

# FREQUENCY TUNING OF ECR ION SOURCES

**FABIO MAIMONE**

# OUTLINE

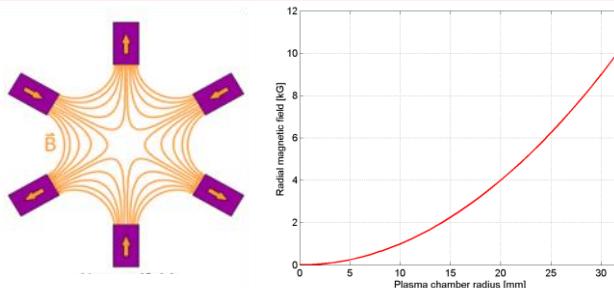
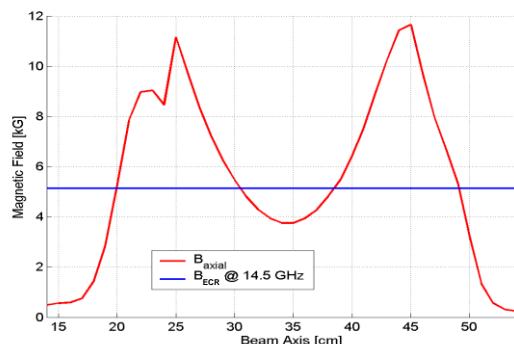
- **Electron Cyclotron Resonance Ion Sources (ECRISs)**
  - Introduction and working principles
  - The ECRIS at GSI
- **ECRIS research and development activities**
  - Electromagnetic field in an ECRIS
  - Frequency Tuning of the ECRIS
  - Piston tuning
  - Frequency tuning and beam shape
  - Pulsed/Afterglow mode
  - High charge state injector microwave system upgrade

# INTRODUCTION

- The Electron Cyclotron Resonance Ion Sources (ECRISs) are suitable devices to provide, in a reliable and continuous way, intense high charge state ion beams to the accelerator facilities for nuclear physics experiments, tumor treatments and for other applications.
- The basic principle of the ECR Ion Source is based on the charged particle magnetic confinement and the electron heating by high power electromagnetic waves at the electron cyclotron resonance frequency.
- ECRIS Characteristics:
  - CW operation (**no limitation of duty cycle**)
  - Pulsed/afterglow operation (**higher intensity compared to CW operation**)
  - High charge states (**injection into LINAC without postacceleration**)
  - No filaments (**reduced maintenance**)
  - Low material consumption (**high efficiency, cost savings**)
  - Effective thermal evaporation of metallic elements (**long lifetimes**)

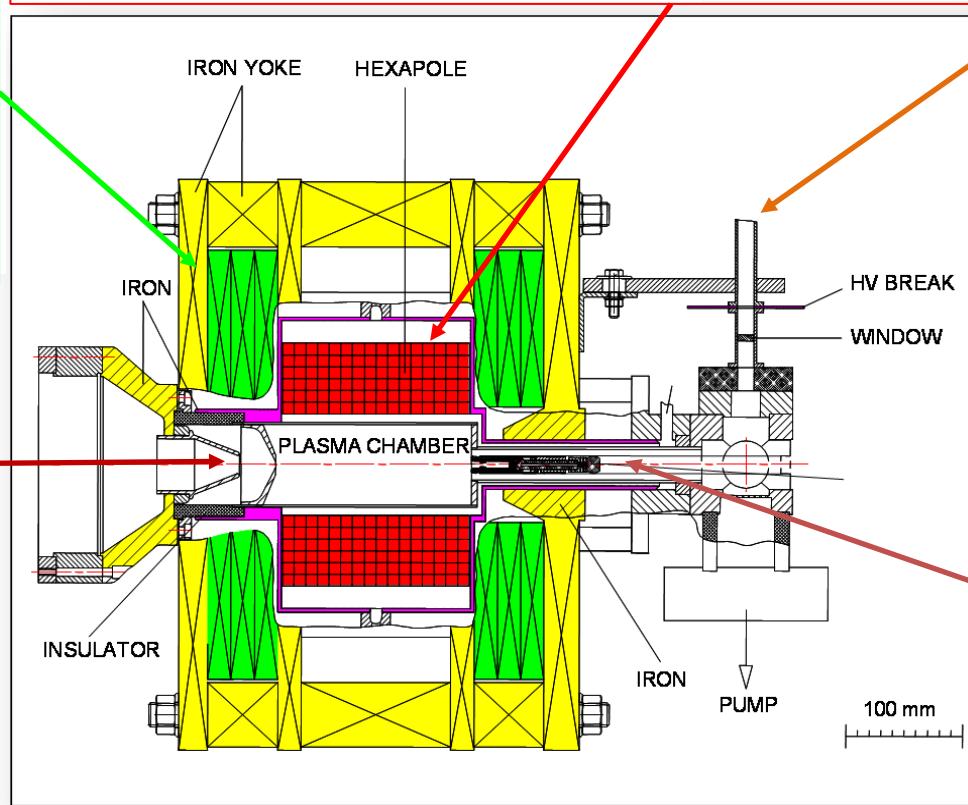
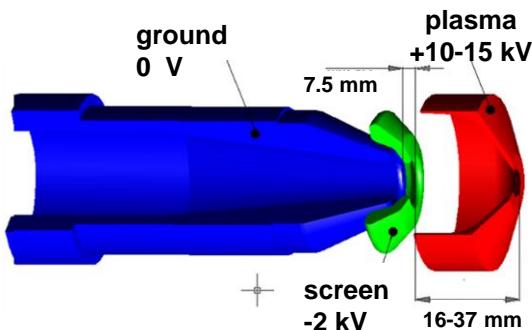
# ECRIS WORKING PRINCIPLES

Two coils for the axial magnetic confinement system



Sextupole for the radial confinement

Ion extraction



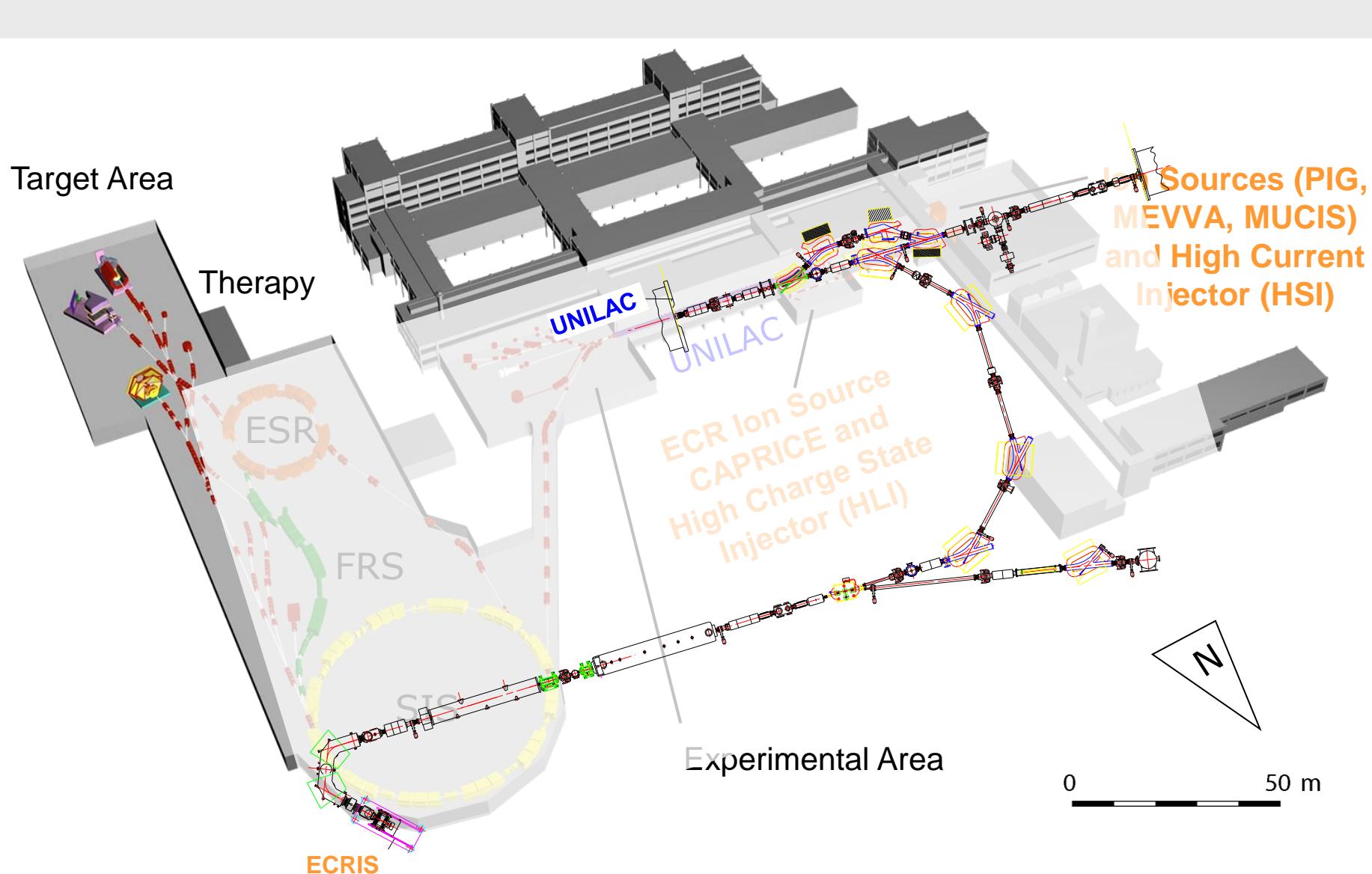
Microwave injection

Wave energy absorption for electrons crossing the surface where ECR condition is fulfilled:

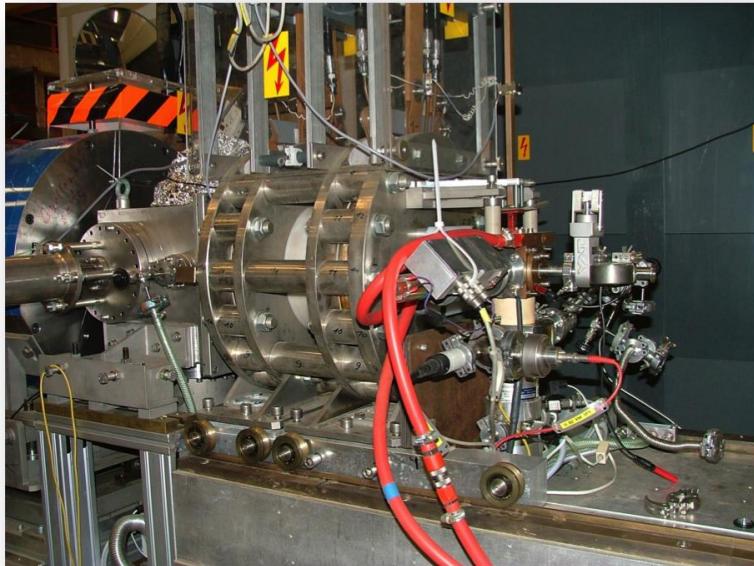
$$B_{ECR} = 2\pi \frac{m_e}{e} f$$

Gas injection

# GSI ACCELERATOR FACILITIES

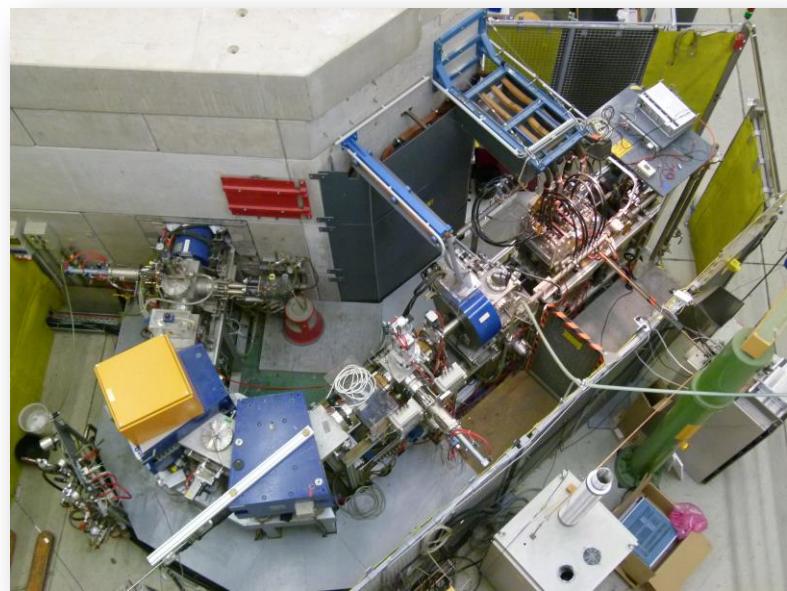
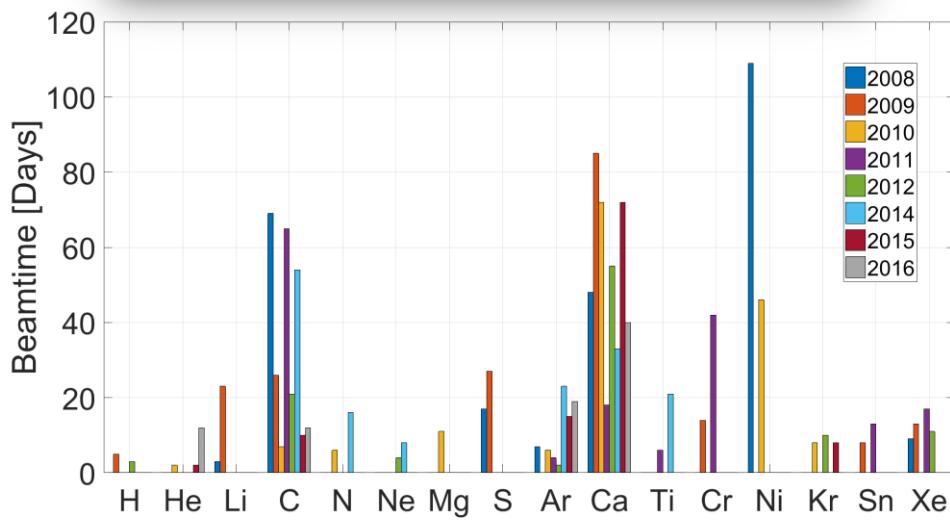


# HIGH CHARGE STATE INJECTOR



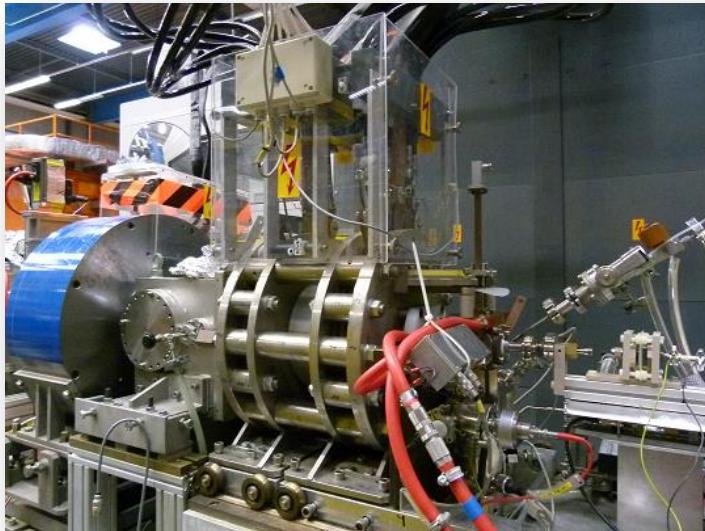
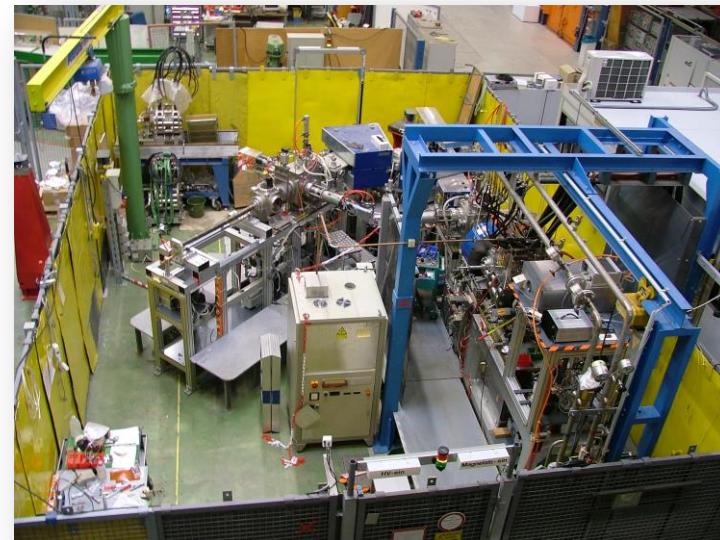
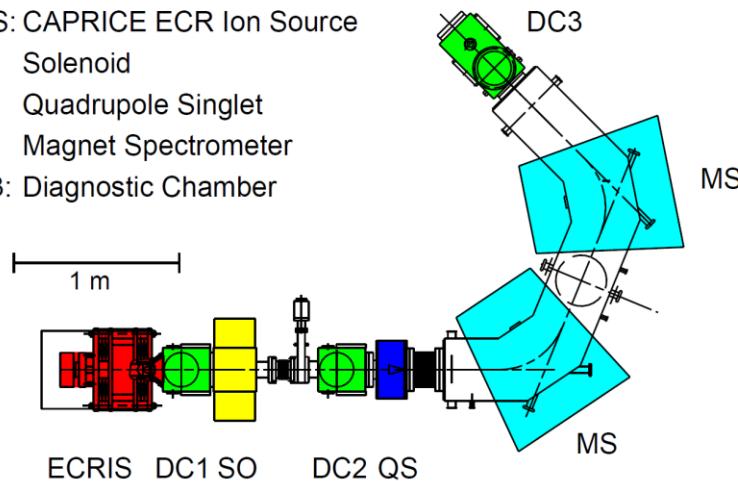
## CAPRICE ECRIS MAIN PARAMETERS

Hexapole field	1...1,2 T
Solenoid field	0,8...1,5 T
$\mu$ W-power	10...800 W (CW mode)
$\mu$ W-frequency	14.5 (12,4...16) GHz
Extraction Voltage [kV]	$\leq 22$
Ion Species	Gas + Metal
Current density	3 mA/cm <sup>2</sup>
Mode	CW or Pulsed



# EIS TESTBENCH

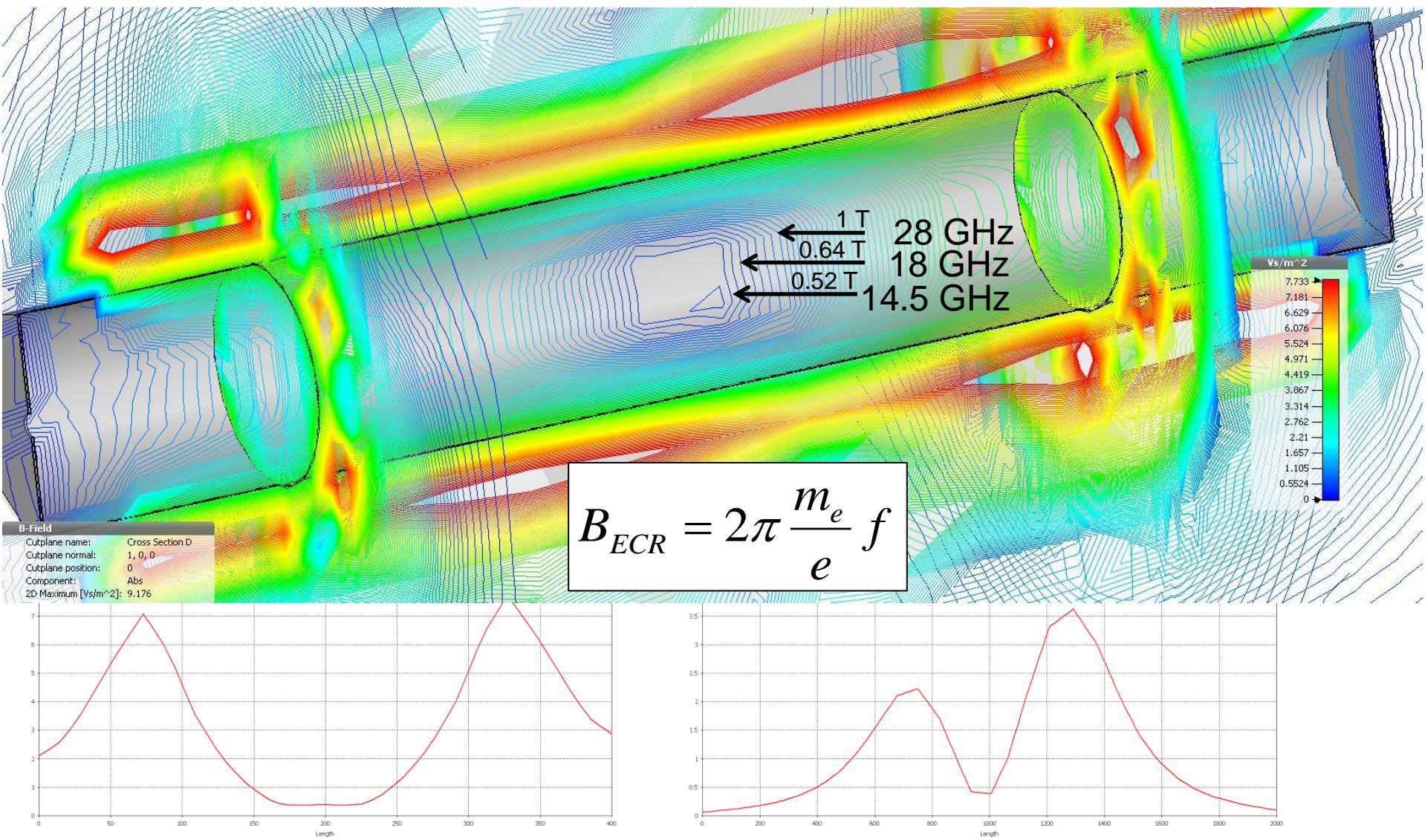
ECRIS: CAPRICE ECR Ion Source  
SO: Solenoid  
QS: Quadrupole Singlet  
MS: Magnet Spectrometer  
DC1-3: Diagnostic Chamber



## R&D ACTIVITIES

- Metal ion production
- Ion extraction and transport
- Microwave-based techniques

# MAGNETIC CONFINEMENT AND ECR SURFACE



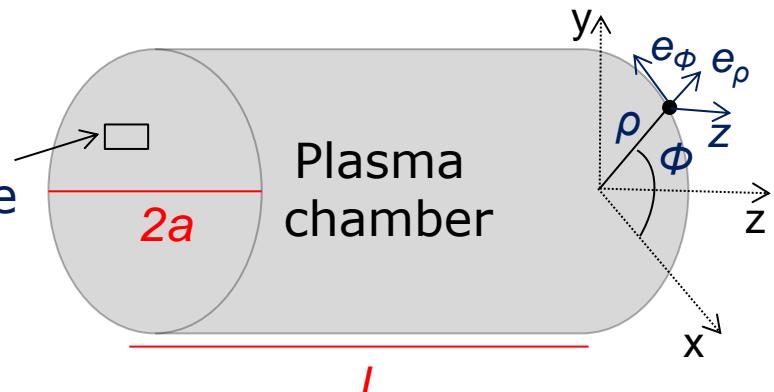
## INSIDE THE PLASMA CHAMBER

A plasma chamber can be represented, in a first order approximation, by a cylinder with a radius  $a$  and length  $l$  filled by a medium with a **certain electric permittivity** and a certain magnetic permeability

$$\left\{ \begin{array}{l} E_\rho = \frac{\mu\omega n}{h^2\rho} C_n J_n \left( \frac{x'_{nv}\rho}{a} \right) \sin n\phi \sin \left( \frac{r\pi z}{l} \right) \\ E_\phi = \frac{\mu\omega x'_{nv}}{h^2 a} C_n J'_n \left( \frac{x'_{nv}\rho}{a} \right) \cos n\phi \sin \left( \frac{r\pi z}{l} \right) \\ E_z = 0 \\ H_\rho = -i \frac{x'_{nv}}{a} \frac{r}{l} \frac{\pi}{h^2} C_n J'_n \left( \frac{x'_{nv}\rho}{a} \right) \cos n\phi \cos \left( \frac{r\pi z}{l} \right) \\ H_\phi = i \frac{n r}{\rho l} \frac{\pi}{h^2} C_n J_n \left( \frac{x'_{nv}\rho}{a} \right) \sin n\phi \cos \left( \frac{r\pi z}{l} \right) \\ H_z = -i C_n J_n \left( \frac{x'_{nv}\rho}{a} \right) \cos n\phi \sin \left( \frac{r\pi z}{l} \right) \end{array} \right.$$

$$\left\{ \begin{array}{l} E_\rho = -\frac{x_{nv}}{a} \frac{r}{l} \frac{\pi}{h^2} C_n J'_n \left( \frac{x_{nv}\rho}{a} \right) \cos n\phi \sin \left( \frac{r\pi z}{l} \right) \\ E_\phi = \frac{n r}{\rho l} \frac{\pi}{h^2} C_n J_n \left( \frac{x_{nv}\rho}{a} \right) \sin n\phi \sin \left( \frac{r\pi z}{l} \right) \\ E_z = C_n J_n \left( \frac{x_{nv}\rho}{a} \right) \cos n\phi \cos \left( \frac{r\pi z}{l} \right) \\ H_\rho = -i \frac{\epsilon\omega n}{h^2\rho} C_n J_n \left( \frac{x_{nv}\rho}{a} \right) \sin n\phi \cos \left( \frac{r\pi z}{l} \right) \\ H_\phi = -i \frac{\epsilon\omega x_{nv}}{h^2 a} C_n J'_n \left( \frac{x_{nv}\rho}{a} \right) \cos n\phi \cos \left( \frac{r\pi z}{l} \right) \\ H_z = 0 \end{array} \right.$$

Waveguide aperture



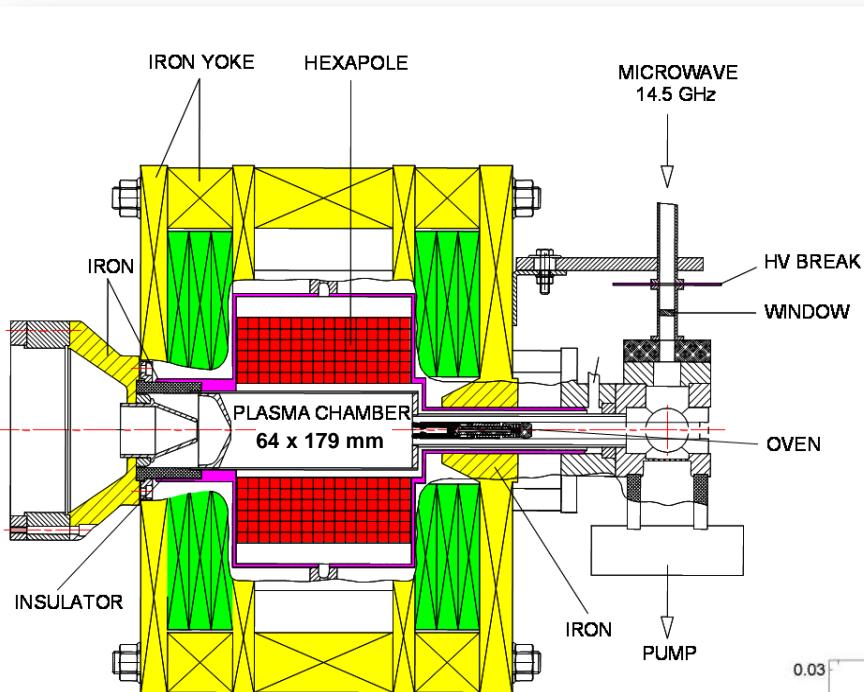
A discrete number of electromagnetic field patterns can exist inside the plasma chamber: the **resonant modes  $TE_{n,v,r}$  and  $TM_{n,v,r}$**

Resonance frequencies

$$\omega = \frac{1}{\sqrt{\epsilon\mu}} \sqrt{\frac{r^2\pi^2}{l^2} + \frac{x'^2_{nv}}{a^2}} \quad \text{TE modes}$$

$$\omega = \frac{1}{\sqrt{\epsilon\mu}} \sqrt{\frac{r^2\pi^2}{l^2} + \frac{x^2_{nv}}{a^2}} \quad \text{TM modes}$$

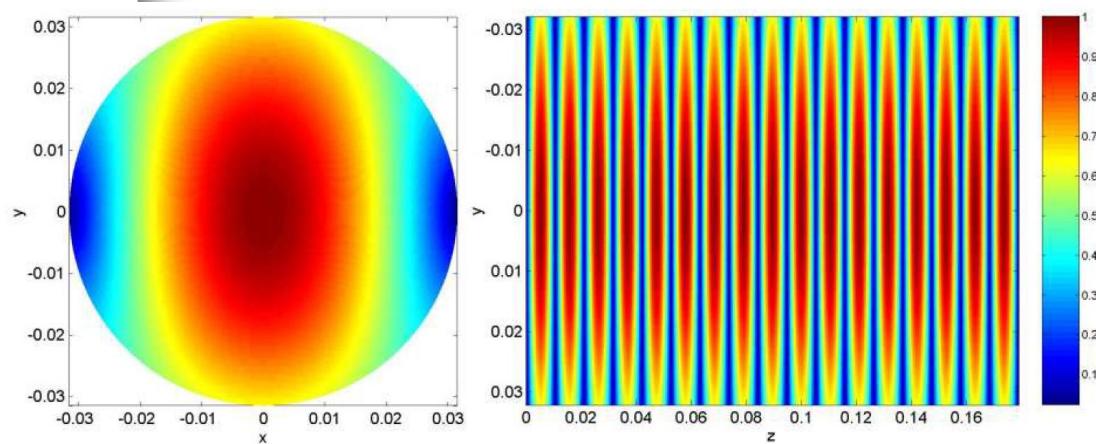
# CAPRICE PLASMA CHAMBER ELECTROMAGNETIC FIELDS



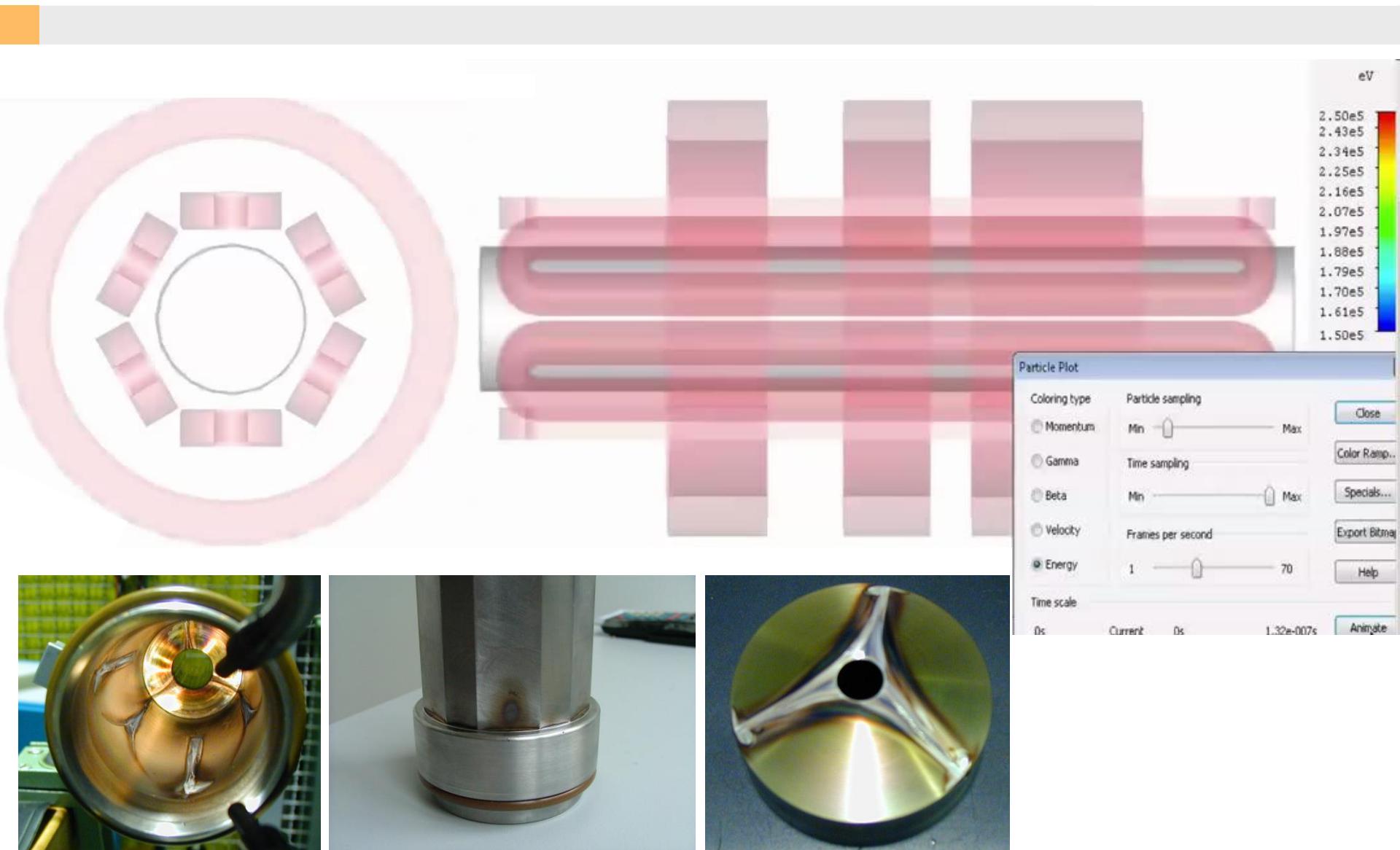
Normalized electric field amplitude for the mode  $TE_{1,1,17}$  in the  $xy$  plane at the  $z$  point where it is maximum and on the  $yz$  plane at  $x = 0$

10 modes close to 14.5  
GHz  $\pm$  50 MHz

Mode	Frequency [GHz]
$TM_{3,1,13}$	14.457219
$TE_{4,2,5}$	14.459947
$TE_{8,1,2}$	14.481914
$TE_{6,1,11}$	14.492060
$TE_{5,1,13}$	14.492060
$TE_{1,1,17}$	14.498241
$TE_{0,2,12}$	14.505304
$TM_{1,2,12}$	14.505304
$TM_{0,3,8}$	14.538578
$TM_{3,2,0}$	14.554128



# CHARGED PARTICLE TRAJECTORY



# ELECTROMAGNETIC FIELDS ON PLASMA PROPERTIES

The motion equation of a charged particle moving in the plasma chamber of an ECRIS can be written as:

$$m \frac{d\vec{v}}{dt} = q\vec{E} + q\vec{v} \times \vec{B} + q\vec{E}_{em} + q\vec{v} \times \mu\vec{B}_{em}$$

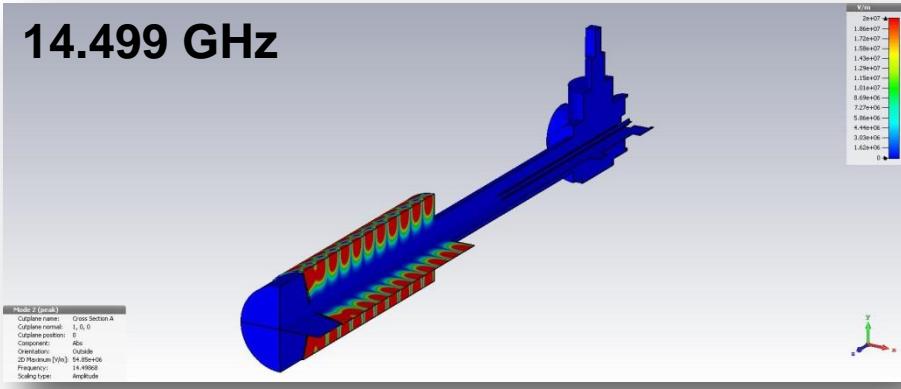
Its solution provides the trajectory of the electrons and the energy gained from the ECR process for different modes.

*Electron energy, energy gain and percentage of confined electrons for different modes  
(plasma chamber length 450 mm and diameter 130 mm)*

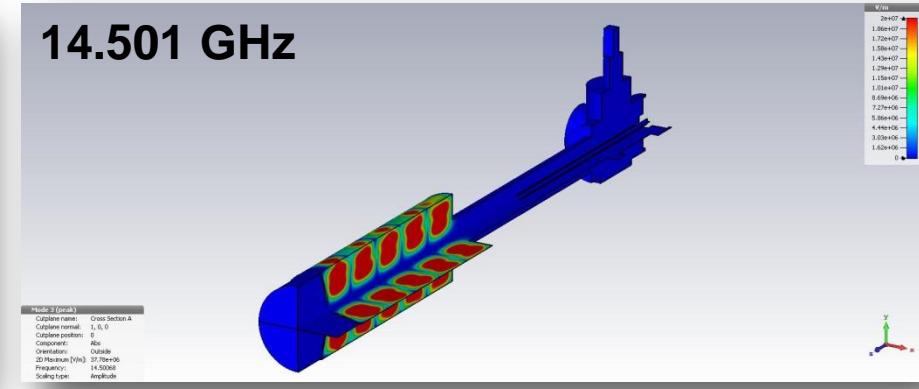
Mode	Frequency [GHz]	Energy [keV]	Energy gain	Confined electrons [%]
$TE_{3,1,13}$	13.952354	13.110	24.97	95
$TE_{4,2,5}$	13.958445	11.892	22.65	93
$TE_{8,1,2}$	13.965417	2.601	4.95	93
$TM_{6,1,11}$	13.995897	0.531	1.01	88
$TM_{5,1,13}$	13.998329	0.562	1.07	87
$TE_{1,1,17}$	14.000643	3.932	7.49	95
$TE_{0,2,12}$	14.000964	3.245	6.18	92
$TE_{1,2,12}$	14.055391	17.793	33.89	95

# CAPRICE ECRIS ELECTROMAGNETIC FIELD

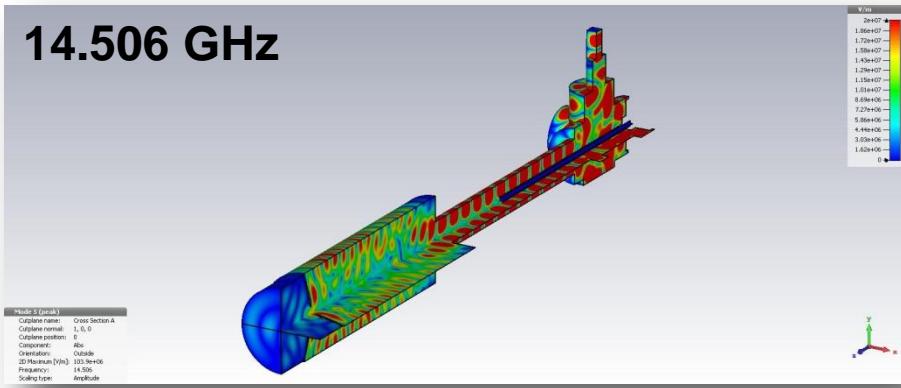
14.499 GHz



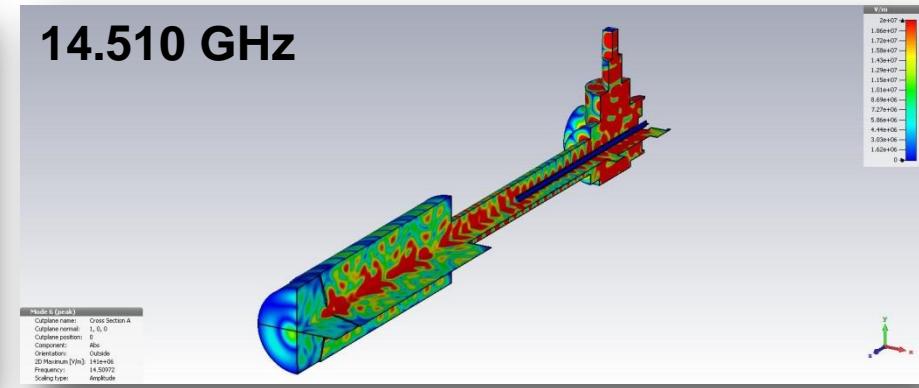
14.501 GHz



14.506 GHz



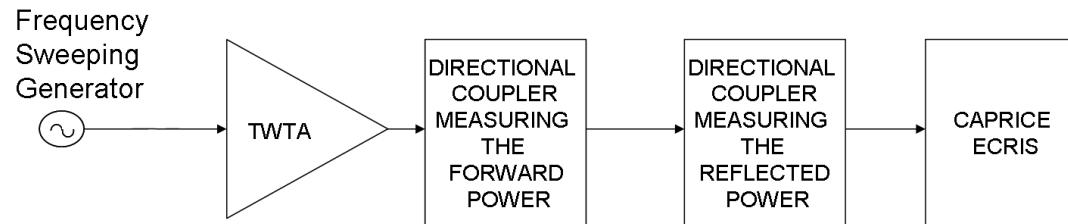
14.510 GHz



CAPRICE ECRIS geometry: Electric field amplitudes for four eigenmodes closed to 14.5 GHz (Vacuum)

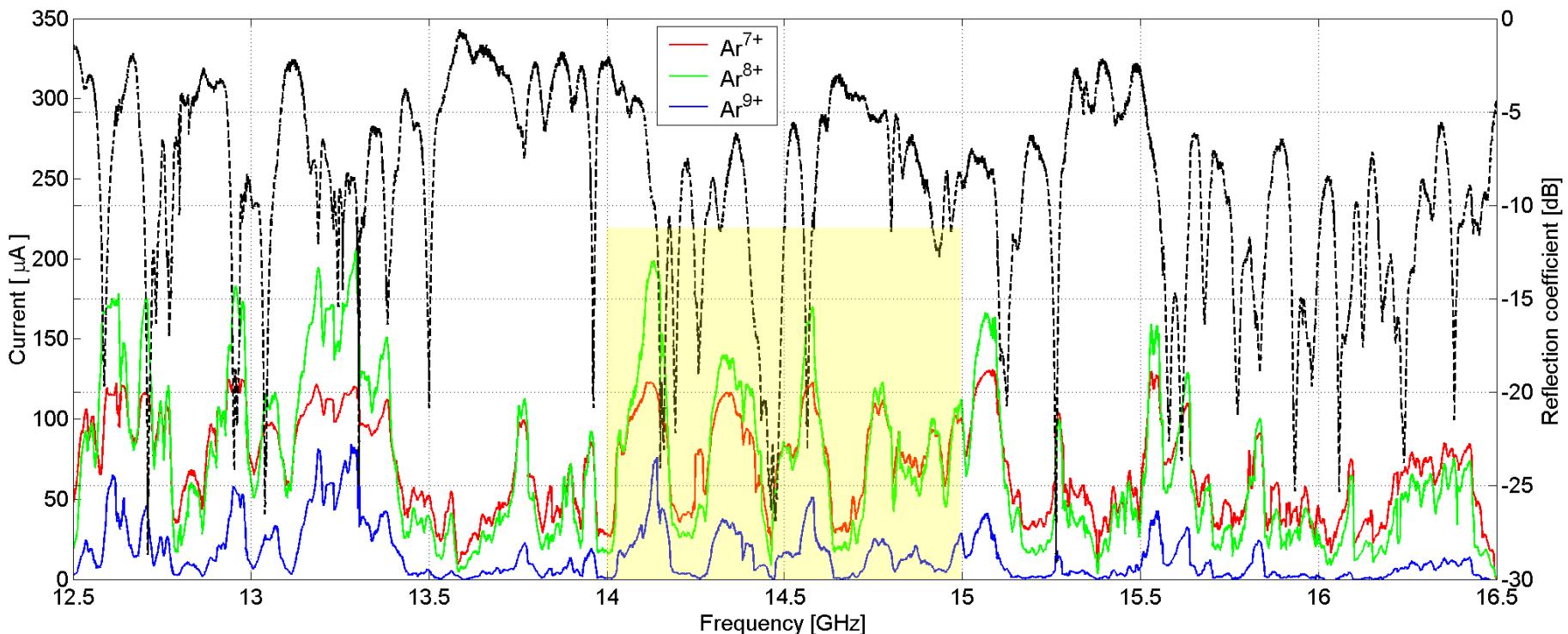
# FREQUENCY TUNING EXPERIMENTAL SET-UP

Block diagram describing the main components of the microwave injection system



- 100 W RF power provided by a TWTA (Traveling Wave Tube Amplifier) driven by a signal generator sweeping in the frequency range of 12.5÷16.5 GHz (steps 200 kHz with a dwell time of 20 ms for each step)
- Two directional couplers of high directivity to measure the forward and the reflected microwave power
- Argon with Helium as mixing gas
- Extraction voltage set to 15 kV and -2 kV screening voltage

# FREQUENCY TUNING EXPERIMENTAL RESULTS 1/2

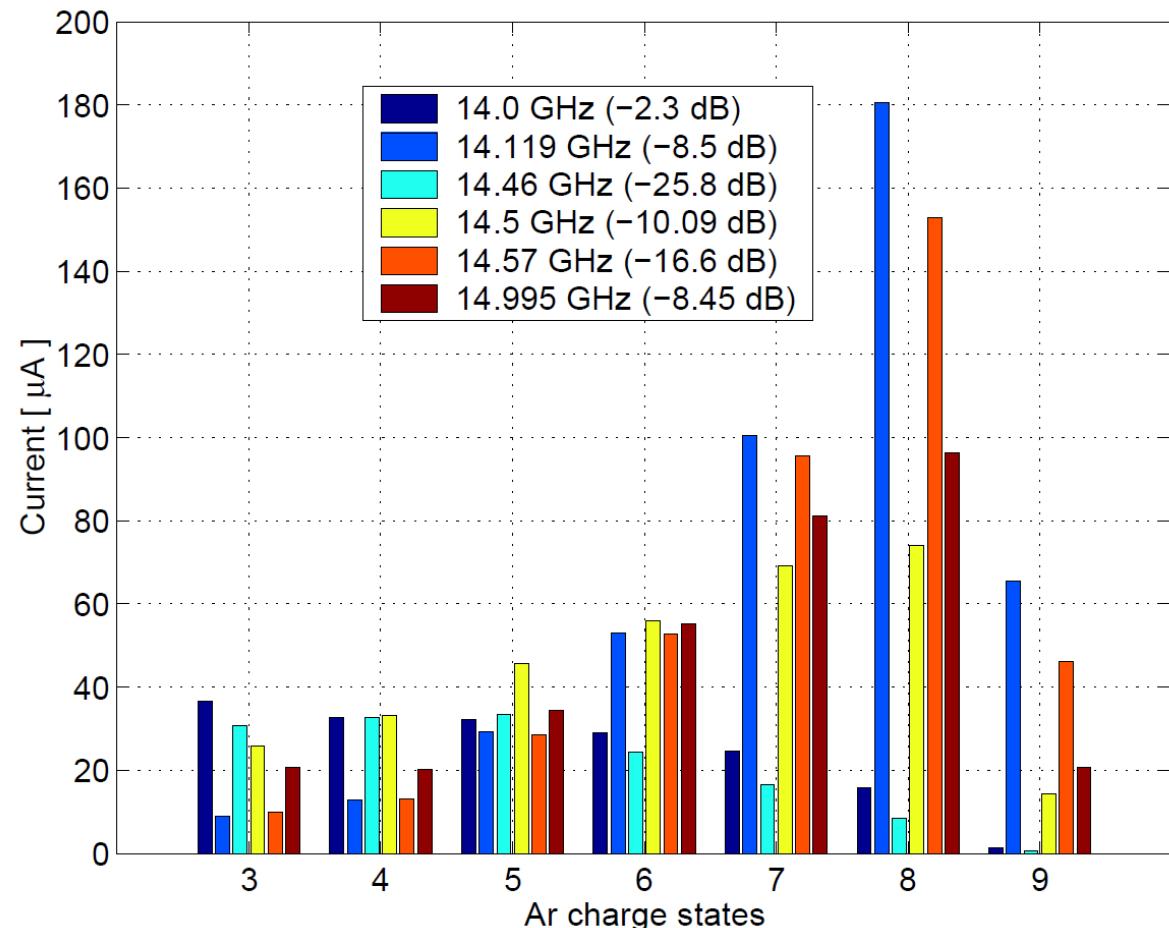


- Unchanged source parameters during the measurement sessions and reproducible experimental results.
- Peaks of the reflection coefficient and current amplitude strongly correlated.
- Current amplitude affected the operative frequency, i.e. the  $\text{Ar}^{8+}$  current ranges from a few  $\mu\text{A}$  up to 200  $\mu\text{A}$ .
- Same evolution of the  $\text{Ar}^{7+}, \text{Ar}^{8+}$  and  $\text{Ar}^{9+}$  currents with different amplitudes in the peak positions and in the minima points.

# FREQUENCY TUNING EXPERIMENTAL RESULTS 2/2

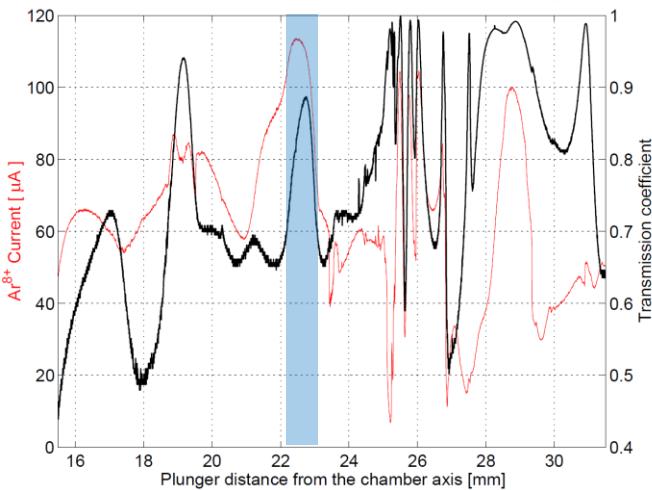
## EFFECT ON THE CHARGE STATES DISTRIBUTION

- For the frequencies where the higher charge states are favoured the current of lower charge states decreases and vice versa.
- The frequency tuning affects mainly the higher charge states production.
- At 14.119 GHz the current enhancement with respect to 14.5 GHz, the normal operation frequency, is 240% for the  $\text{Ar}^{8+}$  and 450% for the  $\text{Ar}^{9+}$ .

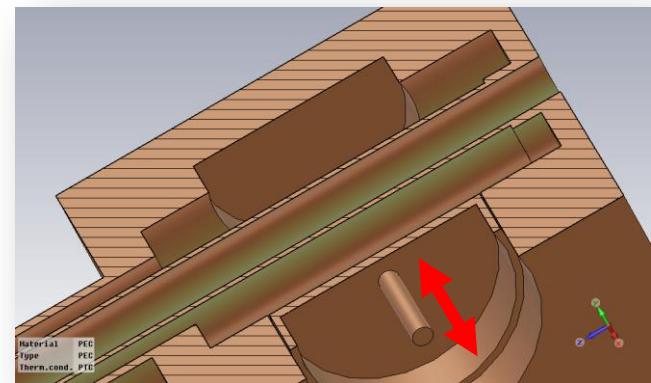


# PISTON TUNING

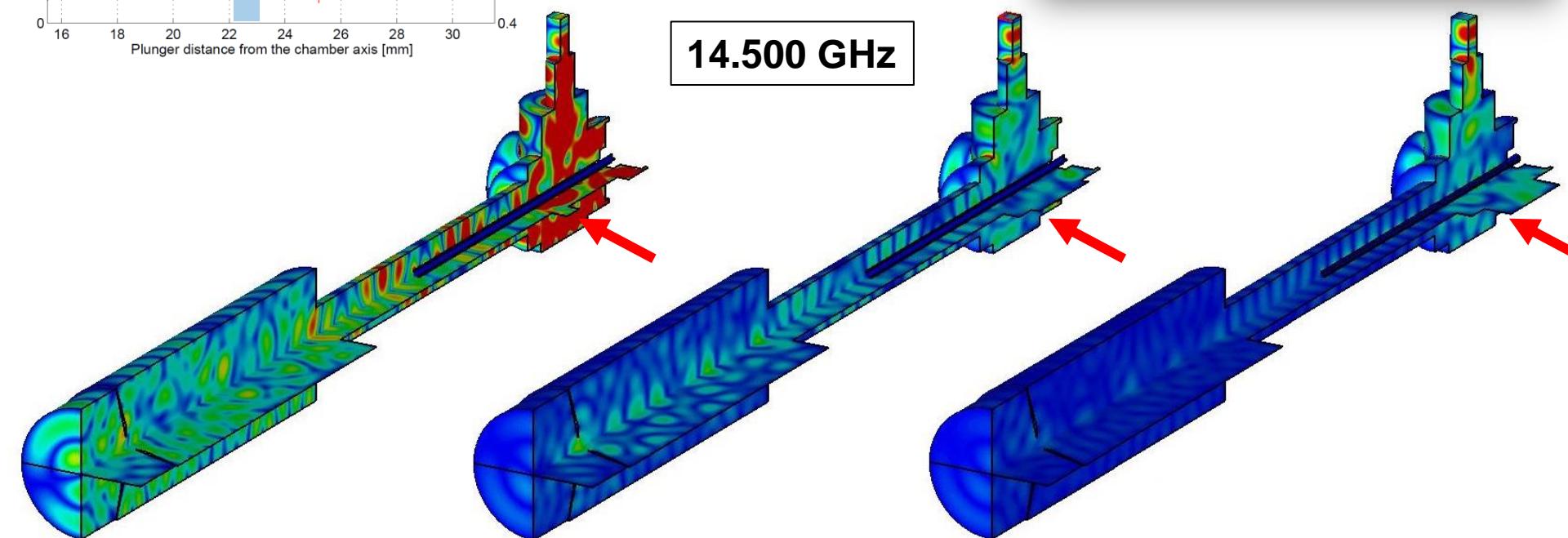
Effect of the tuning of the matching piston on the CAPRICE performances



The  $\text{Ar}^{8+}$  current production is optimized by setting the plunger position to a distance of **22.5 mm from the chamber axis**. At this point the current of  $\text{Ar}^{8+}$  attained its maximum of **115  $\mu\text{A}$**

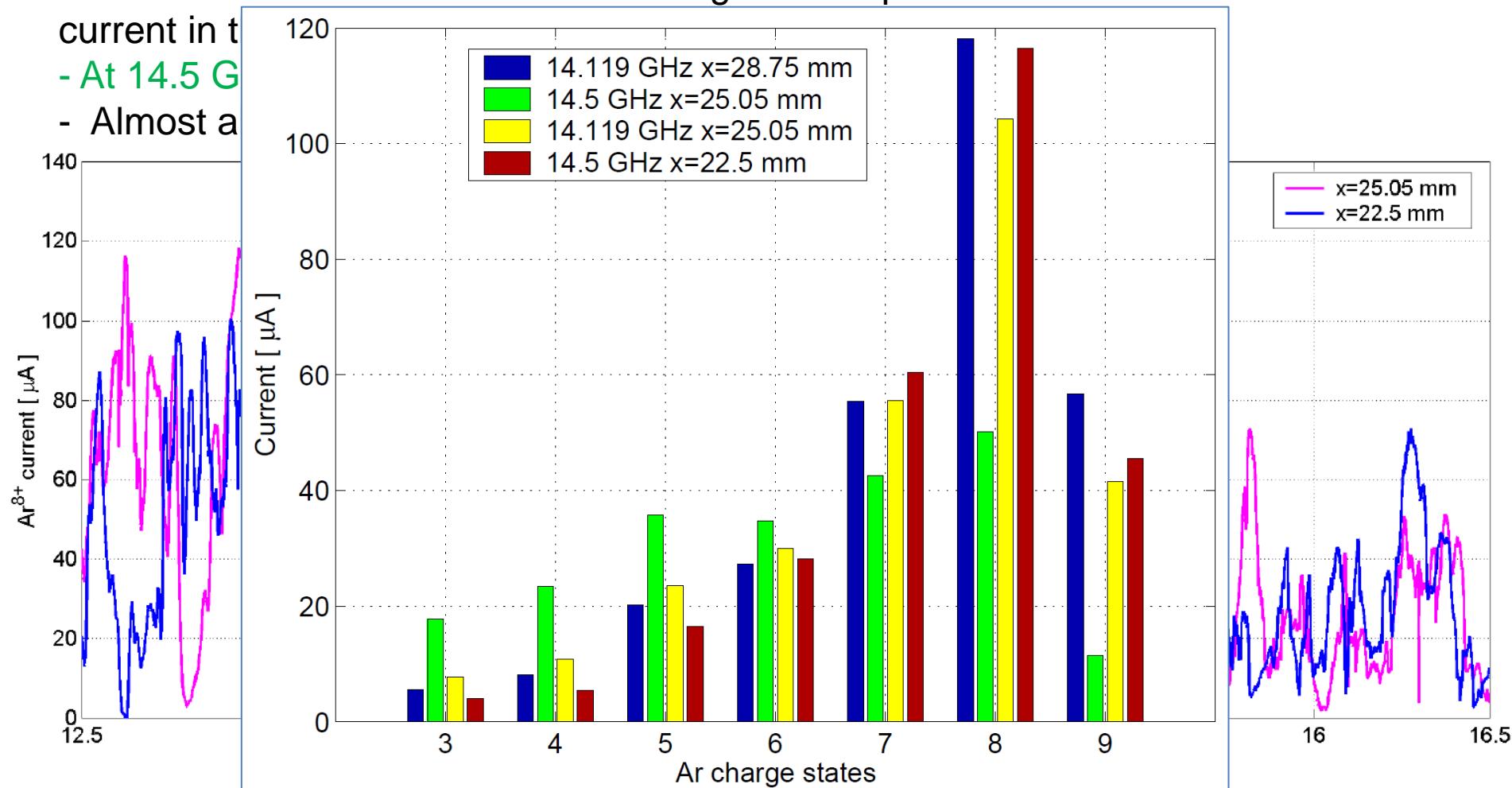


**14.500 GHz**



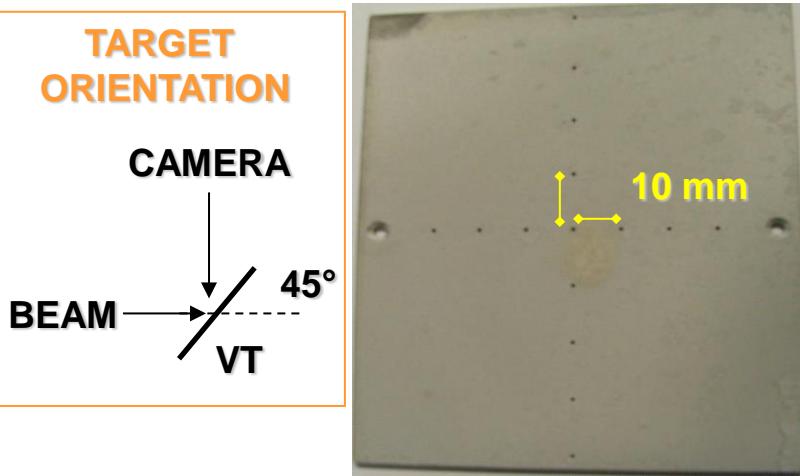
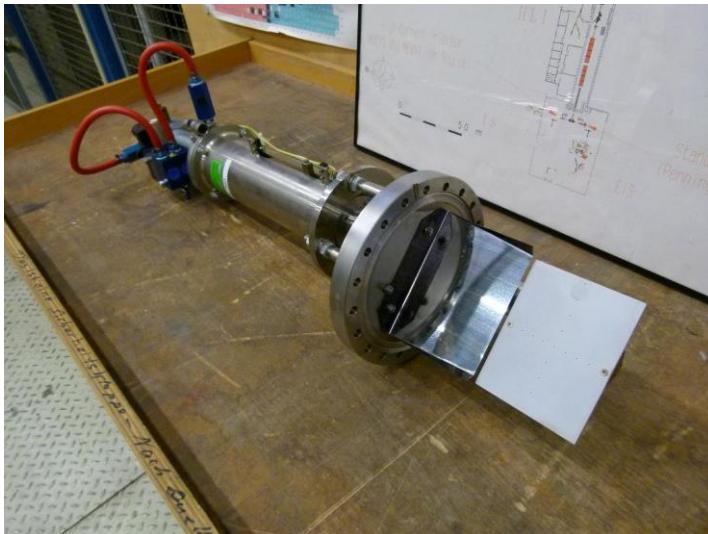
# FREQUENCY TUNING AND PISTON TUNING

- The value of 14.119 GHz does no longer correspond to a maximum of the Ar<sup>8+</sup> current in t
- At 14.5 GHz there is a maximum at Ar charge state 8
- Almost a



# FREQUENCY TUNING EFFECT ON THE BEAM SHAPE 1/2

## VIEWING TARGET EXPERIMENTAL SET-UP



### EIS TESTBENCH BEAM LINE WITH VIEWING TARGETS POSITIONS

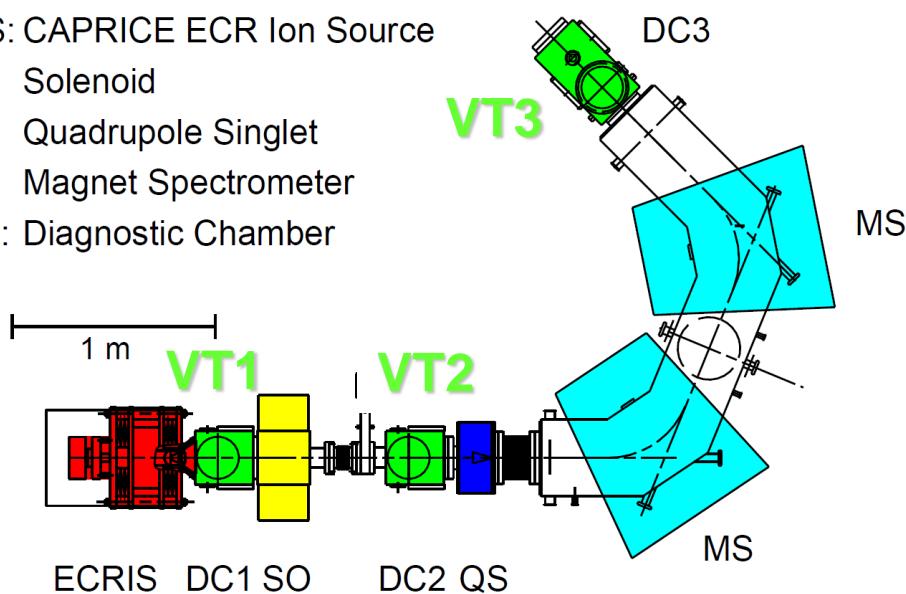
ECRIS: CAPRICE ECR Ion Source

SO: Solenoid

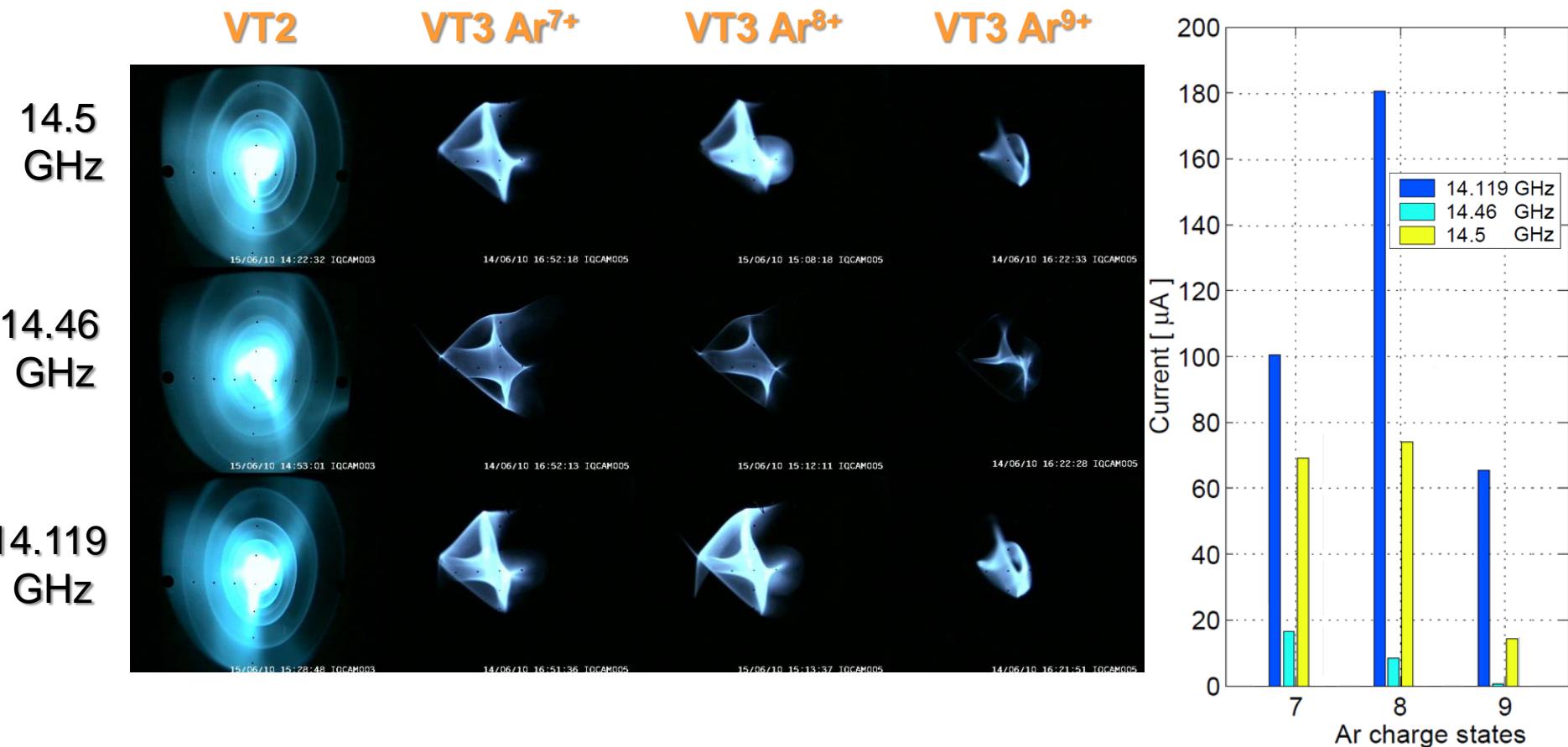
QS: Quadrupole Singlet

MS: Magnet Spectrometer

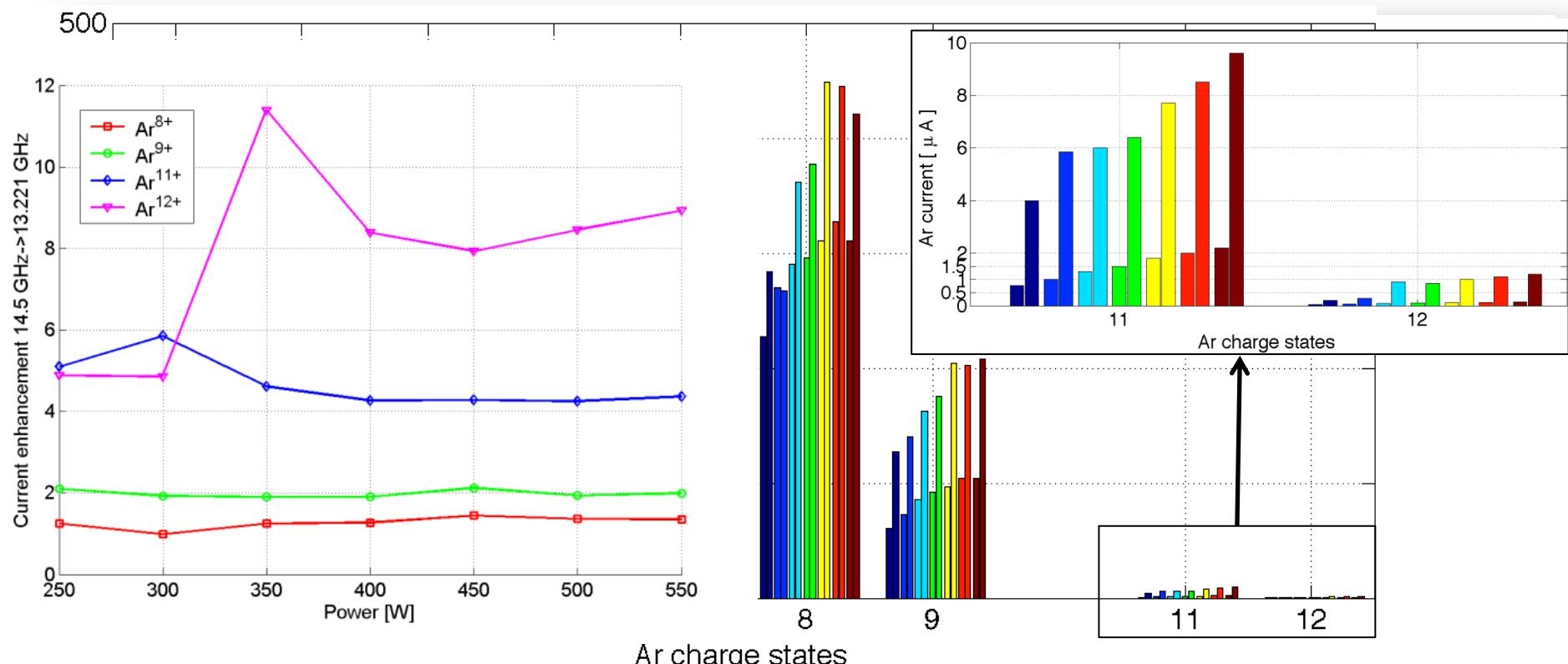
DC1-3: Diagnostic Chamber



# FREQUENCY TUNING EFFECT ON THE BEAM SHAPE 2/2

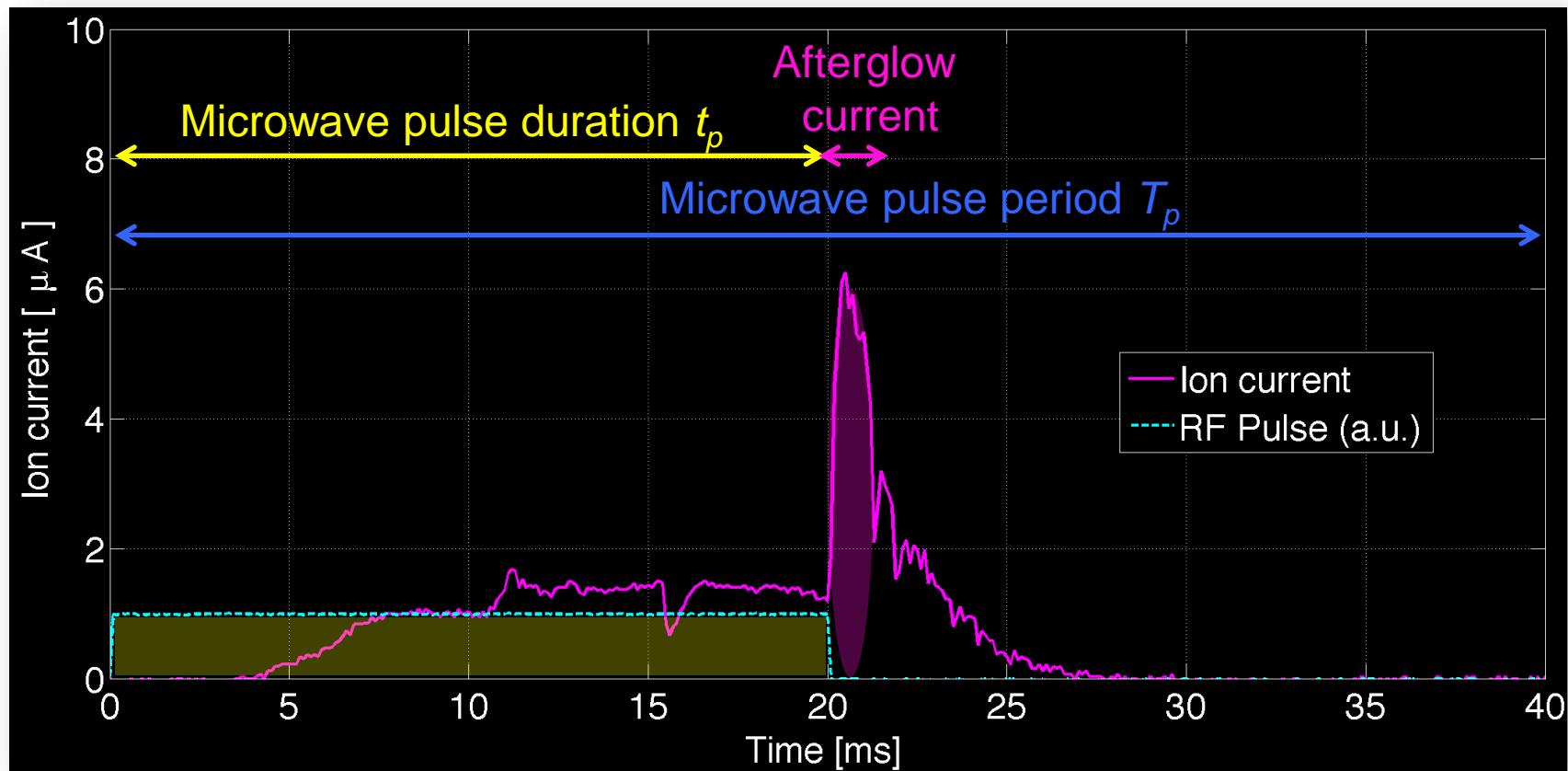


# FREQUENCY TUNING EFFECT ON THE HIGHER CHARGE STATES



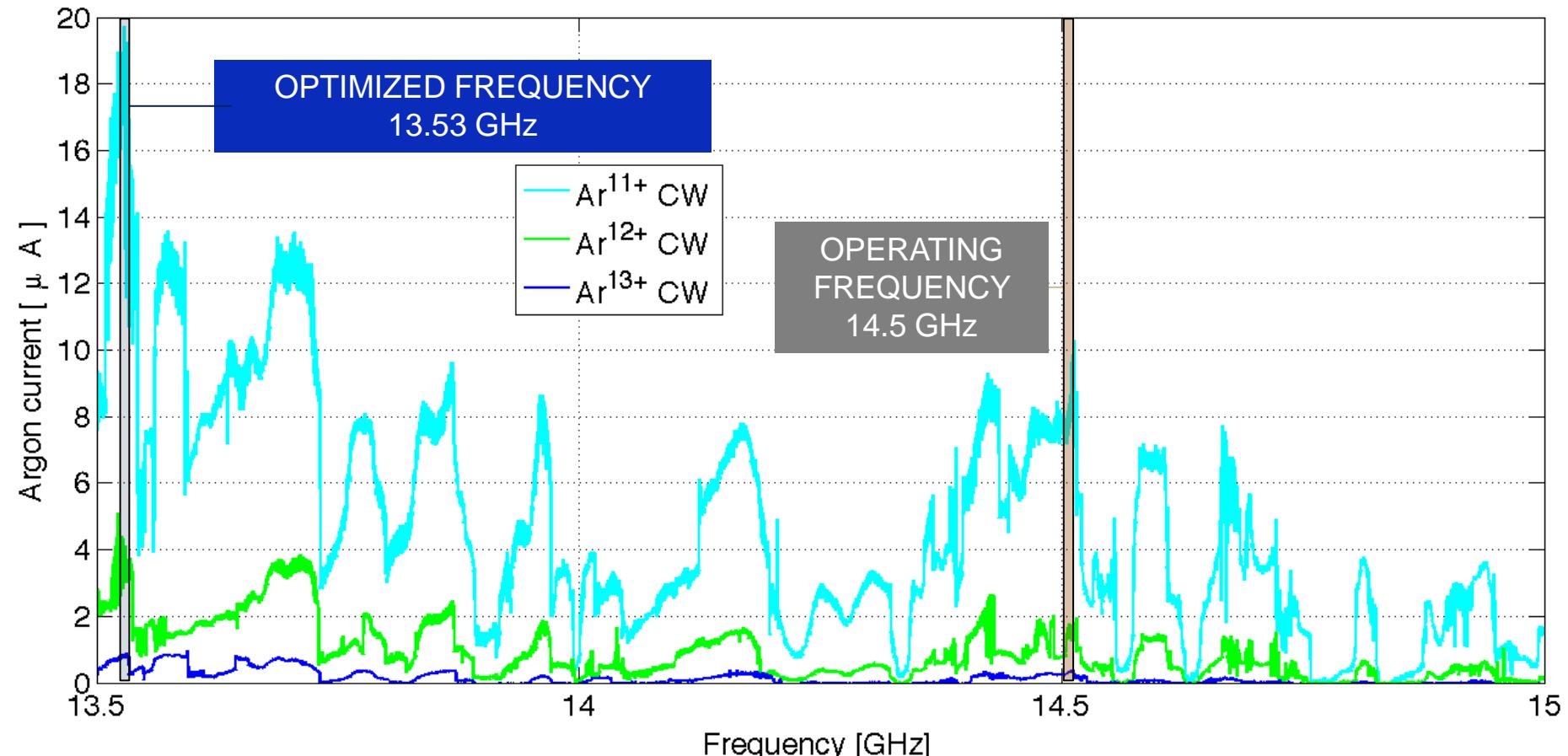
- ECRIS parameters tuned to maximize the production of the  $\text{Ar}^{11+}$  ion current.
- Then frequency sweeps, in the 12.5÷16.5 GHz range (steps 200 kHz with a dwell time of 20 ms for each step) performed while the  $\text{Ar}^{8+}$ ,  $\text{Ar}^{9+}$  and  $\text{Ar}^{11+}$  beam currents were measured.
- For some frequencies, like 13.221 GHz, higher charge states current enhanced with respect to the case of 14.5 GHz

# AFTERGLOW MODE



- By pulsing the microwave power, the extracted current of highly charged ions increases in burst pulses.
- The afterglow current can be optimized by tuning the pulse duration or the pulse period or the duty factor ( $d=t_p/T_p$ ).

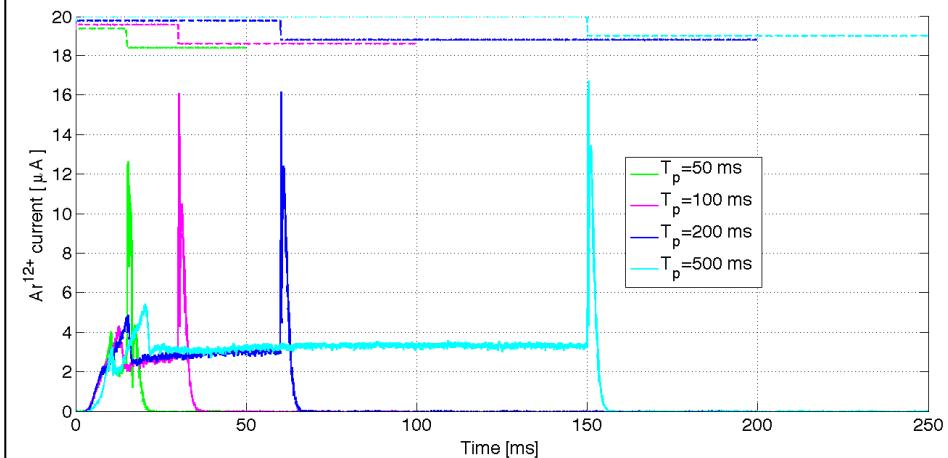
# FREQUENCY TUNING EFFECT AND AFTERGLOW MODE



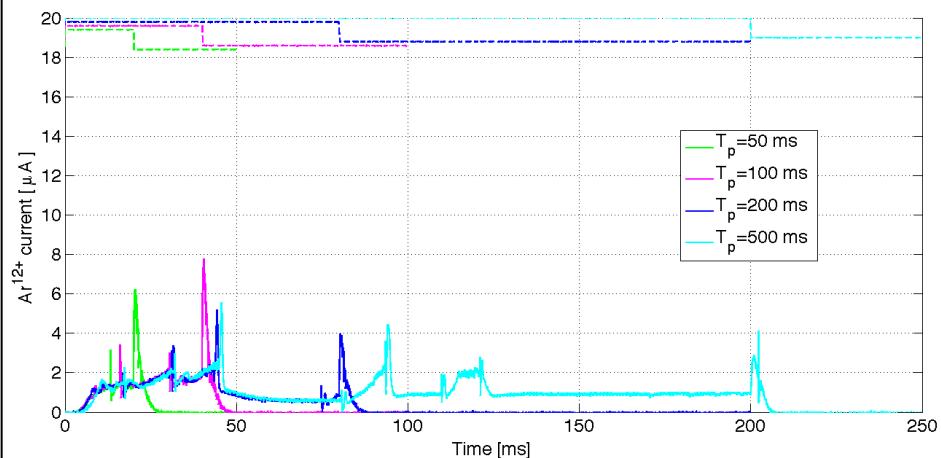
EVOLUTION OF THE  $\text{Ar}^{11+}$ ,  $\text{Ar}^{12+}$ ,  $\text{Ar}^{13+}$  CURRENT WITH THE MICROWAVE FREQUENCY IN CW MODE

# AFTERGLOW MODE OPTIMIZATION

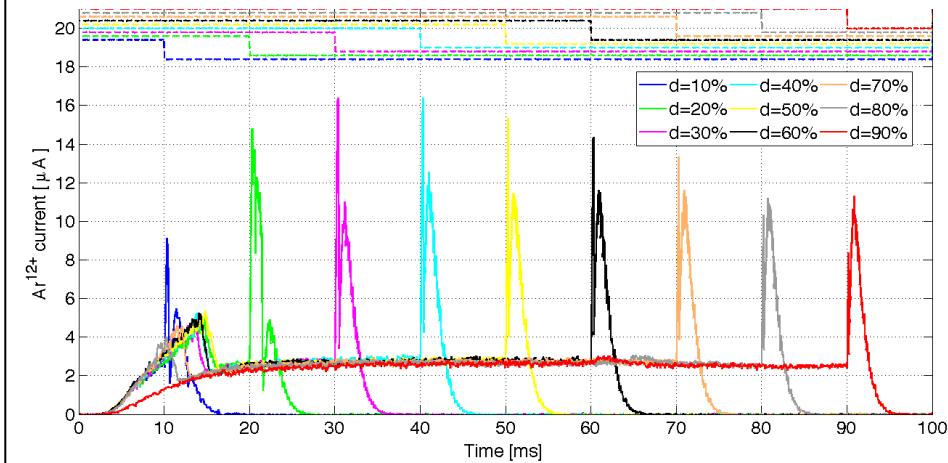
OPTIMIZED FREQUENCY 13.53 GHz



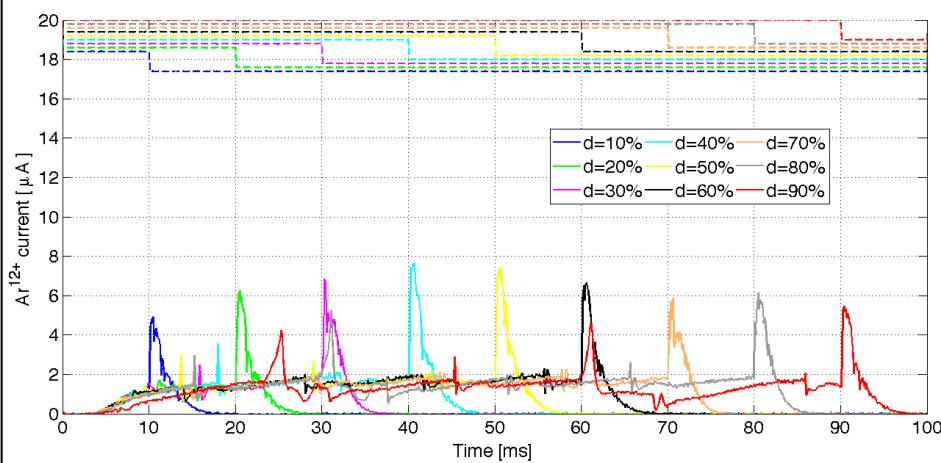
OPERATING FREQUENCY 14.5 GHz



PULSE PERIOD VARIATION AT  $d=30\%$



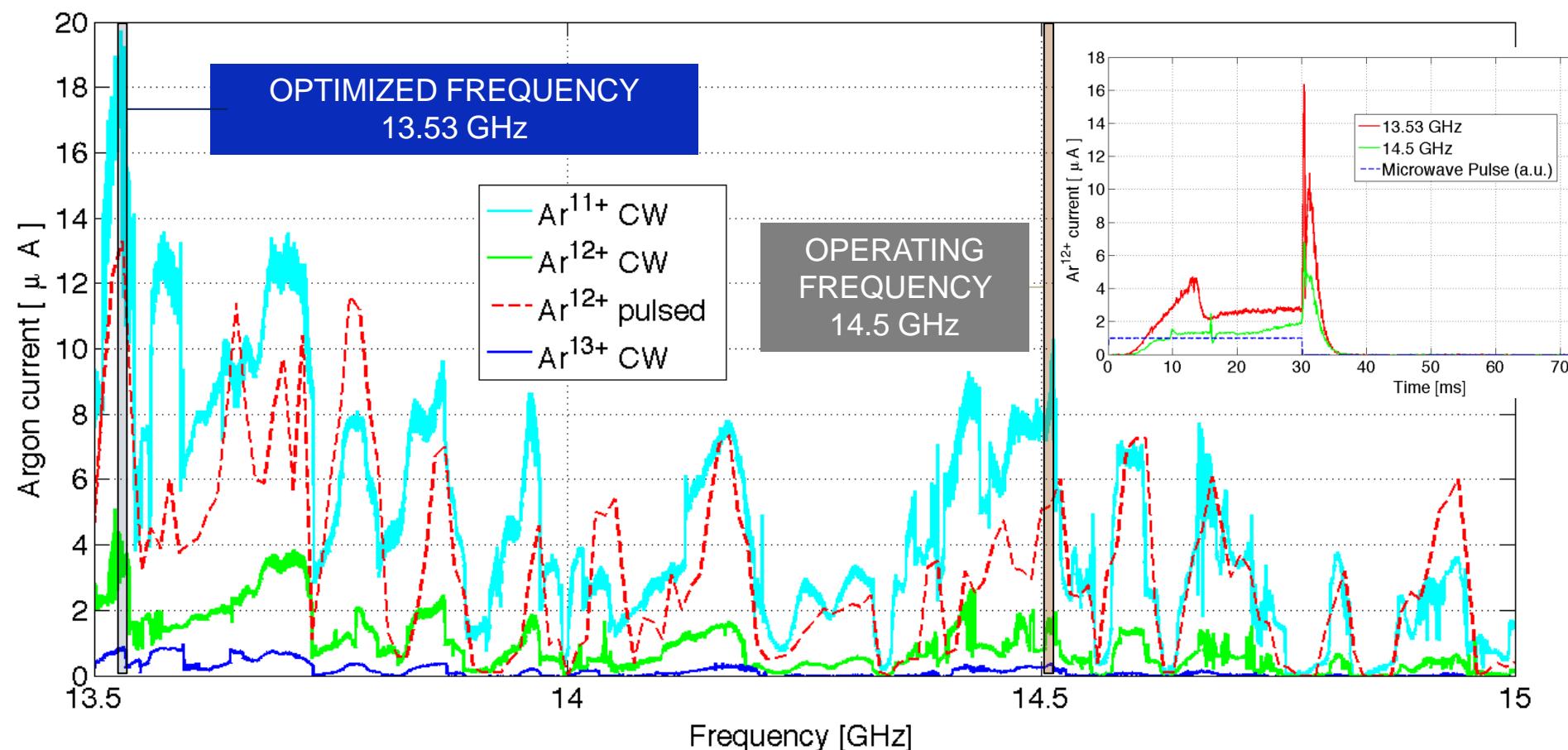
PULSE PERIOD VARIATION AT  $d=40\%$



DUTY CYCLE VARIATION AT  $T_p=100 \text{ ms}$

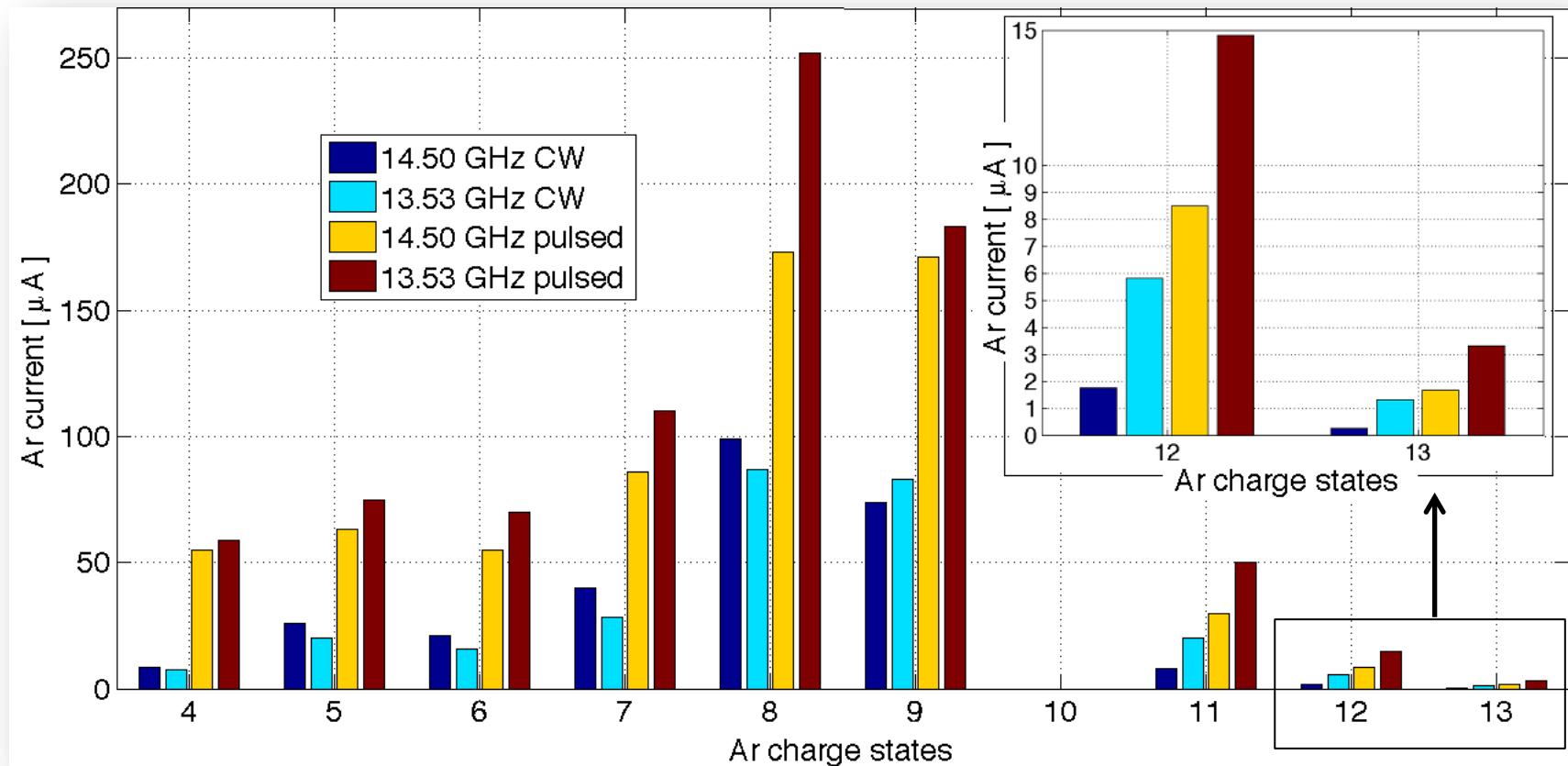
DUTY CYCLE VARIATION AT  $T_p=100 \text{ ms}$

# FREQUENCY TUNING EFFECT AND AFTERGLOW MODE



EVOLUTION OF THE  $\text{Ar}^{11+}$ ,  $\text{Ar}^{12+}$ ,  $\text{Ar}^{13+}$  CURRENT WITH THE MICROWAVE FREQUENCY IN CW MODE

# FREQUENCY TUNING EFFECT AND AFTERGLOW MODE

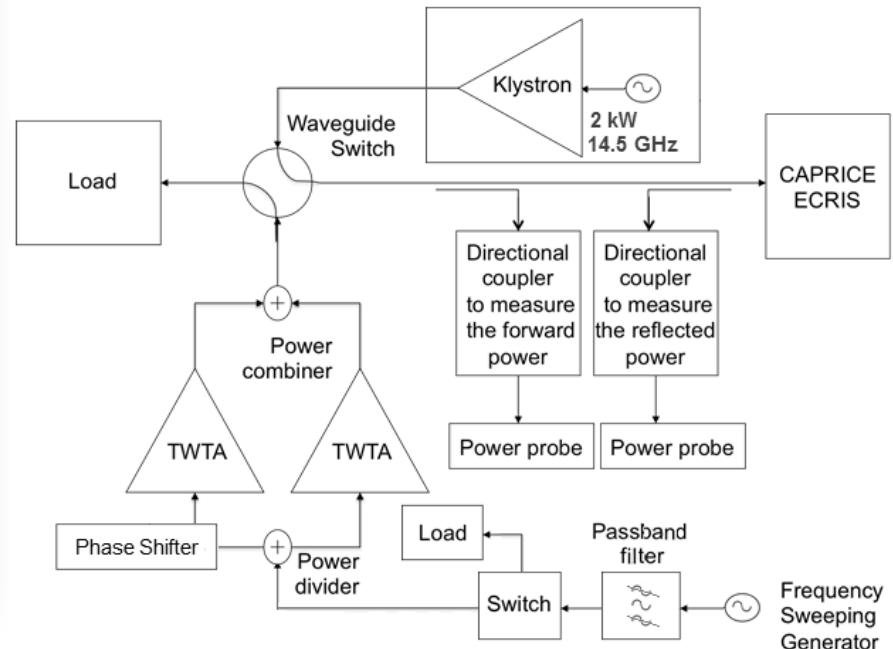


Ar CHARGE STATES DISTRIBUTIONS AT DIFFERENT FREQUENCIES IN CW MODE AND IN PULSED MODE (DUTY CYCLE  $d=30\%$ , PULSE PERIOD  $T_p=100\text{ ms}$ )

# HIGH CHARGE STATES INJECTOR MICROWAVE SYSTEM UPGRADE

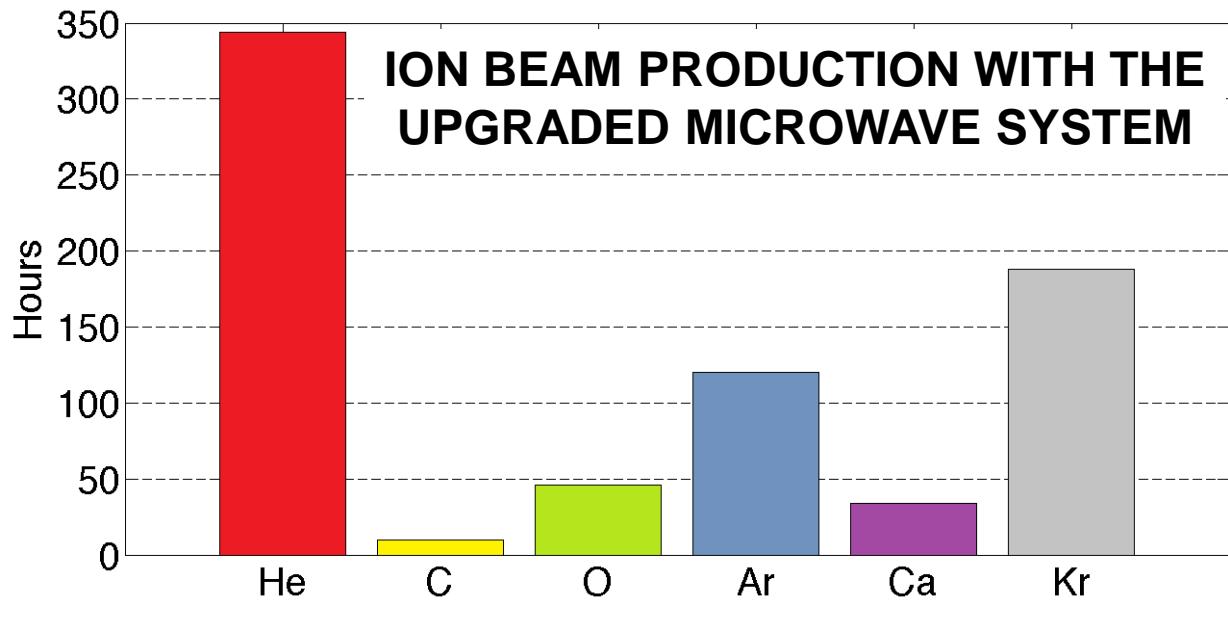


Block diagram describing the main components of the microwave injection system at HLI



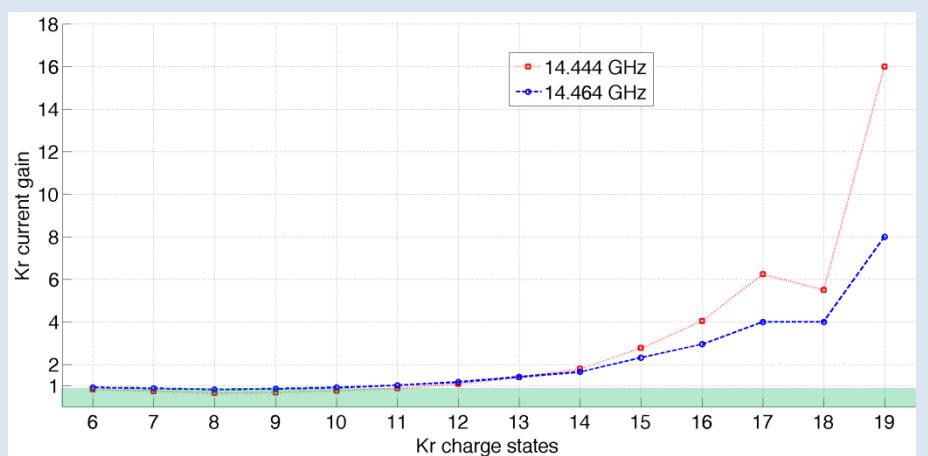
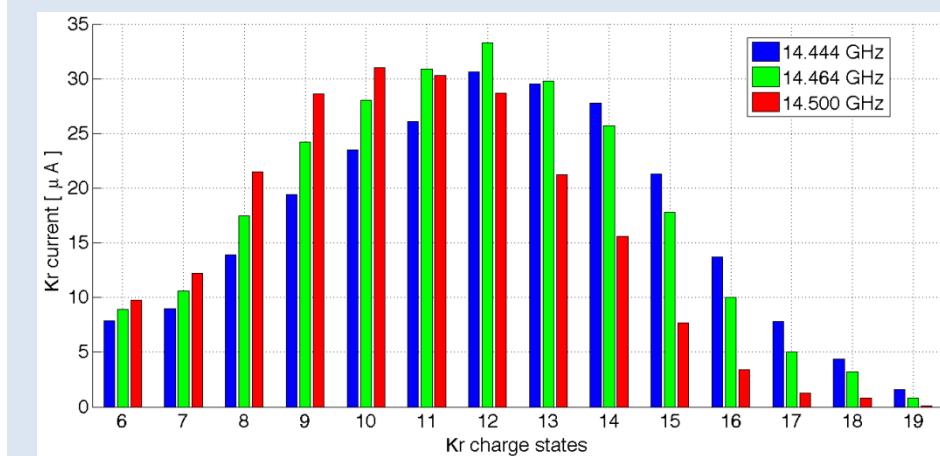
- 2 CPI Traveling Wave Tube Amplifiers: 12.75-14.5 GHz up to 650 W Power
- High isolation WR62 Waveguide Switch
- High Power WR62 3 kW CW Load
- WR62 Waveguide 1.5 kW Power Combiner

# HIGH CHARGE STATES INJECTOR MICROWAVE SYSTEM UPGRADE



### $^{84}\text{Kr}^{13+}$ BEAM

- At 14.464 GHz up to 40% more current of  $^{84}\text{Kr}^{13+}$  provided with respect to the standard operating frequency of 14.500 GHz.
- At 14.444 GHz a  $^{84}\text{Kr}^{19+}$  current gain of 16 times obtained



# CONCLUSIONS AND FUTURE PERSPECTIVES

- A CAPRICE-type ECR Ion Source is routinely used at GSI for the production of high charge state ions of gaseous and metal elements
- The microwave frequency used as an optimizing parameter can strongly modify the charge state distribution thus increasing the ion current of the higher charge states
- The theoretical explanation of the variation of the ion beam properties can be related to variation of the electromagnetic field distribution inside the cavity.
- At the High Charge State Injector of GSI a microwave system including high power wideband amplifiers has been conceived and assembled.
- The frequency tunable devices will be included in the remote control system of GSI.

# THANK YOU FOR YOUR KIND ATTENTION

THE ECRIS TEAM

Ralph Hollinger (Dpt. Leader)

Klaus Tinschert

Ralf Lang

Jan Mäder

Patrick Tedit Patchakui

Me

**POST-DOC POSITION OPEN**

