Mitigation of Runaway Electrons with SMBI on HL-2A tokamak

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Outline

- **Massive Gas Injection and Supersonic Molecular Beam Injection system on HL-2A**
- **Experimental results**
  - Disruption with formation of runaway plateaus following MGI
  - High frequency mode during CQ and its role
  - Mitigation of runaway current by SMBI
- **Summary**

Gas injection techniques on HL-2A

- MGI has been developed on various tokamaks, including AUG, TEXTOR, DIII-D, JET. A new MGI system has been installed on HL-2A tokamak for disruption mitigation.

- SMBI, which is first developed in SWIP and later widely applied on many devices, provides a possible candidate as a fuelling method for future devices. It also has been successfully used for ELM mitigation on HL-2A and other machines.

  (YAO Lianghua,Nucl. Fusion 1998 38 631)

  (W.W. Xiao. et al 2012.Nucl. Fusion 52(11):114027)

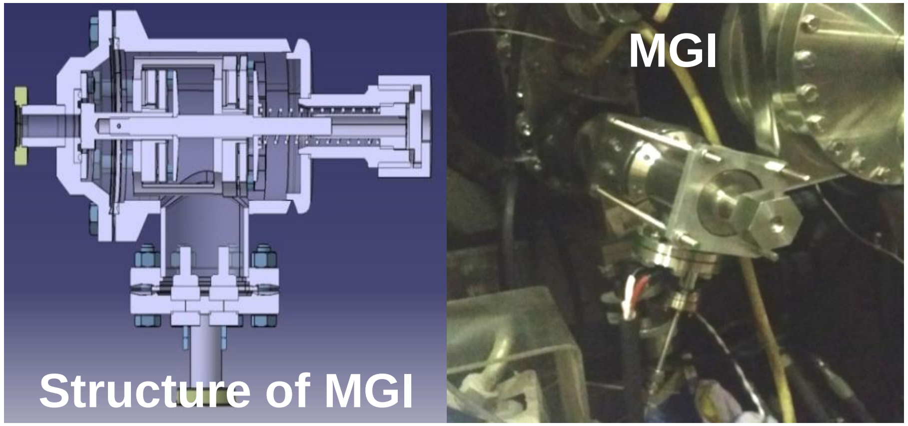
- Dedicated experiments on generation and mitigation of RE have been carried out with MGI combined with SMBI on HL-2A.

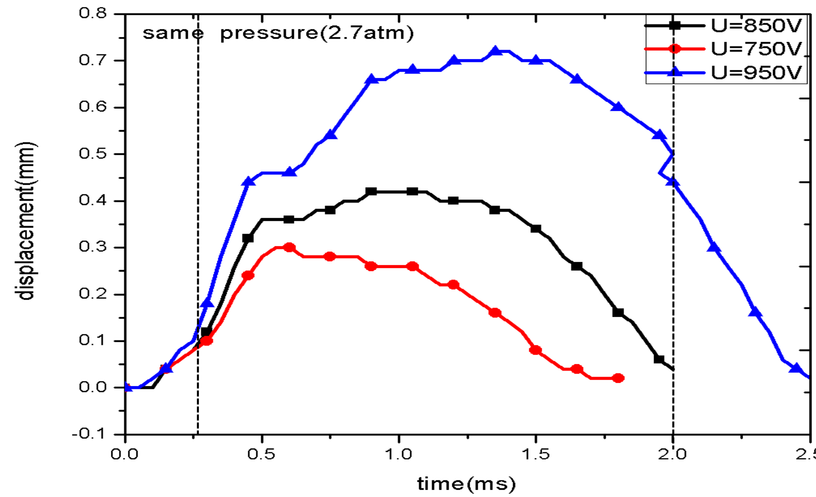
  (Y.P.Zhang,Y.Liu. et al 2012.Physics of Plasma)

Development of the MGI/SMBI system

MGI: open time:<0.25ms; injection time: <2ms ; throughput :10^{23}

working gas pressure :2-14bar





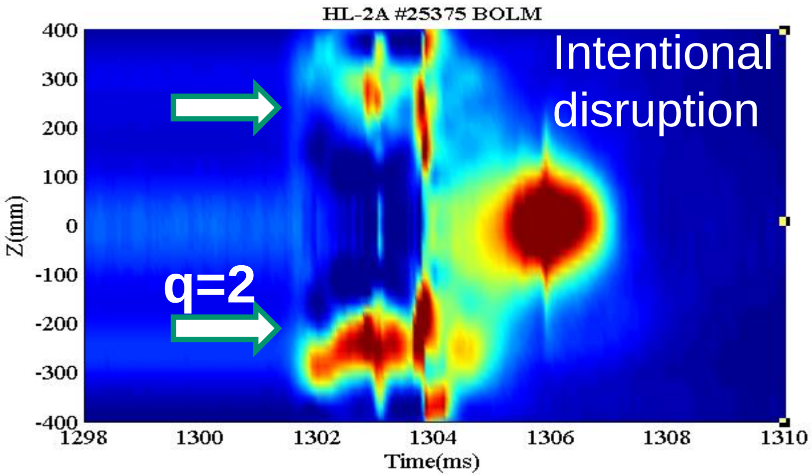
SMBI:open time: 0.2ms; injection time~5-15ms; throughput :10^{22}

Improved SMBI has larger size of nozzle (1mm, 20-80bar), with a advantage of directional motion(1000m/s)

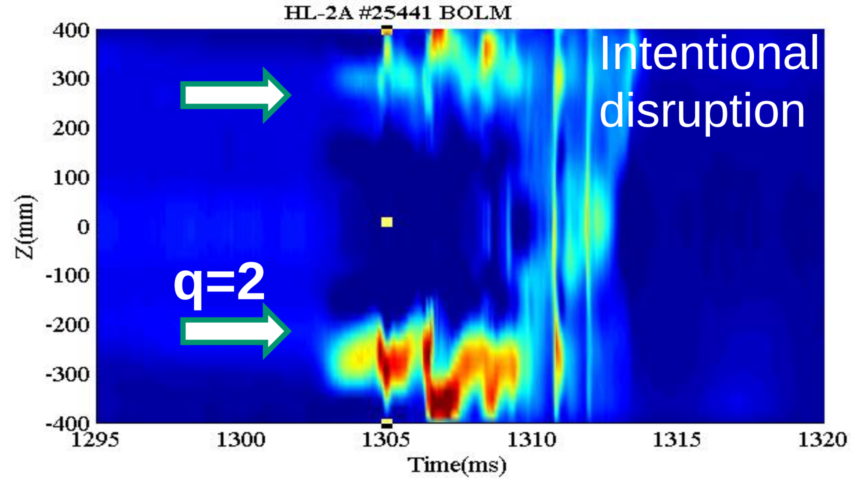
(W.W. Xiao. et al 2012.Nucl. Fusion 52(11):114027)

Gas jet penetration in HL-2A plasma

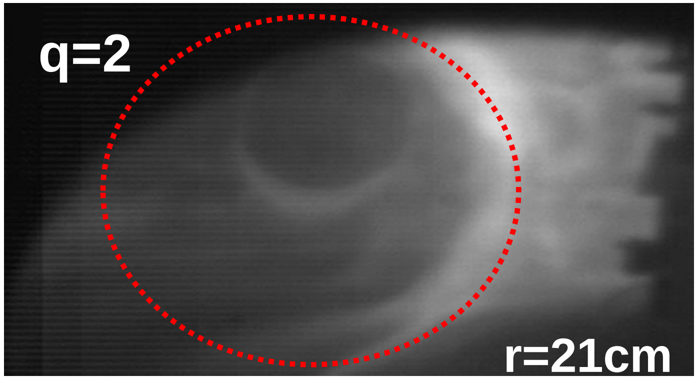
MGI

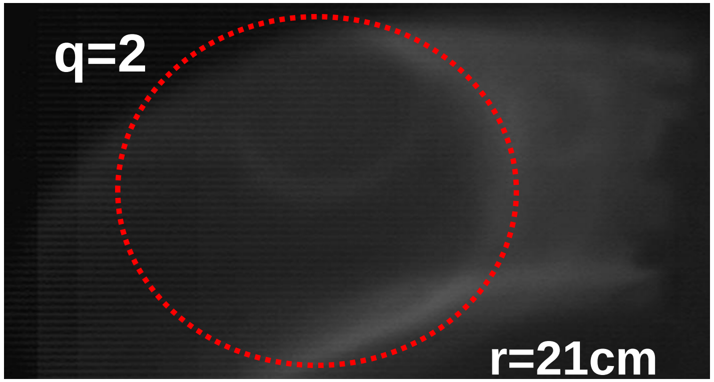


SMBI



Radiated power measured by AXUV array





Fast-framing camera analysis

- **The cold front of gas injected with both techniques can reach the q = 2 surface where it might trigger MHD instabilities.**

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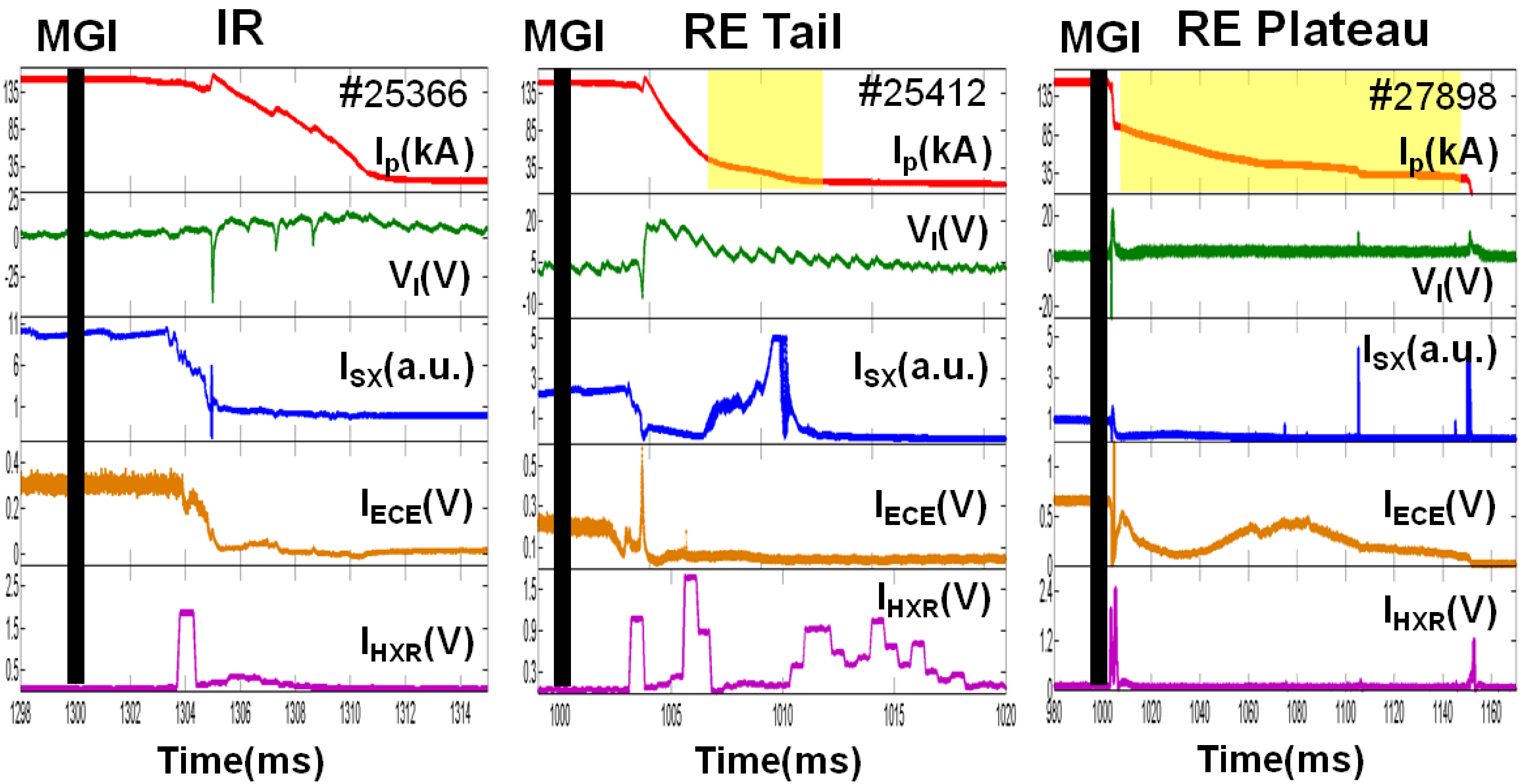
Three types of MGI-induced disruption

➢Generation of runaways with Argon injection.

(B_T=1.38 T, I_p=155 kA , n_e=0.7- 1 × $10^{19} m^{-3}$, Gas: Ar, Throughput: 1.2-7.5 × 10^{20})

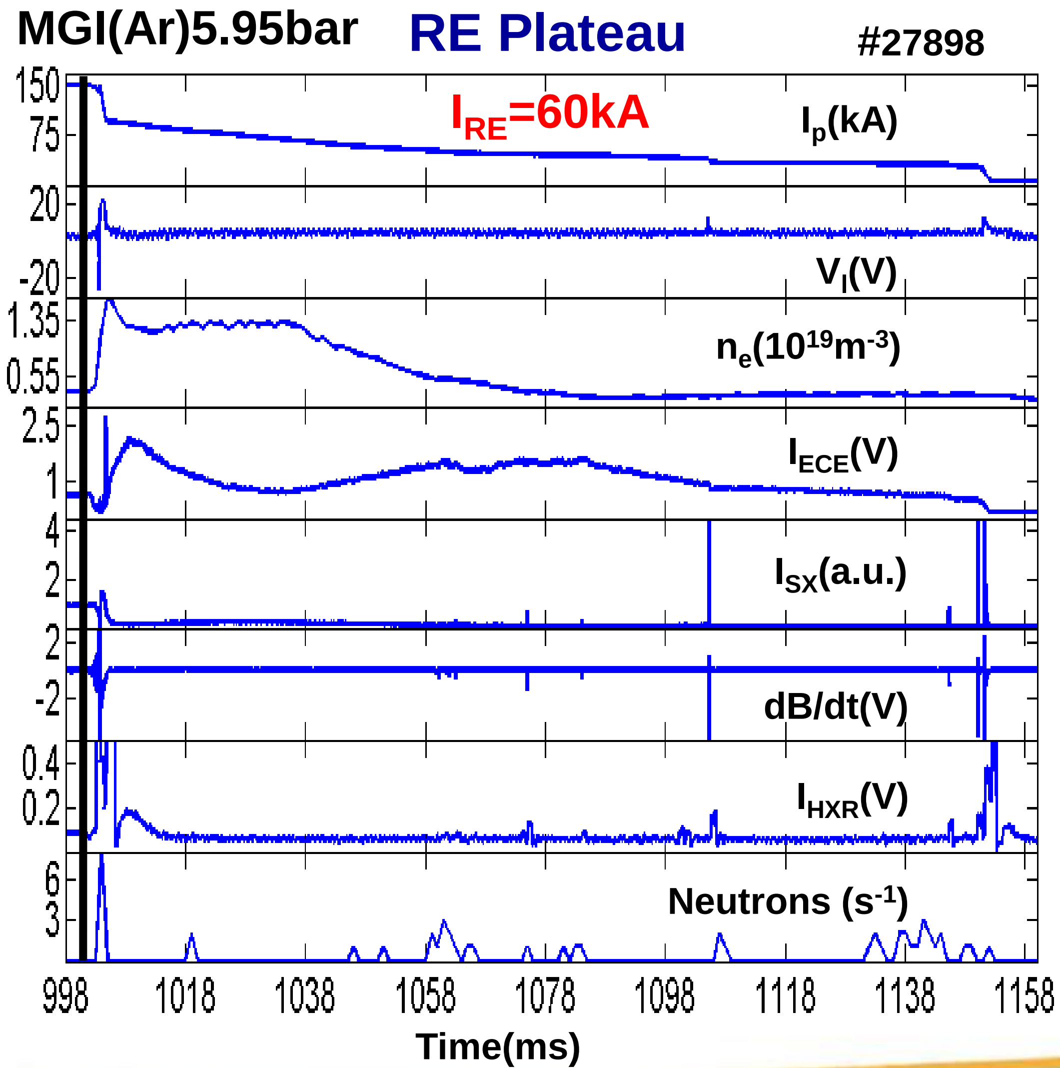


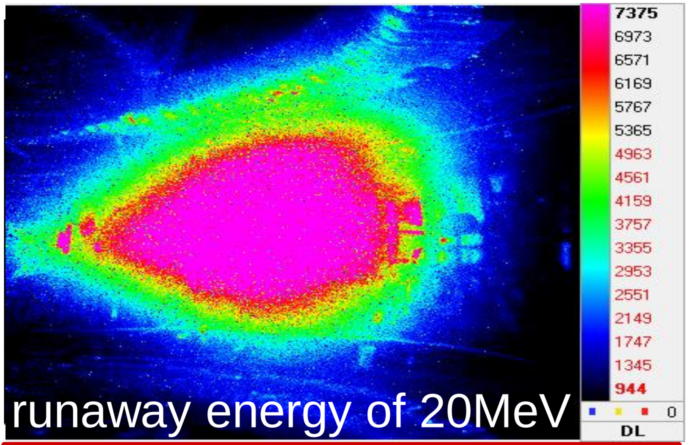
IR(internal reconnection events) ->RE Tail ->RE Plateau.

➢Increasing N_{inj} of Ar leads to different kinds of disruption.

Long-lasting RE plateau at low Bt

Gas：Ar, Ip=138kA, B_T =1.38T, N_e=0.7 x $10^{19}m^{-3}$





The runaway beam formed in the center during RE plateau.

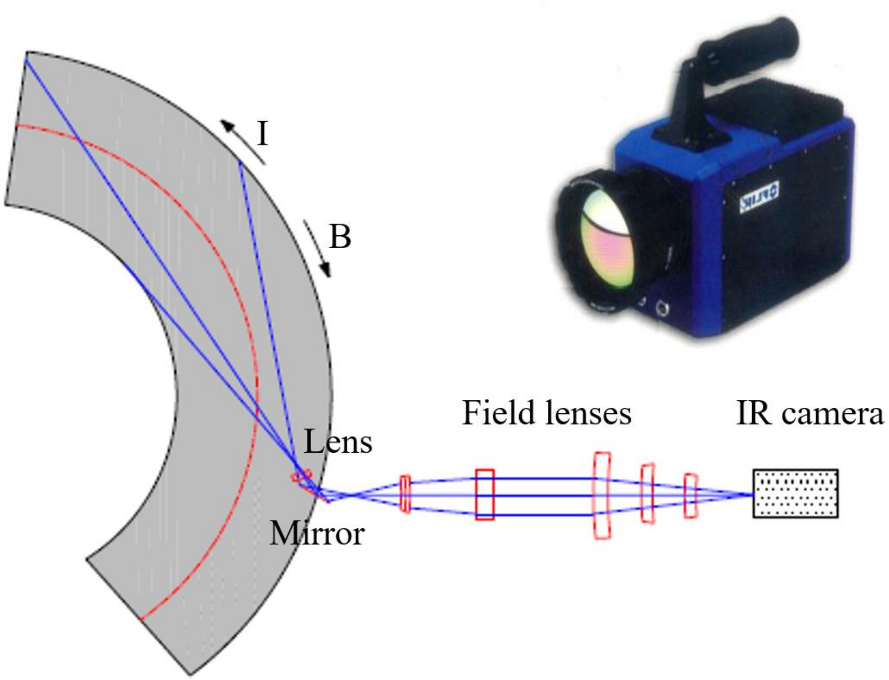
- ➢A runaway plateau is formed, evidenced by their synchrotron emission and by the neutron flux.
- ➢Runaway energy is

$$W_{RE\ MAX} \sim 23\text{Mev}.$$

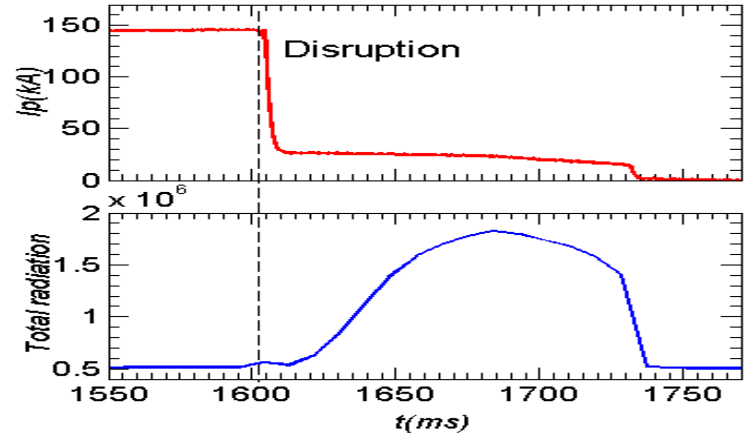
- ➢The RE plateau is achieved at a lower value of B_t = 1.38T.

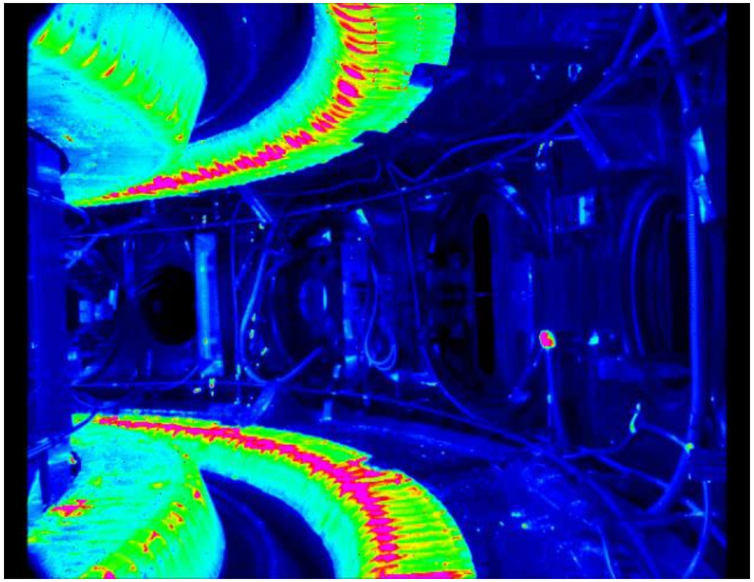
Observations of Runaway discharges

➤The synchrotron radiation, originating from the movement of the highly relativistic runaways, is measured with an infrared thermographic camera.



Infrared periscope system parameters	
Detector	**MCT**
Waveband	**8-9.4μm**
Pixel	**640×512**
Frame rate	**>113Hz (adjustable)**
Integration time	**120μs**

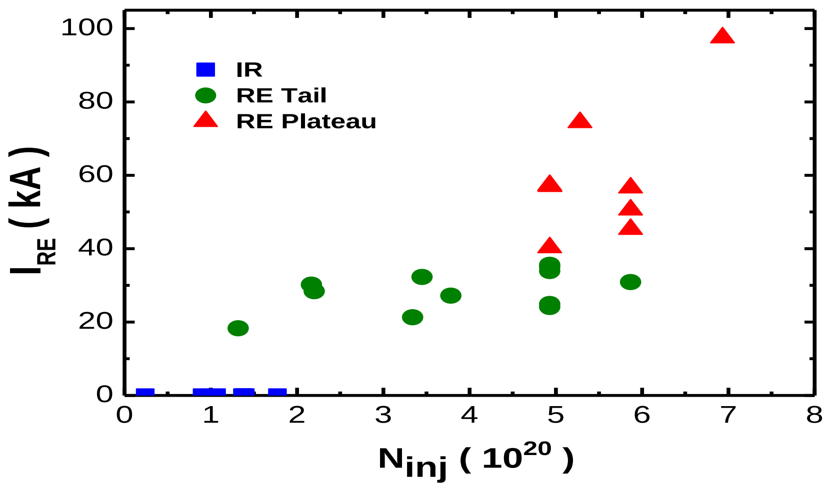


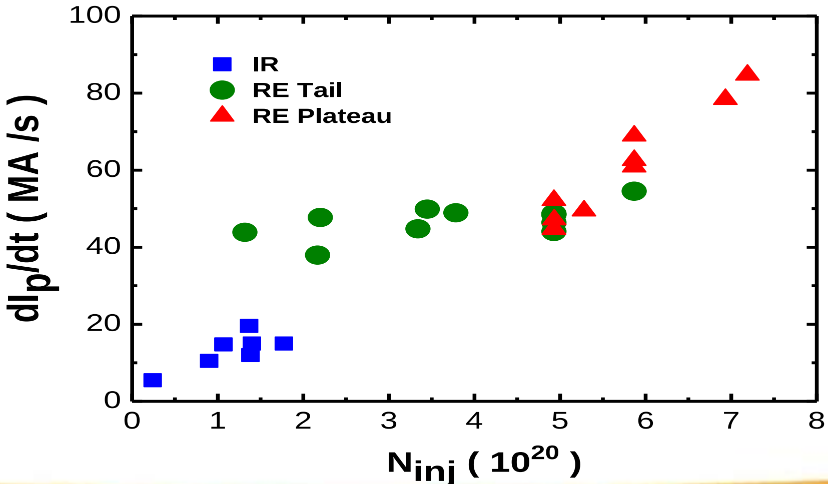


Movie from an IR camera showing synchrotron radiation.

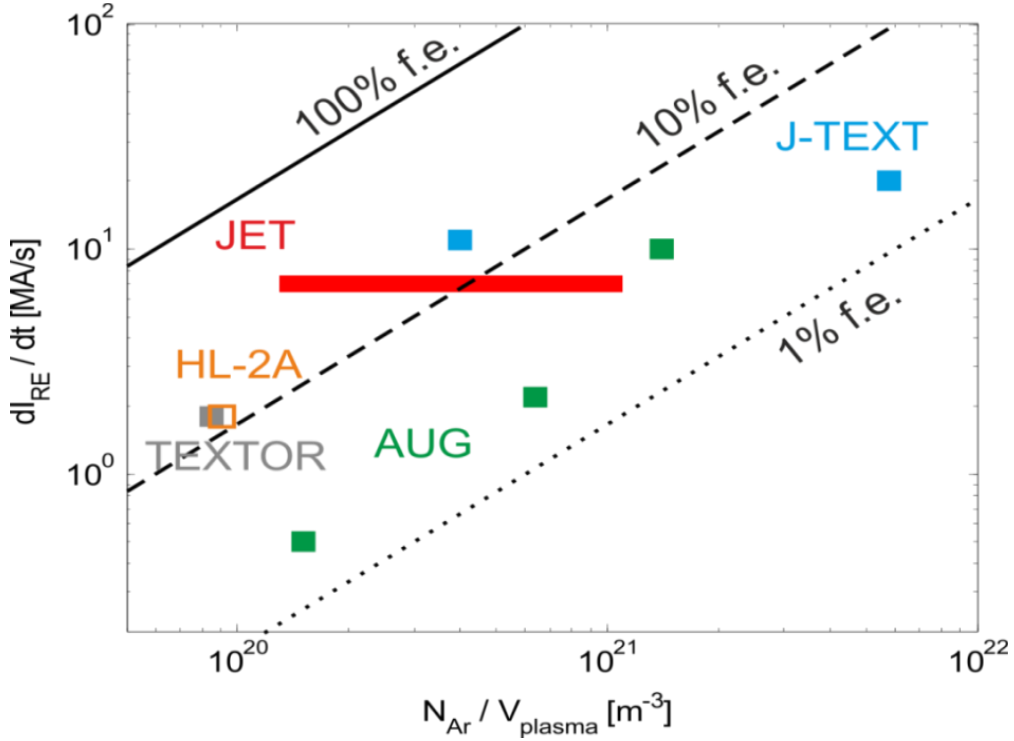
Scan of injected particle number

◆With the maximum of N_{inj} , almost 40% plasma current was converted into runaway current in 1ms.





◆Almost 10% fuelling efficiency has been obtained on HL-2A.



The runaway current decay rate as a function of Ar density.

M. Lehnen, ***ITPA 2016*** , ***Kicking off WG-13***:"*Runaway electrons energy dissipation by high-Z impurities during disruptions*".

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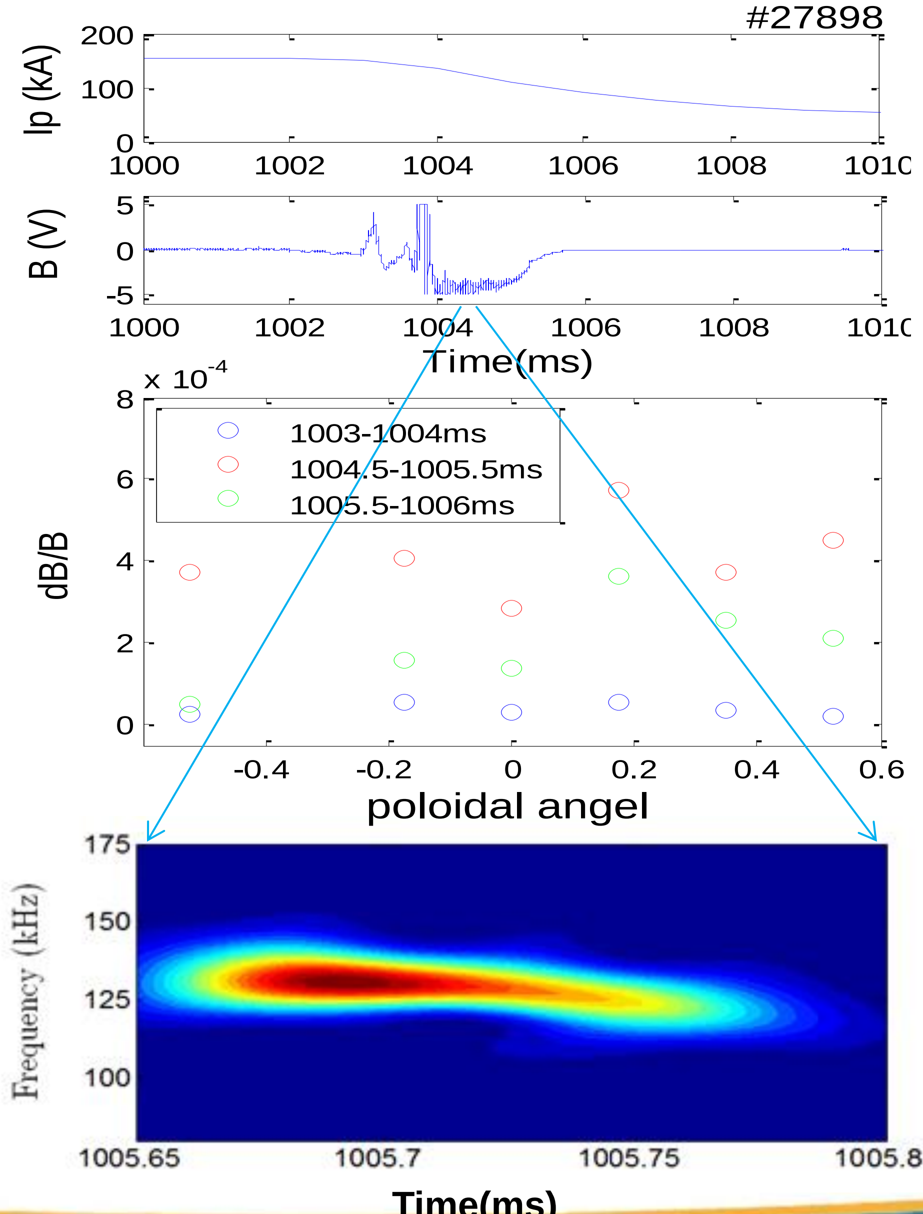
High frequency mode during CQ before RE



Obvious high frequency mode is observed in the magnetic pick-up coils and .

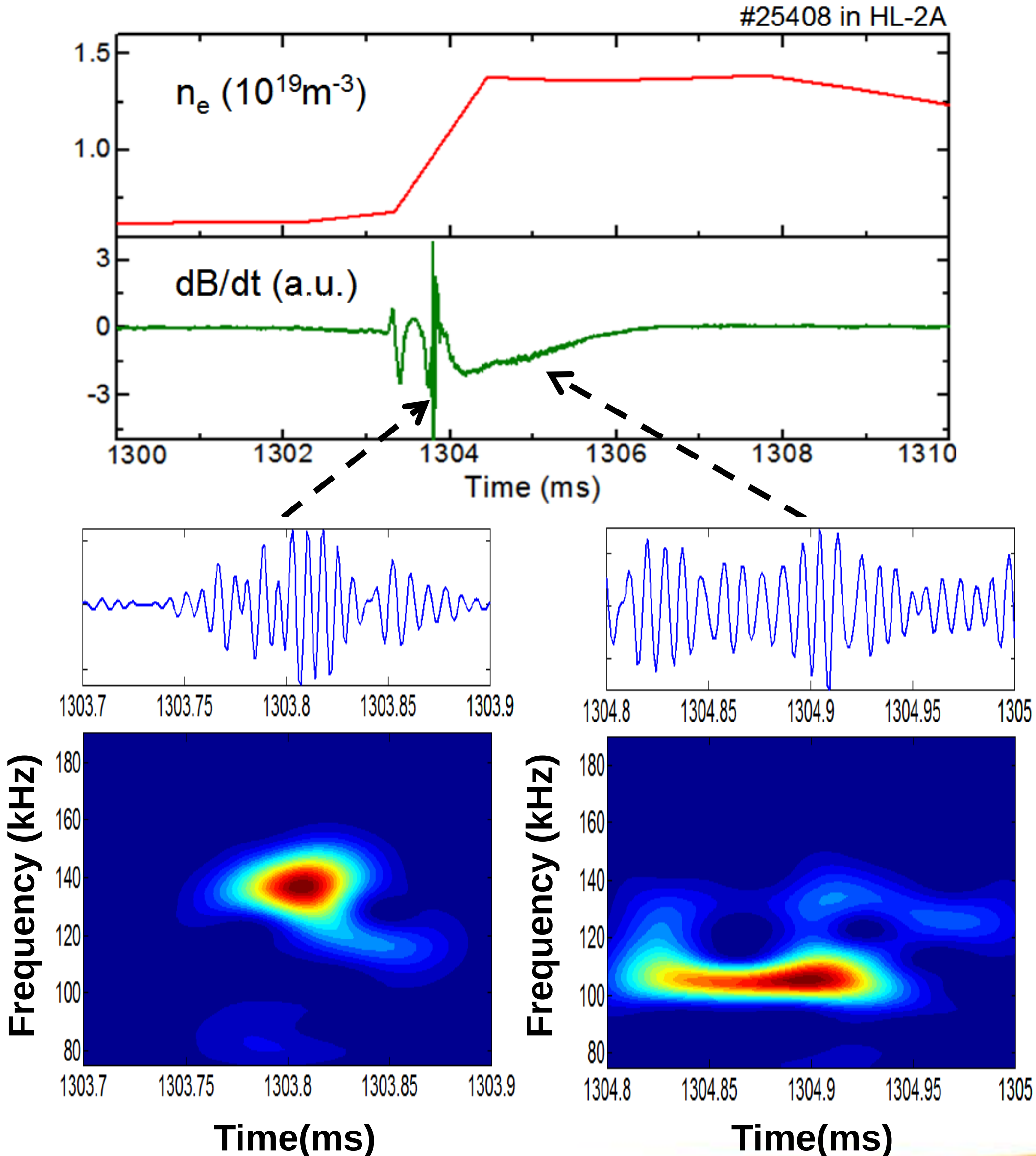
◆ The **high frequency mode** appears at the beginning of the current quench and lasts about 2ms;

◆The mode number is n=1, and m=3 or 2.

◆ Its frequency is about **80-180kHz;**

◆ The magnetic fluctuation level of this mode is estimated as: **$dB/B \approx 6 \times 10^{-4}$** .

The characteristic of the mode frequency



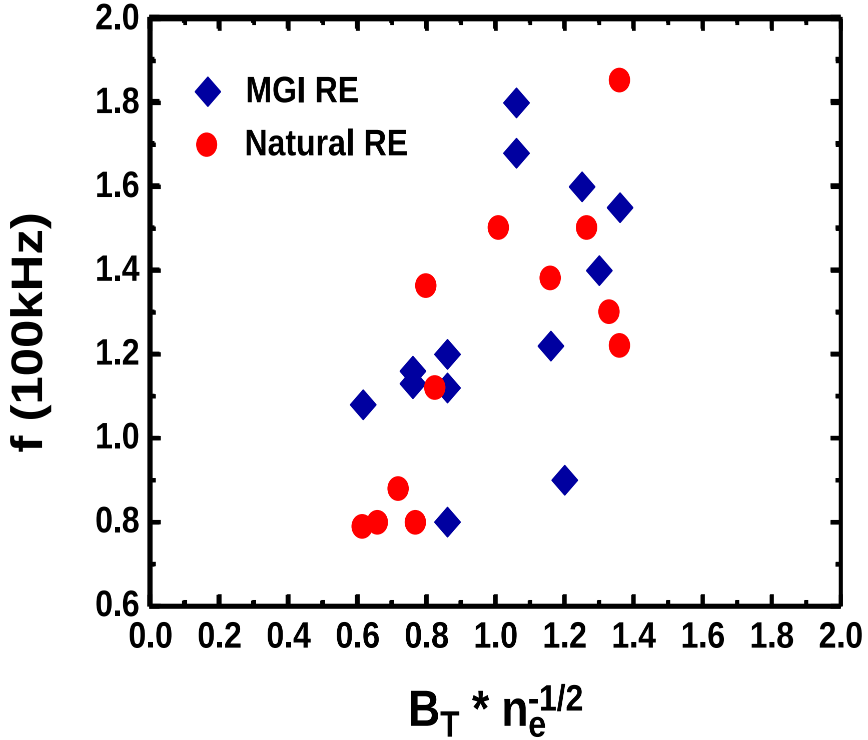
- ➢Slight change in mode frequency during its short lifetime;
- ➢It is found that the mode frequency decreases with the increase of plasma density.

Behavior of the mode frequency

- The mode frequency is higher at low density and decreases with the increase of n_e, suggesting that the mode has the behavior of an Alfvén-like mode.

- The statistical analysis of MGI induced disruption and natural disruption both with RE plateaus also verified the relationship between Alfvén speed $V_A \approx B_T{*}n_e^{-1/2}$ and mode frequency.

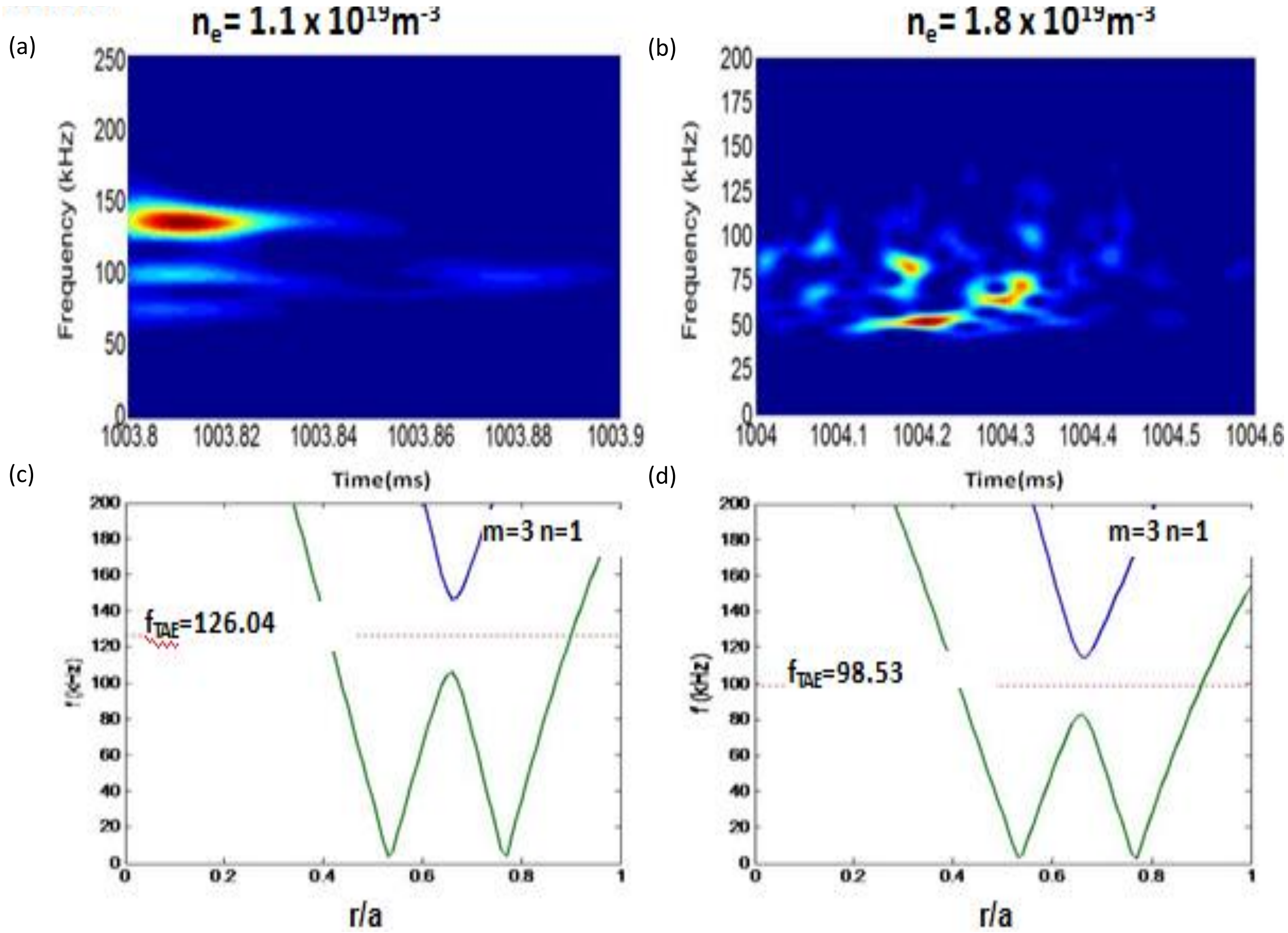
- It is found that the frequency scales roughly with $n_e^{-1/2}$, consistent with the toroidal alfvén eignmode (TAE)



Relationship between the RE current and the mode level $\delta B/B_T$.

Alfvén Spectrum calculation

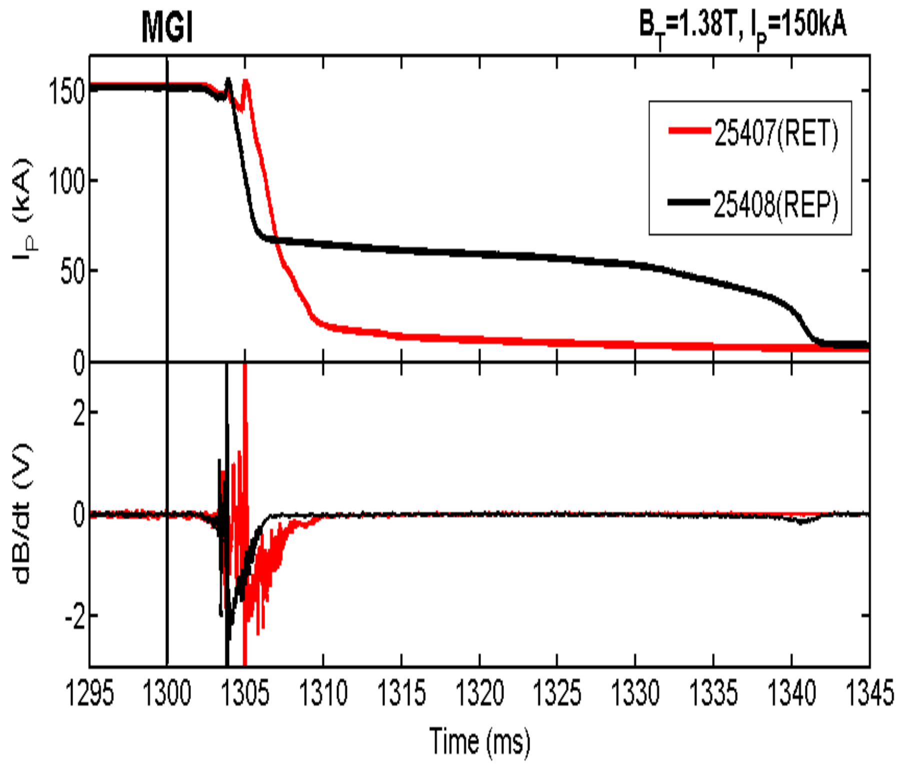
➢*Spectrograms and the Alfvén Spectrum simulations at* ***different electron density****.*

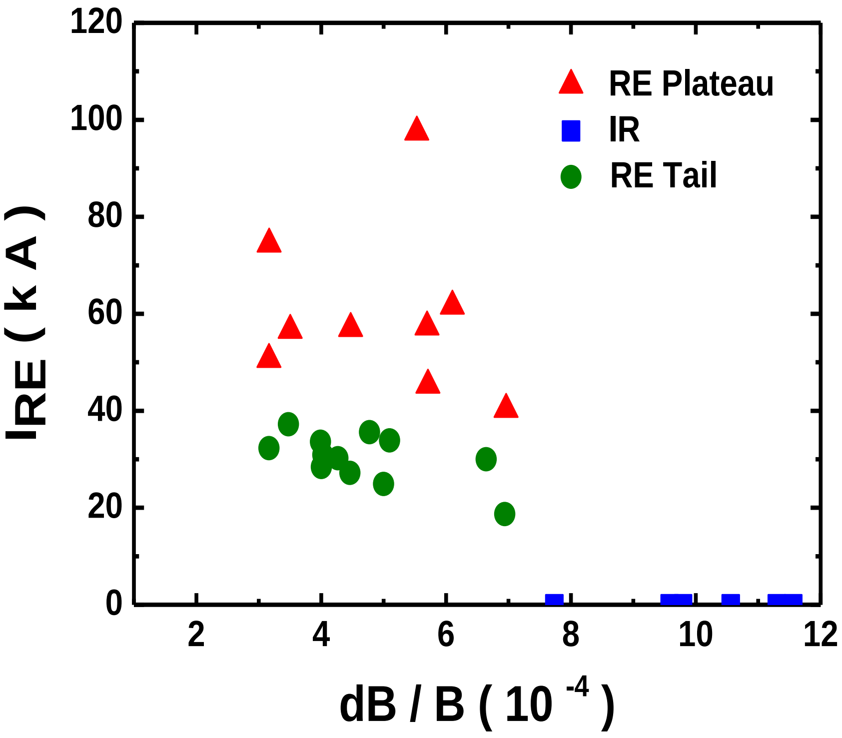


➢The simulated gap frequencies of the TAE modes are in fairly good agreement with experimental measurements

Role of the TAE mode on runaways

•Runaway plateau is easy to form on the condition of low dB/B, and vice versa. The runaway current is invisible when the normalized magnetic fluctuation level exceeds a threshold of about 7.8×10^{-4}.





➢This magnetic mode plays a scattering role on the RE beam strength.
➢Level of dB/B of TAE mode can be controlled by different N_{inj}.

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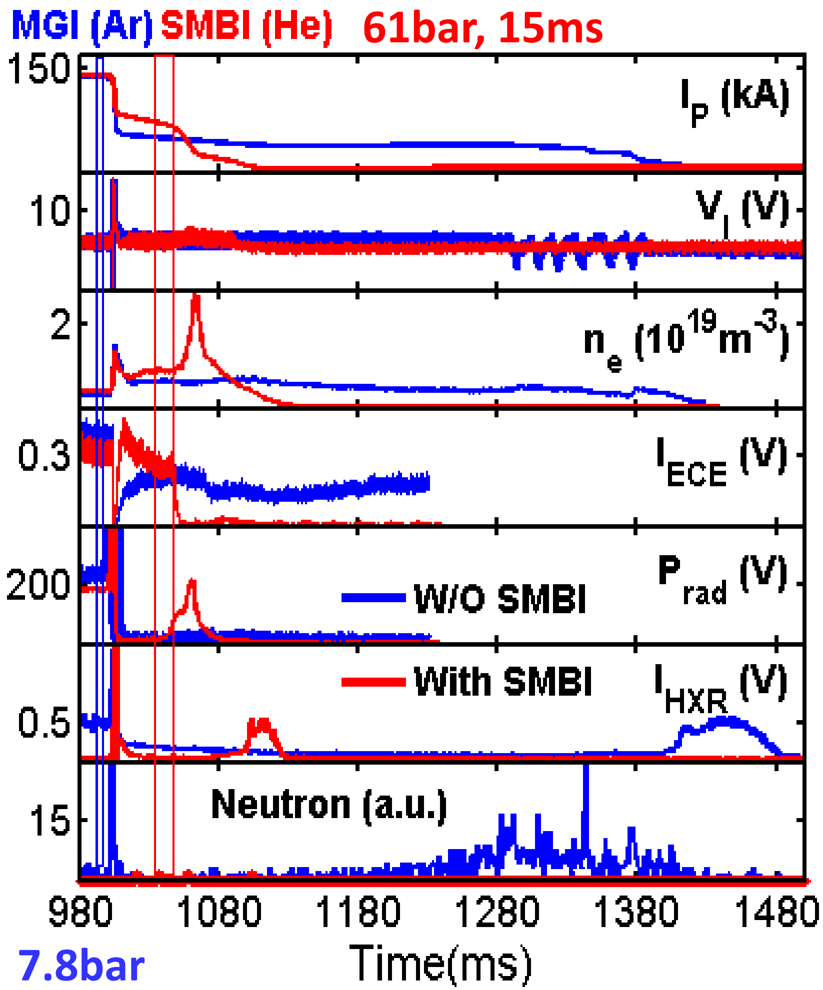
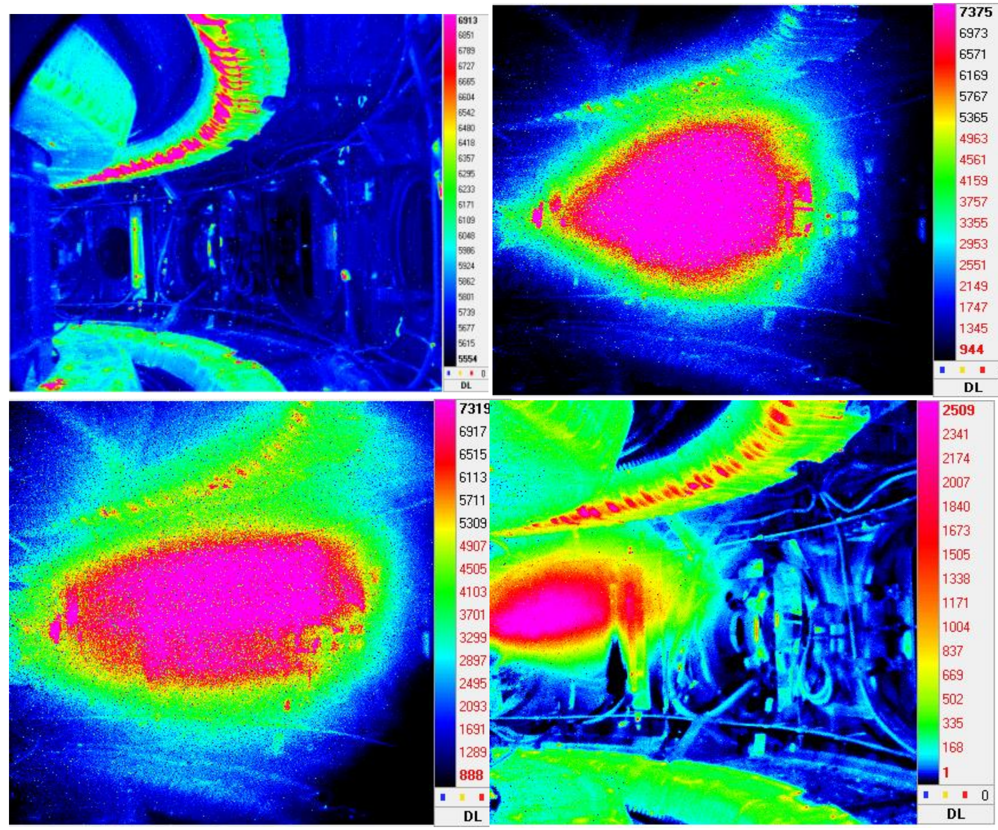
RE mitigation by SMBI

■Runaway current caused by argon injection with MGI was successfully suppressed by SMBI (15ms) with a number of injected helium atoms of about 1.0×10^{21}



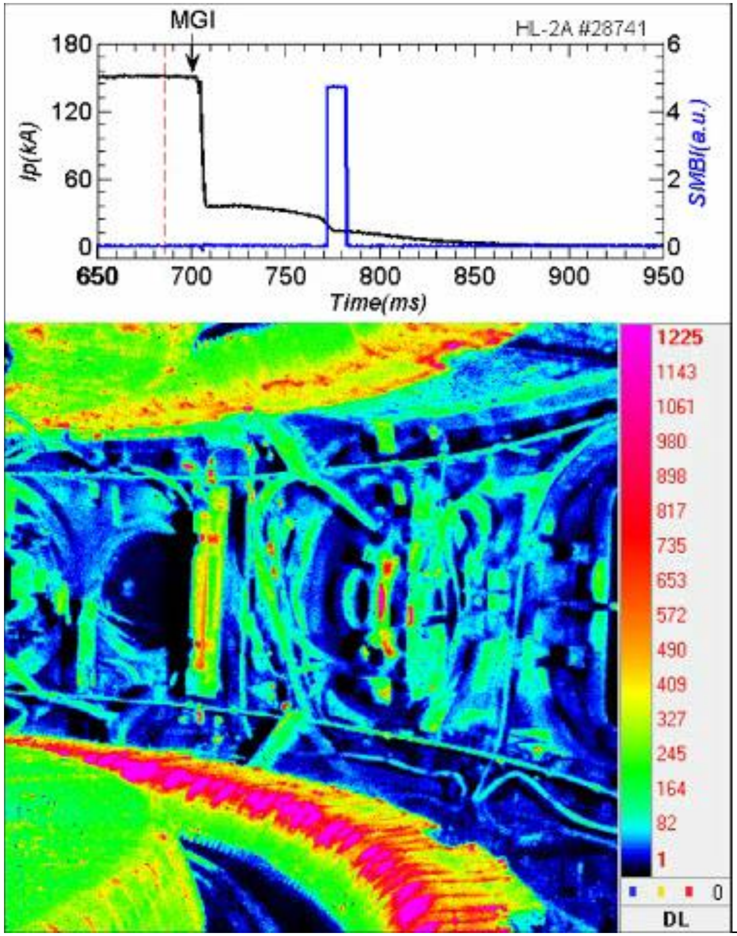
Images by IR camera during RE mitigation



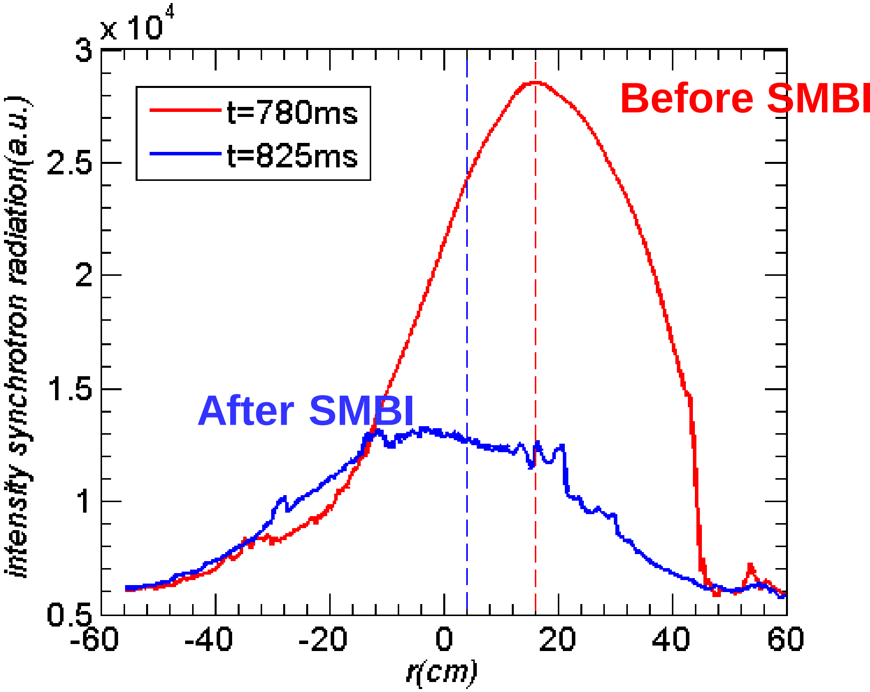
A significant fraction of the runaway magnetic energy is converted into heat flux instead of RE electron kinetic energy.

Images of RE dissipation by SMBI

➢The disruption triggered by MGI and mitigation of RE by SMBI.



Synchrotron radiation before and after SMBI

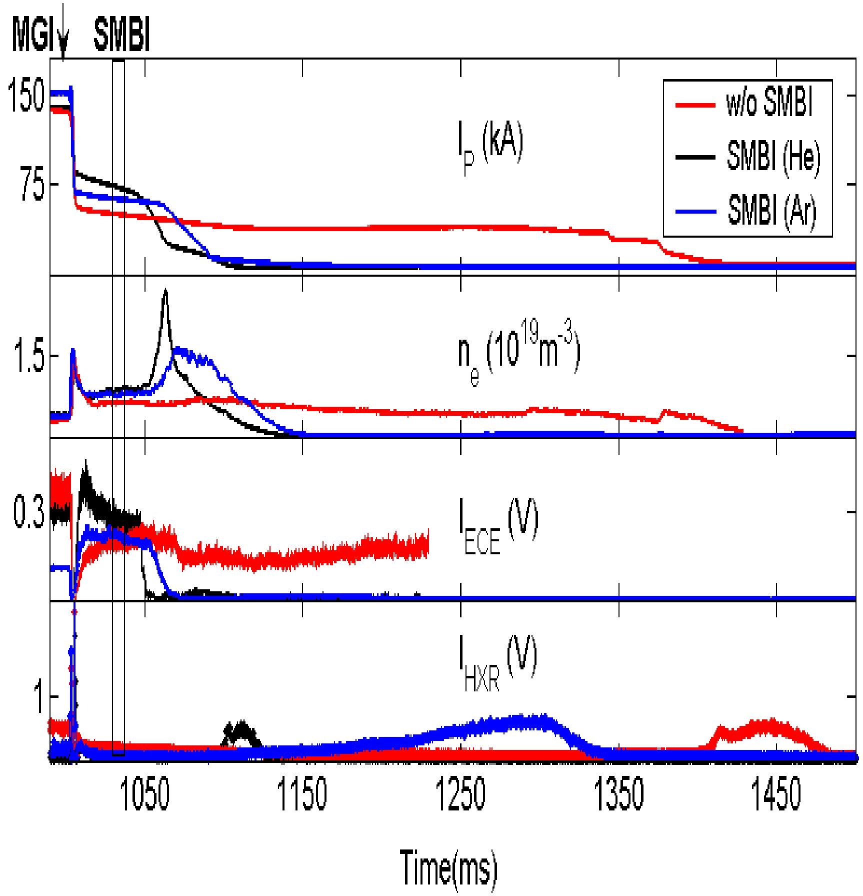


➢Synchrotron emission form runaway electrons are reduced by the SMBI injection of helium;

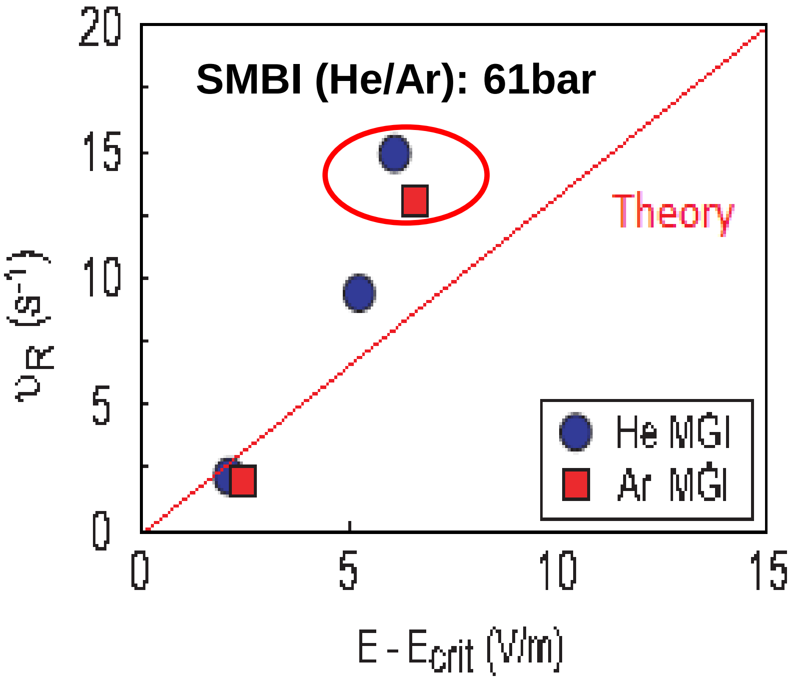
➢It Indicates the loss of RE after SMBI.

RE mitigation by SMBI with different gases

■Comparison of runaway current mitigation for helium injection versus Ar injection



RE current decay rate： $\upsilon_R = I_{RE}^{-1}\, dI_{RE}/dt$

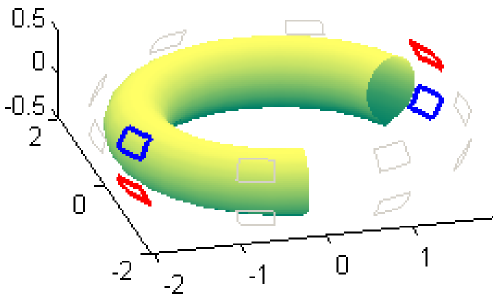


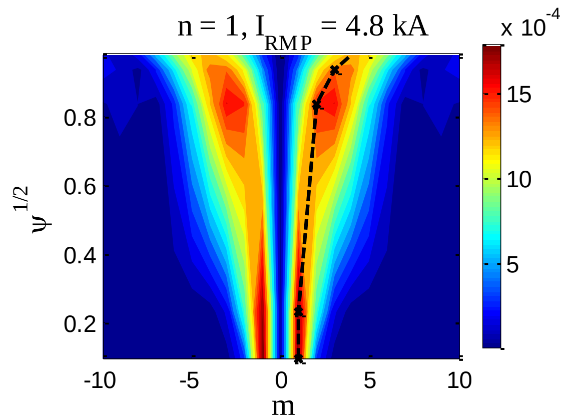
➢With SMBI, both Ar and helium gas can be used for RE dissipation while only the high-Z gases like Ar are proved effective in RE dissipation with MGI.

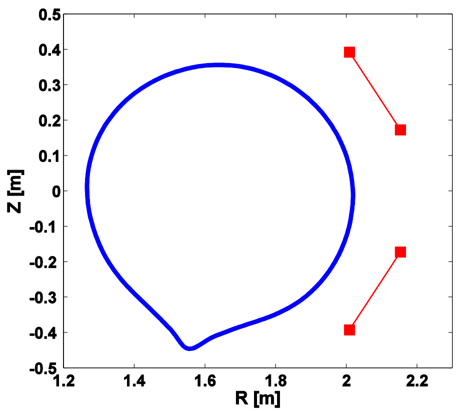
➢It suggests that SMBI has the advantage of deliver low-Z gas for RE dissipation.

Realization of RE mitigation with n=1 RMP coils

n=1 RMP coils on HL-2A tokamak

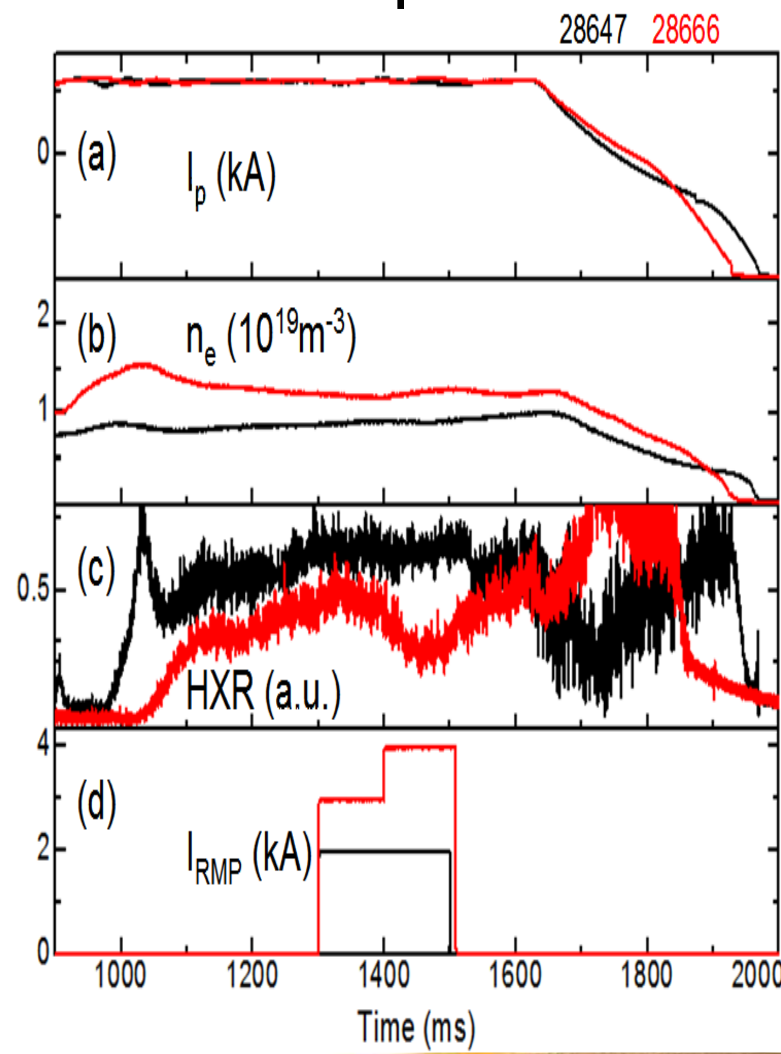






- 2x2 coils with ~4.5kAt
- Odd parity in experiments
- Mutiple n's: n=1,3,5,7, ….

Initial RMP experimental result on RE dissipation

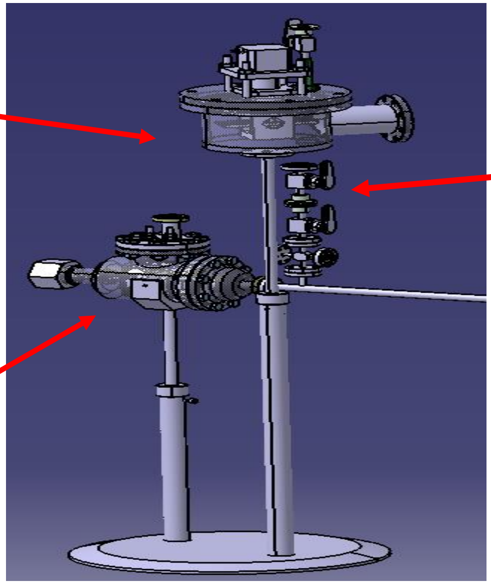


- Successful mitigation of ELMs with RMP coils.
- The HXR radiation drops obviously when the current in RMP coils increase to 4kA.
- Further study of the RE dissipation with RMP in disruption induced by MGI is planned.

Future Plan

- Apply MGI and SMBI for Disruption/REs suppression.
- Develop a new valve for both massive gas and pellet injection.
- Using three SMBIs for radiation asymmetries study.

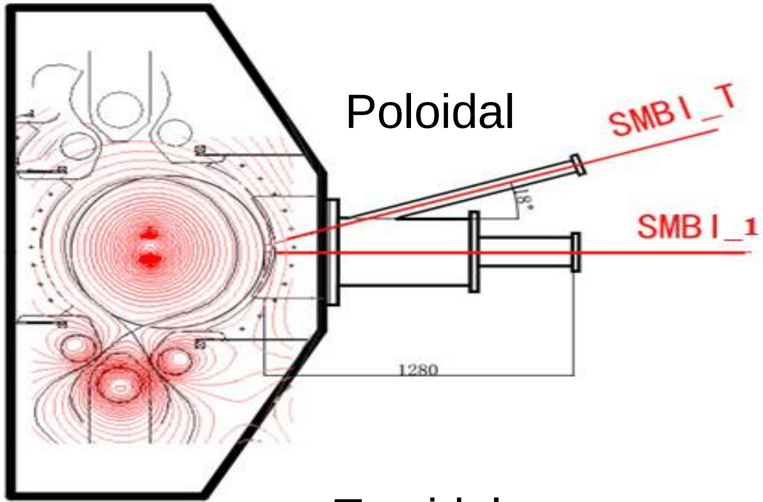
Pellet supplying system

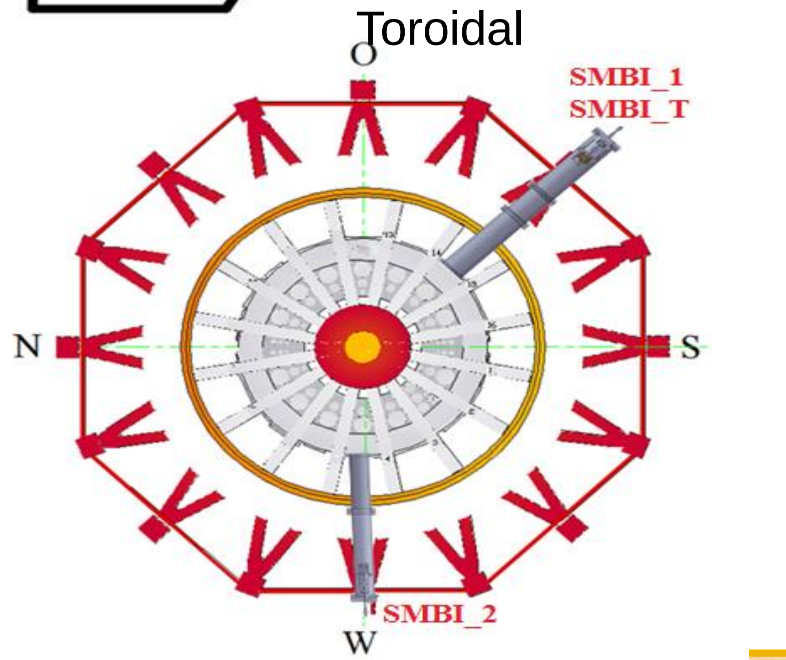


Partition valve

Massive gas injecting valve

New valve combining the massive gas and metal pellet injection





Summary

- Experiments on mitigation of runaway electrons with MGI/SMBI as well as RMP have been carried out on HL-2A tokamak.
- Mitigation of runaway current was successfully implemented with SMBI during disruptions deliberately triggered by MGI.
- A toroidal alfvén eignmode (TAE) was observed during disruptions on HL-2A, which plays a favorable role in scattering runaway electrons, hence limiting the strength of runaway beam.
- More experimental investigation and simulation work are planed to explore the mechanism of RE mitigation with SMBI/MGI.