An improved concept for self-extraction cyclotrons

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Outline

- The principle of self-extraction
- The prototype (2001)
- Some ways to improve the design
- Conceptual study:
  - Method for optimization of the central region
  - Results of beam simulations
    - Extraction efficiency and beam losses
    - Quality of the extracted beam
- Conclusions

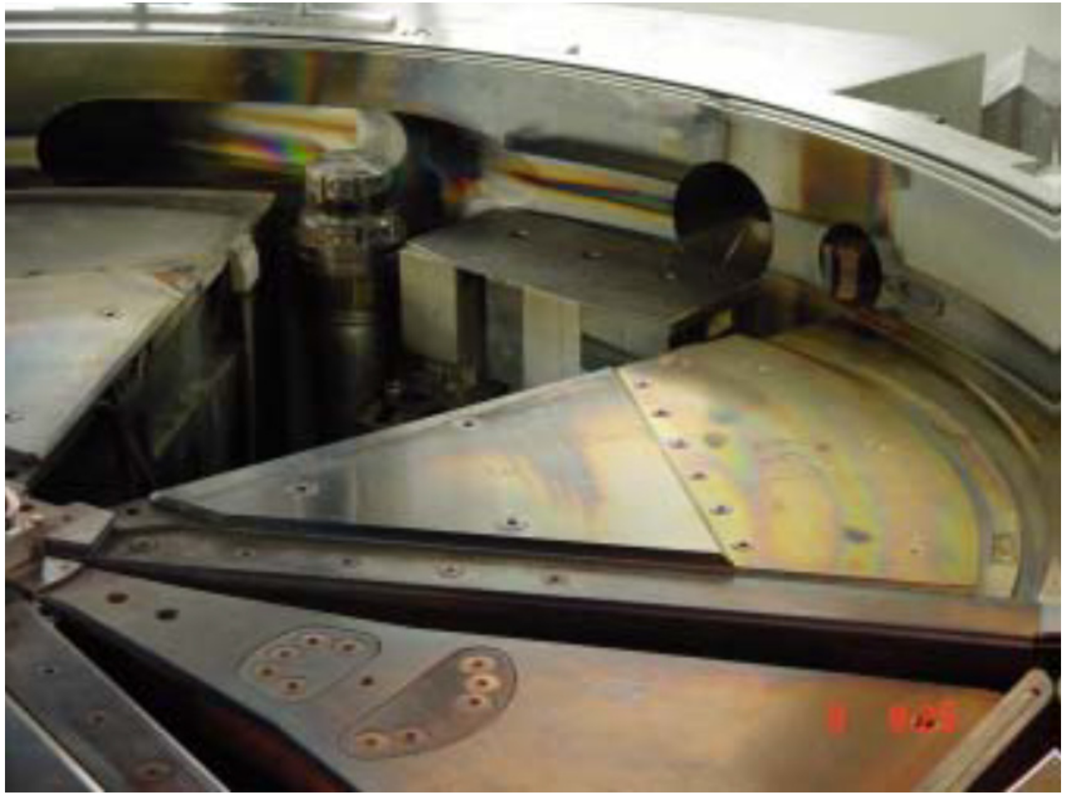
The principle of self-extraction

- This principle is already known for more than 20 years and the prototype was realized by IBA around the year 2000.
- In most cyclotrons the pole gap is relatively large and an extraction system (ESD) is needed 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.
- The cyclotron has some unconventional features:

1. The pole gap decreases quasi-elliptically with radius
2. The pole on which the beam is extracted is radially longer than the other poles
3. A groove is machined in this pole, which creates a sharp dip in te field that acts like a kind of « septurm » and also provides optics for the extracted beam
4. Harmonic extraction coils are used to enhance turn separation
5. A permanent magnet gradient corrector is placed immediately at the pole exit to provide radial focusing to the diverging beam
6. A beam stop (beam separator) intercepts parts of the beam that are not properly extracted

The prototype (2001)

- Extracted beams up to 2 mA
- Extraction efficiency was about 80% at low intensities, but dropped to 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 machine/beamline
- Encouraging but not yet good enough for industrial use
- However, 13 mA proton current could be extracted from the ion source
- Extraction efficiency and emittances were quite well in agreement with simulations

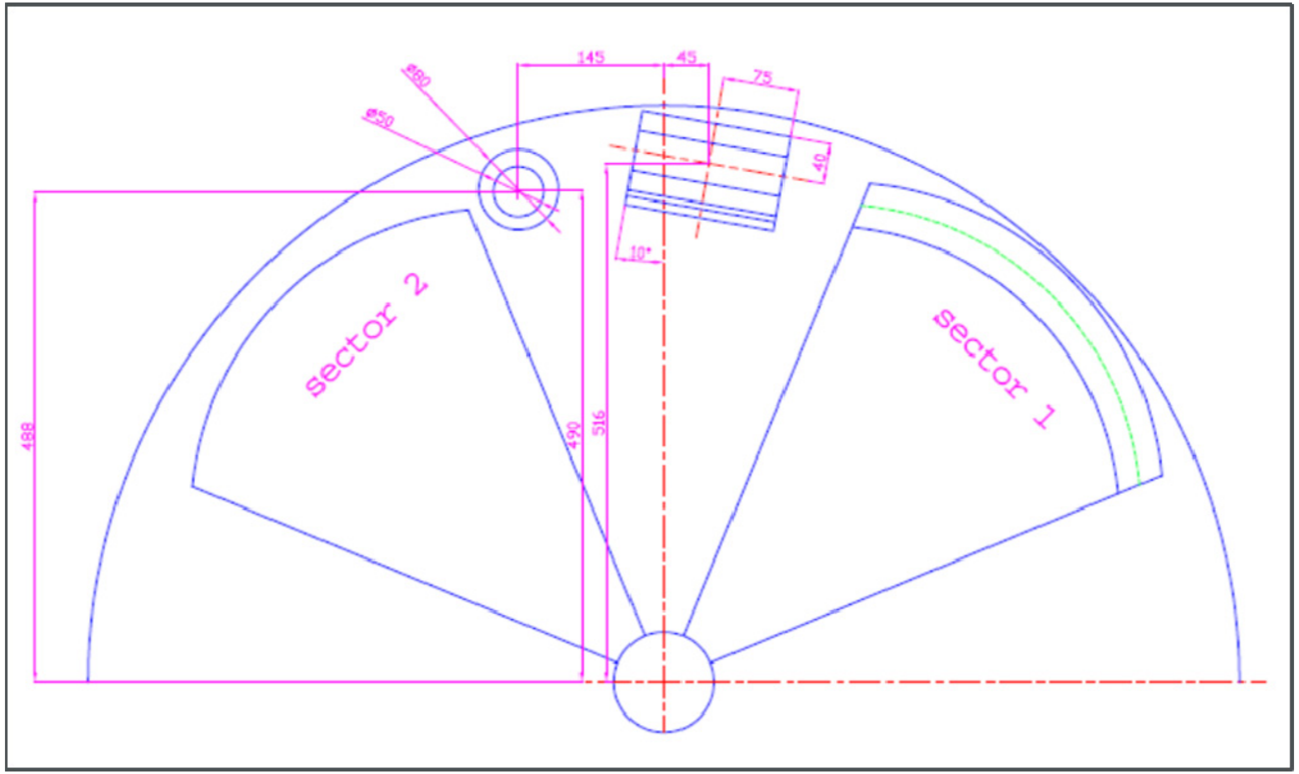


-Longer pole with extraction groove
-Permanent magnet quadrupole
-Beam separator
-Harmonic coils are placed under the pole cover
-Quasi-elliptical gap

Improvements of the design

1. The enhanced turn separation at extraction is no longer created with harmonic coils, but by an off-centering of the ion source.
   - This improves the extraction efficiency.
2. The new design has 2-fold symmetry with 2 internal PIG sources.
   - This allows to (simultaneously) accelerate and extract two beams on the two opposite poles.
3. 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.
4. 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.
5. Collimators are placed strategically on the first turns.
   - This lowers the undesired beam losses at extraction.

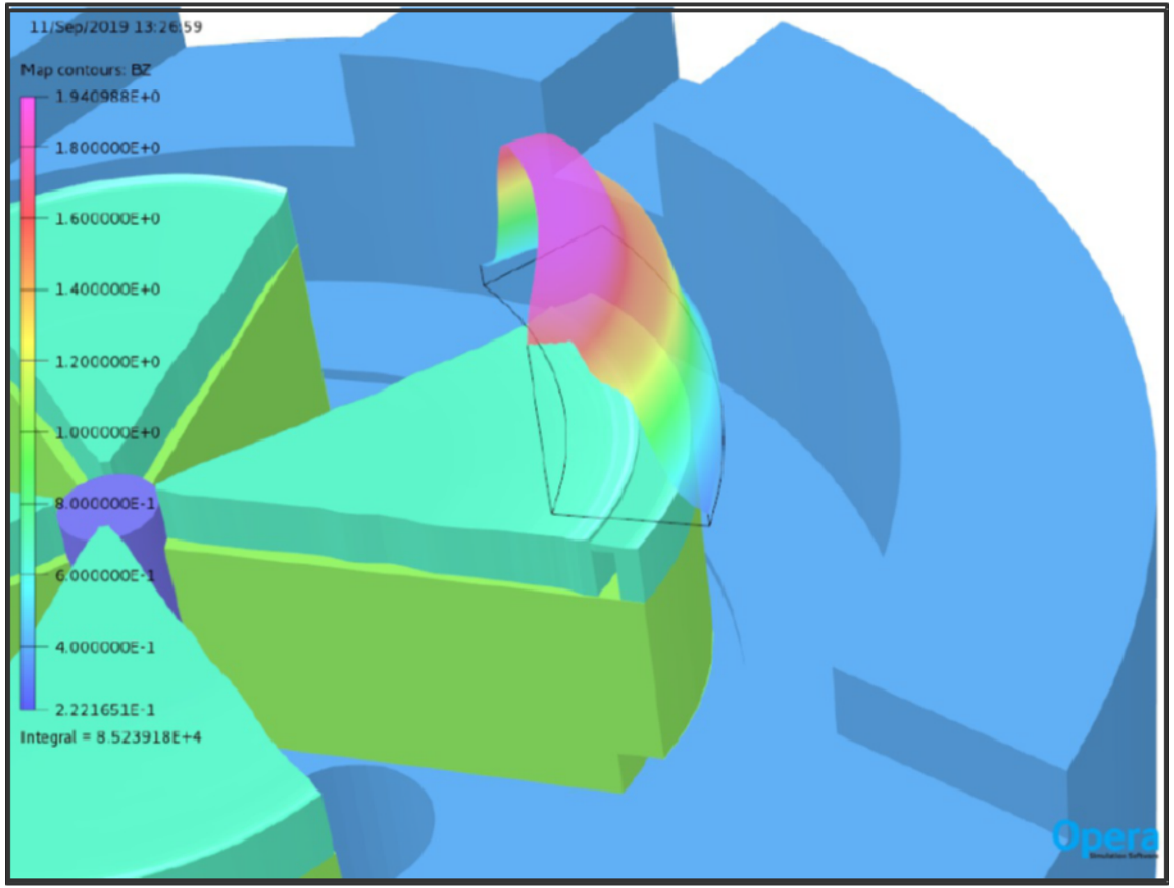
The new design (Patent EP3024306B1)

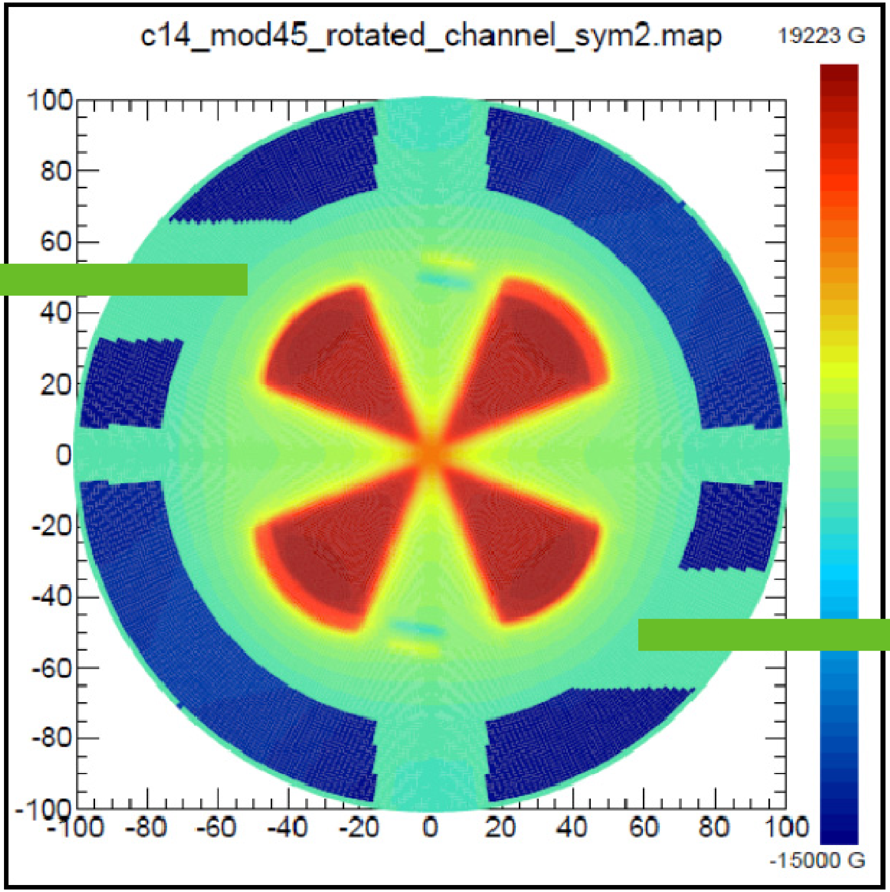


cyclotron type	compact isochronous
particle	proton
injection	dual internal PIG
extraction radius/energy	52 cm; 14 MeV
rotational symmetry	2-fold (quasi 4)
B_{ave} and B_{max}	1.15 T; 1.9 T
quasi-elliptical gap	16 mm < g < 40 mm
pole radius short/long	54 cm/57 cm
gap change at plateau	18 mm => 28 mm
numbers of dees/angle	2; 36°
RF frequency/mode	69.1 MHz; h =4
dee-voltage	55 kVolt
installed RF power	200 kW

- 2-fold symmetry (magnetic as well as central region and dees)
- Iso-gap on equilibrium orbits (pole machining with milling machine)
- « plateau » in longer pole (gap changes from 18 mm to 28 mm)
- Permanent magnets quad (gradient corrector) and BS

New magnetic design

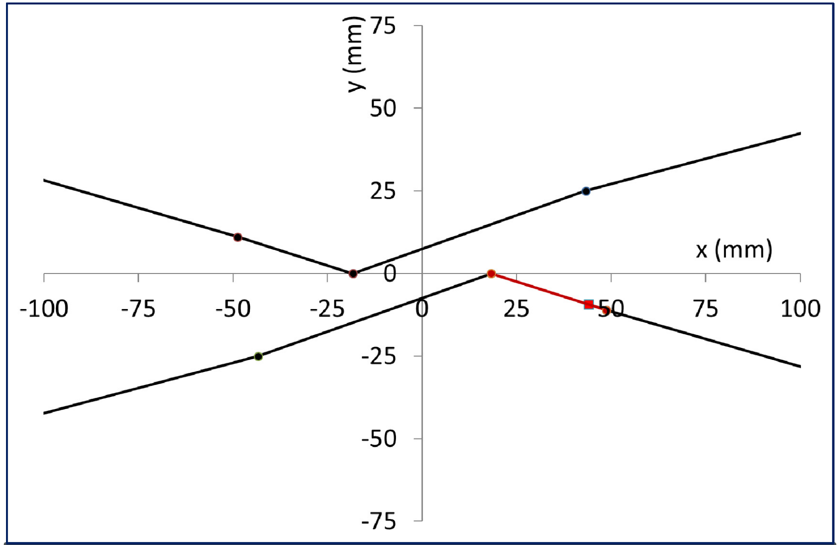




- The sector and pole have specific machining-details in order to construct the optimum field shape and beam optics in the plateau region
- The gap-profiles in short and long pole differ in order to minimize harmonic 2

Find a central region that gives highest extraction efficiency

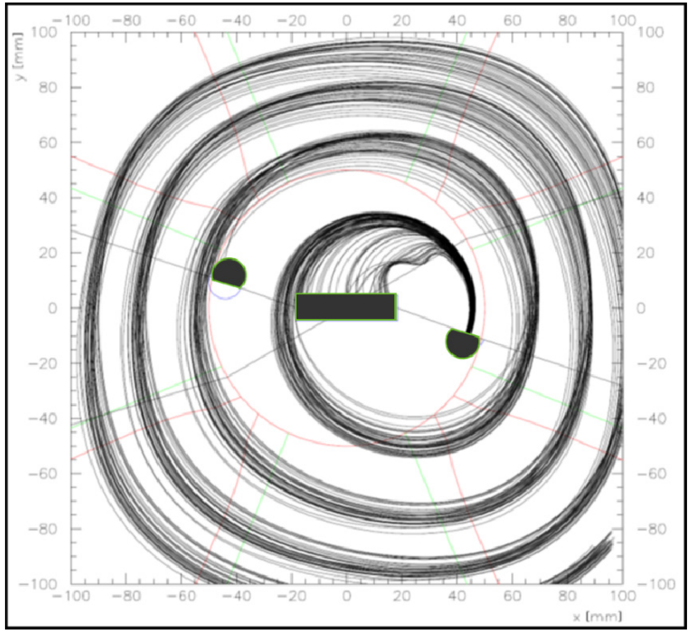
E-fields are normal to straight-gaps: Gaussian dependence on distance



Most important optimization parameters are the position (r,θ) of the ion source and the angle of the first gap

Inject a large phase space that fills the full central region acceptance

number of particles	3000
injection energy	100 eV
RF-phase range	$0° < \Phi_{RF} < 110°$
half-beam width/height	1 mm/2 mm
full (normalized) emittance	0.23/500 π mm mrad



1th turn pass between the two ion sources

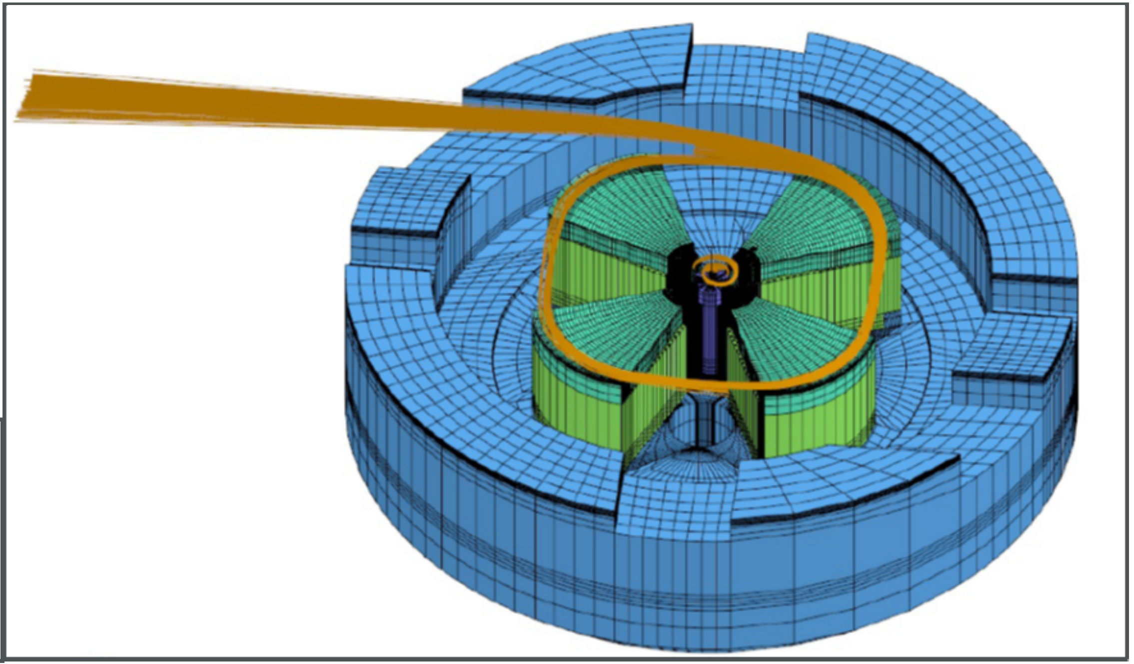
A beam stop removes beam that is not well extracted

2nd ion source further collimates the beam

can be further refined

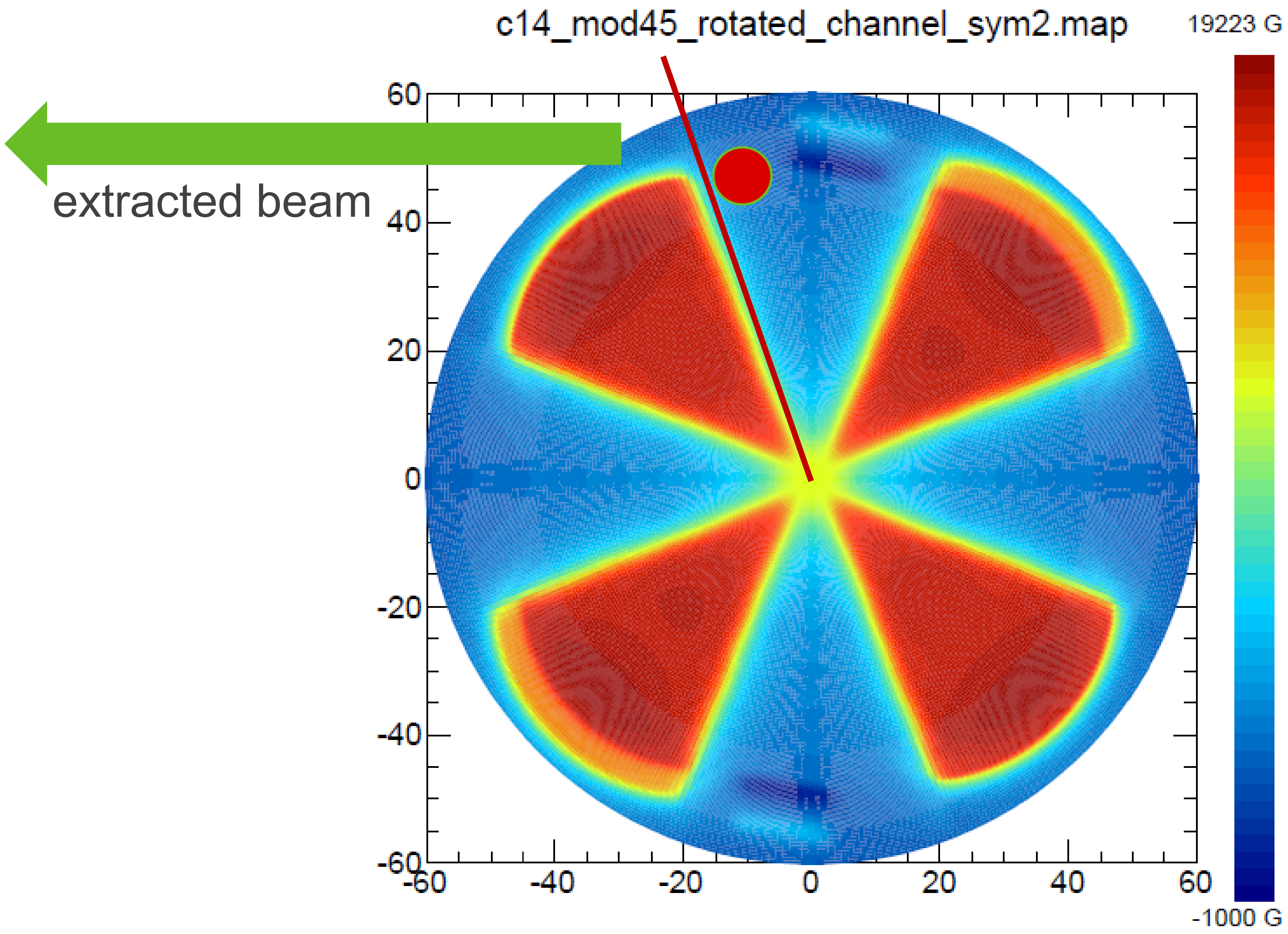
Optimized design

- About 600 CR geometries were evaluated (in an automized manner);
  - in each case 3000 particles were injected into the first gap, accelerated to 14 MeV and extracted
- The best source position (highest extraction efficiency) was found at the radius of 45 mm with the first gap at an angle of -20°
  - This gives a coherent beam oscillation with amplitude of about 20 mm



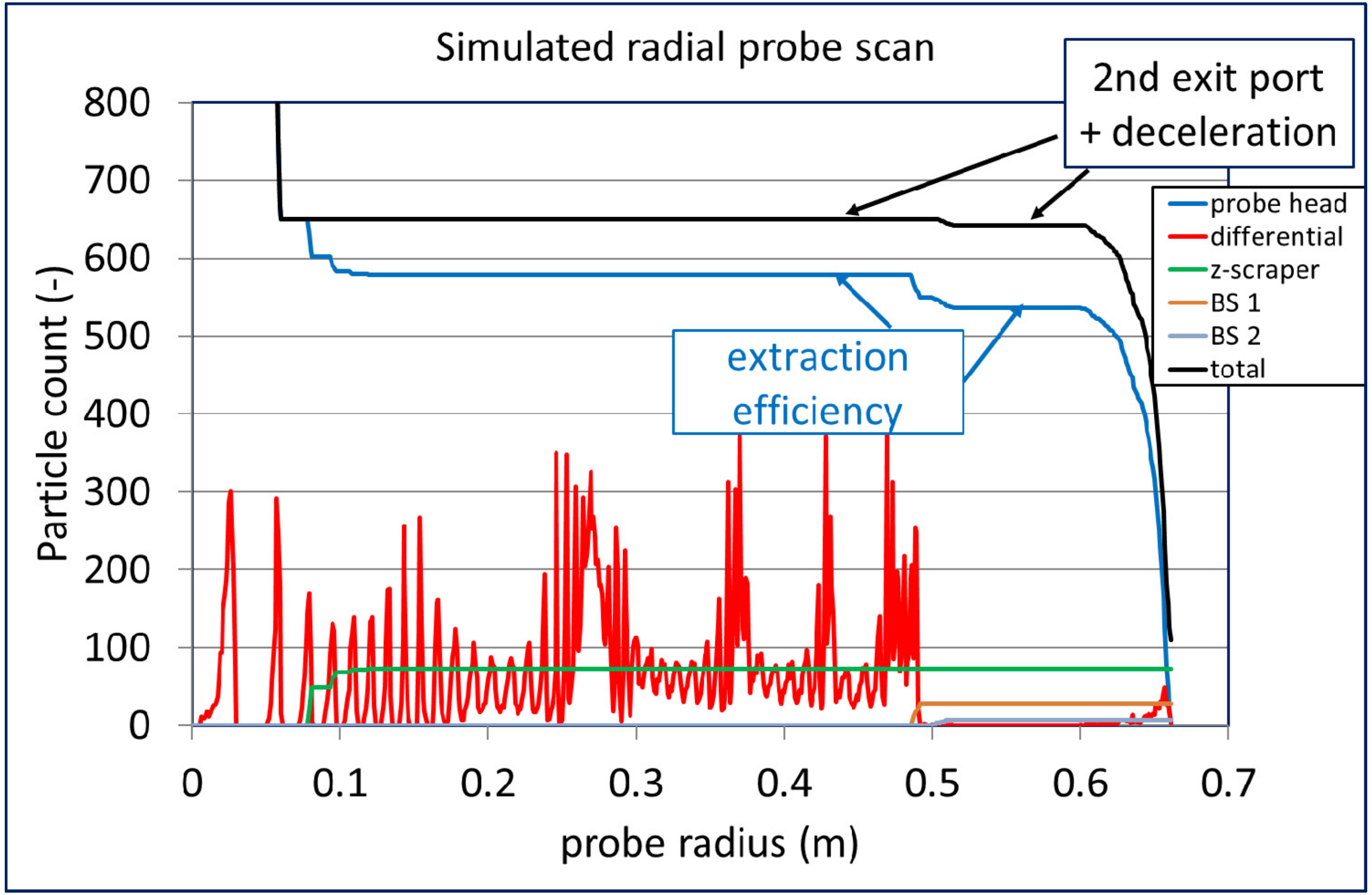
Simulated extracted beam (last 2 turns) super-imposed on the FEM-model

Result: a differential probe track at 120° (just behind BS1)



Result: a differential probe track at 120° (just behind BS1)

- Red curve:
  - differential => the turn pattern.
  - beating pattern due to beam off-center.
  - about 70 turns in the machine.
- Blue curve:
  - differential+integral
  - defines the extraction efficiency
- Losses
  - vertical scraper (12 mm center)
  - beam-separators (BS1+BS2)
- Black curve
  - total particle count
  - a very small fraction decelerates or ends up in the 2nd exit port



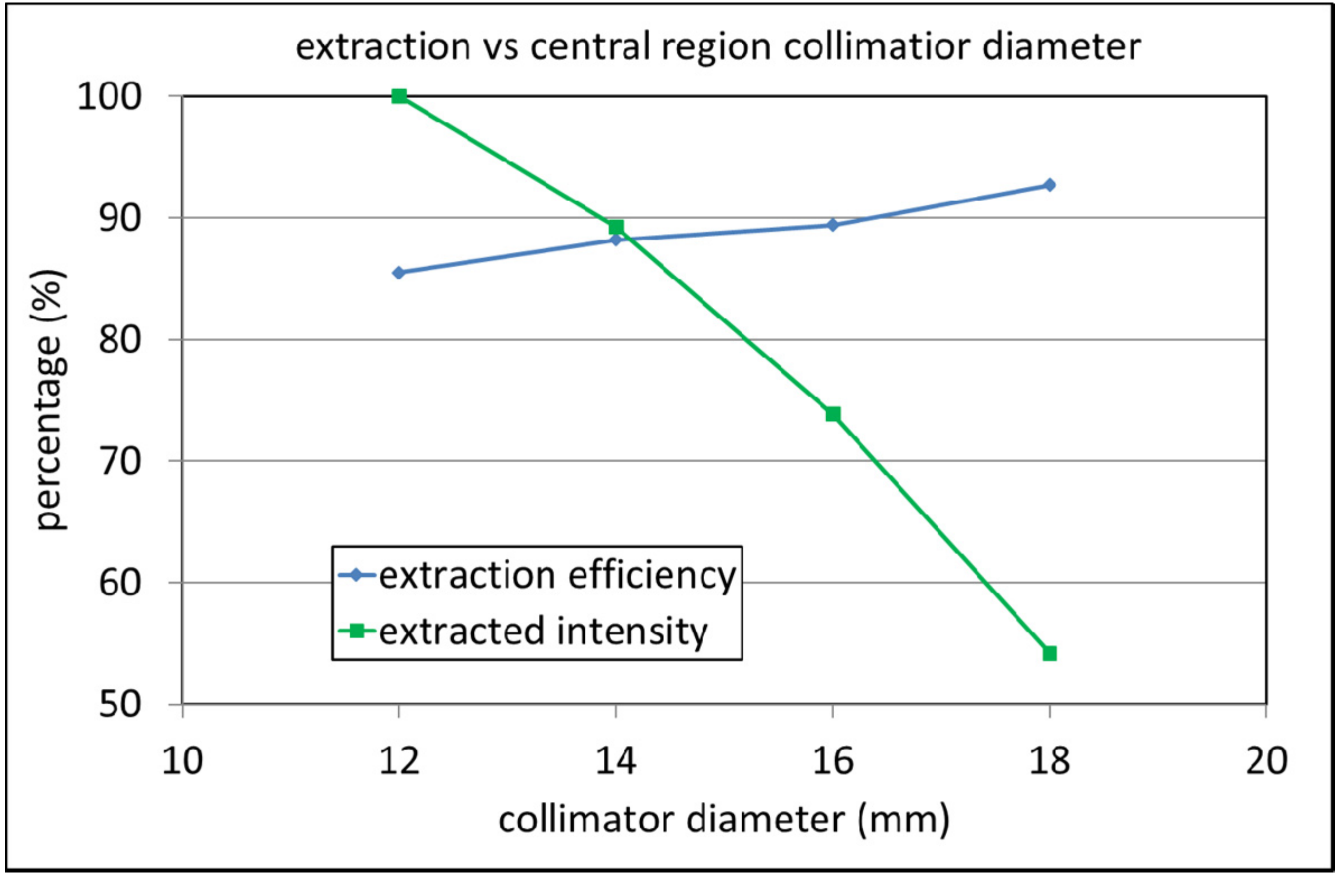
Result: extraction efficiency and losses

- The central region losses seem high but:
  - are for a large part due to the oversized injected phase space
  - And for another part due to intentional beam collimation
  - This is not really an issue
- Total extraction losses
  - only about 7.3% of the accelerated beam; (extraction efficiency 92.7%)
- Only a small part (1.7%) of the accelerated beam ends up in the « wrong » exit port

number of injected particles=3000		
CENTRAL REGION LOSSES		
2nd ion source (18 mm)	398	
dee-connection block	1462	
vertical on dees	497	
vertical beam scraper	73	
number particles accelerated =578		
EXTRACTION LOSSES		
beam separator 1	28	4.8%
beam separator 2	6	1.0%
second exit port	4	0.7%
back-accelerated	4	0.7%
EXTRACTION EFFICIENCY = 92.7%		

Result: effect of beam-collimation in the center on extraction

- In the simulation the 2nd ion source was used as collimator on the first turn
- The extraction efficiency increases from about 85.5% to 92.7 %
  - By increasing this collimator diameter from 12 mm to 18 mm
  - Extraction losses reduce by a factor 2
  - Accelerated beam reduces with 46%
  - High current (13 mA in prototype) can be obtained from a PIG source



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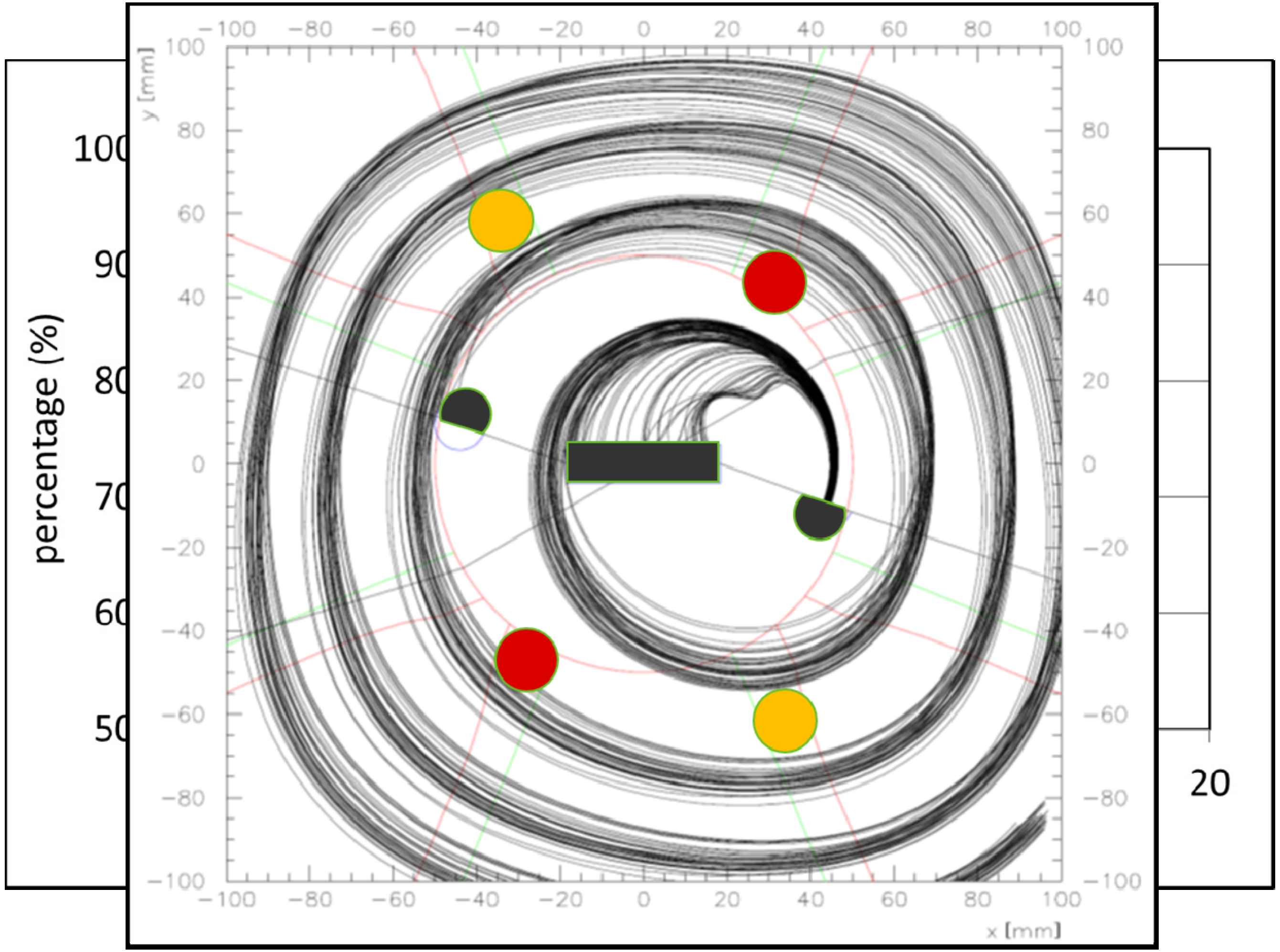
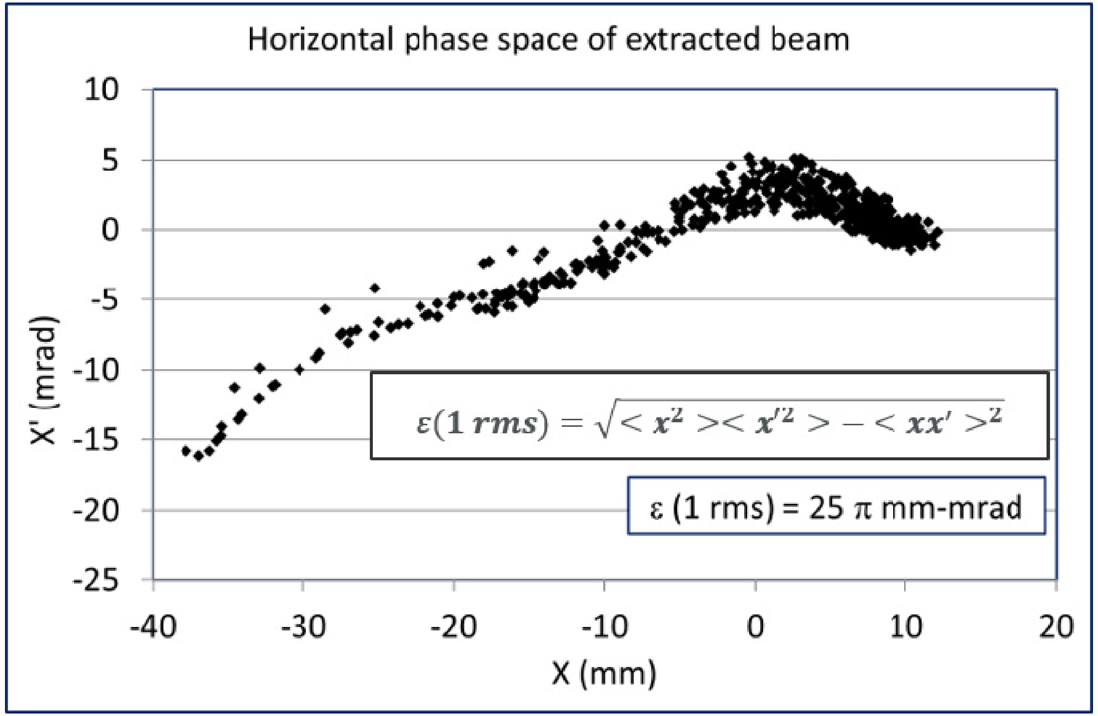
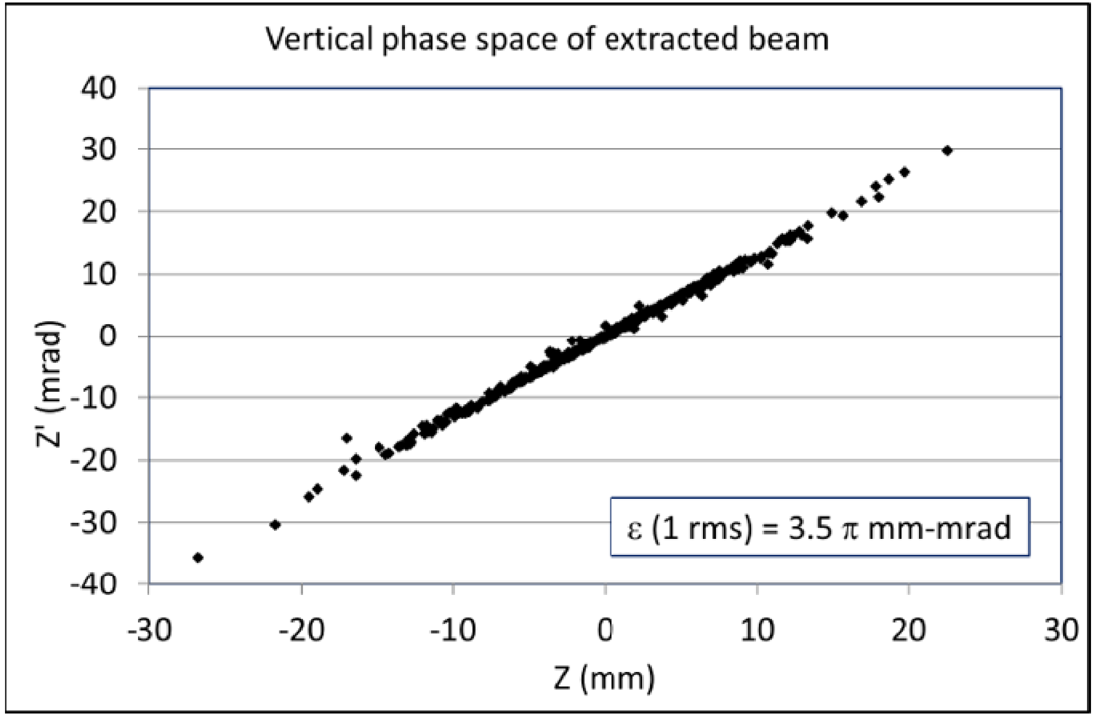


Further fine-tuning of the central-region collimators is possible (sym=2 required)

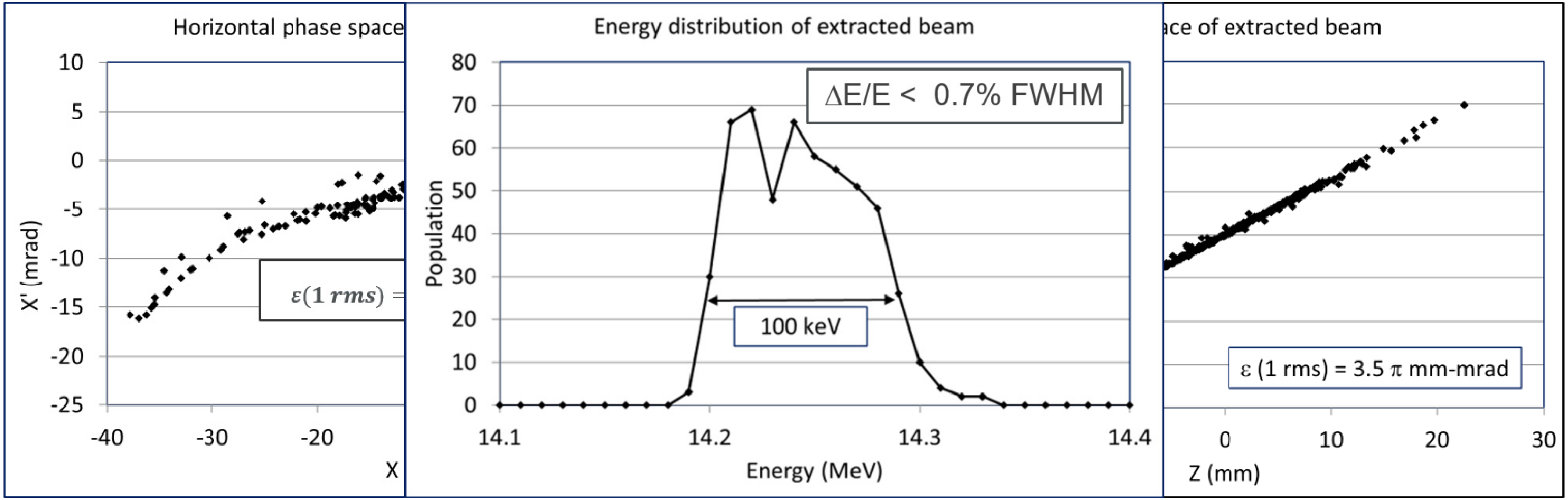
Result: beam quality





- Emittances are a factor 3 better as measured and simulated for the prototype.
- Such a beam can very well be transported to an isotope production target within a beamline with 100 mm aperture quadrupoles.
- The gradient corrector can be configured to match this beam into a first external doublet

Result: beam quality



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- Such a beam can very well be transported to an isotope production target within a beamline with 100 mm aperture quadrupoles.
- The gradient corrector can be configured to match this beam into a first external doublet
- The extracted beam energy spread is less than 0.7 % FWHM

Conclusions

- The improved design looks promising
  - Extraction losses about factor 2 lower compared to prototype
  - Beam emittances about factor 3 lower comparer to prototype
  - High beam intensities (multi-mA per beam?) seem feasible
- Possible applications: medical isotopes, BNCT, injector?
- There seems room for further improvements
  - Reduced minimum vertical gap in extraction pole (from 18 mm to maybe 12 mm)
  - Refining central region collimators + harmonic centering coils
  - Improved dee-voltage regulation loop?
- Continuation: we applied for European Horizon 2020 MSCA two-year fellowship to do a detailed design study
  - 3D Magnet and cavity modelling
  - Design and optimization of 3D central region
  - Beam tracking including space charge

Thank you

Your questions are welcome

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