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Runaway generation and losses during disruptions in the TEXTOR tokamak

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531st Wilhelm and Else Heraeus Seminar
3D versus 2D in Hot Plasmas
30th April – 2nd May 2013,
Physikzentrum Bad Honnef, Germany

Wilhelm und Else Heraeus Stiftung

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Outline

- Runaway generation
  - Dreicer generation,
  - Hot tail generation,
  - Tritium decay,
  - Compton scattering of γ rays from the activated wall,
  - Runaway avalanching.
- Runaway losses
  - Synchrotron radiation,
  - Bremsstrahlung,
  - Plasma instabilities,
  - RE diffusion due to magnetic fluctuations,
  - Unconfined drift orbit losses,
  - Resonance between gyromotion and magnetic field ripple.

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Experiment Setup

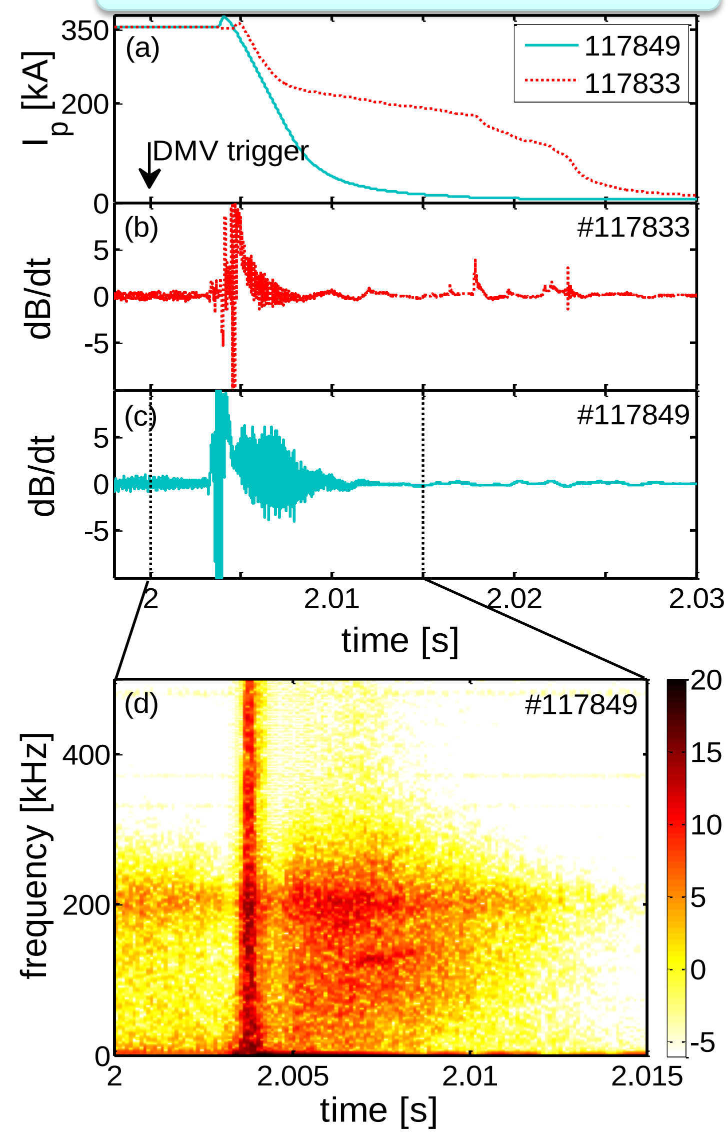
- Disruptions are deliberately triggered by an injection of large amounts of Argon using a fast disruption mitigation valve (DMV) on TEXTOR .

- Plasma parameters:
  - B_t= 1.7-2.6 T,
  - I_P = 300-350 kA,
  - n_e = 2.0×10^{19} m^{-3},
  - R = 1.75 m,
  - a = 0.46 m and
  - N_{Ar} = 2.3×10^{21} - 1.9×10^{22}.

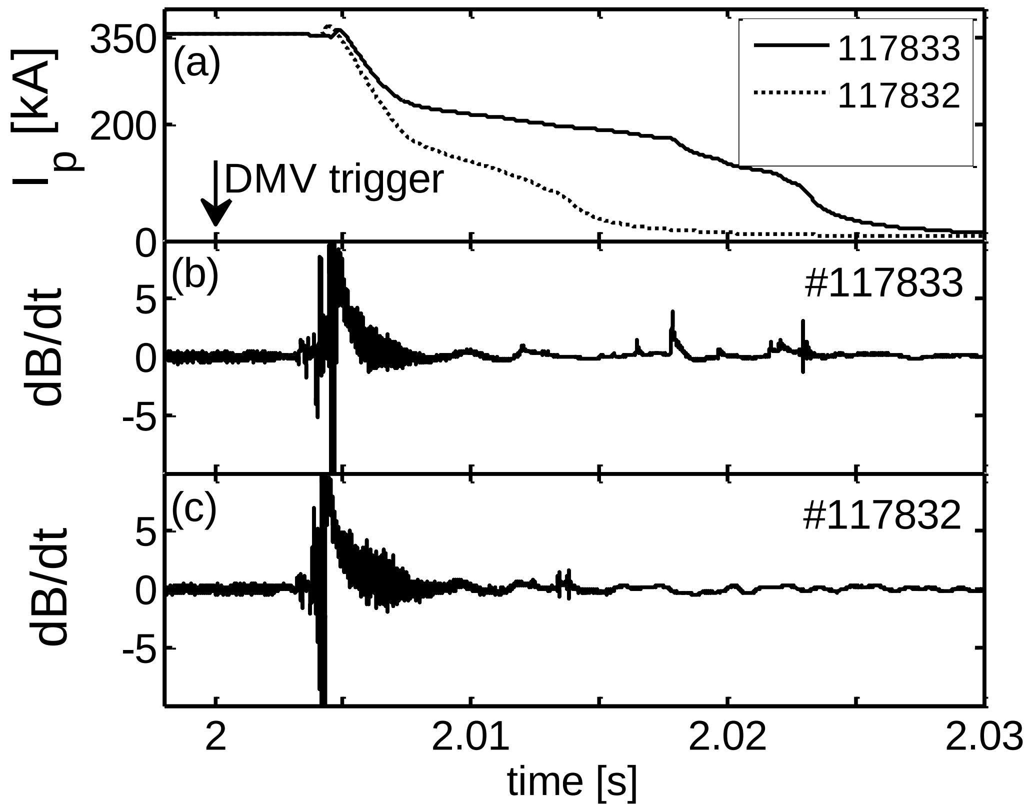
Experimental results (1)

- Different toroidal magnetic field ⇒ different runaway tail.
- Obvious magnetic turbulence is observed in the magnetic pick-up coils.
  - *The magnetic turbulence appears at the beginning of the current quench and lasts from 4 to 8 ms.*
  - *It is a broadband frequency turbulence and most of the power is in the range of 60~260 kHz.*

2.4 T (117833), 1.8 T (117849)



Experimental results (2)



- Even in the same toroidal magnetic field, the RE plateau is not reproducible.
- The magnetic turbulence level could be the reason to cause the difference.

The role of magnetic field fluctuations

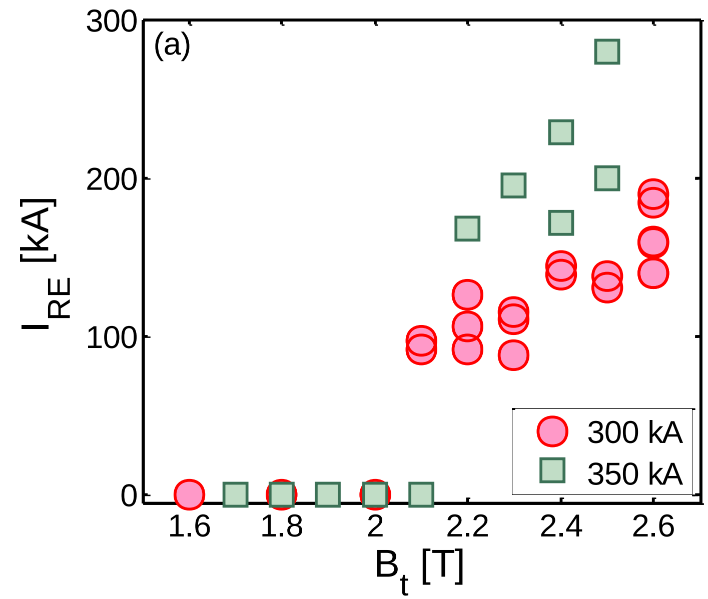
- The characteristic diffusion time associated with magnetic turbulence

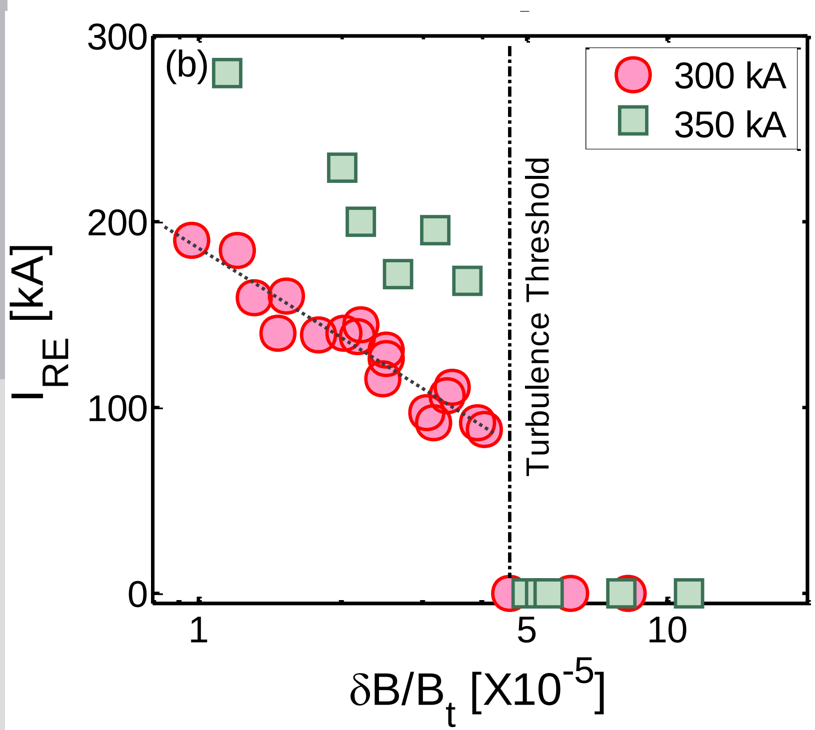
$$\tau_{\delta B} = \frac{a^2}{v_{||} D_M} \gamma^5 \quad \textit{where} \quad D_M \approx \pi q R (\delta B / B_t)^2$$

- In theory, $\delta B/B_t > 0.1\%$ could suppress the runaway avalanche during the disruptions.
- In present tokamak experiments,
  - *External excited magnetic perturbations (Resonant Magnetic Perturbations)* **JT-60U, TEXTOR**
  - *The magnetic fluctuation level is correlated with the hard X-ray signal after the disruptions* **JET**
  - *Intrinsic magnetic turbulence on the de-confinement of runaway electrons during the flattop phase of low density discharges* **TEXTOR**

- Runaways occur after a disruption when the value of B_t exceeds the threshold (~ 2 T) in TEXTOR.

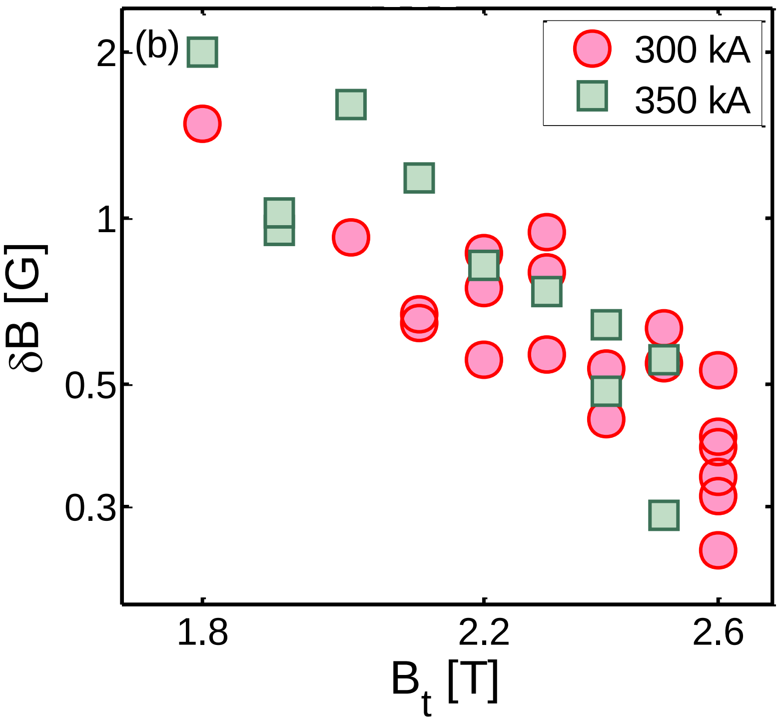
- The runaway tail is not reproducible.

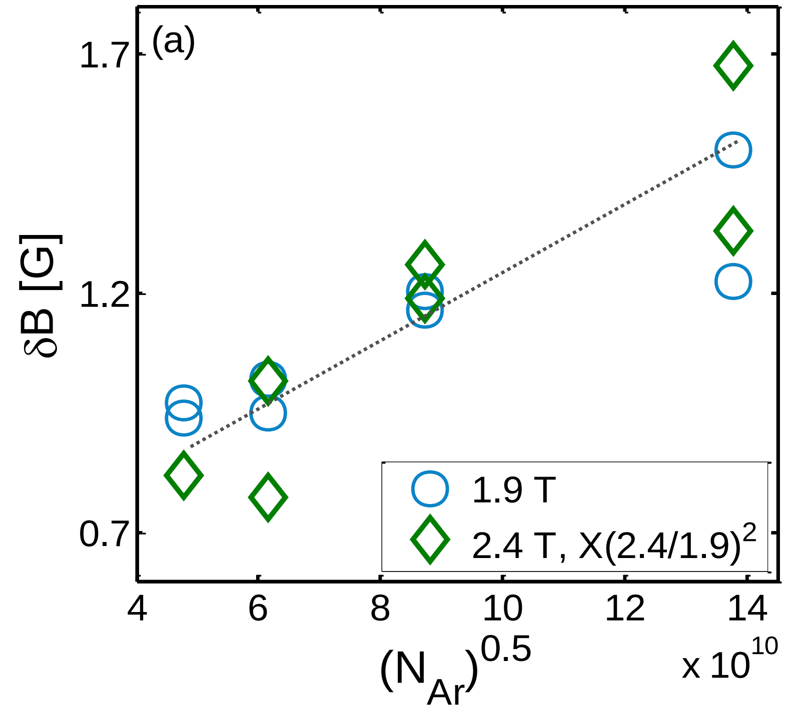




- The runaway current is a function of the maximum magnetic turbulence during the current quench.

- The runaway plateau is almost invisible when the normalized magnetic turbulence exceeds the threshold of about 4.8×10^{-5}.





$$\delta B \propto B_t^{-2}$$

$$\delta B / B_t \propto \sqrt{n_e}$$

The level of magnetic turbulence is strongly dependent on the toroidal magnetic field.

The magnetic turbulence is mainly contributed from the background plasma.

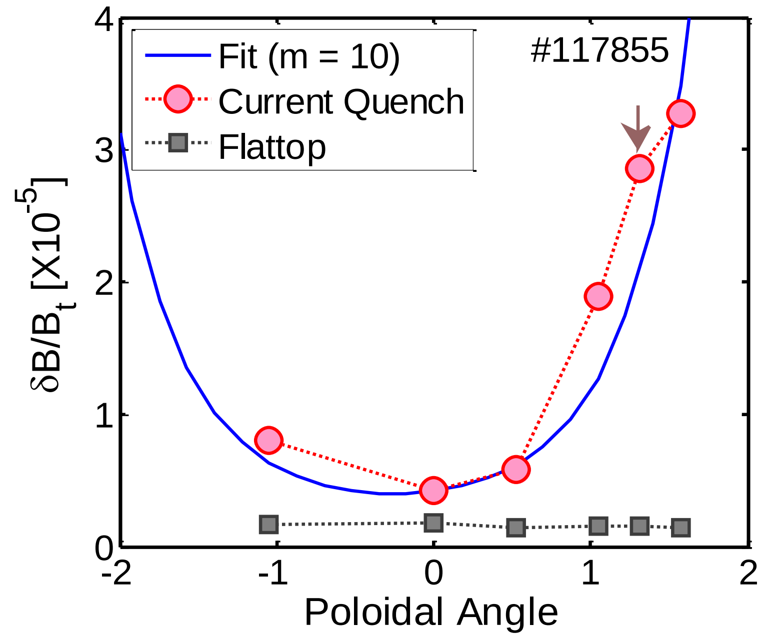
0D model of the current quench

$$\frac{dn_{\mathrm{RE}}}{dt} = f_{\mathrm{prim}} + (1/\tau_{\mathrm{RE}} - 1/\tau_{\mathrm{loss}})n_{\mathrm{RE}}$$

Dreicer generation | Avalanche Process | RE losses

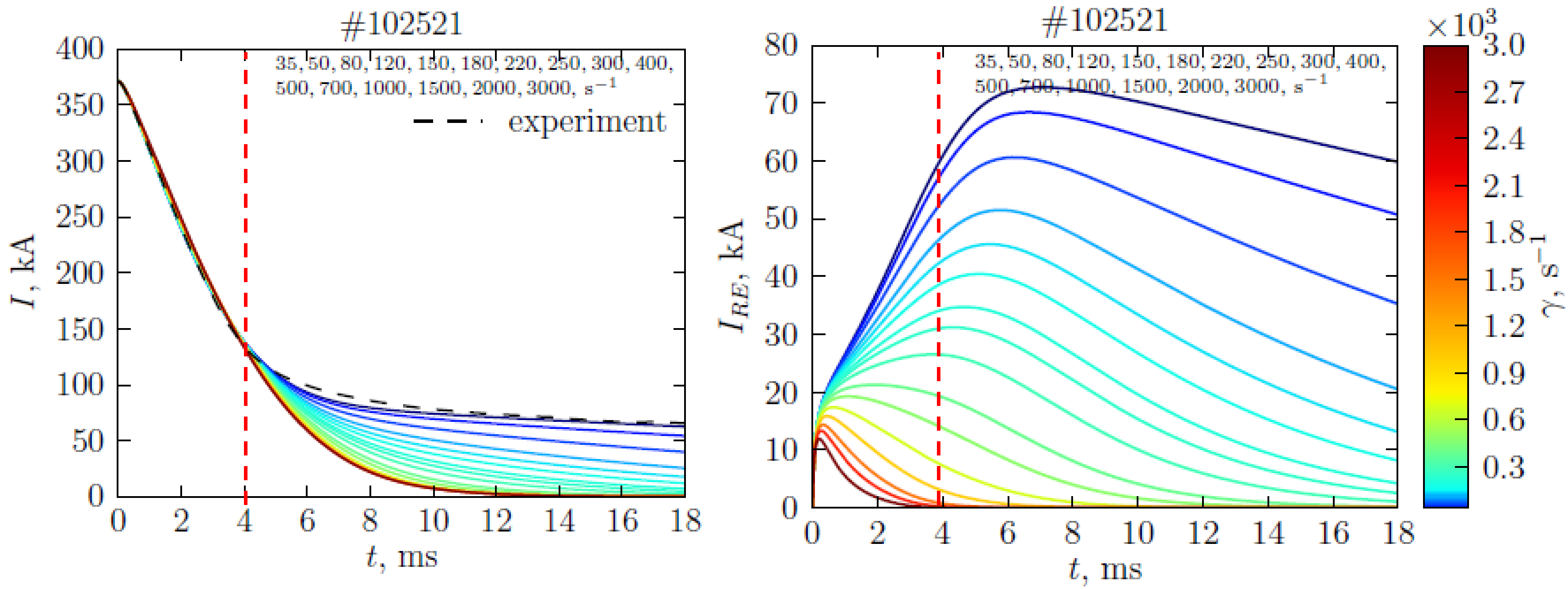
- With high magnetic turbulence, the runaway diffusion time should be shorter than the avalanche growth time and therefore suppress avalanche generation of runaways.
- $1/\tau_{\mathrm{RE}} \sim 260\mathrm{s}^{-1}$ @ B_t = 2.4 T, N_{Ar}= 3.8×10^{21}, R = 1.67 m, a = 0.35 m, q = 2, $v_{//} \approx$ c = 3×10^8 m/s and γ = 3.
- The corresponding threshold of magnetic turbulence is ~ 2.2×10^{-3}.

The measured values (~4.8×10^{-5}) , two magnitude lower?

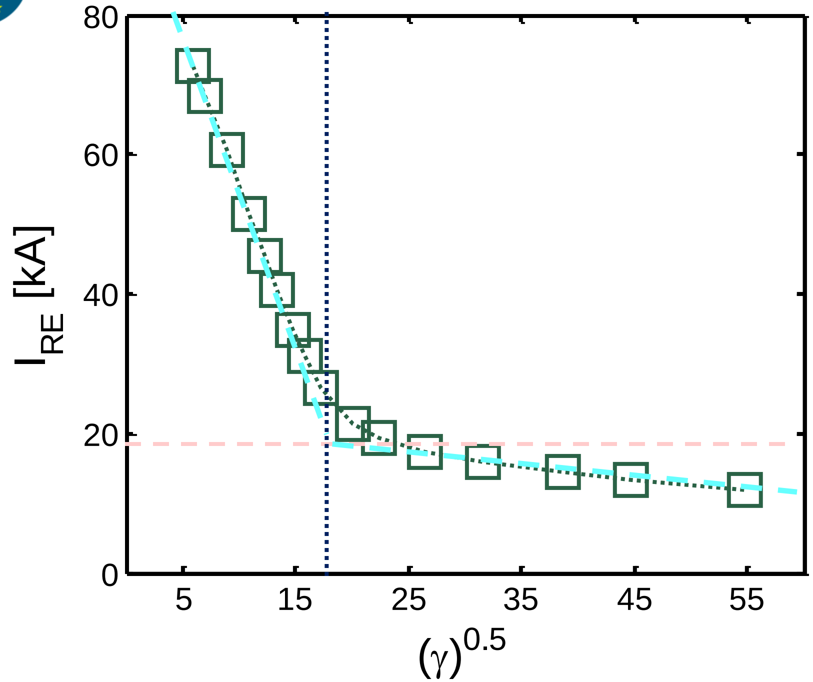


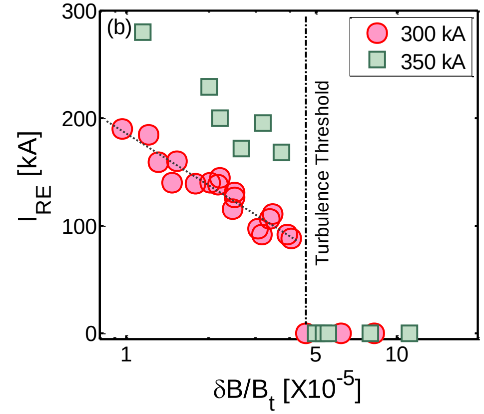
- Magnetic turbulence during the current quench is found to be poloidally asymmetric, which could be caused by the plasma shrinking and moving inward.
- Assuming *m*=10, the plasma movement inwards by 8 cm and shrink to 0.35 m, the simulated signals are similar to the measured ones. The magnetic turbulence level at the plasma edge $\delta B/B_t \approx 2.4\times10^{-3}$.

Simulated results



- Keep all the parameters fixed and vary only $1/\tau_{loss}$ (γ) : 35 → 3000 s^{-1}
- Increasing the loss rate, clearly reduces the runaway current and consequently the plateau amplitude.





❖ *The dependence of the runaway current on the loss rate.*

- There are clearly two regions: a linear decay for γ < 350 s^{-1} and for γ > 350 s^{-1} :
  - *the linear fit to the first region is consistent with experiments;*
  - *The second linear decay appears because of the Dreicer mechanism, which is very powerful but short in time, at this point the avalanche is suppressed.*

Summary of RE losses

- Magnetic turbulence (broadband frequency) is observed at the beginning of the current quench in intended TEXTOR disruptions.
- Runaway suppression has been experimentally found only with magnetic turbulence larger than a threshold.
  - *This gives a consistent explanation for the B_t threshold.*
  - *For shots with lower magnetic turbulence level than the threshold, the runaway current decreases linearly with $\delta B/B_t$.*
- Magnetic turbulence is mainly contributed from the background plasma and the level is strongly dependent on the toroidal magnetic field and plasma electron density.

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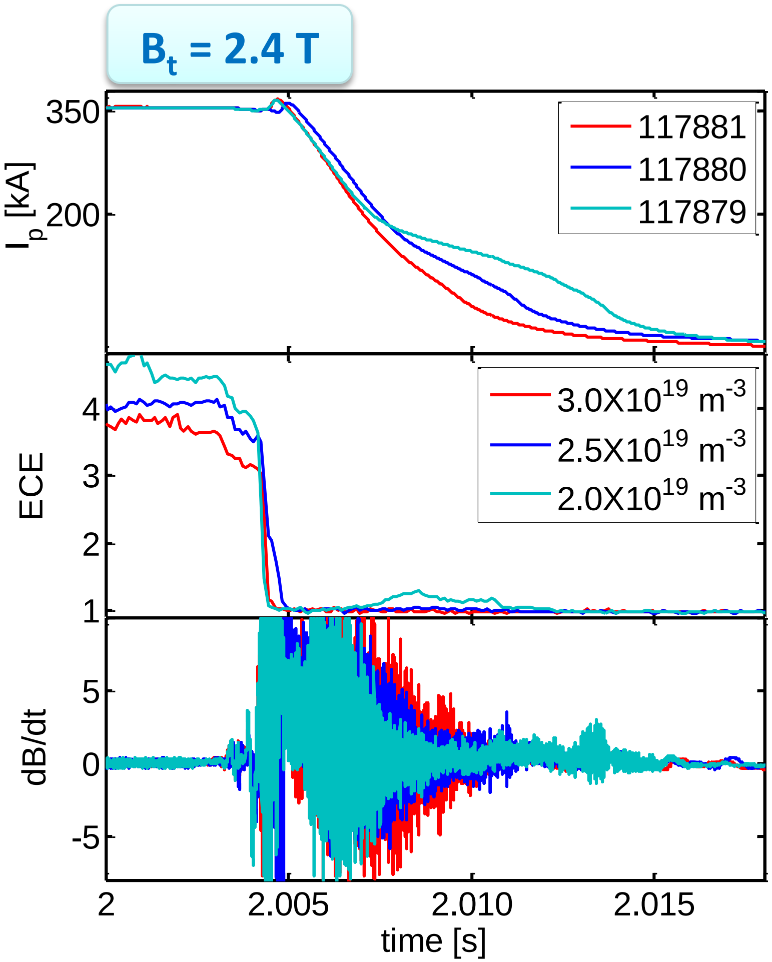
Experimental results

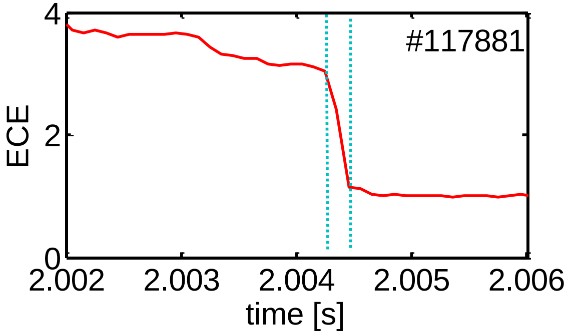


- Setup: Decrease density from 3.0×10^{19} m^{-3} to 2.0×10^{19} m^{-3} with the same plasma current (350 kA) and toroidal magnetic field (2.4 T).
- The different plasma temperature before disruptions $\Rightarrow$ the runaway tail is totally different.
  - The primary generation due to the Dreicer electric field and the loss due to the magnetic turbulence are almost similar.

Hot tail runaway generation

Hot tail runaway generation

- Hot tail runaway electron generation is caused by incomplete thermalization of the electron velocity distribution during rapid plasma cooling [1, 2, 3].
- It is an important runaway generation mechanism in tokamak disruptions if the thermal quench phase is sufficiently fast.
- For TEXTOR, the typical thermal quench time during disruptions is ~200 μs.



[1] P. Helander et al., Phys. Plasmas **11**,5704 (2004)

[2] H. Smith et al., Phys. Plasmas **12**,122505 (2005)

[3] H. M. Smith and E. Verwichte, Phys. Plasmas **15**, 072502 (2008)

0D Model*

$$T = T_{\text{final}} + (T_0 - T_{\text{final}})e^{-t/t_0}$$

⇨ The temperature evolution

$$n = n_{\text{final}} - (n_{\text{final}} - n_0)e^{-t/t_0}$$

⇨ The electron density evolution

$$\tau(t) \simeq H(t - t_0)\frac{n_{\text{final}}}{n_0}\nu_0(t - t_0)$$

⇨ A time delay before the distribution begins to decrease

- ν_0 is the collision frequency and t_0 is the temperature decay time.

⇨ The density of hot tail runaways during the thermal quench

$$n_{\text{run}}^{h} = \int_{v_c}^{\infty} f\, 4\pi v^2 dv \simeq n_0 \frac{2}{\sqrt{\pi}} u_c e^{-u_c^2}$$

- where $u_c = (v_c^3 / v_{T_0}^3 + 3\tau)^{1/3}$

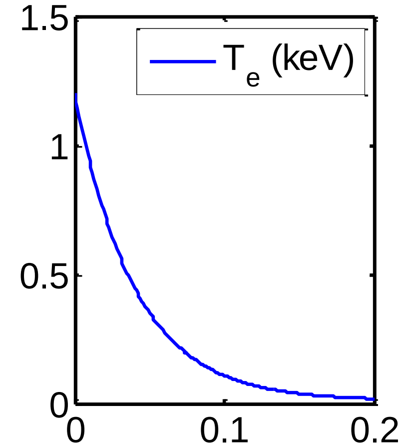
* H. M. Smith and E. Verwichte, Phys. Plasmas **15**, 072502 (2008)

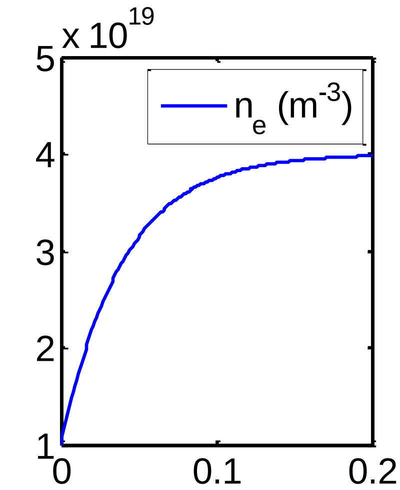
Simulation results (1)

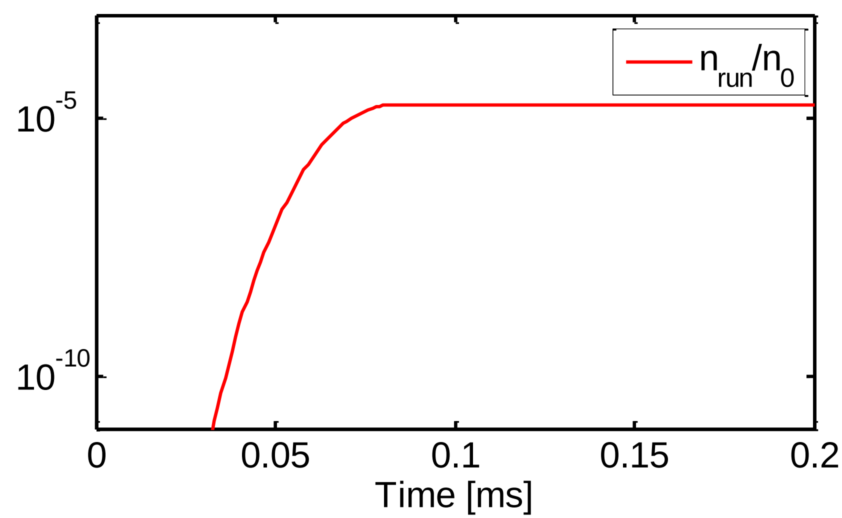
- Parameters
  - T_0 = 1.2 keV, T_{final} = 10 eV;
  - $n_0 = 1.0\times10^{19}$ m^{-3},
  - $n_{final} = 4.0\times10^{19}$ m^{-3};
  - t_{TQ} = 0.2 ms, t_0 = 0.04 ms.

➢ $n_{run}/n_0 \sim 2\times10^{-5}$

I_{RE} ~ 800 A



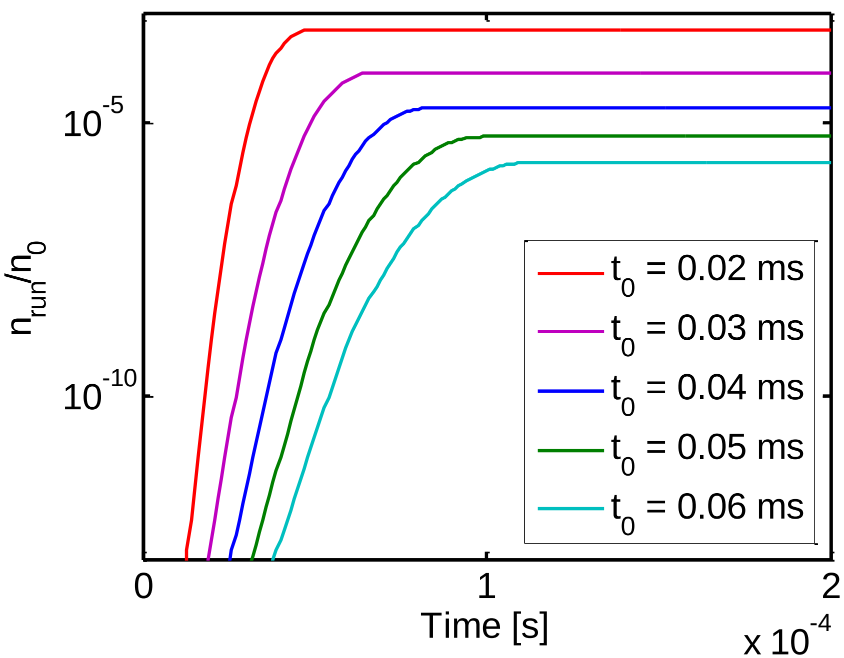




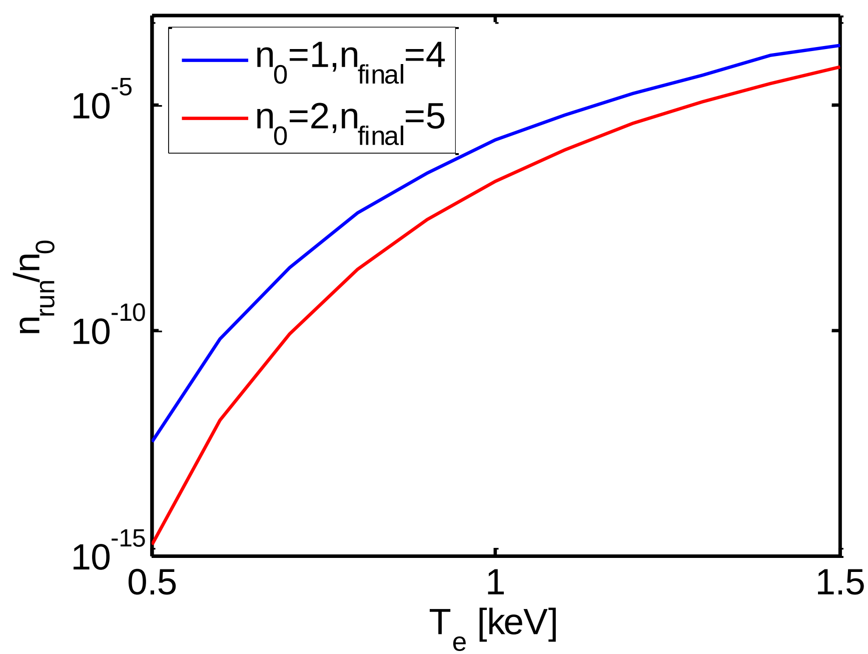
- No loss processes are considered here!

Simulation results (2)

- Decay time scan
  - Hot tail RE generation increases with faster decay.



- Temperature scan
  - Hot tail RE generation increases with higher temperature before the disruptions.



Criteria for hot tail runaway generation

- Criteria for hot tail runaway generation more than the Dreicer mechanism during the disruptions [1]:

$$\nu_0 t_0 < \frac{1}{3}\left(\frac{E_D}{2E_\parallel}\right)^{3/2} \text{ and } \frac{E_D}{E_\parallel} \simeq \left(\frac{\pi T}{2m_e}\right)^{1/2} \frac{3\mu_0 enqR}{B_t}$$

- Using the parameters of a typical TEXTOR discharge,

  $\nu_0 t_0 \simeq 3.0$ while the criterion gives $\nu_0 t_0 < 6.6$.

  - A high-energetic electron tail could form during TEXTOR disruptions.

[1] H. Smith et al., Phys. Plasmas **12**,122505 (2005)

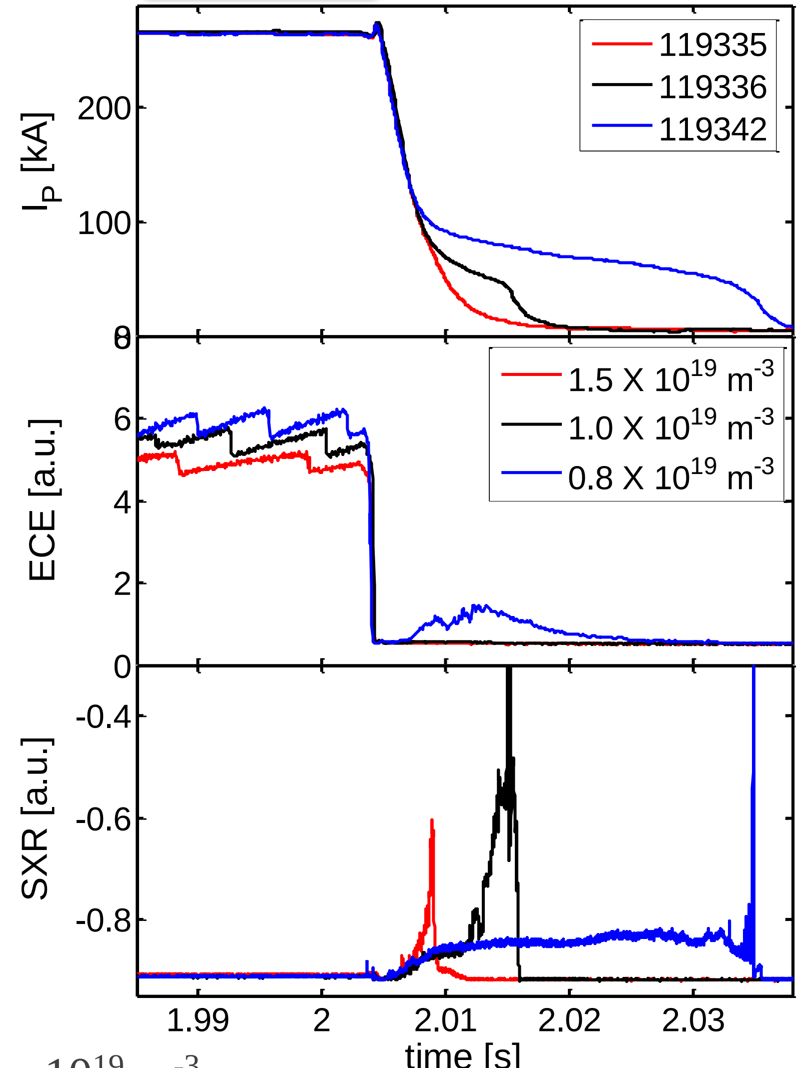
Experimental results (2)

- RE plateau @ B_t = 1.7 T (< 2 T).
  - Setup: Decrease density from 1.5×10^{19} m^{-3} to 0.8×10^{19} m^{-3} with the same plasma current (260 kA) and toroidal field (1.7 T).
  - The different temperature

    ⇒ the different runaway tail.

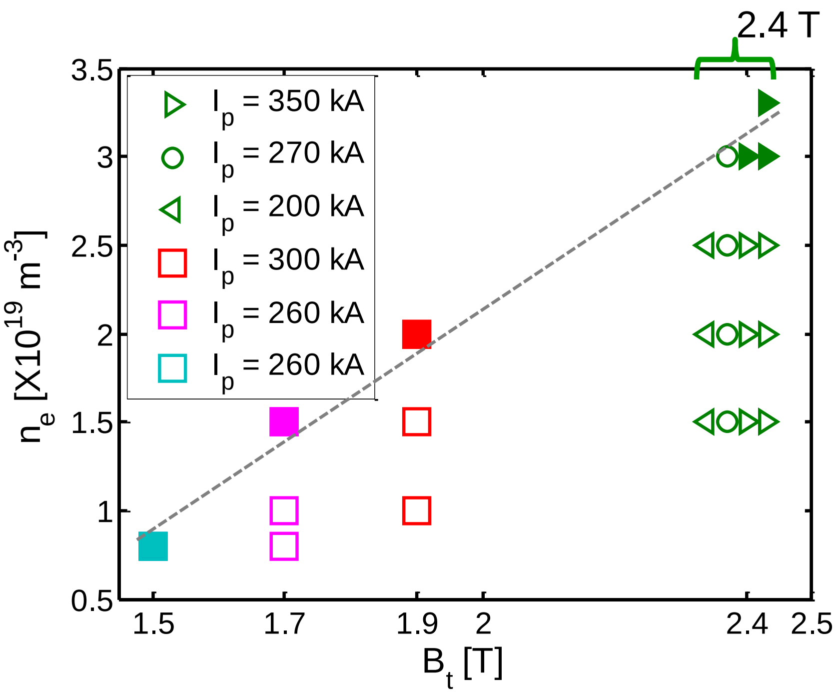
    ⇒ The clear runaway tail @ B_t = 1.7 T and n_e = 0.8 $\times 10^{19}$ m^{-3}

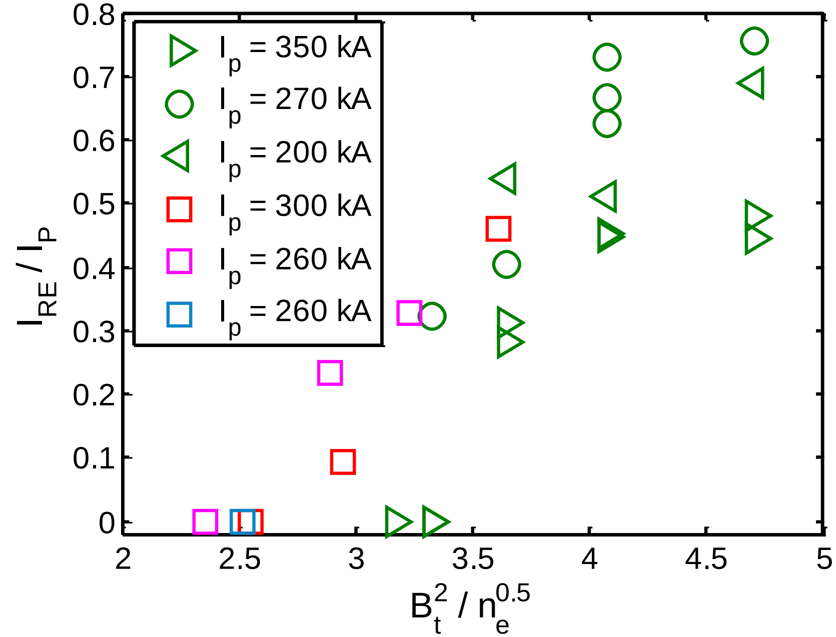
B_t = 1.7 T



*Threshold for REs during the flattop: $n_e \sim 0.7 \times 10^{19}$ m^{-3}.

Experimental results (3)





- Density threshold for RE generation for the fixed B_t and B_t threshold for the fixed n_e;
- The density threshold increases with B_t.
- The runaway current is a function of B_t and n_e (or T_e) before the disruptions.

Valid only in Ohmic discharges!!

Summary

- Hot tail RE generation has been observed in the TEXTOR disruptions.
  - *Simulation results support the experimental observation.*
  - *More REs are generated by hot tail than by the Dreicer mechanism for fast thermal quench.*

- Obvious RE tail is observed at B_t = 1.7 T (< 2 T).

- Density threshold for RE generation is also found in TEXTOR. The density threshold increases with B_t.

Backup

- The occurrence of runaways depends on various factors and no clear runaway generation dependence on plasma parameters is found in theories or experiments until now.
- Runaway generation occurs only above a threshold for the toroidal magnetic field of about 2 T in JET [1], JT-60U [2], Tore Supra [3], and TEXTOR [4].
- A possible explanation is that the whistler wave instability can be excited by runaways for $B_t < 2$ T [5]. ☹

[1] R. D. Gill et al., Nucl. Fusion **42**, 1039 (2002)

[2] R. Yoshino, S. Tokuda and Y. Kawano, Nucl. Fusion **39**, 151 (1999)

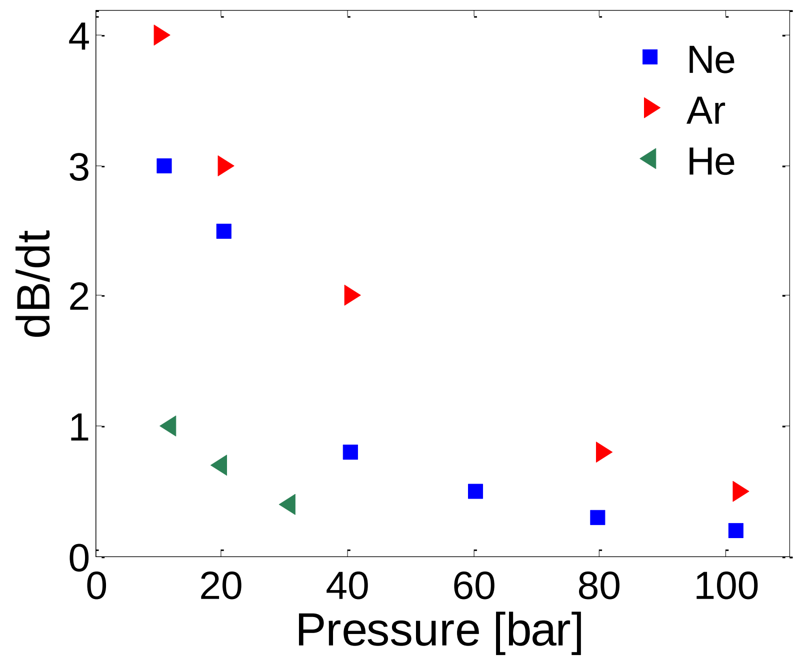
[3] G. Martin, in *Proceedings of the 25th European Physical Society Conference on Plasma Physics, Prague, 1998* (European Physical Society, Prague, Czech Republic, 1998), Vol. 22C, P.3.006

[4] M. Lehnen *et al*., J. Nucl. Mater. **390–391**, 740 (2009)

[5] T. Fülöp, H. M. Smith, and G. Pokol, Phys. Plasmas **16**, 022502 (2009)

Backup

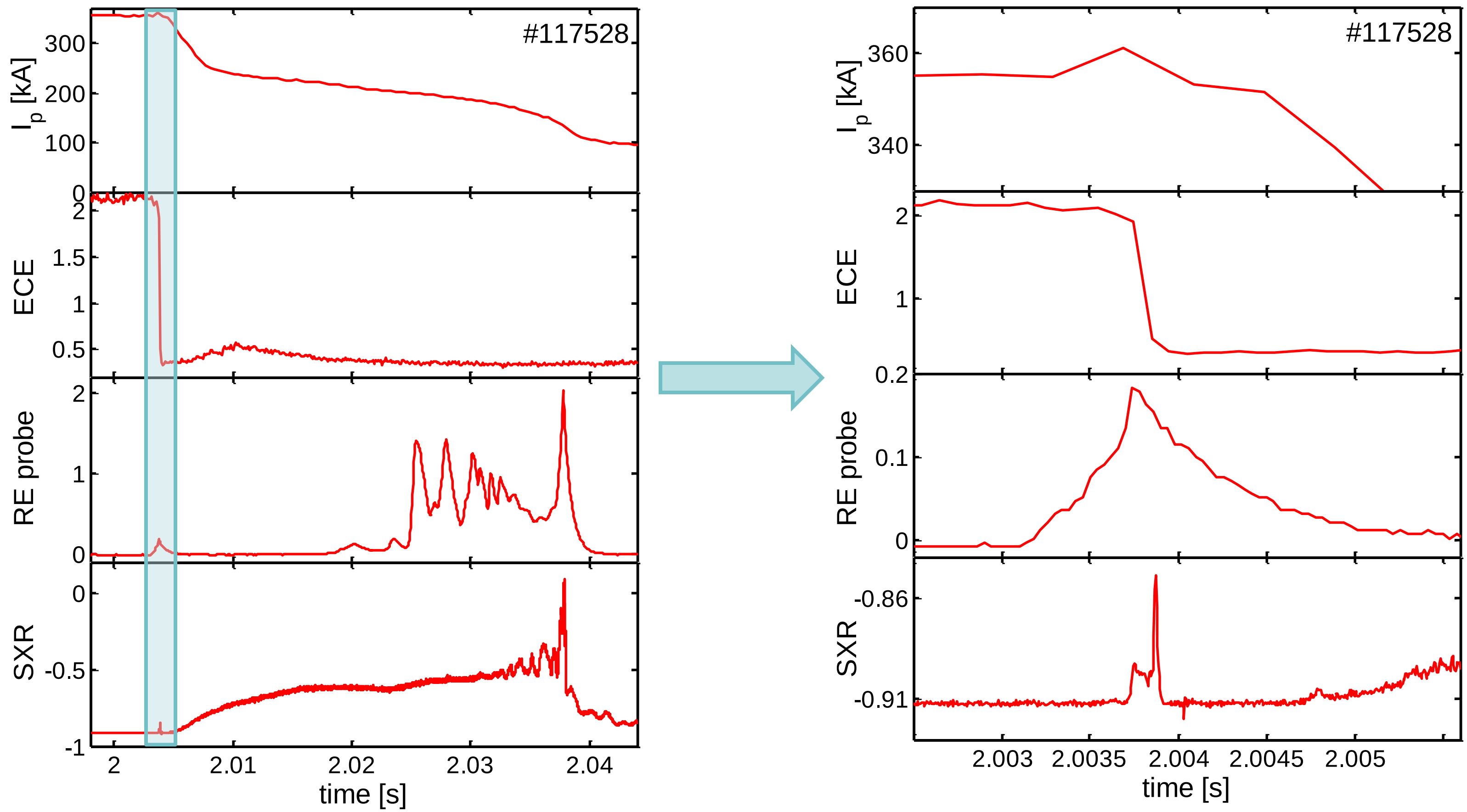
- For discharges performed in different operating gases, e.g. He-2, Ne-10, Ar-20, the amplitude of magnetic fluctuations during current quench increase with increasing ion mass.
- Amplitude of magnetic fluctuations reduce with increasing gas injection for every kind of gas.



* Experimental setup: $B_t = 1.6$ T, $I_P = 300$ kA, $n_e = 2 \times 10^{19}$ m^{-3}

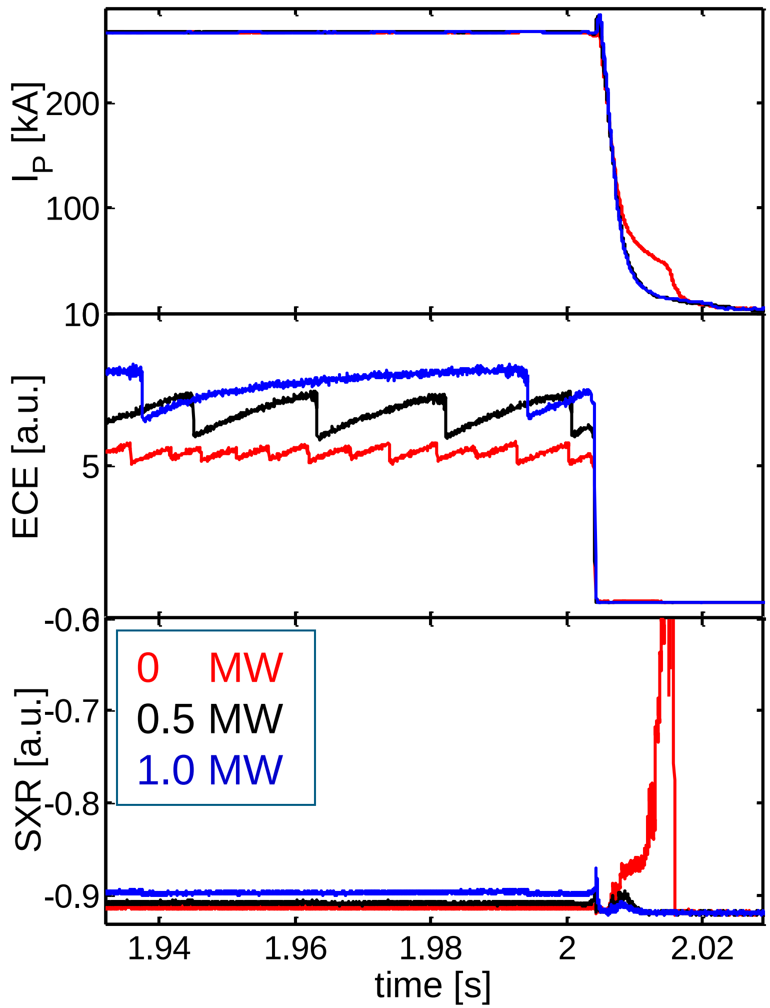
Backup

- High energy electron losses during the thermal quench



Backup

- High energy electron losses possibly due to MHD activities during thermal quench.



B_t = 1.7 T, n_e =1.0 X 10^{19} m^{-3}