Status and perspectives of the Advanced Ion Source for Hadrontherapy (AISHa)

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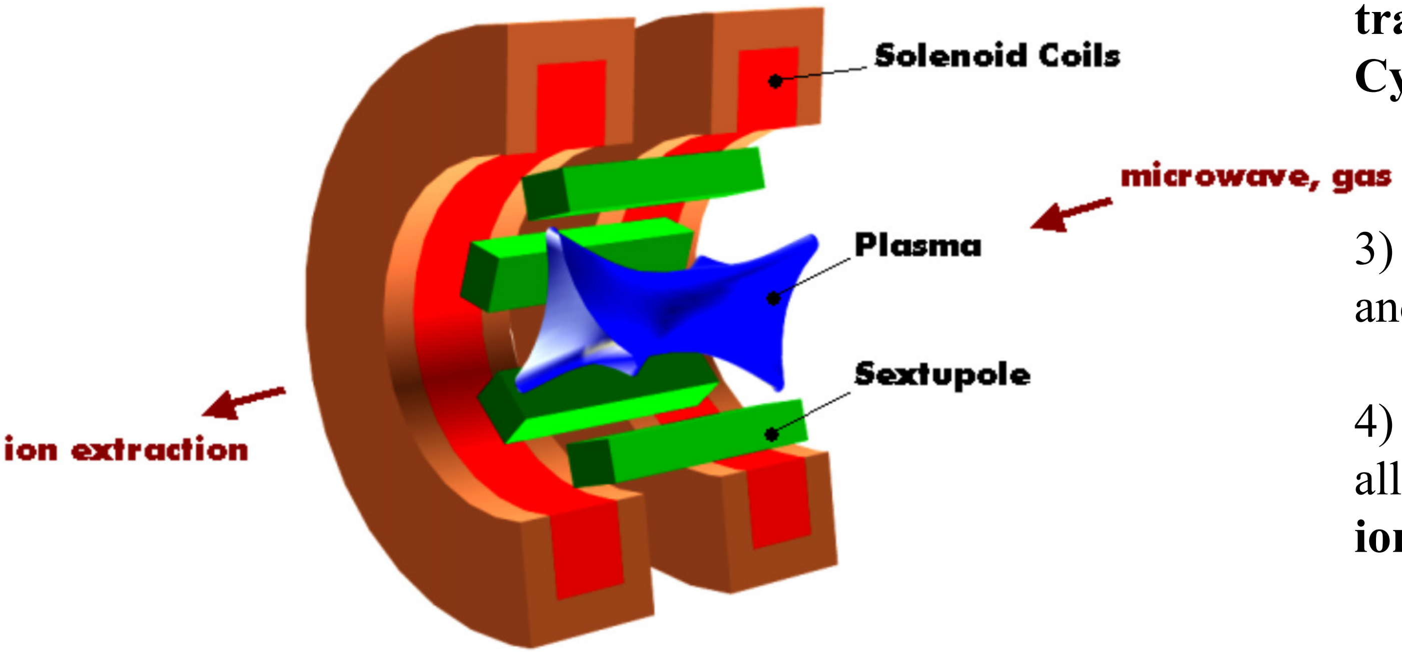
HIAT 2022 | Darmstadt

Outline

- Introduction to Electron Cyclotron Resonance Ion sources (ECRIS)
- The Advanced Ion Source for Hadrontherapy (AISHa)
- The IONS project: from plasma parameters to beam parameters
- The InSPIRIT project: AISHa-2 @Cnao
- Conclusions and perspectives

Electron Cyclotron Resonance Ion sources (ECRIS)

ECRIS are able to generate **high intensity beams** of **highly charged ions** characterized by **low ripple, high reliability and low maintenance**



1) **Electrons flow in a magnetic field** with cyclotron frequency:

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

2) A circularly polarized **EM wave at frequency** ω_{RF} **transfers energy to electrons** if the **Electron Cyclotron Resonance** condition is satisfied:

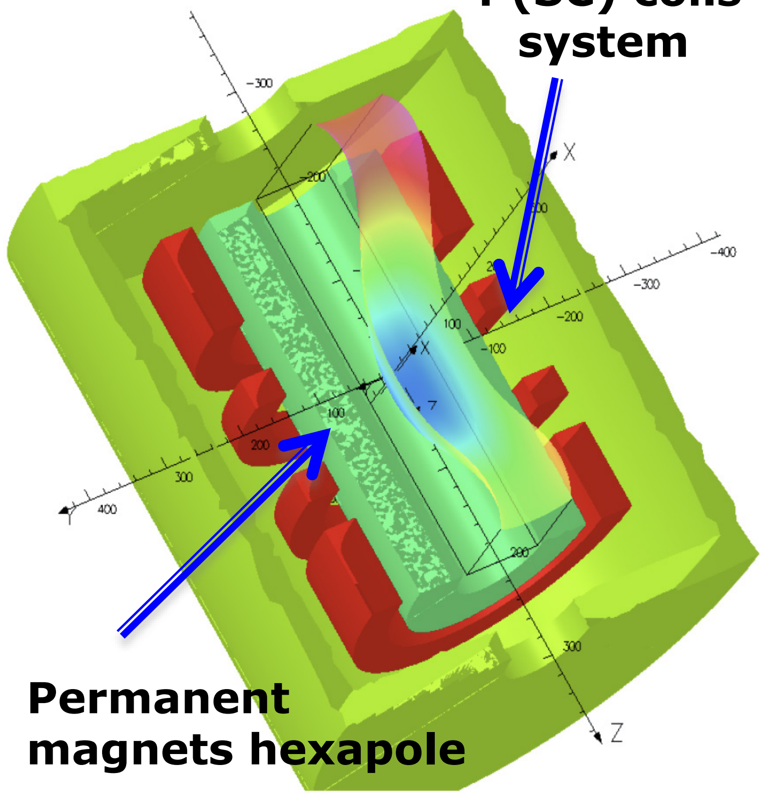
$$\omega_{RF} = \omega_C$$

3) Energetic electrons trigger a step by step **ionization** and **plasma is generated;**

4) **Magnetic plasma confinement** (coils + sextupole) allows increasing plasma lifetime τ_i **to increase mean ion charge state** <q>:

$$< q > \propto \tau_i$$

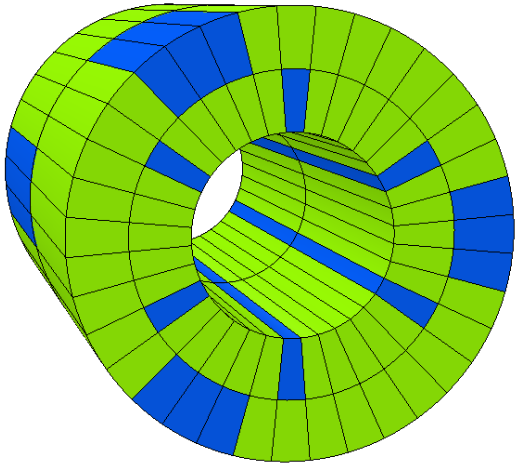
AISHA: the Advanced Ion Source for Hadrontherapy



AISHA is a hybrid ECRIS: the radial confining field is obtained by means of a permanent magnet hexapole, while the axial field is obtained with a **Helium-free superconducting system.**

The **operating frequency of 18 GHz will permit** to maximize the plasma density by employing commercial microwave tubes meeting the **needs of the installation in hospital** environments.

Radial field	1.3 T
Axial field	2.7 T - 0.4 T - 1.6 T
Operating frequencies	18 GHz – 21 GHz
Operating power	1.5 + 1.5 kW (max)
Extraction voltage	40 kV (max)
Chamber diameter / length	Ø 92 mm / 360 mm
LHe	Free
Warm bore diameter	274 mm
Source weight	1400 kg



Green= VAC 745 HR
Blue= VAC677 HR

Grain boundary diffusion process to enhance coercitivity on both materials to avoid demagnetization issues

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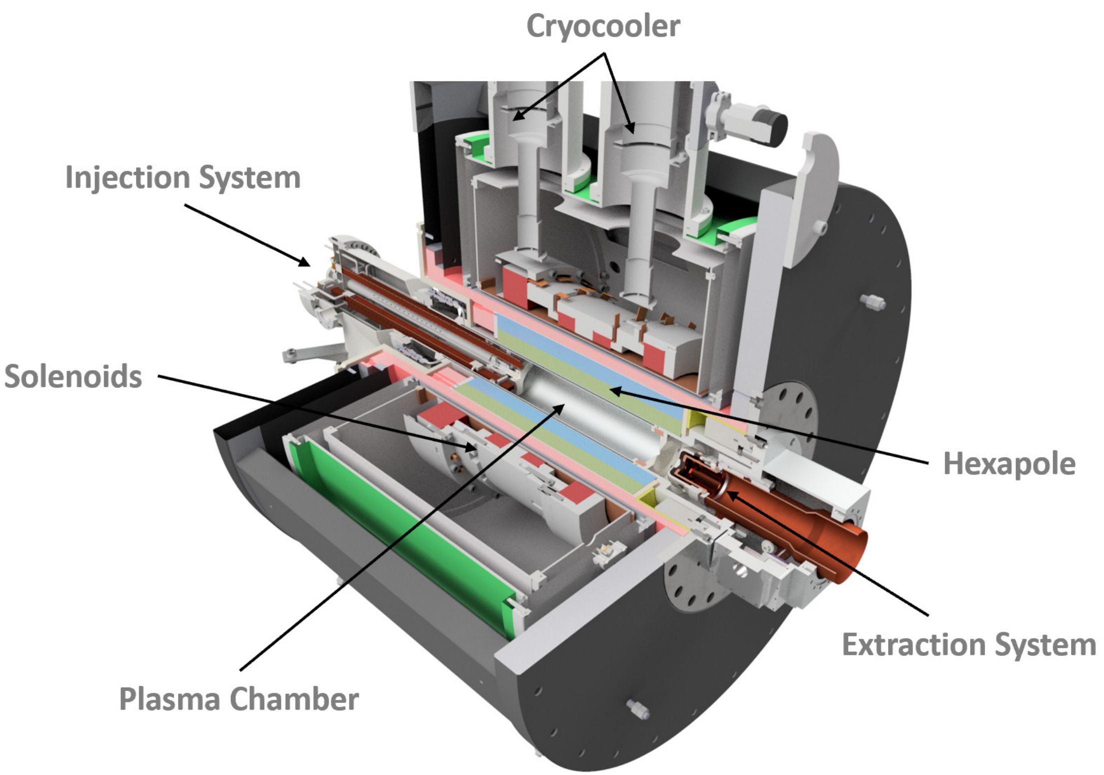
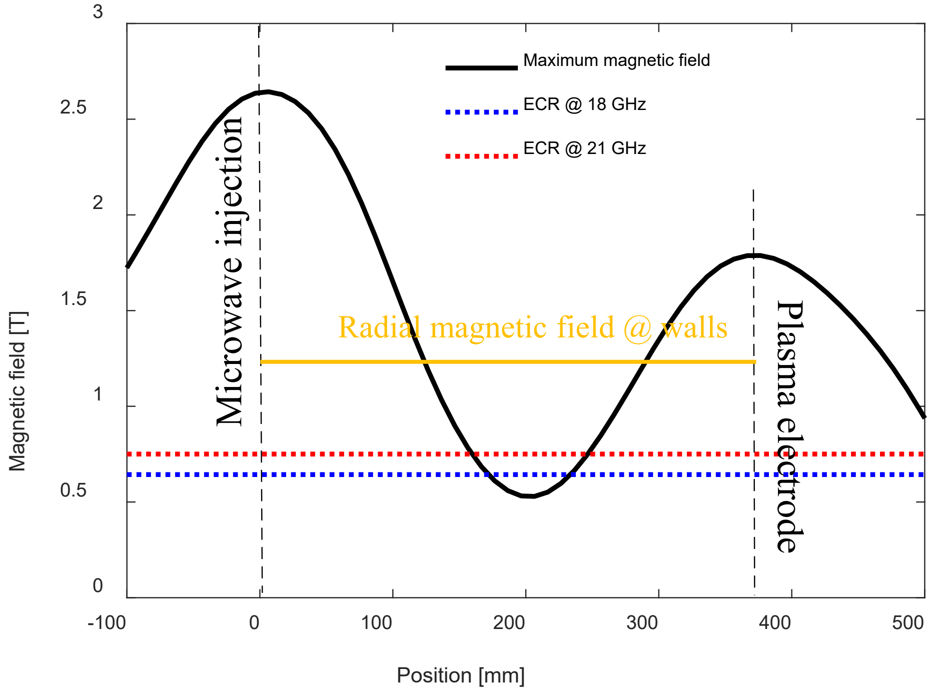
AISHA: the Advanced Ion Source for Hadrontherapy

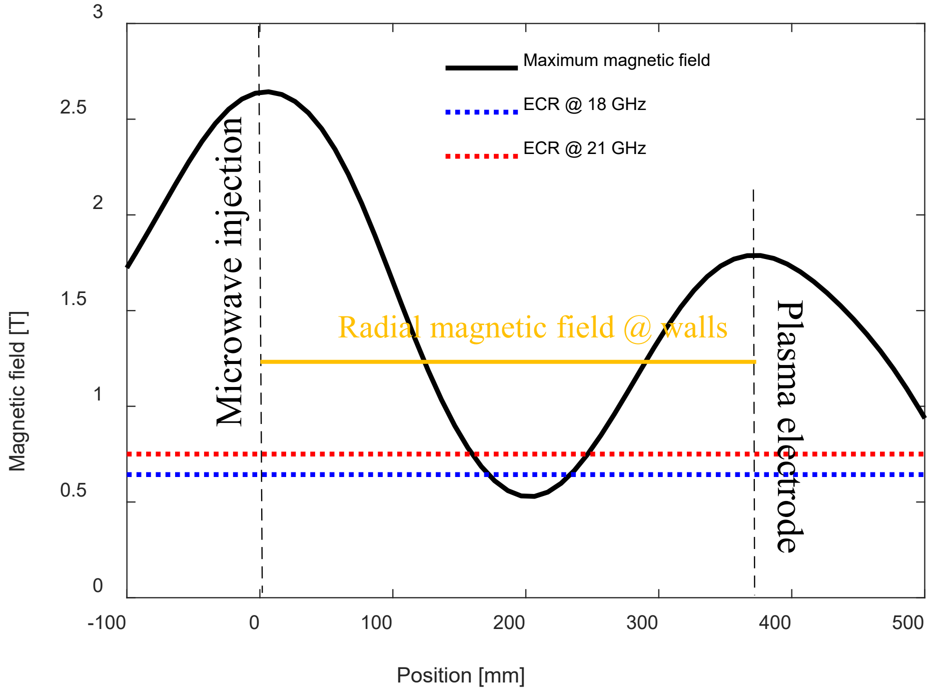




The beam structure depends on the plasma structure

- **Maximum flexibility on the frequency**
  (the plasma structure changes with the cavity frequency)
- **Maximum flexibility on the axial B-field**
  (no matter about the radial one, it is less influent)

AISHA: the Advanced Ion Source for Hadrontherapy



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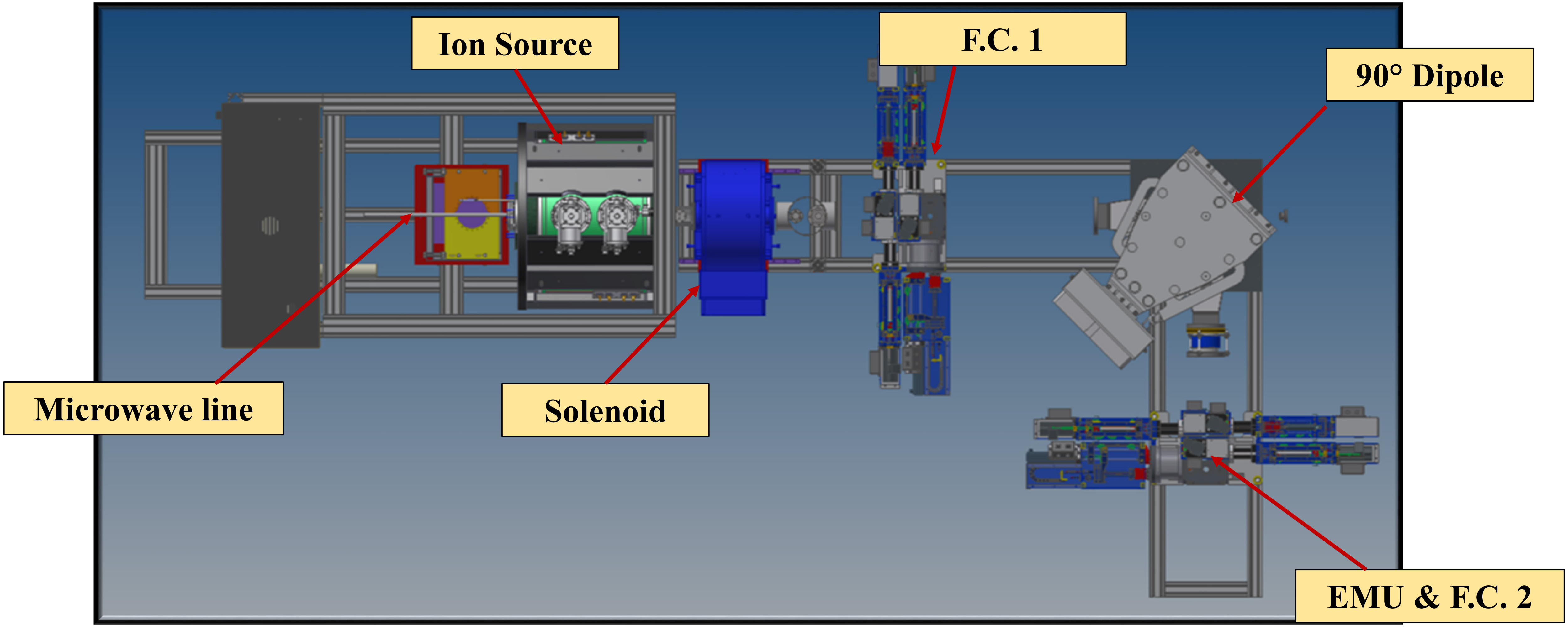
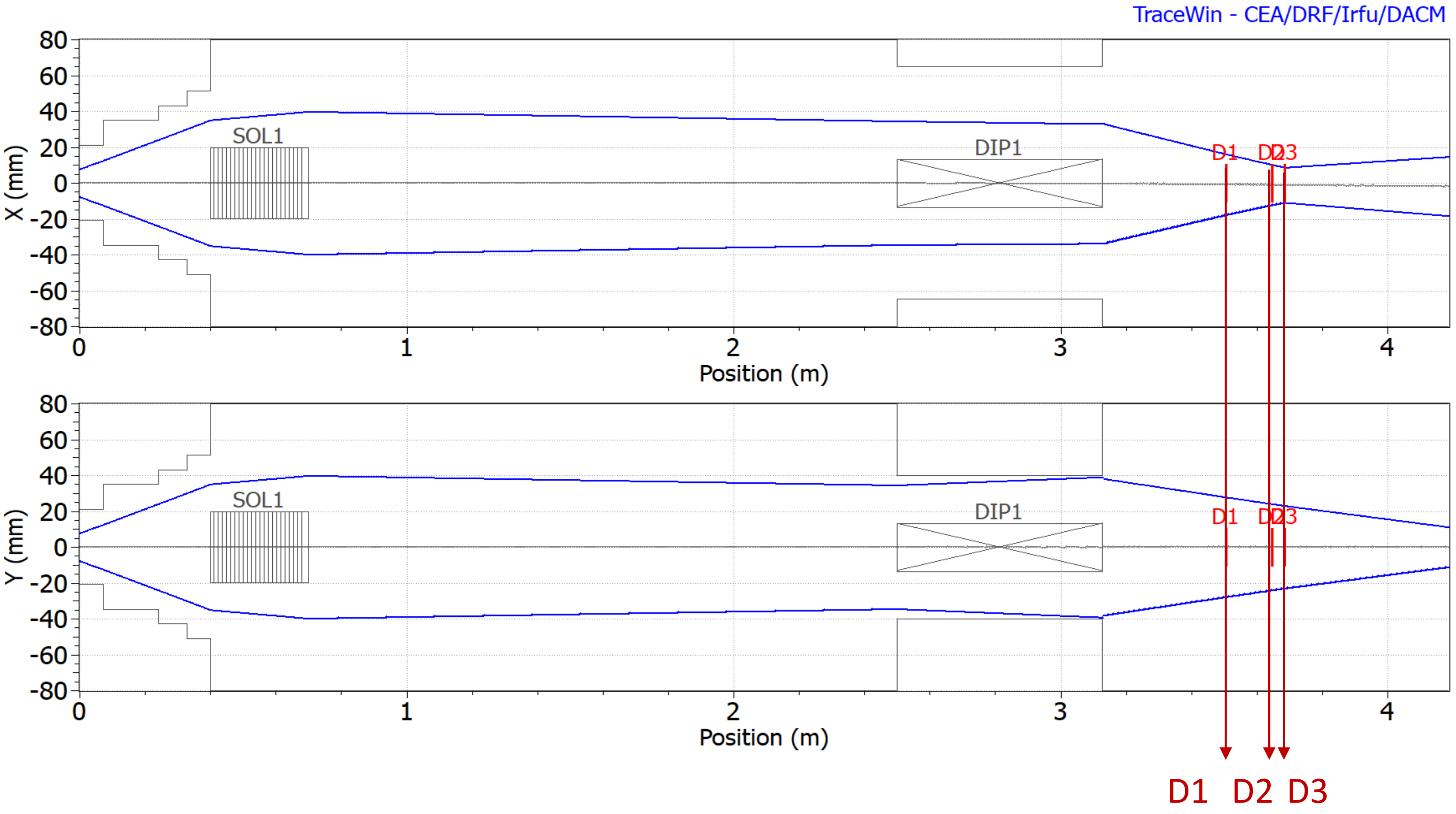
Render view of the AISHa Ion Source and LEBT



AISHa LEBT and Transport

Example of C^{4+} beam transport



Charge State Distribution measured by Faraday Cup

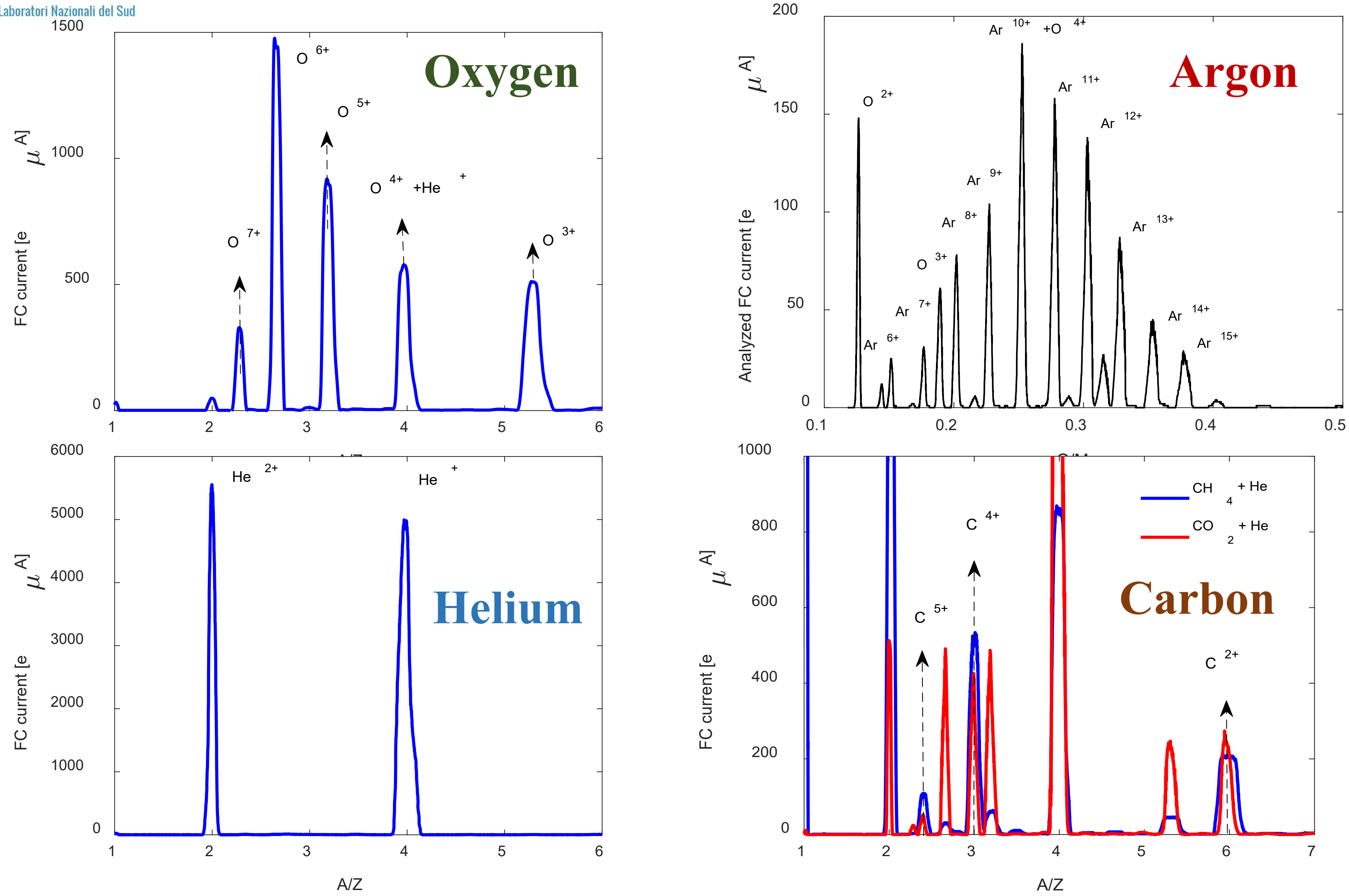
Rms normalized emittance has been measured by a home-made Emittance Measurement Unit (EMU) constituted by a system of 2 slits + 2 wires.

D1: EMU slits

D2: EMU wires

D3: Faraday Cup

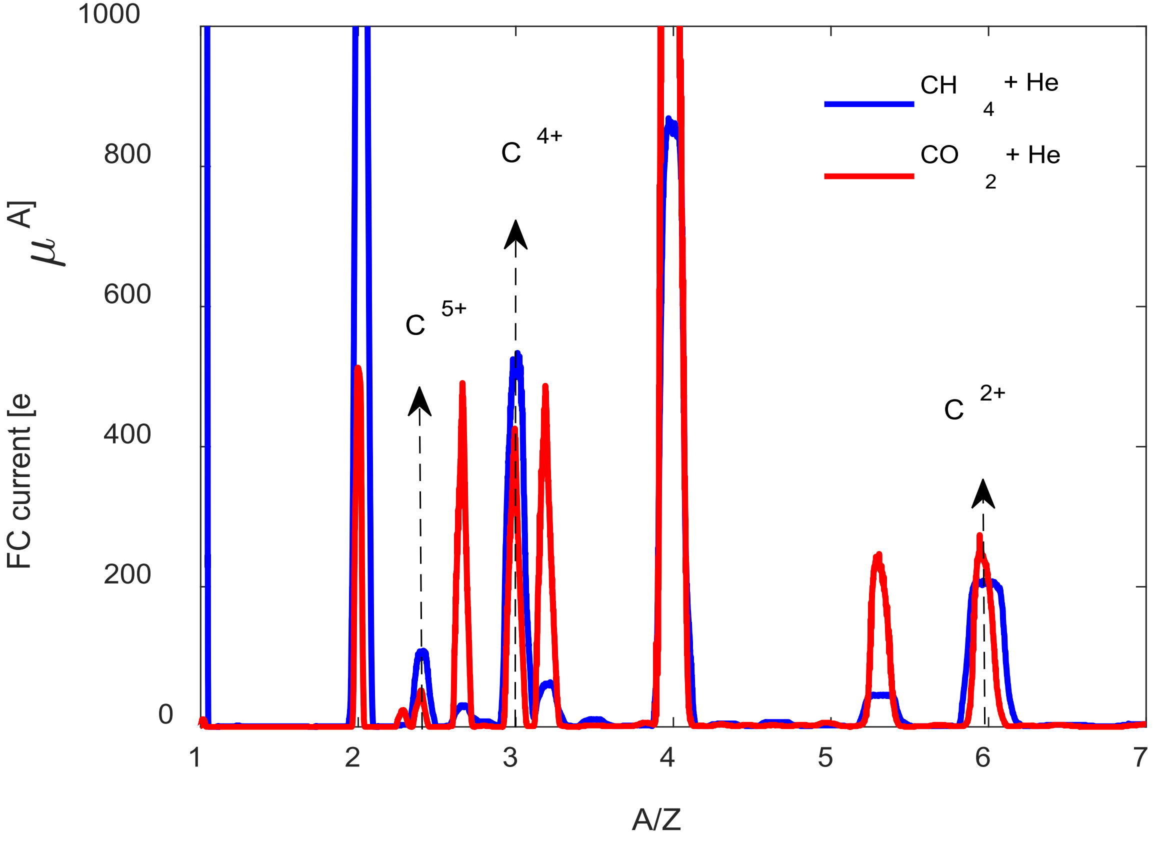
Results from AISHa commissioning: CSD



Charge State Distribution (CSD) of main beams commissioned on the AISHa test bench @18 GHz
MW power: 1.4 kW maximum

Charge state	Beam intensity [eμA]
$^{16}O^{6+}$	1450
$^{16}O^{7+}$	350
$^{16}O^{8+}$	100
$^{12}C^{4+}$	520
$^{12}C^{5+}$	165
$^{40}Ar^{11+}$	155
$^{40}Ar^{12+}$	140
He^{2+}	5400

Results from AISHa commissioning: Carbon CSD



Best peak performance of the CH_4 + He set-up due to the gas mixing effect

CH_4 + He set-up

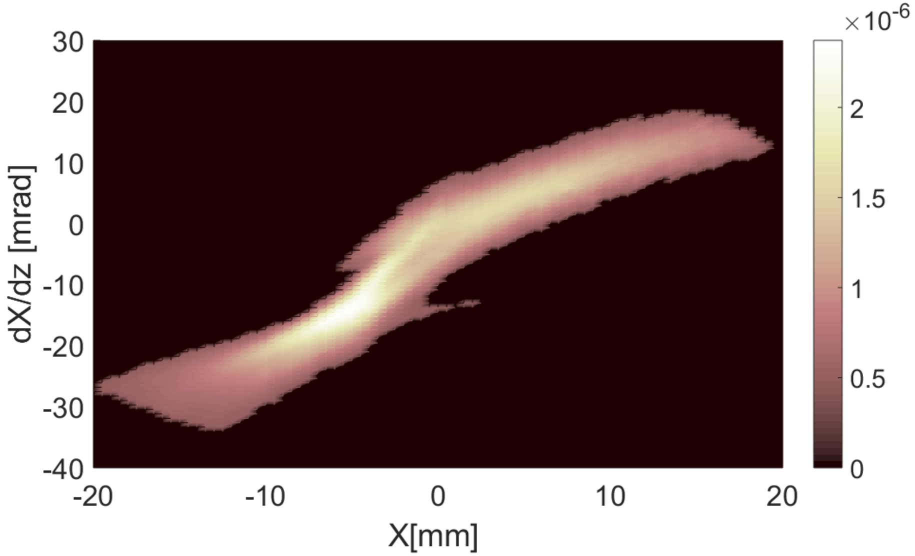
- **Higher peak current: 520 $e\mu A$ (> 20% $w.r.t.$ CO_2 + He);**
- Less stability regions in the source configuration space (high drain currents);
- Higher maintenance (methane covers ion source surfaces)

CO_2 + He set up

- Lower peak current: 420 $e\mu A$
- **More stability regions in the source configuration space;**
- **Lower maintenance w.r.t methane**

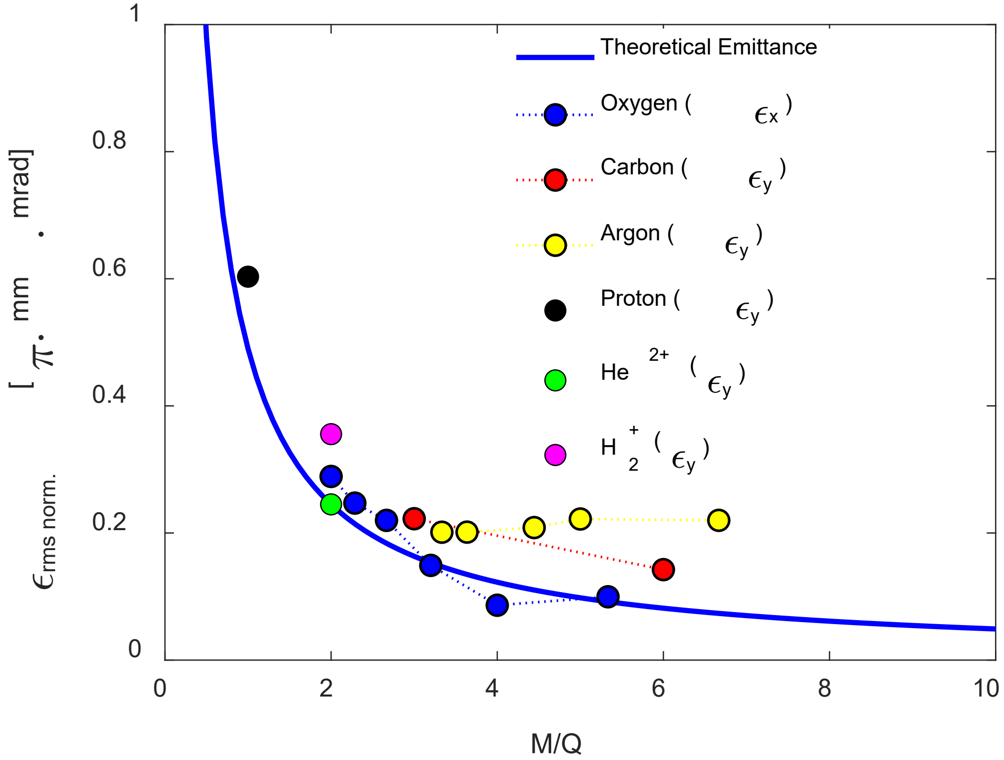
Results from AISHa commissioning: rms norm. emittance measurements

The emittance is the measure of the beam dimensions in the phase space: Invariant for the Liouville's theorem



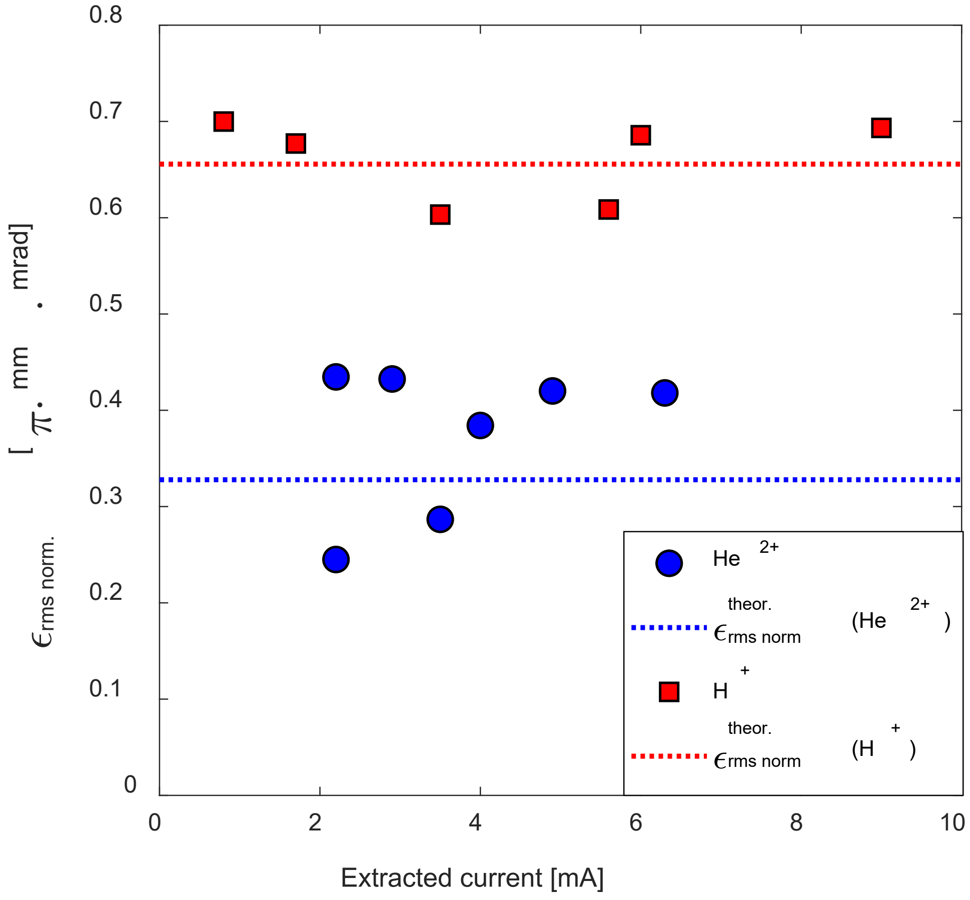
$$\varepsilon^{theor.}_{rms.norm} = 0.032r^2\frac{B_{extr}}{M/Q} + 0.016r\sqrt{\frac{T_i}{M/Q}}$$

neglected term

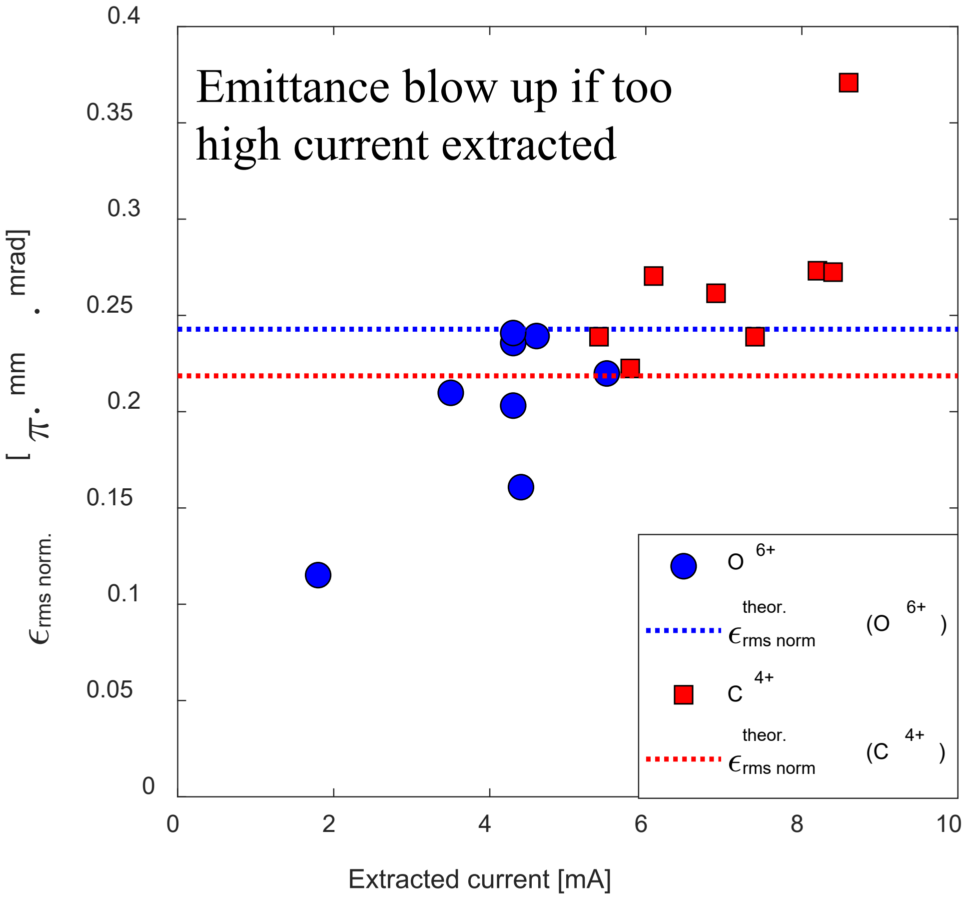


Results from AISHa commissioning: rms norm. emittance measurements

Emittance of fully ionized ions H^+, He^{2+} independent of current.



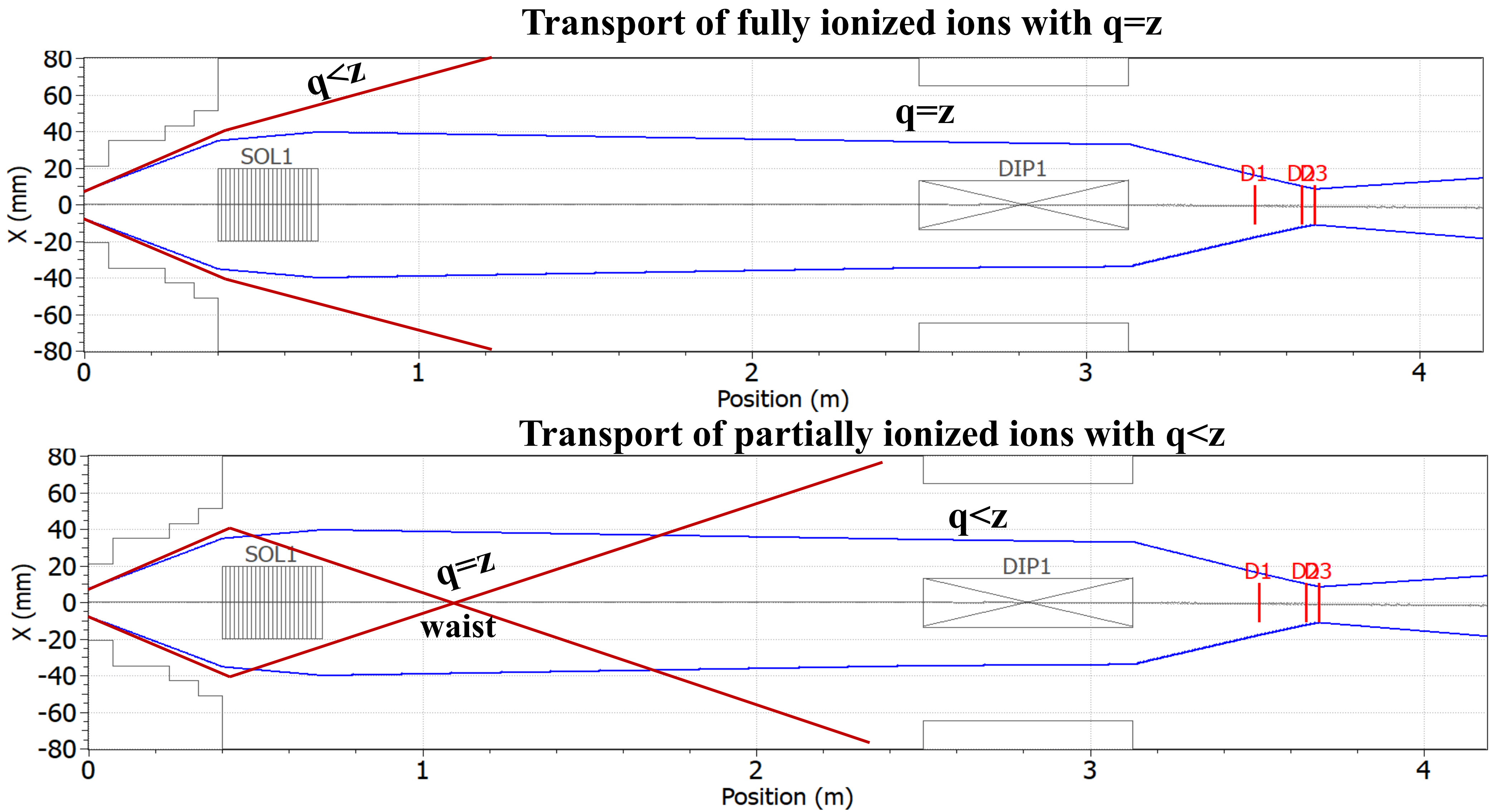
Emittance of partially ionized gas dependent on current



Emittance blow-up due to overfocusing of fully ionized ions

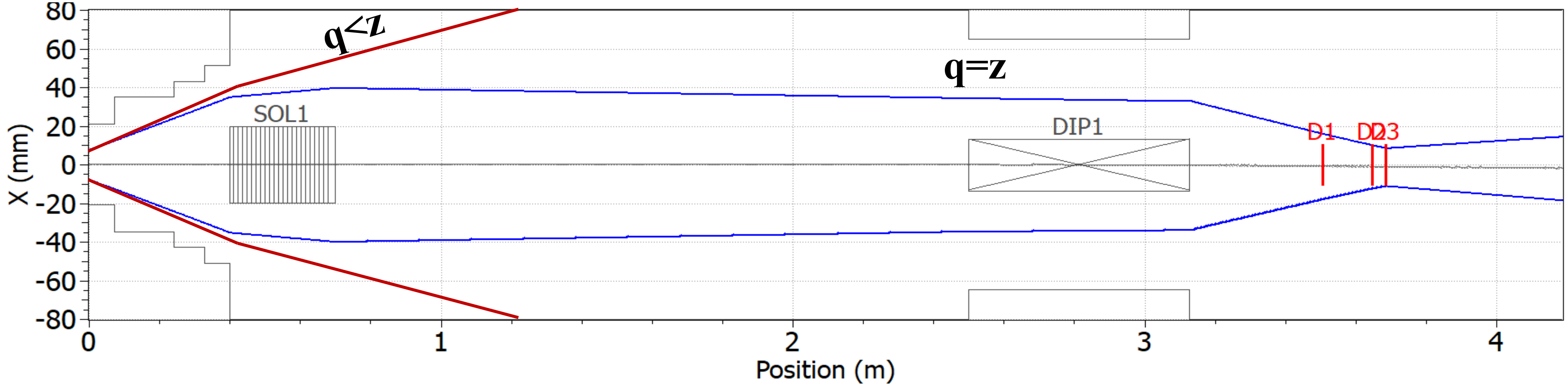
Magnetic rigidity in ion source

$$B\rho \propto \sqrt{\frac{2m\Delta V}{q}}$$



Emittance blow-up due to overfocusing of fully ionized ions

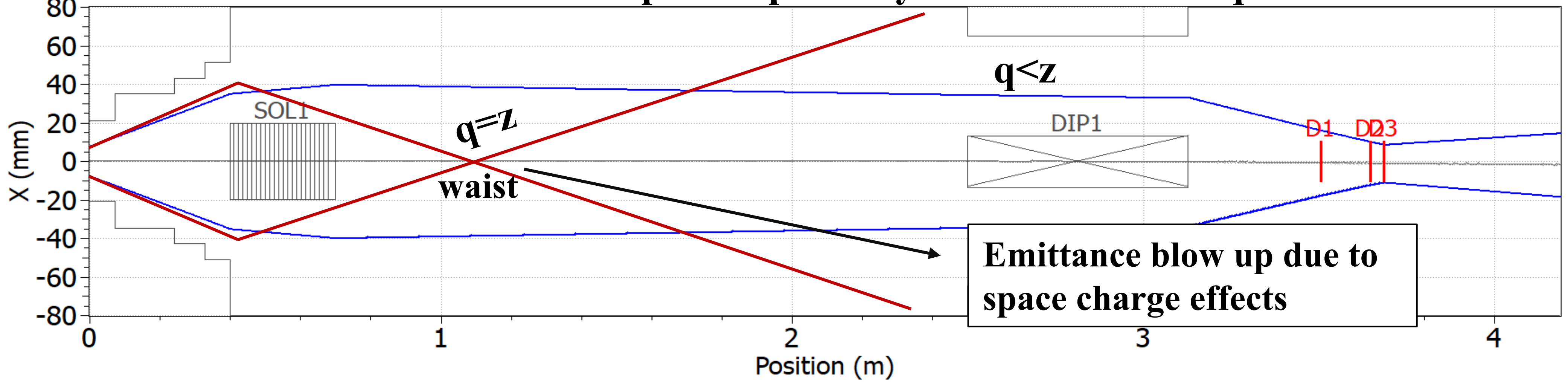
Transport of fully ionized ions with q=z



Magnetic rigidity in ion source

$$B\rho \propto \sqrt{\frac{2m\Delta V}{q}}$$

Transport of partially ionized ions with q<z



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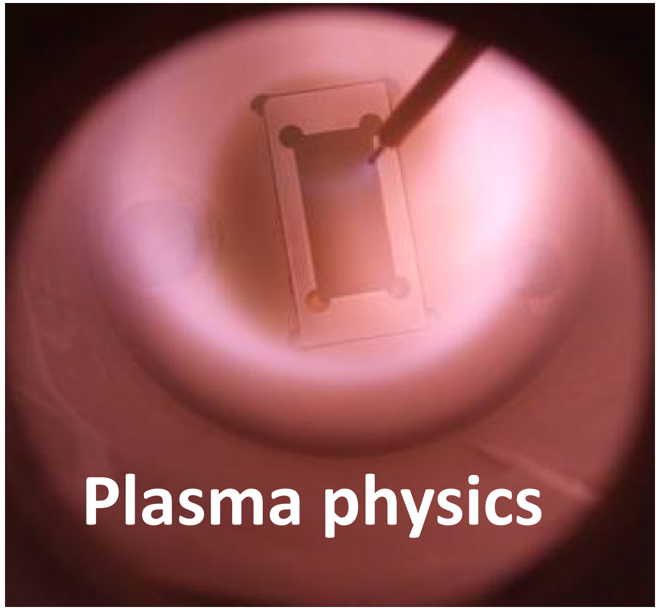
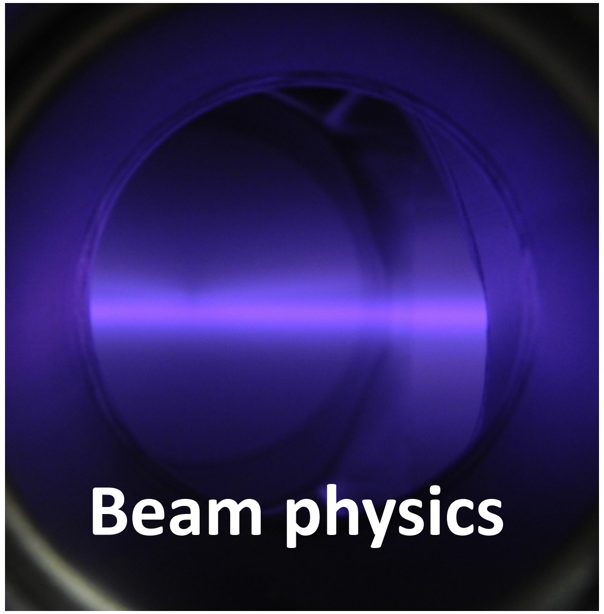
- **The IONS project: from plasma parameters to beam parameters**

R&D on ECRIS
AISHa as testbench of the IONS Experiment



Univocally defined but "complicated" relationship



Plasma properties

Electron density n_e, ion densities n_i, electron temperature t_e, ion temperature t_i, confinement time, etc.

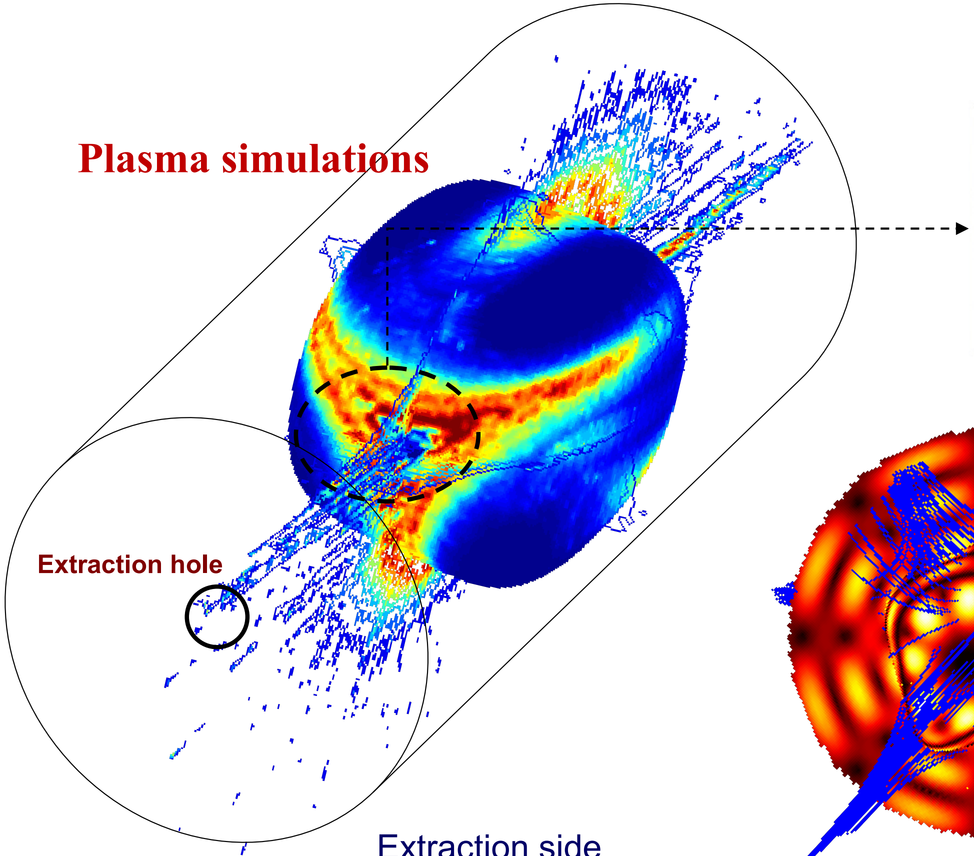
Beam properties

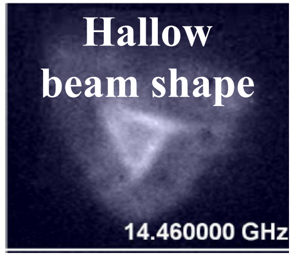
Extracted current, charge state distribution, rms emittance, beam shape, beam energy spread, etc.

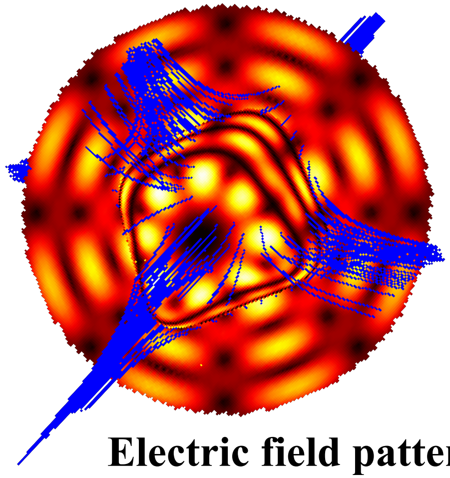
From plasma to beam parameters what already done

Beam shape in LEBT affected by electric field pattern in plasma chamber: Caprice (GSI) 2006.

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







Electric field pattern

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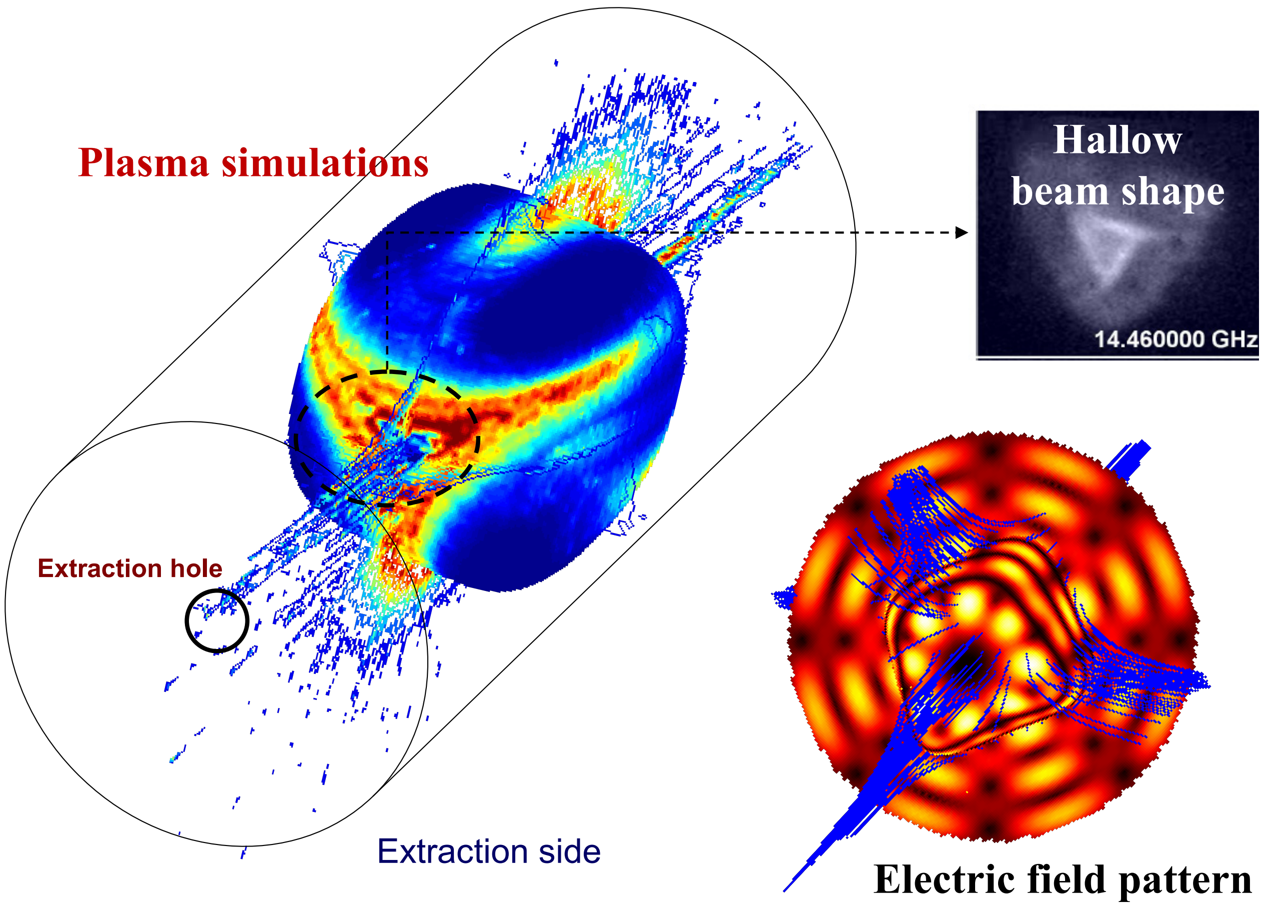
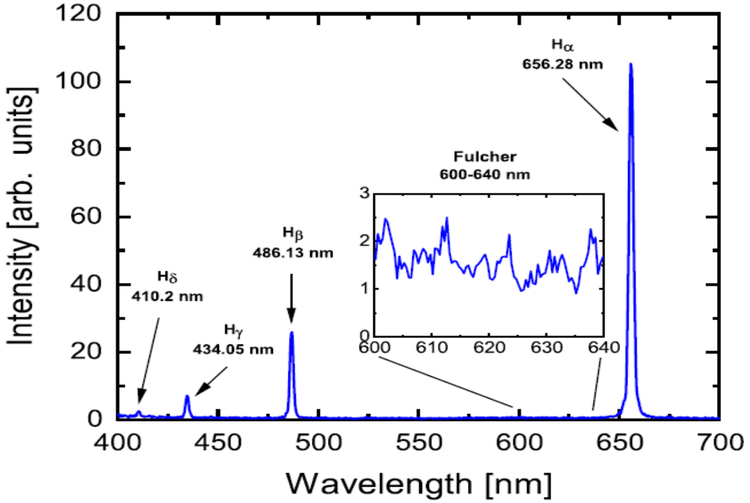


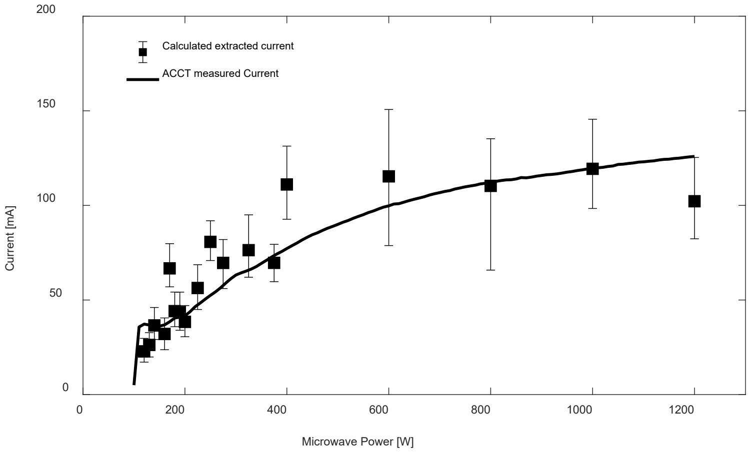
Extracted current and species fraction estimated by OES plasma parameters in the ESS Proton Source

G. Castro, Phyis. Rev AB. 23, 093402 (2020)



Plasma parameters evalauted by OES of a Hydrogen plasma: Balmer lines + Fulcher band

Beam properties (current and species fraction evaluated) calculated by solving 0D balance equation in plasma



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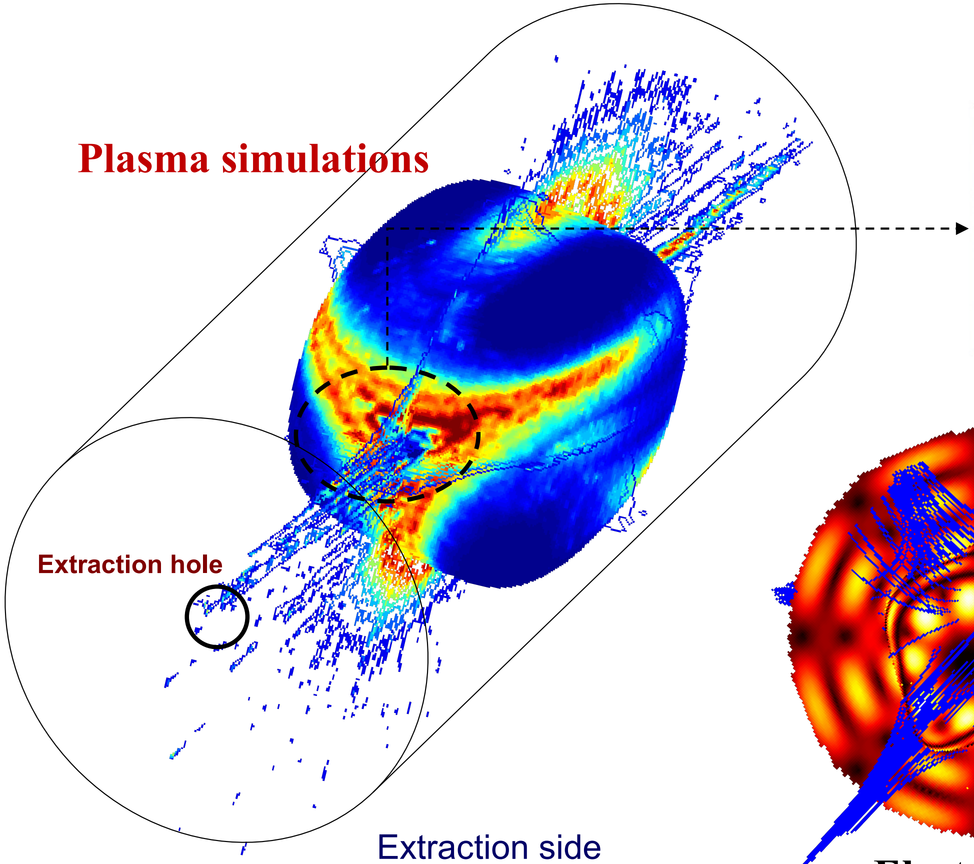

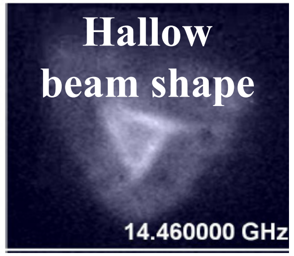

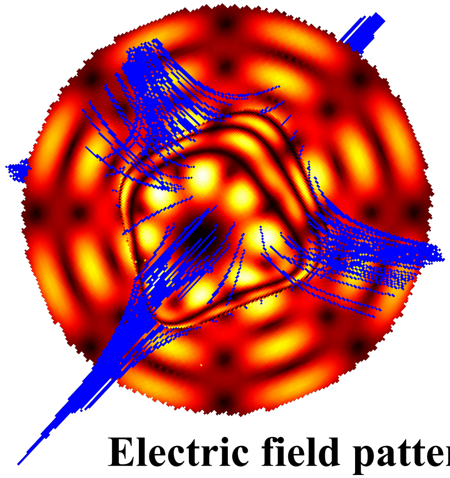

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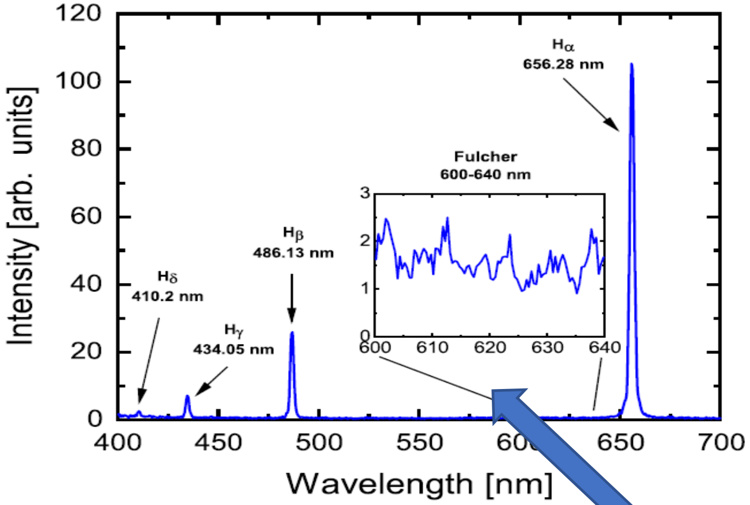

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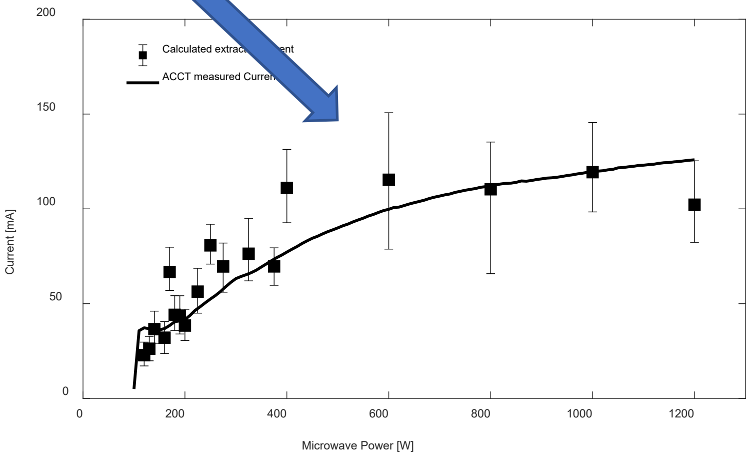

From plasma to beam parameters
Goals of the IONS Experiment -1

Balance equations for an ion having charge state q and number density n^q in equilibrium conditions:

A Balance equation for any charge state q ⟶ non-linear equation system

G. Shirkov et al., NIM A, 302, no. 1, pp. 1–5, 1991

$$\frac{dn^q}{dt} = <\sigma v>^{inz}_{q-1\to q} n_e n^{q-1} - <\sigma v>^{inz}_{q\to q+1} n_e n^q + <\sigma v>^{cx}_{q+1\to q} n_0 n^{q-1} - <\sigma v>^{cx}_{q\to q-1} n_0 n^q - \frac{n^q}{\tau^q} = 0$$

$$<\sigma v> = <\sigma v>(T_e) = \int_{-\infty}^{\infty} \sigma f(v) v\, dv$$

σ cross section, f(v) electron distribution function

Reaction rate coefficient

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Ionization processes

Creation **Destruction**

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Charge exchange processes — **Creation** / **Destruction**

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Ionization processes (Creation, Destruction) — **Charge exchange processes** (Creation, Destruction) — **Plasma losses**

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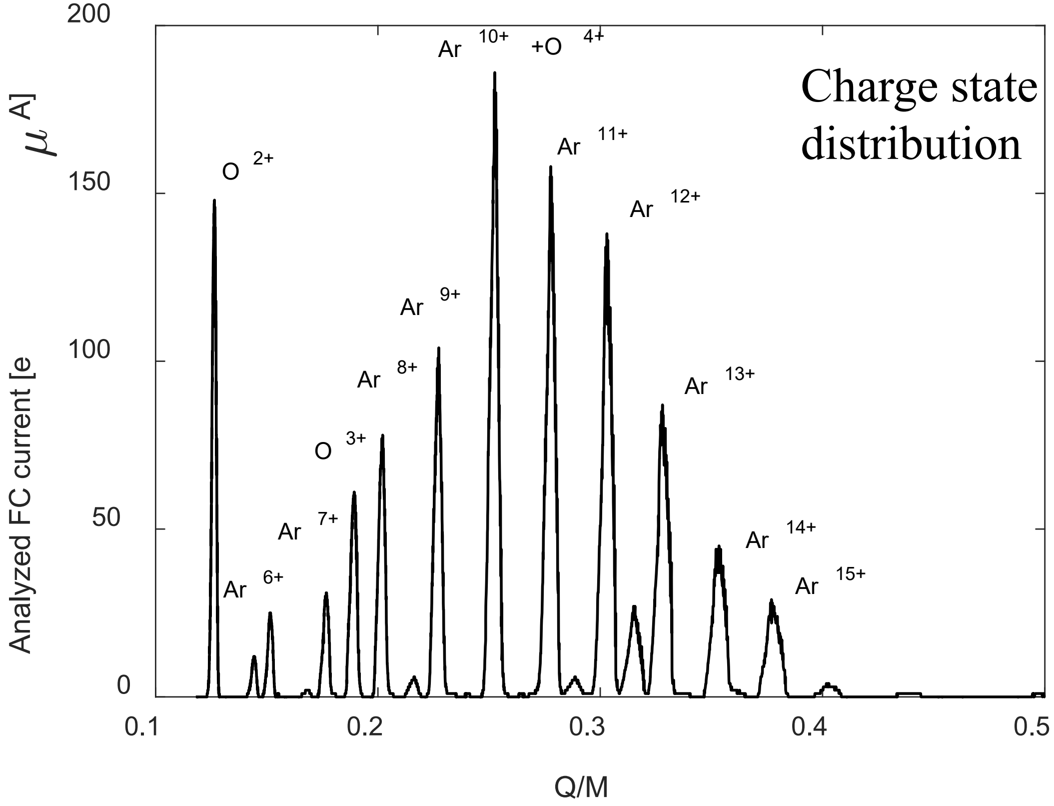
σ cross section, f(v) electron distribution function

Reaction rate coefficient

If cross sections are known (theoretical values), the measure of n_e, t_e, n_0 (pressure) and n^q in plasma can enable to estimate the beam Charge State Distribution

From plasma to beam parameters Goals of the IONS Experiment -1



Benefit of this approach:

- better understand of the source behavior;
- Development of softwares to control the source and the oven;
- Optimization of source operations;

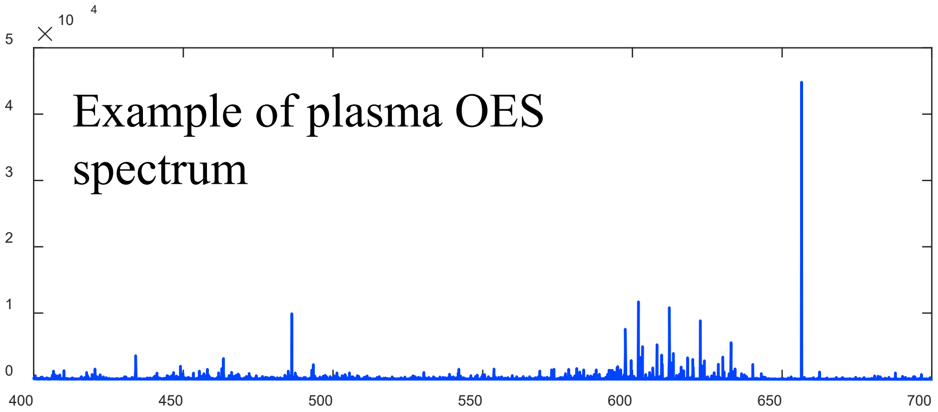
If cross sections are known (<u>theoretical values</u>), the measure of n_e, t_e, n_0 (pressure) and n^q in plasma can enable to estimate the beam <u>Charge State Distribution</u>

R&D on ECRIS
Optical Emission Spectroscopy

Why Optical Emission Spectroscopy (OES)?

OES is a **non-invasive diagnostics** that does **not affect the plasma** and **is not affected by the plasma!**

Just plasma light needed!

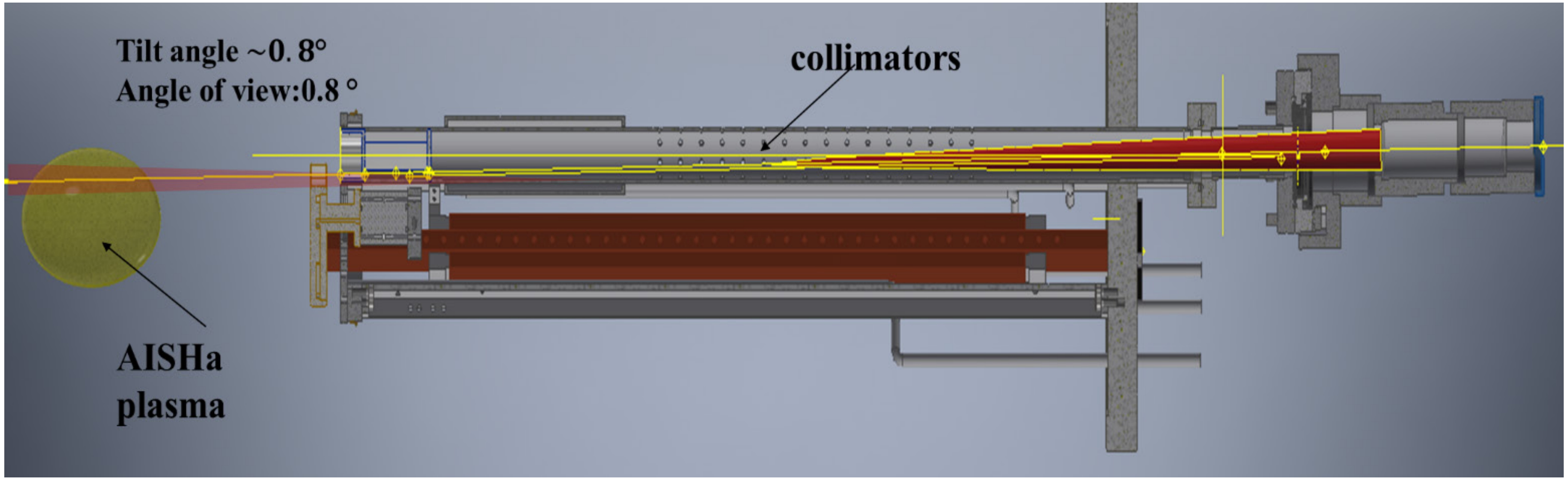


Observable		Obtainable
Emission line shift		Ion drift velocity
Broadening	Doppler	T_i
	Stark	n_e
Splitting Zeeman		Magnetic field
Intensity ratios		T_e, n_e, $N(H)/N(H_2)$
Intensity		N_i

Spectrometer Horiba iHR550

Spectral Range	*150 to 1500 nm w appropiate grating*
Resolution	*~0.04 nm*
Aperture	*f/6.4*
Focal Length	*550 mm*
Scan speed	*160 nm/sec*

Optical coupling for OES diagnostics in the AISHa test-bench



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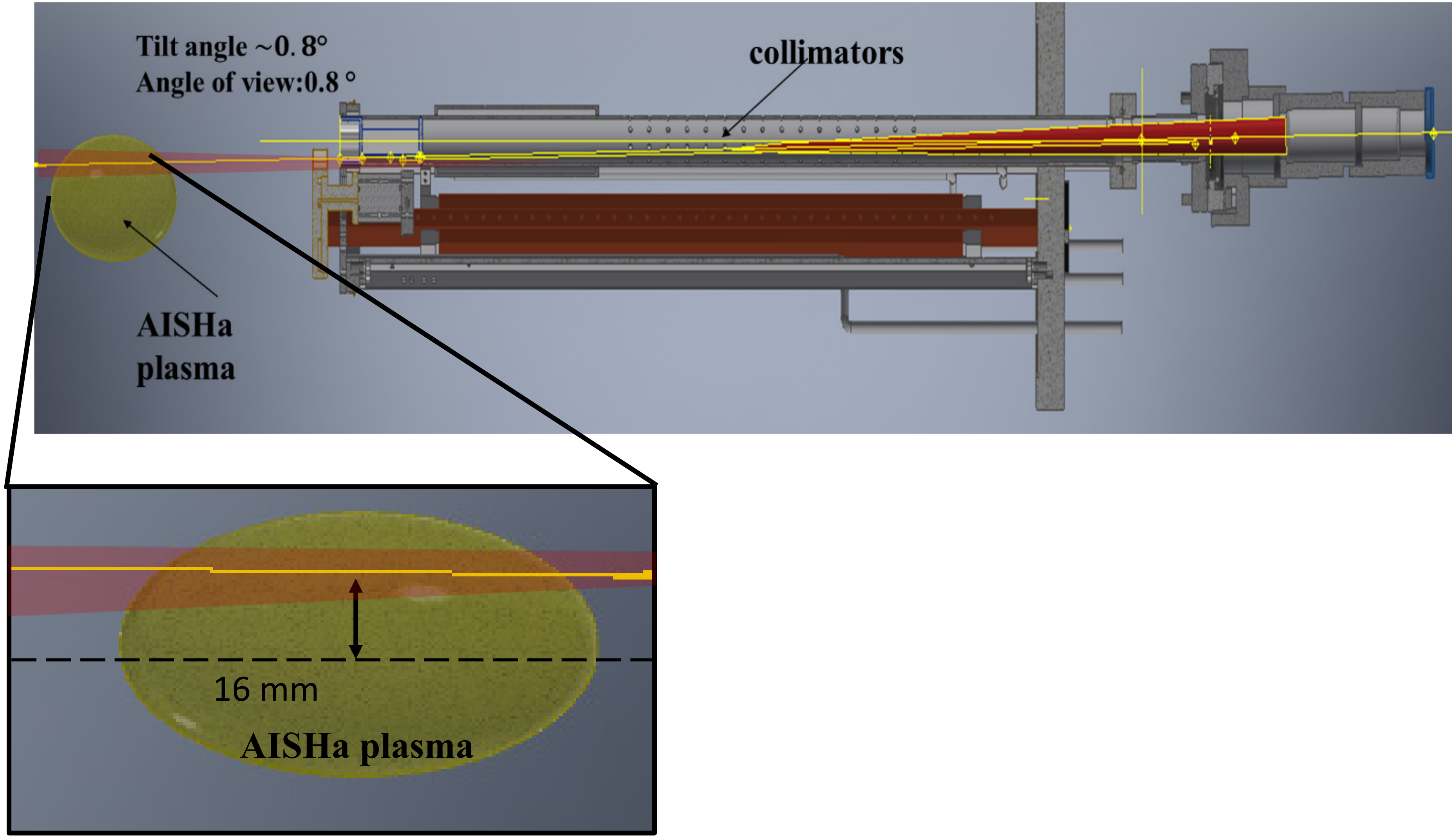

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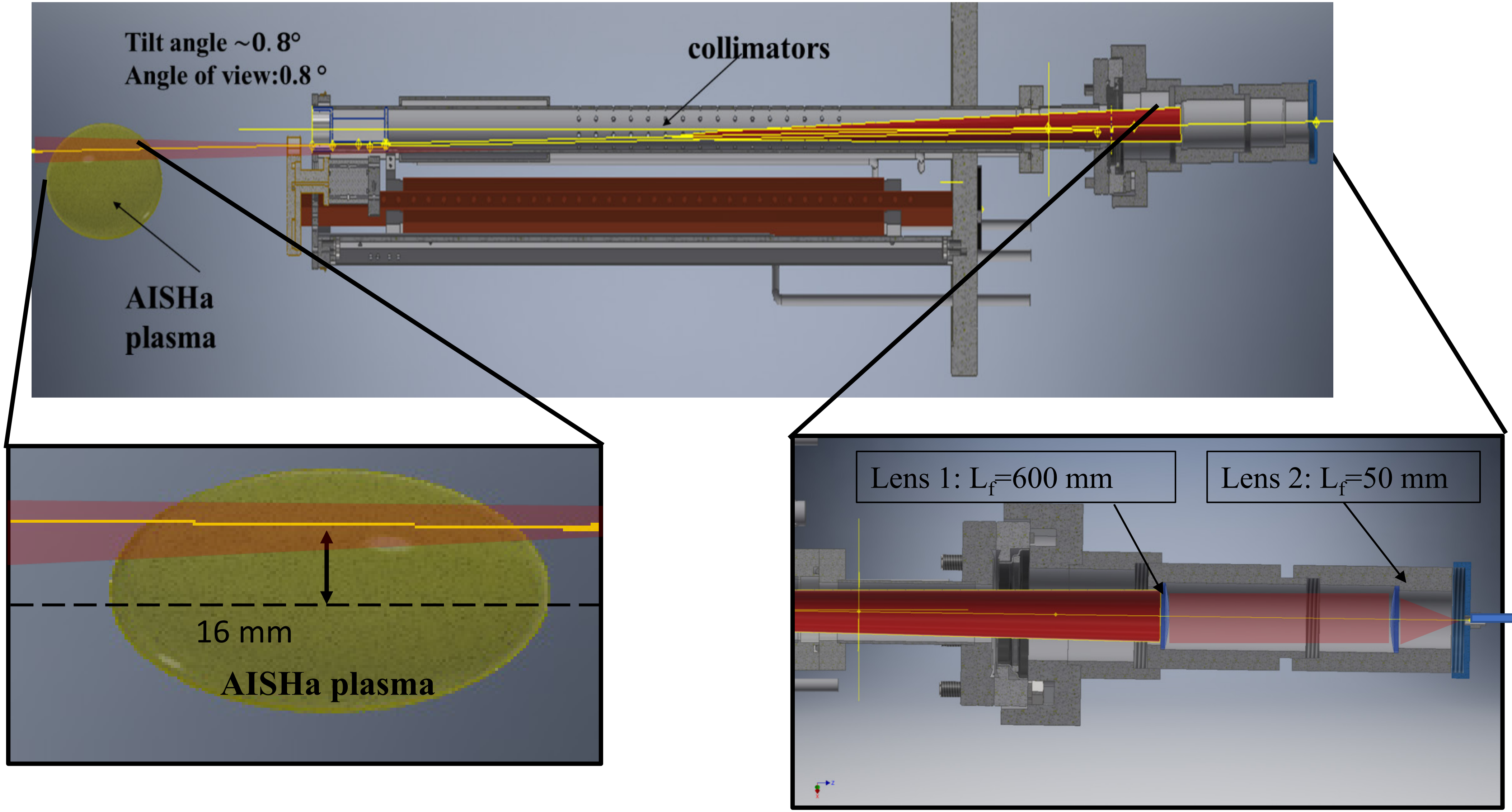

R&D on ECRIS
Goals of the IONS Experiment -2

Ionization processes — **Creation** / **Destruction**

Charge exchange processes — **Creation** / **Destruction**

Plasma losses

$$\frac{dn^q}{dt} = <\sigma v>^{inz}_{q-1\to q} n_e n^{q-1} - <\sigma v>^{inz}_{q\to q+1} n_e n^q + <\sigma v>^{cx}_{q+1\to q} n_0 n^{q-1} - <\sigma v>^{cx}_{q\to q-1} n_0 n^q - \frac{n^q}{\tau^q} = 0$$

Reduction of plasma losses increases the densities of highly charged ions in plasmas!

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AISHa

R&D on ECRIS
Goals of the IONS Experiment -2

Ionization processes (Creation, Destruction) — **Charge exchange processes** (Creation, Destruction) — **Plasma losses**

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Reduction of plasma losses increases the densities of highly charged ions in plasmas!

Plasma losses depend on

1. *Magnetic configuration*
2. *Electric field at ECR surf.*
3. *Plasma diffusion*

R&D on ECRIS
Goals of the IONS Experiment -2

Ionization processes (Creation | Destruction) — **Charge exchange processes** (Creation | Destruction) — **Plasma losses**

$$\frac{dn^q}{dt} = <\sigma v>^{inz}_{q-1\rightarrow q} n_e n^{q-1} - <\sigma v>^{inz}_{q\rightarrow q+1} n_e n^q + <\sigma v>^{cx}_{q+1\rightarrow q} n_0 n^{q-1} - <\sigma v>^{cx}_{q\rightarrow q-1} n_0 n^q - \frac{n^q}{\tau^q} = 0$$

Reduction of plasma losses increases the densities of highly charged ions in plasmas!

Plasma losses depend on

1. *Magnetic configuration* — **Almost optimized (B min. config.)**
2. *Electric field at ECR surf.*
3. *Plasma diffusion*

R&D on ECRIS
Goals of the IONS Experiment -2

Ionization processes (Creation | Destruction) — **Charge exchange processes** (Creation | Destruction) — **Plasma losses**

$$\frac{dn^q}{dt} = <\sigma v>^{inz}_{q-1\to q} n_e n^{q-1} - <\sigma v>^{inz}_{q\to q+1} n_e n^q + <\sigma v>^{cx}_{q+1\to q} n_0 n^{q-1} - <\sigma v>^{cx}_{q\to q-1} n_0 n^q - \frac{n^q}{\tau^q} = 0$$

Reduction of plasma losses increases the densities of highly charged ions in plasmas!

Plasma losses depend on

1. *Magnetic configuration* — **Almost optimized (B min. config.)**
2. *Electric field at ECR surf.* — **Almost optimized (2-3 freq. Heating)**
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R&D on ECRIS
Goals of the IONS Experiment -2

Ionization processes: Creation, Destruction

Charge exchange processes: Creation, Destruction

Plasma losses

$$\frac{dn^q}{dt} = <\sigma v>^{inz}_{q-1\rightarrow q} n_e n^{q-1} - <\sigma v>^{inz}_{q\rightarrow q+1} n_e n^q + <\sigma v>^{cx}_{q+1\rightarrow q} n_0 n^{q-1} - <\sigma v>^{cx}_{q\rightarrow q-1} n_0 n^q - \frac{n^q}{\tau^q} = 0$$

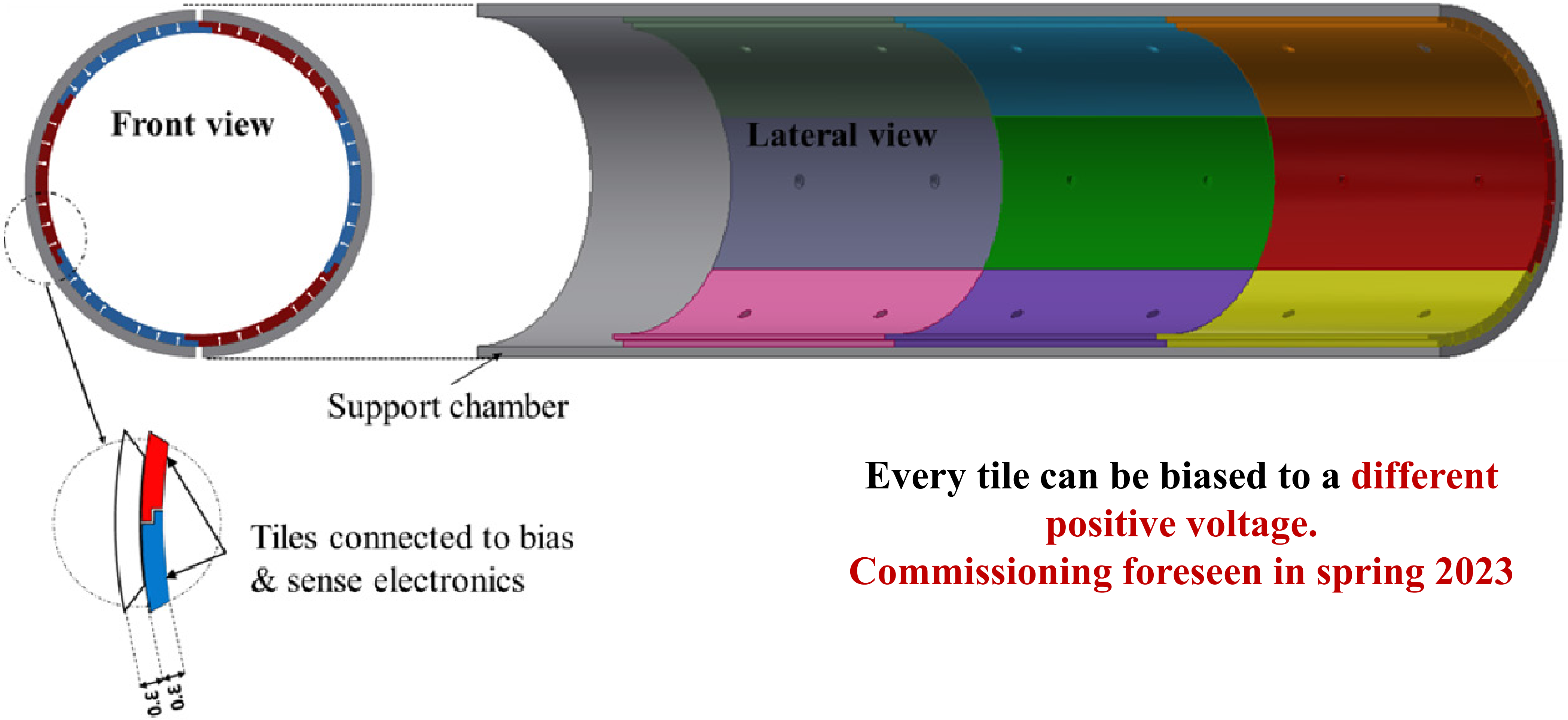
Reduction of plasma losses increases the densities of highly charged ions in plasmas!

Plasma losses depend on

1. *Magnetic configuration* — **Almost optimized (B min. config.)**
2. *Electric field at ECR surf.* — **Almost optimized (2-3 freq. Heating)**
3. *Plasma diffusion* — **Room for improvement!**

R&D on ECRIS
Toward an active plasma chamber -2

Innovative AISHa plasma chamber projected and designed to reduce radial ion losses while allowing water cooling



Every tile can be biased to a different positive voltage.
Commissioning foreseen in spring 2023

New AISHa room@INFN-LNS

The AISHa ion source was moved to a new dedicated room because of the upgrade of the CS Accelerator complex at INFN-LNS

Recommissioning of AISHa and related diagnostics foreseen by winter 2022/2023

Outline

- **Introduction to Electron Cyclotron Resonance Ion sources (ECRIS)**
- **The Advanced Ion Source for Hadrontherapy (AISHa)**
- **The IONS project: from plasma parameters to beam parameters**
- **The InSPIRIT project: AISHa-2 @Cnao**
- **Conclusions and perspectives**

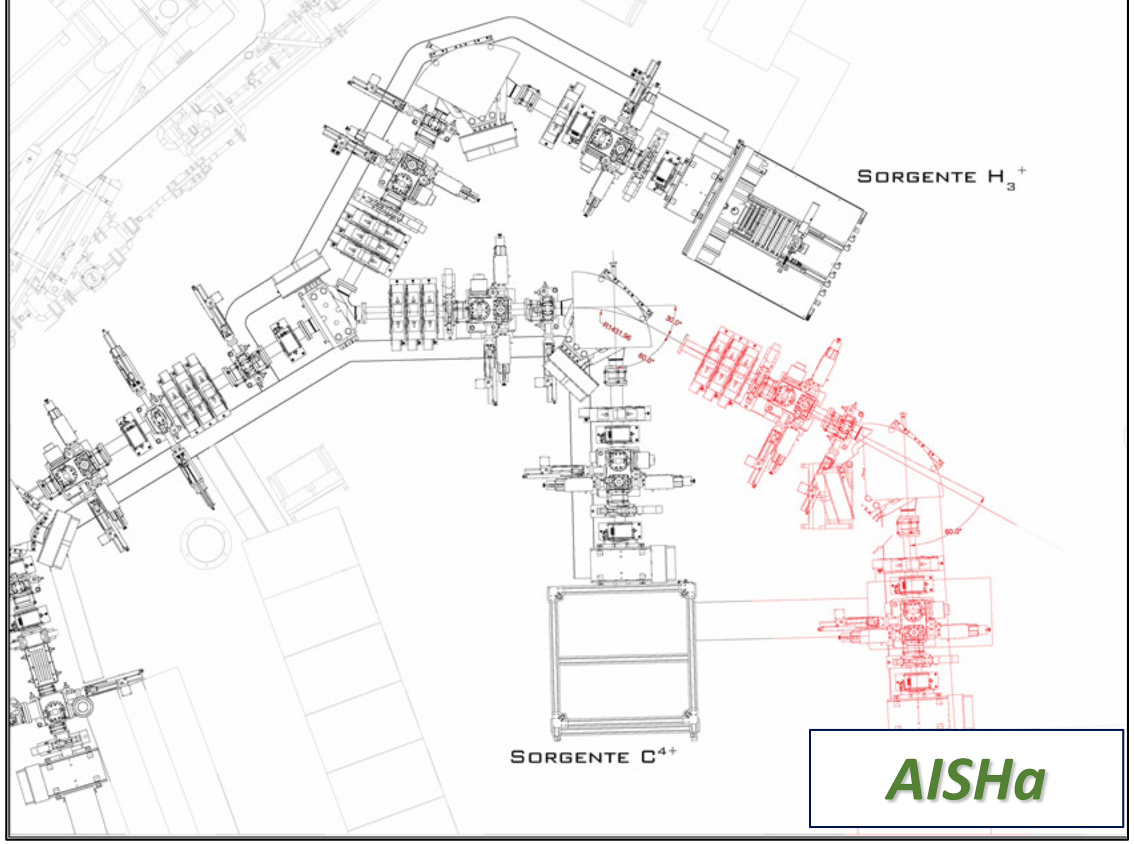
Outline

- **The InSPIRIT project: AISHa-2 @Cnao**

The INSpIRIT project: AISHa-2 at CNAO

INnovative accelerator facility with **S**ources **I**ons for **R**esearch and radiation hardness studies with **I**ndus**T**rial and clinical applications

Funded by Lombardia Government program PO FESR 2014-2020



Motivations

An innovative irradiation facility with an ion source for research and radiation hardness studies with industrial and clinical applications.

Ion	AISHa Performances [uA]	Requirement CNAO [uA]
C^{4+}	520 uA	110
O^{6+}	1200 uA	64
He^{2+}	5400 uA	344
Li^{3+}	To be developed	230
Fe^{19+}	To be developed	175

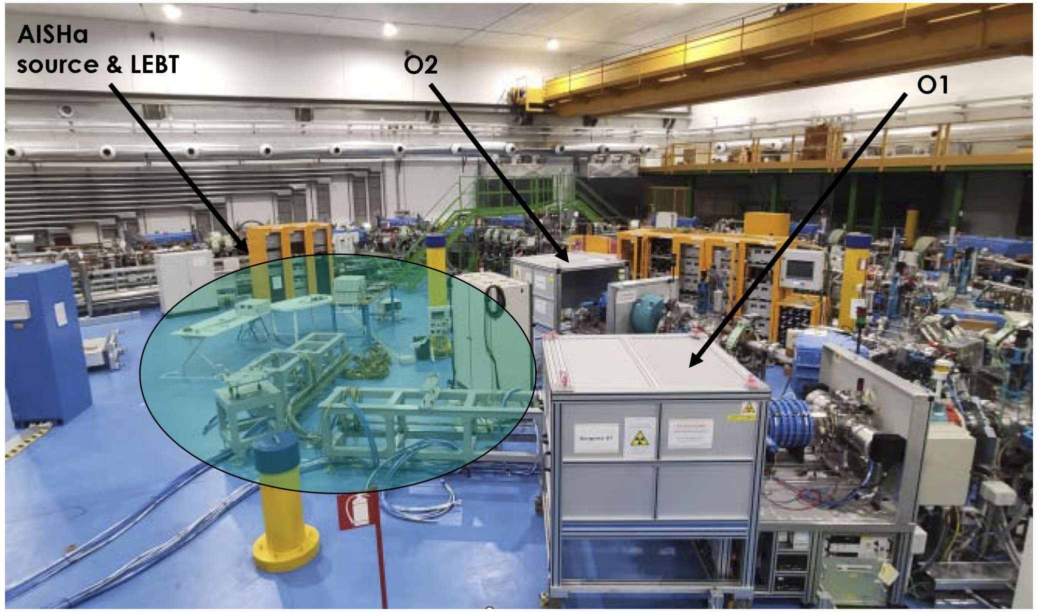
Metal beams are being developed in collaboration with GSI.

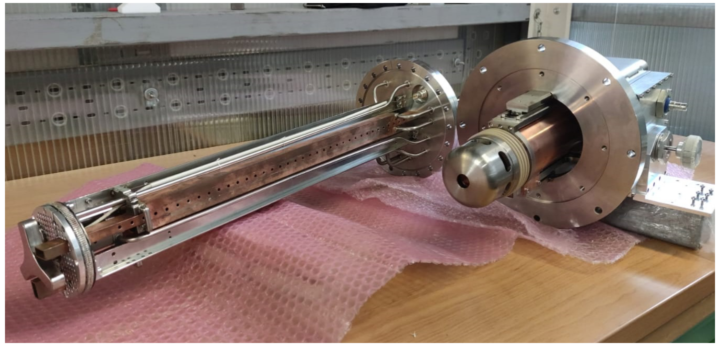
The INSpIRIT project: AISHa-2 at CNAO

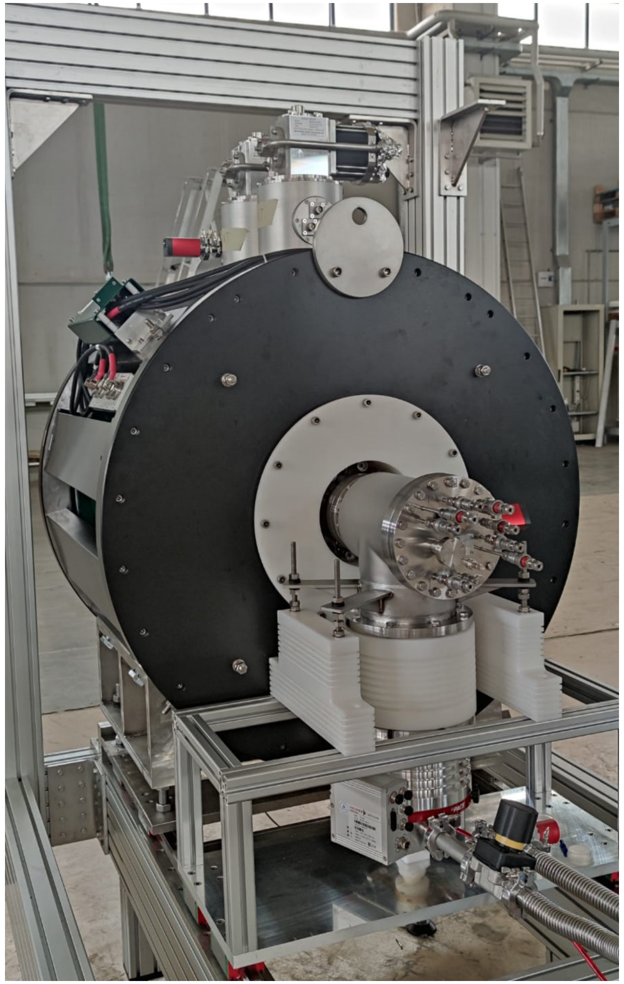
Source and ancillary equipment are being preassembled in INFN-PV.

The first deployment into synchro room is foreseen on 3 September 22, other displacements will be done in several time slots allocated for synchro ordinary maintenance

Commissioning is planned to start in late fall







Conclusions and perspectives

- *The AISHa ion source is a LHe free compact high performance ECR ion source adapted to work in hospital environment developed and commissioned at INFN-LNS.*
- *In the framework of the IONS project, a dedicated OES set-up will be used to relate beam parameters to plasma parameters. Studies on active and passive plasma chambers to improve ECRIS performances are also ongoing.*
- *In the framework of the INSpIRIT project, a copy of the AISHa ion source is being installed at CNAO (Pavia) for research and industrial/clinical applications.*
- *Transfer to the new room in progress, restart of AISHa operations planned in January 2023*

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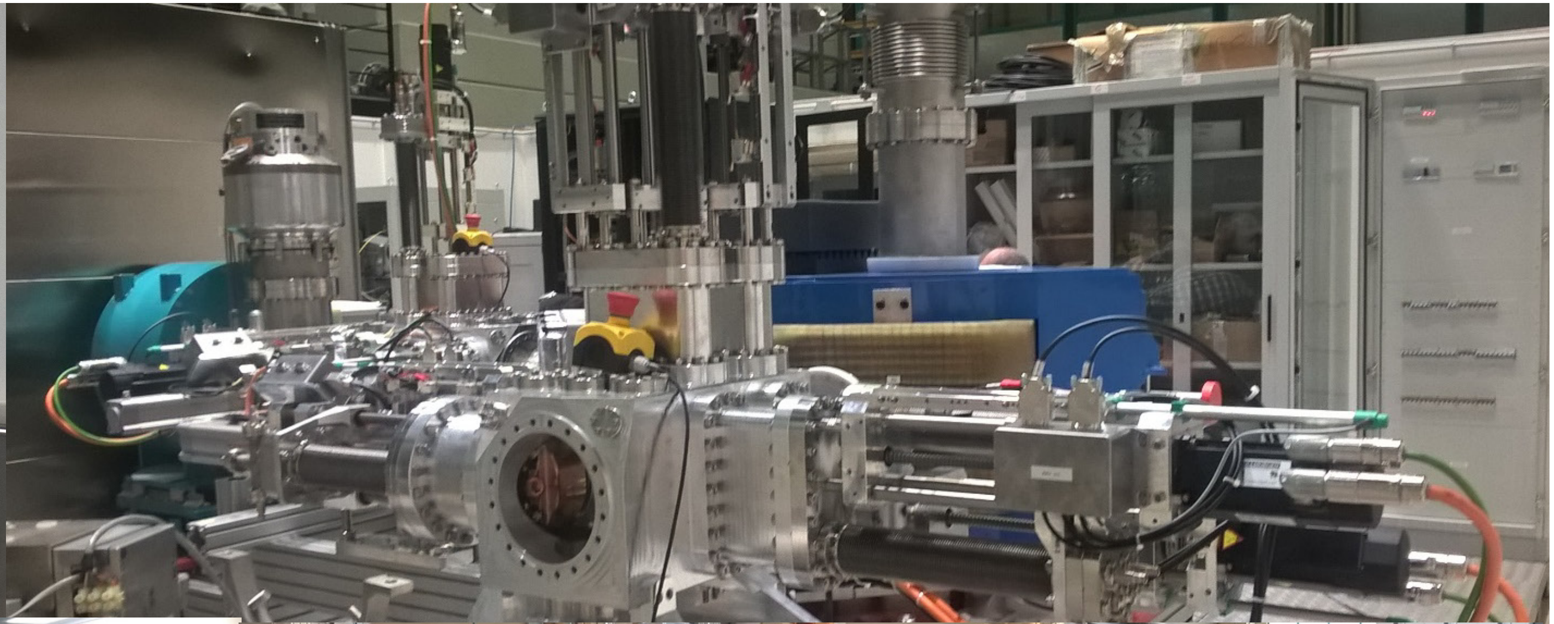
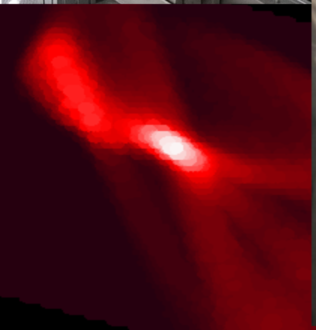
AISHa





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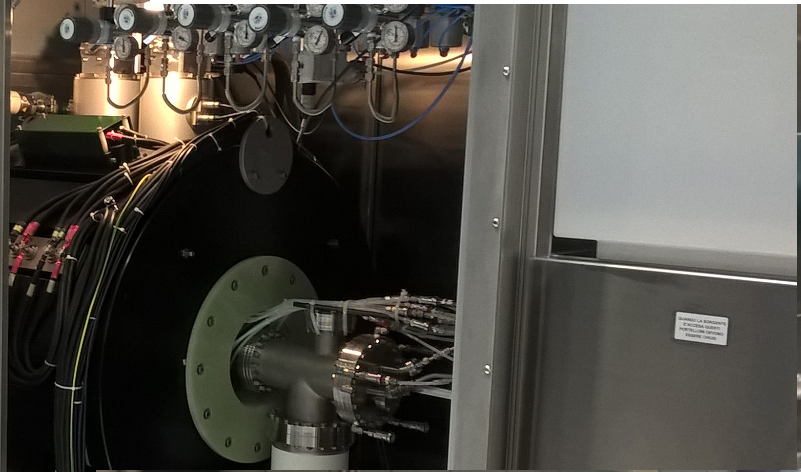
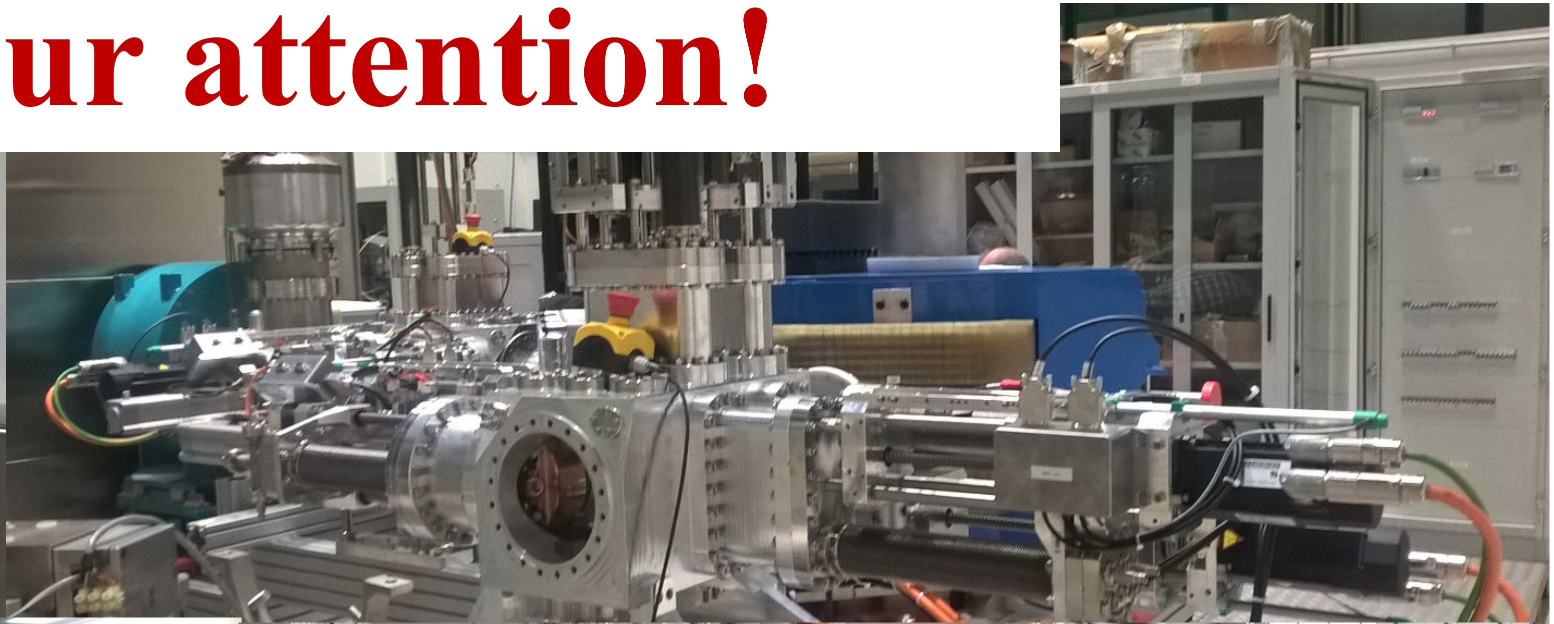
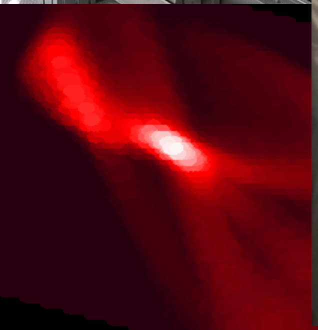
Thank you for your attention!

AISHa







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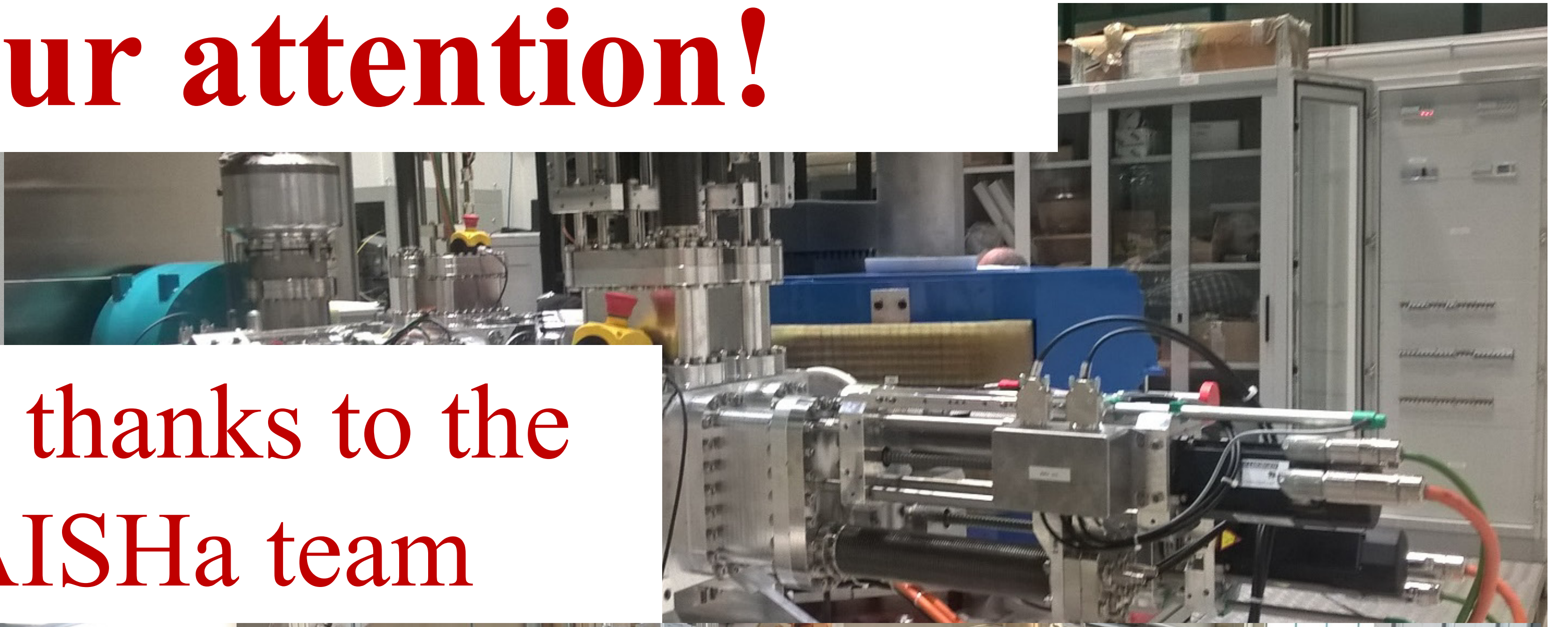
AISHa

Thank you for your attention!



and thanks to the AISHa team