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Time-resolved measurement of ion beam energy spread variation due to kinetic plasma instabilities in CW and pulsed operation of an ECRIS

Ville Toivanen

Juuso Huovila, Hannu Koivisto, Olli Tarvainen

Outline

- Introduction – energy spread ↔ plasma potential
- Kinetic plasma instabilities – a quick reminder
- Experimental method for time-resolved measurement of energy spread variation during an instability event
- Data analysis; an example with some considerations
- Results
  - CW operation with different plasmas
  - Pulsed operation with varied ECRIS magnetic field
- Implications and consequences for ECRIS operation
- Summary and conclusions

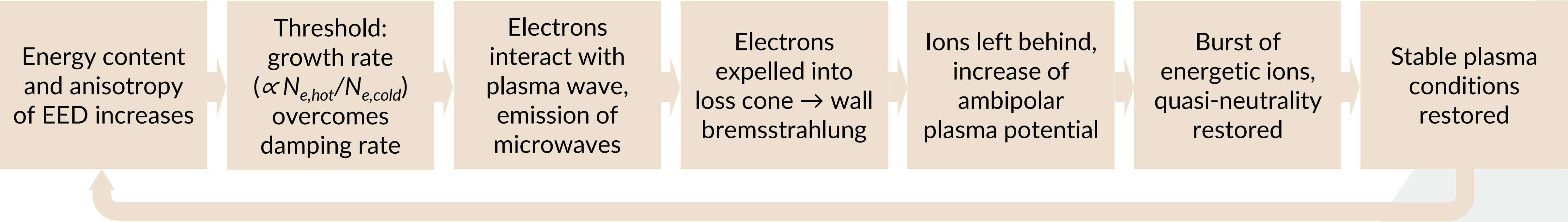
Introduction and motivation

- Energy spread: relevant when assessing the quality of beams → beam transmission, application/user requirements
- Stable plasma: electrostatic focusing effects during beam formation (extraction geometry, plasma-beam boundary) are dominant factors determining the beam energy spread [1]
- During kinetic plasma instabilities the situation changes drastically
  - Instability onset is characterised by sudden increase of plasma potential (~two orders of magnitude)
  - Plasma potential becomes the dominant factor defining the energy spread of extracted beam
- Measurement of energy spread during instability → diagnostic to probe the influence of instabilities on the plasma potential
  - Magnitude, time scales, possible temporal patterns, other characteristics
  - New insight into instability related ECR plasma physics

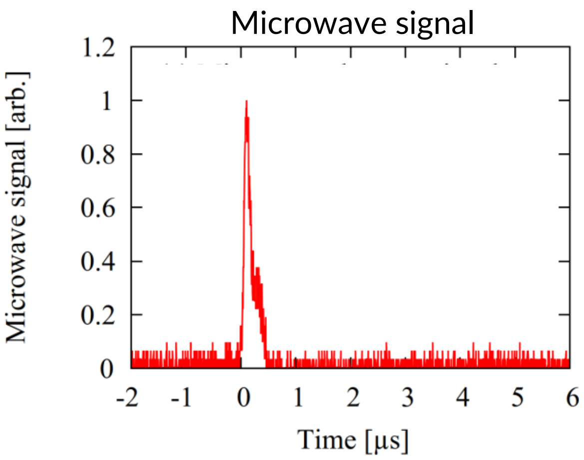
[1] J. Angot, O. Tarvainen, P. Chauveau, S.T. Kosonen, T. Kalvas,T. Thuillier, M. Migliore and L. Maunoury, "The longitudinal energy spread of ion beams extracted from an electron cyclotron resonance ion source", JINST 18 (2023) P04018. doi:10.1088/1748-0221/18/04/P04018

Kinetic plasma instabilities – a quick reminder

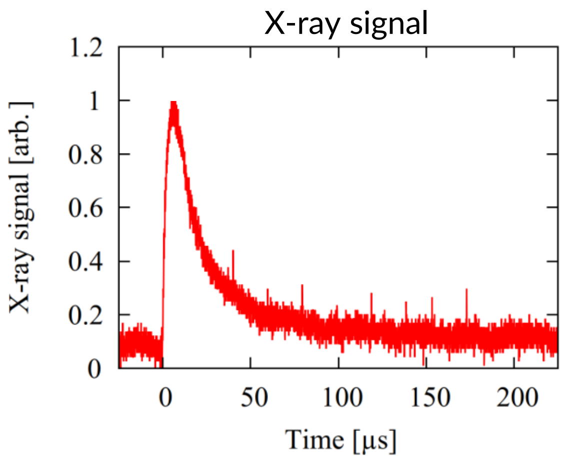
ECRIS plasmas are strongly anisotropic, consisting of cold and hot electrons → non-equilibrium plasma, prone to kinetic (maser-type) instabilities driven by hot electron population



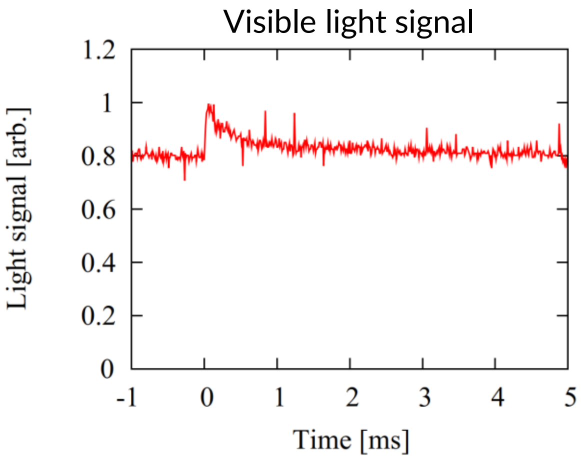
- Energy content and anisotropy of EED increases
- Threshold: growth rate ($\propto N_{e,hot}/N_{e,cold}$) overcomes damping rate
- Electrons interact with plasma wave, emission of microwaves
- Electrons expelled into loss cone → wall bremsstrahlung
- Ions left behind, increase of ambipolar plasma potential
- Burst of energetic ions, quasi-neutrality restored
- Stable plasma conditions restored



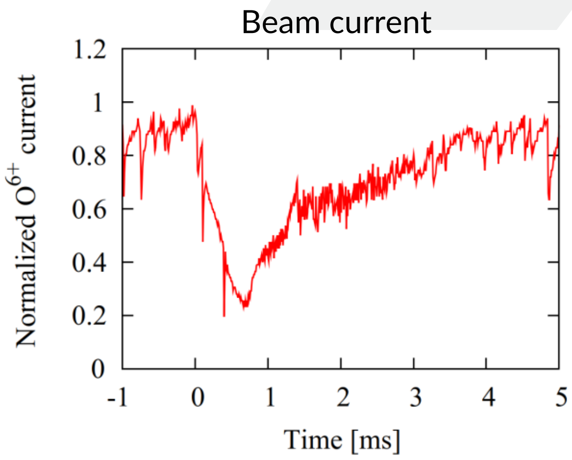
Microwave signal



X-ray signal



Visible light signal



Beam current

Kinetic plasma instabilities – a quick reminder

- Instabilities can occur both in CW and pulsed operation modes
  - CW operation:
    - Plasma heating and confinement leads to build-up of hot electron population → onset of instability

$$\frac{N_{e,hot}}{N_{e,cold}} \uparrow$$

  - Pulsed operation:
    - During the plasma decay following the µW switch-off, the loss rate of cold electrons is higher than the better confined hot electrons → onset of instability

$$\frac{N_{e,hot}}{N_{e,cold} \downarrow}$$

- Consequences: oscillation of beam current and beam energy, limitation of parameter space for source performance optimization, decreased beam transmission efficiency, increase of beam impurities, …

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Time-resolved measurement of ion beam energy spread

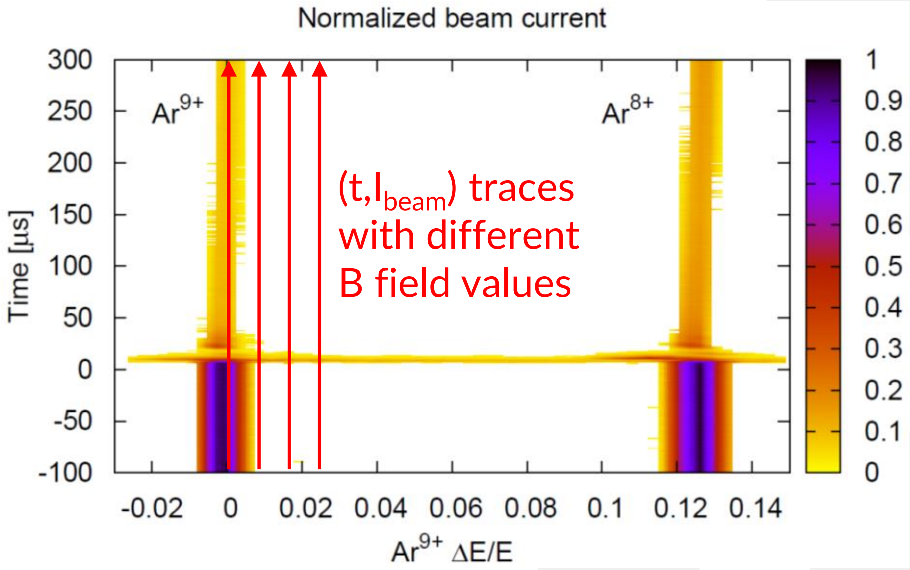
Experimental method and setup

- Main idea: dipole magnet used as an energy analyzer for extracted ion beam
- Temporal evolution of beam current recorded at different dipole *B* fields
- Energy spread increase during instability causes beam current to ”spread” momentarily to higher *B* fields
  - Dipole *B* field scan ↔ scan of energy variation of the ion species of interest

- Data combined to reveal energy spread variation
- Repetitive measurement process → automatisation
  → MSc thesis of J. Huovila [1]

- CW and pulsed operation: a choice of trigger signal
  - CW operation: x-ray or µW bursts from plasma
  - Pulsed operation: leading or trailing edge of µW pulse

Example from old CW operation data [2]:



(t, I_{beam}) traces with different B field values

$\Delta E/E \propto B_{dipole}$

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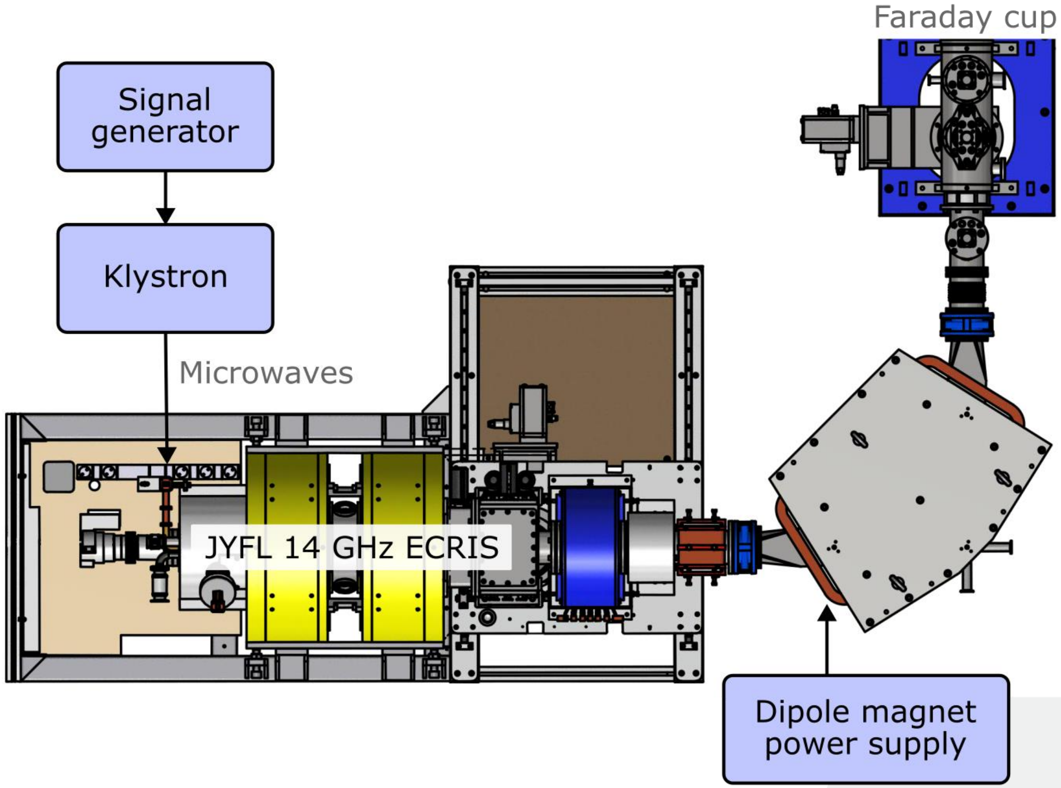
[1] J. Huovila, MSc thesis, University of Jyväskylä (2023). http://urn.fi/URN:NBN:fi:jyu-202305022805
[2] O. Tarvainen *et al.*, "Limitation of the ECRIS perfor-mance by kinetic plasma instabilities", *Rev. Sci. Instrum.* 87 (2016) 02A703.

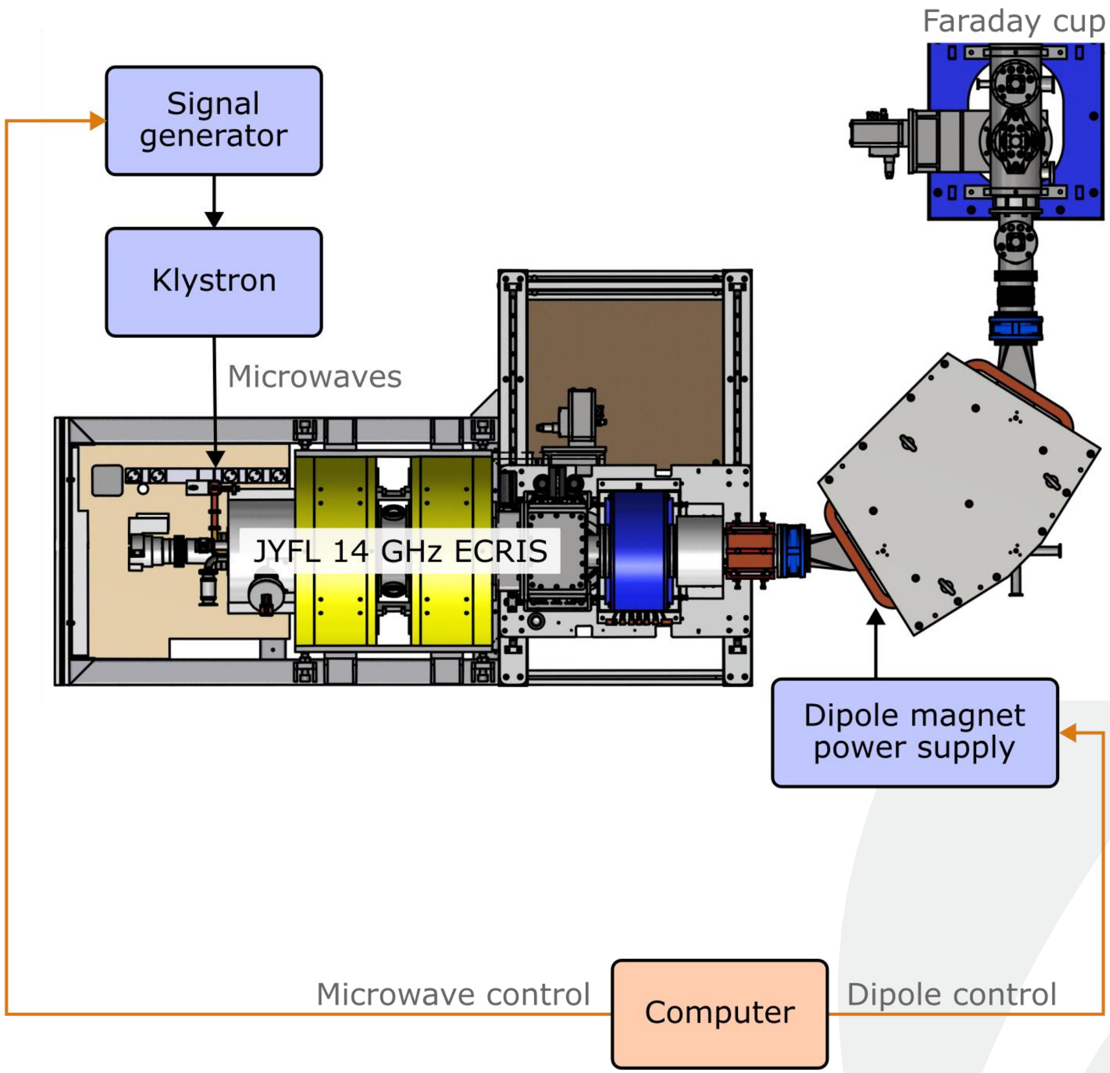
Experimental method and setup

- Experiments performed on JYFL 14 GHz ECRIS



Experimental method and setup

- Experiments performed on JYFL 14 GHz ECRIS
- A dedicated computer runs the measurement procedure and data acquisition
  - Controls µW pulse pattern and dipole sweep



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- Experiments performed on JYFL 14 GHz ECRIS
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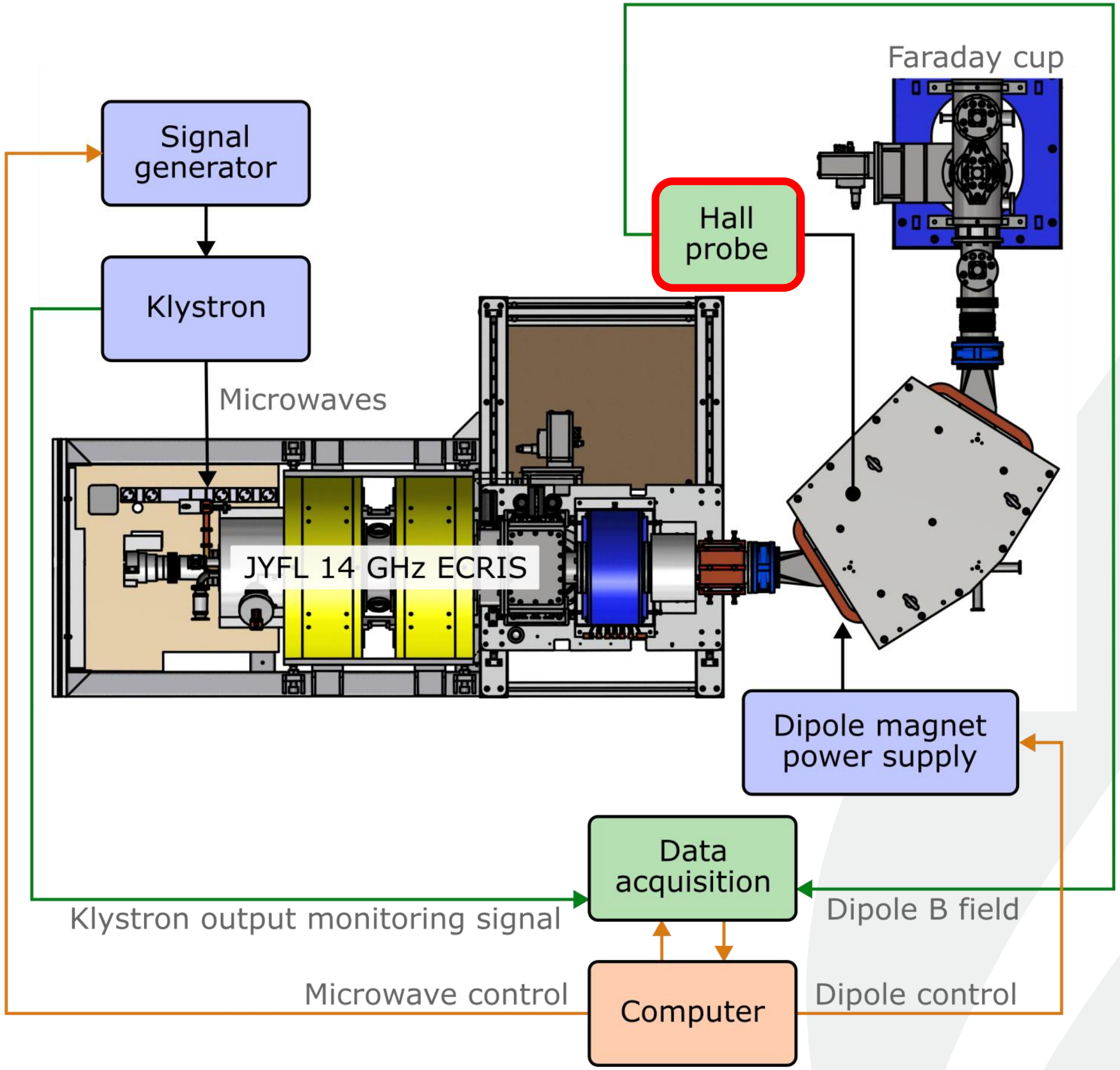
- Klystron output signal to trigger and synchronize data acquisition
- Dipole *B* field measured with a Hall probe



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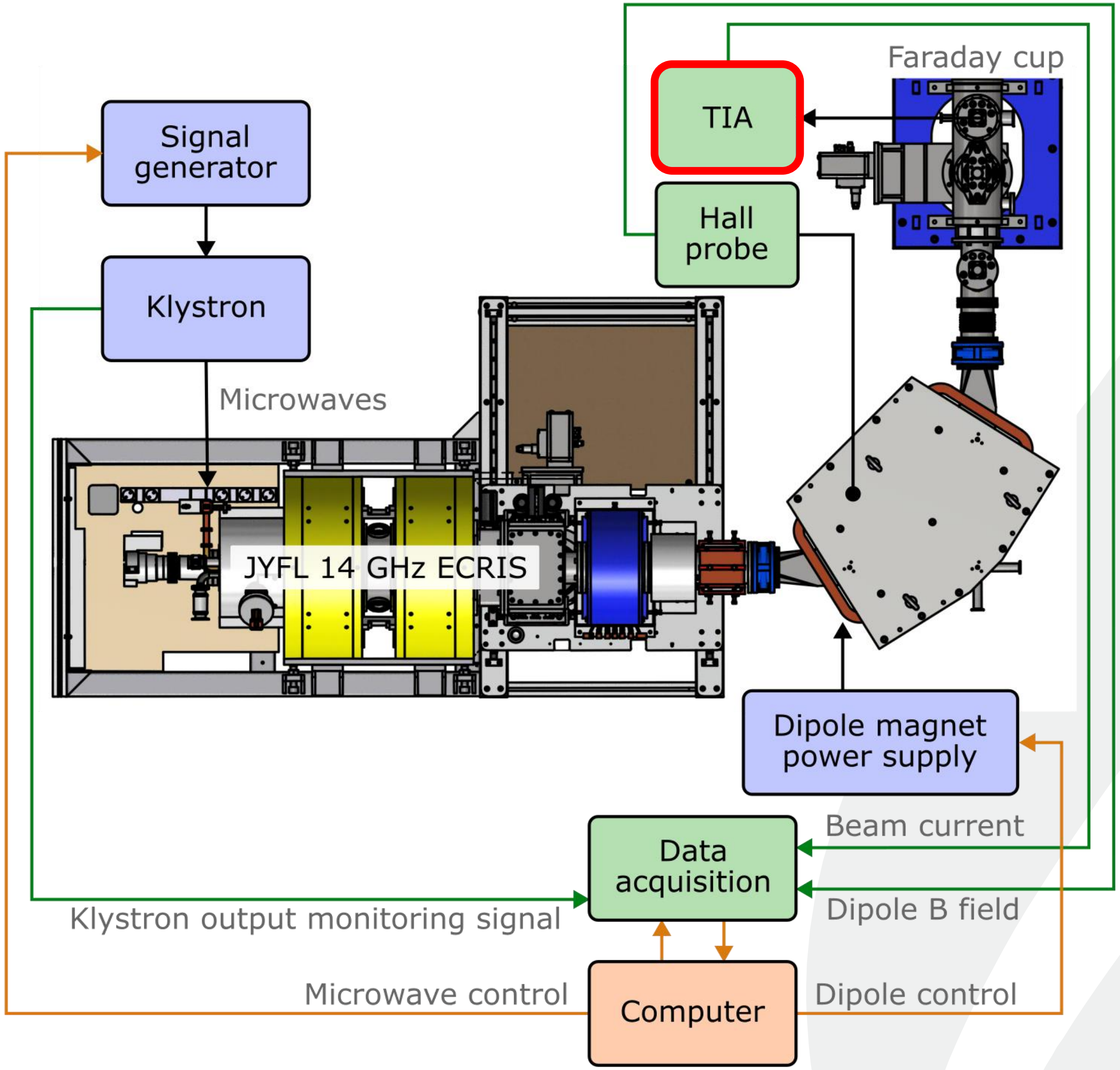

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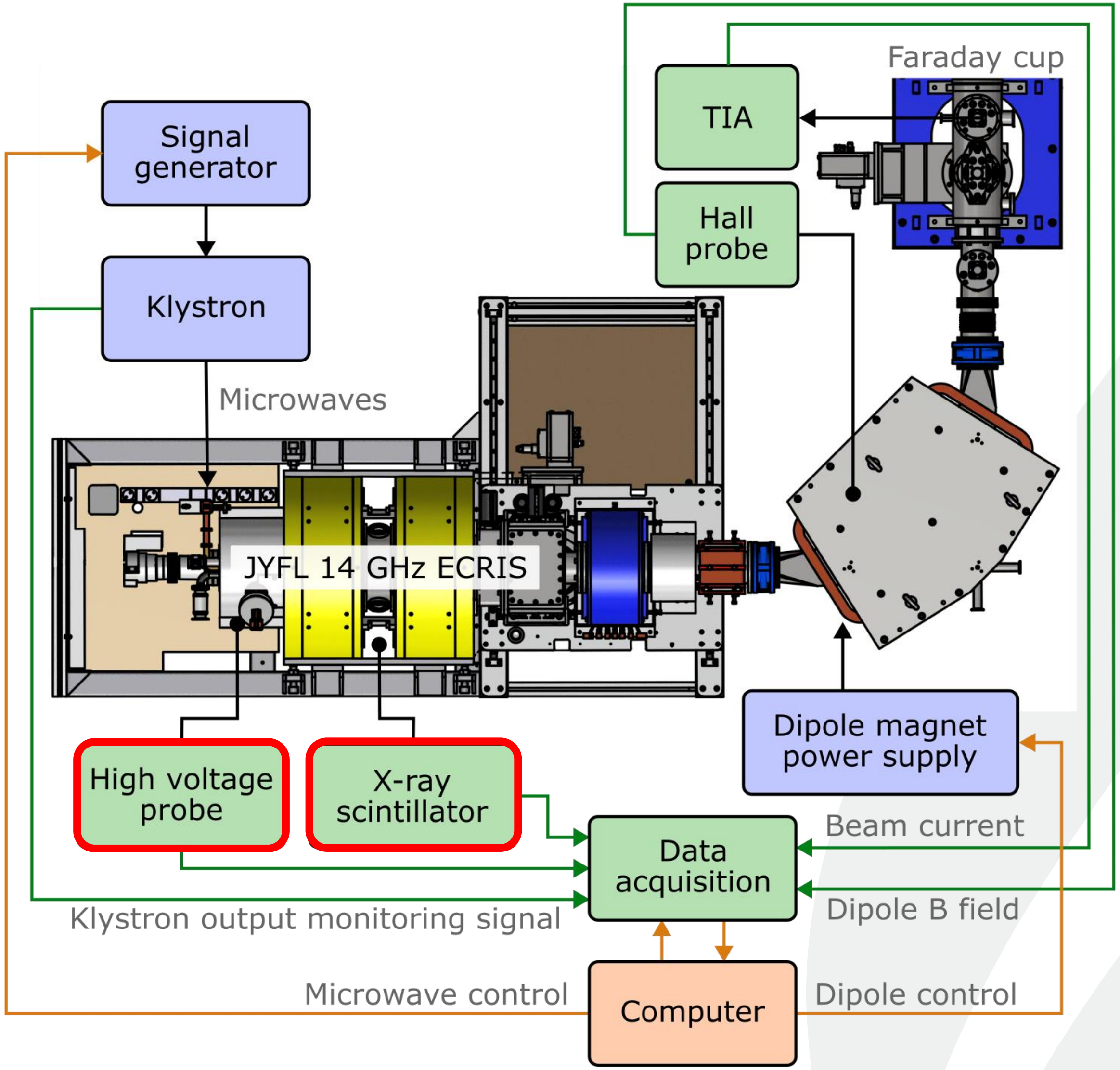
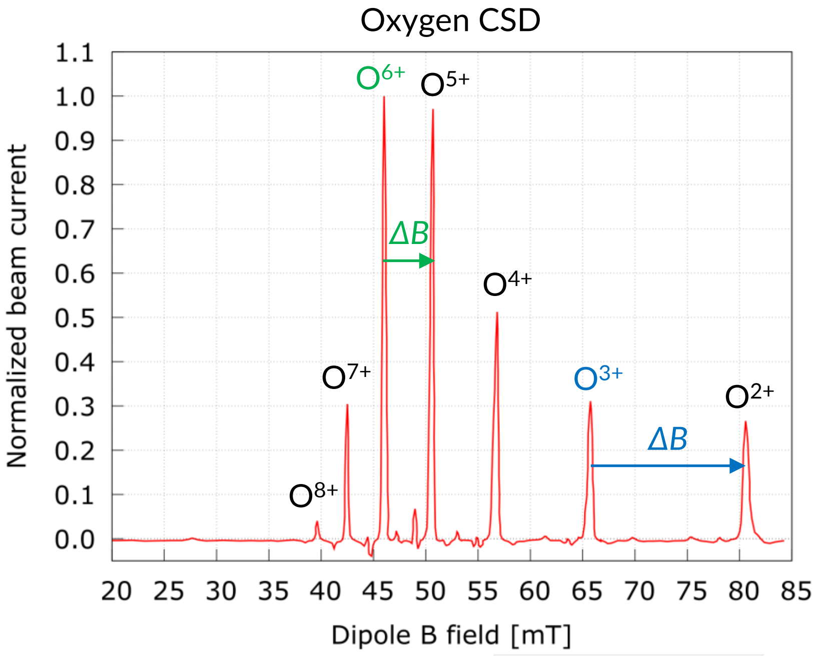
- X-ray scintillator to monitor x-ray bursts from plasma (correlation with instabilities)
- HV probe to monitor source potential



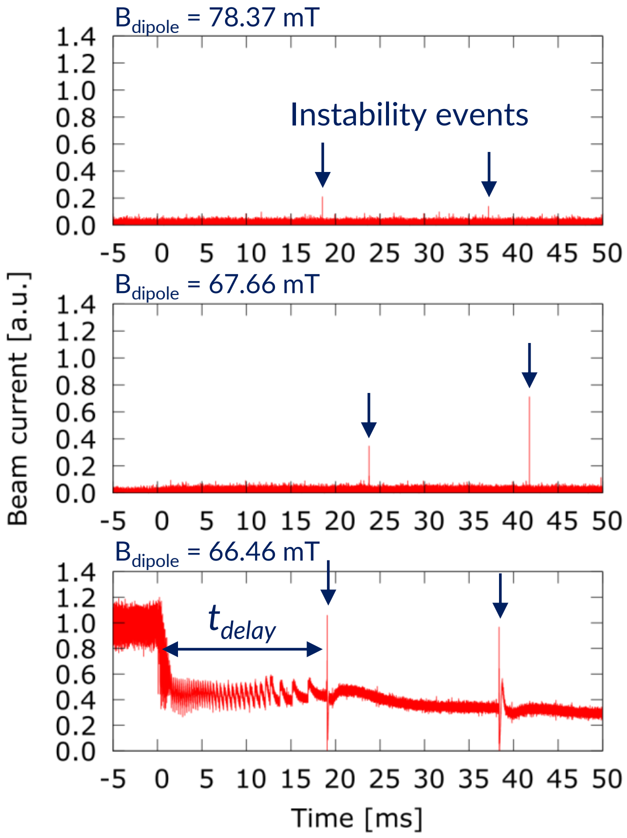
Data analysis – possibilities and challenges

- The onset of kinetic instability influences the whole plasma ion population → freedom in choosing the studied ion species
- Main challenge: overlap with neighboring species at higher *B* field → limits measurable energy spread increase
- Lower charge states are preferable, because they have the wider separation from neighboring charge states
- Impurities pose additional challenge by limiting free *B* field regions



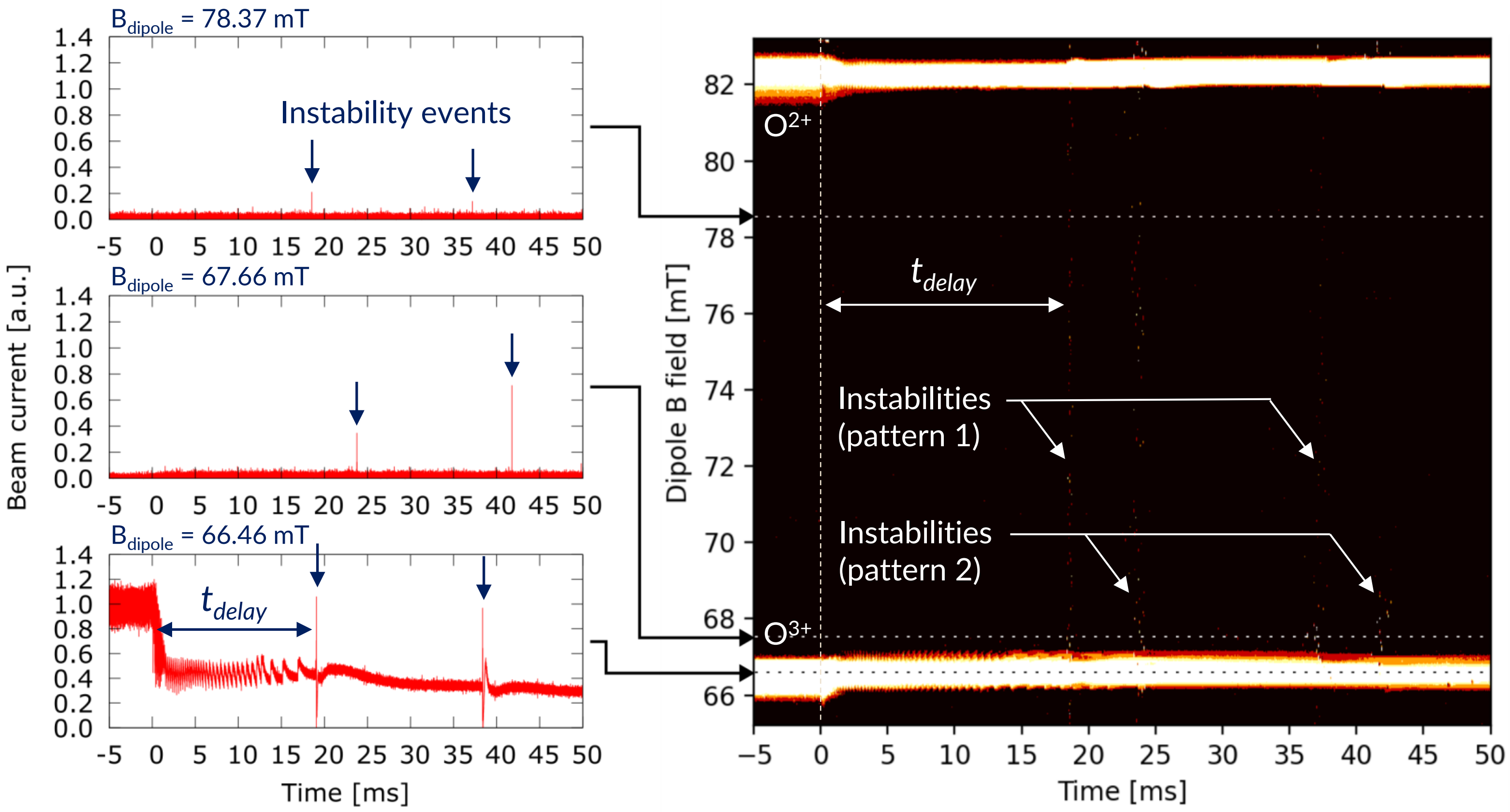
ΔB = Available space to measure current ”spreading” during instability to determine energy spread increase for O^{6+} and O^{3+}

Data analysis – an example for pulsed operation



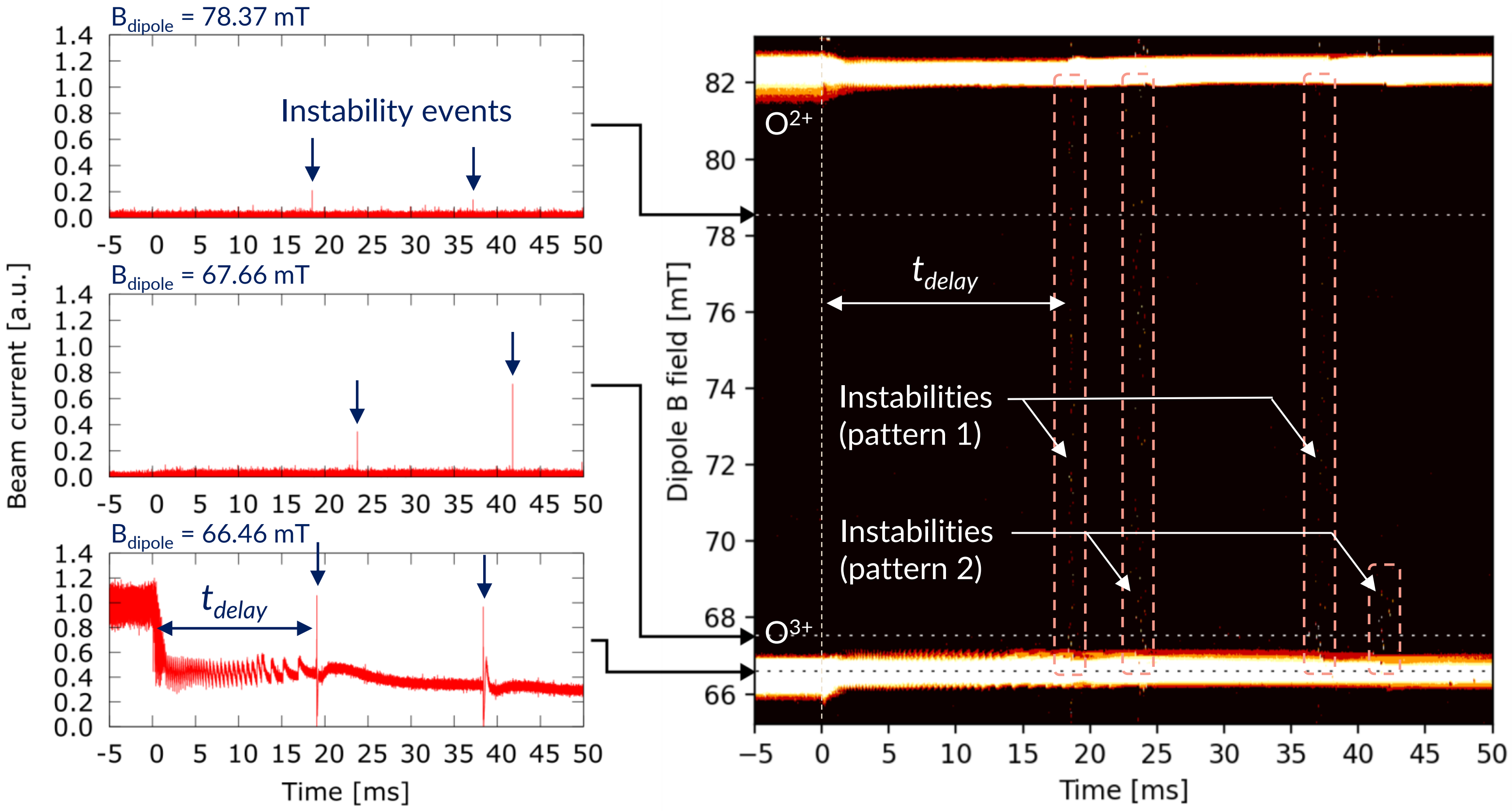
- Oxygen plasma, 300 W microwave power, B_{min}/B_{ECR} = 0.67, 10 kV extraction
- Independent beam current traces measured with varied dipole *B* fields, microwave switch-off at *t=0*
  - Traces on the left: measured at dipole field corresponding to the center of the $^{16}O^{3+}$ beam (bottom plot) and at two higher dipole fields
- Instability transient (peak) in beam current has a time scale of a few microseconds
- Delay time (t_{delay}) from the microwave switch-off to the occurrence of the first instability event is very repeatable pulse-to-pulse
  - But: a few discrete patterns of consecutive instability events are observed
    - Top and bottom plots → pattern 1
    - Middle plot → pattern 2

Data analysis – an example for pulsed operation



- Individual traces combined into a colormap plot (t, B_{dipole}, I_{beam})
- Increased energy spread causes ”spreading” of beam current at higher dipole fields during the onset of instability
- Multiple consecutive instability events observed
- The discrete patterns of instability onsets are overlaid in the colormap, gives an illusion of increased number of events per pulse

Data analysis – an example for pulsed operation



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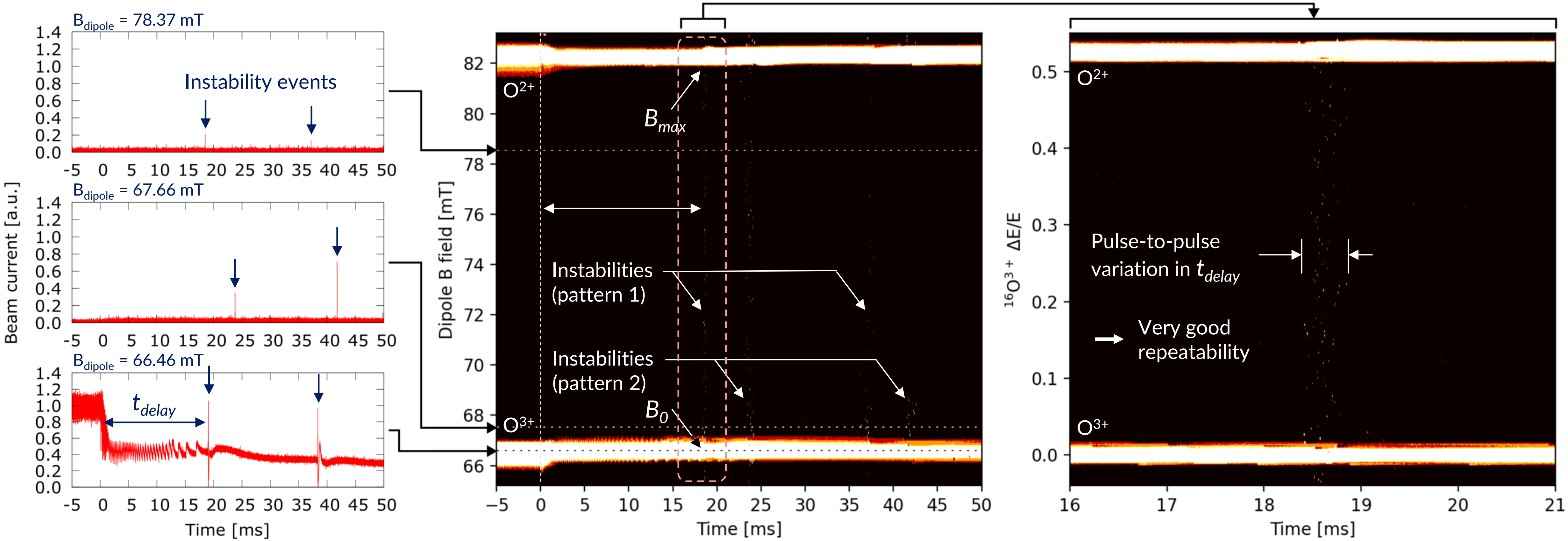

$$\frac{\Delta E}{E} = \frac{B_{max}^2 - B_0^2}{B_0^2}$$

$$\Delta V_p = \left(\frac{\Delta E}{E}\right) V_s$$

V_s = source potential

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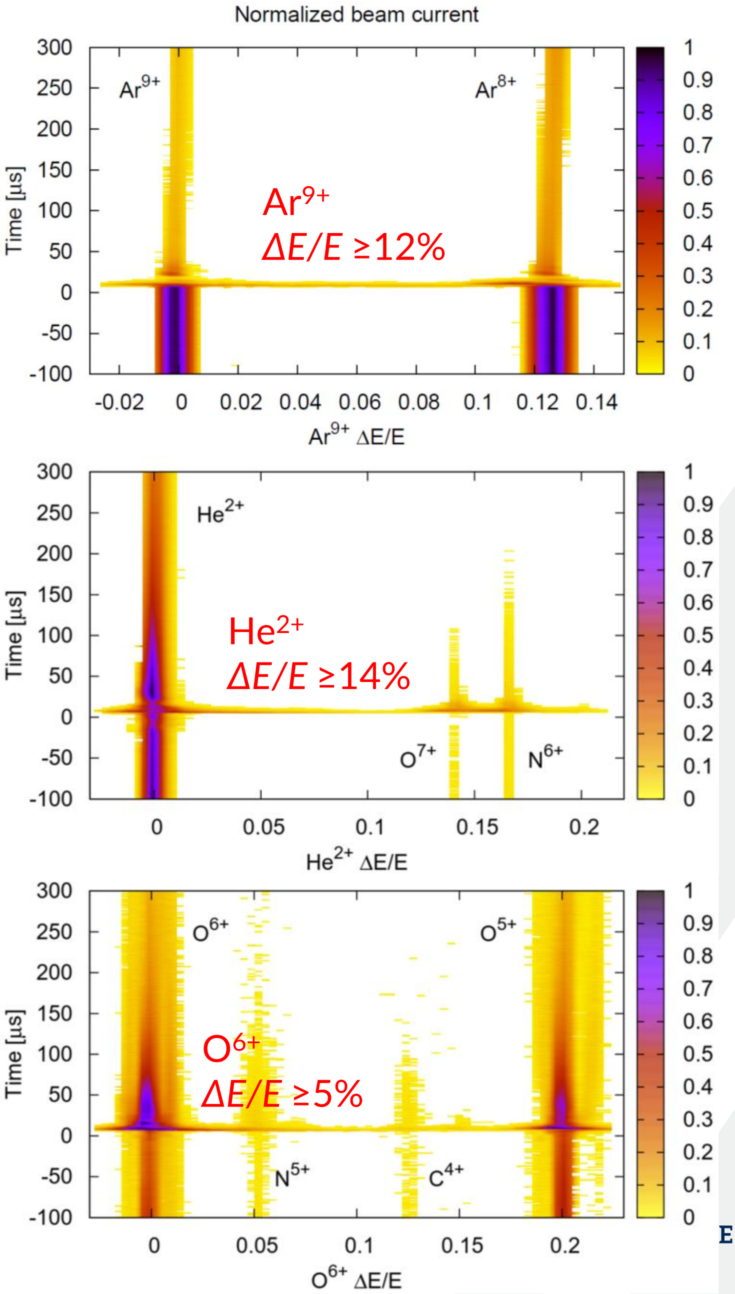
Experimental results

Results – CW operation

- Measured with JYFL 14 GHz ECRIS, published in Refs. [1,2]
  - Effect of instabilities studied with Ar, He and O plasmas
  - Data acquisition synchronized to instability-induced x-ray bursts
- Significant increase in *ΔE/E* observed at the onset of instability in all studied cases and plasmas
  - Highest *ΔE/E* increase ≥15% → ΔV_p ≥1.5 kV
  - But: overlap in all studied cases → lower limit estimates only
- Time scale: *ΔE/E* increase lasts a few microseconds – same as in pulsed operation



Ar^{9+}
ΔE/E ≥12%

He^{2+}
ΔE/E ≥14%

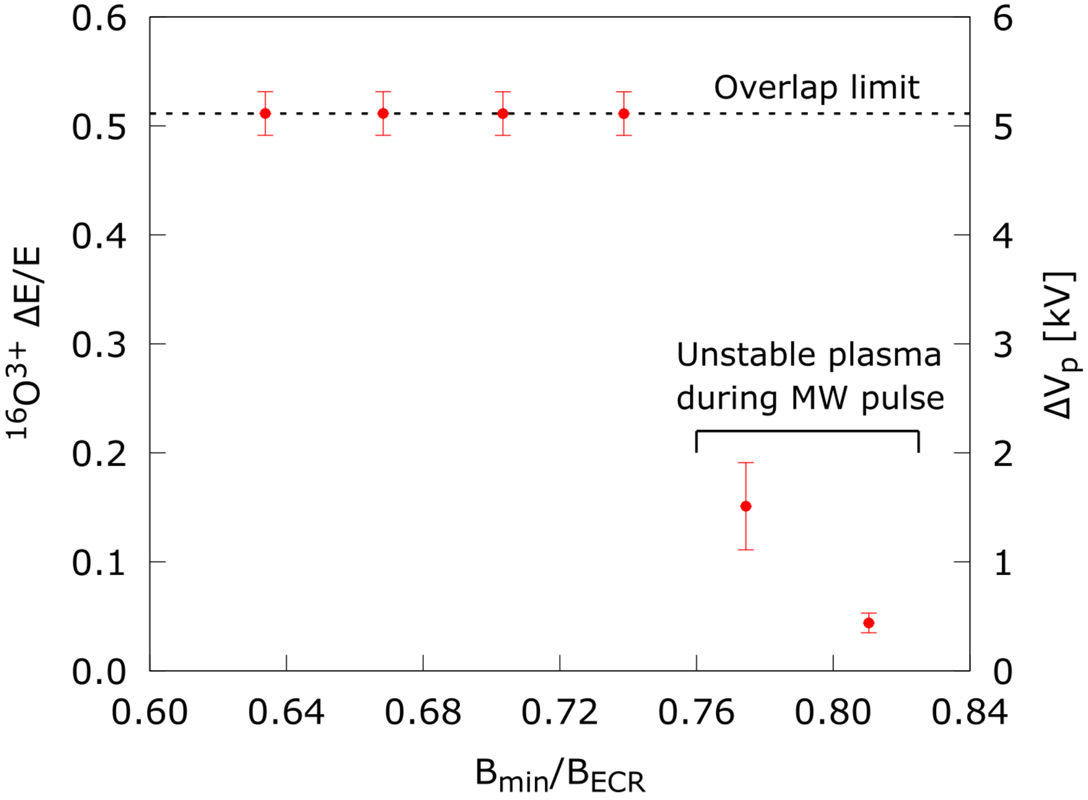
O^{6+}
ΔE/E ≥5%

[1] O. Tarvainen *et al.*, "Limitation of the ECRIS perfor-mance by kinetic plasma instabilities", *Rev. Sci. Instrum.* 87 (2016) 02A703.
[2] O. Tarvainen *et al.*, "The biased disc of and electron cyclotron resonance ion source as a probe ofinstability-induced electron and ion losses", *Rev. Sci. Instrum.* 90 (2019) 123303.

Results – pulsed operation

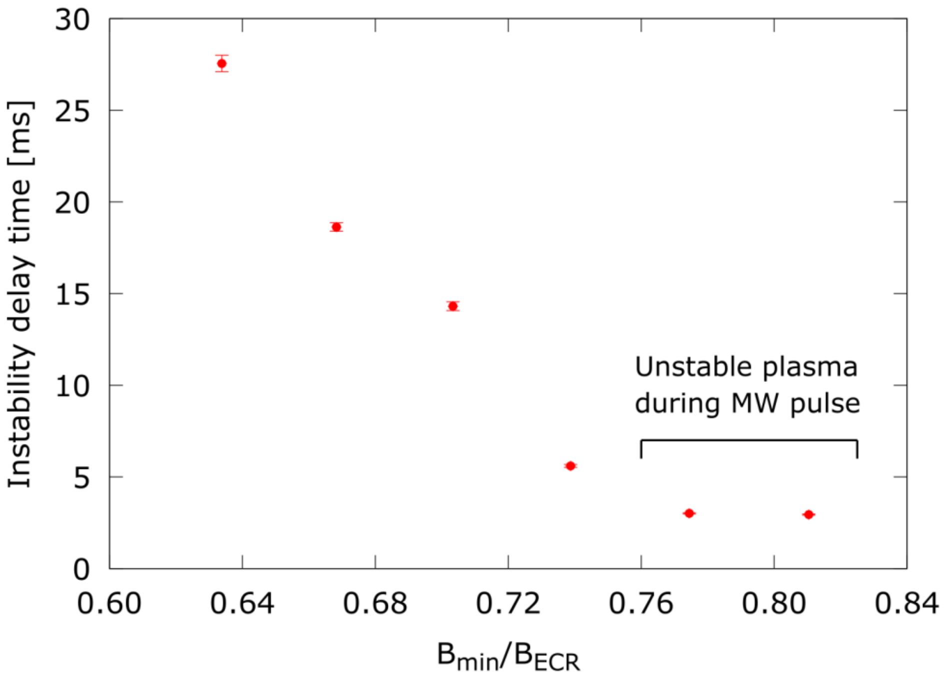
- Oxygen plasma, 300 W µW power (1 Hz, 50% duty cycle), varied *B* field
- Two regions for *ΔE/E* behaviour:

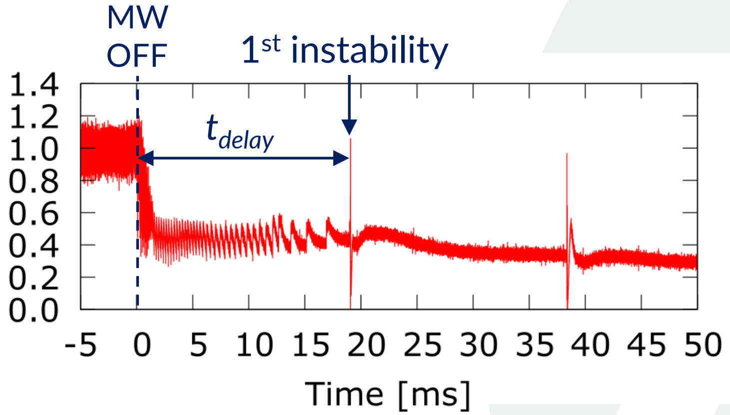
1. $B_{min}/B_{ECR} < 0.76$
   - Stable plasma during µW pulse
   - *ΔE/E* increase ≥51% → ΔV_p ≥5.1 kV
   - Still lower limit values due to overlap!
2. $B_{min}/B_{ECR} > 0.76$
   - Plasma becomes unstable during µW pulse
   - Significant drop in *ΔE/E* increase (15% and 4%)
   - Instability provides a channel for the plasma to expel energy during the µW pulse → mitigates the energy released during plasma decay



Results – pulsed operation

- Delay time to 1st instability decreases with increasing B_{min}/B_{ECR} ratio
- Agrees with previous pulsed operation instability experiments based on x-ray and microwave emissions [1]
- Decrease in delay is associated with increased density and anisotropy of hot electrons due to enhanced heating with lower B field gradients at higher B_{min}/B_{ECR}
- Delay decreases also when plasma is unstable during µW pulse → ratio of hot to cold electron densities triggers instability onset, not plasma energy content (which presumably is decreased with unstable plasma)



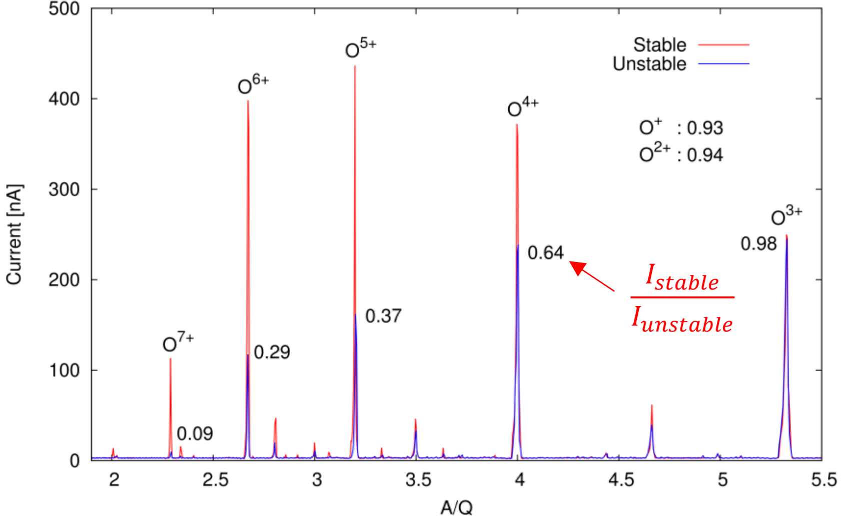


[1] I. Izotov *et al.*, "Cyclotron instability in the afterglow mode of minimum-B ECRIS", *Rev. Sci. Instrum.* 87 (2016) 02A729.

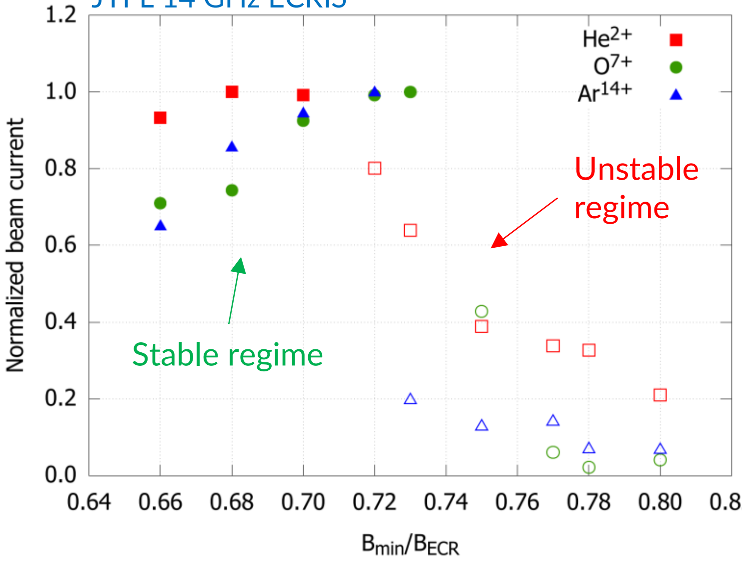
Implications/consequences for ECRIS operation

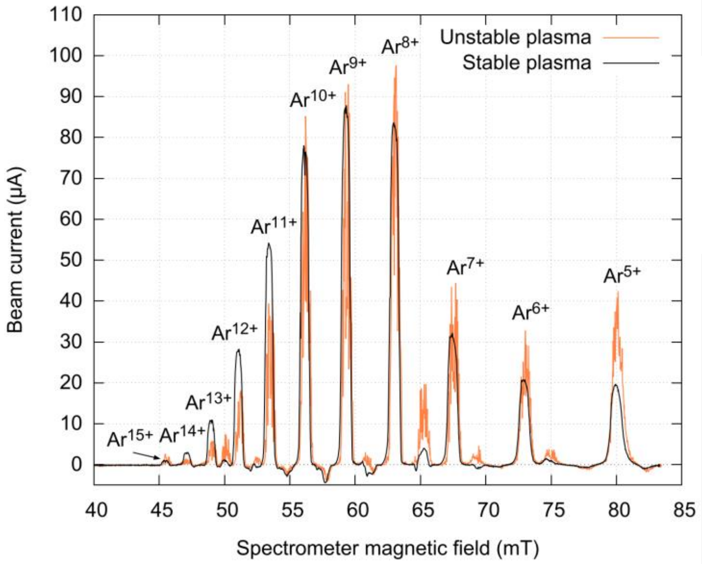
- Degradation of high charge state performance
  - Well-established consequence of unstable plasma
  - Strong impact on high charge states
  - Especially relevant in CW operation
  - Examples:
    - JYFL 14 GHz ECRIS [1]
    - 14.5 GHz PHOENIX CB-ECRIS [2]

14.5 GHz PHOENIX CB-ECRIS



JYFL 14 GHz ECRIS

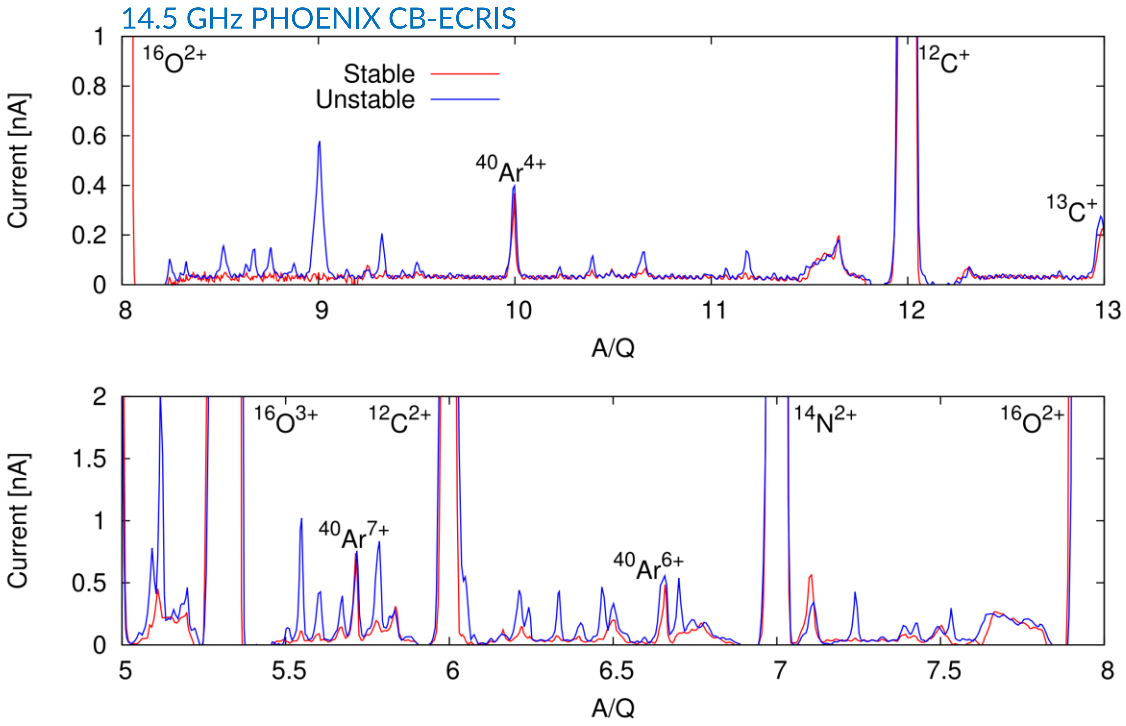




[1] V. Toivanen *et al.*, ”Diagnostic techniques of minimum-B ECR ion source plasma instabilities", *Rev. Sci. Instrum.* 93 (2022) 013302.
[2] O. Tarvainen *et al.*, "Plasma instabilities of a charge breeder ECRIS", *Plasma Sources Sci. Technol.* 26 (2017) 105002.

Implications/consequences for ECRIS operation

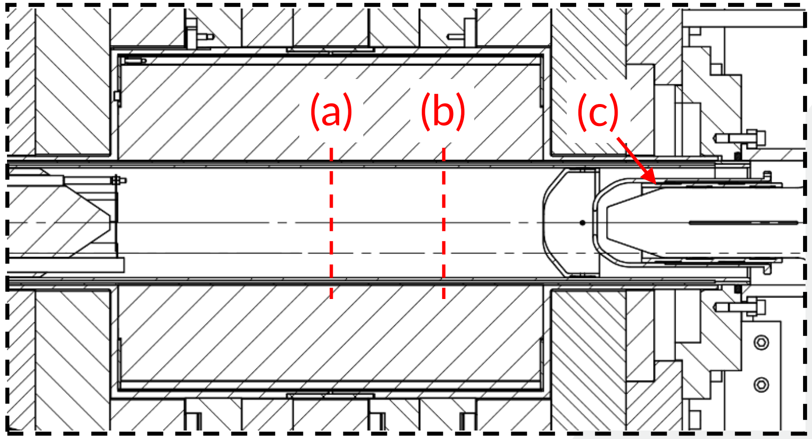
- Desorption of impurities from chamber walls
  - Energetic ion bombardment releases impurities from the walls into the plasma → CSD contamination
  - An example: unstable vs. stable plasma operation of PHOENIX CB-ECRIS [1,2]
    - An order of magnitude increase in impurity currents in the extracted n+ ion beam
    - Impurity peaks correspond to elements from the structures surrounding the plasma

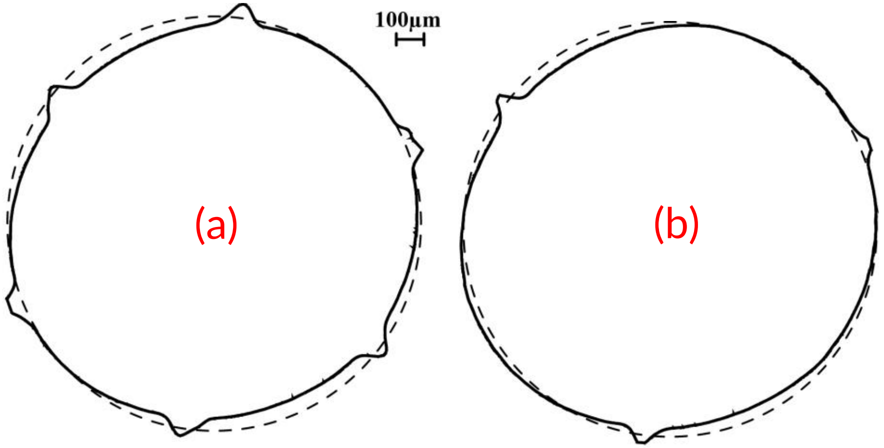


[1] O. Tarvainen *et al.*, "Plasma instabilities of a charge breeder ECRIS", *Plasma Sources Sci. Technol.* 26 (2017) 105002.
[2] O. Tarvainen *et al.*, "The effect of plasma instabilities on the background impurities in charge breeder ECRIS", *AIP Conf. Proc.* 2011 (2018) 070006.

Implications/consequences for ECRIS operation

- Chamber erosion
  - Energetic ions sputter the structures around the plasma
  - Prolonged (pulsed) operation can lead to significant structural degradation
  - An example: 6 month argon operation of CERN GTS-LHC in pulsed afterglow mode [1]
    - 100 µm deep sputter marks
    - Fe seen in CSD (SS chamber)
    - Coating of insulators


GTS-LHC plasma chamber



Values amplified by a factor of 100

[1] D. Küchler *et al.*,"Never run your ECR ion source with argon in afterglow for 6 months!", *in Proc. ECRIS'16*, Busan, Korea, Aug. 2016, p.WEPP03, ISBN 978-3-95450-186-1.

Summary and conclusions

- Plasma potential experiences a significant increase at the onset of kinetic instability
  - The absolute values still remain elusive, but experiments show that they can be ≥1.5 kV in CW operation and ≥5.1 kV in pulsed operation
  - The energy spread of the extracted beam increases accordingly (≥15% in CW, ≥51% in pulsed operation)
- One should be aware of this phenomenon, as it can influence the ECRIS operation
  - Degraded performance, increase of impurities, chamber erosion, momentary loss of beam transmission
- In pulsed operation experiments instabilities were observed with all ECRIS settings, suggesting that instabilities could be present always in pulsed operation
- The method presented here has challenges (overlap) but is still promising for further use/development
  - Improve conditions, limit impurities
  - Room for further experiments; more parametric studies, characteristics of subsequent instability events, …

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Thank you for your attention