Investigation of Runaway Electron Dissipation in DIII-D Using a Gamma Ray Imager

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This case is for weak collisional dissipation ($E/E_{crit} \sim 4$)

Inversion reveals growing RE population at high energy
… and development of non-monotonic ...

These are the fundamental measurements of the GRI!

Paz-Soldan et al. PRL 2017
Runaway electrons (REs) produced during disruptions can damage tokamak wall

Melting of plasma facing components in JET

Impact of REs in TEXTOR
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- REs have energy up to 10-100 MeV
- Beam of REs can carry majority of flat-top plasma current

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  RE kinetic energy up to 20+ MJ
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- Localized impact of REs can cause severe damage of plasma facing components in ITER
- Investigations of RE mitigation are crucial for future tokamaks

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Impact of REs in TEXTOR
Outline

• Generation of runaway electrons (REs) in tokamak disruptions
• RE detection: bremsstrahlung radiation
• Development of Gamma Ray Imager on DIII-D
• Access to RE investigation in the quiescent regime (QRE)
• Dissipation of REs in QRE under varying conditions
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Runaway electrons are produced by strong electric field during disruptions

- Toroidal electric field is small during normal discharges (~0.1 V/m)
- It increases by x100 in tokamak disruptions
- Strong electric field can accelerate electrons up to relativistic energies (10-100 MeV)

RE plateau
REs can be decelerated by frequent collisions and synchrotron radiation

- Suprathermal electrons naturally run away under strong enough electric field
- Minimal electric field is necessary to overcome friction force and accelerate even high-energy electrons:
  
  \[ E_c \approx 5.2 \times 10^{-22} \left( n_e + \frac{n_b}{2} \right) \text{ [V/m]} \]  
  
  (Rosenbluth 1997)
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REs can lose their energy via collisions.

Other possible channel of energy losses is via synchrotron radiation.

Massive injection of impurities and high \( B_T \) can be used to decelerate REs.
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REs are observed by their emission of radiation

Electrons are observed by their emission of:

- **Cyclotron radiation** (mm waves, antennas)
- **Synchrotron radiation** (infrared waves, CCD cameras)
- **Bremsstrahlung radiation** (gamma rays, scintillators)

![Graph showing relative sensitivities of DIII-D diagnostics to RE energy](image-url)

*Hollmann et al. PoP 2015*
Measurement of bremsstrahlung radiation provides information on RE spatial and energy distribution

\[ \gamma \text{ rays are emitted in cones based on RE energy} \]

\[ f_e(E_\parallel, E_\perp) \text{ produces unique bremsstrahlung spectrum} \]

\[ \text{Measurement of bremsstrahlung radiation can provide information on RE distribution, RE energy, and energy evolution} \]
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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
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- BGO crystal is sensitive to gammas with $E_\gamma > 100$ keV (> 1 MeV in GRI)
- Absorption 88% @ 10 MeV
- Sensitivity 6 mV/MeV
- Rise time 80 ns, decay 100 μs (in GRI)
DIII-D gamma ray imager spans entire plasma poloidal cross-section

DIII-D toroidal cross-section

DIII-D poloidal cross-section
GRI went through a recent upgrade: doubled number of channels

Up to 29 detectors
GRI went through a recent upgrade: doubled number of channels

Up to 56 detectors
GRI went through a recent upgrade: doubled number of channels, improved detector holder

Also a non-conductive, quickly populated detector holder was implemented:
GRI went through a recent upgrade: doubled number of channels, improved detector holder, added rear shielding.

A non-conductive, quickly populated detector holder was implemented:

And an additional rear shielding against backscattered gammas was installed:

220 kg of lead, 5 cm thick att. by 10x
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Background
Quiescent regime provides convenient access to investigate RE dissipation

Quiescent RE regime (QRE):
- discharges at very low density (1/10 of usual) with minimal fueling and slowly changing density
- when density is lower than a threshold – REs are observed
- BGO detector shows increasing gamma flux while plasma density decreases

During disruptions plasma parameters change in order of magnitude on a ms time scale – making them difficult to control and measure
What about the energy of gammas?
What about the energy of gammas?

- $T_1$
- $T_2$
- $T_3$
- $T_4$

Detector signal [V]

- $10^{-1}$
- $10^{-2}$
- $10^{-3}$
- $10^{-4}$

Time [s]

- 0
- 2
- 4
- 6
- 8

Noise level

Gas puff
More high-energy gammas while density decreases

- Time traces are comprised of pulses from distinct gamma particles
- Gamma particles are analyzed by pulse height analysis (PHA)
REs increase their energy while density decreases

- Time traces are comprised of pulses from distinct gamma particles
- Gamma particles are analyzed by pulse height analysis (PHA)
- Bremsstrahlung spectrum hardens in the course of time
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Different mechanisms affect RE dissipation

- Loop voltage (E field) accelerates RE
- Collisions (background density) and synchrotron radiation (B_t field) both decelerate RE
- Pitch-angle scattering can lead to increase in synchrotron radiation
- QRE is ideal to scan parameters affecting RE dissipation
Scenario of $B_T$ scan to isolate synchrotron effect

1) slow decrease of plasma density until high ECE signal indicates strong population of suprathermal electrons

2) gas puffing to increase the density above the critical value

3) varying of $B_T$ during the dissipation phase
Consider gamma spectrum over a few time windows:

\[
B_T (T) \\
\text{ne} (10^{19} \text{ m}^{-3}) \\
\log_{10} \text{External HXR}
\]
Consider gamma spectrum over a few time windows:
Consider gamma spectrum over a few time windows:
Consider gamma spectrum over a few time windows:
Synchrotron radiation limits hardness of gamma spectrum

$B_T$ increase affects high-energy REs at the most.
Synthetic diagnostic is used to calculate gamma spectra

- Synthetic diagnostic can be used to calculate gamma spectra for certain RE spectra
- It takes into account detector sightline and equilibrium fields
- A mono-energetic electron produces a spray of HXRs
  - \( E_\gamma \leq E_e \)
Obtain RE spectrum from gamma spectrum: inversion is possible going from high energy down

- Onion peel method from high energy down can be used to go from gamma to electron spectrum
  - It must assume zero pitch angle
  - and spatial homogeneity
Inversion to gamma particle distribution function shows formation of the bump in RE distribution function

- RE spectrum hardens in the course of time
- Flattening and inversion of RE distribution function ("bump") is observed for low-energy REs
Non-monotonic feature has been found in the modelling

Interplay between acceleration of REs by E field, and deceleration by collisions and synchrotron radiation leads to formation of the bump

Aleynikov et al. PRL 2015

Paz-Soldan et al. PRL 2017
Scenario of $n_e$ scan to isolate collisional effect

1) slow decrease of plasma density until high ECE signal indicates strong population of suprathermal electrons

2) gas puffing to increase the density above the critical value

3) varying of final $n_e$ during the dissipation phase
Collisional drag reduces the number of high energy REs

- RE spectrum shows fewer high energy REs at high density
Gamma Ray Imager is an effective tool for investigation of RE at DIII-D capable of measuring RE distribution

- Bump in RE distribution function is observed for low-energy REs
  - Synchrotron radiation limits the hardness of RE spectrum
- Collisional drag reduces the number of high energy REs
- Non-monotonic feature has been also found in the modelling