InnovaTron: An innovative industrial high-intensity cyclotron for large-scale production of medical radioisotopes

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Marie Skłodowska-Curie Actions

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Outline

- Overview of the InnovaTron project:
  - General aspects
  - The prototype of the self-extracting cyclotron
  - Simulation strategies

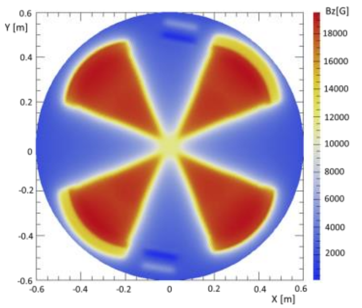
- Beam tracking including space charge:
  - Bunch acceleration after the first gap
  - Bunch formation at the ion source
  - Simulations of the emission of ions from the plasma meniscus

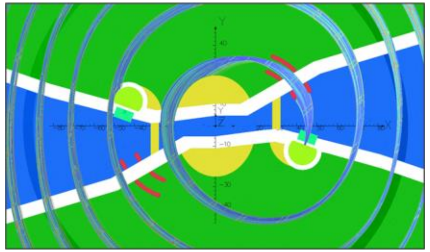
- Conclusions and next steps

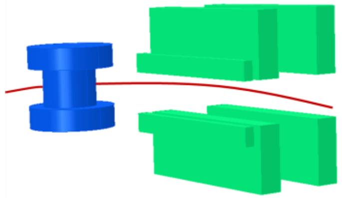
Overview of the InnovaTron project

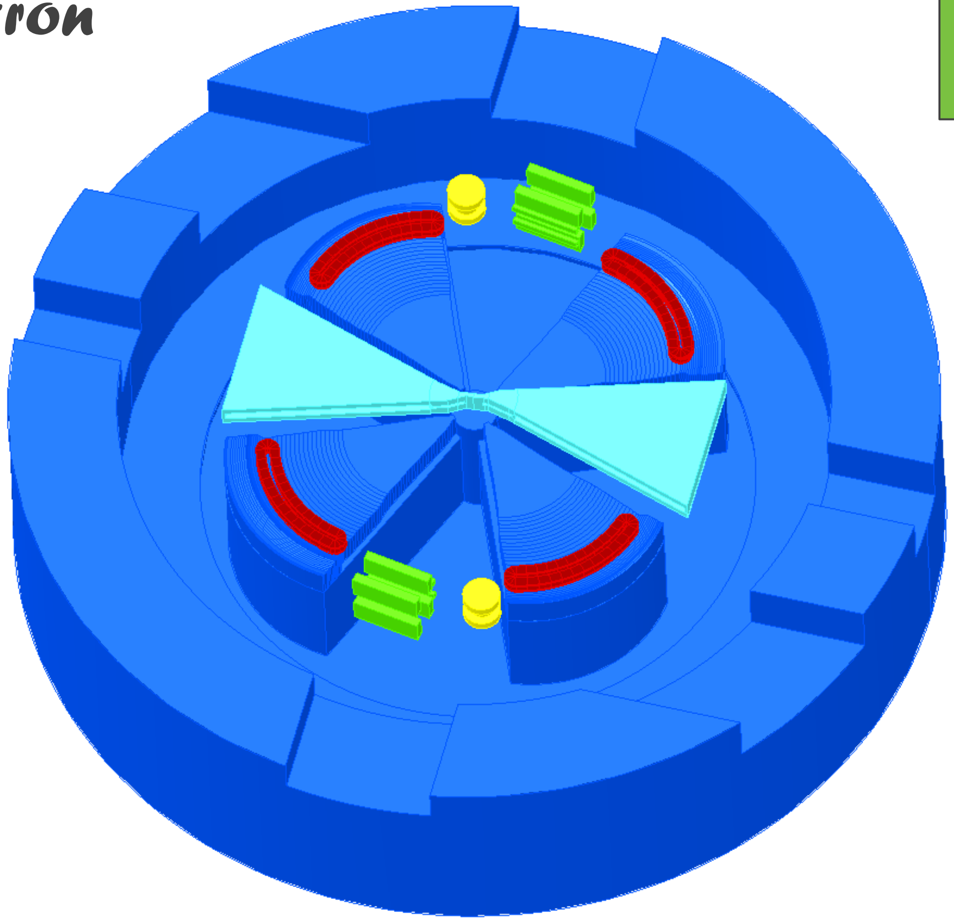
Overview of the InnovaTron project

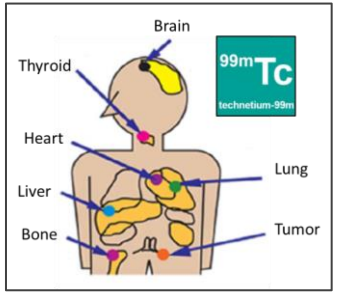
Self-extracting cyclotron

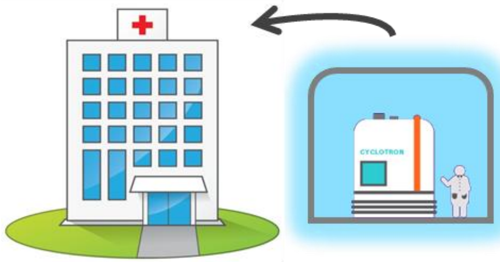












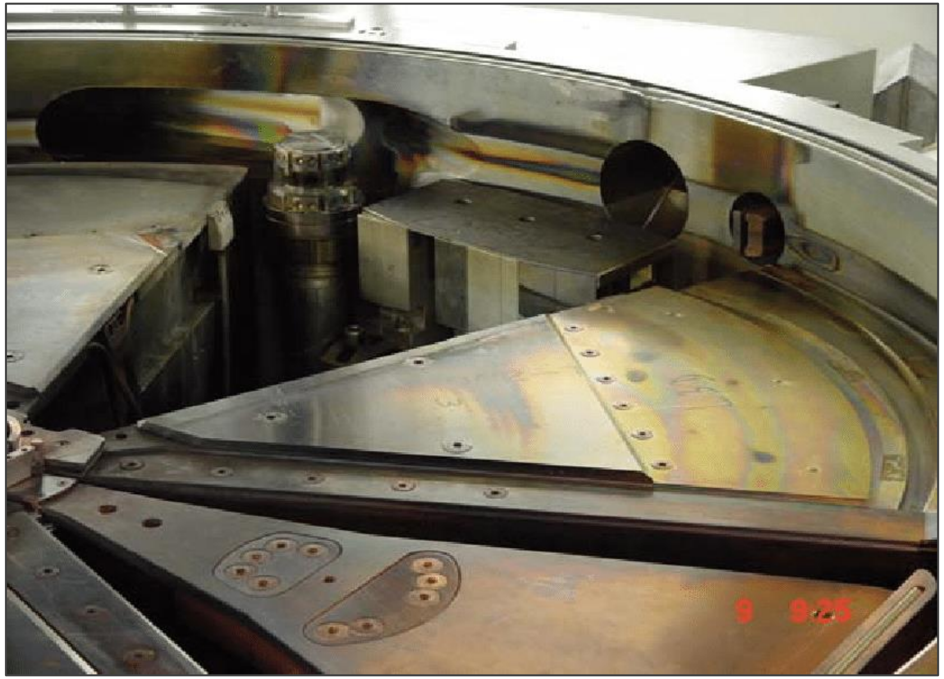
InnovaTron project

The prototype (2001)

- Acceleration of protons up to 14 MeV.
- Self-extraction was successfully proven by extracting a **current up to 2 mA**.
- **Extraction efficiency was about 80% at low currents and 70-75% at high currents**

  This drop was partly due to an increase of the dee-voltage ripple resulting from the noisy PIG-source and beam-loading.
- Not so good beam quality ⟶ too much activation of the cyclotron/beamline.
- Good agreement between simulations and measured beam-quality and extraction efficiency at low currents.

Encouraging results but not good enough for industrial purposes.



Key goals of the InnovaTron project:

- Proton current higher than 5 mA.
- Extraction efficiency higher than 95%.
- Beam quality at least a factor three higher than the prototype.

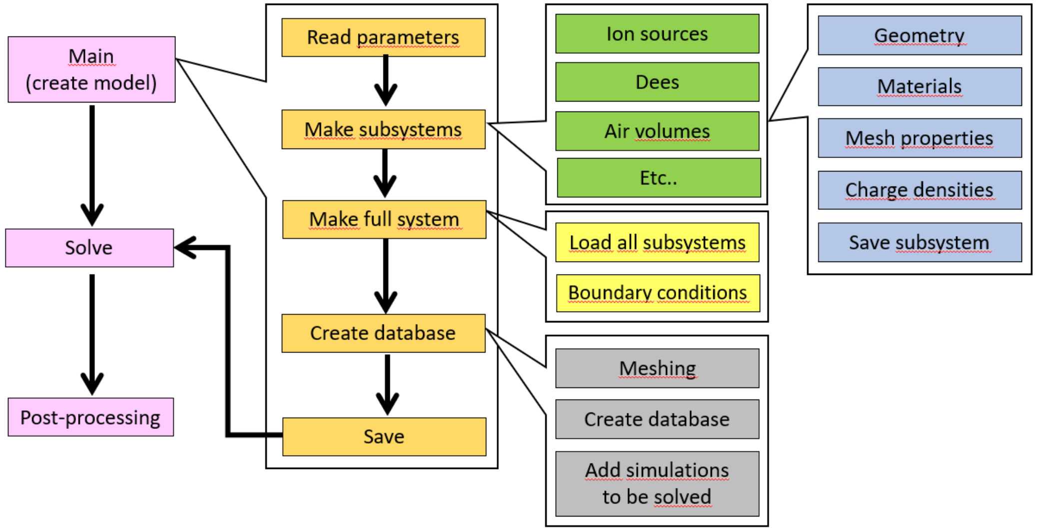
Simulation strategies

The cyclotron design consists in an iterative process of sub-system optimization and ultimately of the full cyclotron design, using 3D FEM tools and the precise 3D beam tracking in the simulated cyclotron electric and magnetic fields.

Development of parametrized tools to generate FE (Finite Element) models of the cyclotron components.

Development of a high-level script allowing automated optimization of cyclotron settings by 3D beam tracking from the ion source up to extraction, aiming for the highest possible extraction efficiency

Example: Macro for central region design



Example: Data from the high-level script for the automated optimization of the dee voltage, current in the harmonic coils on the long and on the short poles.

Extraction efficiency [%] 1° exit port	Dee voltage 55.17 KV	Harmonic coils currents on the long poles					
		-0.35	-0.3	-0.25	-0.2	-0.15	-0.1
Harmonic coils current on the short poles	-0.35	59.2	63.1	68.5	76.0	78.7	78.4
	-0.3	59.8	67.0	78.4	82.1	82.2	81.1
	-0.25	60.9	77.2	87.7	87.9	84.9	84.3
	-0.2	81.8	89.6	89.4	89.2	83.7	69.0
	-0.15	91.3	87.3	82.2	68.5	52.3	45.7
	-0.1	76.9	66.3	65.0	72.5	67.6	12.6

Beam tracking including space charge

Space charge simulations

- It is important to consider space charge effects already at the ion source.

- Two important issues to overcome in the simulations:

  1) In simulations of beam tracking in a cyclotron with an internal ion source, the beam phase space at the injection position is not well known. Usually, you must make an educated guess of particle distribution at this position.

  2) The electric field between chimney and puller extracts and accelerates ions from the source in a restricted time window, i.e. in a restricted RF phase range. Space charge forces start to act during the process of bunch creation in the first gap and they can not be neglected. It is important to simulate the bunch formation.

- Stepwise approach to study the space charge effects in the InnovaTron cyclotron:

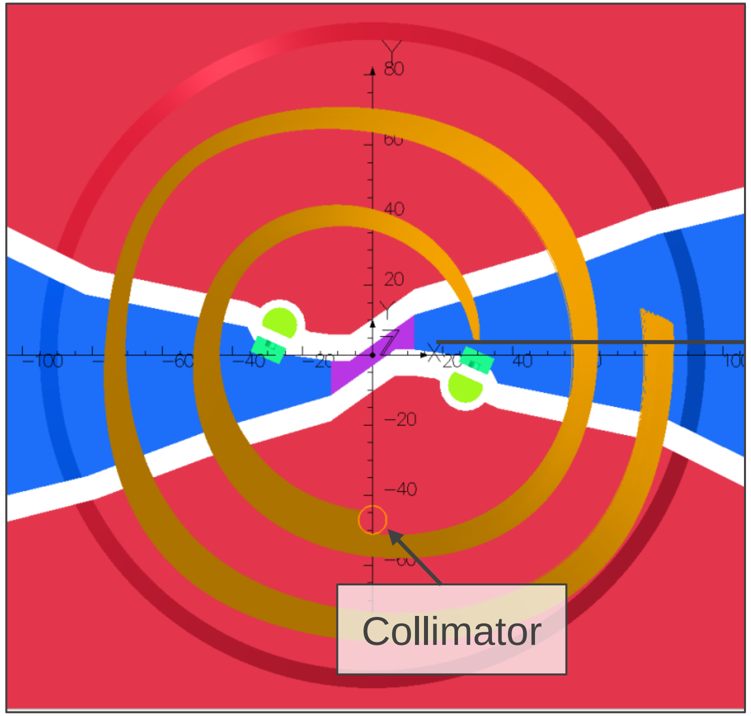
  ✓ **Simulations of bunch acceleration after the first gap;**

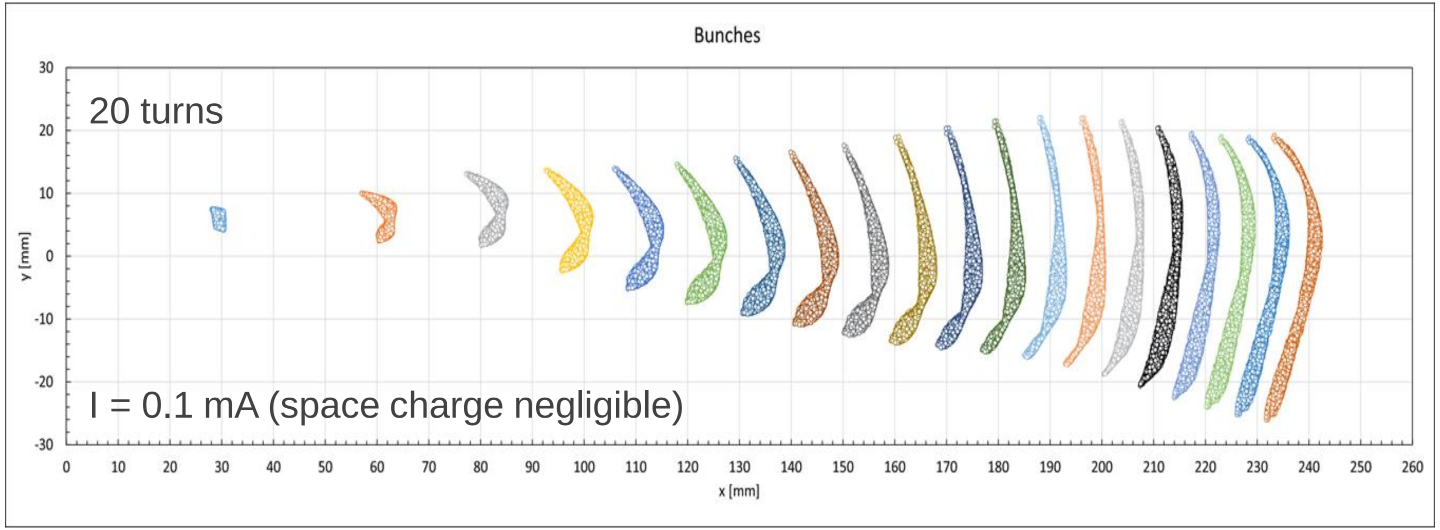
  ✓ **Simulations of bunch creation at the ion source in the first gap and the space charge forces acting during this process;**

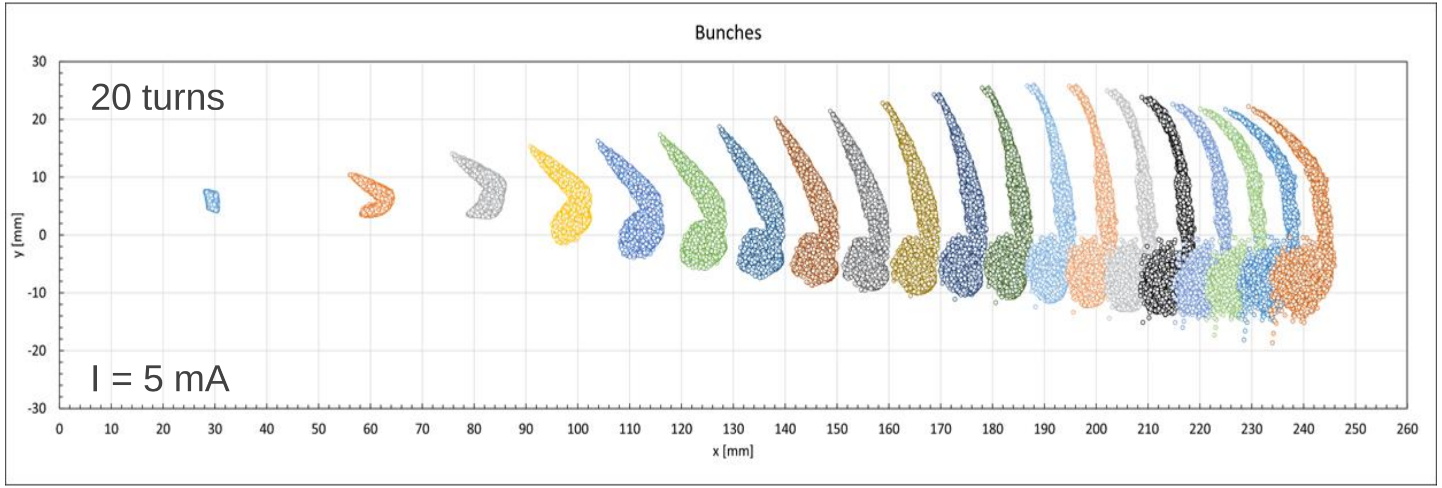
  ✓ **Opera simulations (Scala solver) to find the plasma meniscus, the extracted beam current from the chimney and the beam phase space (ongoing activity).**

Simulations of bunch acceleration after the first gap

The bunch at the starting tracking position has been obtained by tracking of a beam from the ion source (no space charge) and by processing the beam properties at a chosen time step integration.

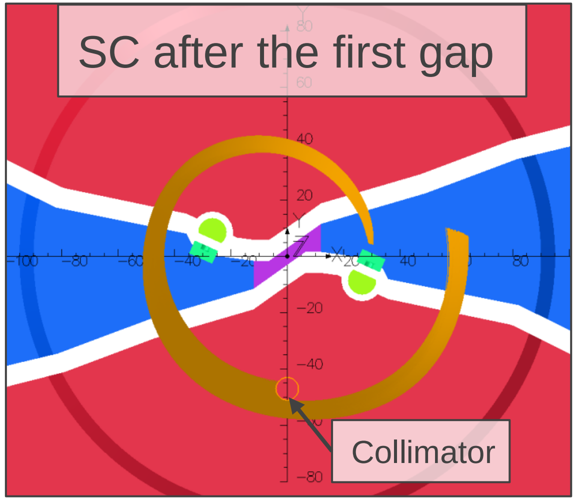


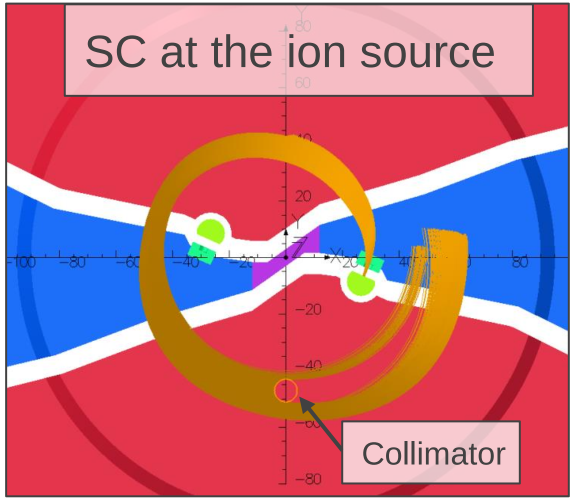


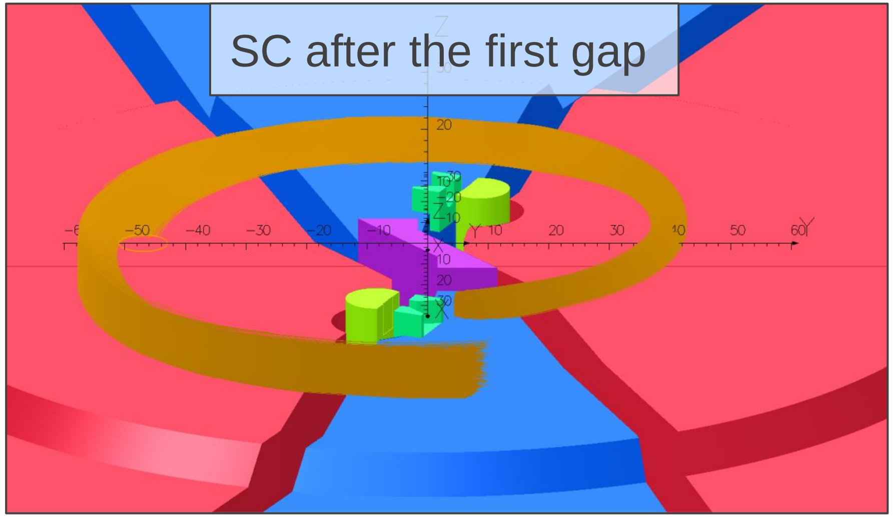


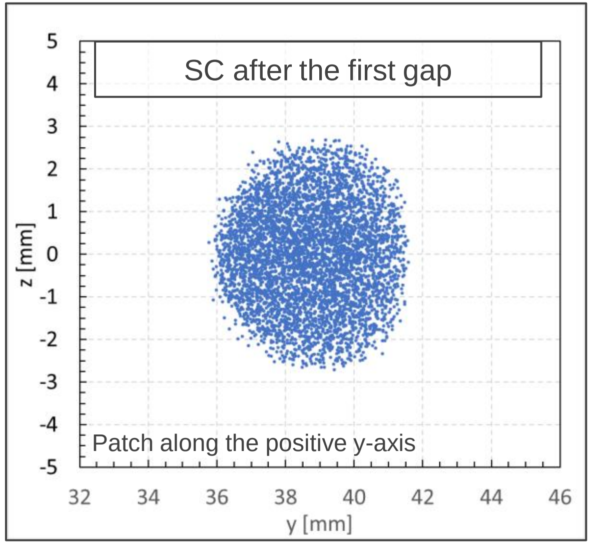
Simulations of bunch formation at the ion source

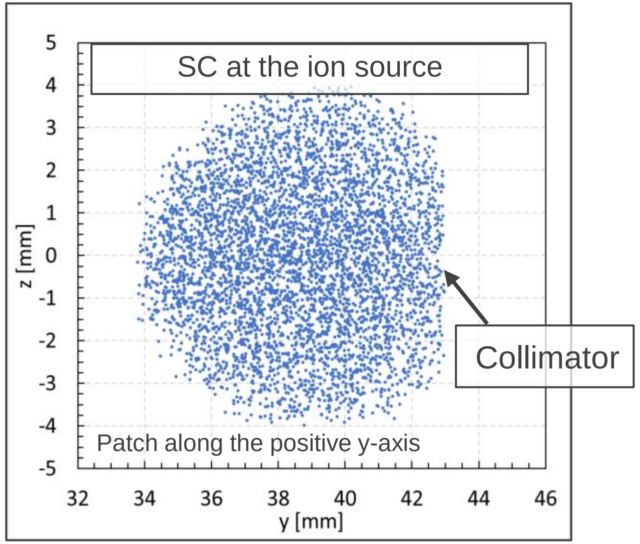
SC = Space Charge

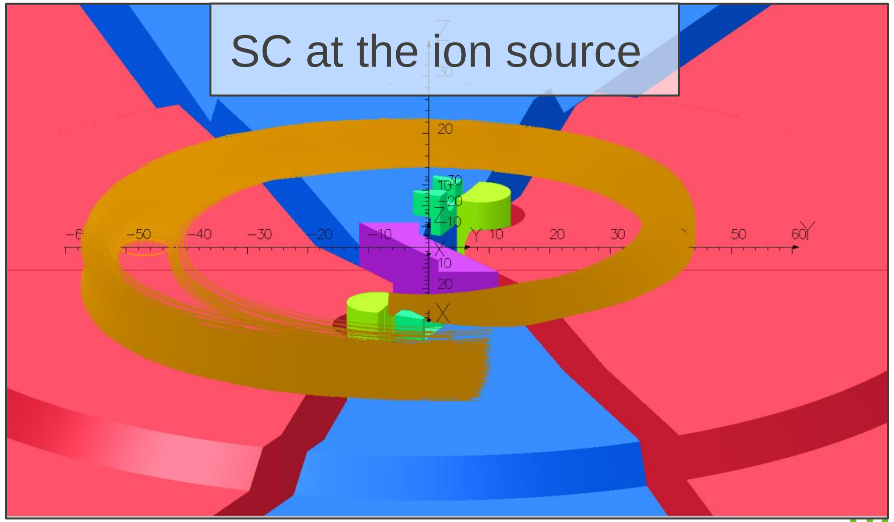






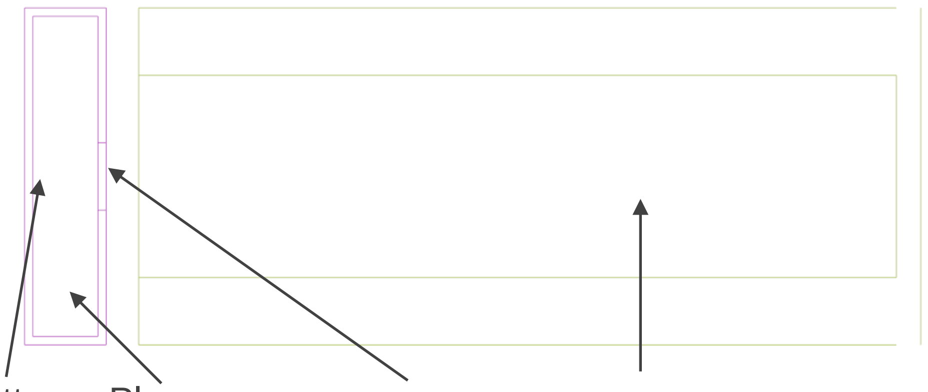






Simulations of the emission of ions from the meniscus of a plasma

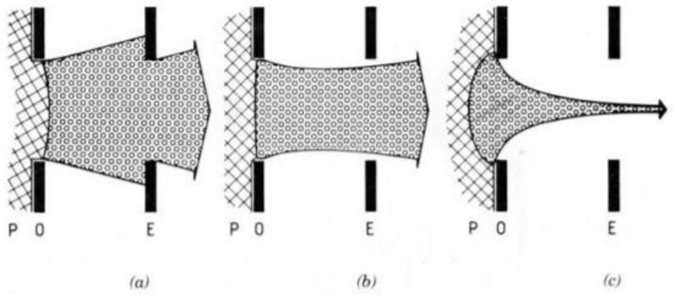
Opera model



User specified Bohm variables on the emitter surface:
- Particle mass
- Particle charge
- Electron temperature
- Meniscus voltage
- Current density

Multi-particle problem

Plasma meniscus: boundary layer between the plasma and the extracted ion beam. The depth, position and curvature of this layer depend on the plasma density and temperature of electrons and ions for a given puller voltage and gap geometry.



(a) overdense plasma
(b) intermediate density plasma
(c) underdense plasma

Plasma physics + space charge problems

Ion current density that can be extracted (Bohm's theory)

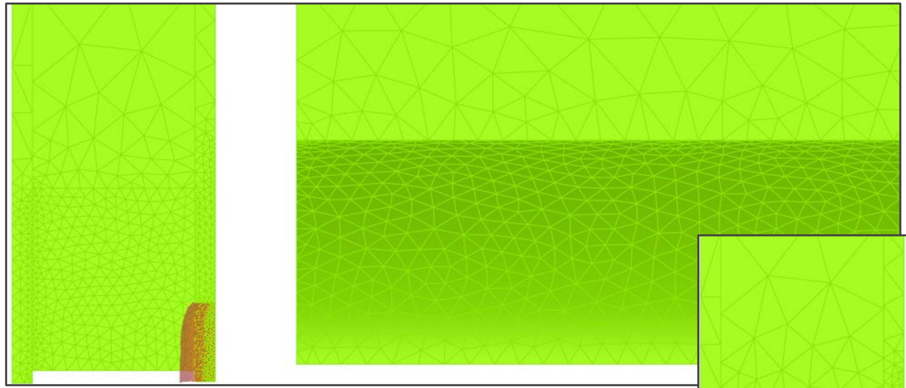
$$J_i = q_i\, n_i^{plasma}\, e^{-\frac{1}{2}} \sqrt{\frac{k\,T_e}{m_i}}$$

Maximum ion current density that can be extracted (Child's law for SCLC)

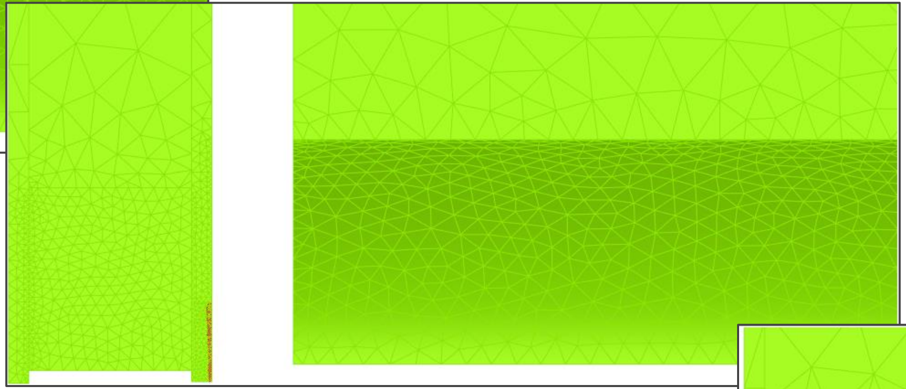
$$J = \frac{I}{S} = \frac{4\epsilon_0}{9} \sqrt{\frac{2e}{m_p}} \frac{V^{3/2}}{d^2}$$

The SCALA solver gives a DC solution. We will approximate the RF starting condition by assembling multiple DC solutions, one for each step in the accepted RF phase interval.

Simulations of the emission of ions from the meniscus of a plasma

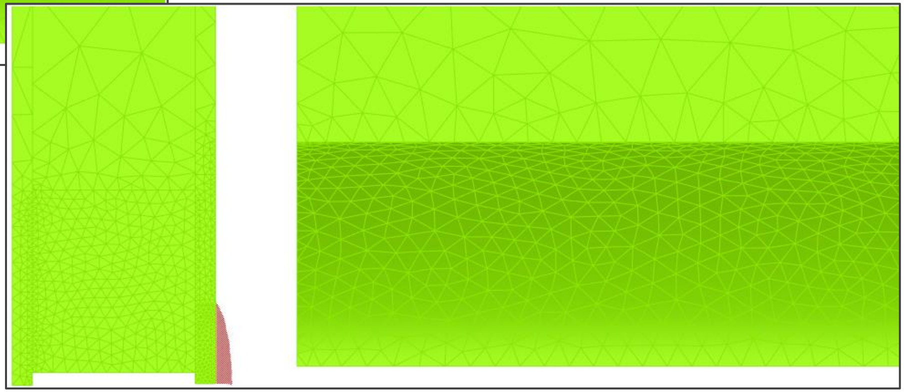


J_i = 0.25 A/cm^2
I_{ext} = 13.4 mA



J_i = 6.5 A/cm^2
I_{ext} = 261.4 mA

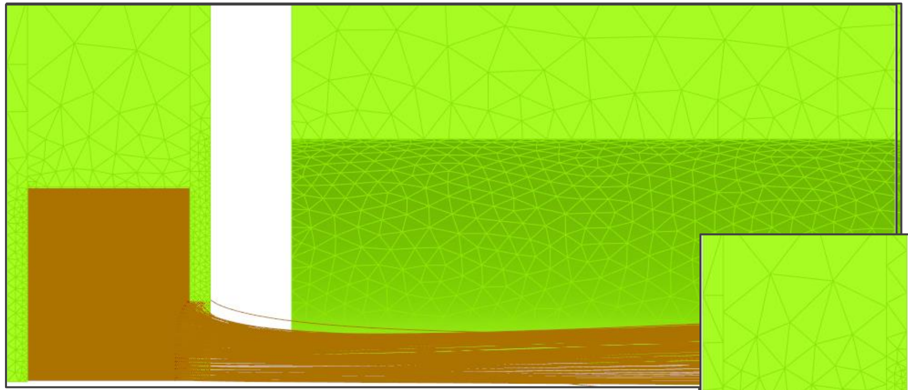
J_i = 12.3 A/cm^2
I_{ext} = 575.7 mA



Plasma meniscus shape and extracted current vary with the current density at emitter surface

Plasma meniscus shape also vary with voltage puller and gap geometry.

Simulations of the emission of ions from the meniscus of a plasma



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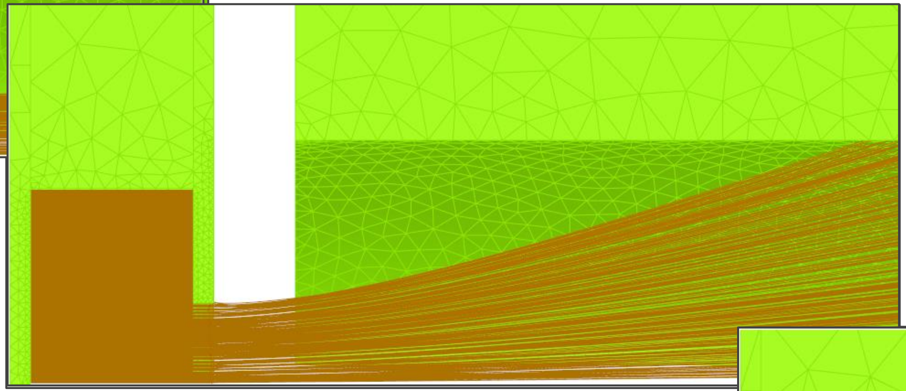

J_i = 6.5 A/cm^2
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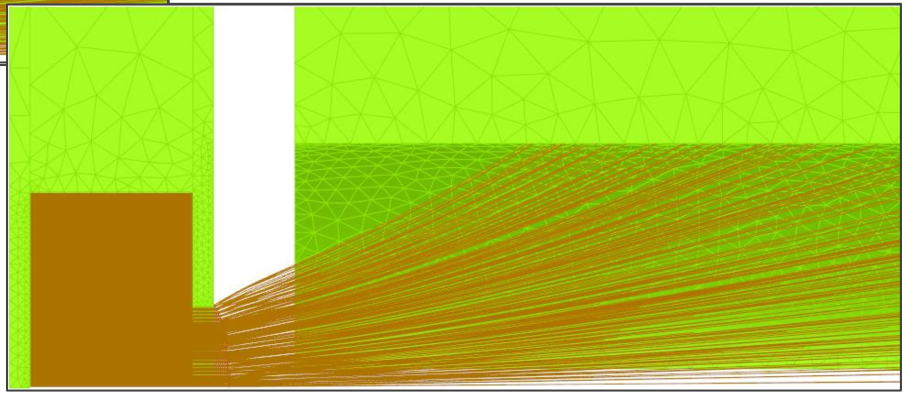

J_i = 12.3 A/cm^2
I_{ext} = 575.7 mA

Plasma meniscus shape and extracted current vary with the current density at emitter surface

Plasma meniscus shape also vary with voltage puller and gap geometry.

Conclusions and next steps

Conclusions and next steps

- A research project, named InnovaTron, is ongoing at IBA to study an improved concept of self-extraction in low and medium energy cyclotrons to be used for production of medical isotopes.

- The project has been funded by the European Union in the framework of the Horizon 2020 Marie Curie Actions – Individual Fellowship programme.

- The principle of self-extraction was successfully proven in the prototype (2001) where a proton current up to 2 mA was extracted. However, there is room for improvement.

- An enhanced turn separation at extraction is fundamental to maximize the extraction efficiency. Several methods are currently under study:
  - Acceleration of a well centered beam and use of harmonics coils at the extraction
  - Acceleration of a well centered beam and use of harmonics coils close to the cyclotron center
  - Off-centering of the ion sources (harmonic coils not used).

  Specific optimization tools have been developed for this purpose, but this work is still ongoing.

- Space charge calculations have been started. We simulated the bunch acceleration starting after the first gap. The next step is to include the bunch formation at the ion source in the simulations including the beam particle distribution on the plasma meniscus.

Thank you for your attention