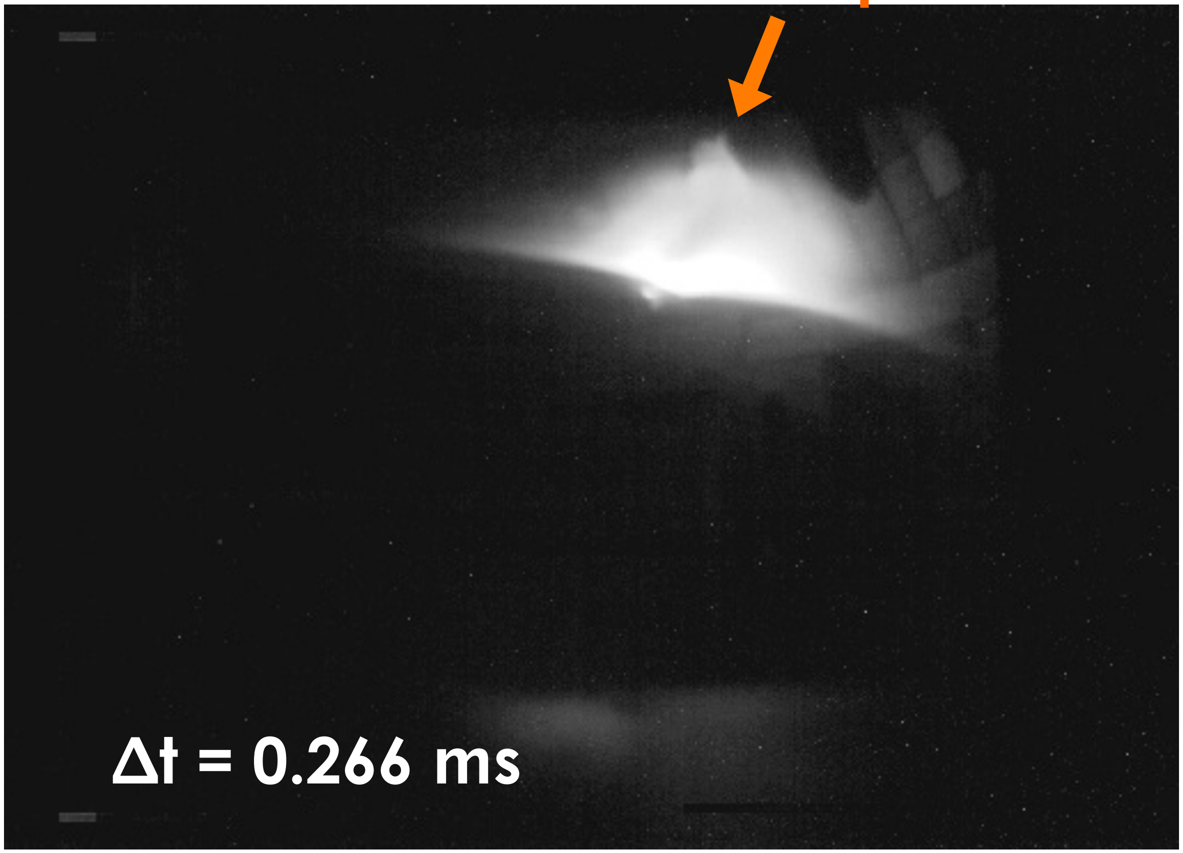


Ne-I filter (640 nm)

SPI rapidly injects impurities, to shutdown plasma



Ne-I filter (640 nm)

SPI rapidly injects impurities, to shutdown plasma

SPI port

Ne-I filter (640 nm)

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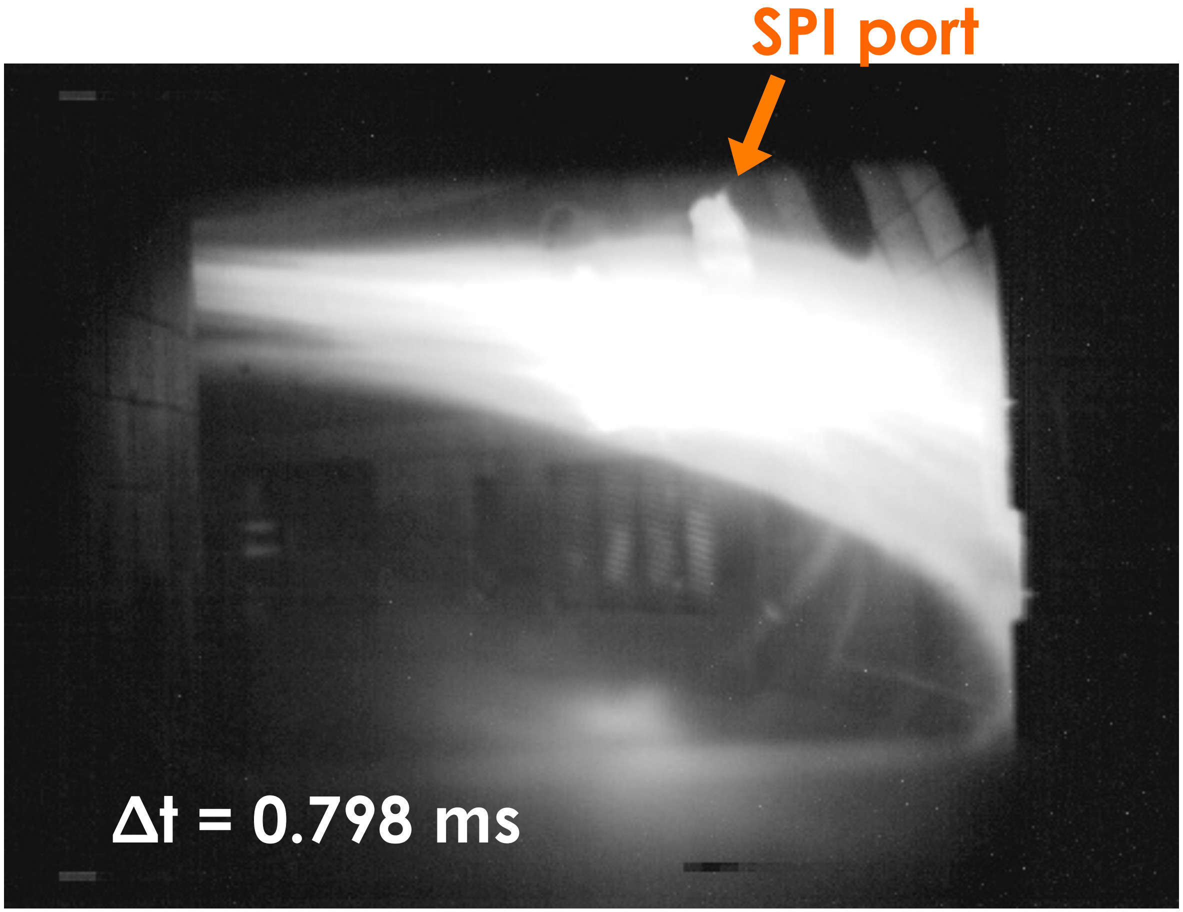

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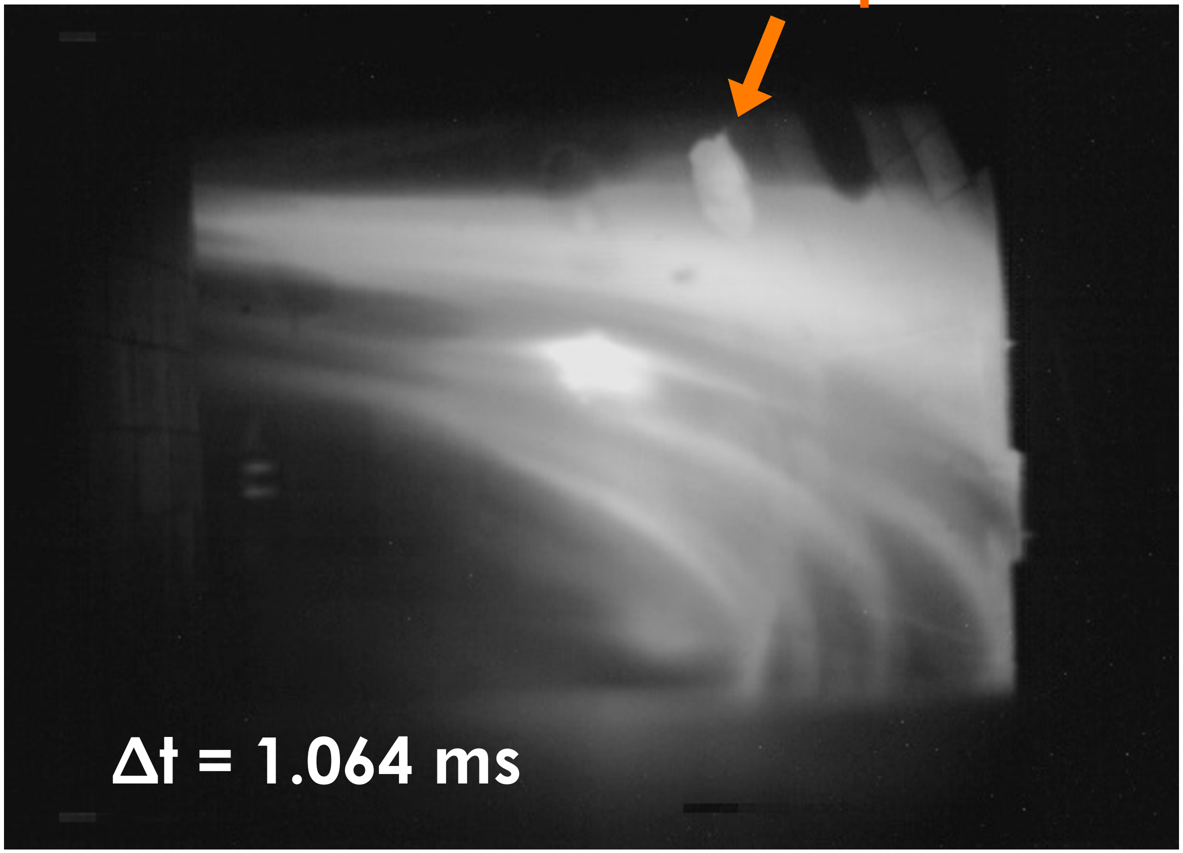

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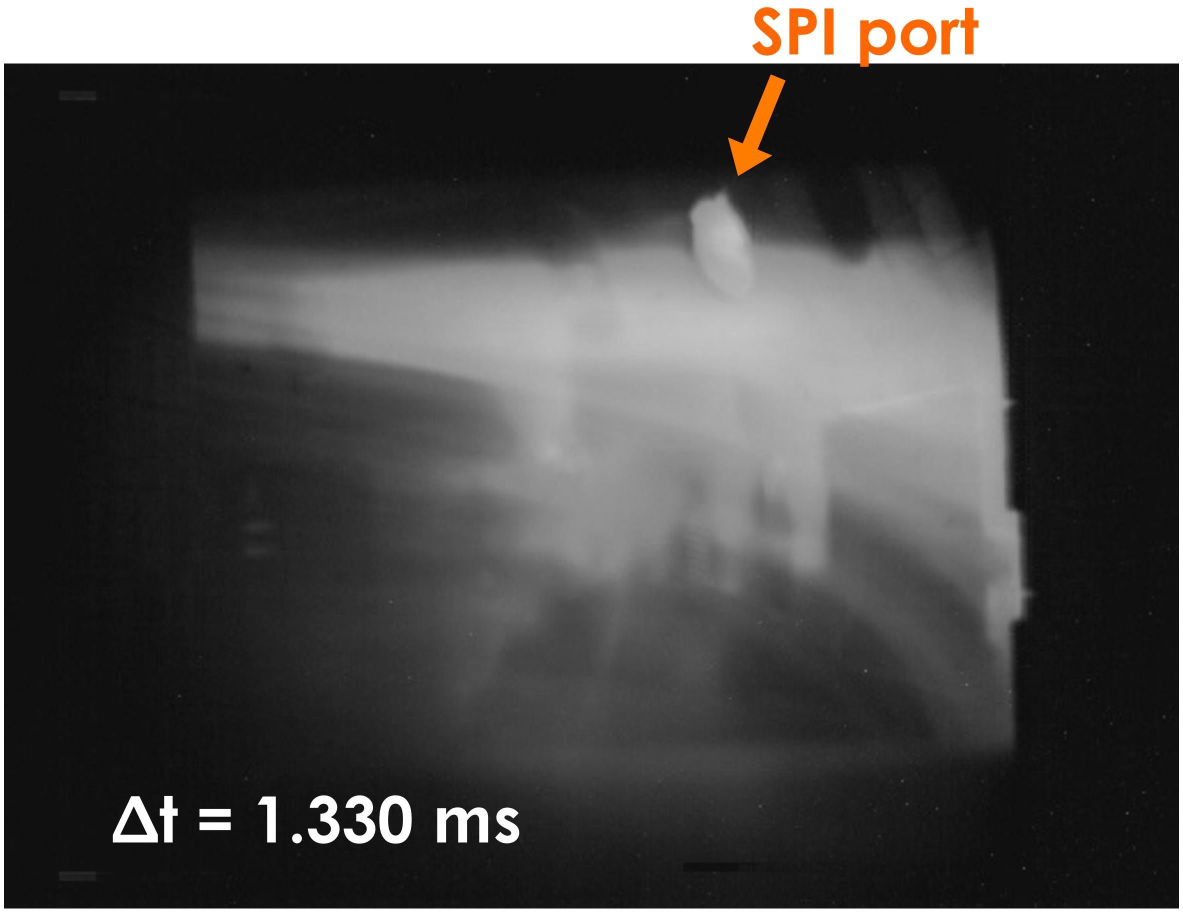

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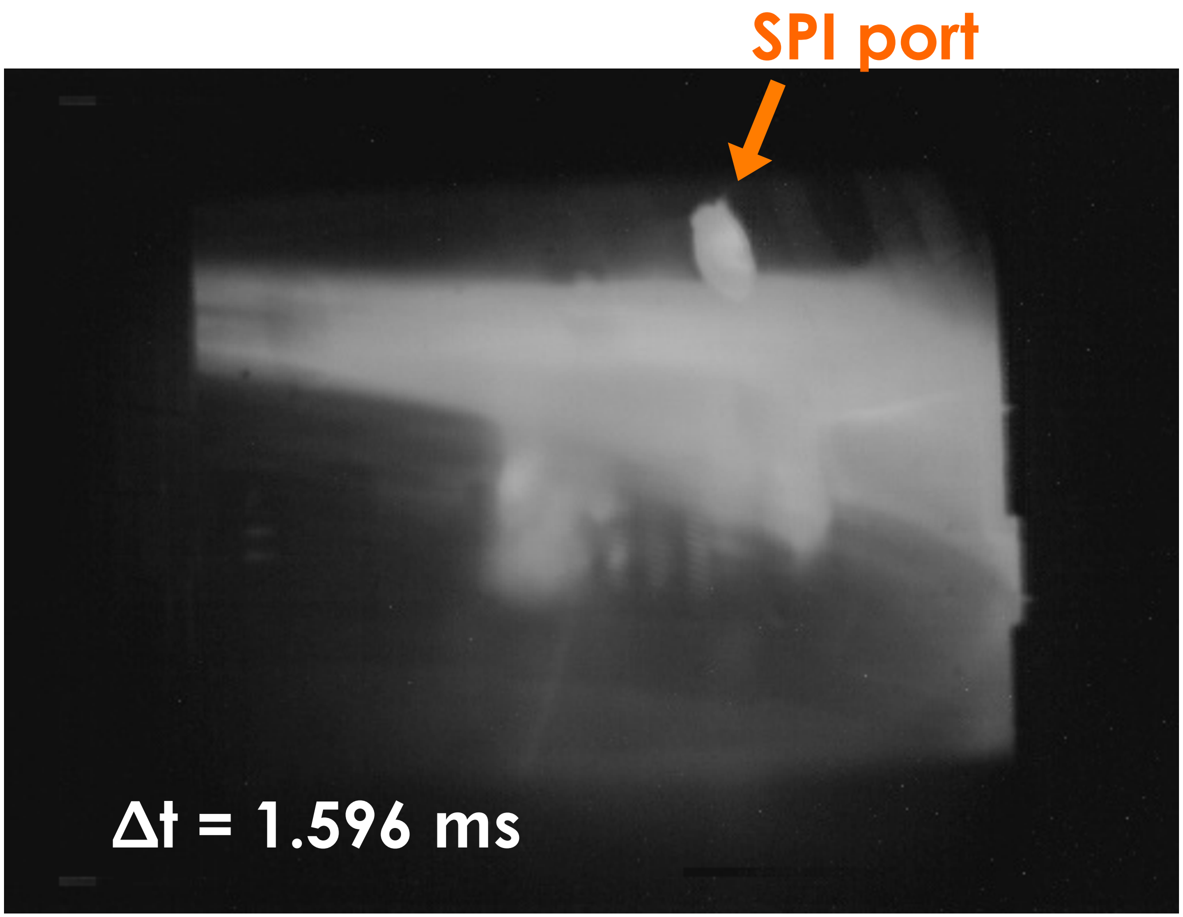

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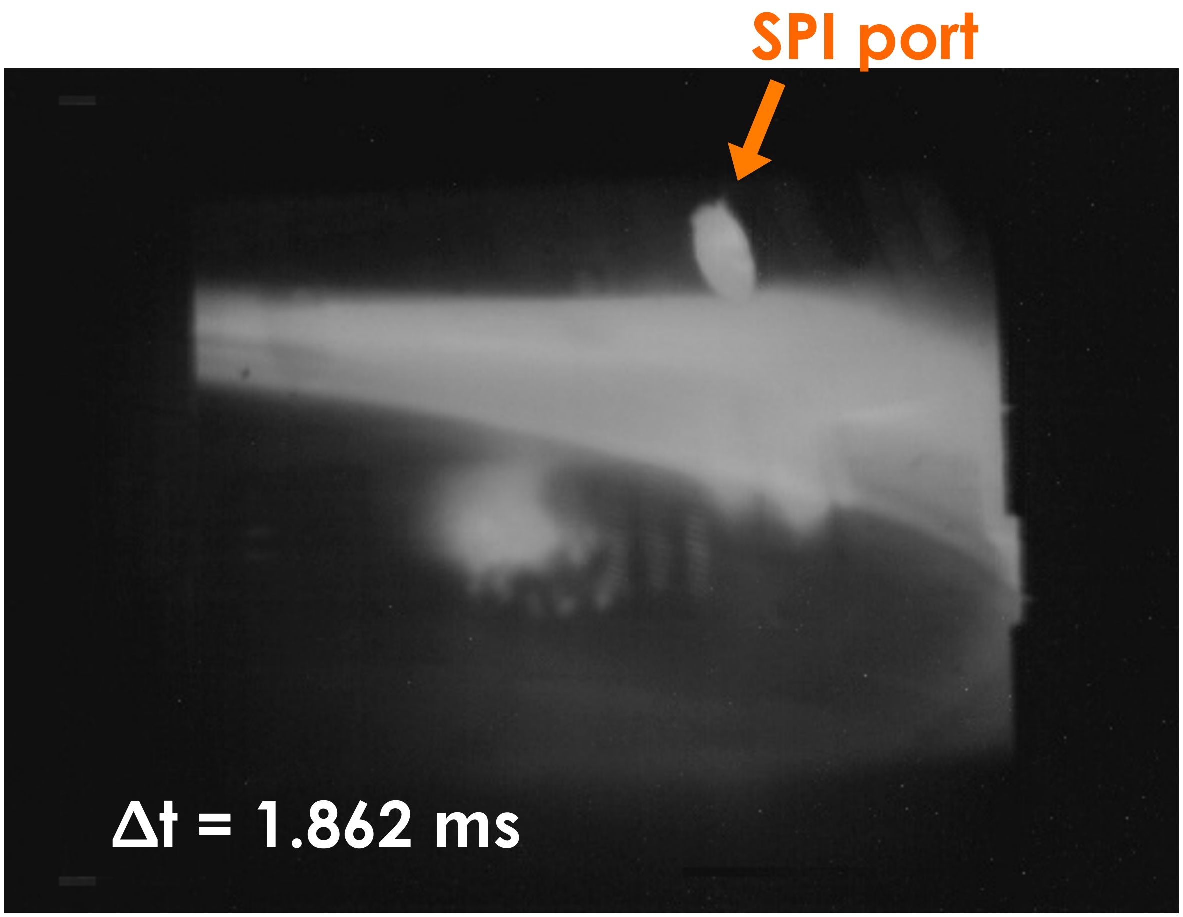

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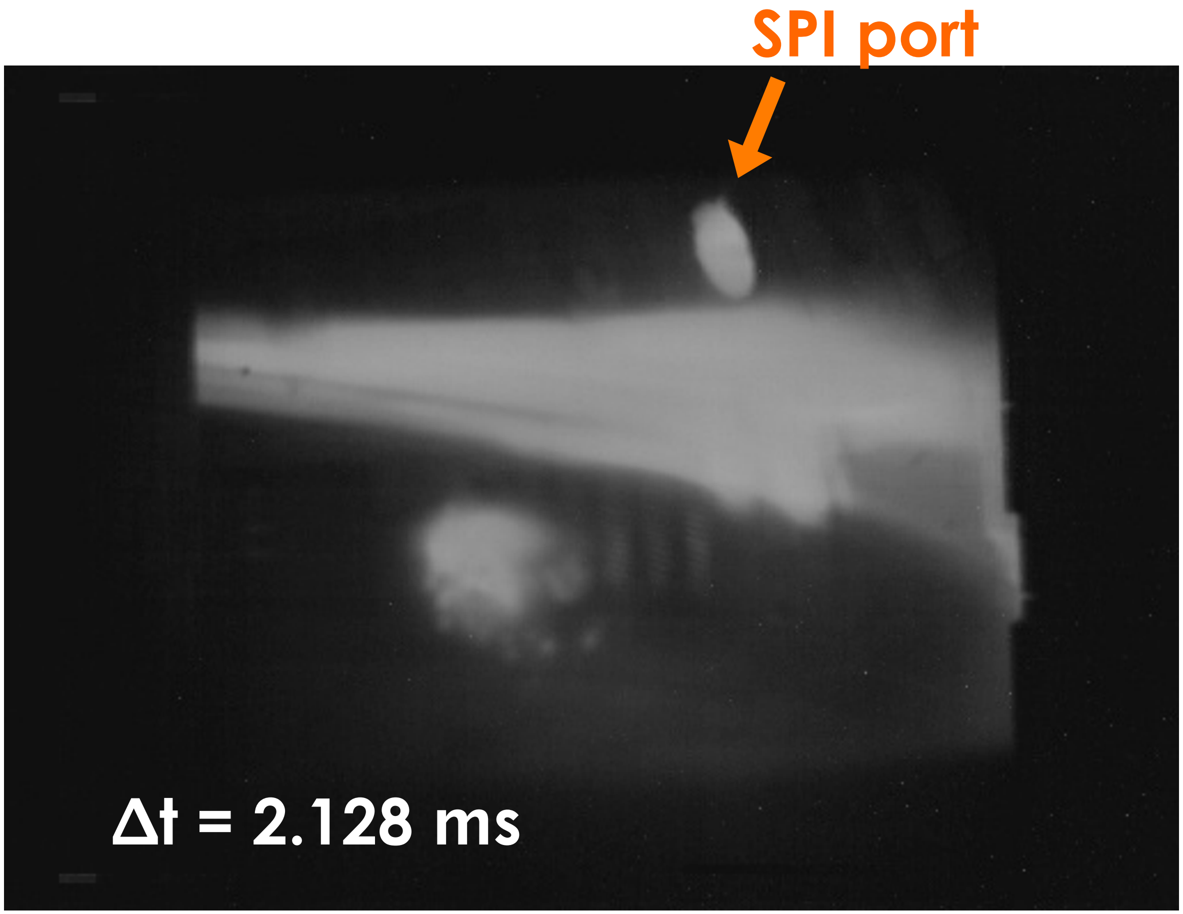

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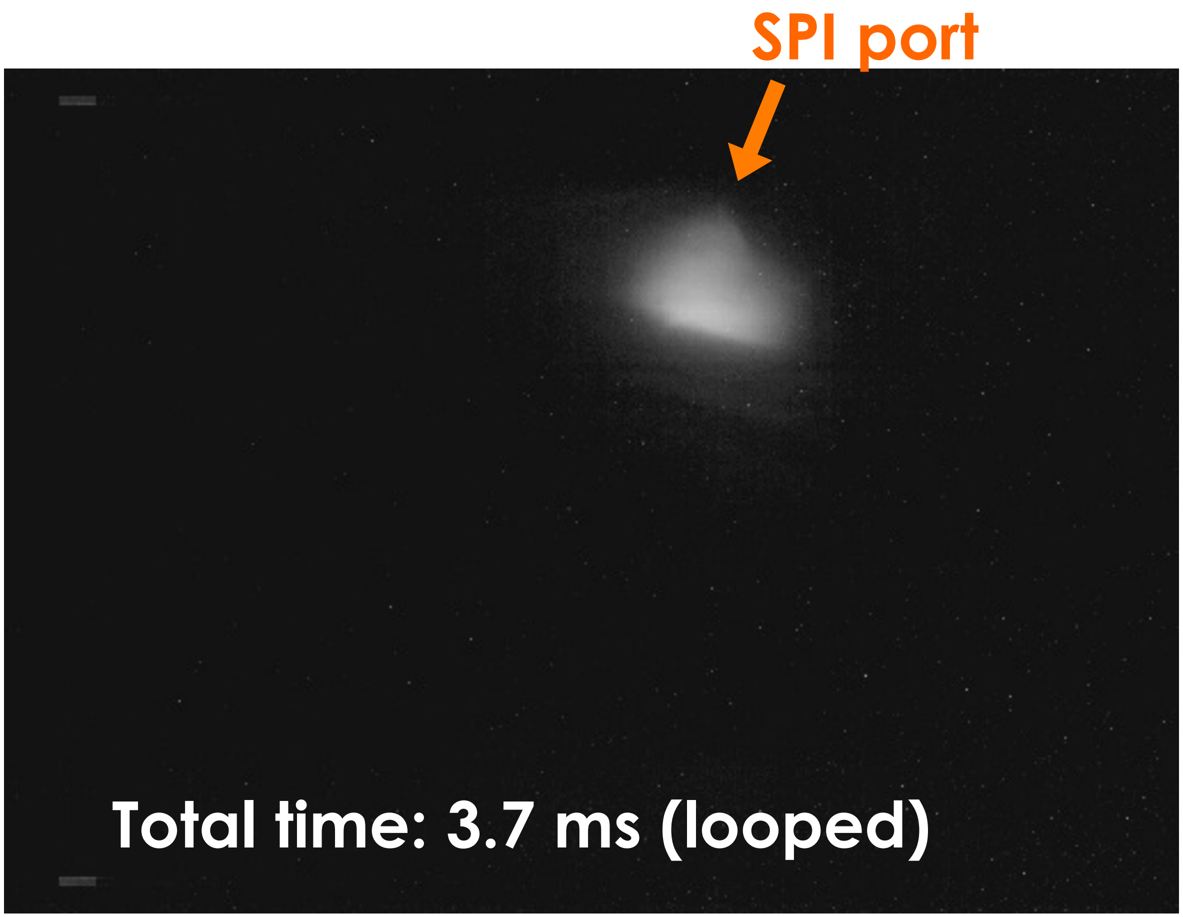
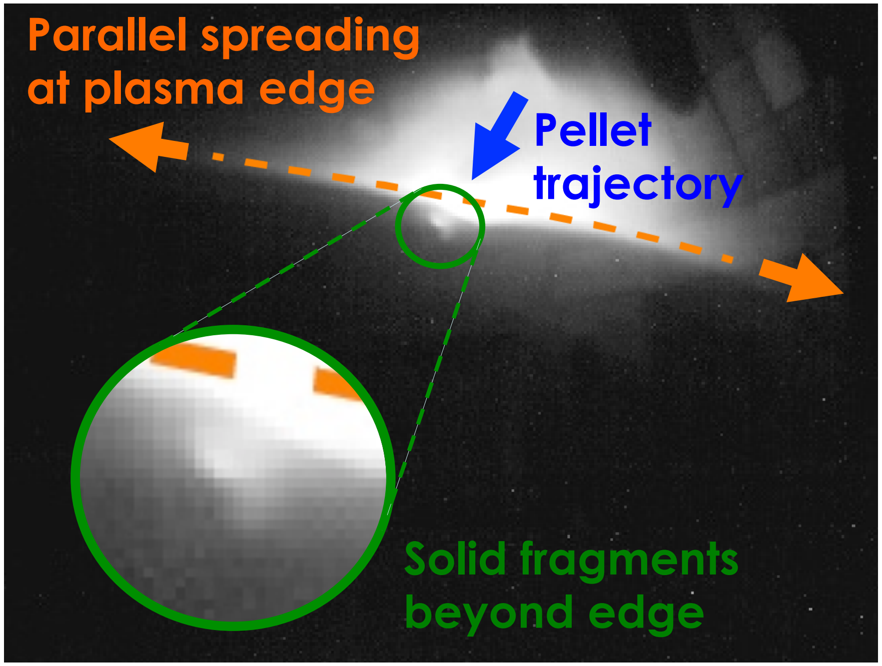
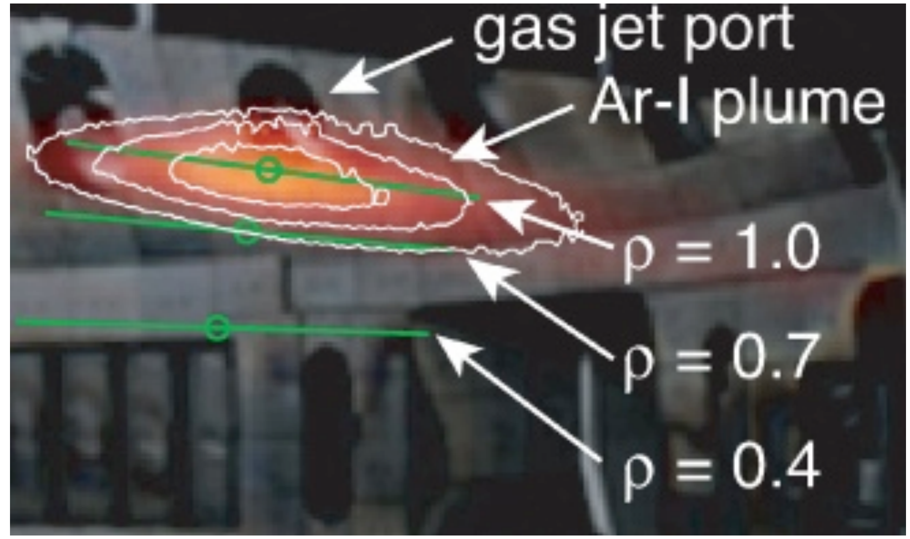


Ne-I filter (640 nm)

Solid fragments enhance impurity transport into plasma





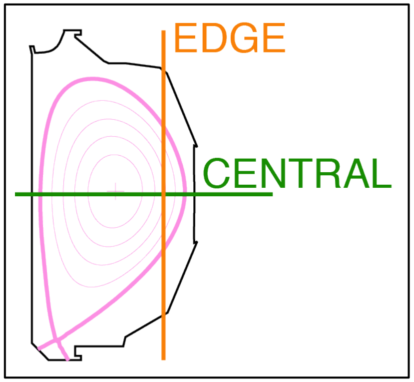
From Hollmann et al., Nucl. Fusion (2008)

- **For SPI, radial penetration of solid pellet fragments observed**
  - Ballistic transport enhances particle deposition in core

- **For MGI, gas pulse is initially stopped at plasma edge**
  - MHD mixing is dominant mechanism for radial transport

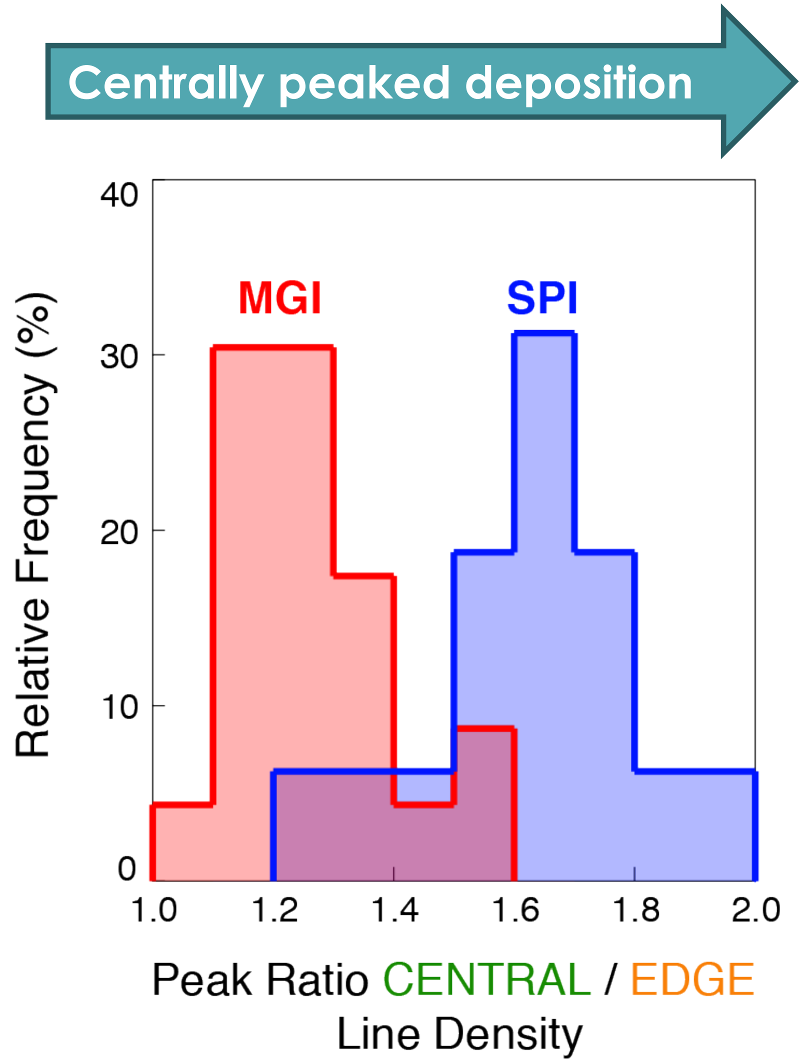
SPI achieves more centrally peaked particle deposition than MGI

- **Core deposition characterized by ratio of interferometer chords**



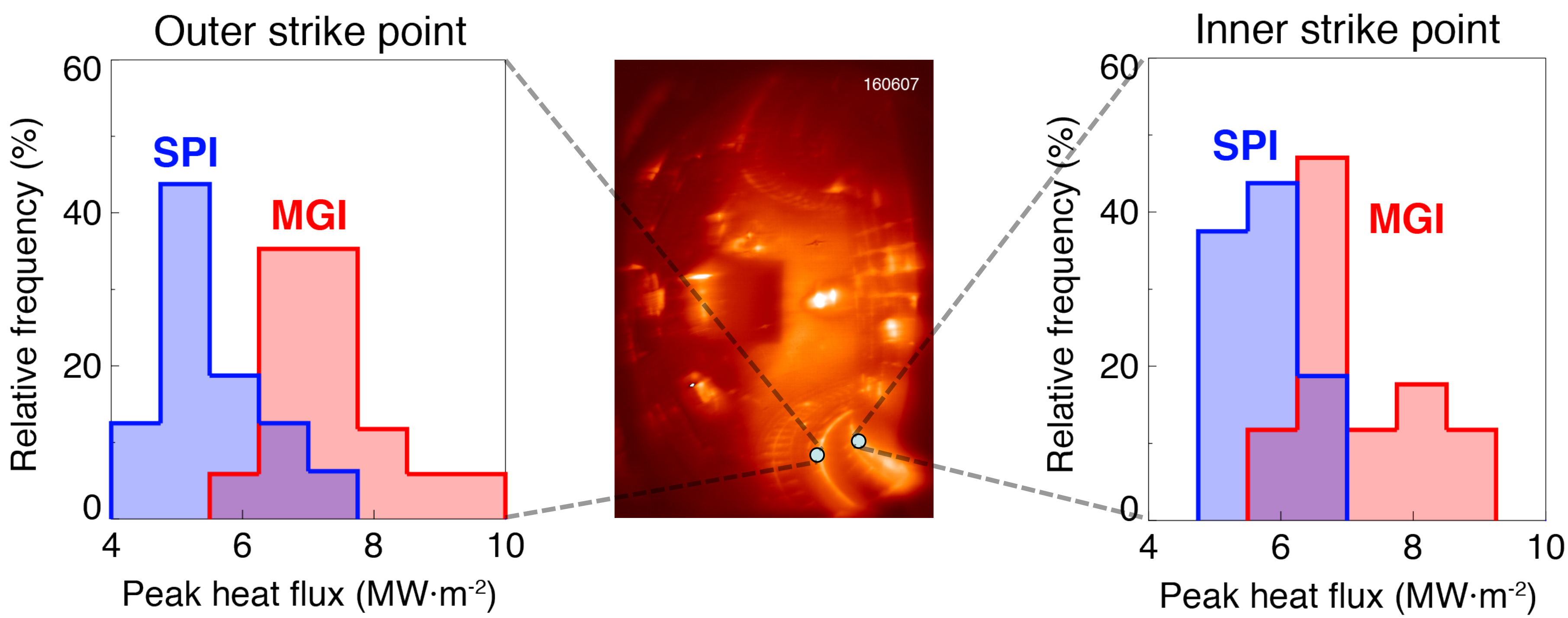
- **Compared to MGI, SPI deposits more particles in the core relative to the edge**

- **Peaked deposition is desirable:**
  - Allows more effective dissipation of core thermal energy for TQ mitigation
  - Favorable for RE seed suppression



SPI mitigates divertor heat loads more effectively than MGI

- **25% reduction in peak heat flux, at both divertor strike points**



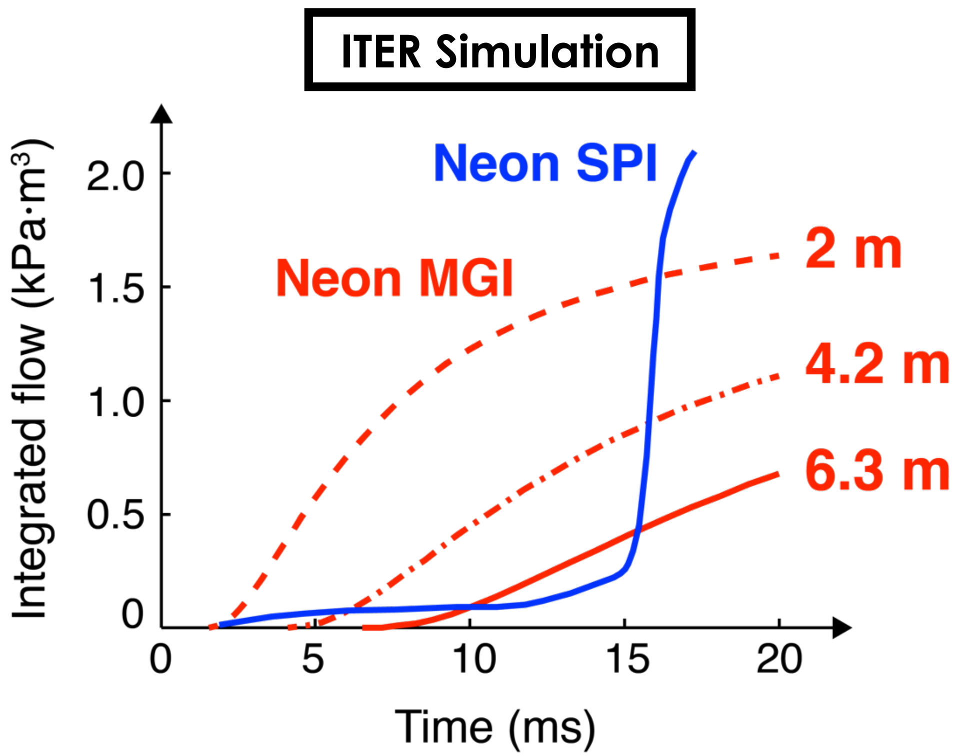
SPI provides more effective TQ mitigation due to:

- More rapid particle delivery
- Higher total particle assimilation
- More centrally peaked particle deposition

SPI particle delivery extrapolates to ITER better than MGI

- **SPI:** Pellet remains solid until just outside plasma
  - ➔ **Particle delivery is abrupt, even at larger distances**
- **MGI:** Gas pulse becomes spread out due to limited conductance of delivery tube
  - ➔ **Particle delivery slows significantly with increasing distance**

Figure adapted from Baylor et al, Fusion Sci. Tech. (2015)



Differences in mitigation already seen on DIII-D, but expected to be greater on ITER!

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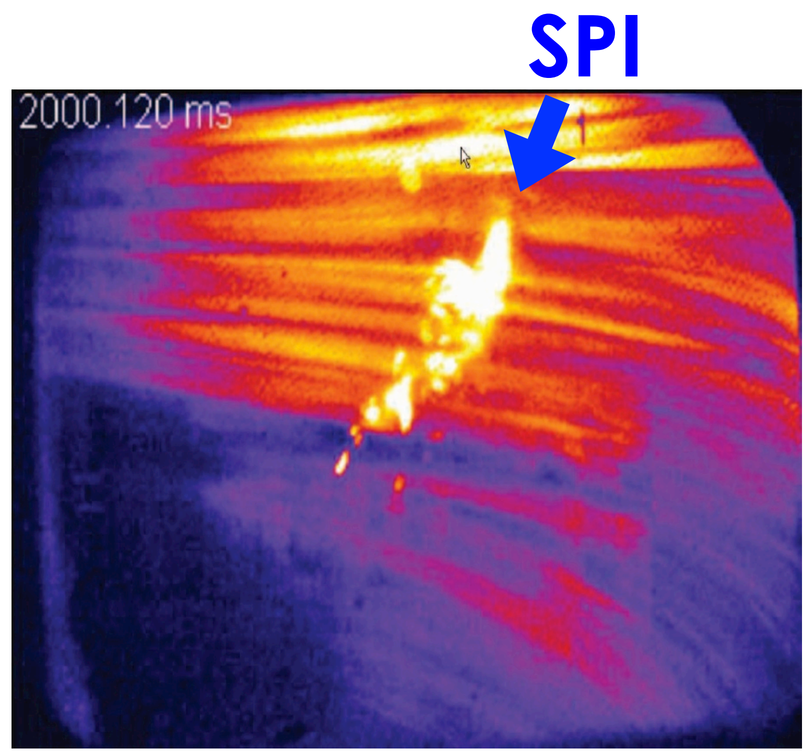
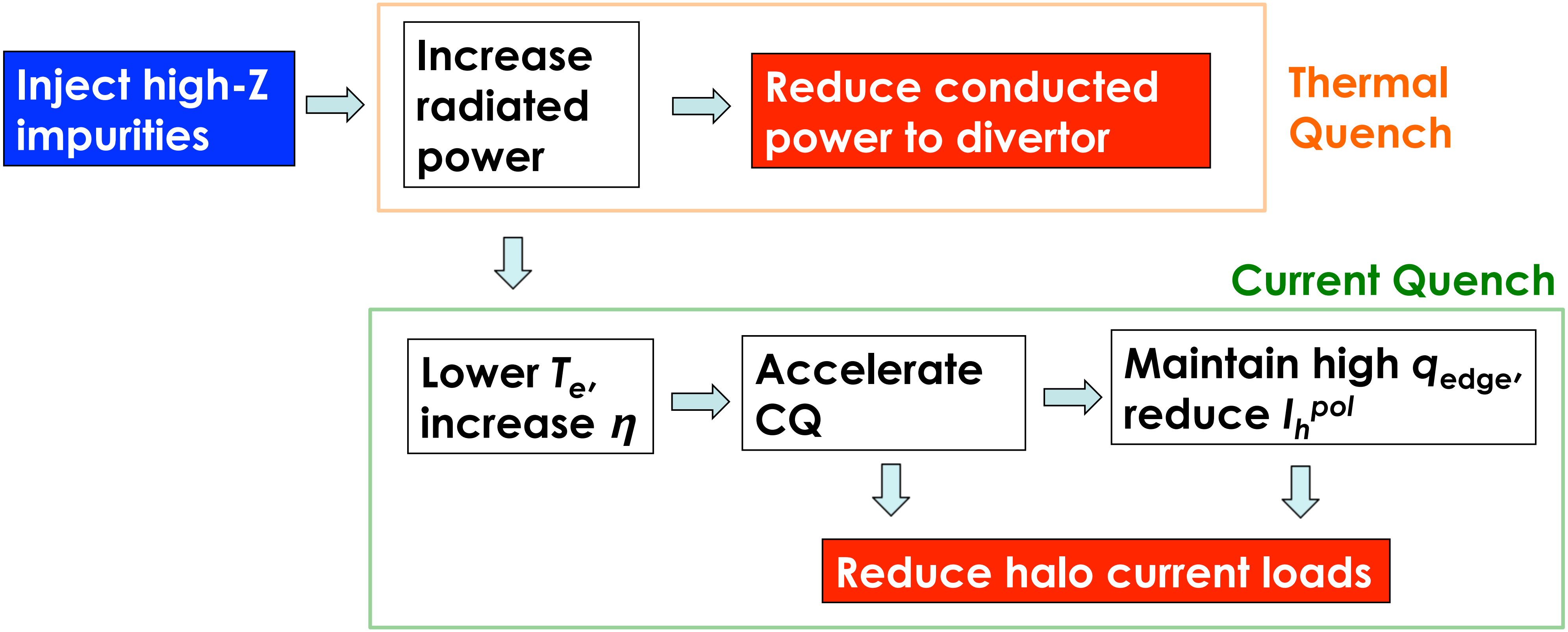


Basic process of disruption mitigation



Some aspects of disruption mitigation are conflicting

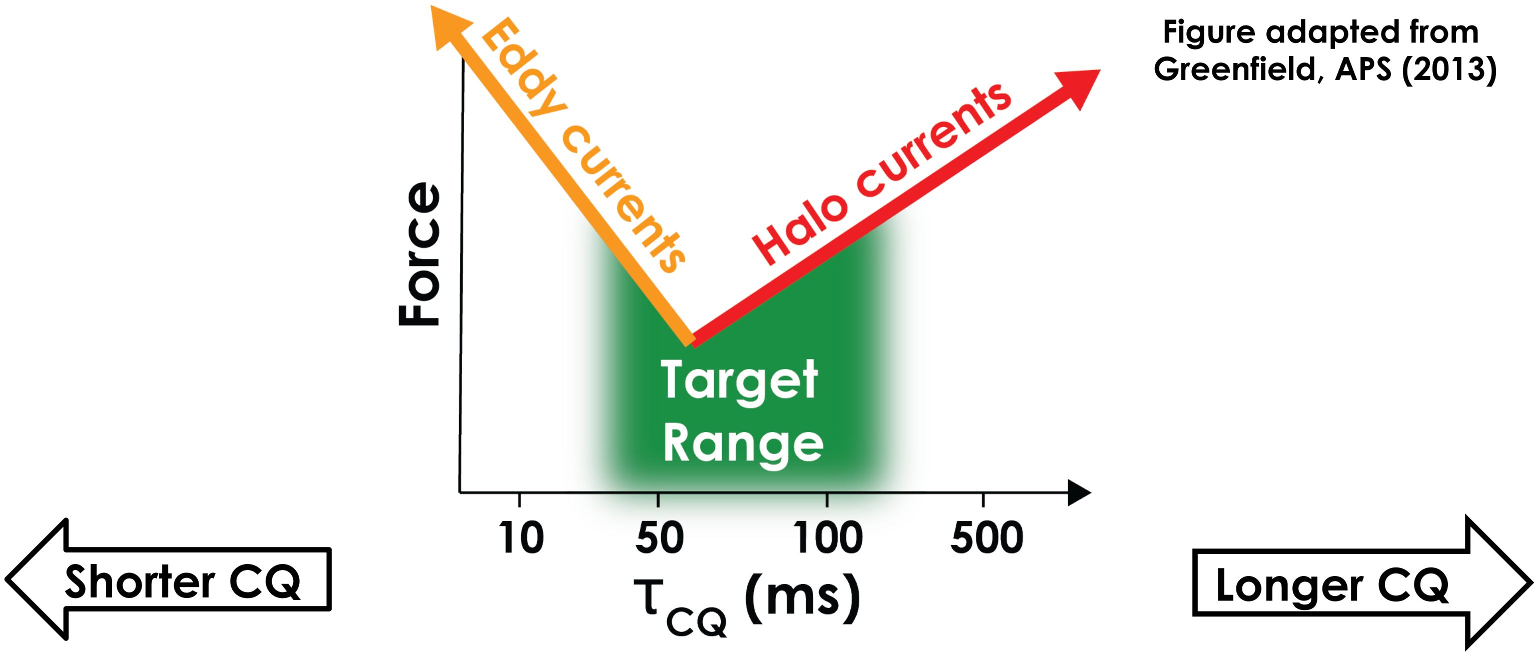


Figure adapted from Greenfield, APS (2013)

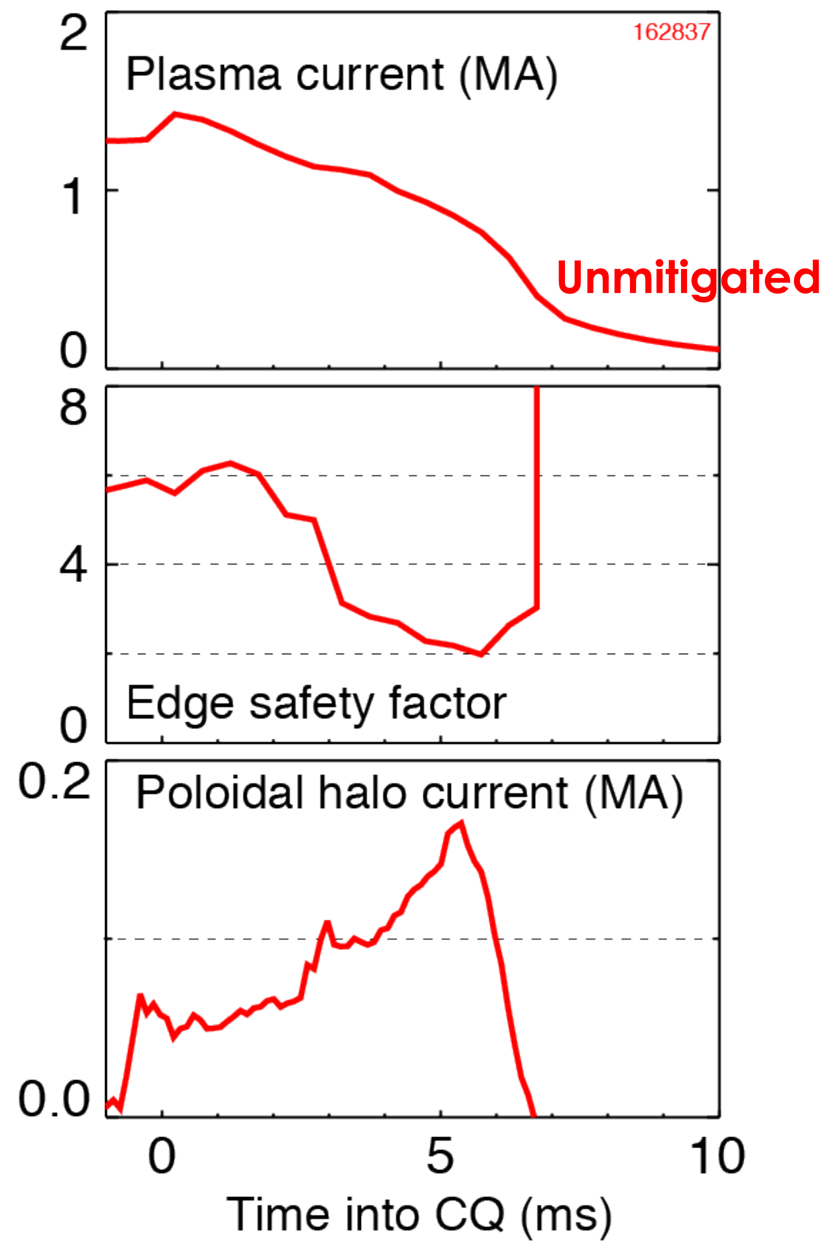
- High eddy current forces in blanket modules
- Enhanced drive for RE growth by the avalanche mechanism
- High TQ heat loads to divertor surfaces
- High halo current forces on vacuum vessel

CQ properties vary widely with pellet composition

- **Electromagnetic loads determined by CQ properties:**
  - Current decay
  - Safety factor
  - Poloidal halo currents

- **Edge safety factor governs halo currents:**

$$\textbf{Poloidal halo currents} \sim \frac{1}{\textbf{safety factor}}$$



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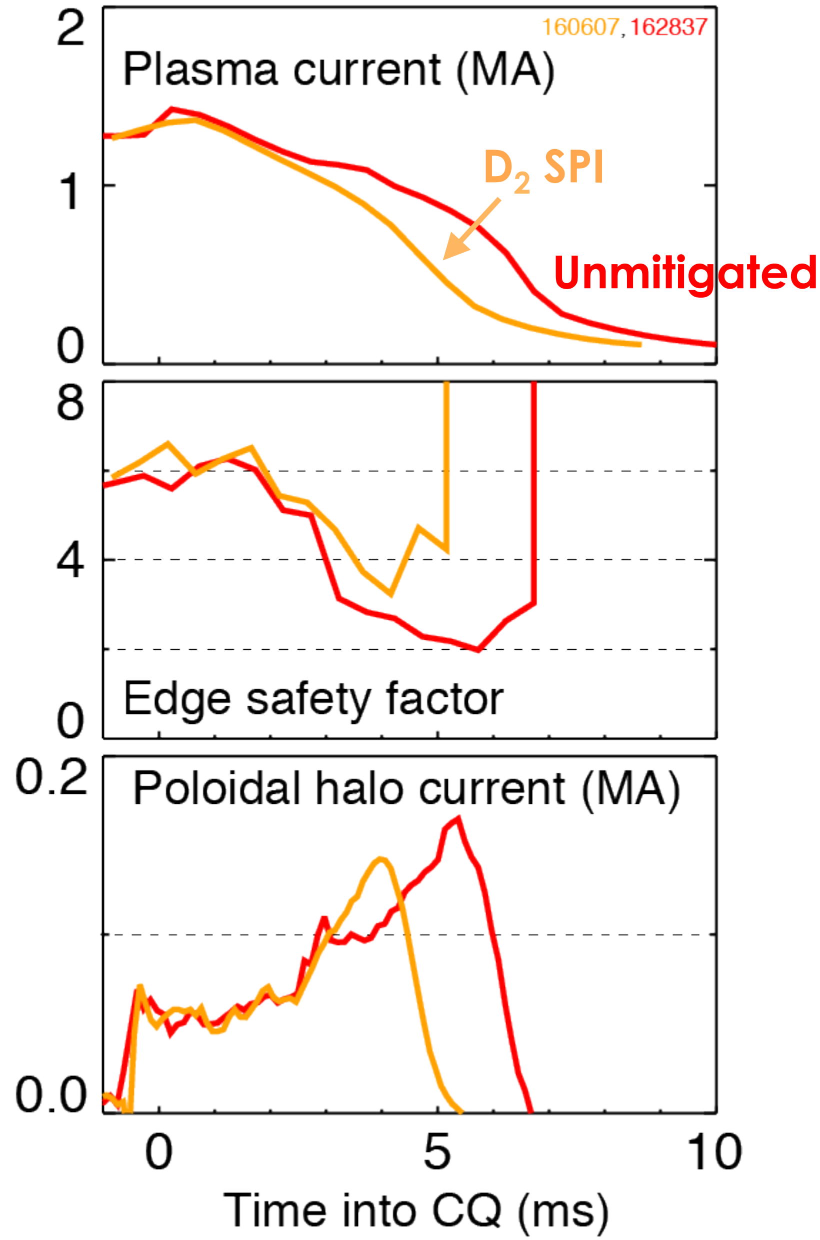

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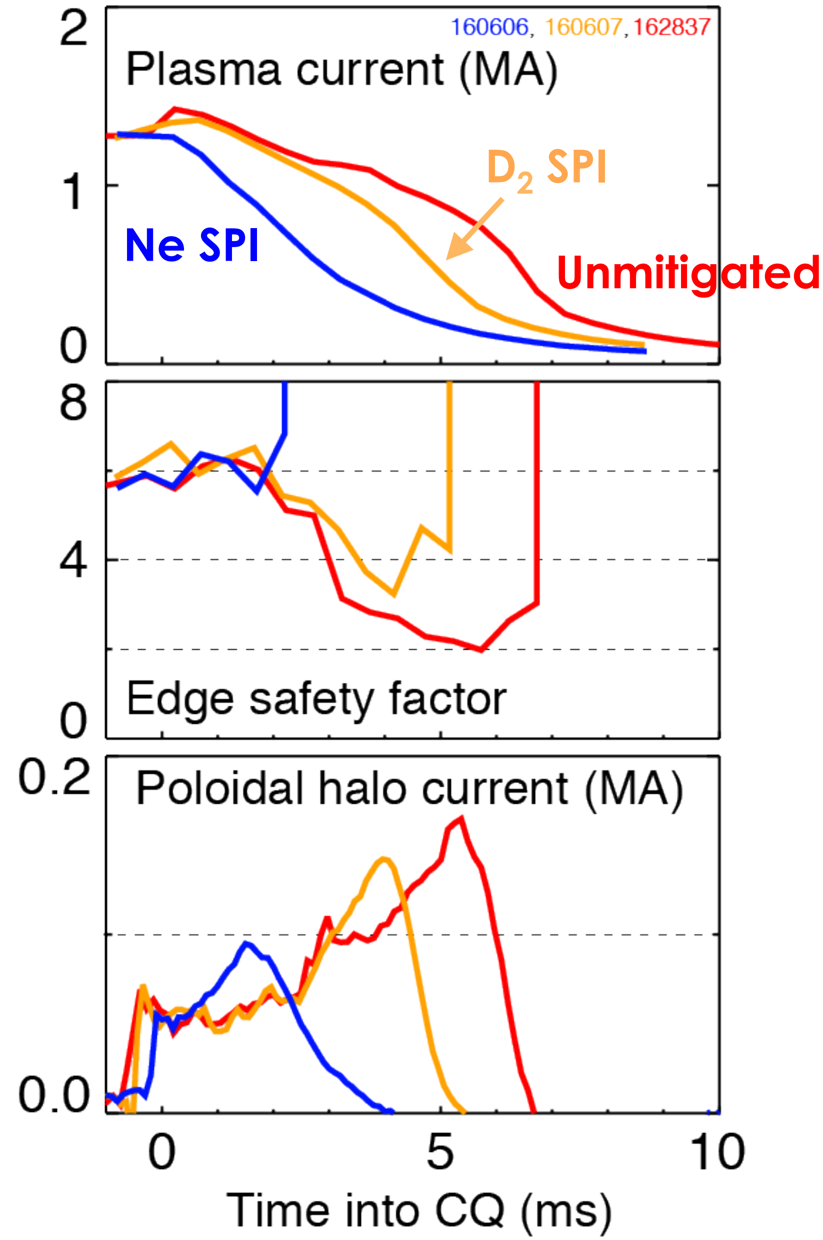

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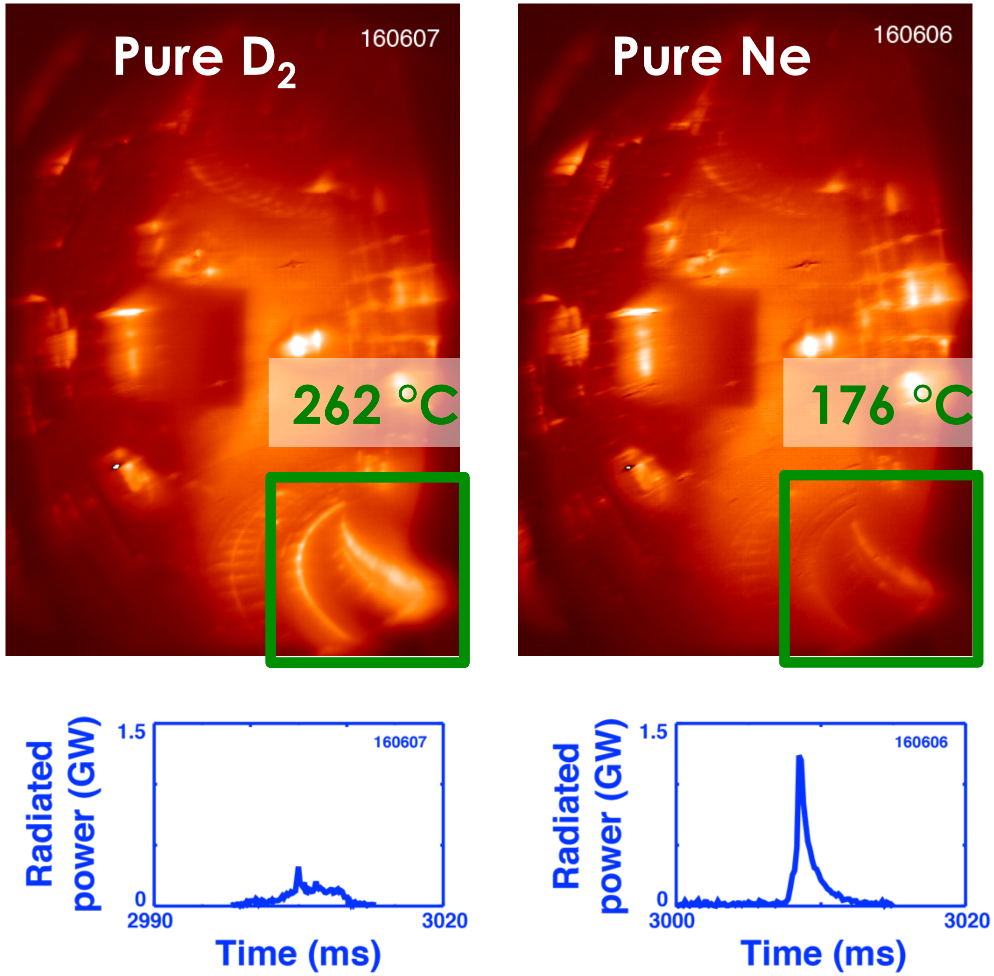
TQ energy balance can also vary widely with pellet composition

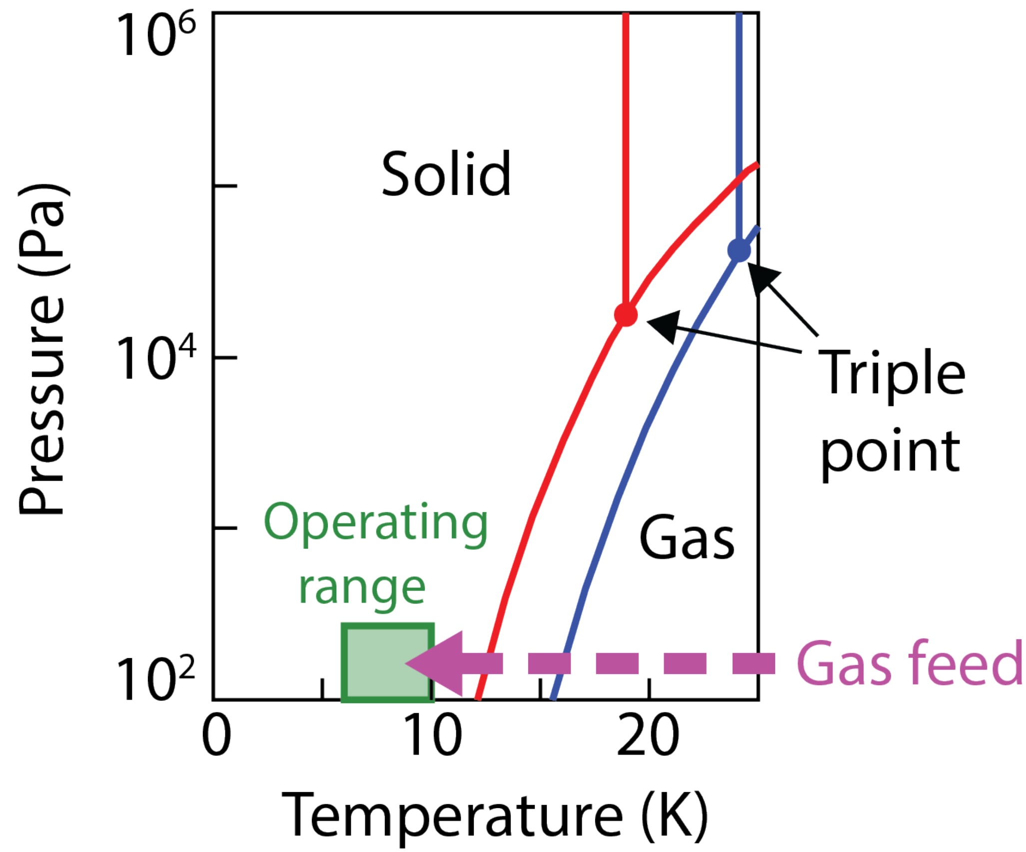
- Images show post-disruption surface temperatures
- Strong reduction in temperatures at divertor strike points, by ~100 °C
- Radiated power greatly increased



Mixed species shattered pellets allows control of disruption properties

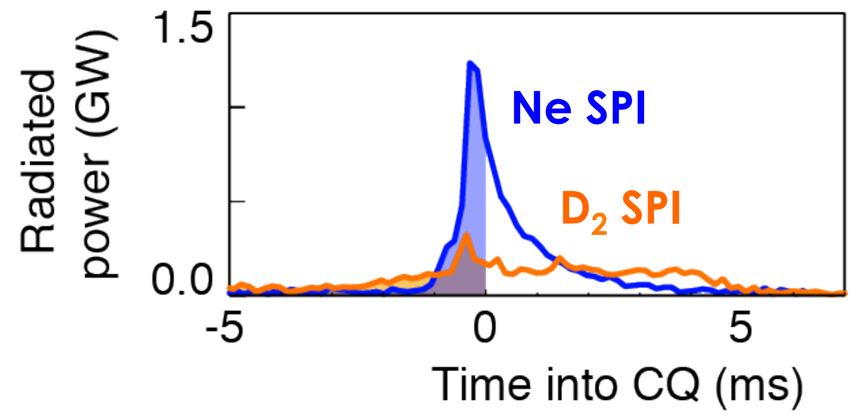
- **Mixture of deuterium (main ion species) and neon (high-Z radiating impurity)**
- **Homogeneous mixture of Ne/D_2 ice**
- **Pellet composition is variable, by selection of gas quantities**

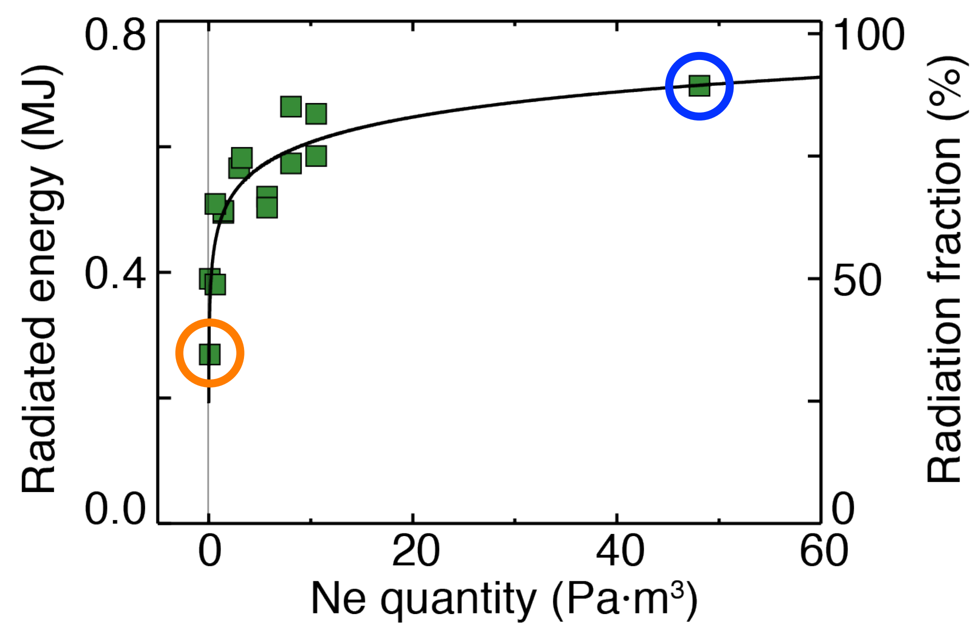
D_2, Ne phase diagram



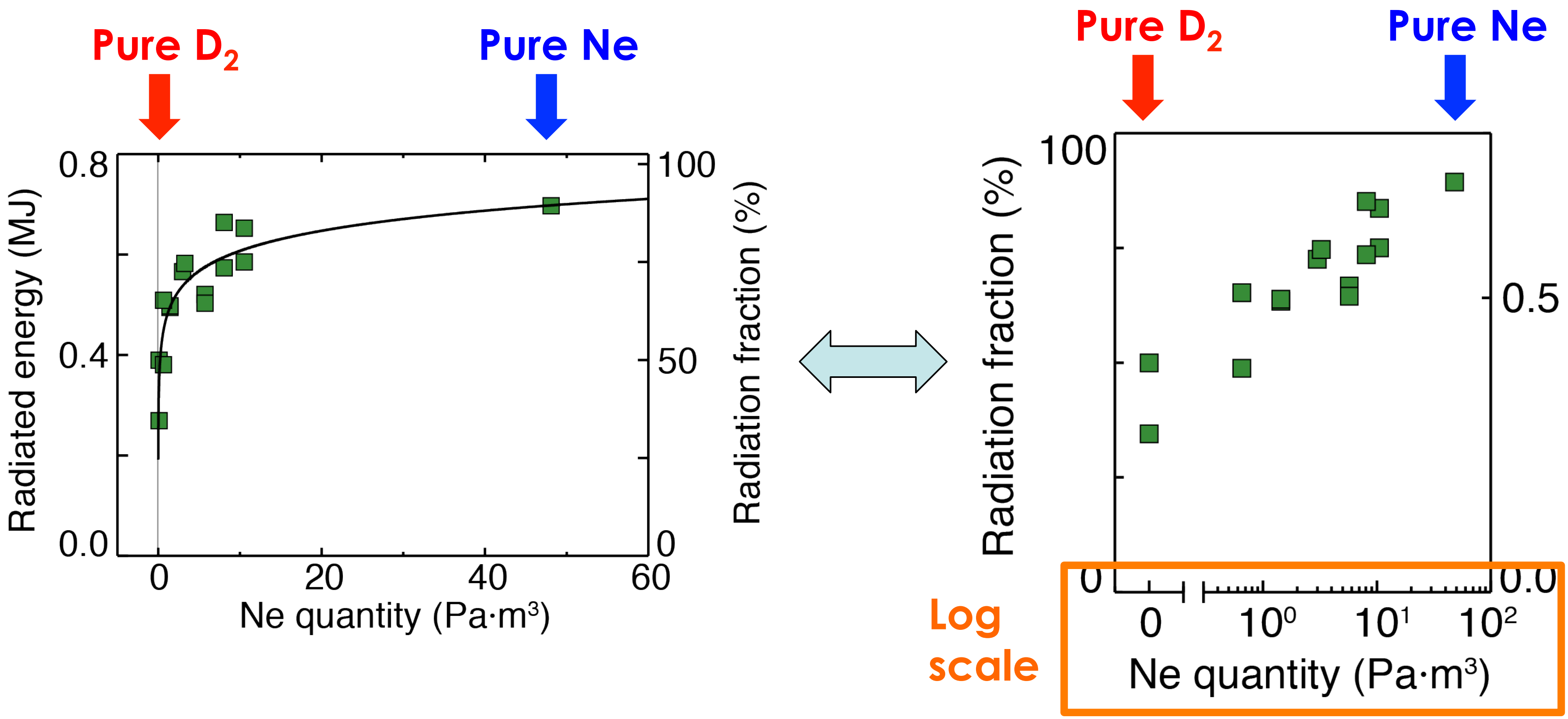
TQ Radiation Fraction Increases Continuously with Neon Quantity

- **TQ radiation fractions vary continuously with neon quantity**
- **At low neon limit, carbon radiation sets a lower bound**
- **Neon is a very efficient radiator, so curve 'saturates'**
- **Similar results have been seen with MGI on Alcator C-Mod and JET**



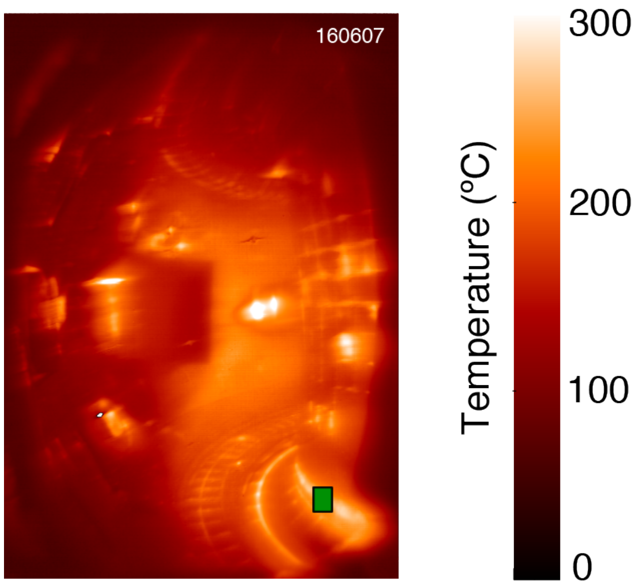


Most disruption properties saturate with neon quantity

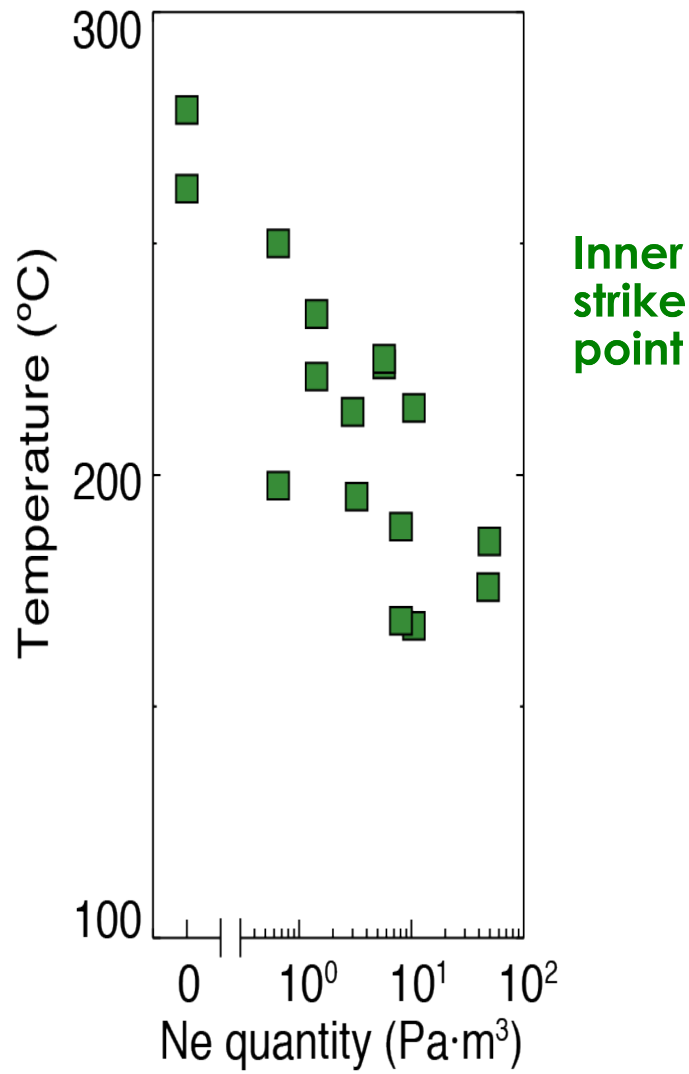


Divertor Temperatures Lower Due to Increased Radiation Fraction

- **First wall temperatures calculated from full-view IR periscope data**



- **Divertor heating strongly reduced**



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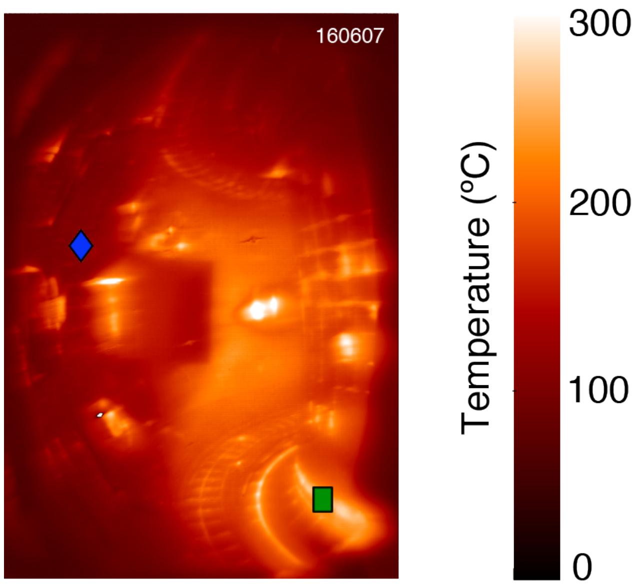
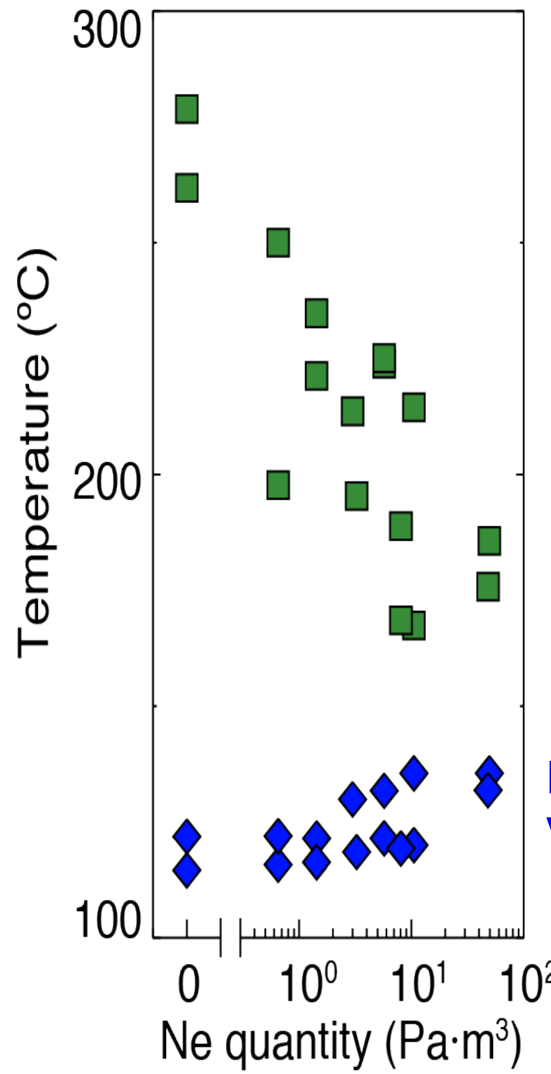
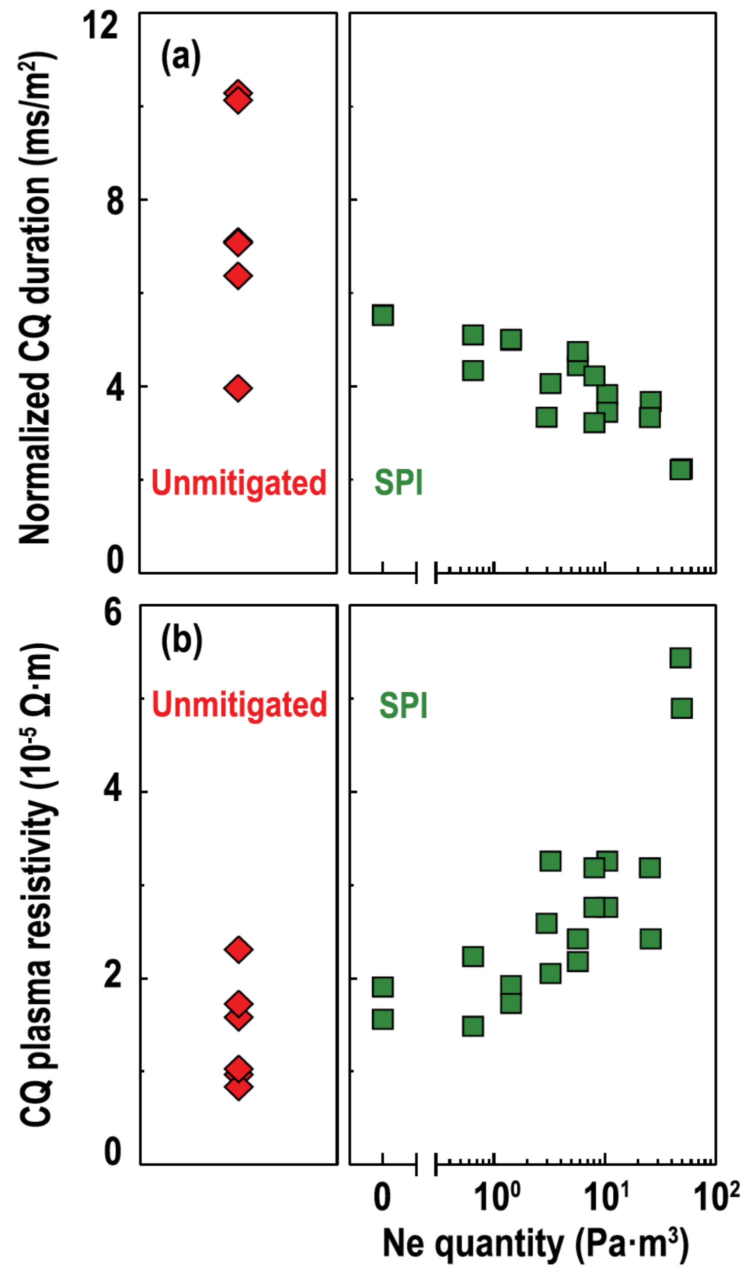


- **Divertor heating strongly reduced, while wall heating only slightly elevated**



SPI accelerates CQ, by making post-TQ plasma more resistive

- **Up to a factor 5 decrease in CQ duration**
- **Expect bigger change for ITER-like wall**
- **CQ resistivity estimated from analytical model fit**
- **Pre-disruption: T_e = 2 keV (Z_{eff} = 2), η = 4×10^-8 Ωm**



Basics of halo current mitigation

- **CQ plasma is very cold, so halo currents flow parallel to (helical) field lines:**

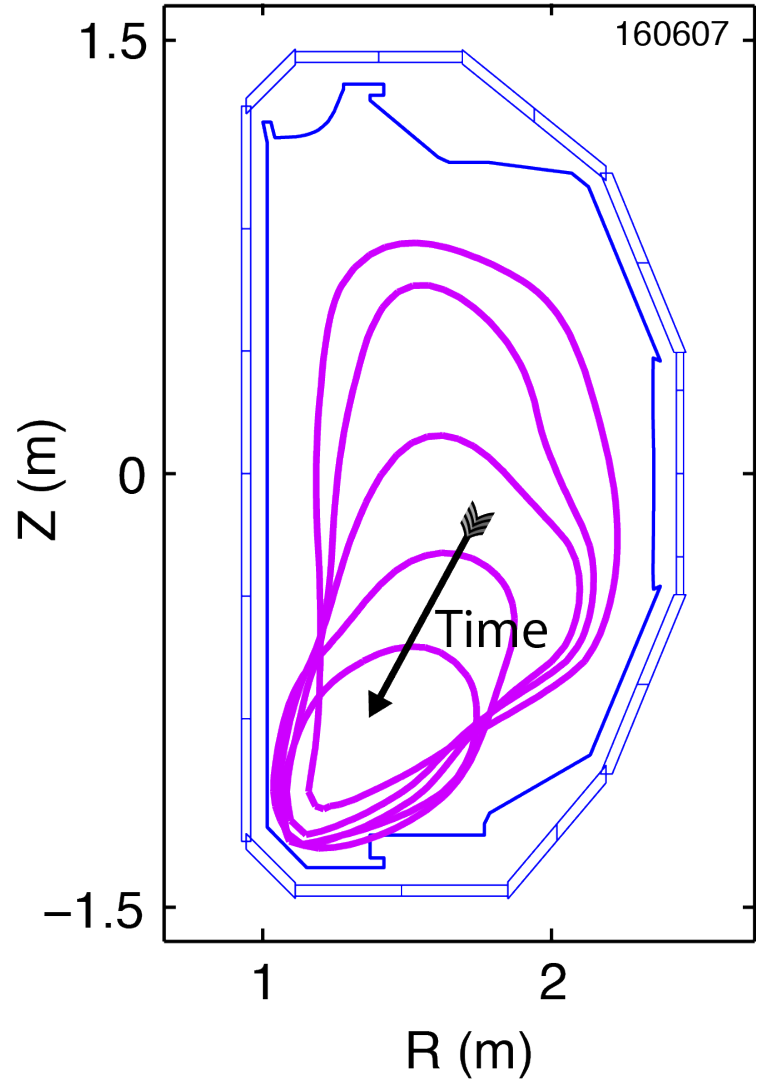
  $$\mathbf{j \times B = grad\ p \approx 0}$$

- **Poloidal halo currents contribute most to vessel forces:**

  $$\mathbf{I_h^{pol} \times B_T = F_Z}$$

- **Direction of the magnetic field matters:**

  The higher the safety factor, the lower the poloidal halo currents (and forces)



High CQ Safety Factor Maintained by Increasing Neon Quantity

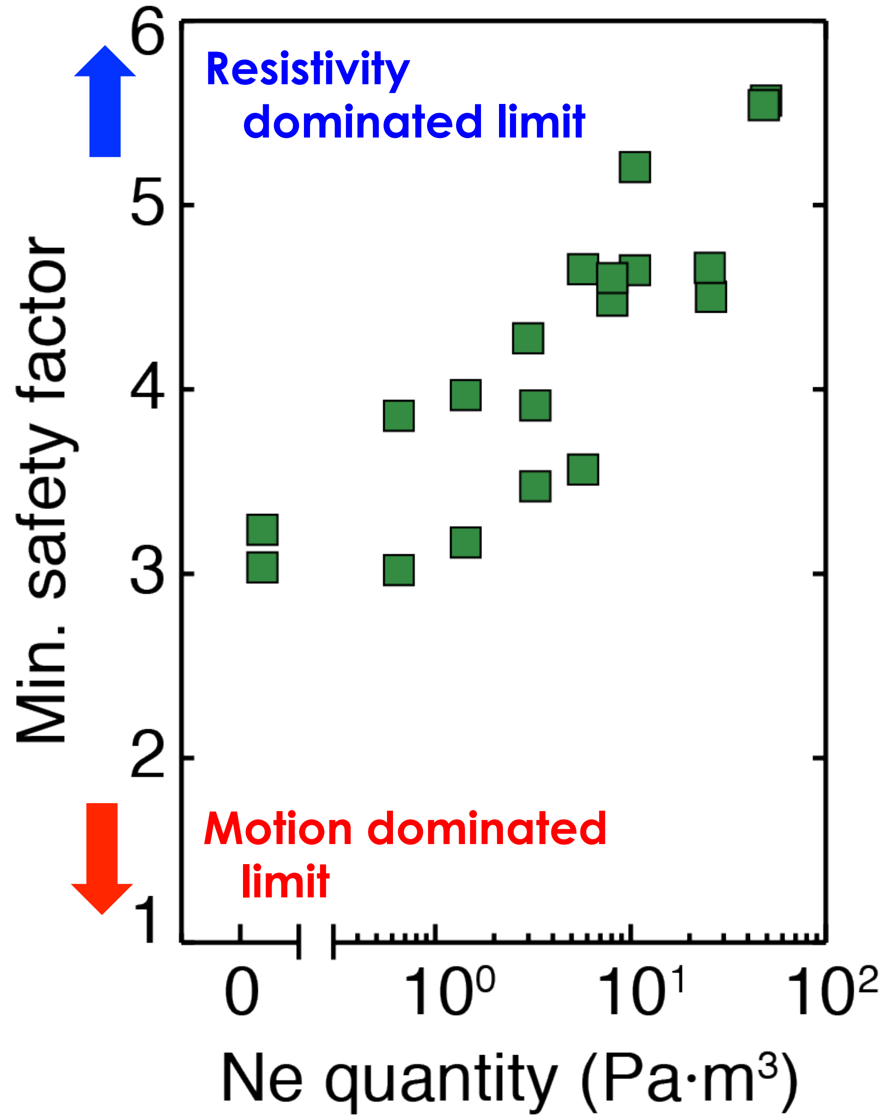
- **Safety factor determined by two competing effects:**

$$q_{edge} \sim \frac{a^2}{I_p^{core}}$$

Limiting due to Vertical motion

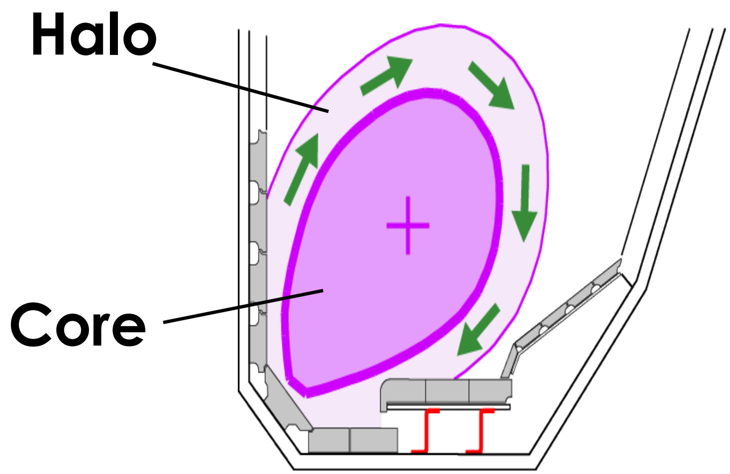
Resistive current decay

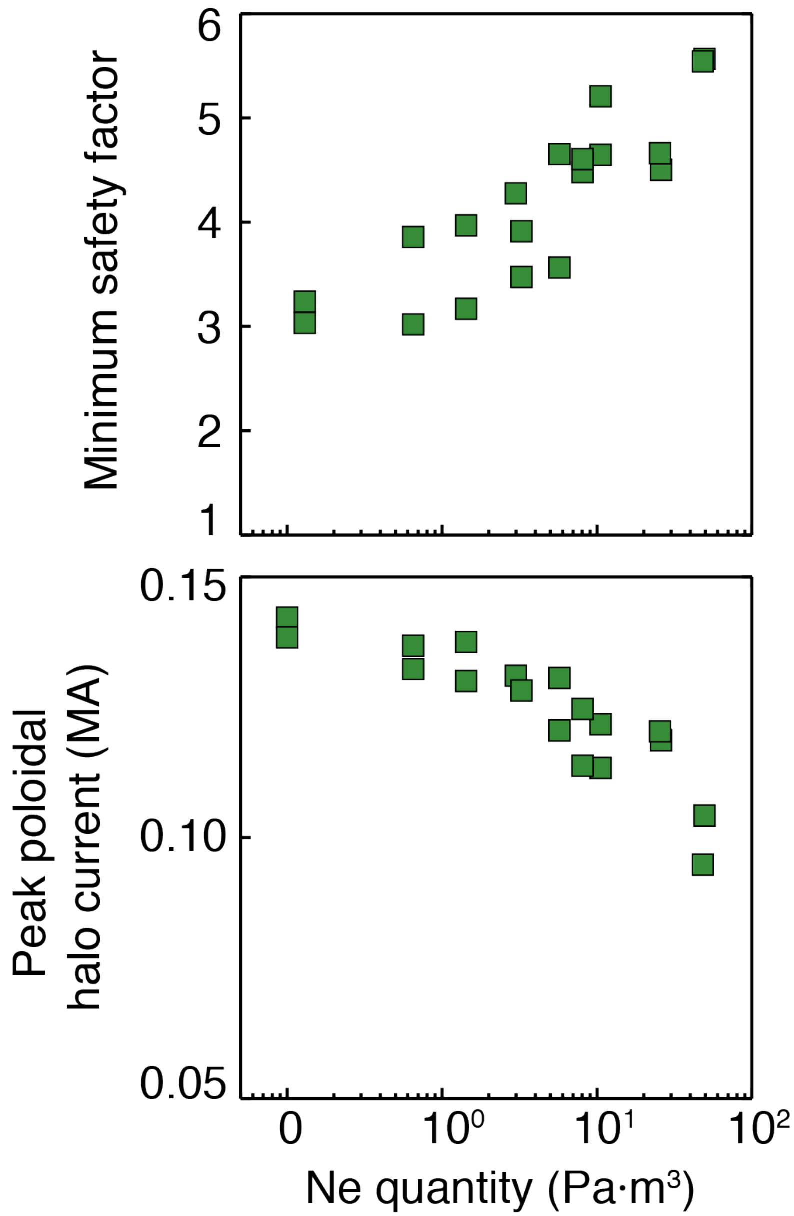
- **Neon maintains high safety factor throughout disruption**



Poloidal Halo Currents Continually Reduced Due to Force-free Constraint

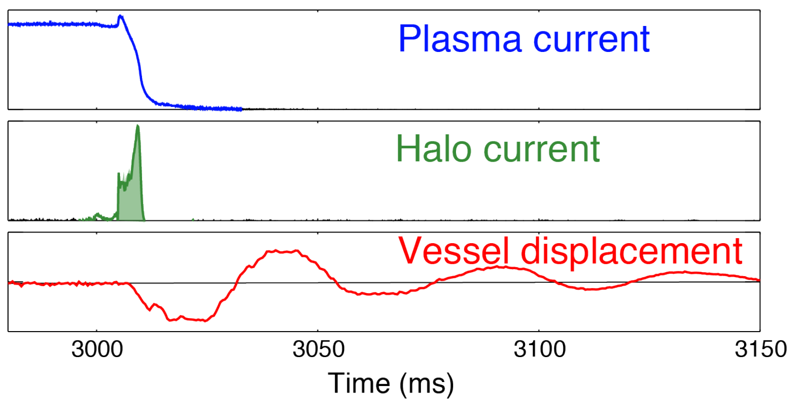
- **Poloidal halo currents** are measured in **divertor legs**

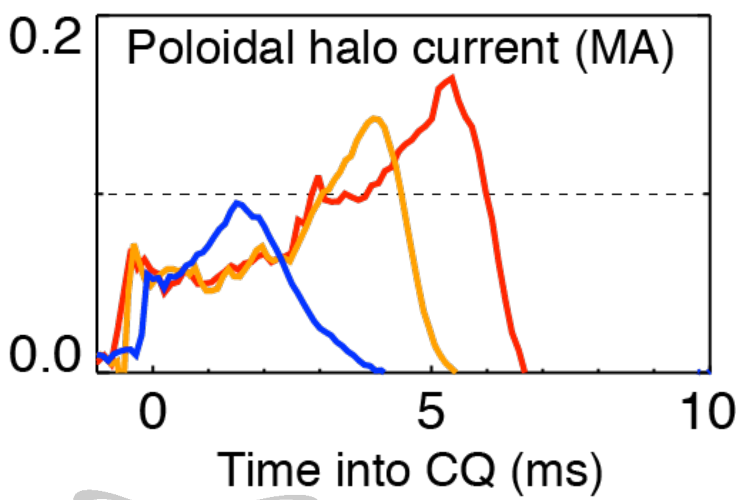


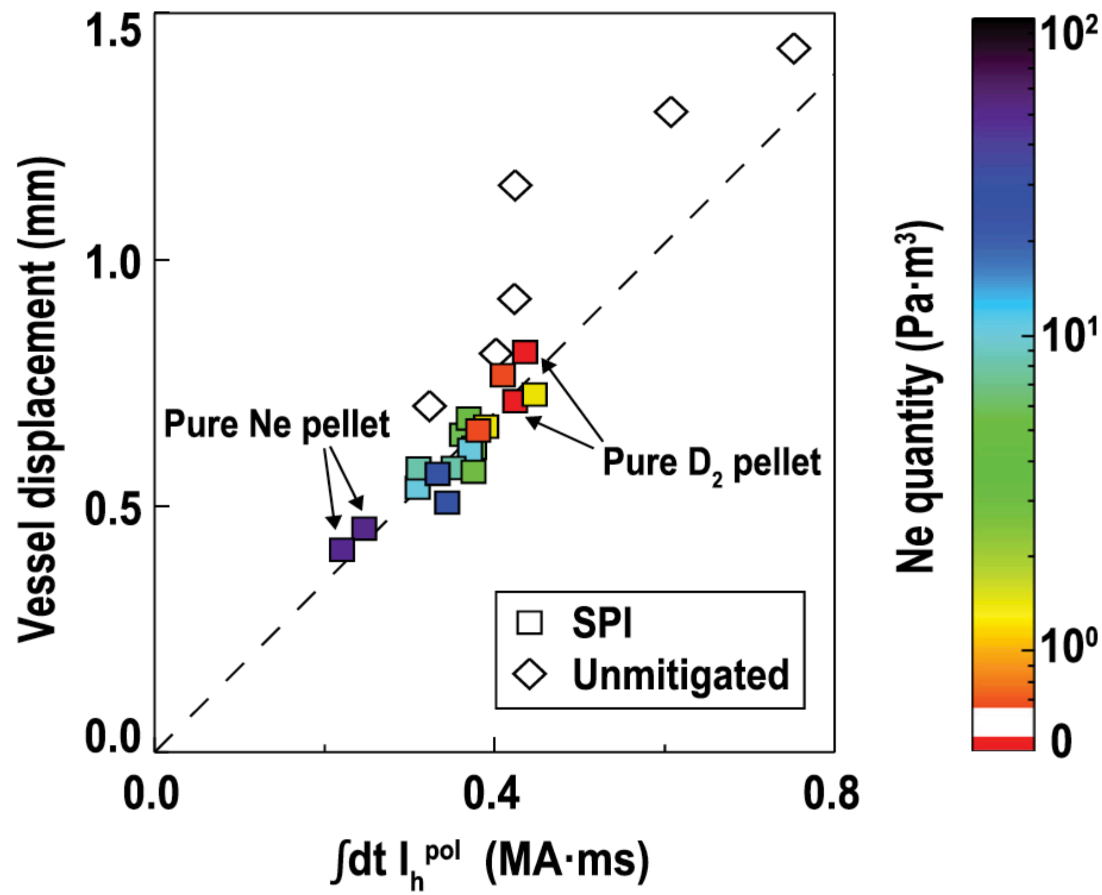


Reduced Amplitude/Duration of Halo Currents Reduce Vessel Displacement

- **Vessel displacement determined by total *impulse* from halo currents**
  - Vacuum vessel behaves as damped oscillator with $\tau_{vessel} > \tau_{CQ}$







D. Shiraki et al, PoP 23 (2016) 062516

Neon/deuterium SPI can mitigate, and control, disruption loads

Inject high-Z impurities →

Thermal Quench

Increase radiated power → Reduce conducted power to divertor

↓

Current Quench

Lower T_e, increase η → Accelerate CQ → Maintain high q_{edge}, reduce I_h^{pol}

↓

Reduce halo current loads

- Each of these disruption properties to be varied continuously by changing the neon quantity

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SPI also has potential for suppressing or dissipating runaway electrons in ITER

- **(Next section)**

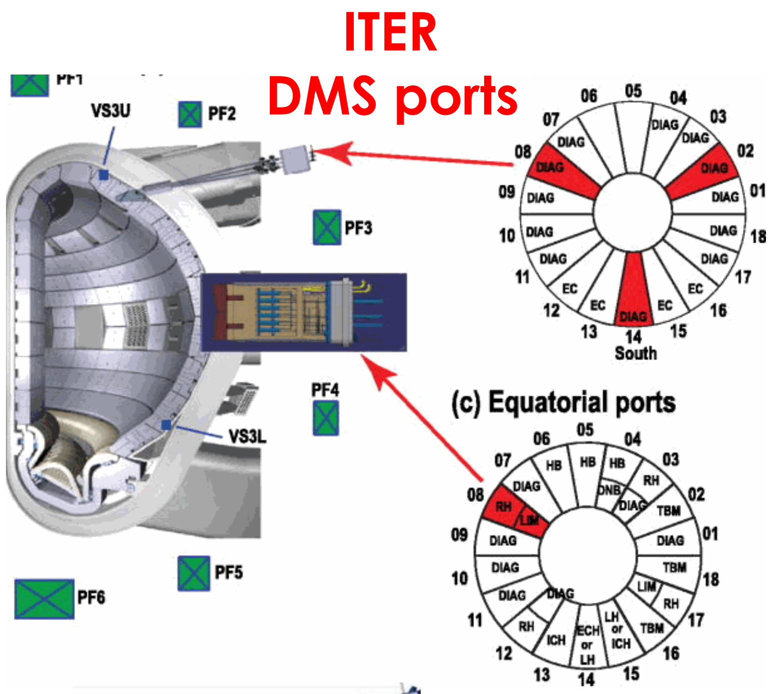
Important issues for ITER still need to resolved

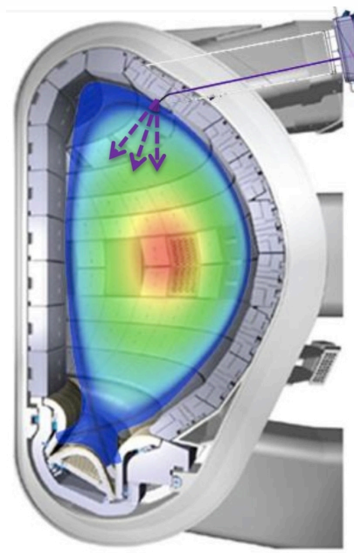
- **Radiation asymmetries**

- **ITER will require multiple shattered pellets to act together**

- **DMS performance may depend on ITER injection geometry**

- **Compatibility of opposing needs for thermal mitigation and halo currents, vs. eddy currents and RE avalanche**





Outline

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  - Background
  - Comparisons with massive gas injection
  - Effect of SPI on disruption properties
- **Runaway electron physics studies**
  - Post-disruption runaway electron suppression/dissipation
  - Quiescent runaway regime
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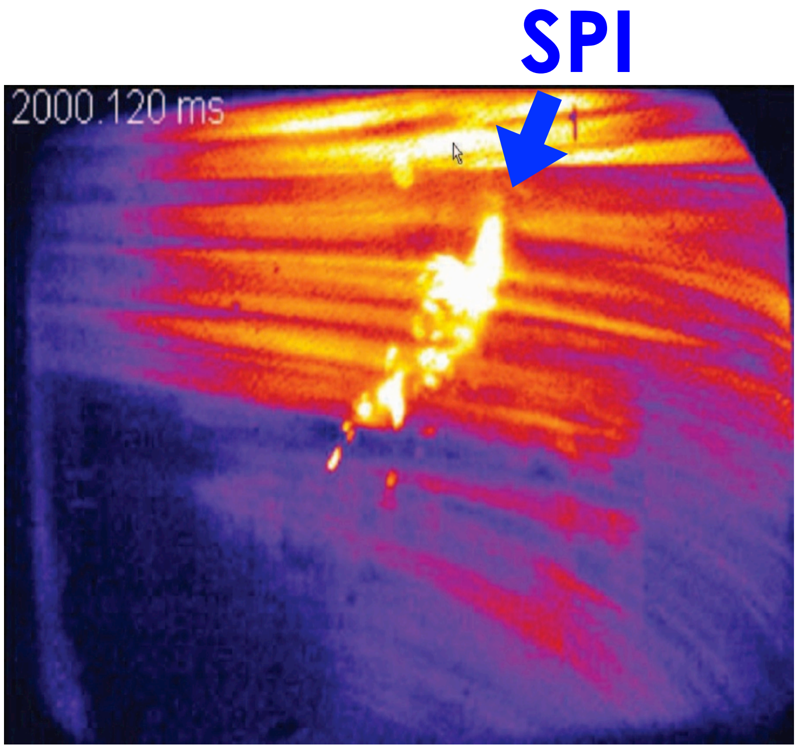
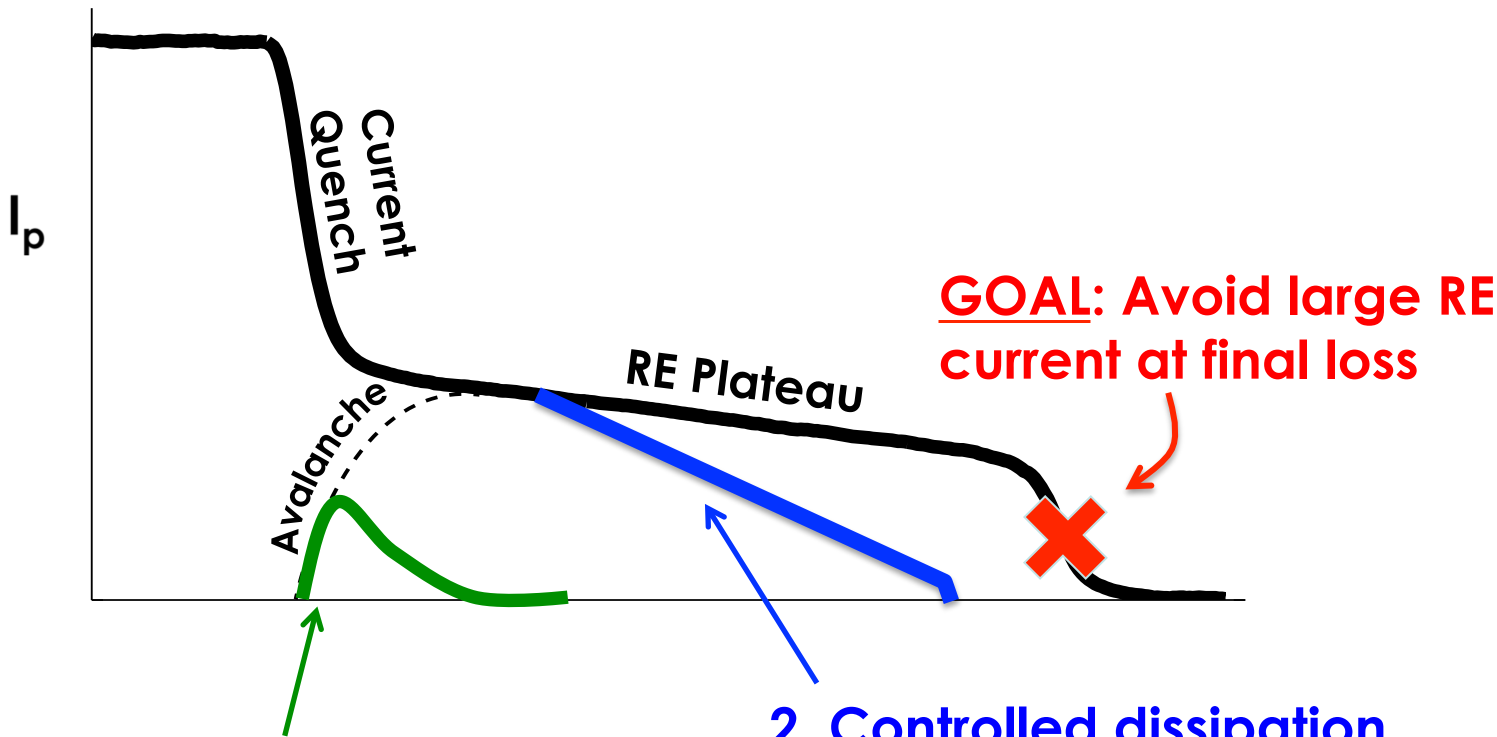


Runaway electron avoidance/mitigation has several approaches



0. Disruption avoidance

1. Suppress or “stunt” RE seed from avalanching

2. Controlled dissipation of RE plateau via massive impurity injection

Collisional suppression of runaways will require very high densities in ITER

- **In DIII-D, MGI and SPI able to mitigate disruption loads without generating runaways**

- **In ITER, avalanche gain is much higher! ~ $e^{\wedge}I_p$**

- **Open question:** ***How much would we need to raise the density, and is this achievable?***

- **With enough electrons in the plasma, electron collisions alone can suppress avalanche growth → 'Rosenbluth' density (×100 increase)**

- **Other dissipation mechanisms likely important (see later)**

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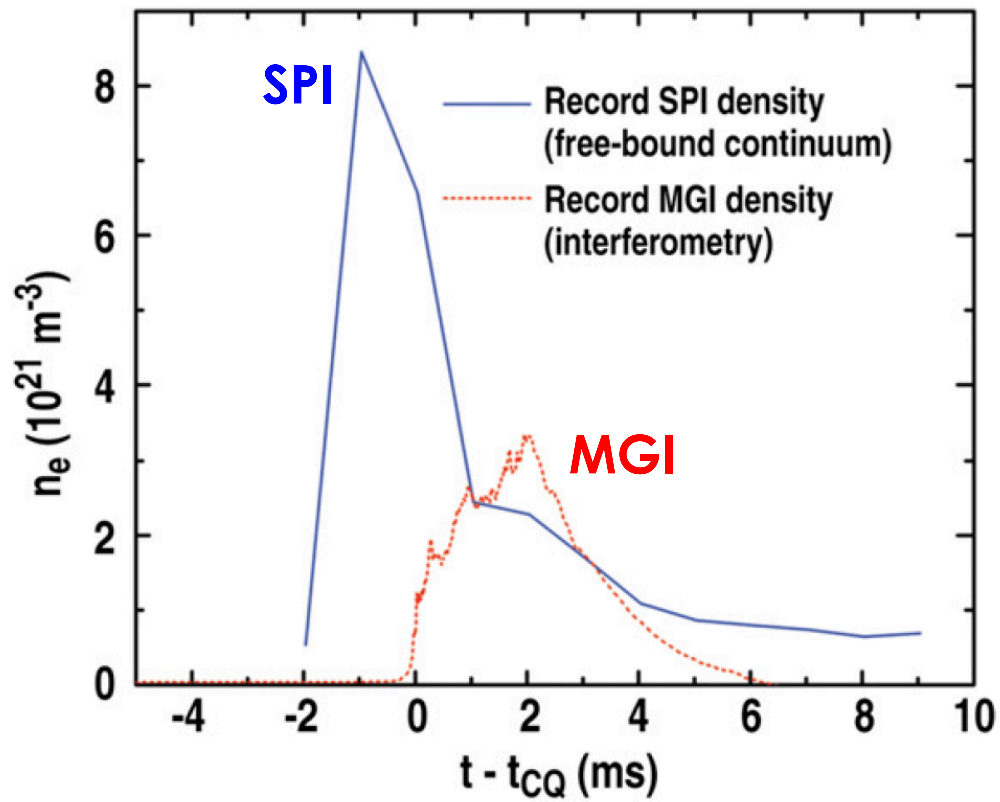
SPI has achieved record densities on DIII-D

- Early work on SPI focused on achieving highest plasma density possible
- Large D_2 pellets injected (12× larger than used for TQ/CQ mitigation)
- Record densities ~20% of 'Rosenbluth' density were achieved



N. Commaux et al, NF 50 (2010) 112001

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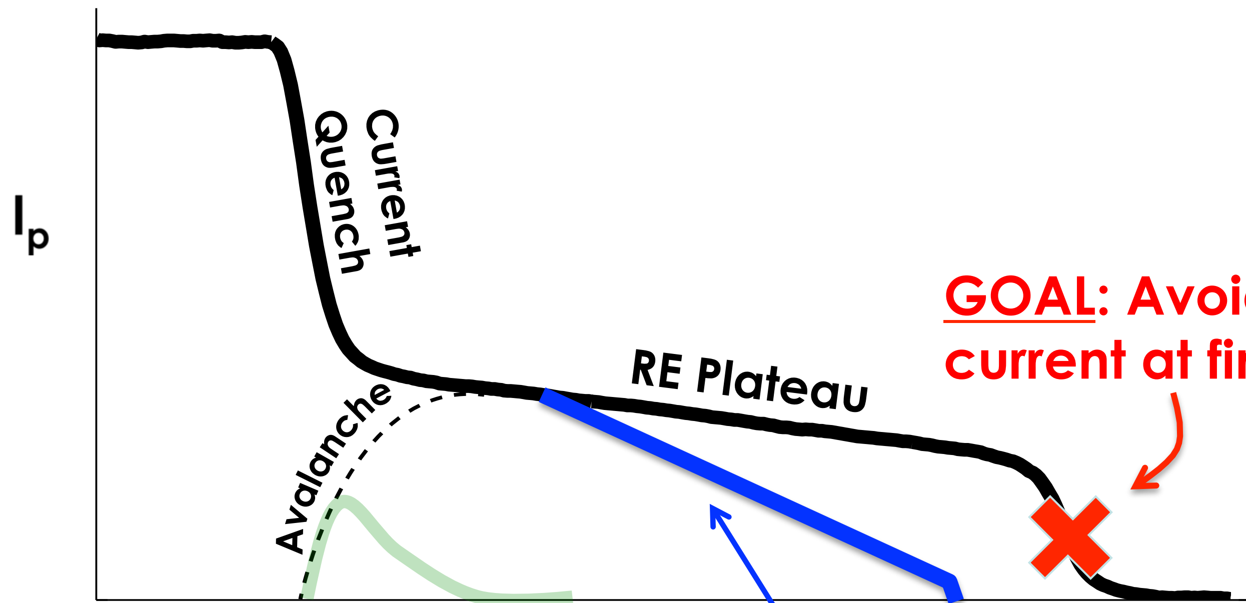

0. Disruption avoidance

1. Suppress or “stunt” RE seed from avalanching

2. Controlled dissipation of RE plateau via massive impurity injection

GOAL: Avoid large RE current at final loss

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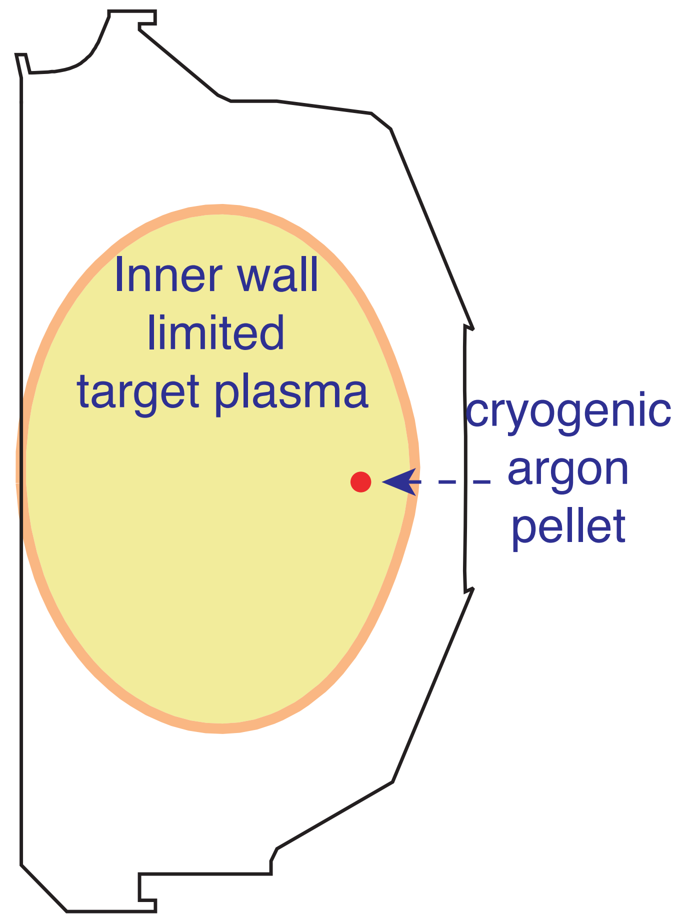
DIII-D can generate sustained post-disruption RE plateaus

- **Disruptions in DIII-D *typically* do <u>not</u> generate runaways**

- **A specific 'recipe' for RE production has been developed:**
  - Low elongation inner-wall limited plasma shape
  - Low plasma density
  - High magnetic field (B_T)
  - Electron cyclotron heating
  - Argon 'killer' pellet to create disruption



- **Argon pellet injector specifically built to generate runaways**

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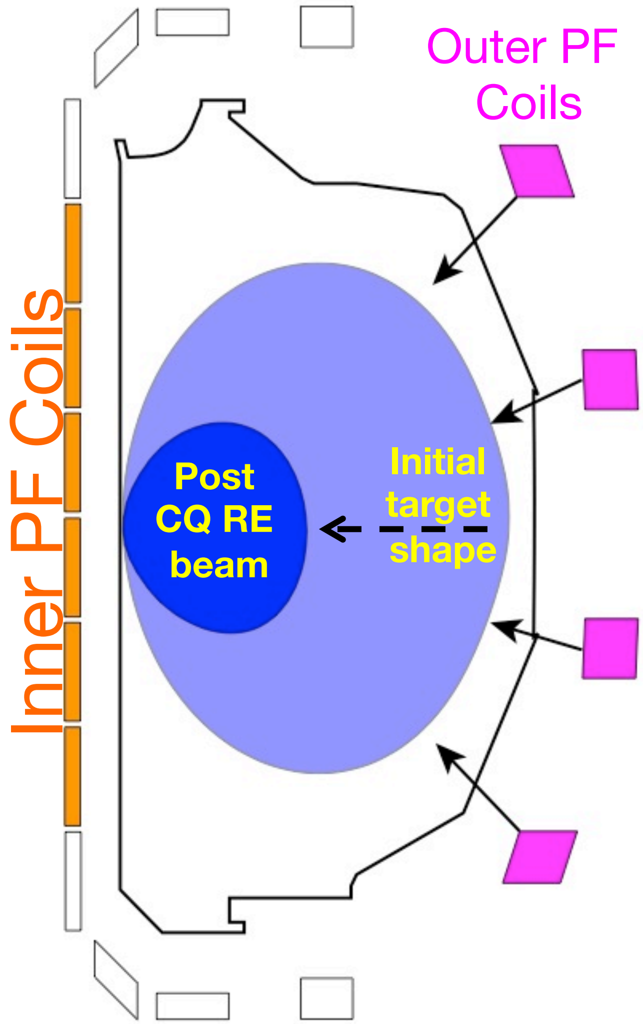
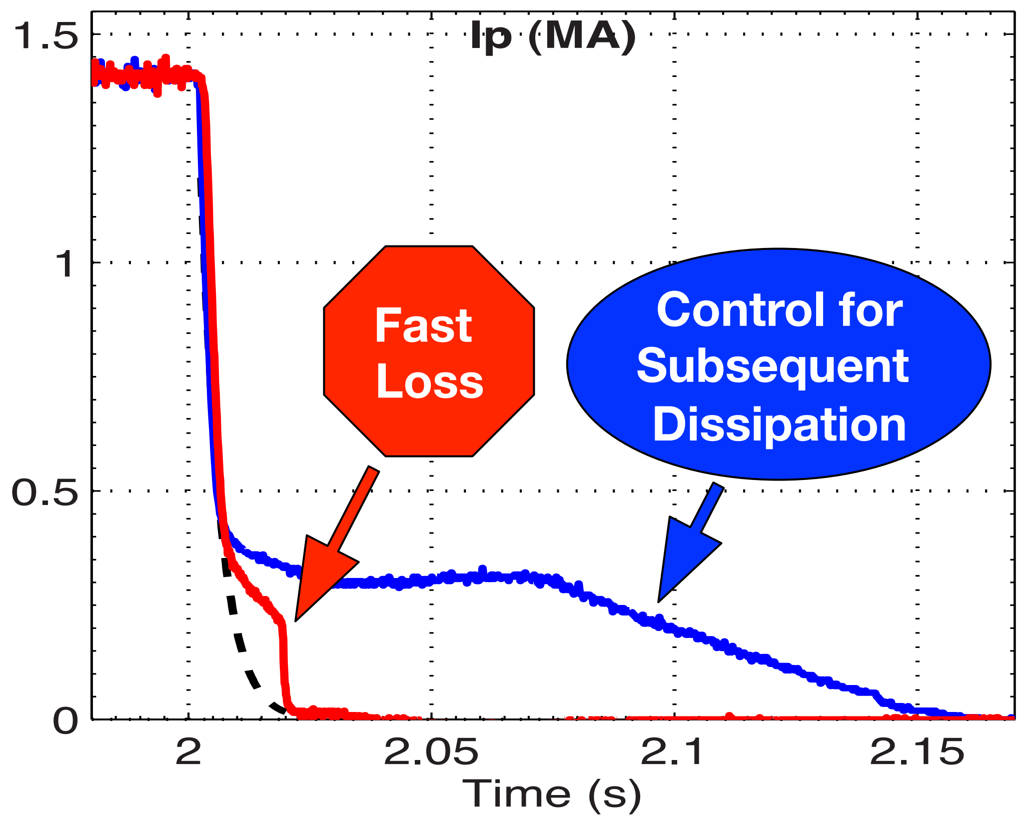
Plasma control system can control position of RE beam following the CQ



- **RE beam typically lost when radial force balance compresses it into inner wall**



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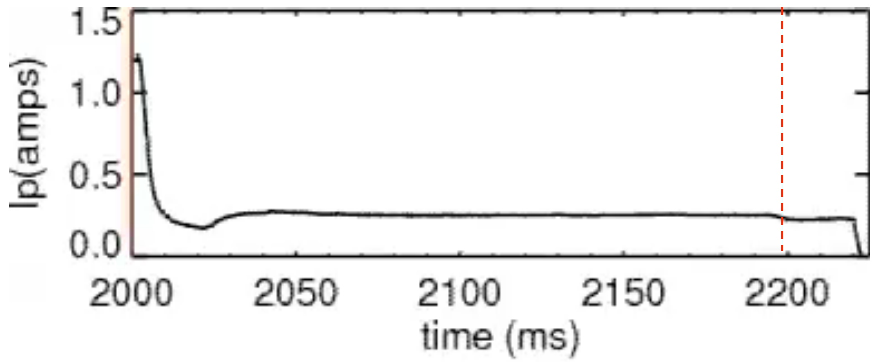
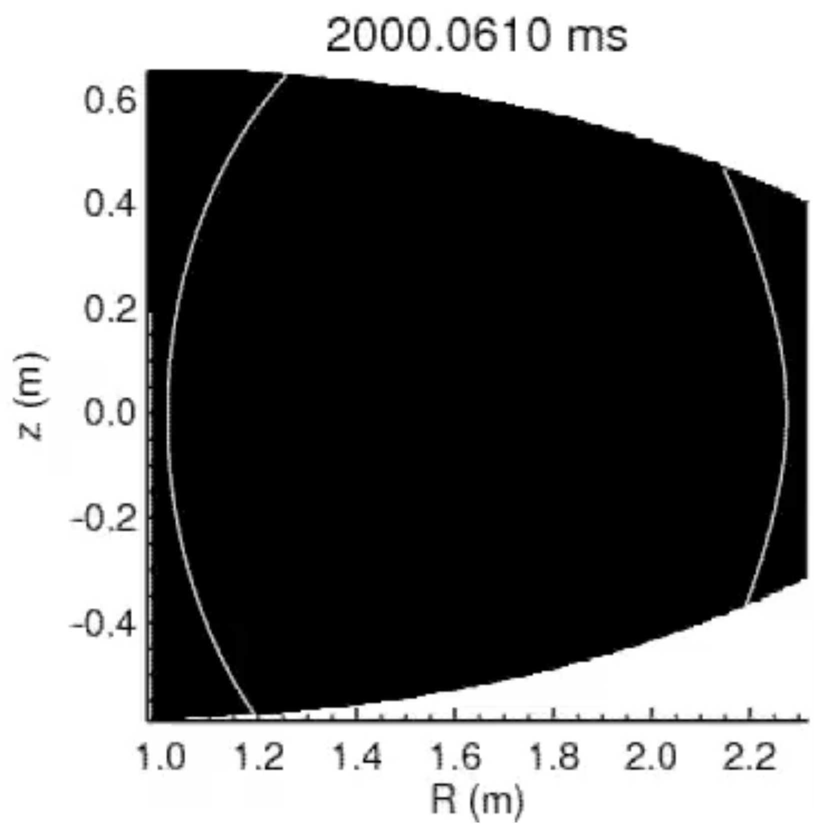
RE plateau can be maintained on DIII-D, for hundreds of milliseconds



Plasma current



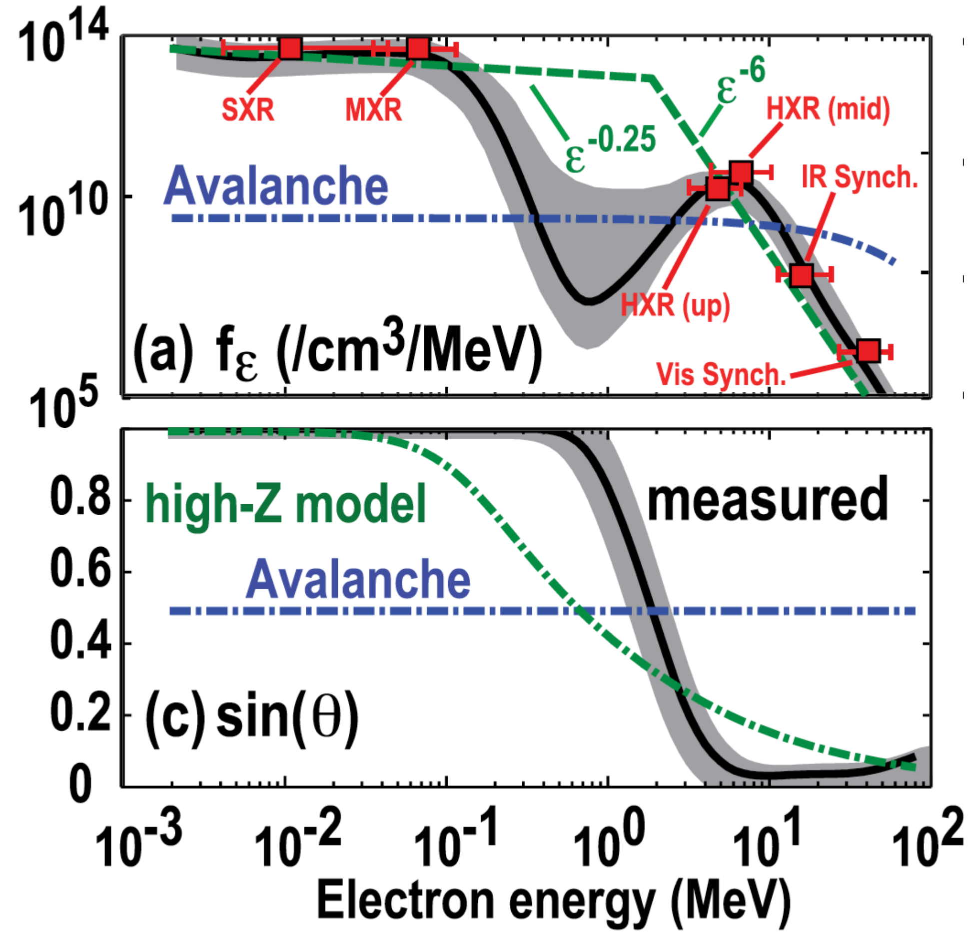
RE synchrotron emission

+

Last closed flux surface

RE distribution function can be estimated from a wide set of diagnostics

- Compared to avalanche theory, distribution skewed towards low energy
- Synchrotron losses may be limiting peak RE energy
- Estimating f(E) in a post-disruption RE plateau remains challenging!
  - Other regimes may be better (see later)



E.M. Hollmann et al, PoP 22 (2015) 056108

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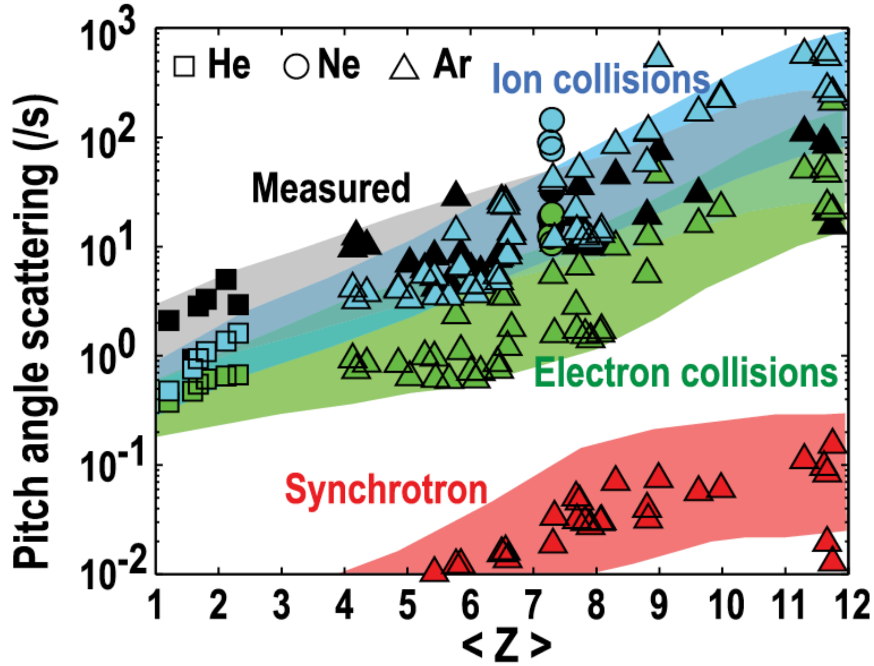
Pitch-angle scattering off high-Z impurity ions appears important

- Varying the impurity content of the background plasma can vary the mean ion charge <Z>

- Ion collisions contribute dominantly to pitch-angle scattering

- Pitch-angle scattering can dissipate RE current

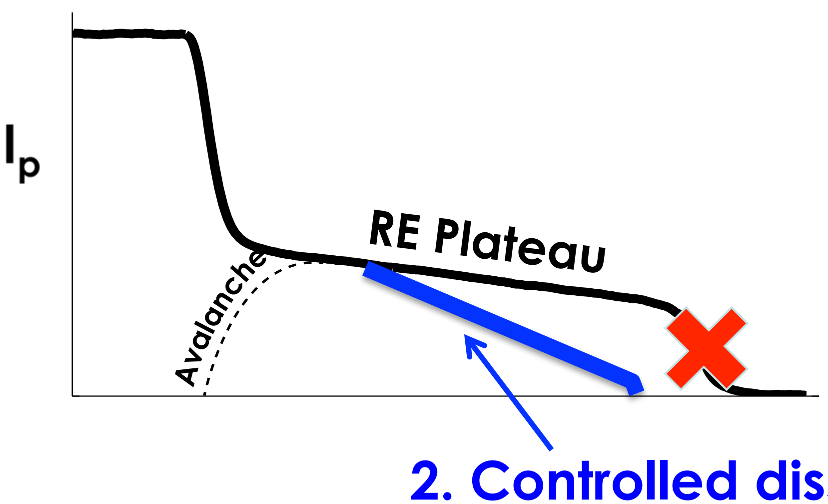


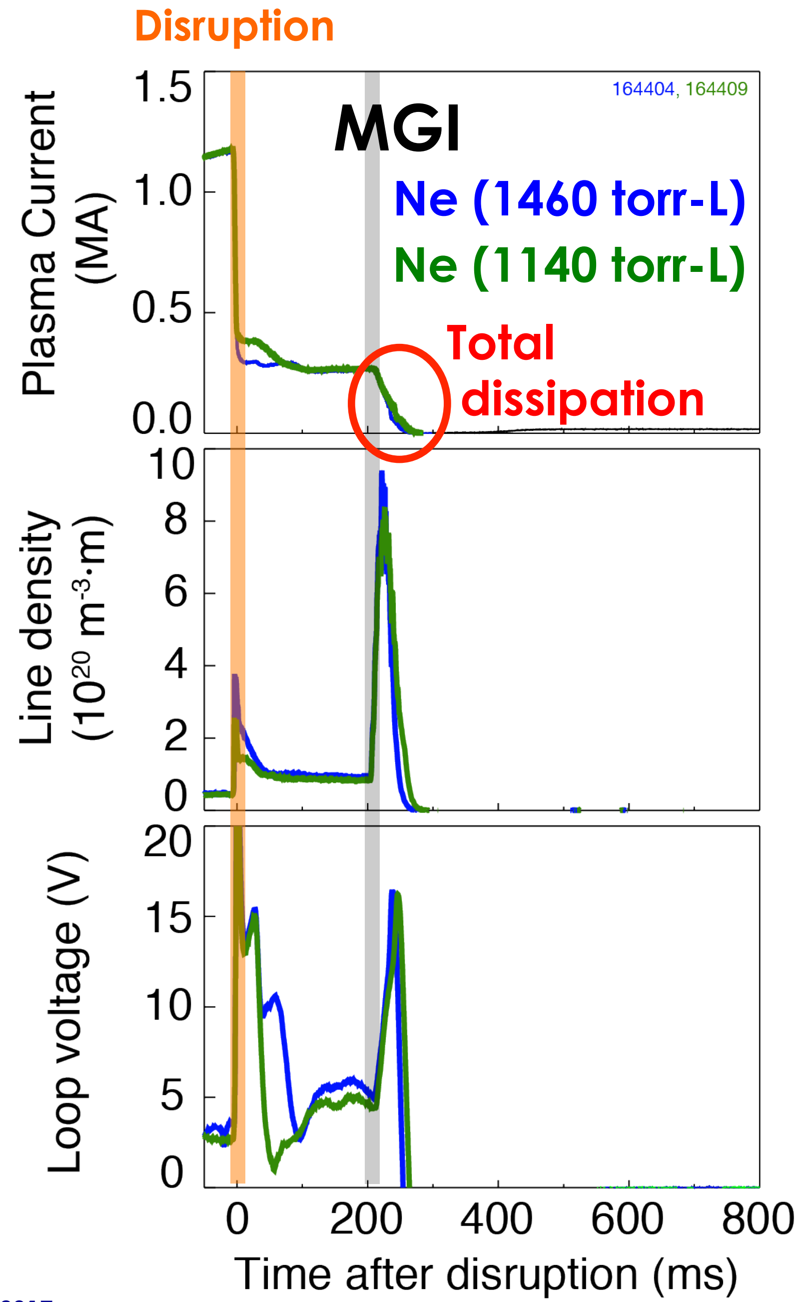
E.M. Hollmann et al, PoP 22 (2015) 056108

With large quantities, complete dissipation of RE plateau has been seen

- Ohmic coil applies loop voltage to balance the dissipation, and sustain the RE current

- If the dissipation is large enough, RE current goes to zero





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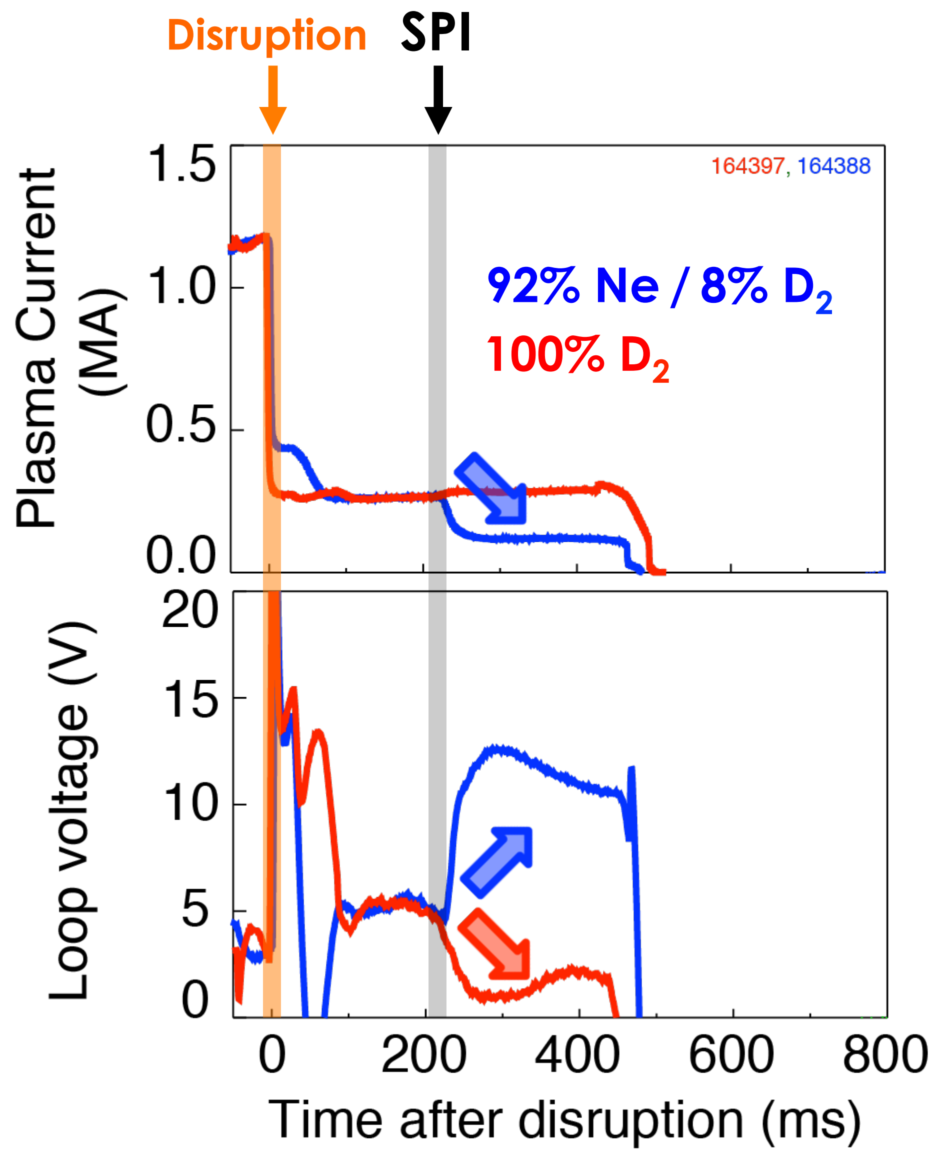
RE current dissipation can be increased or decreased, depending on injection

- **Plasma control system feedback controls the RE current**
- **Amount of loop voltage needed is a measure of overall dissipation**
- **Residual argon from the killer pellet causes dissipation of the runaways**
  - Background plasma is 5%-10% Ar+



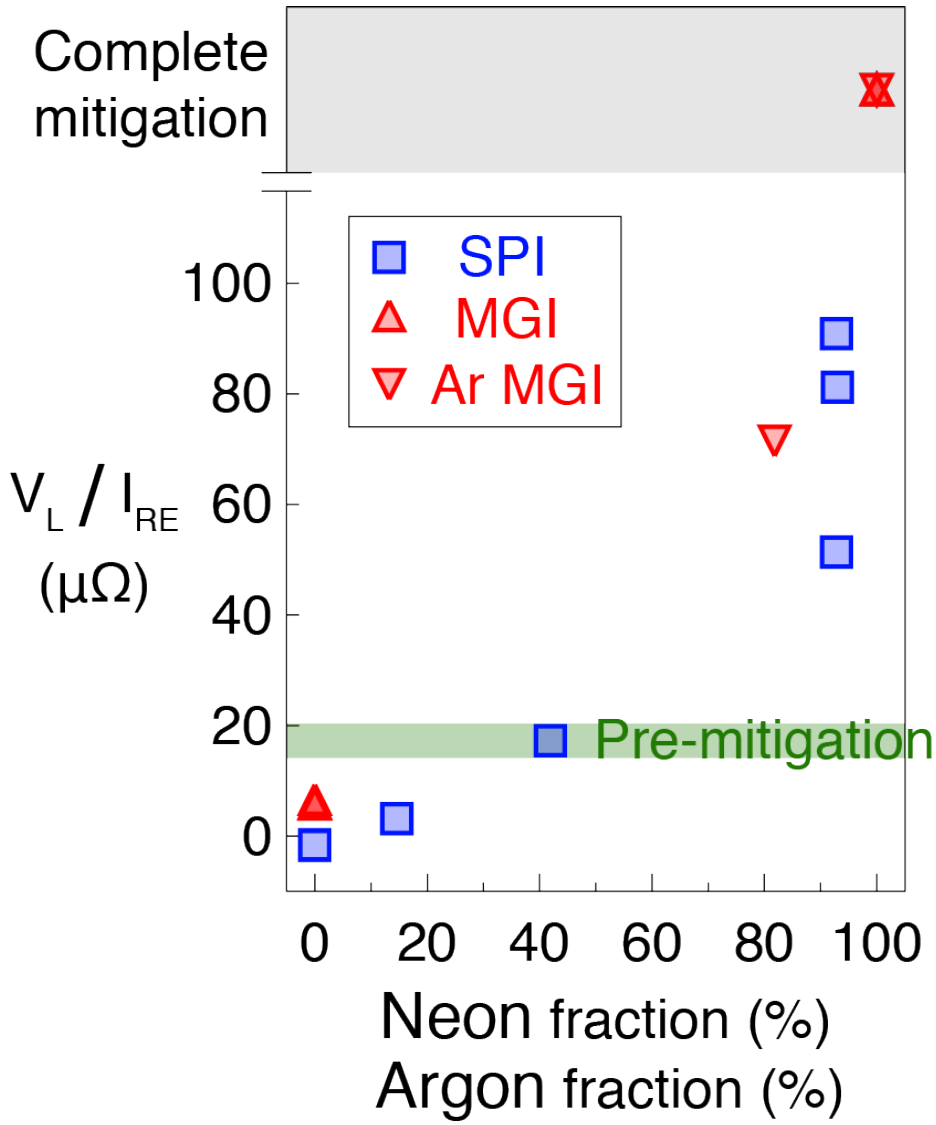
Massive impurity injection can dissipate post-disruption RE beams

- **Measure 'effective resistance' of RE beam:**

  loop voltage / runaway current

- **Variety of injection schemes (gas, pellets, high-Z, low-Z) tested**

- **Initial results: Impurity species makes a large difference, but injection technique (SPI v. MGI) does not**



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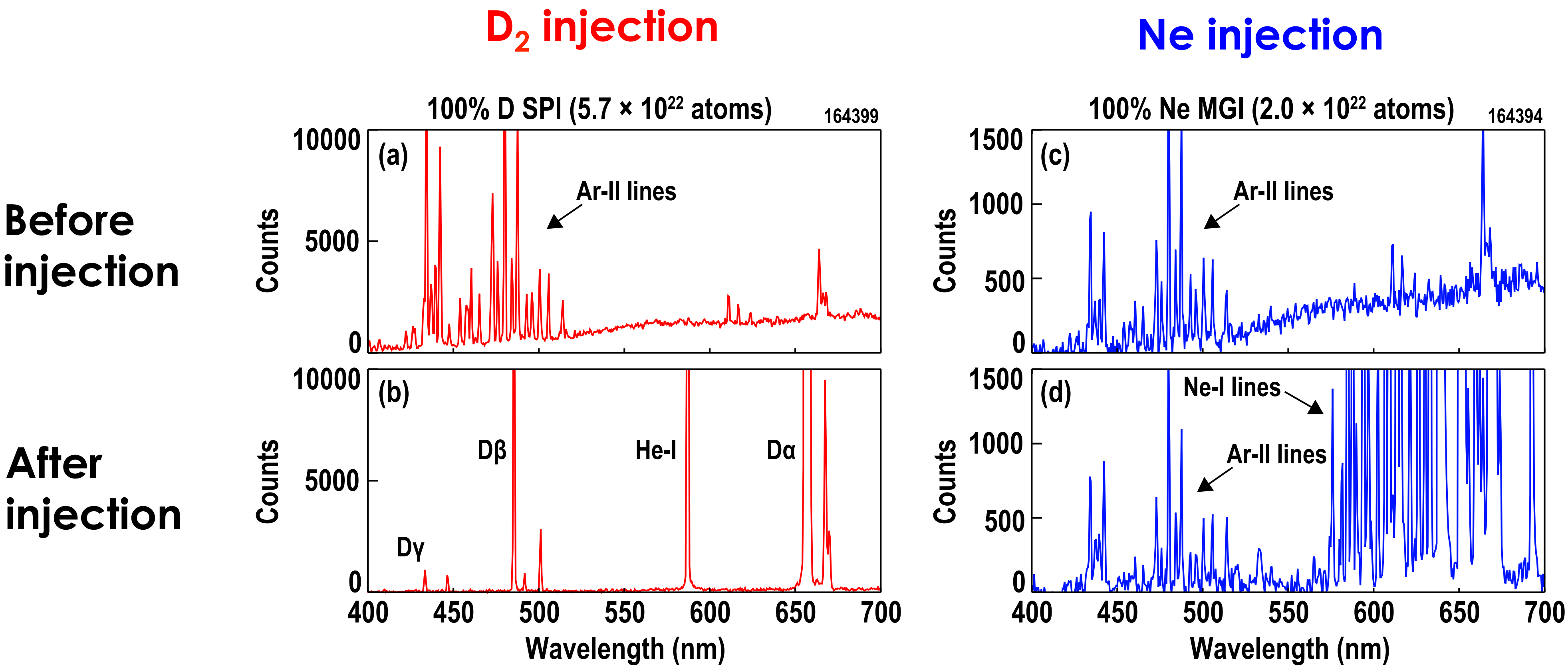
High- and low-Z impurities have opposite effect on RE beam

- **Visible survey spectrometer shows that D_2 injection 'purges' residual Ar in plasma**



Transport of impurities in the RE beam, and optimal injection schemes, are still under study

- **Similar dissipation levels observed for MGI and SPI**
- **Indicates that shattered pellets are ablated near the edge of the RE beam**
- **SPI timescales < MGI timescales << RE beam evolution timescales**

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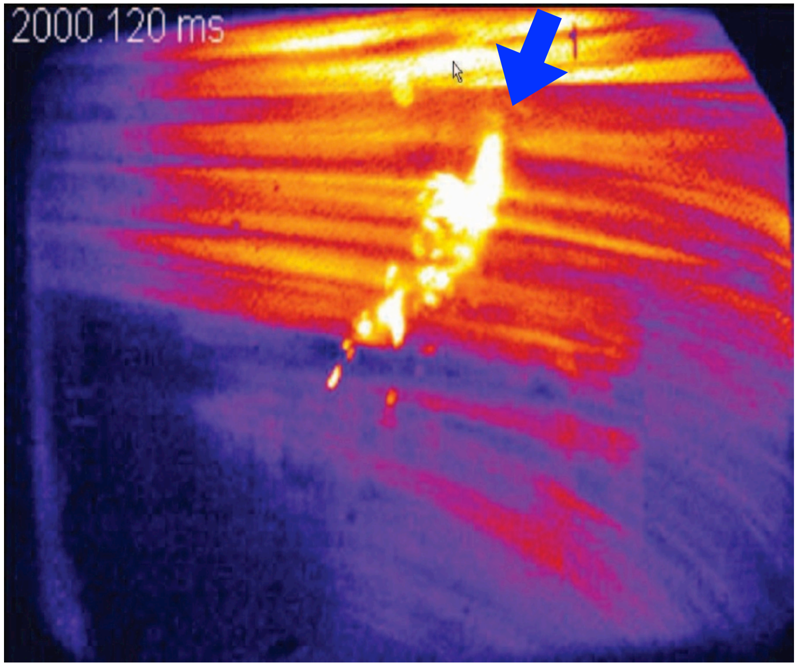
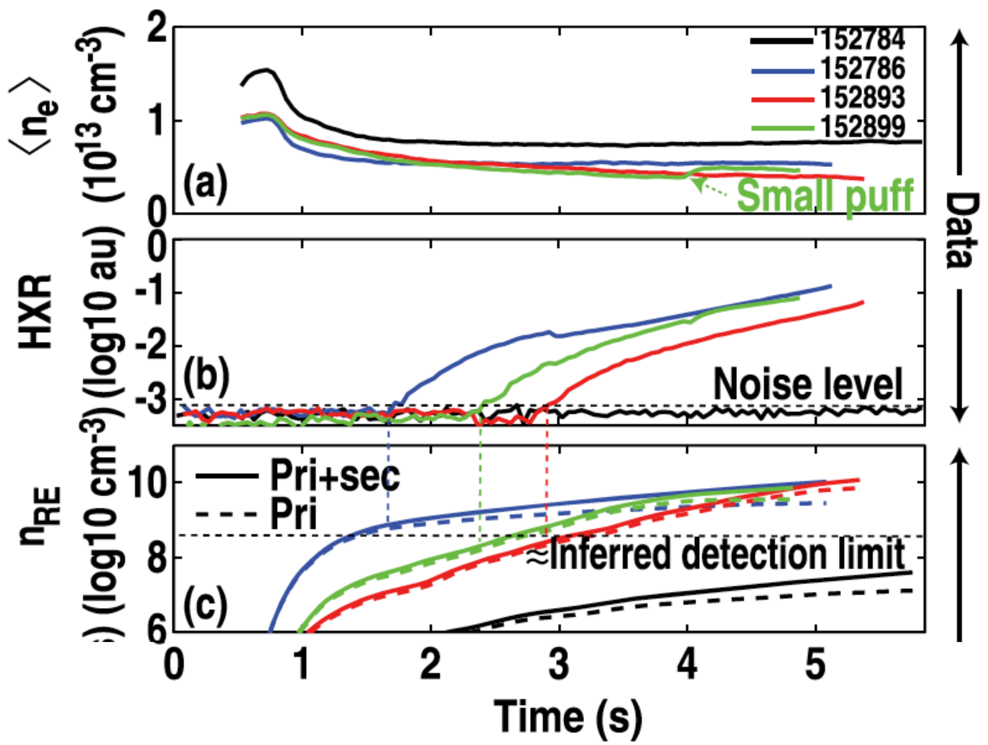
SPI



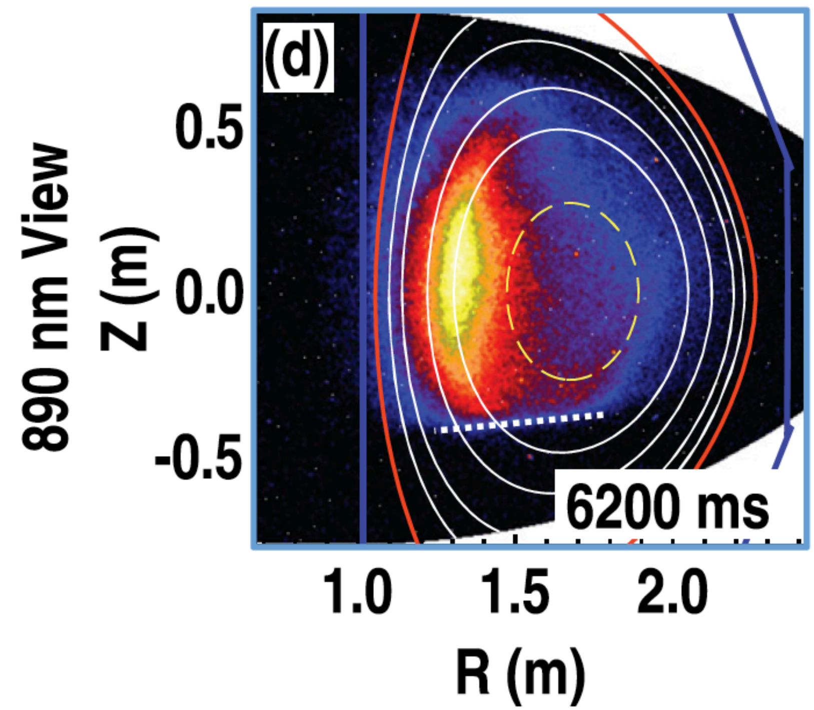
Quiescent Runaway Electrons (QREs) allow controlled studies

- **"It is desirable to obtain… data under well-controlled, reproducible, well-diagnosed conditions, i.e., *not during disruptions*"**
  - R.S. Granetz et al, PoP 21 (2014) 072506



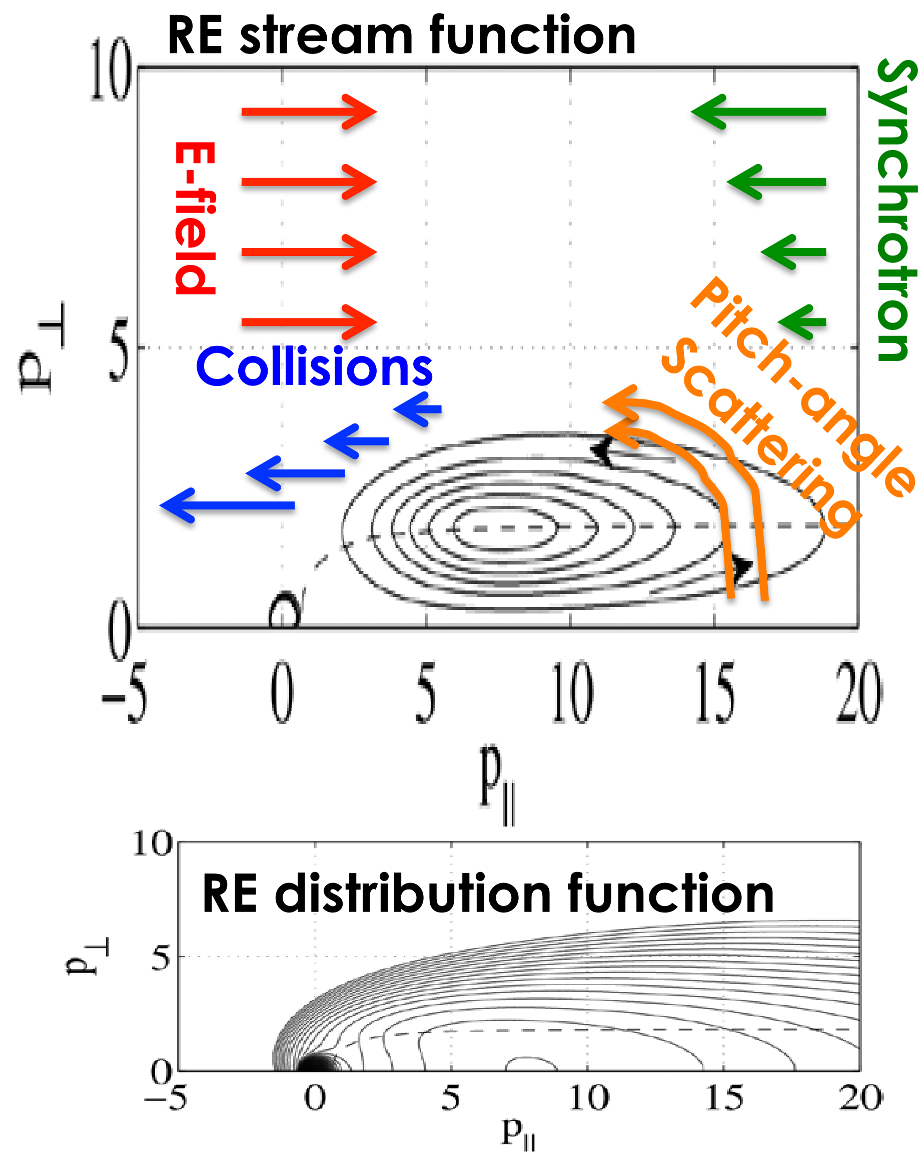
C. Paz-Soldan et al, PoP 21 (2014) 022514

- **Runaways formed during flat-top plasma at low density**



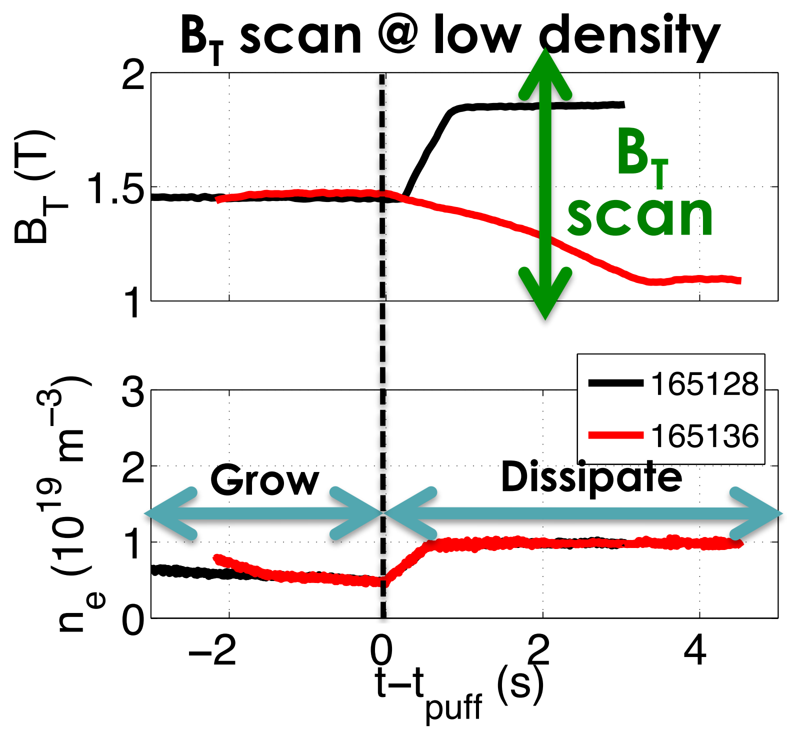
Runaway Electrons Experience Several Mechanisms Whose Interplay Determines f(E) Shape and Dissipation

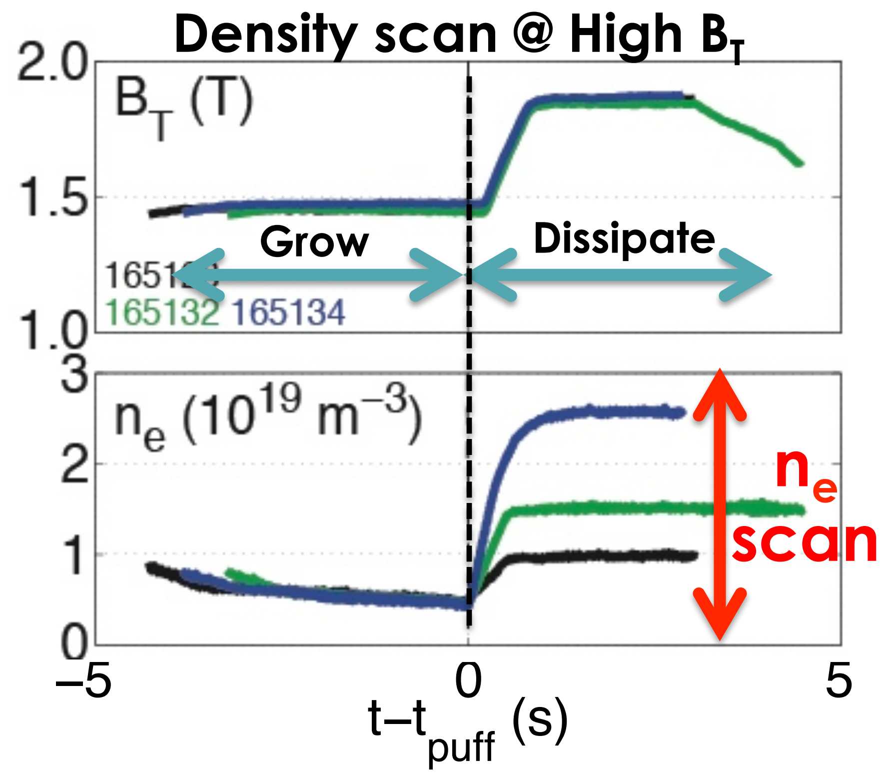
- Acceleration due to E-field vs. drag from collisions
  - E/E_{crit}
- Energy loss to synchrotron
  - t-rad-hat
- Pitch angle scattering on ions, from parallel to perp
  - Z_{eff}



J. Decker et al, PPCF '16

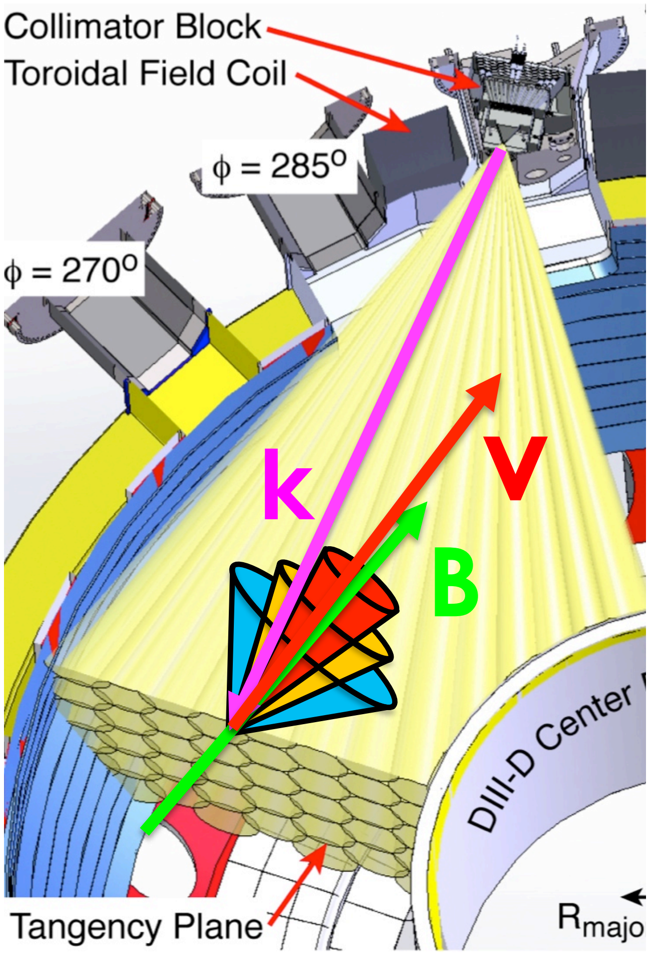
In order to affect synchrotron, collisions, and scattering Experimental approach is to vary B_T, density, Z_{eff}

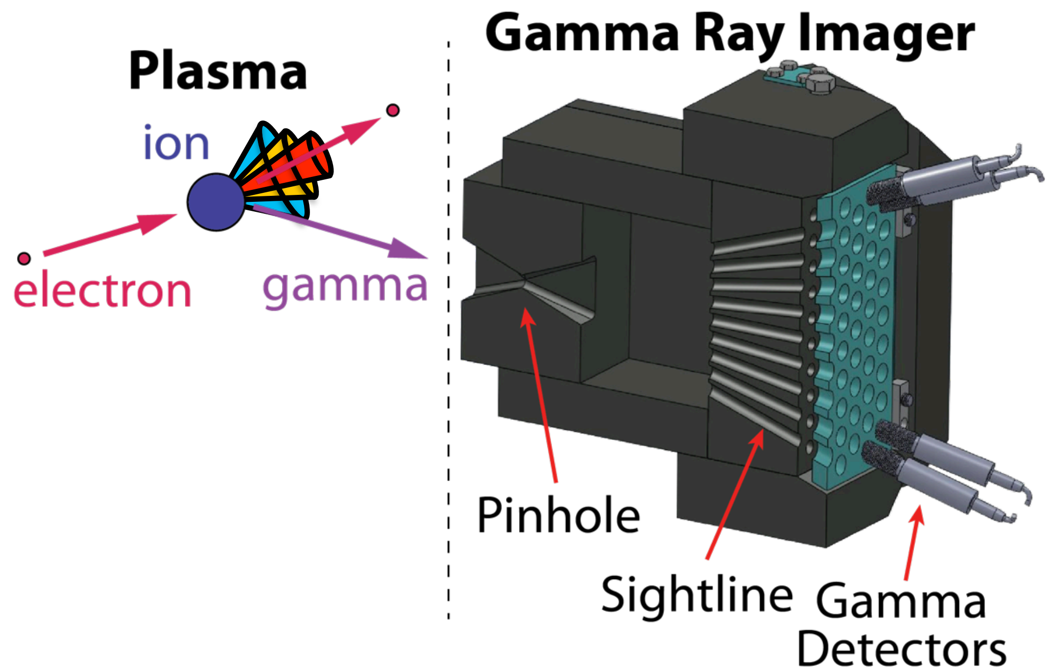




- Low density QRE regime yields improved actuator control and very long timescales for improved diagnosis

New Gamma Ray Imager (GRI) deployed to measure spatial and energy-resolved f(E)

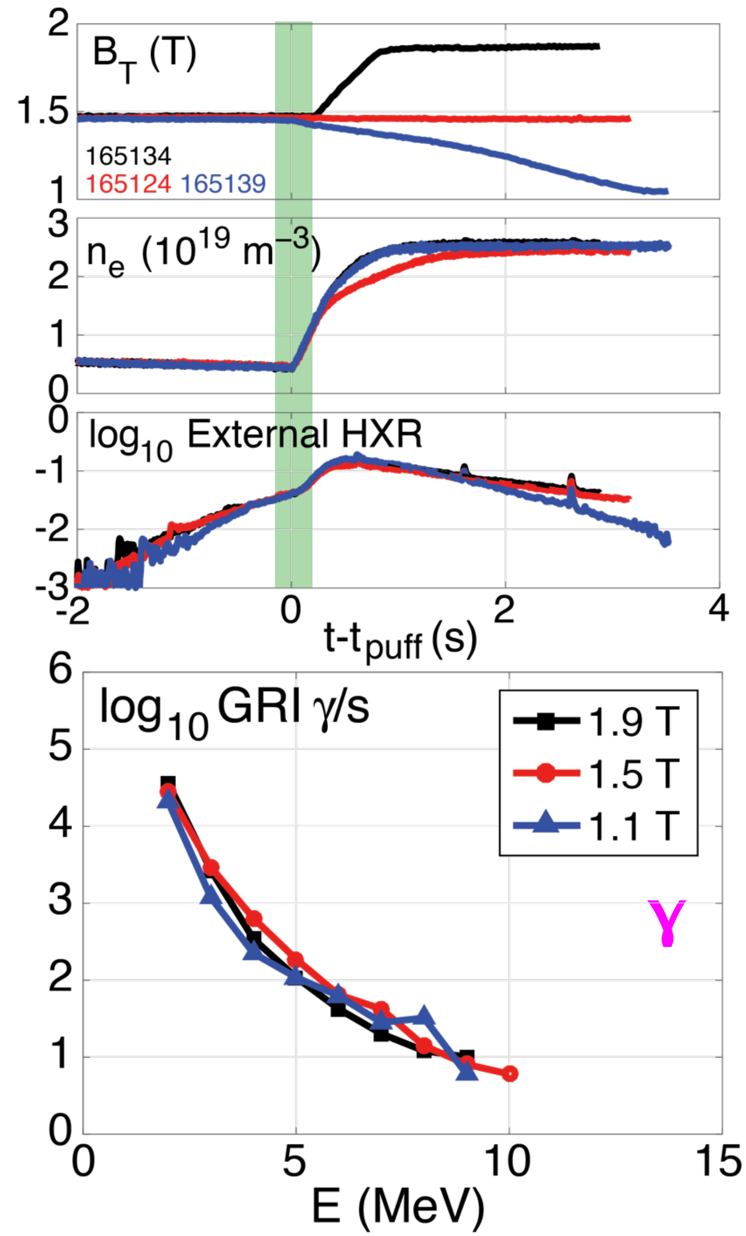




- **GRI detects individual gammas, and by 'counting' them determines their energy distribution as a function of time**

GRI spectrum 'hardness' varies based on BT level: Synchrotron energy limit likely observed

- **Consider 3 shots with very similar RE seed populations**
- **Vary B_T within the shot**
- **Lower B_T discharges contain higher energy gammas**



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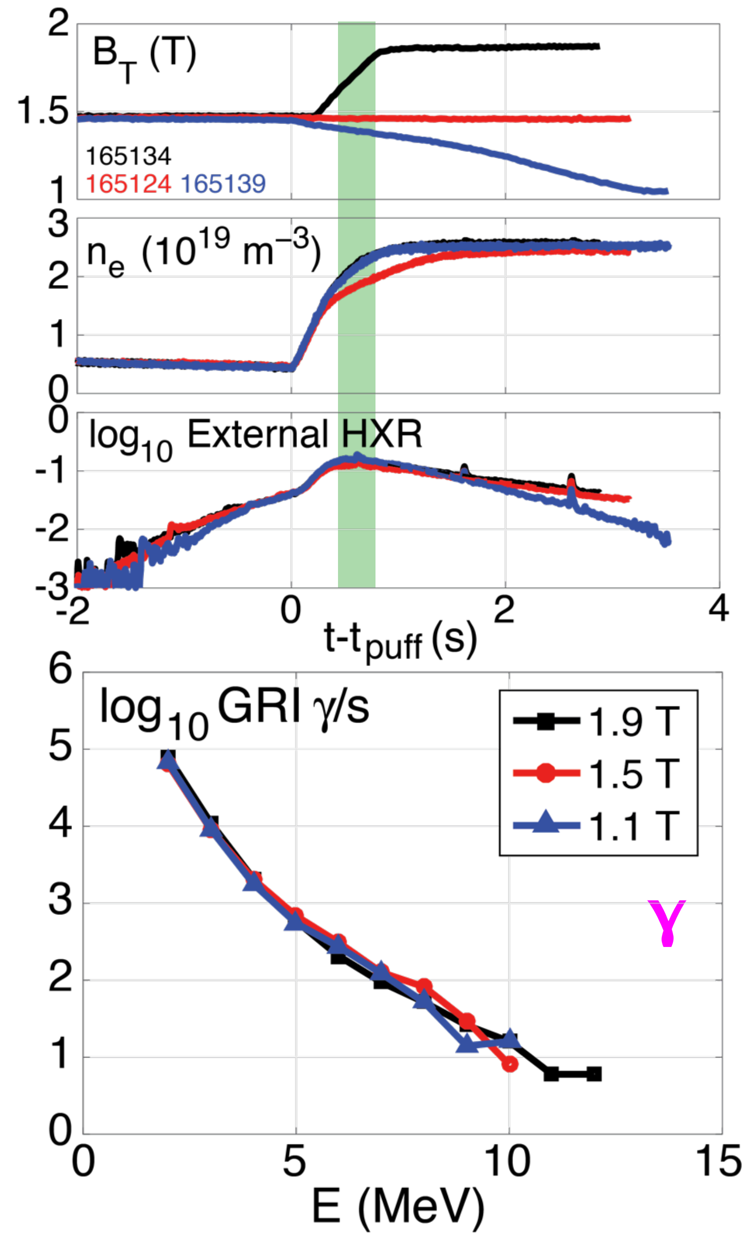

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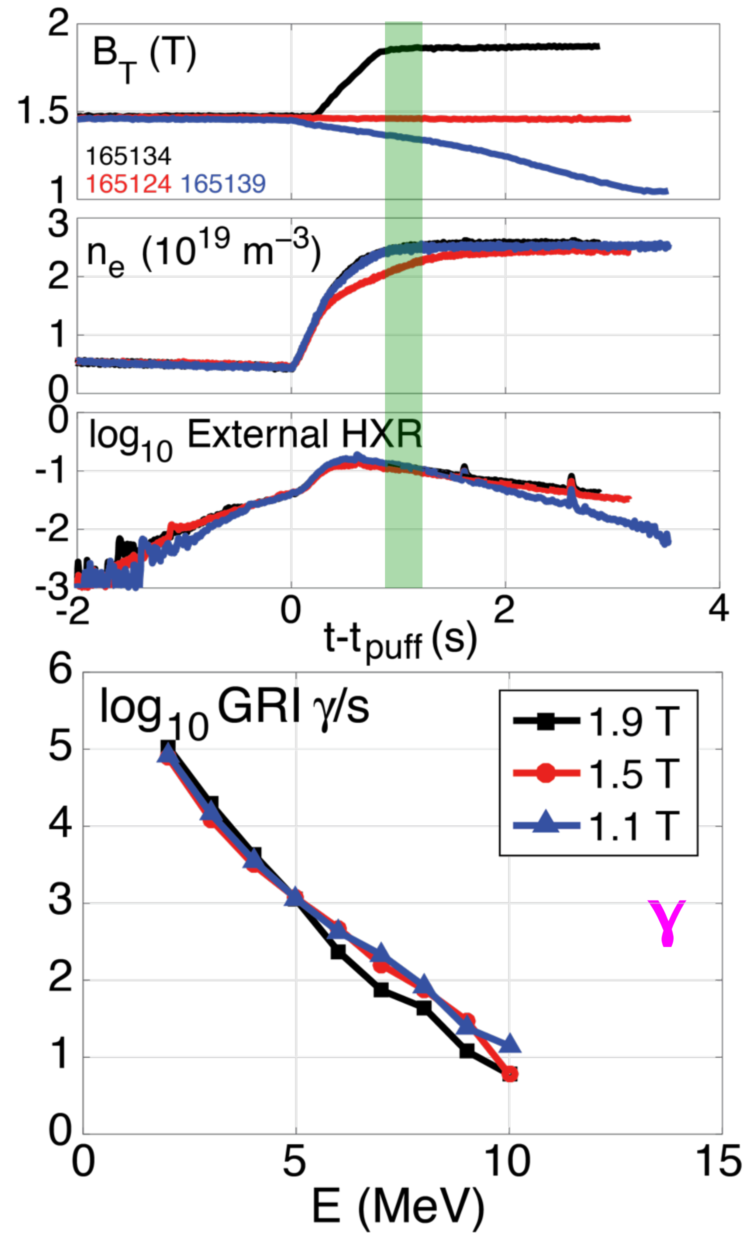

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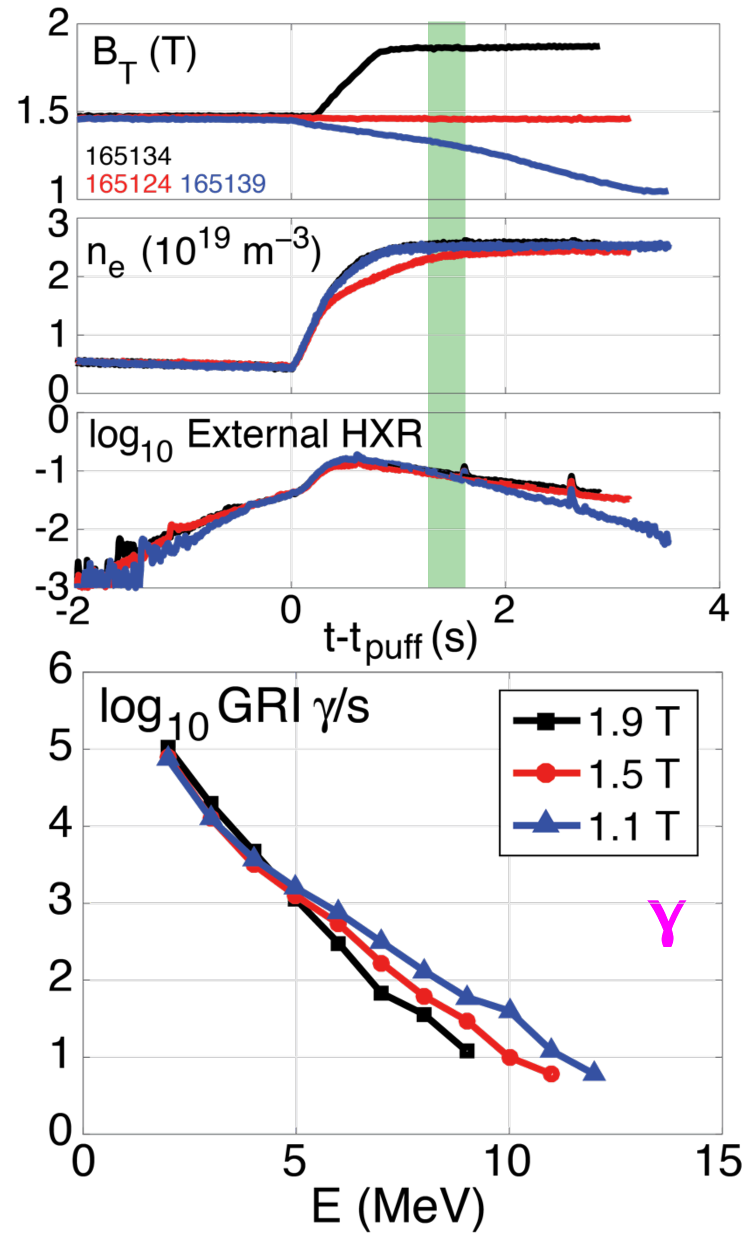

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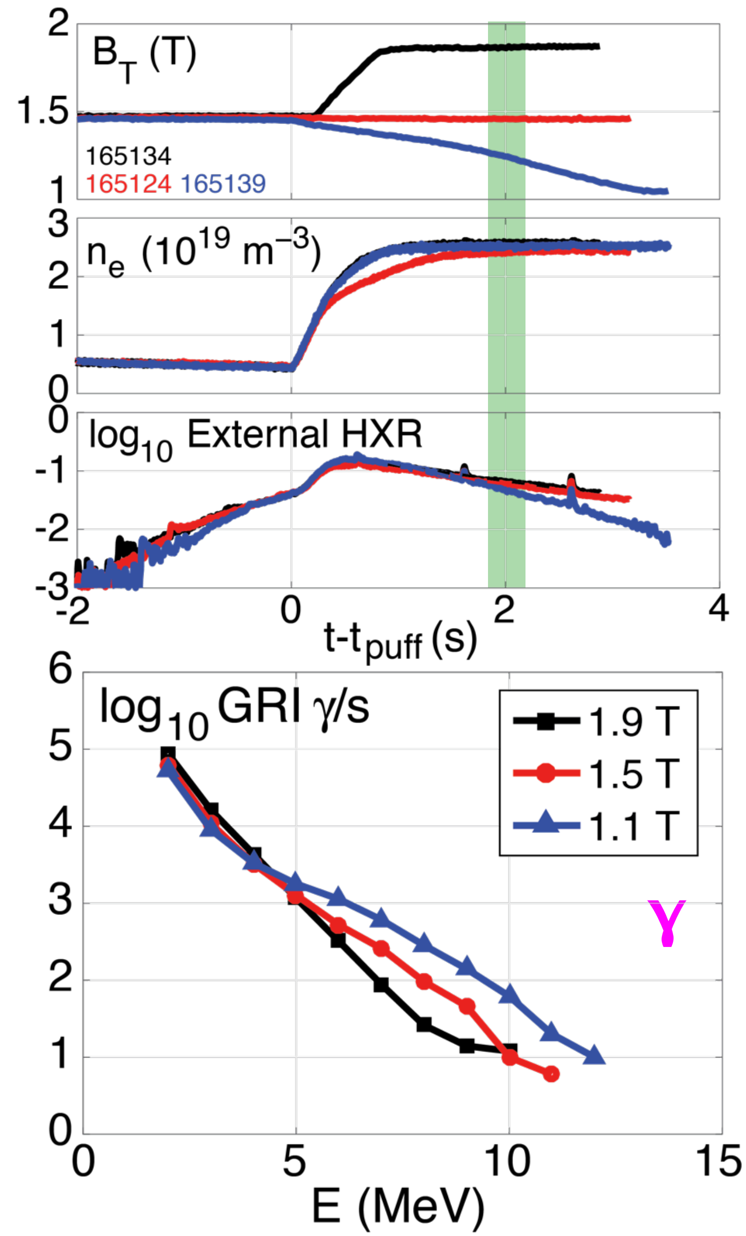

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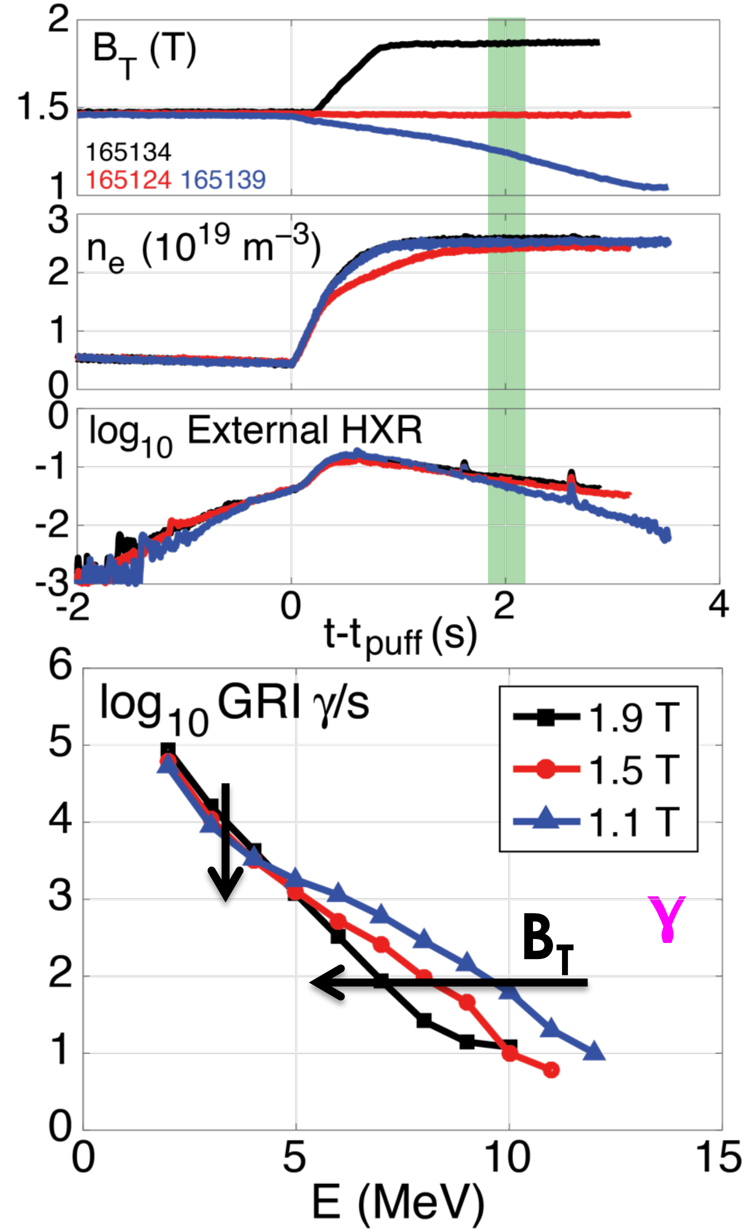
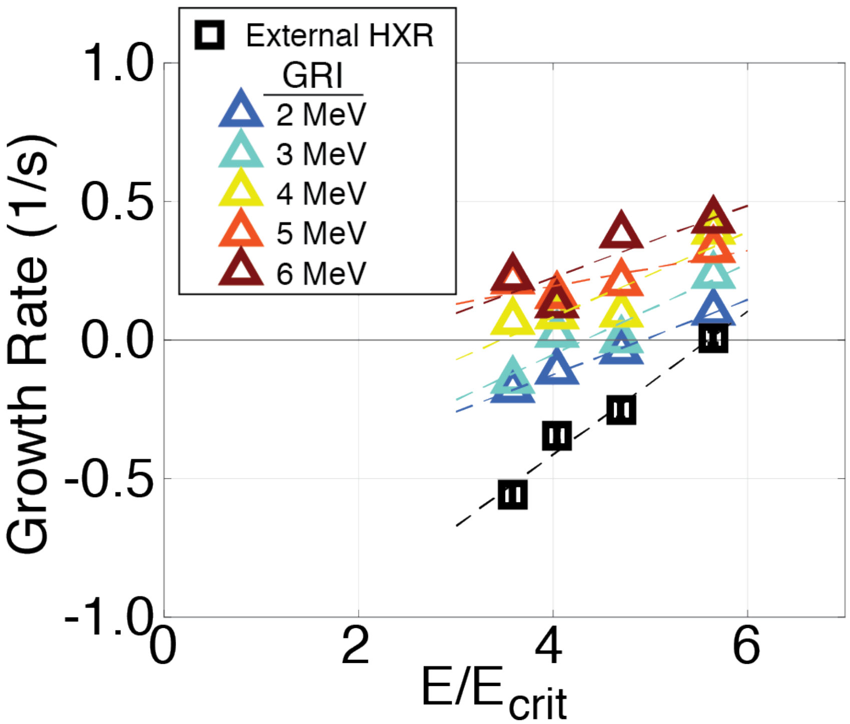
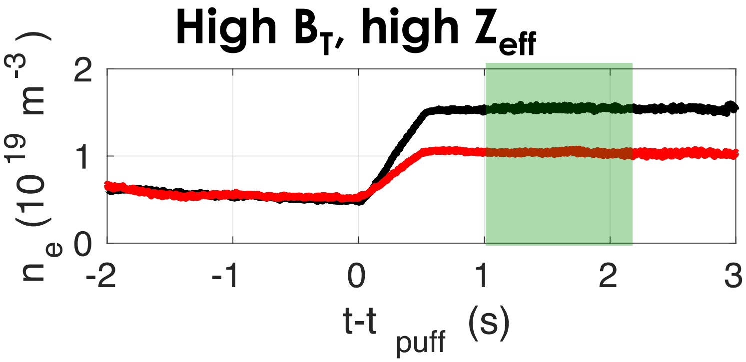
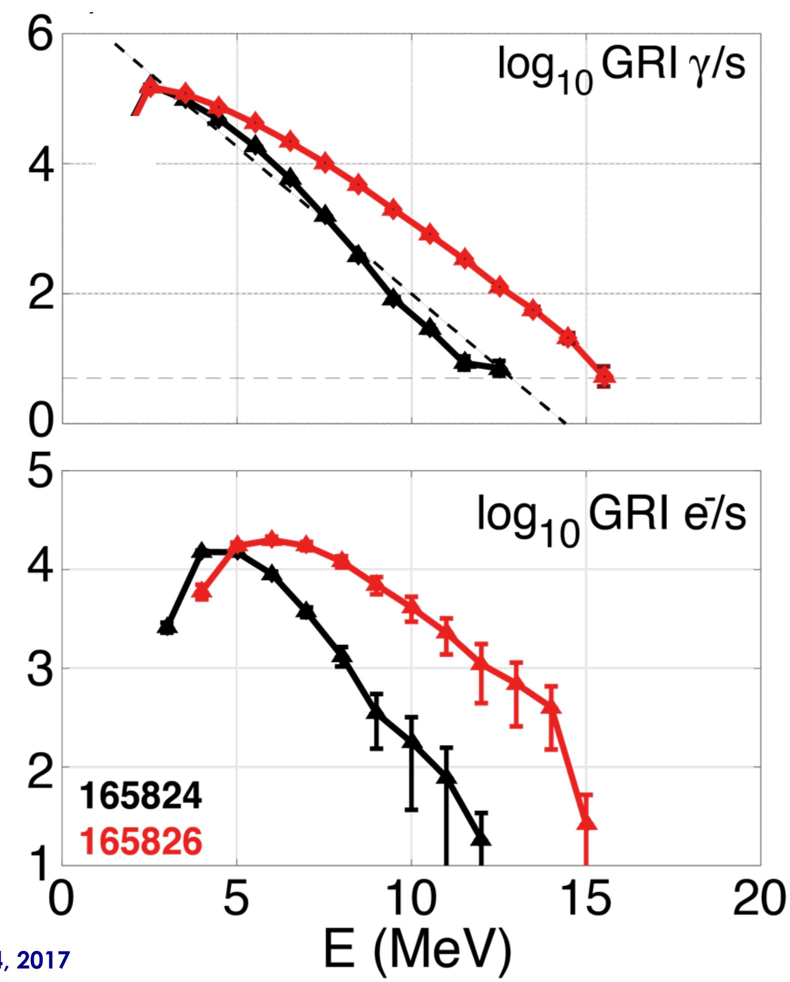


Increasing electron density lowers E/E_{crit} and shows fewer REs at high energy due to slower RE growth rate

- **Transition between growth/decay measured, theory comparisons underway**







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Summary

- **Shattered pellet injection has been selected for the ITER DMS**
  - Faster delivery, higher assimilation, and deeper fueling, compared with MGI
  - More favorable scaling with device size than MGI
  - Mixing pellet species allows disruption parameters to be controlled
  - Suppression or dissipation of runaways may be possible
  - Important issues for ITER DMS design still being studied

- **Runaway electron dissipation physics models being developed**
  - Post-disruption RE beams can be generated, controlled, and sustained
  - Collisional suppression by SPI still uncertain
  - High-Z impurity injection can dissipate RE plateaus, but transport of impurities within beam being studied
  - QRE regime allows repeatable well-controlled measurements