Frequency tuning effect on the bremsstrahlung spectra, beam intensity and shape in a 10 GHz, permanent magnet ECR ion source

G.Rodrigues[1],Narender Kumar[1],Kedar Mal[1], Y.Mathur[1], D.Kanjilal[1] and A.Roy[2]

[1]Inter University Accelerator Centre,New Delhi,India

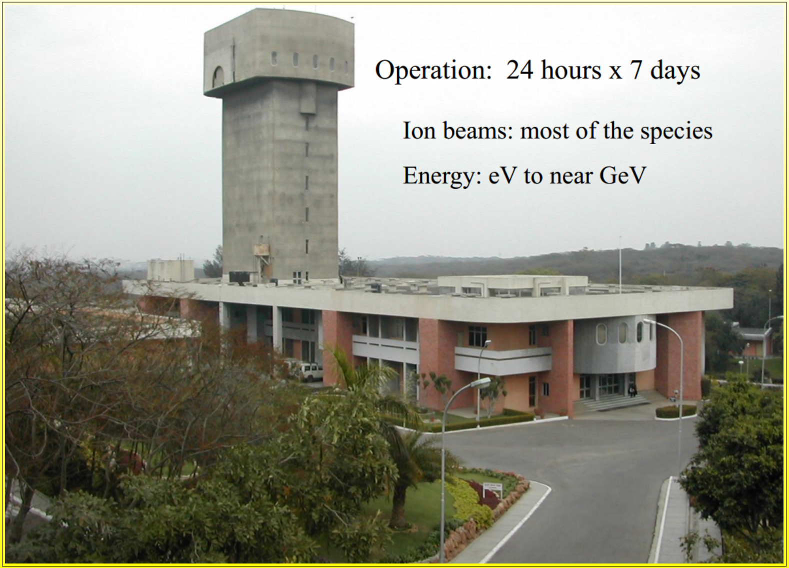
[2]Variable Energy Cyclotron Centre,Kolkota,India

21^{st} **International Workshop on ECR Ion Sources, 2014**

Outline

1. Introduction
   - Overview of Accelerator and Ion Sources
   - Frequency tuning technique
   - Advantages of the frequency tuning technique
   - Observations in various ECR ion sources
2. Experimental details
   - Ion source and beamline
   - Details of the ECR cavity
   - X-ray measurement set-up
   - Measurements of x-rays and beam intensities
   - Beam shape measurements
3. 3D simulations using CST Microwave Studio
   - Description of CST Particle Studio
   - CST model of the 10 GHz NANOGAN ECR Source
   - Particle tracking for TE_{117} mode
   - Particle tracking at 10.46 GHz
4. Conclusions

View of the Inter University Accelerator Centre



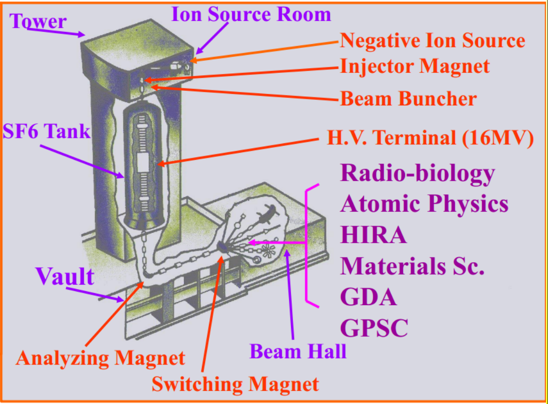
15 UD Pelletron at IUAC, New Delhi

15UD Pelletron Accelerator at IUAC

Tank height: 26.5 m
Diameter: 5.5 m
Pressure: 86 PSI
SF_6 gas

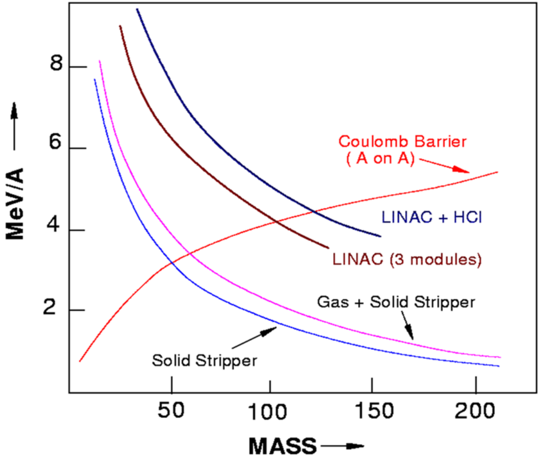
Ions accelerated:
H to Au beams

Currents: ~ 1 -50 pnA
Energy : 30 – 270 MeV

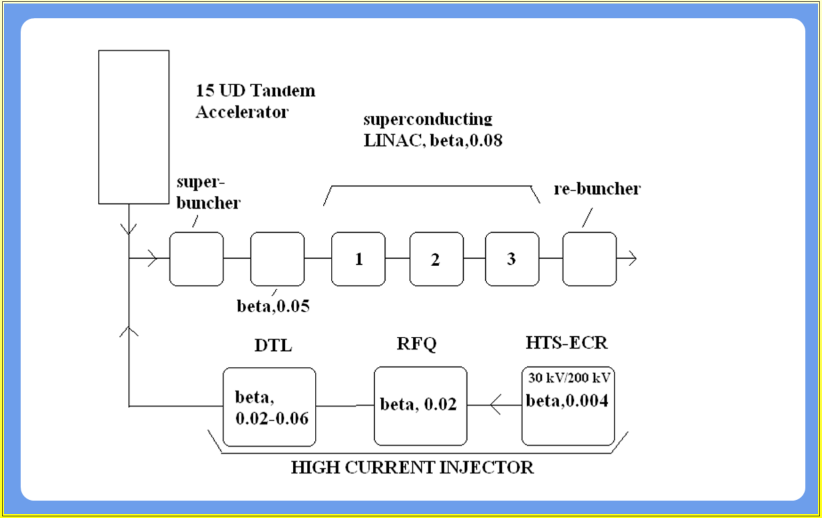


Special Features:
1. Off-set QP in Terminal
2. Earthquake Protection
3. Compressed Geometry Tubes

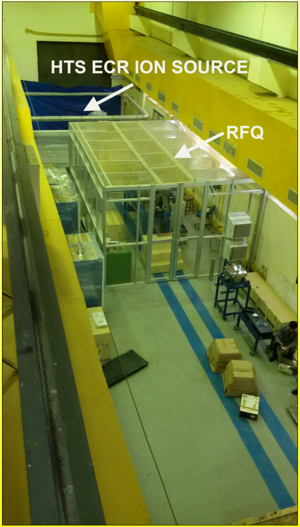
Development of a High Current Injector



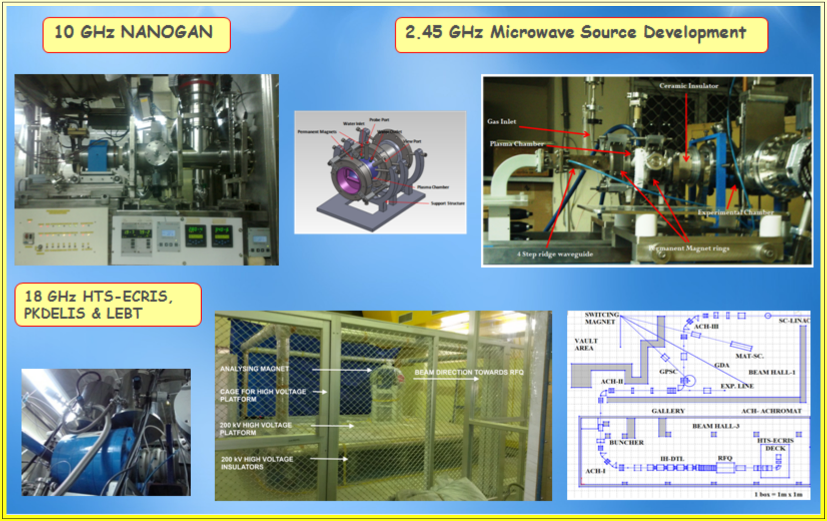
Schematic of High Current Injector



Status of Beam Hall III



Status of ECR/Microwave Sources



Why study the frequency tuning effect?

Why study the frequency tuning effect?

L.Celona et al., Rev. Sci. Instrum. 79(2),023305 (2008)

Why study the frequency tuning effect?

- The performance of an ECRIS is critically dependant on the resonant absorption of microwave power.

L.Celona et al., Rev. Sci. Instrum. 79(2),023305 (2008)

Why study the frequency tuning effect?

- The performance of an ECRIS is critically dependant on the resonant absorption of microwave power.
- Experiments show that even slight changes in the frequency ~MHz strongly influences the beam intensities, shape, emittance, brightness and stability

L.Celona et al., Rev. Sci. Instrum. 79(2),023305 (2008)

Why study the frequency tuning effect?

- The performance of an ECRIS is critically dependant on the resonant absorption of microwave power.
- Experiments show that even slight changes in the frequency ~MHz strongly influences the beam intensities, shape, emittance, brightness and stability
- Extracted currents are sensitive to small changes in the rf frequency ($< 1\ \%$)

L.Celona et al., Rev. Sci. Instrum. 79(2),023305 (2008)

Why study the frequency tuning effect?

- The performance of an ECRIS is critically dependant on the resonant absorption of microwave power.
- Experiments show that even slight changes in the frequency ˜MHz strongly influences the beam intensities, shape, emittance, brightness and stability
- Extracted currents are sensitive to small changes in the rf frequency (< 1 %)
- Constant endeavour to improve the beam quality, intensity and stability

L.Celona et al., Rev. Sci. Instrum. 79(2),023305 (2008)

Advantages of the frequency tuning technique

Advantages of the frequency tuning technique

- No modifications required in the hardware of the ion source

Advantages of the frequency tuning technique

- No modifications required in the hardware of the ion source
- Permits to overcome the limitations of frequency scaling law and magnetic field

Advantages of the frequency tuning technique

- No modifications required in the hardware of the ion source
- Permits to overcome the limitations of frequency scaling law and magnetic field
- Therefore, the potential of existing devices can be exploited.

Advantages of the frequency tuning technique

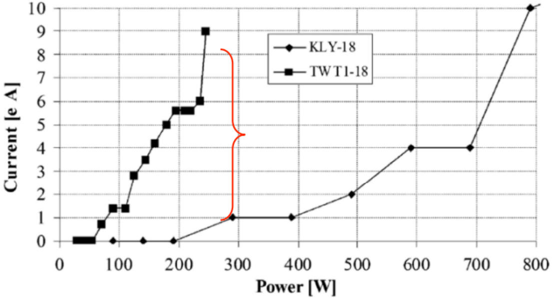
- No modifications required in the hardware of the ion source
- Permits to overcome the limitations of frequency scaling law and magnetic field
- Therefore, the potential of existing devices can be exploited.
- Variable frequency microwave generators can be used

Advantages of the frequency tuning technique

- No modifications required in the hardware of the ion source
- Permits to overcome the limitations of frequency scaling law and magnetic field
- Therefore, the potential of existing devices can be exploited.
- Variable frequency microwave generators can be used
- Efficiency of beam extraction is enhanced

First indications of Frequency Tuning Effect

Signs about the importance of the frequency tuning effect came already in 2004 from an experiment carried out on SERSE [A. Galatà, Tesi di Laurea]



Comparison between trends of O^{8+} at 18 *GHz* for klystron (up to 800 W) and TWT1 operating in the same range of frequency.

TWT → BROADBAND GENERATOR?

Courtesy: S.Gammino

Frequency tuning effect in various ECR ion sources

V. Toivanen et al., Rev. Sci. Instrum.81, 02A319 (2010)

Frequency tuning effect in various ECR ion sources

- In few of the experiments performed, the formation of hollow beams was observed just after source extraction before the solenoid focusing element

V. Toivanen et al., Rev. Sci. Instrum.81, 02A319 (2010)

Frequency tuning effect in various ECR ion sources

- In few of the experiments performed, the formation of hollow beams was observed just after source extraction before the solenoid focusing element
- Reason: space charge effects or/and due to mode parameters $TE_{n,l,m}$ where n,l > 1
- Understanding bremsstrahlung spectrum of cold, warm, and hot electrons, and the electron distribution function is necessary to study how characteristics of the beam are influenced by the frequency tuning.

V. Toivanen et al., Rev. Sci. Instrum.81, 02A319 (2010)

Frequency tuning effect in various ECR ion sources

S. Gammino et al., Proceedings of CYCLOTRONS, Lanzhou, China, 2010

S. Gammino et al., Proceedings of Linear Accelerator Conference, LINAC, Japan, 2010

Frequency tuning effect in various ECR ion sources

- S. Gammino et al.,have shown that the number of energetic electrons which are populating the spectrum tail slightly changes when passing from one frequency to the other mostly because of variations in the warm population density but the slope of the bremsstrahlung spectra was observed to remain unchanged

S. Gammino et al., Proceedings of CYCLOTRONS, Lanzhou, China, 2010
S. Gammino et al., Proceedings of Linear Accelerator Conference, LINAC, Japan, 2010

Frequency tuning effect in various ECR ion sources

- S. Gammino et al.,have shown that the number of energetic electrons which are populating the spectrum tail slightly changes when passing from one frequency to the other mostly because of variations in the warm population density but the slope of the bremsstrahlung spectra was observed to remain unchanged
- Experimental results did not show the trend where-in a large number of x-rays seemed to correspond to higher $< q >$ and more intense beam current

S. Gammino et al., Proceedings of CYCLOTRONS, Lanzhou, China, 2010
S. Gammino et al., Proceedings of Linear Accelerator Conference, LINAC, Japan, 2010

Frequency tuning effect in various ECR ion sources

- S. Gammino et al.,have shown that the number of energetic electrons which are populating the spectrum tail slightly changes when passing from one frequency to the other mostly because of variations in the warm population density but the slope of the bremsstrahlung spectra was observed to remain unchanged
- Experimental results did not show the trend where-in a large number of x-rays seemed to correspond to higher $< q >$ and more intense beam current
- Distinguish between microwave generator to plasma chamber coupling and excited mode to plasma coupling

S. Gammino et al., Proceedings of CYCLOTRONS, Lanzhou, China, 2010
S. Gammino et al., Proceedings of Linear Accelerator Conference, LINAC, Japan, 2010

Frequency tuning effect in various ECR ion sources

- S. Gammino et al.,have shown that the number of energetic electrons which are populating the spectrum tail slightly changes when passing from one frequency to the other mostly because of variations in the warm population density but the slope of the bremsstrahlung spectra was observed to remain unchanged
- Experimental results did not show the trend where-in a large number of x-rays seemed to correspond to higher $< q >$ and more intense beam current
- Distinguish between microwave generator to plasma chamber coupling and excited mode to plasma coupling
- Mode spatial structure plays the main role in ECRIS

S. Gammino et al., Proceedings of CYCLOTRONS, Lanzhou, China, 2010
S. Gammino et al., Proceedings of Linear Accelerator Conference, LINAC, Japan, 2010

Frequency tuning effect in various ECR ion sources

G.Rodrigues et al., Rev. Sci. Instrum.85, 02A944 (2014)

Frequency tuning effect in various ECR ion sources

- Using a lower frequency type of ECR source would help have a better separation between various modes

G.Rodrigues et al., Rev. Sci. Instrum.85, 02A944 (2014)

Frequency tuning effect in various ECR ion sources

- Using a lower frequency type of ECR source would help have a better separation between various modes
- Measurement of bremsstrahlung spectra may give further information on the distribution of cold and warm electrons which can explain the probable ionization processes

G.Rodrigues et al., Rev. Sci. Instrum.85, 02A944 (2014)

Frequency tuning effect in various ECR ion sources

- Using a lower frequency type of ECR source would help have a better separation between various modes
- Measurement of bremsstrahlung spectra may give further information on the distribution of cold and warm electrons which can explain the probable ionization processes
- At IUAC, New Delhi, a compact 10 GHz NANOGAN ECR ion source was used

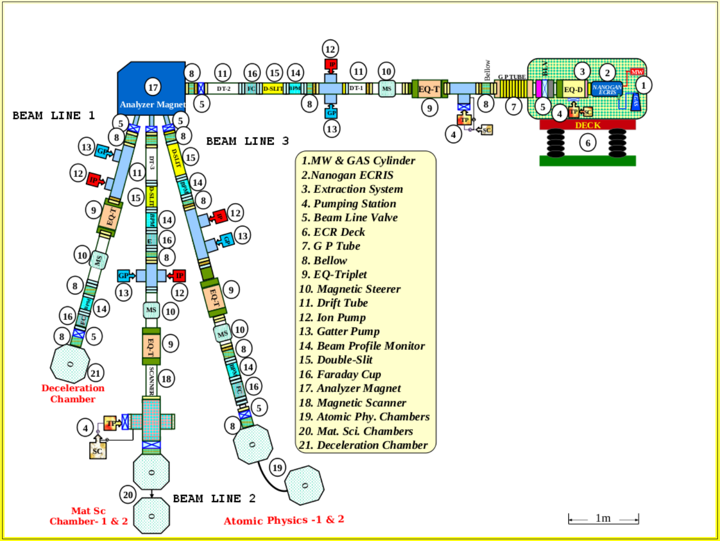
G.Rodrigues et al., Rev. Sci. Instrum.85, 02A944 (2014)

Frequency tuning effect in various ECR ion sources

- Using a lower frequency type of ECR source would help have a better separation between various modes
- Measurement of bremsstrahlung spectra may give further information on the distribution of cold and warm electrons which can explain the probable ionization processes
- At IUAC, New Delhi, a compact 10 GHz NANOGAN ECR ion source was used
- The frequency tuning effect on the beam intensity, shape and bremsstrahlung spectra were studied

G.Rodrigues et al., Rev. Sci. Instrum.85, 02A944 (2014)

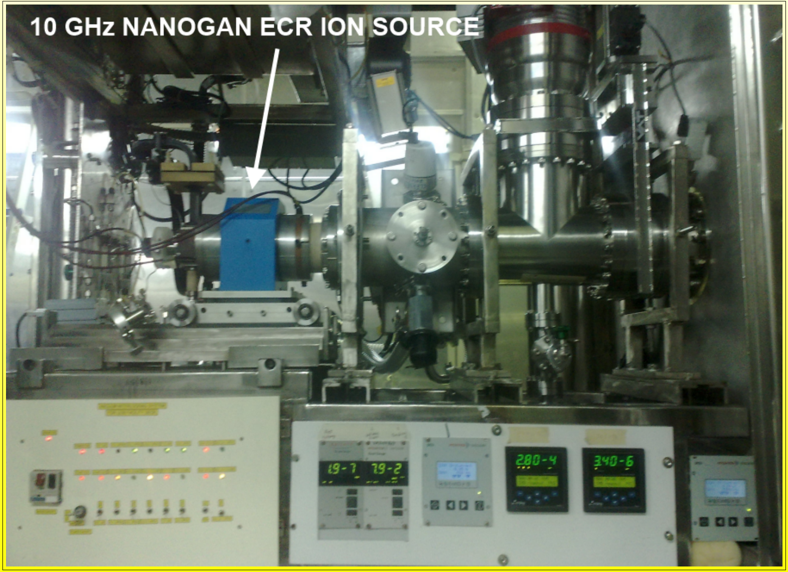
Low Energy Ion Beam Facility



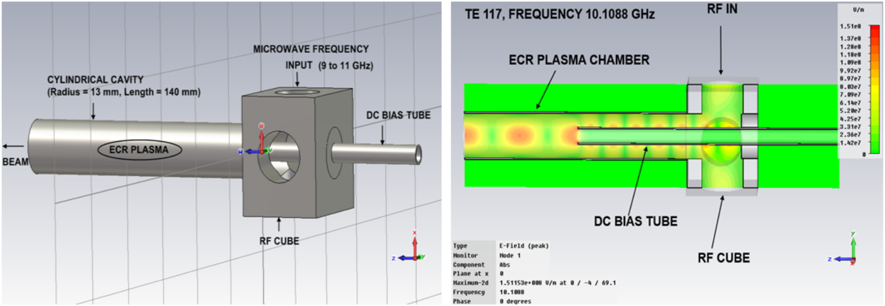
View of the 400 kV platform

View of the experimental beamlines

10 GHz NANOGAN ECR source on 400 kV platform



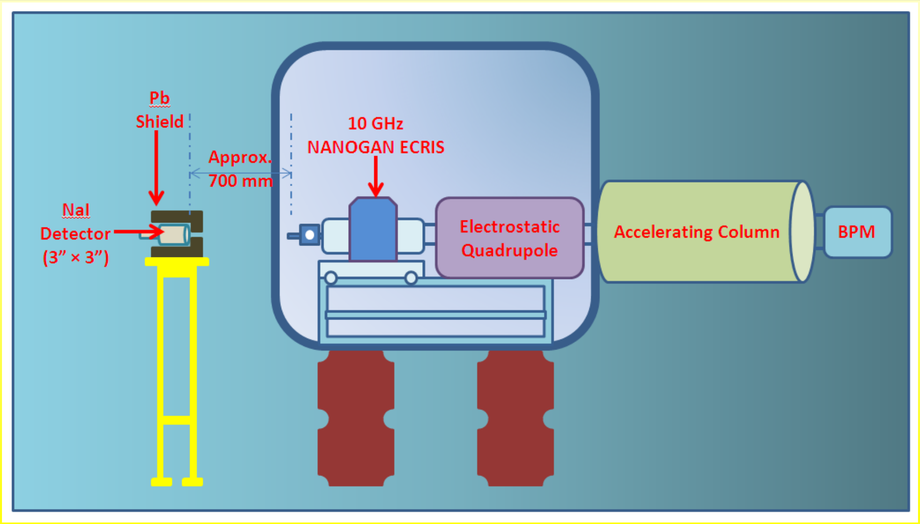
Model of the ECR cavity, calculation of dominant mode



Vacuum modes of the cavity

Mode type	Calculated frequency (GHz)
TM_{012}	9.0823955987
TE_{116}	9.3238928884
TM_{013}	9.3926442931
TM_{014}	9.8105232596
TE_{117}	10.0914719844
TM_{015}	10.3229699816
TE_{118}	10.9102418779
TM_{016}	10.9166750733

X-ray measurement set-up



Details of experiment

Details of experiment

- Experiments were performed for two beams, ^{16}O and ^{40}Ar

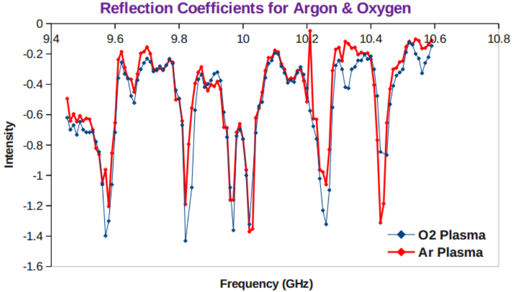
Details of experiment

- Experiments were performed for two beams, ^{16}O and ^{40}Ar
- Frequency was varied from ˜9.5 to 10.5 GHz

Details of experiment

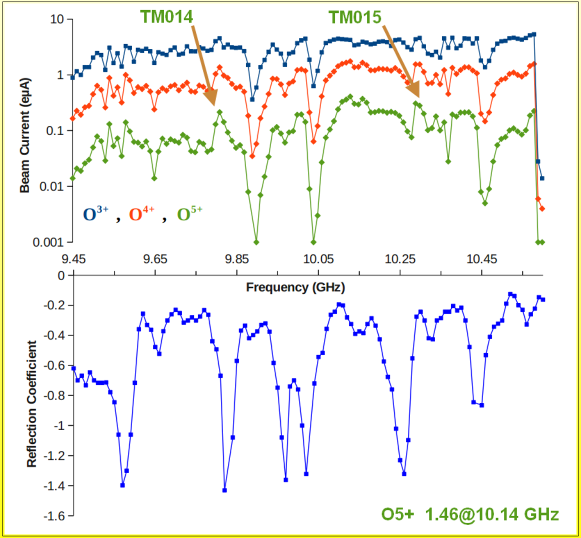
- Experiments were performed for two beams, ^{16}O and ^{40}Ar
- Frequency was varied from ~9.5 to 10.5 GHz
- Beam currents, x-ray and beam shapes were measured

Reflection co-efficient for two plasmas

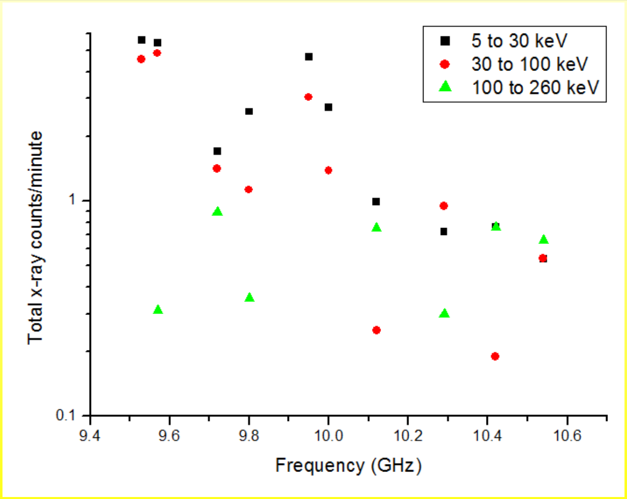


Parameters @ 10 GHz	Argon	Oxygen
RF Power	53 W, 8 W	27 W, 5 W
Ext Voltage	12 kV	12 kV
DC bias voltage	-118 V	-88 V
Deck Voltage	88 kV	88 kV
Injection Pressure	5.6 E-6 torr	8.4 E-6 torr
Optimized for	Ar^{9+}	O^{5+}

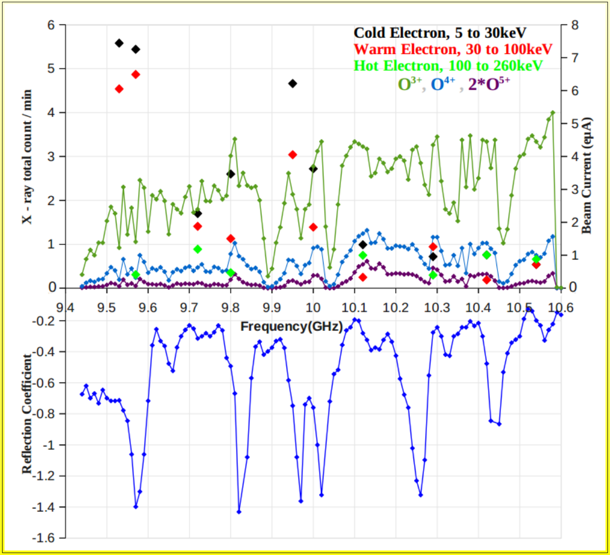
Measurements with oxygen plasma



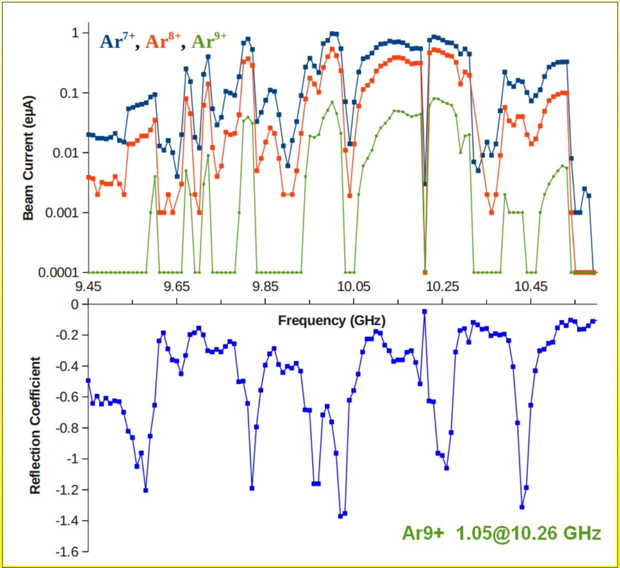
Measurements with oxygen plasma



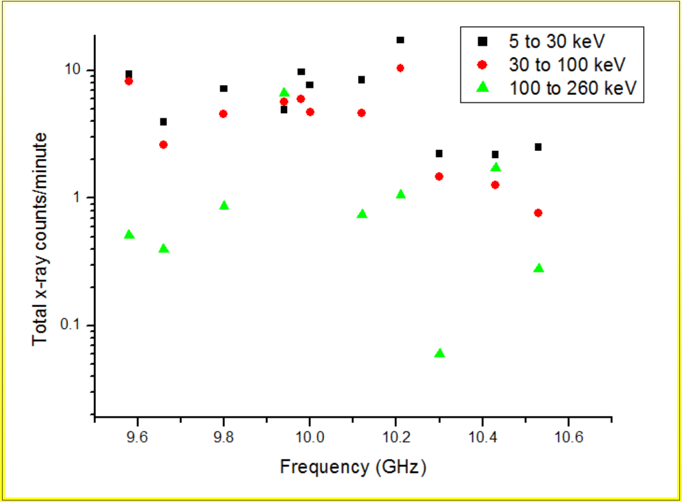
Measurements with oxygen plasma



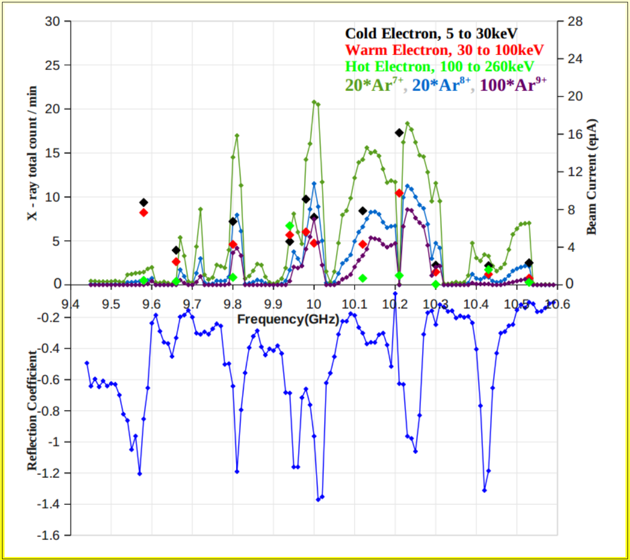
Measurements with argon plasma



Measurements with argon plasma



Measurements with argon plasma

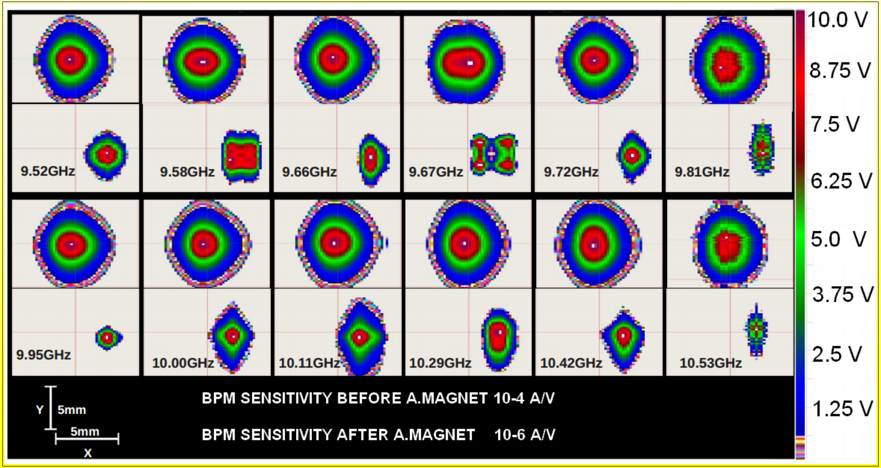


Calculated and observed frequencies

From 9 to 11 GHz	
Mode Type	**Calculated Mode (GHz)**
TM 012	9.0823955987
TE 116	9.3238928884
TM 013	9.3926442931
TM 014	**9.8105232596**
TE 117	**10.0914719844**
TM 015	**10.3229699816**
TE 118	10.9102418779
TM 016	10.9166750733

Observed Resonance frequencies(GHz)	
Argon Plasma	**Oxygen Plasma**
9.60	9.58
9.67	9.66
9.72	9.73
9.81	**9.81**
9.95	9.94
10.00	10.02
10.13	**10.10**
10.23	10.21
10.30	**10.30**
10.39	10.38
10.42	10.41
10.53	10.58

Digitised beam shapes at various frequencies for O^{5+}



CST Particle Studio

CST Particle Studio

- It is a specialist tool for designing and analysing the electromagnetic components for accelerating and guiding charged particle beams

CST Particle Studio

- It is a specialist tool for designing and analysing the electromagnetic components for accelerating and guiding charged particle beams
- Incorporates powerful electromagnetic field solvers for calculating the external fields, an efficient particle tracking algorithm and sophisticated emission models

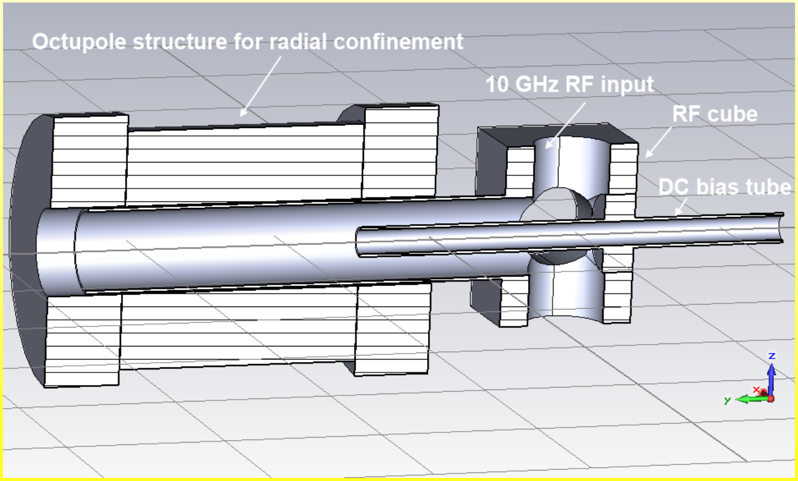
CST Particle Studio

- It is a specialist tool for designing and analysing the electromagnetic components for accelerating and guiding charged particle beams
- Incorporates powerful electromagnetic field solvers for calculating the external fields, an efficient particle tracking algorithm and sophisticated emission models
- The magnetic fields are imported from the magneto-static solver to solve the motion of the electrons at specific calculated modes of the cavity.

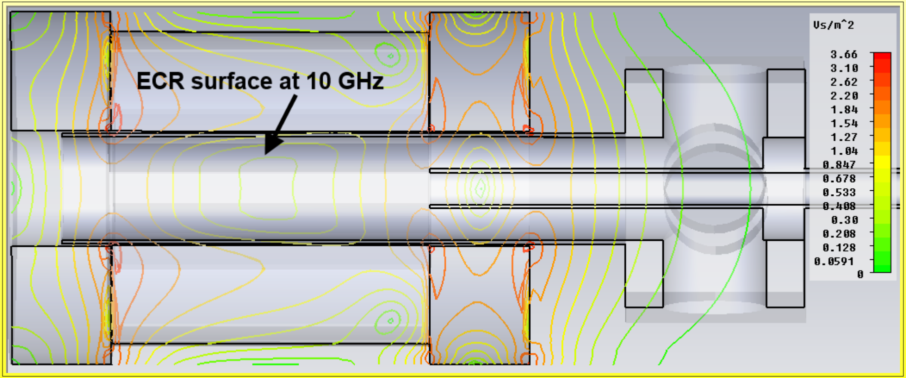
CST Particle Studio

- It is a specialist tool for designing and analysing the electromagnetic components for accelerating and guiding charged particle beams
- Incorporates powerful electromagnetic field solvers for calculating the external fields, an efficient particle tracking algorithm and sophisticated emission models
- The magnetic fields are imported from the magneto-static solver to solve the motion of the electrons at specific calculated modes of the cavity.
- The particles are pushed through the computational domain by interpolating the field values to their location and calculating the EM forces

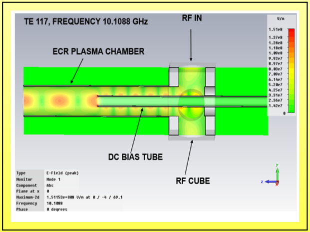
Model of permanent magnet ECR source

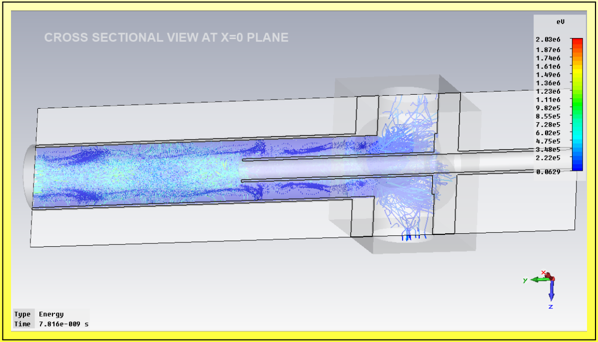


Magnetic field calculation

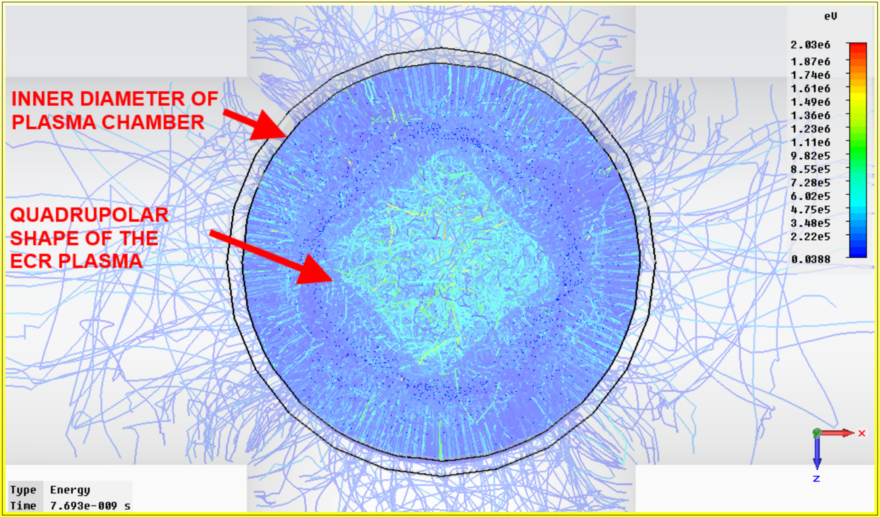


Longitudinal view

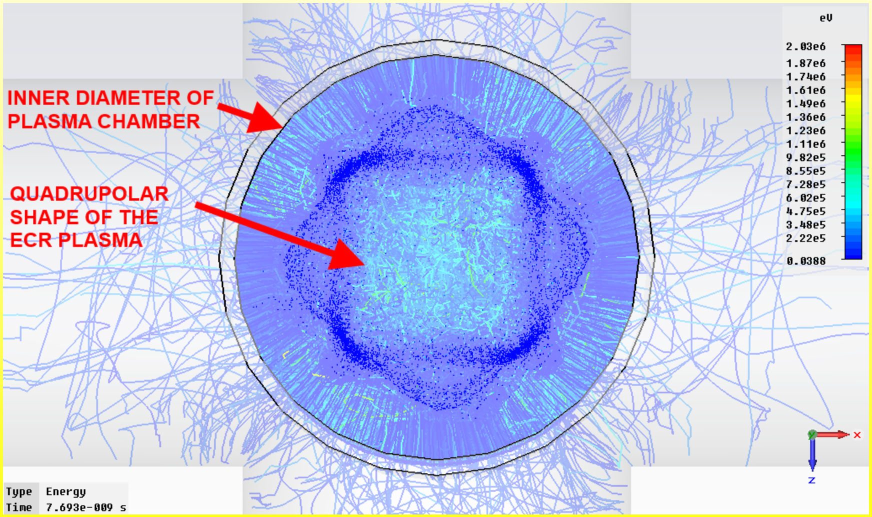




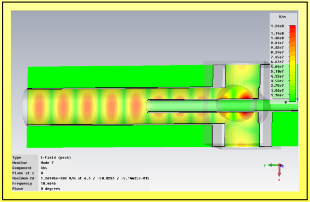
View of the electron trajectories at injection side

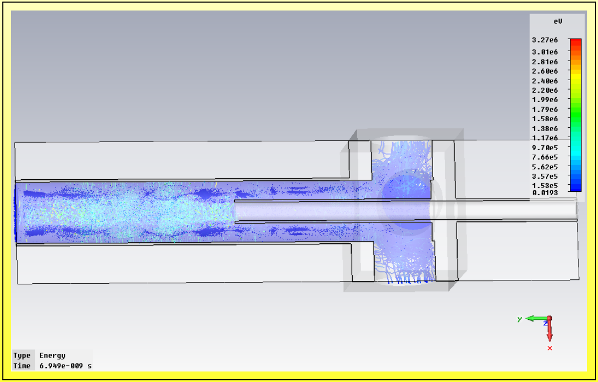


View of the electron trajectories at extraction side

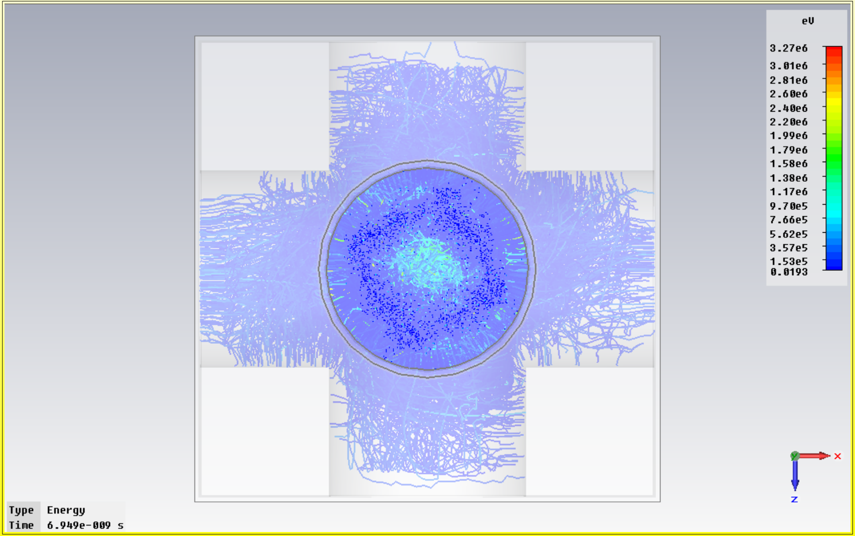


Longitudinal view





View of the electron trajectories



Conclusions

- There is a strong absorption of microwave power at various frequencies whenever the reflection co-efficient showed a minimum value
- The effect was seen for the higher charge states
- The shape of the beam as a function of frequency clearly shows a strong variation at BPM1
- Warm and cold electron components were found to be directly correlated with the beam intensity enhancement in case of Ar^{9+}, not for O^{5+}
- Particle tracking shows the evolution of the quadrupolar structure of the ECR plasma which is modified by the electromagnetic fields in the cavity

Thank You


ECRIS-2014
NIZHNY NOVGOROD, RUSSIA
24-28 AUGUST 2014
Institute of Applied Physics
of the Russian Academy of Sciences