Impact of initial plasma current and injected argon quantity on the runaway electron seed distribution

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ORAU

= Motivation =

- **Various systems of pellet and massive gas injection are routinely used in disruption studies on DIII-D**
- **Runaway electron (RE) plateau experiments are usually triggered by Ar killer pellets:**
  - Very reliable RE plateau generation
- **Disruptions triggered by Ar MGI:**
  - 60-70% success rate of RE plateau generation
- **There is no clear explanation of such results**

Formation of RE plateau in DIII-D using Ar MGI can be a hard thing: Example

177028	no RE plateau
177029	no RE plateau
177030	OK
177031	OK
177032	no RE plateau
177033	OK
177034	no RE plateau
177035	OK
177036	OK
177037	OK
177038	OK
177040	OK
177041	no RE plateau
177042	OK
177043	OK
177044	no RE plateau
177045	no RE plateau
177046	OK
177047	no RE plateau

RE plateau experiment in May 2018

- triggered by Ar MGI
- **60% success rate**
- hardware issues are not included

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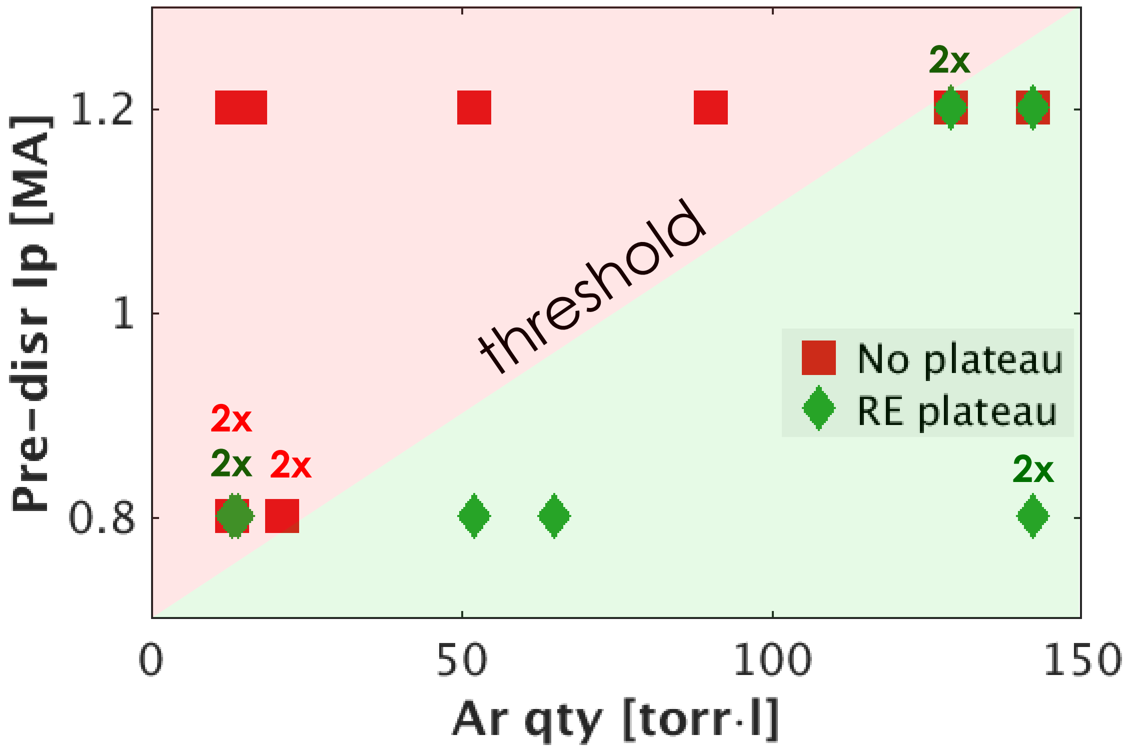
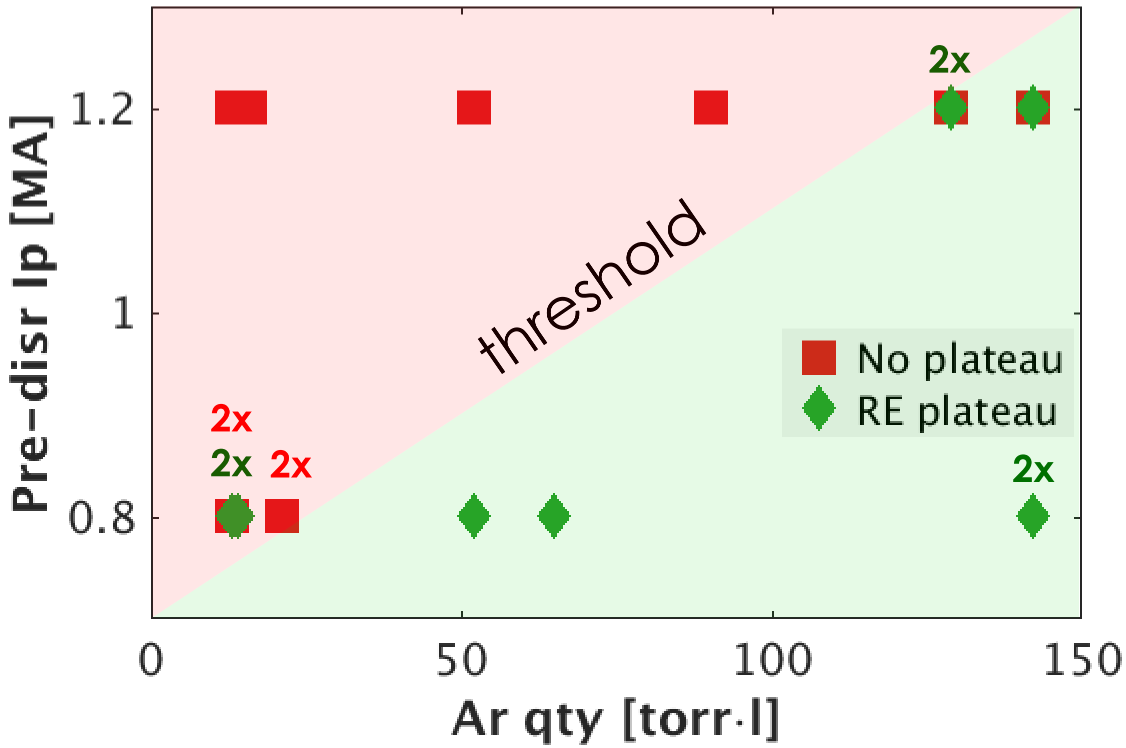
Formation of RE plateau depends on amount of injected Ar



More Ar injected – higher success of RE plateau formation

Formation of RE plateau depends on amount of injected Ar



More Ar injected – higher success of RE plateau formation

Large pre-disruption plasma current increases the Ar threshold

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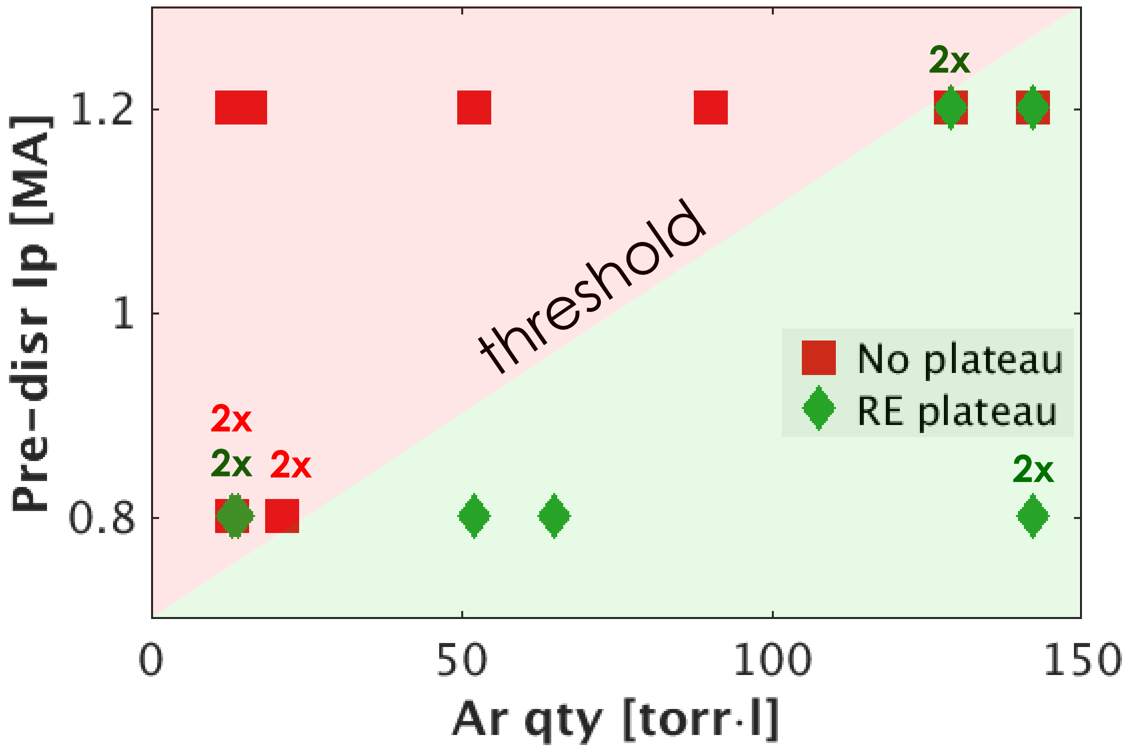


More Ar injected – higher success of RE plateau formation

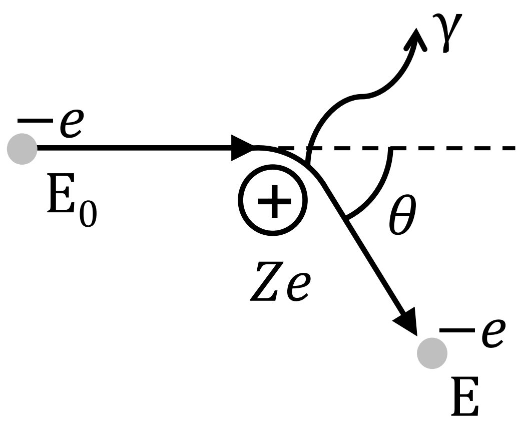
Large pre-disruption plasma current increases the Ar threshold

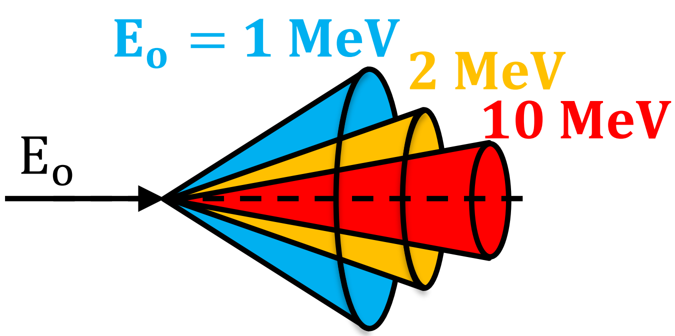
Can both dependencies be explained?

= Key diagnostics =

- DIII-D is equipped with many world-class diagnostics
- Some diagnostics are not common among machines
- Gamma Ray Imager and Ion Cyclotron Emission diagnostic (measures fast magnetic fluctuations) are essential for RE studies

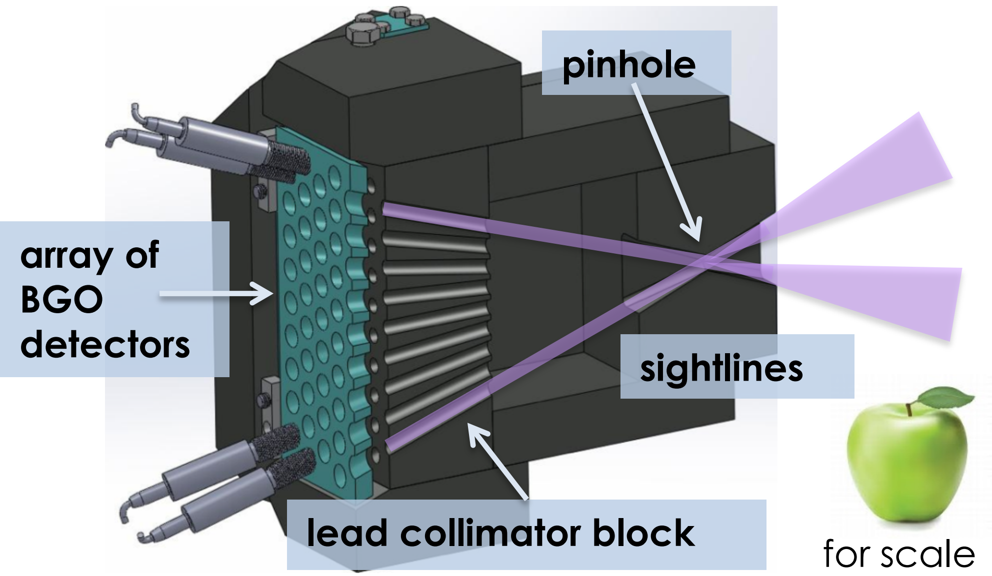
Bremsstrahlung radiation provides information on energy and distribution of REs





- γ rays are emitted in cones based on RE energy
- $f_e(E_\parallel, E_\perp)$ produces unique bremsstrahlung spectrum

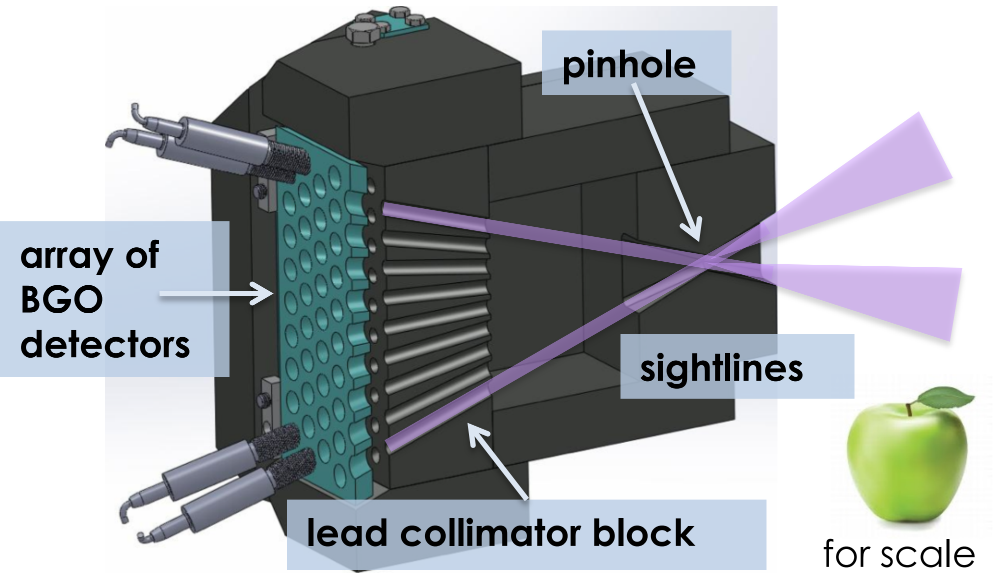
DIII-D gamma ray imager (GRI) provides 2D view of RE bremsstrahlung emission

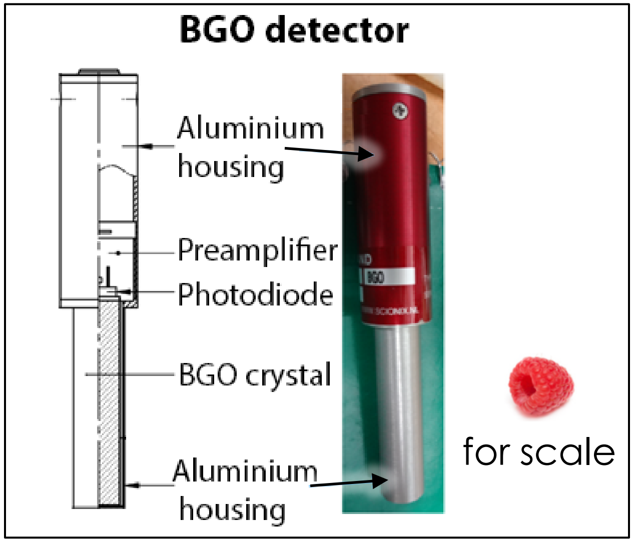


- GRI is a pinhole camera
- Its array consists of gamma scintillator detectors (up to 123 places)
- Body and collimator block are made of lead (≈ 190 kg)

Pace et al. RSI 2016

DIII-D gamma ray imager (GRI) provides 2D view of RE bremsstrahlung emission





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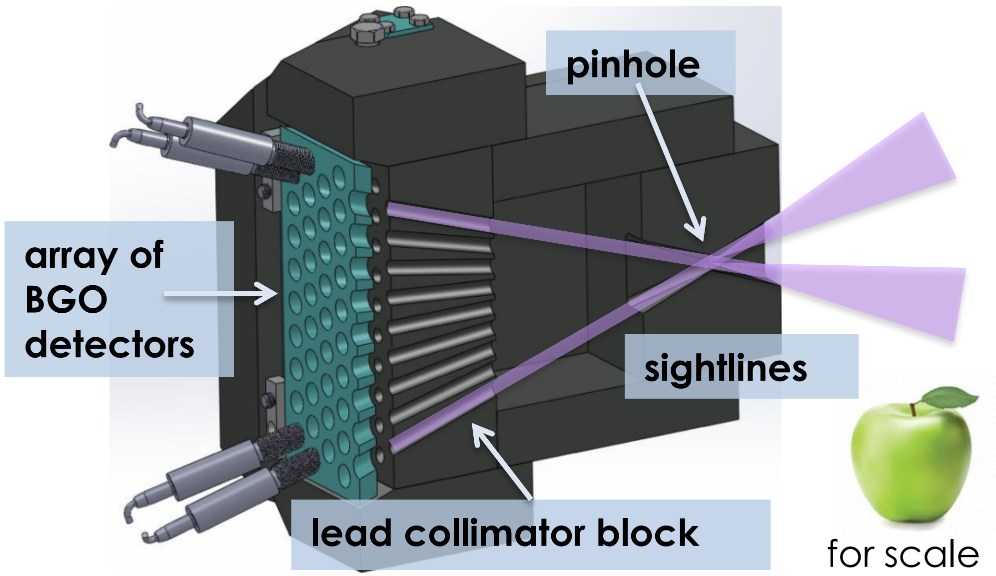

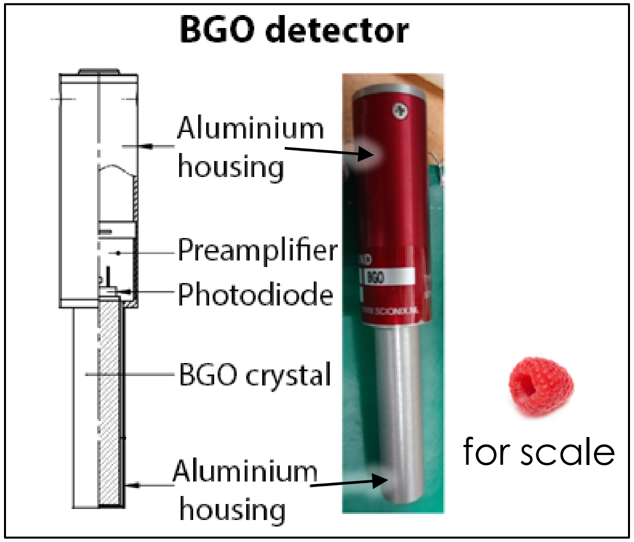

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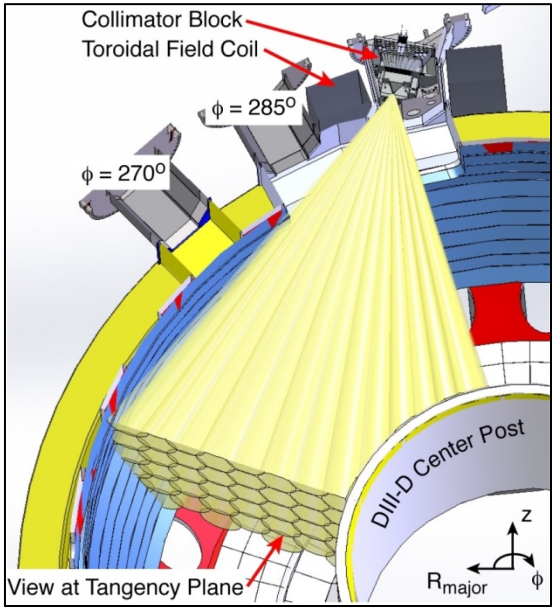
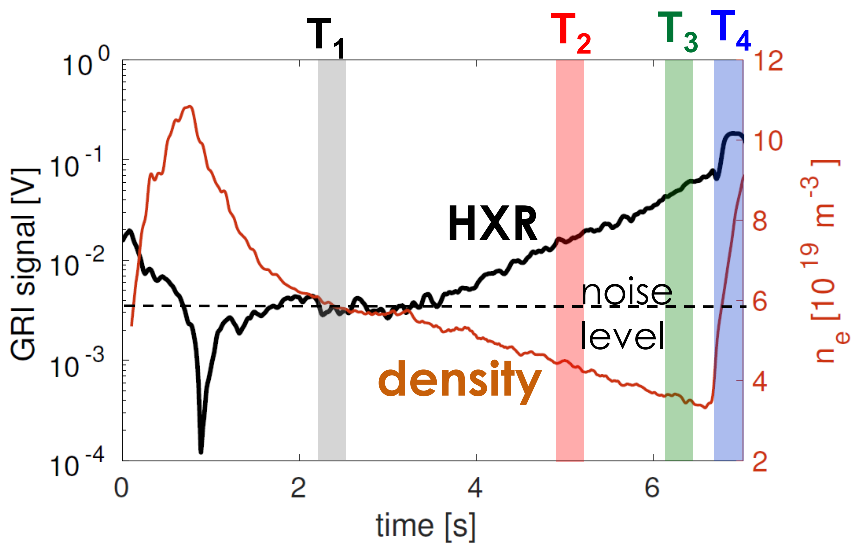


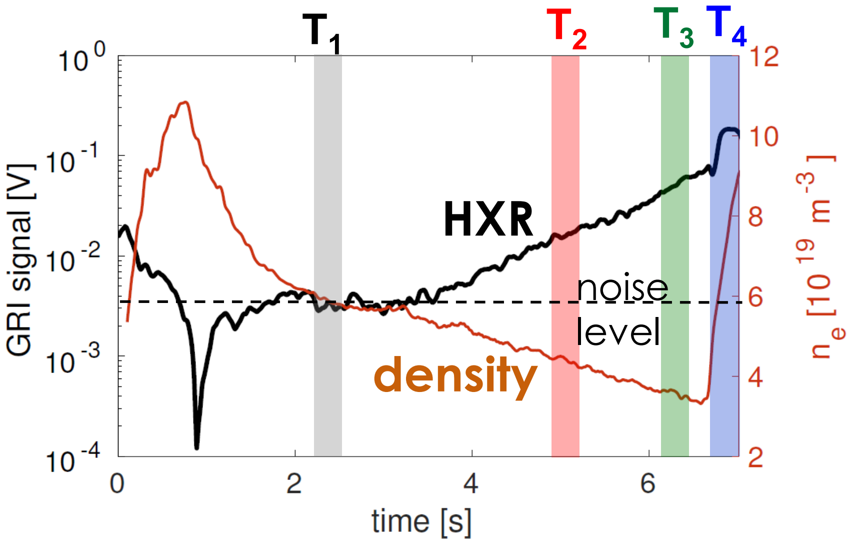
DIII-D toroidal cross-section

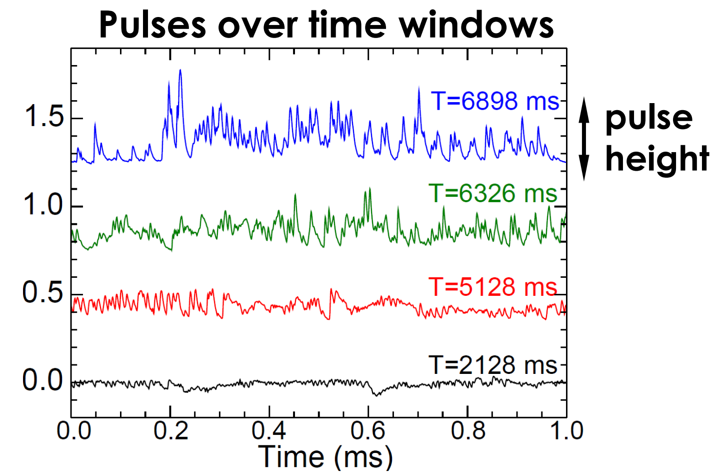
Bremsstrahlung spectra can be found using pulse height analysis. Example: QRE shot



- **Time traces are comprised of pulses from distinct gamma particles**

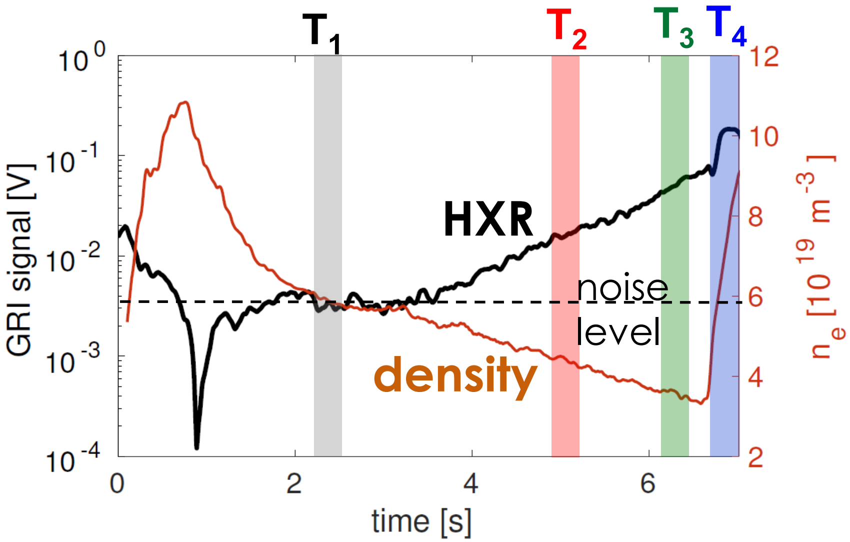
Bremsstrahlung spectra can be found using pulse height analysis. Example: QRE shot

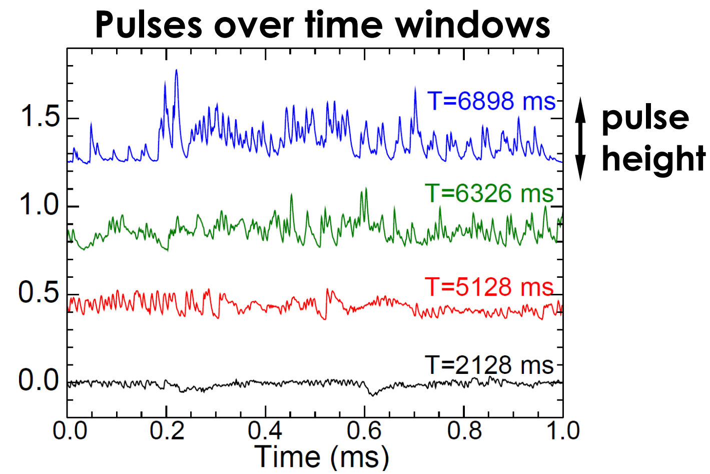


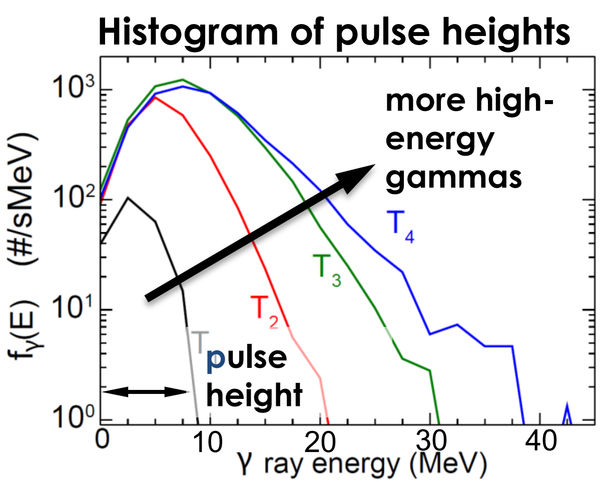


- **Time traces are comprised of pulses from distinct gamma particles**
- **Gamma particles are analyzed via pulse height analysis (PHA)**

Bremsstrahlung spectra can be found using pulse height analysis. Example: QRE shot







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- Bremsstrahlung spectrum hardens in the course of time

Cooper et al. RSI 2016

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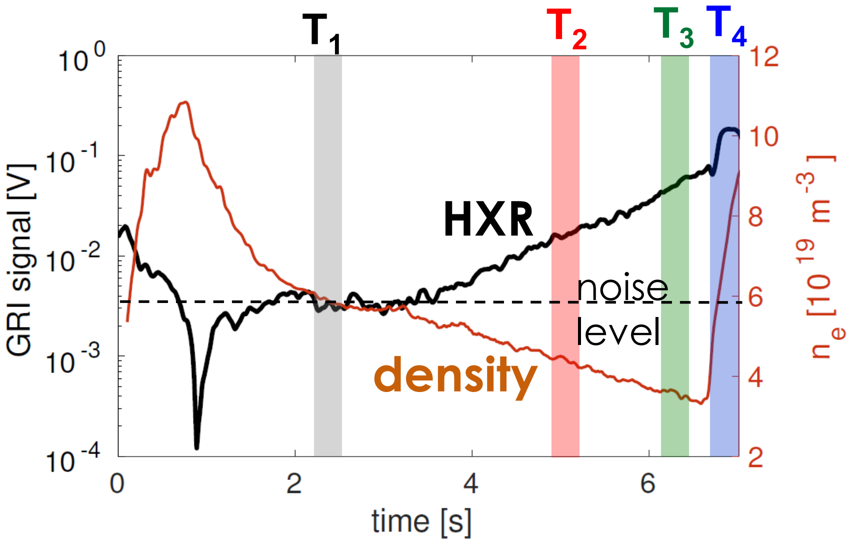
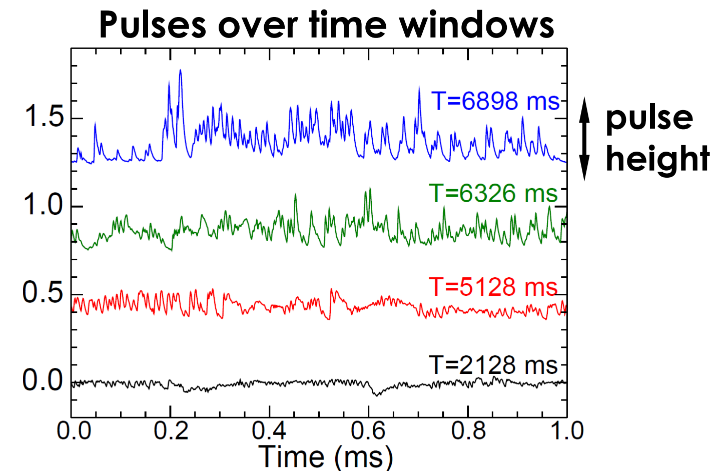
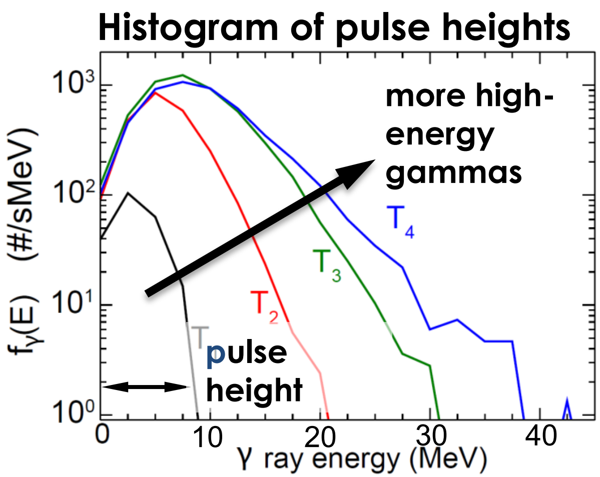






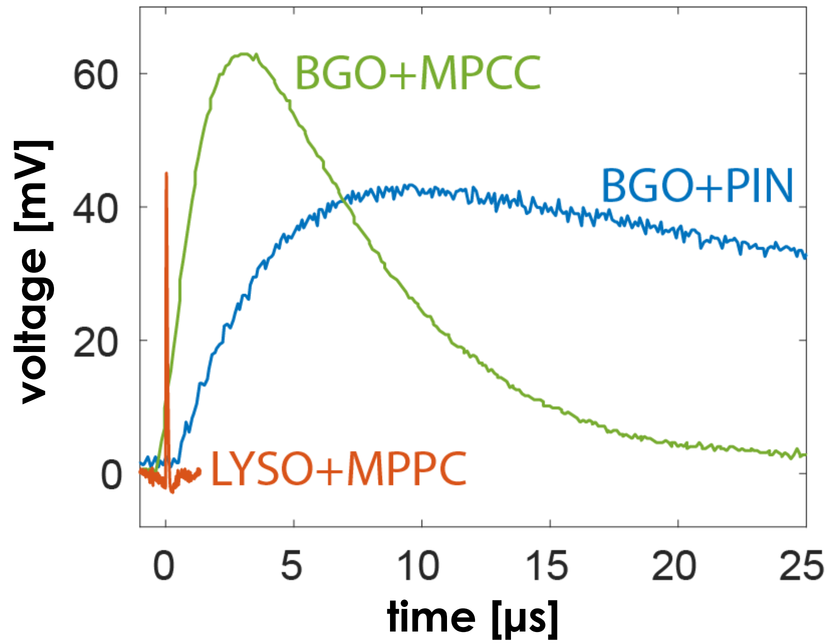
- Time traces are comprised of pulses from distinct gamma particles
- Gamma particles are analyzed via pulse height analysis (PHA)
- Bremsstrahlung spectrum hardens in the course of time
- This talk is about RE plateau, though PHA technique is the same

Cooper et al. RSI 2016

Measurements during the RE plateau regime are challenging

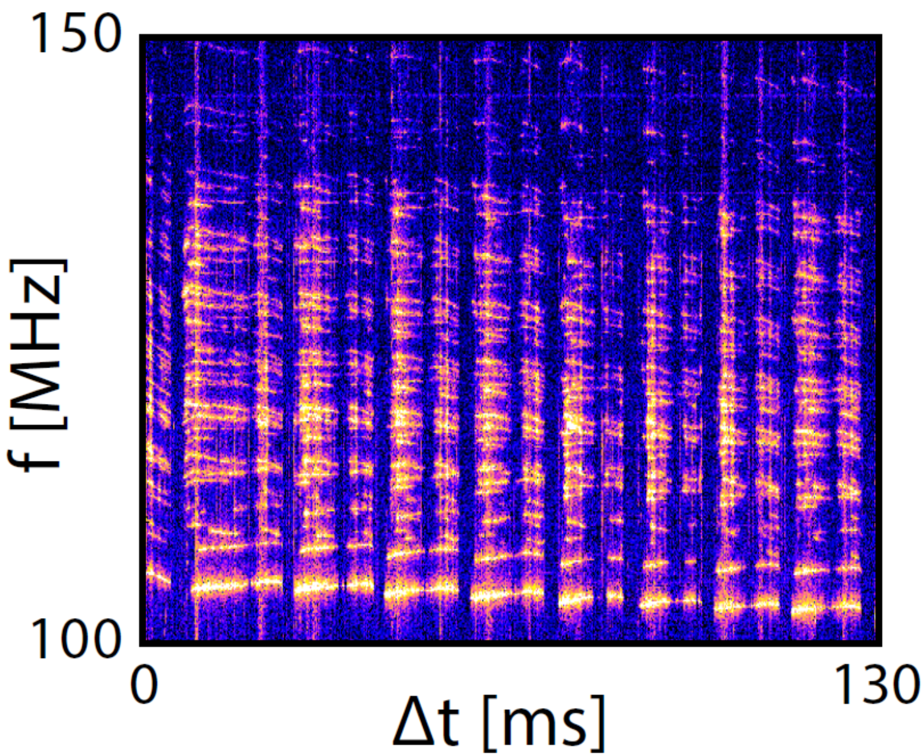
- **Gamma flux due to bremsstrahlung emission is higher by 10^3–10^4 in RE plateau regime compared to QRE**
- **BGO detectors are usually saturated after the disruption**
- **New LYSO+MPPC detectors are capable to measure during the post-disruption stage**

Collaboration with
U. Milano-Bicocca



Response of gamma detectors to a single gamma-pulse

Whistler waves were discovered in QRE regime – need to pay close attention to plasma kinetic instabilities



Whistler waves in QRE shot in DIII-D

- **Energetic REs can lead to the excitation of plasma waves**
- **Plasma waves can increase the dissipation of REs**
- **New paths to mitigate RE generation via induced kinetic instabilities could be discovered**
- **Measurements of high-frequency magnetic fluctuations are necessary during RE experiments**

Spong et al. PRL 2018

Two outboard mid-plane systems detect high-frequency toroidal magnetic field fluctuations

System 1: 2015 ICRF antenna in receiver mode

- Outer straps regularly digitized

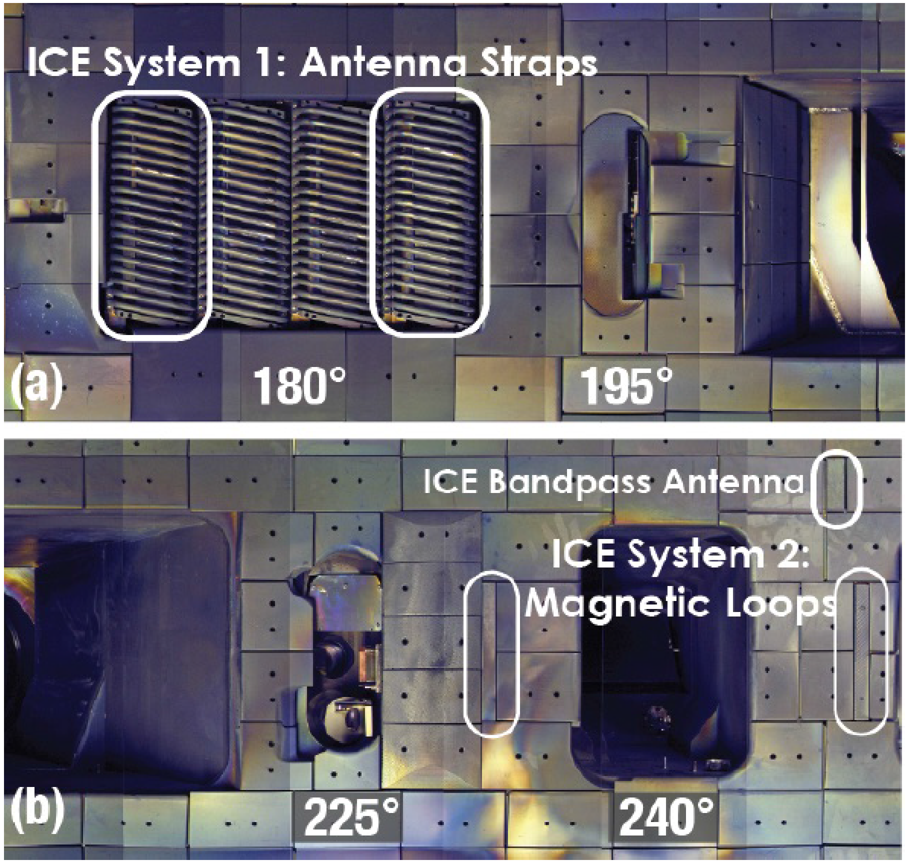
System 2: 2017 $\tilde{B}_{\varphi}$ RF Loops

- 2 loops regularly used
- Incorporated into carbon tiles

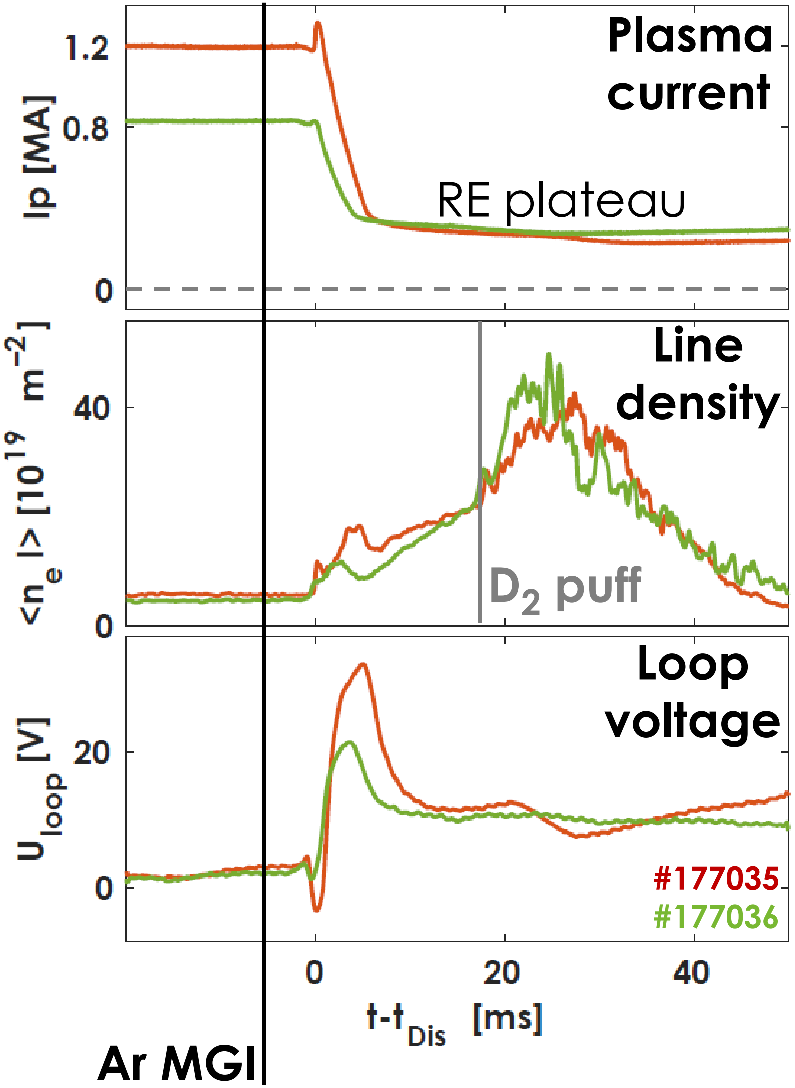
Another tile antenna used with bandpass filters

Watson and Heidbrink RSI 2003
Thome et al. RSI 2018 (accepted)

ICE diagnostic on DIII-D



= Scenario of experiment =



- Ar MGI
- Ar amount 10−150 torr·l
- Plasma current 0.8 and 1.2 MA

- (Delayed D_2 puff to "purge" Ar, reduce plasma resistivity and achieve long-lived RE plateau)

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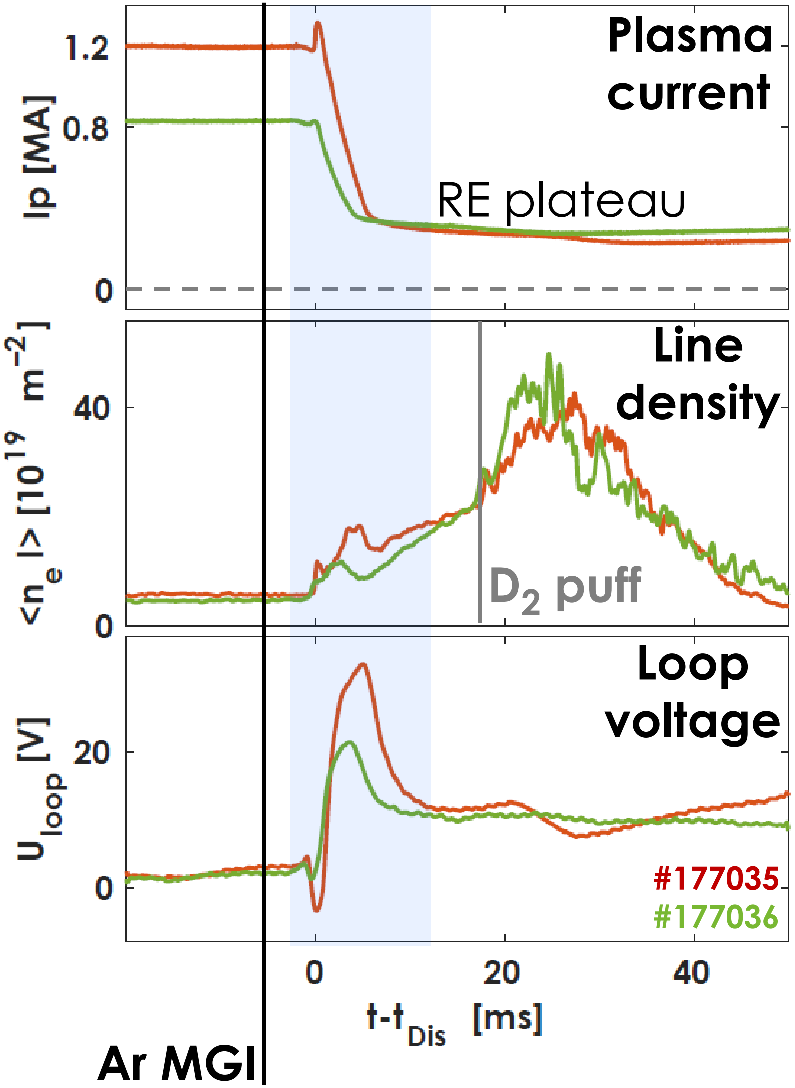

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This talk is about RE plateau formation

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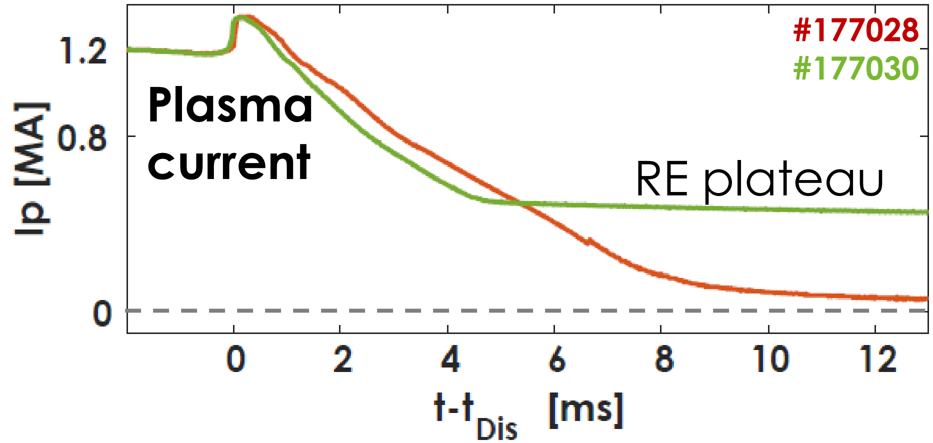
RE losses during CQ might be the reason of plateau failure

- **RE plateau is not formed every time:**
  50 torr·l Ar – no RE plateau
  130 torr·l Ar – RE plateau



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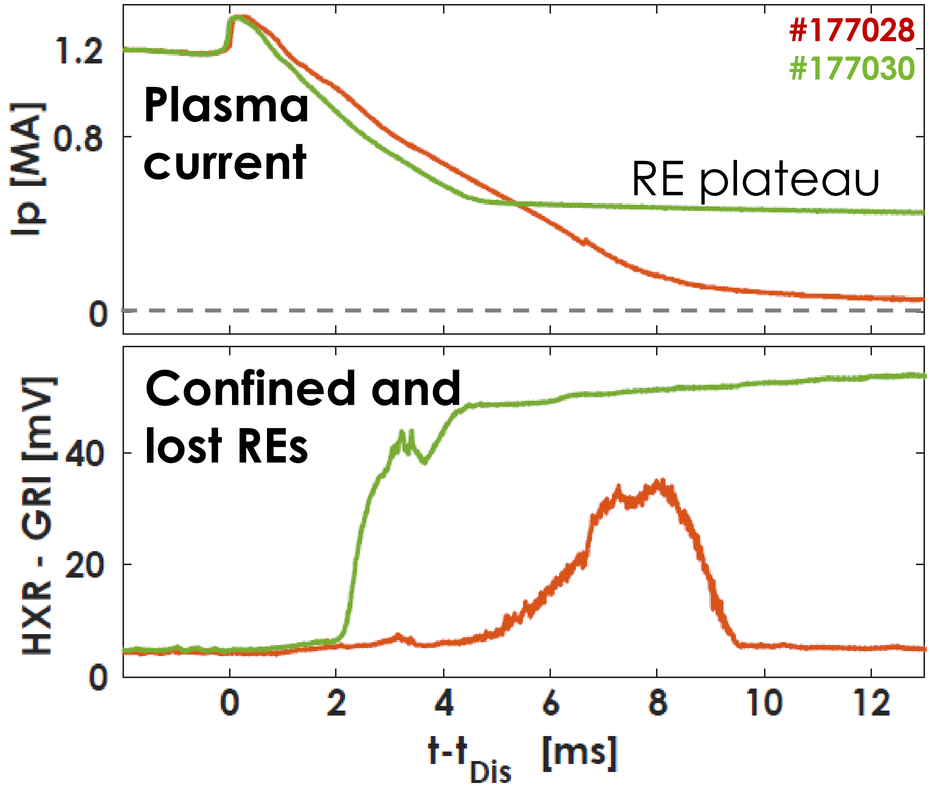
- **Large Ar injection leads to quick RE plateau build-up**



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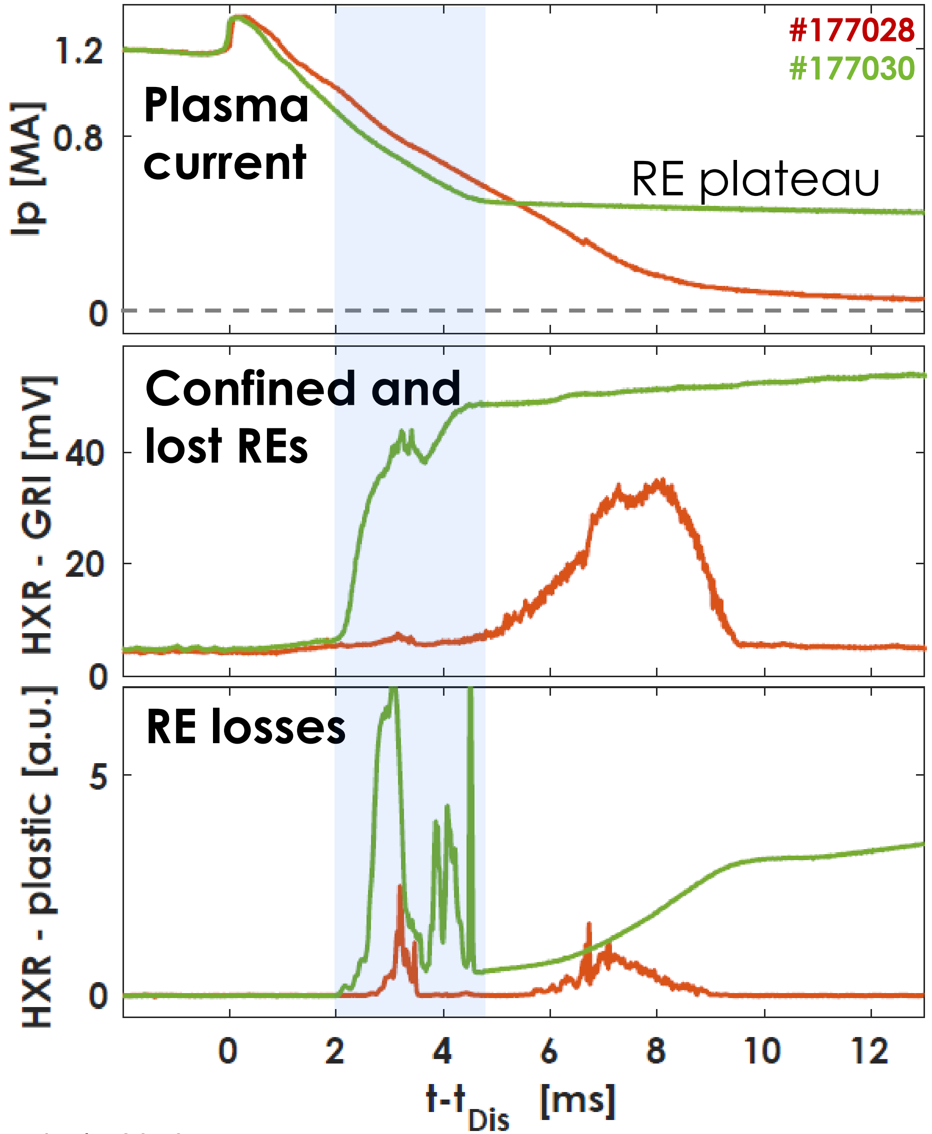

A. Lvovskiy/TSDW/July 2018

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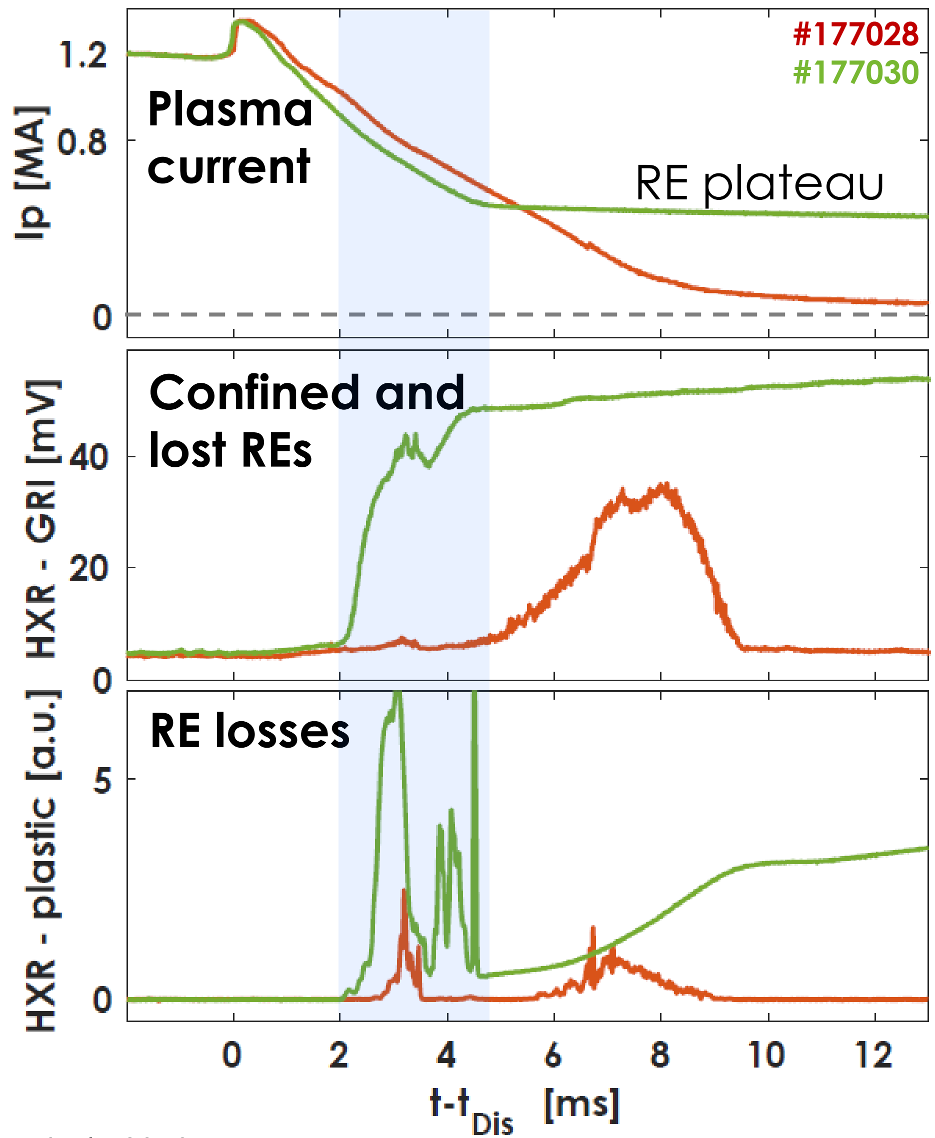
- REs are actively lost during CQ

- Interplay between generation and losses of REs can be a key to RE plateau formation



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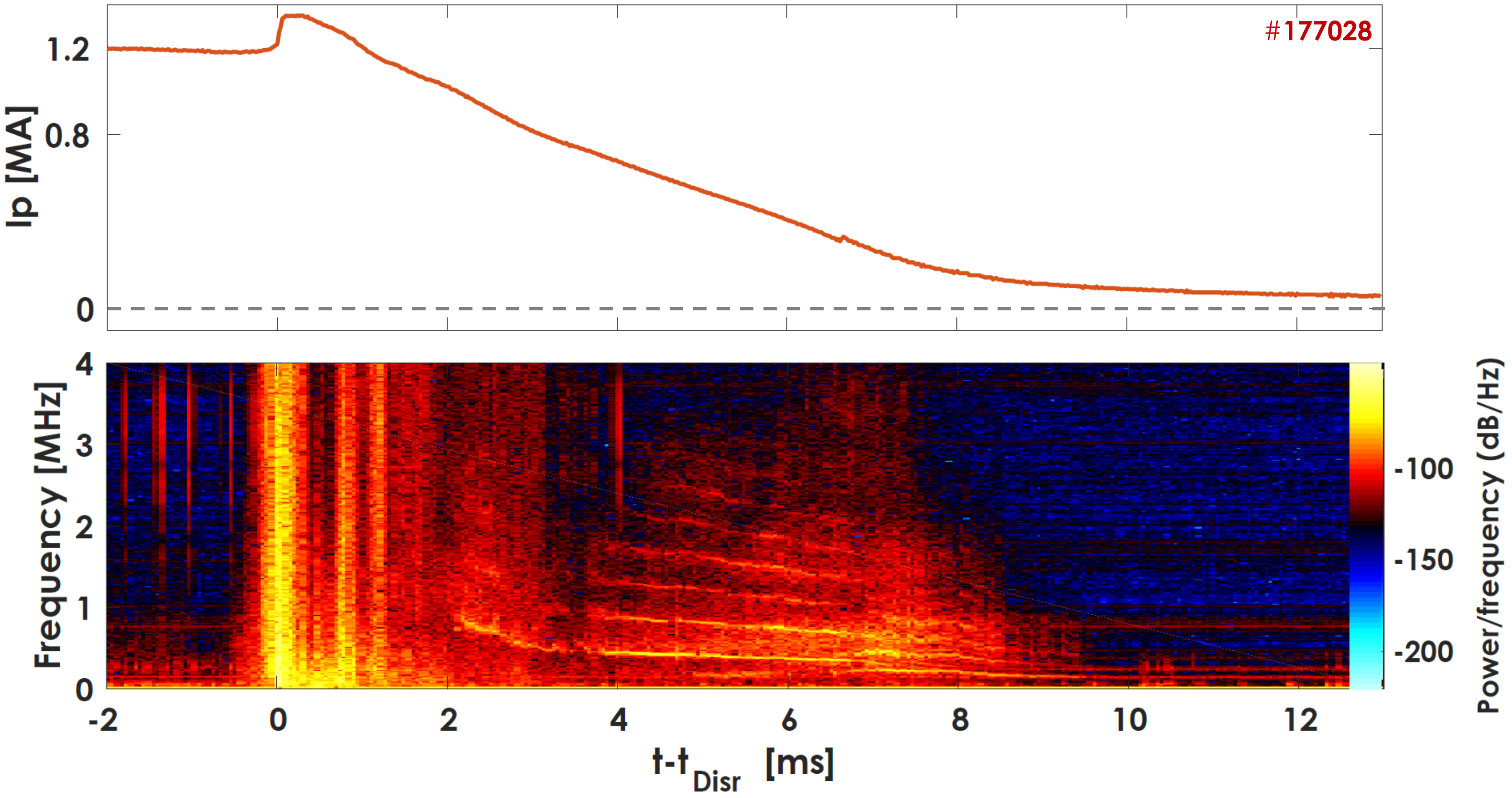
A. Lvovskiy/TSDW/July 2018

No RE plateau cases correlate with clear fast magnetic signals

No plateau case



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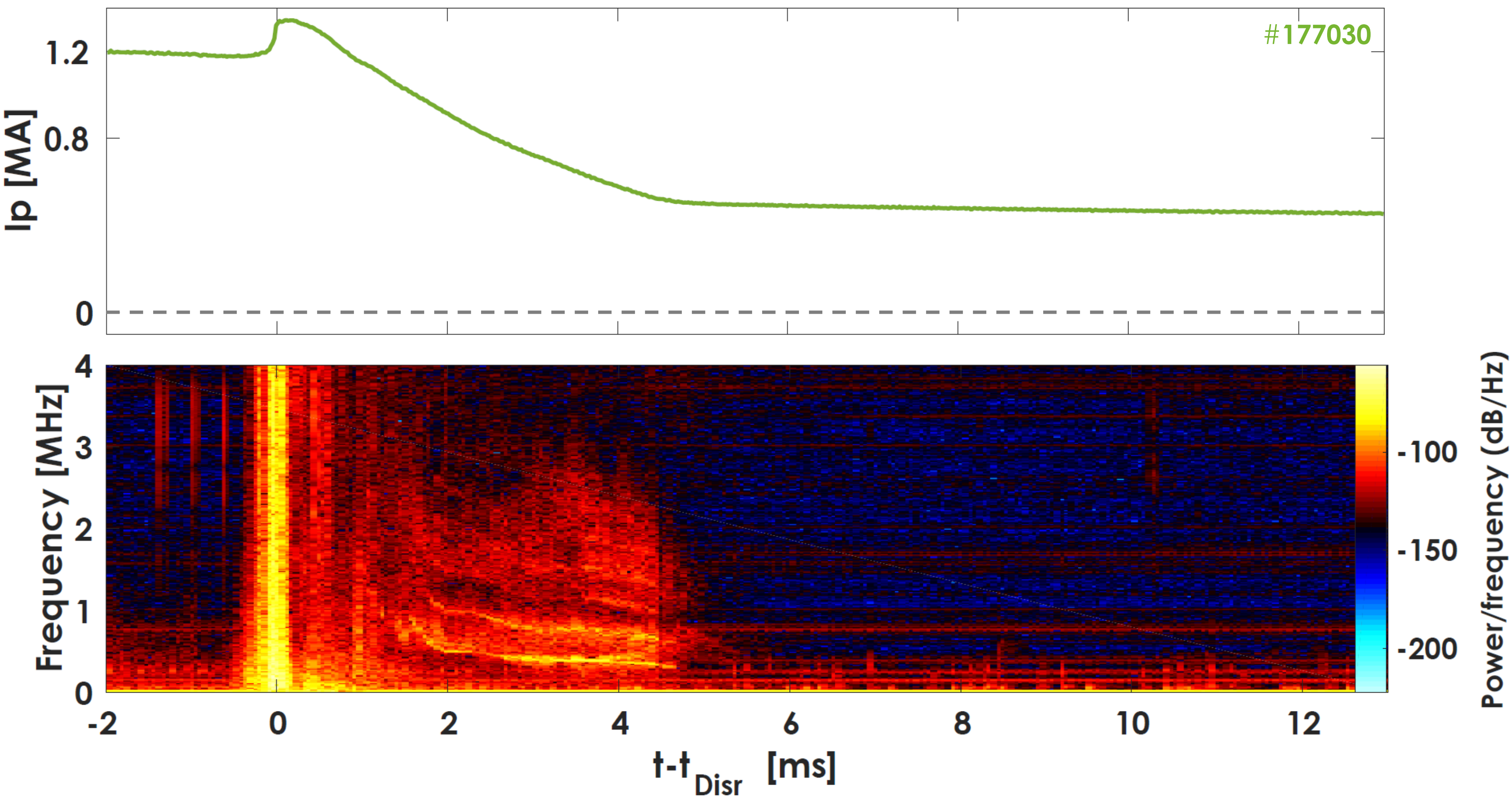
RE plateau case



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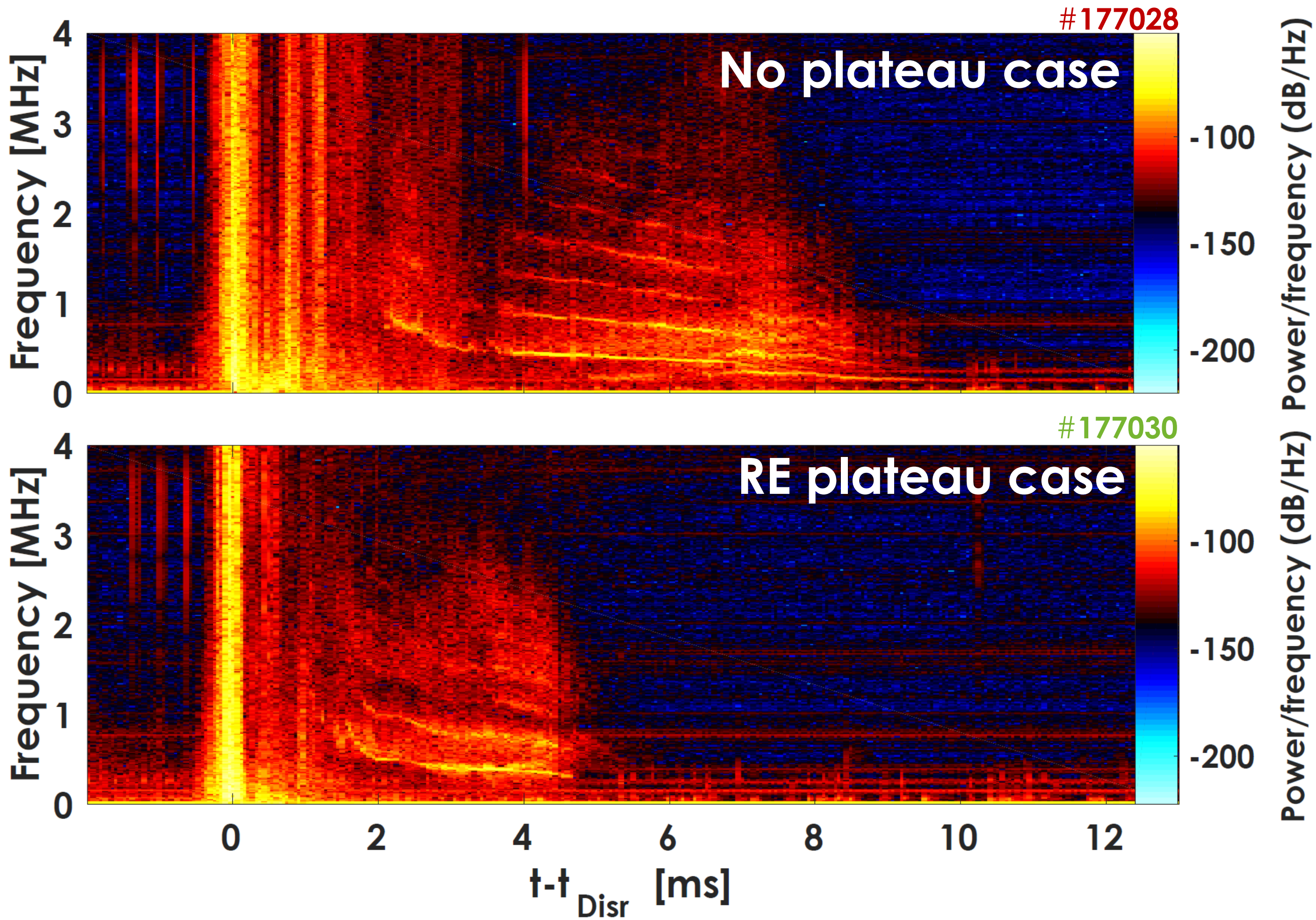
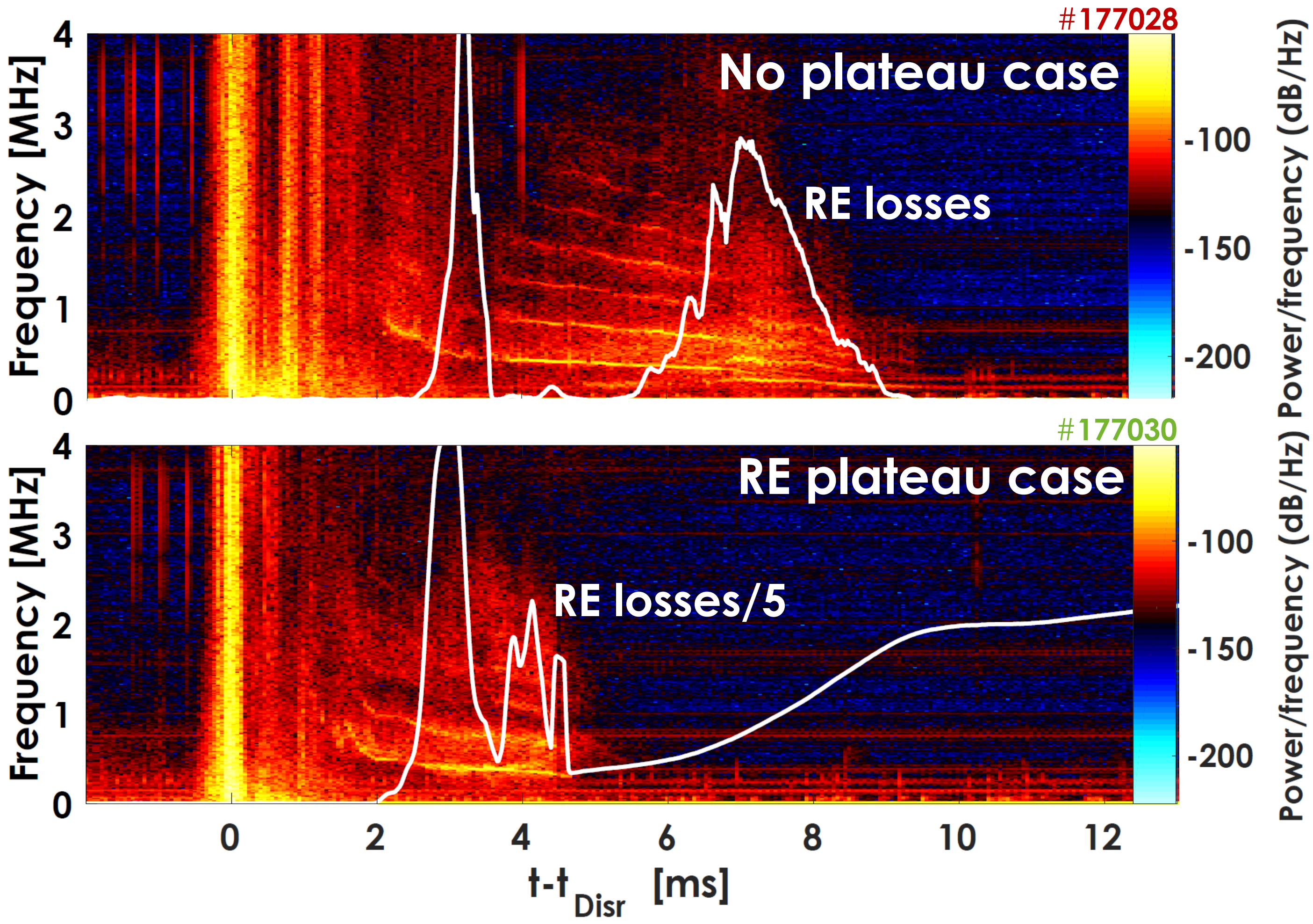


Frequency range	**0.1–3 MHz**
Duration	**3–10 ms**

RE losses correlate with fast magnetic signals



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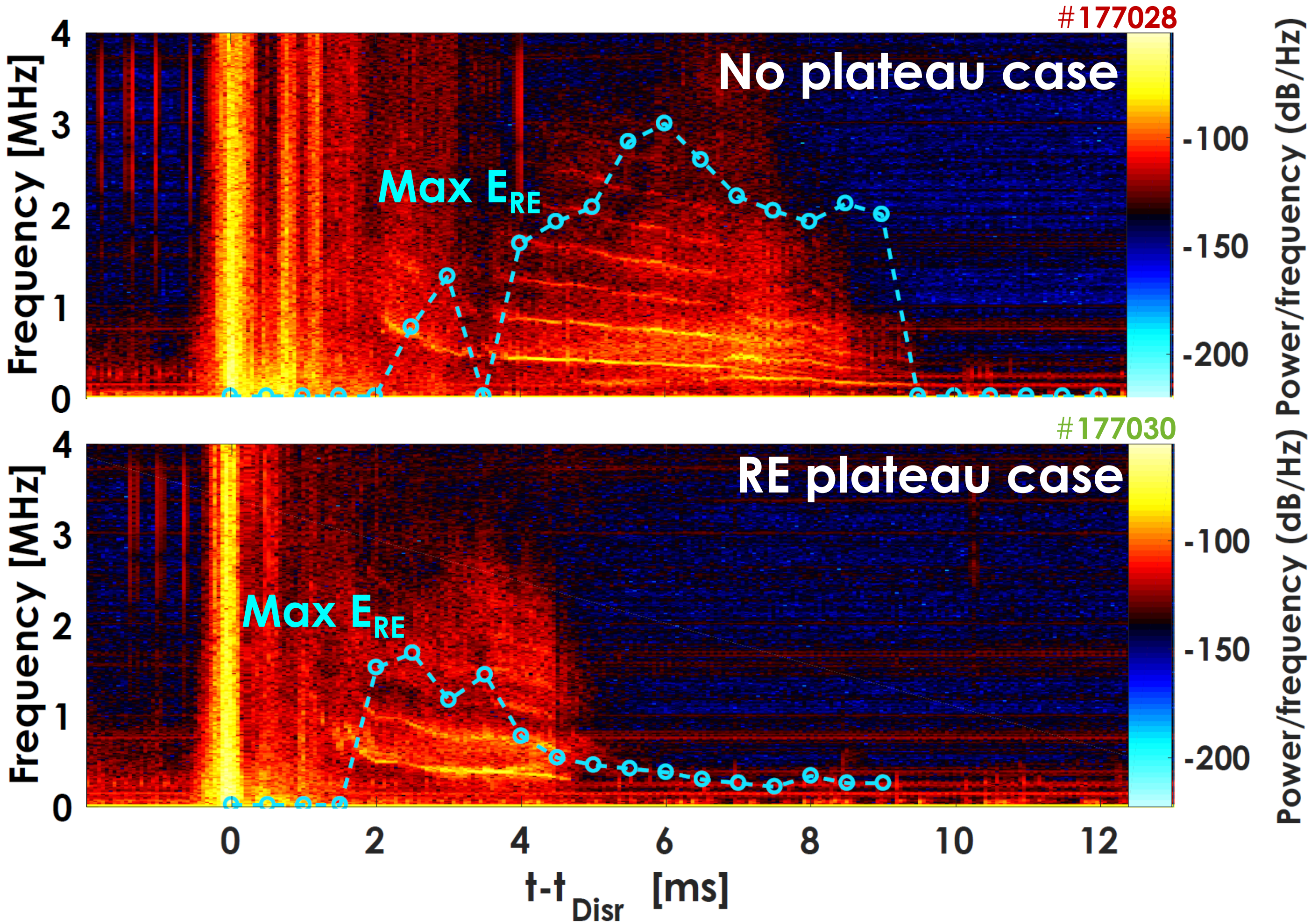
Fast magnetic signals correlate with population of high-energy REs



Possible mechanism of suppression of RE plateau generation:

CQ

↓

Large U_{loop}

↓

Large population of high-energy REs

↓

Large instabilities

↓

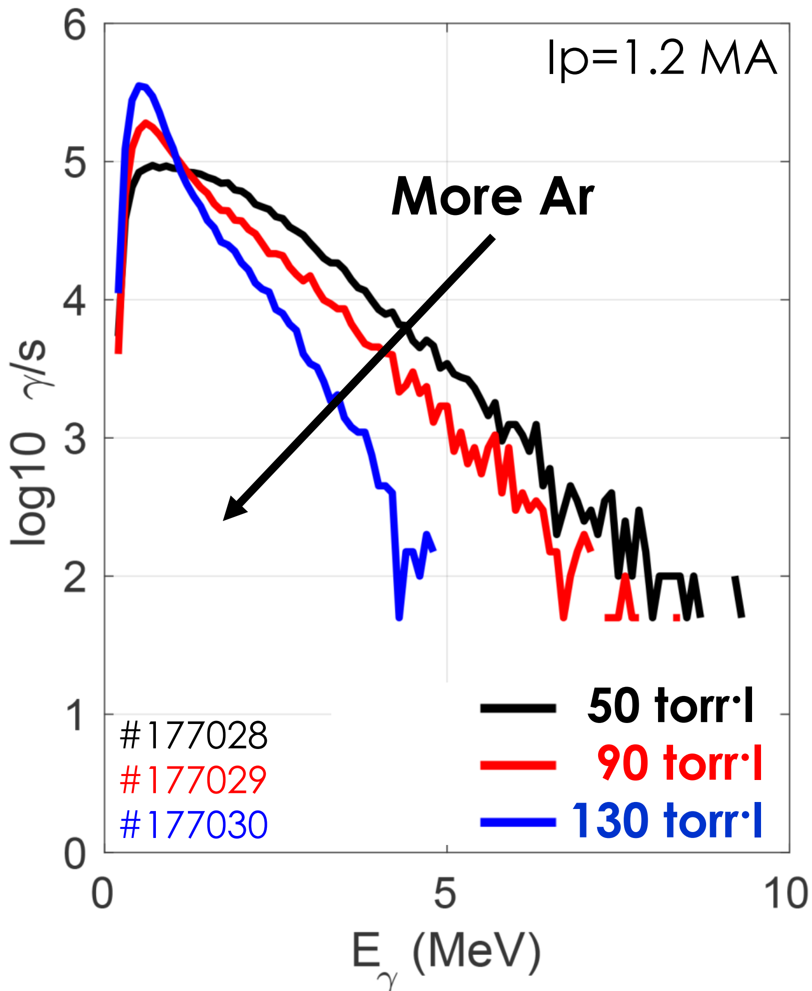
Loss of seed REs

↓

No RE plateau

= Analysis of RE bremsstrahlung spectra =

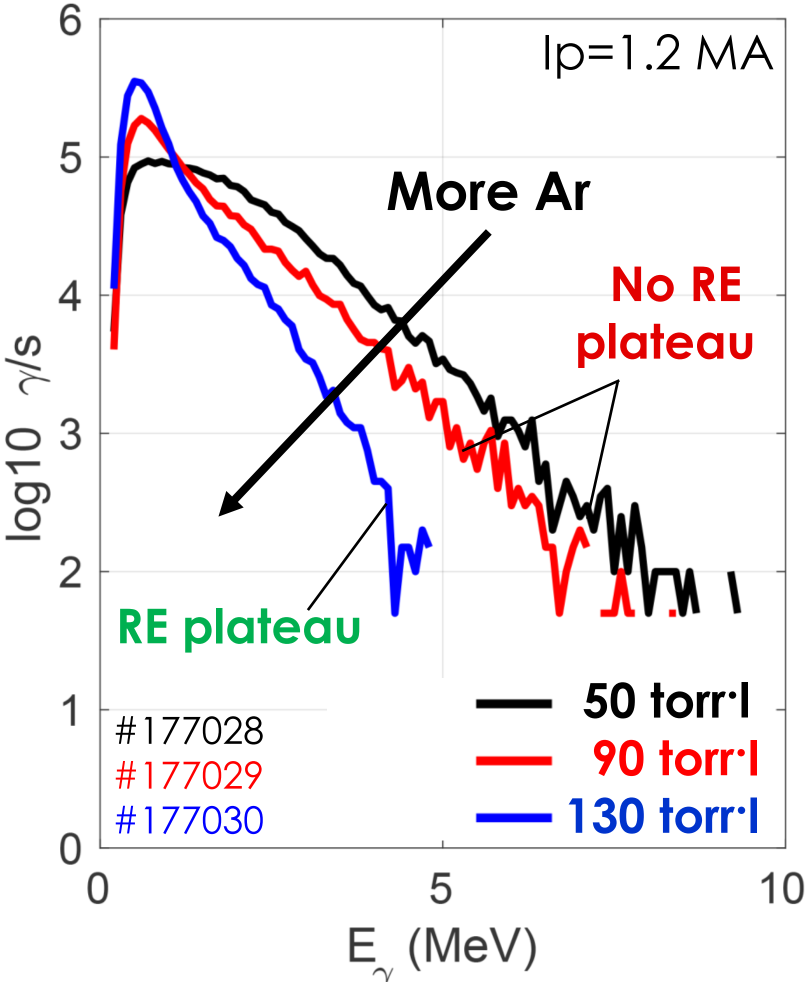
Example: Ar quantity scan



- Bremsstrahlung spectra of REs were obtained using GRI and PHA
- Integration time:
  first 10 ms (~ CQ time)
- Accurate inversion to RE distribution function during disruptions is complicated
- Though HXR and RE spectra are usually similar

= Analysis of RE bremsstrahlung spectra =

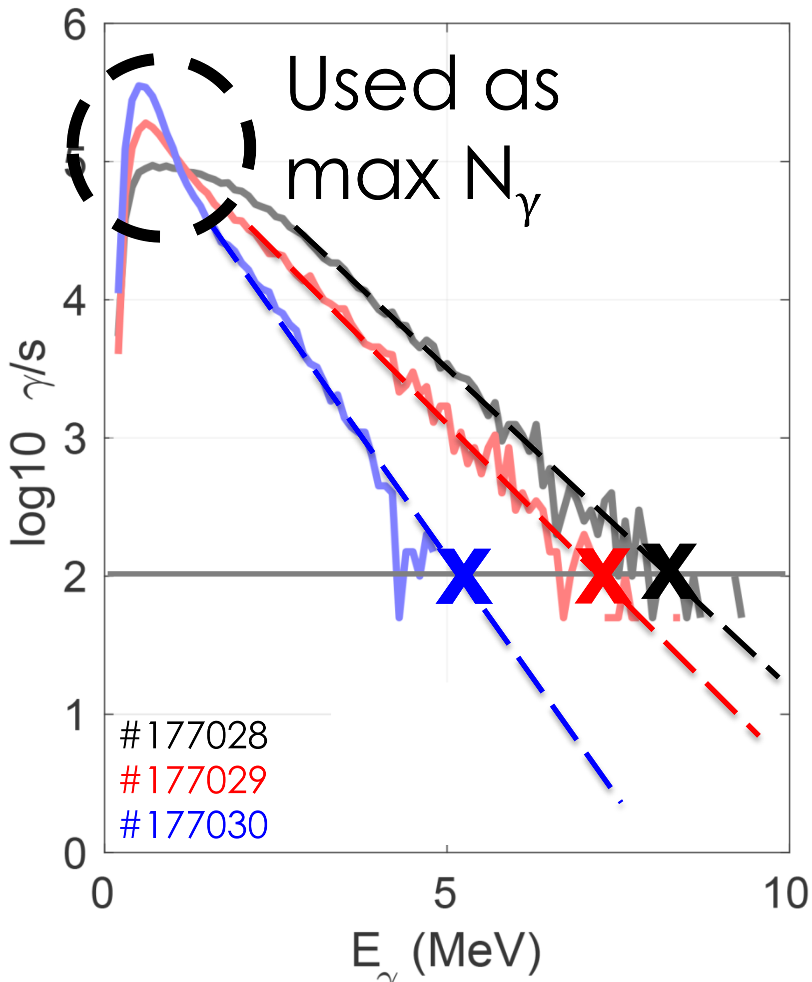
Example: Ar quantity scan



- **Increased Ar quantity reduces the number of high-energy REs and correlates with successful RE plateau formation**

= Analysis of RE bremsstrahlung spectra =

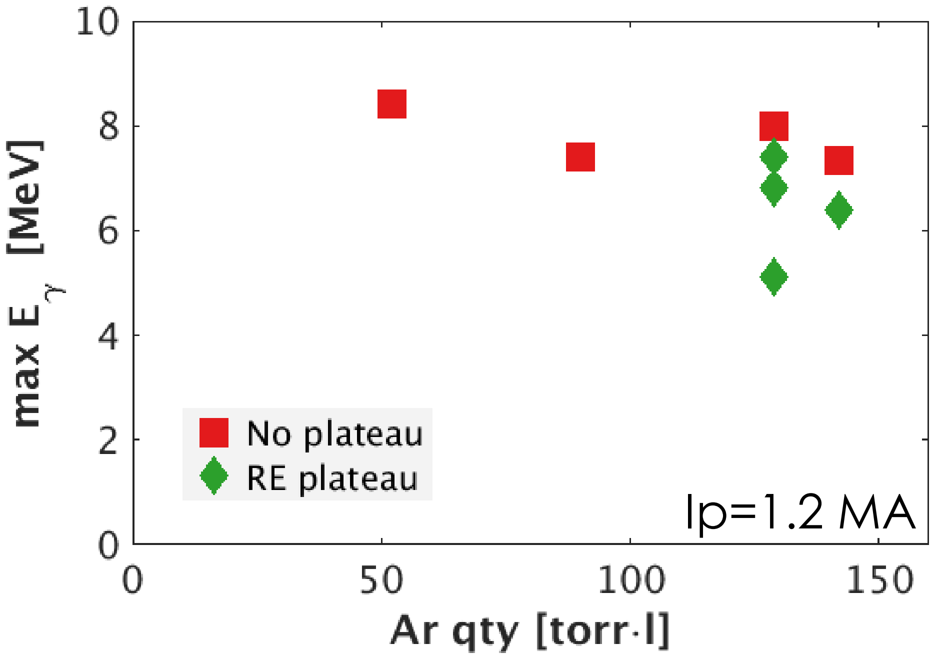
Example: Ar quantity scan



- **Increased Ar quantity reduces the number of high-energy REs and correlates with successful RE plateau formation**

Used as max E_γ (or max E_{RE})

High-energy REs? No RE plateau? Add more Argon



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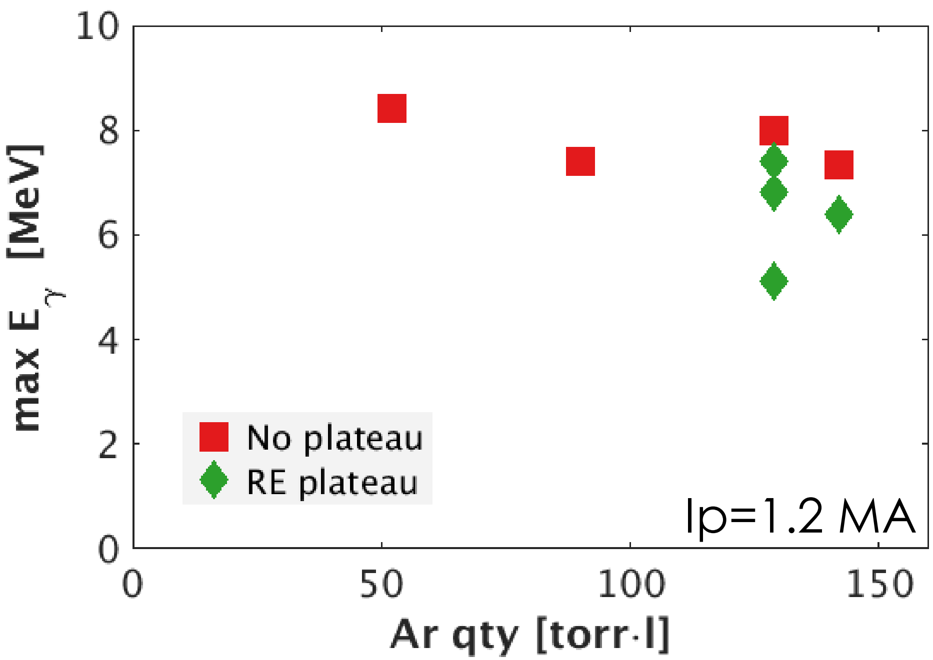
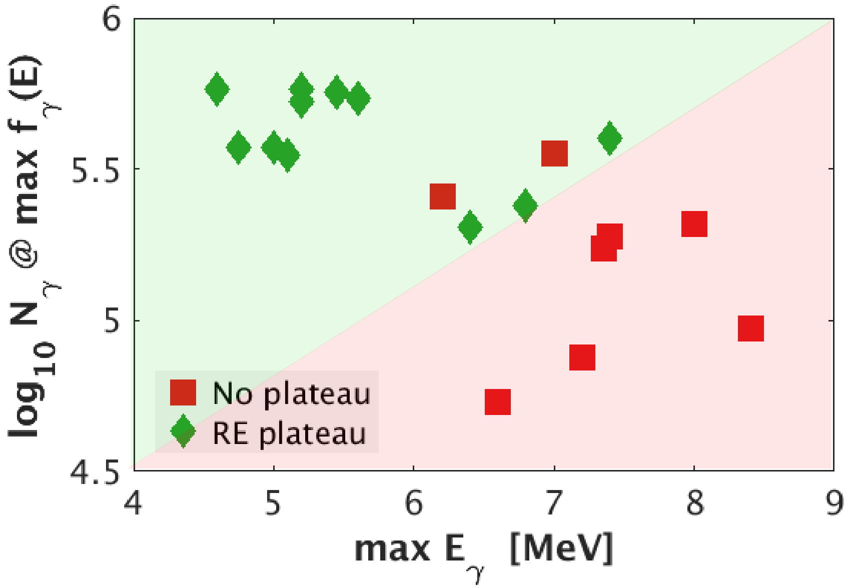
- **Large high-energy RE tail correlates with no RE plateau cases**

High-energy REs? No RE plateau? Add more Argon



- **Increased Ar quantity reduces the number of high-energy REs and correlates with successful RE plateau formation**
- **Large high-energy RE tail correlates with no RE plateau cases**
- **This is why we observed the threshold on injected Ar for successful generation of RE plateau**

Large power of observed modes correlates with high-energy RE tail



- **No RE plateau cases correlate with less steep HXR distribution function (more high-energy REs and less low-energy REs)**

- **RE distribution function most likely shifts towards higher energies in no plateau cases**

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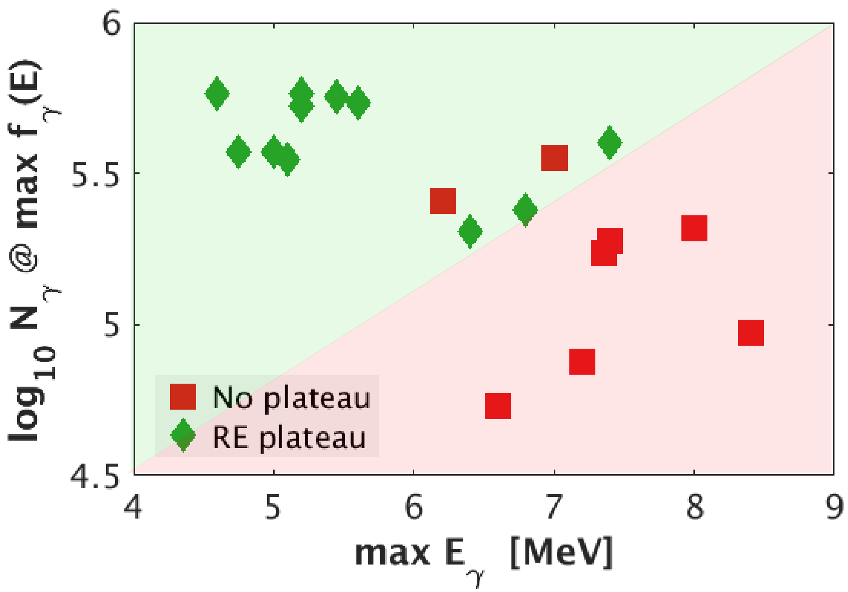
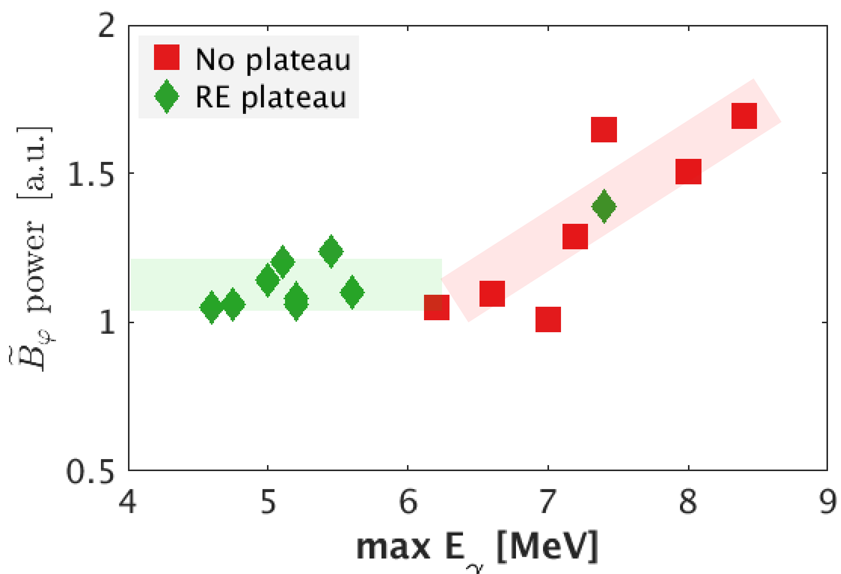


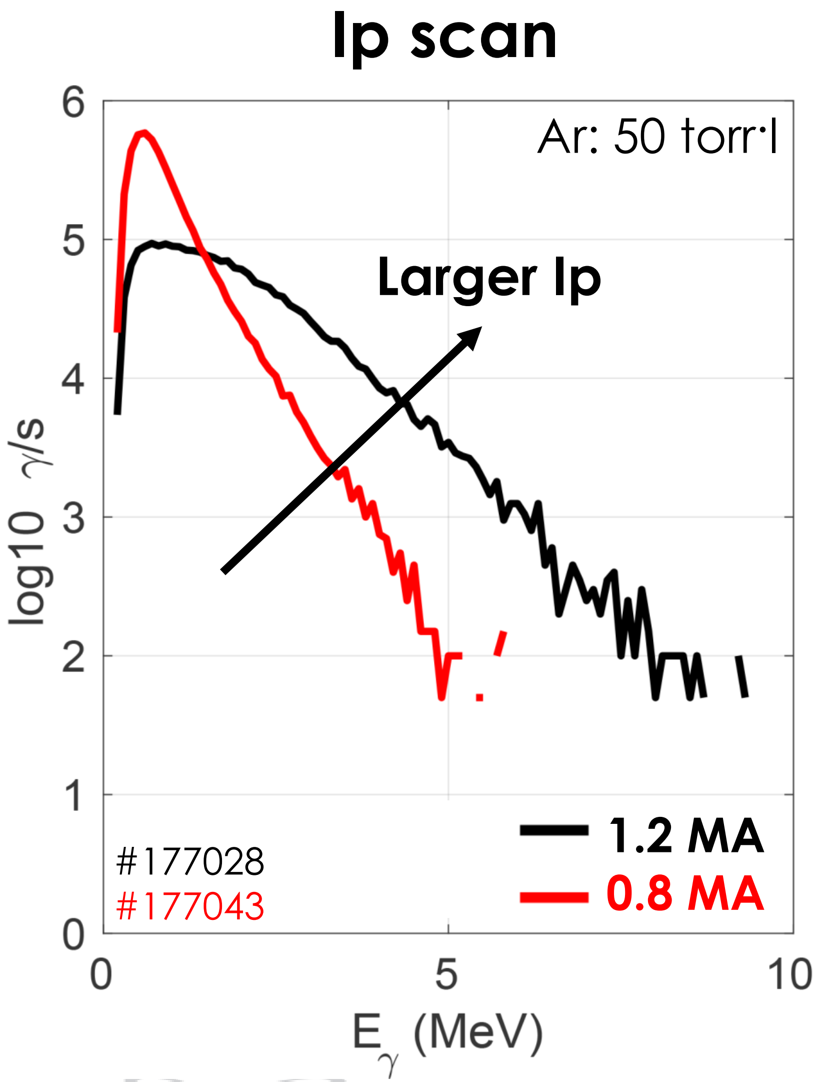


- No RE plateau cases correlate with less steep HXR distribution function (more high-energy REs and less low-energy REs)

- RE distribution function most likely shifts towards higher energies in no plateau cases

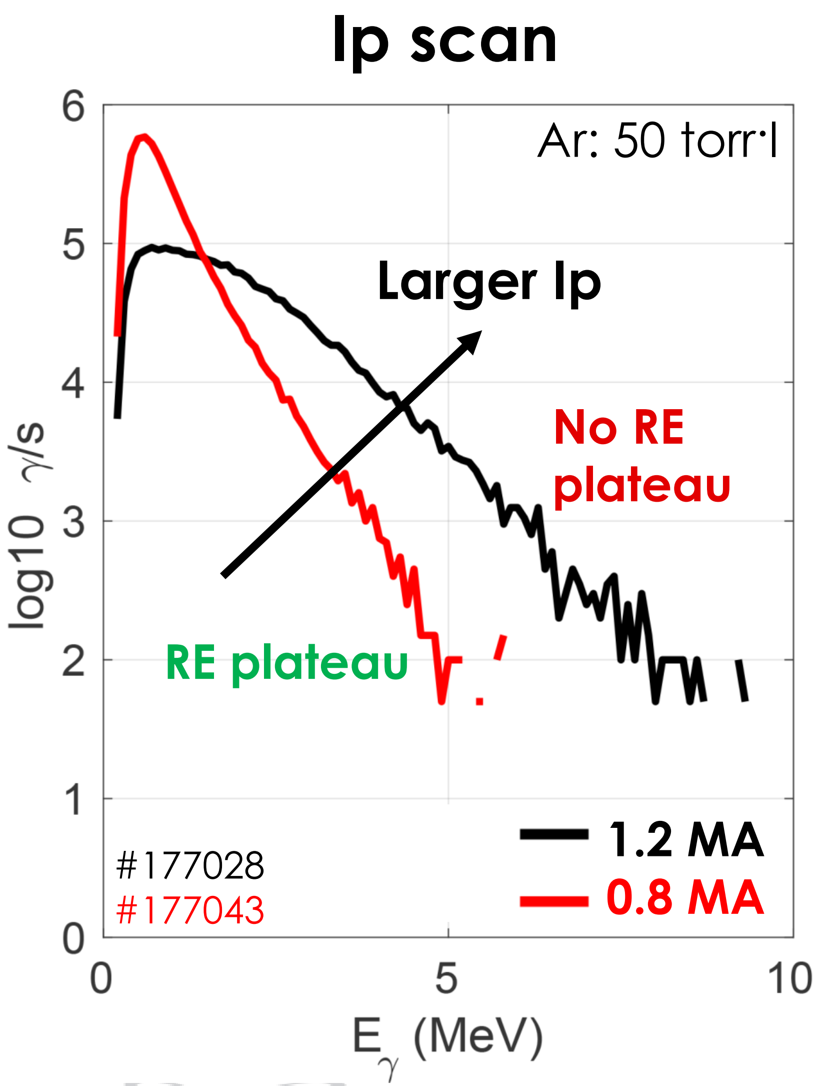
- Autopower of fast magnetic signals increases with increase of max E_{RE}

Large Ip cases correlate with high-energy RE tail



- **Increased pre-disruption Ip increases the max energy of REs**

Large Ip cases correlate with high-energy RE tail



- Increased pre-disruption Ip increases the max energy of REs
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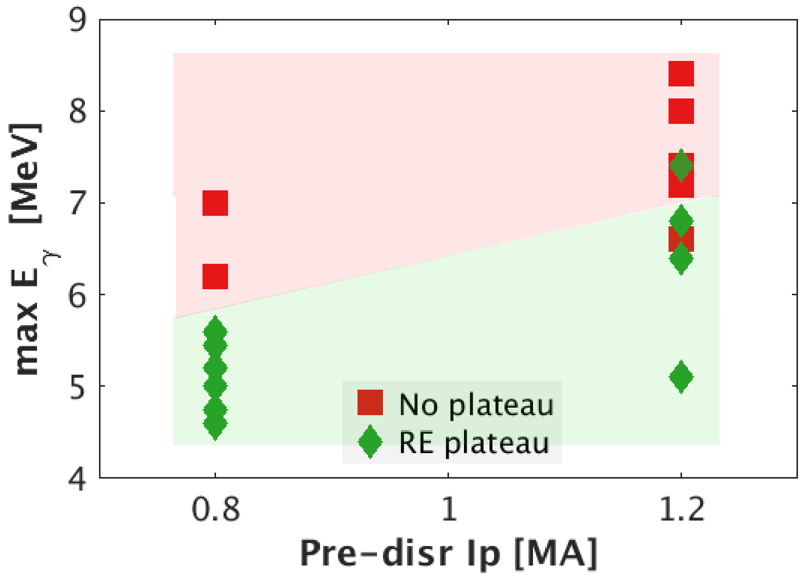
Larger Ip – more high-energy REs – more likely failure of RE plateau



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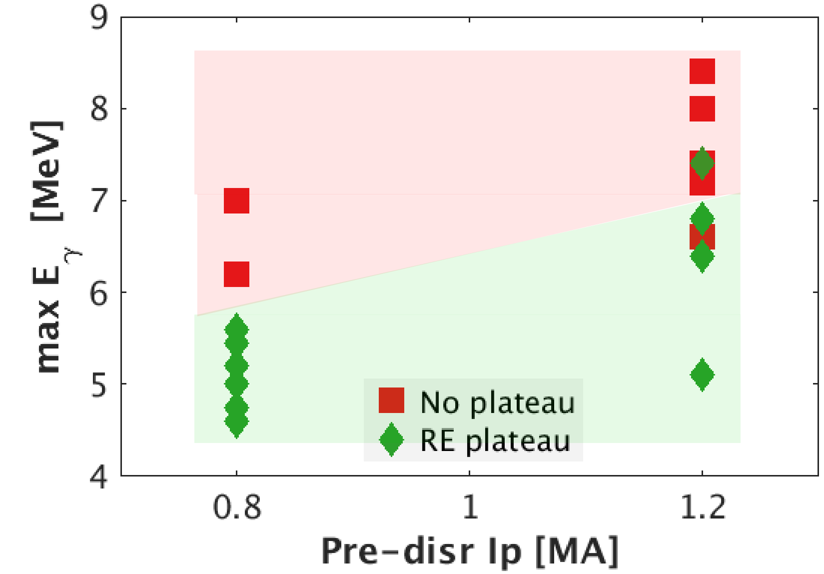
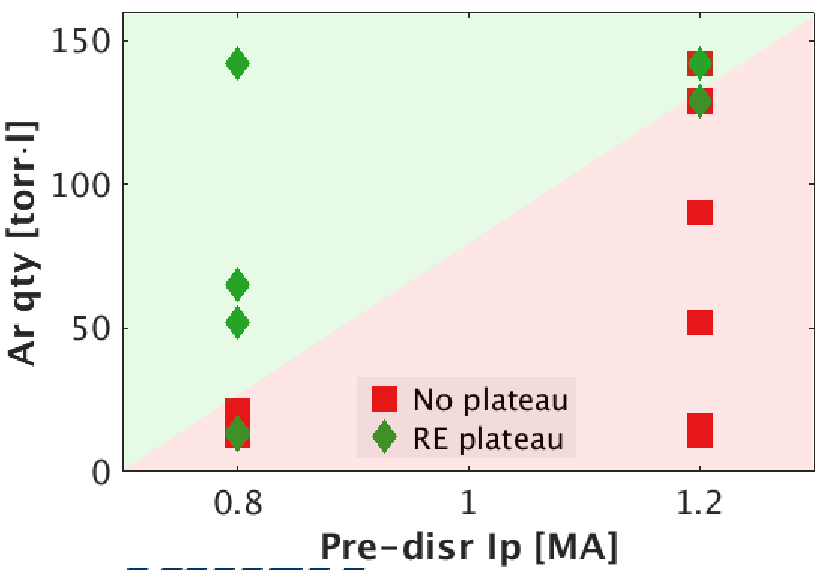
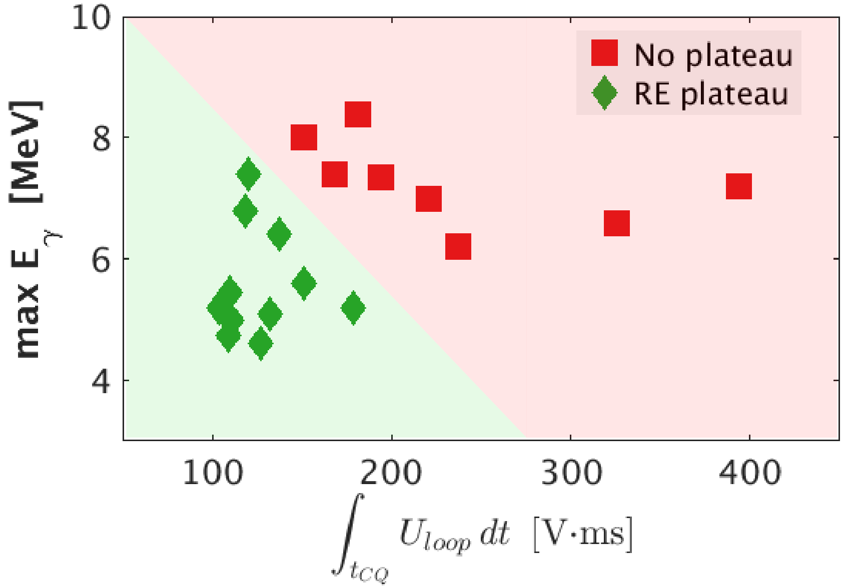




- **Increased pre-disruption Ip increases the max energy of REs**
- **Large high-energy RE tail correlates with no RE plateau cases**

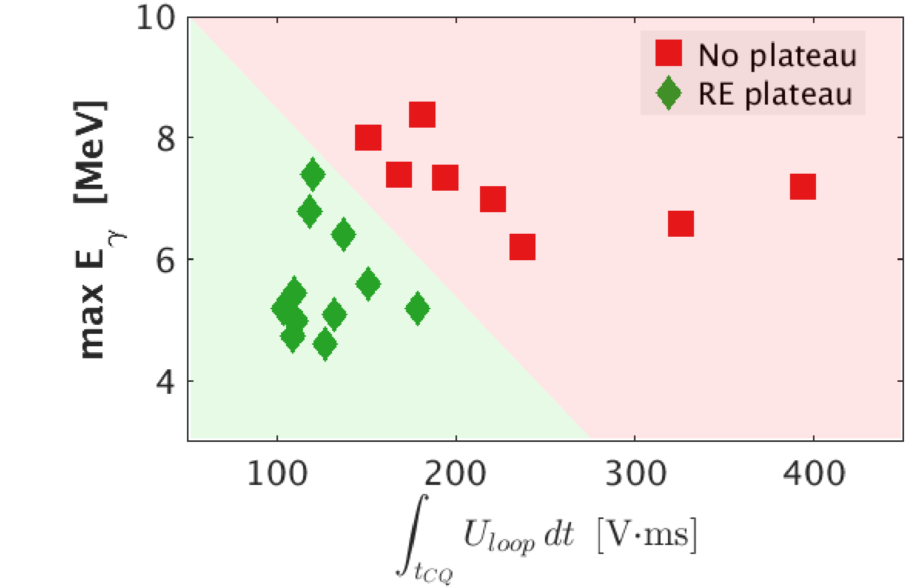
- **This is why Ar threshold depends on Ip**

Large loop voltage correlates with no plateau cases



- **Large pre-disruption Ip provides more magnetic flux**
- **Large U_{loop} leads to higher acceleration of REs and greater E_{RE}**
- **Large high-energy RE tail correlates with no RE plateau cases**

Large loop voltage correlates with no plateau cases



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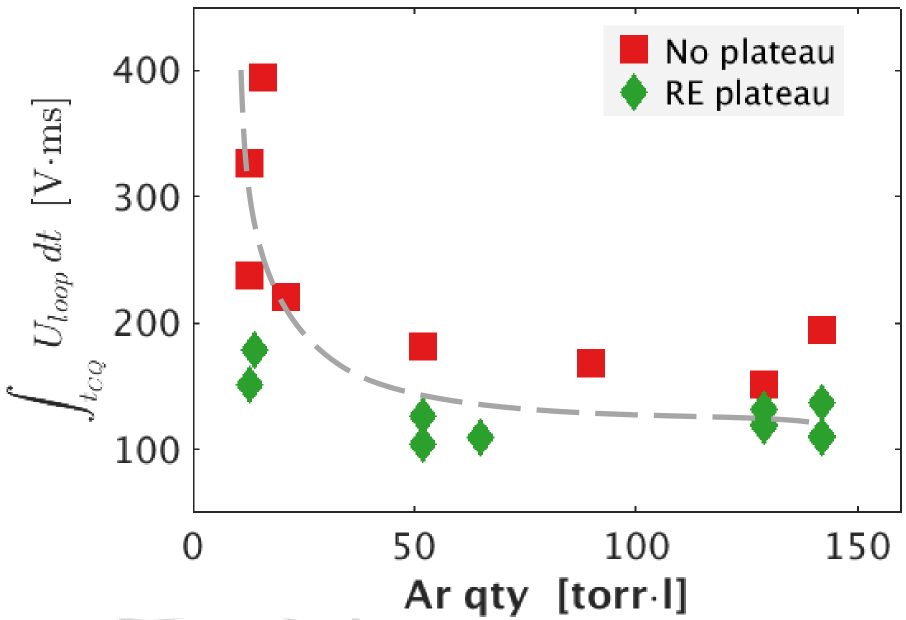


- **Large amounts of Ar reduce the loop voltage**

= Actuators of possible mechanism of RE plateau suppression: =

Large integrated U_{loop}

↓

Large population of high-energy REs

↓

Large instabilities

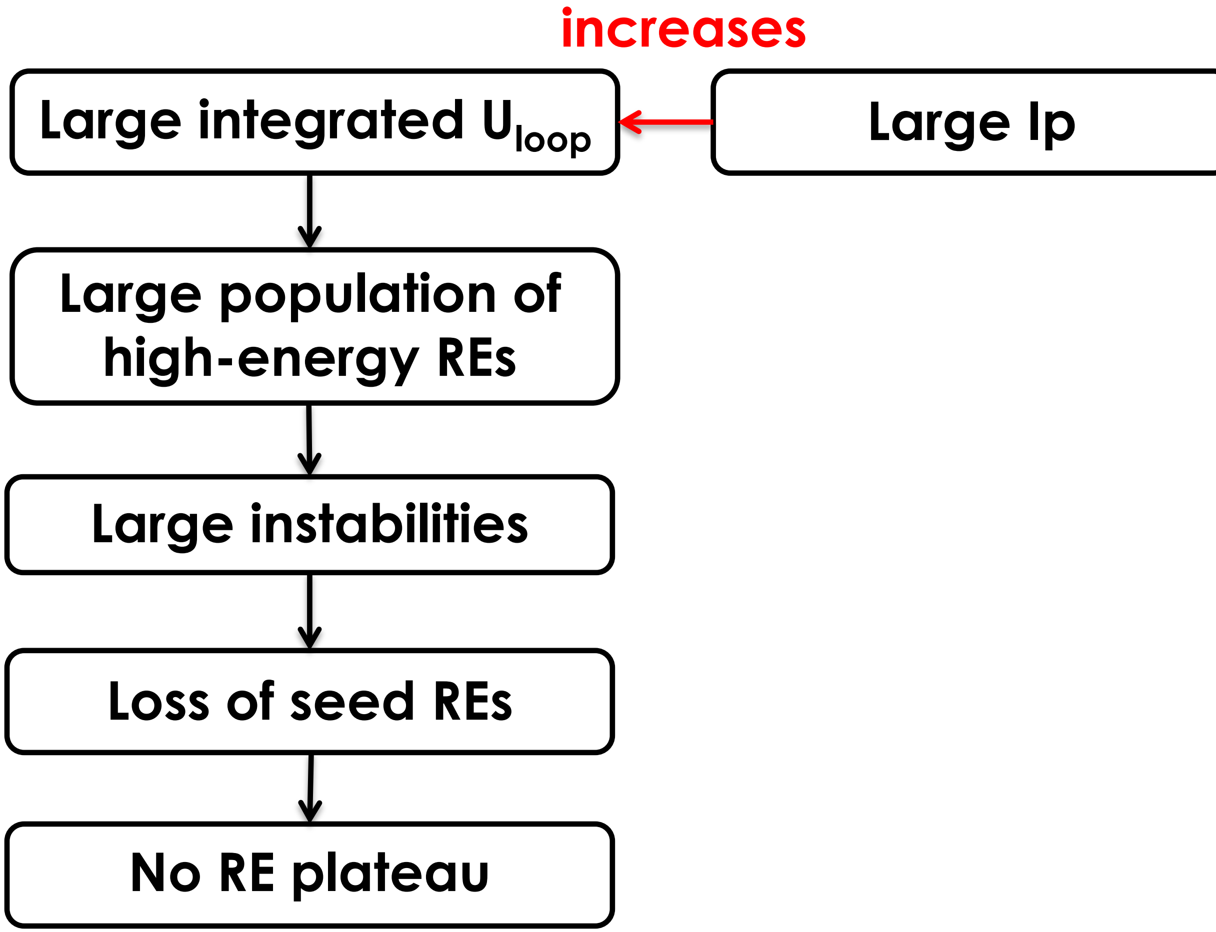
↓

Loss of seed REs

↓

No RE plateau

= Actuators of possible mechanism of RE plateau suppression: =



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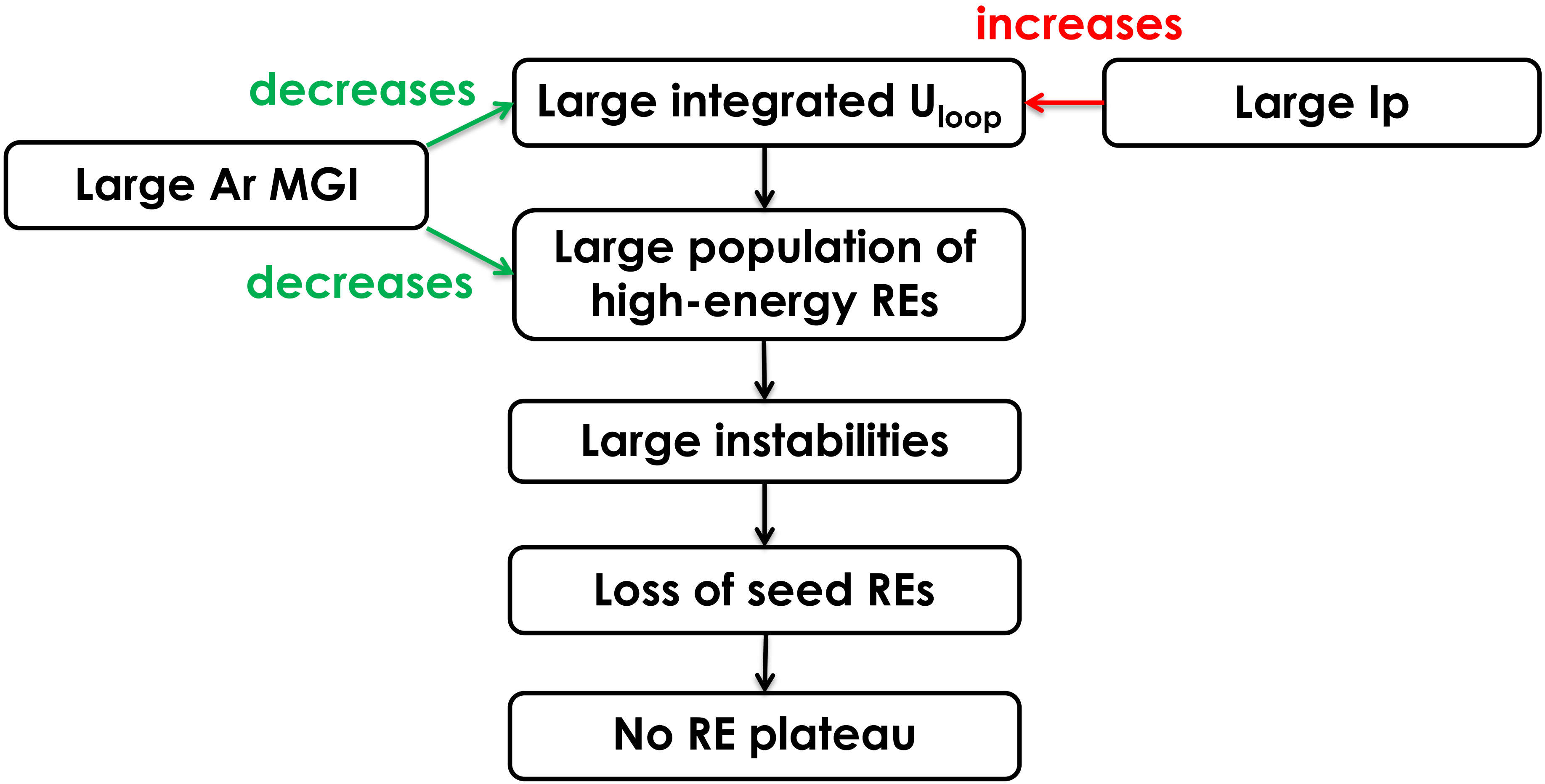
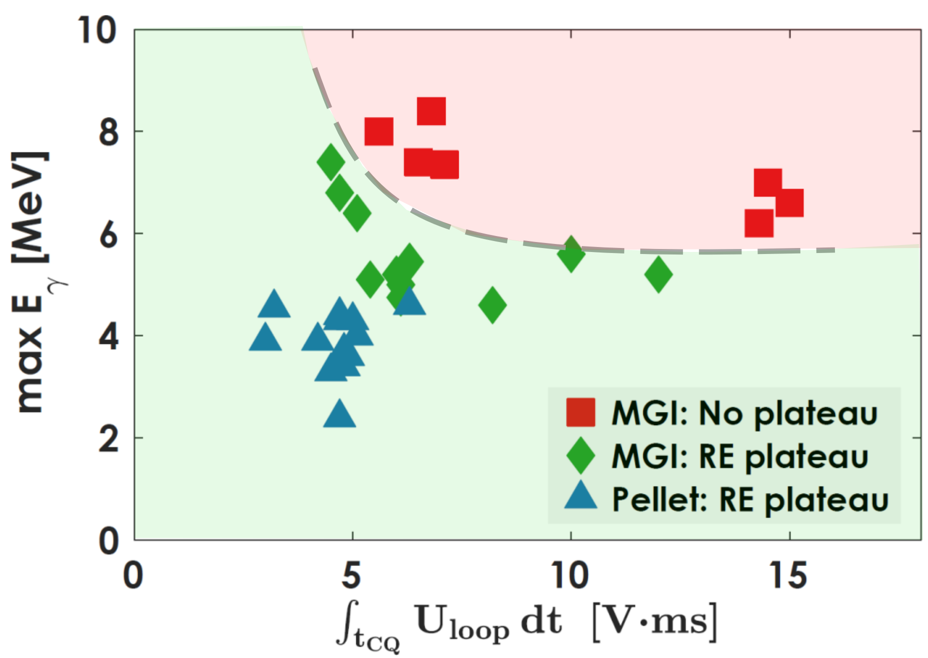


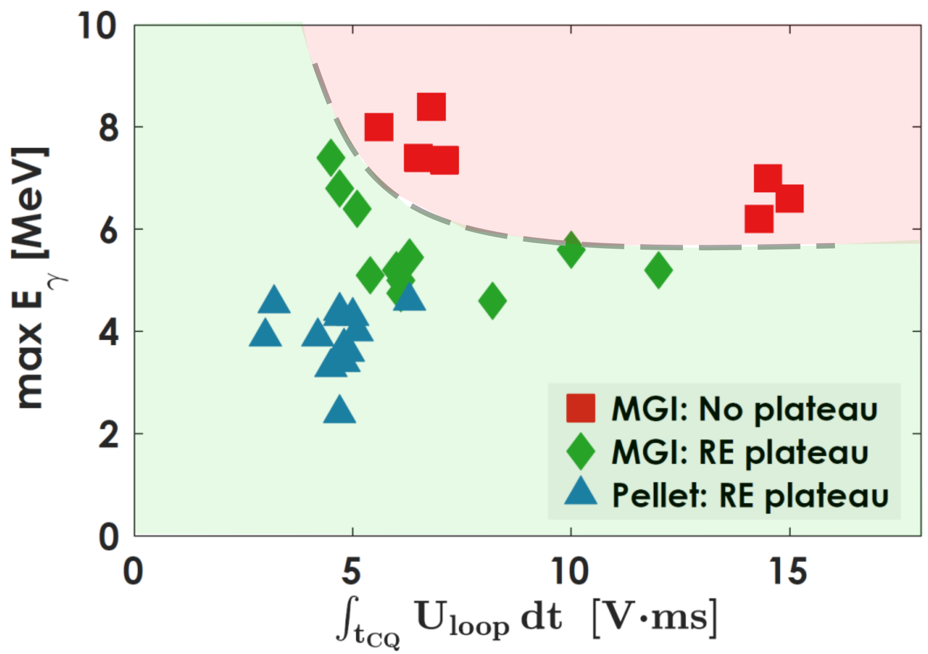
= Ar pellet case vs Ar MGI: reliable production of RE plateau and no instabilities =



Ar pellets vs Ar MGI:

- 1.5-2.5x times larger Uloop
- 2-3x times shorter t_{CQ}
- t_{CQ} and Uloop both are much more consistent
- **Smaller integrated Uloop**
- **2-3x times smaller max E_γ**

= Ar pellet vs Ar MGI: reliable production of RE plateau and no kinetic instabilities =



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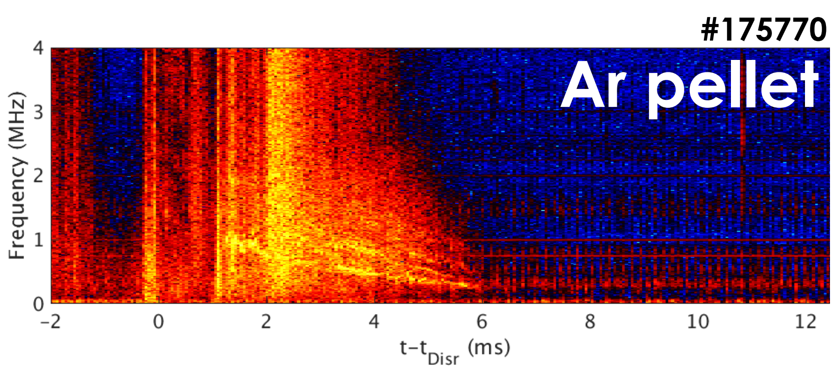
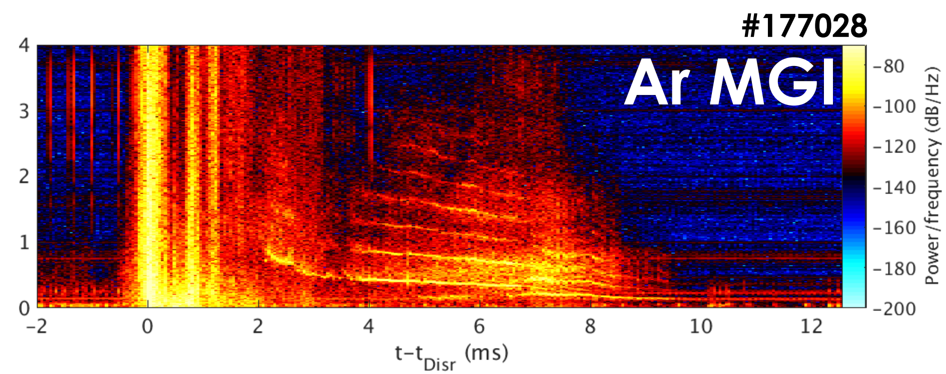
- 2-3x times shorter t_{CQ}
- t_{CQ} and Uloop both are much more consistent
- **Smaller integrated Uloop**
- **2-3x times smaller max E_γ**
- **No or almost no fast magnetic modes**





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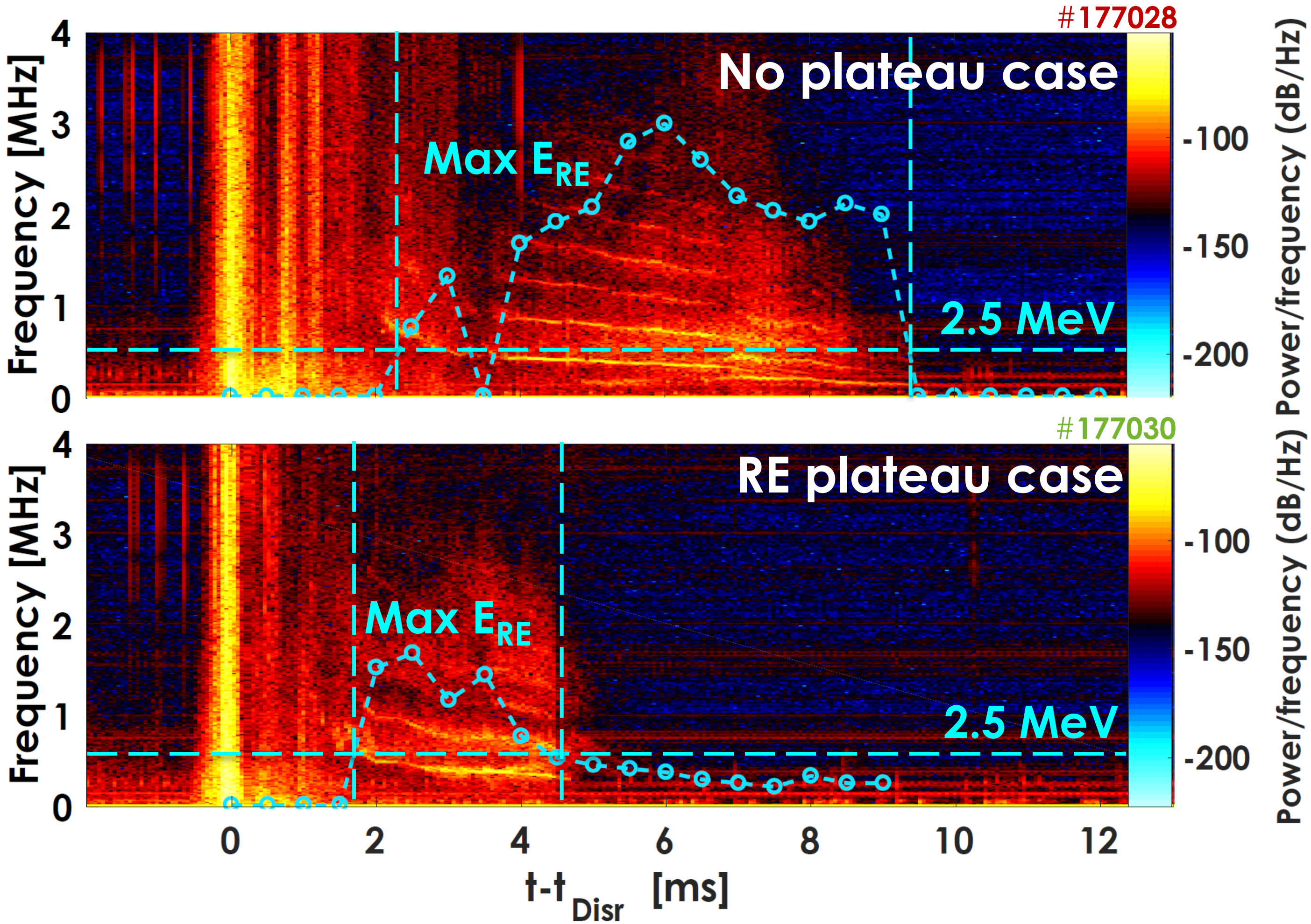
= Kinetic instabilities appear when E_{RE} > 2.5 MeV =



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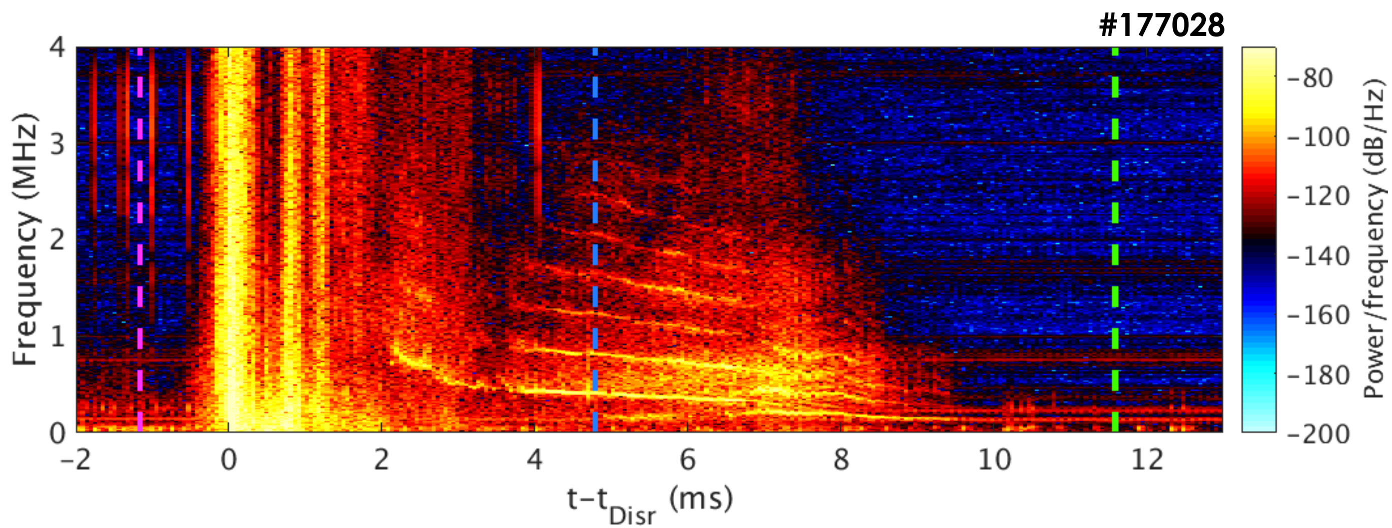
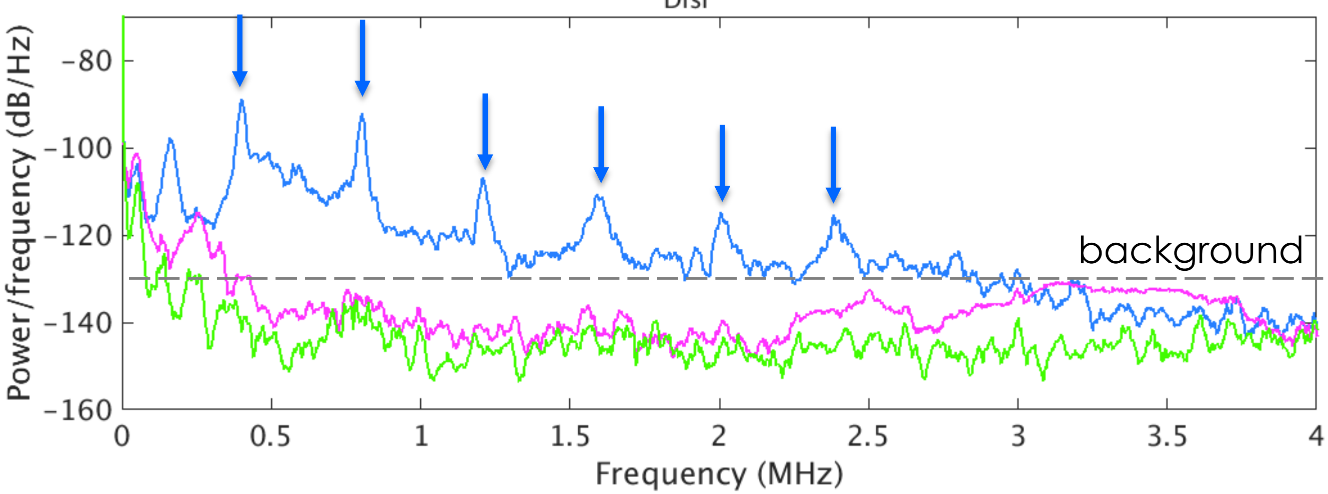
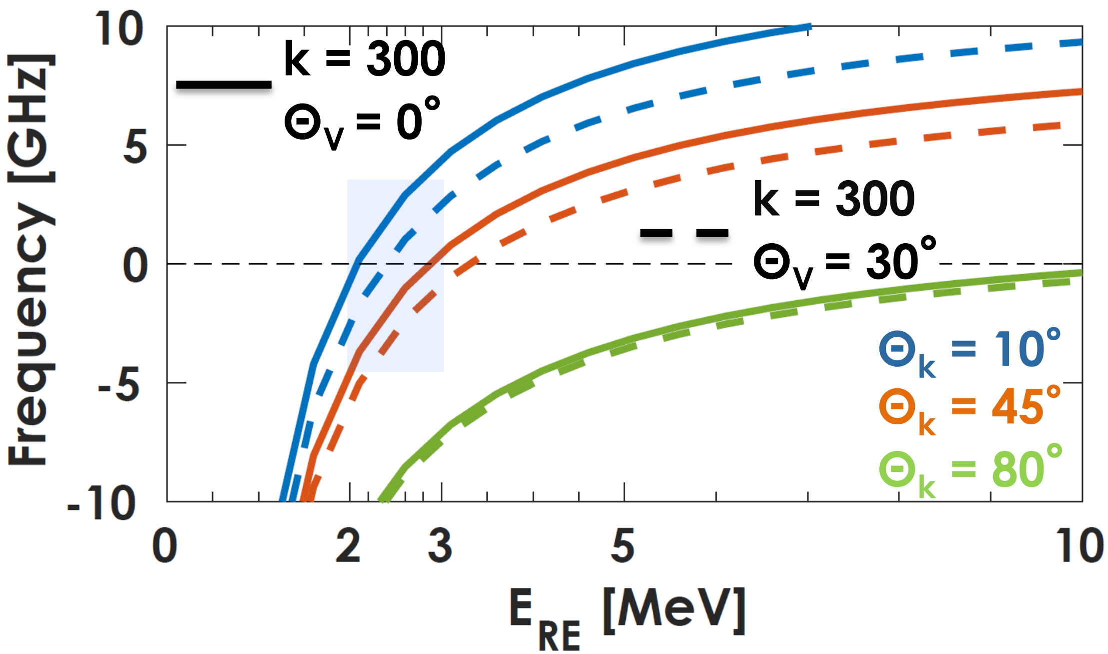
Modes go every 400 kHz up to 3 MHz





Peaks:	400 kHz
	800 kHz
	1200 kHz
	1600 kHz
	2000 kHz
	2400 kHz
Interval:	400 kHz
Width:	25 kHz

Magnetized plasma oscillations is a possible candidate



Anomalous Doppler resonance for different $|k|,\ k_{\parallel}, V_{\parallel}$

Dispersion relation [2]:

$$\omega = \omega_{pe} \frac{k_{\parallel} c}{\sqrt{k^2 c^2 + \omega_{pe}^2}}$$

Resonance:

$$\omega = \frac{\omega_{ce}}{\gamma} - k_{\parallel} V_{\parallel}$$

- **Observed oscillations are at low frequencies**
  - $\omega_{osc} \approx 0.3 \ldots 3\ MHz$
  - $\omega_{osc} \lesssim \omega_{ci} \sim 10\ MHz$
- **Possible plasma waves are magnetized electron plasma wave [1,2] and magnetosonic-whistler wave [3]**
- **Anomalous Doppler resonance is a possible driving mechanism**

[1] Parail and Pogutse NF 1978
[2] Aleynikov and Breizman NF 2015
[3] Fülöp et al. PoP 2006

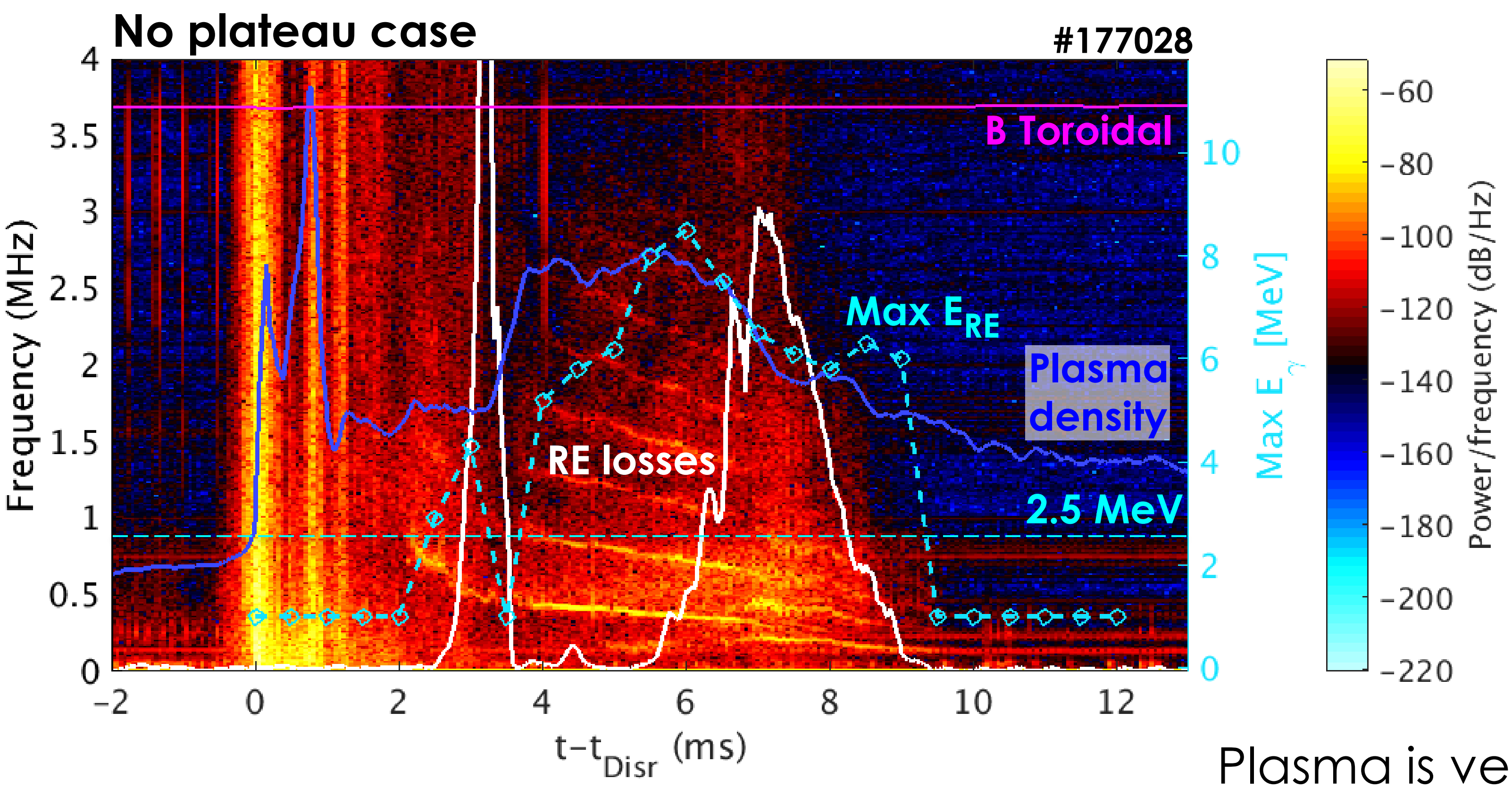
Summary

- **Disruptions triggered by Ar MGI often produce no RE plateau**
- **Larger Ar quantity more reliably leads to RE plateau formation**
- **Increased pre-disruption Ip requires more Ar injected**
- **No RE plateau cases correlate with**
  - high loop voltage
  - large number of high-energy REs
  - intense fast magnetic modes in the range 0.1–3 MHz
    - modes exist when E_{RE} > 2–3 MeV
    - possible candidate is magnetized electron plasma waves

- **Disruptions triggered by Ar pellet reliably produce RE plateau**
- **Key differences of Ar killer pellet compared to Ar MGI:**
  - a few times smaller loop voltage
  - a few times smaller maximum energy of REs
  - almost no kinetic instabilities during CQ

Backup

Modes correlate with E_{RE}, plasma density and RE losses



$$\omega = \frac{k_{\parallel} c}{\sqrt{1 + k^2 c^2 / \omega_{pe}^2}} \Rightarrow \omega \propto n_e^{-1} \ldots n_e^{-1/2}$$

Plasma is very perturbative during disruptions to do scan of parameters

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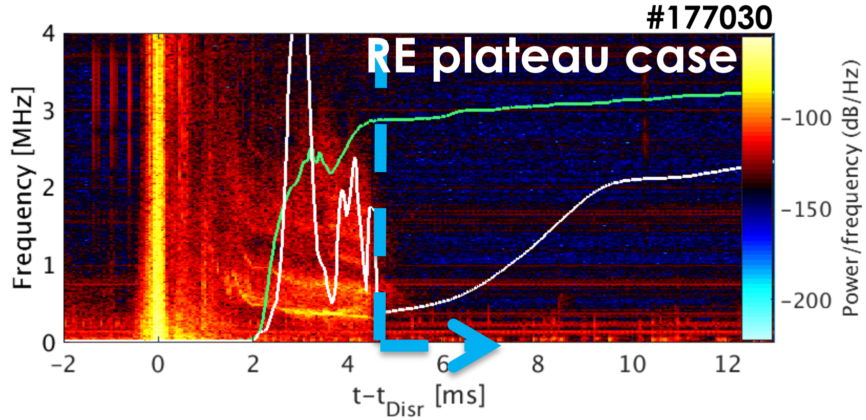
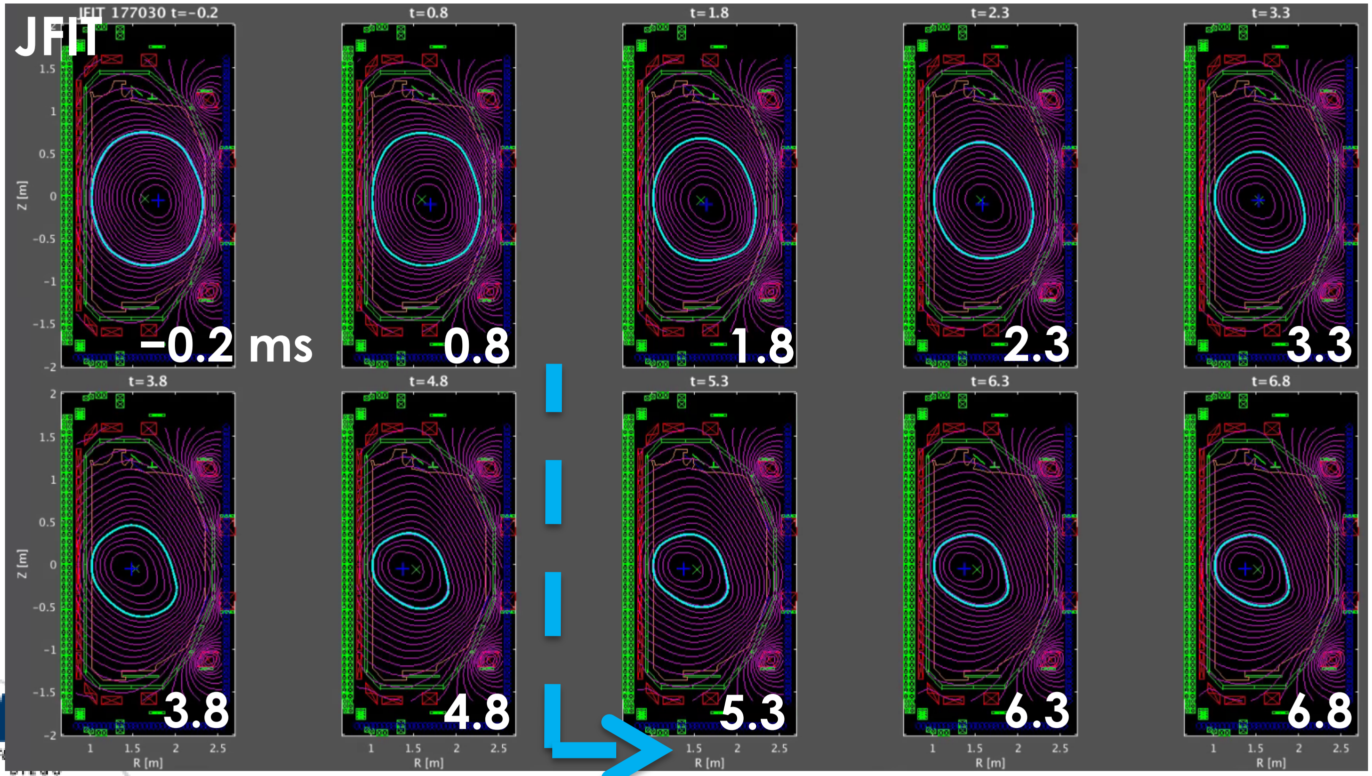
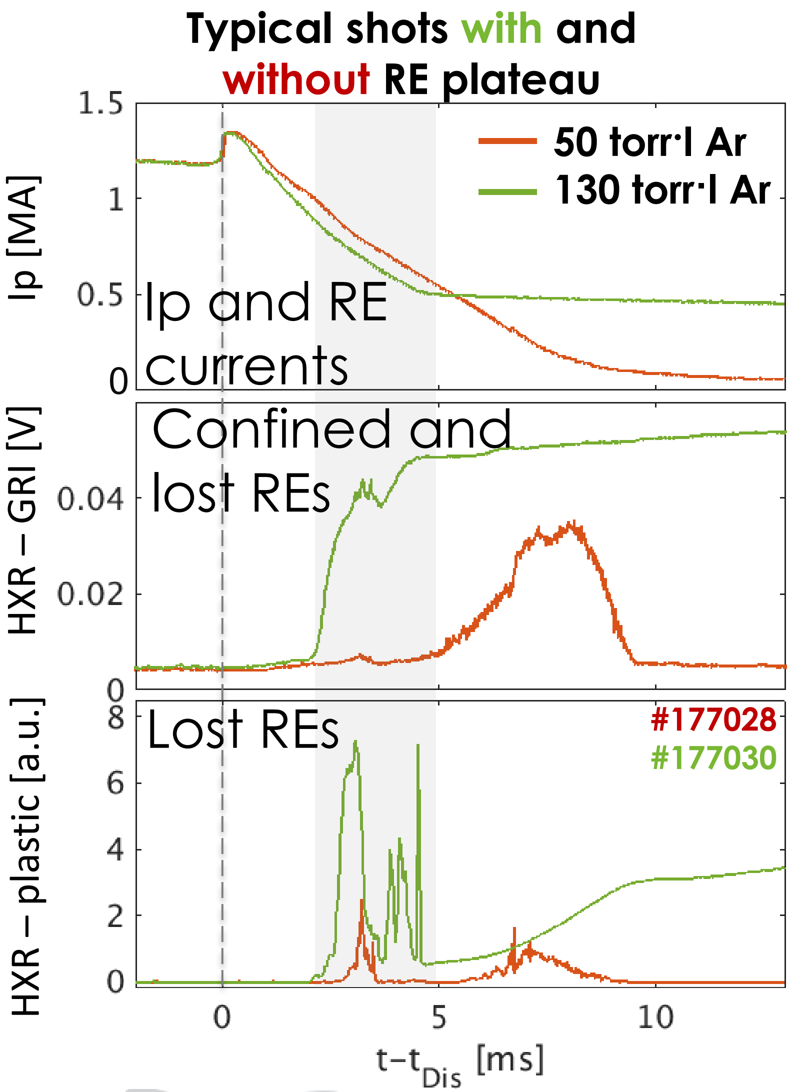
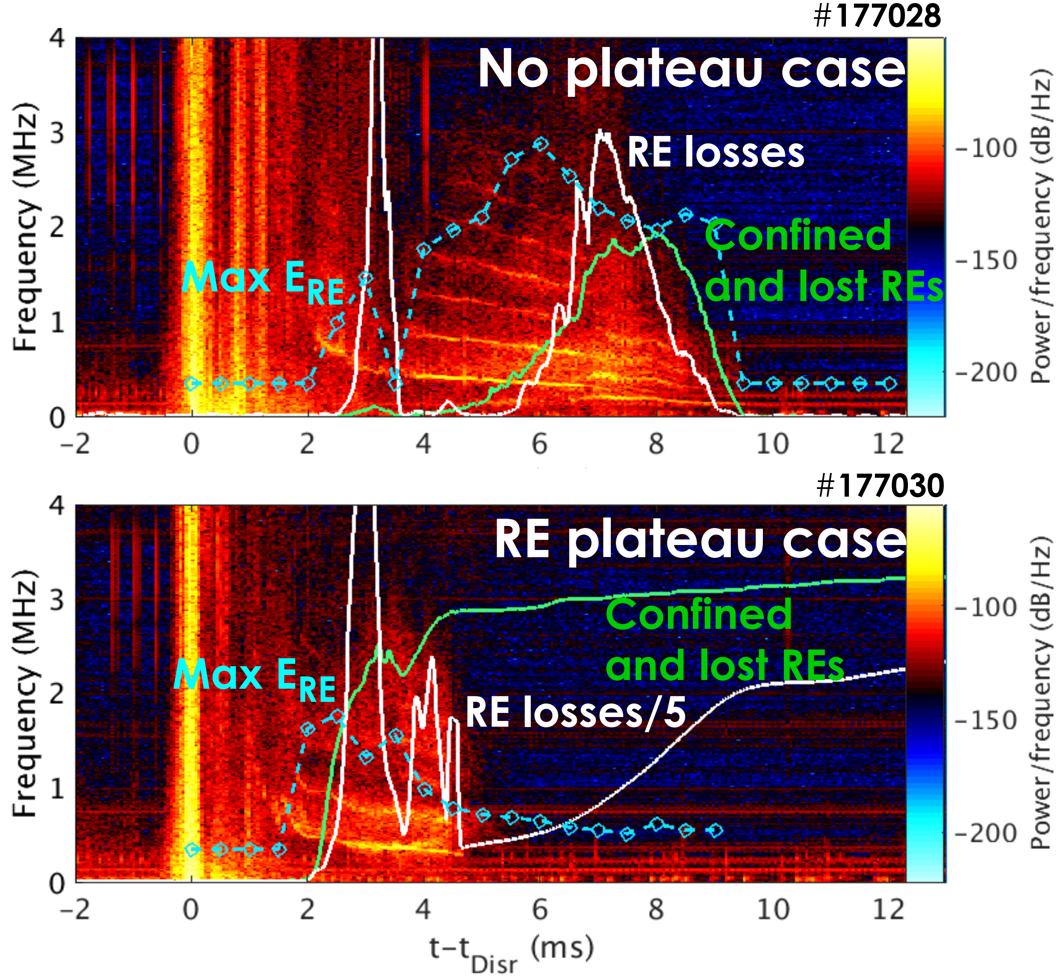
Modes do NOT disappear because of possible plasma movement far from fast magnetic loops





Intense RE losses correlate with fast magnetic signals





Is there connection with RE distribution function?

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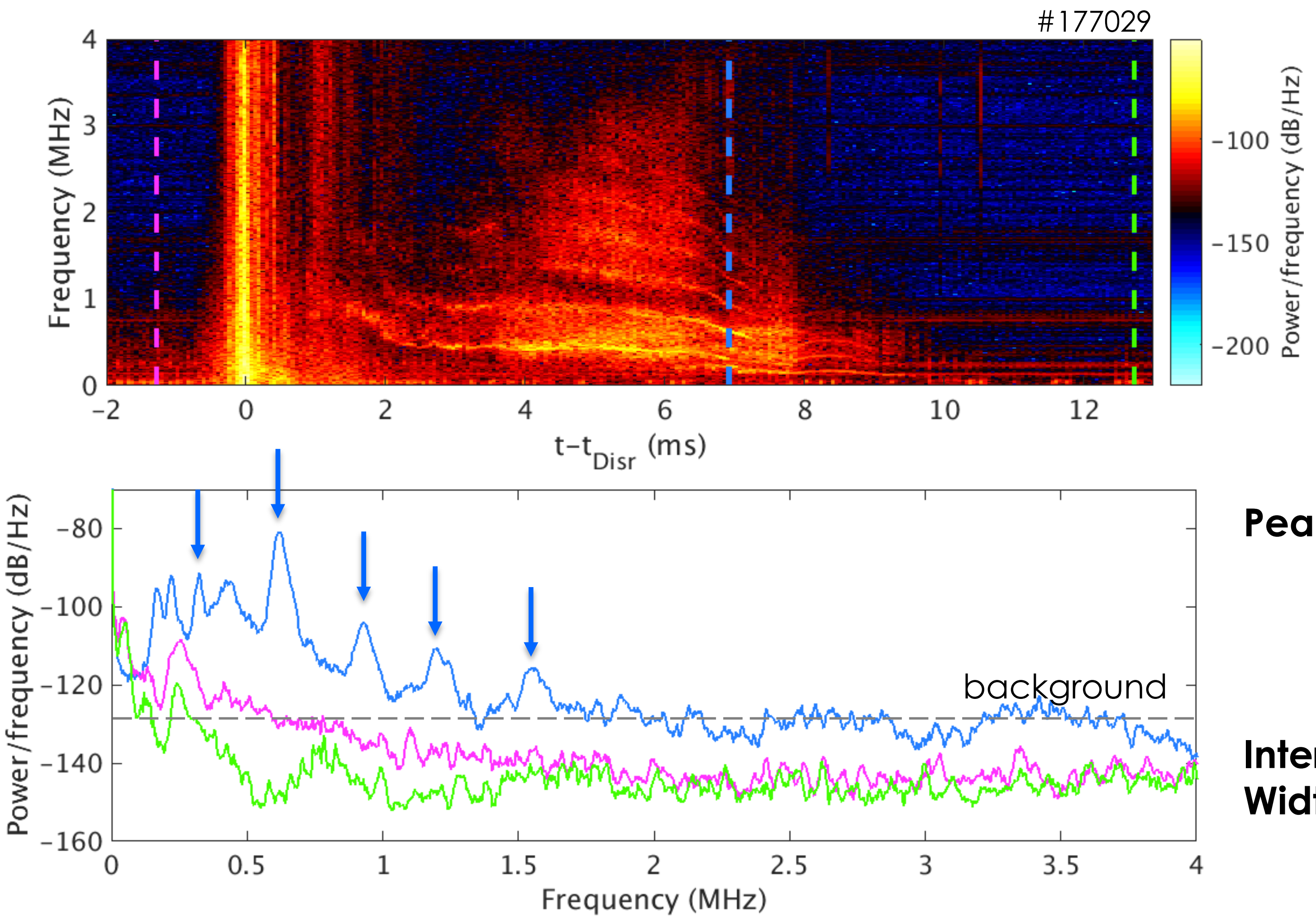
Modes go every 300 kHz up to 1.5-3 MHz (different shot)



Peaks: 320 kHz
620 kHz
930 kHz
1200 kHz
1550 kHz

Intervals: 300 kHz

Widths: 50 kHz

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