CYC2022

23rd International Conference on Cyclotrons and their Applications

December 5-9, 2022 • Beijing, China

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

G. D'Agostino and W. Kleeven

grazia.dagostino@lns.infn.it

Certified B Corporation | Life, Science.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 886190

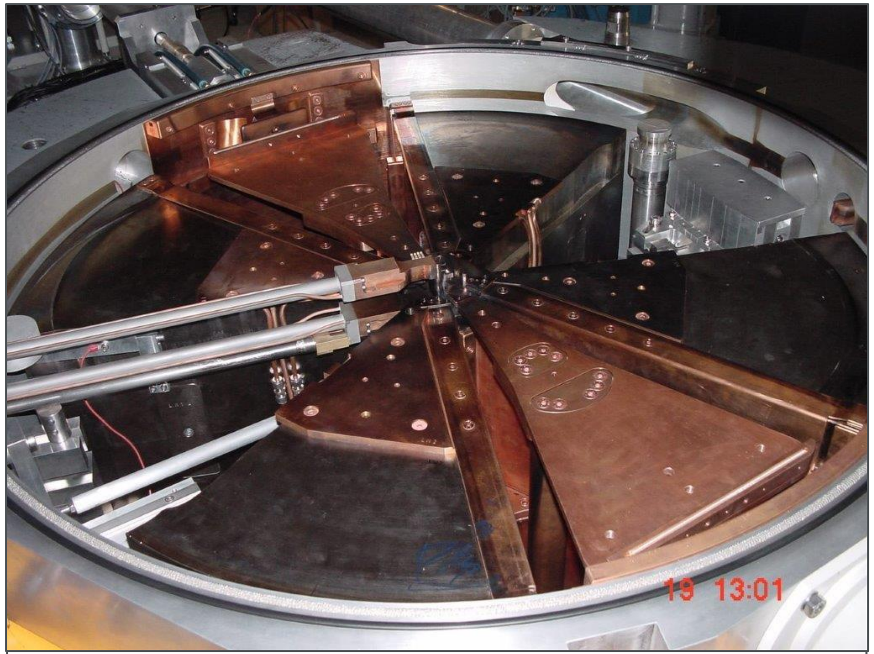
iba

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.

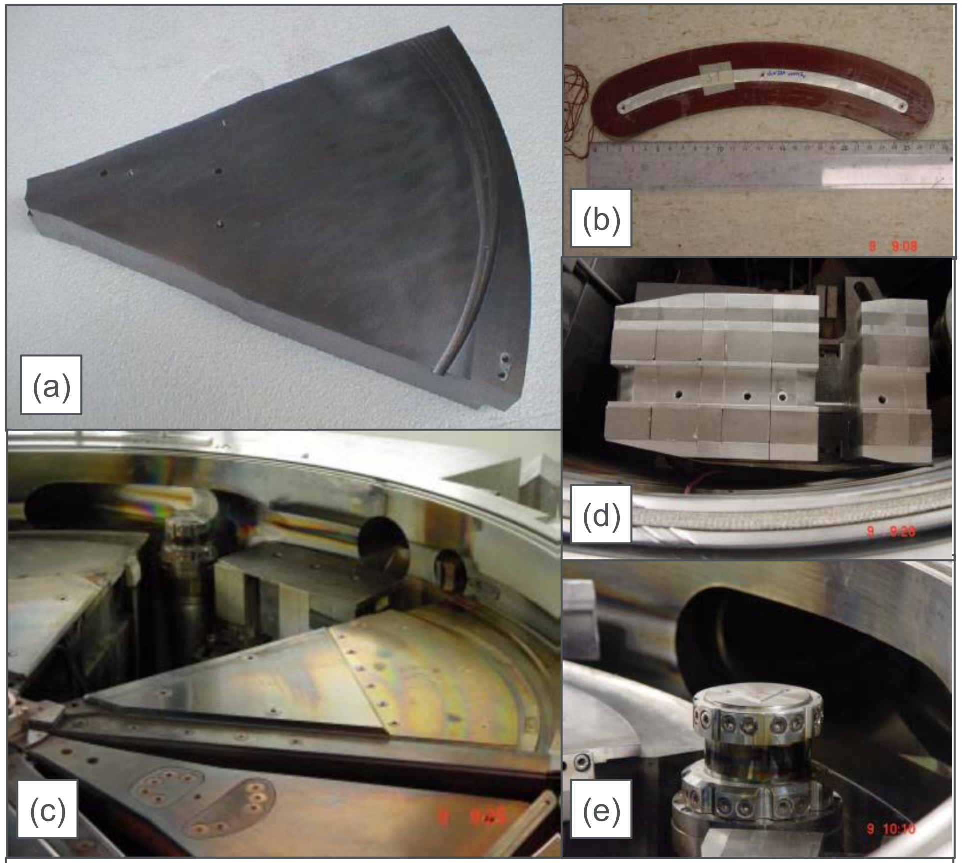


The self-extracting cyclotron.

Protect, Enhance and Save Lives

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

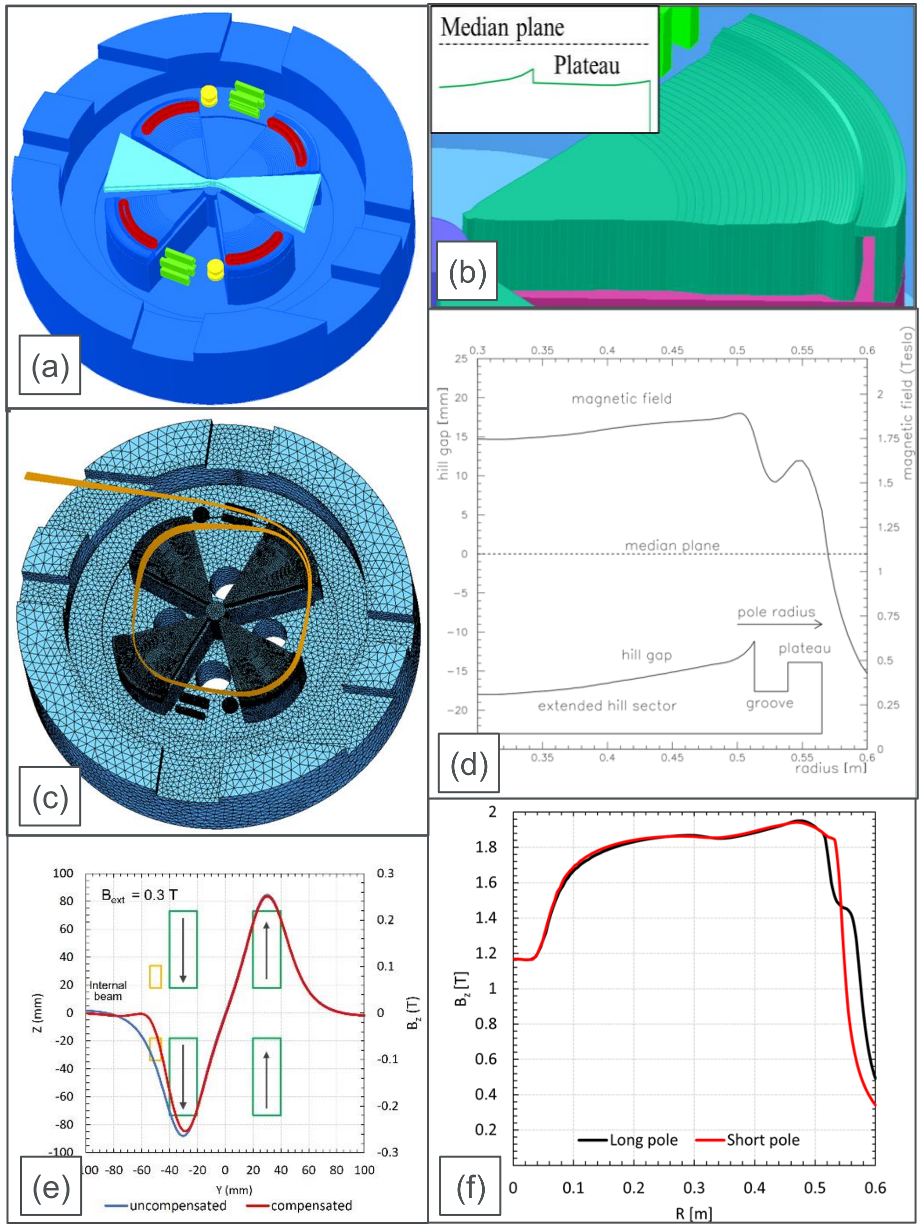
The prototype (2001)

- 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.



Protect, Enhance and Save Lives

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.

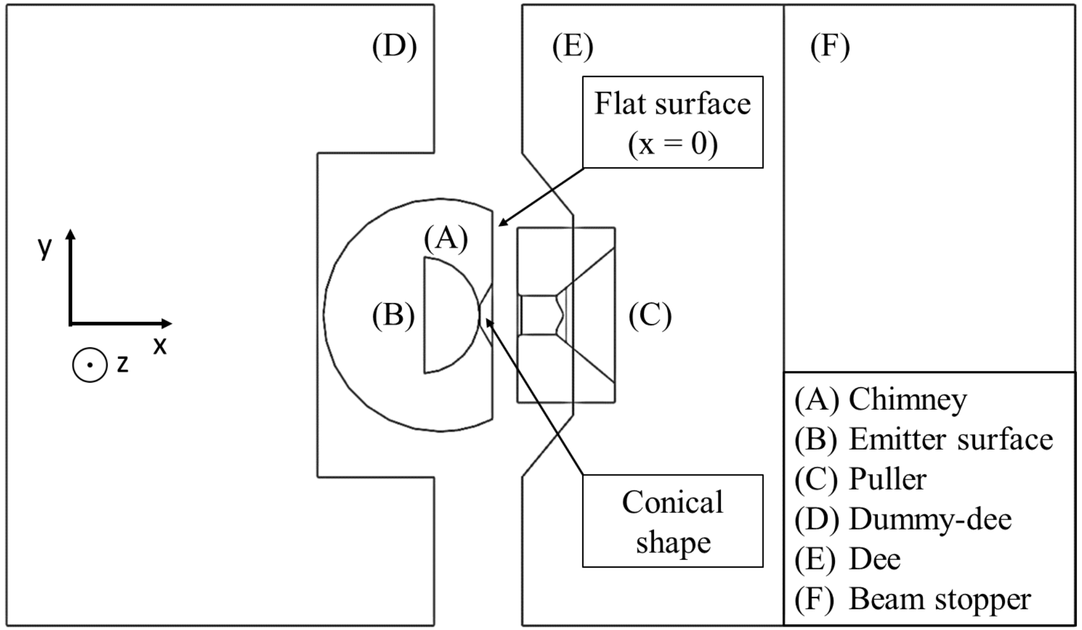
3. **Bunch formation in the first accelerating gap and 3D full beam tracking including space charge**

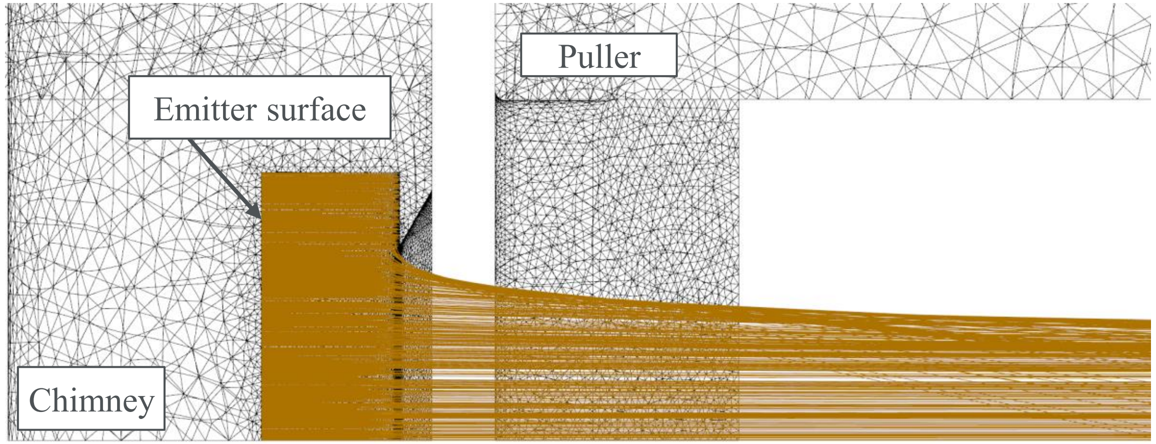
Protect, Enhance and Save Lives

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

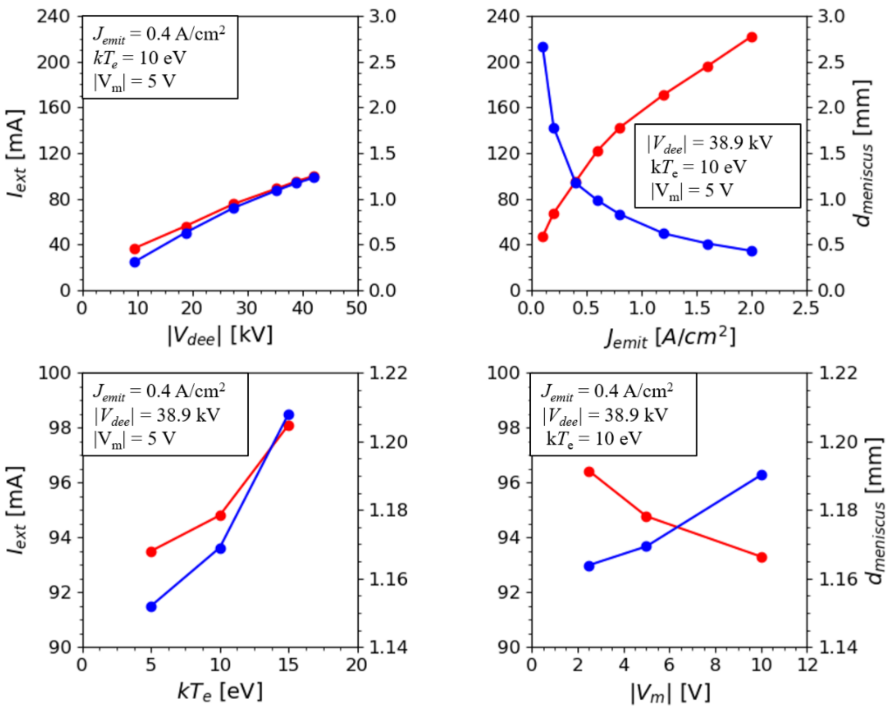
Protect, Enhance and Save Lives

Step 1: Scala simulations

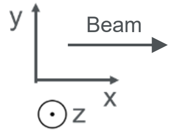
Solve a SCALA model of the first accelerating gap to find the meniscus shape and beam phase space on it

- 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.

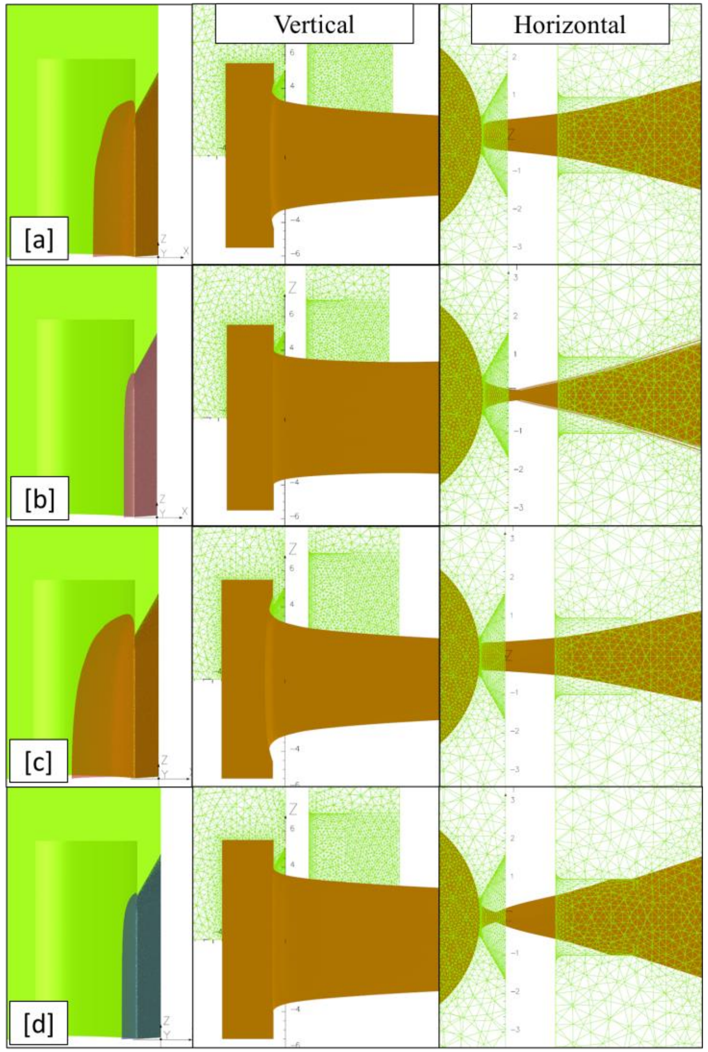


V_{dee} = 42.1 kV
J_{emit} = 0.4 A/cm²
I_{ext} = 100 mA

V_{dee} = 9.5 kV
J_{emit} = 0.4 A/cm²
I_{ext} = 36.4 mA

V_{dee} = 38.9 kV
J_{emit} = 0.2 A/cm²
I_{ext} = 67.4 mA

V_{dee} = 38.9 kV
J_{emit} = 2 A/cm²
I_{ext} = 222 mA



Protect, Enhance and Save Lives

Step 2: Tosca simulations

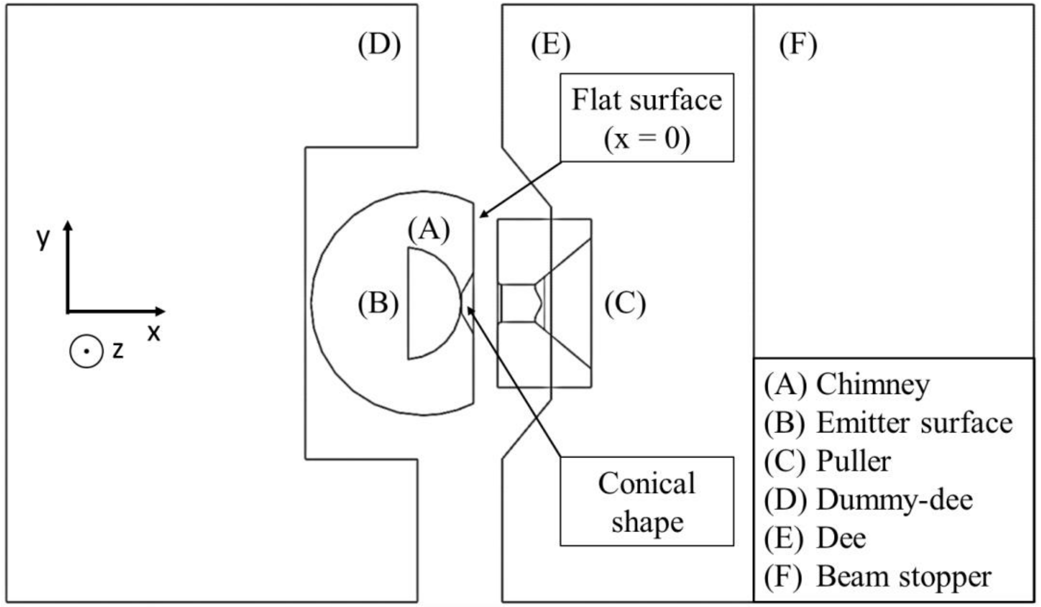
Fit the meniscus and beam phase space on it and solve a TOSCA model of the cyclotron central region

- 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.

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

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

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

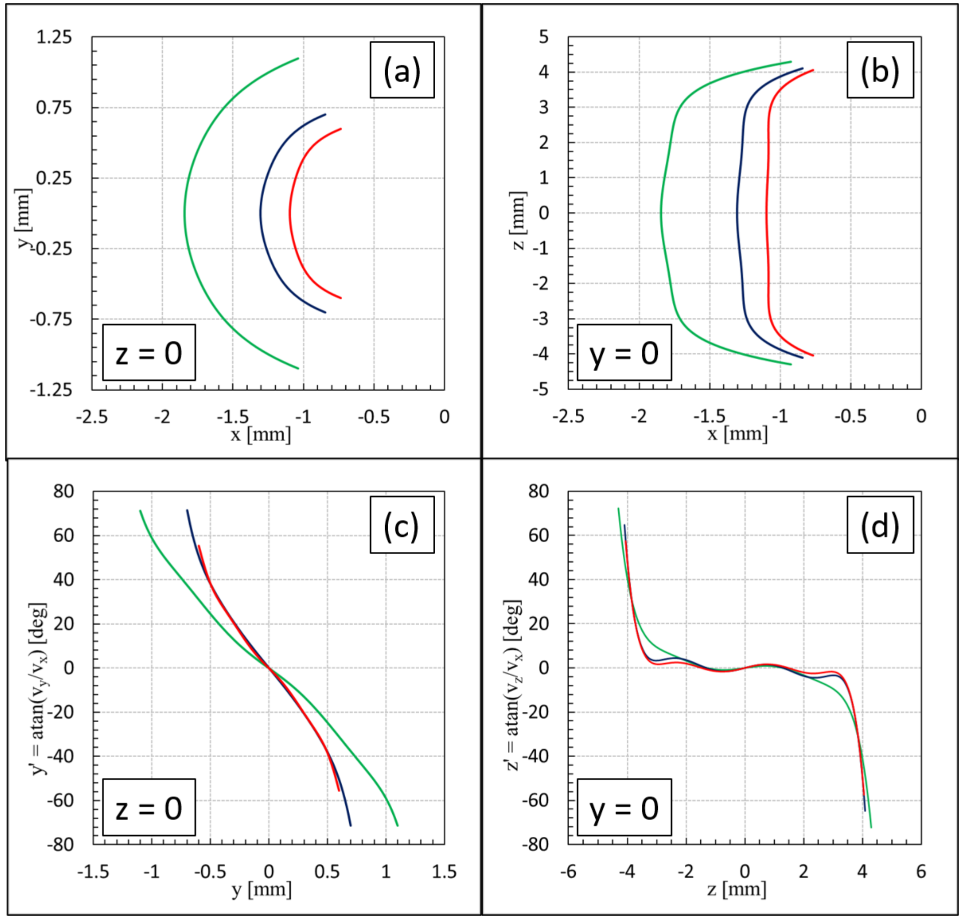


- The representation also allows to create a file with particle starting conditions for tracking.

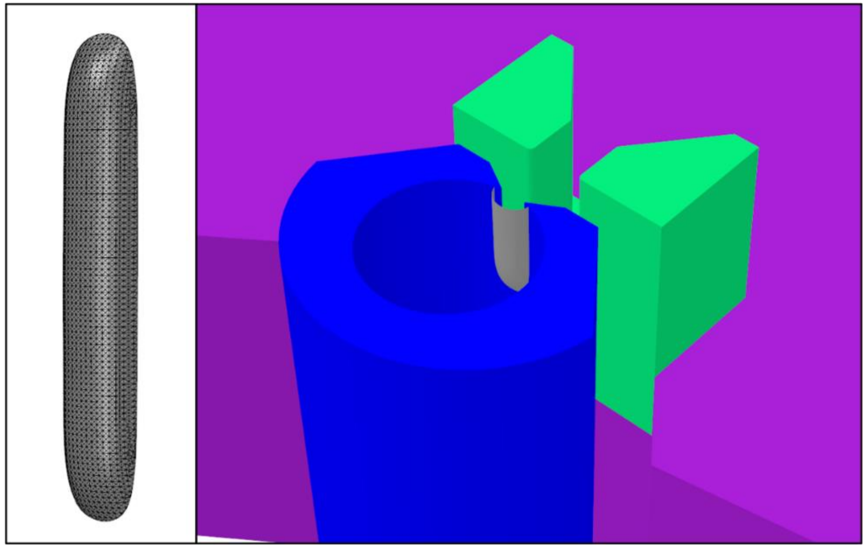
Protect, Enhance and Save Lives

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

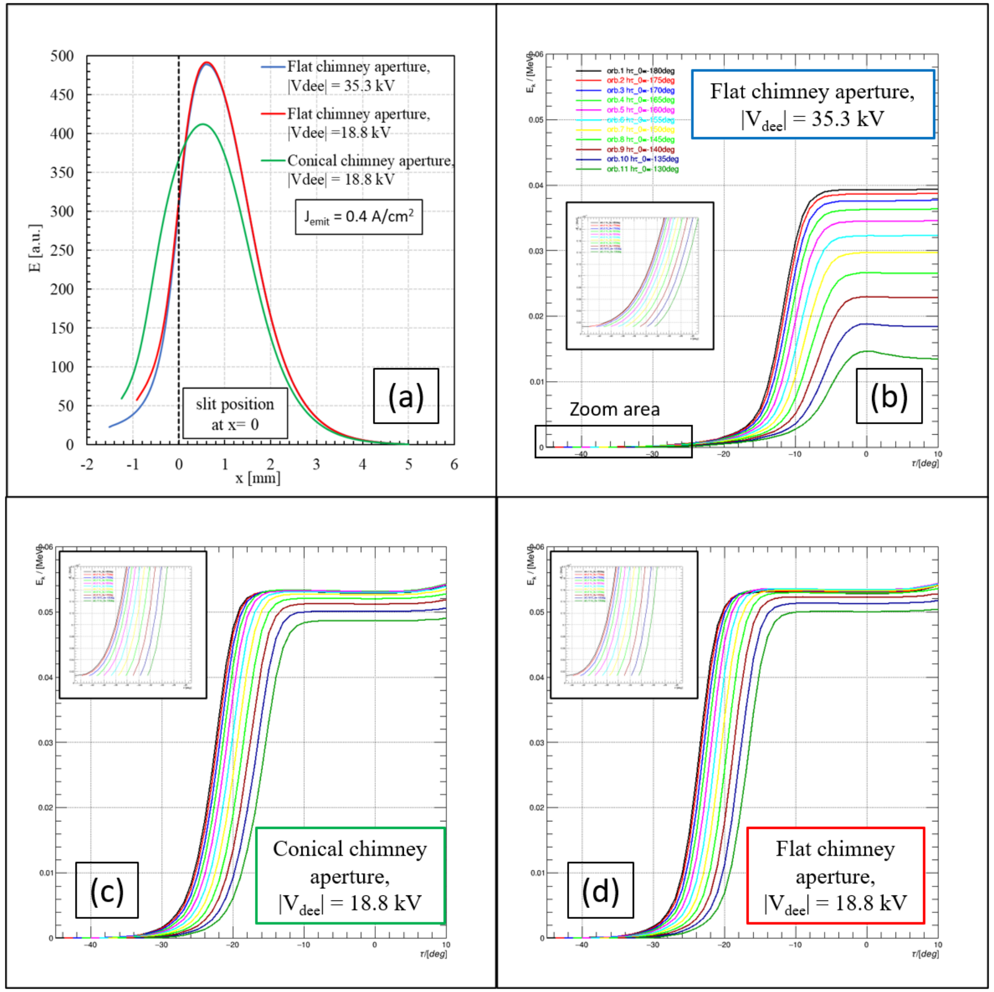


- The meniscus surface is modelled in OPERA as a wire-edge structure with a triangular mesh.
- The TOSCA model of the central region is solved by putting the meniscus surface at ground potential.

Protect, Enhance and Save Lives

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.



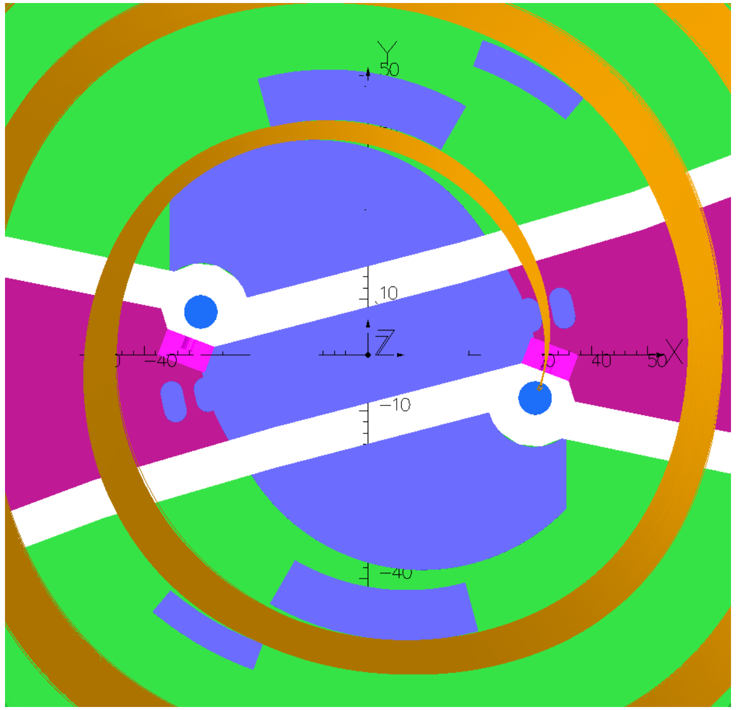
Protect, Enhance and Save Lives

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.

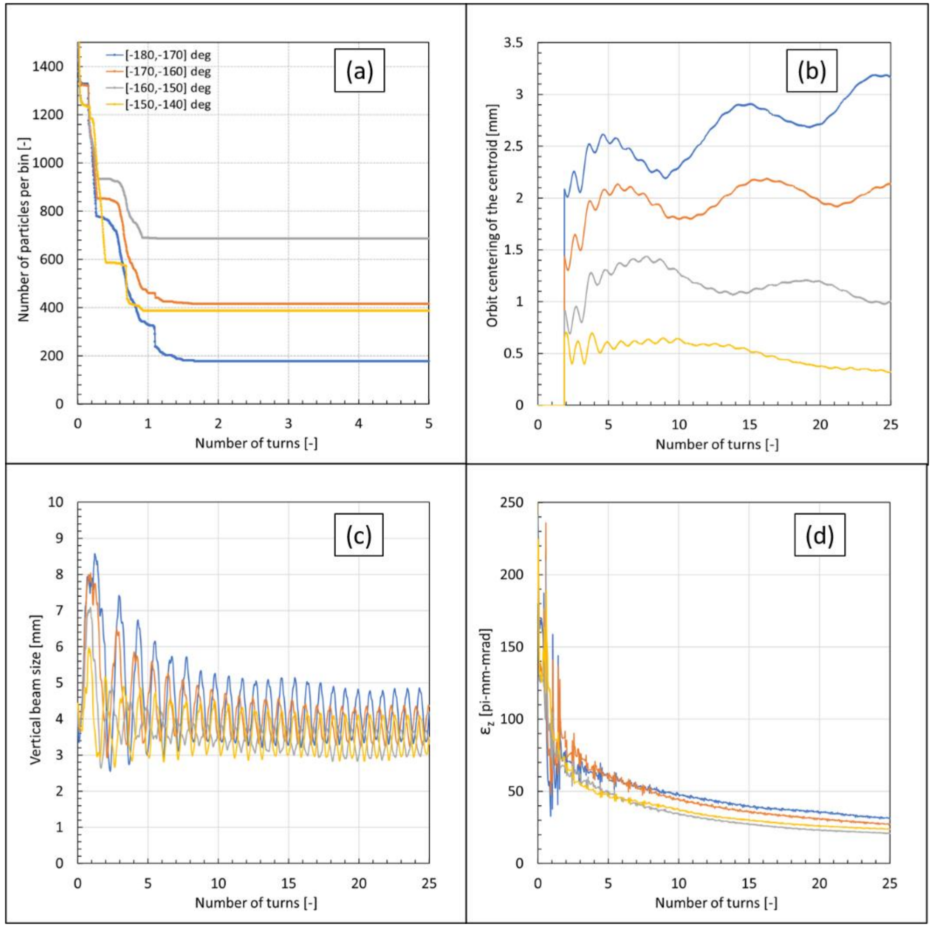
3D full beam tracking including space charge

- 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

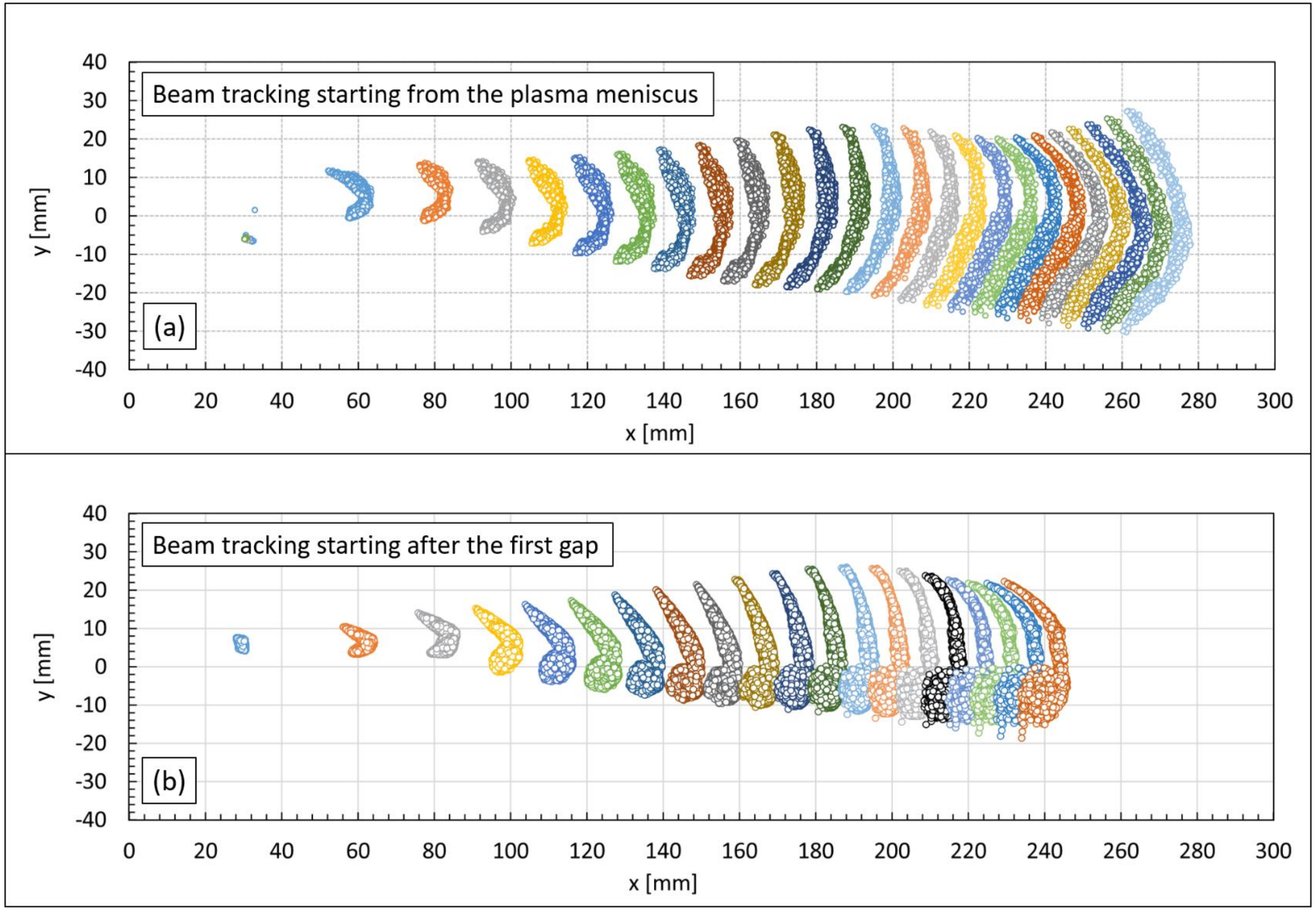


3D full beam tracking including space charge

- 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



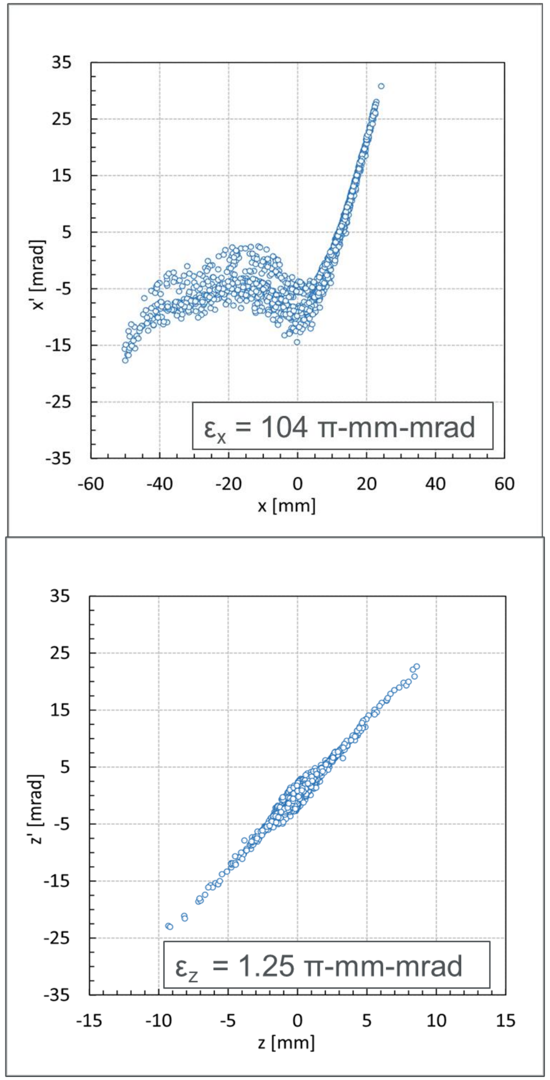
Shape of the accelerated bunches by their projection on the xy-plane, followed during 25 turns at moments when the RF phase equals zero

"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.



Protect, Enhance and Save Lives

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