High-intensity cyclotrons

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About me

- Accelerator physicist
- Main research topic:
  High-intensity cyclotrons
- Modelling and simulation:
  - Cyclotron magnet
  - Magnetic extraction elements
  - Cyclotron central region
  - Beam dynamics also in presence of space charge
- Use of FEM software (Opera) and specific beam dynamics codes

2015

Master degree in Physics
University of Catania & INFN-LNS

2019

PhD in Physics
University of Catania & INFN-LNS
+
1year post-doc position at INFN-LNS

2020

EU – Marie Curie – IF
two-year project
IBA, Belgium

2022

Researcher
Permanent staff
member at INFN-LNS

High-intensity compact cyclotrons

❑ Why are the cyclotrons suitable for high-intensity beams?

- Cyclotrons are simple and compact
- Efficient and cost-effective multi-turn concept (only few RF cavities needed)
- CW operation is naturally possible

Cyclotrons follow the mantra: *better, smaller, cheaper*

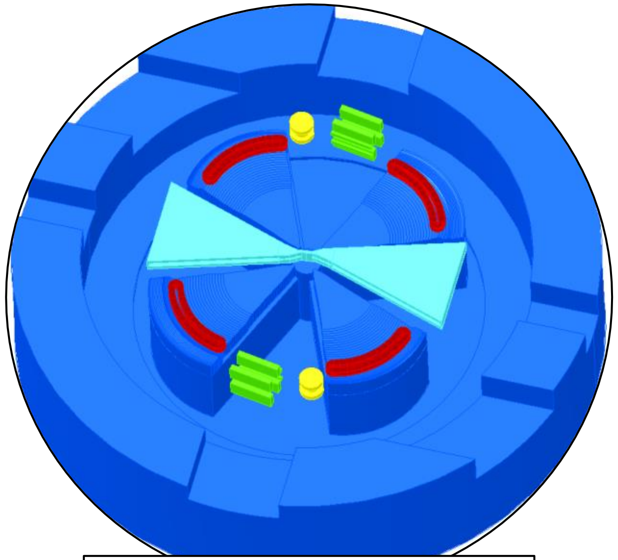
❑ Which aspects are critical?

- Injection
- Intensity limitations from space charge
- Extraction: clean extraction! → activation
- Technical and personnel safety
- Other issues: vacuum induced losses, ion induced gas desorption, high energy density when stopped in material, foil related issues, …

❑ Applications

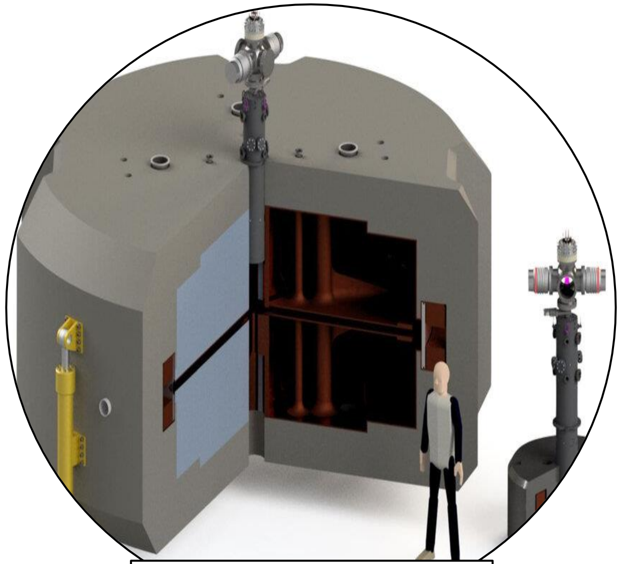
- Experiments searching for rare processes, especially in nuclear and particle physics
- Large-scale production of conventional and new frontier medical radioisotopes
- Boron Neutron Capture Therapy (BNCT)

Research projects involving cyclotrons



InnovaTron project
EU-MSCA-IF

- Ion species: H^+
- Energy: 14 MeV
- Intensity: up to 5 mA
- Ion source: Internal
- Extraction: Self-extraction
- Applications: large-scale production of medical radioisotopes



IsoDAR project
MIT

- Ion species: H_2^+
- Energy: 60 MeV/A
- Intensity: 5 mA
- Ion source: External
- Extraction: Electrostatic deflector
- Applications: search for sterile neutrinos

Upgrade of the superconducting cyclotron of INFN-LNS

- Ion species: H_2^+ - ^{208}Pb
- Energy: 10-80 MeV/A
- Intensity: up to tens of µA
- Ion source: External
- Extraction: Two electrostatic deflectors
- Applications: Nuclear physics experiments and protontherapy

Increase of a factor 100

Central region studies

☐ Design goals:

- Good horizontal and vertical beam centering
- Vertical beam focusing
- Matching of the beam phase space with respect to the cyclotron eigenellipse
- Good longitudinal acceptance
- Minimization of beam losses
- Orbit turn separation

☐ Constraints:

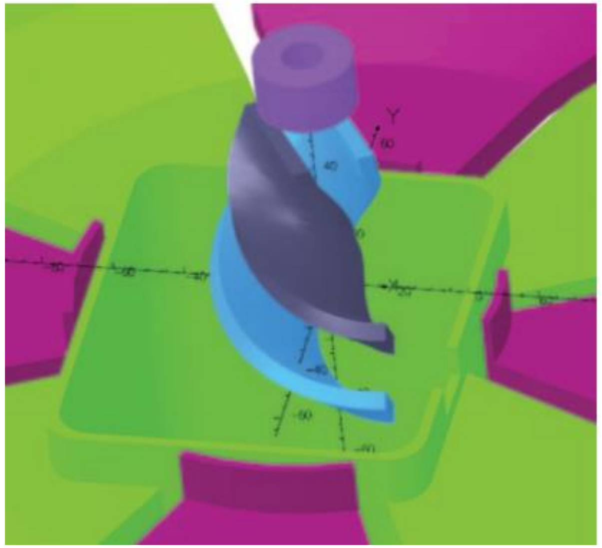
- Magnetic structure
- Accelerating structure

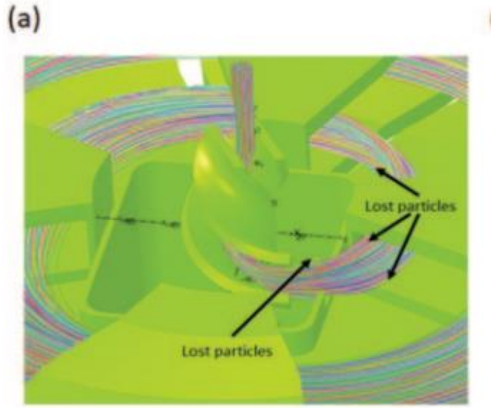
The achievement of the design goals is not easy due to **space charge effects**:

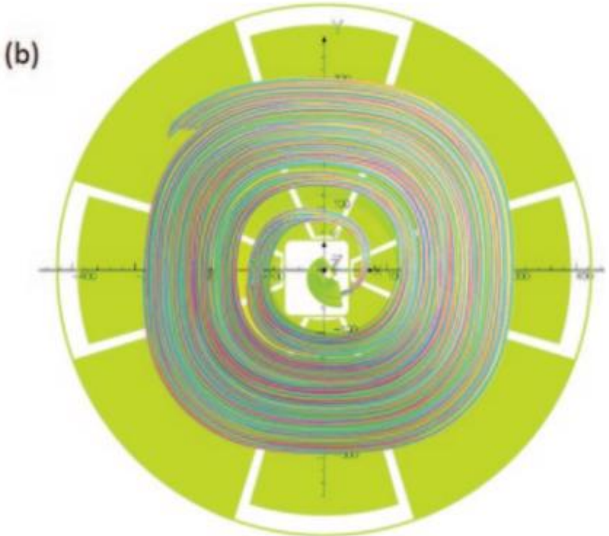
- The Coulomb forces between the charged particles create a self-field which acts on the beam particles, leading to beam blow-up and defocusing in both transverse planes.
- Space charge effects induce energy spread with possible loss of turn separation.
- These effects are generally proportional to the beam intensity.

Central region studies – External ion source

Central region of the **IsoDAR test-bench cyclotron** (E_{max} = 1 MeV/A)

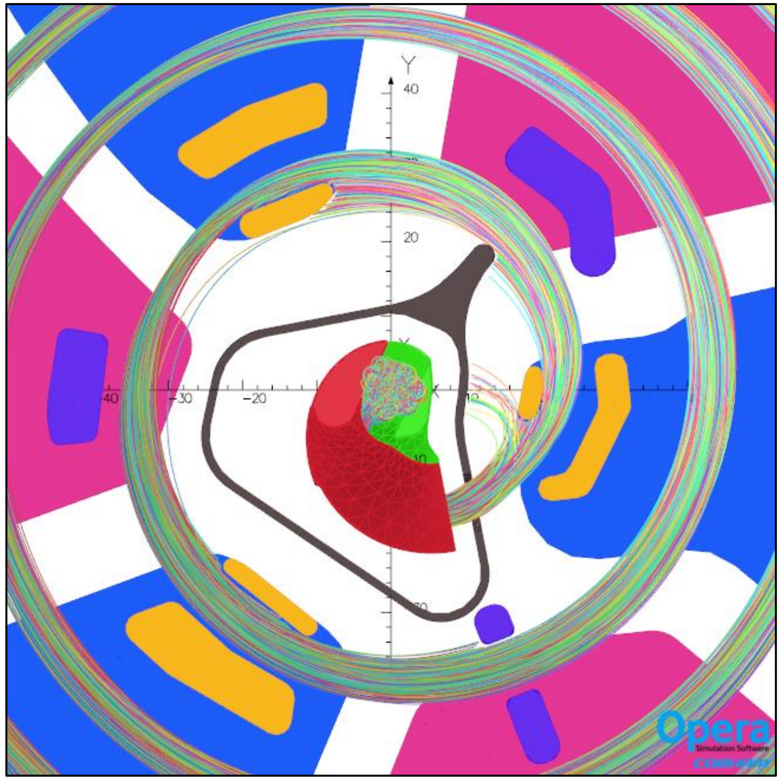






Particle losses in the cyclotron centre due to the emittance growth through the spiral inflector and transverse defocusing at the inflector exit.
The spiral inflector also introduces a RF-phase spread effect.

New central region of **the superconducting cyclotron of INFN-LNS**



Increase of the injection efficiency equal to 65%

Central region studies – Internal ion source

- In high-intensity cyclotrons with internal ion source, understanding beam dynamics under space charge contributes to an optimum design.

- A quantitative self-consistent approach is needed for accurate simulation of the beam extracted from the internal ion source and accelerated under space charge conditions.

- Our approach consists of three steps:
  - Simulation of the meniscus shape and beam phase space on it.
  - Simulation of the central region including the meniscus
  - Simulation of the bunch formation in the first accelerating gap and 3D full beam tracking including space charge

InnovaTron cyclotron – Principle of self-extraction

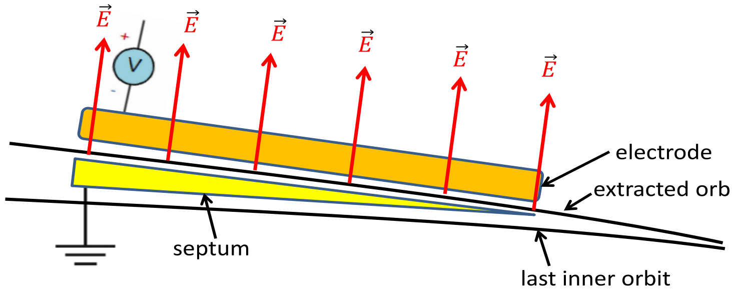
- ☐ In a cyclotron, the average magnetic field starts to decrease near the maximum pole radius.
- ☐ There are two limits:
  - Limit of acceleration → loss of isochronism

$$\frac{dE}{dn} = q\,V_{rf} \cos(\phi) = \Delta E_{max} \cos(\phi)$$

  - Limit of radial stability → it occurs at r such that B·r is maximum $n = \frac{r}{B}\frac{dB}{dr} = -1$
- ☐ If the pole gap is relatively large, the first limit is reached earlier than the other one and an electrostatic deflector (ESD) is used to transfer the beam from the isochronous region to the radially unstable region where the beam can exit.
- ☐ **Self-extraction is based on creating a sharper transition between both regions such that the unstable zone can be reached by acceleration without an ESD.**

Electrostatic deflector

A DC radial E-field creates an initial angular kick

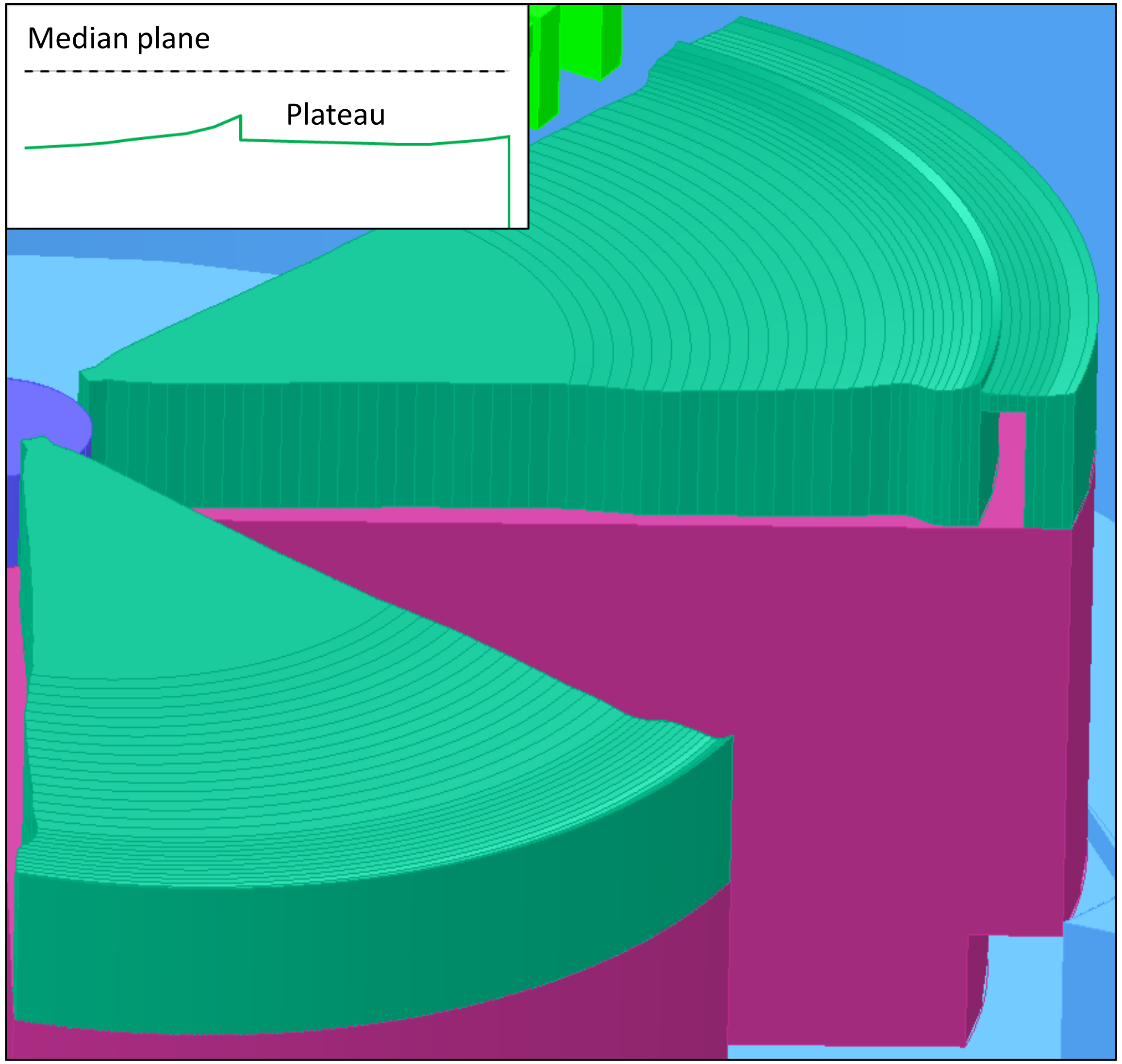


Turn separation inversely proportional to the energy ($R \propto \sqrt{E}$) => Turns pile up closely together near the extraction radius. => Possible important beam losses and induced heat-load on the septum. => The electrostatic deflector strongly limits the maximum beam current

InnovaTron cyclotron – Magnet design

Unconventional extraction method: special shaping of the cyclotron magnetic field and the use of harmonic coils to increase the turn separation in the extraction process.

Cyclotron Type	Compact Isochronous
particle	proton
injection	dual internal PIG-source
extraction radius/energy	52 cm; 14 MeV
rotational symmetry	2-fold (quasi 4)
B_{ave} and B_{max}	1.15 T; 1.9 T
quasi-elliptical gap	16 mm < g < 40 mm
minumum gap at extraction	18 mm
pole radius short/long	54 cm/57 cm
number of dees/angle	2; 36°
RF frequency/mode	69.1 MHz; h = 4
dee-voltage	55 kV
available RF power	200 kW



Thank you for your attention