Observation of rapid frequency chirping instabilities driven by runaway electrons in a tokamak

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Abstract.

We report the first observation of chirping instabilities driven by runaway electrons (REs) in a tokamak. The instabilities are accessed during the post-disruption RE beam stage in a low density background plasma ($n_e < 10^{19}$ m^{-3}) on DIII-D. The chirping instabilities are observed when a decelerating loop voltage is applied to the RE beam. The frequency chirping is detected in two distinct frequency bands: 0.1–10 MHz and 30–80 MHz. The mode frequency increases linearly when the toroidal magnetic field sensed by the RE beam increases. The frequency chirps by 0.3–2.4 MHz on a timescale of 1 ms. Modification of the RE distribution function is directly measured during the chirping in the low-frequency band consistent with the hole-clump model for frequency chirping. The low-frequency instabilities also correlate with an increase of intermittent RE loss from the plasma. These observations provide a novel experimental platform for fundamental studies of nonlinear chirping. They also support continued investigation of opportunities to utilize kinetic instabilities for RE mitigation in a tokamak reactor.

Keywords: runaway electrons, frequency chirping, kinetic instabilities

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1. Introduction

Energetic particles often drive instabilities through wave-particle resonances. The frequency of an instability can sweep gradually as background plasma parameters evolve or it can change rapidly due to nonlinear evolution of the energetic-particle distribution function. In the fusion community, the latter phenomenon is termed frequency "chirping". Chirping of instabilities driven by energetic particles is common in natural, laboratory, and fusion plasmas. Energetic electrons drive chirping "chorus" waves in the magnetosphere [1, 2]. Rising tones, falling tones, and relatively steady "hiss" are all observed under different circumstances [3]. In the laboratory, energetic electrons drive rising tones in Terrella experiment [4] and both rising and falling tones in magnetic mirror [5–7] and linear [8,9] devices. In fusion devices, fast-ion driven chirping instabilities are extremely common in a wide variety of frequency bands [10,11]. Upward, downward, and bifurcating chirps are all observed [12].

Although there is general agreement in both the space and fusion communities that nonlinear trapping plays an essential role, the precise physical mechanism is more contentious. Most likely, the mechanism differs for different cases. An early paper [13] suggested that the chirping magnetospheric chorus instability actually was jumping between different eigenmodes with closely spaced frequencies but this is an unlikely explanation for most observations. Theoretical papers in both the space [14] and fusion [15] communities have emphasized the important role of spatial variations in mode properties. But, even in a spatially uniform plasma, chirping can occur. The Berk-Breizman model [11, 16], famous in the fusion community, shows that the formation of "clumps" and "holes" in the phase space of the resonant particles can cause frequency chirping. Chen and Zonca [17] stress that the Berk-Breizman model occurs in an adiabatic limit where the resonant particles barely alter the mode structure and dispersion but that, in a non-adiabatic limit, the energetic particles directly alter the dispersion relation of the mode, as in the well-known fishbone instability [18]. A recent paper [19] argues that magnetospheric chorus is in the non-adiabatic regime.

It is widely recognized that, by altering the constants-of-motion, the wave-particle interaction alters the orbits of the energetic particles. Chorus modes scatter energetic electrons into the loss cone [20, 21]. Similarly, chirping fast-ion instabilities often expel energetic ions from a fusion device [10, 22].

This letter reports the first observation of chirping instabilities driven by runaway electrons (REs) in a tokamak. Chirping in two distinct frequency bands is observed. For one of the instabilities, modification of the distribution function is directly measured with hard X-ray spectroscopy. In addition to their intrinsic interest, these observations could be of practical importance, as kinetic instabilities that modify the RE distribution function may mitigate damage by runaways in a tokamak reactor.

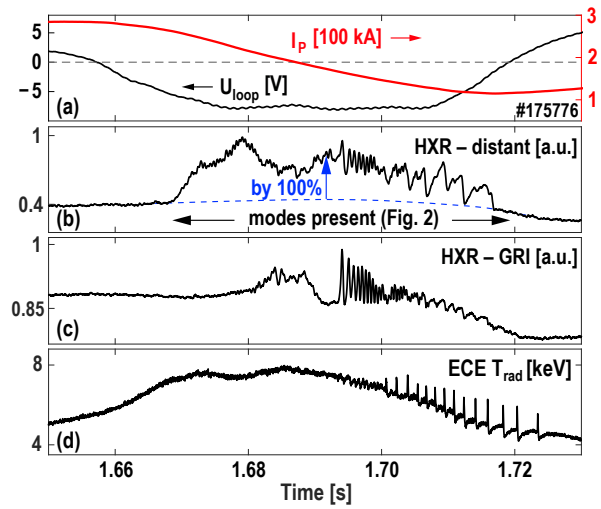

Figure 1: Time traces of (a) plasma current I_p and loop voltage U_{loop}, (b) RE loss signal by the distant HXR detector, (c) HXR signal from confined REs by the GRI, (d) ECE signal at 87.5 GHz.

2. Experiment and diagnostics

The frequency chirping driven by REs is observed during disruption mitigation experiments on the DIII-D tokamak. DIII-D is a tokamak with a D-shaped cross-section, major radius $R_0 = 1.67$ m, minor radius $a = 0.67$ m [23]. The toroidal magnetic field $B_\phi = 2.2$ T is kept constant during the experiments, providing characteristic electron and deuteron cyclotron frequencies of $f_{ce} = 60$ GHz and $f_{ci} = 15$ MHz respectively. In these experiments disruptions that generate a strong RE beam (with a current up to hundreds kA and RE energy up to 20 MeV) are deliberately triggered by an injection of a small argon pellet [24]. The resultant post-disruption runaway plasma is cold ($\approx$1 eV), dense, has a large fraction of the high-Z impurity. Argon is purged from the plasma by a secondary injection of deuterium gas [25], originally deployed with the intention of extending the runaway stage and reducing the transformer flux required to run the current. Besides the argon removal from the plasma this also significantly reduces the thermal electron density (from $1{\cdot}10^{20}$ m^{-3} to $<1{\cdot}10^{19}$ m^{-3}, close to the noise level of a CO_2-interferometer equal to about $3{\cdot}10^{18}$ m^{-3}). This provides access to a RE beam at low collisionality that lasts more than a second and allows large variability of the applied voltage. The chirping instabilities are observed when a negative (decelerating) loop voltage is applied (up to -7.5 V, comparable in magnitude to the voltage required for a plasma breakdown).

The RE energy distribution function is diagnosed via collimated tangential measurements of the hard X-ray (HXR) bremsstrahlung radiation from the central plasma using the Gamma Ray Imager (GRI) [26–28] and inversion from HXR to RE spectra [29, 30]. RE loss to the tokamak wall is measured using a distant HXR scintillating plastic detector [31]. This detector is placed in a few meters from the

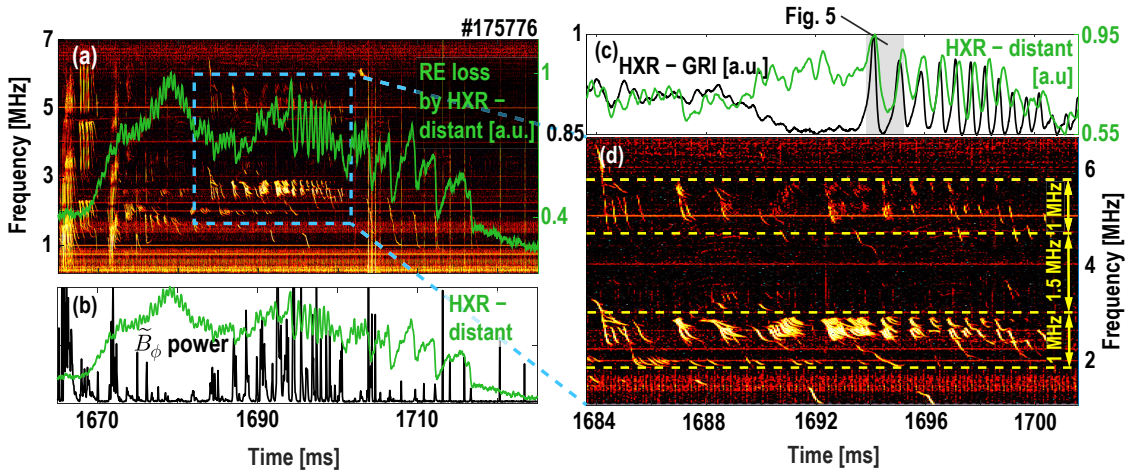

Figure 2: (a) Spectrogram of magnetic fluctuations and RE loss signal by the distant HXR detector, (b) power of magnetic fluctuations $\tilde{B}_\phi$ in the frequency range 1–10 MHz and RE loss signal, (c,d) magnified region of the spectrogram shown in (a).

tokamak and observes volumetric bremsstrahlung emission; interaction between lost REs and the wall material causes fast increase of its signal. Fast fluctuations of the toroidal magnetic field are detected by a magnetic loop mounted at the low-field side on the mid-plane and digitized at 200 MHz [32].

3. Observations of frequency chirping

When a decelerating loop voltage is applied to the RE beam, the RE loss rate increases by up to 100% as shown by the strong fluctuations of the distant HXR detector signal in Figure 1. Considering these fluctuations as quasi-periodic, the frequency of this burst cycle changes from 1.5–2 kHz to 0.6 kHz over the observation time of 60 ms. The GRI signal showing the bremsstrahlung radiation from confined REs has a shifted phase compared to the RE loss signal. When the frequency of the HXR fluctuations decreases, sub-millisecond spikes of the electron cyclotron emission (ECE) can be seen with an increasing amplitude.

The observed picture suggests that confinement of REs is affected by instabilities. Fluctuations of the toroidal magnetic field $\tilde{B}_\phi$ are indeed measured by the fast magnetic loop. The spectrogram in Figure 2(a) shows that the RE loss signal transiently increases when the magnetic fluctuations are present. These magnetic instabilities have a sub-millisecond chirping timescale and lie in the frequency range 0.1–7 MHz. The power of magnetic fluctuations presented in Figure 2(b) shows a clear small-scale temporal correlation with the RE loss signal. However, the RE loss magnitude and the power of magnetic fluctuations are not directly correlated throughout the entire pulse. The chirping nature of the instabilities as well as two separate frequency bands between 2–3 MHz and 5–6 MHz can be seen in the magnified spectrogram shown in Figure 2(d). The HXR signal by the distant detector is seen delayed with respect to the GRI measurements

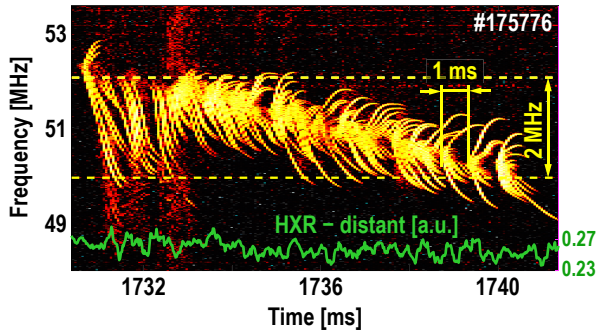

Figure 3: Upward and downward frequency chirping in the high-frequency range and RE loss by the distant HXR detector.

in Figure 2(c). The delay increases from 100 μs to 150 μs throughout this period and can be considered as a characteristic time of RE radial transport.

Chirping instabilities are also observed at much higher frequencies of tens of MHz. An example of clear upward and downward chirping at 50 MHz is shown in Figure 3. Unlike the low-frequency instabilities, the high-frequency instabilities do not drive any significant RE loss.

While the toroidal magnetic field B_ϕ is kept constant during the experiment, a shift in plasma position from side-effect of a large voltage applied to the RE beam allows the dependence of the instability frequency f on local B_ϕ to be studied. The loop voltage changes on the timescale of tens of ms, which is too fast for the control system to supply enough power to the plasma position coils and to keep the position of the RE beam constant. As a result, when the loop voltage is negative and the RE current ramps down, the RE beam shrinks (minor radius a changes from 0.55 m to 0.40 m) and moves to the high-field side (from major radius $R = 1.70$ m to 1.55 m) since it is limited on the inner wall. As the toroidal magnetic field in a tokamak varies like $B_\phi \propto 1/R$, the RE beam moving radially senses the change of B_ϕ.

The frequency of instabilities in the low-frequency range and the toroidal magnetic field with respect to the radial location of the RE current centroid are both shown increasing in Figure 4(a). The dependence $f(B_\phi)$ for a selected mode is close to linear and plotted in Figure 4(b). A case when the line-averaged thermal electron density n_e is decreasing during the argon purge while the RE beam does not move (local $B_\phi \approx$ constant) is presented in Figure 4(c,d). The dependence $f(n_e)$ observed in the experiment best matches n_e^{-1}. A linear dependence $f(B_\phi)$ is also obtained for a mode tracked in the high-frequency range as shown in Figure 4(e,f).

4. Modification of RE distribution function

Measurements of the HXR bremsstrahlung radiation produced when REs interact with background impurities allow reconstruction of the HXR spectrum, which can be inverted to yield the RE distribution function. The HXR spectrum measured from

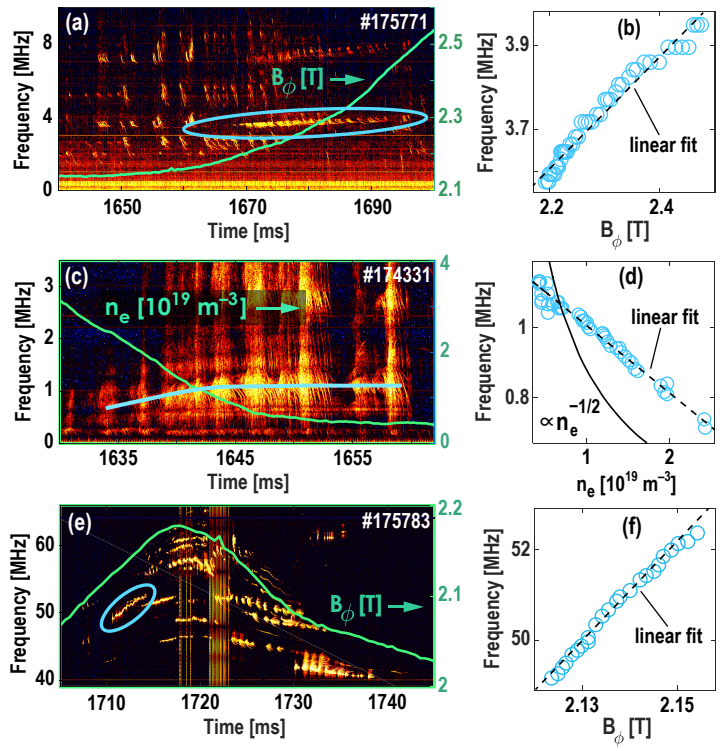

Figure 4: Dependence of frequency chirping in the low-frequency range on (a,b) the toroidal magnetic field B_ϕ and (c,d) the line-averaged thermal electron density n_e while local $B_\phi \approx$ constant. (e,f) Dependence of frequency chirping in the high-frequency range on B_ϕ. Tracked modes are highlighted.

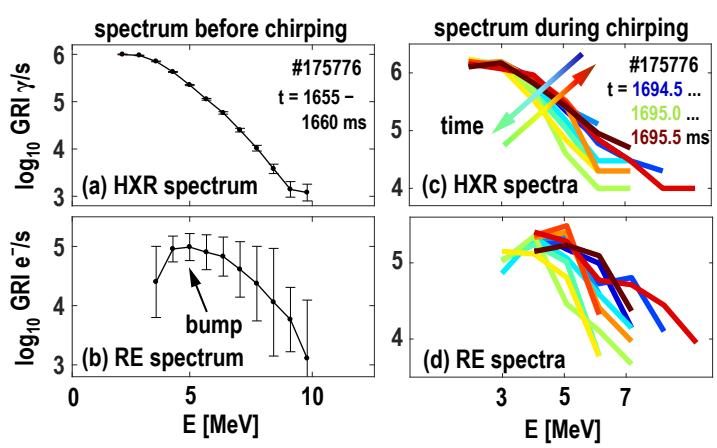

Figure 5: HXR and RE spectra obtained (left) before chirping occurs ($U_{loop} \approx -1$) and (right) during a single chirping event ($U_{loop} \approx -8$ V).

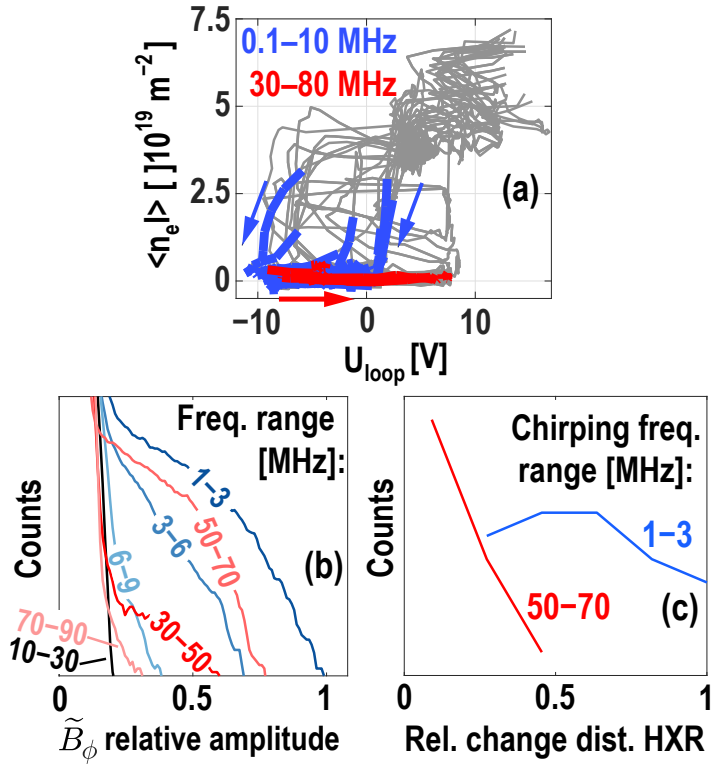

Figure 6: (a) Operational space of frequency chirping in low and high frequency ranges; time increases along the arrows. (b) Relative amplitude of magnetic fluctuations $\tilde{B}_\phi$ in different frequency ranges. (c) Relative change of RE loss signal by the HXR distant detector during frequency chirping in different frequency ranges.

the central plasma during the runaway stage before U_{loop} ramps down is shown in Figure 5(a). The inverted RE energy distribution function, shown in Figure 5(b), has a non-monotonic feature (bump) at 5 MeV suggesting a presence of free energy to drive kinetic instabilities; formation of the bump is discussed in detail in Ref. [33]. When U_{loop} ramps down and the frequency chirping occurs, the HXR and RE spectra show a modification of the RE distribution function during a single chirping event as presented in Figure 5(c,d). During each chirp the HXR and RE spectra shift to lower energies and relax back on a timescale of 1 ms.

5. Operational space and generality of observations

A survey of 15 discharges with frequency chirping is summarized in Figure 6(a) using the operational space parametrized by the mid-plane line integrated electron density $\langle n_e l \rangle$ and U_{loop}. The chirping modes can be divided in two groups. The first group is detected in the low-frequency range 0.1–10 MHz, the second group in the high-frequency range 30–80 MHz. The low-frequency instabilities are observed when U_{loop} is negative and $\langle n_e l \rangle$ is extremely low (close to the noise baseline level). There are a few cases when $\langle n_e l \rangle$ is above the baseline, but rapidly decreases after a deuterium injection, thus

likely being close to the baseline in outer regions of the RE beam. The high-frequency instabilities are observed only when $\langle n_e l \rangle$ is near the baseline. They are initially detected when $\mathrm{U_{loop}}$ is negative, but can still persist to positive $\mathrm{U_{loop}}$ as $\mathrm{U_{loop}}$ ramps up.

The relative amplitude of magnetic fluctuations $\tilde{B}_\phi$ measured during the periods with chirping modes is shown in Figure 6(b). It is calculated for both low- and high-frequency ranges sub-divided into smaller frequency bands. The $\tilde{B}_\phi$ amplitude is maximized for the modes in the band 1–3 MHz and then quickly decreases over 3–6 MHz and 6–9 MHz. The $\tilde{B}_\phi$ amplitude in the range 50–70 MHz is the second largest but is much smaller in other high-frequency bands.

The relative change of the RE loss signal measured by the distant HXR detector is presented for chirping in both low- and high-frequency ranges in Figure 6(c). Larger effect on the HXR amplitude can be seen for chirping in the lower frequency range.

No clear dependence for the frequency change Δf during chirping is observed. Δf typically changes by 0.3–2.4 MHz on time scales of 0.1–0.2 ms (local width) and 0.3–1.8 ms (full width from the beginning to the end).

6. Discussion

6.1. Possible mechanism of frequency chirping

Frequency chirping and direct measurements of modification of the RE energy distribution function are consistent with the Berk-Breizman model explaining such phenomena by formation of holes and clumps in the phase space of the distribution function of energetic particles.

A possible mechanism of the instabilities is proposed as follows. A decelerating loop voltage creates a strong non-monotonic feature at the RE distribution function providing a source of free energy to drive the instabilities. These instabilities can interact with REs having matching transit frequencies ($f_{\mathrm{tr}} = v_{e\|}/2\pi qR$, where $v_{e\|}$ is the RE speed along the field line and q is the safety factor) increasing their radial transport and RE loss. Safety factor is estimated to be increasing from 3 on-axis to 15 at the edge based on the equilibrium reconstruction with HXR constraints of the RE current profile. Fast pitch-angle scattering of REs by these instabilities can cause the ECE bursts observed on 0.1 ms timescale in Figure 1(d). Fast relaxation of the RE energy distribution function ($\sim$ 1 ms) can explain the frequency chirping. Detailed study of the resonance condition requires more comprehensive mode structure data and is planned for future work.

The lack of a clear modification in either the RE distribution function or the RE loss during high-frequency chirps is may be due to the chirping occurring in a different portion of the phase space than the GRI observes or that their impact on the RE distribution function is very limited.

6.2. Candidate instabilities

The observed RE-driven kinetic instabilities show frequency chirping and linear dependence $f(B_\phi)$ as is typical for Alfvénic instabilities, although the expected Alfvénic density dependence has not been observed. The specific mode of detected Alfvénic instability is difficult to identify without knowledge of the toroidal and poloidal structure, but a simple estimate can be made based on their frequency. For plasma parameters observed in the experiment, the measured frequencies lie between the ion cyclotron frequency ($f_{ci} = eB_\phi/2\pi m_i \approx 15$ MHz, where m_i is the mass of a deuteron) and the Alfvén frequency ($f_A = v_A/2\pi R_0 \approx 1.5$ MHz on-axis, where v_A is the Alfvén velocity and R_0 is the DIII-D major radius). This is a typical frequency range of compressional Alfvén eigenmodes [34]. However, we cannot exclude that some lower-frequency Alfvénic modes are observed upshifted in the experiment due to a very low plasma density. The frequency dependence $f \propto n_e^{-1}$ found in the experiment is stronger than a typical Alfvénic dependence $f \propto n_e^{-1/2}$. This is possibly explained by plasma non-uniformity when the density changes during the argon purge. Observation of the different frequency sub-bands as presented in Figure 2(d) is supposedly caused by the boundary conditions in the tokamak and the periodic variations in the magnetic field strength seen by the passing runaways [35].

6.3. RE control in a tokamak

The observed frequency chirping adds a new phenomenon to the list of kinetic instabilities driven by REs in tokamaks; these have noticeably expanded over the last years as a result of search for RE mitigation techniques [36]. Among them are strong hundreds kHz magnetic perturbations discovered during tokamak disruptions leading to the failure of RE current formation [37–39] and claimed to be caused by the excitation of toroidal Alfvén eigenmodes (TAEs) increasing the radial transport of REs [40, 41]. TAEs driven by energetic electrons supposedly accelerated after magnetic reconnection have been recently reported in Ohmic plasmas [42]. RE-driven 100 MHz whistler waves have been recently observed in DIII-D [35,43]. Though a direct effect of whistlers at this frequency range on RE loss has not been experimentally verified, an increased pitch-angle scattering of REs has been shown in experiment and modelling [44, 45]. Another example of recent findings is RE-driven kinetic instabilities observed at a few MHz during the current quench on DIII-D [46]. Few MHz instabilities correlate with intermittent RE loss and have been proposed as a possible cause for a non-sustained RE current. It is under investigation whether the same Alfvénic instabilities are responsible both for the present frequency chirping and for the MHz modes observed during the current quench. These findings support continued research on RE-driven kinetic instabilities in order to understand their applicability for RE control in a tokamak reactor.

7. Conclusion

Frequency chirping driven by REs has been observed for the first time on the DIII-D tokamak. They are detected in a low density post-disruption runaway plasma when a decelerating voltage is applied. The frequency chirps by 0.3–2.4 MHz on a timescale of 1 ms in two distant frequency ranges 0.1–10 MHz and 30–80 MHz. The frequency of the instabilities increases linearly as the toroidal magnetic field increases in agreement with Alfvénic scaling. The RE energy distribution function measured before the onset of instabilities has a non-monotonic feature suggesting the presence of free energy to drive kinetic instabilities. Fast modification of the RE distribution function is directly measured during the chirping in the low-frequency band. The low-frequency instabilities also correlate with an increase of an intermittent RE loss from the plasma. The observations of RE-driven frequency chirping provide novel plasma conditions to study these instabilities and support further research to investigate opportunities for RE control in a tokamak.

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References

[1] Burtis W J and Helliwell R A 1969 *Journal of Geophysical Research* **74** 3002–3010 URL http://doi.wiley.com/10.1029/JA074i011p03002

[2] Tsurutani B T and Smith E J 1974 *Journal of Geophysical Research* **79** 118–127 ISSN 01480227 URL http://doi.wiley.com/10.1029/JA079i001p00118

[3] Li W, Thorne R M, Bortnik J, Tao X and Angelopoulos V 2012 *Geophysical Research Letters* **39** URL http://doi.wiley.com/10.1029/2012GL053206

[4] Maslovsky D, Levitt B and Mauel M E 2003 *Physical Review Letters* **90** 185001 ISSN 0031-9007 URL https://link.aps.org/doi/10.1103/PhysRevLett.90.185001

[5] Viktorov M E, Shalashov A G, Mansfeld D A and Golubev S V 2016 *EPL (Europhysics Letters)* **116** 55001 ISSN 0295-5075 URL http://stacks.iop.org/0295-5075/116/i=5/a=55001?key=crossref.5f5d874af955783831646d619263c9f4

[6] Shalashov A G, Viktorov M E, Mansfeld D A and Golubev S V 2017 *Physics of Plasmas* **24** 032111 ISSN 1070-664X URL http://aip.scitation.org/doi/10.1063/1.4978565

[7] Shalashov A G, Gospodchikov E D and Viktorov M E 2019 *Plasma Physics and Controlled Fusion* **61** 085020 ISSN 0741-3335 URL https://iopscience.iop.org/article/10.1088/1361-6587/ab27a5

[8] Van Compernolle B, An X, Bortnik J, Thorne R M, Pribyl P and Gekelman W 2015 *Physical Review Letters* **114** 245002 ISSN 0031-9007 URL https://link.aps.org/doi/10.1103/PhysRevLett.114.245002

[9] Tejero E M, Crabtree C, Blackwell D D, Amatucci W E, Ganguli G and Rudakov L 2016 *Physics of Plasmas* **23** 055707 ISSN 1070-664X URL http://aip.scitation.org/doi/10.1063/1.4946020

[10] Heidbrink W W 2008 *Physics of Plasmas* **15** 055501 ISSN 1070-664X URL http://aip.scitation.org/doi/10.1063/1.2838239

[11] Breizman B N and Sharapov S E 2011 *Plasma Physics and Controlled Fusion* **53** 054001 ISSN 0741-3335 URL http://stacks.iop.org/0741-3335/53/i=5/a=054001

[12] Gryaznevich M and Sharapov S 2006 *Nuclear Fusion* **46** S942–S950 ISSN 0029-5515 URL http://stacks.iop.org/0029-5515/46/i=10/a=S11

[13] Nunn D 1974 *Journal of Plasma Physics* **11** 189 ISSN 0022-3778 URL http://www.journals.cambridge.org/abstract_S0022377800024600

[14] Helliwell R A 1967 *Journal of Geophysical Research* **72** 4773–4790 ISSN 01480227 URL http://doi.wiley.com/10.1029/JZ072i019p04773

[15] Zhang H S, Lin Z and Holod I 2012 *Physical Review Letters* **109** 025001 ISSN 0031-9007 URL https://link.aps.org/doi/10.1103/PhysRevLett.109.025001

[16] Berk H L, Breizman B N and Ye H 1992 *Physical Review Letters* **68** 3563–3566 ISSN 0031-9007 URL https://link.aps.org/doi/10.1103/PhysRevLett.68.3563

[17] Chen L and Zonca F 2016 *Reviews of Modern Physics* **88** 015008 ISSN 0034-6861 URL https://link.aps.org/doi/10.1103/RevModPhys.88.015008

[18] McGuire K, Goldston R, Bell M, Bitter M, Bol K, Brau K, Buchenauer D, Crowley T, Davis S, Dylla F, Eubank H, Fishman H, Fonck R, Grek B, Grimm R, Hawryluk R, Hsuan H, Hulse R, Izzo R, Kaita R, Kaye S, Kugel H, Johnson D, Manickam J, Manos D, Mansfield D, Mazzucato E, McCann R, McCune D, Monticello D, Motley R, Mueller D, Oasa K, Okabayashi M, Owens K, Park W, Reusch M, Sauthoff N, Schmidt G, Sesnic S, Strachan J, Surko C, Slusher R, Takahashi H, Tenney F, Thomas P, Towner H, Valley J and White R 1983 *Physical Review Letters* **50** 891–895 ISSN 0031-9007 URL https://link.aps.org/doi/10.1103/PhysRevLett.50.891

[19] Tao X, Zonca F and Chen L 2017 *Geophysical Research Letters* **44** 3441–3446 ISSN 00948276 URL http://doi.wiley.com/10.1002/2017GL072624

[20] Kennel C F and Petschek H E 1966 *Journal of Geophysical Research* **71** 1–28 ISSN 01480227 URL http://doi.wiley.com/10.1029/JZ071i001p00001

[21] Thorne R M, Ni B, Tao X, Horne R B and Meredith N P 2010 *Nature* **467** 943–946 ISSN 0028-0836 URL http://www.nature.com/articles/nature09467

[22] Heidbrink W W and Danielson J R 1994 *Physics of Plasmas* **1** 4120–4122 ISSN 1070-664X URL http://aip.scitation.org/doi/10.1063/1.870822

[23] Luxon J 2002 *Nuclear Fusion* **42** 313 ISSN 00295515 URL http://stacks.iop.org/0029-5515/42/i=5/a=313

[24] Evans T E, Taylor P L and Whyte D G 1998 *Proceedings of 17th IAEA FEC, EXP3/07, Yokohama, Japan* URL https://inis.iaea.org/collection/NCLCollectionStore/_Public/31/011/

31011383.pdf?r=1&r=1

[25] Shiraki D, Commaux N, Baylor L, Cooper C, Eidietis N, Hollmann E, Paz-Soldan C, Combs S and Meitner S 2018 *Nuclear Fusion* **58** 056006 ISSN 0029-5515 URL http://stacks.iop.org/0029-5515/58/i=5/a=056006

[26] Cooper C M, Pace D C, Commaux N, Eidietis N W, Hollmann E M and Shiraki D 2016 *Review of Scientific Instruments* **87** 11E602 URL https://aip.scitation.org/doi/abs/10.1063/1.4961288

[27] Pace D C, Cooper C M, Taussig D, Eidietis N W, Hollmann E M, Riso V, Van Zeeland M A and Watkins M 2016 *Review of Scientific Instruments* **87** 043507 ISSN 0034-6748 URL http://scitation.aip.org/content/aip/journal/rsi/87/4/10.1063/1.4945566

[28] Dal Molin A, Martinelli L, Nocente M, Rigamonti D, Abba A, Giacomelli L, Gorini G, Lvovskiy A, Muraro A, Tardocchi M and Contributors J 2018 *Review of Scientific Instruments* **89** 10I134 ISSN 0034-6748 URL http://aip.scitation.org/doi/10.1063/1.5038803

[29] Paz-Soldan C, Cooper C M, Aleynikov P, Pace D C, Eidietis N W, Brennan D P, Granetz R S, Hollmann E M, Liu C, Lvovskiy A, Moyer R A and Shiraki D 2017 *Physical Review Letters* **118** 255002 ISSN 0031-9007 URL http://link.aps.org/doi/10.1103/PhysRevLett.118.255002

[30] Paz-Soldan C, Cooper C M, Aleynikov P, Eidietis N W, Lvovskiy A, Pace D C, Brennan D P, Hollmann E M, Liu C, Moyer R A and Shiraki D 2018 *Physics of Plasmas* **25** 056105 ISSN 1070-664X URL http://aip.scitation.org/doi/10.1063/1.5024223

[31] Heidbrink W W 1986 *Review of Scientific Instruments* **57** 1769–1770 ISSN 0034-6748 URL http://aip.scitation.org/doi/10.1063/1.1139176

[32] Thome K E, Pace D C, Pinsker R I, Meneghini O, del Castillo C A and Zhu Y 2018 *Review of Scientific Instruments* **89** 10I102 ISSN 0034-6748 URL https://aip.scitation.org/doi/abs/10.1063/1.5035561

[33] Lvovskiy A, Paz-Soldan C and Eidietis N W *Runaway electron beam dynamics at low plasma density in DIII-D (submitted to Nuclear Fusion)*

[34] Heidbrink W W 2002 *Physics of Plasmas* **9** 2113–2119 ISSN 1070-664X URL http://aip.scitation.org/doi/10.1063/1.1461383

[35] Spong D A, Heidbrink W W, Paz-Soldan C, Du X D, Thome K E, Zeeland M A V, Collins C, Lvovskiy A, Moyer R A, Austin M E, Brennan D P, Liu C, Jaeger E F and Lau C 2018 *Physical Review Letters* **120** 155002 URL https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.120.155002

[36] Paz-Soldan C, Eidietis N W N, Hollmann E M E, Aleynikov P, Carbajal L, Heidbrink W W, Hoppe M, Liu C, Lvovskiy A, Shiraki D, Spong D A, Brennan D P D, Cooper C C M, Del-Castillo-Negrete D, Du X, Embreus O, Fulop T, Herfindal J, Moyer R A, Parks P B and Thome K K E 2019 *Nuclear Fusion* **59** 066025 ISSN 0029-5515 URL http://iopscience.iop.org/article/10.1088/1741-4326/ab1769

[37] Zeng L, Koslowski H R, Liang Y, Lvovskiy A, Lehnen M, Nicolai D, Pearson J, Rack M, Jaegers H, Finken K H, Wongrach K and Xu Y 2013 *Physical Review Letters* **110** 235003 ISSN 0031-9007 URL http://link.aps.org/doi/10.1103/PhysRevLett.110.235003

[38] Zeng L, Chen Z, Dong Y, Koslowski H, Liang Y, Zhang Y, Zhuang H, Huang D and Gao X 2017 *Nuclear Fusion* **57** 046001 ISSN 0029-5515 URL http://stacks.iop.org/0029-5515/57/i=4/a=046001

[39] Liu Y, Tan Y, Gao Z, Xu Y, Hu Y, Chai S, Jiang Y, Ke R, Zhong H and Wang W 2016 *Physics of Plasmas* **23** 120706 ISSN 1070-664X URL http://aip.scitation.org/doi/10.1063/1.4973230

[40] Fülöp T and Newton S 2014 *Physics of Plasmas* **21** 080702 ISSN 1070-664X URL http://aip.scitation.org/doi/10.1063/1.4894098

[41] Papp G, Lauber P W, Schneller M, Braun S, Koslowski H R and Team T 2014 *Proceedings of the 41th EPS Conference, Berlin, Germany, 2014* URL http://ocs.ciemat.es/EPS2014PAP/pdf/P2.032.pdf

[42] Chu N, Sun Y, Gu S, Wang H, Hu Y, Shi T, Chen D, Gu X, He K, Jia M, Lin S, Liu H, Qian J, Ren J, Shen B, Ti A, Wang S, Xie J, Xu M, Xue M, Yan N, Zang Q, Zeng L, Zhang J, Zhang T,

Zhang Y, Zhong G, Zhou C and Zhou R 2018 *Nuclear Fusion* **58** 104004 ISSN 0029-5515 URL http://stacks.iop.org/0029-5515/58/i=10/a=104004

[43] Heidbrink W W, Paz-Soldan C, Spong D A, Du X D, Thome K E, Austin M E, Lvovskiy A, Moyer R A, Pinsker R I and Zeeland M A V 2019 *Plasma Physics and Controlled Fusion* **61** 014007 ISSN 0741-3335 URL http://stacks.iop.org/0741-3335/61/i=1/a=014007

[44] Liu C, Hirvijoki E, Fu G Y, Brennan D P, Bhattacharjee A and Paz-Soldan C 2018 *Physical Review Letters* **120** 265001 ISSN 0031-9007 URL https://link.aps.org/doi/10.1103/PhysRevLett.120.265001

[45] Liu C, Shi L, Hirvijoki E, Brennan D P, Bhattacharjee A, Paz-Soldan C and Austin M E 2018 *Nuclear Fusion* **58** 096030 ISSN 0029-5515 URL http://stacks.iop.org/0029-5515/58/i=9/a=096030

[46] Lvovskiy A, Paz-Soldan C, Eidietis N W, Molin A D, Du X D, Giacomelli L, Herfindal J L, Hollmann E M, Martinelli L, Moyer R A, Nocente M, Rigamonti D, Shiraki D, Tardocchi M and Thome K E 2018 *Plasma Physics and Controlled Fusion* **60** 124003 ISSN 0741-3335 URL http://stacks.iop.org/0741-3335/60/i=12/a=124003