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

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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)

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

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 an advantage of directional motion (1000m/s)

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.

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

- Increasing \(N_{\text{inj}}\) of Ar leads to different kinds of disruption.

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

Increasing \(N_{\text{inj}}\) of Ar leads to different kinds of disruption.
Long-lasting RE plateau at low B_t

Gas: Ar, \( I_p = 138\, \text{kA} \), \( B_T = 1.38\, \text{T} \), \( N_e = 0.7 \times 10^{19}\, \text{m}^{-3} \)

- A runaway plateau is formed, evidenced by their synchrotron emission and by the neutron flux.
- Runaway energy is \( W_{RE \, MAX} \approx 23\, \text{MeV} \).
- The RE plateau is achieved at a lower value of \( B_t = 1.38\, \text{T} \).

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 \( W_{RE \, MAX} \approx 23\, \text{MeV} \).
- The RE plateau is achieved at a lower value of \( B_t = 1.38\, \text{T} \).
Observations of Runaway discharges

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

<table>
<thead>
<tr>
<th>Infrared periscope system parameters</th>
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<tbody>
<tr>
<td>Detector</td>
</tr>
<tr>
<td>Waveband</td>
</tr>
<tr>
<td>Pixel</td>
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<tr>
<td>Frame rate</td>
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<td>Integration time</td>
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Movie from an IR camera showing synchrotron radiation.
With the maximum of $N_{\text{inj}}$, 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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Summary
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 2 ms;
- The mode number is \( n=1, \text{ and } m=3 \) or 2.
- Its frequency is about 80-180 kHz;
- The magnetic fluctuation level of this mode is estimated as: \( \frac{\text{dB}}{\text{B}} \approx 6 \times 10^{-4} \).
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.
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 eigenmode (TAE).

**Relationship between the RE current and the mode level $\delta B/B_T$.**
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 $7.8 \times 10^{-4}$.

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

![Graph showing the role of the TAE mode on runaways](image-url)
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Summary
Runaway current caused by argon injection with MGI was successfully suppressed by SMBI (15ms) with a number of injected helium atoms of about $1.0 \times 10^{21}$.

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 from runaway electrons are reduced by the SMBI injection of helium;
- It indicates the loss of RE after SMBI.
Comparison of runaway current mitigation for helium injection versus Ar injection

- 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

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.

New valve combining the massive gas and metal pellet injection
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 eigenmode (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 planned to explore the mechanism of RE mitigation with SMBI/MGI.