SATIF-16
May 28-31, 2024

SATIF-16 Shielding aspects of Accelerators, Targets and Irradiation Facilities

IONS UP TO NEON @ MEDAUSTRON

Monte Carlo simulations for use of ions up to neon in the ion therapy synchrotron facility MedAustron

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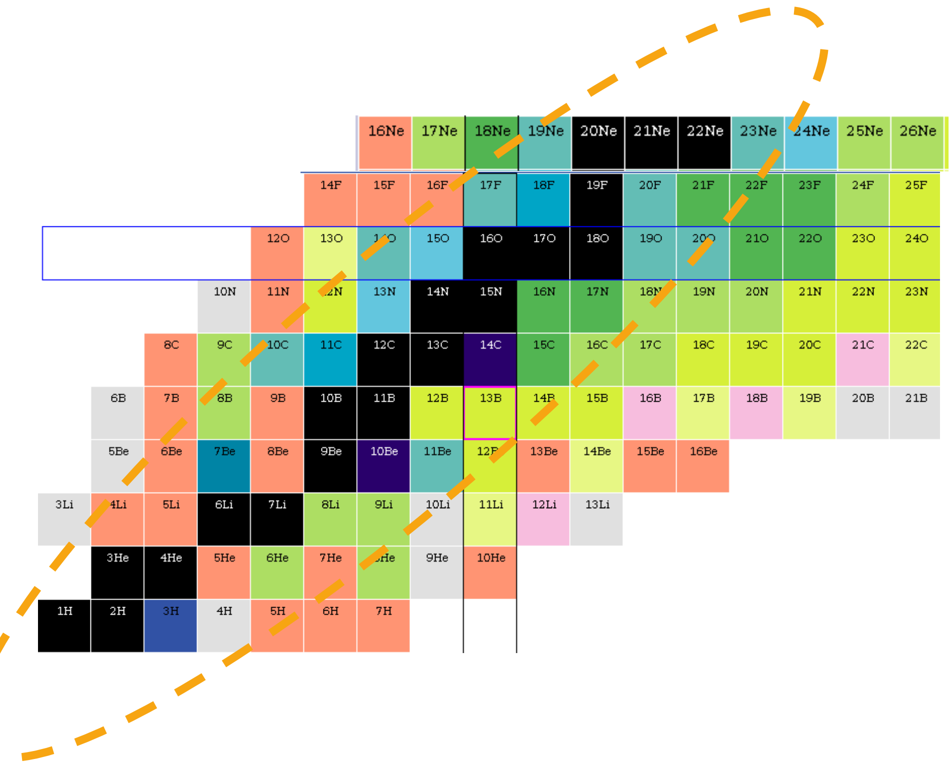
MedAustron
Ion Therapy Center

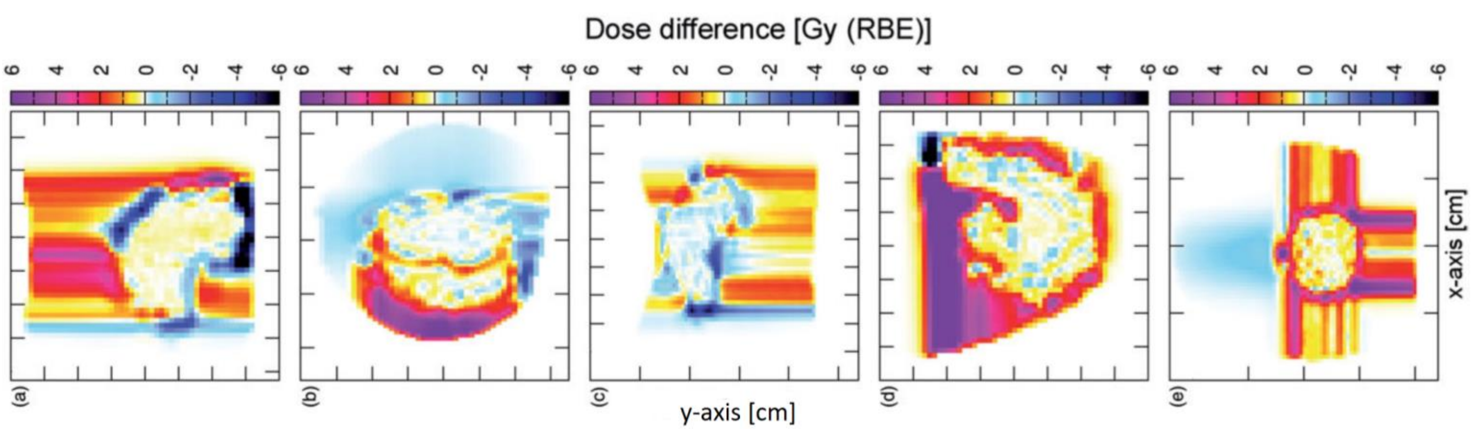
MEDAUSTRON – ENVIRONMENTAL IMPACT ASSESSMENT (EIA)



- For accelerators >50 MeV → EIA
- EIA 2010: protons and carbon ions
  - But our scientists also need helium, and maybe, in a couple of years, oxygen
- Step-wise completion
  - Last planned step (taking IR with gantry into operation) in 2021
- Changes to EIA only possible before all steps are completed
- → change according to §18b to include other ions up to neon needs to be approved before end of 2021
- → assessment of other ions necessary

MOTIVATION

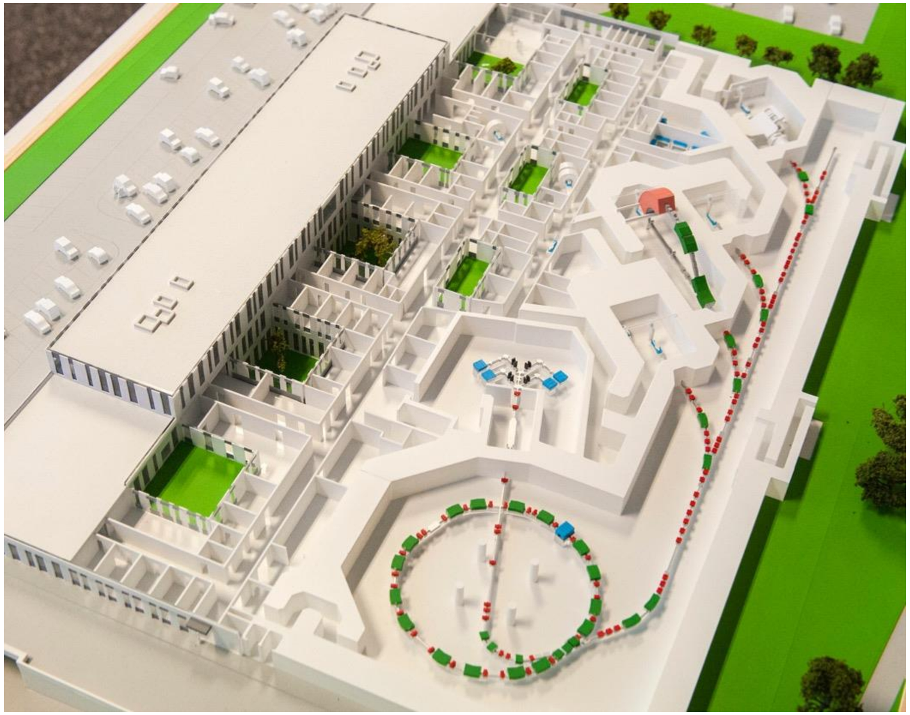
- We want to stay ahead of the state-of-the-art (clinical and non-clinical research)
- Get patients the best possible treatment
- Summary:
  - „Helium is the better proton"
  - „Oxygen is the better carbon"



Knäusl B., Fuchs H., Dieckmann K., Georg D. Can particle therapy be improved using helium ions? – A planning study focusing on pediatric patients. (2016)

WHAT DO WE NEED?

- Most interesting: Helium & Oxygen
- But… if we do the calculations for 2 ion species, why not more?
    - Once the simulations are set up, the additional effort is minimal
    - We are more flexible in the future
    - Better overall picture
- Topics we need to cover:
    - Prompt radiation (i.e. shielding)
    - Air activation
        - Inhalation
        - Gamma submersion
        - Released to environment
- Change in calculation of operational limits



FLUKA SIMULATIONS

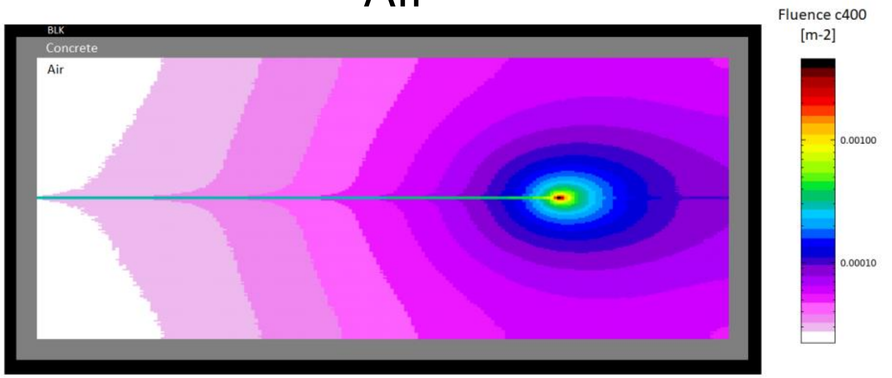
- Performed by Michael Bauer (Master's thesis[1])

- Generic geometries
    - Based on PhD theses by Feldbaumer & Jägerhofer (EIA 2010)

- Simulations:
    - Shielding in IR with heavy concrete
    - Shiedling in IR with standard concrete
    - Air activation (simpler geometry)

    - All stable nuclides up to Ne-22
        - Including those from EIA2010
    - At maximum energy of 400 MeV/u

Air

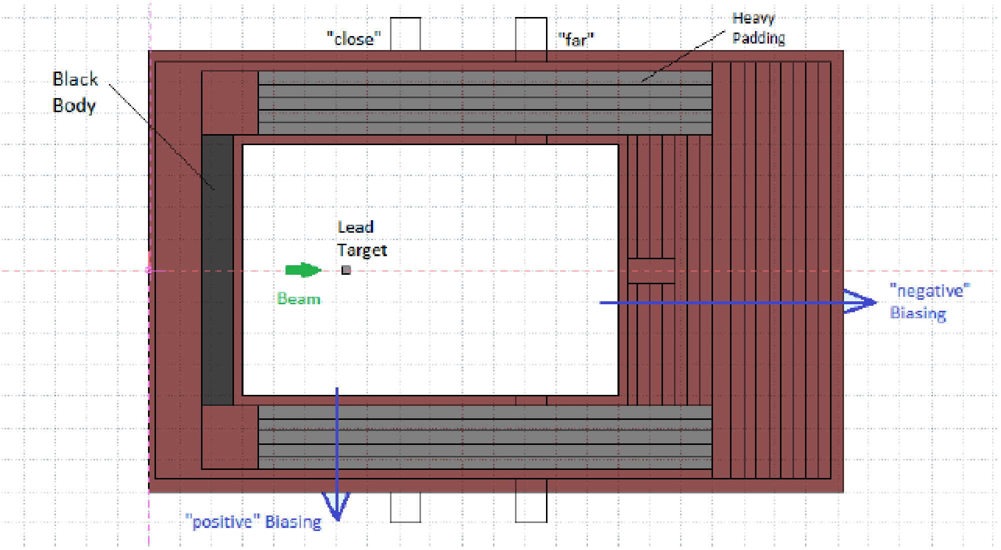


Shielding

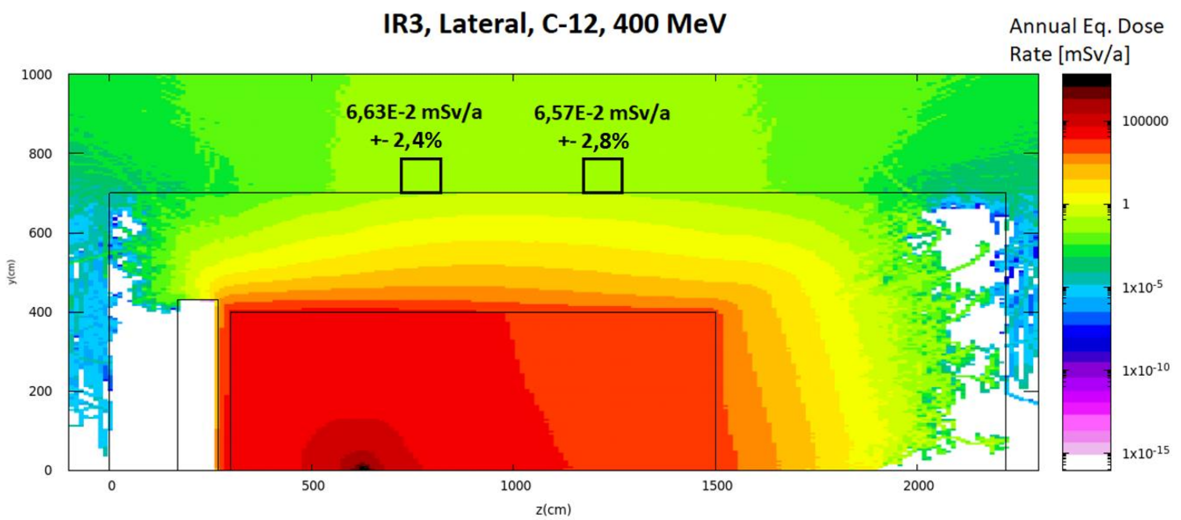
[1]Bauer, Michael. *Validation of MedAustron's Shielding Concept for Primaries Z ≤ 10*. 2020, https://doi.org/10.34726/hss.2020.84680.

SHIELDING RESULTS

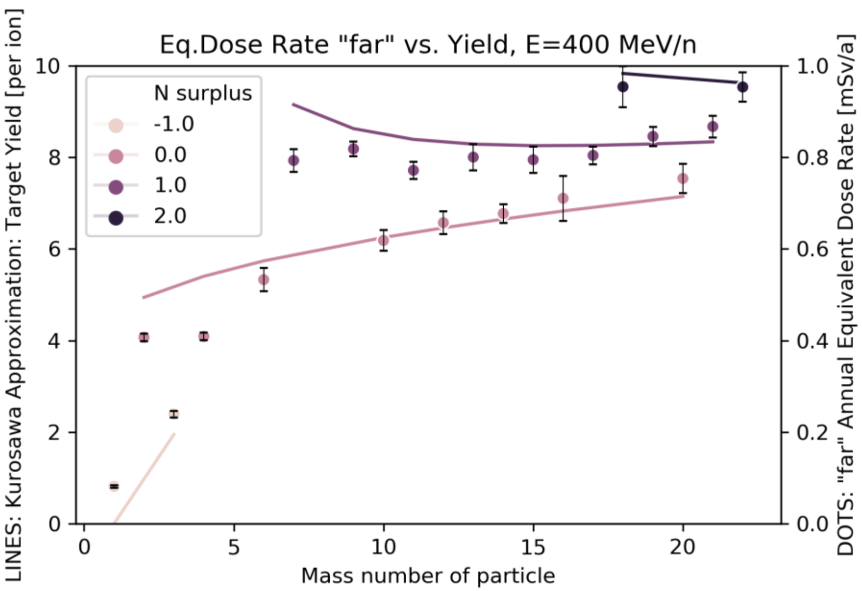
- Scoring at 2 „worst-case“ positions
- Results match previous results & measurements for carbon ions



C-12. 400 MeV/u	Detektor „far“. 2020		Jägerhofer. 2012 [9]	
	mSv/a	Uncertainty (%)	mSv/a	Uncertainty (%)
IR1	8.39e-04	9.4%	1.14e-03	15.8%
IR3	6.57e-02	2.8%	5.53e-02	2.3%



SHIELDING RESULTS – ALL



- Eq. dose proportional to neutron yield
- Which depends on energy, mass (no. of neutrons, protons) of primary and target

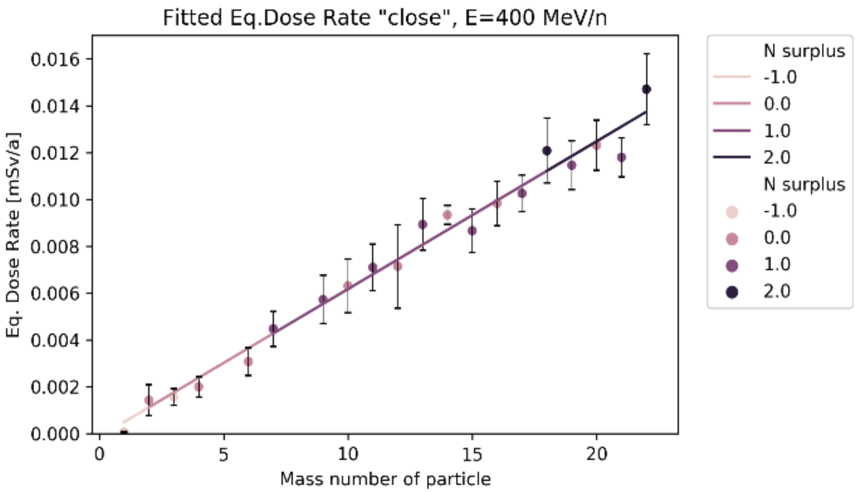
$$Y = 1.5\text{e}{-06} \cdot \frac{E_p^2}{N_T^{1/3}} \left(A_p^{1/3} + A_T^{1/3}\right)^2 N_p \frac{A_p}{Z_p^2}$$

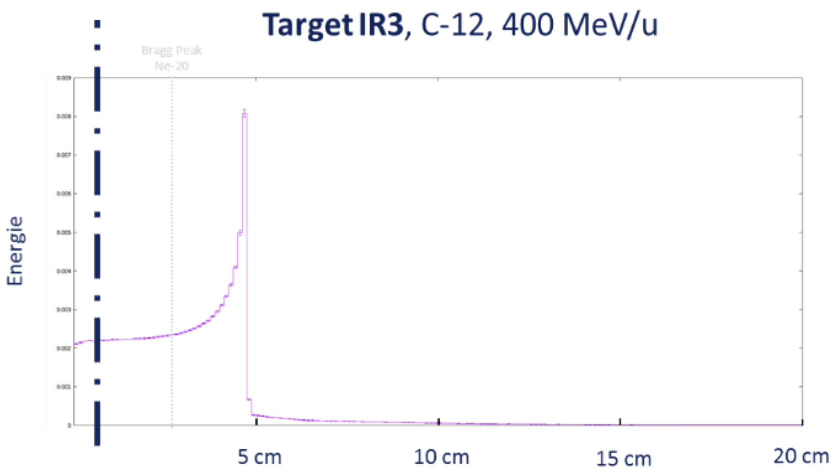
T. Kurosawa *u. a.*, „Neutron yields from thick C, Al, Cu, and Pb targets bombarded by 400 MeV/nucleon Ar, Fe, Xe and 800 MeV/nucleon Si ions", *Phys. Rev. C*, Bd. 62, Nr. 4, S. 044615, Sep. 2000, doi: 10.1103/PhysRevC.62.044615.

SPECIAL CASE: THIN TARGET

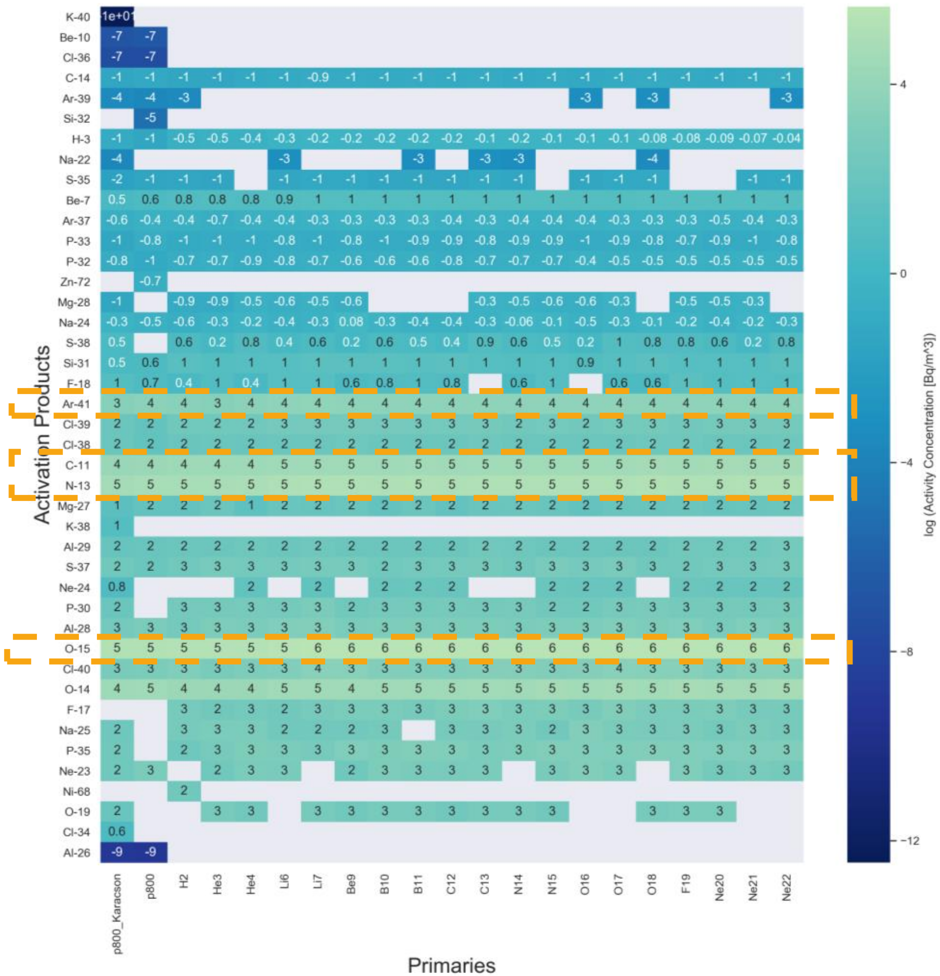
- Thin targets: Bragg peak is not in the target
- For research room, thin targets are also possible → need to be considered

- Relationship with neutron surplus only true for thick targets





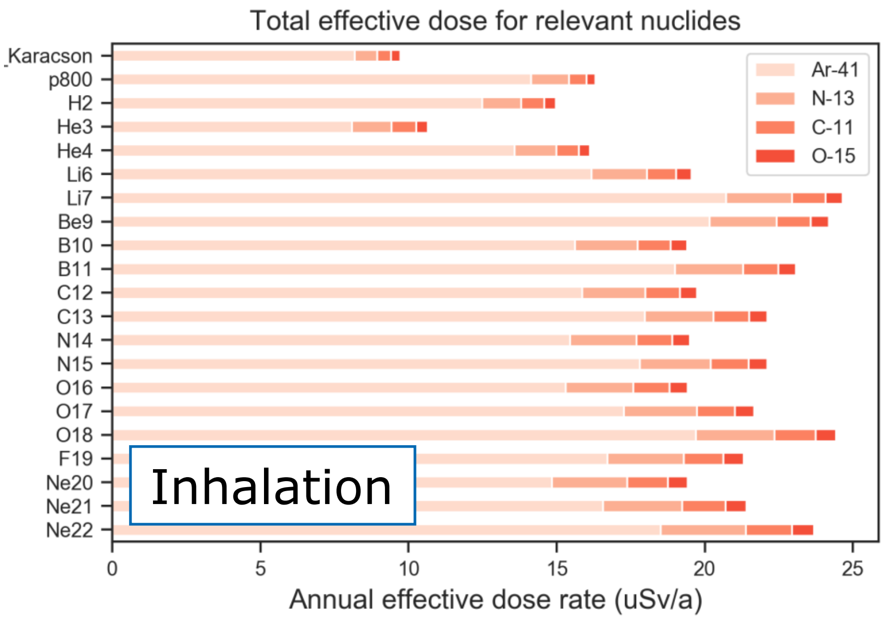
AIR ACTIVATION

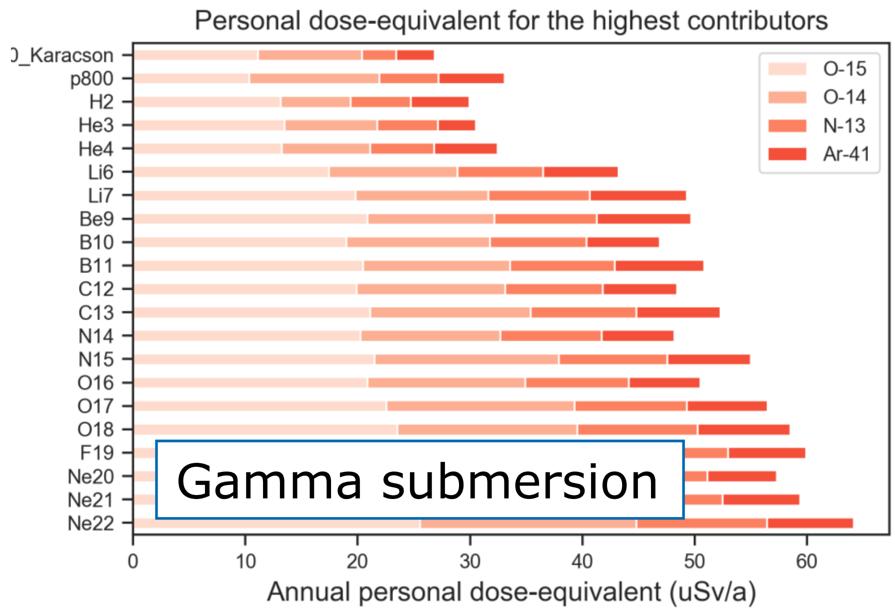


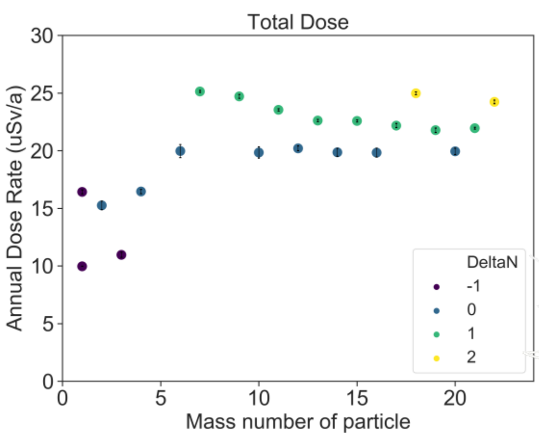
- Maximum primary rate
- Irradiation time = air exchange time
- Few differences in the most relevant nuclides produced by the different primaries
- For dose calculations all nuclides with half-lives >100s were included
    - Dose due to inhalation and gamma submersion calculated with python script

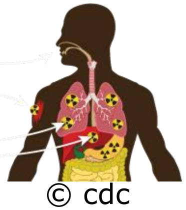
ICRP Publication 107
ICRP Publication 119
T. Otto, „Personal dose-equivalent conversion coefficients for 1252 radionuclides“, *Radiat. Prot. Dosimetry*, Bd. 168, Nr. 1, S. 1–10, Jän. 2016
R. Engelbrecht, „Dosisfaktoren bei Inkorporation von gasförmigen C-11, N-13, O-15“, Seibersdorf Labor GmbH

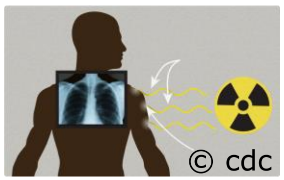
DOSE DUE TO AIR ACTIVATION

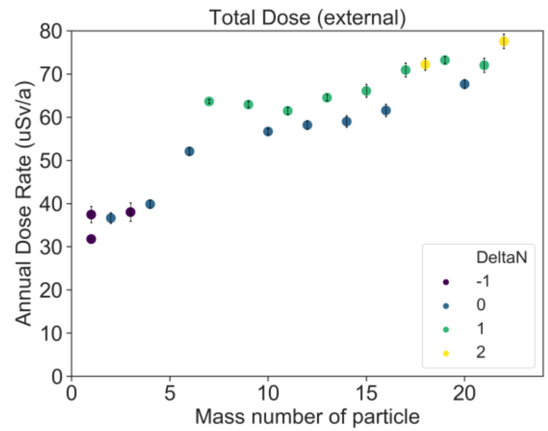








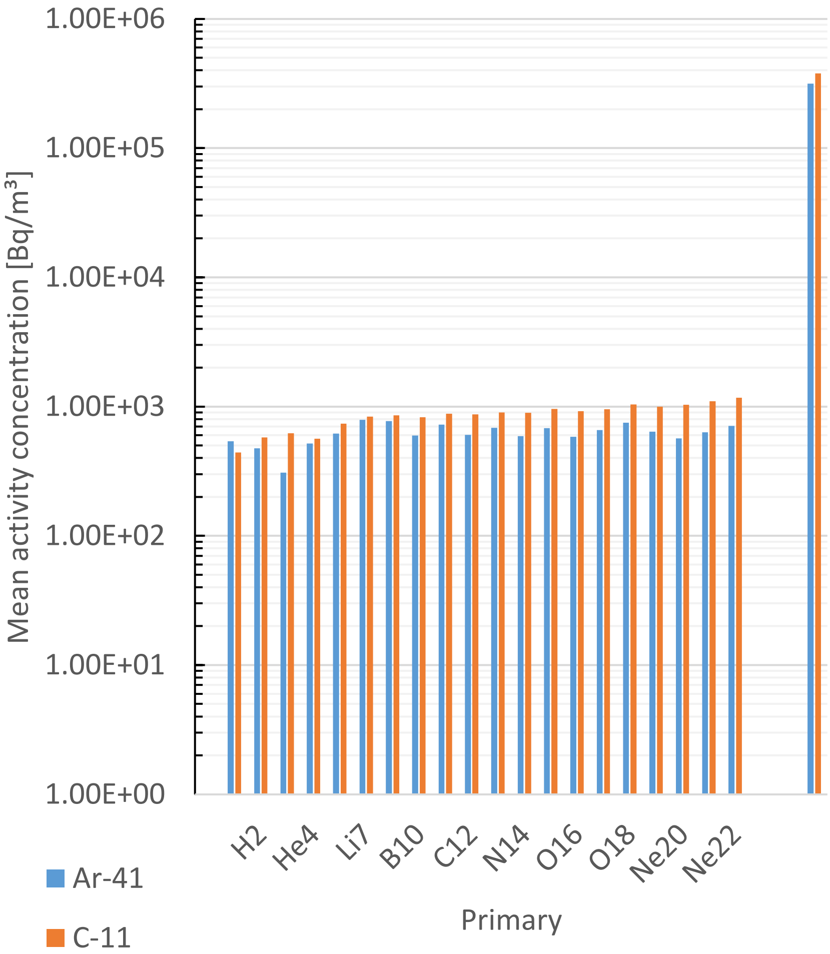




AIR EMISSIONS

- Most relevant nuclides: C-11 and Ar-41
- Same nuclides as those already considered for the atmospheric dispersion calculations in 2010
- We already have activity concentration limits for C-11 and Ar-41
  - Order of magnitude: 1e5 Bq/m³
- All nuclides produced by the primaries up to neon have less than 1e3 Bq/m³
  - 2 orders of magnitude below limits

- Conservative assumptions:
  - No dilution with outside air
  - Constant irradiation (8800h per year)
  - Maximum particle rate



DOSE BUDGET

Teilchenart: Protonen (H+)

Bestrahlungsraum	Teilchenanzahl	Limit
IR1 (≤250MeV)	2.83E+14	7.8E+15
IR1 (800MeV)	3.11E+13*	1.8E+16
IR2	3.91E+14	-
IR3	2.90E+14	-
IR4	2.28E+14	-

Teilchenart: Kohlenstoffionen (C6+)

Bestrahlungsraum	Teilchenanzahl	Limit
IR1	1.31E+13	7.8E+14
IR2	1.85E+13	4.7E+14
IR3	-	4.7E+14

~200µSv for inhalation and gamma submersion doses

$$D = \sum_j \sum_i N_{i,j} \cdot \gamma_{i,j} < 5{,}8\ \text{mSv}$$

Raum	Teilchen	Anzahl $N_{i,j}$	Dosisfaktor $\gamma_{i,j}$ [zSv/prim.]	Dosis [mSv]
IR1	H+ (<250 MeV)	2.83E+14	0.25	7.06E-05
	H+ (800MeV)	3.11E+13*	19.91	6.19E-04
	C6+	1.31E+13	19.25	2.52E-04
IR2	H+	3.91E+14	0.77	3.01E-04
	C6+	1.85E+13	93.95	1.73E-03
IR3	H+	2.90E+14	0.77	2.23E-04
	C6+	------	93.95	------
IR4	H+	2.28E+14	0.77	1.75E-04
	C6+	---------	------	------
			Summe Dosis D [mSv]:	**3.37e-03**

- Previously: limits on number of each ion species and room separately
- Now: Number of particles used to calculate dose outside „worst-case" spot outside shielding
  - Flexible regarding ion species and room

Zepto = 1e-21

SUMMARY

→ we got the permit to proceed with ions up to neon in 2021

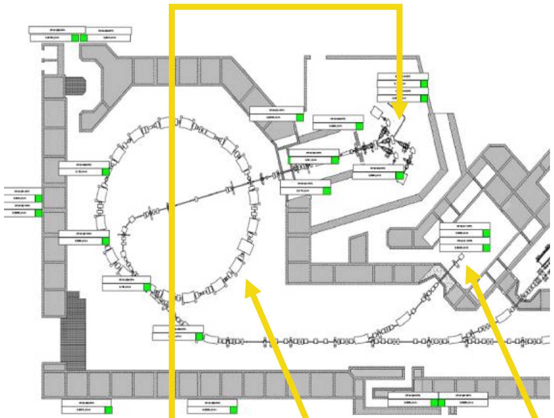
- Dose budget concept → allows flexible use of ion species and irradiation rooms
- In general, the neutron yield (which depends on primary and target energy and masses) is a good predictor for the impact of different ion species

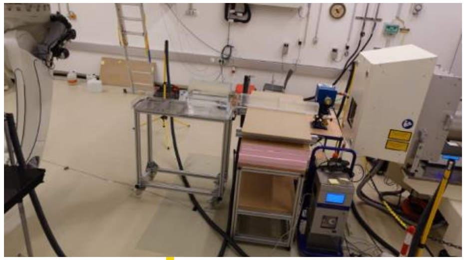
- We used very conservative assumptions
- Still, even with „worst-case" scenarios it will be difficult to exceed limits
- Realistically, we will be far below limits

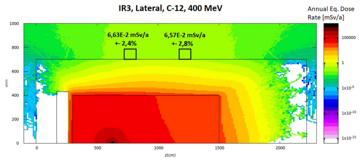
- Even though a defined number of primaries for a heavier ion species will result in higher doses, in reality, treatment plans with heavier ions use fewer primaries, actually resulting in lower doses!

→ Helium ions are in the final stages of commissioning for research groups

CURRENT STATUS OF HELIUM







2020

Simulations, calculations and documentation of effects of ions up to neon on RP

Q2 2021

§18b EIA permission granted for using ions up to neon

Q2 2022

Injector commissioning competed

Q2 2023

Synchrotron commissioning completed

Q1 2024

HEBT and IR1 commissioning completed

March 2024

RP measurements to confirm shielding and air activation

ongoing

commissioning of the Medical Front-End components in IR1 to provide modulated scanning pencil beams calibrated in intensity

Q2 2025

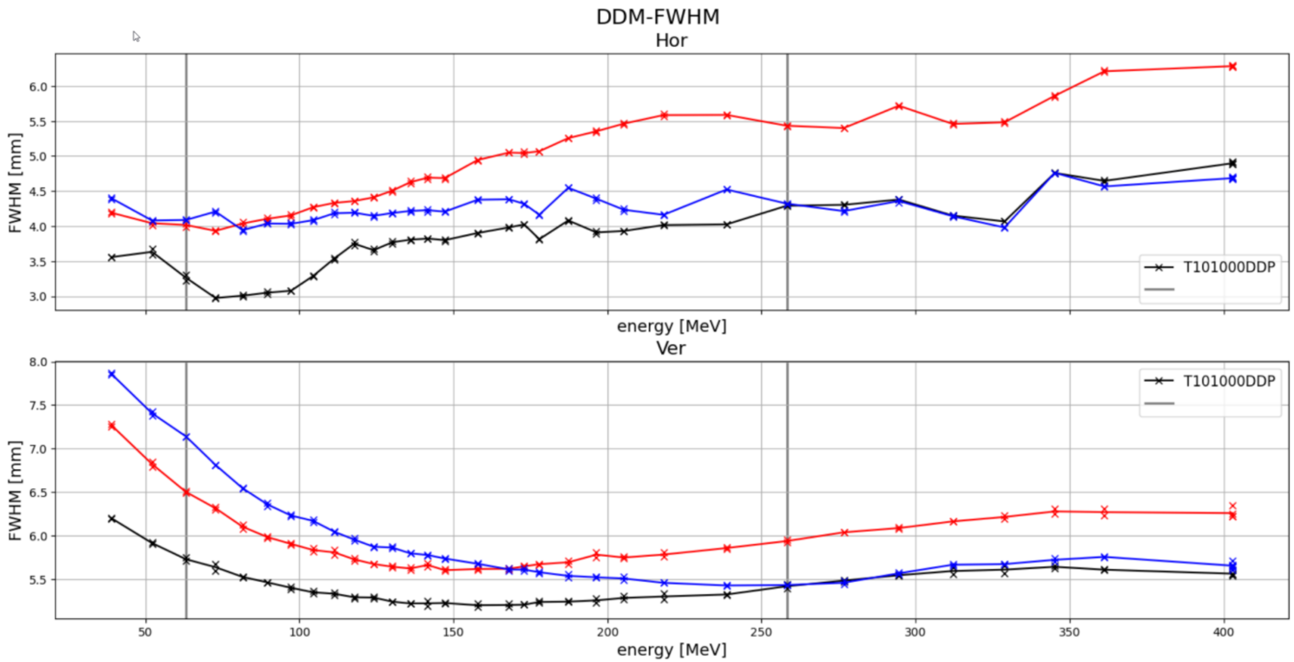
Project end

Supernanogan Ion Source (Pantechnik)
4He^{2+} extracted @ 8 keV/u; ~690 µA

LINAC → 7.1 MeV/u,
32% transmission efficiency, ~190 µA

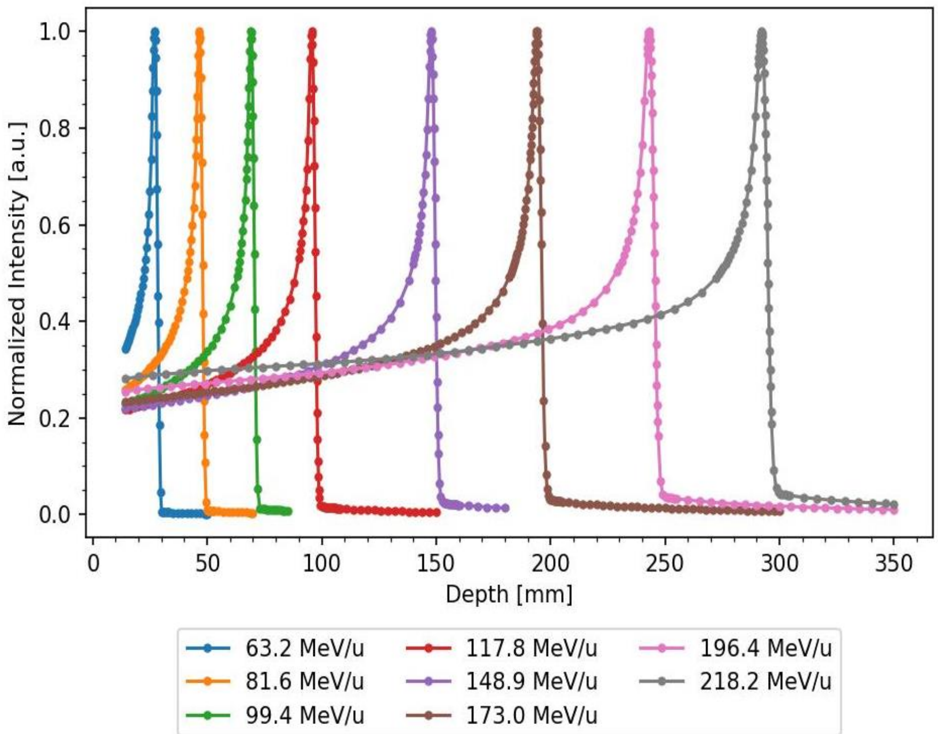
HEBT &IR1 COMMISSIONING

- Spot Size Adjustments and Steering completed for DEG100 and SL 10,5,2 s and DEG10 SL 10
- Beam FWHM and Beam Position fulfill the user requirements in the "Clinical Range": 63.2 - 258.2 MeV/u

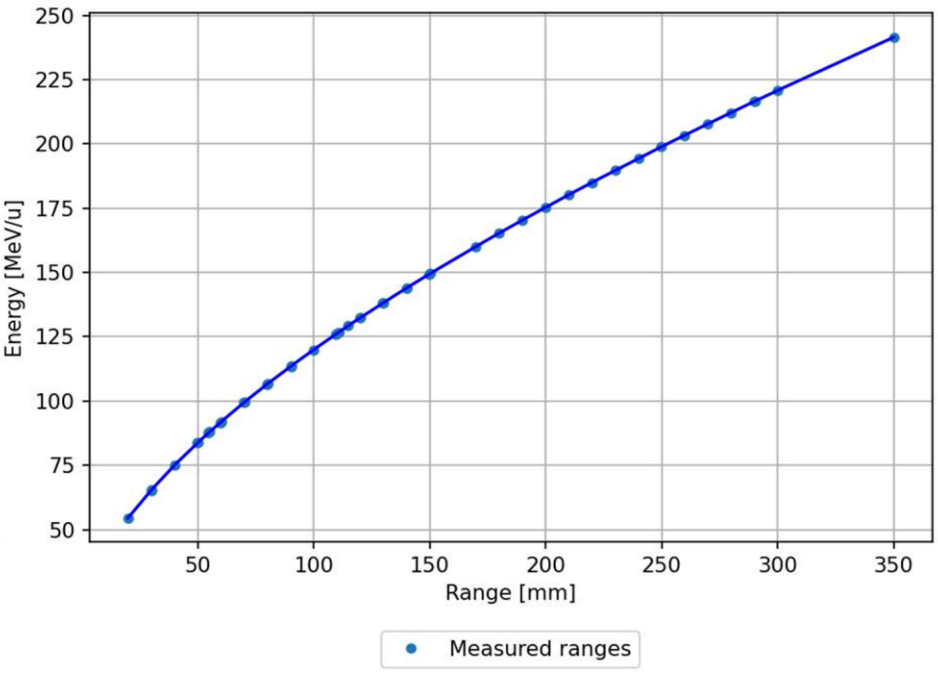


- **black: optics for small beam size**
- **red: optics for larger beam size**
- **blue: mixed optics for a small beam size at higher energies and controlled at lower energies**

RANGE MEASUREMENTS IN IR1



Nine exemplary 4He2+ range meas. in water at ICM



$^4He^{2+}$ energies vs. range measured at ICM from 63.2-241.5 MeV/u, covering a potential clinical range in water from 3-30 cm

THANK YOU TO…

Michael Deutsch
Lukas Jägerhofer
Michael Bauer
Nadia Gambino
Hermann Fuchs