Mixed-beam generation in ECR ion sources

L. Celona, G. Castro, O. Leonardi, S. Gammino

Istituto Nazionale di Fisica Nucleare- Laboratori Nazionali del Sud
Catania, ITALY

M. Galonska

GSI Helmholtzzentrum für Schwerionenforschung GmbH
Darmstadt, GERMANY



Outline

- *Review of Hadrontheraphy ion sources and usual performance.*

- *Feasibility of extracting $^{12}C^{6+}$ (with minimal $^{16}O^{8+}$ contamination) at clinically usable intensities using ion sources suitable for clinical installation.*

- *Prospects of generating mixed $^{12}C^{3+}$ and $^{4}He^{1+}$ beams without $^{16}O4^{+}$ contamination*

-*Tailoring and monitoring the He:C ratio of mixed beams extracted*

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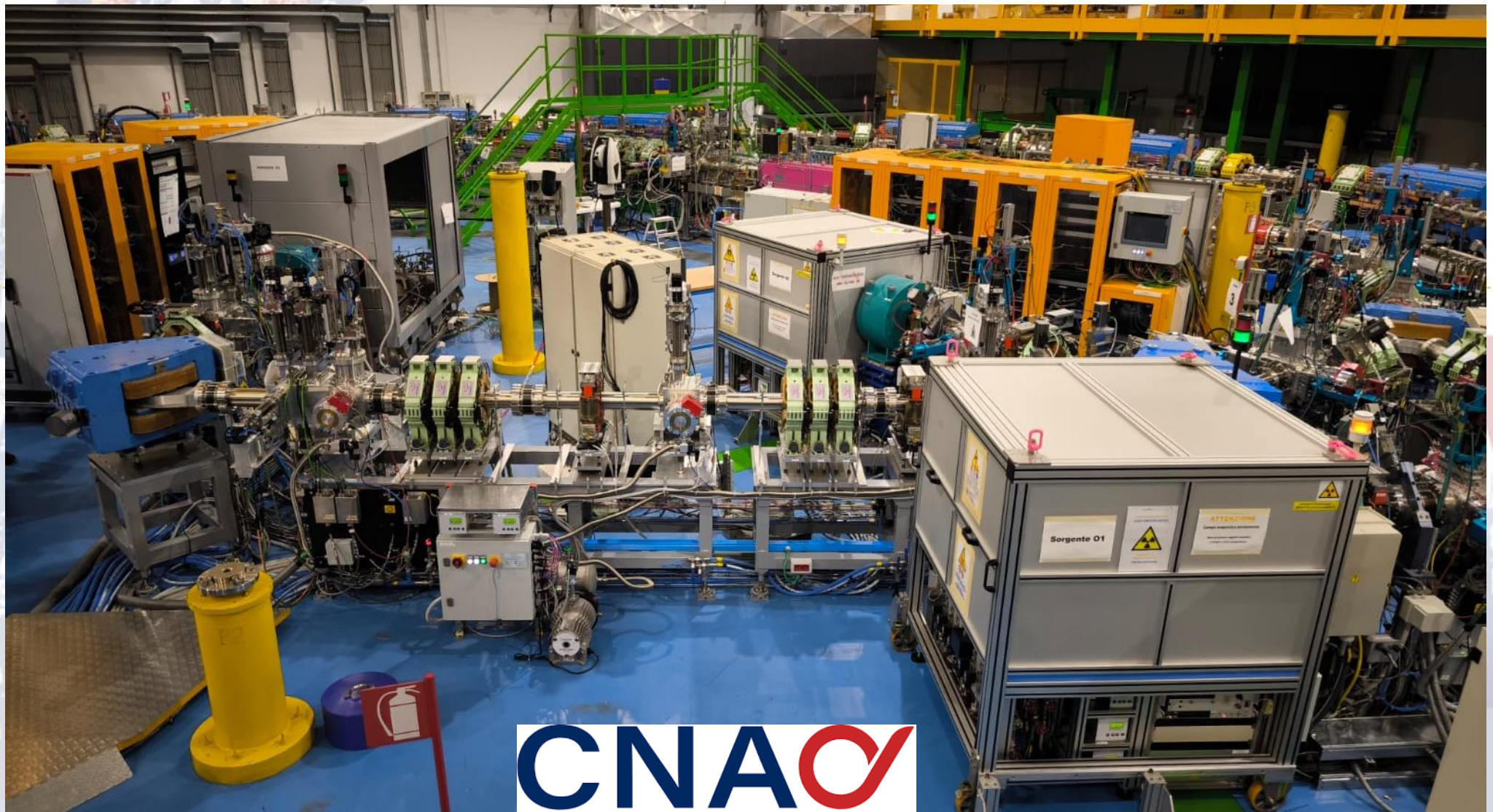
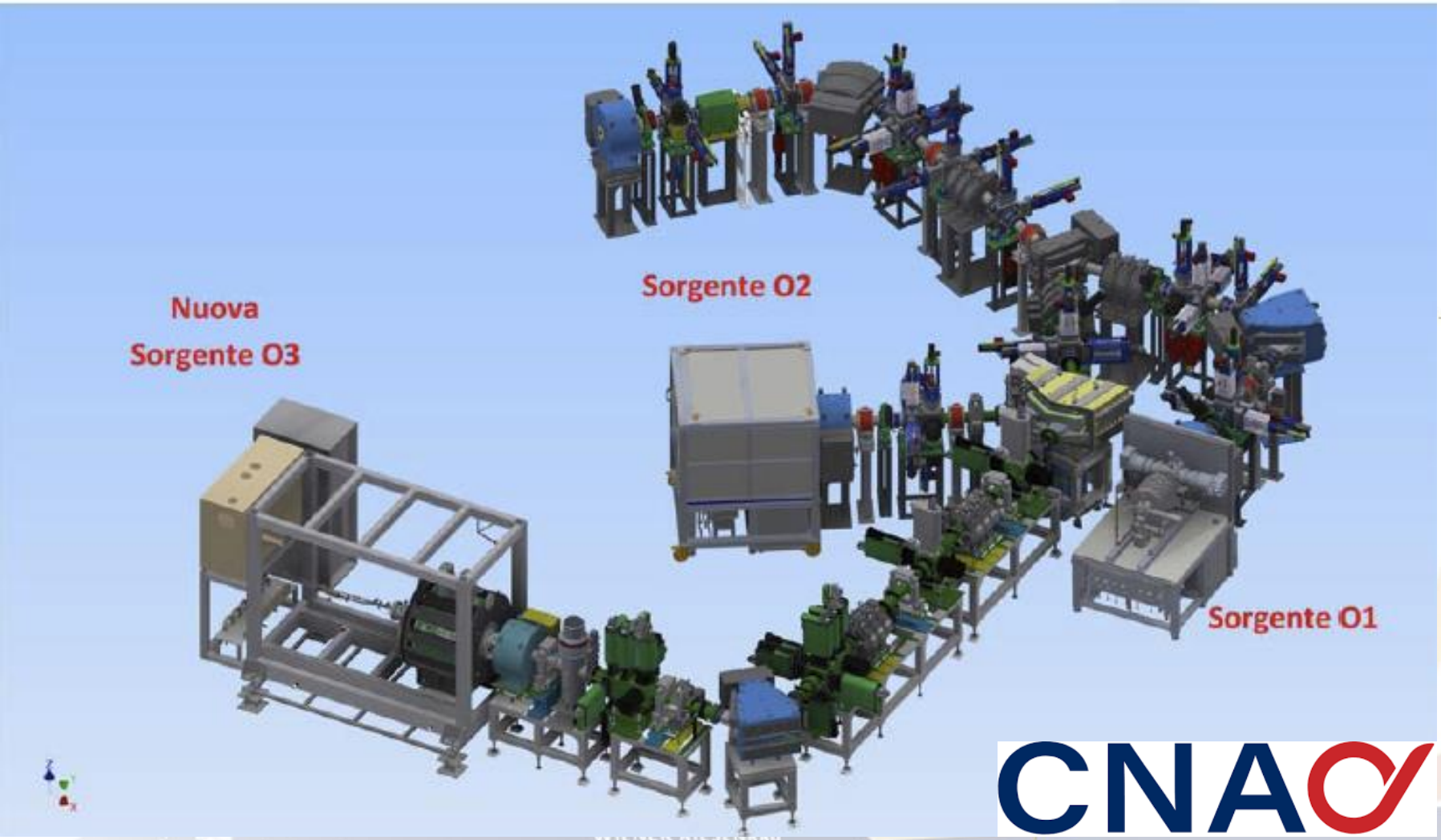
CNAO IS layout

Mixed Ion Beams 26



CNAO IS layout



- Two Pantechnik **SUPERNANOGAN**

- **AISHa source** for **Helium, Lithium, Oxygen and Iron** for new clinical protocols (He, O, Li, Fe) and biological/material experiments for space radiation research.

PK Supernanogan



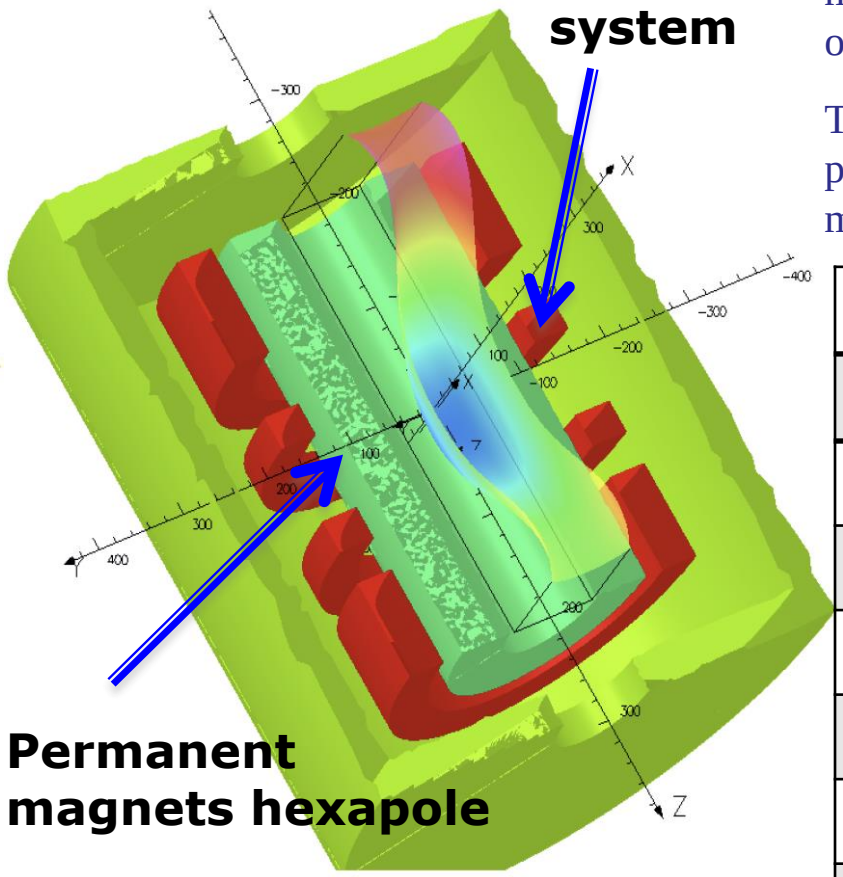
Ions	Current (request) [μA]	Current (avail.) [μA]	After improvements by INFN-LNS [μA]	Emittance (request) π mm.mrad	Emittance (new extractor) π mm.mrad	Stability [99,8%]
C^{4+}	200	200	250	0.75	0.56	36 h
H_2^+	1000	1000		0.75	0.42	2 h
H_3^+	700	600	1000	0.75	0.67	8 h
He^+	500	500		0.75	0.60	2 h

A safer choice, commercial option, we adopted for CNAO: short time available.

Significant improvements have been provided by INFN-LNS: frequency tuning effect, gas control, extractor reliability, etc.

AISHA

Advanced Ion Source for HAdrontherapy



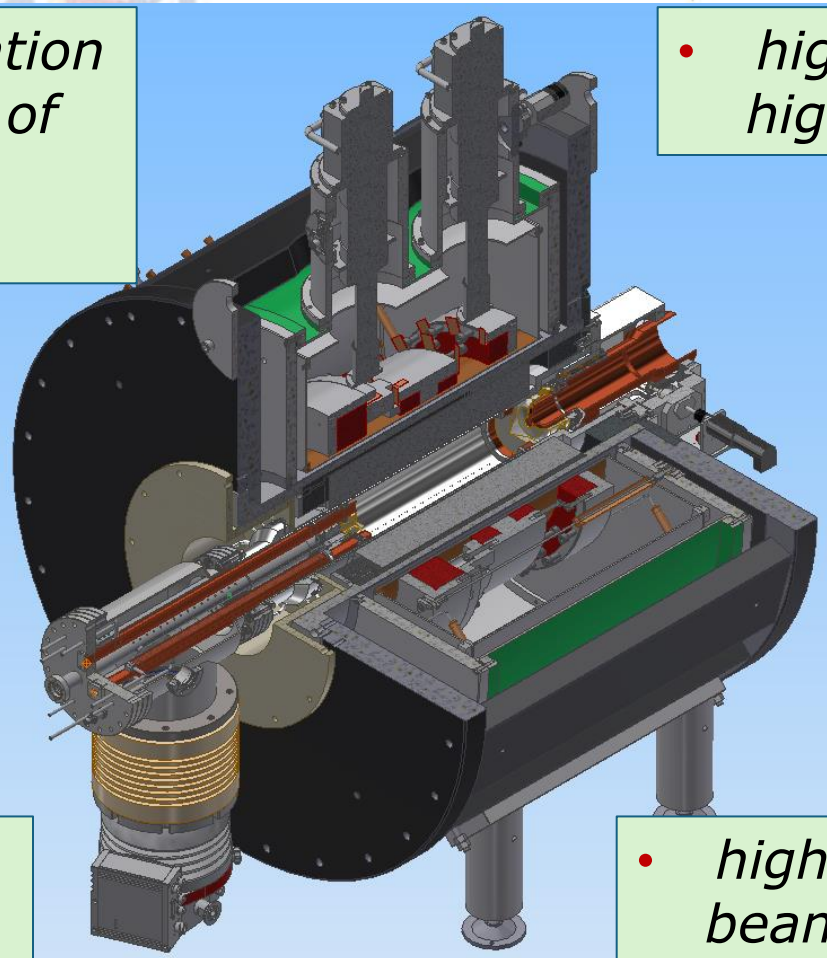
AISHA is a hybrid ECRIS: the radial confining field is obtained by means of a permanent magnet hexapole, while the axial field is obtained with a **Helium-free superconducting system.**

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

AISHA

- *low space occupation and minimization of electrical consumption*
- *high stability and high reproducibility*



- *low maintenance time*
- *highly charged ion beams with low ripple*

The beam structure depends on the plasma structure

- **Maximum flexibility on the frequency**
- **Maximum flexibility on the axial B-field**

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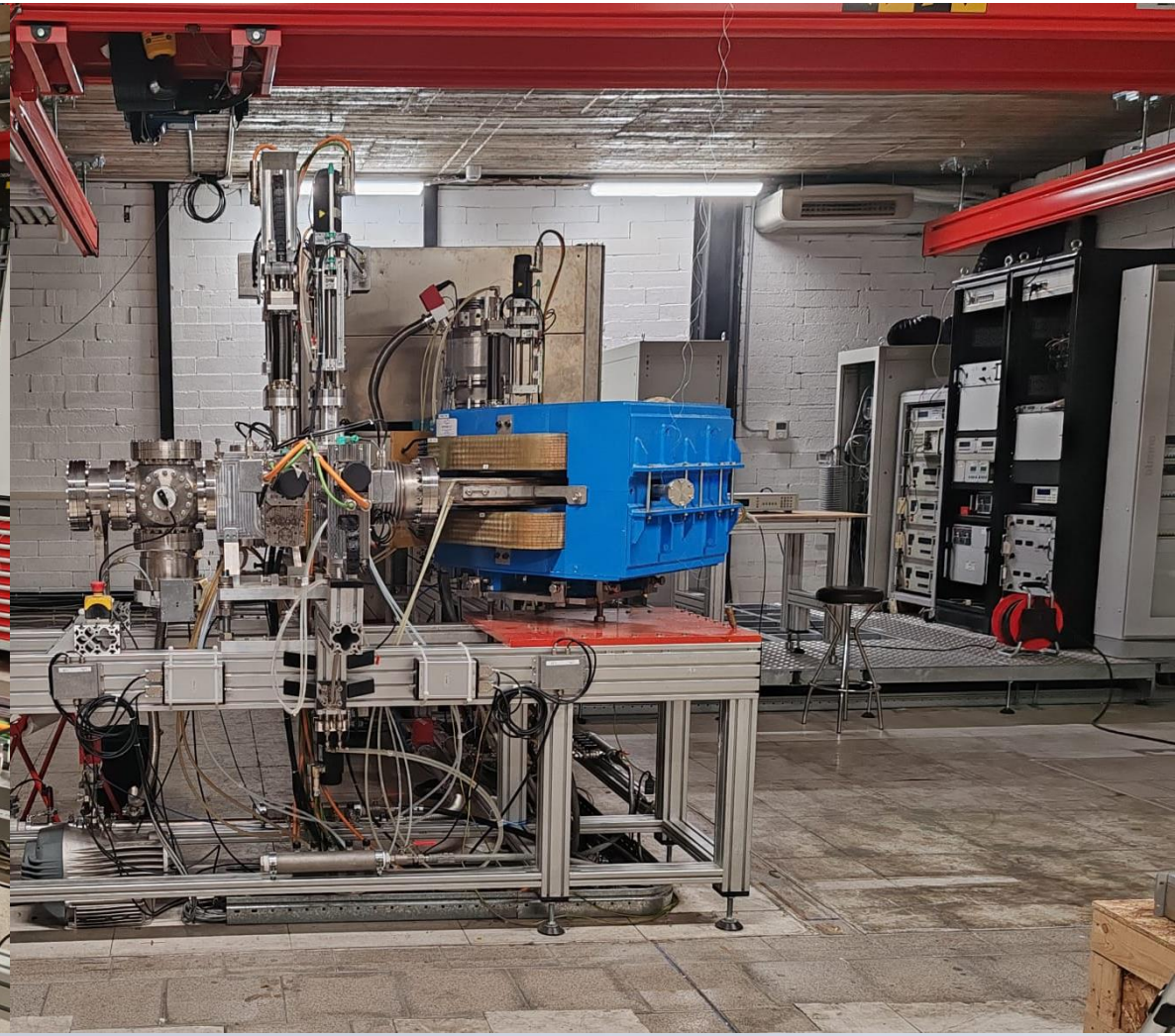
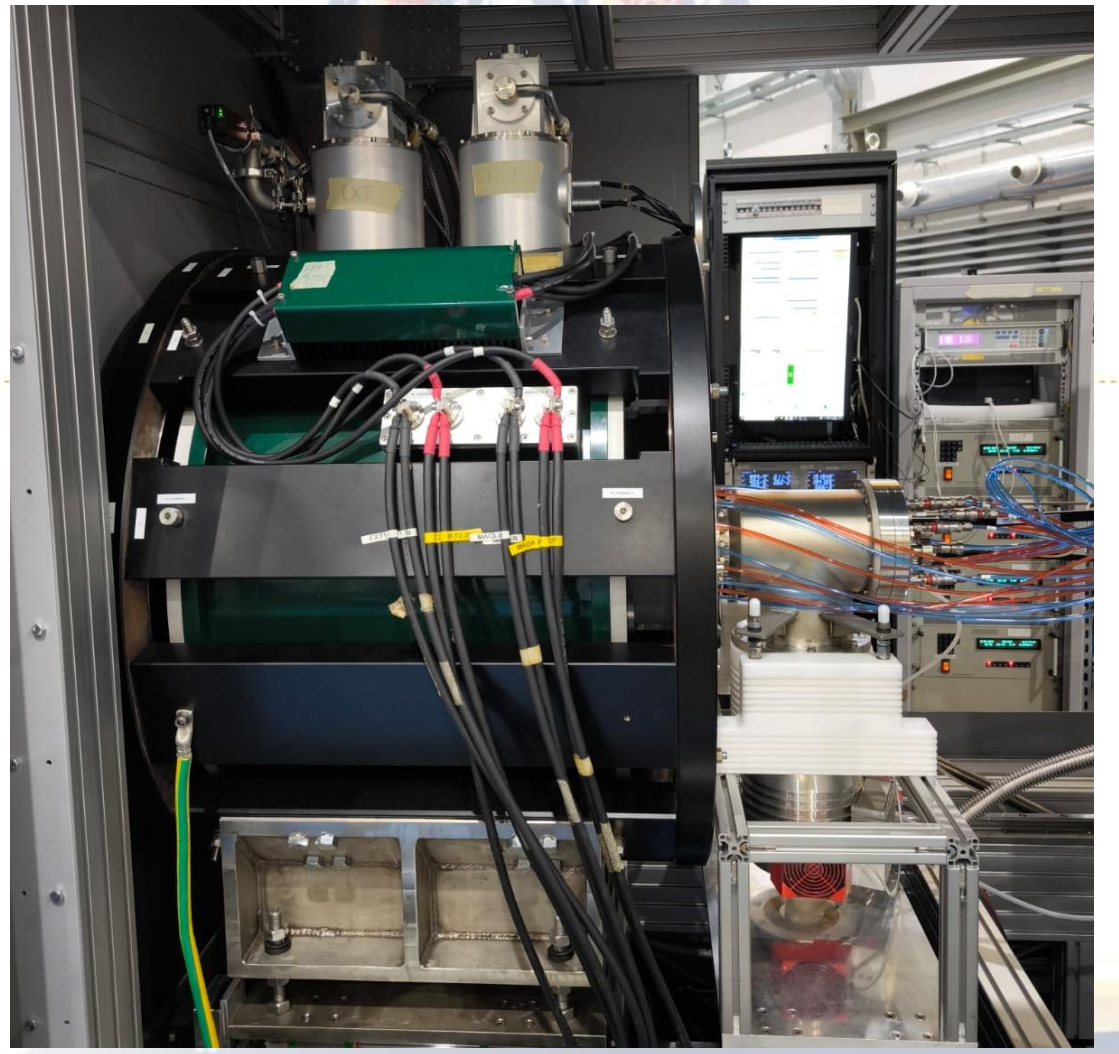
AISHa reinstallation at new TELAMONES (TEst LAboratory for MOdelling New Ecr ion Sources) facility at LNS

Mixed Ion Beams 26



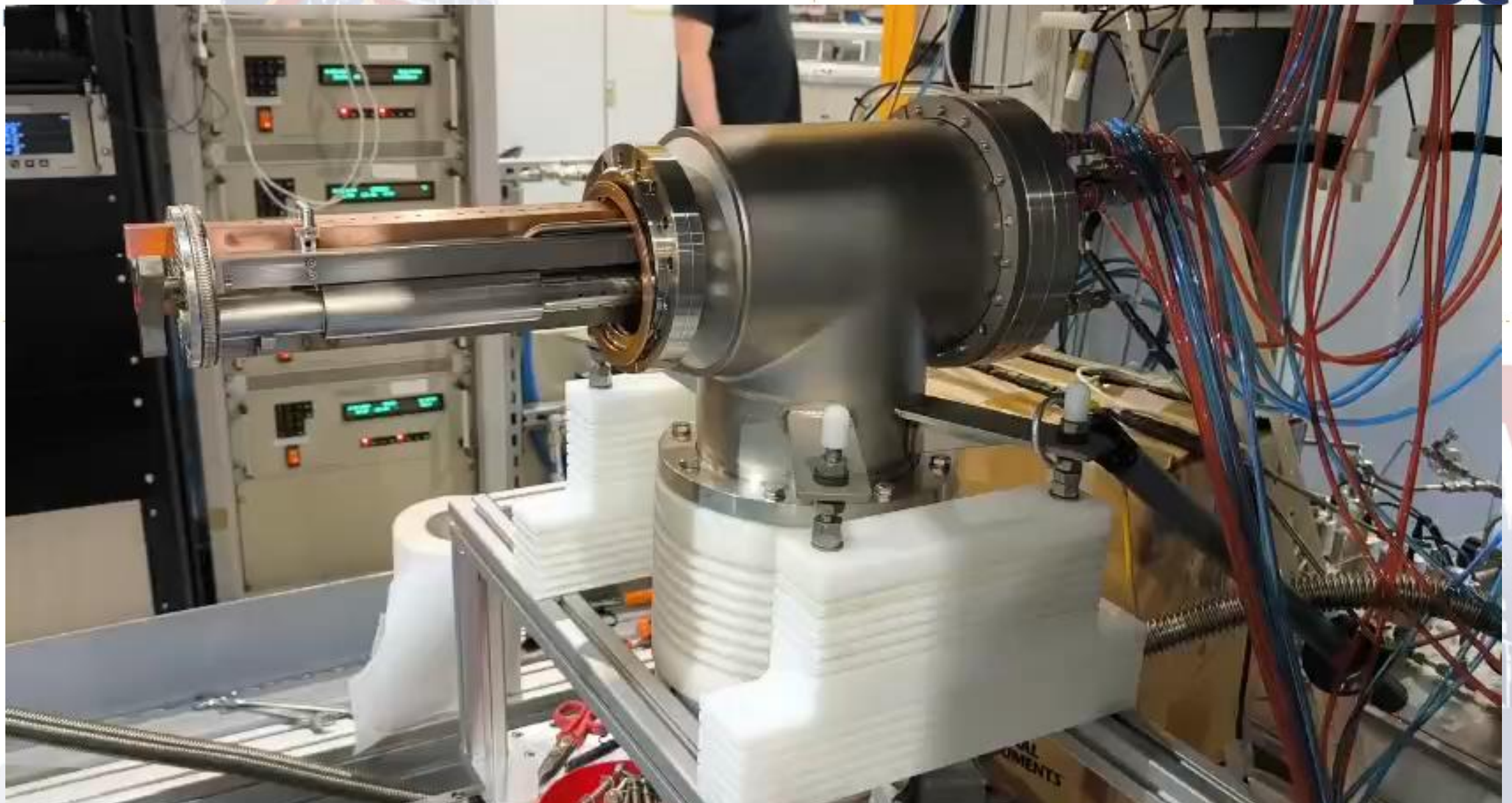


AISHa-2 @ CNAO



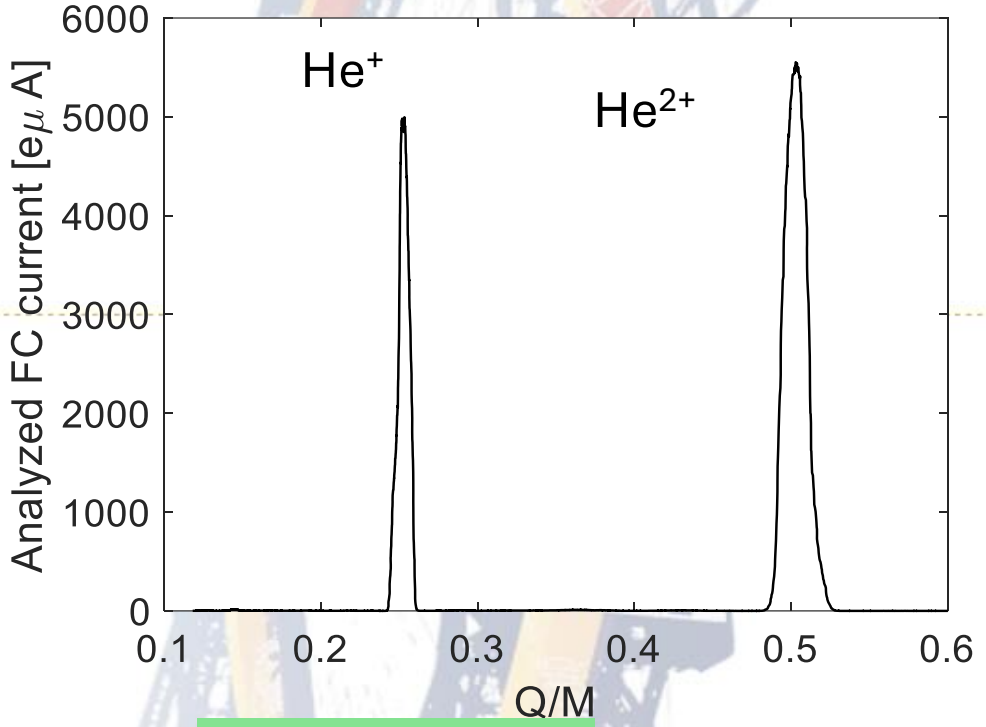
- In the frame of IRPT, the italian national grant for hadrontherapy, and of the INSPIRIT program of the Lombardy region →second AISHa source @CNAO.
- Beam development requested (gas and solid). GSI STO oven will be used.
- Currenty operating 24H/24H 7/7 providind a few mA of He^{2+} for synchrotron commissioning

AISHa-2 after 67 days continuos operations



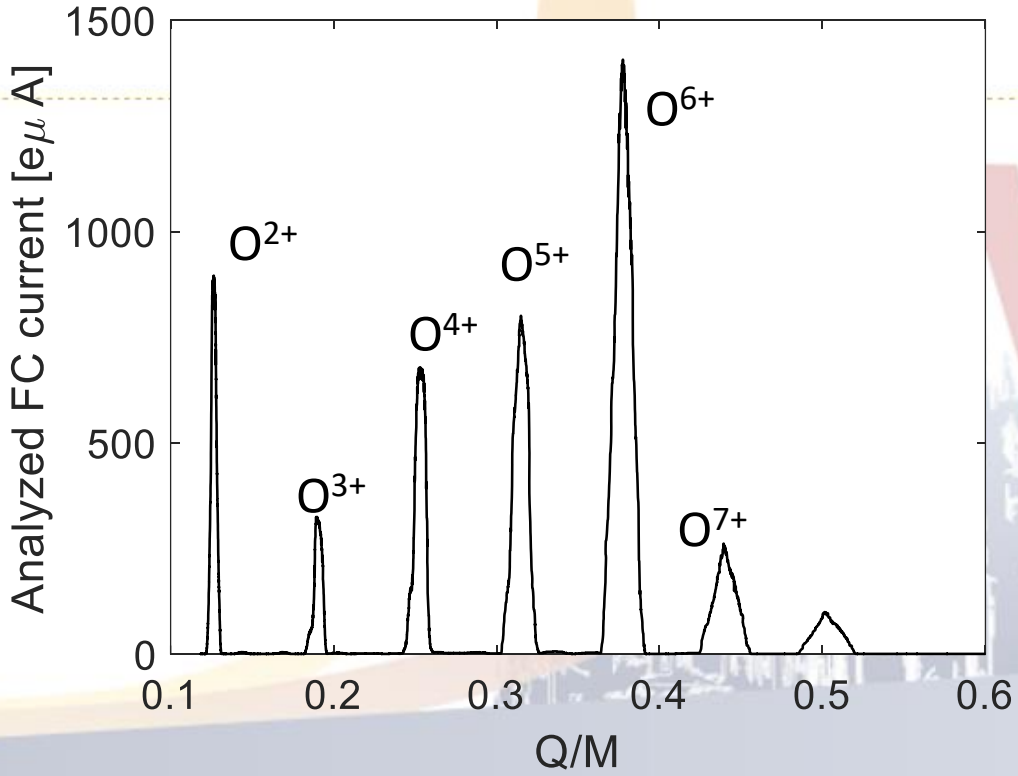
AISHa Carbon
(17.3-18.4 GHz – 1.5 kW max)

Helium



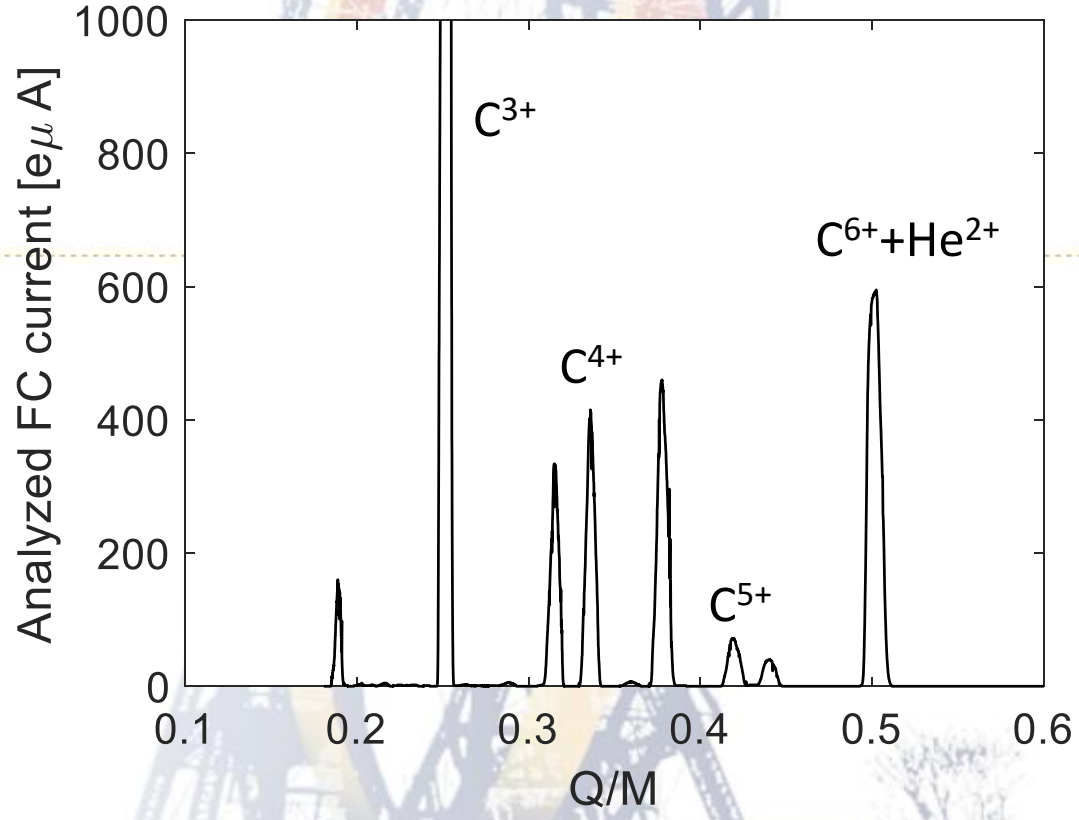
O^{6+} > 1.6 emA
O^{7+} > 0.35 emA
O^{8+} > 0.1 emA

O^2 + He (4:1)

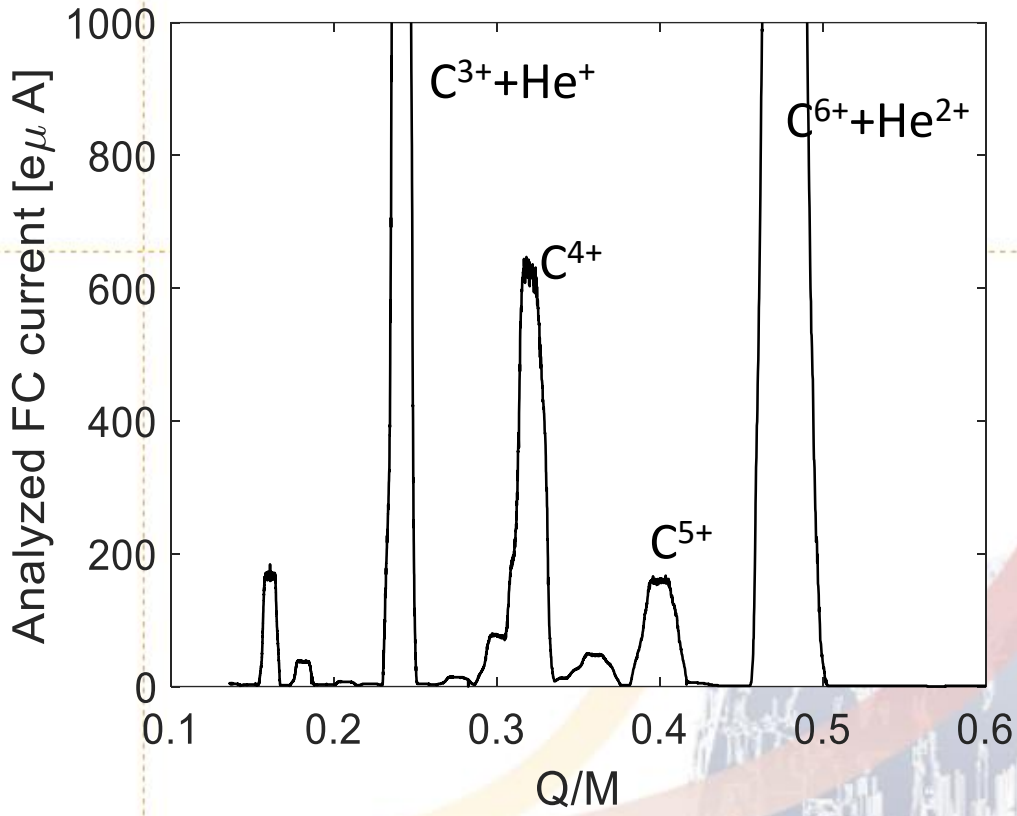


AISHa Helium and Oxygen SFH (17.3-18.4 GHz – 1.5 kW max)

CO^2+He (~1: 1)



CH^4+He (~10: 1)



Very high drain current (up to 18 mA) with more than 10 mA between Helium and Hydrogen.

AISHa performances
SFH (17.3-18.4 GHz – 1.5 kW max)

Charge state	Beam intensity [eμA]	$\varepsilon_{rms.norm}$ $[\pi \cdot mm \cdot mrad]$
$^{16}O^{6+}$	1400	0.2198
$^{16}O^{6+}$	225	0.115
$^{16}O^{7+}$	350	0.247
$^{12}C^{4+}$	650	0.272
$^{12}C^{4+}$	150	0.222
$^{12}C^{5+}$	165	---
$^{40}Ar^{11+}$	155	0.201
$^{40}Ar^{12+}$	140	0.201
He^{2+}	5400	0.418
He^{2+}	700	0.245

Emittance measurements

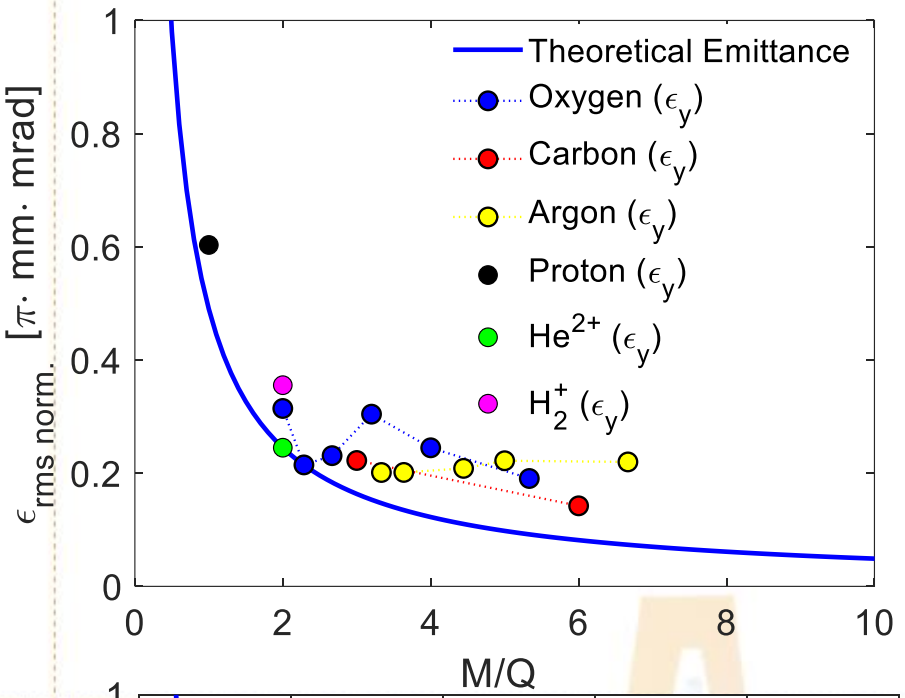
Source stability is a close synonym of good beam quality produced (almost one-to-one corrispondence)

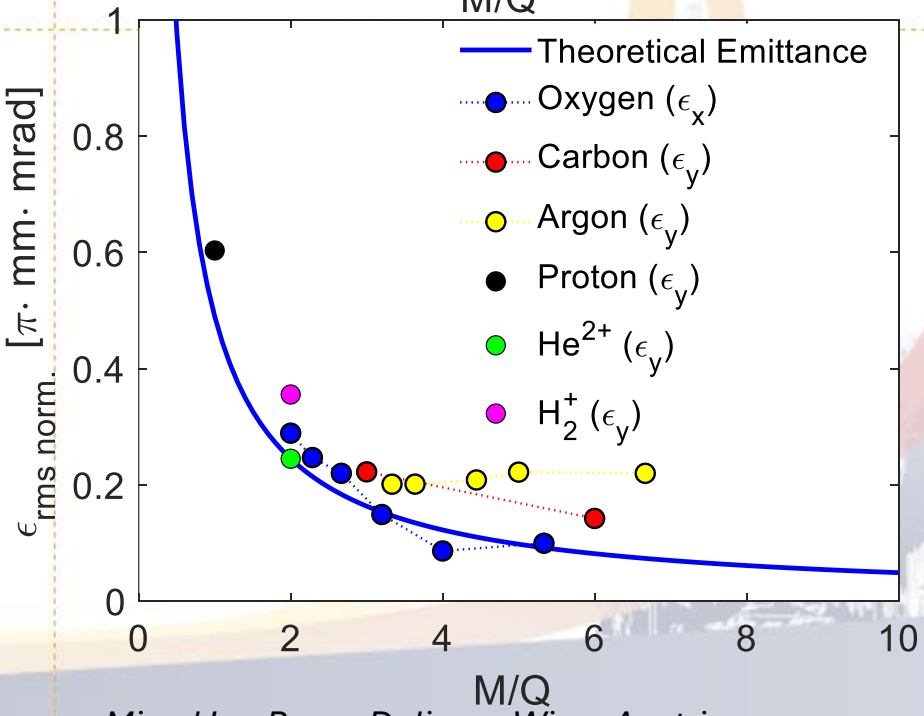
Beam ripple was the reference during our measurements

A key role is played by the amount of neutrals injected into the chamber (fine control of such flux and its stability make the difference)

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

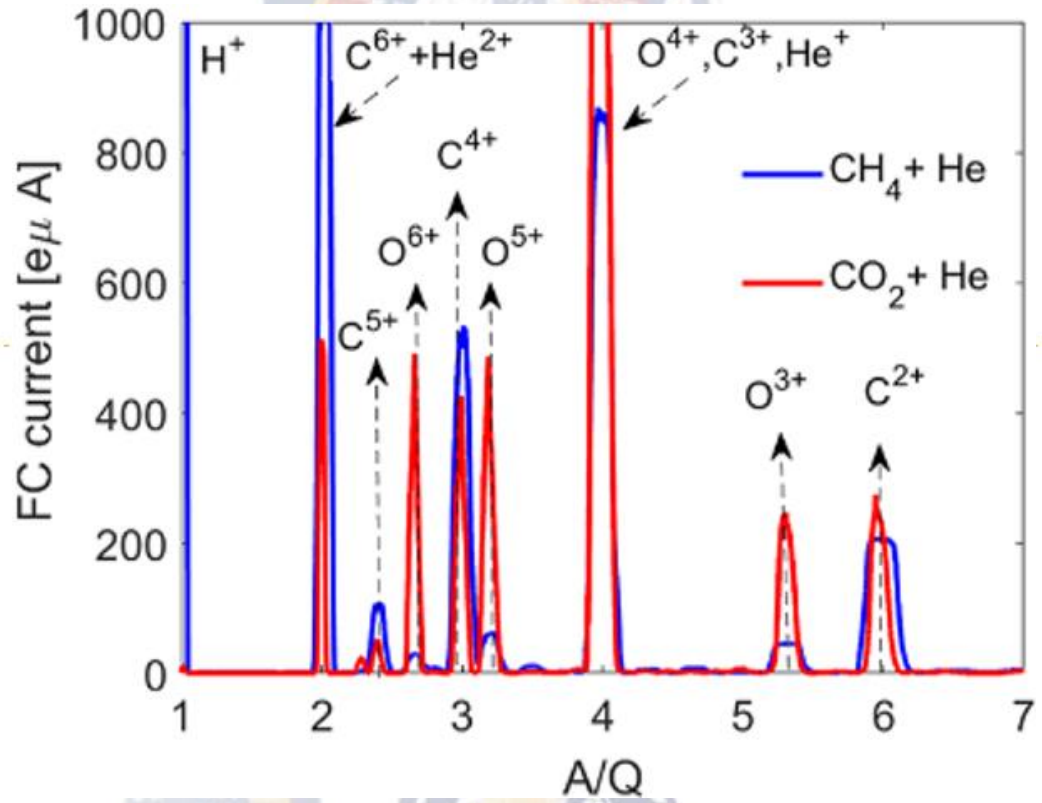
neglected term





Spectra analysis

Feasibility of extracting $^{12}C^{6+}$ (with minimal $^{16}O^{8+}$ contamination) at clinically usable intensities



Both cases: C4+ optimization			
A/Q	**Charge state**	**CO_2+He**	**CH_4+He**
6	C^{2+}	≈270μA	≈210μA
5.33	O^{3+}	≈250μA	----- (memory ≈30 μA)
4		C^{3+}, He^{+}, O^{4+}	C^{3+}, He^{+}
3.2	O^{5+}	≈490μA	----- (memory ≈35μA)
3	C^{4+}	≈450μA	≈550μA
2.66	O^{6+}	≈500μA	----- (memory≈20μA)
2.4	C^{5+}	≈50μA	≈110μA
2.28	O^{7+}	23μA	-----
2		C^{6+}, He^{2+}, O^{8+}	C^{6+}, He^{2+}, H_2^{+}

From C^{4+} and C^{5+} we can evaluate C^{6+} and from O^{6+} and O^{7+} we can evaluate O^{8+}

C^{6+} balance equation

Transport losses

$$\frac{dn_6}{dt} = n_e S_5 n_5 - \frac{n_6}{\tau_6} - R_6 n_6$$

at regime: $\frac{dn_6}{dt} = 0$

$$\frac{n_6}{n_5} = \frac{n_e S_5^C}{1/\tau_6 + R_6} = \frac{n_e S_5^C \tau_6}{1 + R_6 \tau_6}$$

C^{6+} production rate from C^{5+} → $S_5^C = \langle \sigma v \rangle_{C^{5+} \to C^{6+}}$

Losses → $R_6 = n_e \alpha_6 + \sum_j n_j \, k_{C6,j}^{CX}$

- Electron recombination negligible
- Charge exchange dominant: nj represent the contribution of neutrals

$$\sum_j n_j \, k_{C6,j}^{CX} = n_{CO_2} k_{CO_2}^{CX} + n_{CO} k_{CO}^{CX} + n_O k_O^{CX} + n_{O_2} k_{O_2}^{CX} + \cdots$$

representing all the j residual gas species with a single effective neutral species of density n_0 → $\boxed{R_q = n_0 k_q^{CX}}$

$$I_q \propto qe \frac{n_q}{\tau_q} \quad \to \frac{I_{q+1}}{I_q} \simeq \frac{q+1}{q} n_e \tau_q \, S_q$$

$$\frac{I_6}{I_5} = \frac{6}{5} \frac{n_6/\tau_6}{n_5/\tau_5} = \frac{6}{5} \frac{n_6}{n_5} \cdot \frac{\tau_5}{\tau_6} = \frac{6}{5} \frac{n_e S_5^C \tau_5}{1 + R_6 \tau_6}$$

O^{8+} balance equation

Transport losses

$$\frac{dn_8}{dt} = n_e S_7^O n_7 - \frac{n_8}{\tau_8} - R_8 n_8$$

at regime: $\frac{dn_8}{dt} = 0$

$$\frac{n_8}{n_7} = \frac{n_e S_7^O}{1/\tau_8 + R_8} = \frac{n_e S_7^O \tau_8}{1 + R_8}$$

O^{8+} production rate from O^{7+} → $S_7^O = \langle \sigma v \rangle_{O^{7+} \to O^{8+}}$

Losses → $R_8 = n_e \alpha_8 + \sum_j n_j \, k_{O8,j}^{CX}$

representing all the j residual gas species with a single effective neutral species of density n_0 → $R_q = n_0 k_q^{CX}$

- Electron recombination negligible
- Charge exchange dominant: nj represent the contribution of neutrals

$$I_q \propto qe \frac{n_q}{\tau_q} \quad \to \frac{I_{q+1}}{I_q} \simeq \frac{q+1}{q} n_e \tau_q S_q$$

$$\frac{I_8}{I_7} = \frac{6}{5}\frac{n_8/\tau_8}{n_7/\tau_7} = \frac{8}{7}\frac{n_8}{n_7} \cdot \frac{\tau_7}{\tau_8} = \frac{8}{7}\frac{n_e S_7^O \tau_7}{1 + R_8 \tau_8}$$

O^{8+}/C^{6+} current ratio

$$\frac{\frac{I^{O8+}}{I^{O7+}}}{\frac{I^{C6+}}{I^{C5+}}} = \frac{\frac{8}{7}\frac{n_e S_7^O \tau_7}{1+R_8\tau_8}}{\frac{6}{5}\frac{n_e S_5^C \tau_5}{1+R_6\tau_6}} = \underbrace{\frac{8}{7}\cdot\frac{5}{6}}_{\sim 1}\cdot\frac{\cancel{n_e} S_7^O \tau_7}{\cancel{n_e} S_5^C \tau_5}\cdot\frac{1+R_6\tau_6}{1+R_8\tau_8} \quad \Rightarrow \quad \frac{I^{O8+}}{I^{C6+}} = \frac{I^{O7+}}{I^{C5+}}\cdot\frac{S_7^O}{S_5^C}\cdot\frac{\tau_7}{\tau_5}\cdot\frac{1+R_6\tau_6}{1+R_8\tau_8}$$

$$\frac{I^{O8+}}{I^{C6+}} = \frac{I^{O7+}}{I^{C5+}}\cdot\frac{\langle\sigma v\rangle_{O^{7+}\to O^{8+}}}{\langle\sigma v\rangle_{C^{5+}\to C^{6+}}}\cdot\frac{\tau_{O^{7+}}}{\tau_{C^{5+}}}\cdot\frac{1+R_6\tau_6}{1+R_8\tau_8} \quad \rightarrow \quad \frac{I^{O8+}}{I^{C6+}} = \frac{I^{O7+}}{I^{C5+}}\cdot Q_1\cdot Q_2\cdot Q_{CX}(n_0)$$

Atomic physics: *production rate coefficients*

Losses: *charge exchange / electron recombination*

Plasma confinement: *confinement / transport losses*

Q1- Atomic physics

$$C^{5+} \xrightarrow[490\ \text{eV}]{\text{remove last electron}} C^{6+}$$

$$O^{7+} \xrightarrow[871\ \text{eV}]{\text{remove last electron}} O^{8+}$$

Assuming Maxwellian EEDF and by using Lotz formula:

kTe	$\frac{\langle\sigma v\rangle_{O^{7+}\rightarrow O^{8+}}}{\langle\sigma v\rangle_{C^{5+}\rightarrow C^{6+}}}$
1 keV	0.27
2 keV	0.34
3 keV	0.38
5 keV	0.41

An average value is that can be fairly assumed is :

$Q_1 \approx 0.34$

Atomic physics states that oxygen's path to reaching a fully stripped state is three times less efficient than that of carbon

Q2- Plasma confinement

$$\tau_q = \tau_0 e^{\frac{qe\Delta\varphi}{kT_i}} = \tau_0 e^{q\beta}$$

with: $\beta = e\Delta\varphi / kT_i$

In ECRIS plasmas, the highly charged ions are considered to be electrostatically confined by a negative dip in the positive plasma potential.
This potential dip influences the ion confinement, affecting the extracted ion currents and the charge-state distribution.

We may use the spectrum to evaluate β

$$\frac{\frac{I^{O7+}}{I^{O6+}}}{\frac{I^{C5+}}{I^{C4+}}} = \underbrace{\frac{7}{6}\cdot\frac{4}{5}}_{0.9333}\cdot\frac{S_6^O\tau_6}{S_4^C\tau_4} = \frac{23/490}{50/440}$$

$\frac{S_6^O\tau_6}{S_4^C\tau_4} \rightarrow 0.32$, $\frac{23/490}{50/440} \rightarrow 0.413$

$\Rightarrow 0.9333 \cdot 0.32 \cdot e^{2\beta} = 0.413 \Rightarrow \beta = \frac{e\Delta\varphi}{kT_i} \sim 0.162$

$$\boxed{Q_2 = \frac{\tau_{O7}}{\tau_{C5}} = e^{(7-5)\beta} = e^{2\beta} = 1.38}$$

Q_{CX}- Losses #1

Charge exchange dominate over other losses.

$$O^{8+} + X \rightarrow O^{7+} + X^{+}$$

$$C^{6+} + X \rightarrow C^{5+} + X^{+}$$

It is directly connected with the gas "knob" of the ion source.

$$Q_{\mathrm{CX}} = \frac{1 + R_6\tau_6}{1 + R_8\tau_8}$$

where:

$$R_q = n_0 k_q^{CX} = n_0 \sigma_q^{CX} v_{\mathrm{rel}}$$

Ions lost frequency

Charge exchange Rate coefficient

$$k_q^{CX} = \langle \sigma_q^{CX} v_{\mathrm{rel}} \rangle$$

$$Q_{\mathrm{CX}}(n_0) = \frac{1 + n_0 k_6^{CX}\tau_6}{1 + n_0 k_8^{CX}\tau_8}$$

with: $n_0 = \frac{p}{k_B T_0}$

$$Q_{\mathrm{CX}}(p) = \frac{1 + \frac{p}{k_B T_0} k_6^{CX}\tau_6}{1 + \frac{p}{k_B T_0} k_8^{CX}\tau_8}$$

Müller–Salzborn parametrization for charge exchange (single capture approximation)
A. Müller and E. Salzborn,," *Physics Letters A* **62**, 391–394 (1977).

$$\sigma_{\mathrm{CX}} \simeq 1.43 \times 10^{-12} q^{1.17} E_{ion}^{-2.76} \quad \mathrm{cm}^2$$

IF the neutral target is the same, ionization energy E_{ion} is the same

$$\frac{\sigma_{O8}}{\sigma_{C6}} = \left(\frac{8}{6}\right)^{1.17} \simeq 1.40$$

Therefore, charge exchange cross-section of O^{8+} is **40%** higher than C^{6+}

Q_{CX}- Losses #2

$$Q_{CX} = \frac{1 + R_6\tau_6}{1 + R_8\tau_8}$$

$$R_q = n_0 k_q^{CX} = n_0 \sigma_q^{CX} v_{rel}$$

$$\frac{R_{O8}}{R_{C6}} = \frac{n_0 \sigma_{O8}^{CX} v_{rel}}{n_0 \sigma_{C6}^{CX} v_{rel}} = \frac{\sigma_{O8}}{\sigma_{C6}} = \left(\frac{8}{6}\right)^{1.17} \simeq 1.40$$

$$\frac{\tau_{O8}}{\tau_{C6}} = e^{(8-6)\beta} = e^{2\beta} = 1.38$$

x=$R_6\tau_6$

$$R_8\tau_8 = 1.4\,R_6 \cdot 1.38\tau_6 = 1.93 \cdot x$$

$$Q_{CX} = \frac{1 + x}{1 + 1.93 \cdot x}$$

$$\frac{I^{O8+}}{I^{C6+}} = \frac{I^{O7+}}{I^{C5+}} \cdot Q_1 \cdot Q_2 \cdot Q_{CX} = 0.2 \cdot \frac{1 + x}{1 + 1.93 \cdot x}$$

$\frac{23}{50}$ 0.34 1.38

$$x(n_0) = n_0 \sigma_6 v_{rel} \tau_6$$

$$\frac{I_{O8}}{I_{C6}}(n_0) = 0.2 \cdot \frac{1 + n_0 \sigma_6 v_{rel} \tau_6}{1 + 1.93 n_0 \sigma_6 v_{rel} \tau_6}$$

$$x(p) = \frac{p}{k_B T_0} \sigma_6 v_{rel} \tau_6$$

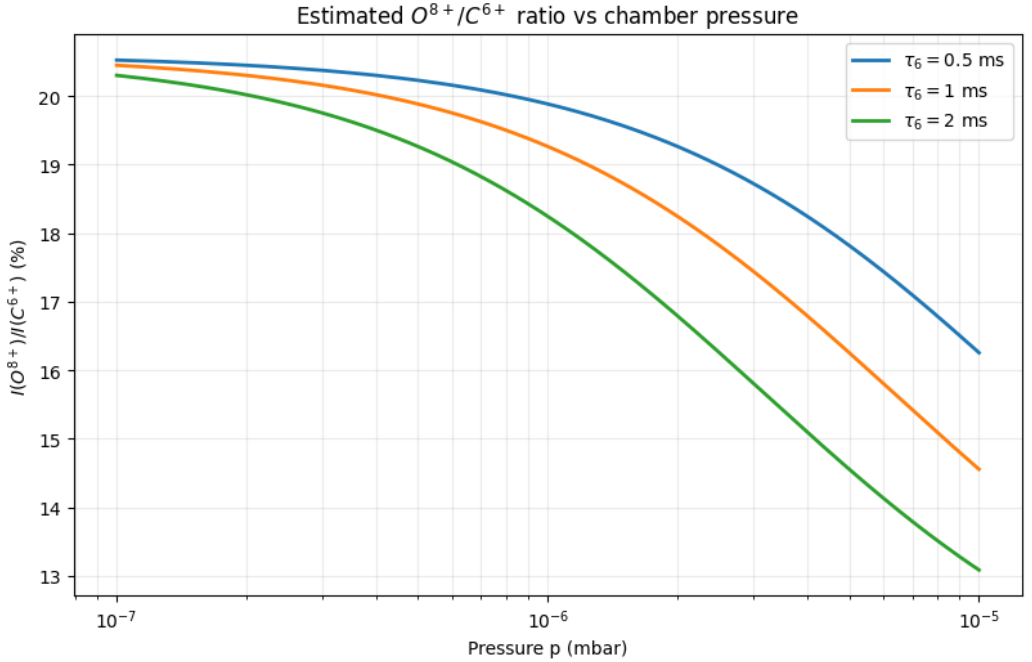
$$\frac{I_{O8}}{I_{C6}}(p) = 0.2 \cdot \frac{1 + \frac{p}{k_B T_0} \sigma_6 v_{rel} \tau_6}{1 + 1.93 \frac{p}{k_B T_0} \sigma_6 v_{rel} \tau_6}$$

O^{8+}/C^{6+} Current ratio

$$\frac{I_{O8}}{I_{C6}}(p) = 0.2\,\frac{1+\frac{p}{k_B T_0}\sigma_6 v_{\mathrm{rel}}\tau_6}{1+1.93\frac{p}{k_B T_0}\sigma_6 v_{\mathrm{rel}}\tau_6}$$

For low preassures Q_{cx} negligible $\quad \frac{I_{O8}}{I_{C6}} = 0.2 = 20\%$

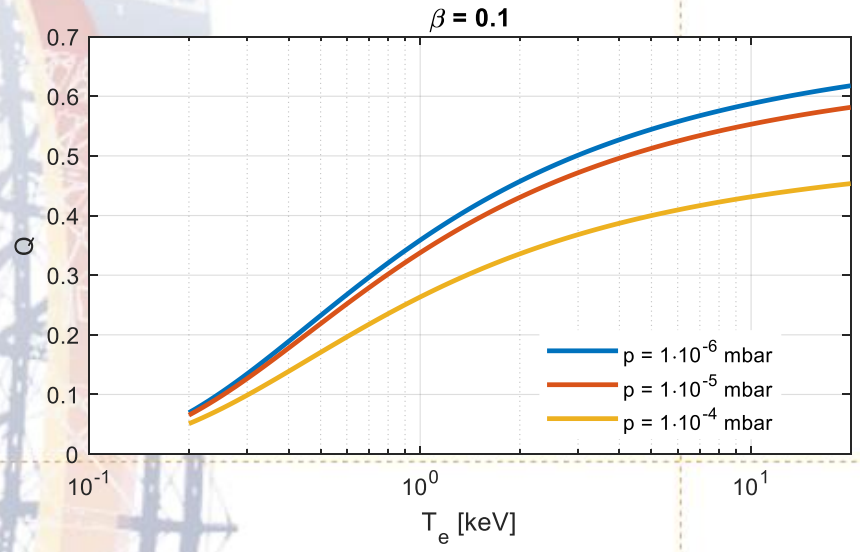
For high preassures $\quad \frac{I_{O8}}{I_{C6}} \to 10\%$

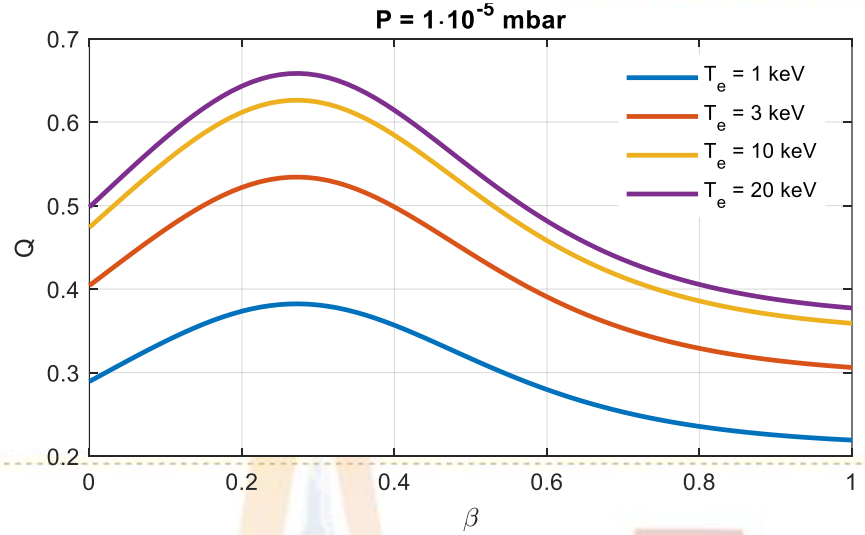


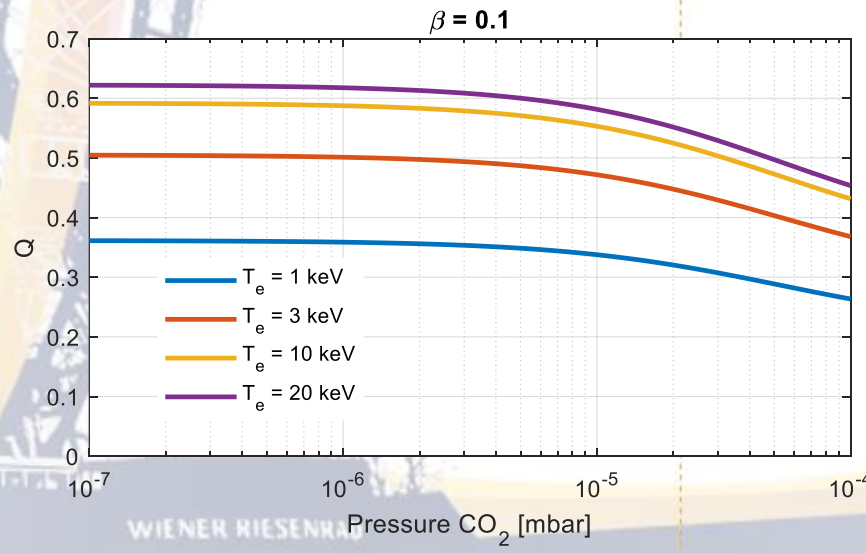
Neutral pressure has a strong impact on O^{8+} current BUT...
May we accept a source detuning?

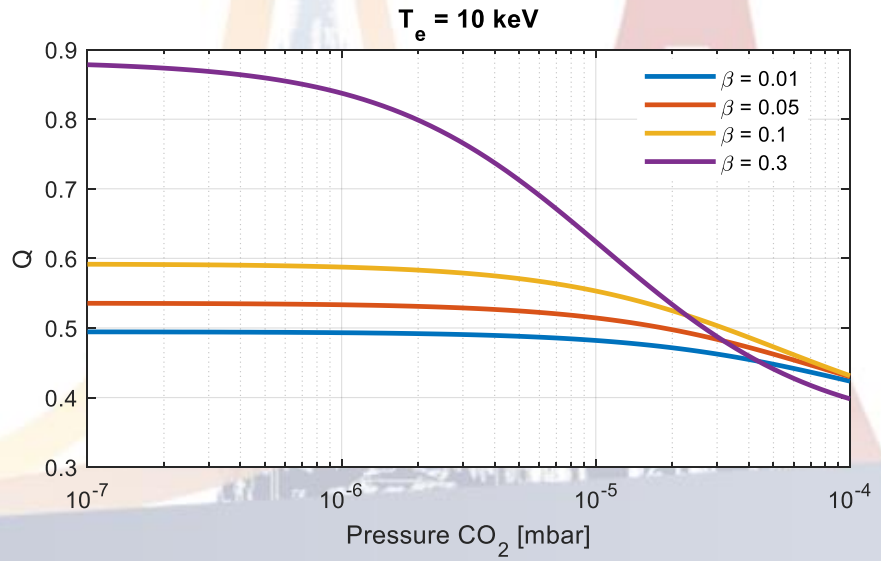
O^{8+}/C^{6+} Current ratio

$$\frac{I_{O^{8+}}}{I_{C^{6+}}} = Q \frac{I_{O^{7+}}}{I_{C^{5+}}}$$









Selective ICRH as an additional purification knob

Physical mechanism: resonantly heat an oxygen precursor to increase its radial losses and reduce the population available for further ionization.

$$O^{q+} \xrightarrow{\text{ICRH}} \text{ion heating} \rightarrow \text{reduced confinement} \rightarrow\downarrow O^{8+}$$

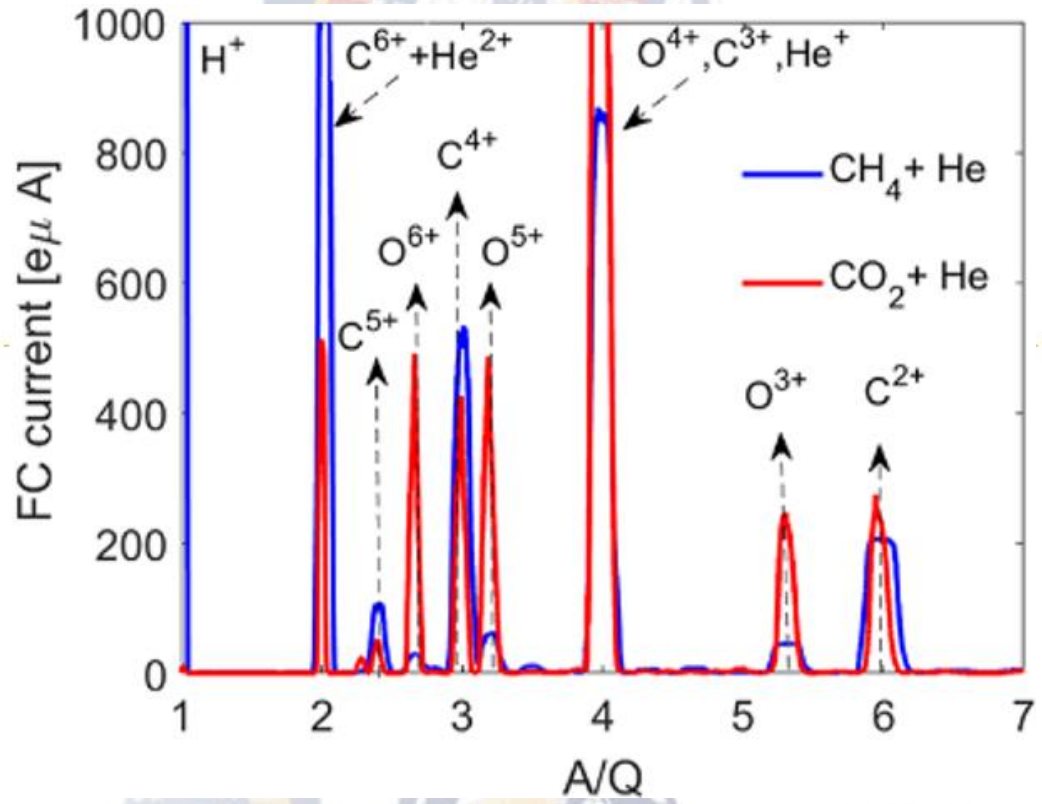
$$f_{\text{ICR}} = \frac{qeB}{2\pi m} \simeq 15.24 \frac{q}{A} B[\text{T}]\ \text{MHz}$$

Ion	q/A	Comment
O^{4+}	0.250	Avoid: identical to C3+
O^{5+}	0.3125	Best candidate
C^{4+}	0.3333	separated by ~6.7% from O5+
O^{6+}	0.375	possible alternative
C^{5+}	0.4167	separated by ~11% from O6+

Gas tuning shifts the charge-state distribution; selective ICRH could provide an additional species-selective suppression of the oxygen pathway.

Target: deplete O^{5+} while preserving $C^{4+} \rightarrow C^{5+} \rightarrow C^{6+}$ production chain.

$^{12}C^{3+}$ and $^{4}He^{+}$ beams without $^{16}O^{4+}$ contamination



Both cases: C4+ optimization			
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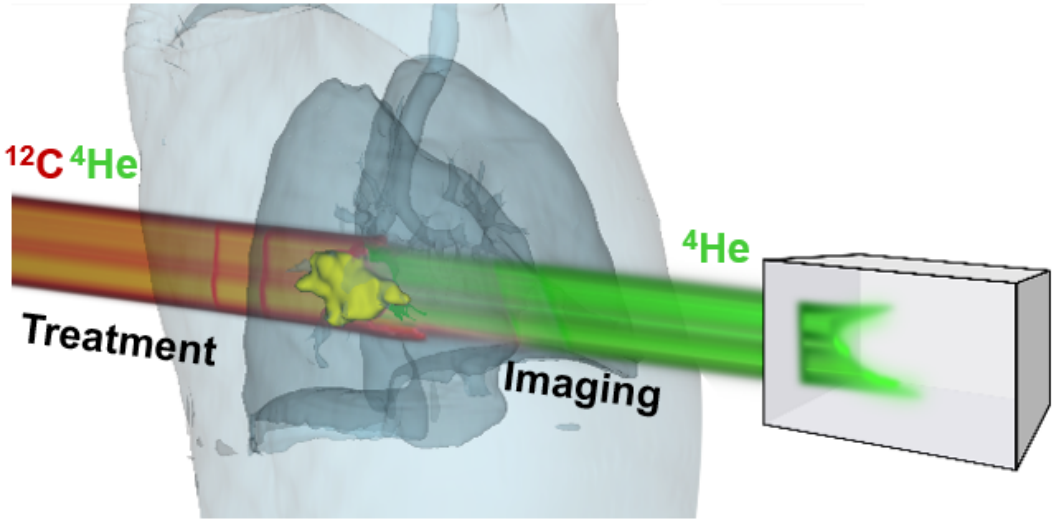
4		C^{3+}, He^{+}, O^{4+}	C^{3+}, He^{+}
3.2	O^{5+}	≈490μA	----- (memory ≈35μA)
3	C^{4+}	≈450μA	≈550μA
2.66	O^{6+}	≈500μA	----- (memory≈20μA)
2.4	C^{5+}	≈50μA	≈110μA
2.28	O^{7+}	23μA	-----
2		C^{6+}, He^{2+}, O^{8+}	C^{6+}, He^{2+}, H_2^{+}

Best soultion is achieved by feeding the source with CH_4 + He → Michael's work @GSI with active monitoring of He:C ratio

Dual isotope beams: Carbon radiotheraphy and helium online monitoring



courtesy of C. Graeff / L. Volz

- Particle therapy: Bragg peak based
- Highly localised dose distribution / highly conformal
- But: steep dose gradient → sensitivity to range uncertainties
  - inter-/intra-fractional anatomic changes
  - Uncertainties in planning
  - Patient set-up
  - Motion induced range variation
- One solution: mixed carbon-helium ion beams (90 % C, 10 % He*)
  - Similar mass-to-charge-ratio
  - Range of He ~3 times larger than C at same energy/nucleon
  - Carbon for irradiation
  - Helium passes patient for online monitoring

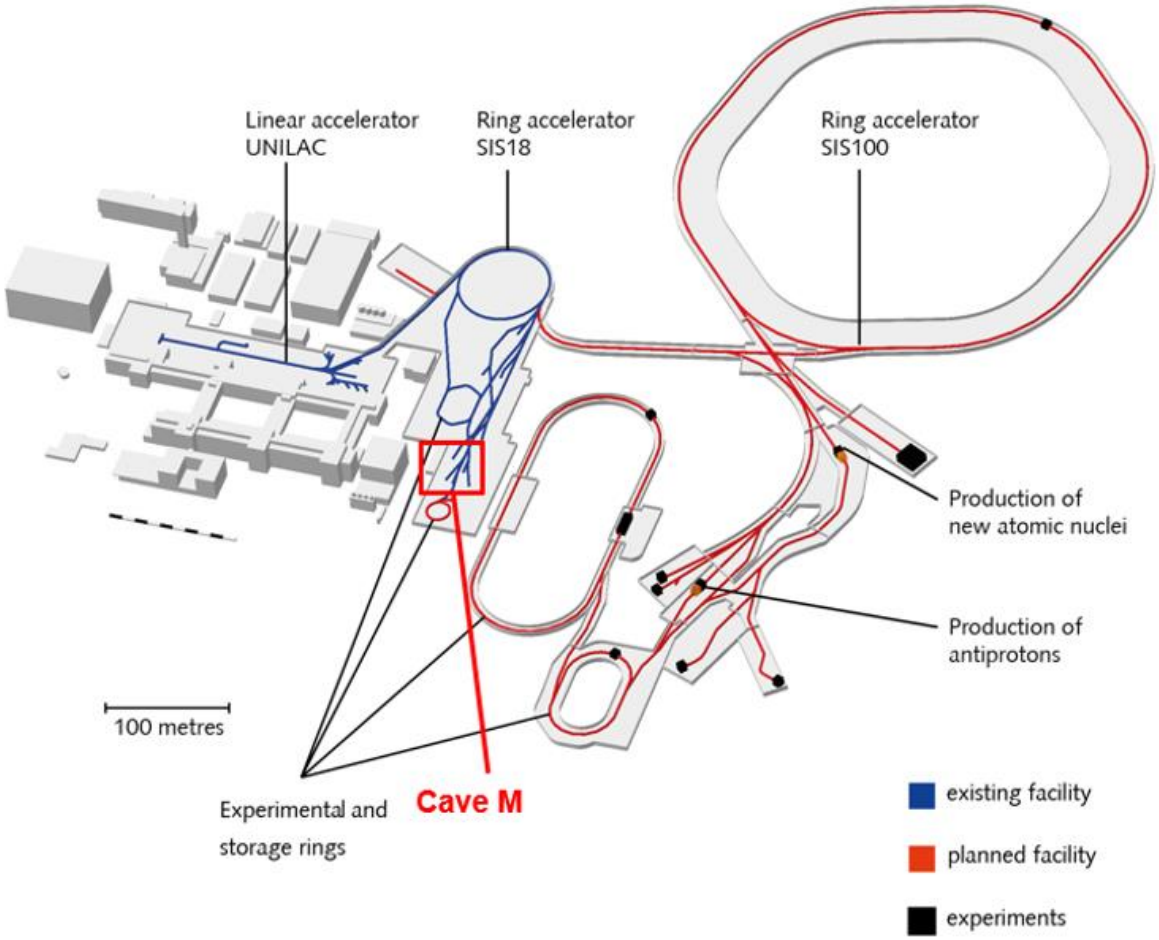
➢ Online range verification: extraordinary increase in precision of conformal dose

*extra dose < 1 %

- C. Graeff et al (2018), https://doi.org/10.1016/j.ejmp.2018.06.099
- L. Volz et al (2020), Phys. Med. Biol. 65 055002
- D. Mazzucconi et.al (2018), https://doi.org/10.1002/mp.13219
- Ch. Graeff, L. Volz, M. Durante, Prog. Part. Nucl. Phys., vol. 131, p. 104046, Jul. 2023
- Jennifer J Hardt et al., 2024 Phys. Med. Biol. in press.

M. Galonska et al., **FIRST DUAL ISOTOPE BEAM PRODUCTION FOR SIMULTANEOUS HEAVY ION RADIOTHERAPY AND RADIOGRAPHY,** https://proceedings.jacow.org/ipac2024/pdf/WEAN1.pdf

GSI complex and FAIR



- Heavy ion research centre for fundamental research
- Ions from protons to uranium
- Flexibility (energies, intensities, settings)
- Parallel operation
- Slow extraction capabilities
- Pilot scheme for carbon ion beam therapy (1997 – 2008)
- Former therapy room ‘Cave M’ unrestricted by Medical Product Acts

M. Galonska et al., **FIRST DUAL ISOTOPE BEAM PRODUCTION FOR SIMULTANEOUS HEAVY ION RADIOTHERAPY AND RADIOGRAPHY,** https://proceedings.jacow.org/ipac2024/pdf/WEAN1.pdf

General requirements

Requirements:

- Ion beam: carbon and helium with constant ratio over spill
- Fraction helium approx. 10 % (particles)
- Energy: 225 MeV/u, intensity: 1e8 / s in a 2…3 s spill
- Minimum oxygen contamination in the beam

Ion source:

Approx. 150 µA $^{12}C^{3+}$ upstream UNILAC largely sufficient

→≈ 4 to 5 µA He^{+}

Combinations:

CH_4 und ^4He: C^{3+}, $^4He^{+}$
CH_4 und ^3He: C^{4+}, $^3He^{+}$
CO_2 und ^3He: C^{4+}, $^3He^{+}$

- Each combination feasible from ECRIS
- Works for UNILAC as well
- But not for SIS18

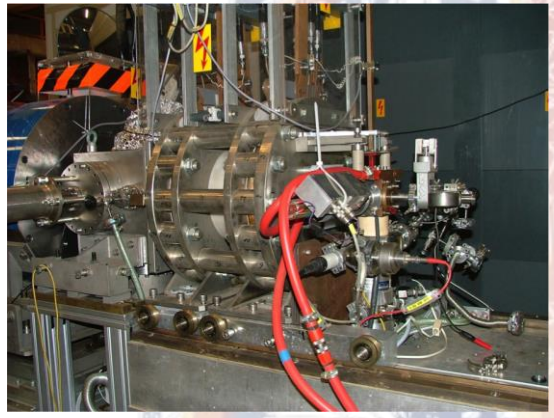
CH_4 und ^4He: C^{3+}, $^4He^{+}$

difference in A/Z: $^3He/^{12}C$: 0.5%, $^4He/^{12}C$: 0.065%
contaminant: $^{16}O^{4+}$

M. Galonska et al., **FIRST DUAL ISOTOPE BEAM PRODUCTION FOR SIMULTANEOUS HEAVY ION RADIOTHERAPY AND RADIOGRAPHY,** https://proceedings.jacow.org/ipac2024/pdf/WEAN1.pdf

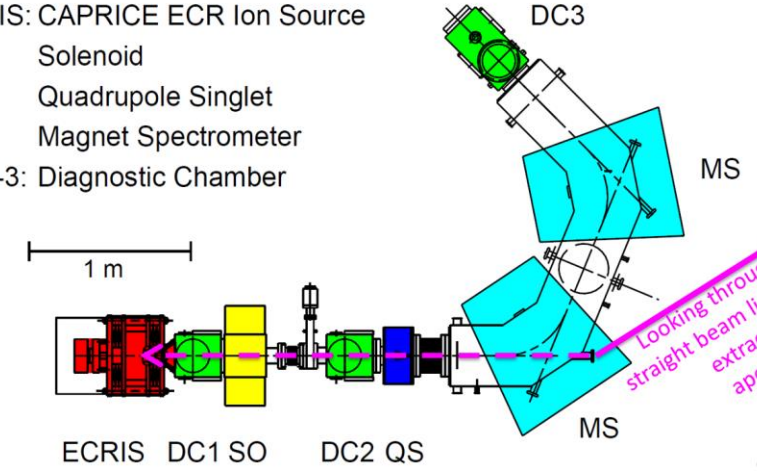
Experimental setup

Ion source

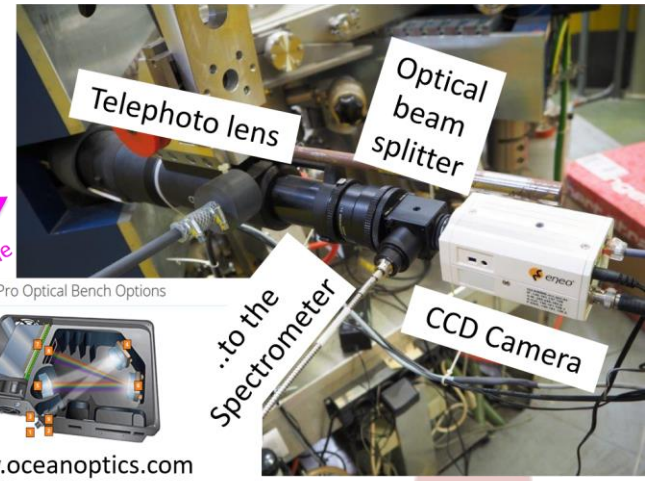


LEBT

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



Optical spectrometer



ECR ion source

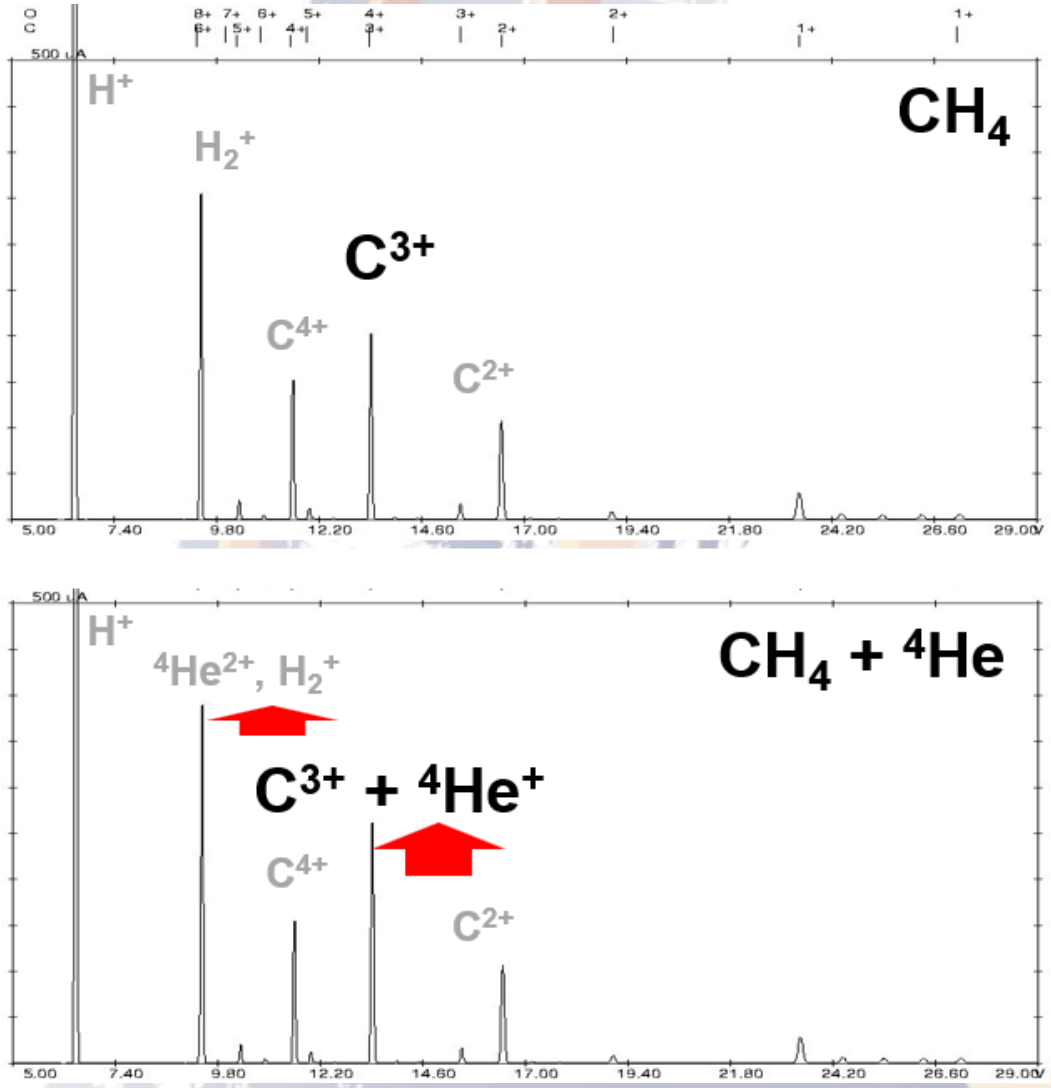
- **Used for therapy at GSI**
- **Medical centres use ECR ion sources**

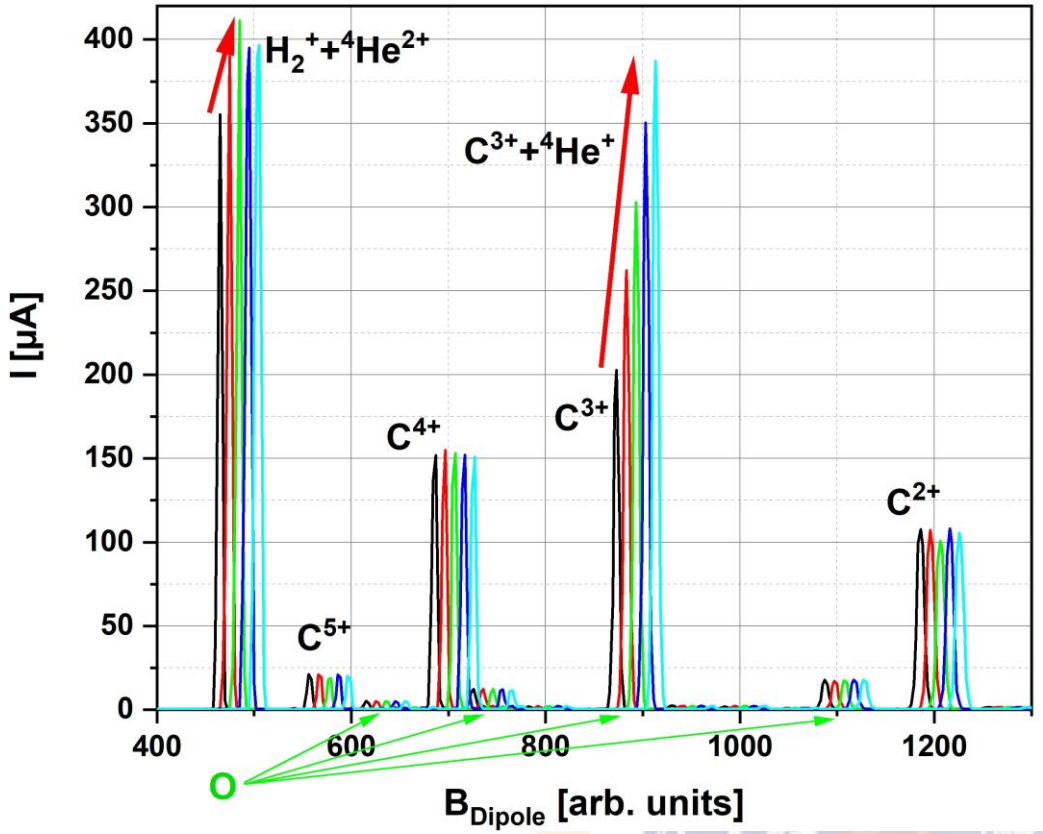
Measurement of

- **Mass spectra (no distinction between $C^{3+}/^4He^+$)**
- **Beam current (no distinction between $C^{3+}/^4He^+$)**
- **Optical emsission lines (approximate C-to-He ratio)**

M. Galonska et al., **FIRST DUAL ISOTOPE BEAM PRODUCTION FOR SIMULTANEOUS HEAVY ION RADIOTHERAPY AND RADIOGRAPHY,** https://proceedings.jacow.org/ipac2024/pdf/WEAN1.pdf

Mass spectra

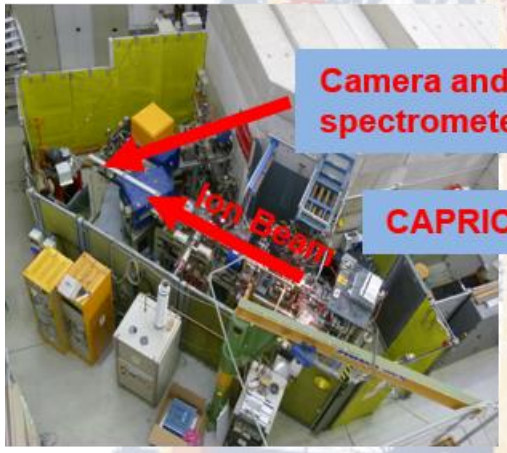


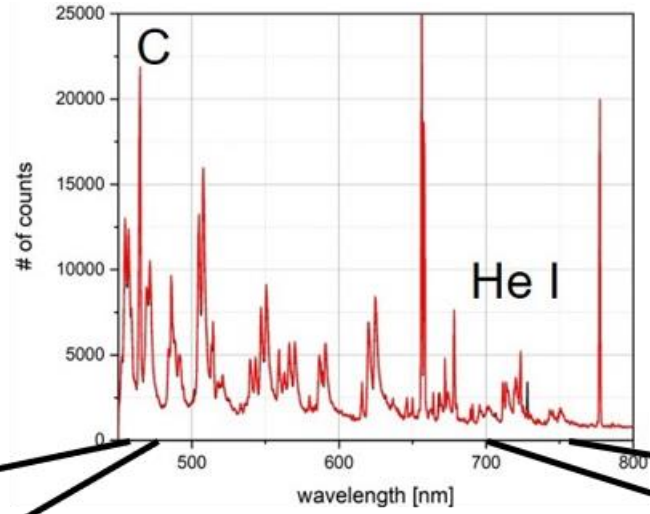


Mass spectra
(shifted on momentum axes)

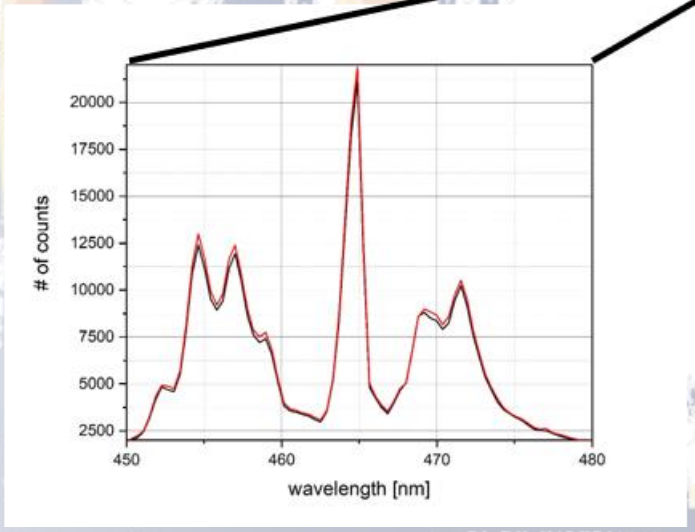
M. Galonska et al., **FIRST DUAL ISOTOPE BEAM PRODUCTION FOR SIMULTANEOUS HEAVY ION RADIOTHERAPY AND RADIOGRAPHY,** https://proceedings.jacow.org/ipac2024/pdf/WEAN1.pdf

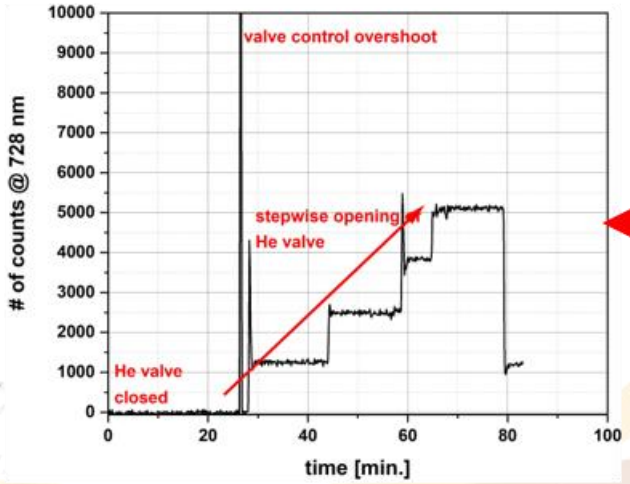
Optical emission lines

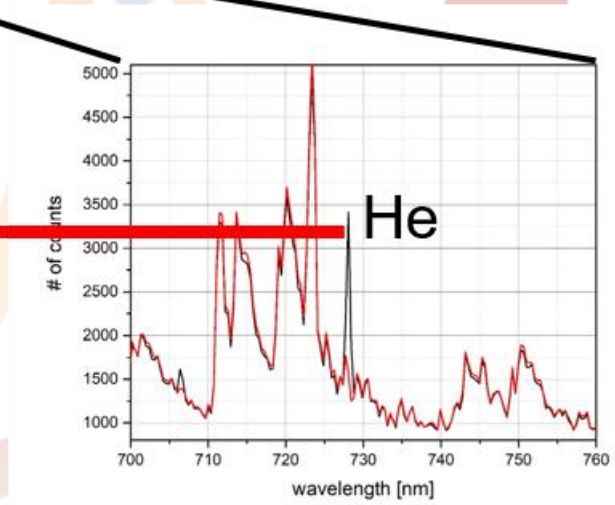




-- w/o He
-- w/ He



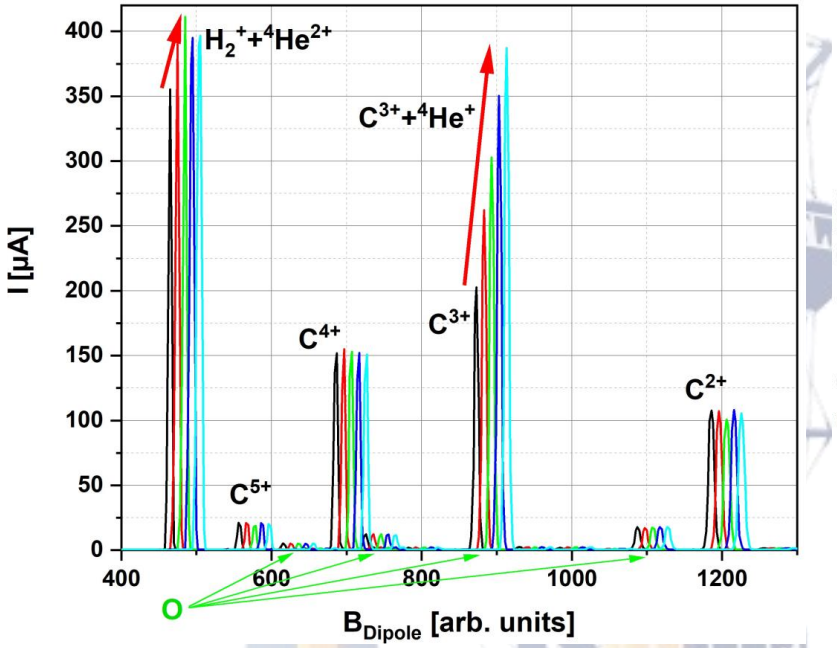


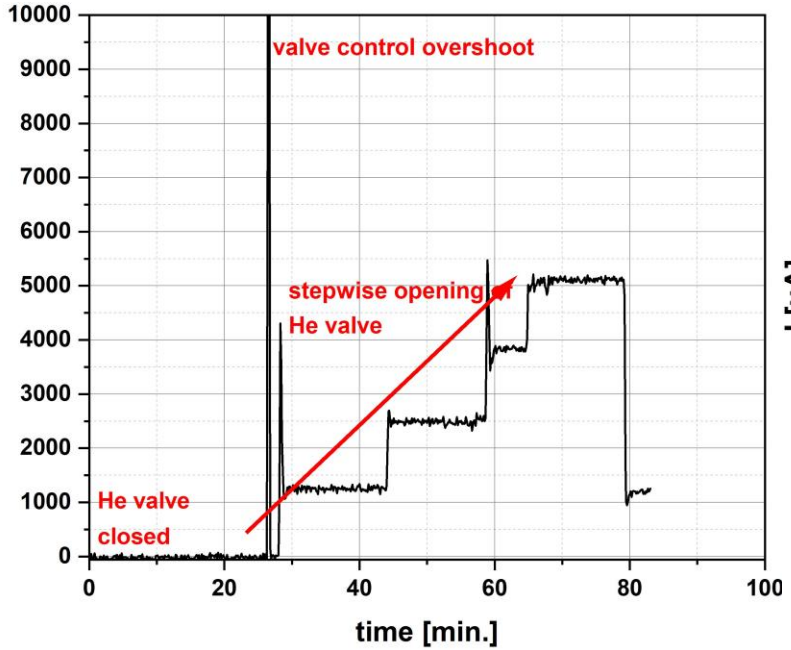


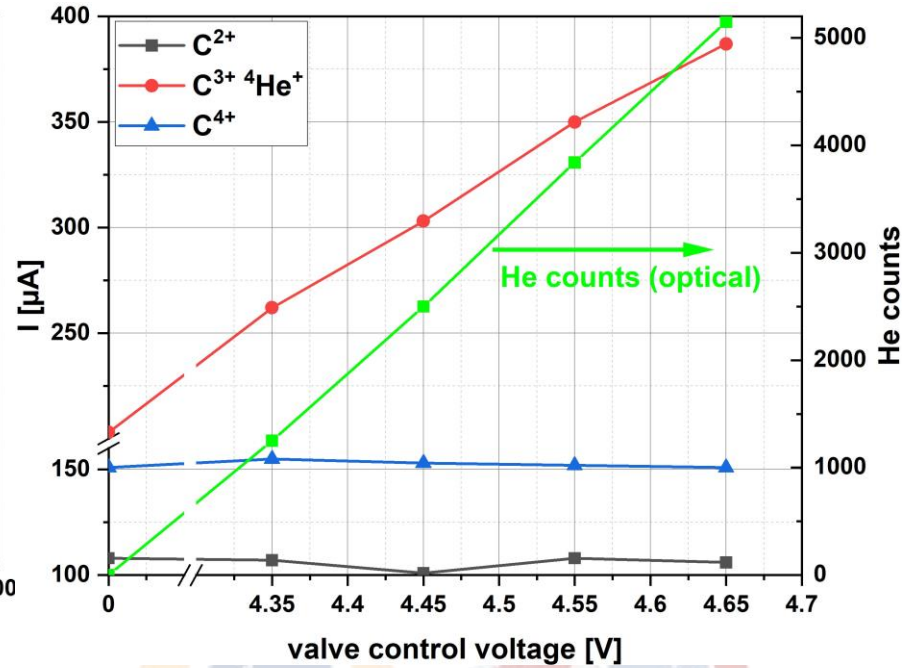
M. Galonska et al., **FIRST DUAL ISOTOPE BEAM PRODUCTION FOR SIMULTANEOUS HEAVY ION RADIOTHERAPY AND RADIOGRAPHY,** https://proceedings.jacow.org/ipac2024/pdf/WEAN1.pdf

Current and counts

Stepwise adding Helium



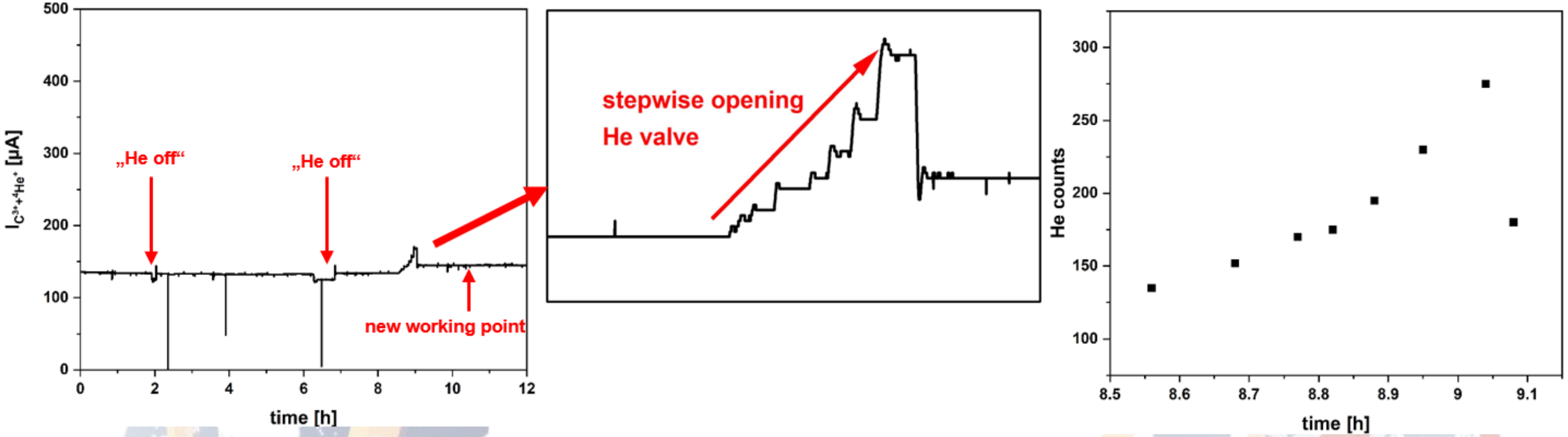




- Correlation between current and counts, needs to calibrated → adjusting C-to-He ratio
- True particle numbers only from detectors in biophysics cave

M. Galonska et al., **FIRST DUAL ISOTOPE BEAM PRODUCTION FOR SIMULTANEOUS HEAVY ION RADIOTHERAPY AND RADIOGRAPHY,** https://proceedings.jacow.org/ipac2024/pdf/WEAN1.pdf

Ion source stability

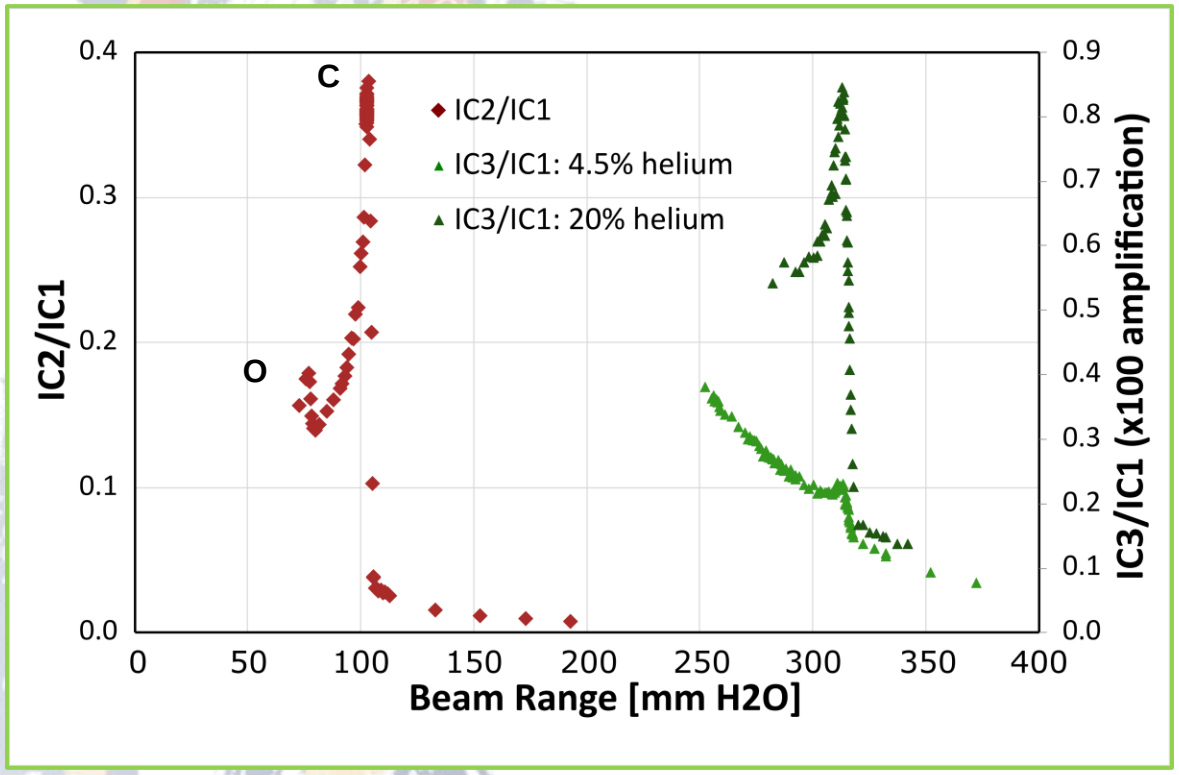


Current over time
in beam transformer

Optical lines
(manually, sadly..)

M. Galonska et al., **FIRST DUAL ISOTOPE BEAM PRODUCTION FOR SIMULTANEOUS HEAVY ION RADIOTHERAPY AND RADIOGRAPHY,** https://proceedings.jacow.org/ipac2024/pdf/WEAN1.pdf

Depth-dose-profiles: Biophysics cave



courtesy of C. Graeff / L. Volz et al.

- ~1000 Spills, time resolved data
- Depth dose profiles
- Position (Matrix IC / films)
- Single particle measurements
- Scintillator / high speed camera
- Fast extracted beam (plasma phyics cave)
- ….

Two ‘working points‘:

4.5 % He and 20 % He (relation to C)
7 % oxygen too high, but stable

M. Galonska et al., **FIRST DUAL ISOTOPE BEAM PRODUCTION FOR SIMULTANEOUS HEAVY ION RADIOTHERAPY AND RADIOGRAPHY,** https://proceedings.jacow.org/ipac2024/pdf/WEAN1.pdf

INFN LNS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

CNAO

FAIR

GSI

Mixed Ion Beams 26

Perspectives

- **ECR ion sources offer considerable flexibility** for the production of mixed ion beams, but beam composition and stability remain critical issues.
- **C^{6+} production with minimal O^{8+} contamination is challenging.** Preliminary estimates indicate that oxygen contamination may remain significant, even after conventional source optimization.
- **Gas tuning and magnetic confinement optimization** are the primary tools for controlling the charge-state distribution. Selective ICRH could provide an additional purification mechanism.
- **Mixed C^{3+}/He^{+} beams are feasible**, and optical emission spectroscopy offers a promising approach for monitoring and controlling the He ratio.
- **Close integration between ion-source development, accelerator requirements/develpments and clinical needs is essential**, particularly regarding beam intensity, composition and acceptable contamination levels.

Towards mixed beams and multi-ion radiotherapy

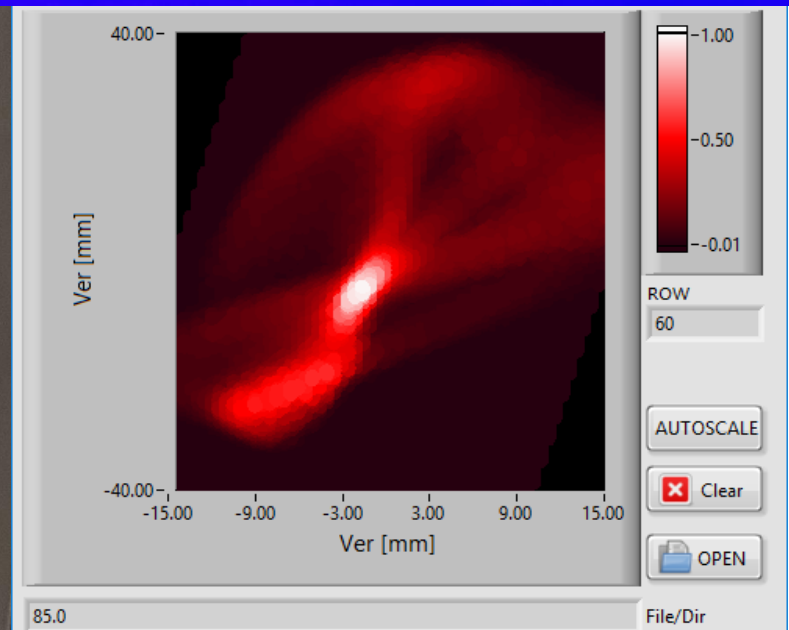
Mixed-ion beam production may pave the way towards future multi-ion cancer treatments, potentially combining carbon, helium and oxygen beams.

This approach requires coordinated development of the ion source and accelerator, together with reliable online diagnostics to monitor and control the beam composition and relative ion intensities throughout the acceleration and delivery chain.

L. Celona et al., 1st Workshop on Workshop on Mixed Ion Beam Delivery, Wien, Austria

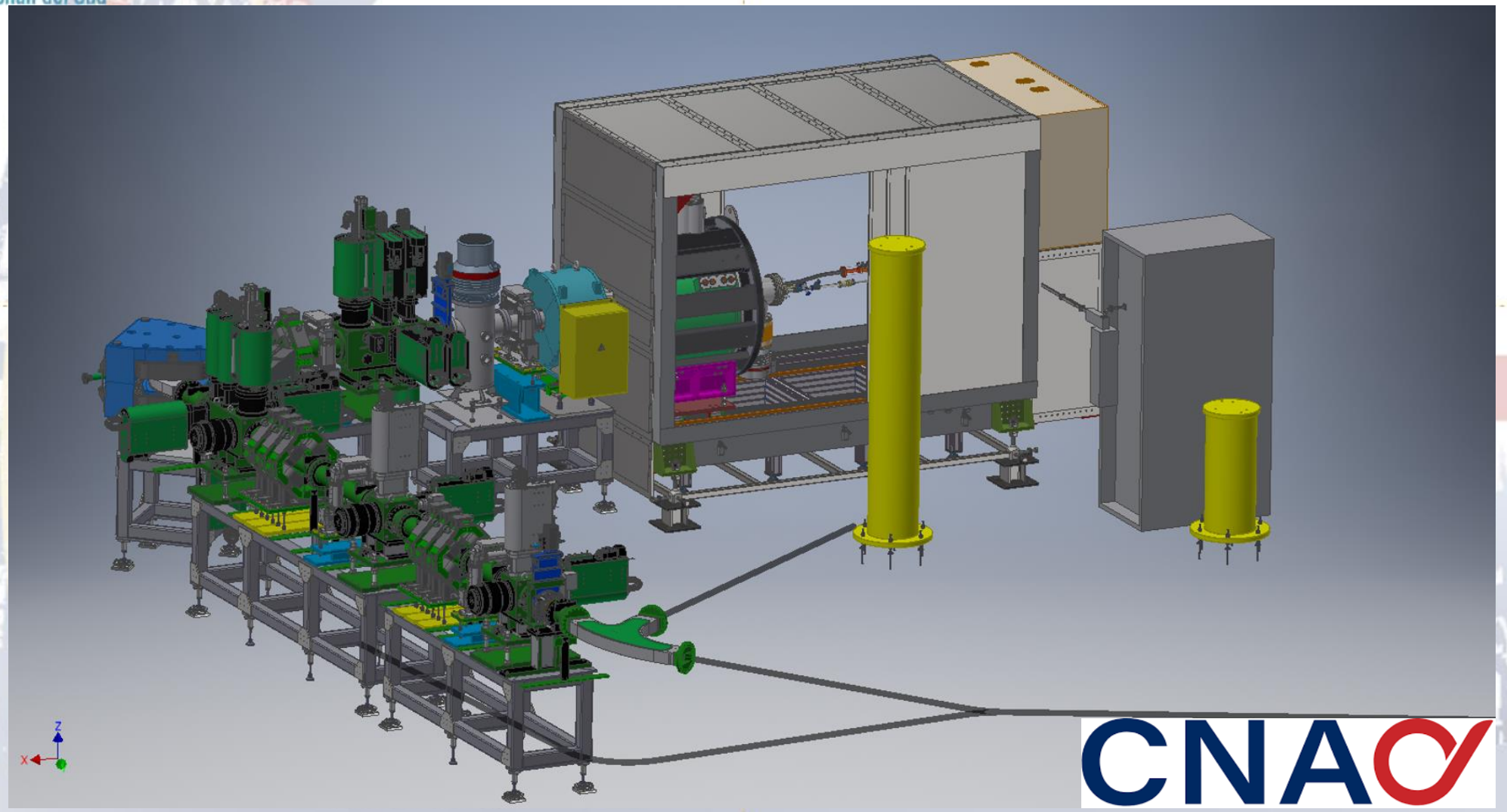


A: 41.5278 K
B: 41.3278 K
C1: 2.9578 K
D1: 3.0920 K
C2: 3.0760 K
D2: 3.4279 K
C3: 3.0961 K
D3: 3.5200 K
C4: 3.1438 K
D4: 51.4090 K
C5: 3.1920 K
D5: 56.4508 K



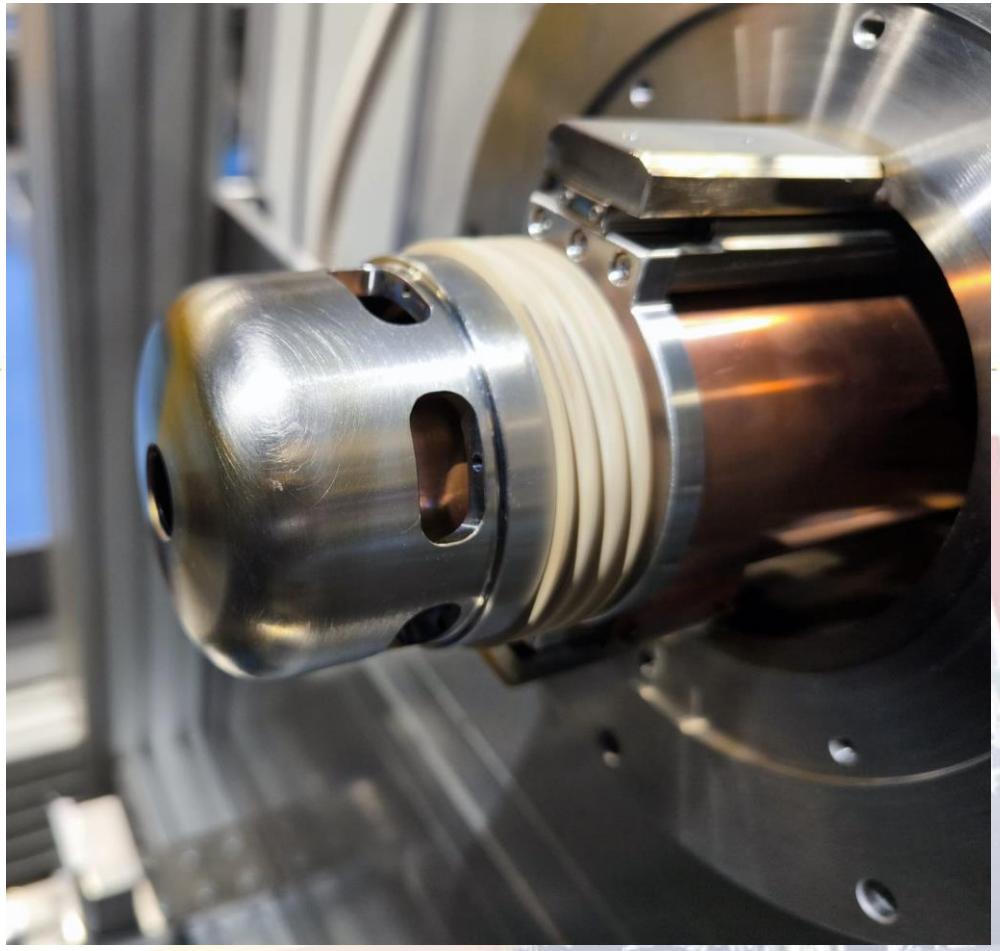
Thanks for your attention!

AISHa and LEBT



AISHa-2 after 67 days continuos operations





TELAMONES & FTP rooms (TEst LAboratory for MOdelling New Ecr ion Sources) (Flexible Plasma Trap)

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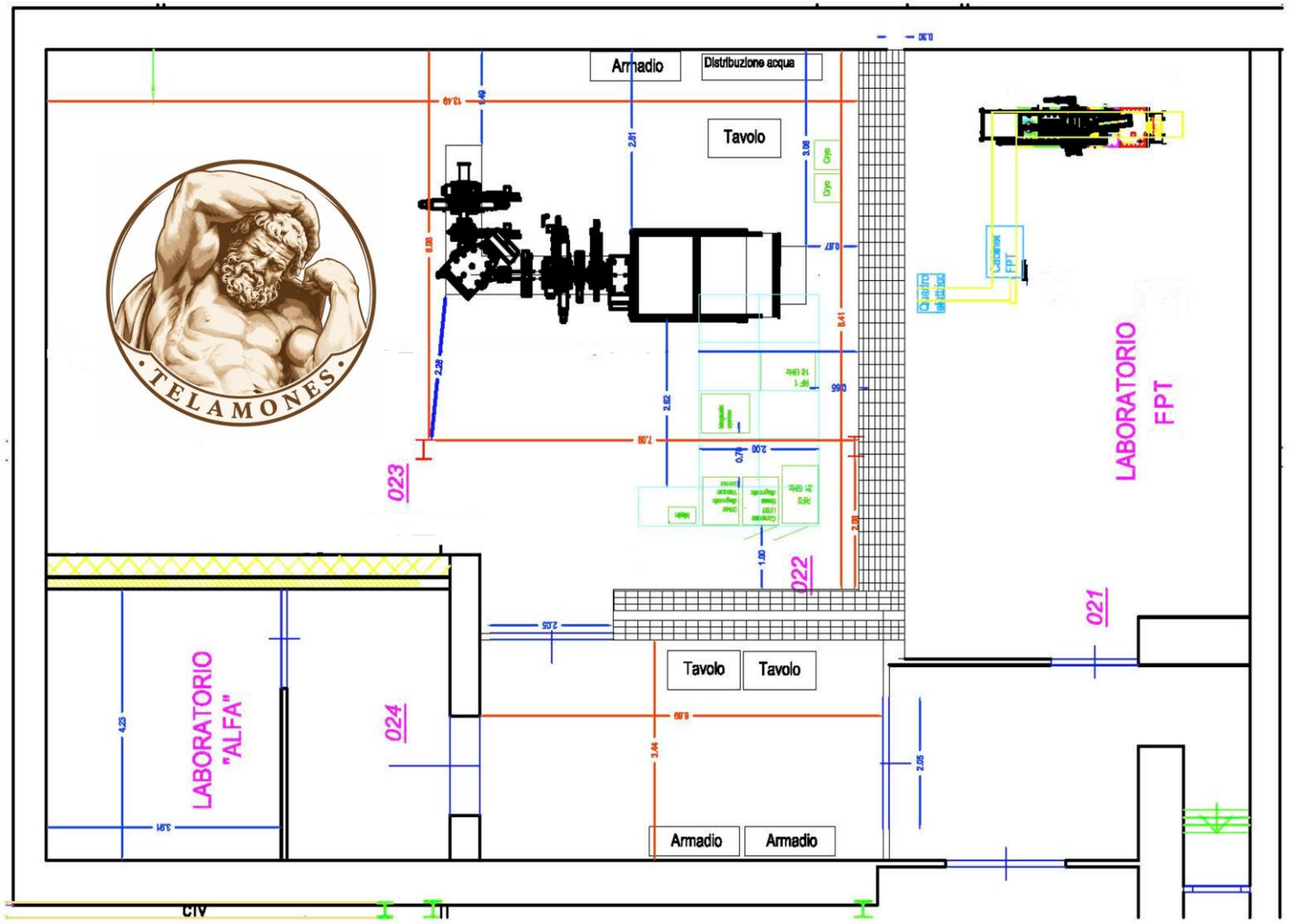
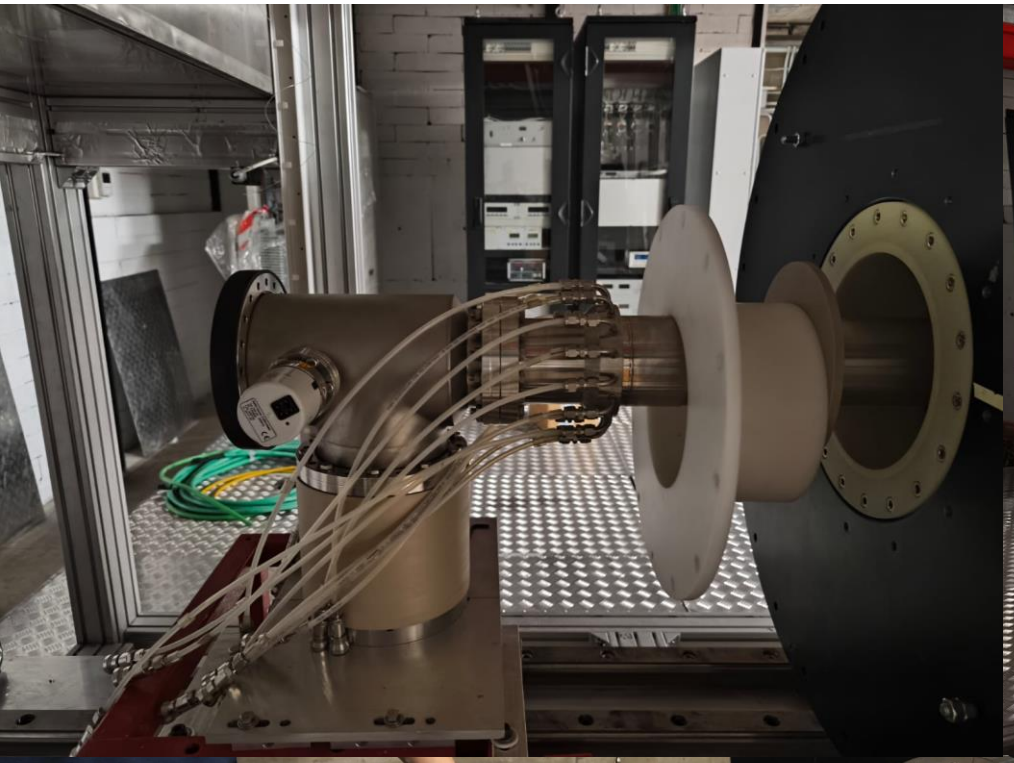
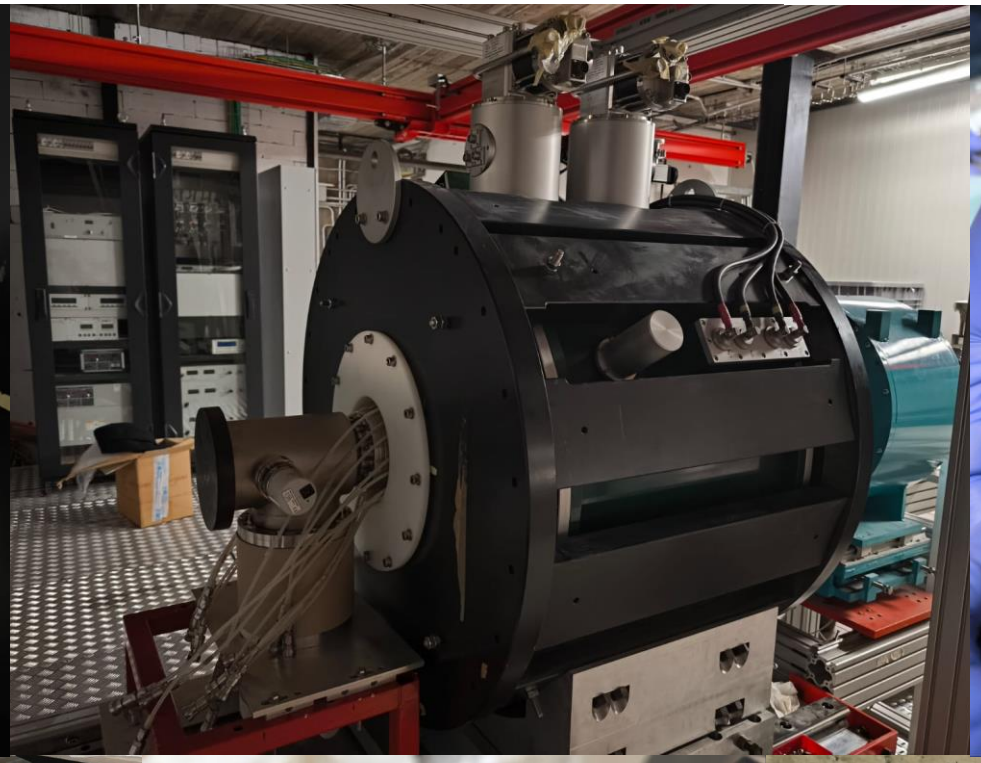
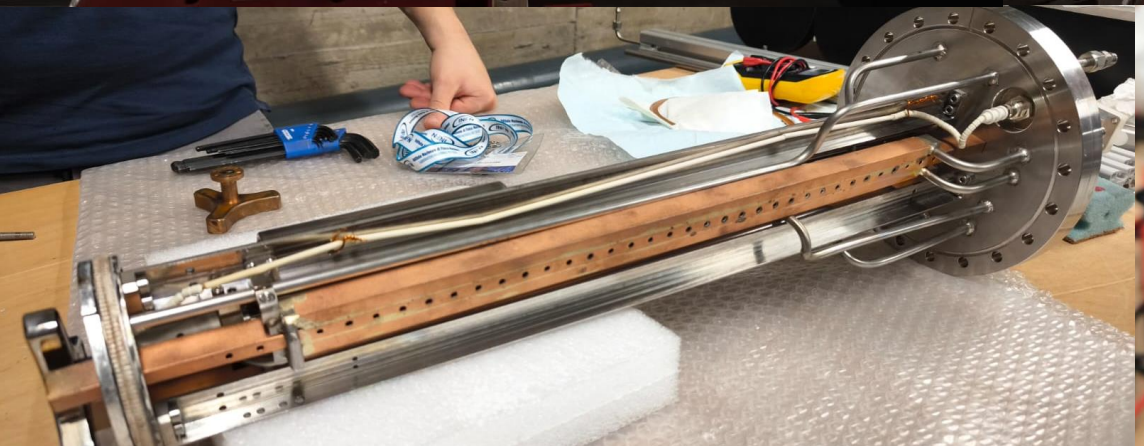
Plasmas for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry

ASHa



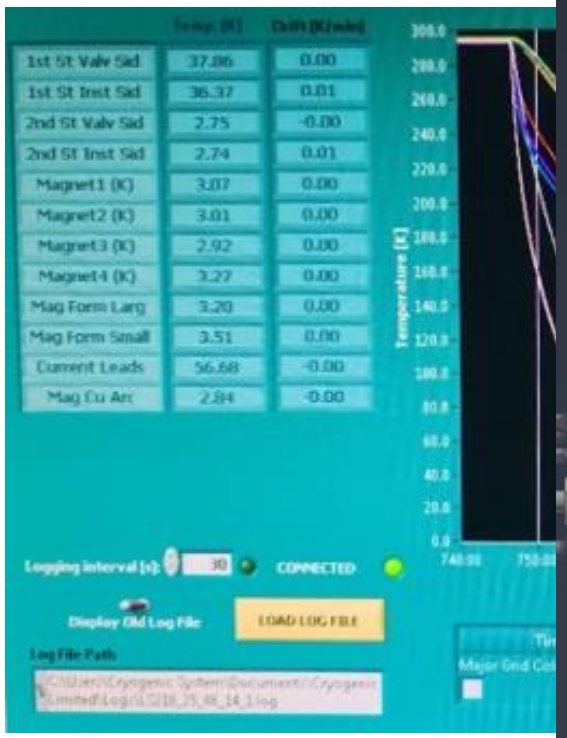
AISHa reinstallation

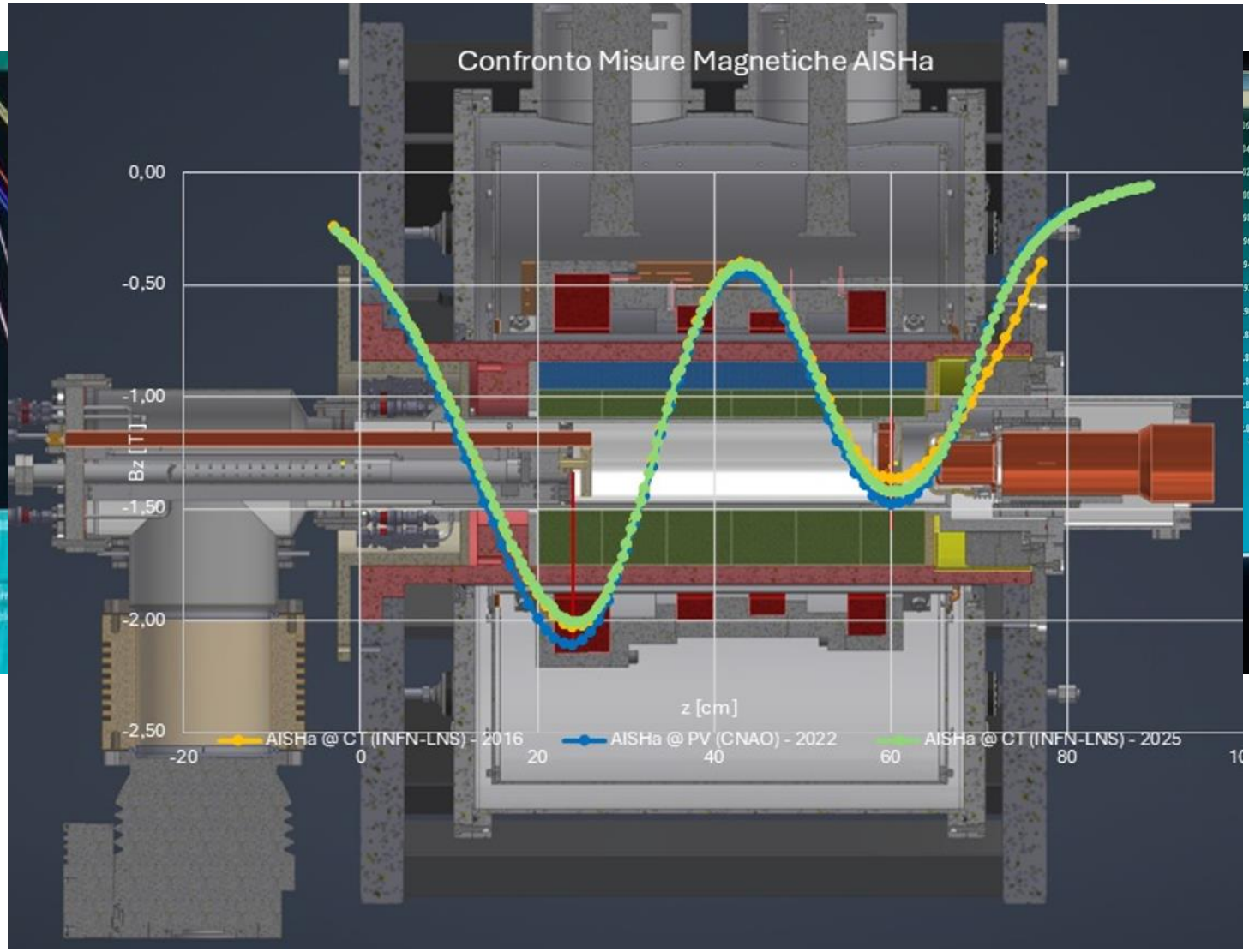



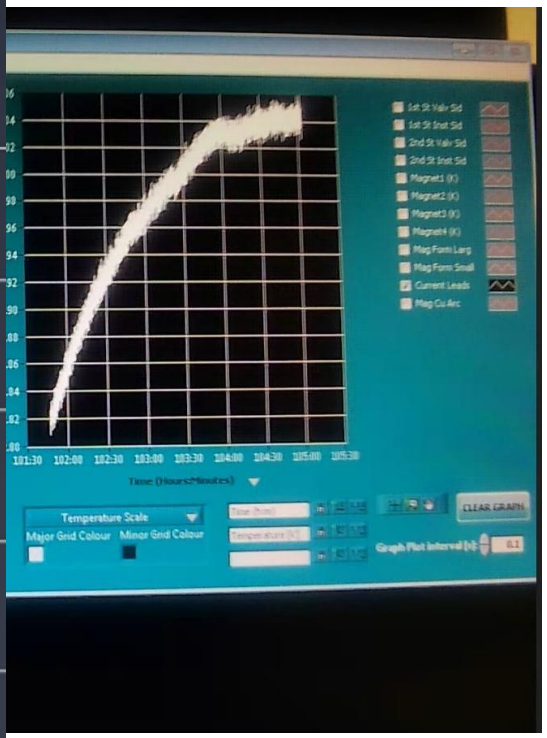




AISHa restart







L. Celona et al., 27th International Workshop on ECR Ion Sources, S. Francisco, USA

Where we stopped...

IONS

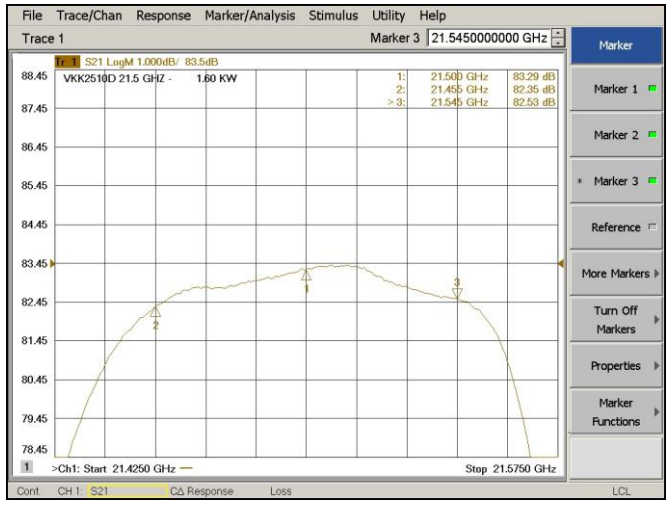
ION Source developments @ INFN-LNS

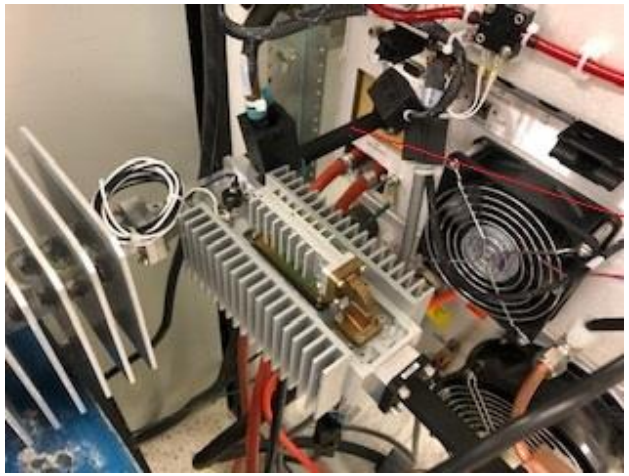
- Connection between Plasma Parameters (n_e, T_e, T_i, τ_i) and Ion beam parameters (extracted current, Charge state distribution, beam emittance and shape) for the different working conditions. This will help to improve source performance while minimizing emittance.
- Upgrading and development of the beam diagnostics to permit the correlation between beam parameters and plasma parameters;
- Minimization of the losses in the ionization chamber by using active (multi splitted chamber) and passive methods (wall covering) able to change actively the Electron Energy Distribution Function;
- Development of the Optical Emission Spectroscopy as a diagnostic tool to evaluate the Electron Energy Distribution Function (EEDF) in a non-invasive way;

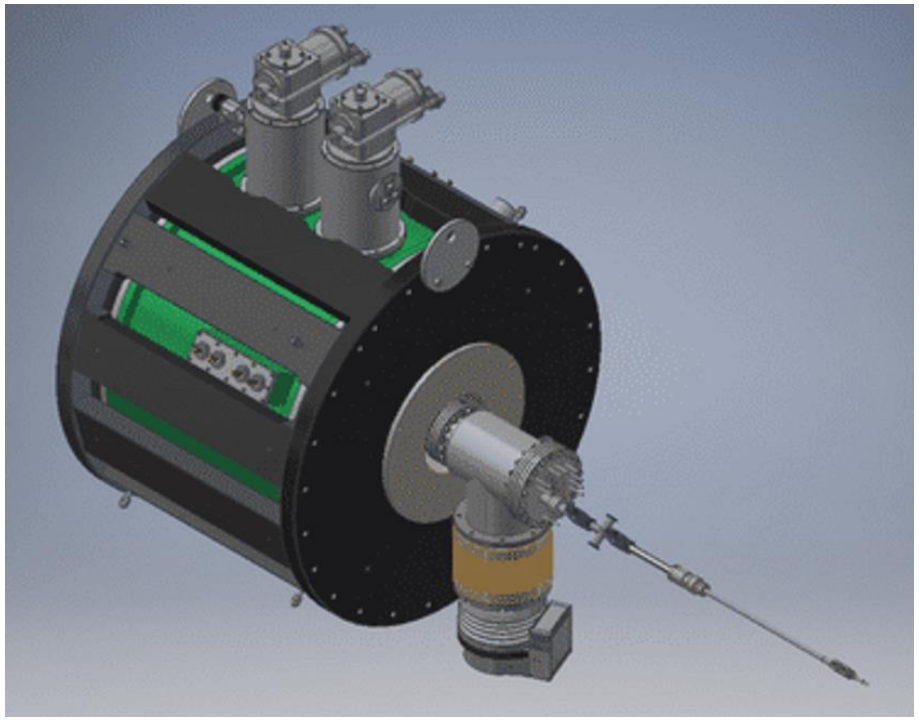
CSNV, 16 June 2021, INFN-LNS

Others....

- **Source recommissioning @18 GHz (1.5 kW)**
- **21 GHz source operations (1.5 kW)**
- **TFH operations – Evaluation of energy transfer at different frequencies**
- **Metallic beam development (AISHa adaptation for the GSI oven already done)**
- **LNS & CNAO beam development**







21 GHz klystron (SN/001) is ready to be coupled with AISHa at LNS.