Runaway electron beam dynamics in DIII-D: energy distribution, current profile, and RE-driven instabilities

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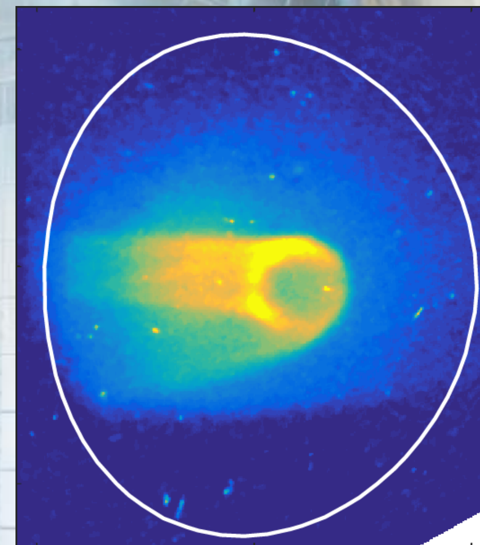

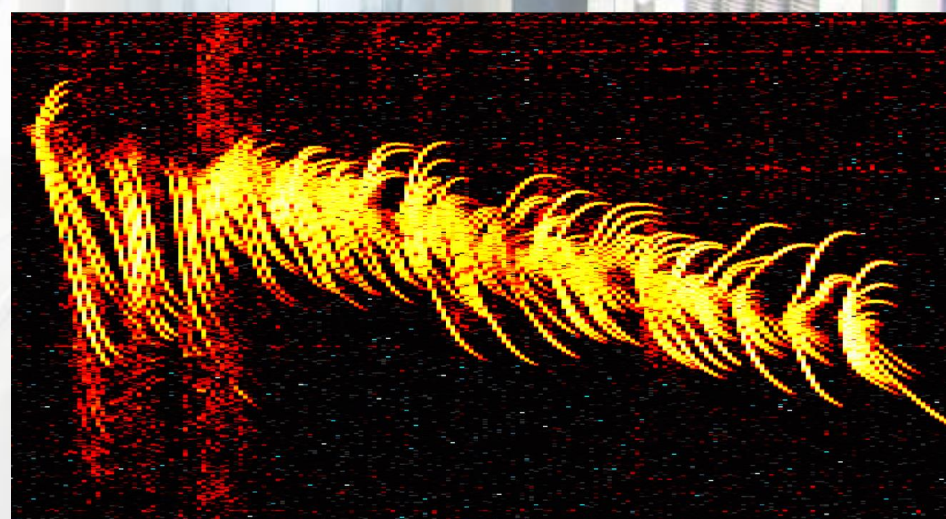

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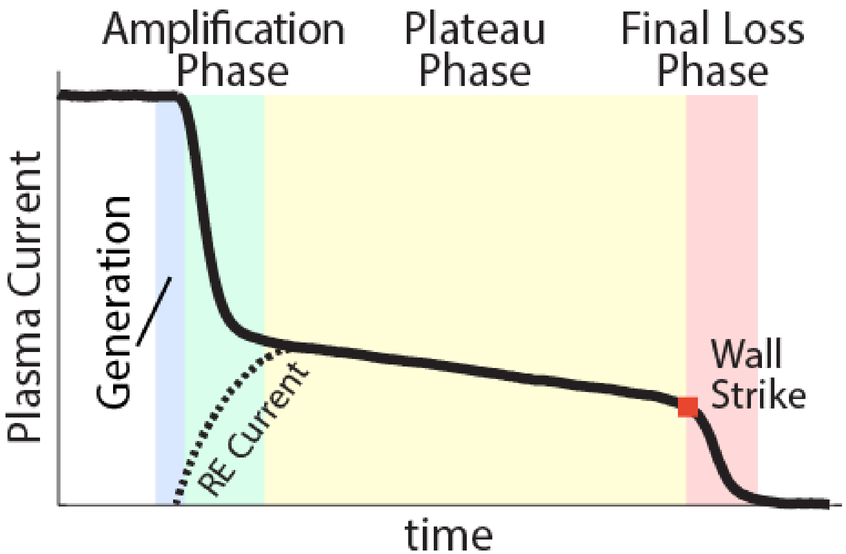
Runaway electrons (REs) produced during disruptions can damage tokamak wall



Formation and loss of RE beam

- **Localized impact of high-energy RE beam can damage tokamak wall**
- **ITER mitigation strategy if disruption cannot be avoided [1]:**
  - Massive impurity injection to dissipate thermal and magnetic energy and prevent formation of REs
  - This approach has yet to be proven
- **Studying of post-disruption runaway plasma remains important**
- **This talk:**
  - **Equilibria of RE beam in DIII-D**
  - **RE-driven instabilities in DIII-D**

[1] Breizman *et al* NF 2019

Outline

New physics of RE beam:

- Energy distribution function
- Current density profile
- Internal MHD instability
- External kink instability
- Frequency chirping instabilities

Outline

New physics of RE beam:

- **Energy distribution function**
- Current density profile
- Internal MHD instability
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Motivation

Measurements of f(E) provides information on:

- maximum energy of REs
- major current carriers
- balance between accelerating and dissipating factors
- possibility of RE-driven instabilities

Energy distribution function of RE beam is generally poorly diagnosed

- **How to predict RE physics in ITER?**
  - Measure REs in existing tokamaks and verify RE models
- **Easy to say, but difficult to do:**
  - Energy range from 0.1 to 30 MeV
  - Current from 0.1 to 1 MA

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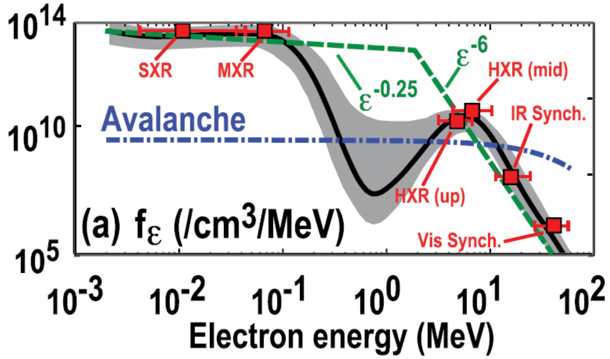
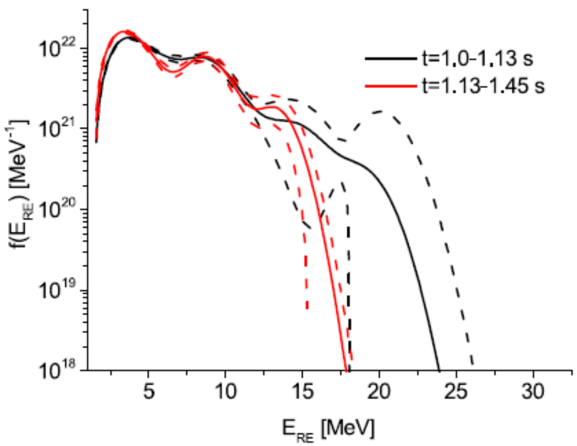


Hollmann2015 (DIII-D): no data in range 0.1−10 MeV



Nocente2018 (ASDEX-U): no spatial measurements

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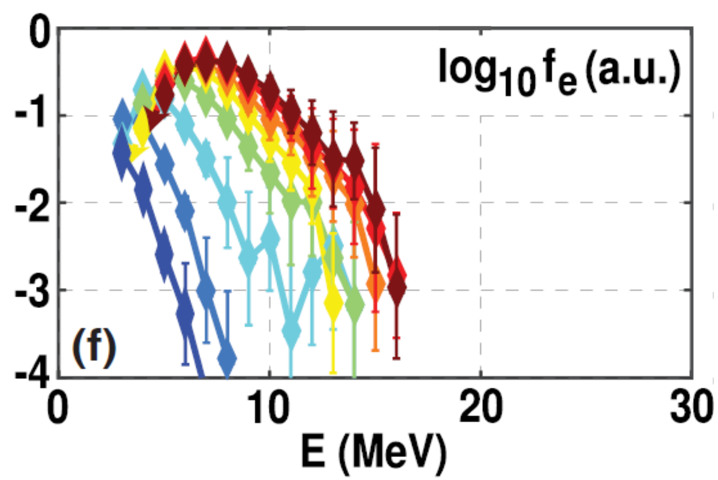
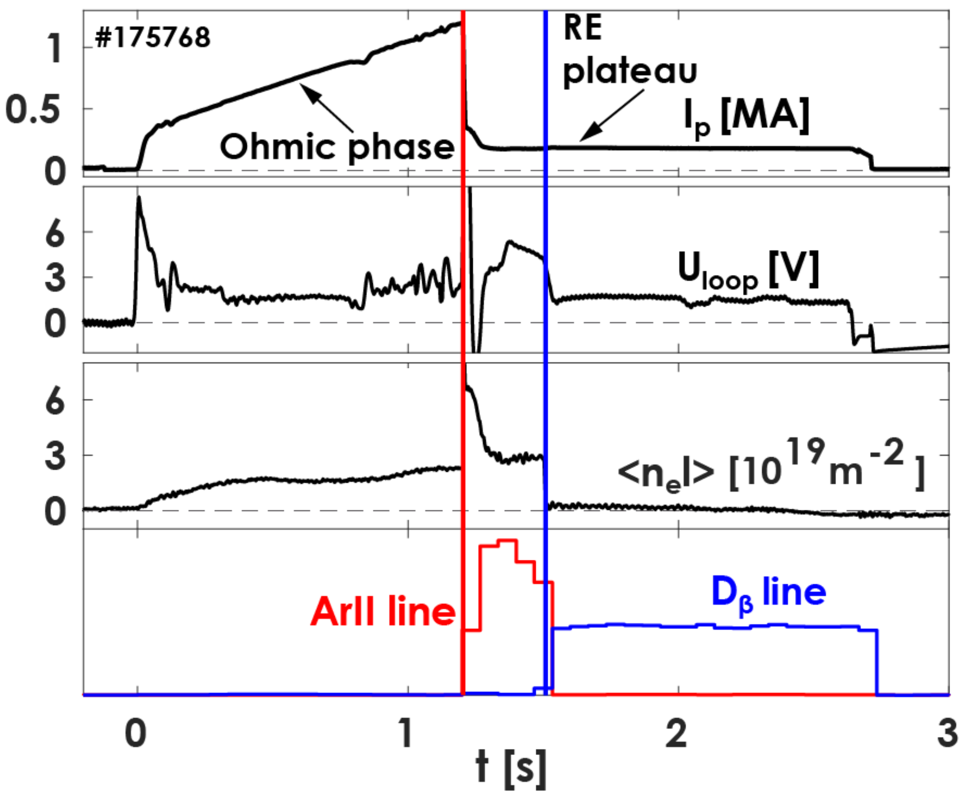


Paz-Soldan2017 (DIII-D): Ohmic plasma, effects specific to RE plateau can be missed

Energy distribution function of RE beam is generally poorly diagnosed. But we can do it now on DIII-D



- RE energy distribution can be constrained via hard X-ray (HXR) bremsstrahlung measurements and using recent advances in:
  - New scenario: low-current RE beam in low-density plasma

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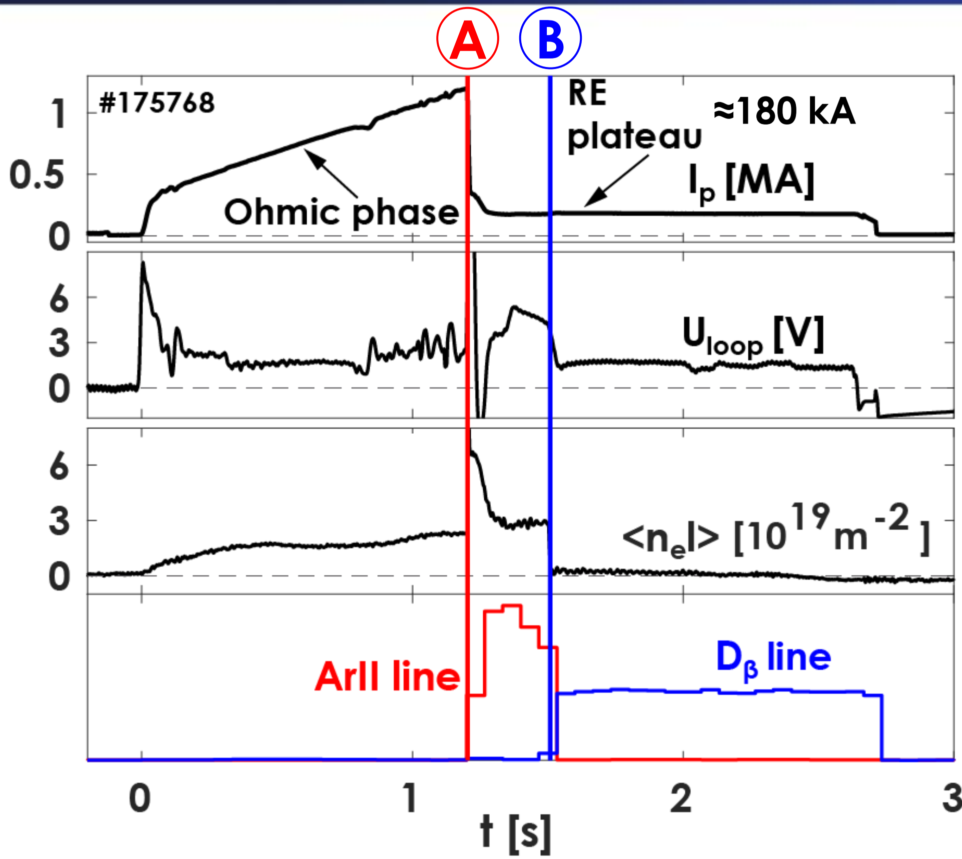

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  - **New scenario: low-current RE beam in low-density plasma**

⇒ Low, measureable HXR flux ($\propto nZ^2$)
⇒ Long-lasting RE plateau
⇒ Large variability of applied voltage

A Injection of small Ar pellet → disruption and formation of RE beam

B D_2 massive gas injection → purge of Ar from RE beam

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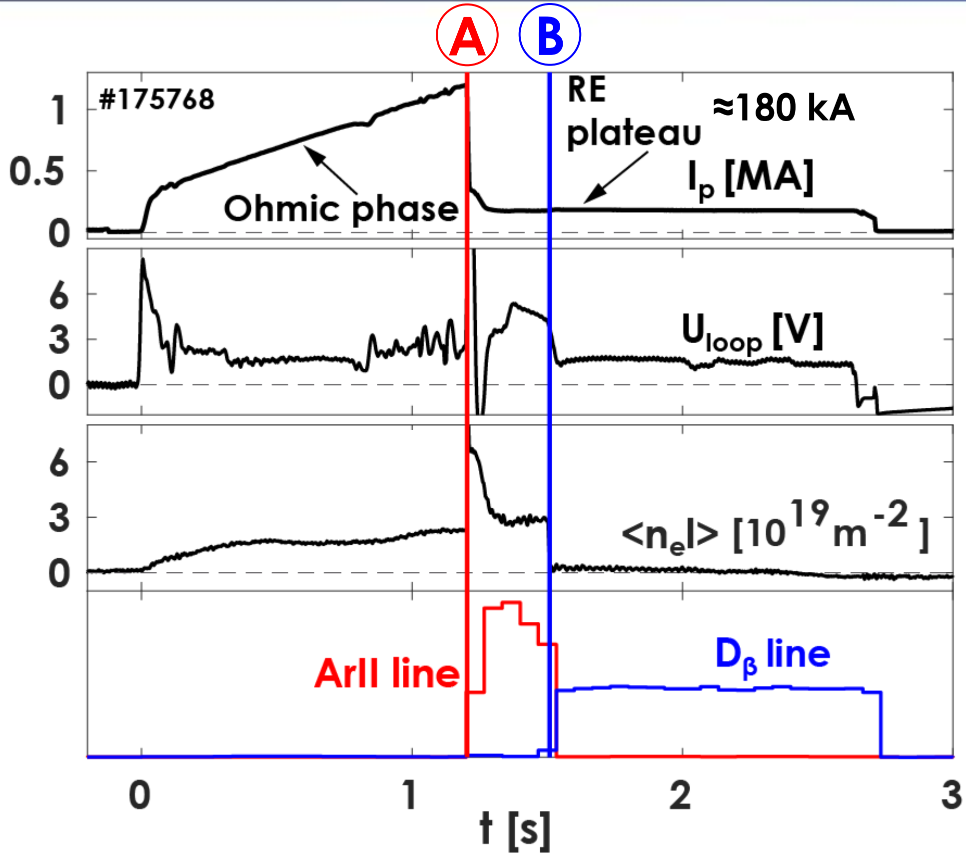

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  – **Gamma Ray Imager upgrade: ultrafast gamma detector [1,2]**

  ⇒ Time resolution increased by 1000x
  ⇒ MHz counting capabilities

[1] Dal Molin *et al* RSI 2018
[2] Nocente *et al* RSI 2018

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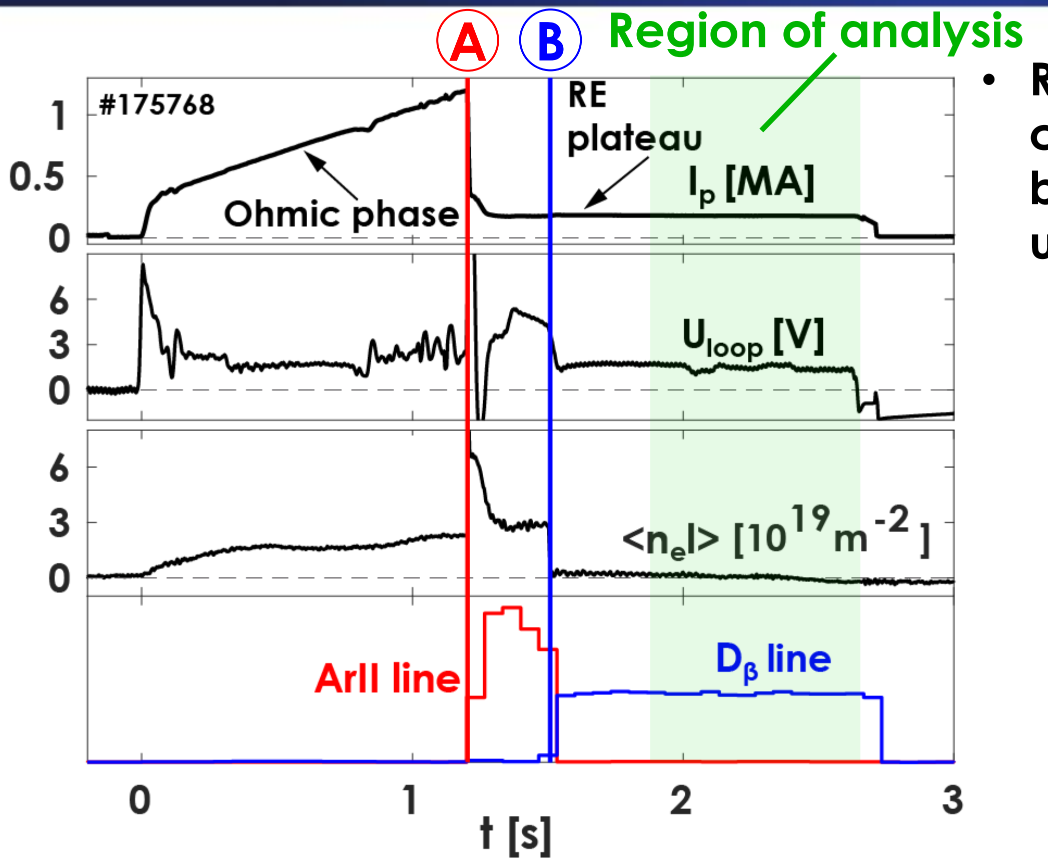

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(B) **D_2 massive gas injection → purge of Ar from RE beam**

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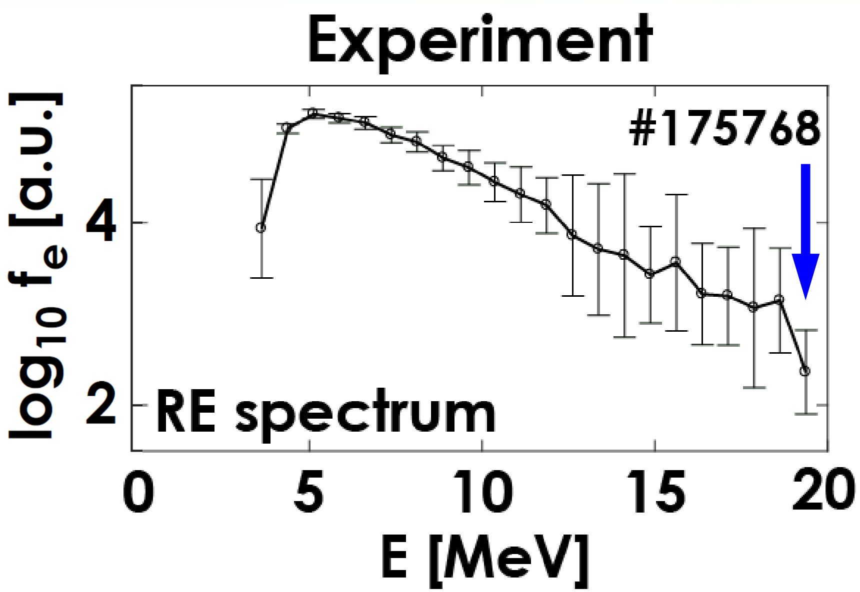
RE energy distribution function conserves over observation period and has bump at 5–6 MeV



- **Measured RE distribution function has maximum energy up to 20 MeV**
  - Consistent with other machines reporting REs up to 20–30 MeV

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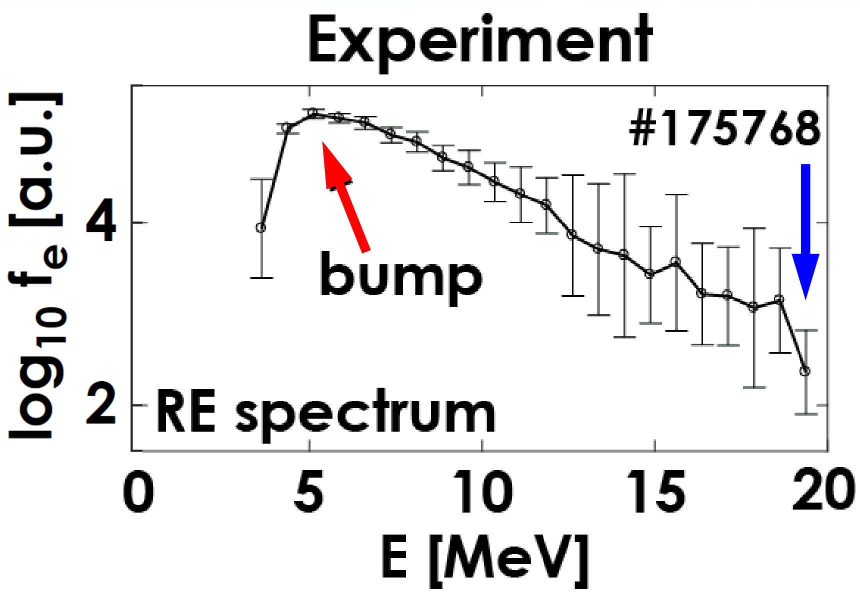

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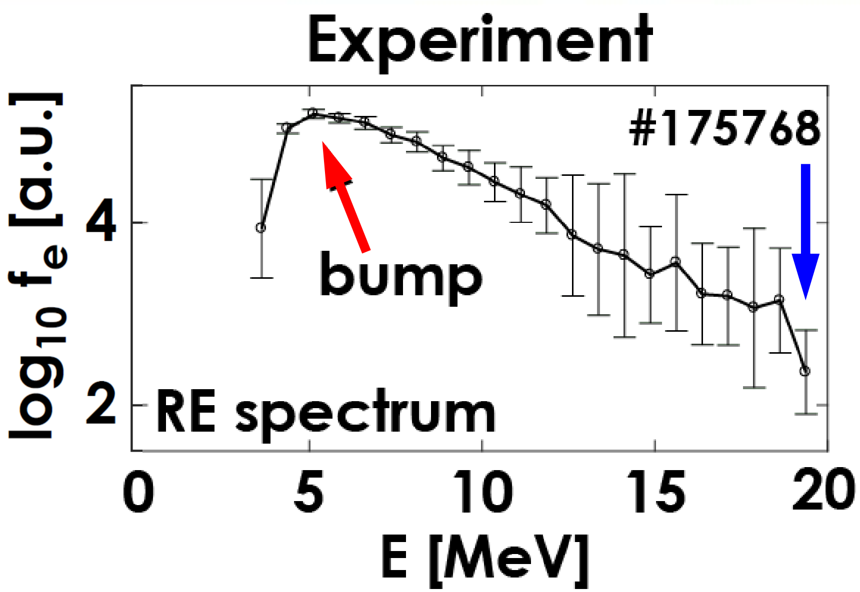

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  - This can be explained by collisional damping: $E_\varphi/E_C = 1–2$, $\tau_{coll} = 7$ ms (D_2 bound electrons are important!)
  - Synchrotron damping is small: $\tau_{rad} = 160\ \tau_{coll}$

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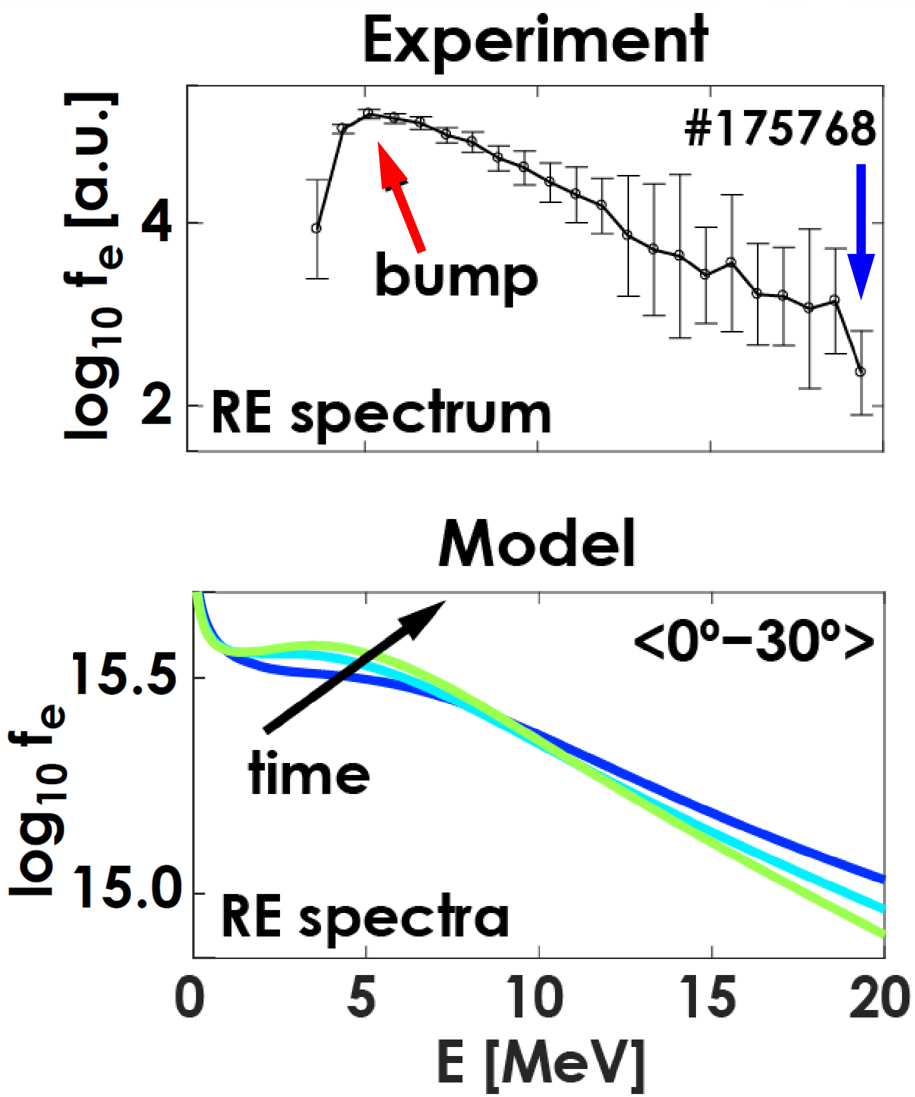

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- **Main features are captured via 0D-2V Fokker-Plank modelling**

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Outline

New physics of RE beam:

- **Energy distribution function**
- Current density profile
- Internal MHD instability
- External kink instability
- Freq. chirping instabilities

Conclusion

Energy distribution function of RE beam is obtained via HXR measurements:

- quasi-stationary in low density plasma
- has a bump at 5 MeV
- Fokker-Plank modelling qualitatively matches the experiment

Outline

New physics of RE beam:

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Motivation

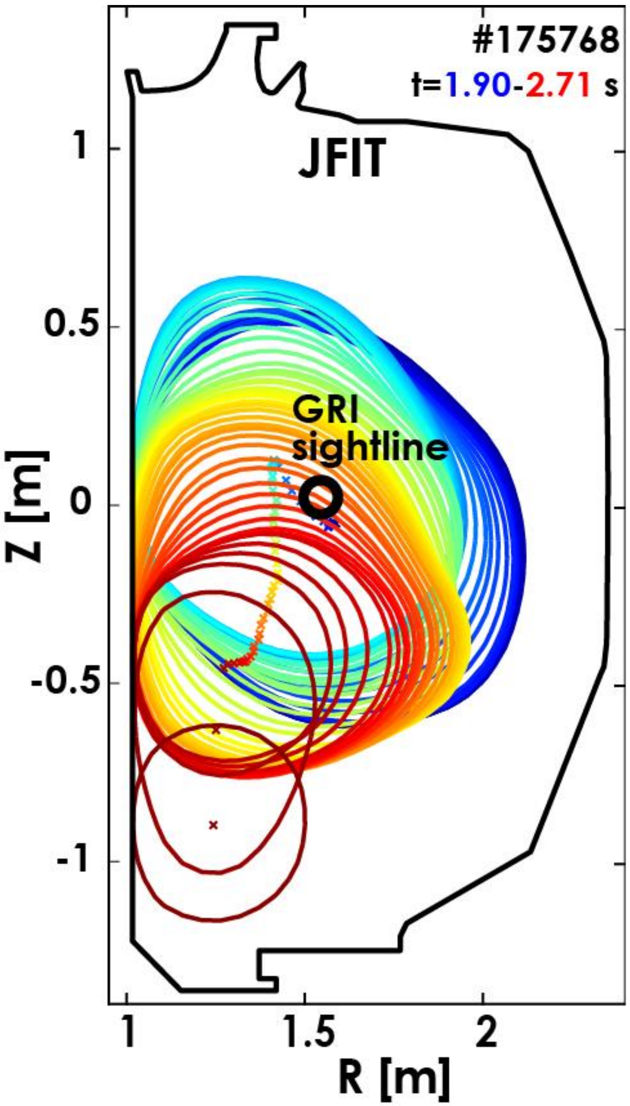
Peaking of post-disruption RE beam current profile is predicted in simulations [1−3]

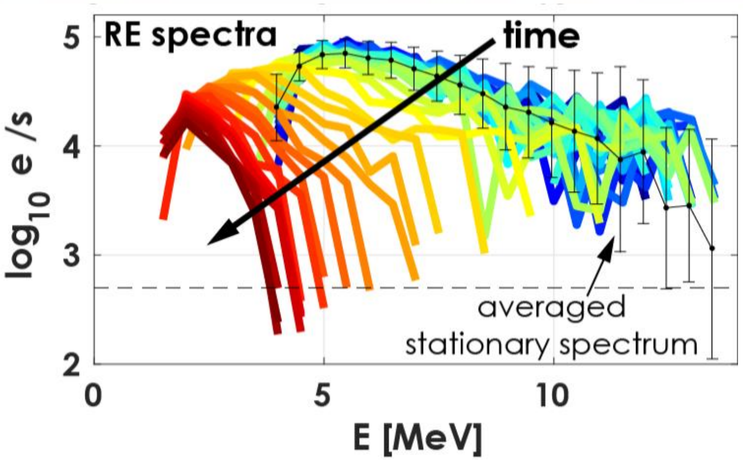
JET reported experimentally observed peaked profile [4, 5]

Models show excitation of MHD instabilities driven by peaked RE current profile [6−9]

[1] Eriksson *et al* PRL 2004
[2] Smith *et al* PoP 2006
[3] Martin-Solis *et al* NF 2017
[4] Gill *et al* NF 2000
[5] Loarte *et al* NF 2011
[6] Smith *et al* PPCF 2009
[7] Matsuyama *et al* NF 2017
[8] Aleynikova *et al* PPR 2006
[9] Bandaru *et al* PRE 2019

Current profile of RE beam is resolved via vertical scan





- **f(E) shifts to lower energies when RE beam moves (300 ms)**

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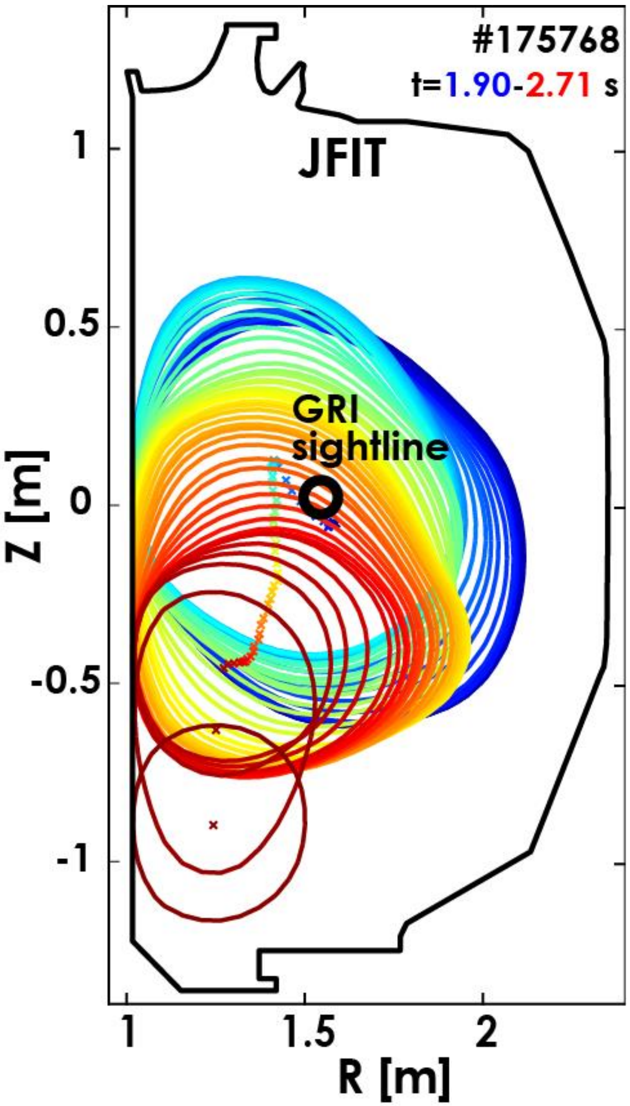

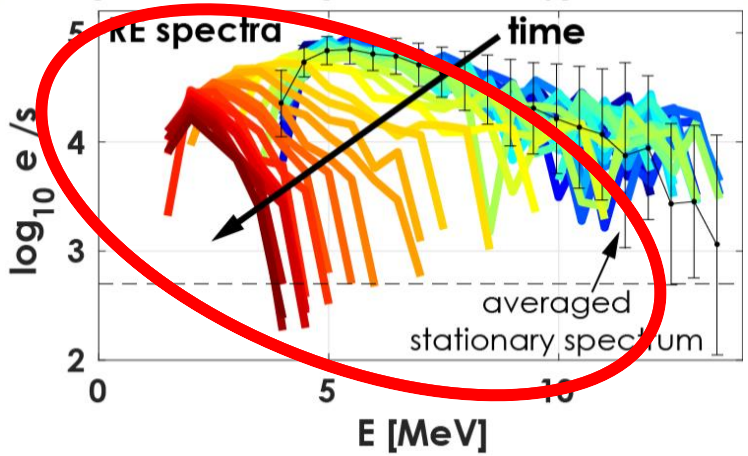

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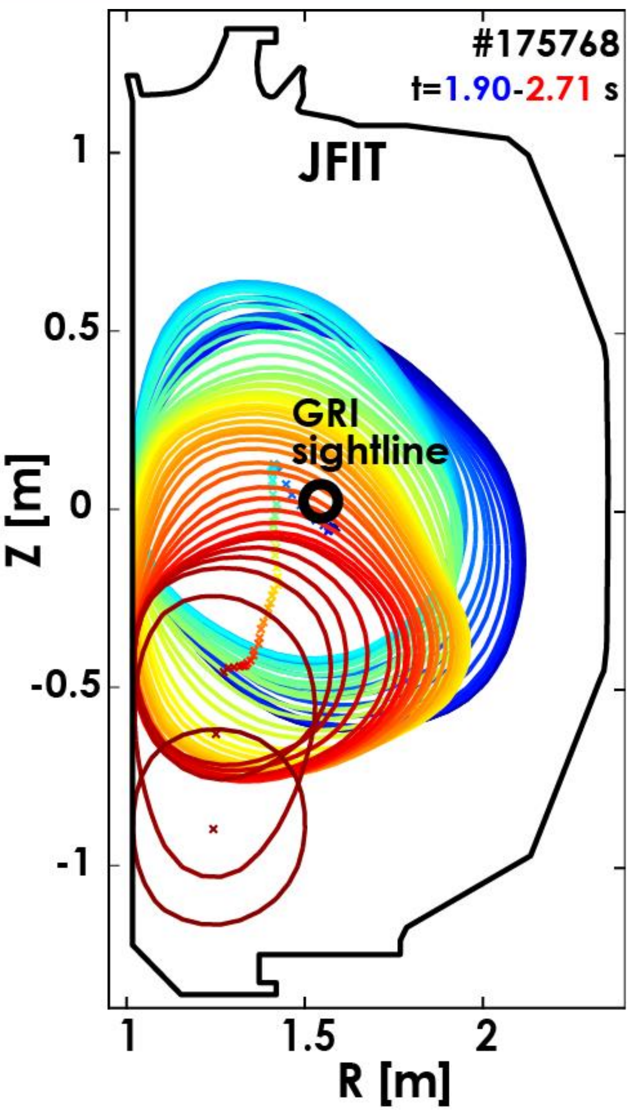

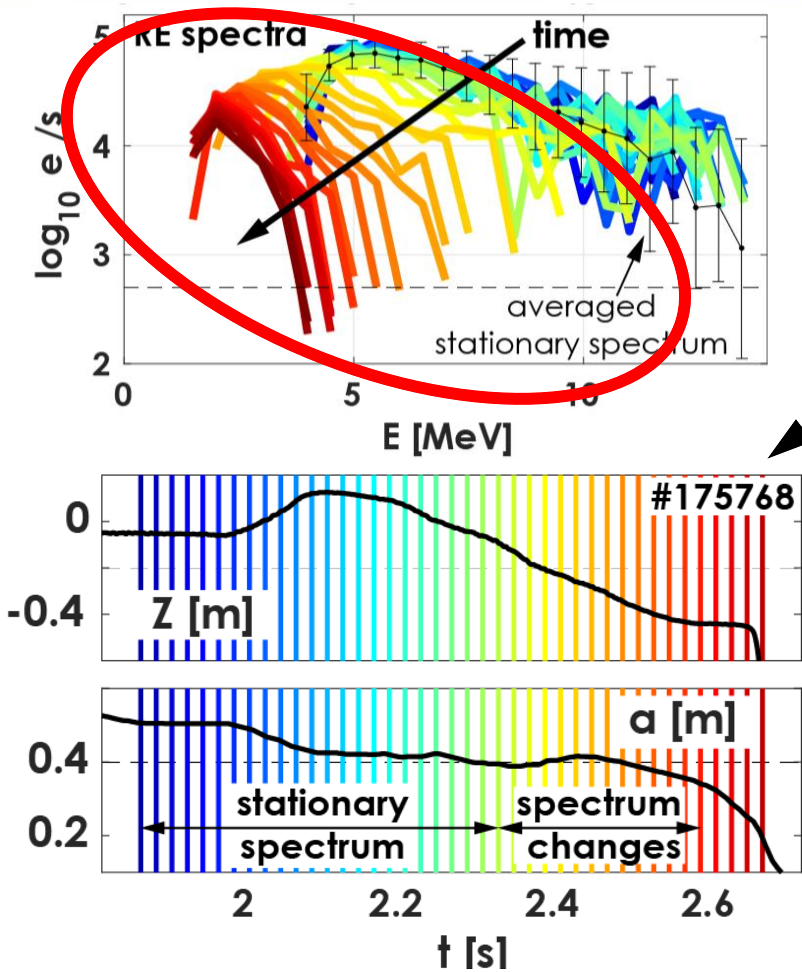

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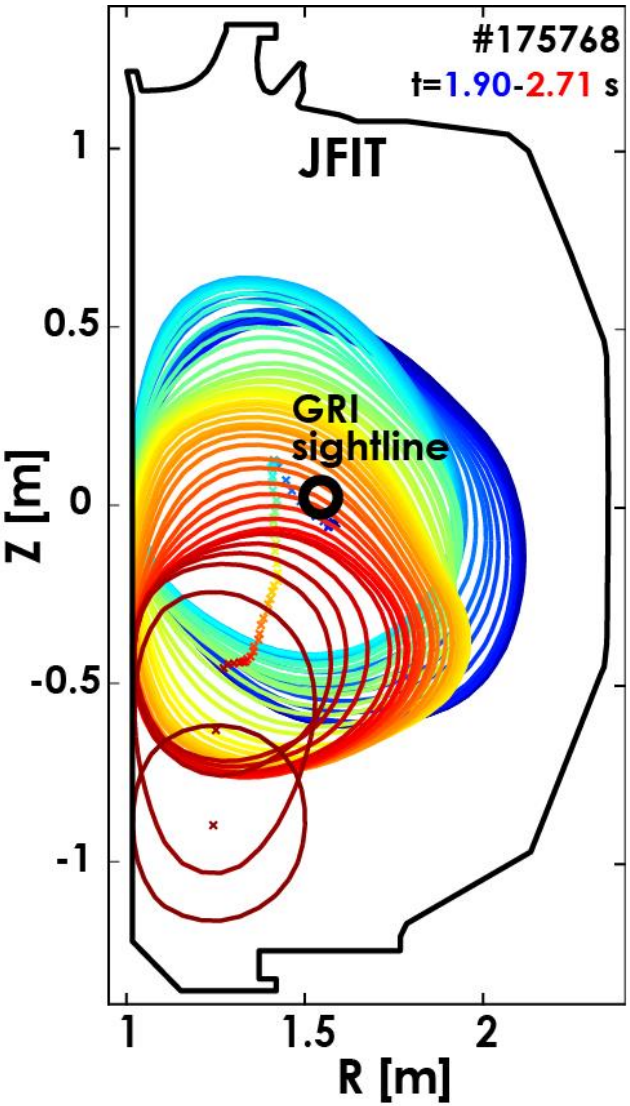
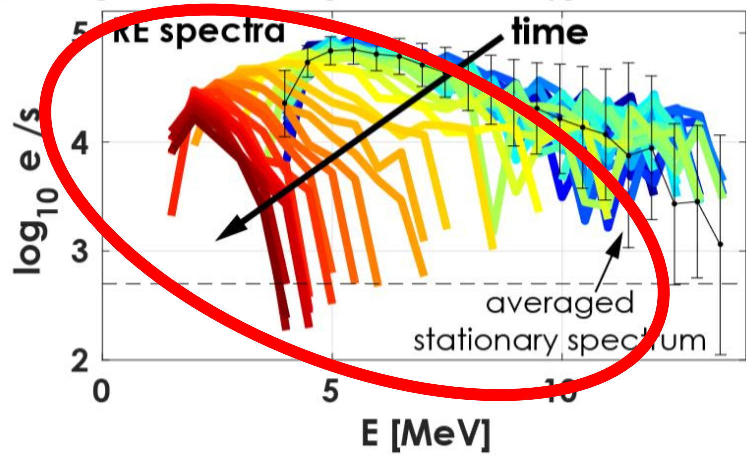
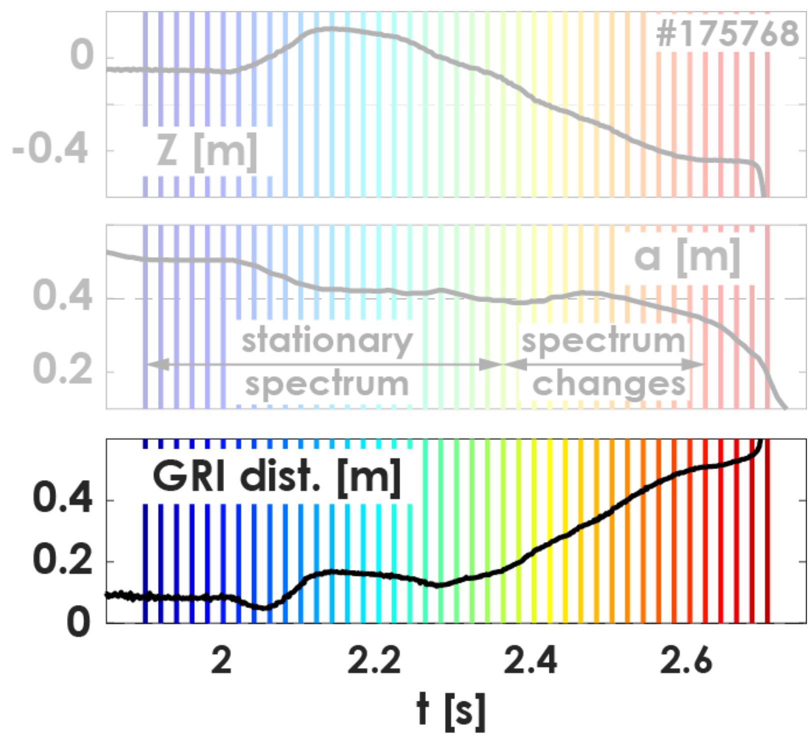
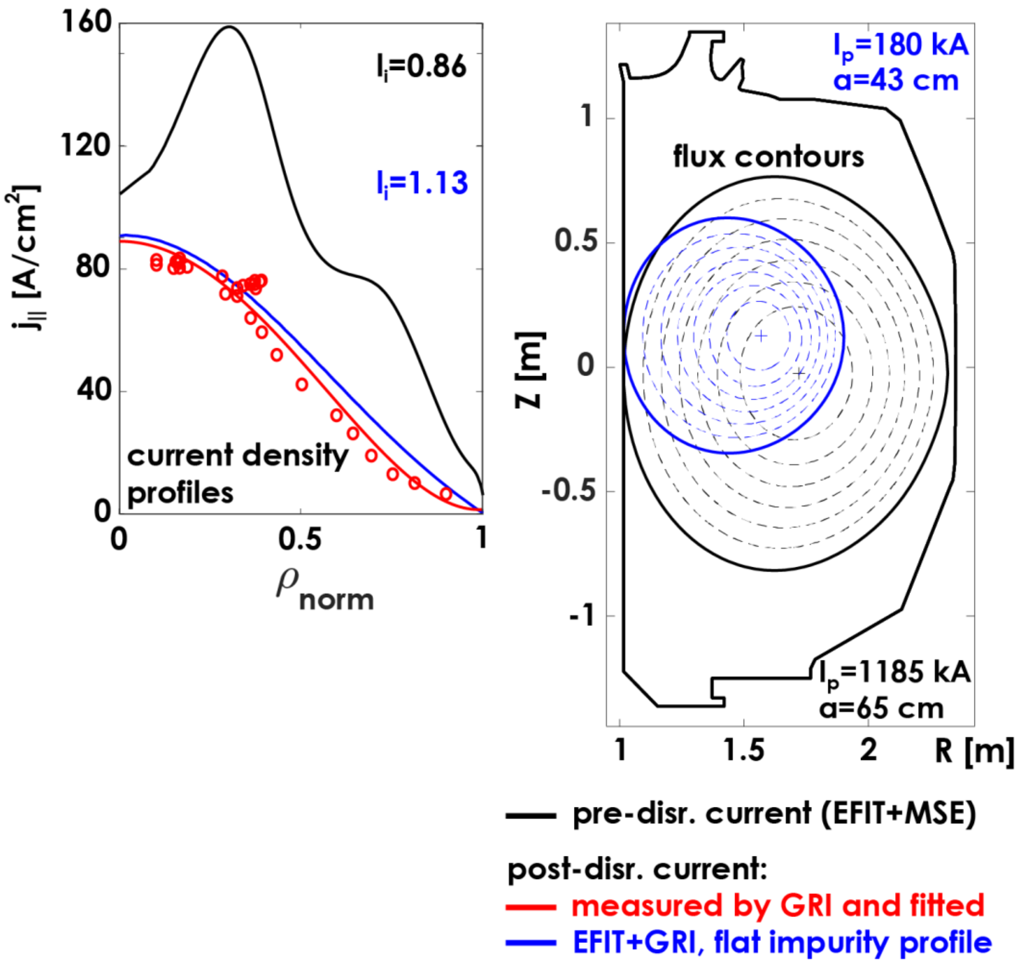






- f(E) shifts to lower energies when RE beam moves (300 ms)
- Beam passes the GRI sightline but keeps constant radius
- As a result, RE beam energy distribution function is spatially resolved providing current density profile

Post-disruption RE current is peaked but stable



- **Post-disruption current profile is more peaked than pre-disruption current with greater l_i=1.13 vs 0.86**

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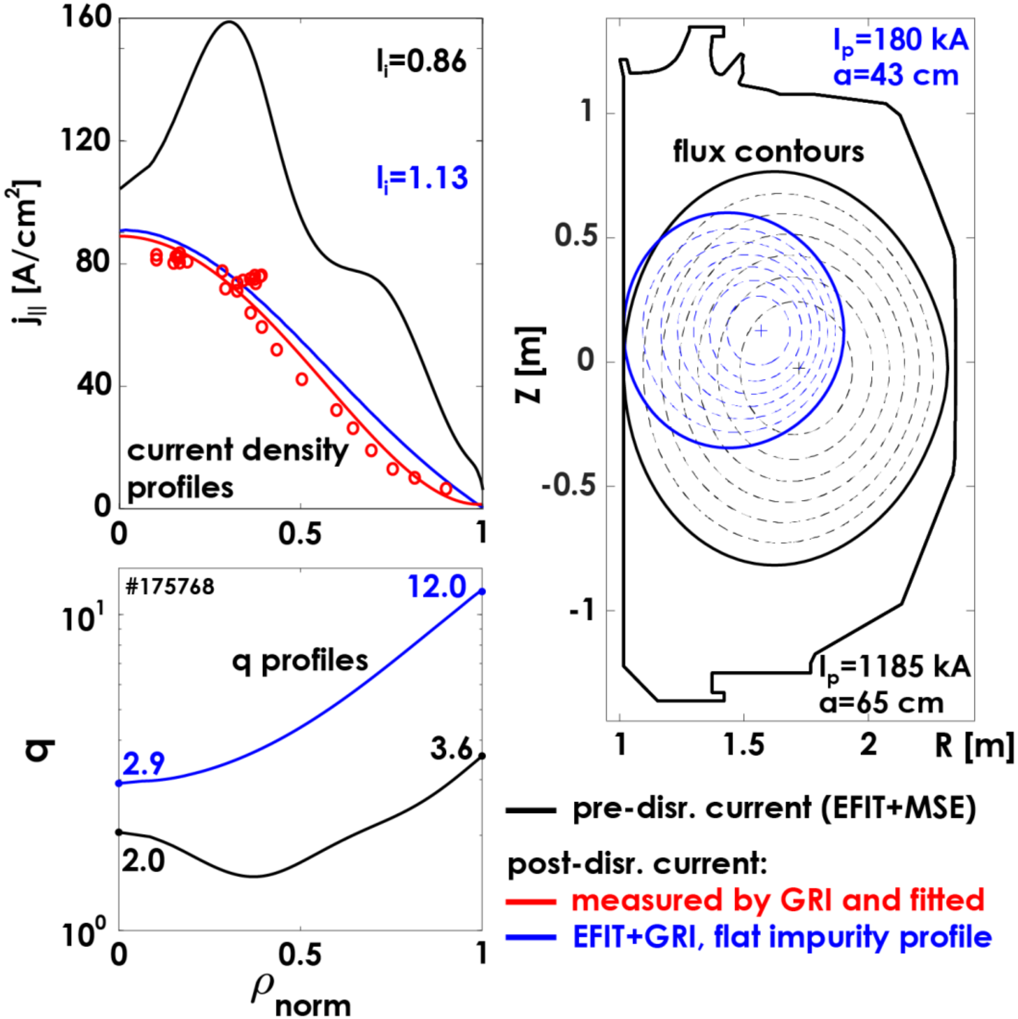
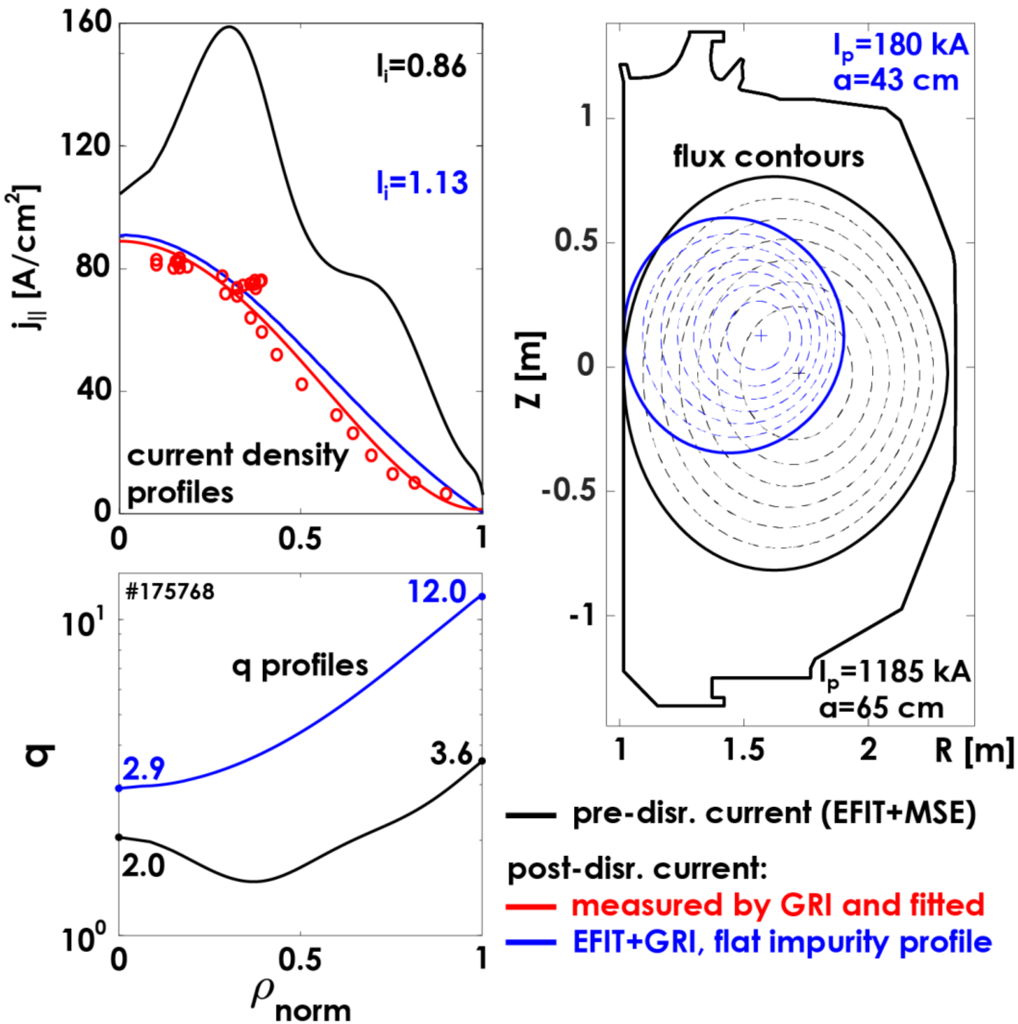


- **Post-disruption current profile is more peaked than pre-disruption current with greater l_i=1.13 vs 0.86**
- **Post-disruption relatively small RE current (180 kA) is found stable likely due to elevated q profile**
- **RE plateau sustains as long as there is transformer flux to drive it (observed up to 1.5 s)**

Post-disruption RE current is peaked but stable



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- Post-disruption relatively small RE current (180 kA) is found stable likely due to elevated q profile
- RE plateau sustains as long as there is transformer flux to drive it (observed up to 1.5 s)
- It is unclear when peaking takes place (during CQ [1,2] or/and high-Z RE plateau [3])

[1] Eriksson *et al* PRL 2004
[2] Smith *et al* PoP 2006
[3] McDevitt *et al* PPCF 2019

Outline

New physics of RE beam:

- Energy distribution function
- **Current density profile**
- Internal MHD instability
- External kink instability
- Freq. chirping instabilities

Conclusion

RE current density profile is measured by taking moments of spatially resolved RE energy distribution function

Compared to pre-disruption plasma, it is found be more peaked with greater l_i, but has elevated q profile and much greater q_a

No MHD instabilities are observed presumably due to relatively small RE current and high q_a

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New physics of RE beam:

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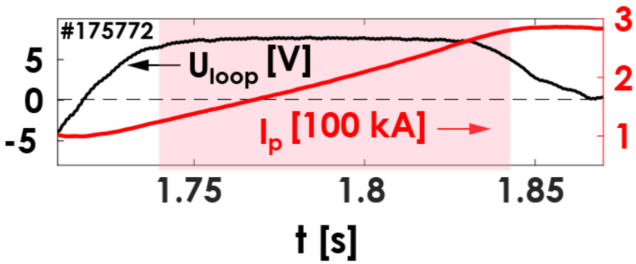
Motivation

180 kA RE beam has peaked current profile but is found to be MHD stable in DIII-D

Small-scale MHD instabilities might increase RE dissipation while large-scale can cause complete RE loss

To study MHD stability, RE beam is deliberately destabilized in DIII-D by ramping solenoid current

RE beam instability is observed when large accelerating voltage is applied



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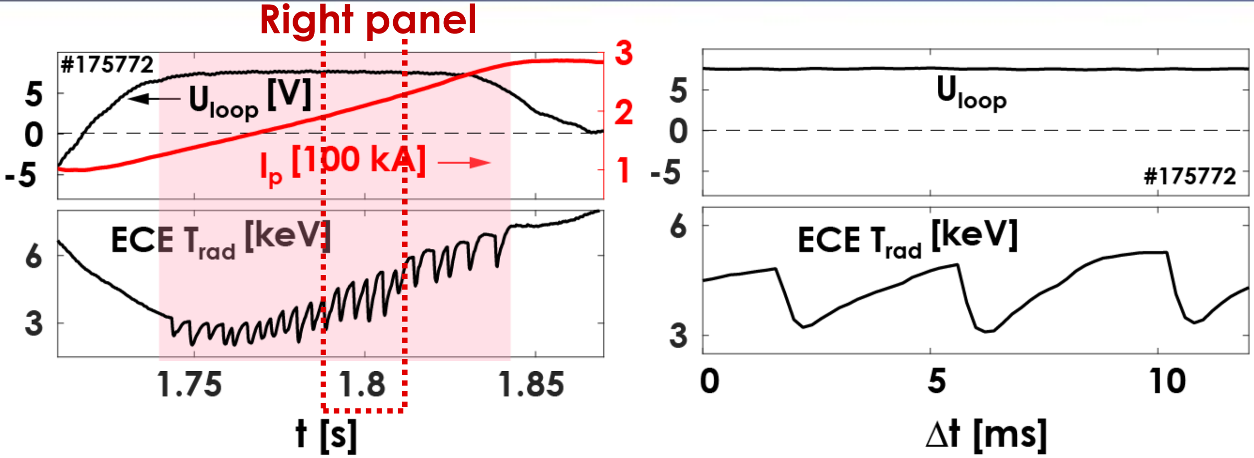

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- **ECE shows fast fall and slow rise**

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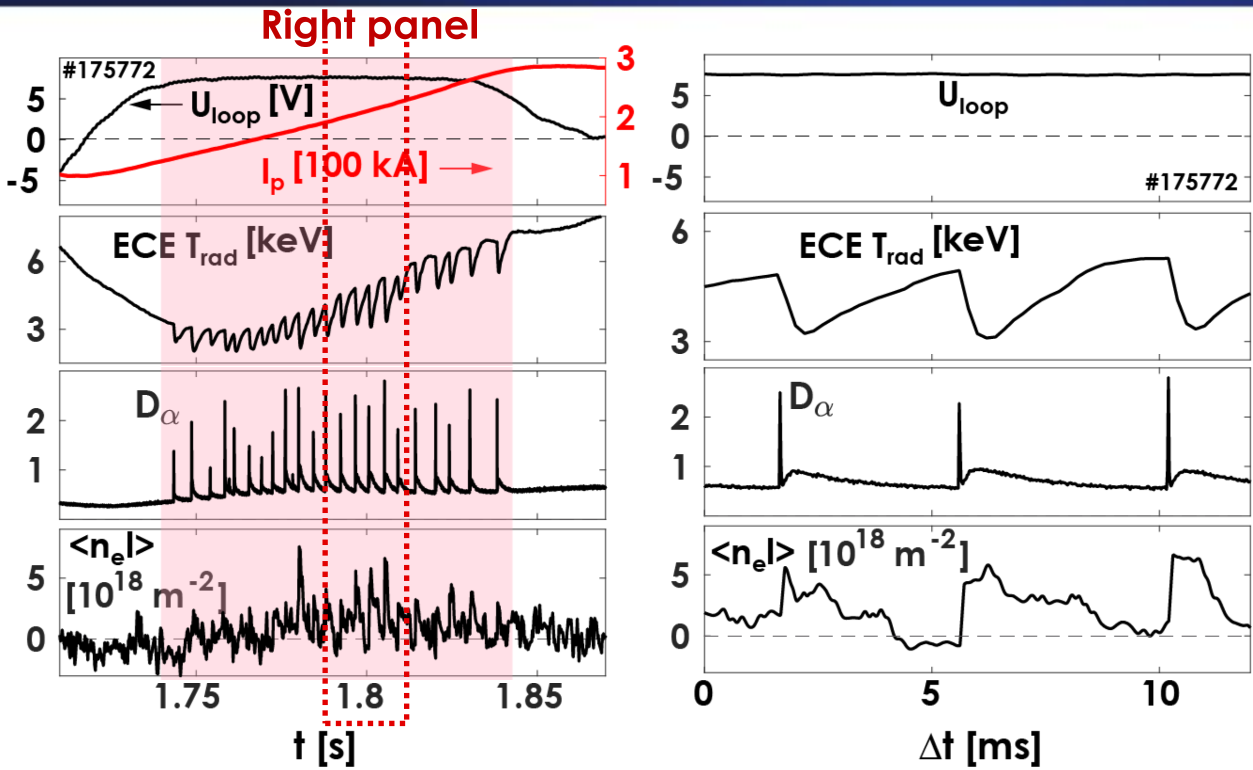

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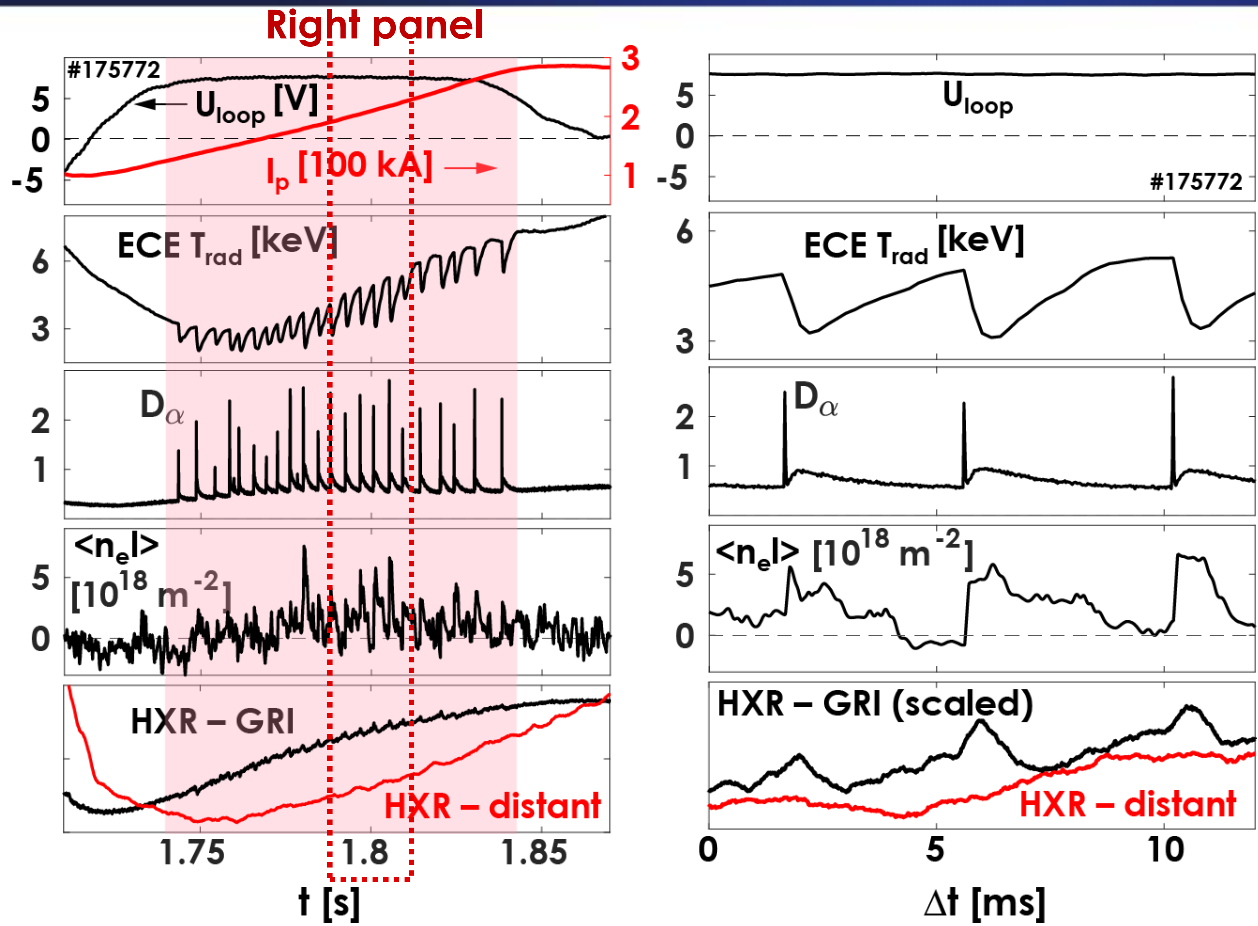

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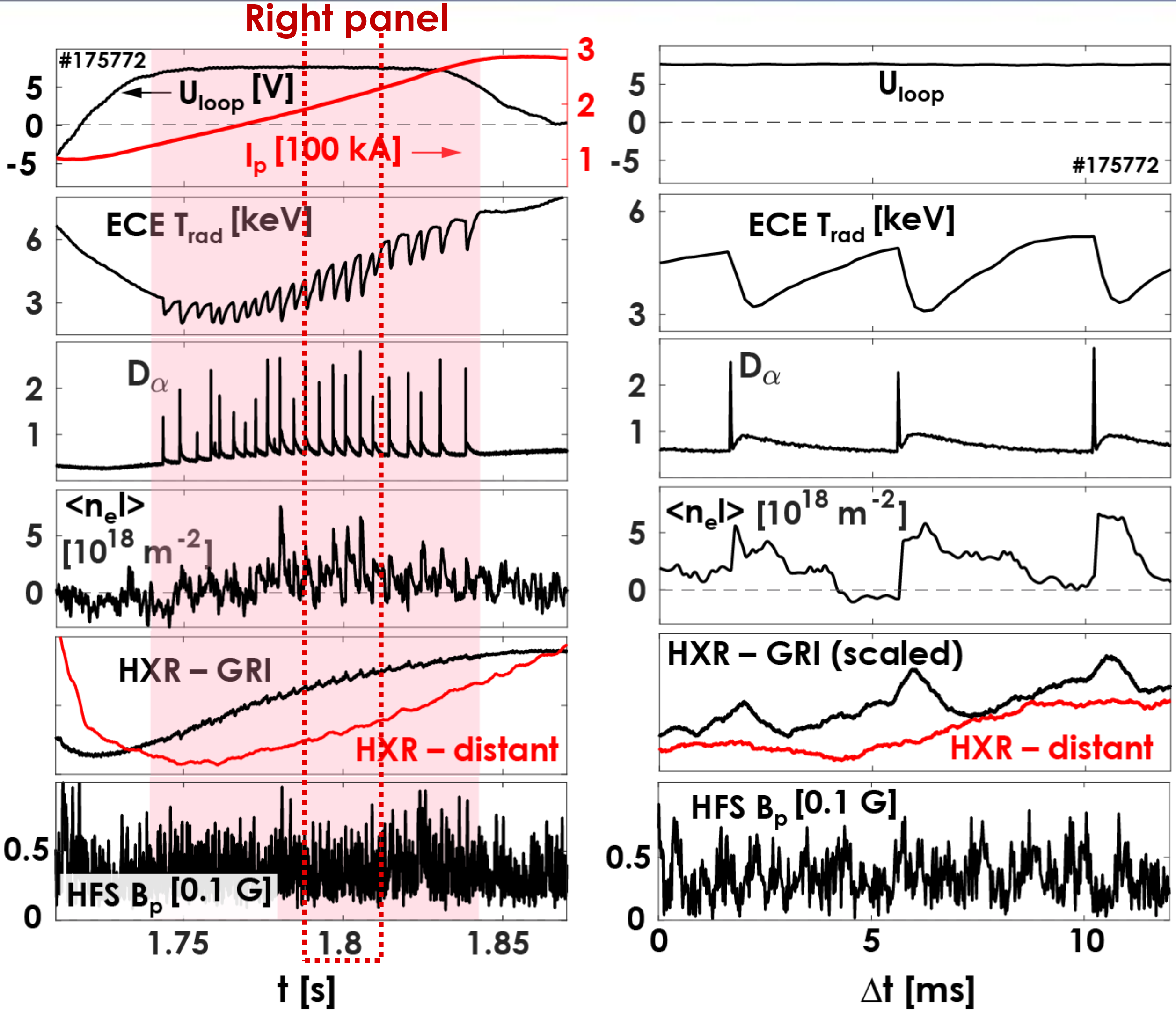

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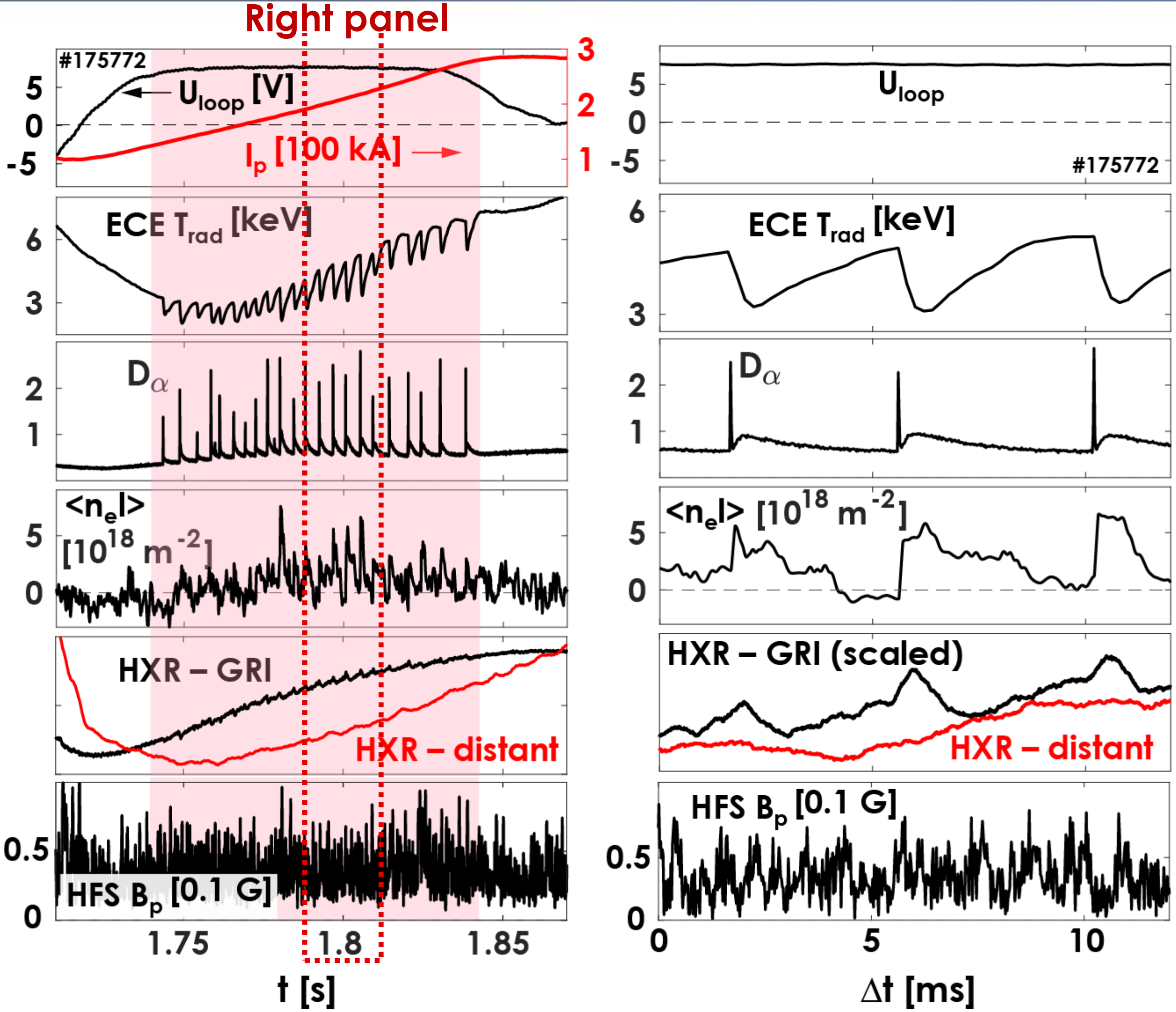

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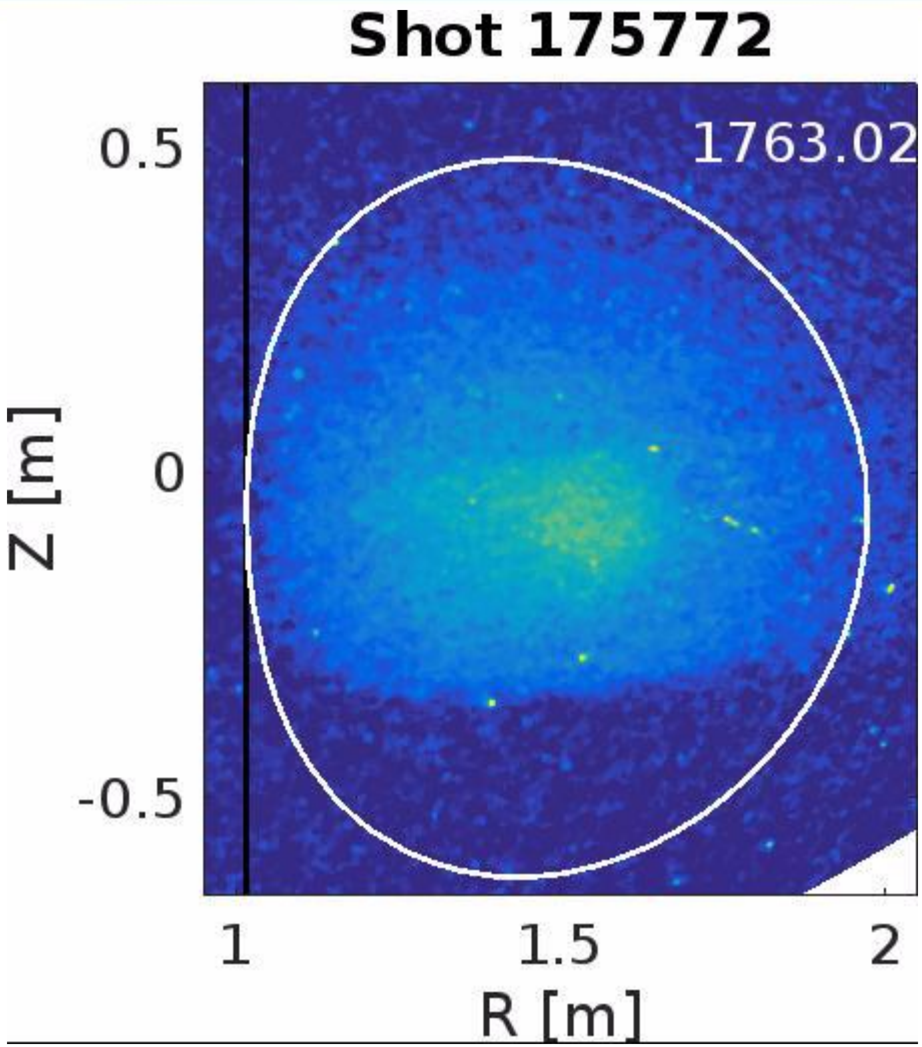
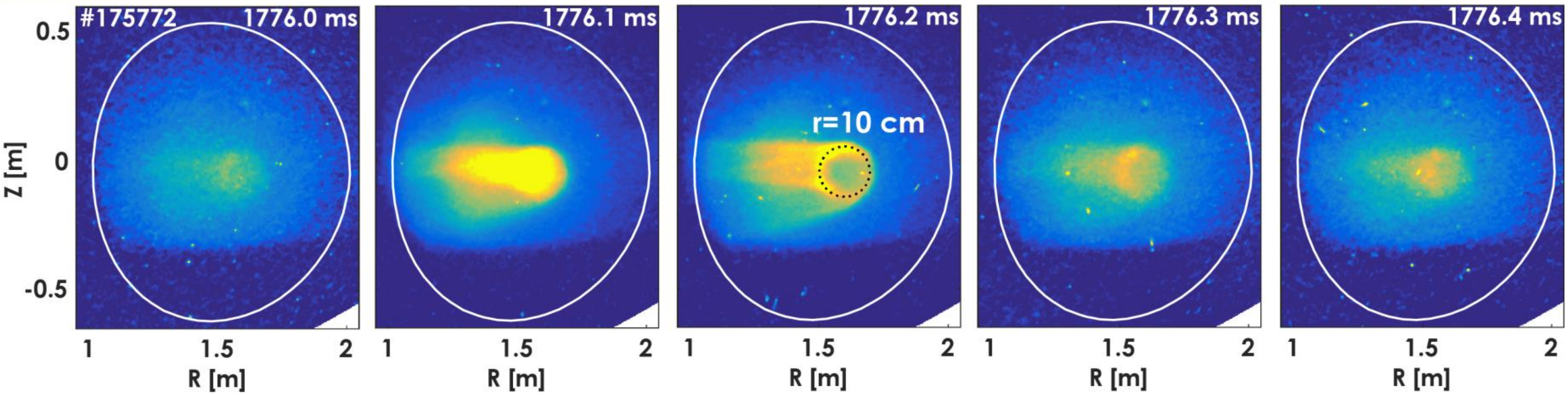
- **What could it be?**

Beam instability correlates with flashes of visible radiation

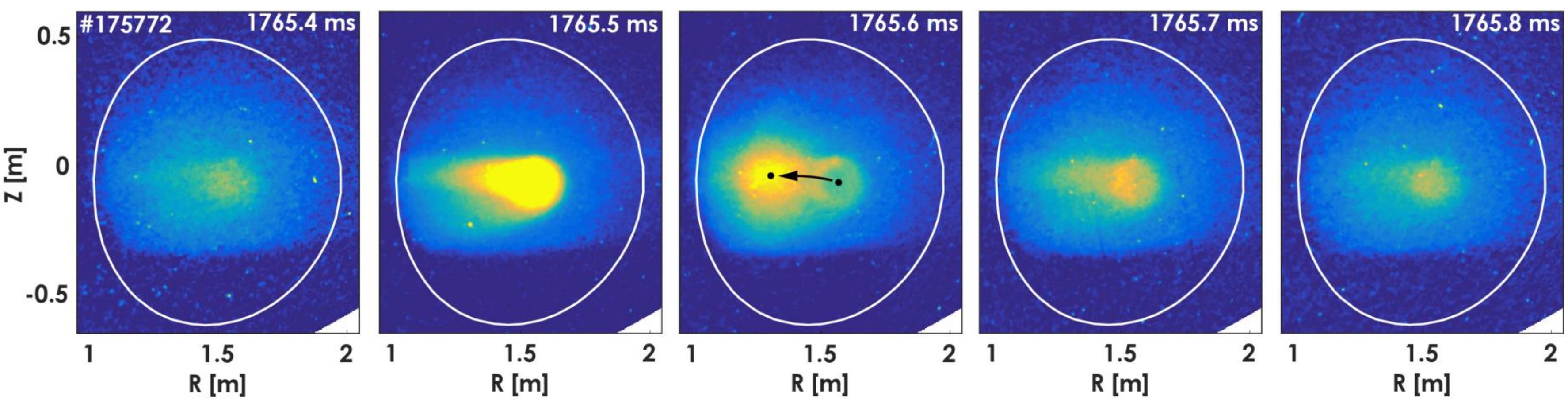


[Video]

Flashes of visible radiation localized in RE beam core

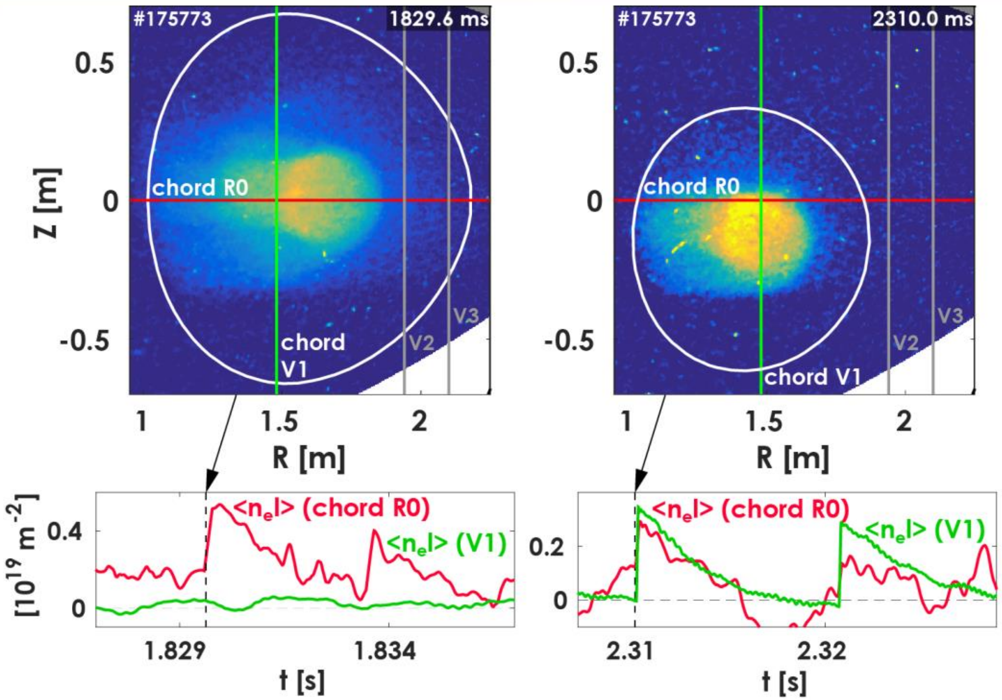


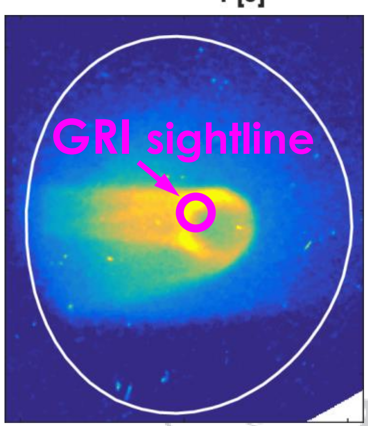
Flashes of visible radiation turn from solid circles into rings

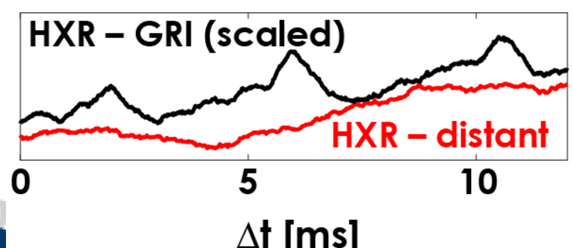


Sometimes toroidal movement of flashes can be seen

Ideal internal kink instability leading to sawtooth-like relaxation of RE current profile is proposed

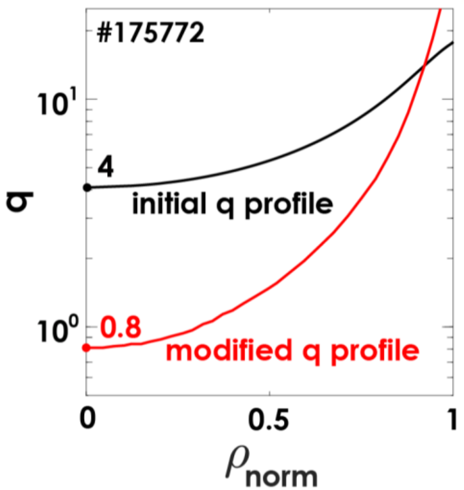






- **Radiation is broadband and isotropic which excludes fast pitch-angle scattering and known kinetic instabilities**
- **Possible mechanism of internal kink instability:**
  - RE current profile peaks under applied accelerating voltage
  - Peaked current profile excites internal kink modes
  - Internal kink leads to sawtooth-like relaxation of RE current profile
  - As a result, ECE drops, but density, radiation and GRI spike
  - No RE loss and external magnetics

MARS-F modelling suggests excitation of internal 1/1 kink mode



- Initial stable current profile is modified to obtain q_0=0.8 at constant full current

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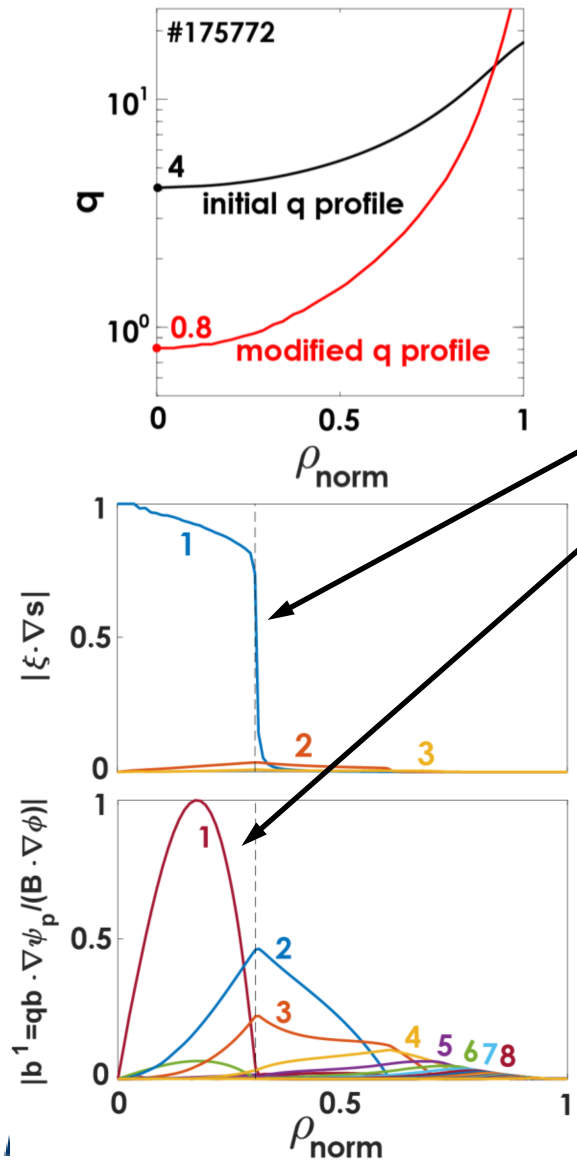

- Initial stable current profile is modified to obtain q_0=0.8 at constant full current
- Peaked current profile leads to strong ideal internal 1/1 kink mode according to MARS-F simulations

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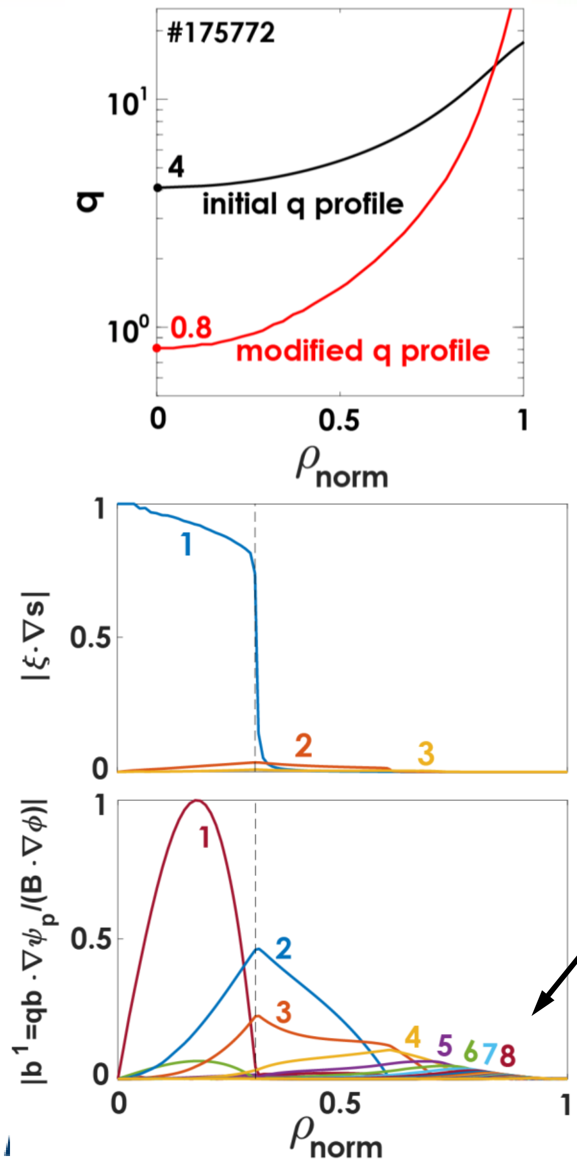

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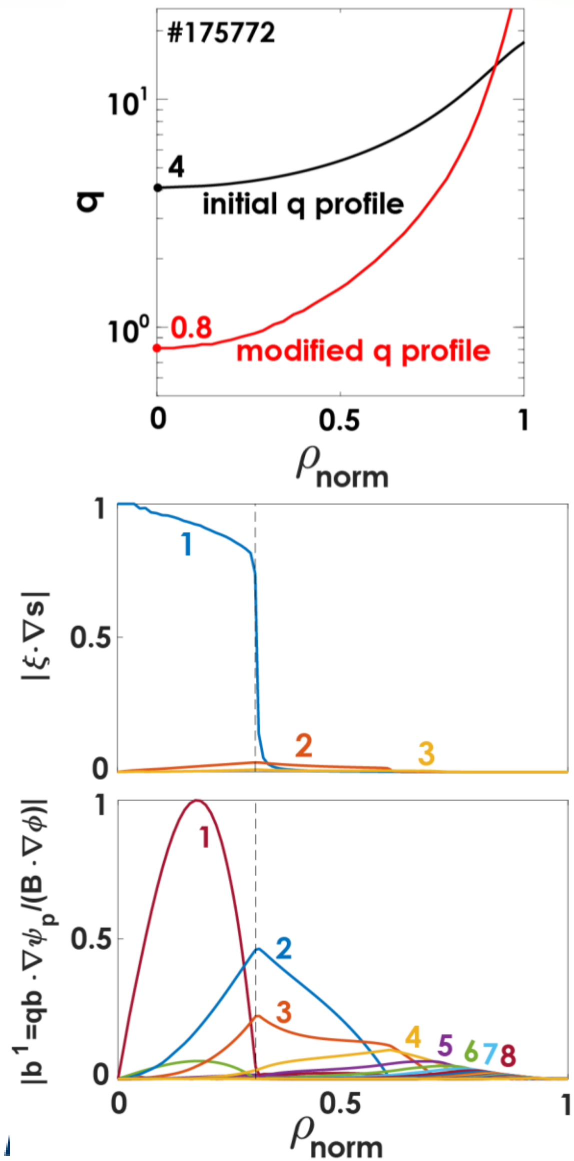
- Peaked current profile leads to strong ideal internal 1/1 kink mode according to MARS-F simulations
- Weak edge modes support lack of external magnetic signals detected in experiment

MARS-F modelling suggests excitation of internal 1/1 kink mode



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- Weak edge modes support lack of external magnetic signals detected in experiment
- **Both experiment and modelling show no effect of internal kink on RE loss and global confinement**

Outline

New physics of RE beam:

- Energy distribution function
- Current density profile
- **Internal MHD instability**
- External kink instability
- Freq. chirping instabilities

Conclusion

RE beam internal MHD instabilities are observed at large accelerating voltage

Accel. voltage presumably leads to peaked current profile driving instabilities

MARS-F modelling suggest formation of internal 1/1 kink mode

Both experiment and modelling show no effect of internal instabilities on RE loss

Outline

New physics of RE beam:

- Energy distribution function
- Current density profile
- Internal MHD instability
- **External kink instability**
- Freq. chirping instabilities

Motivation

200–300 kA RE beam is stable to global MHD instabilities in DIII-D likely due to large edge q (q_a>10)

RE beams with low q_a are predicted in ITER, but MHD stability is rarely studied [1]

Estimates for JET suggest q_a<2 as MHD limit for RE beam [2]

External kink modes and termination of RE beam are observed at low q_a in DIII-D

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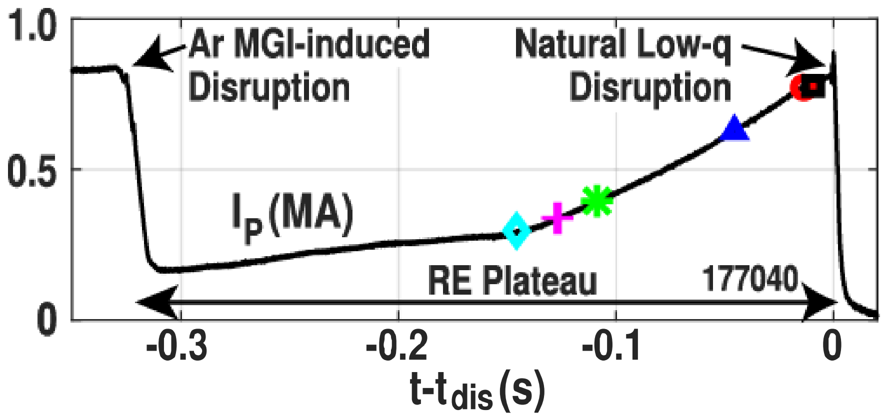
[1] Aleynikova *et al* PPR 2016
[2] Reux *et al* NF 2015

MHD instabilities are observed on the path to low q_a with eventually major disruption of RE beam



[1]

- **Same initial conditions: post-disruption RE beam in low-density plasma**
- **1 MA RE beam is accessed due to programming mistake providing very low $q_a \approx 2$**

[1] Paz-Soldan *et al* PPCF 2019

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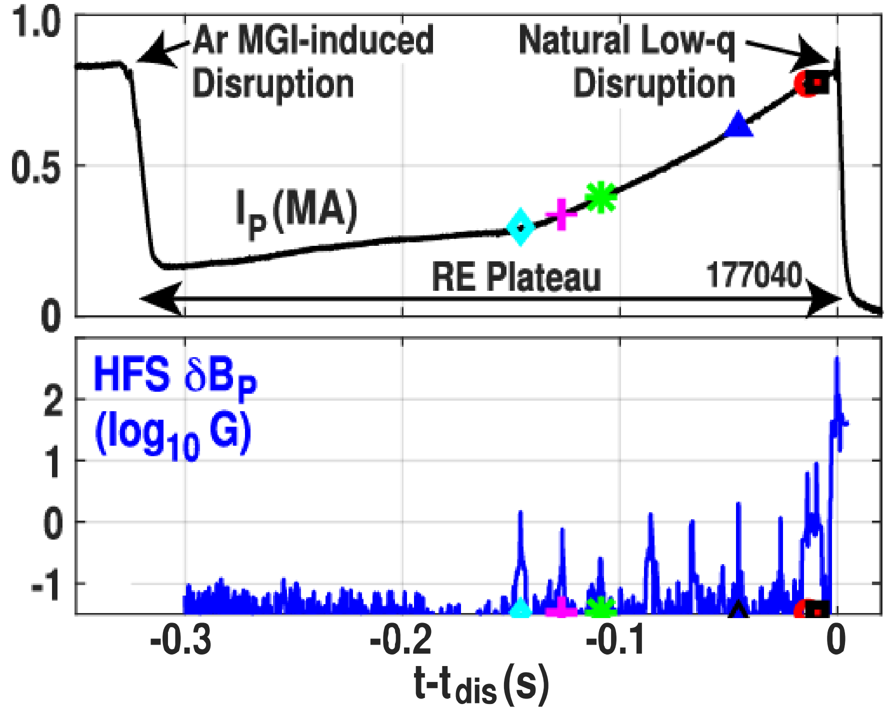

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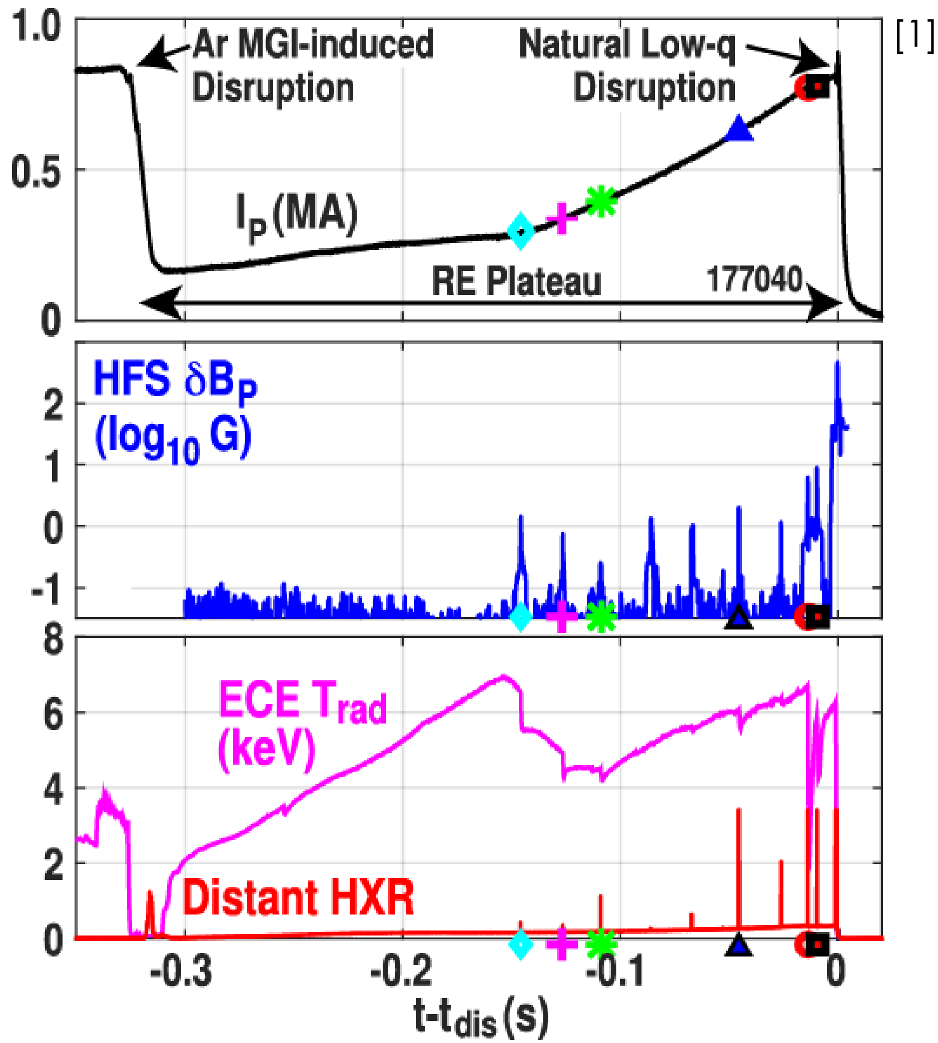

- Same initial conditions: post-disruption RE beam in low-density plasma
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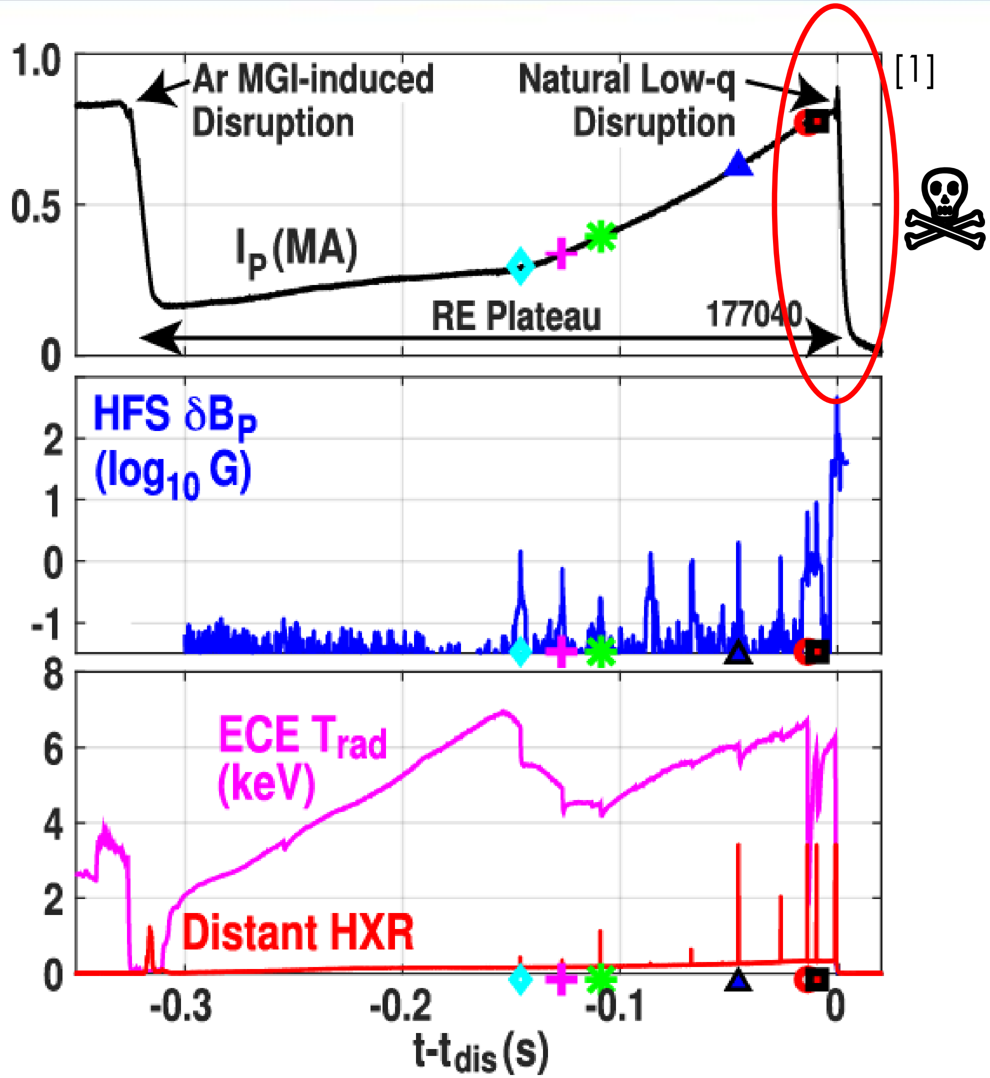
- Magnetic signals reveal isolated bursts with increasing amplitude
- Each burst comes with HXR spikes indicating RE loss
- ECE signal shows drops also indicating RE loss

[1] Paz-Soldan *et al* PPCF 2019

MHD instabilities are observed on the path to low q_a with eventually major disruption of RE beam



- Same initial conditions: post-disruption RE beam in low-density plasma
- 1 MA RE beam is accessed due to programming mistake providing very low $q_a \approx 2$
- Magnetic signals reveal isolated bursts with increasing amplitude
- Each burst comes with HXR spikes indicating RE loss
- ECE signal shows drops also indicating RE loss
- Finally, complete RE loss is observed at $\delta B_p = 1$ kG

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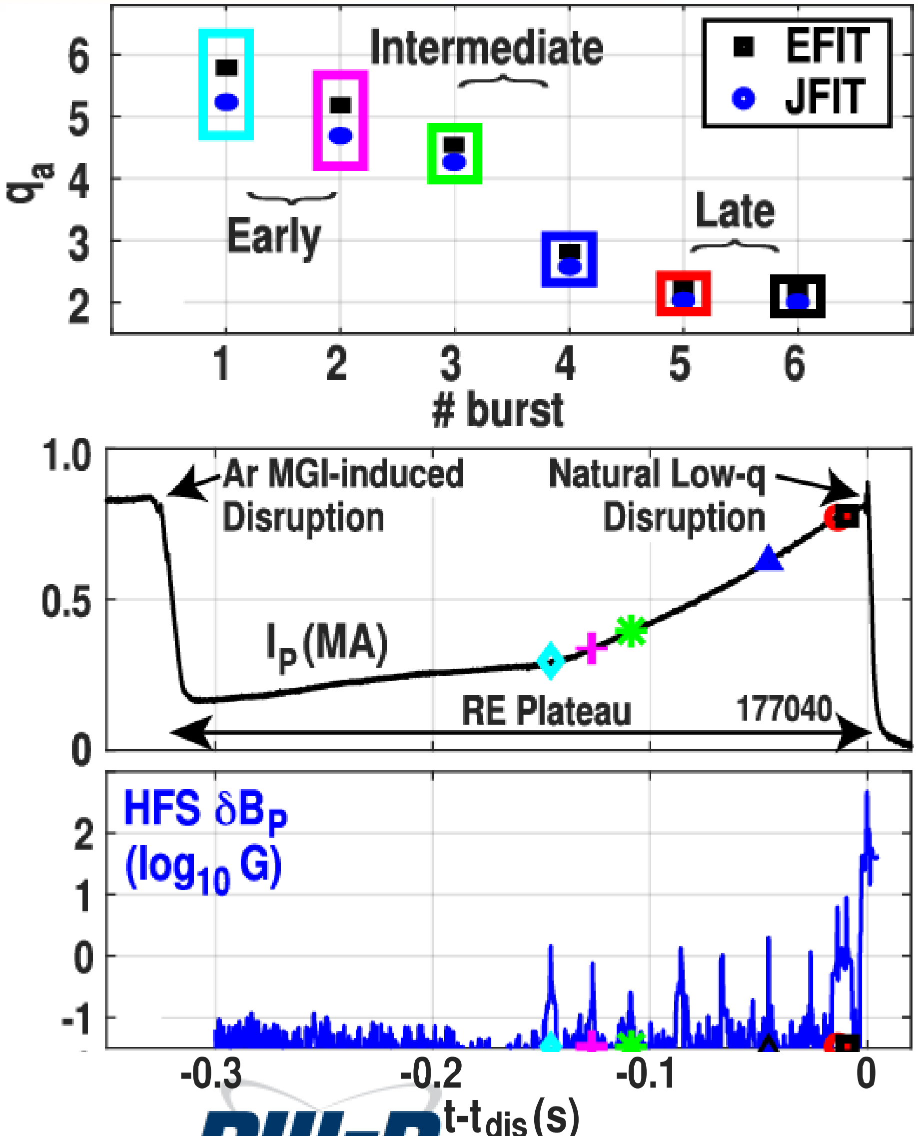
A. Lvovskiy/TSDW/August 2019

[1] Paz-Soldan *et al* PPCF 2019

Equilibrium fitting with JFIT and EFIT reveals weaker instabilities at high q_a and killer instabilities at $q_a \approx 2$



[1]

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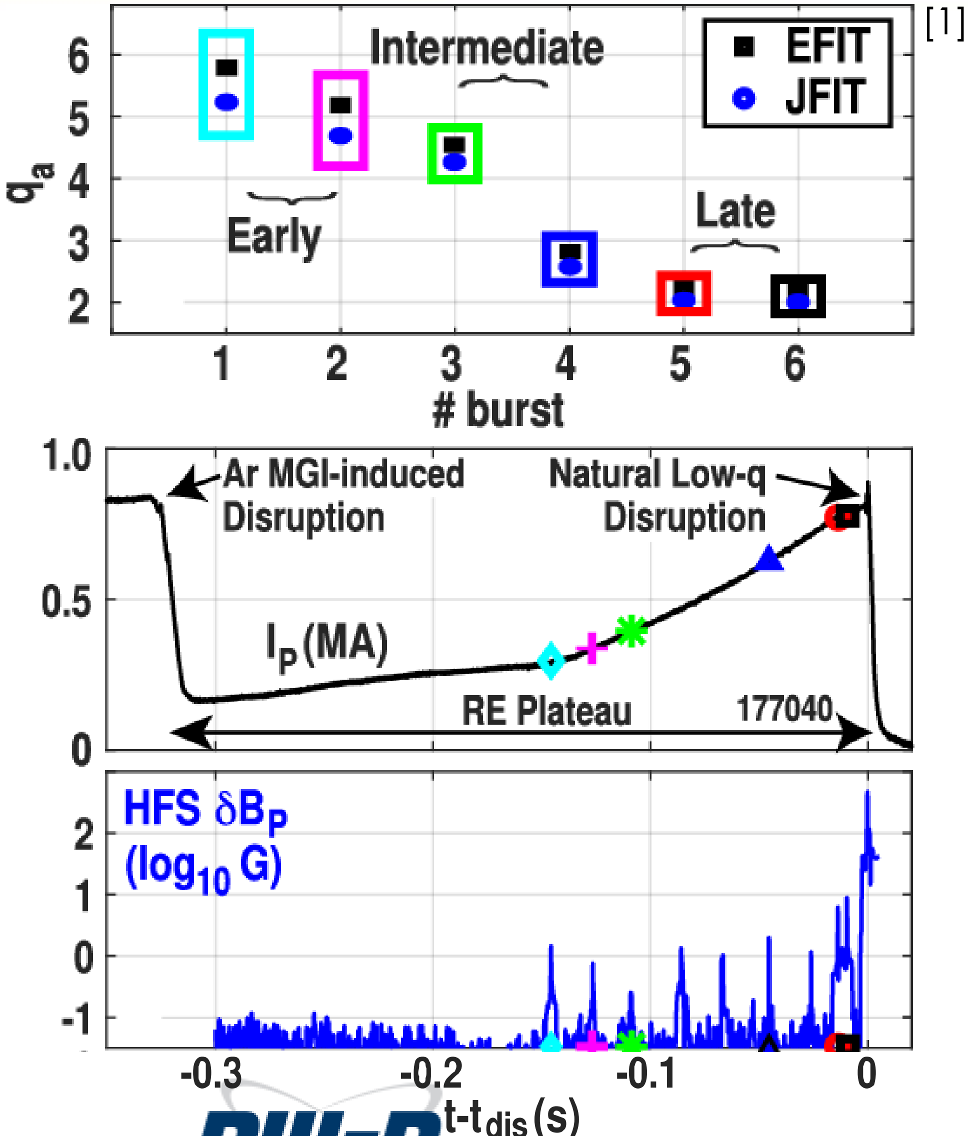
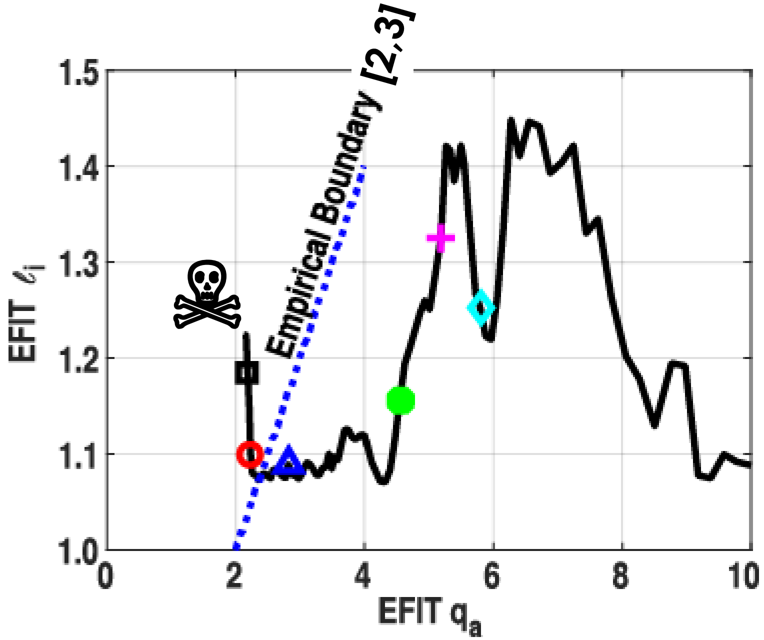


- As RE current increases, q_a decreases, and magnetic bursts become larger
- Conventional operating space picture is accurate for RE equilibria



[1] Paz-Soldan *et al* PPCF 2019
[2] Chang *et al* PPCF 1987
[3] Snipes *et al* NF 1988

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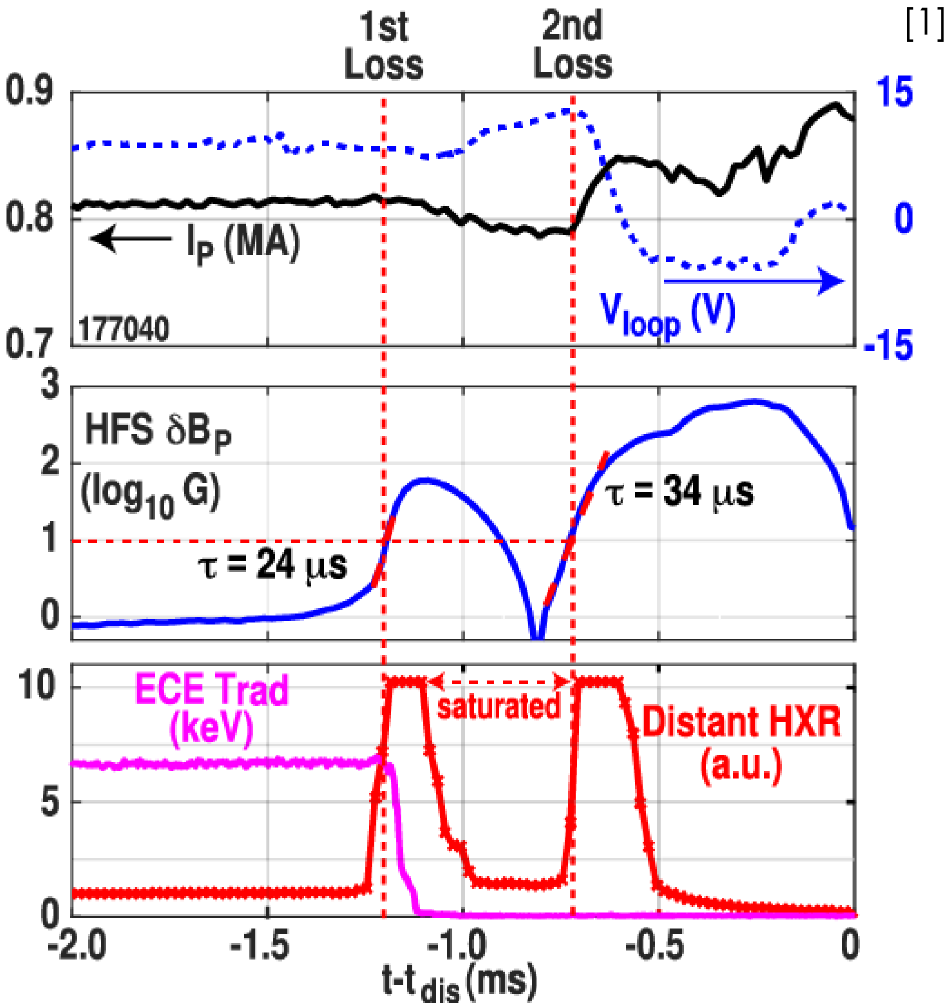
A. Lvovskiy/TSDW/August 2019

Final RE lost is caused by huge (1 kG) and fast (10 μs) external kink mode



- **All REs are lost when δB_p reaches 1 kG**
- **Magnetic measurements compared to MARS-F modelling show 2/1 kink mode at low q_a [2]**
- **Early instabilities (at large q_a) are different: likely internal or resistive kinks [2]**
- **RE spatial loss becomes less localized as instabilities get larger**

[1] Paz-Soldan *et al* PPCF 2019
[2] Y.Q. Liu *et al* To be submitted to NF

Outline

New physics of RE beam:

- Energy distribution function
- Current density profile
- Internal MHD instability
- **External kink instability**
- Freq. chirping instabilities

Conclusion

Killer kink instabilities are observed at large I_{RE} and low q_a

Stability limit is the same as for regular plasma

External or (external + internal) kinks are excited at $q_a \approx 2$

$\delta B_p = 1$ kG terminates RE beam

Prediction of RE evolution in ITER must take MHD stability into account

In more detail: Paz-Soldan *et al* PPCF 2019

Outline

New physics of RE beam:

- Energy distribution function
- Current density profile
- Internal MHD instability
- External kink instability
- **Frequency chirping instabilities**

Motivation

RE-driven kinetic instabilities get increasing attention [1-14]

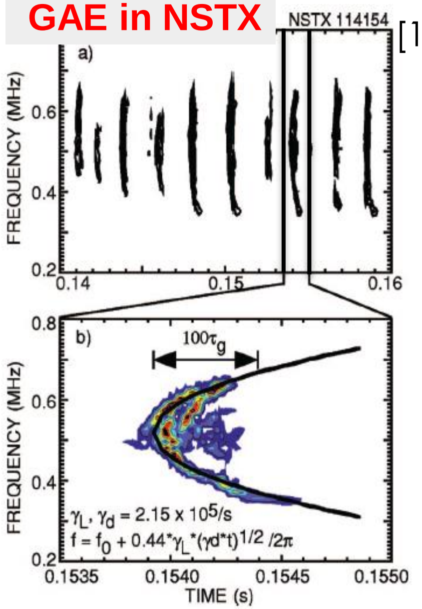
They can increase RE dissipation and be beneficial for RE mitigation in ITER

Kinetic instabilities are excited in DIII-D during RE plateau under applied large decelerating voltage

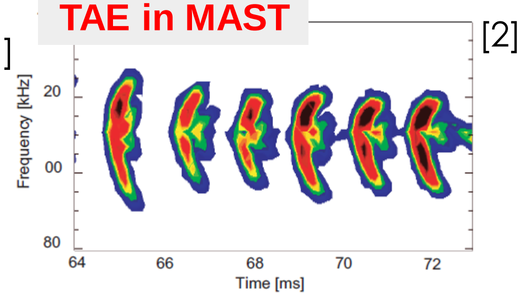
[1] Fülöp *et al* PoP 2006
[2] Pokol *et al* PPCF 2008
[3] Fülöp *et al* PoP 2009
[4] Zhou *et al* PPCF 2013
[5] Fülöp *et al* PoP 2014
[6] Papp *et al* EPS-2014
[7] Fredrikson *et al* NF 2014
[8] Aleynikov *et al* NF 2015
[9] Chu *et al* NF 2018
[10] Spong *et al* PRL 2018
[11] Heidbrink *et al* PPCF 2018
[12] Liu *et al* PRL 2018
[13] Liu *et al* NF 2018
[14] Lvovskiy *et al* PPCF 2018

Frequency chirping instabilities are observed for the first time driven by runaway electrons in tokamak

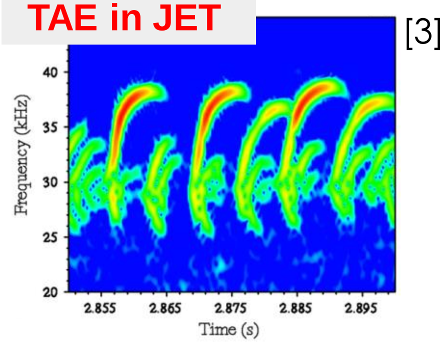
GAE in NSTX



TAE in MAST



TAE in JET



- **Energetic particles can drive instabilities through wave-particle resonances**
- **Frequency chirping instabilities are often observed driven by fast ions in tokamaks**

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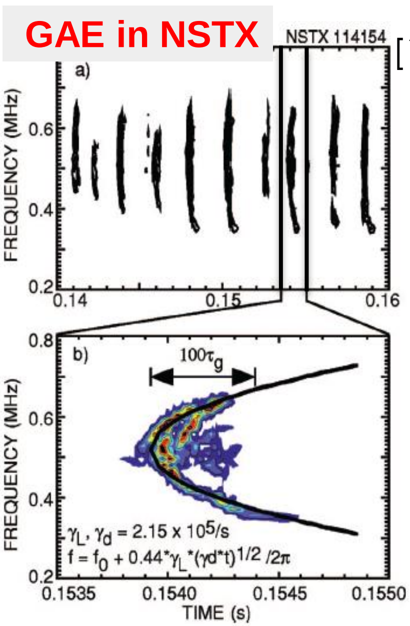
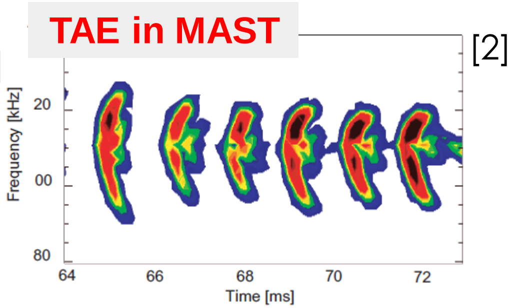
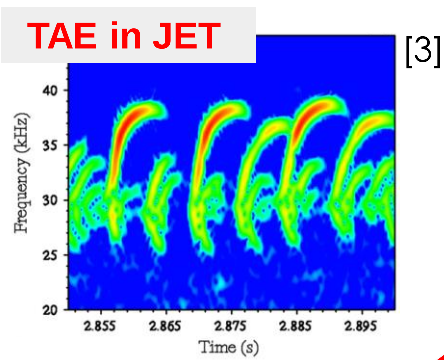
A. Lvovskiy/TSDW/August 2019

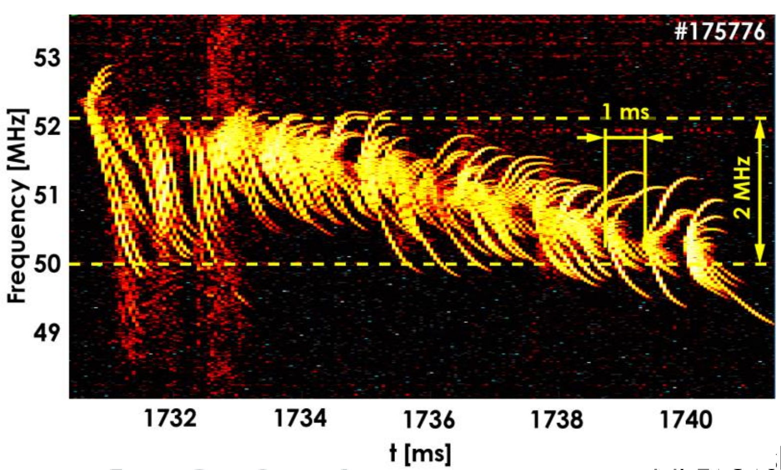
[1] Fredrickson *et al* PoP 2006
[2] Pinches *et al* PPCF 2004
[3] Berk *et al* NF 2006

Frequency chirping instabilities are observed for the first time driven by runaway electrons in tokamak





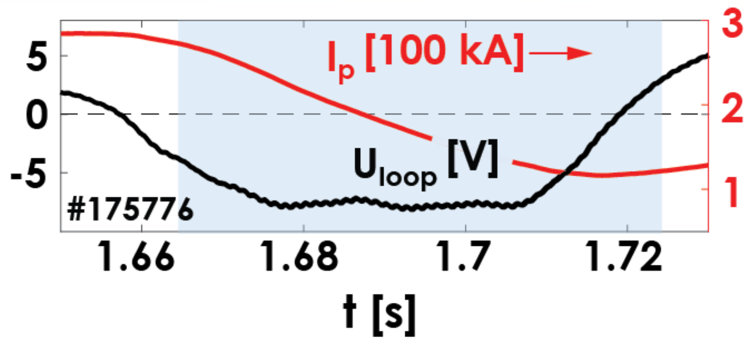




- **Energetic particles can drive instabilities through wave-particle resonances**
- **Frequency chirping instabilities are often observed driven by fast ions in tokamaks**
- **This talk: discovery of rapid frequency chirping driven by runaway electrons (REs) in DIII-D**
  (2018 DIII-D Frontier Science Campaign)
- **These MHz-range chirping instabilities correlate with modification of RE distribution function and increased RE loss**

[1] Fredrickson *et al* PoP 2006
[2] Pinches *et al* PPCF 2004
[3] Berk *et al* NF 2006

RE loss increases under decelerating loop voltage



- Same initial conditions: post-disruption RE beam in low-density plasma
- Large decelerating voltage with magnitude comparable with breakdown voltage is applied to RE beam

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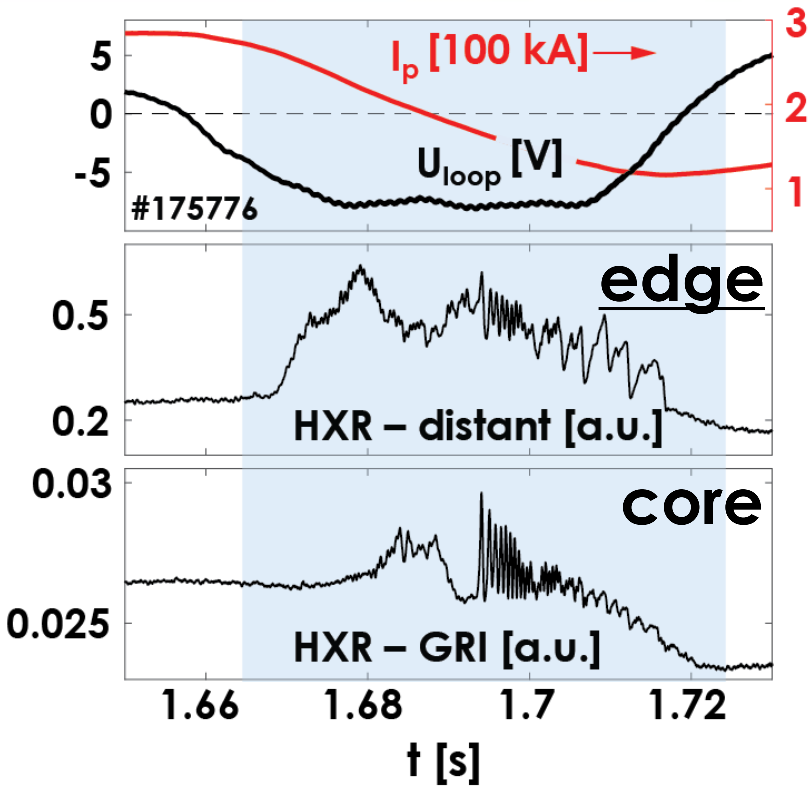

- Same initial conditions: post-disruption RE beam in low-density plasma
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- This causes large fluctuations of <u>edge</u> and core hard X-ray signals (from <u>lost</u> and confined REs)

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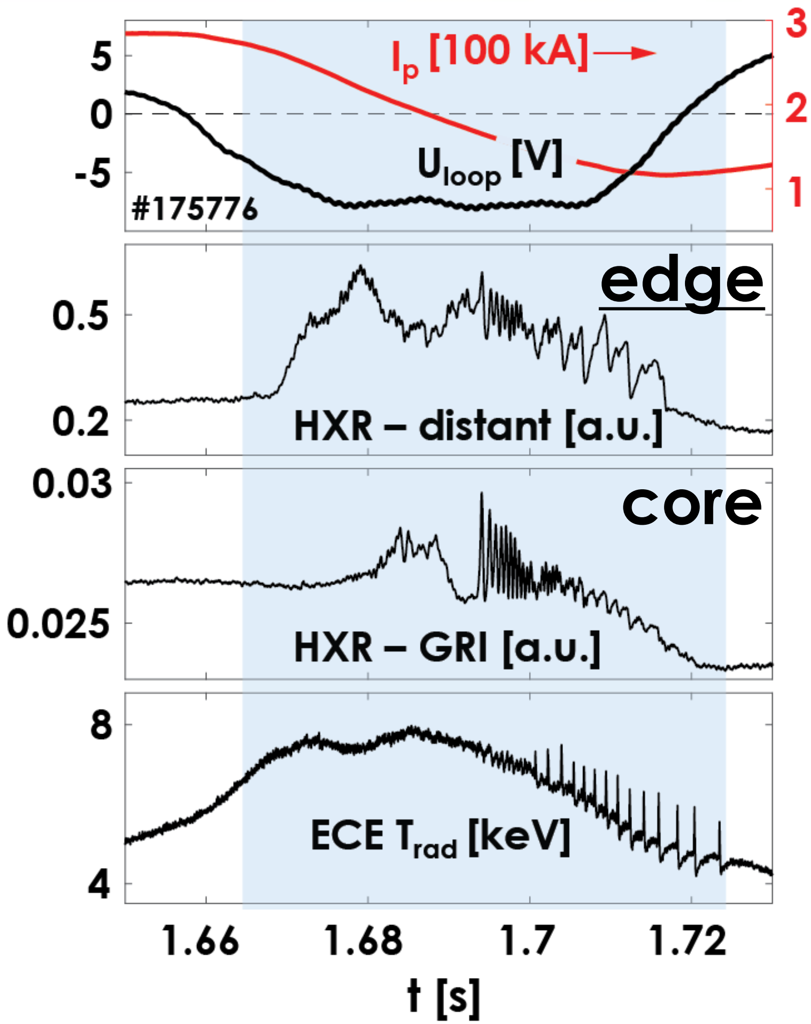

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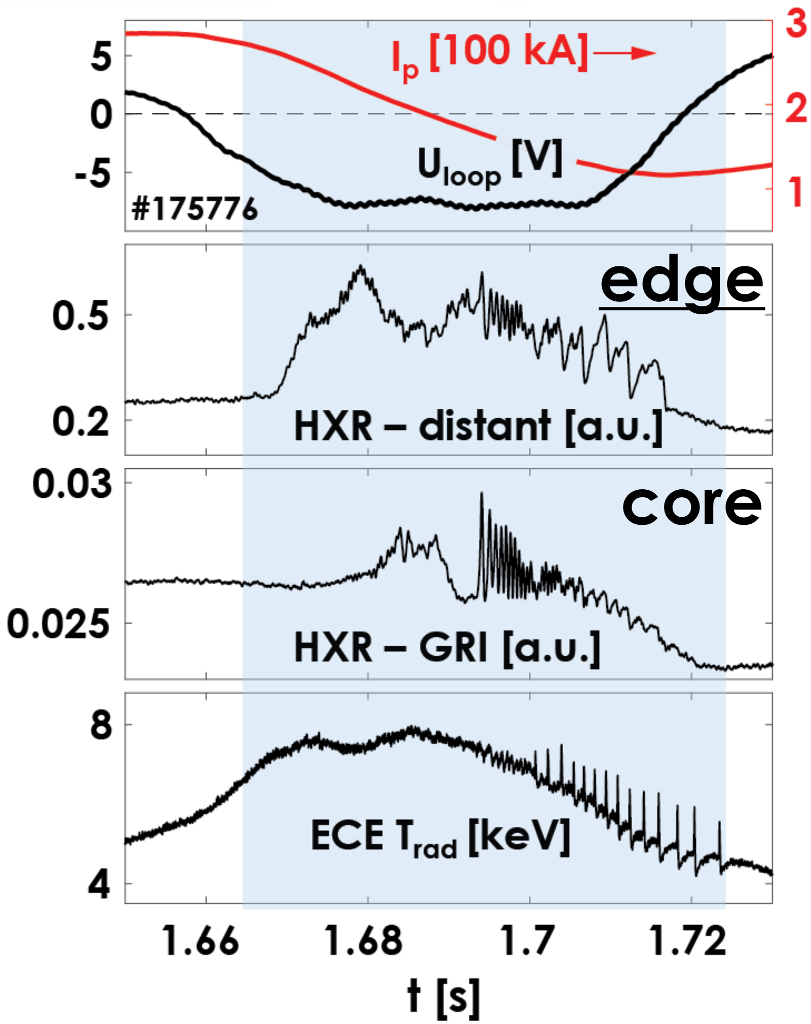
- **Large decelerating voltage with magnitude comparable with breakdown voltage is applied to RE beam**
- **This causes large fluctuations of edge and core hard X-ray signals (from lost and confined REs)**
- **Also, spikes of ECE are detected**

RE loss increases under decelerating loop voltage



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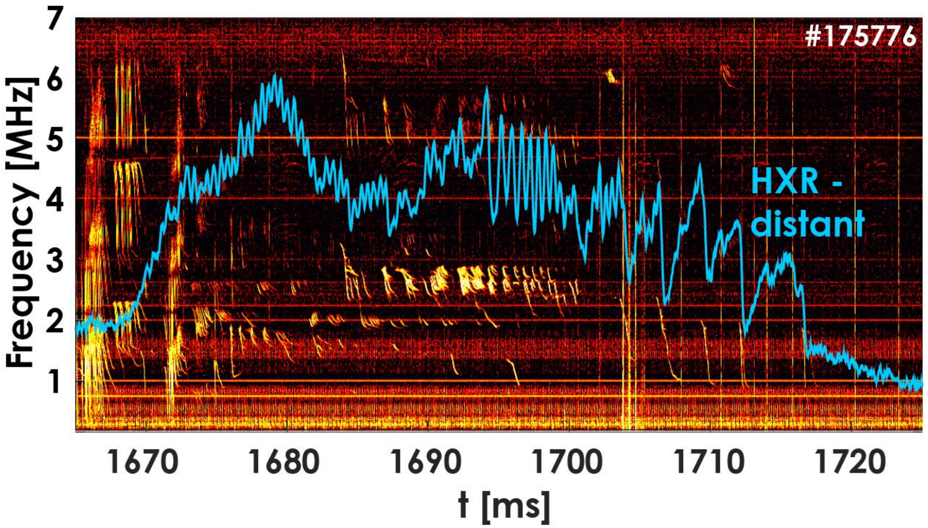
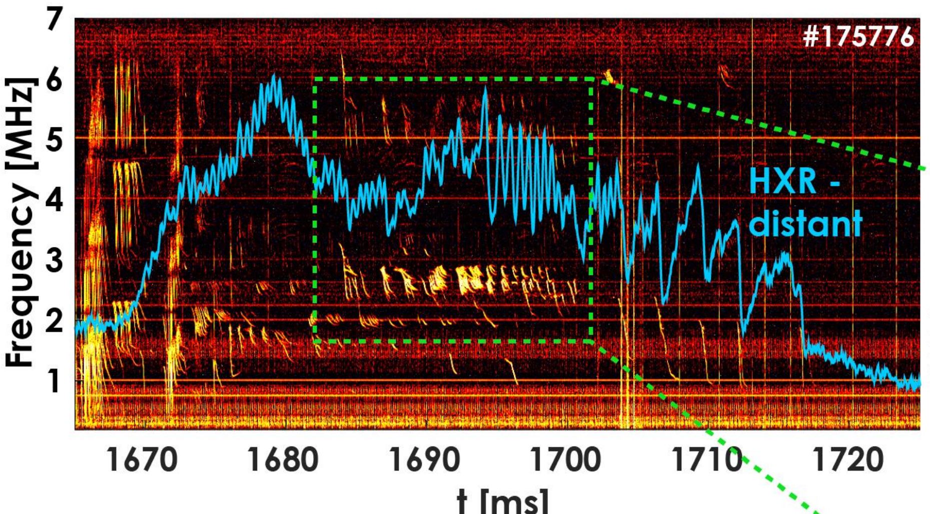
- Large decelerating voltage with magnitude comparable with breakdown voltage is applied to RE beam
- This causes large fluctuations of edge and core hard X-ray signals (from lost and confined REs)
- Also, spikes of ECE are detected
- **These are clear signs of RE-driven instabilities**

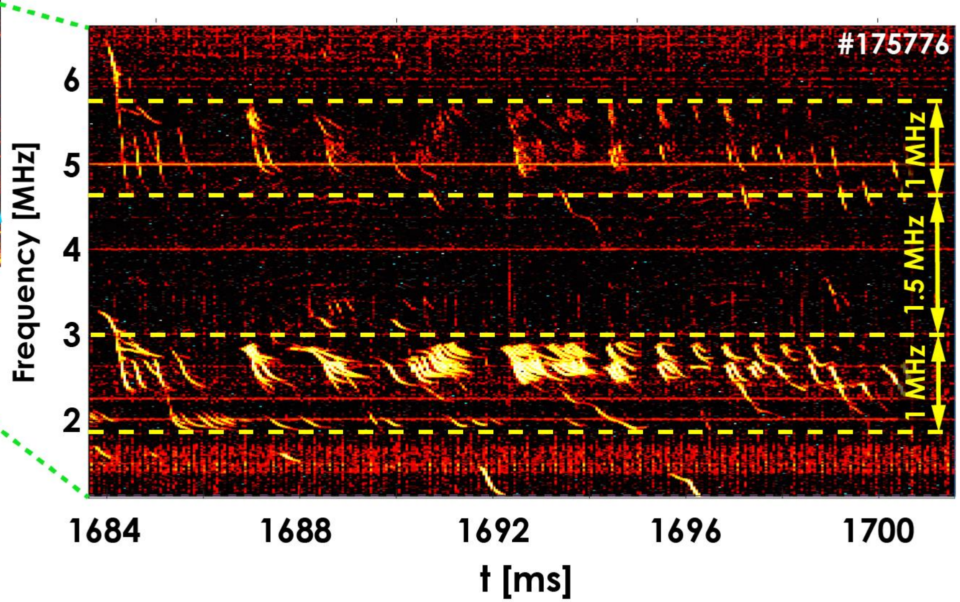
RE loss correlates with magnetic fluctuations at 1–7 MHz



- **Fluctuations of toroidal magnetic field are seen in spectrograms**

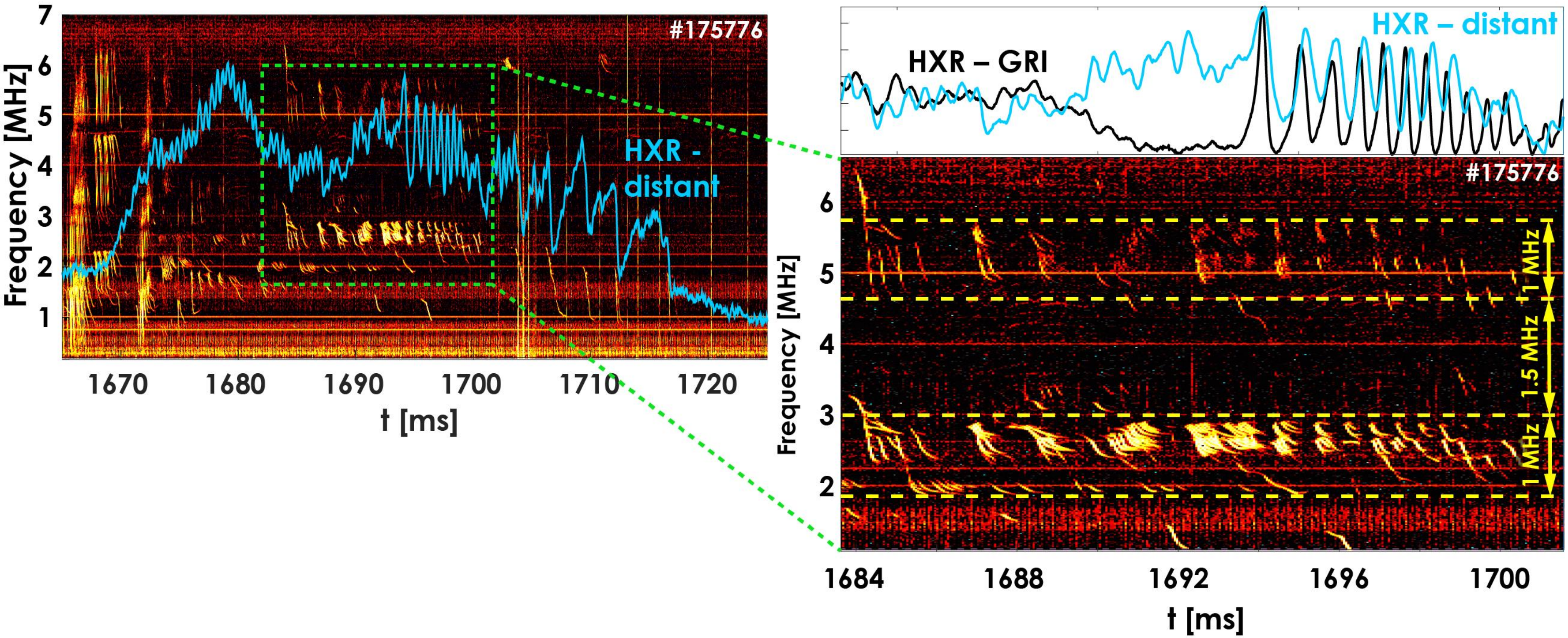
RE loss correlates with magnetic fluctuations at 1–7 MHz





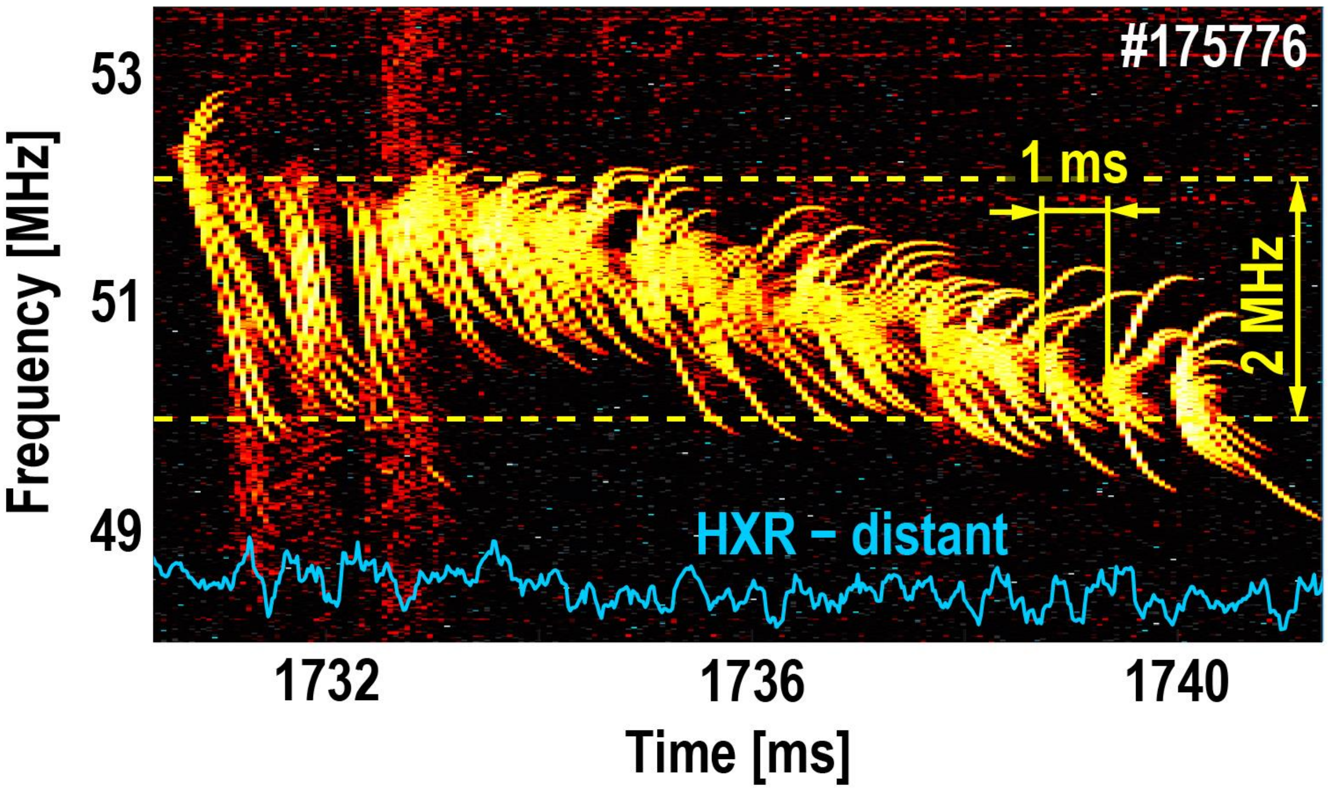
- Fluctuations of toroidal magnetic field are seen in spectrograms
- They have clear chirping nature

RE loss correlates with magnetic fluctuations at 1–7 MHz



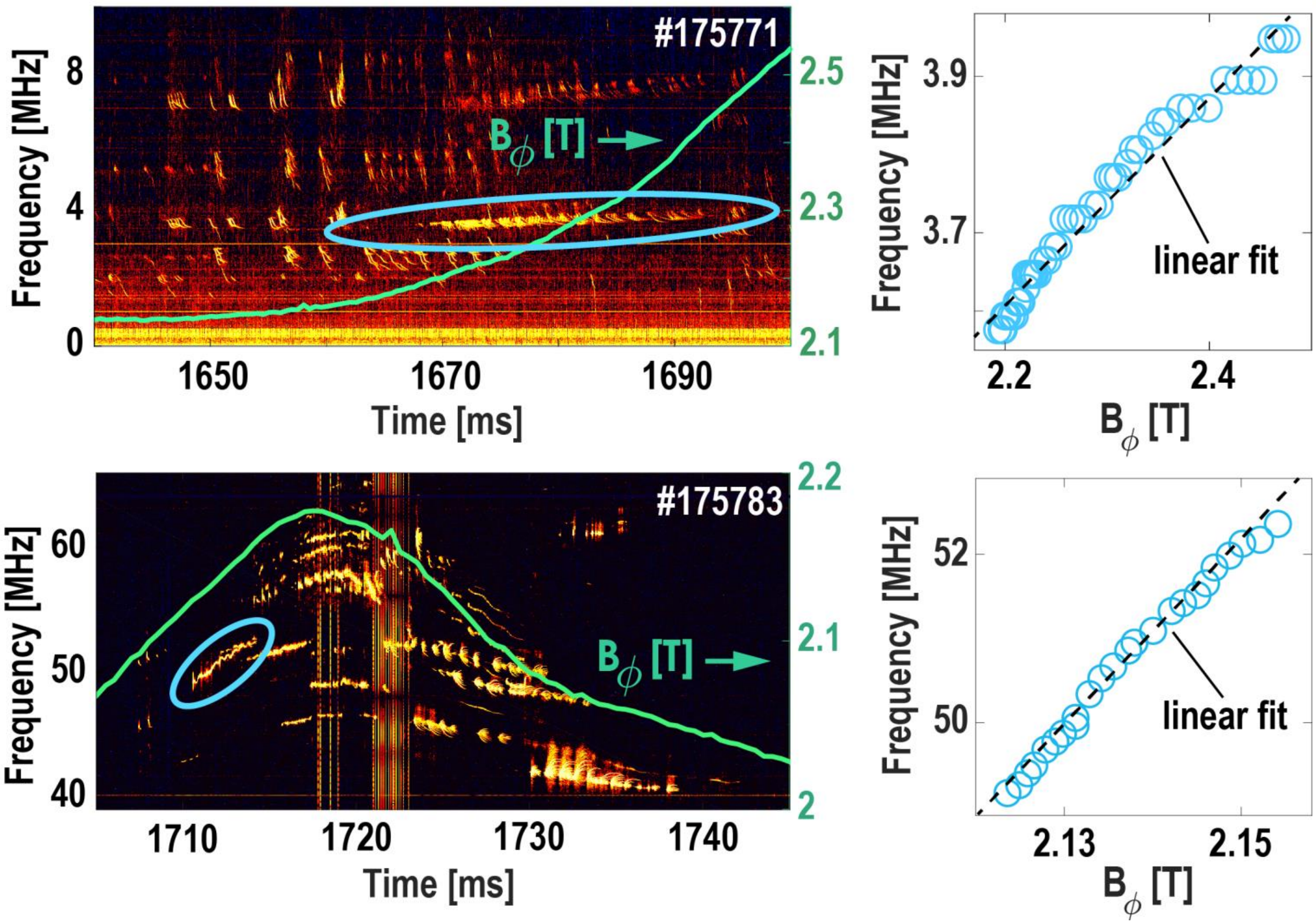
- Fluctuations of toroidal magnetic field are seen in spectrograms
- They have clear chirping nature and correlate with RE loss signal

High frequency range magnetic fluctuations (30–80 MHz) drive no significant RE loss



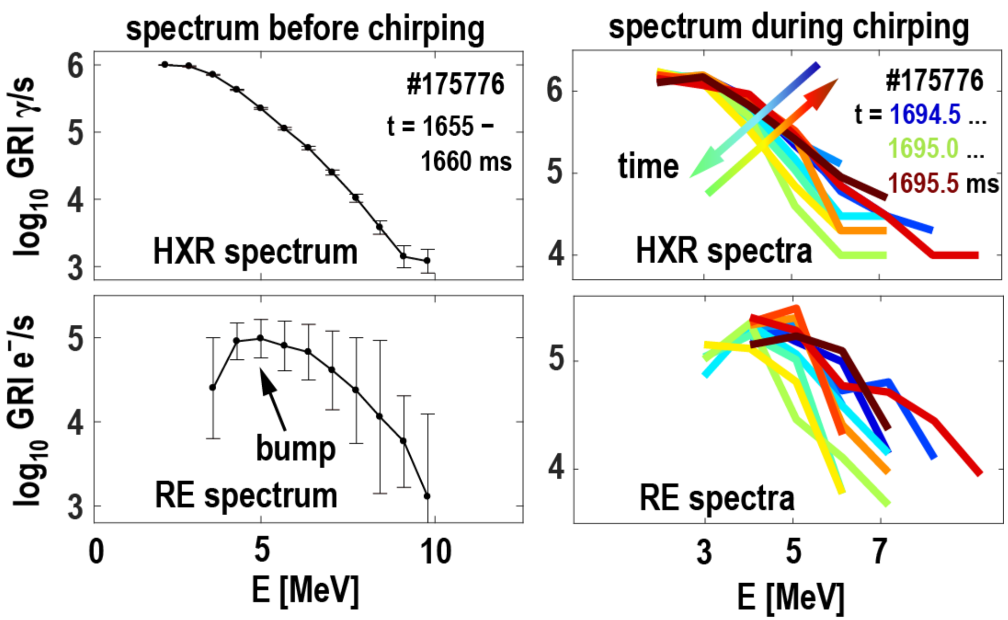
- Two frequency bands of magnetic fluctuations: 1–10 MHz and 30–80 MHz
- High frequency fluctuations do not drive any significant RE loss

Frequency of instabilities has Alfvénic dependence on B_ϕ



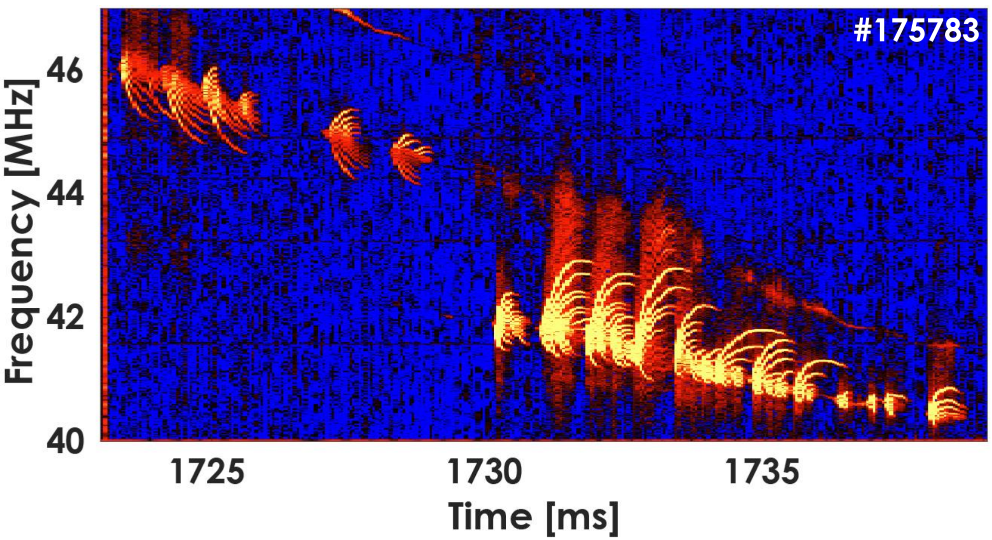
- RE beam moves to HFS and senses increasing B_ϕ
- $f(B_\phi)$ dependence is Alfvénic: $f_A \propto v_A \propto B_\phi$

Modification of RE energy distribution function is measured during frequency chirping



- RE distribution function measured before chirping observed has a bump
- Bump is a potential source of free energy to drive instabilities
- Its formation can be explained via RE acc. by electric field and collisional damping on D_2 bound electrons
- Relaxation of RE f(E) during chirping events is directly measured
- This supports interactions between REs and instabilities

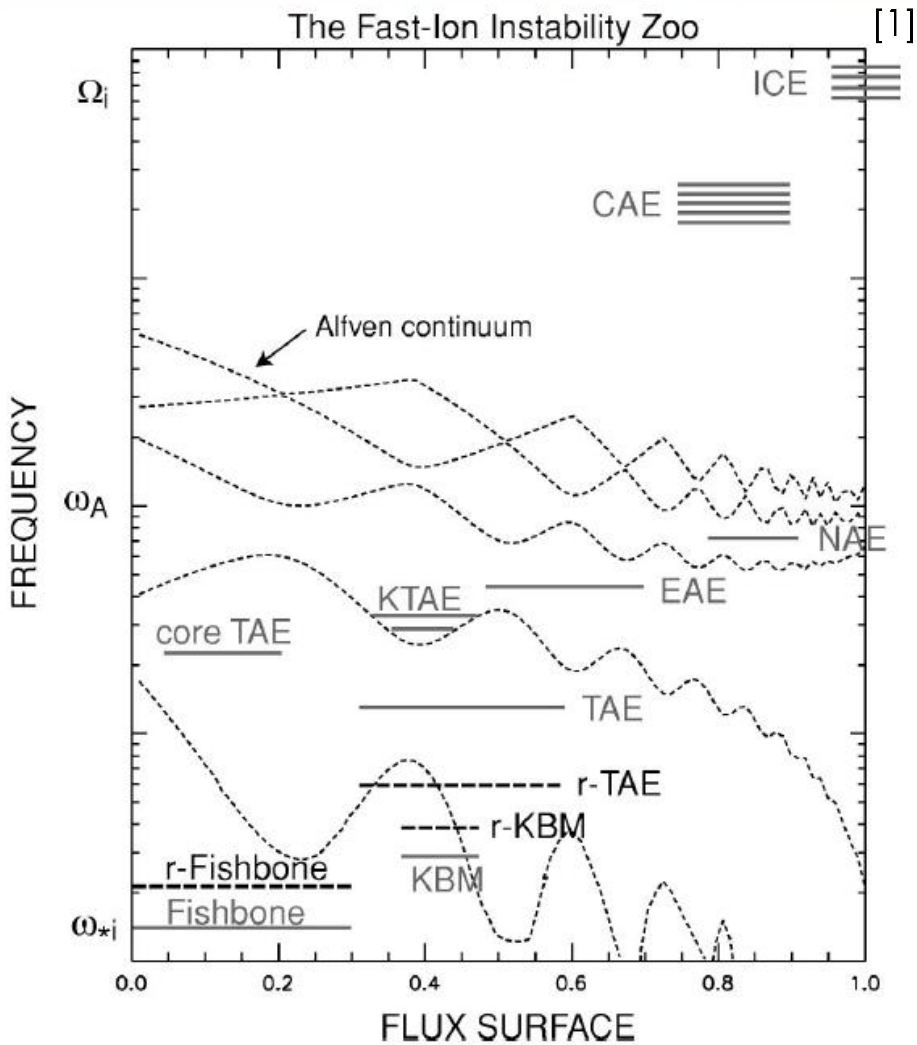
Possible mechanism of instabilities: REs drive Alfvénic waves, which scatter REs and increase RE loss



- Decelerating loop voltage presumably leads to strong non-monotonic feature (bump) at RE distribution function
- This excites Alfvénic waves
- Alfvénic waves interact with REs, scatter them and increase RE loss
- Fast relaxation of RE distribution function can explain freq. chirping consistent with hole-clump model [1]
- Fast pitch-angle scattering of REs can cause the observed ECE spikes

[1] Berk, Breizman, Ye PRL 1992

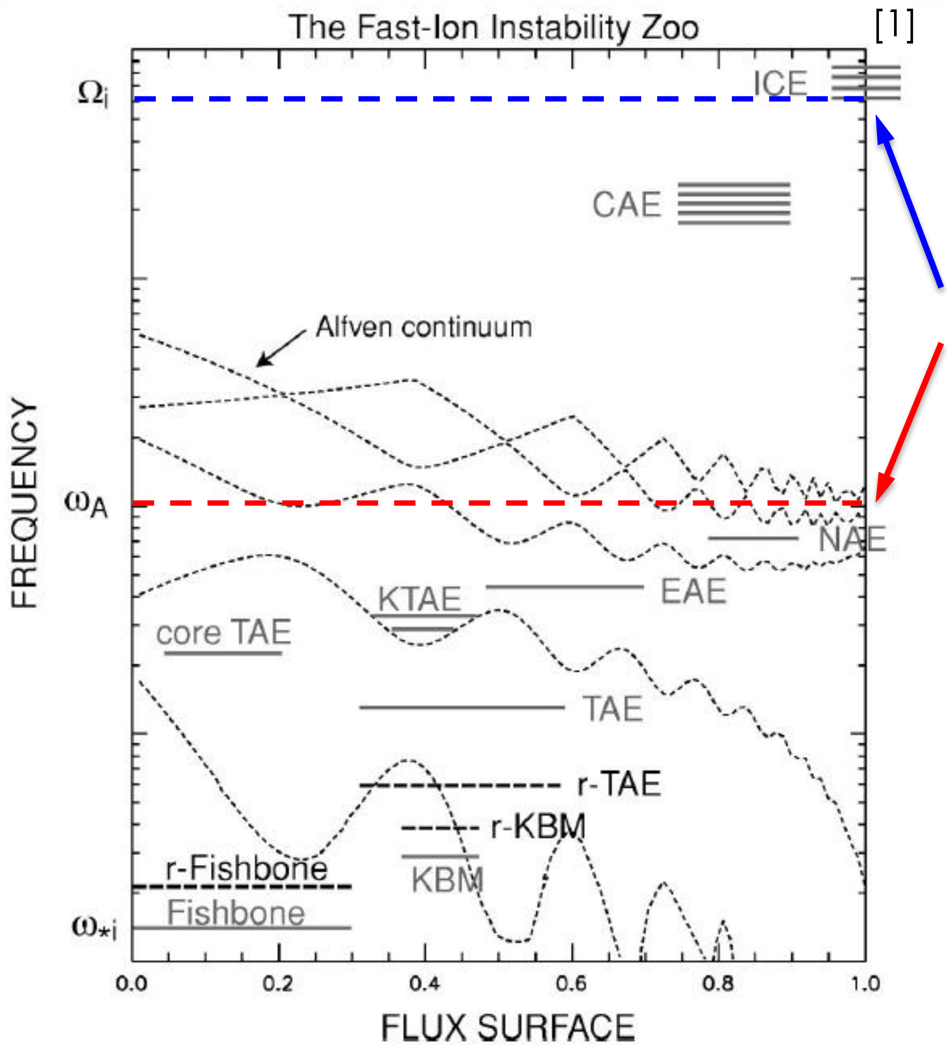
Compressional Alfven eigenmodes are most likely candidates for observed instabilities



- **Frequency of observed instabilities lies between 1–10 MHz**

[1] Heidbrink PoP 2002

Compressional Alfven eigenmodes are most likely candidates for observed instabilities

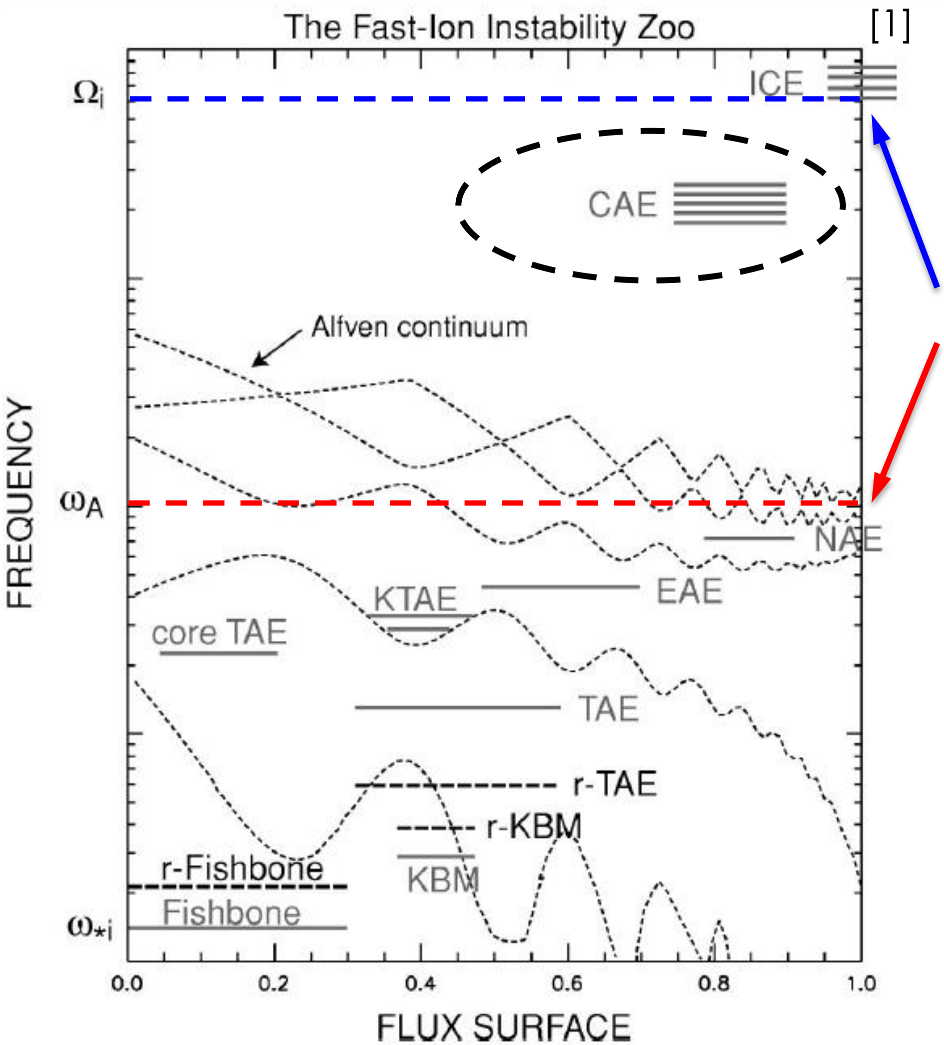


- **Frequency of observed instabilities lies between 1−10 MHz**

- **For given plasma parameters:**
  - $f_{ci} \approx 15$ **MHz**
  - $f_A \approx 1.5$ **MHz**

[1] Heidbrink PoP 2002

Compressional Alfven eigenmodes are most likely candidates for observed instabilities



- **Frequency of observed instabilities lies between 1−10 MHz**
- **For given plasma parameters:**
  - $f_{ci} \approx 15$ **MHz**
  - $f_A \approx 1.5$ **MHz**
- **Compressional Alfven eigenmodes (CAEs) are most likely candidates for kinetic instabilities in the observed frequency region**
- Separated loops needed for measurements of toroidal and poloidal numbers (planned)

[1] Heidbrink PoP 2002

Outline

New physics of RE beam:

- Energy distribution function
- Current density profile
- Internal MHD instability
- External kink instability
- **Frequency chirping instabilities**

Conclusion

RE-driven frequency chirping instabilities are observed for the first time under decelerating voltage

Low-frequency instabilities (1−10 MHz) correlate with intermittent RE loss

Modification of RE distr. function is measured during chirping in low-frequency range consistent with hole-clump model

Instabilities are likely CAEs driven by non-monotonic RE distr. function

Summary

- **RE beam equilibria and RE-driven instabilities are studied in low density post-disruption plasma**
- **Spatially resolved RE beam energy distr. funct. obtained for the first time**
  - It has a bump at 5 MeV observed only in the core suggesting possibility of kinetic instabilities
- **RE beam current density profile is constrained via HXR measurements**
  - It is more peaked than the pre-disruption plasma but found to be stable likely due to its elevated q profile
- **RE beam MHD instabilities are excited at large accelerating voltage**
  - Presumably internal 1/1 kink instabilities are observed at low current and large q_a, but these instabilities drive no RE loss
  - As RE current increases and q_a decreases, magnetic bursts become larger and cause RE loss
  - RE beam is completely lost when $q_a \approx 2$ and $\delta B_p = 1$ kG
- **RE-driven frequency chirping instabilities are observed for the first time**
  - Low-frequency (1−10 MHz) modes increase RE loss
  - Likely Compressional Alfven Eigenmodes (CAEs)

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Summary

1. **Spatially resolved RE beam energy distr. func. obtained for the first time**
   - It has a bump at 5 MeV observed only in the core suggesting possibility of kinetic instabilities
2. **RE beam current density profile is constrained via HXR measurements**
   - It is more peaked than the pre-disruption plasma but found to be stable likely due to its elevated q profile
3. **RE beam MHD instabilities are excited at large accelerating voltage**
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   - As RE current increases and q_a decreases, magnetic bursts become larger and cause RE loss
   - RE beam is completely lost when $q_a \approx 2$ and $\delta B_p = 1$ kG
4. **RE-driven frequency chirping instabilities are observed for the first time**
   - Low-frequency (1−10 MHz) modes increase RE loss
   - Likely Compressional Alfven Eigenmodes (CAEs)

In more detail:

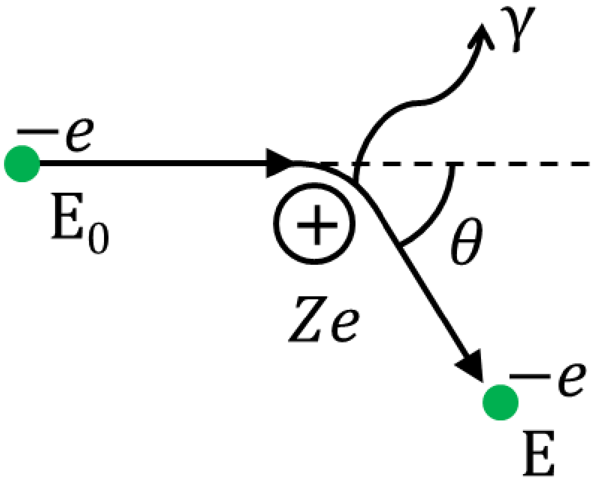
[1,2,3] Lvovskiy *et al* To be submitted to NF
[3] Paz-Soldan *et al* PPCF 2019
[3] YQ Liu *et al* To be submitted to NF
[4] Lvovskiy *et al* Submitted to NF

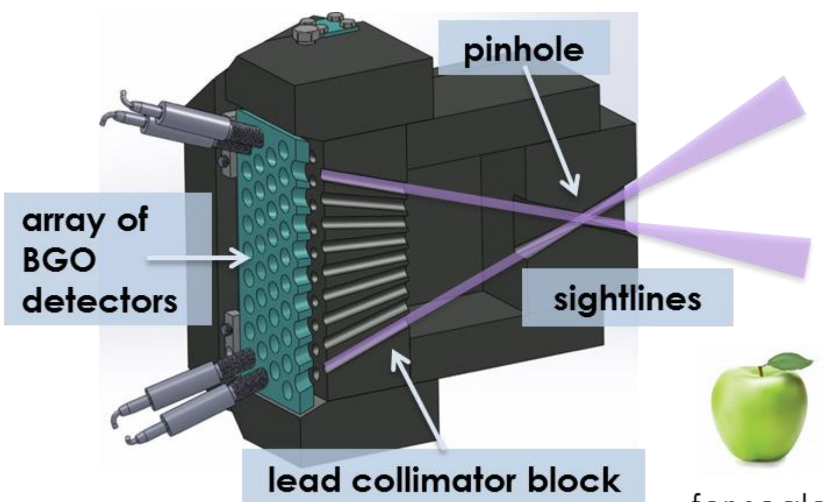
Acknowledgments and Disclaimer

- This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under U.S. DOE Frontier Science Program and Award DE-FC02-04ER54698.

Backup slides

Backup: Bremsstrahlung radiation provides information on energy and distribution of REs





- When electron changes its trajectory it emits photons
- MeV electrons → MeV γ rays
- γ rays (HXRs) are forward beamed based on RE energy
- $f_e(E_\parallel, E_\perp)$ produces unique bremsstrahlung spectrum
- DIII-D gamma ray imager (GRI) provides 2D view of RE bremsstrahlung emission [1–4]

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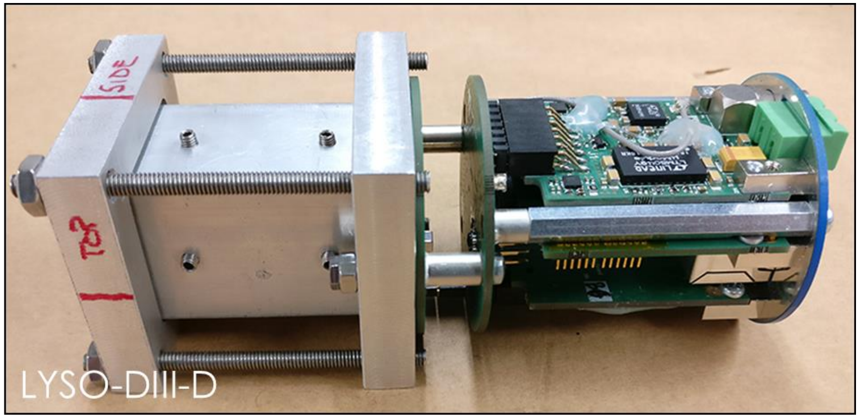
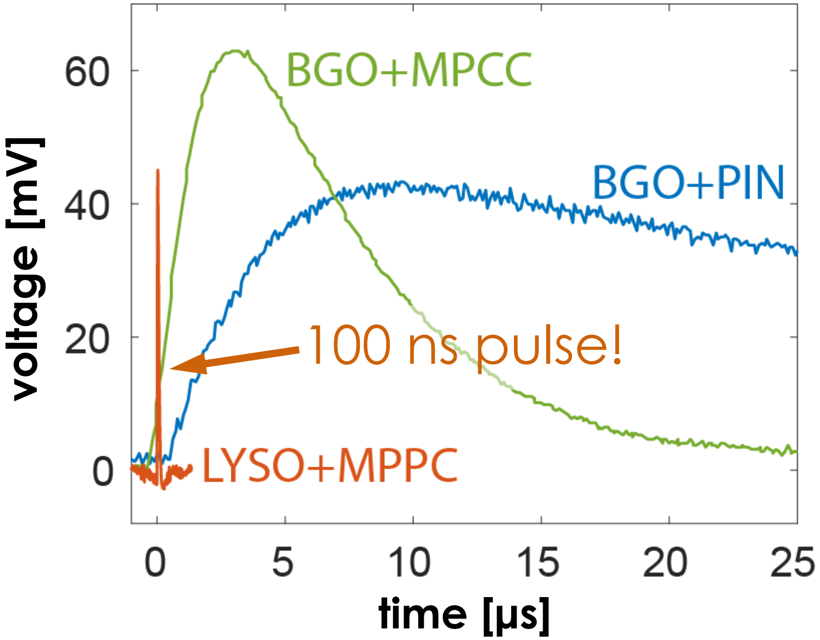
[1] Pace *et al*. RSI 2016
[2] Cooper *et al*. RSI 2016
[3] Paz-Soldan *et al*. PRL 2017
[4] Paz-Soldan *et al*. PoP 2018

Backup: Measurements during the RE plateau regime are challenging – upgrade with fast gamma detectors

- Gamma flux due to bremsstrahlung emission is higher by 10^3–10^4 in RE plateau regime compared to QRE
- BGO detectors are usually saturated after the disruption
- New LYSO+MPPC detectors are capable to measure during the post-disruption stage

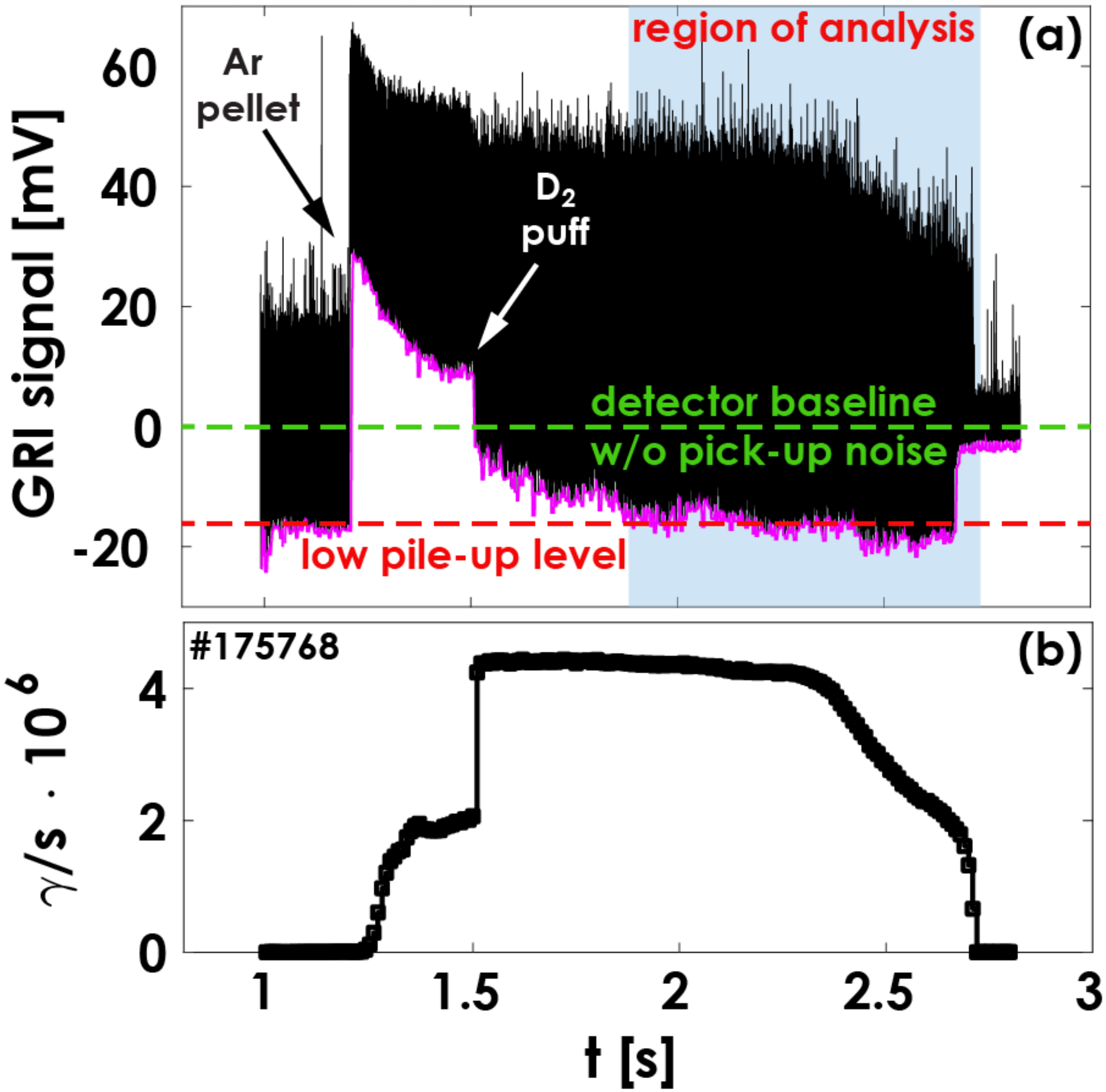
Collaboration with U. Milano-Bicocca



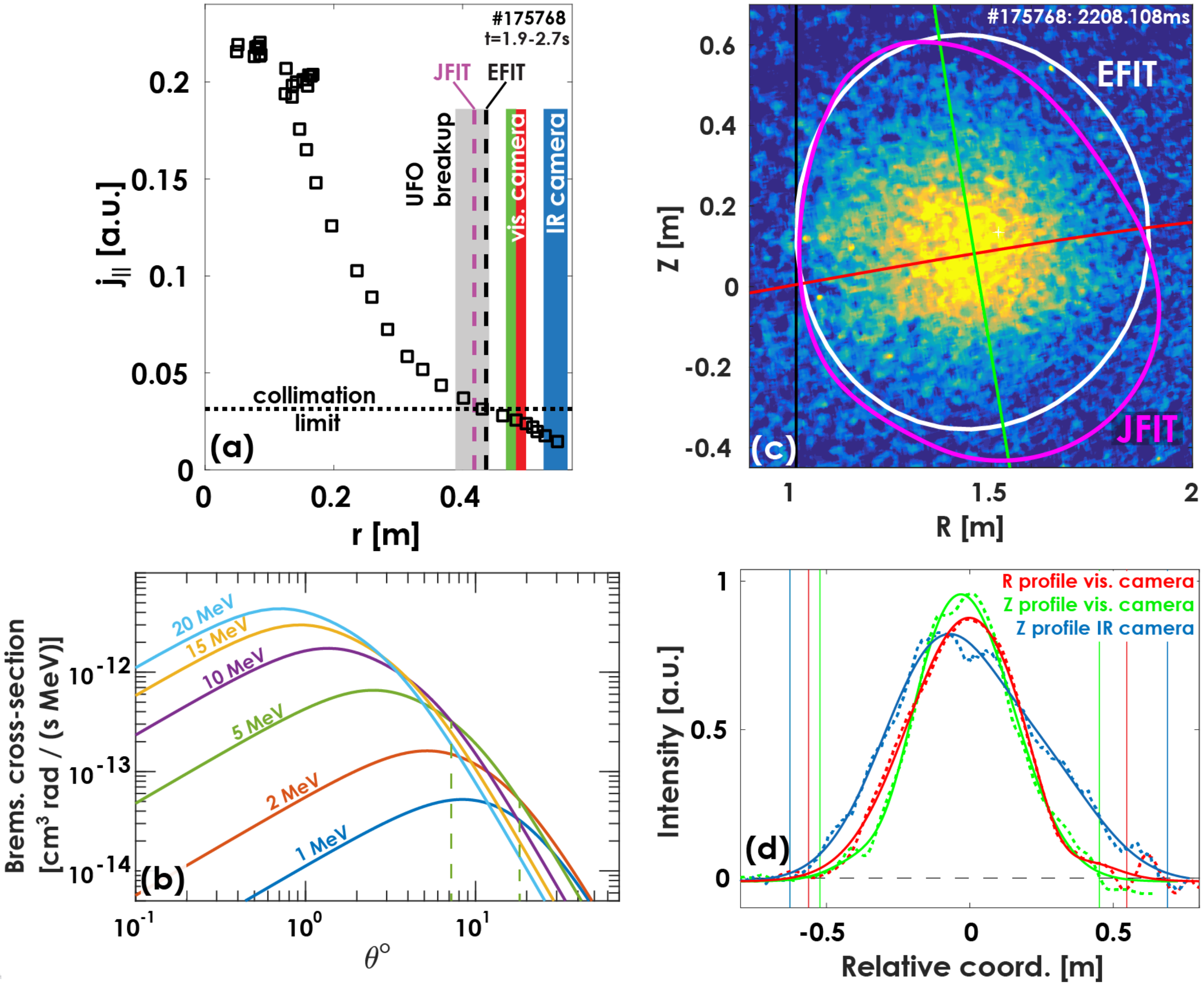


Response of gamma detectors to a single gamma pulse

Backup: HXR spectrum is obtained at small pile-up level



Backup: on determination of RE beam radius



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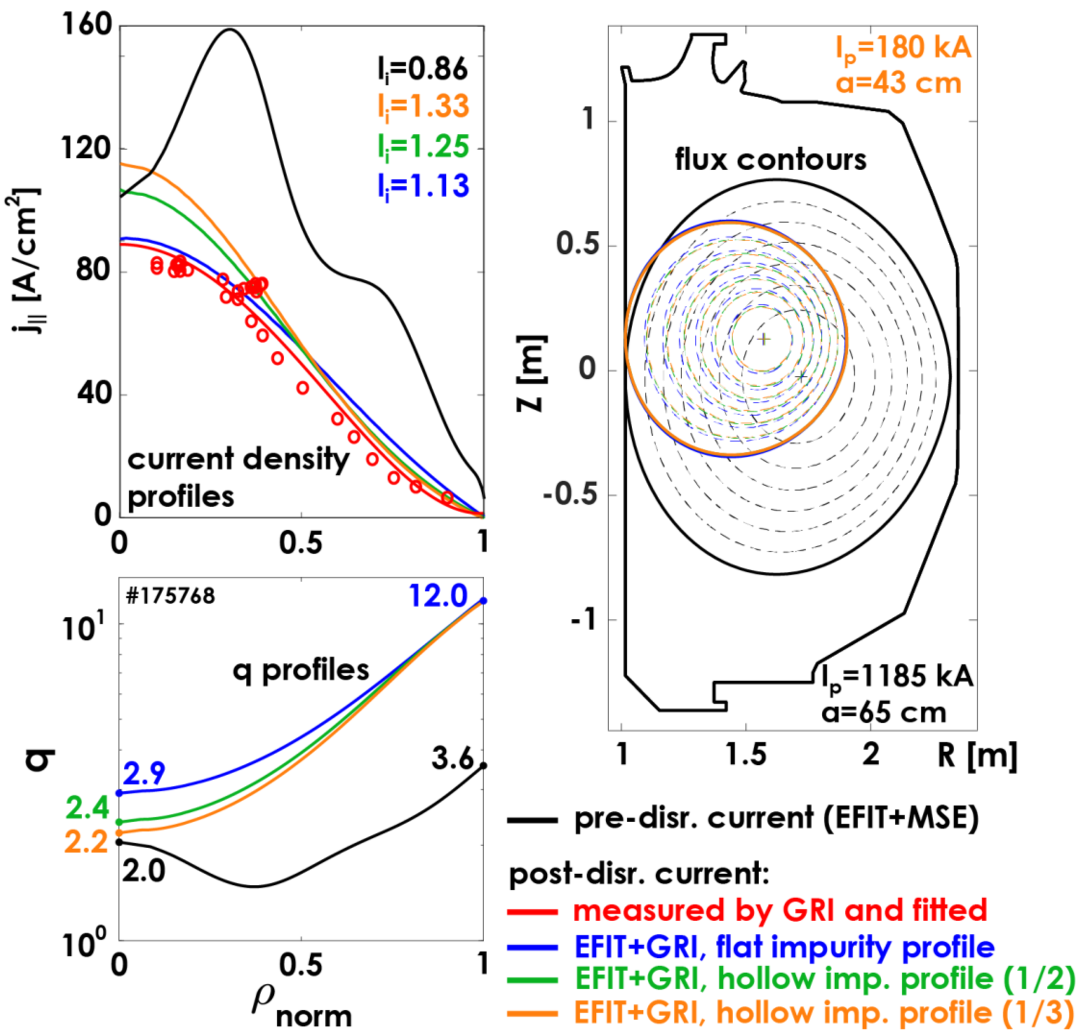
A. Lvovskiy/TSDW/August 2019

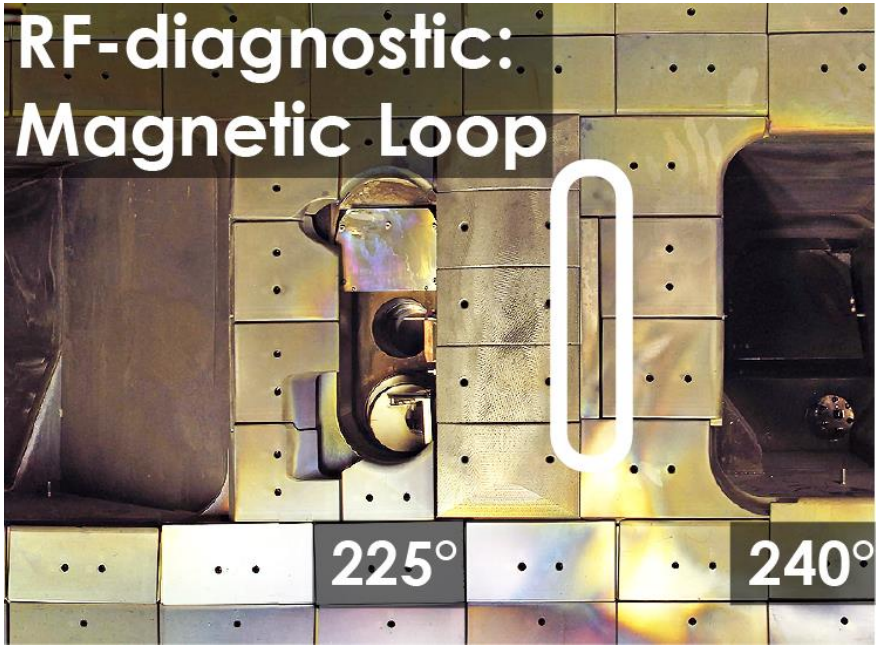
Backup: RE current profile for hollow impurity profile



- **Post-disruption current profile is more peaked than pre-disruption current with greater l_i=1.13 vs 0.86**
- **Post-disruption relatively small RE current (180 kA) is found stable likely due to elevated q profile**
- **RE plateau sustains as long as there is transformer flux to drive it (observed up to 1.5 s)**
- **Peaking observed even for flat impurity profile**

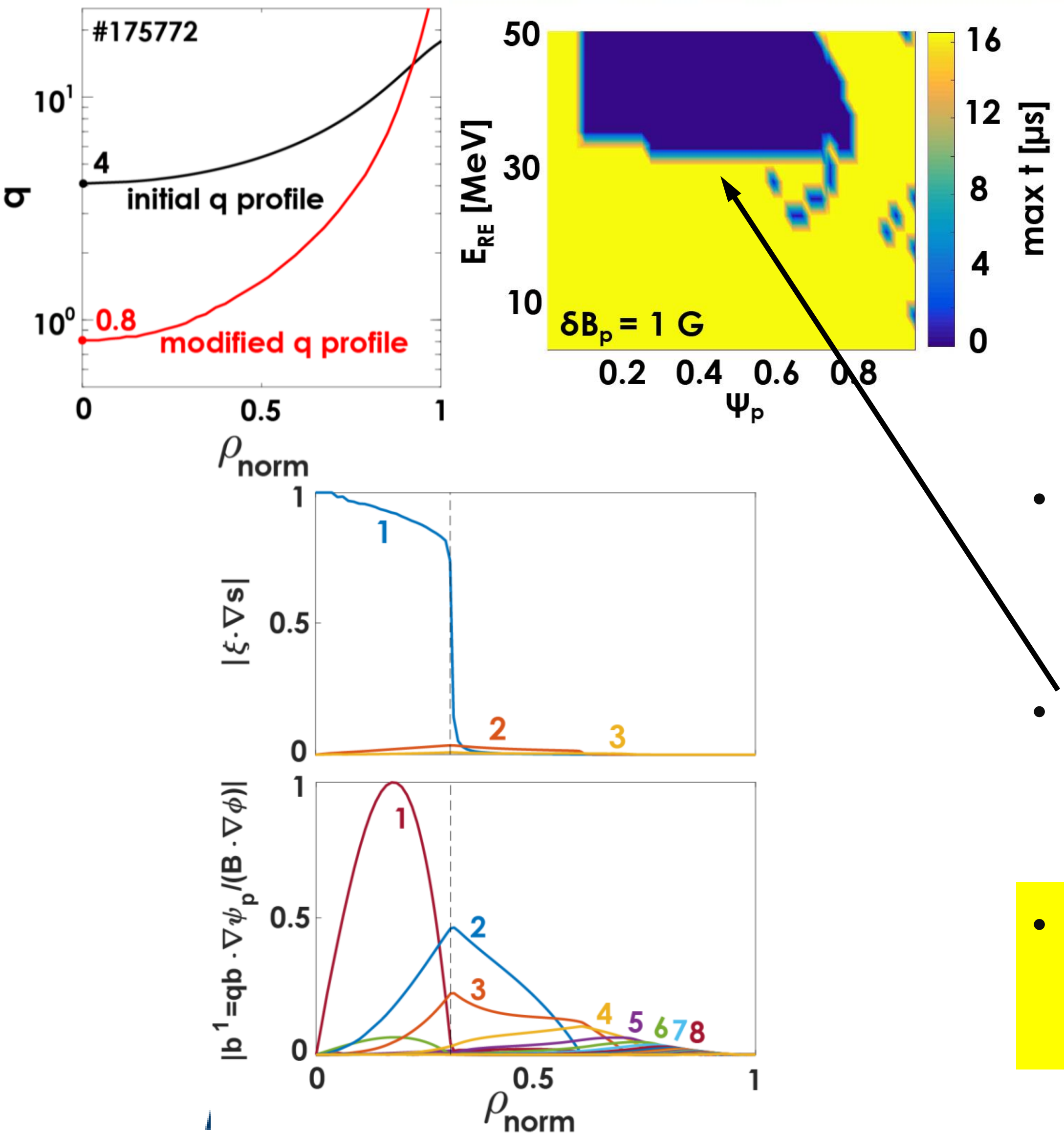
Backup: RE-driven plasma waves are detected via high-frequency measurements of magnetic signals

- **Energetic REs can lead to excitation of plasma waves *(like fast ions)***
- **Plasma waves can increase dissipation of REs**
- **New paths to mitigate REs via kinetic instabilities can be potentially discovered**
- **High-frequency fluctuations of toroidal magnetic field are detected by RF-diagnostic [1,2]**



[1] Watson and Heidbrink RSI 2003
[2] Thome *et al*. RSI 2018

Backup: Even 1 G fluctuations can cause loss of only 30+ MeV REs



Initial stable current profile is modified to obtain q_0=0.8 at constant full current

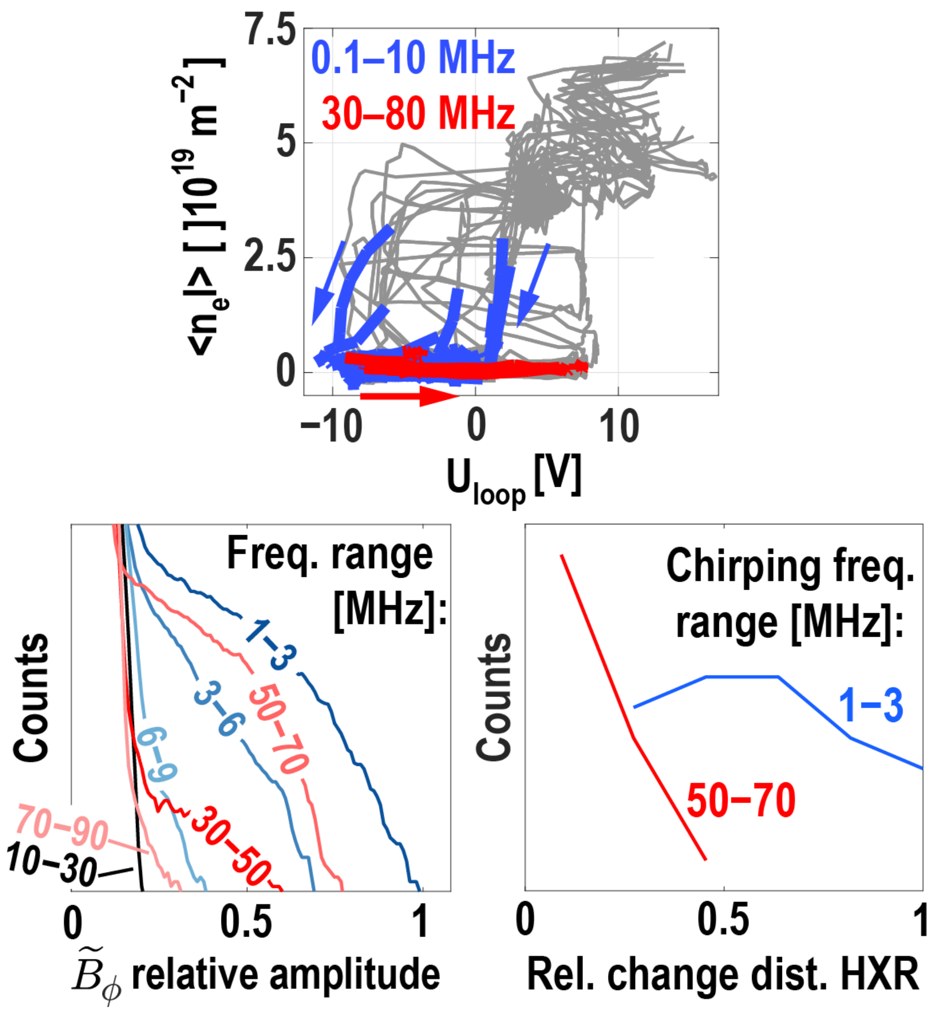
Peaked current profile leads to strong ideal internal 1/1 kink mode according to MARS-F simulations

- Weak edge modes support lack of external magnetic signals detected in experiment

- Poloidal fluctuations even as large as 1 G lead to loss of only 30+ MeV REs

- **Both experiment and modelling show no effect of internal kink on RE loss and global confinement**

Backup: Chirping in low frequency range causes strongest RE loss



- Instabilities are observed in two distinct frequency ranges: 1−10 MHz and 30−80 MHz
- They are triggered at low plasma density and decelerating voltage
- Low freq. chirping (1−3 MHz) causes the strongest magnetic fluctuations
- Low freq. chirping (1−3 MHz) causes the strongest change of RE loss signal
- Δf changes by 0.3−2.4 MHz on 0.1 ms (local width) and 0.3-1.8 ms (full width) time scales

Backup: Operational space of MHD and kinetic instabilities