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Study on Kinetic instabilities in Electron Cyclotron Resonance Plasma

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Contents

- A Brief outline of ECR ion sources
- Introduction to kinetic instabilities
- Modelling of magnetic field in ECRIS
- Construction of 3D ECR zone
- Experiments to detect instabilities
- Experimental results
- Conclusion and Future scope

Electron Cyclotron Resonance Ion Sources (ECRIS) Working Principle

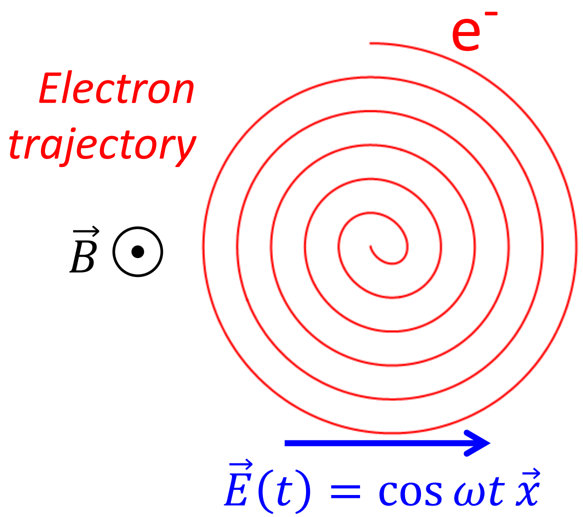
- For a given magnetic field line nonrelativistic electrons have a fixed revolution frequency (called electron cyclotron frequency) given by

$$\omega = \frac{eB}{m}$$

- The frequency of microwave is chosen so that there is a resonance between electron cyclotron frequency and the heating frequency.

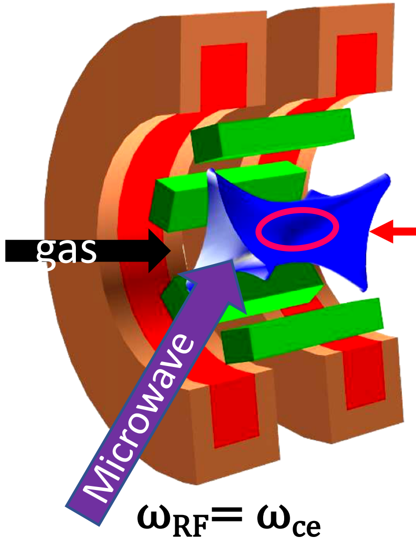
$$\omega_{RF} = \omega_{ce}$$

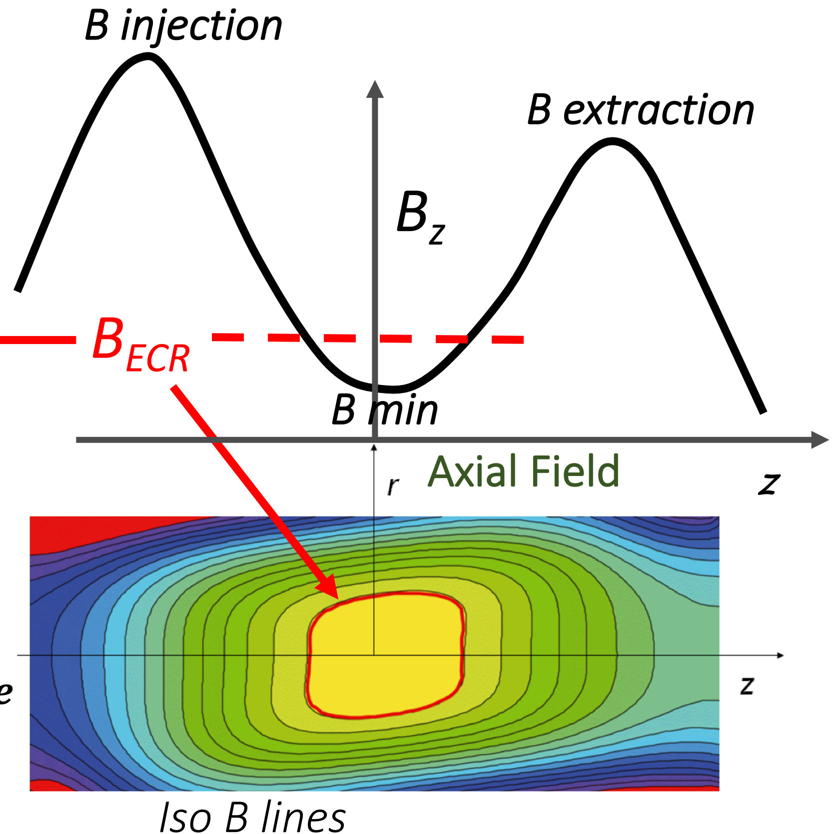
- Highly energic electrons collide with neutrals to create ions.



Electron Cyclotron Resonance Ion Sources (ECRIS) Magnetic Confinement (1/2)

- It is necessary to **confine electrons** to allow them to get sufficient energy to ionize atoms.
- In ion source charged particles are confined in **magnetic bottles**, where the axial confinement of charged particle is provided by solenoidal magnetic field and radial confinement by hexapolar field.
- ECR surface ($|B|=B_{ECR}$) is closed.

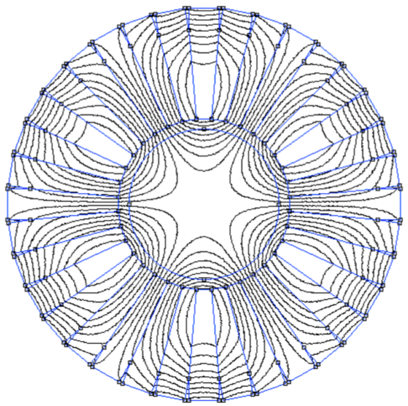


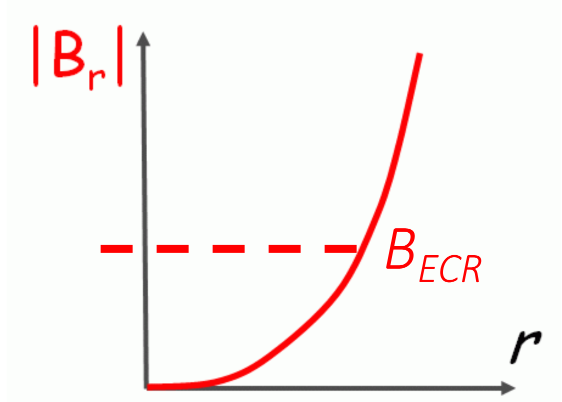


$\omega_{RF} = \omega_{ce}$

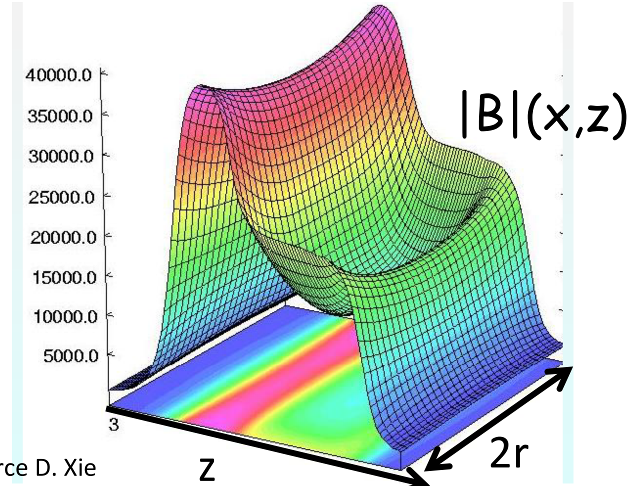
$B_{ECR} = \omega_{RF}\, m/e$

Source RIKEN, Nakagawa





Hexapolar Field



Source D. Xie

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Electron Cyclotron Resonance Ion Sources (ECRIS) Magnetic Confinement (2/2)

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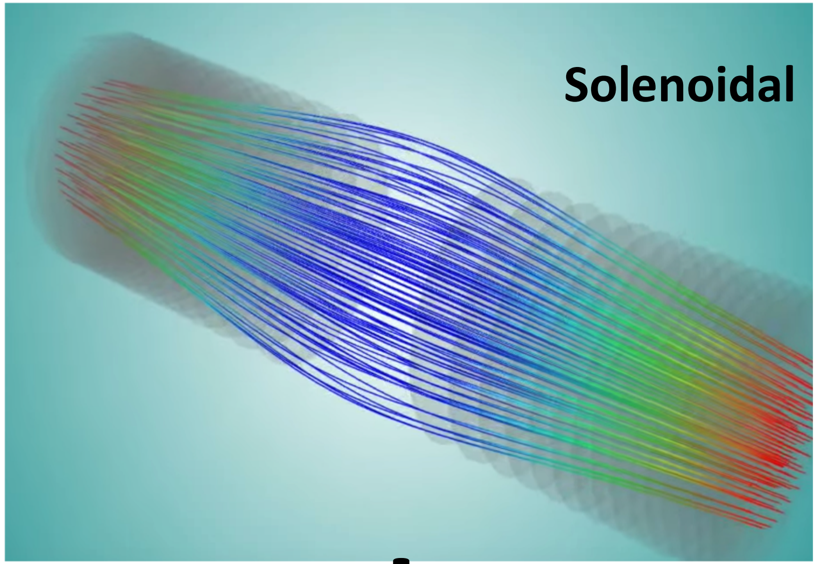

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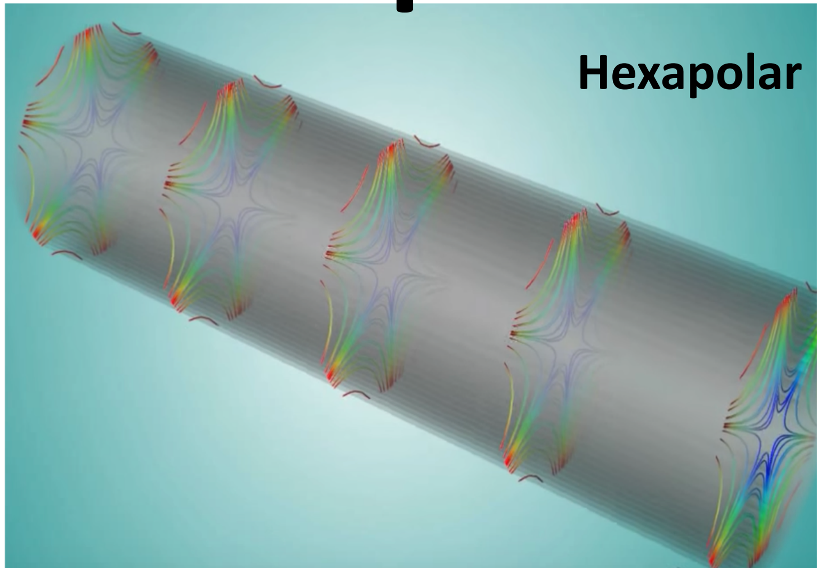

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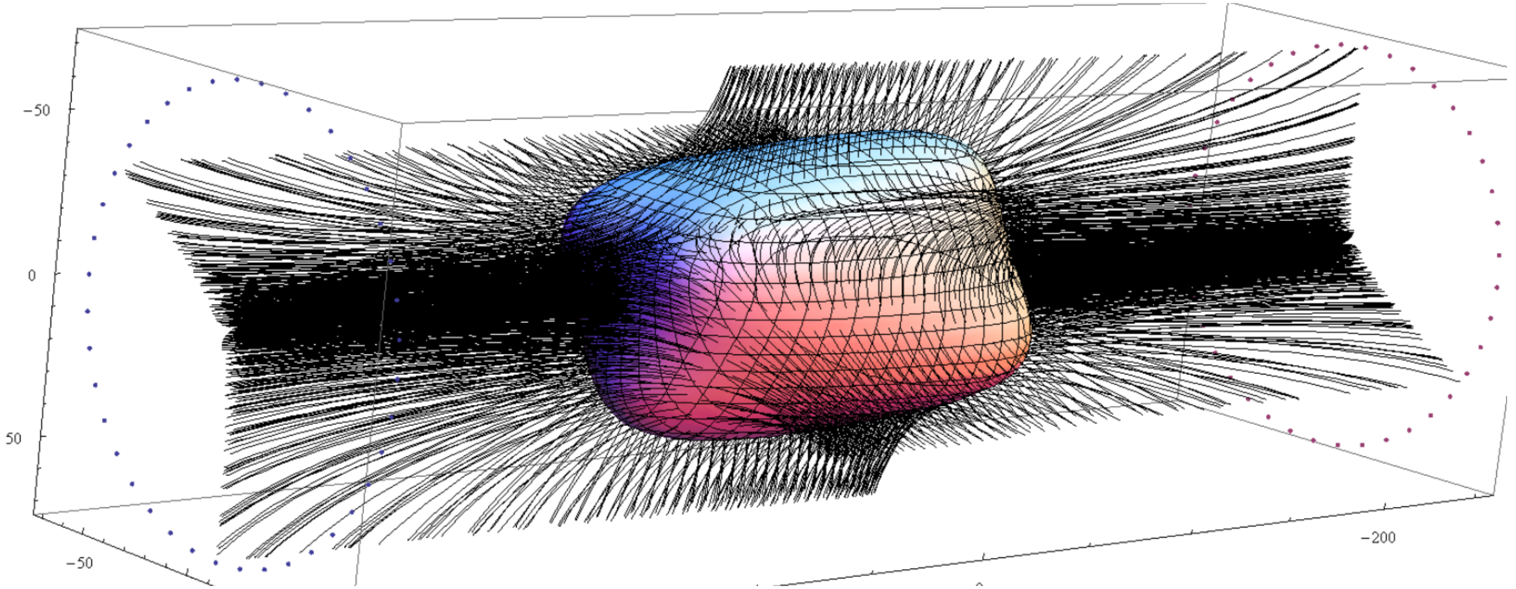
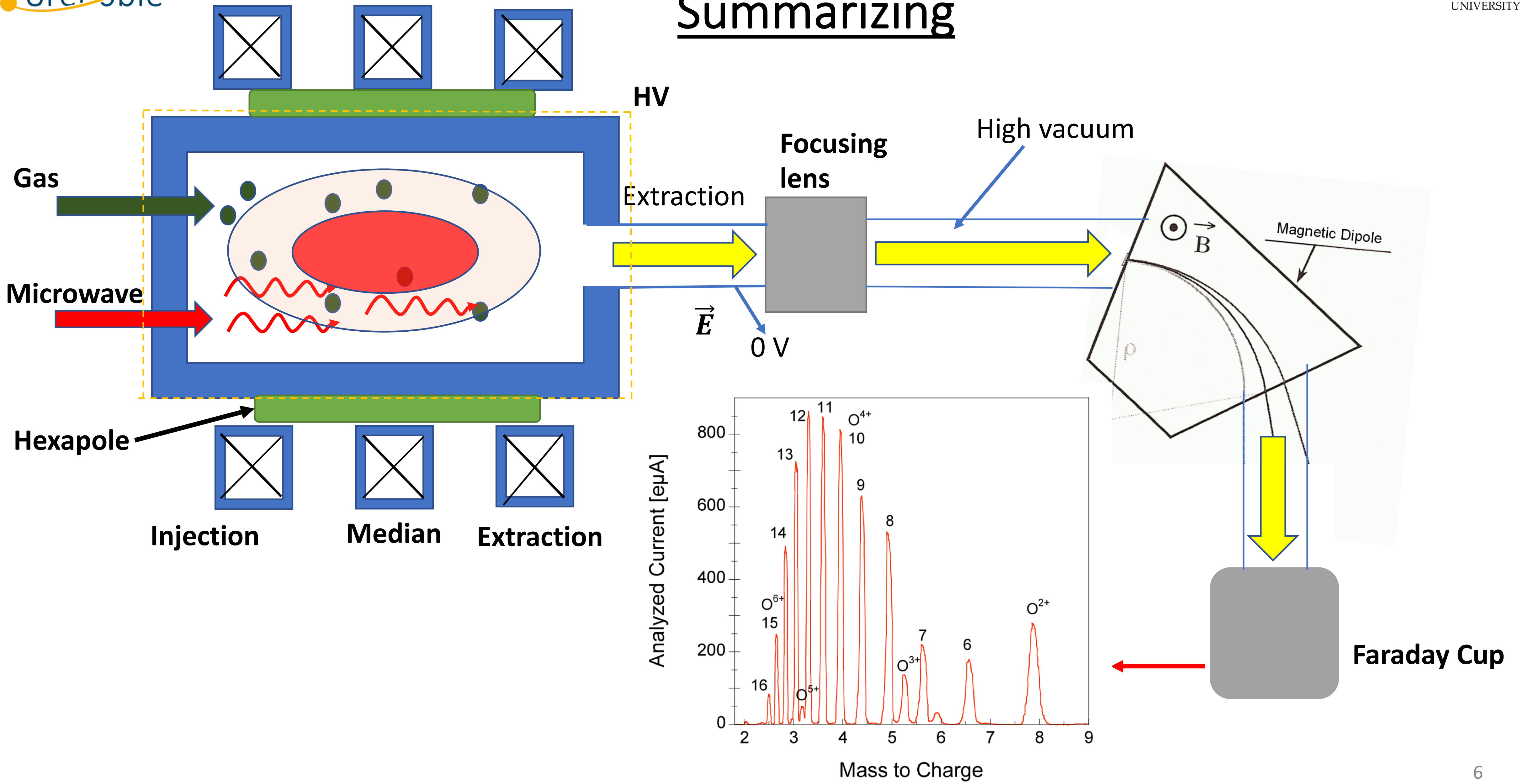
Total Magnetic field



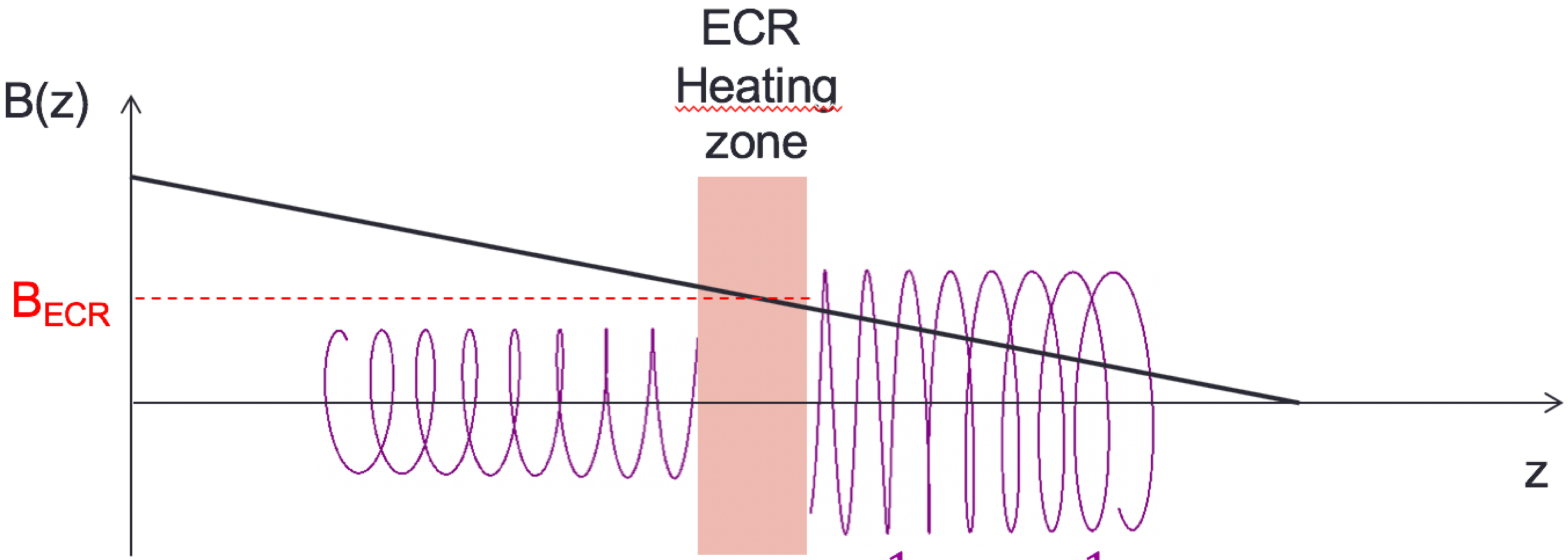
Source:www.far-tech.com

Electron Cyclotron Resonance Ion Sources (ECRIS)
Summarizing



Magnetic Field : Gradient Effect on ECR

- When electrons pass through the ECR surface they are **slightly accelerated**
- The parallel velocity $v_{\parallel}$ is unchanged, while $\boldsymbol{v_{\perp}}$ **increases .**
- The ECR zone thickness is correlated to **the local magnetic field gradient**
  - **The lower the gradient, the higher the energy gain per pass**



$$\frac{1}{2}m{v_{\parallel}}^2 + \frac{1}{2}m{v_{\perp}}^2 \Rightarrow \frac{1}{2}m{v_{\parallel}}^2 + \frac{1}{2}m(v_{\perp} + \delta v_{\perp})^2$$

Kinetic Instabilities

- Motivation:

Kinetic instabilities is one of the main factors affecting the **performance of ECRIS** , it leads to periodic **fast oscillations** of extracted beam current and thus hinders temporal stability of the beam.

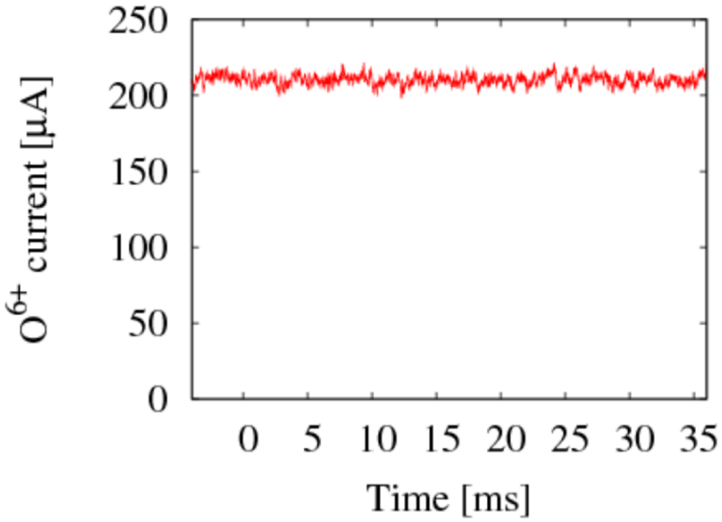
- Cause:

Due to anisotropy in electron velocity distribution function.

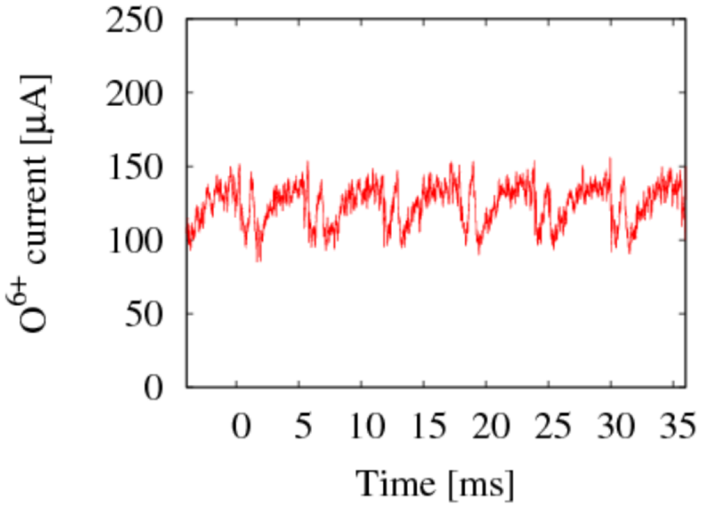
- Detection method:

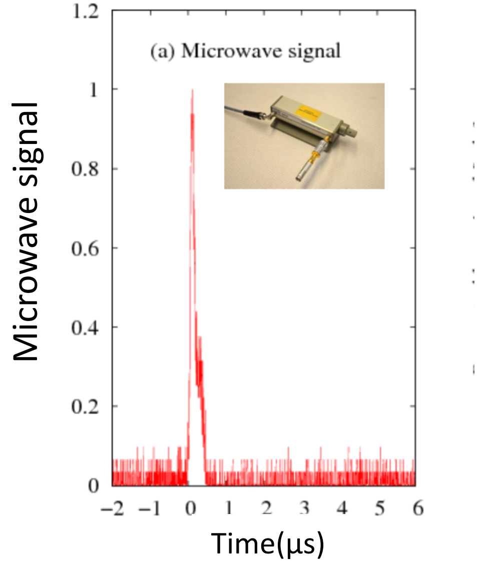
1. Variation of **average beam current** of highly charged ions.
2. Emits strong **Bremsstrahlung** radiation
3. Emits **microwave** radiation

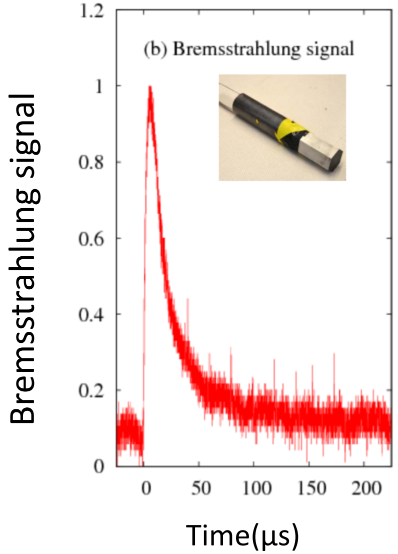
Stable



unstable

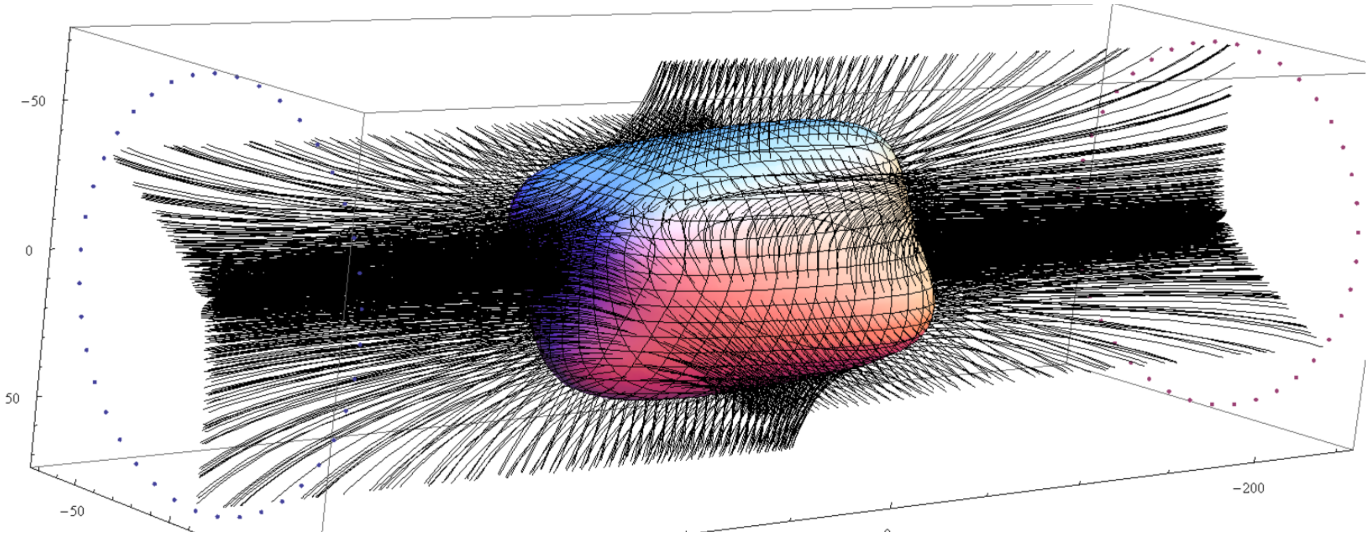






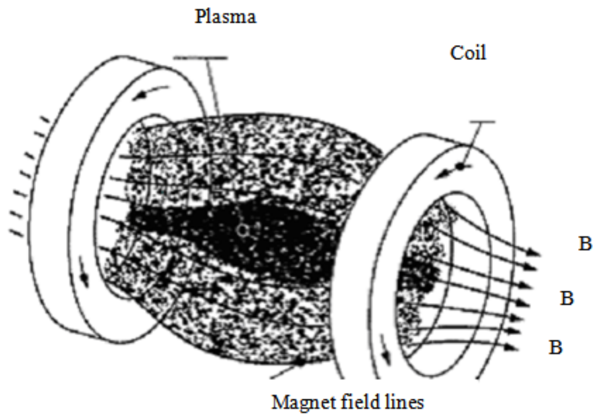
Goal of the Thesis

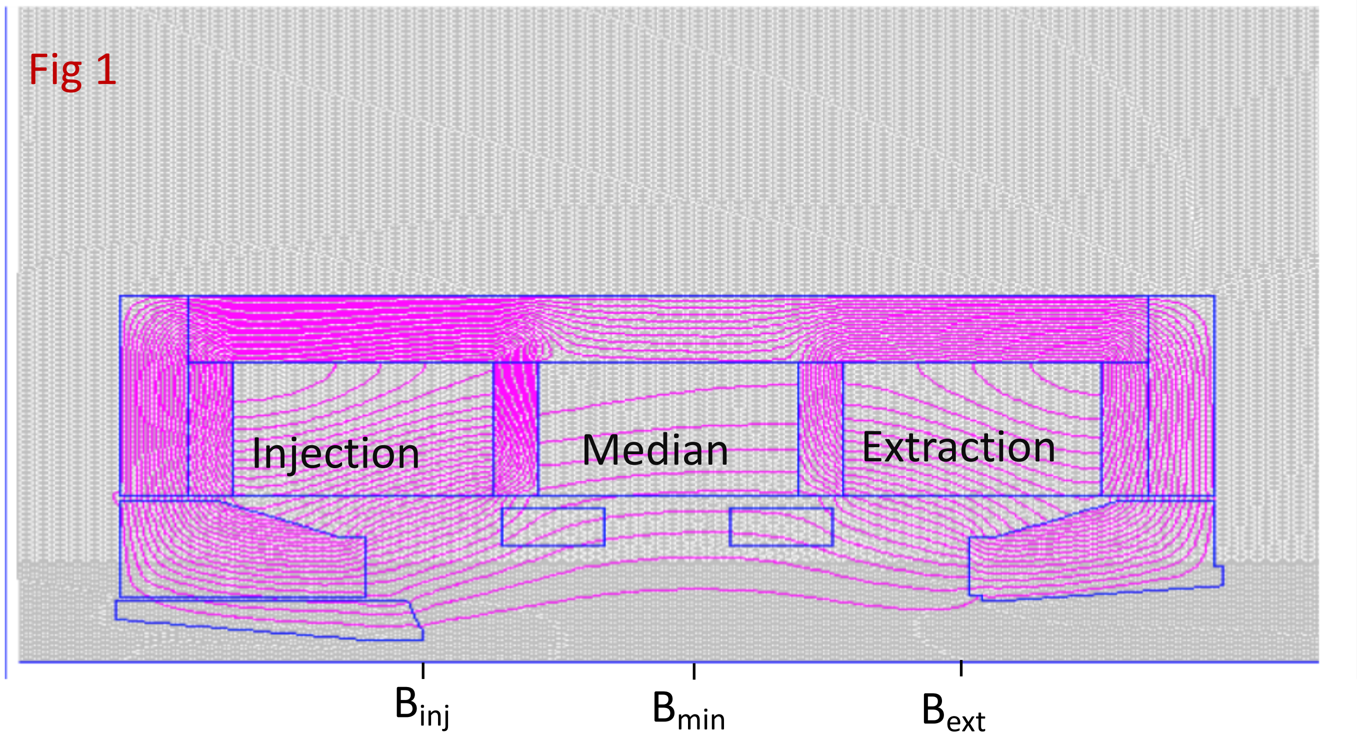
- ❑ Investigation of role of **magnetic field** configuration in the appearance of **instability.**
- ❑ Electron Cyclotron Resonance surface **geometry** plays a key role.
- ❑ An efficient computational tool must be developed to calculate the ECR surface geometry taking into consideration the **heating frequency, injection coil,median** and **extraction** coil current and **radial magnetic field** which can be extended to 5 parameters for some ion source like Phoenix Booster.
- ❑ To perform experiments to detect the instable regions and to **cross examine the ECR regions** corresponding to instable regions.

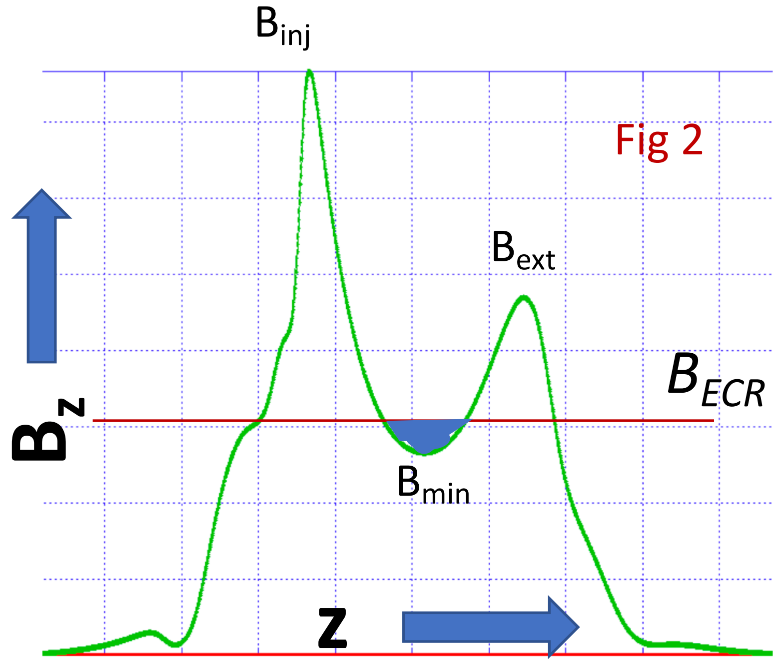


Magnetic field : Modelling Solenoid 1/2

- Consists of tunable solenoidal magnetic field and hexapolar field.
- Solenoidal magnetic field profile is obtained using finite element solver softwares like FEMM, POISSON, RADIA etc for a given set of : Injection median and extraction currents







Magnetic field : Modelling Solenoid 2/2

- The axial solenoidal magnetic field on axis (obtained from RADIA) is used to develop completely analytical field as a function of coil currents parameters
- A six degree polynomial fit on axial magnetic field is obtained

$$B_z(r=0,\theta=0,z) = A_0 + A_1 z + A_2 z^2 + A_3 z^3 + A_4 z^4 + A_5 z^5 + A_6 z^6$$

- The coefficients of the fit gives the B field in off axis locations.

$$B_r(r,z) = \frac{1}{2}A_1 r - A_2 r z - A_3\left(\frac{3}{2}rz^2 - \frac{3}{8}r^3\right) - A_4\left(2rz^3 - \frac{3}{2}r^3 z\right) - A_5\left(\frac{5}{2}rz^4 - \frac{15}{4}r^3z^2 + \frac{5}{16}r^5\right) - A_6\left(3rz^5 - \frac{15}{2}r^3z^3 + \frac{15}{8}r^5 z\right)$$

$$B_z(r,z) = A_0 + A_1 z + A_2\left(z^2 - \frac{1}{2}r^2\right) + A_3\left(z^3 - \frac{3}{2}r^2 z\right) + A_4\left(z^4 - 3r^2z^2 + \frac{3}{8}r^4\right) + A_5\left(z^5 - 5r^2z^3 + \frac{15}{8}r^4 z\right) + A_6\left(z^6 - \frac{15}{2}r^2z^4 + \frac{45}{8}r^4z^2 - \frac{5}{16}r^6\right)$$

[J Rodney et al].

- Fit-of-fit can be obtained by solving the equation

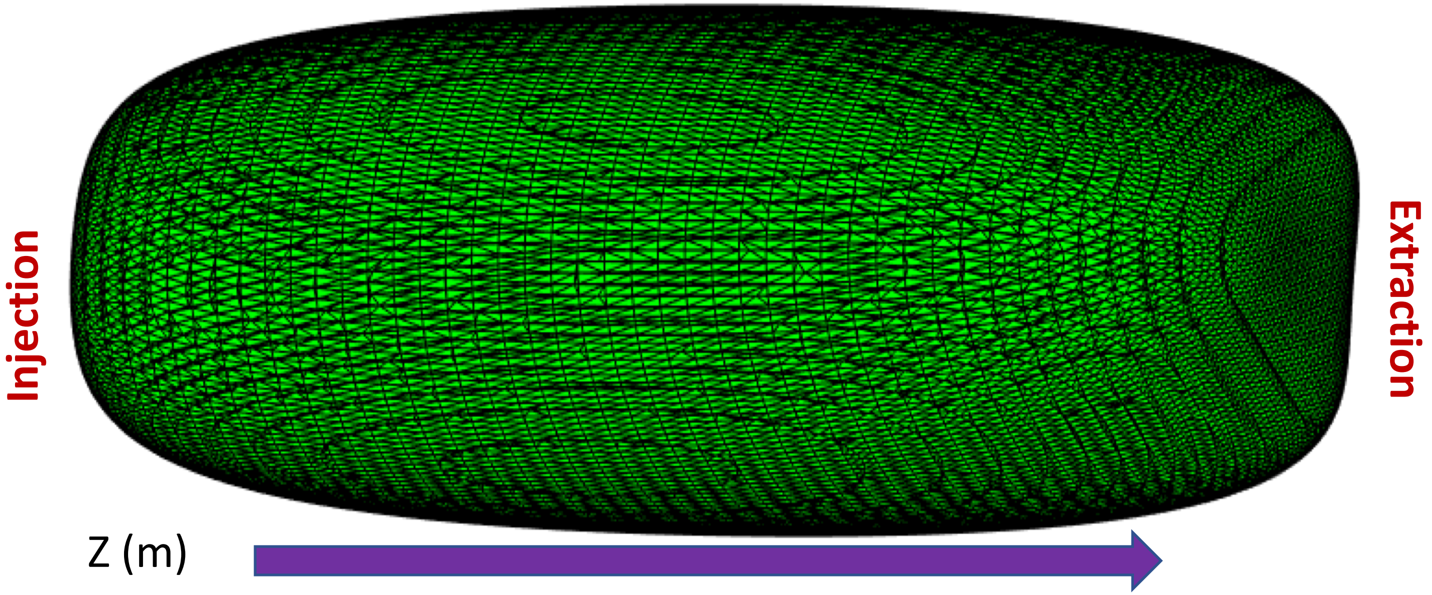
$$A_{0,1,2\ldots,7}(I_1,I_2,I_3) = \Sigma_{i=1,3}\Sigma_{j=1,3}\, a_{i,j}\, I_i^{(j-1)}$$

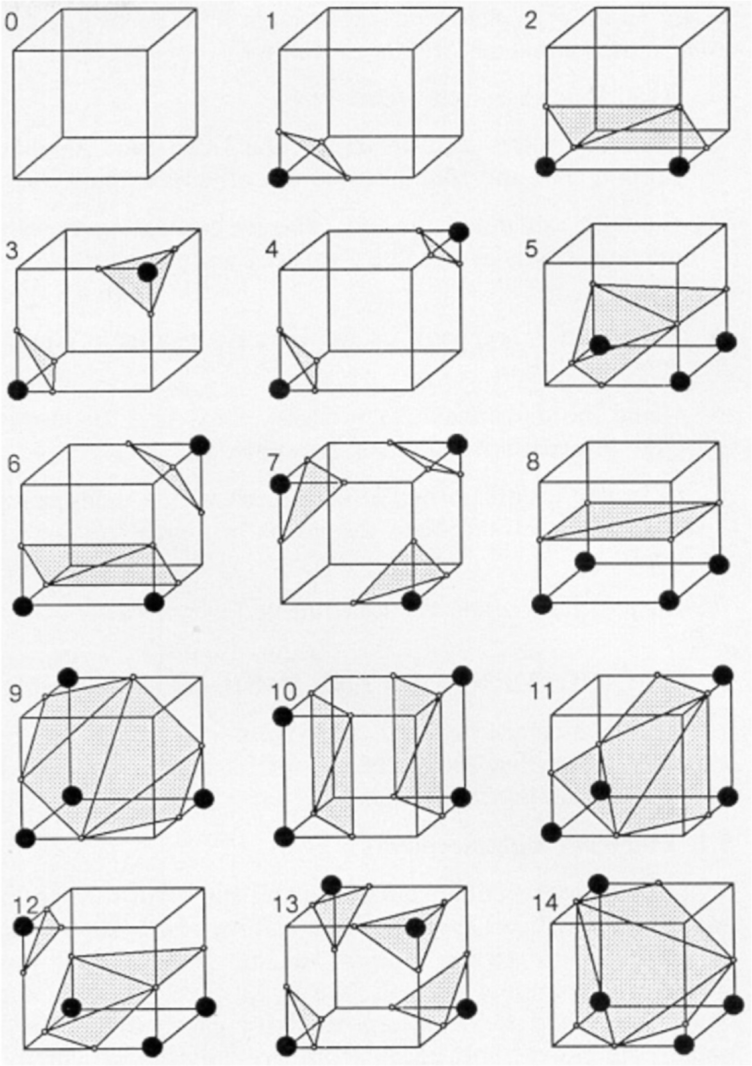
I_1=Injection current; I_2=Median current;
I_3 =Extraction Current

- ❑ **Now** **analytical solenoidal** **field is obtained and the hexapolar field can be calculated analytically since it is permanent magnet.**

ECR zone

- Based on total magnetic field data the closed resonance surface or the ECR zone can be built.
- 3D ECR **surface is constructed** using **Marching Cube algorithm** , popular algorithm for isosurface extraction.
- ECR surface is divided into triangles
- **The triangular mesh defines the ECR surface**



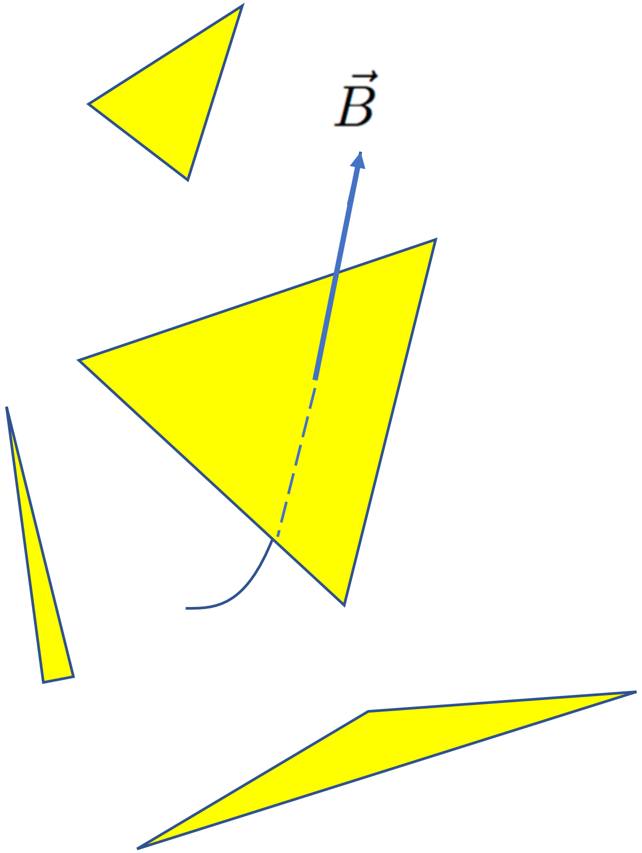


W.E Lorensen & H.E Cline, *Com graphics, 1987*

ECR zone: Magnetic field gradient

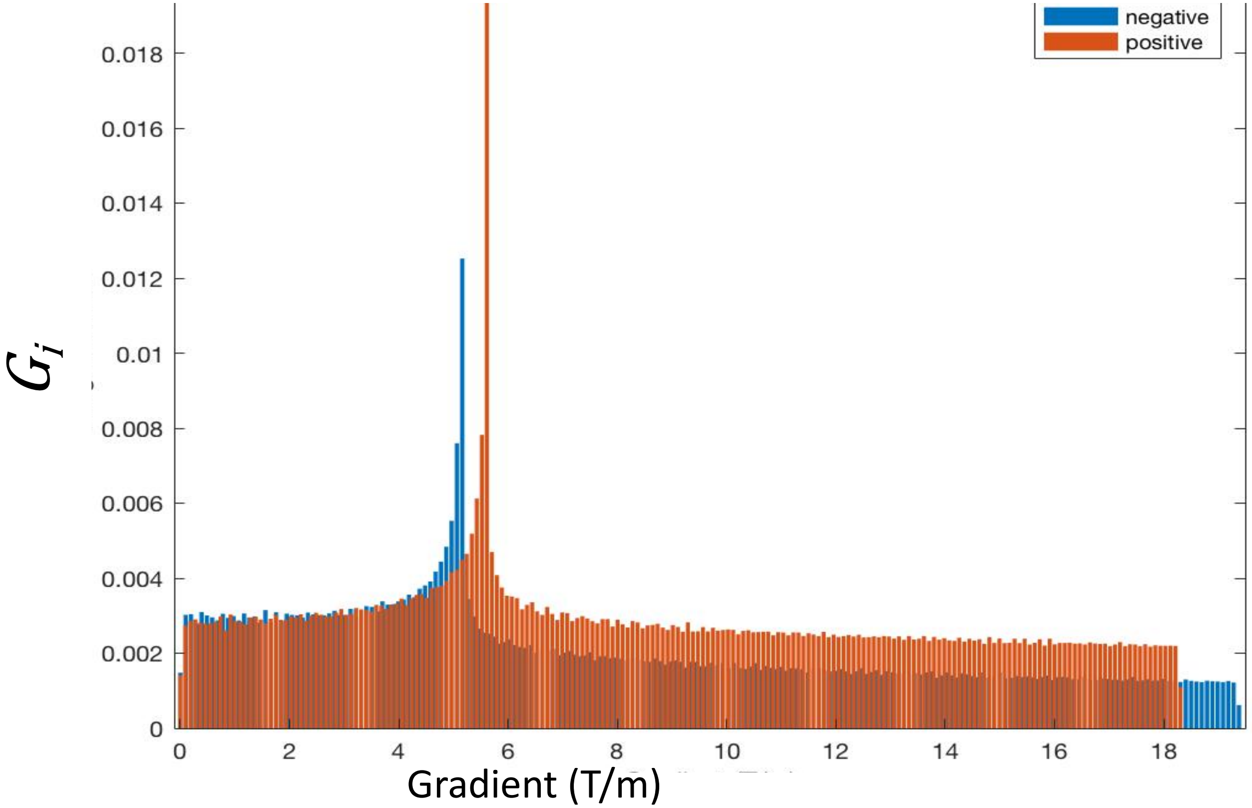
- The **gradient** of magnetic field line **along the direction of B field** through **centroid** of each and every triangle in the ECR zone is defined.

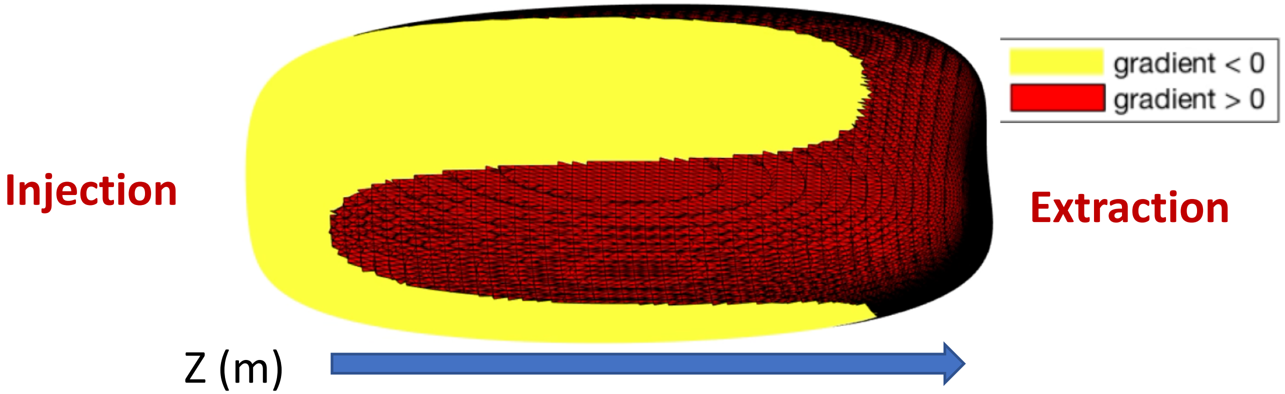
- Since the triangles have different size, a **proper weighting** must be given in order to obtain the gradient of entire ECR surface.

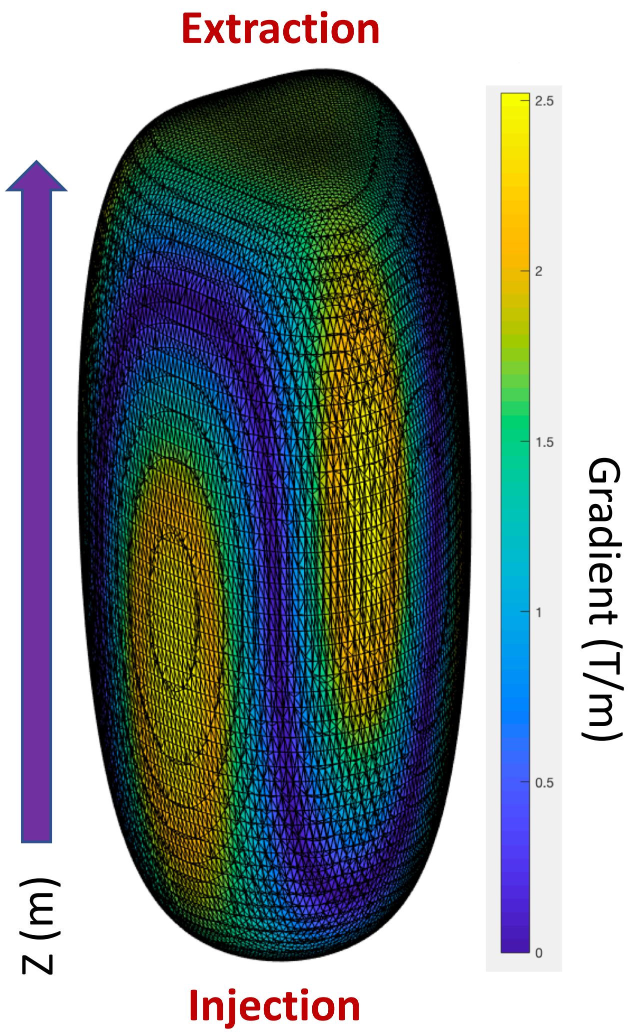


$$Weighted\ Gradient\ G_i = \frac{(Gradient\ at\ centroid\ \boldsymbol{i}) * Area\ of\ triangle\ \boldsymbol{i}}{Total\ Surface\ Area\ of\ ECR\ zone}$$

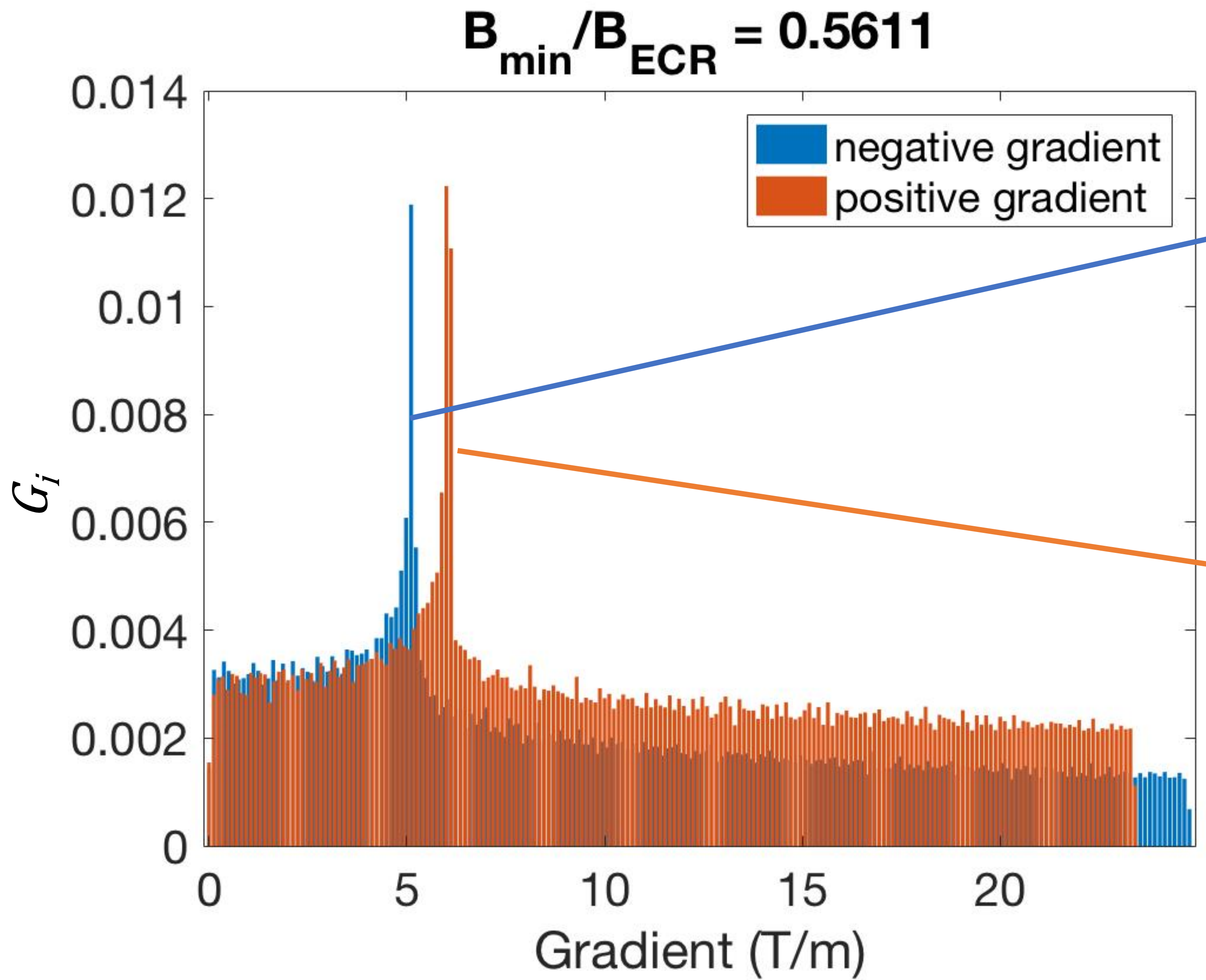
ECR Zone: Gradient distribution histogram

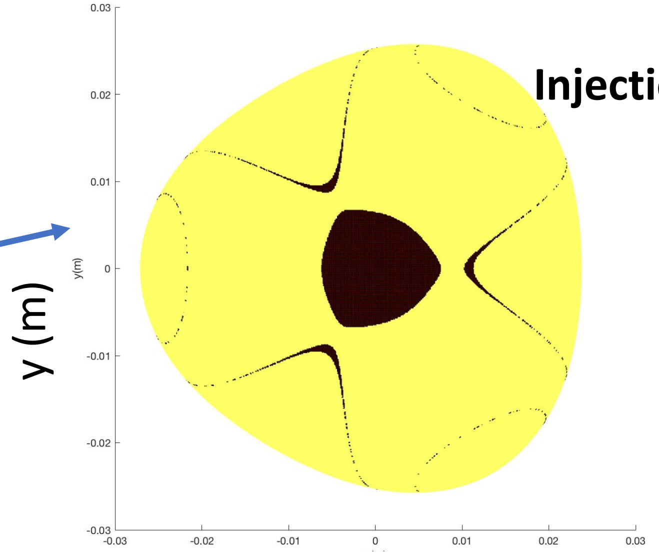


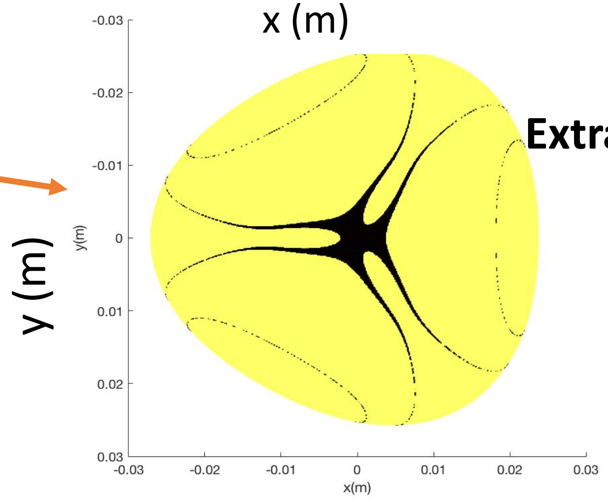




ECR Zone: Histogram peaks location

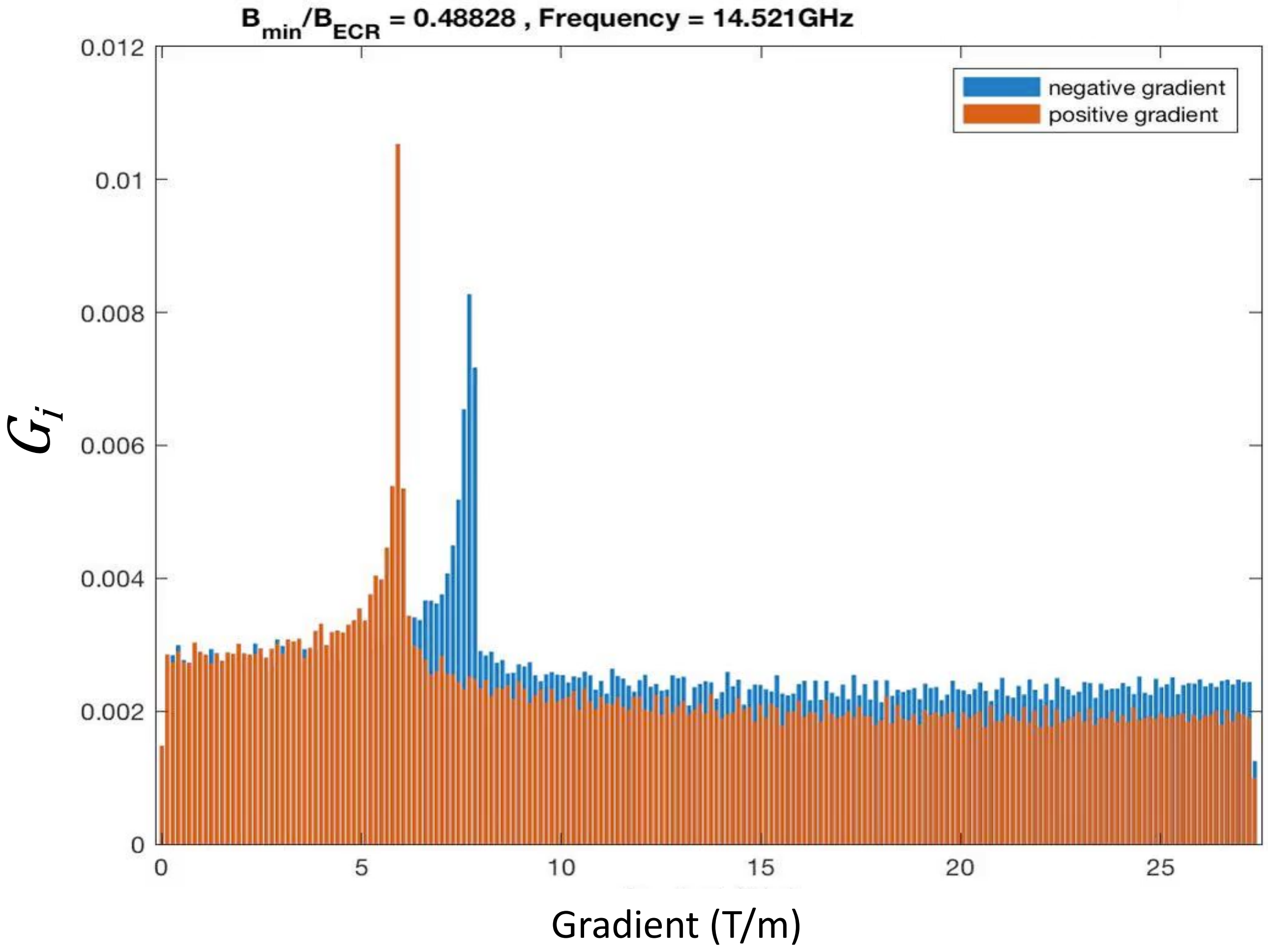






ECR zone: Evolution of histogram with B_{min} / B_{ECR}

- **It has been observed that the gradient peaks interchange as the ratio B_{min} /B_{ECR} increases.**



Experiment

- Experiments were performed in PHOENIX charge breeder and 14 GHz ECR-2 source at JYFL, Finland.
- Primary objective

1. To find the variation of **instability threshold** with magnetic field.
2. To study the effect of heating frequency on instability threshold.

- Detection of instability

1. **Faraday cup** for detection of extracted beam current
2. **Scintillator and Photo multiplier** tube for x-ray detection (fig 1).
3. **Microwave detector** diode for microwave detection (fig 2)

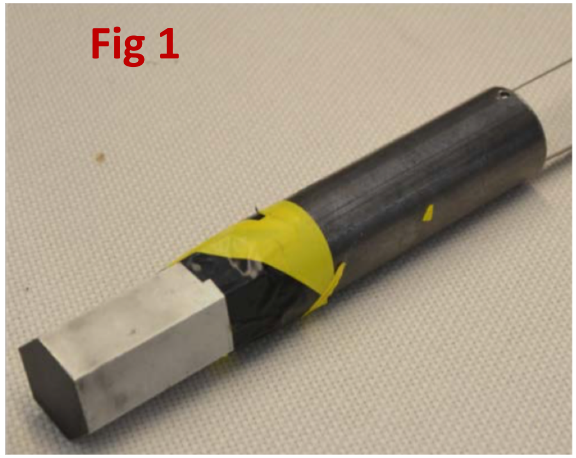


Fig 1

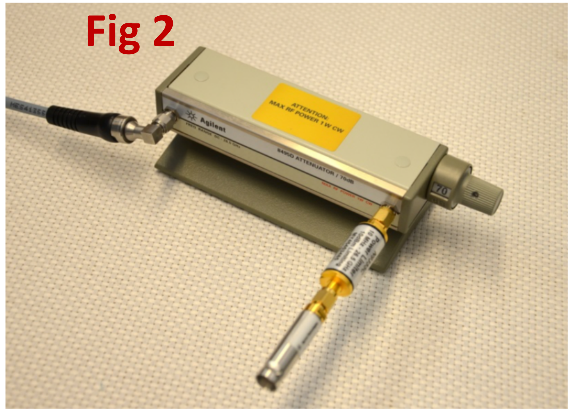
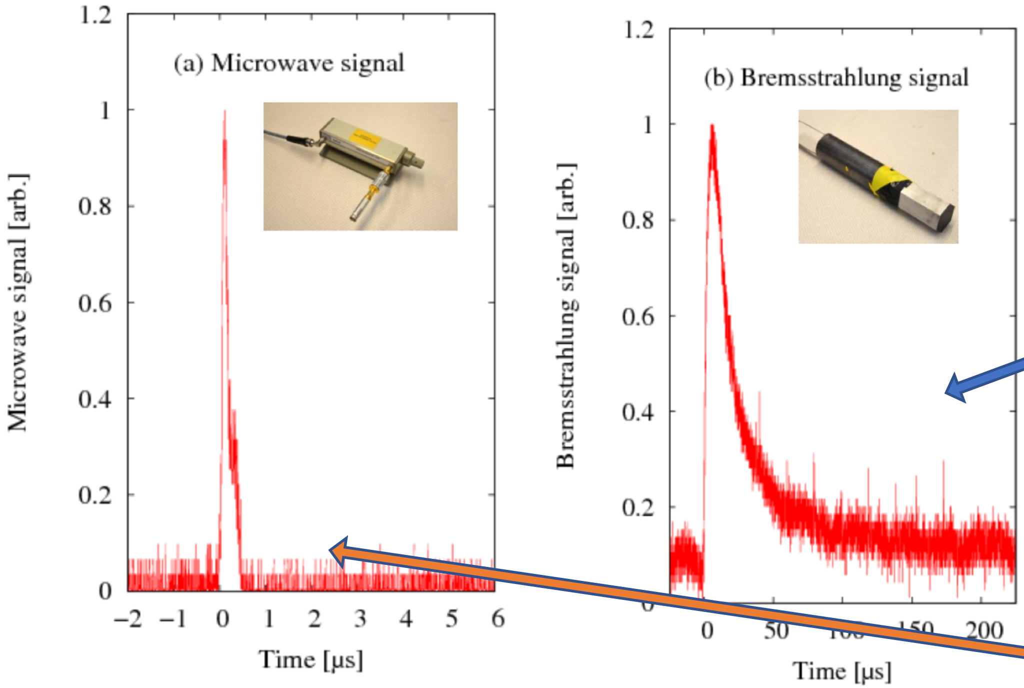
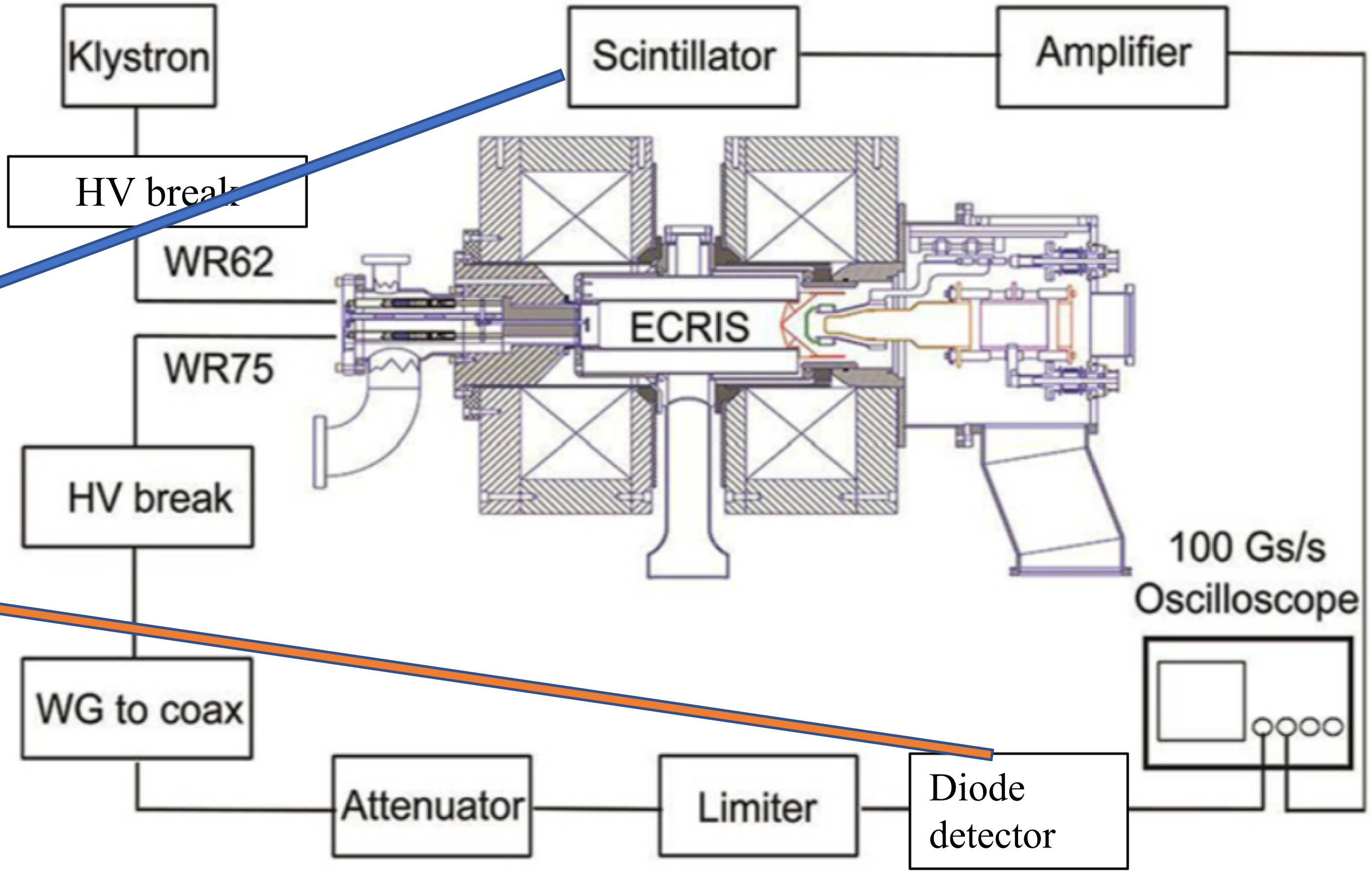


Fig 2

Experiment: Setup





The same set of experiments were repeated :

- For PHOENIX charge breeder
- With different **heating frequencies**

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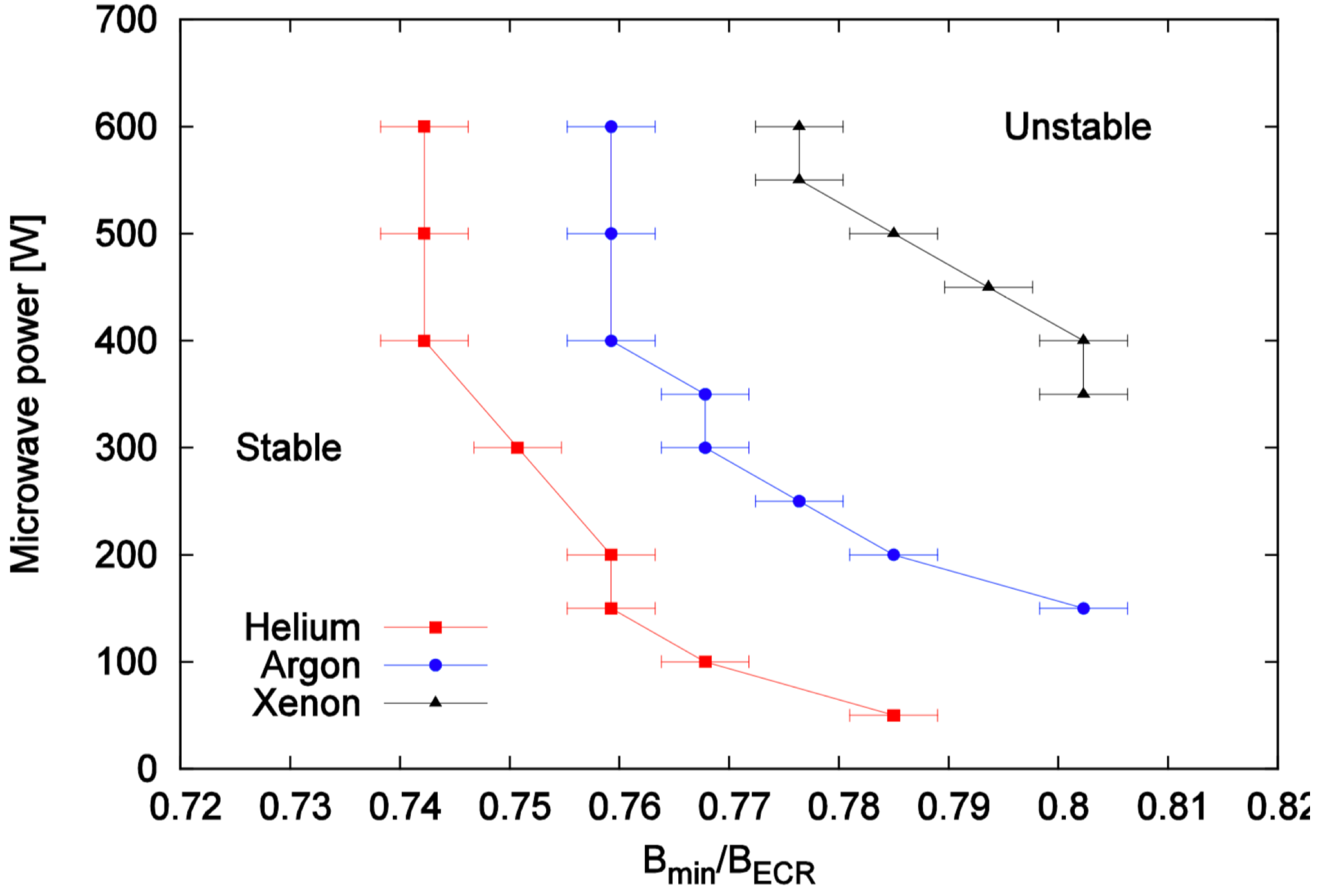
Experiment: Observations 1

- Instability threshold depends on **B_{min} / B_{ECR}** as shown in graph.
- It was also observed that instability threshold also depends on **peak merging** of gradient histogram.



Olli et.al Rev. Sci .Inst (2016)

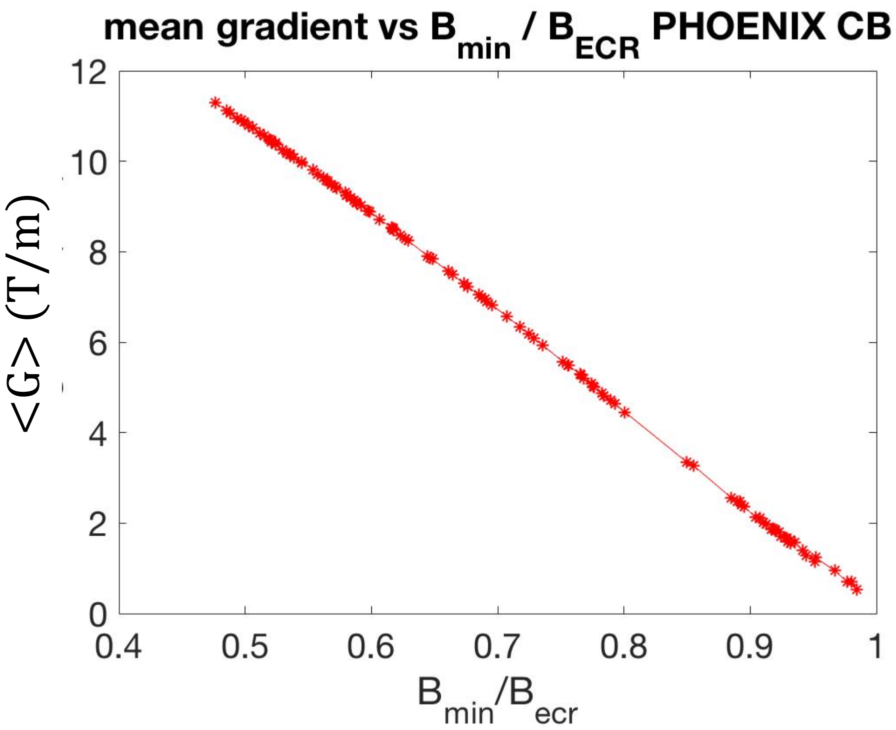
Results: 1

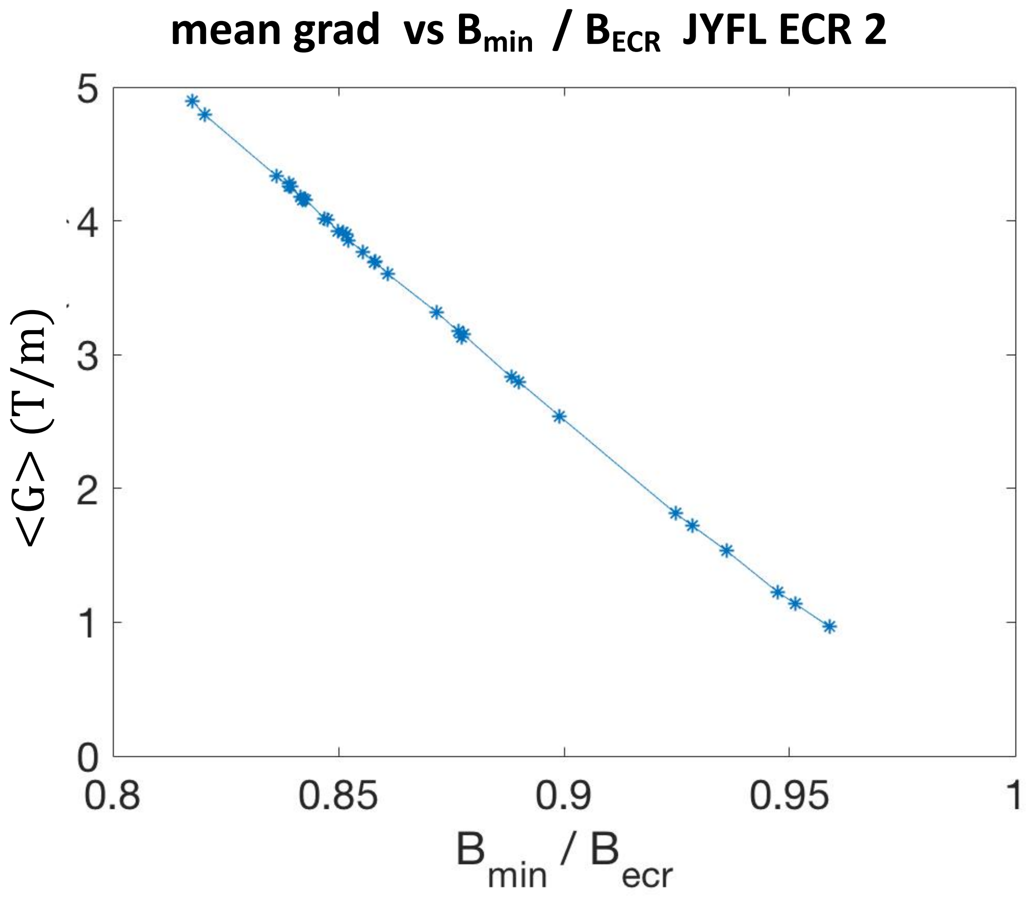
- Obtained a generalized relation between **Mean Gradient** of ECR surface and $\mathbf{B_{min} / B_{ECR}}$

- A **linear relation** is obtained and it is found that

$$B_{min}/B_{\mathrm{ECR}} \propto (1/\langle G \rangle)$$

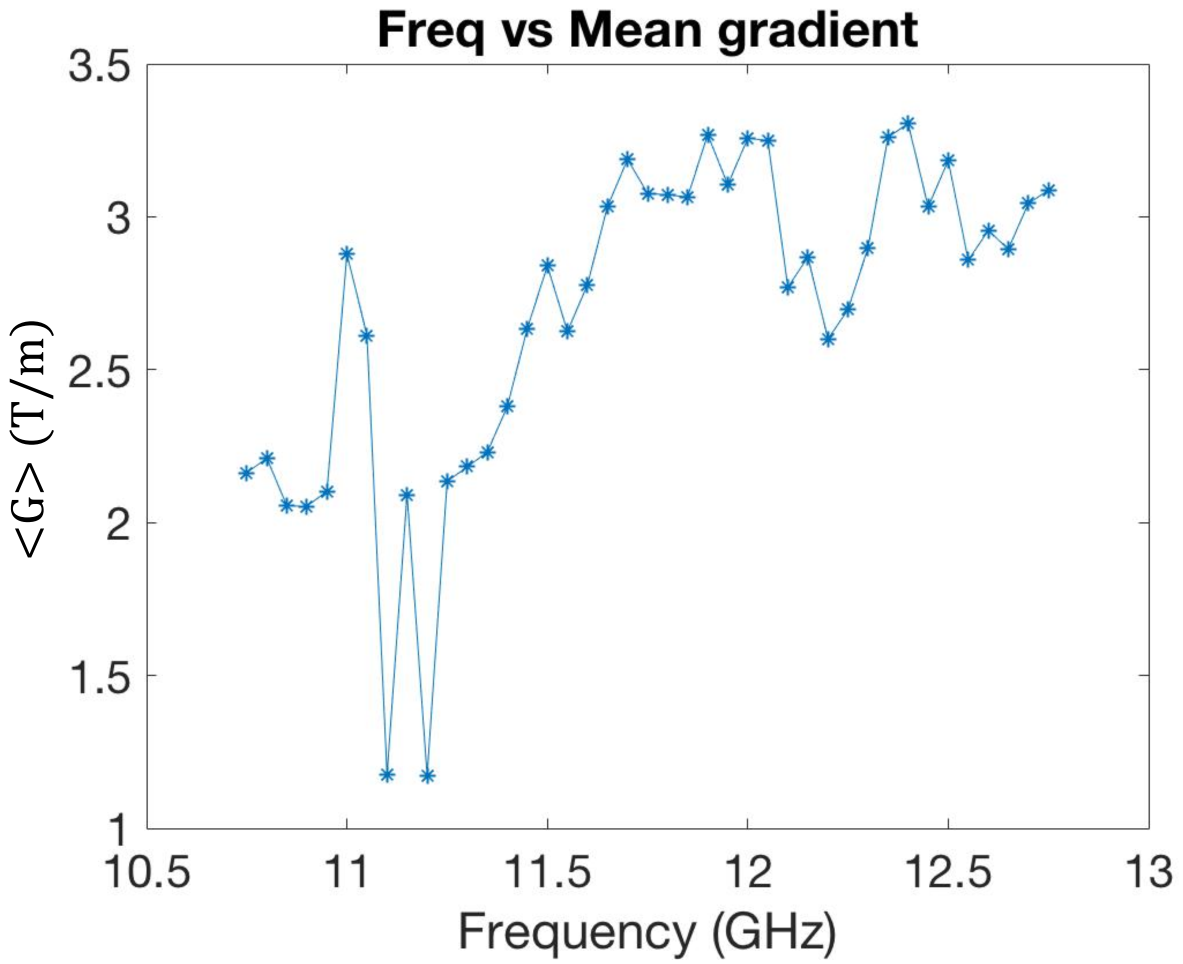
- This result gives more physical significance to B_{min} / B_{ECR}





Investigation of heating frequency on instability

- Effect of **heating frequency on instability threshold** is studied.
- TWTA (traveling-wave tube amplifier) was used as an RF generator with frequency ranging from 10.7 to 12.5 GHz in JYFL- ECR 2



Conclusion

- Fast computational tool for obtaining 3D ECR zone and its magnetic field parameters has been obtained

- A relation connecting B_{min} /B_{ECR} and average ECR gradient <G> is obtained.

- Instability threshold can be affected by lot of parameters like **pressure**, **microwave power**, **type of gas** etc however it is also observed that **gradient distribution histogram** plays a crucial role in instability threshold.

- The relation connecting heating frequency with instability threshold should be studied further.

Future Prospects

- Instability threshold experiments to be done in PHOENIX V3 (at LPSC) as well as also with PHOENIX charge breeder with extra iron rings (5 parameters for the axial magnetic field fit).
- To study the Electron Energy Distribution Function (EEDF) of escaping electrons from magnetic at instability threshold.
- Study the relation connecting EEDF and Bremsstrahlung radiation emitted at instability threshold.

Thank you