ION SOURCE UPGRADES AT MEDAUSTRON ION THERAPY CENTER

Nadia Gambino, Greta Guidoboni, Matthias Kausel, Clemens Maderböck, Szymon Myalski, Liviu Penescu, Valeria Rizzoglio, Rainer Rockenbauer, Claus Schmitzer, Elisabeth Renner.

26th International Workshop on ECR Ion Sources, 15-19 September 2024, GSI Darmstadt

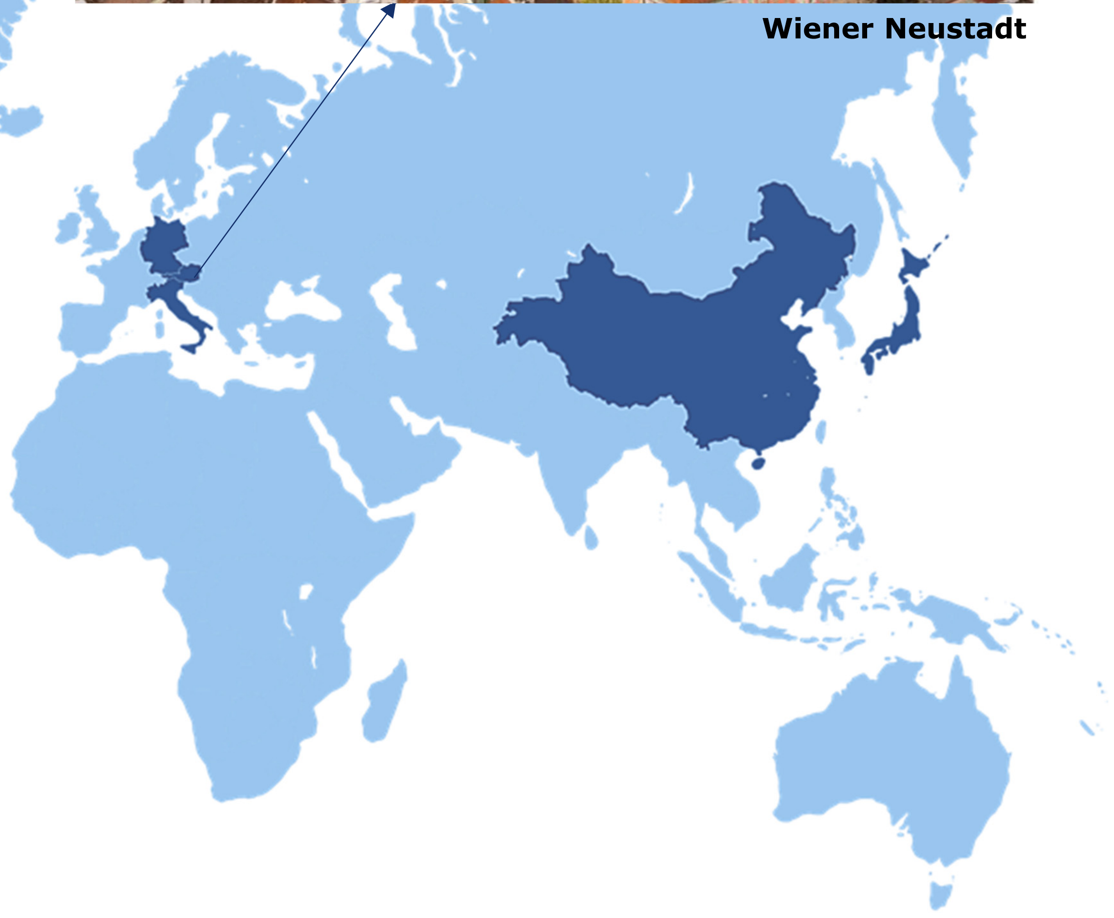
OUTLINE

- About MedAustron
    - Roadmap and current status
- Ion Source Commissioning
    - Helium commissioning from S3 up to IR1
    - Clinical Carbon Ion Source (S2) commissioning in Pulsed Mode
    - Proton Ion Source Performances (S1) in Double Frequency Heating
- Future Perspectives
    - Design of fourth Ion Source Branch (S4)

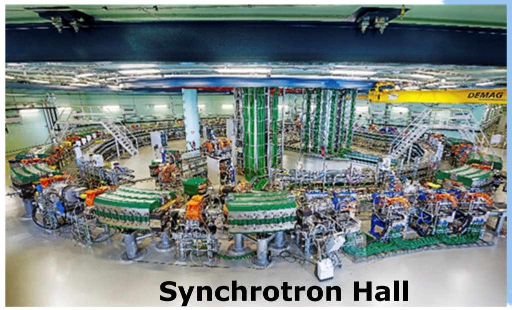
ABOUT MEDAUSTRON

- One of the 6 comparable proton and carbon ion therapy centers worldwide located in Wiener Neustadt, 50 km from Vienna, Austria
- Approximately 300 employees from 20 different countries
- Expertise in designing, building, commissioning, certifying and operating a particle therapy facility

Wiener Neustadt



MedAustron



Synchrotron Hall

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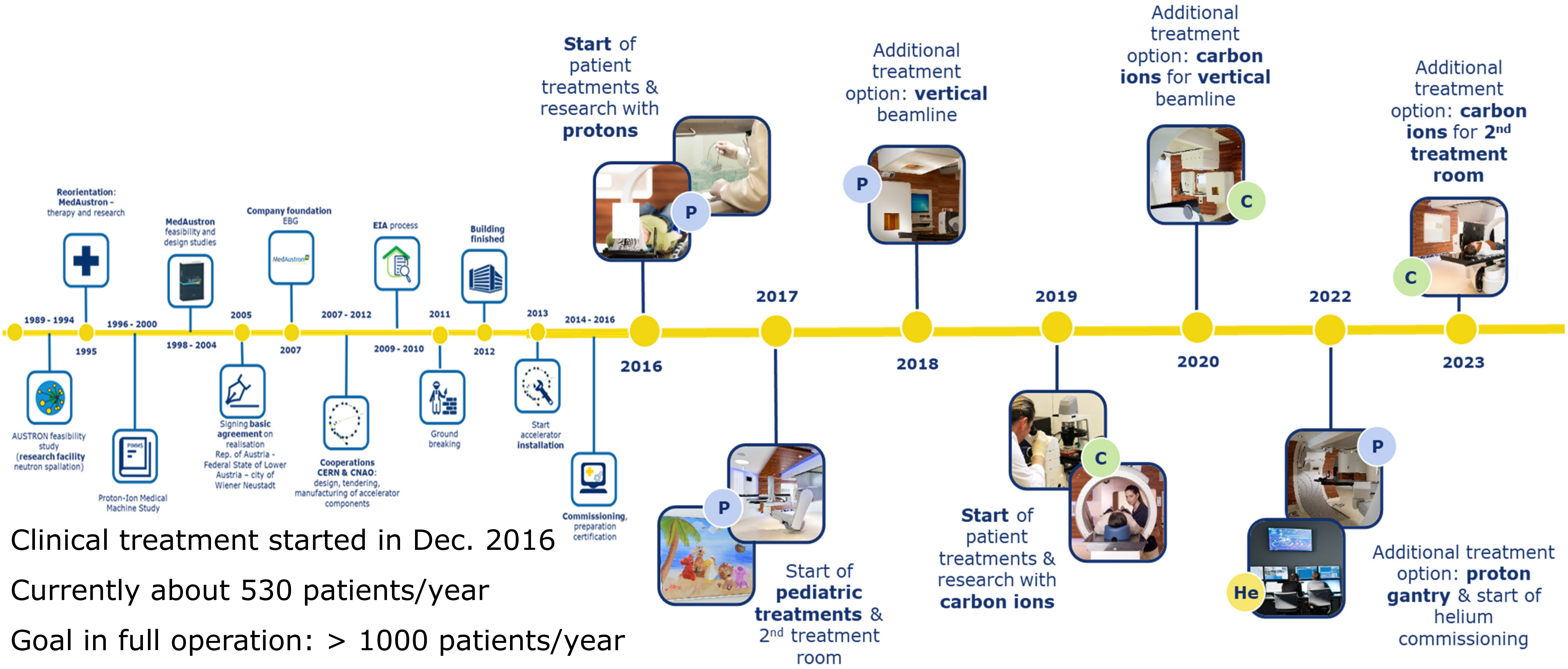
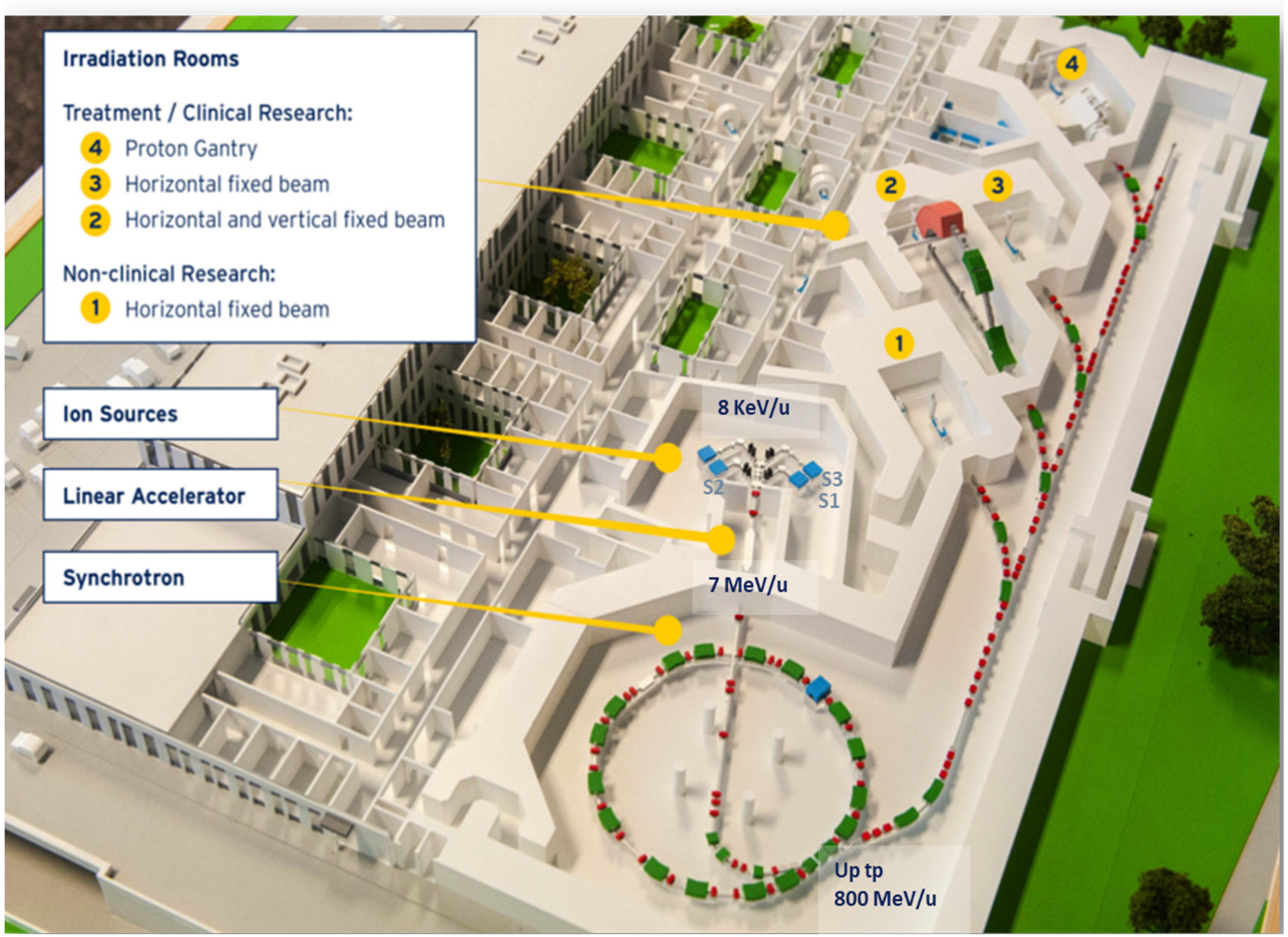
MEDAUSTRON ROADMAP



- Clinical treatment started in Dec. 2016
- Currently about 530 patients/year
- Goal in full operation: > 1000 patients/year
- Commissioning is completed, but development projects ongoing (IR5,MATEO, PMO, HelioS3..)
- Current uptime: >98 %

ACCELERATOR LAYOUT



Main Machine Parameters

- 4 irradiation rooms, three clinical (IR1, IR2, IR4), one non-clinical research room (IR1)
- Extracted beam after Ion Sources: 8 KeV/u
- Extracted Beam after RFQ: 400 KeV/u
- Extracted beam after LINAC: 7 MeV/u
- Accelerated energies into the Synchrotron (77 m diam): 62-252 MeV/u for protons and 120-402 MeV/u for carbon ions
- Extraction via third order resonance betatron core
- HEBT line equipped with a Double bend achromat Deflection Module, a PSS – Phase Stepper Shifter and a telescope system for the clinical beamlines (closes the dispersion)
- Intensities: p: $1 \cdot 10^{10}$ p/s, c: $5 \cdot 10^{8}$ p/s,
- NEW helium: $3 \cdot 10^{8}$ p/s

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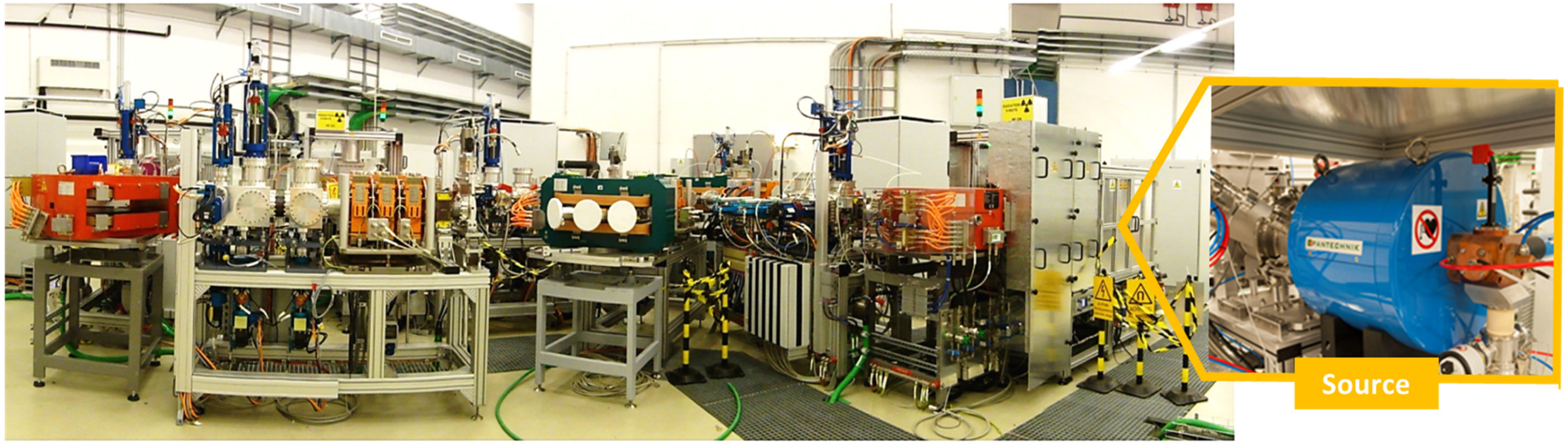
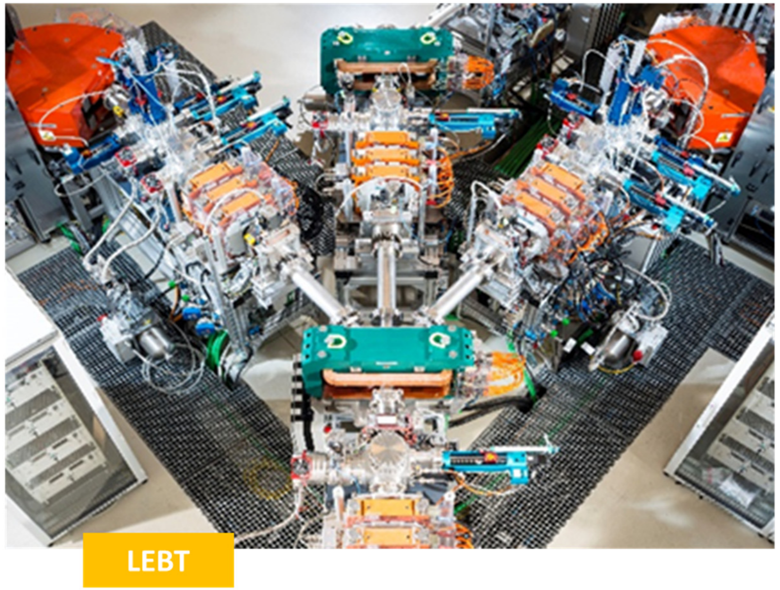
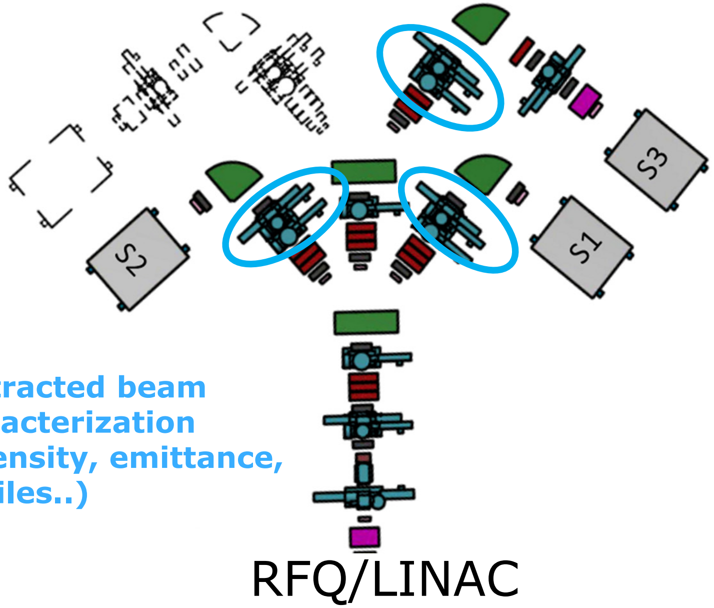
THE INJECTOR HALL







*extracted beam characterization (intensity, emittance, profiles..)

- Three identical ECRIS from Pantechnik always accessible
- Particle type selected by switching magnets
- Various beam diagnostics up to RFQ entrance (Faraday Cups, Slits and Wire Scanners, Current Transformers)
- Two clinical ion sources (S1 and S2) for proton and carbon ion beam production
- S3 transferred in a so-called "**test system**" independent of MAPTA, longer beamline!

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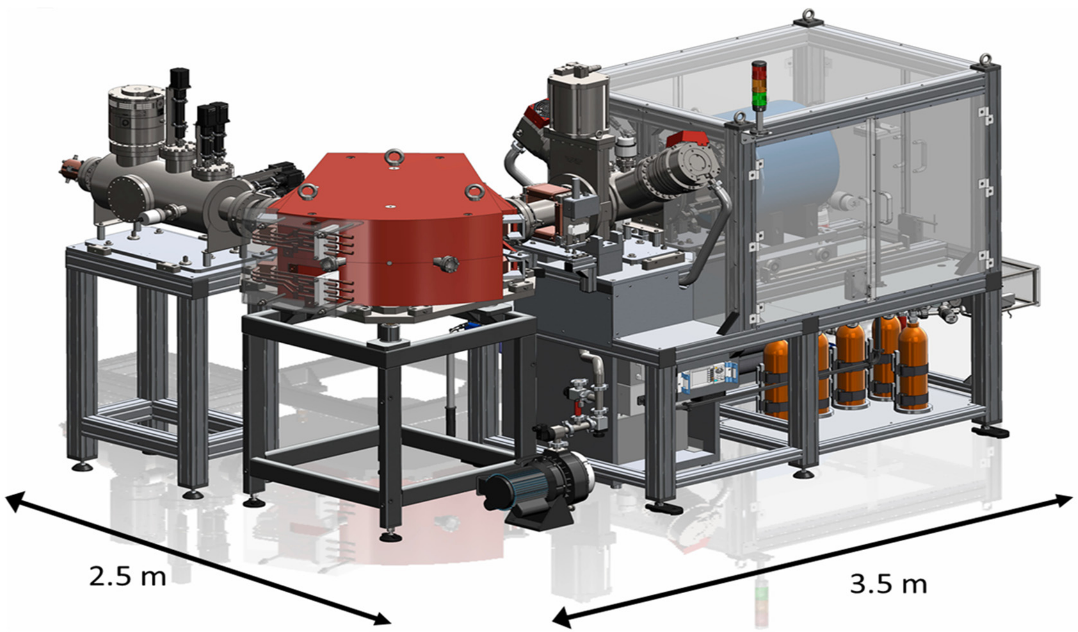
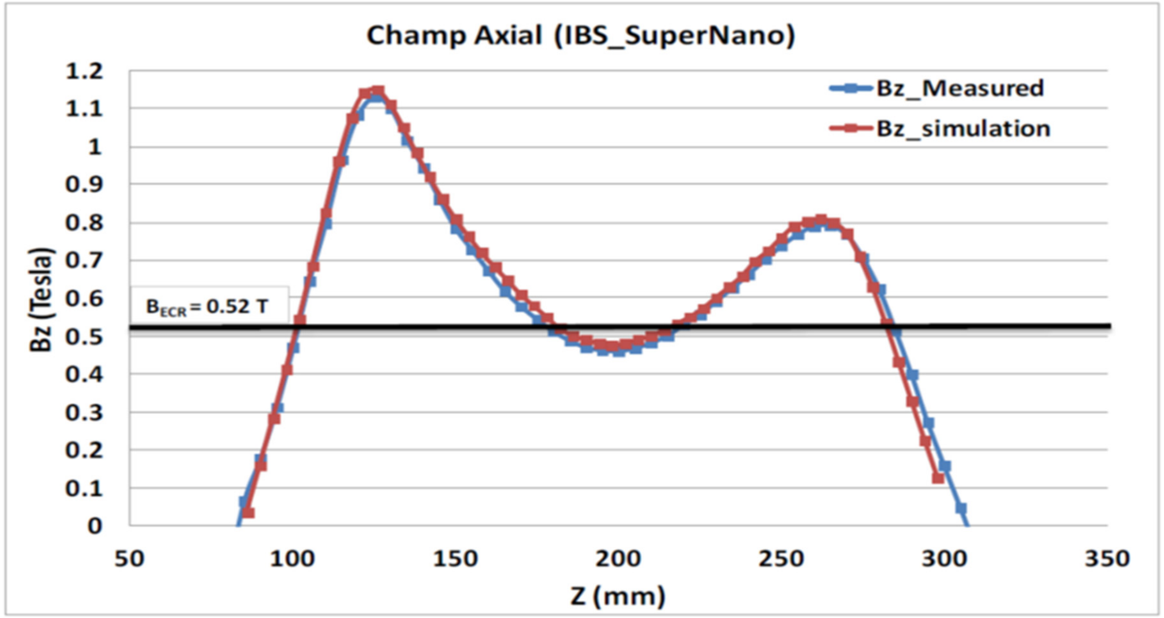
SUPERNANOGAN IS

- Equipped fully with permanent magnets (solenoid and hexapole fields)
- Operated in CW mode and in Pulsed Mode
- HV operated at 24 KV for p and c and at 16 kV for he
- Provided also with a DC Bias and RF Stab Tuner





Bfield @ inj./min /ex.: 1.15 T / 0.47 T / 0.81 T, Brad 1.04 T, Brad 1.04 T

Typ. Operational Parameters	H_3^+	C_{12}^{4+}	He_4^{2+}
RF Frequency (GHz)	14.4-14.51	14.4-14.51	14.4-14.51
RF Power (W)	8-10	100-150	32-35
Injection Pressure (mbar)	$1 \cdot 10^{-4}$	$2.5 \cdot 10^{-5}$	$5 \cdot 10^{-5}$
Gas Mix	H_2	CO_2+He	He
Ex. current	650 uA	100 uA	690 uA

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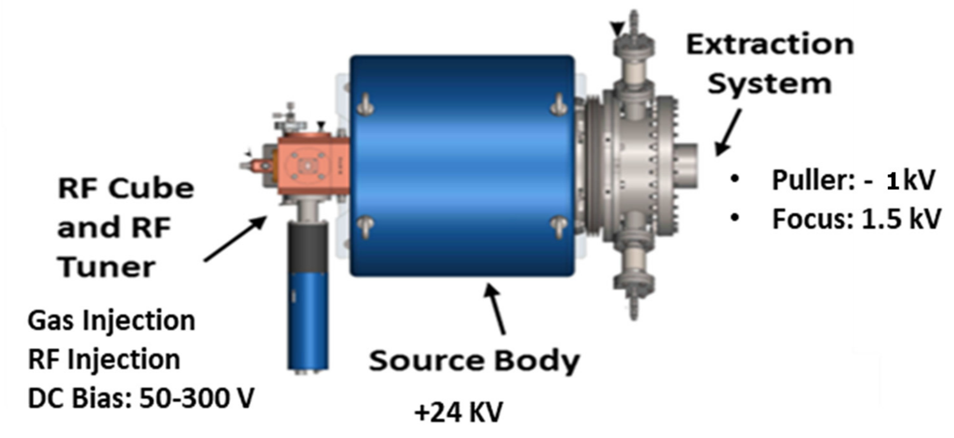

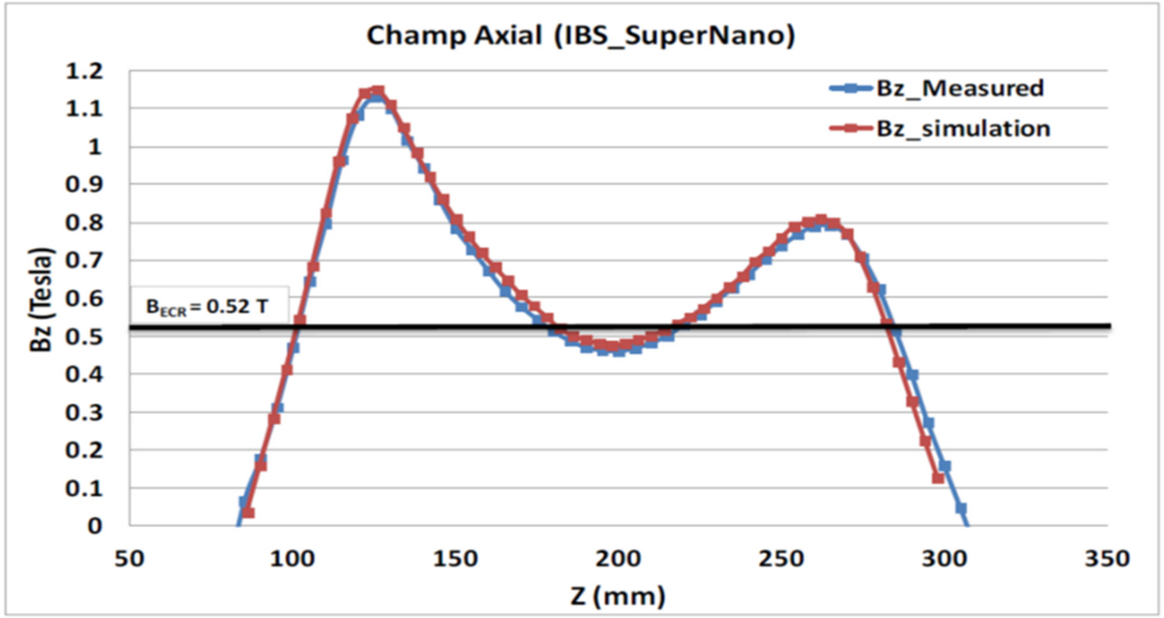

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ION SOURCE COMMISSIONING

- **Helium commissioning from S3 up to IR1**
- Clinical Carbon Ion Source commissioning in Pulsed Mode
- Proton Ion Source Performances in Double Frequency Heating

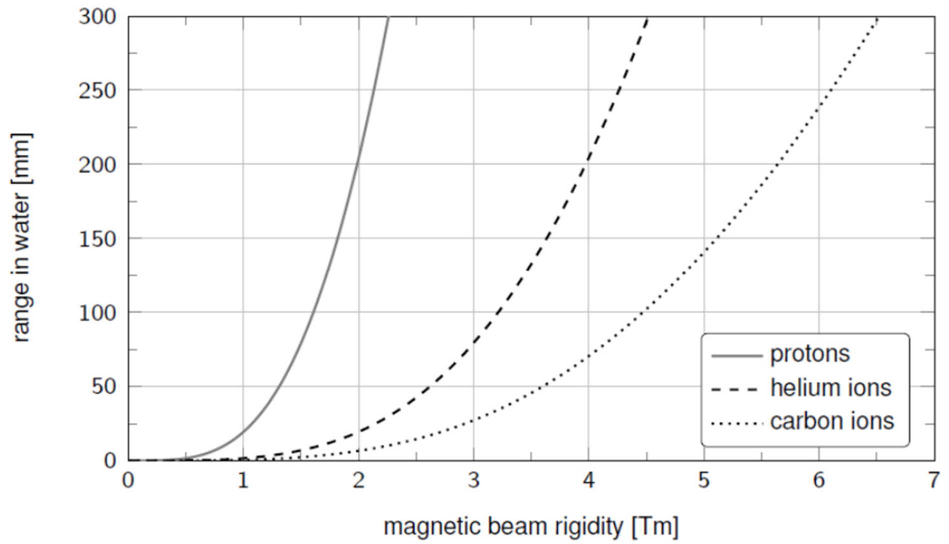
BENEFITS AND TIMELINE FOR HELIUM COMM.

At Medaustron helium ion beams commissioned for the non-clinical research team (NCR) and, due to their promising properties, for future medical treatment.

Timeline for the commissioning:

- Q2/2022 Injector commissioning completed
- April 2023 Synchrotron commissioning completed
- Q2/2024 HEBT and IR1 commissioning completed
- Q3/2024 Commissioning of Medical Front-End components (to provide modulated scanning pencil beams calibrated in intensity) completed

End project foreseen in Q1/2025 with finalization of acceptance tests from by NCR team and finalization of the documentation



Advantages of helium ion beams

- Reduced scattering with respect to proton ions
- Linear-Energy-Transfer (LET) located between protons and carbon ions
- Potentially lower neutron dose than with proton beams, suited for pediatric tumors

	2021				2022				2023				2024			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Milestones		***Source***		***LEBT***		***LINAC***		***MEBT***				***Main Ring***				***IR1***

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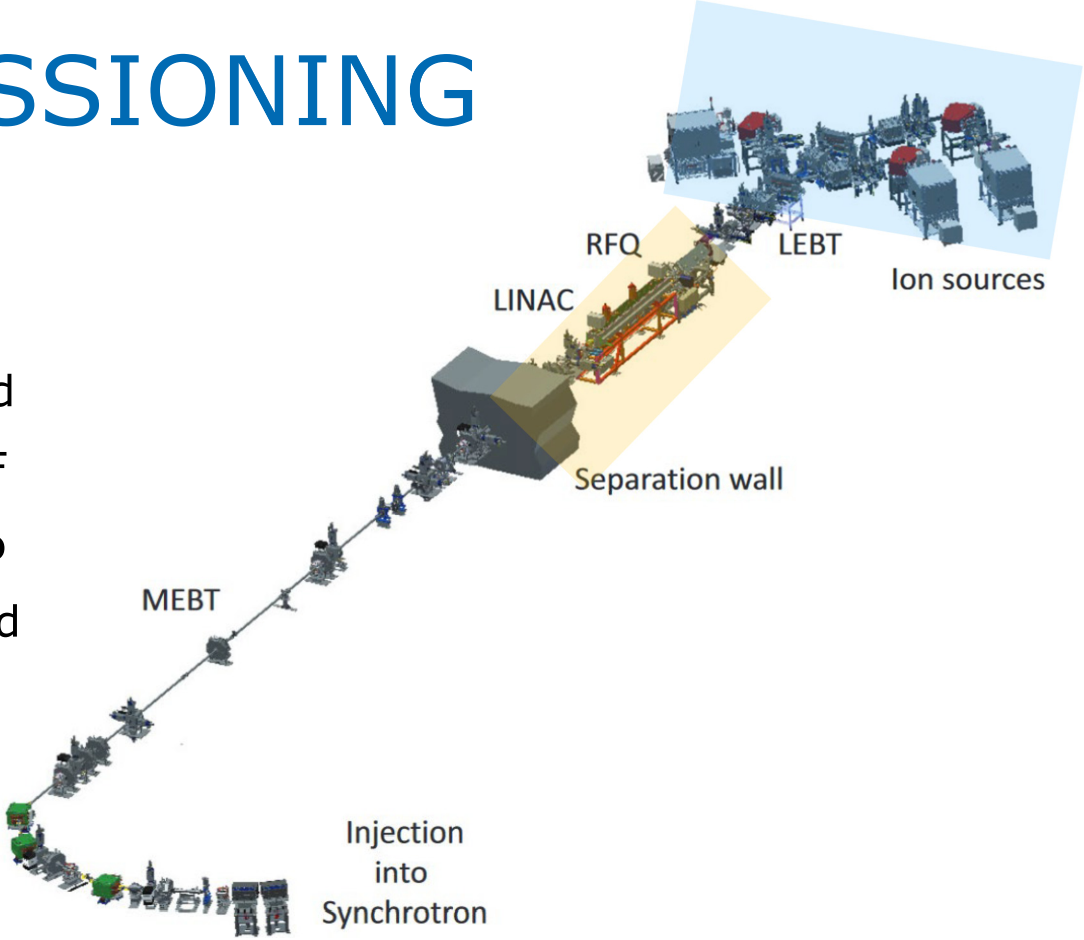
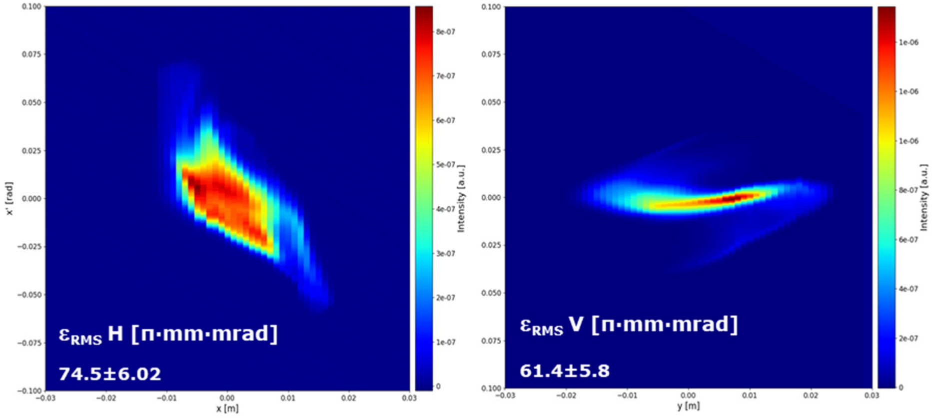
HELIUM INJECTOR COMMISSIONING

1. $^4He^{2+}$ extracted current from IS: ~690 uA, main effort required to put the S3 branch into operation
2. 90% final beam transmission from Source to LEBT reached
3. In LINAC $^4He^{2+}$ accelerated to 7.1 MeV/u (verified via TOF meas.), main challenge: **different charge to-mass ratio (1/2)** respect to the design one **(1/3)**, many beam based optimizations required, not many sim. tool available!





$^4He^{2+}$ Emittance Measured after the dipole spectrometer with. slit/profile scan method - ICIS2021, N. Gambino,..C. Schmitzer..et. al.

Final transmission efficiency from the Low-Energy-Transfer-Line (LEBT) to LINAC section of 32% and extracted currents of ~ 190 μA

M. Kausel, N. Gambino, L. Penescu et. al, Injector and Synchrotron commissioning of He ion beam at MedAustron, IPAC 2023

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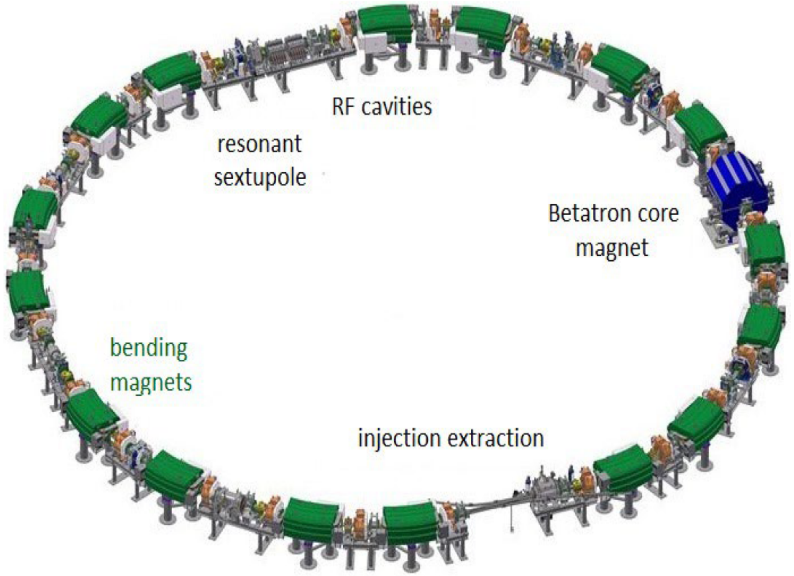
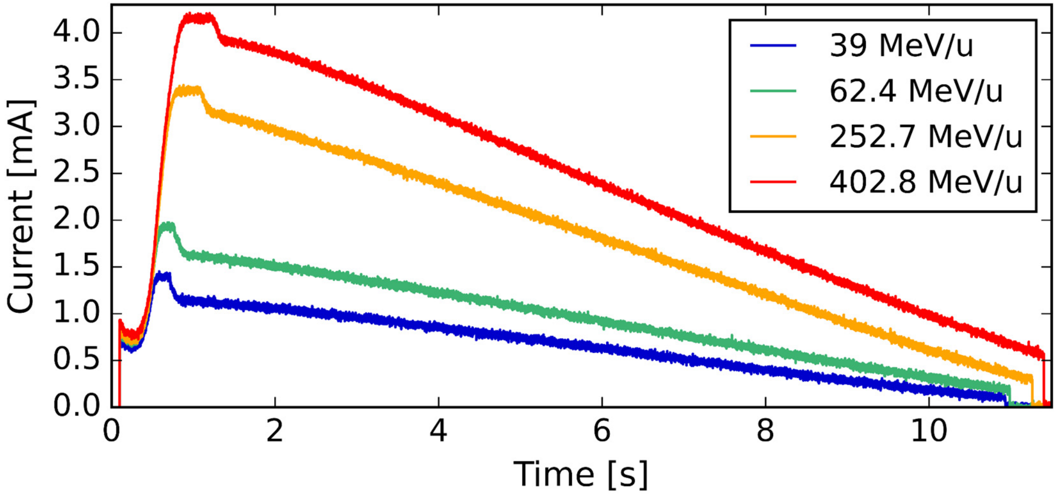
HELIUM SYNCHROTRON COMMISSIONING

- Carbon settings as initial conditions
- Orbit&optics correction at flat-bottom energy, before acceleration
- RF capture and accel. with min. losses
- Optics optimization at flat-top energy, after acceleration
- RF manipulations to prepare for beam extraction towards HEBT
- Beam extracted via a third-order resonant betatron core magnet





Extracted beam current from the synchrotron for four main energies. Constant flux for 10 sec spill-length with average intensity of **5×10^9** particles at flat top obtained

Table 1: Measured beam properties in the synchrotron

Energy	**62MeV/u**	**252MeV/u**
Hor. Tune Q_x at extraction	1.6672	1.6671
Hor. Chromaticity ξ_x	-5	-4
Norm. Emittances ε_x/ ε_y [π.mm.mrad]	0.78/0.84	0.76/0.75
dp/p before/after RF Phase Jump [%]	0.06 / 0.7	0.05 / 0.5
Beam loss at Capture /Acceleration [%]	13/5	10/10
Flat-Top energy efficiency [%]*	82	80

N. Gambino, M. Kausel, ..M. Pivi, F. Plassard..et. al, Injector and Synchrotron commissioning of He ion beam at MedAustron, IPAC 2023 (and IPAC 2024)

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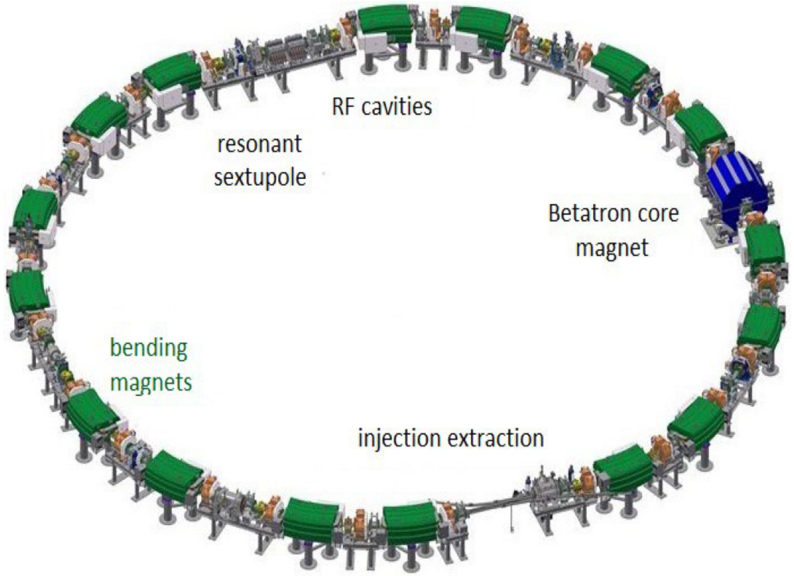
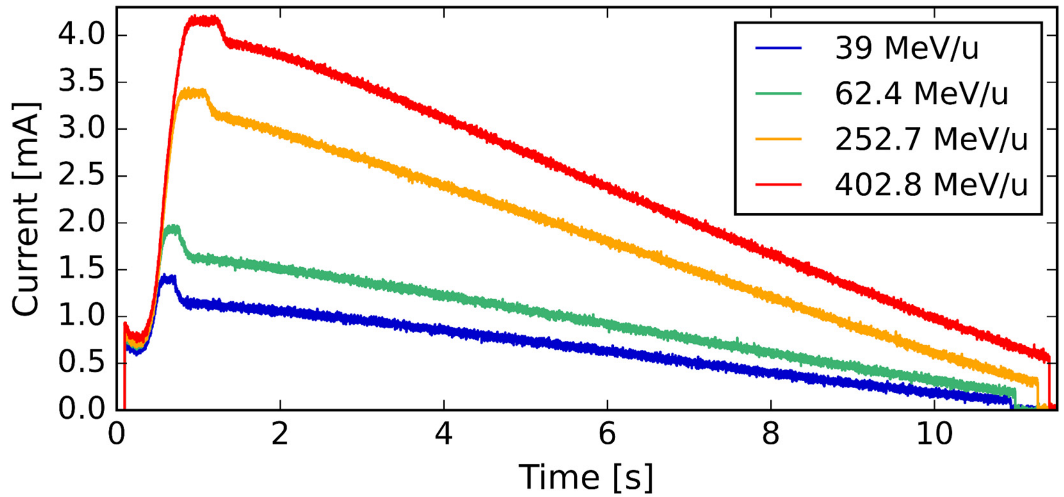


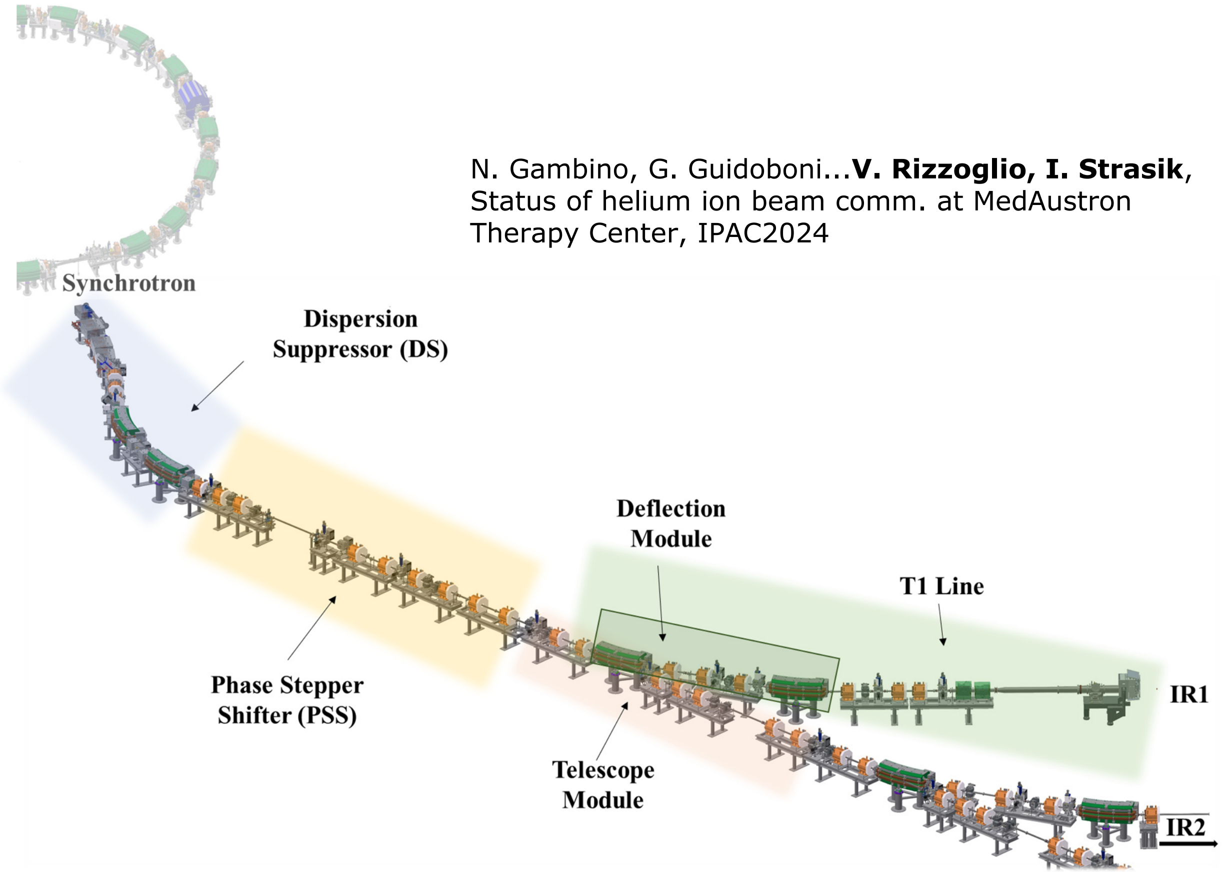


Extracted beam current from the synchrotron for four main energies. Constant flux for 10 sec spill-length with average intensity of **5×10^9** particles at flat top obtained

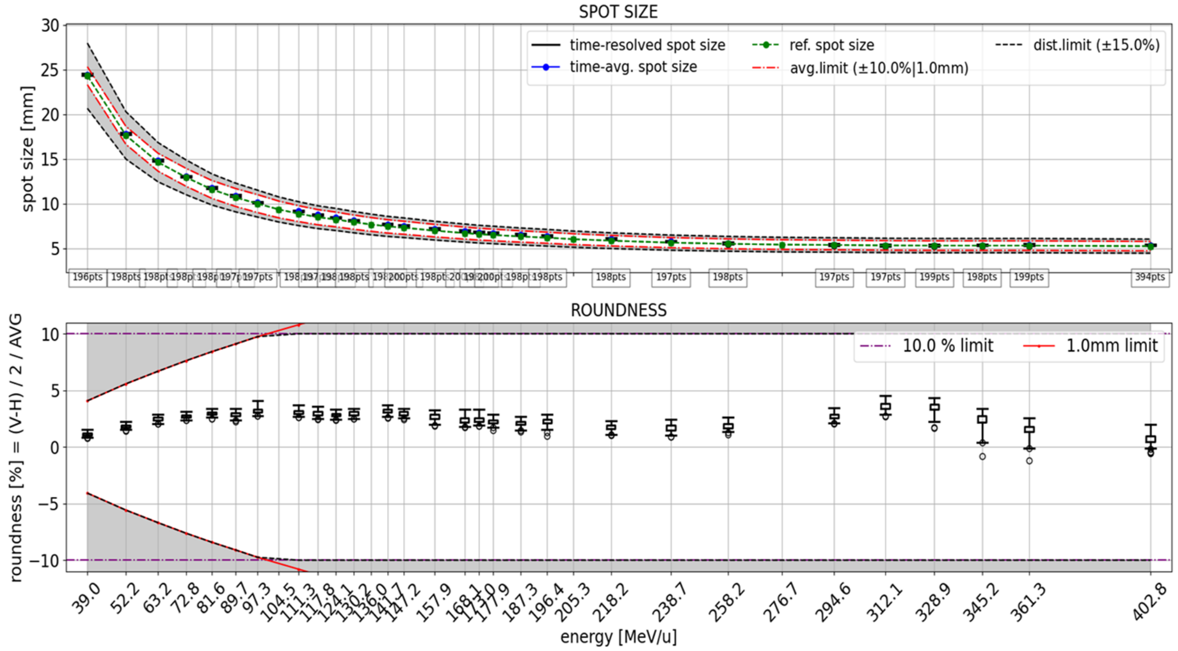
beam capture efficiency ~90%
acceleration to extraction efficiency >90%
>80% of injected beam extracted with high reproducibility

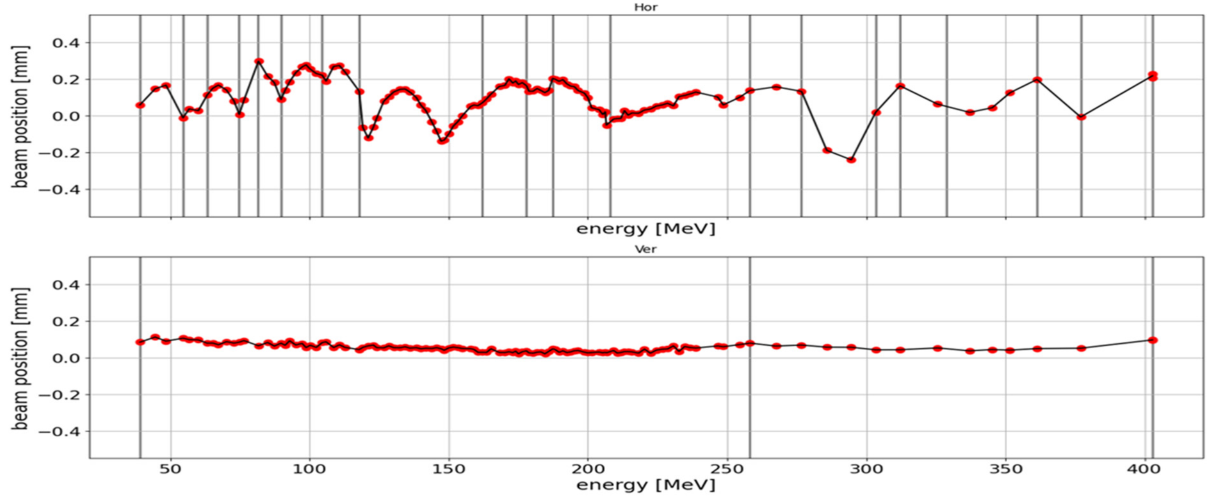
N. Gambino, M. Kausel, ..M. Pivi, F. Plassard..et. al, Injector and Synchrotron commissioning of He ion beam at MedAustron, IPAC 2023 (and IPAC 2024)

HEBT COMM. IN IR1



N. Gambino, G. Guidoboni...**V. Rizzoglio, I. Strasik**, Status of helium ion beam comm. at MedAustron Therapy Center, IPAC2024





- Large energy interval ranging from 39 MeV/u to 402 MeV/u from the High Energy Transfer Line (HEBT) up to IR1 commissioned with support of Monte Carlo simulations
- Beam Steering and Optics Matching (spot size adjustments) for the Beam Size performed

Final beam spot size and roundness for 32 energies, beam roundness (ellipticity) at ICM within 3 % for all energies. Final beam size and steering at ICM for 39.8-402.8 MeV/u

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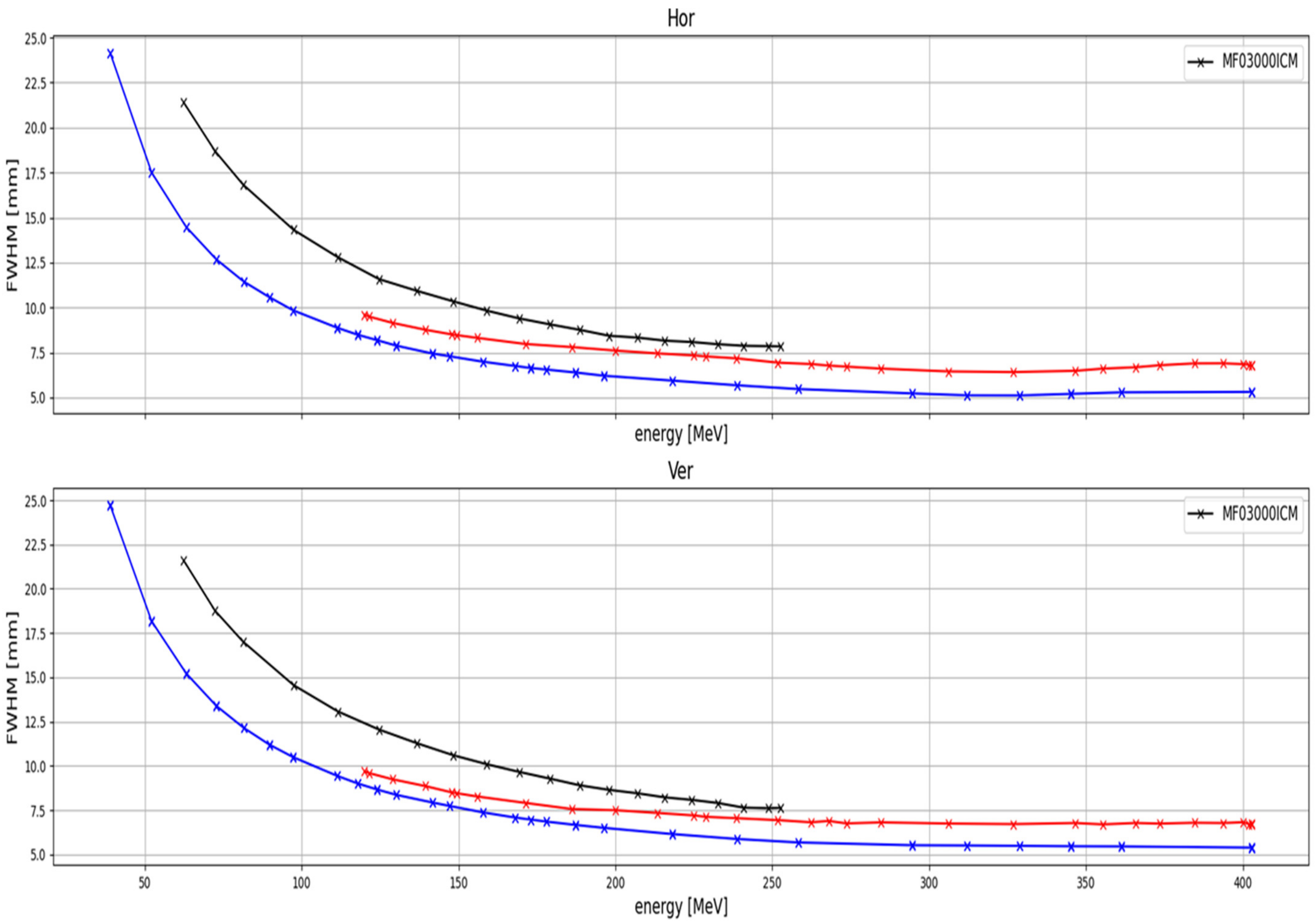
HELIUM BEAM PROPERTIES VS. REQUIREMENTS

USER REQUIREMENTS (NCR TEAM) FOR 4HE^{2+} AT ISOCENTER MONITOR

Energy Range	Spot Size	Beam Position
39.8-402.8 MeV/u “Clinical Range”: 63.2 - 258.2 MeV/u	5-6 mm within clinical energy range	±0.5 mm

Beam properties in terms of energy range, spot-size and beam position fulfill user requirements

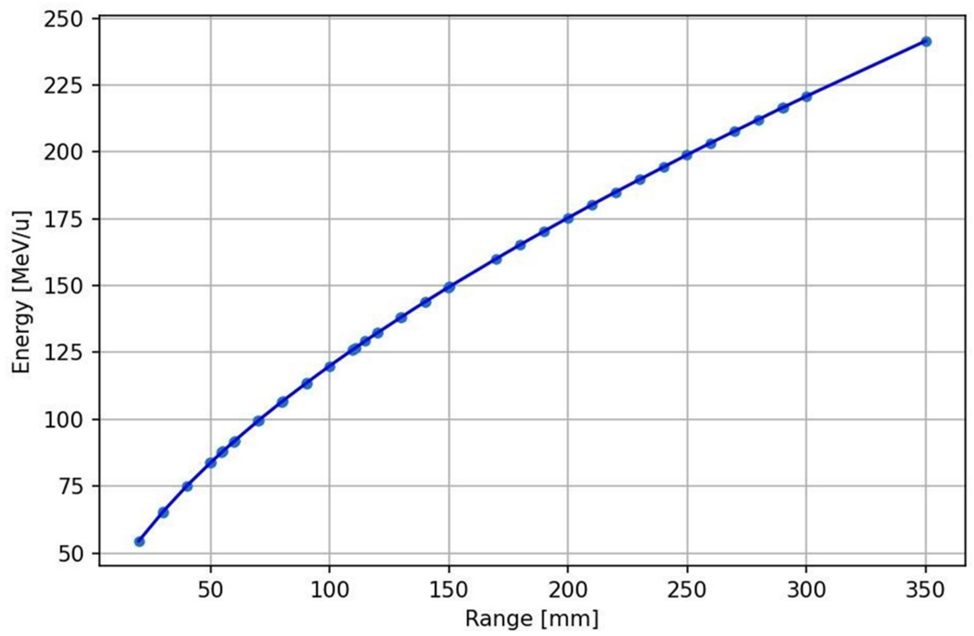


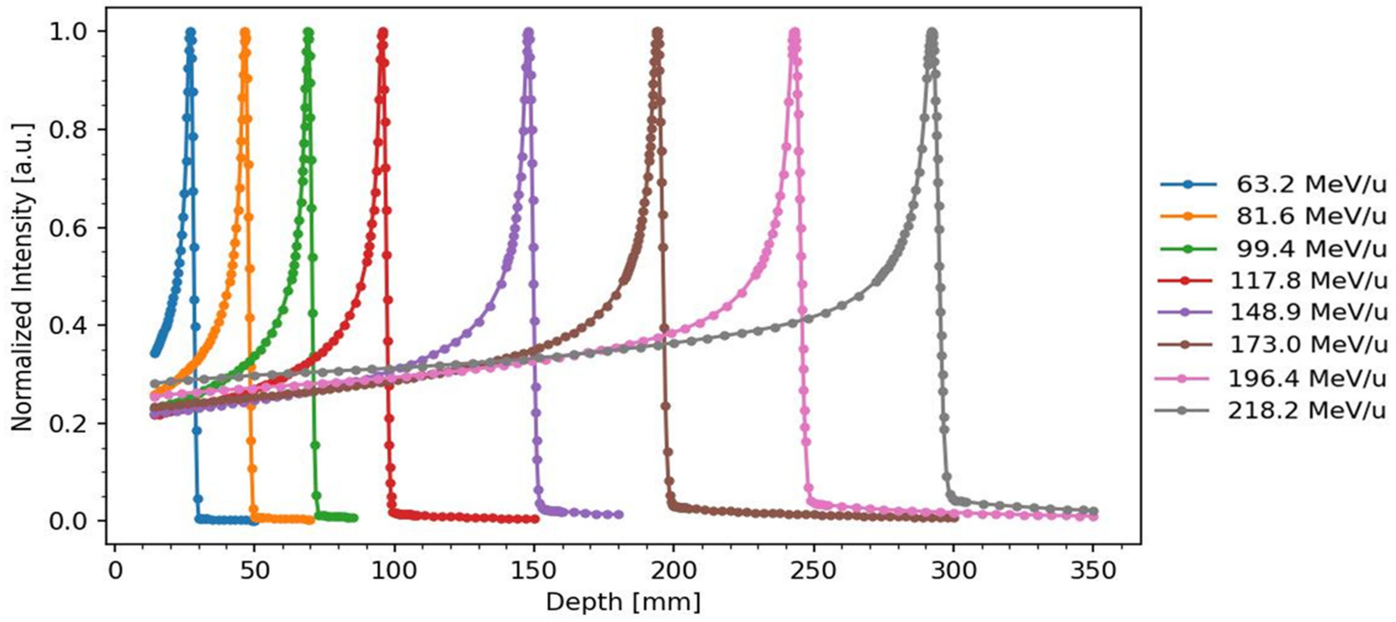
Beam FWHM versus measured energy isocenter for proton (black), carbon (red) and helium (blue) ions

RANGE MEASUREMENTS IN IR1

- First Range measurements performed with PTW PEAKFINDER™
- Final energies tuned assisted by Monte Carlo simulations (OpenGate v9.3 based upon Geant4 v10.3)
- $4He^{2+}$ energies vs. range measured at ICM from 63.2-241.5 MeV/u, covering a potential clinical range in water from 3-30 cm
- Nine exemplary $4He^{2+}$ range meas. in water at ICM

Courtesy of Hermann Fuchs





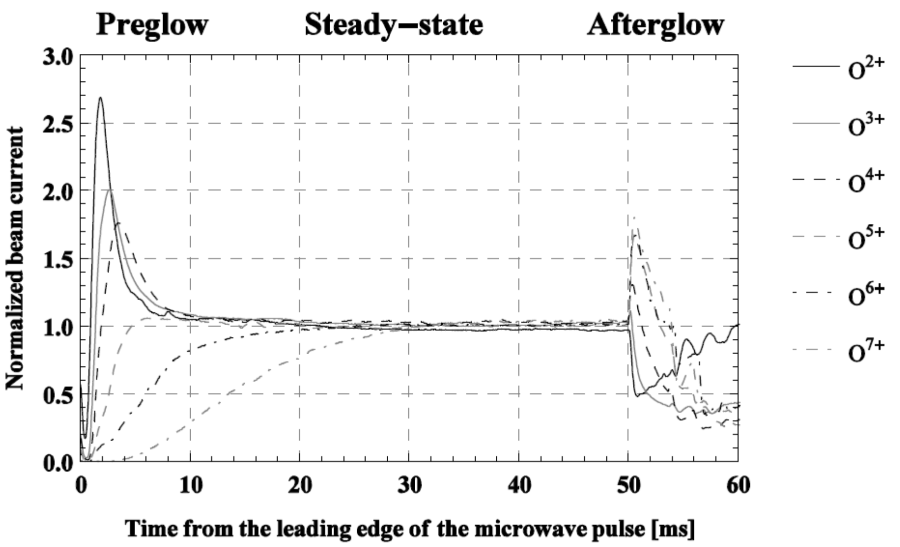
ION SOURCE COMMISSIONING

- Helium commissioning from S3 up to IR
- **Clinical Carbon Ion Source commissioning in Pulsed Mode**
- Proton Ion Source Performances in Double Frequency Heating

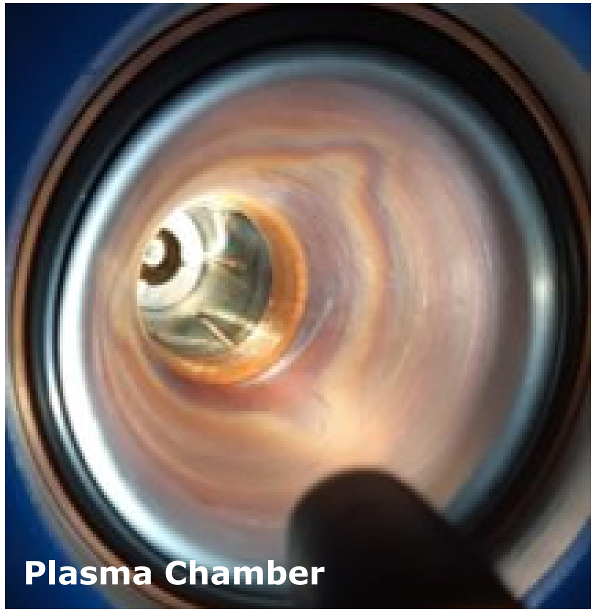
MOTIVATION FOR PULSED MODE OPERATION

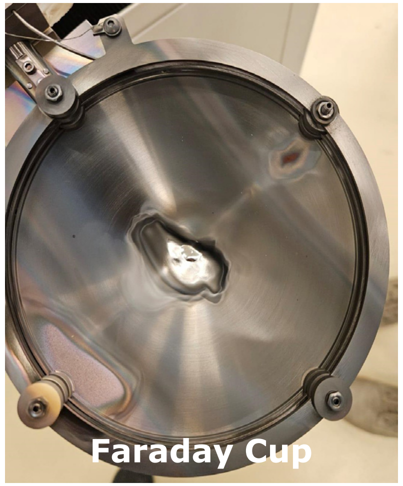
By implementing pulsed mode operation (PMO) the source duty cycle drops dramatically (decrease of a factor 480 at least)

- Beam on demand during treatment
- Reduction of component degradation
- Reduction of maintenance activities for the IS
- Use Pre-Glow or Steady-State part of the pulse?



Pulsed Operation of ECR Ion Sources - Plasma Physics and Diagnostics, O. Tarvainen et al., Conference Paper · July 2011





TIMELINE FOR CLINICAL ROLL-OUT

2021	2022	2023	2024

PHASE I: 2021/2022

Feasibility Studies on S3 Branch

Planning commissioning on S2

Commissioned during nights and weekend shifts!

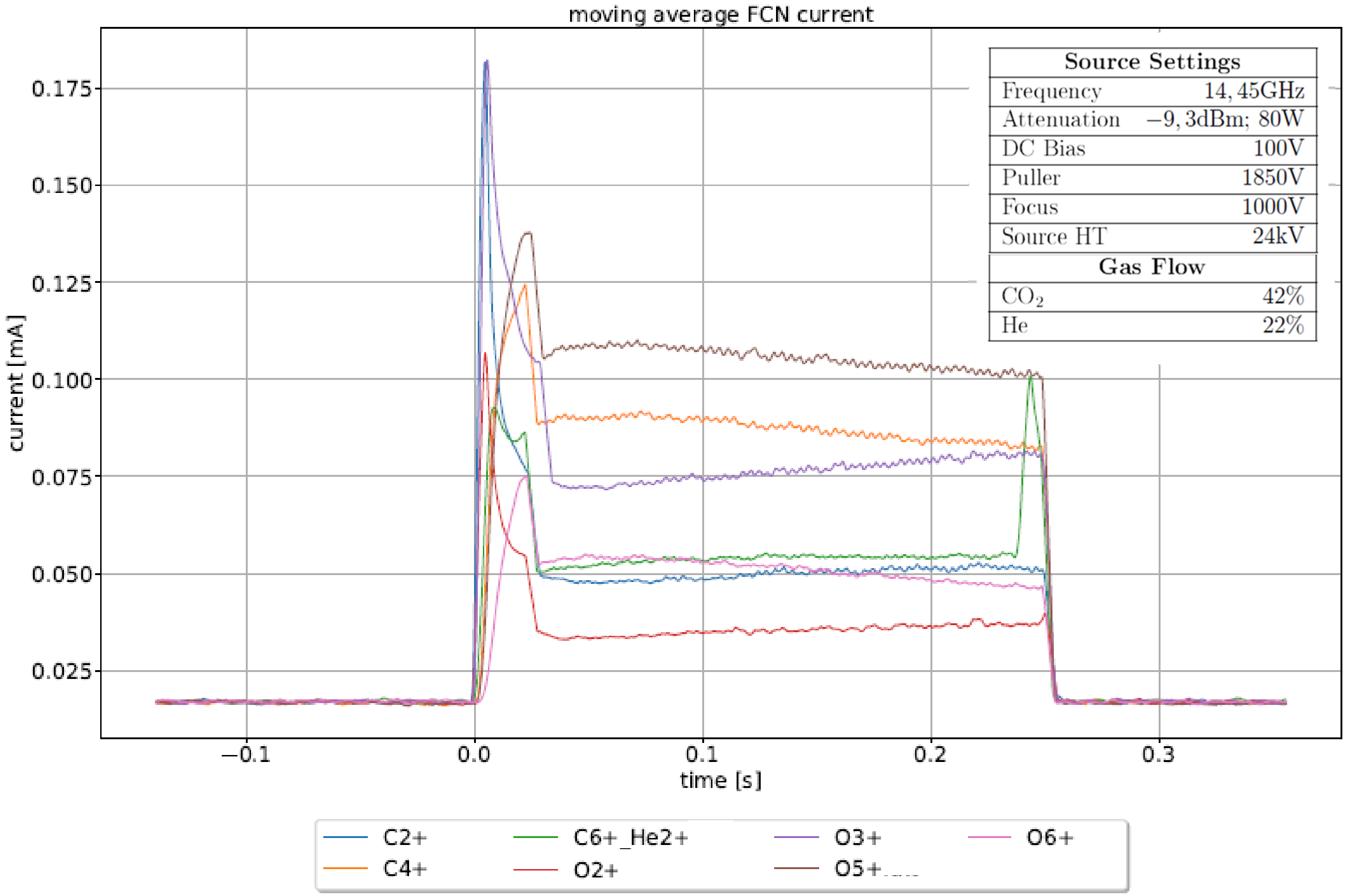
- Beam Properties up to the room as in CW mode
- Keep the CW mode operational (back-up in case of instabilities. and for emittance and profile meas.)

PHASE II: 2023/2024

- Beam Commissioning on S2
- Implement Required Software and Hardware Changes/Adaptations (FEC, Source Panel, BDs etc.)
- Adapt Commissioning Tools
- Training for operations team (OPS), allow re-tuning of the ion source-setpoint as in CW mode for certain parameters (RF Power and Gas Mixing)
- Clinical Activation by end of June 2024
- Update necessary documentation (QA, Source Manual..)

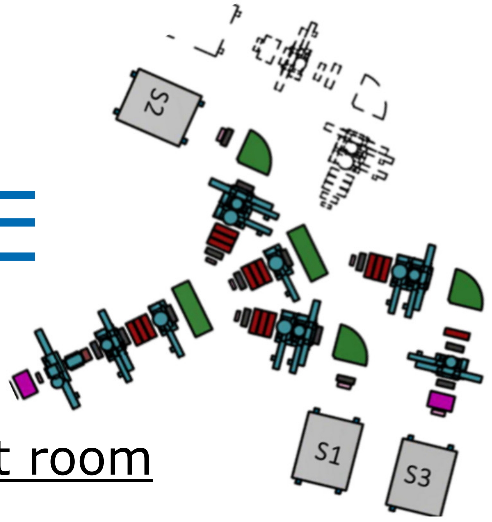
PHASE I: FEASIBILITY STUDIES ON S3

- 250 ms pulse length @80 W of RF Power
- Starting Condition was the S2 set-point
- Reproduced theoretical pulsed mode shape
- Initial assumption was to use the pre-glow signal to further reduce the RF power, but steady state was used
- Distance between plasma lens and puller nose had to be changed (to 27 mm from 35 mm nominal)
- Extensive 2D gas scans and power scans



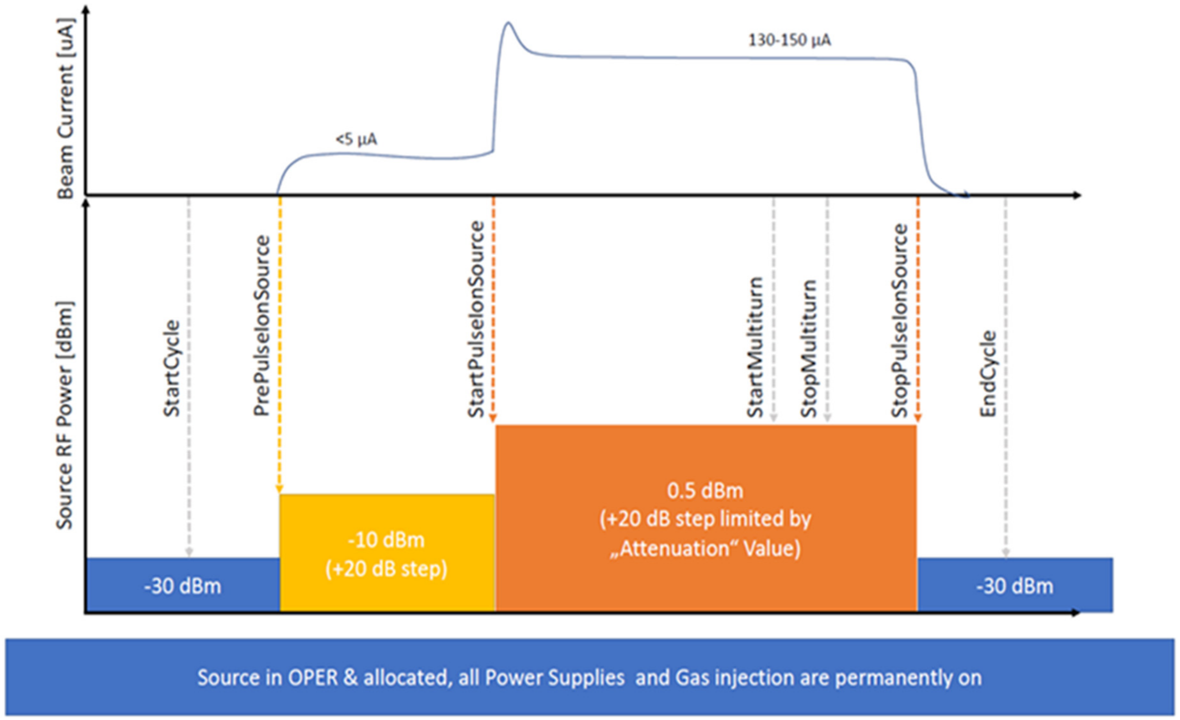
Pulsed Operation of an ECR Ion Source – Projekt Arbeit - R.Rockenbauer, May 2022

PHASE II:
COMMISSIONING ON CLINICAL SOURCE



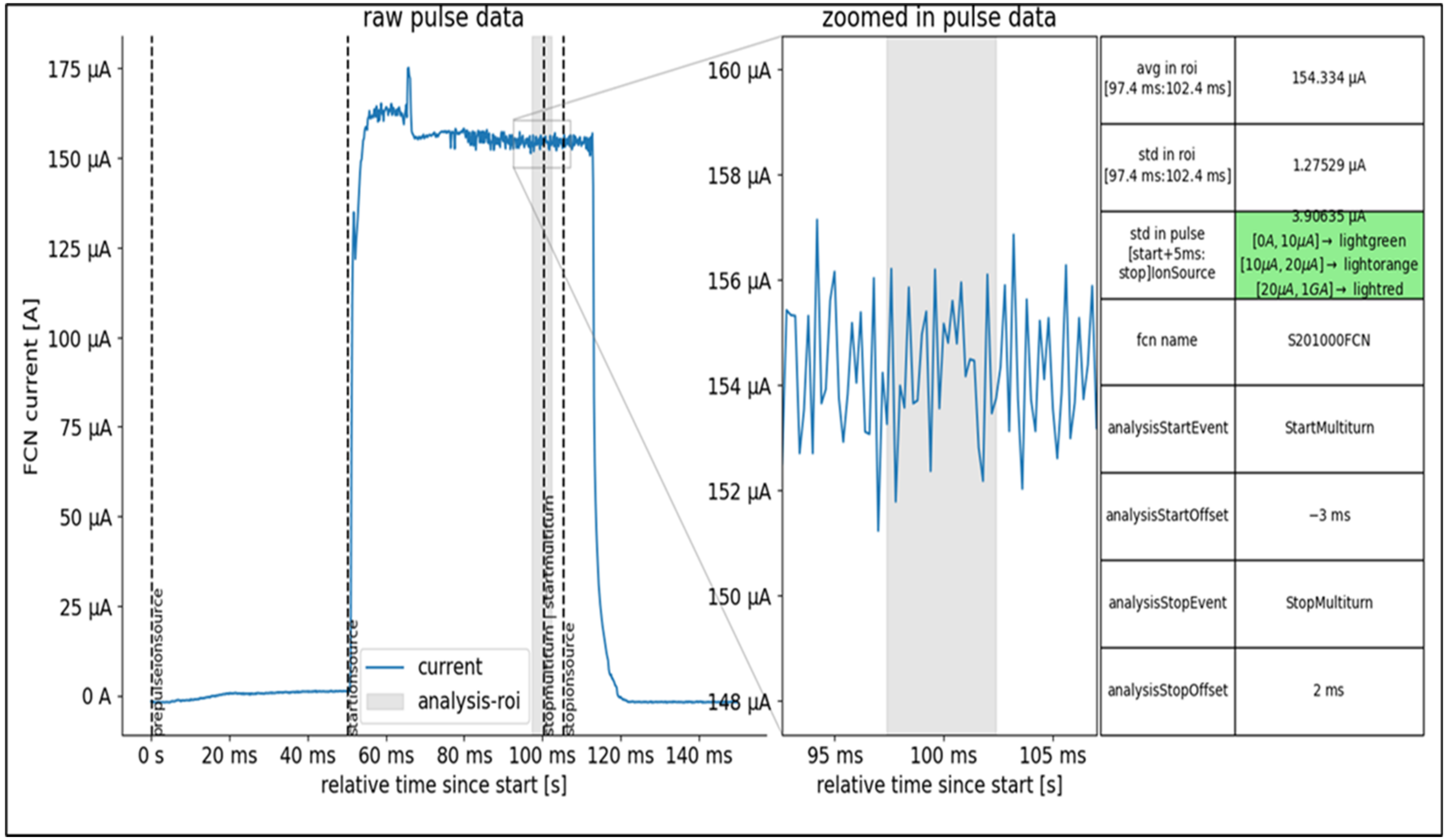
- <u>Full-fill same stability@beam properties as in CW mode up to treatment room</u>

- Same set-up as S3, but with no external trigger box (implementation of pulsing within the source FEC)
- Use of breakout board in order to monitor the drain currents
- Introduction of a <u>pre-pulse</u> (few watts of FWD power) as pulse shape measured on S3 was not reproducible on S2!



TYPICAL STABLE PULSE

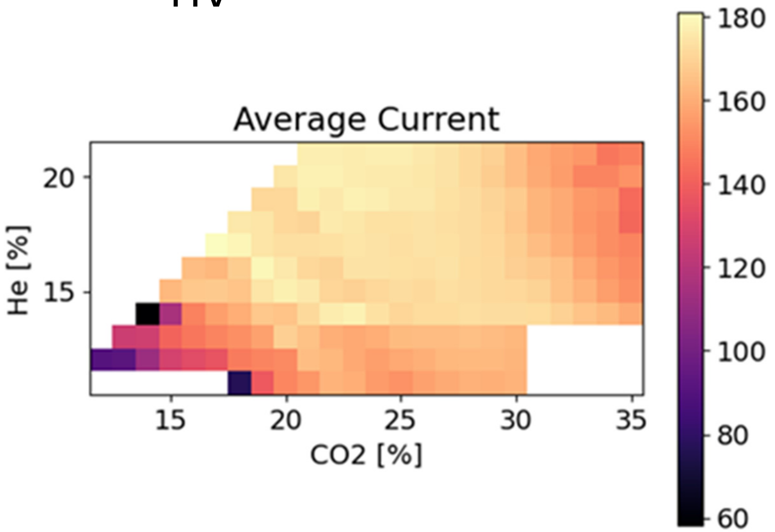
- Used Steady State part of the pulse, more stable, better reproducibility
- Similar RF powers as in CW mode (80-90 W)
- Used 110 ms pulse length
- Injection at around 75 ms
- 1 pulse/10 sec (spill length)



New comm. tools were developed to measure the pulse when requesting a cycle and calculate the mean current current within the injected part of pulse (EFE opening time +/- some ms)

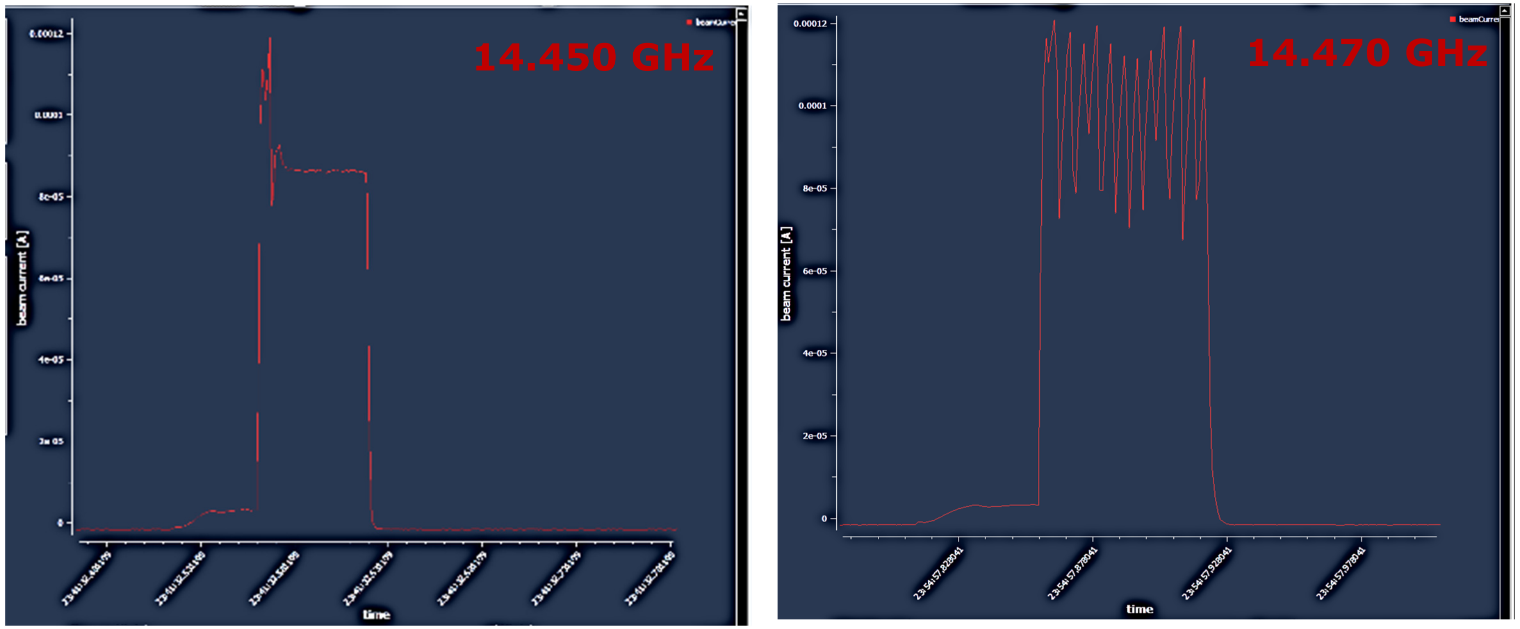
SOURCE SET-POINT SCANS

- Performed extensive scans of
  - Frequency
  - Gas Mixing
  - Attenuation
  - HV



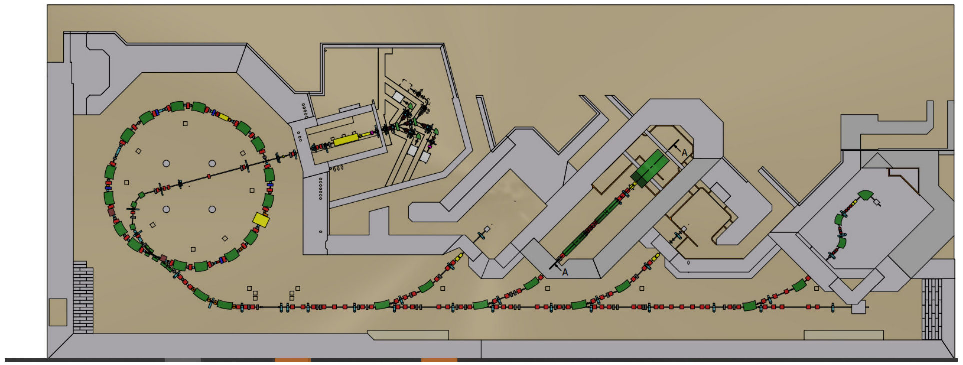
Example 2D gas scan as a function of extracted $12C^{4+}$ current

The frequency scan turned to be the key parameter to tackle current instabilities within the pulse

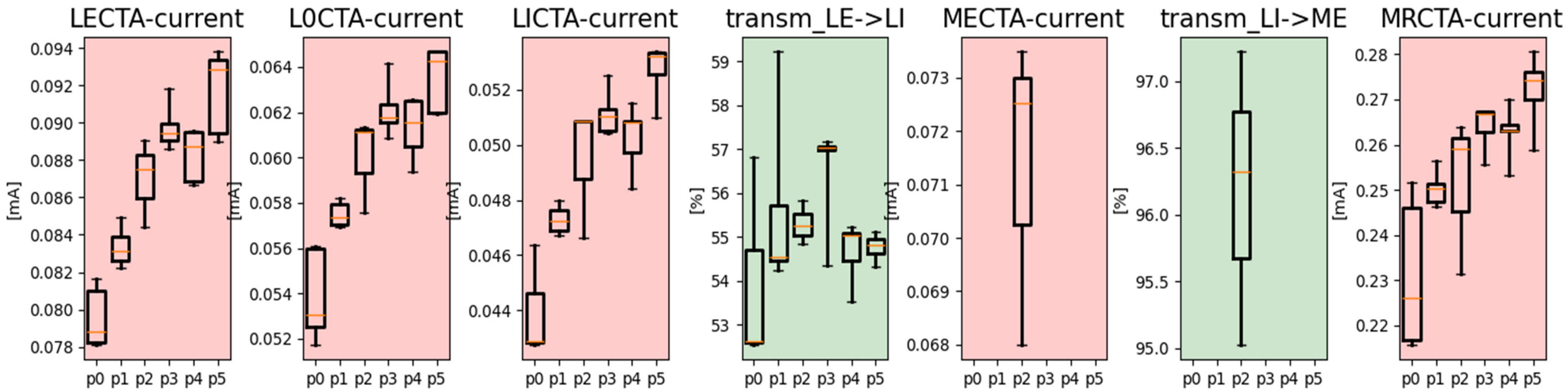


Example of "good" pulse shape (left) measured on the S2-01-000-FCN-A via MACS at 14.450 GHz and "bad" pulse shape measured at 14.470 GHz (right)

SOURCE SCANS UP TO THE TREATMENT ROOM



- Scan of RF power while monitoring all Current Transformer Monitors up to the MR (LE-CTA, LI-CTA, MEBT-CTA and MainRing-CTA)
- Important for source-retuning procedure for the operators (linear increase of current needed, by only increasing the RF power)



- **p0: - 1.4 dbm**
- **p1: - 1.2 dbm**
- **p2: - 1 dbm**
- **p3: - 0.8 dbm**
- **p4: - 0.6 dbm**
- **p5: - 0.4 dbm**

RF power range: 70-95 W

Linear intensity increase reached, but several scans at the source level where needed!

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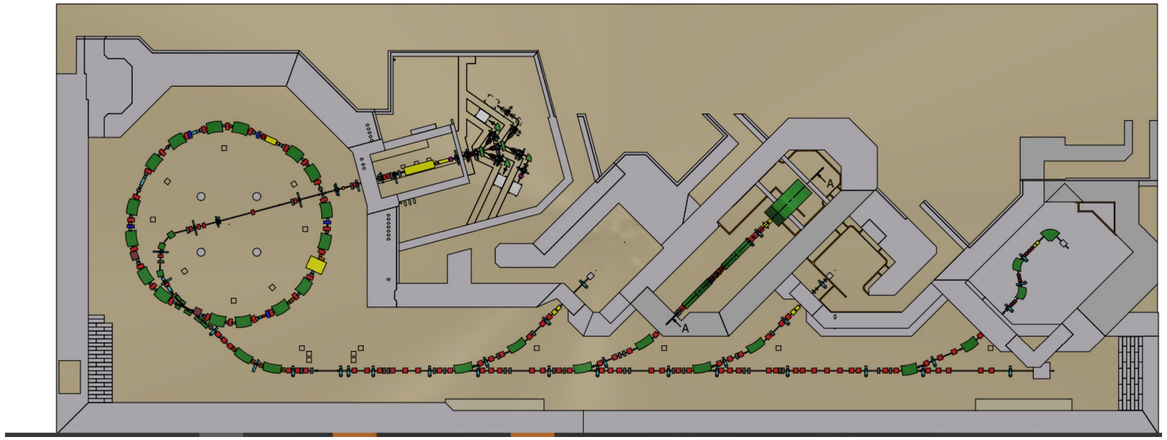
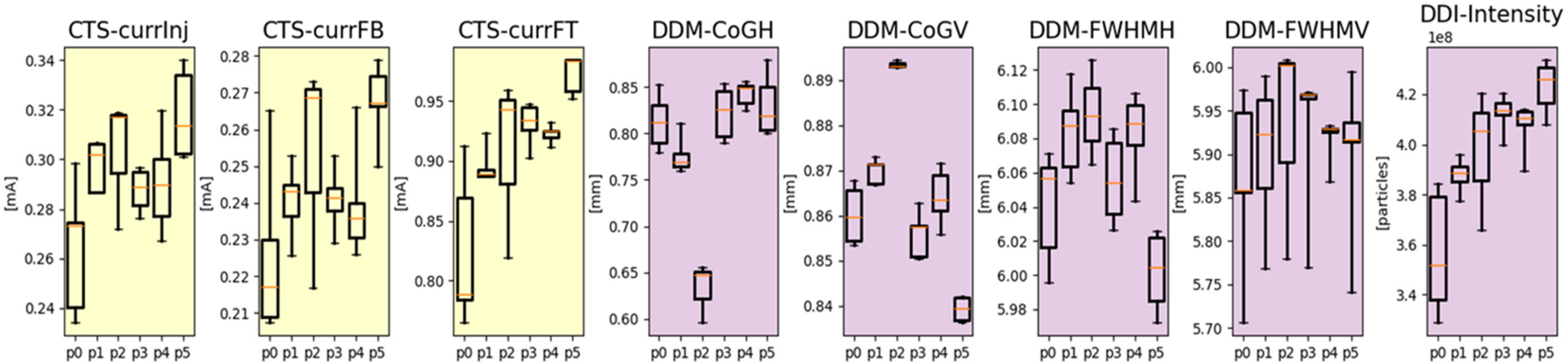
SOURCE SCANS UP TO THE TREATMENT ROOM



- Monitoring of CTS current and @injection, flat bottom and flat top
- Monitoring of beam CoG, FWHM and Intensity at the DDM
- Verified Beam Properties up to the room! Example shown for 120 MeV/u beam in IR2H Beamline



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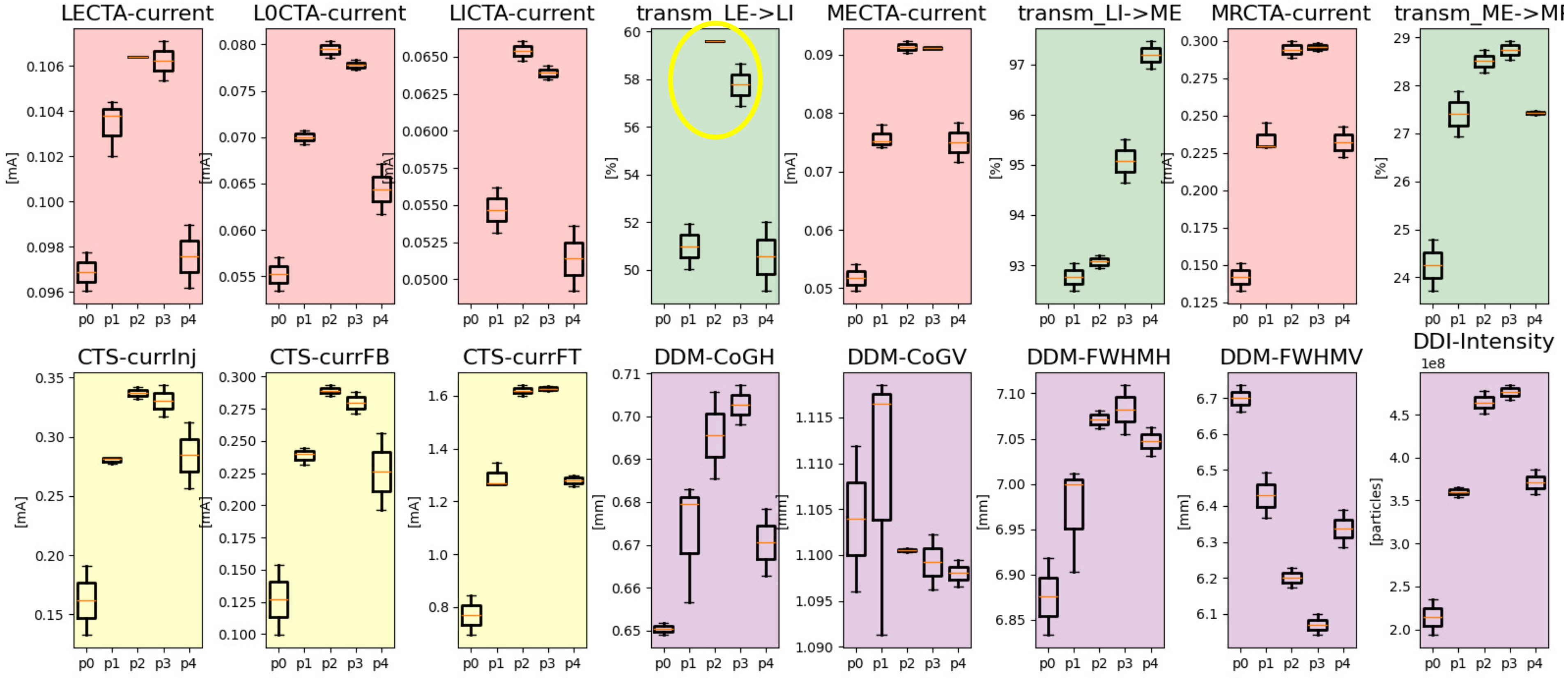
RF power range: 70-95 W

INFLUENCE OF HV OFFSET

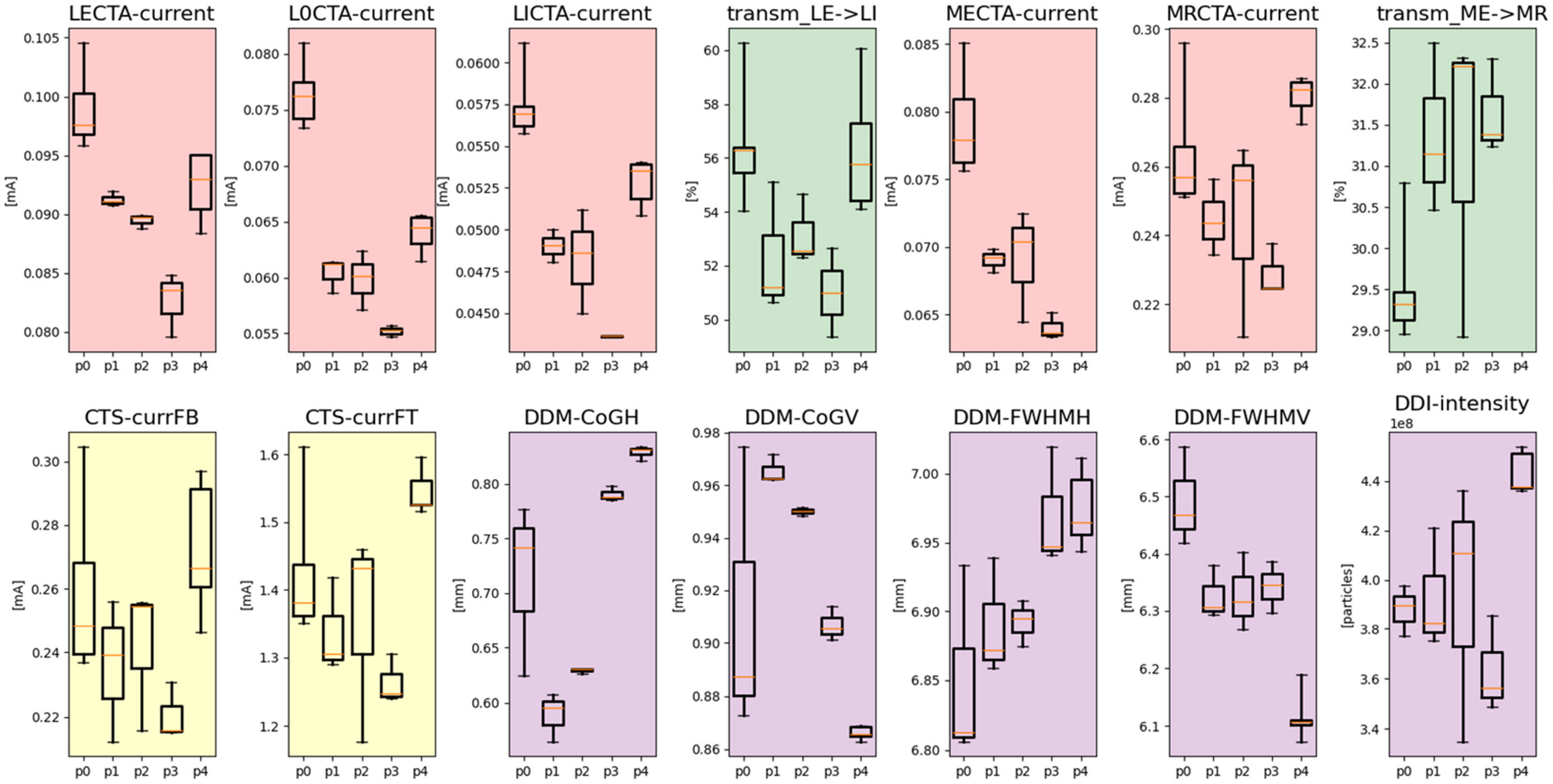


Small Offset on HV (+120V) gave a big improvement for the transmission from LEBT to LINAC, no influence on beam energy (validated with TOF meas.)

- **p0: 23940 V**
- **p1: 24000 V**
- **p2: 24060 V**
- **p3: 24120 V**
- **p4: 24180 V**

Reduction of space charge?

REPRODUCIBILITY TESTS UP TO TREAT. ROOM



402 Mev/u:
p0 = Latest averaged QA data CW mode
p1: QA pulsed 15.02
p2: QA pulsed 16.02
p4: QA pulsed 28.01
p5: QA pulsed 27.01

Beam properties comparable to CW mode (example shown for IR2V line for 10 different energies)

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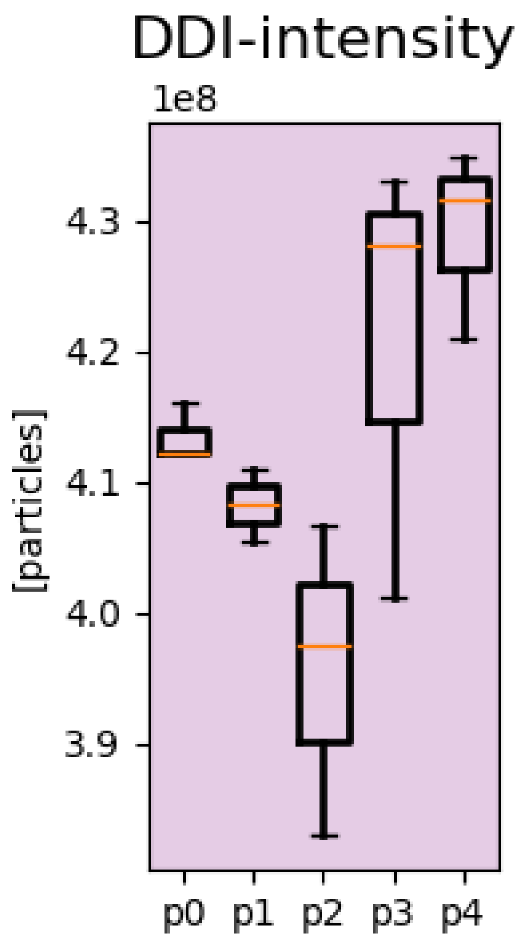
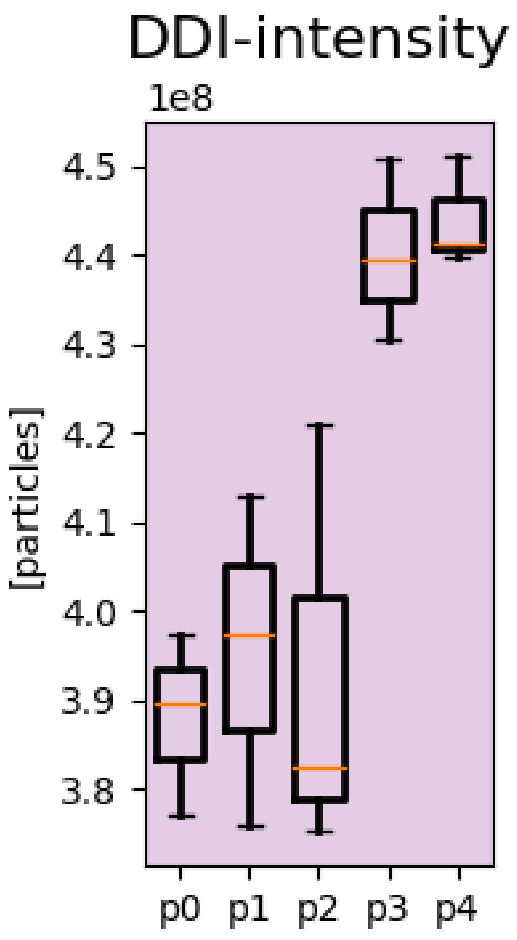
REPRODUCIBILITY TESTS UP TO TREAT. ROOM



120 Mev/u

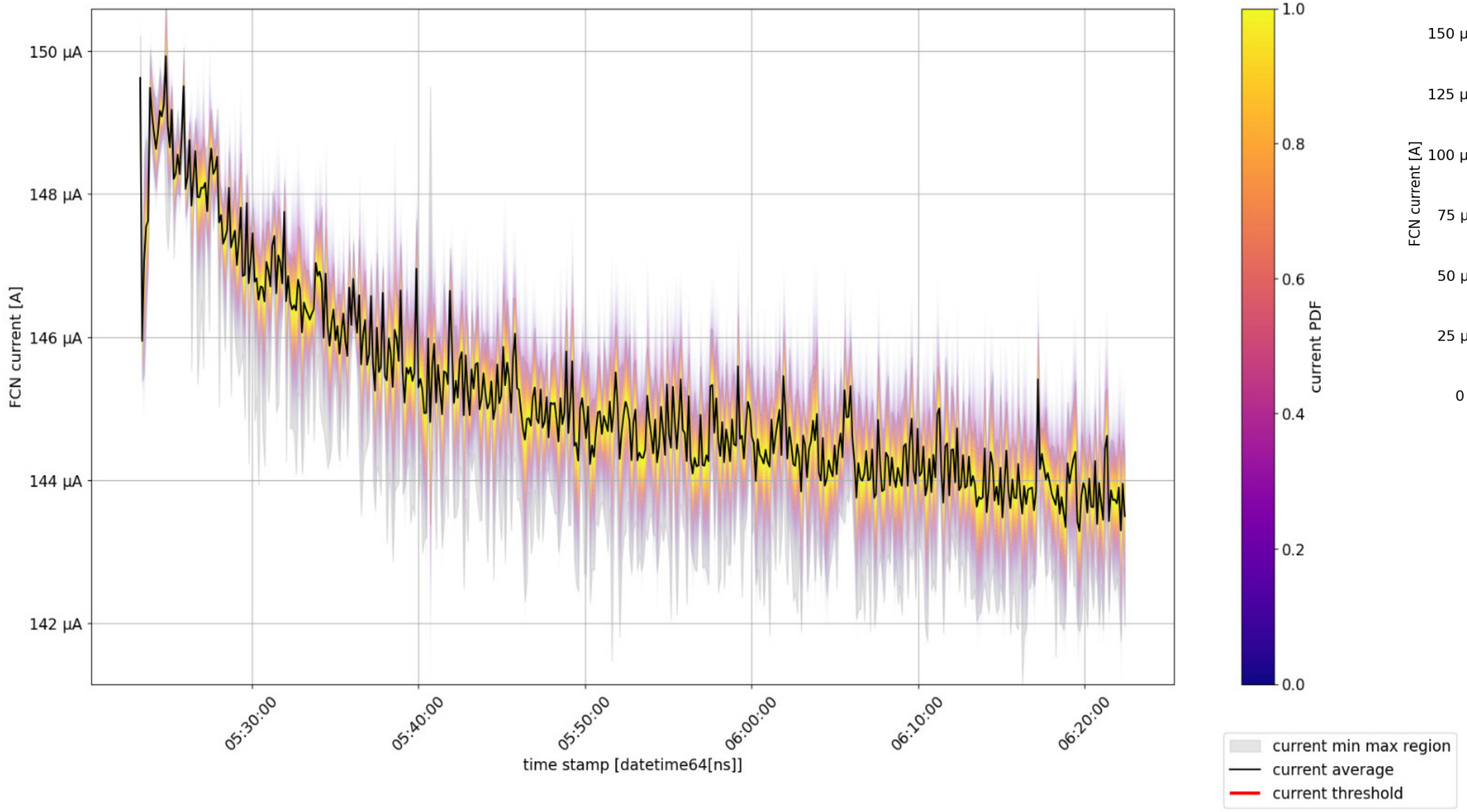


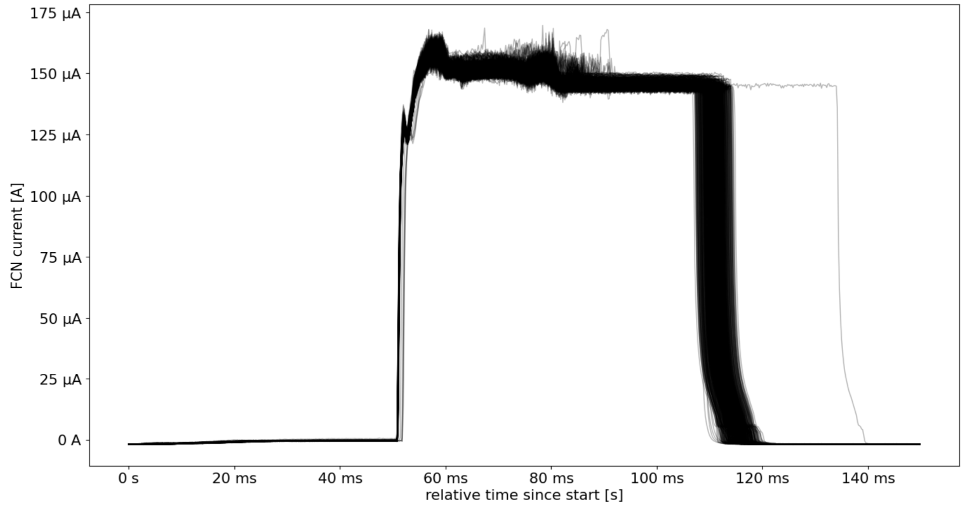
402 Mev/u

- Simulated the clinical scenario:
  - pulsing after stand-by of many hrs
- Source stabilizes at about 10% higher intensity at the beginning of the shift
- After about 30 min of cont. pulsing intensity decreases again
- Effect is pronounced for highest energy
- Higher intensity still be within the acceptable range

p0 = latest QA CW mode
p1: QA CW mode beginning shift
p2: QA pulsed mode beginning shift
p3: QA pulsed after pulsing for 20 min
p4: QA pulsed after source in stand by for about 60 min

LONG TERM STABILITY TESTS





- Example of one of the many stability tests..
- Pulsed used now every weekend and ready to be used for clinical treatment

- Long term stability showed very stable pulses
- Beam validated clinically within end of June
- We find out that in pulsed mode operation sensitivity to sparks is higher!

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ION SOURCE COMMISSIONING

- Helium commissioning from S3 up to IR
- Clinical Carbon Ion Source commissioning in pulsed mode
- **Proton Ion Source Performances in Double Frequency Heating**

DOUBLE FREQUENCY HEATING

- Used two-close frequency heating approach (between 13.75 and 14.5 GHz) with Δf < GHz)
- Tuning of input power of the two frequencies

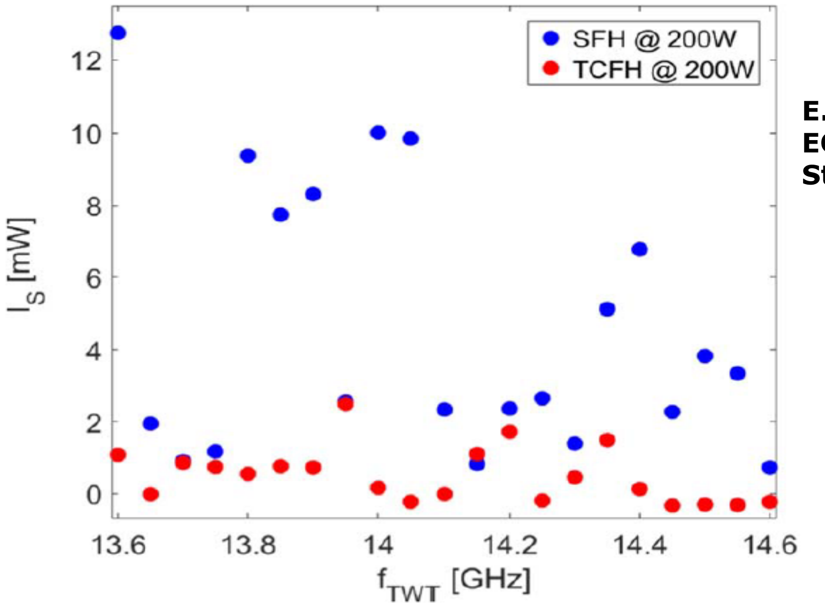

Figure 17. Comparison of the I_S parameter for single and double frequency heating at fixed power. TCFH damps the instability almost over the entire frequency set.

E. Naselli et. al, Impact of two-close-frequency heating on ECR ion source plasma radio emission and Stability, Plasma Sources Sci. Technol. 28 (2019) 085021E

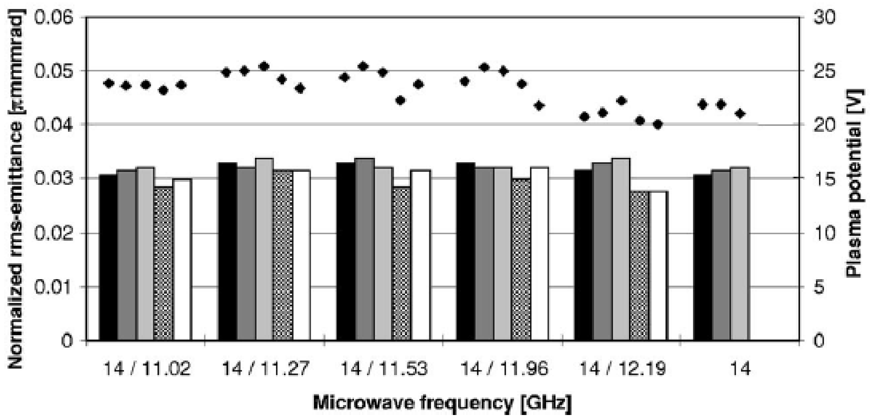

FIG. 3. The emittance values of O^{7+} ion beam and the plasma potentials with different frequencies and combinations of primary/secondary powers.

O. Tarvainen et al, Emittance and plasma potential measurements in double-frequency heating mode with the electron cyclotron resonance ion source at the university of Jyvýskylý, Review of Scientific Instruments 77, 03A309 (2006)

Benefits

- Reduction of plasma kinetic instabilities
- Higher beam current
- Higher charge state (10-20%)
- Reduction of the beam emittance?
- Use for proton where we are sensitive to emittance growth

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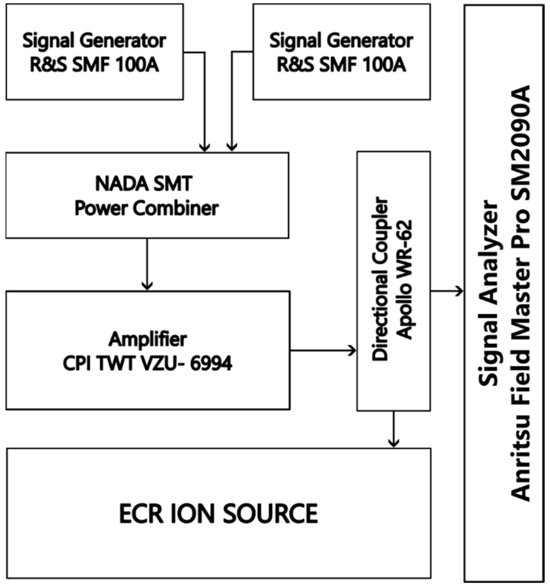
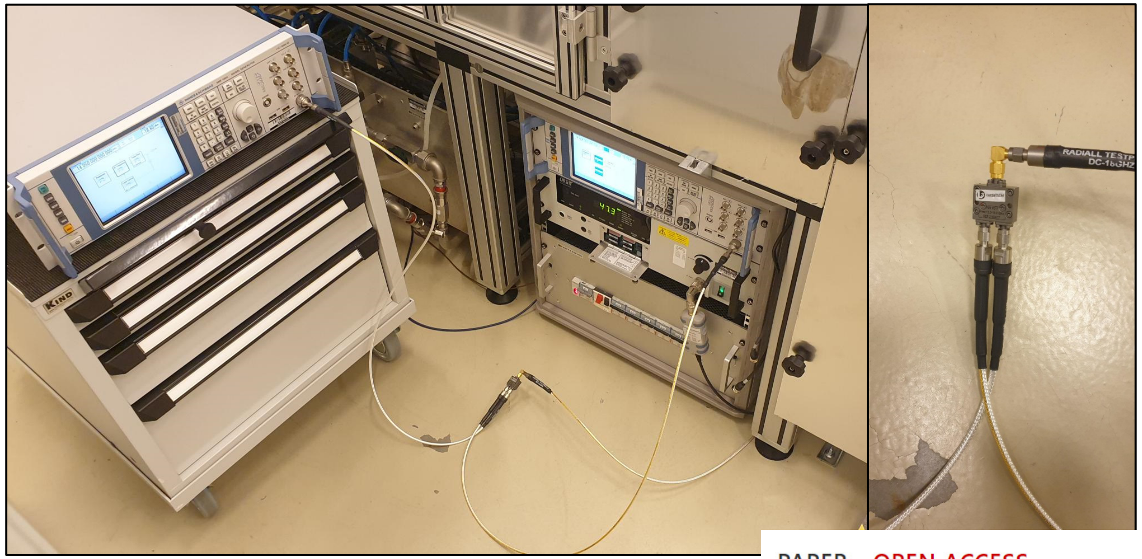
EXPERIMENTAL APPROACH





- First tests conducted at INFN-LNS of Catania
- Two R&S SMF100A Signal Generators are combined using an Nada ATM power combiner
- Signal is amplified via same CPI TWT amplifier
- Forward and reflected power measurements on directional coupler using Anritsu Signal Generator

Strategy:

- Decrease the forward RF power of both frequencies, while keeping the same beam parameters (current, stability, intensity and emittance requirements etc.)
- Various source scans performed

PAPER • OPEN ACCESS

Performance increase for a medical proton beam ECRIS through dual frequency heating at MedAustron ion therapy center

R Rockenbauer[1], C S Schmitzer[1] and N Gambino[1]

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Citation R Rockenbauer *et al* 2024 *J. Phys.: Conf. Ser.* **2743** 012080
DOI 10.1088/1742-6596/2743/1/012080

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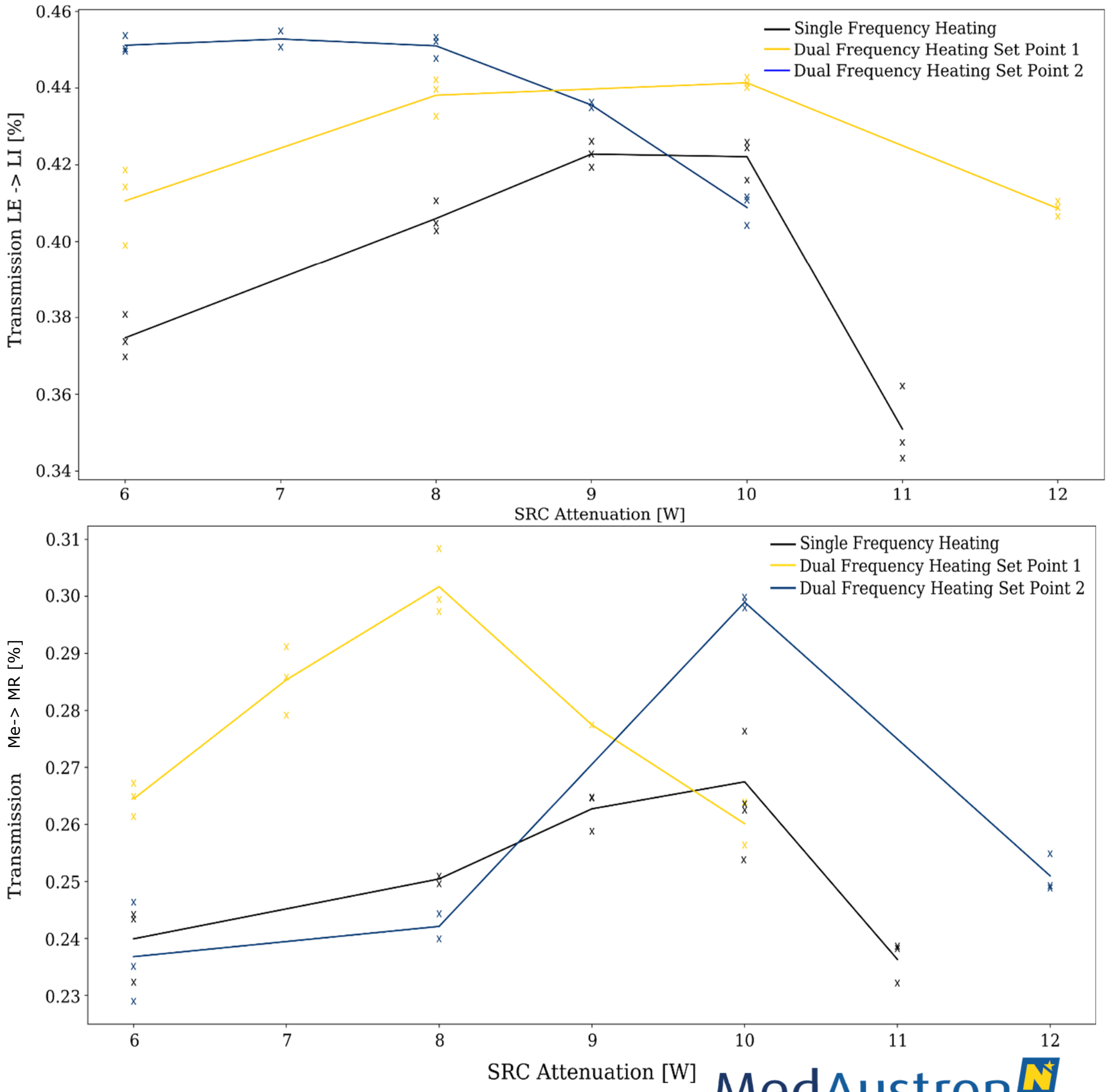
OVERALL MACHINE PERFORMANCES IN DFH

- Improvements through DFH for the proton source:
  - At equal input power:
    - Improved transmission from LE to LIN
    - Improved overall current up to the room
  - No changes to the machine optics
  - Improved transmission across a wider power range
    - Possible <u>countermeasure for machine intensity drifts over time</u>
  - Improved in room particle count
    - Potential <u>treatment time reduction</u>

Transmission LEBT-LINAC and MEBT-MR in %



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SIMULATION OF TREATMENT TIME DURATION

	SFH		DFH SET POINT 1			DFH SET POINT 2		
UNIT	[s]	[min]	[s]	[min]	DFH/SFH RATIO [%]	[s]	[min]	DFH/SFH RARTIO [%]
Head Adenoma Small	148.96	02:29	141.57	02:22	-4.96	141.6	02:22	-4.94
Head Anaestehsia ATRT Small	288.28	04:48	271.14	04:31	-5.95	271.01	04:31	-5.99
H&N PE Carcinoma Medium	422.49	07:02	378.48	06:18	-10.42	378.53	06:19	-10.40
H&N Sarcoma Large	532.68	08:53	468.42	07:48	-12.06	469.23	07:49	-11.91
Pancreas Carcinoma Medium	343.28	05:43	291.09	04:51	-15.20	292.03	04:52	-14.93
Pelvis Chordoma Large	1232.55	20:33	956.17	15:56	-22.42	957.83	15:58	-22.29
Prostate Carcinoma Small	271.58	04:32	231.36	03:51	-14.81	232.23	03:52	-14.49
Prostate Carcinoma Large incl. LN	930.07	15:30	749.23	12:29	-19.44	752.49	12:32	-19.09
CSA 17x14	2067.28	34:27	1734.25	28:54	-16.11	1737.64	28:58	-15.95
CSA 20x20	1966.08	32:46	1608.78	26:49	-18.17	1612.17	26:52	-18.00

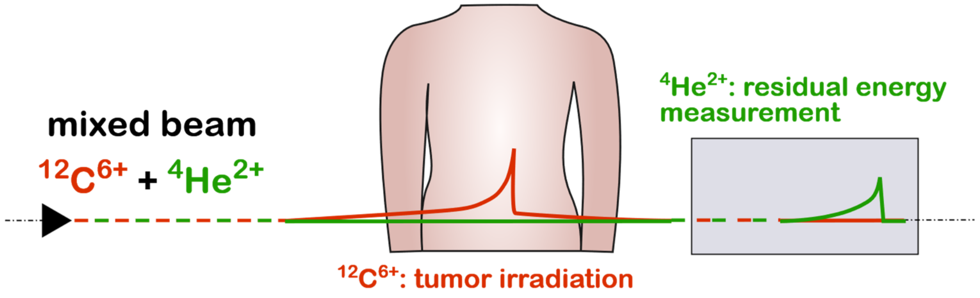
- Treatment time simulation based on DDI intensity for 4 energies: 252MeV, 207MeV, 148.2MeV, 62.4MeV
- Based on average patient data -> 4 additional patients possible
- Future studies will follow!

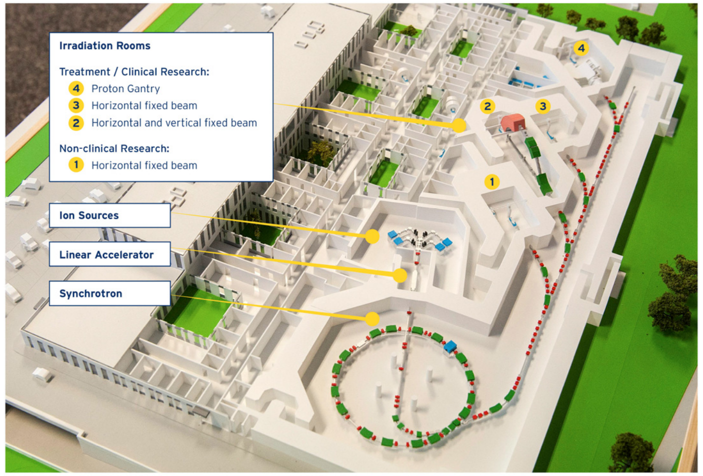
FUTURE PERSPECTIVES & CONCLUSIONS

- Future Perspectives
  - Mixed Beams Applications
  - Design of fourth Ion Source Branch (S4)

FEASIBILITY STUDY: MIXED BEAMS @ MEDAUSTRON?

Objective: Assess the feasibility of delivering a **mixed beam for nonclinical research (IR1)**





M. Kausel et. al, IPAC'24, 10.18429/JACoW-IPAC2024-THPR42
E. Renner et. al, IPAC'24 10.18429/JACoW-IPAC2024-THPR43

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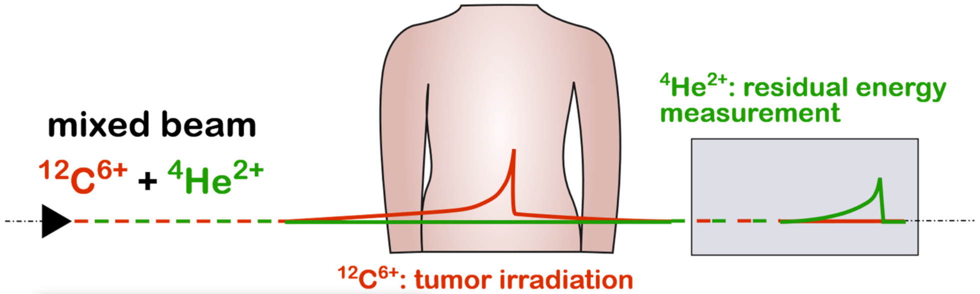
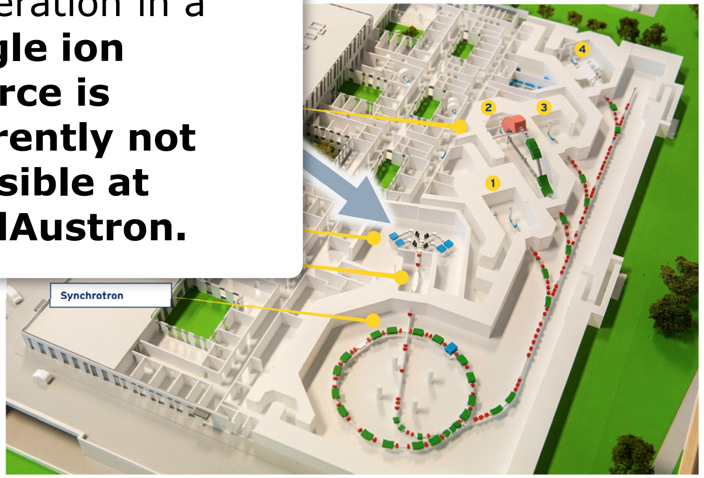


Mixed beam generation in a **single ion source is currently not possible at MedAustron.**



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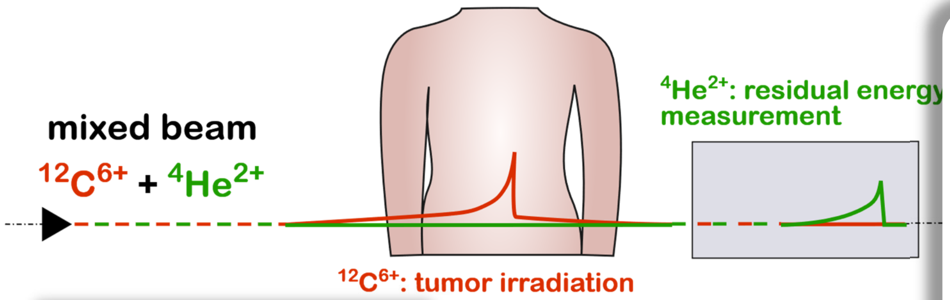

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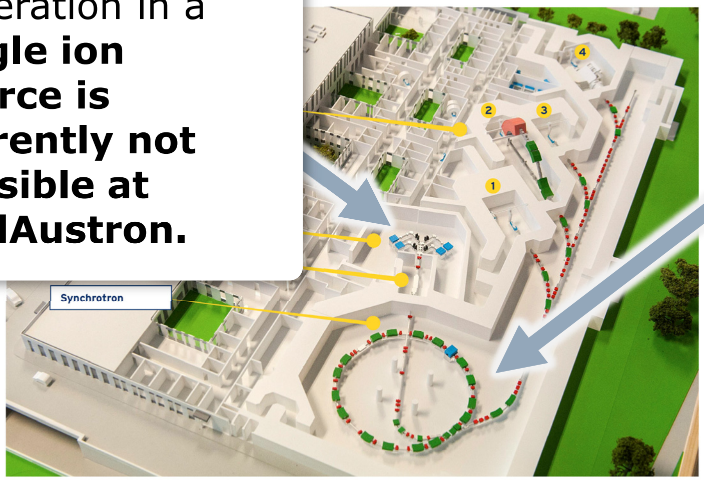


Investigate <u>sequential injection into the synchrotron</u> as (temporary) alternative production scheme:

1st injector pulse: **Inject He-2+**

2nd pulse: **Inject C-6+**

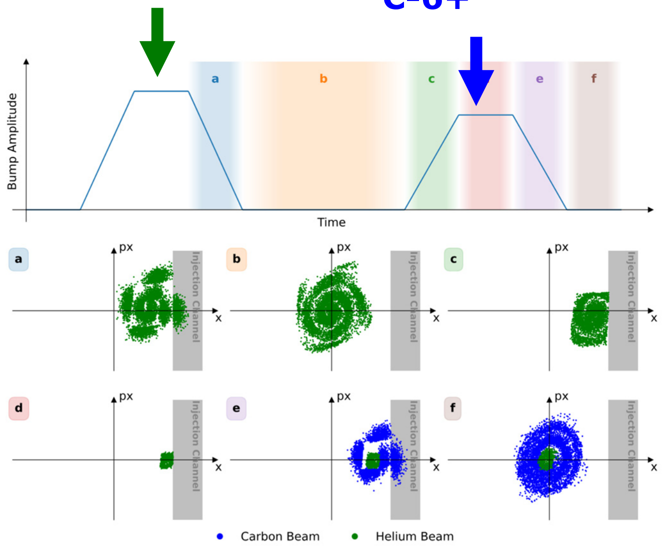


Fig. 3: Horizontal phase space during double multiturn injeciton

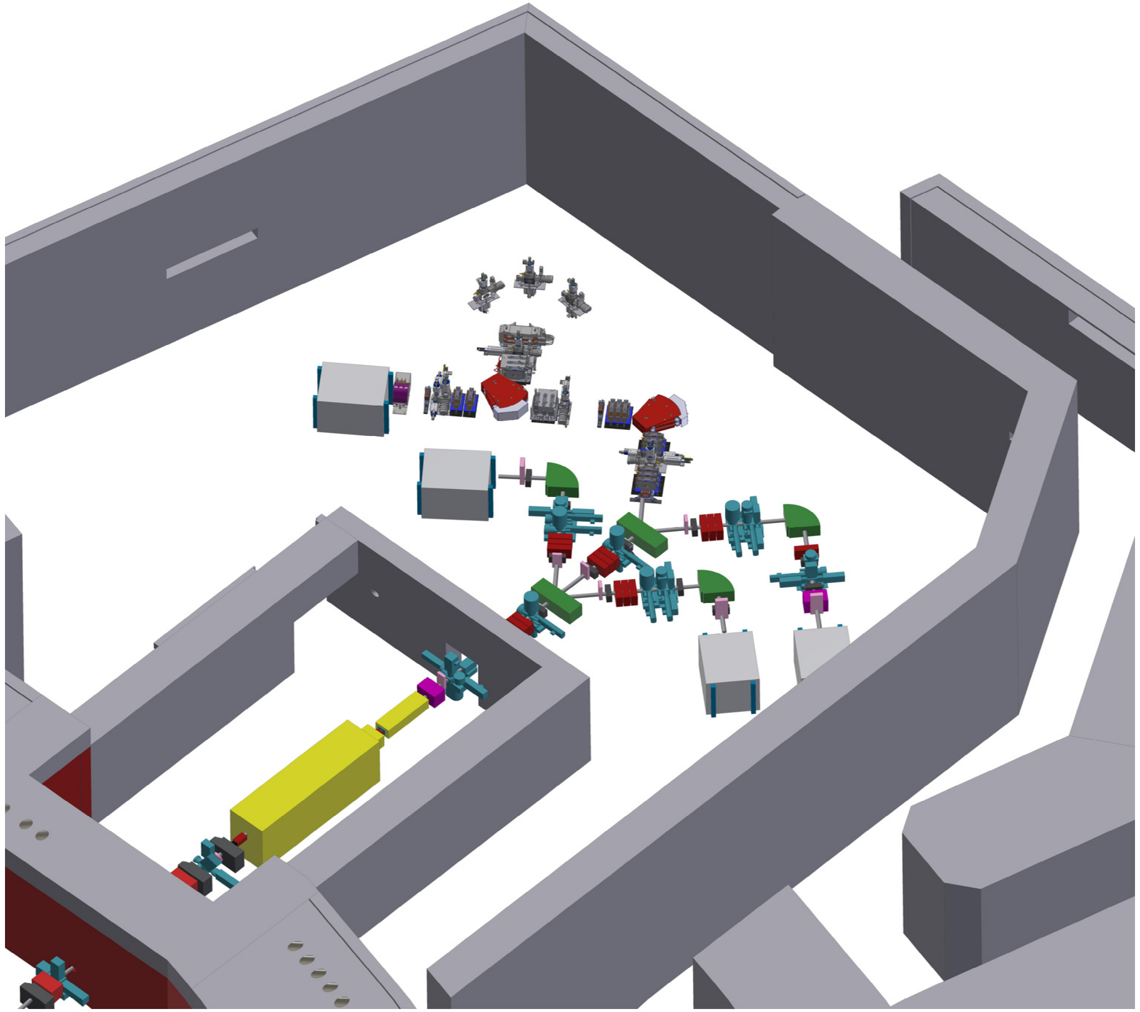
- *<u>Aim</u>*: Facilitate first mixed beam studies **with existing infrastructure.**
- *<u>Procedure</u>*: Produce the two ion species in separate ion sources and **"mix" them during a sequential injection into the synchrotron.**
- Pulse injector twice, while ramping synchrotron only once.
- *<u>Status</u>*: Technological feasibility demonstrated, but several open problems to be solved for obtaining a useful beam.

M. Kausel et. al, IPAC'24, <u>10.18429/JACoW-IPAC2024-THPR42</u>
E. Renner et. al, IPAC'24 <u>10.18429/JACoW-IPAC2024-THPR43</u>

FEASIBILITY STUDY: FOURTH ION SOURCE BRANCH (S4)

Idea: Design study in collaboration with TU Wien for 4th ion source branch to

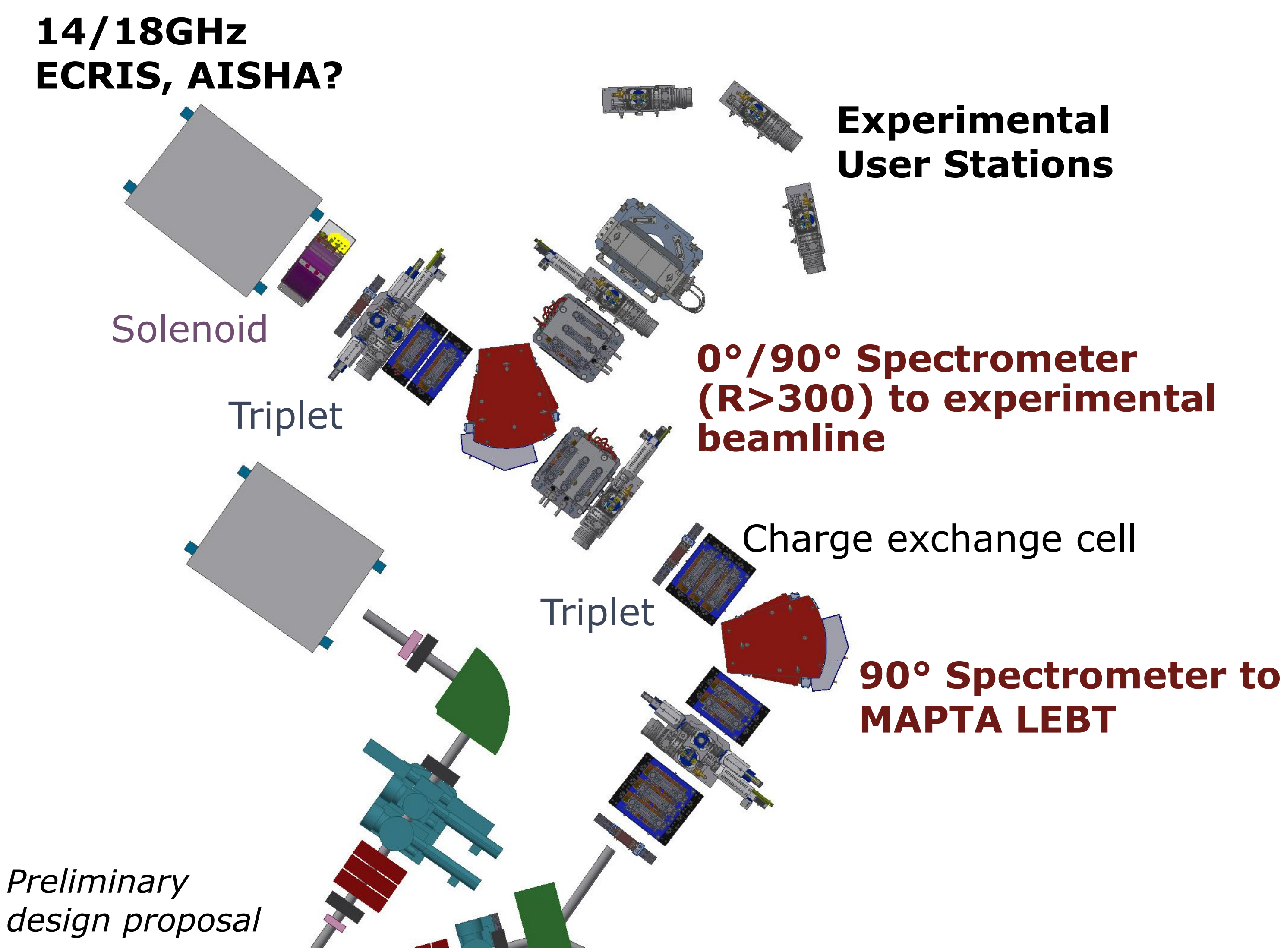
- expand ion beam spectrum delivered to the synchrotron,
- provide research beam line for low energy ion physics experiments of external users.



"Wishlist" for 4th ion source branch:

- Higher beam currents
- Higher charge states of heavy ions (Xe)
- More ion species (N, O, Ne)
- Mixed He_{+2}/C_{+6} beams

MAIN REQUIREMENTS FOR THE S4 BRANCH



Preliminary beam requirements:

- C+6 100uA
- O+8 70uA
- Xe+30 1uA

- Feasibility study ongoing
- Prepare for funding application
- Potential kick off Q3-2025

CONCLUSIONS

- The clinical world of ion sources is "nasty":
  - Stable and reproducible beam 24/24 hours is the priority(+/- 2.5% on current fluctuations), high purity
  - Relatively low intensities (hundreds of *μA* to tens of *mA*, but depends on the type of accelerator!) and charge states between $1^{+} \leq q \leq 6^{+}$ max
  - Small emittance for proper beam matching at the next main acc. entrance
  - Beam Redundancy for High MTBF (Mean Time Between Failure)
  - Low Maintenance with minimal power consumption
  - Well defined procedures for non-expert personnel operating the source on daily base (re-tunings, start-up etc.)
- Pulsed Mode fully commissioned, stability and beam property requirements fulfilled
  - implementation of SADS system for online monitoring of the leakage currents planned
- Helium is almost fully commissioned and will be handed over to the user beg. 2025., according to timeline
- At MedAustron all three ion sources are now fully operational, fourth branch is under discussion
- Further tests in DFH planned, results for overall reduction of the treatment time are promising

THANKS FOR YOUR ATTENTION!

Main Acknowledgements (beside main authors):

- **Fabio Farinon, Lorenz Fischl, Richard Haider, David Mitterecker, Mauro Pivi, Fabien Plassard, Andrei Prochazka, Matthias Sturm, Marijo Vrkasevic, Christoph Bloch**
- **All members of MTA and OPS departments of MedAustron**
- **Prof. Willhem from TuWien, Austria**
- **Other centers/companies for productive discussions on helium comm. and pulsed mode: HIT, Siemens**