Observation of Rapid Frequency Chirping Instabilities Driven by Runaway Electrons in DIII-D

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Frequency chirping instabilities are observed for the first time driven by runaway electrons in tokamak.

- Energetic particles can drive instabilities through wave-particle resonances.
- Frequency chirping instabilities are often observed driven by fast ions in tokamaks.

GAE in NSTX

TAE in MAST

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- This talk: discovery of rapid frequency chirping driven by runaway electrons (REs) in DIII-D

Frequency chirping instabilities are observed for the first time driven by runaway electrons in tokamak

- Energetic particles can drive instabilities through wave-particle resonances
- Frequency chirping instabilities are often observed driven by fast ions in tokamaks
- This talk: discovery of rapid frequency chirping driven by runaway electrons (REs) in DIII-D
- MHz instabilities increase RE loss
- While poorer confinement is undesirable for fast ions, it can be beneficial for RE control and mitigation in tokamaks

Outline

• Experiment and diagnostics
• Frequency chirping
• RE distribution function
• Operating space
• Possible driving mechanism and candidate instability
• RE-driven instabilities at higher collisionality
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RE-driven instabilities are accessed in low density post-disruption runaway plasma under decelerating voltage.

Post-disruption RE beam is deliberately produced in DIII-D after injection of small Ar pellet.
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Argon impurity is purged from RE beam by D₂ massive gas injection

- This 1) drastically reduces thermal electron density by two orders of magnitude and 2) provides large variability of applied loop voltage
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- Post-disruption RE beam is deliberately produced in DIII-D after injection of small Ar pellet
- Argon impurity is purged from RE beam by D_2 massive gas injection
  - This 1) drastically reduces thermal electron density by two orders of magnitude and 2) provides large variability of applied loop voltage
  - RE-driven instabilities are observed when large decelerating loop voltage is applied to initially stable RE beam (→ next slide)
RE loss increases under decelerating loop voltage

- Large decelerating voltage with magnitude comparable with breakdown voltage is applied to RE beam
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- This causes large fluctuations of wall and core hard X-ray signals (from lost and confined REs)
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- Also, spikes of ECE are detected
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- These are clear signs of RE-driven instabilities
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RE-driven plasma waves are detected via high-frequency measurements of magnetic signals

- Energetic REs can lead to excitation of plasma waves (*similar to fast ions*)

- High-frequency fluctuations of toroidal magnetic field are detected on DIII-D by RF-diagnostic [1,2]

- RF-diagnostic provides measurements up to 200 MHz

[2] Thome et al. RSI 2018
Bremsstrahlung radiation provides information on energy and distribution of REs

- When electron changes its trajectory it emits photons
- MeV electrons $\rightarrow$ MeV $\gamma$ rays
- $\gamma$ rays (HXR$s$) are forward beamed based on RE energy
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- $f_e(E_\parallel, E_\perp)$ produces unique bremsstrahlung spectrum
- DIII-D Gamma Ray Imager (GRI) provides 2D view of RE bremsstrahlung emission [1–4]

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[3] Paz-Soldan et al. PRL 2017
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See also poster on RE orbit tomography by Luke Stagner on Thursday

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[3] Paz-Soldan et al. PRL 2017
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- Now take a closer look at these instabilities
RE loss correlates with magnetic fluctuations at 1–7 MHz

- Fluctuations of toroidal magnetic field are seen in spectrograms
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- Fluctuations of toroidal magnetic field are seen in spectrograms
- They have clear chirping nature and correlate with RE loss signal
High frequency range magnetic fluctuations (30–80 MHz) show no correlation with RE loss

- Two frequency bands of magnetic fluctuations: 1–10 MHz and 30–80 MHz
- High frequency fluctuations do not drive observable RE loss
Frequency of instabilities has Alfvénic dependence on $B_\phi$

- RE beam moves to HFS and senses increasing $B_\phi \propto 1/R$ ($n_e=$constant)
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- RE beam moves to HFS and senses increasing $B_\phi \propto 1/R$ ($n_e=$constant)
- $f(B_\phi)$ dependence is Alfvénic: $f_A \propto v_A \propto B_\phi$ for both frequency bands
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Modification of RE energy distribution function is measured during frequency chirping.

- RE distribution function measured before chirping observed has a bump.
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- Bump is a potential source of free energy to drive instabilities
- Formation of the bump can be explained by interplay between RE acceleration by electric field and collisional damping on $D_2$ bound electrons [1]

[1] Lvovskiy et al. RE beam dynamics at low plasma density in DIII-D. Submitted to Nucl. Fusion
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- Relaxation of RE f(E) during chirping events is directly measured
- This supports interactions between REs and instabilities

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Chirping in low frequency range causes strongest RE loss

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- They are triggered at low plasma density and decelerating voltage
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- Low freq. chirping (1–3 MHz) causes the strongest magnetic fluctuations ($\Delta \vec{B}_\phi$)
Chirping in low frequency range causes strongest RE loss

- Instabilities are observed in two distinct frequency ranges: 0.1–10 MHz and 30–80 MHz.
- They are triggered at low plasma density and decelerating voltage.
- Low freq. chirping (1–3 MHz) causes the strongest magnetic fluctuations ($\Delta B_\phi$).
- Low freq. chirping (1–3 MHz) causes the strongest change of RE loss signal ($\Delta HXR$).
- $\Delta f$ changes by 0.3–2.4 MHz on 0.1 ms (local width) and 0.3-1.8 ms (full width) time scales.
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Possible mechanism of instabilities: REs drive Alfvénic waves, which scatter REs and increase RE loss

- Decelerating loop voltage presumably leads to strong non-monotonic feature (bump) at RE distribution function

- This excites Alfvénic waves

- Alfvénic waves interact with REs, scatter them and increase RE loss

- Fast relaxation of RE distribution function can explain frequency chirping consistent with the hole-clump model [1]

- Fast pitch-angle scattering of REs can cause the observed spikes of ECE

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- Compressional Alfvén eigenmodes (CAEs) are the most likely candidates for kinetic instabilities in the observed frequency region
- Separate loops will be installed to measure toroidal numbers and polarization

See poster by Genevieve Degrandchamp on Thursday for details

Cherenkov resonance is a possible driving mechanism

- **Anomalous Doppler** and **Cherenkov resonances** are possible excitation mechanisms

\[ \omega = k_{||} V_{||} - \frac{\omega_{ce}}{\gamma} \]

Satisfied at **large** \( k_{||} \)

\( (k_{||} = 50-300 \text{ m}^{-1}) \)

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- **Assume cold plasma dispersion relation at small** \( k \parallel \approx k < 5 \text{ m}^{-1} \)

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  \]

- **Cherenkov resonance** is satisfied for experimental conditions
Resonant RE orbits can be used to locate the RE bump

- Plasma equilibrium and RE orbits are calculated for the early stage of chirping instabilities
- Analysis of toroidal ($\omega_\phi$) and poloidal ($\omega_\theta$) transit frequencies provides wave-particle resonances:

$$\Omega_{nm} = n\omega_\phi - m\omega_\theta - \omega = 0$$

Example of $n/m=1/3$ resonant mode

Assumed: pitch-angle = −1 (WRT to current)
frequency = 3 MHz
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- Analysis of toroidal ($\omega_\phi$) and poloidal ($\omega_\theta$) transit frequencies provides wave-particle resonances:
  \[ \Omega_{nm} = n\omega_\phi - m\omega_\theta - \omega = 0 \]
- Calculations of RE loss on resonant orbits can be used for bump localization (modelling input is welcome!)

Example of resonant modes for $n = 0...4$ and $m = 0...10$
Assumed: pitch-angle = −1 (WRT to current) frequency = 3 MHz
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RE-driven MHz instabilities are also observed at high plasma collisionality

Focus so far: RE plateau

- Chirping instabilities are accessed during the RE plateau at very low plasma density
RE-driven MHz instabilities are also observed at high plasma collisionality

- Chirping instabilities are accessed during the RE plateau at very low plasma density
- RE-driven instabilities are also detected right after impurity injection – during the current quench, when plasma is dense
  - Most prominent after massive gas injection
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- These instabilities can be responsible for failure of RE beam formation
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- RE-driven instabilities are also detected right after impurity injection – during the current quench, when plasma is dense
  - Most prominent after massive gas injection
- These instabilities can be responsible for failure of RE beam formation
- Great interest for RE control in tokamaks!
RE-driven instabilities observed during formation of post-disruption RE beam sometimes presumably kill it [1]

- Disruptions without formation of RE beam show clear extended fluctuations of magnetic signals during the current quench

- RE loss correlates with MHz magnetic fluctuations in the frequency range of 0.1–3 MHz

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- RE loss correlates with MHz magnetic fluctuations in the frequency range of 0.1–3 MHz
- These magnetic fluctuations appear when RE energy $E_{RE}$ exceeds 2.5–3 MeV
- Varying pre-disruption $I_p$ and amount of injected Ar we can switch between cases w/ and w/o RE beam

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CAEs can be excited by REs with bump-on-tail $f(E)$ via Cherenkov resonance [1]

- Collisional and pitch-angle scattering of REs by argon nuclei can lead to formation of RE distribution function with bump-on-tail [2,3]

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- Quasilinear simulations show excitation of CAEs via Cherenkov resonance
- Multiple modes can lead to stochastic motion of REs towards the wall
- This increases RE radial transport

[3] Chang Liu et al. PRL 2018
RE-driven frequency chirping instabilities are observed for the first time in a tokamak

- Instabilities are accessed in low density RE plateau under applied decelerating loop voltage
- Frequency chirps by 0.3–2.4 MHz on timescale of 1 ms
- There are two frequency regions: 1–10 MHz and 30–80 MHz
  - Low-frequency instabilities correlate with increased RE loss
- Modification of RE energy distribution function is measured during chirping in low-frequency region consistent with hole-clump model
- Candidate modes are CAEs driven by non-monotonic RE distribution function via Cherenkov resonance
- Similar frequency instabilities correlated with intermittent RE loss are also observed at high plasma collisionality – during current quench
  - They are presumably responsible for non-sustainable RE beam
  - Modelling shows excitation of CAEs and increased RE radial transport
Rapid frequency chirping instabilities driven by runaway electrons are observed for the first time in a tokamak.

- Instabilities are accessed in low density post-disruption runaway plasma under applied decelerating voltage in DIII-D.
- Frequency chirps by 0.3–2.4 MHz on timescale of 1 ms.
- There are two distinct frequency regions: 1–10 MHz and 30–80 MHz.
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Magnetic spectrogram of frequency chirping instabilities driven by runaway electrons in DIII-D

Lvovskiy et al. Observation of rapid frequency chirping instabilities driven by runaway electrons in a tokamak. Submitted to Nucl. Fusion.
Approximate phase space sensitivity of RE diagnostics

Pitch Angle (θ, deg)

E (MeV)

Electron Cyclotron Emission (ECE)

Visible Synchrotron Emission (SE)

Gamma Ray Imager (GRI)

Distant HXR Detectors

Paz-Soldan et al. PoP 2018
Backup: RE spectrum is reconstructed from HXR spectrum using onion-peel method

- Onion peel method from high energy down can be used to go from HXR to electron spectrum
  - Zero pitch angle and spatial homogeneity are assumed

HXR and RE spectra in the experiment
Backup: 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]
Backup: 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 spectrum hardens in the course of time

[Cooper et al. RSI 2016]
Backup: Measurements during the RE plateau regime are challenging – upgrade with fast gamma detectors

- 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
Backup: Frequency dependence on $n_e$ is stronger than Alfvénic

- Frequency decreases as $n_e^{-1}$ while typical Alfvénic dependence is $n_e^{-1/2}$
- Possibly explained by plasma non-uniformity during the argon purge
Backup: More energetic RE distribution leads to no RE beam

- Cases without RE beam correlate with more energetic RE distribution
- Increased argon quantity reduces the number of high-energy REs and correlates with successful RE beam formation
- Integrated power of MHz frequency magnetic signals increases with increase of max $E_{\text{RE}}$
- Increased pre-disruption plasma current increases the maximum energy of REs
Backup: Possible mechanism of suppression of RE beam formation with two actuators

- Small Ar MGI
  - Increases
- Current quench
  - Larger $\int U_{loop} \, dt$
  - Increases
- Larger population of high-energy REs
  - More powerful instabilities
- Loss of seed REs
  - No RE beam
- Large Ip
  - Increases