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Self-consistent simulation of the plasma meniscus and the space charge dominated beam extracted from it in the central region of cyclotrons with an internal ion source

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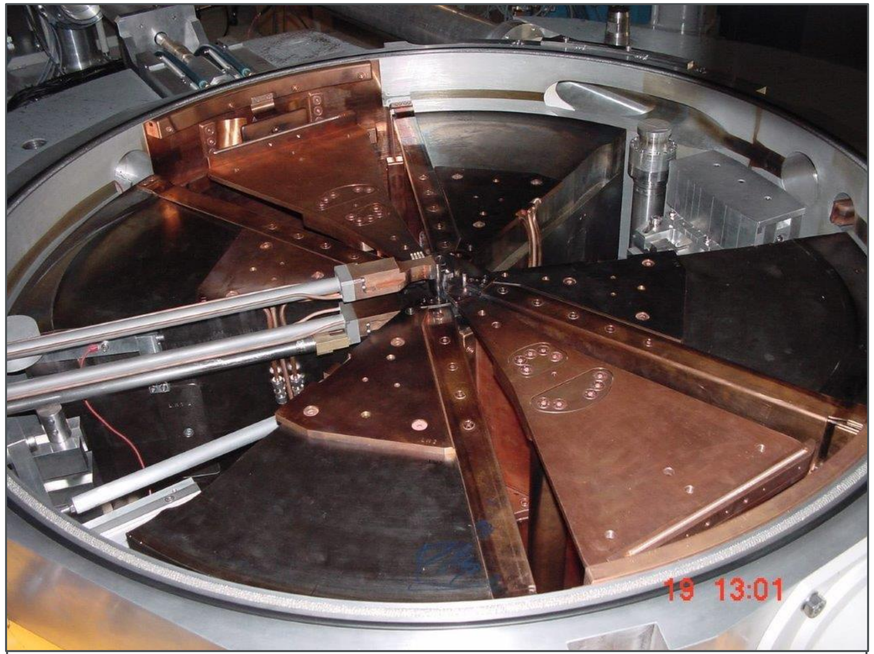
Outlook

- The self-extracting cyclotron:
  - The principle of self-extraction
  - The prototype
  - The improvements of the design (InnovaTron project, EU-H2020-MSCA)
- Self-consistent simulation of the space charge dominated beam in the central region:
  - Scala simulations
  - Tosca simulations
  - Bunch formation with space charge
- Full beam tracking with space charge
- Optimization of cyclotron settings
- Summary

The principle of self-extraction

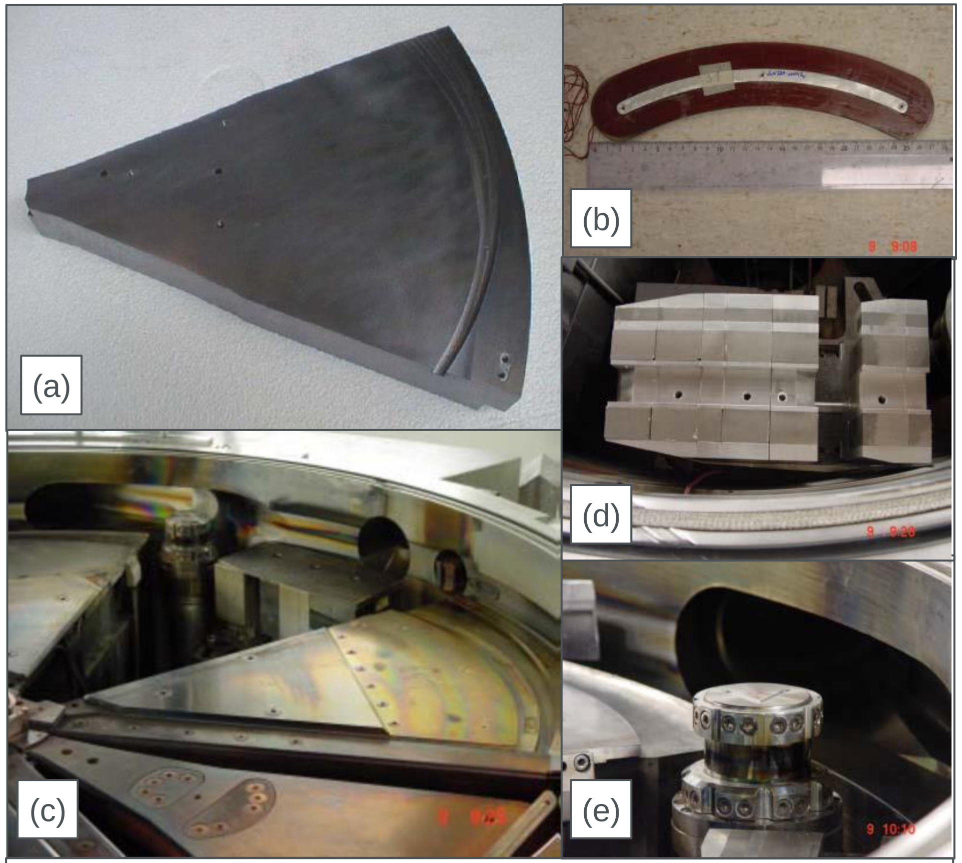
- In most cyclotrons, the pole gap usually is large.
- An extraction system is needed to transfer the beam from the isochronous region to the radial unstable region where the beam can exit.
- **Self-extraction: fast transition between both regions such that the radial unstable zone can be reached by acceleration without an extraction device.**
- **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.
- A prototype was built and tested by IBA around 2000.



The self-extracting cyclotron.

The prototype (2001)

- The pole gap decreases quasi-elliptically with radius.
- The pole on which the beam is extracted is radially longer than the other ones.
- A groove is machined in the long pole, that acts like a kind of “septum” and provides optics for the extracted beam.
- Harmonic coils are used to enhance turn separation at extraction.
- A permanent magnet gradient corrector is placed at extraction to provide radial and vertical focusing to the diverging beam.
- A beam stop (beam separator) intercepts small fractions of the beam that are not properly extracted.



The self-extracting cyclotron

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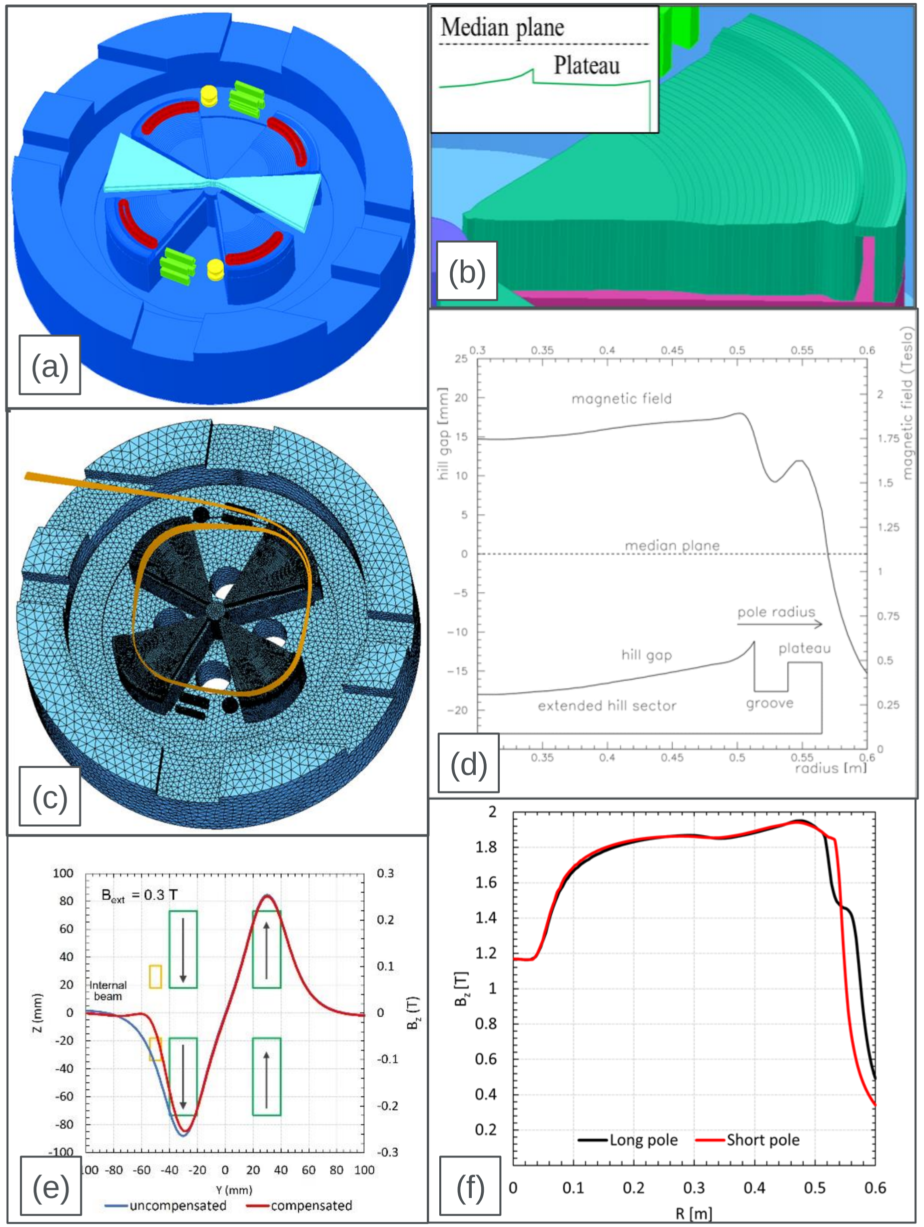
The prototype (2001)

- Acceleration of protons at 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.
- Encouraging results but there was room for improvement for high-intensity industrial applications.

InnovaTron project (EU-H2020-MSCA programme)

MAGNET OPTIMIZATION

- The new design has 2-fold symmetry and can work with 2 internal PIG sources.
- The groove in the longer pole is replaced by a step-like shape (plateau).
    - This lowers the strong magnetic sextupole component in the extraction path and thereby substantially enhances the quality of the extracted beam.
- The quasi-elliptical gap is no longer constant along circles but constant along equilibrium orbits.
    - This provides a sharper transition towards extraction and therefore enhances the extraction efficiency.
- A new gradient corrector has been designed to provide radial focusing to the extracted beam.



Simulation of space charge dominated beam in the central region

- In high-intensity cyclotrons with internal ion source, understanding beam dynamics under space charge will contribute 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:

1. **SCALA simulations**:

   Solve a SCALA model of the first accelerating gap to find the meniscus shape and beam phase space on it.

2. **TOSCA simulations**:

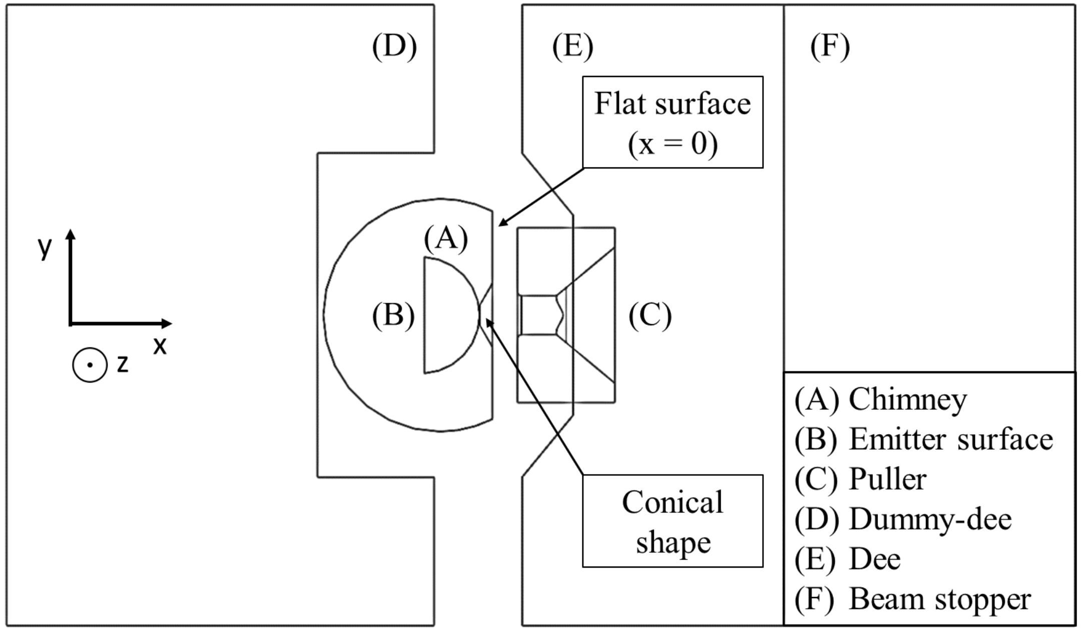
   Fit the meniscus and beam phase space on it and solve a TOSCA model of the central region. Here the meniscus surface is put at 0 V. This provides the 3D electric field map everywhere in the central region, including the source-puller gap.

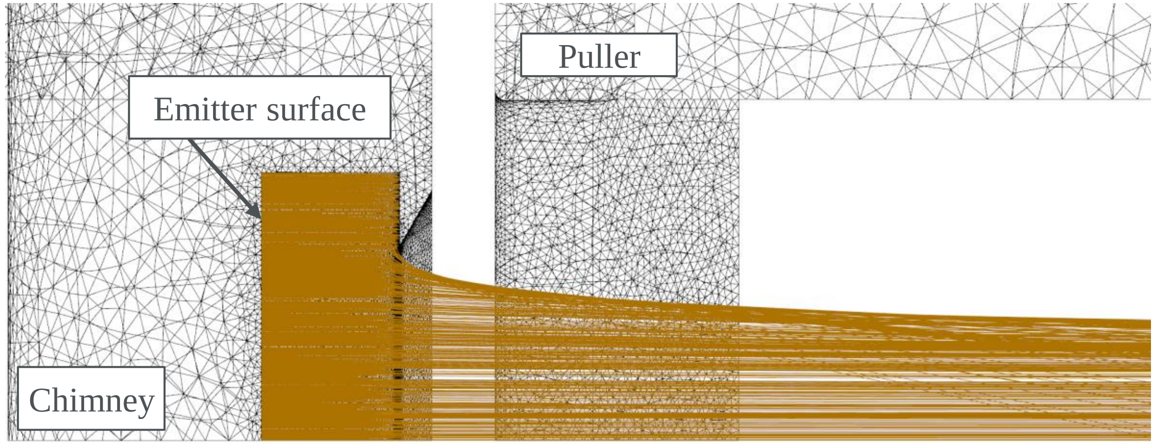
3. **Bunch formation in the first accelerating gap and 3D full beam tracking including space charge**

Step 1: Scala simulations

Solve a SCALA model of the first accelerating gap to find the meniscus shape and beam phase space on it

- The **plasma free-surface module of SCALA** is used.
- SCALA does not simulate the plasma itself.
- Beamlets are emitted from a surface and extracted by an electrostatic field.
- We only need to model the local geometry of the source-puller gap.





Step 1: Scala simulations

Solve a SCALA model of the first accelerating gap to find the meniscus shape and beam phase space on it

- The meniscus is determined by the **Child-Langmuir condition**: the external electric field on the surface is cancelled by the space charge electric field.
- The meniscus is found in an iterative process.
- **We assume that the meniscus shape and position can be found by solving the problem for the rms-value of the gap-voltage.**
  - The electric field in a cyclotron central region is not DC but RF.
  - The RF frequency is so high that the meniscus will move only weakly in the RF electric field:

$$s = v_B \frac{T}{4} = \sqrt{\frac{kT_e}{m_p}} \frac{1}{4\, f_{RF}} \approx 0.1\, mm$$

with $v_B = \sqrt{\frac{kT_e}{m_p}}$ (Bohm's velocity), $kT_e \approx 10$ eV, $f_{RF} = 70$ MHz

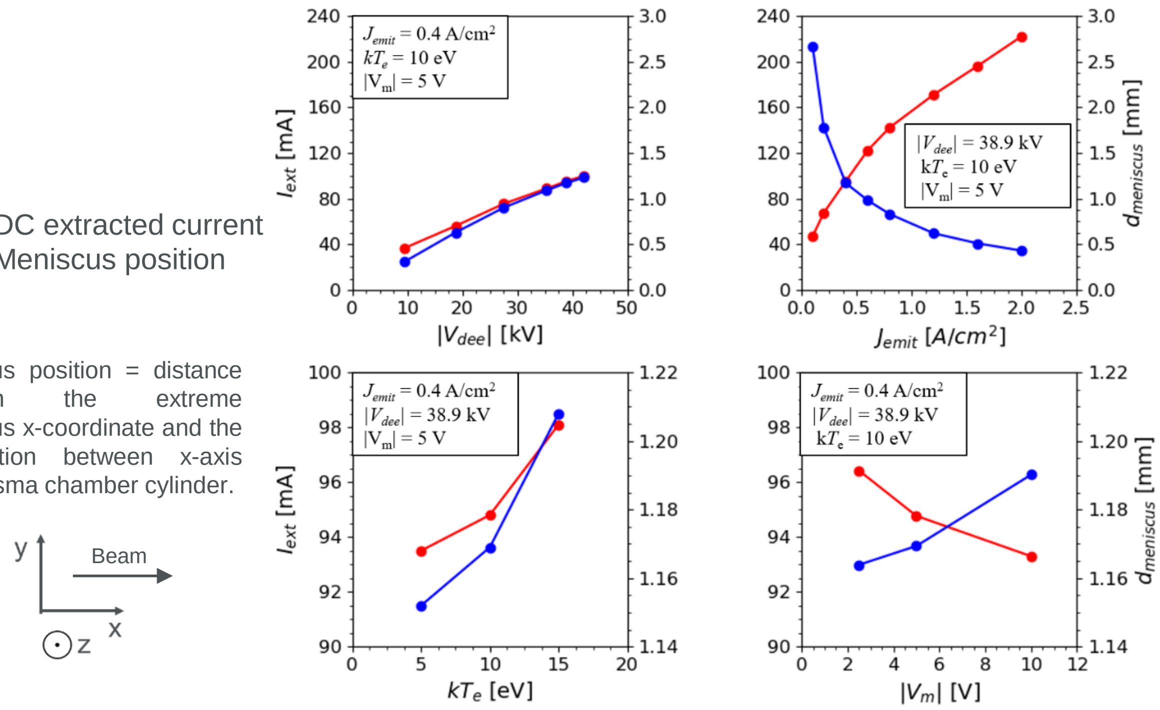
Step 1: Scala simulations

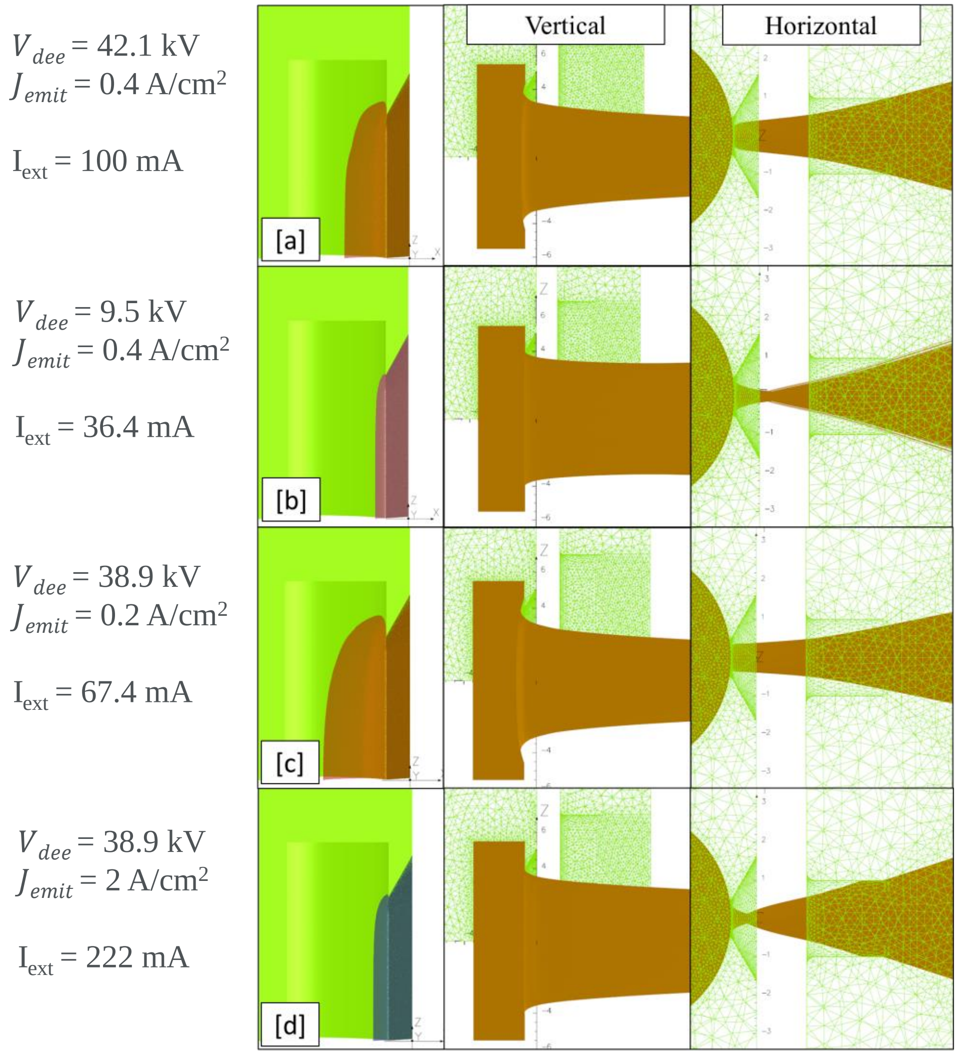
Solve a SCALA model of the first accelerating gap to find the meniscus shape and beam phase space on it

- Input parameters:
  - dee-voltage V_{dee}
  - emitter current density J_{emit}
  - electron temperature T_e ← Less critical
  - meniscus voltage V_m ← Less critical

DC extracted current
Meniscus position

Meniscus position = distance between the extreme meniscus x-coordinate and the intersection between x-axis and plasma chamber cylinder.





Step 2: Tosca simulations

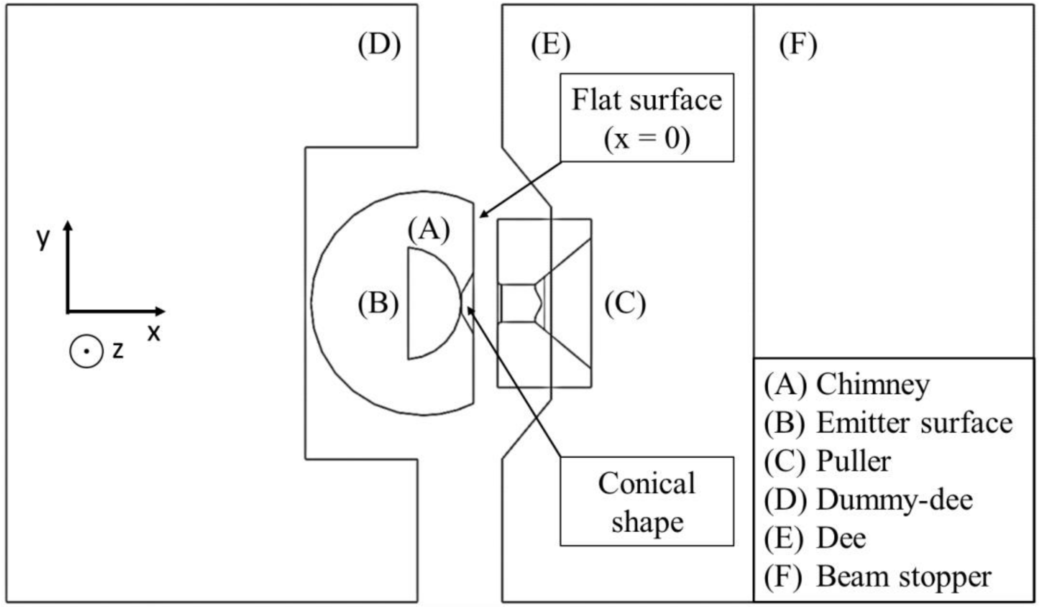
Fit the meniscus and beam phase space on it and solve a TOSCA model of the cyclotron central region

- We extract particle position coordinates, velocity components and beamlet current at the meniscus intersection from the beamlets calculated by SCALA.
- We fit x, y', z' and the beamlet current as a function of y and z.
- We use a double polynomial fit up to order 7 (the sum of y and z exponents) and consider the symmetry of the model.

$$x(y,z) = \sum_{n=0}^{3}\sum_{m=0}^{3} a_{nm}\, y^{2n}\, z^{2n}$$

$$y'(y,z) = y\sum_{n=0}^{3}\sum_{m=0}^{3} b_{nm}\, y^{2n}\, z^{2m}$$

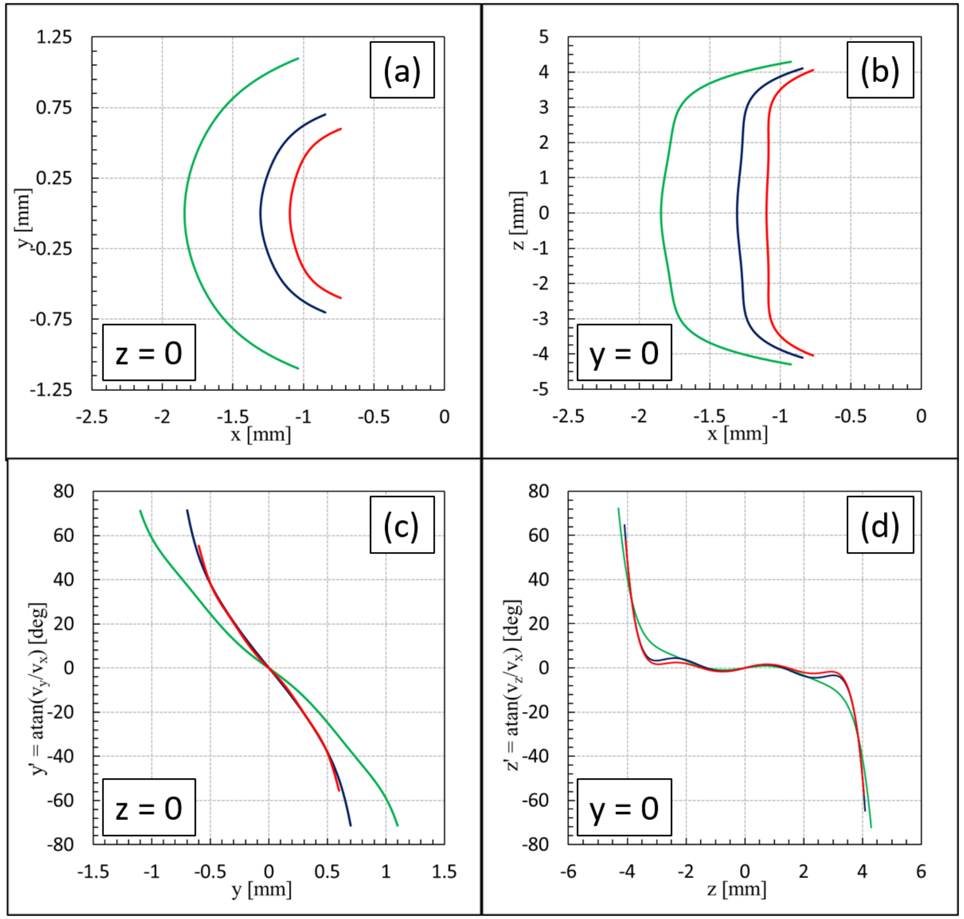
$$z'(y,z) = z\sum_{n=0}^{3}\sum_{m=0}^{3} c_{nm}\, y^{2n}\, z^{2m}$$



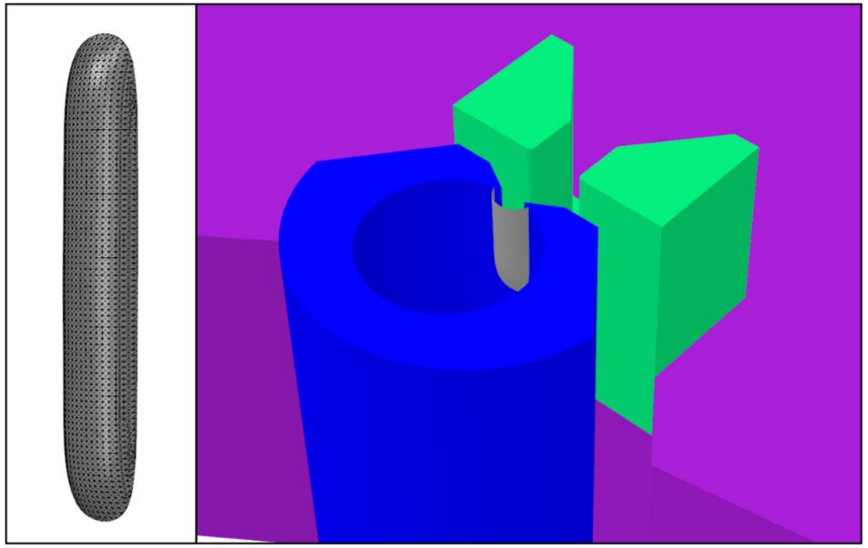
- The representation also allows to create a file with particle starting conditions for tracking.

Step 2: Tosca simulations

Fit the meniscus and beam phase space on it and solve a TOSCA model of the central region



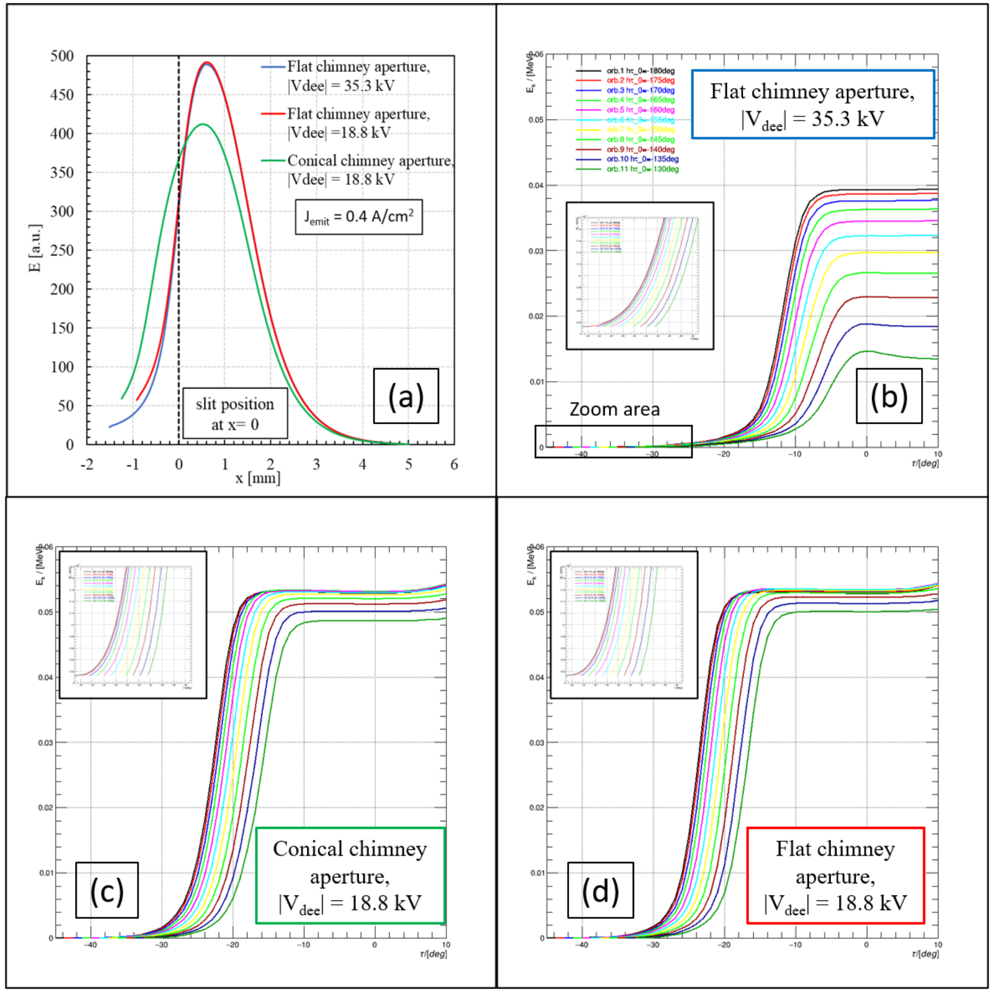
Green: V_{dee} = 38.9 kV, J_{emit} = 0.4 A/cm^2
Blue: V_{dee} =18.8 kV, J_{emit} = 0.4 A/cm^2
Red: V_{dee} = 38.9 kV, J_{emit} = 2 A/cm^2



- The meniscus surface is modelled in OPERA as a wire-edge structure with a triangular mesh.
- The TOSCA model of the central region is solved by putting the meniscus surface at ground potential.

Step 2: Tosca simulations – Electric field in the source-puller gap

- The electric field drops quickly in the space in between the meniscus and the chimney slit ($x < x_{slit}$).
- The chimney aperture acts like a sort of “Faraday cage” that screens the electric field.
- Particles must leave early from the meniscus surface in order to be able to cross the gap.
- Later starting phases are not properly accelerated by the central region.
- The best case in the figure is (d): higher energy gain and smaller energy spread. A phase range of about 40° can be accepted and accelerated.

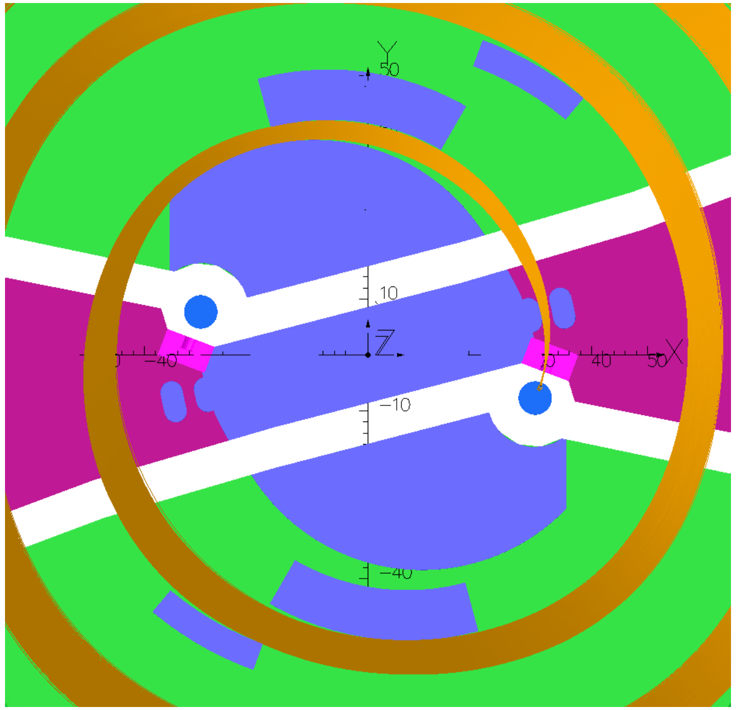


Step 3: Bunch formation with space charge in the first gap

- The beam tracking starts from the meniscus.
- Particle starting conditions are created with y and z generated randomly and the other variables (x, y', z') calculated from the fits.
- The user specifies the wished RF phase width of the bunch and number of time-steps that are needed to complete the bunch formation.
- The bunch will be sliced according to the number of time-steps.
- For each new step, the bunch is re-defined by adding the additional slice and then advanced with updated space charge self-field.
- After completion, the tracking proceeds at full space charge of the bunch.

3D full beam tracking including space charge

- The central region was optimized to obtain good beam centering, vertical focusing and RF phase-width selection of 40°.
- Starting beam:
  - We used a SCALA solution that provided 100 mA on the meniscus (J_{emit}=0.4 A/cm^2)
  - 100000 particles were sampled in a RF phase range of 180° covering the full acceleration period



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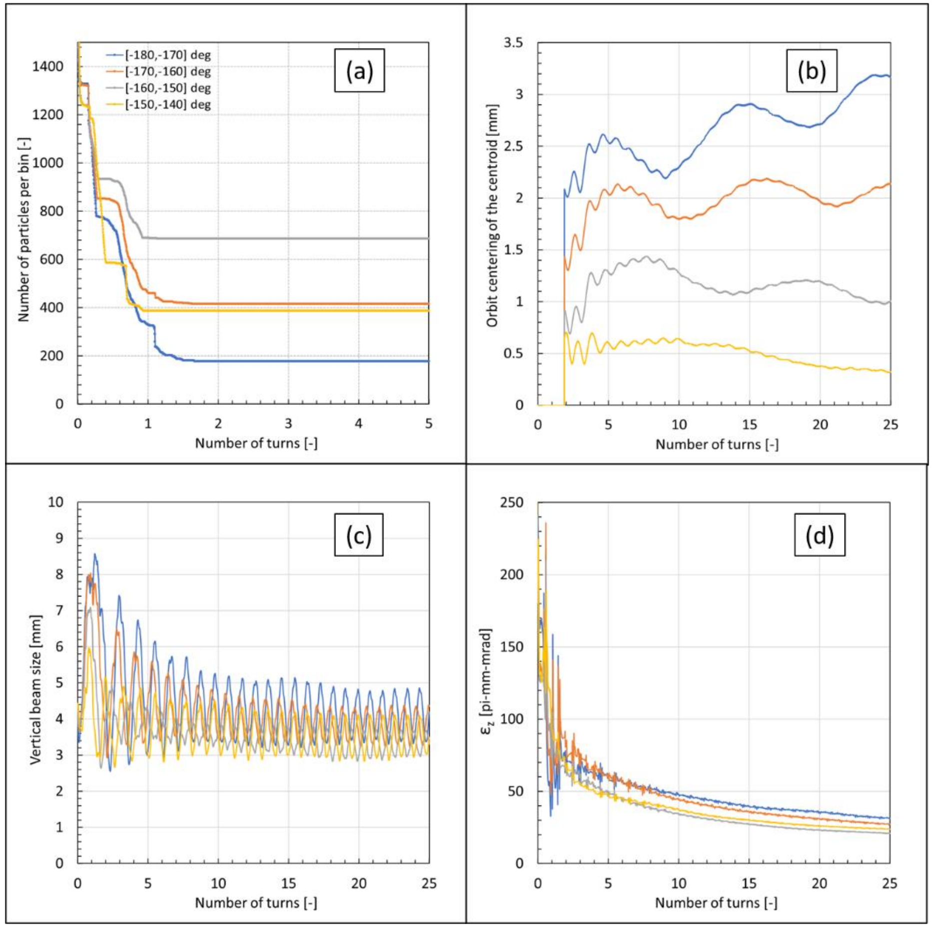
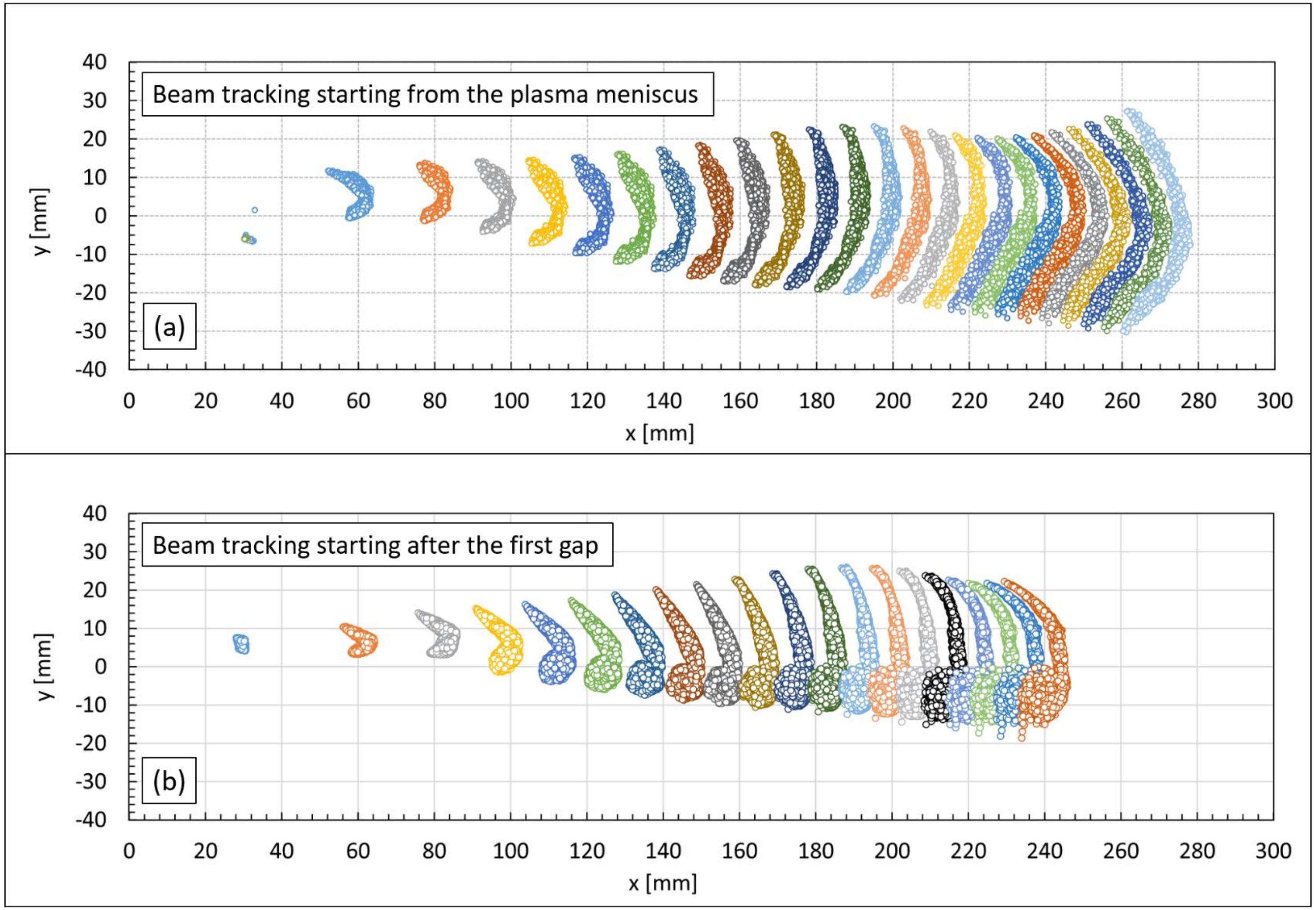
3D full beam tracking including space charge

- Number of turns equal to 25
- Beam centroid off-centering < 3 mm
- Only 1.7% (1.7 mA) is captured for acceleration
- Only particles in the phase range between -180° and -140° are accepted.
- High losses in the first two turns:
  - about 88.7% on the chimney+puller+puller collimators
  - about 5.8% in the phase selecting collimators
  - about 3.9% vertically on the dees and dummy dees
- Losses due to the unfavorable transit time factor and strong horizontal over-focusing at the chimney exit
- No losses after two turns



3D full beam tracking including space charge



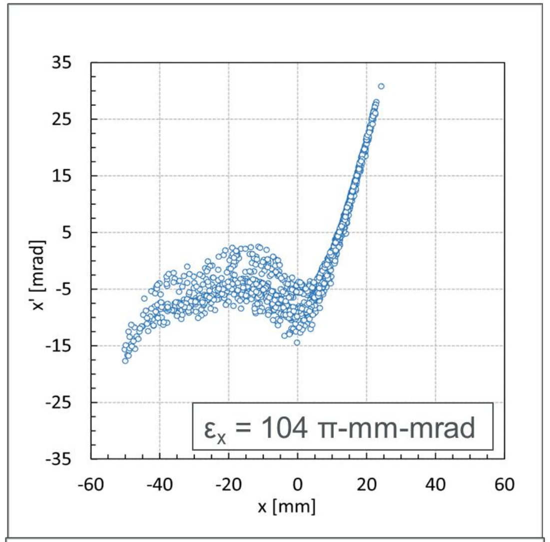
Shape of the accelerated bunches by their projection on the xy-plane, followed during 25 turns at moments when the RF phase equals zero

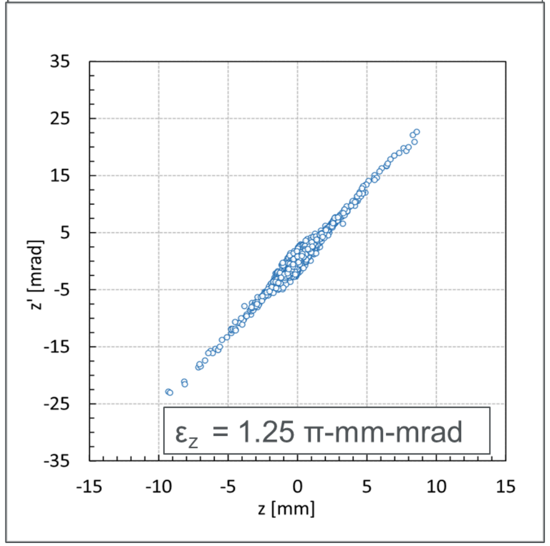
"Earlier" simulation:

- Bunch started just beyond the source-puller gap
- Average beam current of 5 mA
- Horizontal and vertical emittances of about 20 π mm-mrad (1σ)
- Total bunch length of about 3 mm (corresponding to 30° RF width)
- The vortex motion seems to be observed

Optimization of cyclotron settings

- Extracted beam optimization is a long and difficult process as it depends on multiple parameters and requires full beam tracking from the ion source up to the cyclotron exit.
- An optimization program was written to optimize cyclotron settings (such as harmonic coils, V_{dee}) that maximize the extraction efficiency.
- The program uses standard optimization routines to optimize a task (project).
- The code has been tested (without space charge) for a beam of 2000 particles, tracked from the ion source position up to extraction.
- We found an extraction efficiency of 91% with 7.7% losses on the first beam separator and 1.3% of particles extracted towards the 2nd exit port.





Summary

- The magnet of the self-extracting cyclotron has been improved within the InnovaTron project (2-years EU-H2020-MSCA project ended last July).
- An effort has been made to more accurately simulate the bunch formation in the first accelerating gap under space charge conditions for a cyclotron with internal ion source.
- More studies are needed to further improve space charge simulations in the cyclotron central region.
- A software-tool was developed, that optimizes the cyclotron settings for obtaining highest extraction efficiency.

Thank you