

Joint Universities Accelerator School

JUAS 2019

Archamps, France, 18<sup>th</sup> – 20<sup>th</sup> February 2019

# Analytical & numerical design of a normal-conducting, iron-dominated electro-magnet

Case study – Tutorial – Mini Workshop

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CERN



# Introduction



- The goal is to practice elements learned during the lectures
- Students will design, specify and optimize a ,real‘ magnet
- Sample case: Bending magnet for the [MedAustron](#) medium-energy beam transfer line
- Work in groups of 3 persons during 2 half-days
- At the end, students are expected to deliver a written magnet design report



# Programme



- Short introduction to MedAustron
- Magnet input parameters, requirements and constraints
- Exercise 1:
  - Analytical design (paper & pencil) to derive the main parameters
  - Expected results: detailed parameter list, magnet cross-section (yoke & coils) ready for entering the model in FE-code
- Exercise 2:
  - Numerical field computations and optimization of the pole profile
  - Expected results: optimized magnet cross-section (pole profile)



# Introduction to MedAustron

MedAustron is located in Wiener Neustadt (50 km south of Vienna) next to the future site of the new hospital

## Medical Treatment

- Tumour treatment
- Clinical research

## Non-clinical Research (NCR)

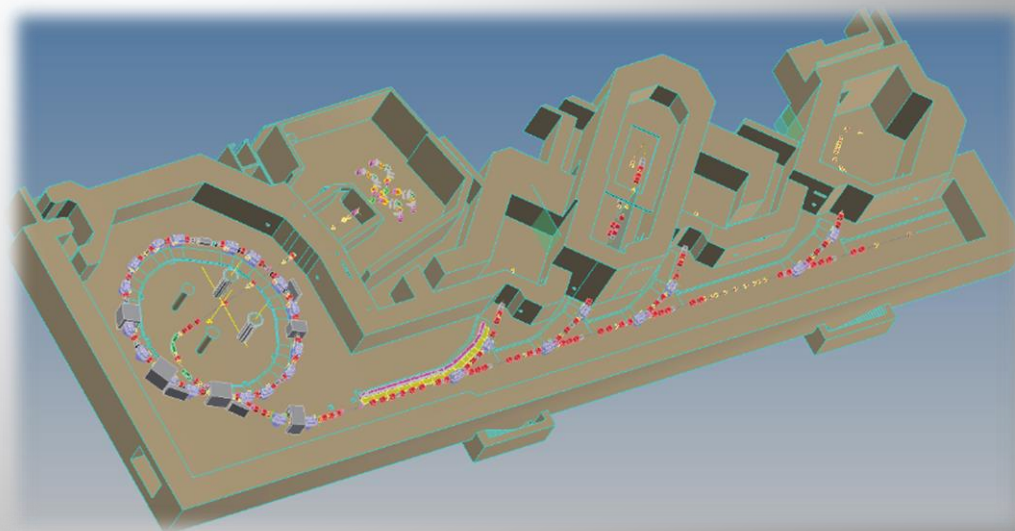
- Medical Radiation Physics
- Radiation biology
- Experimental physics





# Accelerator Main Parameters

- Synchrotron based (circumference 76 m)
- Ion species: protons and carbon ions
  - Optionally and at a later stage other ions with  $q/m > 1/3$  are possible
- Energy range
  - Proton: 60-250 MeV (medical)
    - Higher proton energy provided for experimental physics: up to 800 MeV
  - Carbon: 120-400 MeV/n
- Cycle time > 1 second





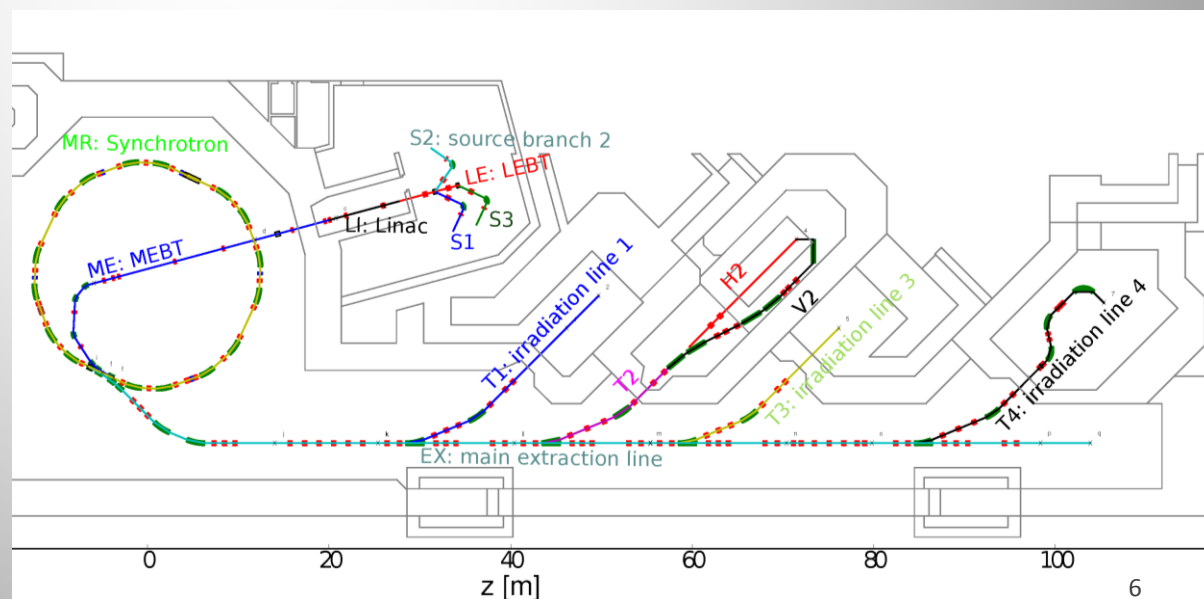
# Irradiation rooms

## Medical facility:

- IR2
  - Horizontal and vertical beam
  - Protons and carbon ions
- IR3
  - Horizontal beam
  - Protons and carbon ions
- IR4
  - Gantry
  - Protons

## Non-clinical research facility:

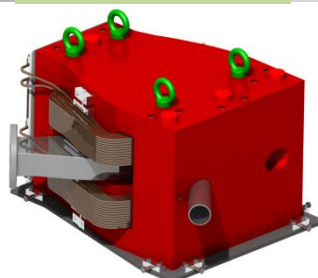
- IR1
  - Horizontal beam line
  - Protons (up to 800 MeV) and carbon ions



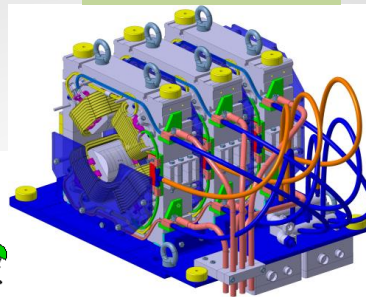


# Magnet families

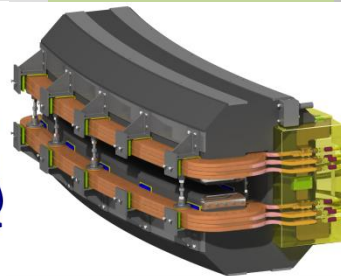
3 Spectrometers



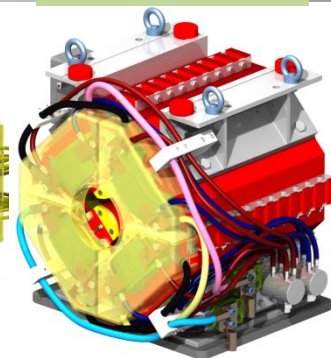
6 LEBT Triplets



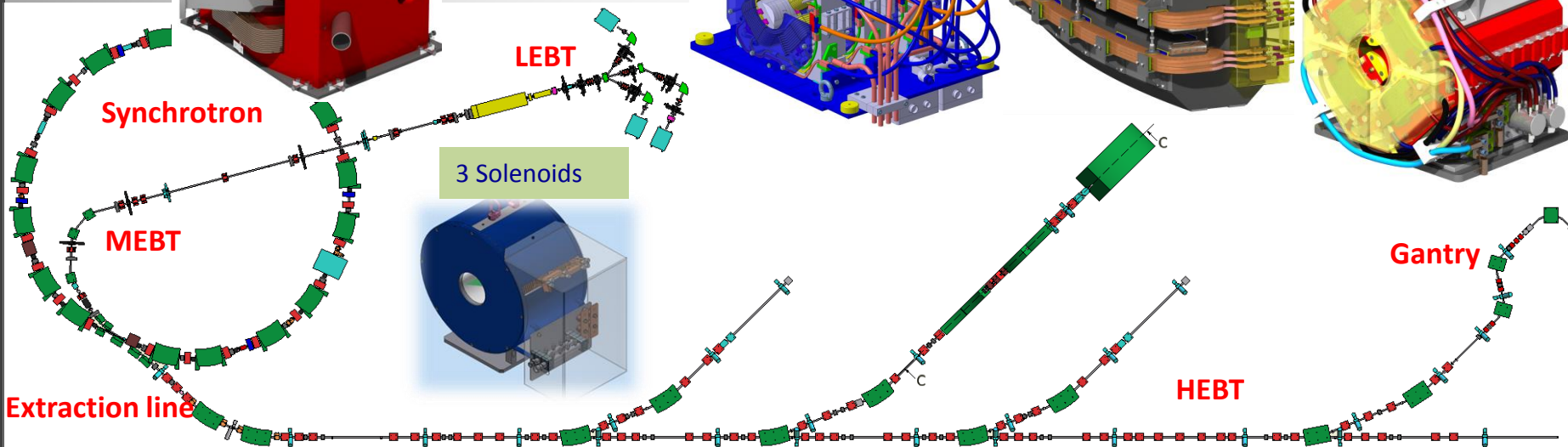
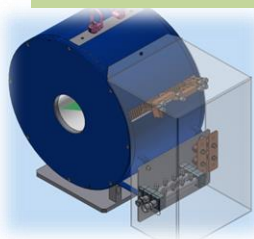
12 HEBT Dipoles



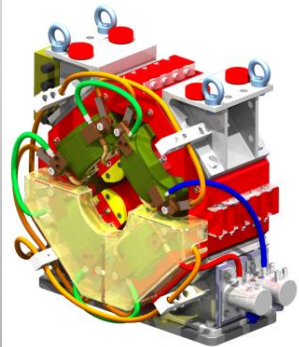
76 HEBT Quads



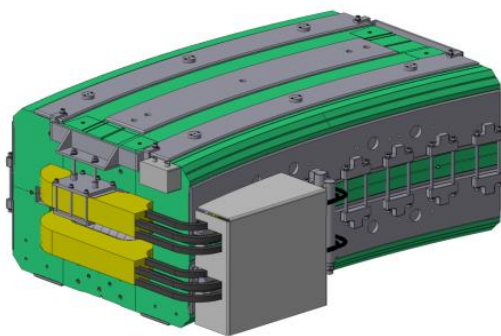
3 Solenoids



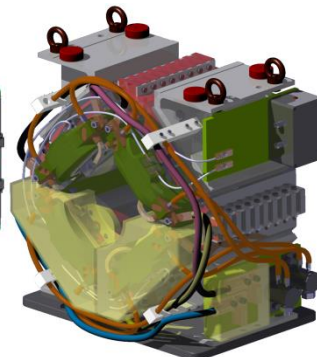
3 MEBT Dipoles



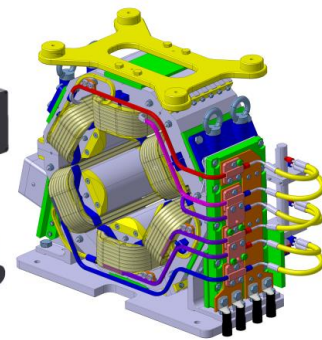
10 MEBT Quads



16 Ring Dipoles



24 Ring Quads

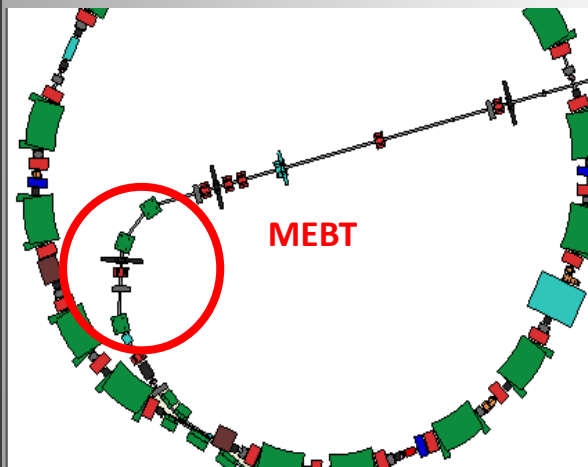


5 Ring Sextupoles



# Beam parameters

Required: Three bending magnets for the medium-energy beam transfer line between the Linac and the Synchrotron



Parameter	Value	Unit
Particle type	Protons, C <sup>6+</sup>	
Beam energy	7	MeV/u
Length of beam line	40.9	m
Beta function $\beta_x, \beta_y$	$\sim 10$	m
Beam size $\sigma_x, \sigma_y$	+/- 10	mm
Margin for closed orbit distortions	+/- 10	mm





# Functional specification

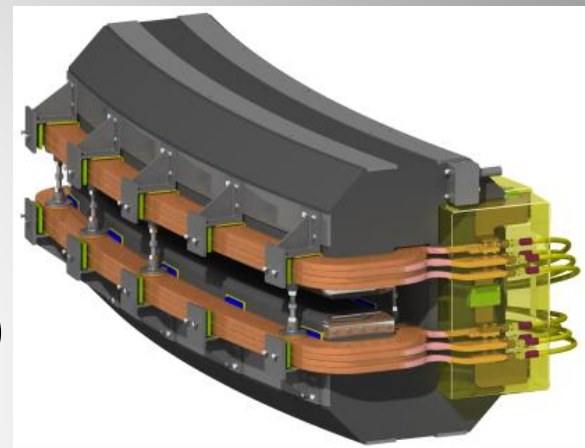
Parameter	Value	Unit
Number of magnets	3	
Bending angle	36	deg
Beam entry/exit angle	18	deg
Operation mode	quasi DC	
Ramp rate	0.3	T/s
Horizontal good-field region	+/- 20	mm
Vertical good-field region	+/- 23	mm
Field quality inside GFR $\Delta B/B_0$	$< +/- 1 \cdot 10^{-3}$	
Max. <a href="#">overall</a> magnet length per magnet	0.8	m
Max. available water pressure drop	0.8	MPa
Inlet water temperature	25	°C
Max. converter current	650	A
Max. converter voltage (3 magnets in series)	160	V



# Exercise 1: Analytical design

The following parameters should be defined or derived:

- Magnet shape (straight/curved)?
- Flux density  $B$
- Aperture height  $h$
- Excitation current  $NI$  (ampere-turns)
- Magnetic length  $l_{mag}$  and iron length  $l_{iron}$  ( $k = 0.55$ )
- Pole width and yoke thickness
- Current density  $j$ , nominal current  $I$  and number of turns  $N$
- Dissipated power  $P$ , coil resistance  $R$ , dc voltage  $V$
- Coil size (width, height) and conductor material
- Pressure drop  $\Delta p$ , Temperature rise  $\Delta T$
- Conductor size (height, width, cooling hole diameter) and insulation thickness
- Coolant flow  $Q$  and flow velocity  $u_{avg}$  Reynolds number  $Re$



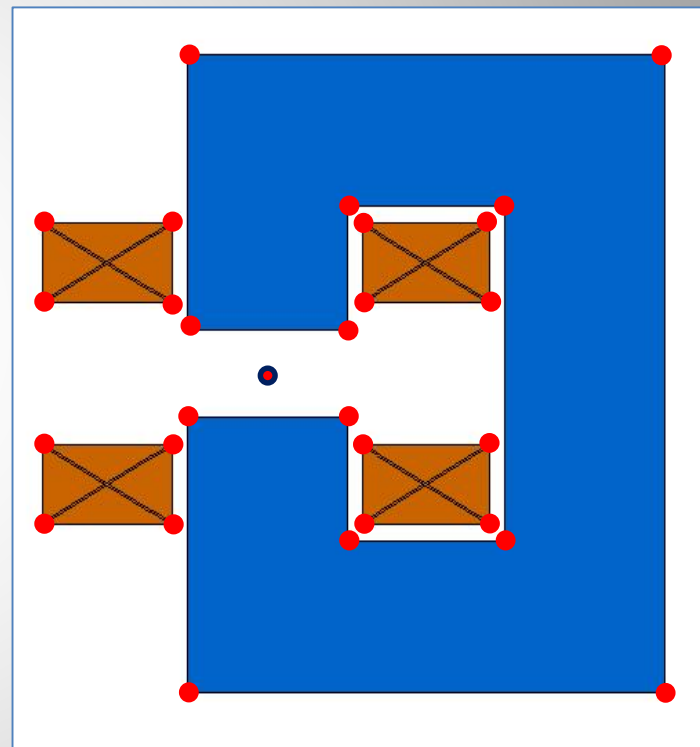
Hint: reasonable assumptions are not forbidden!



# Exercise 1: Analytical design

For the computer work with FEMM, you will need the following magnet parameters:

- Aperture height
- Pole width (< 130 mm)
- Yoke dimensions (horizontal and vertical)
- Coil window width and height
- Coil dimensions (width and height)
- Coil position
- Coil excitation (ampere-turns)



Hint: prepare a sketch identifying the key-point coordinates (x/y) wrt the beam axis



## Exercise 2: Numerical design

### 2D Numerical calculations with FEMM:

- FEMM: 2D FE code for magnetics, electrostatic, heat flow and current flow problems with graphical pre- and post-processors
- Licensed under the terms of the [Aladdin Free Public License](#)
- Input via GUI or scripts (LUA or Octave scripting engine)
- More info (wiki) and download from the web:
- <http://www.femm.info/wiki/HomePage>



## Exercise 2: Numerical design



The goal of this exercise is:

- Download, install and get familiar with FEMM (→ [homework](#))
- Enter a simple dipole geometry (yoke + coils) using nodes, segments and block labels
- Define and set the necessary material parameters
- Apply the correct boundary conditions
- Analyze the results:
  - field lines, flux distribution, central field, field along the axis and the GFR, current density, etc...
- Optimize the pole profile to improve the field quality



# Design report

Students are expected to deliver a written magnet design report which should include at least:

- detailed magnet parameter list summarizing the outcome of the analytical design
- explanation for your design choice
- magnet cross-section based on analytical calculations with yoke and coil shape
- optimized cross-section (pole profile) based on numerical computations fulfilling the field quality requirements
- Results from the numerical simulation (field quality plot)
- Note: the reports will be evaluated and contribute (3 points out of 20) to the total score together with the results of the exam
- Please send the final report (1 per group) in electronic form to the JUAS secretary
- Submission deadline: **Monday, 11<sup>th</sup> March 2019**



(Good luck...)

... and it is not forbidden to ask  
questions!