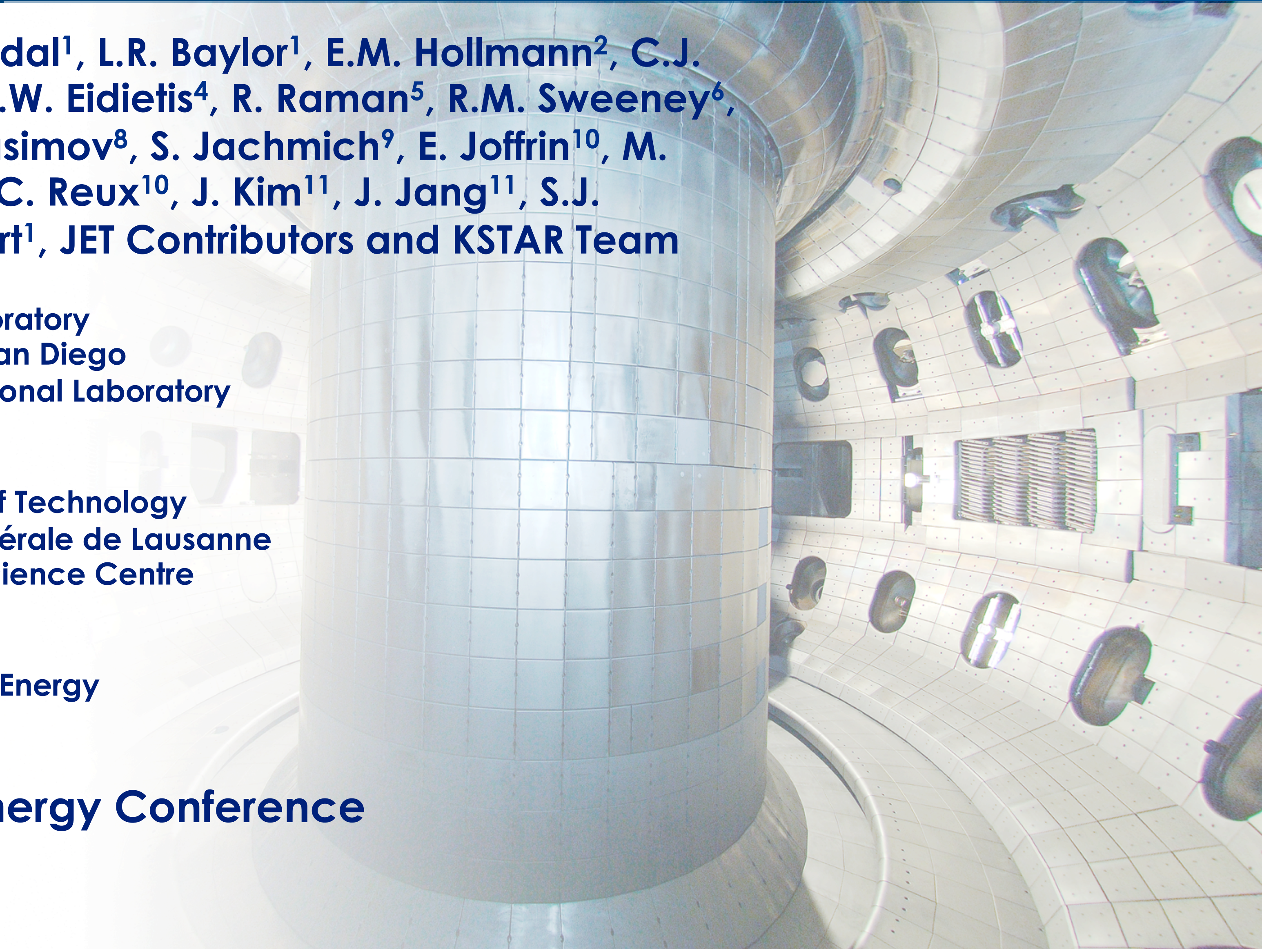
DIII-D and International Research Towards Extrapolating Shattered Pellet Injection Performance to ITER



D. Shiraki[1], J.L. Herfindal[1], L.R. Baylor[1], E.M. Hollmann[2], C.J. Lasnier[3], I. Bykov[2], N.W. Eidietis[4], R. Raman[5], R.M. Sweeney[6], U. Sheikh[7], S.N. Gerasimov[8], S. Jachmich[9], E. Joffrin[10], M. Lehnen[9], S. Silburn[8], C. Reux[10], J. Kim[11], J. Jang[11], S.J. Meitner[1], T.E. Gebhart[1], JET Contributors and KSTAR Team

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[3] Lawrence Livermore National Laboratory
[4] General Atomics
[5] University of Washington
[6] Massachusetts Institute of Technology
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Presented at the

28th IAEA Fusion Energy Conference
(Virtual)

May 14th, 2021

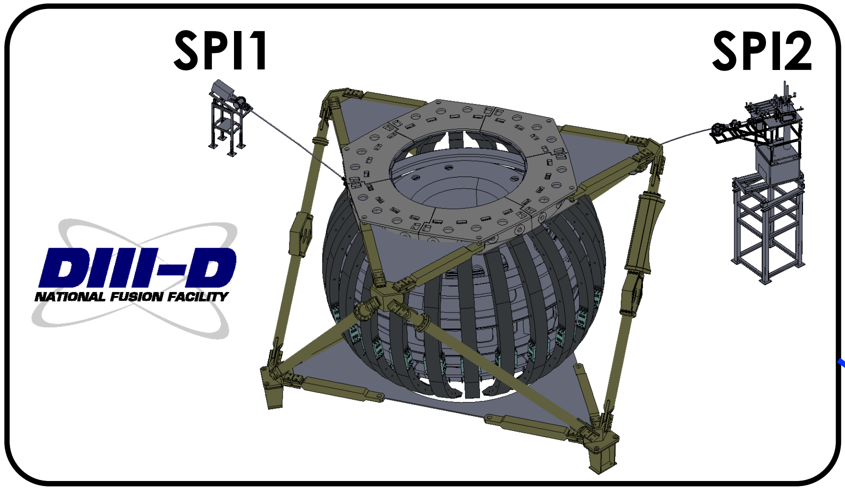
Global SPI performance predictable from validated modeling tested at DIII-D, JET, and KSTAR

- **Neon SPI dynamics primarily driven by global energy balance instead of MHD**
  - Predictive model tested on DIII-D data, also applied successfully to JET and KSTAR experiments
  - Empirical scalings of assimilation consistent with this
  - Multi-pellet shutdowns also described by this picture

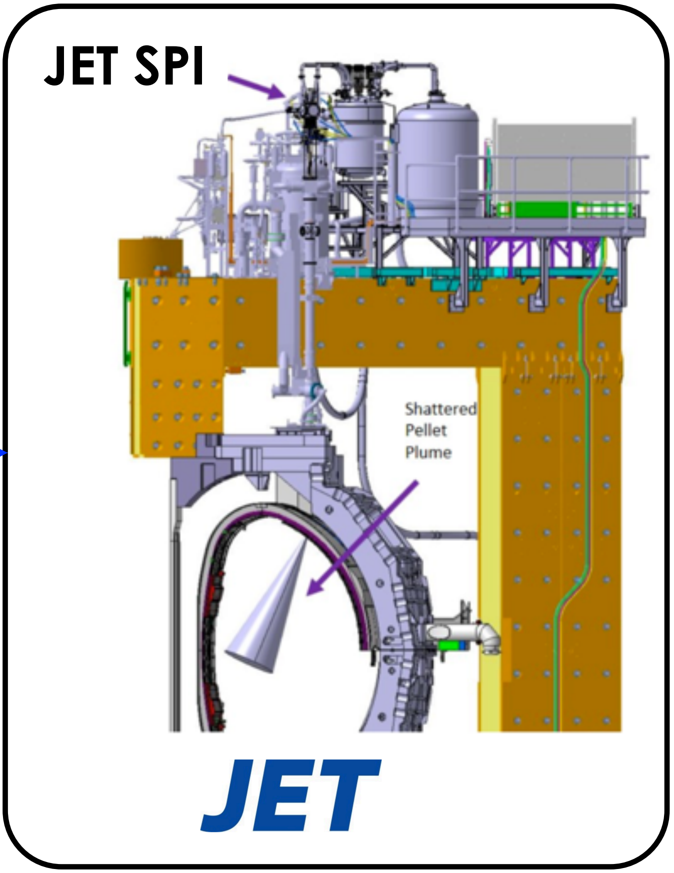
- **Neon SPI generates asymmetric TQ radiation, due to localized SPI particle source**
  - Peaking factor estimates from DIII-D are close to ITER surface melt limits

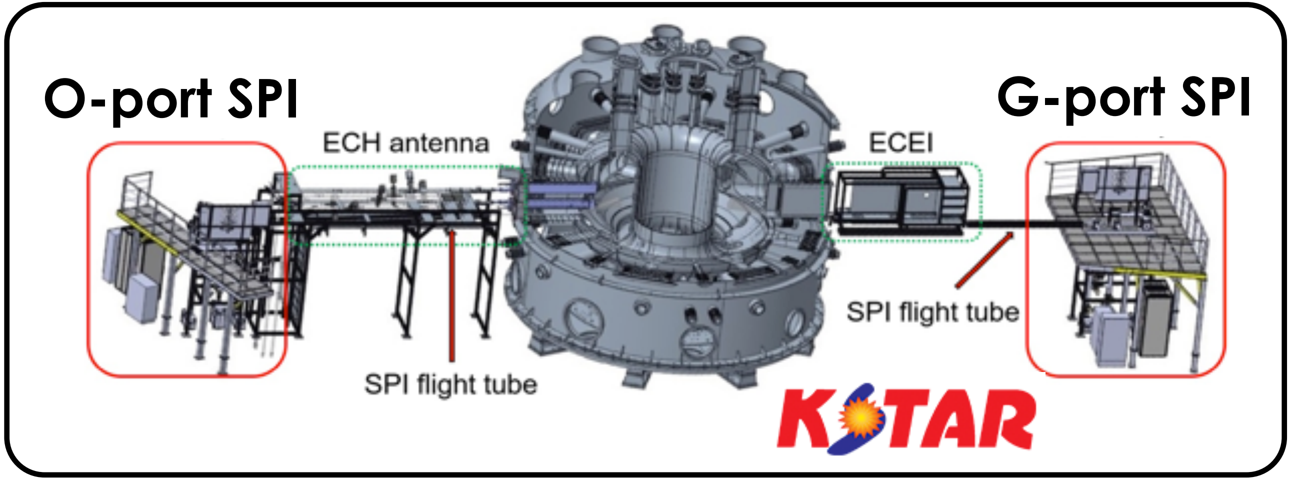
- **Deuterium SPI dynamics driven by MHD growth**
  - Data from DIII-D, JET, and KSTAR support this picture

SPI modeling developed at DIII-D has now been tested on KSTAR and JET data



Predictive KPRAD Modeling



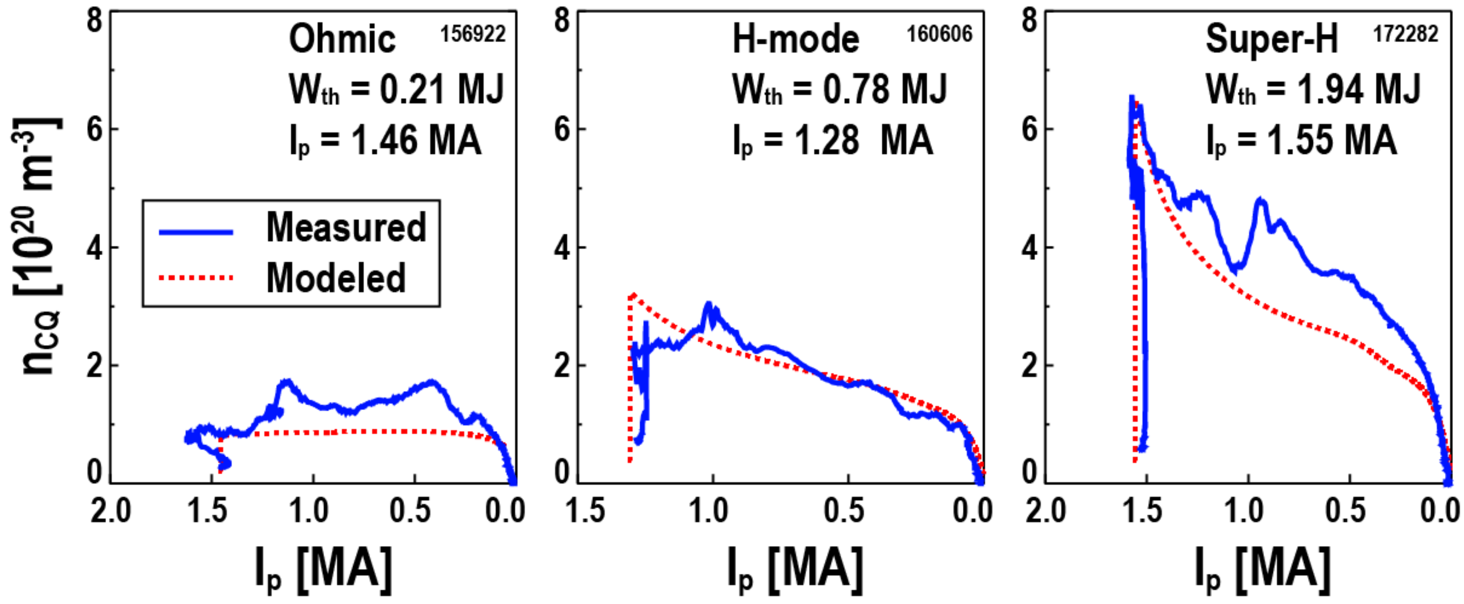


See also:

- EX-5/1220 (S. Jachmich)
- EX-5/831 (J. Kim)

Global energy balance drives disruption dynamics during neon SPI

- **Predictable from 0D KPRAD[1,2] simulations with SPI ablation model[3], which tracks:**
  - Species-dependent, shielding-limited ablation of SPI plume
  - Main-ion and impurity ionization, recombination, and radiation
  - Ohmic heating
  - Inductive coupling to wall currents



- **Simulations do NOT include MHD or particle transport effects**
- **Particle assimilation determined instead by global energy balance**

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[1] D. Whyte et al. J. Nucl. Mater. **313** (2003) 1239

[2] E. Hollmann et al. Contrib. Plasma Phys. **48** (2008) 260

[3] P. Parks, TSDW (2017) Princeton, NJ

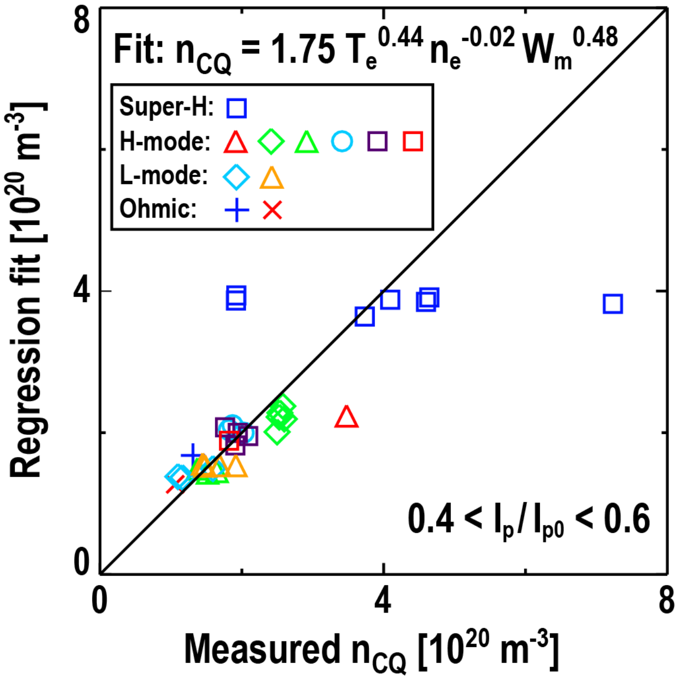
Empirical scalings for CQ density are also consistent with global energy balance being the dominant physics

- **For given pellet size/composition, CQ densities are predictable from only globally averaged parameters**

$$\underbrace{\bar{n}_{\mathrm{CQ}}}_{\text{CQ density}} = \underbrace{C \cdot T_{\mathrm{e}}^{\alpha_T} \cdot \bar{n}_{\mathrm{e}}^{\alpha_n} \cdot W_{\mathrm{m}}^{\alpha_{\mathrm{m}}}}_{\text{Pre-SPI plasma parameters}}$$

- **Regression fit from large DIII-D database**
  - 0.8 MA ≤ I_p ≤ 1.6 MA
  - 0.1 MJ ≤ W_{th} ≤ 2.0 MJ

DIII-D SPI database, with 7 mm Ne pellet



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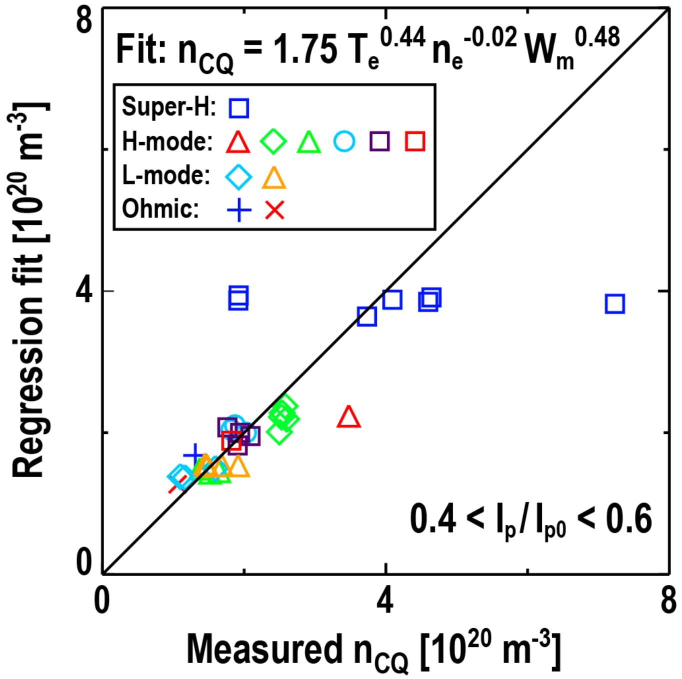
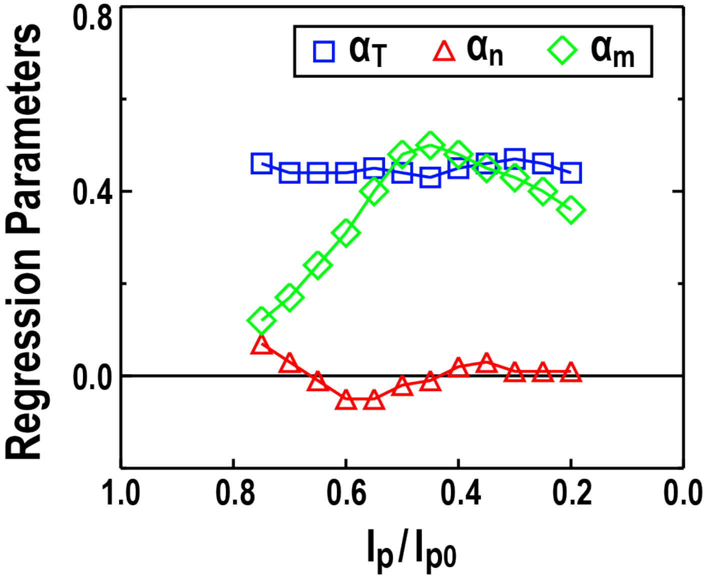
- **Regression fit from large DIII-D database**
  - 0.8 MA ≤ I_p ≤ 1.6 MA
  - 0.1 MJ ≤ W_{th} ≤ 2.0 MJ

- **Early assimilation depends primarily on electron temperature**

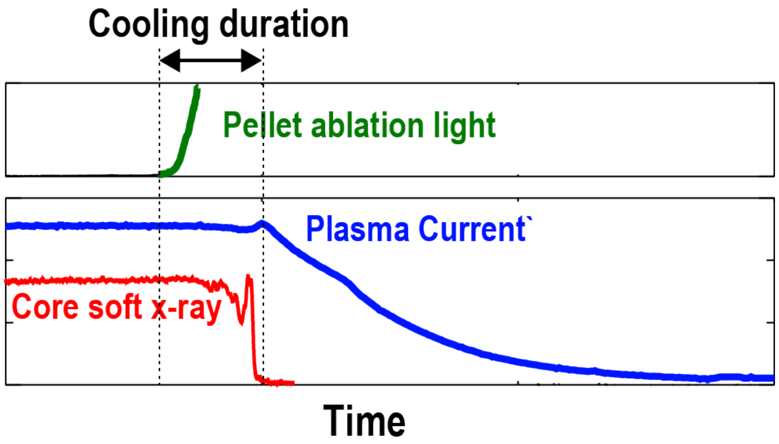
- **Ohmic dissipation of W_{mag} sustains ionization later in CQ**

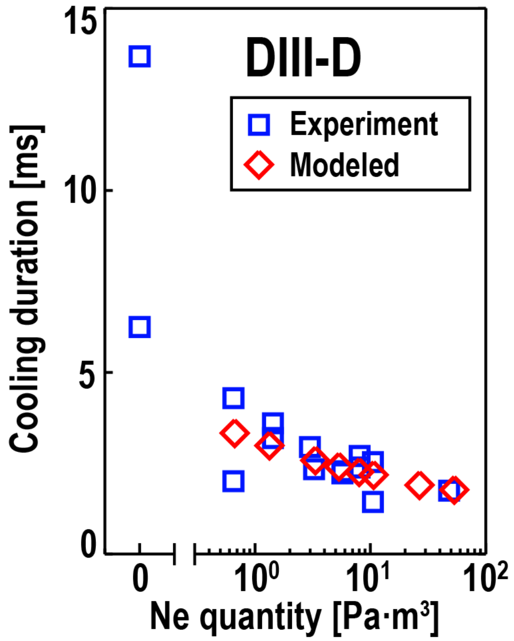
DIII-D SPI database, with 7 mm Ne pellet

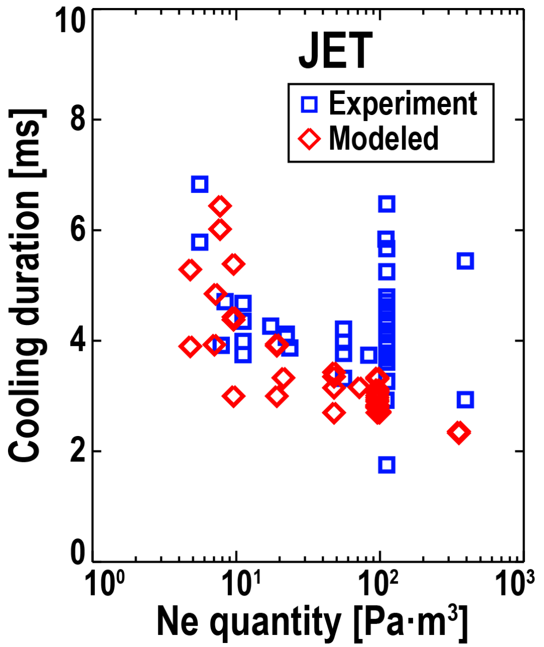




Cooling duration trends are matched by KPRAD, governed primarily by injected neon quantity

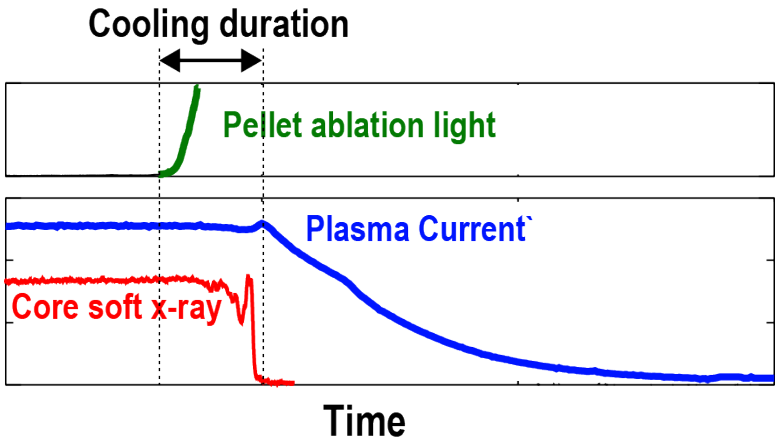






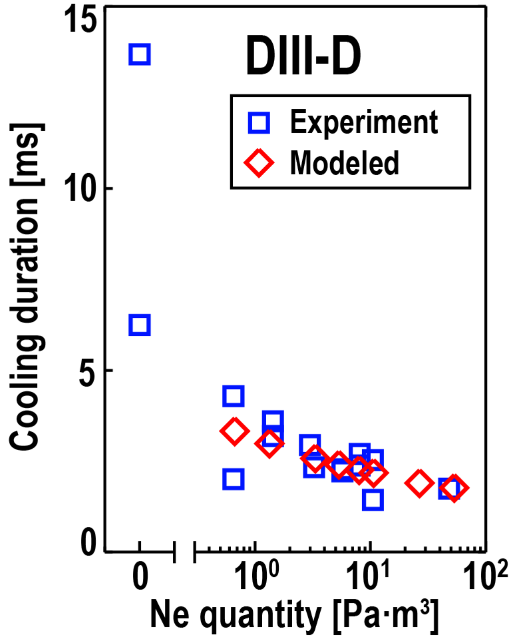
- **Cooling duration gives upper bound on time for injection to contribute to TQ mitigation**

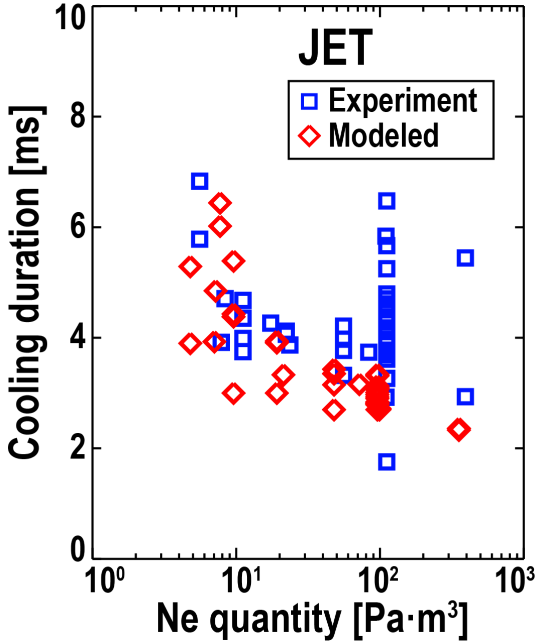
Cooling duration trends are matched by KPRAD, governed primarily by injected neon quantity

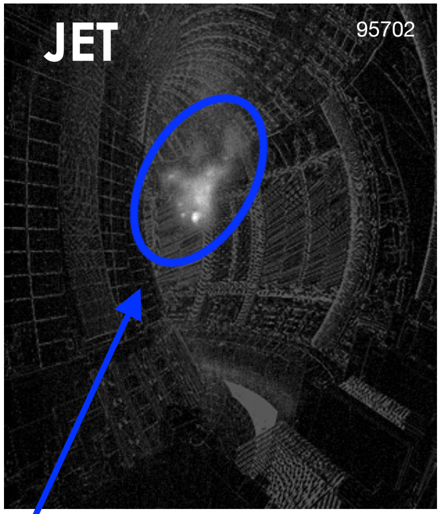


- **Cooling duration gives upper bound on time for injection to contribute to TQ mitigation**

- **Particles unablated by this time (end of TQ) travel ballistically through CQ plasma with minimal assimilation**
  - Consistent with fast camera images



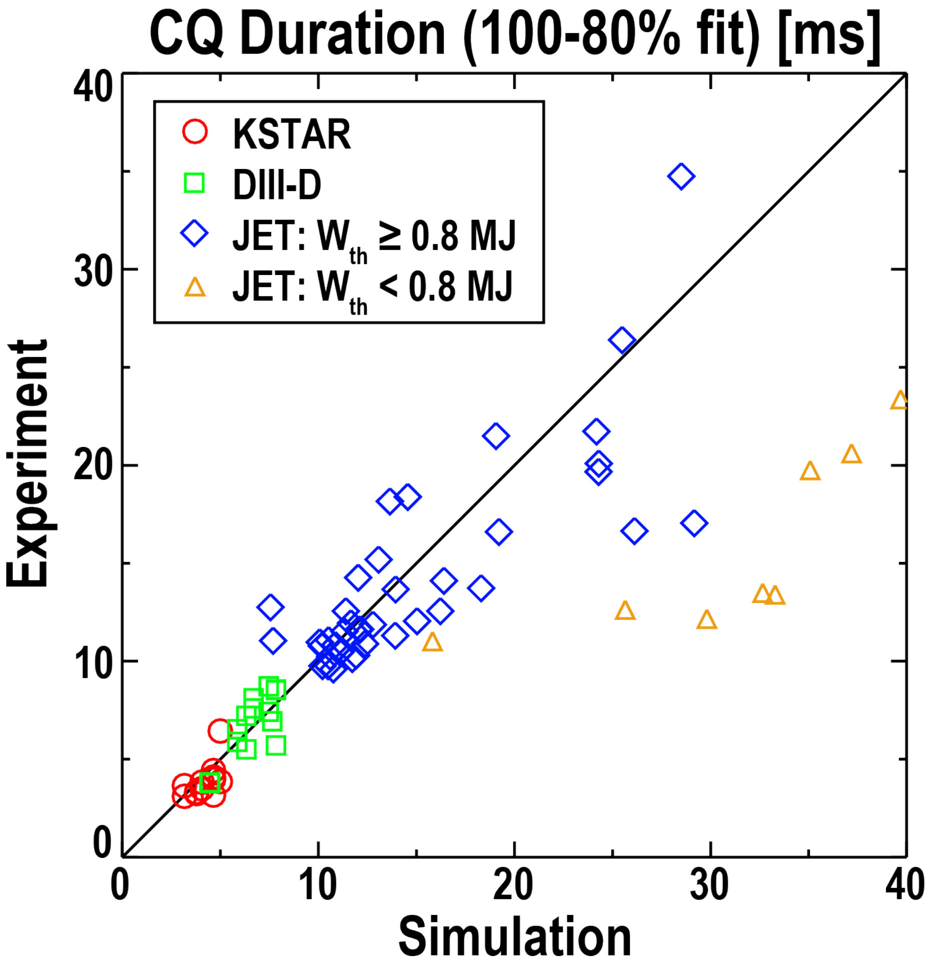




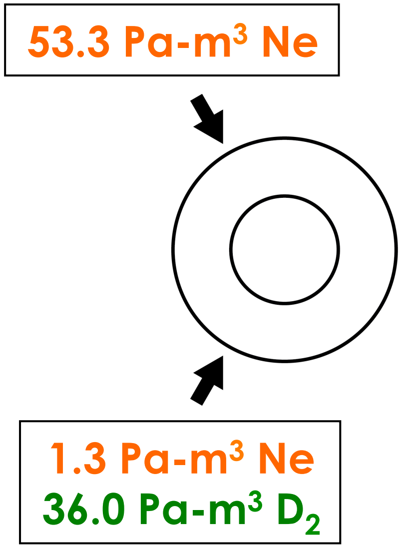
Unassimilated fragments

CQ rates are quantitatively predictable, determined largely by neon assimilation and resulting post-TQ plasma resistivity

- **Model accurate except at lowest energy (W_{th} < 0.8 MJ)**
  - Difficult to accurately model ablation rates at low temperature
- **Model accounts for both plasma parameters and injection species mixture**
  - Predictive capability required for ITER DMS to determine appropriate injection quantities/species
- **Simulations are accurate across device size, giving confidence in projectability**

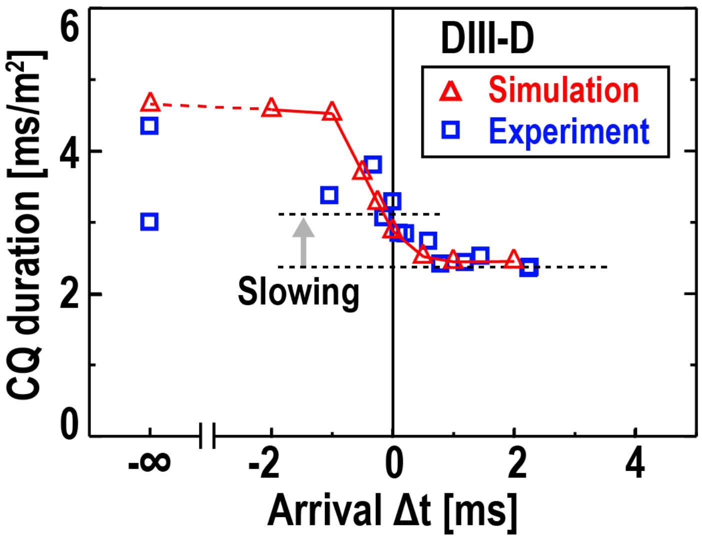


Dual-SPI performance matched by KPRAD, consistent with global energy balance being primary physics over 3D effects

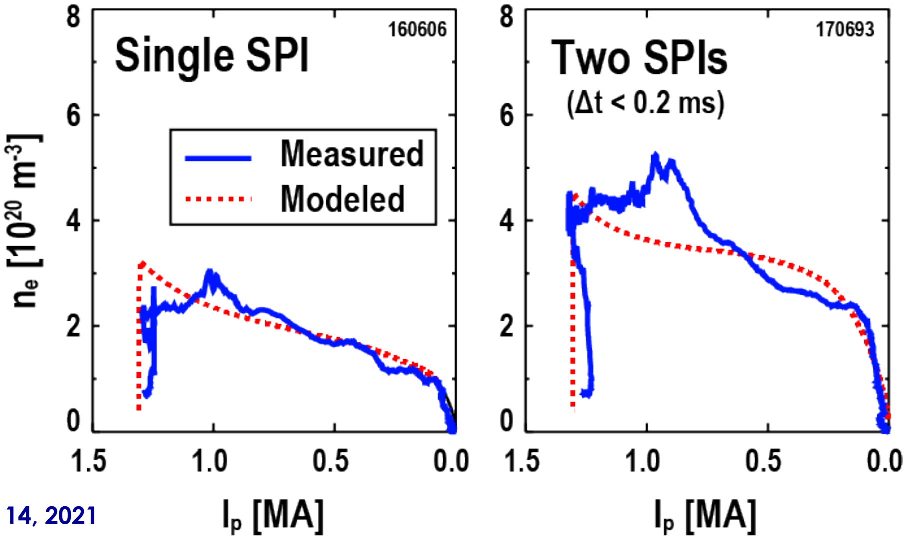


53.3 Pa-m^3 Ne

1.3 Pa-m^3 Ne
36.0 Pa-m^3 D_2



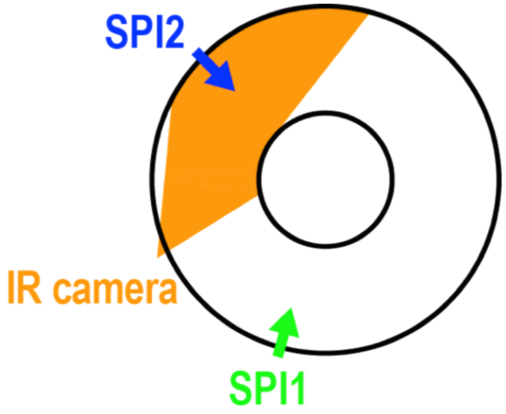
- **Synchronous pellets (Δt=0) result in less neon assimilation and a slower CQ**
- **0D simulations match experiment by accounting for additional deuterium**
  - Does not account for separate injection locations
- **Additional density rise from second SPI matched by KPRAD**

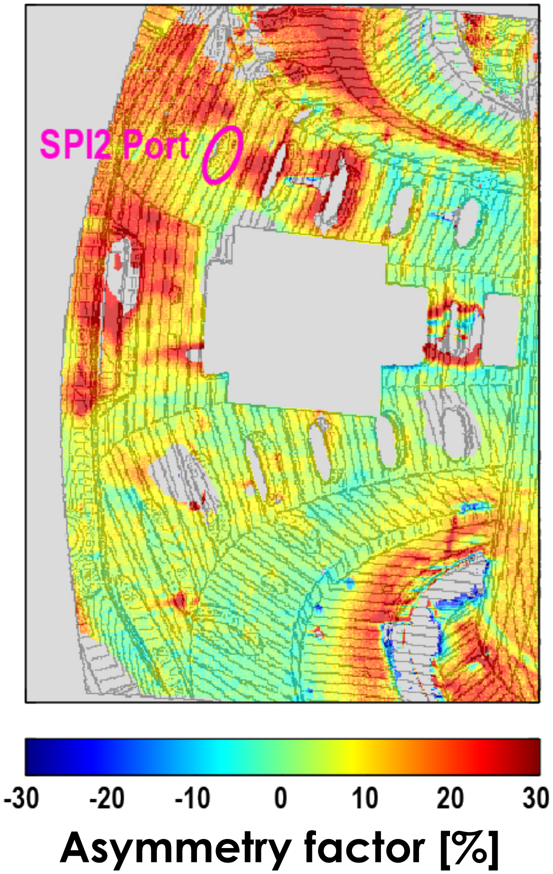


- **Other physics, such as MHD or localized particle sources, are primarily important for higher-order effects (such as asymmetries)**

TQ radiation asymmetry due to localized injection source is observed experimentally and in extended-MHD simulations

- **Asymmetries observed from comparing first-wall IR thermography for different SPI systems**
- **Radiation peak is broadly centered around SPI port**
  - Due to rapid localized injection, rather than MHD heat flux
- **Estimated TQ toroidal peaking factor = 1.9 +0.5/-0.3**
  - Consistent with DIII-D NIMROD simulations[1]
- **Close to ITER surface melt limit[2] (peaking factor ~ 2)**
  - Not yet known if multiple SPIs reduce peaking





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[1] C. Kim, et al., This conference

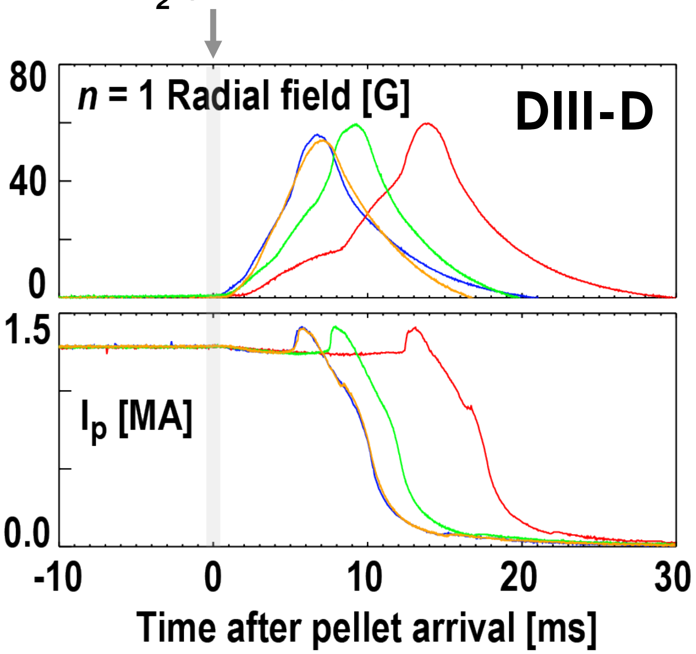
[2] M. Sugihara, et al., Nucl. Fusion **47** (2007) 337

MHD growth determines disruption timescales following deuterium SPI

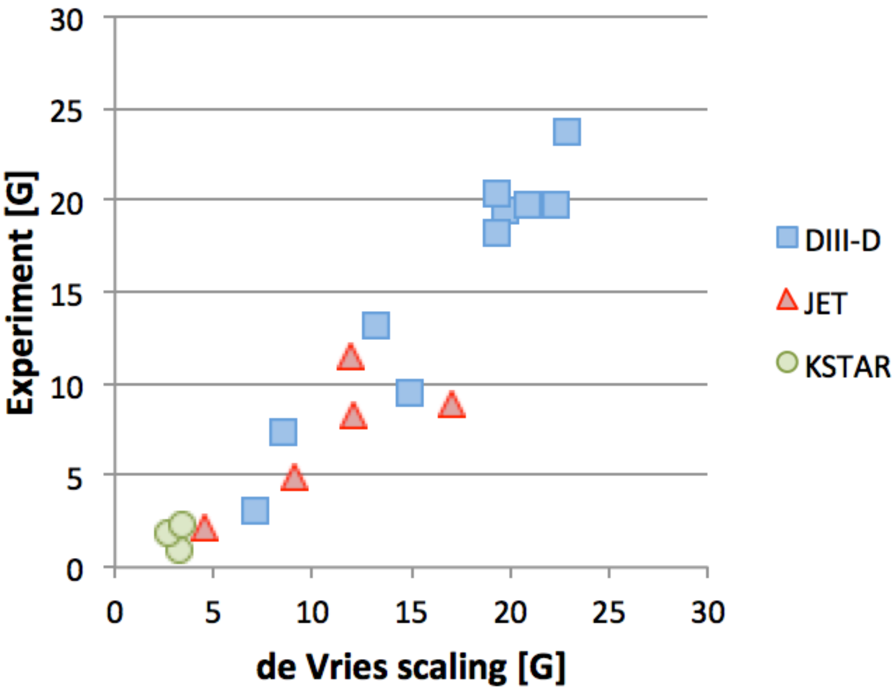
- **Deuterium SPI important for RE mitigation, by increasing collisional dissipation and decreasing hot-tail seed formation through dilution cooling**

- **Without neon impurity radiation, MHD growth becomes important process**

D_2 SPI Arrival



- **In all three devices, TQ occurs when *n*=1 MHD amplitude reaches critical value[1]**



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[1] P.C. de Vries, et al., Nucl. Fusion **56** (2016) 026007

A Novel Path to Runaway Electron Mitigation via Deuterium Injection and Current-Driven Kink Instability

Produced by:

C. Paz-Soldan[1]

On behalf of:

C. Reux[2], Y.Q. Liu[3], N. Eidietis[3], S. Silburn[4], K. Aleynikova[5], P. Aleynikov[5], S. Sridhar[2], E. Joffrin[2], A. Lvovskiy[3], L. Bardoczi[3], X. Du[3], S. Gerasimov[4], F. Rimini[4], G. Szepesi[4], V. Bandaru[5], M. Hoelzl[5], G. Papp[5], G. Pautasso[5], L. Baylor[6], D. Del-Castillo Negrete[6], D. Spong[6], E. Hollmann[7], Z. Popovic[7], I. Bykov[7], C. Liu[8], C. Zhao[8], S. Jardin[8], S. Jachmich[9], M. Lehnen[9], O. Ficker[10], E. Macusova[10], D. Carnevale[11], C. Sommariva[12], A. Manzanares[13], the DIII-D Team and JET Contributors*

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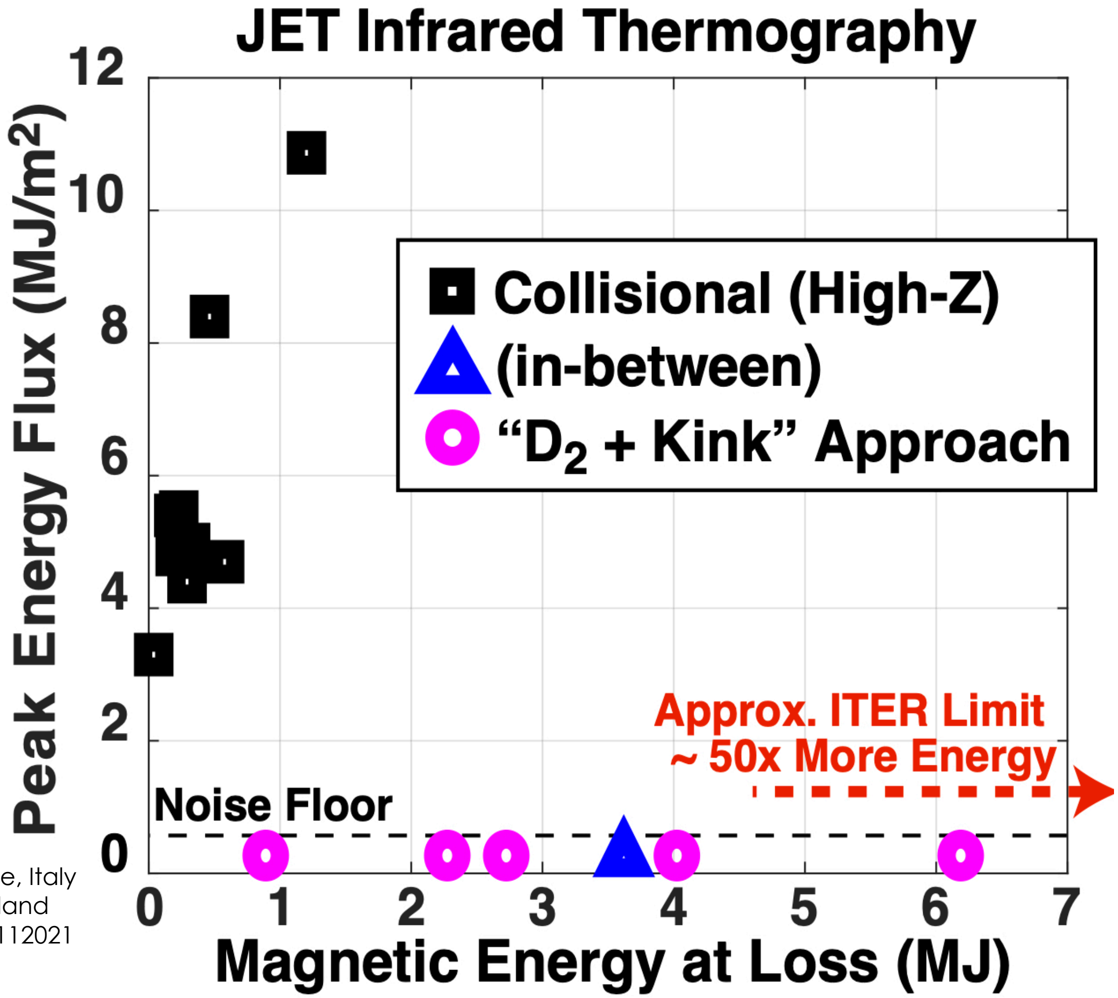
[13]CIEMAT, Madrid, Spain, *See the author list of E. Joffrin et al. 2019 Nucl. Fusion 59 112021



Presented at:

IAEA-FEC Conference (Remote)
May 14th 2021

Contrasting Approaches Highlights Key Differences

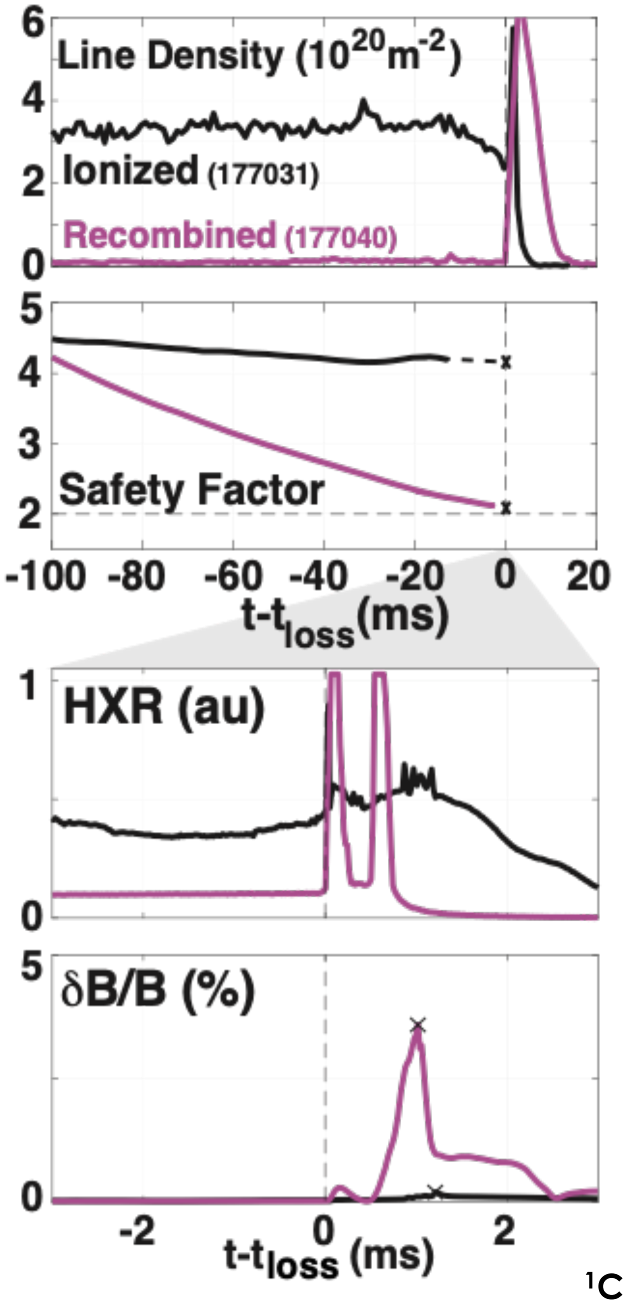
Conventional Approach:

- **Inject High-Z (Ar/Ne)**
- **Collisionally dissipate REs**

New Approach:[1,2]

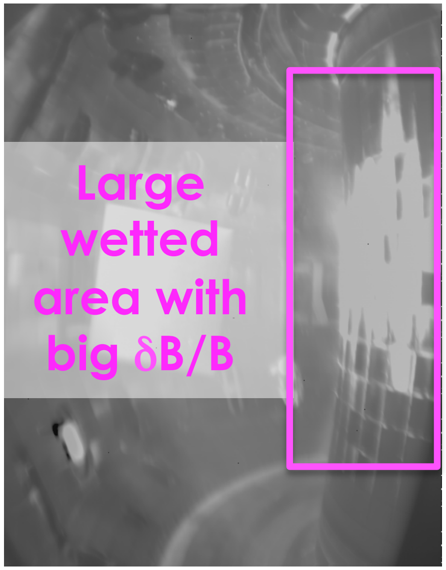
- **Inject D_2 → collisionless**
  - via high-Z expulsion and bulk recombination[3]
- **Access bigger & faster MHD kink instabilities**
- **~100% REs instantaneously dumped to the first wall**

Only New Approach Avoids First Wall Heating



Localized losses with small δB/B

Conventional: q ~ 4



Large wetted area with big δB/B

D2 + Kink: q ~ 2

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[1] C. Reux et al, Phys. Rev. Lett 2021

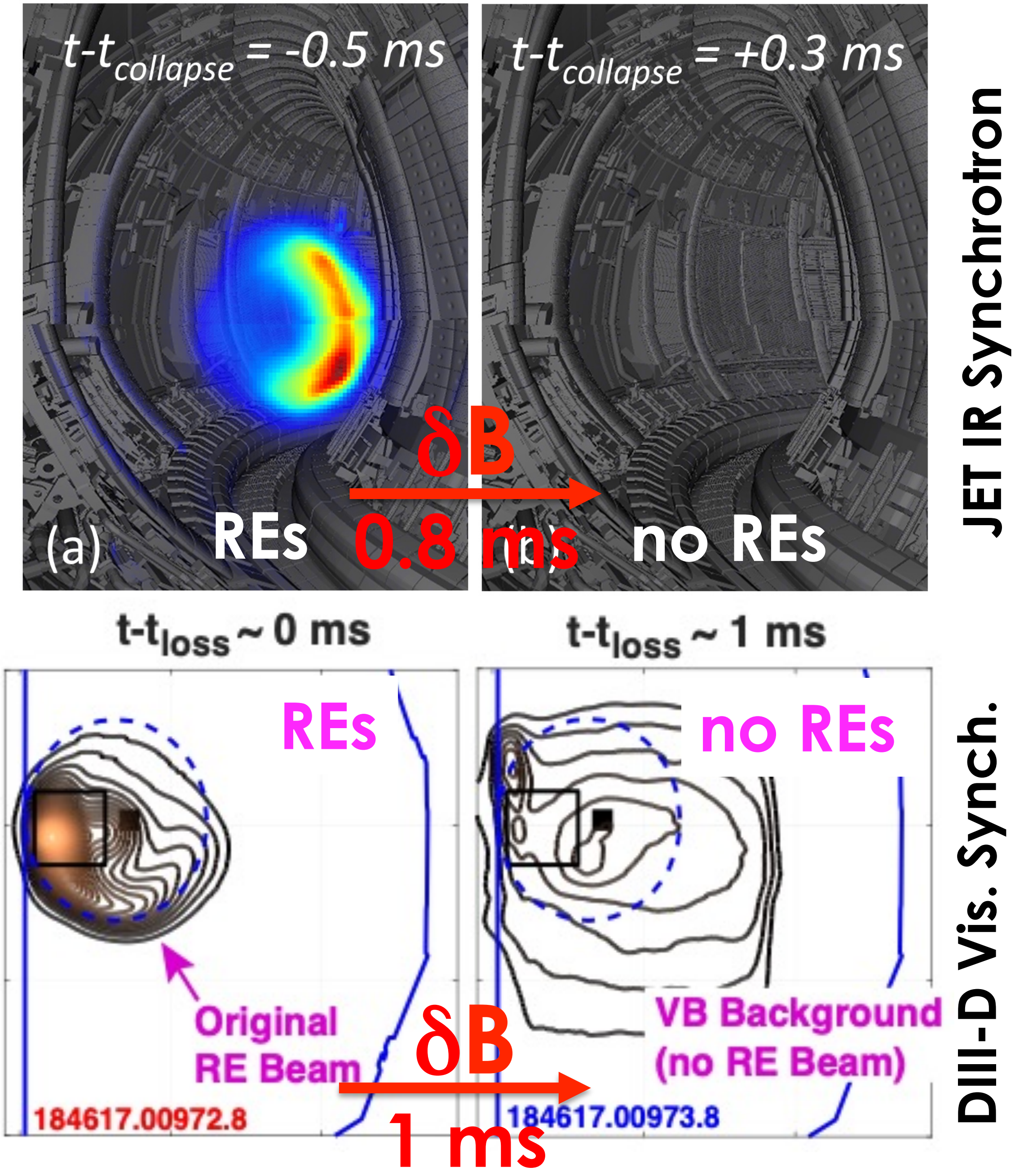
[2] C. Paz-Soldan et al, Plas. Phys. Contrl. Fus 2019

[3] E. Hollmann et al, Phys. Plasma 2020

Synchrotron Emission Confirms Full RE Termination on Sub-Millisecond Timescales

- **After D_2 injection: REs can persist very long time**
  - Up to 5 seconds in DIII-D

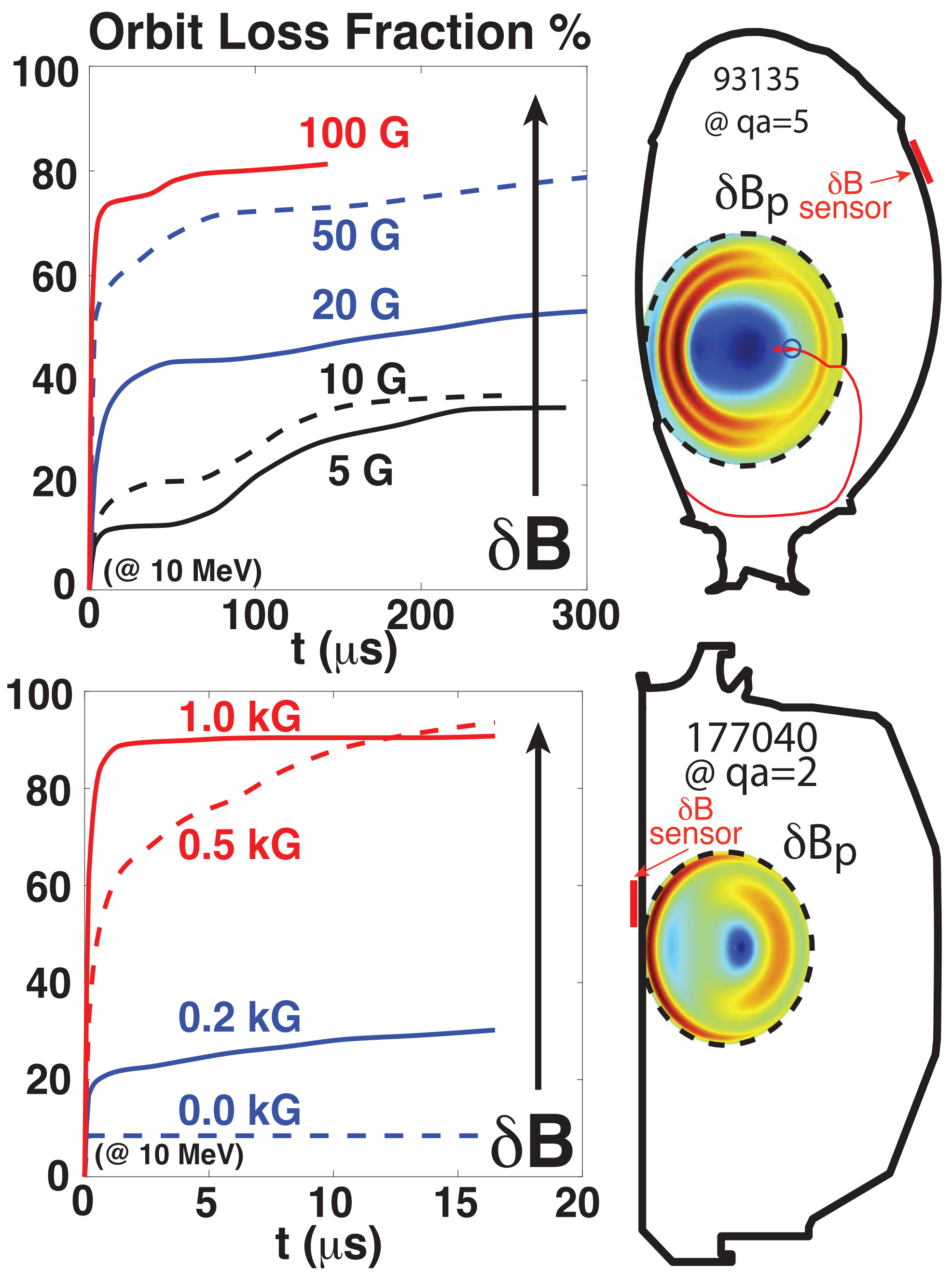
- **After crossing MHD instability boundary REs vanish in < 1 ms**



MHD Model + Orbit Following w/ Observed δB/B Levels Confirms Nearly all RE Orbits are Lost to the First Wall

- **RE orbits followed in linear MHD eigenmode structure scaled to experimental δB**

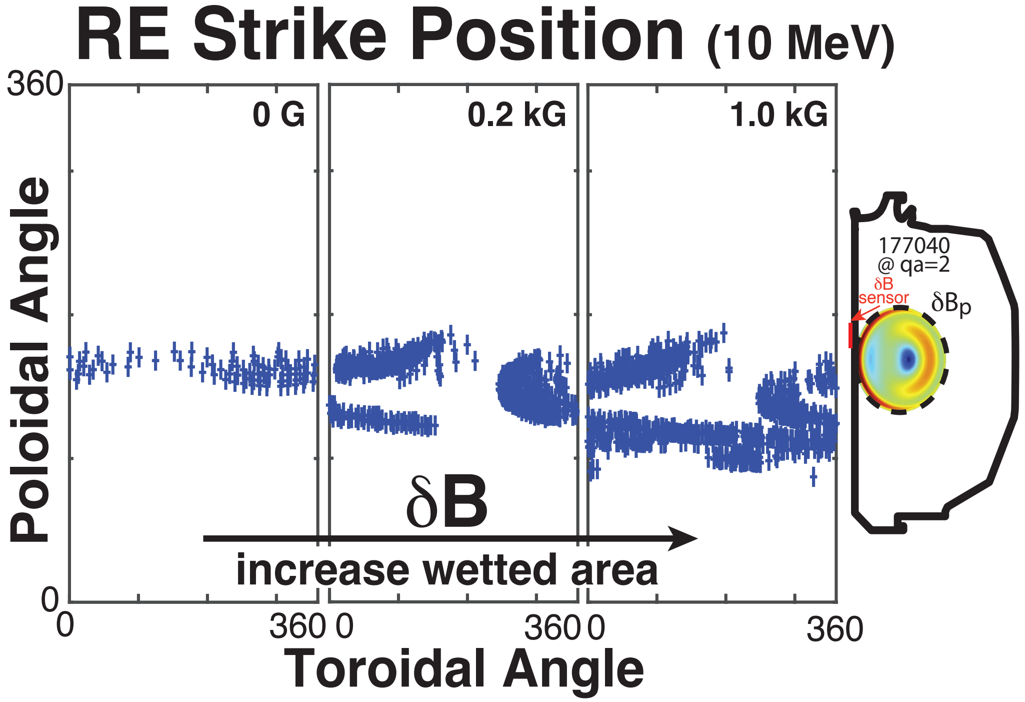
- **δB/B at experimentally relevant values (~ 5%) causes most orbits to be lost to the first wall**



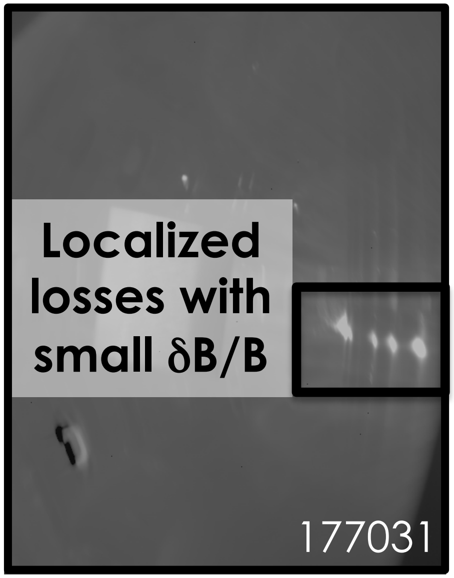
MHD Model + Orbit Following w/ Observed δB/B Levels Confirms Nearly all RE Orbits are Lost to the First Wall

- **RE orbits followed in linear MHD eigenmode structure scaled to experimental δB**
- **δB/B at experimentally relevant values (~ 5%) causes most orbits to be lost to the first wall**
- **RE kinetic energy disperses into a large wetted area**
  - Reduced peak heat flux

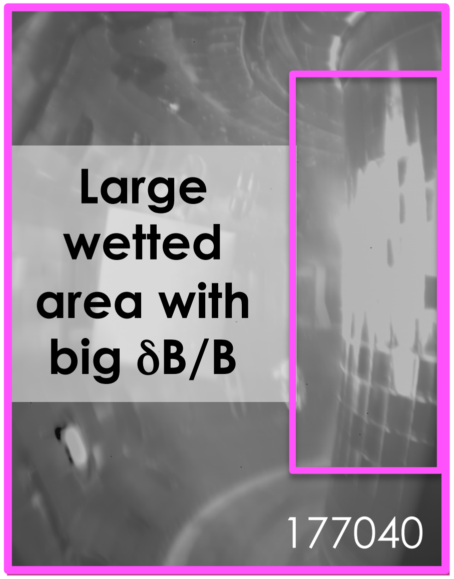
Improved Scenario for Kinetic Energy Handling


RE Strike Position (10 MeV)

small δB

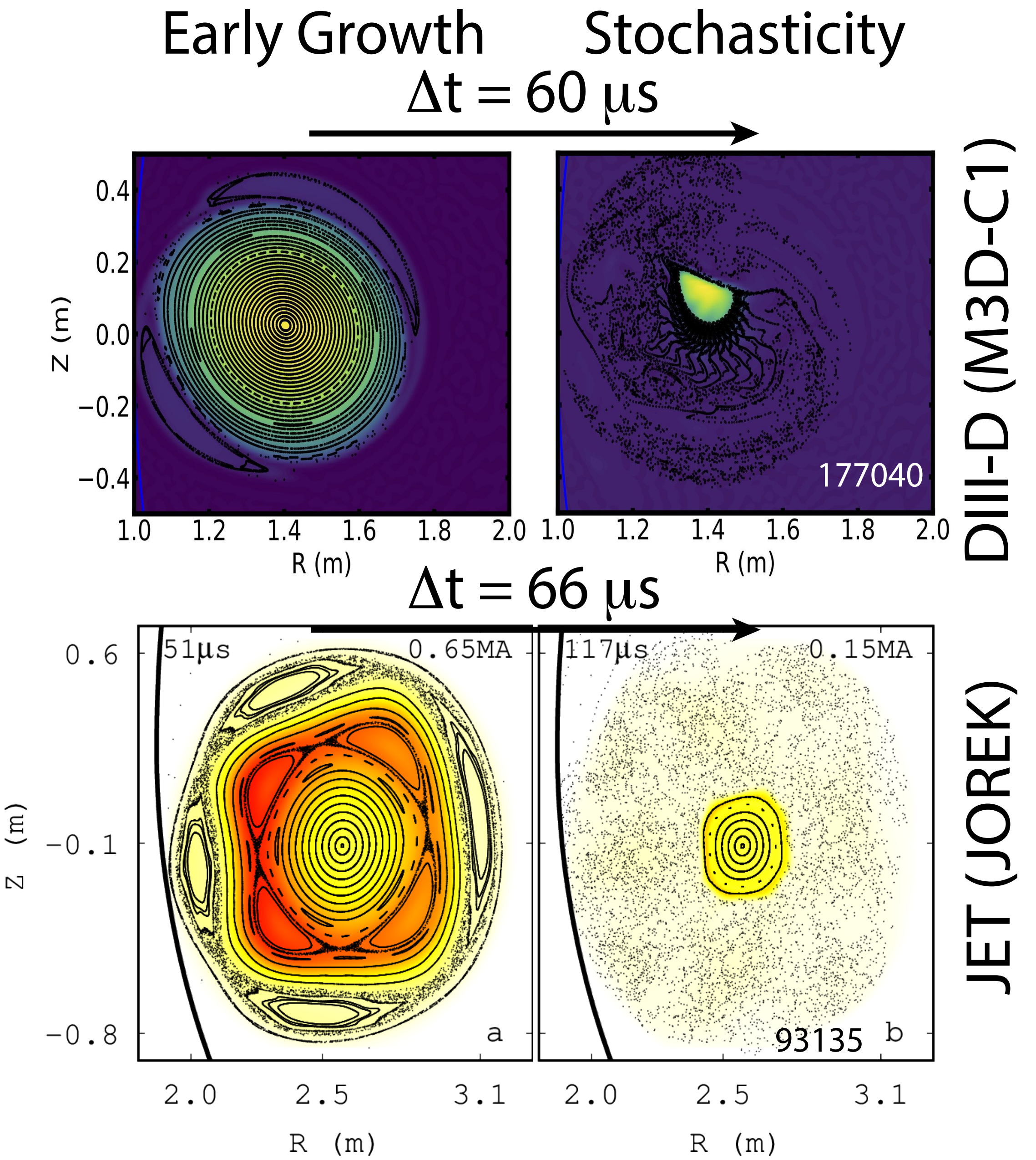

Localized losses with small δB/B

large δB


Large wetted area with big δB/B

Extended MHD Modeling Reproduces Total Loss

- **M3D-C1 and JOREK with RE fluid model deployed**
- **Near-total stochasticity found in both simulations**

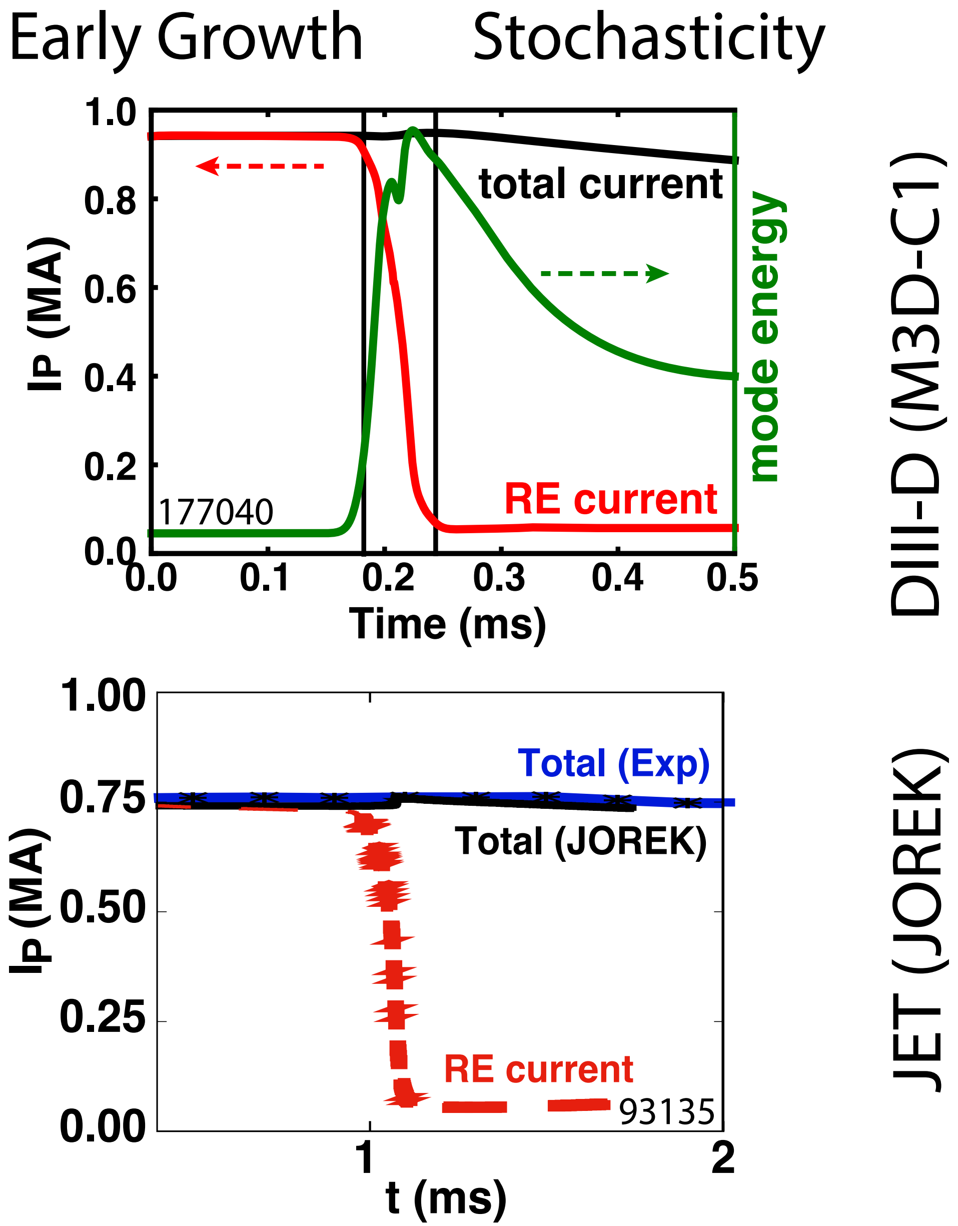


C. Liu et al, Phys. Plasmas (in preparation, 2021)
V. Bandaru et al, Plas. Phys. Contl Fus. 2021

Extended MHD Modeling Reproduces Total Loss Prompt RE → Ohmic Current Transfer in DIII-D and JET

- **M3D-C1 and JOREK with RE fluid model deployed**
- **Near-total stochasticity found in both simulations**
- **Prompt loss of REs drives current transfer to the bulk**
- **Dissipation of magnetic energy into line radiation**
  - … Not back into RE energy

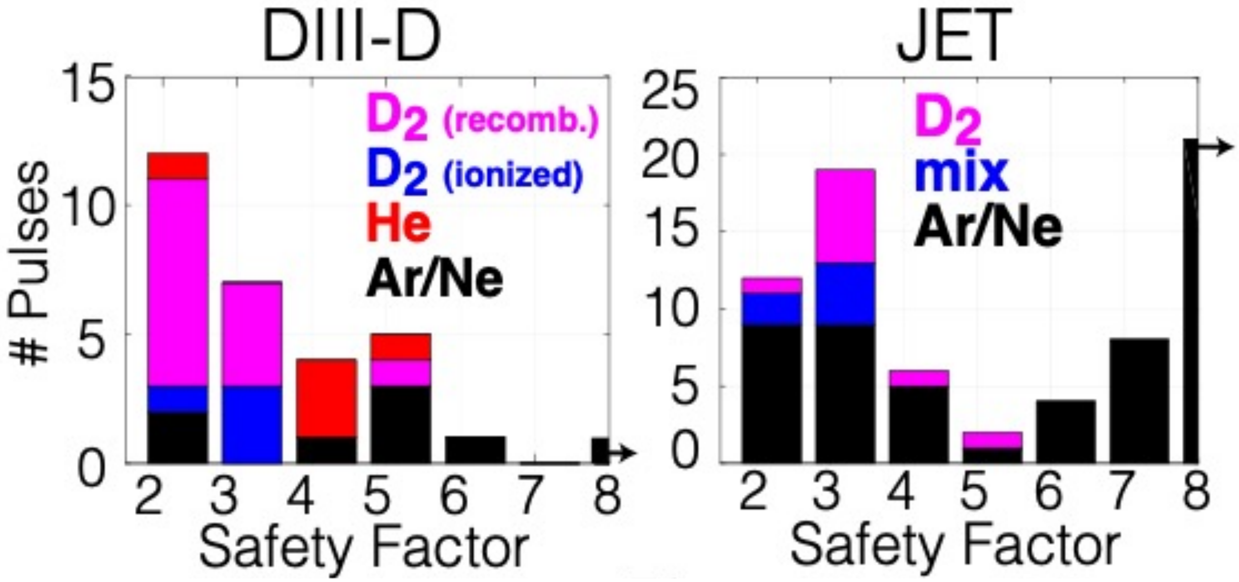
Best-Case Scenario for Magnetic Energy Handling



C. Liu et al, Phys. Plasmas (in preparation, 2021)
V. Bandaru et al, Plas. Phys. Contl Fus. 2021

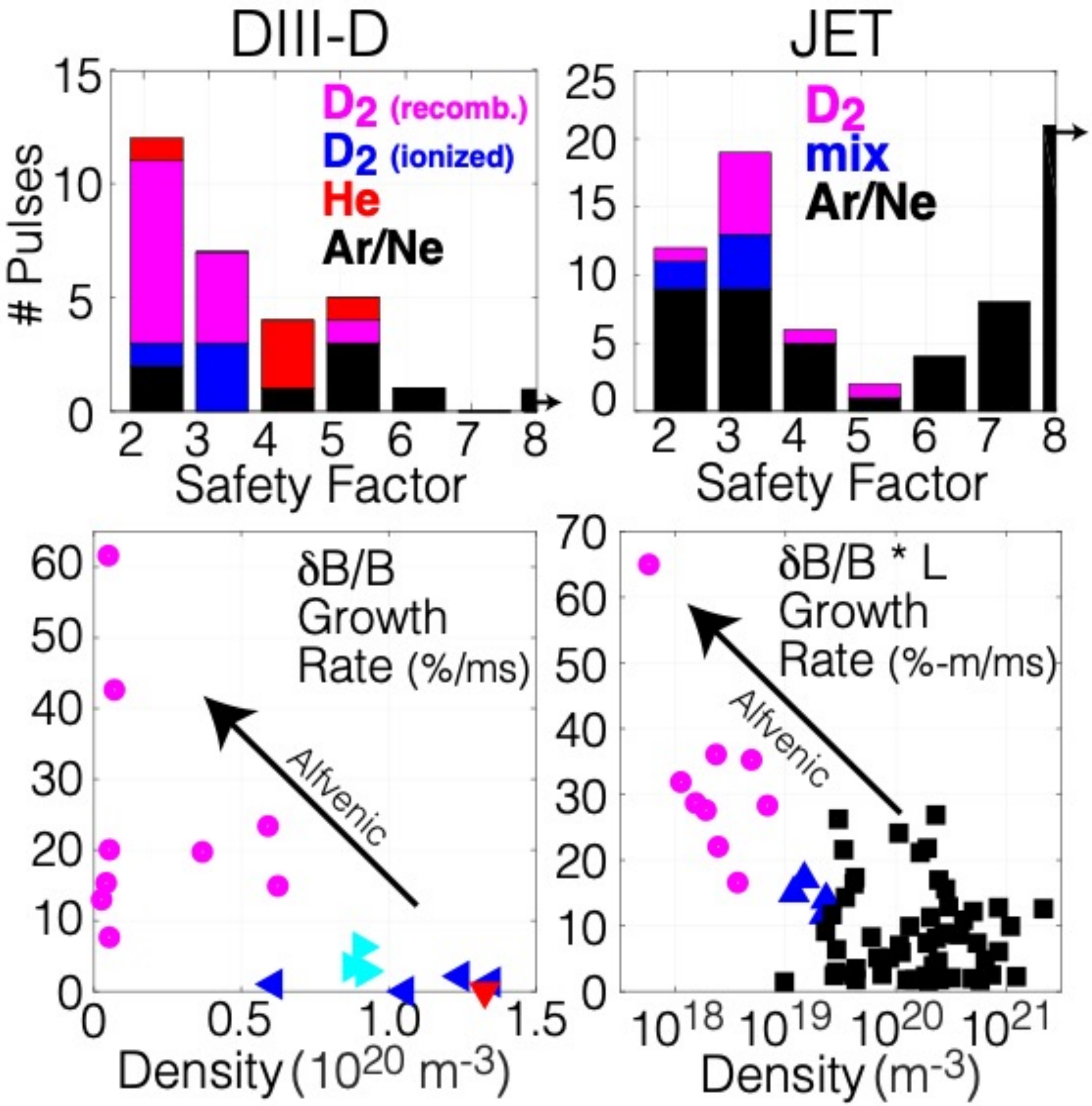
D_2 Injection: 1) Facilitates Low Safety Factor Access 2) Accelerates Alfvenic Instability by Reducing Density

- **D_2 cases tend to evolve to lower safety factor (more unstable)**
  - … not guaranteed
  - … nor essential



D_2 Injection: 1) Facilitates Low Safety Factor Access 2) Accelerates Alfvenic Instability by Reducing Density

- **D_2 cases tend to evolve to lower safety factor (more unstable)**
  - … not guaranteed
  - … nor essential
- **Key D_2 affect: bulk recombination**
  - Decreases density
  - Shortens Alfven time
  - ***Accelerates MHD***



New Approach Deployment in ITER DMS Will Likely Involve Multiple Loss Events (& Pellets?)

- **ITER's RE beam expected to access low safety factor**
  - Kink should be accessible
- **ITER's avalanche gain (~ 10^{20}) still an issue**
  - "Remnant" REs will re-avalanche
- ***Multiple, but benign, loss events are foreseen***
- **Goal: keep recombination & promote large $\delta B/B$**

Validation Needed
@ High RE Current / Gain
… in ITER Pre-FPO Phase

Candidate ITER DMS Scheme