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Energy Reduction of Varian's ProBeam 250 MeV Cyclotron to 226 MeV

Varian's Proton Solutions (VPS) Business Unit

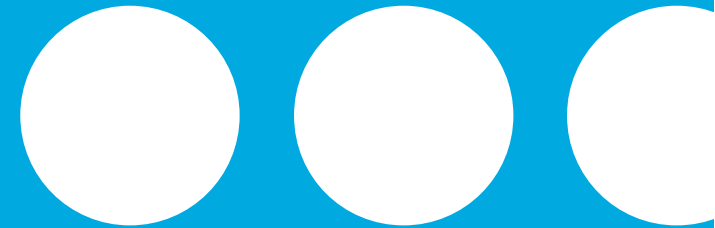
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CYCLOTRONS 2019, Cape Town, South Africa, 27th Sep 2019



Agenda

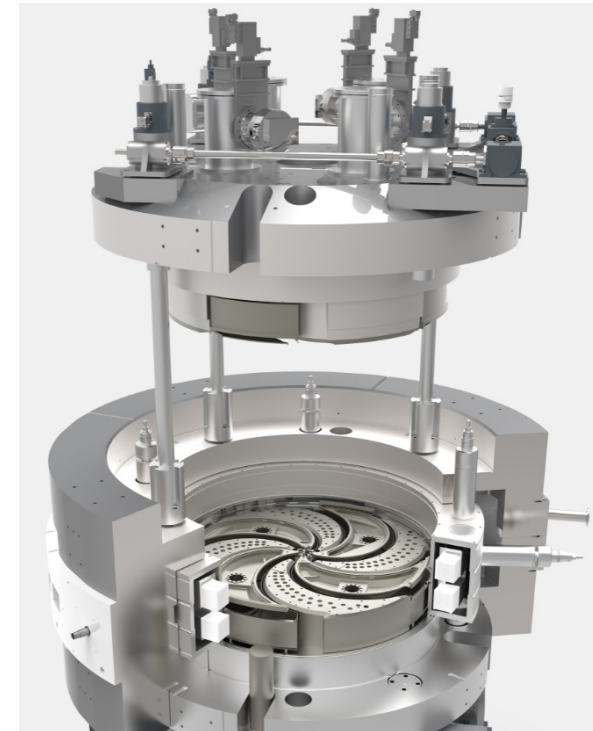
- **Varian's ProBeam AC250 cyclotron**
- **Why energy reduction from 250 to 226 MeV?**
- **AC226 basics concept & FOIK integration into series production**
- **Magnetic shimming for 226 MeV**
- **Particle tracking and beam extraction for 226 MeV**
- **Status FOIK AC226 cyclotron commissioning**
- **Conclusion**



Varian's AC250 superconducting cyclotron

Powerful source for ProBeam proton therapy systems

- Varian's Proton Solutions (VPS) business unit:
 - Our vision: world without fear of cancer
 - Worldwide provider of single- and multi-room solutions
 - Small series production in Troisdorf, Germany
 - Sides in clinical operation, installation or commissioning phase
- AC250: compact isochronous four sector proton cyclotron:
 - Fixed extraction energy: 250 MeV
 - Current of extracted beam: up to 800 nA
 - Extraction efficiency (CYC exit / output central region): up to 80%
 - Outer iron diameter: 3.2 m, total weight: 90 t

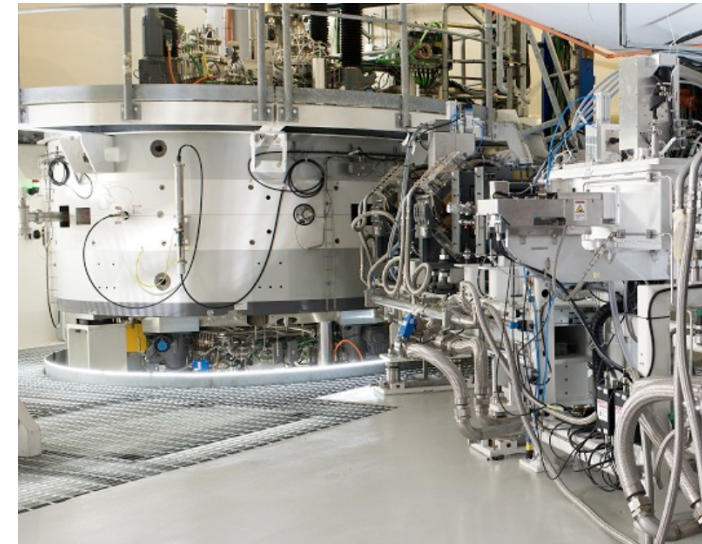


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Reduction of extraction energy: from AC250 to AC226

AC250 somewhat oversized, VPS decision to redesign to 226 MeV

- Analysis of clinical cases:
 - Vast majority of treatments using less than 30 cm WET (water equivalent thickness)
 - Required maximum beam energy at the patient is 218 MeV
- Energy degrader required to lower beam energy:
 - Negative side product: significant, needless reduction of beam current
 - Considering a few, unavoidable MeV losses, optimal CYC energy is 226 MeV
- Benefits of new AC226 cyclotron:
 - Lower building cost due to lower shielding requirements
 - Lower requirement for extracted beam current while maintaining the same dose rate at gantry isocenter
 - Increased lifetime and maintenance intervals of components



Basic concept for 226 MeV

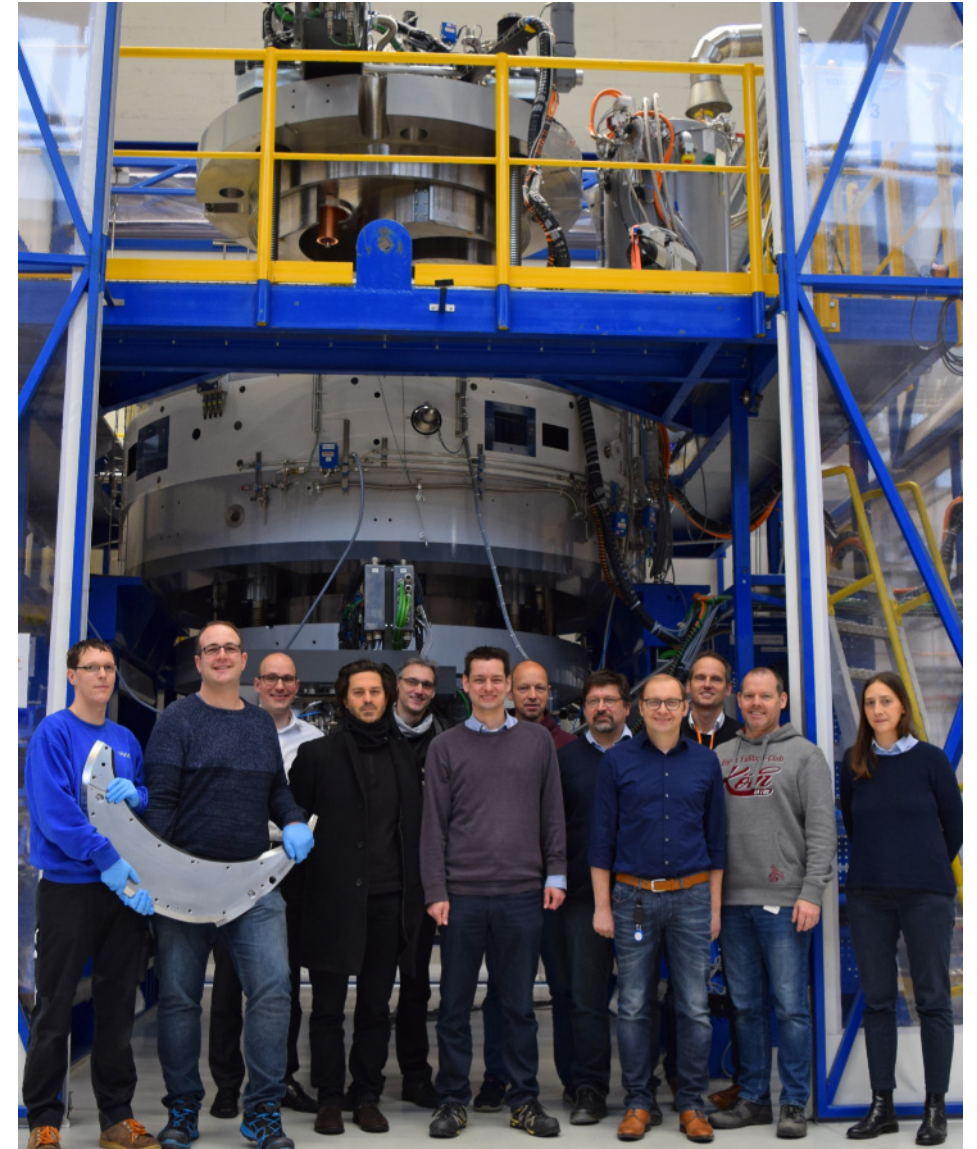
Minimum design changes to ensure fast integration into ongoing production

- No major changes (magnet poles, sc coil, cryostat, cavity system) neither required nor intended
- Consequently, cyclotron extraction radius remains the same: 816 mm (septum position entrance ED1)
- Adaption of radial shape of averaged magnetic field by lowering I_{coil} and new magnetic shimming
- Modification of high power RF amplifier to 70.3 MHz
- Tuning range of cavity system (4 spiral shaped dees, 8 stems with movable shorting plates) sufficient for 70.3 MHz

Parameter	226 MeV	250 MeV
B_{extr}	2.82 T	2.98 T
B_0	2.27 T	2.35 T
I_{coil}	~148 A	~162 A
f_{RF}	70.3 MHz	72.8 MHz
#turns	~580	~650

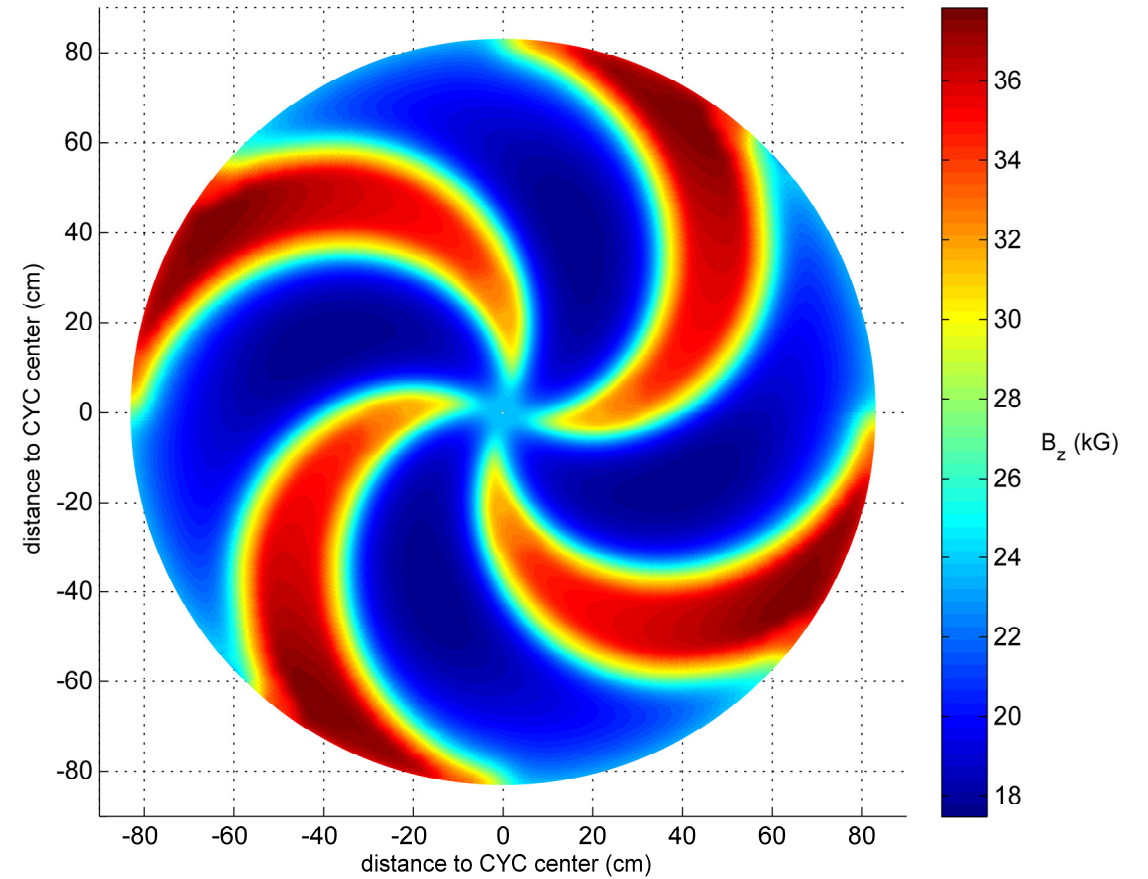
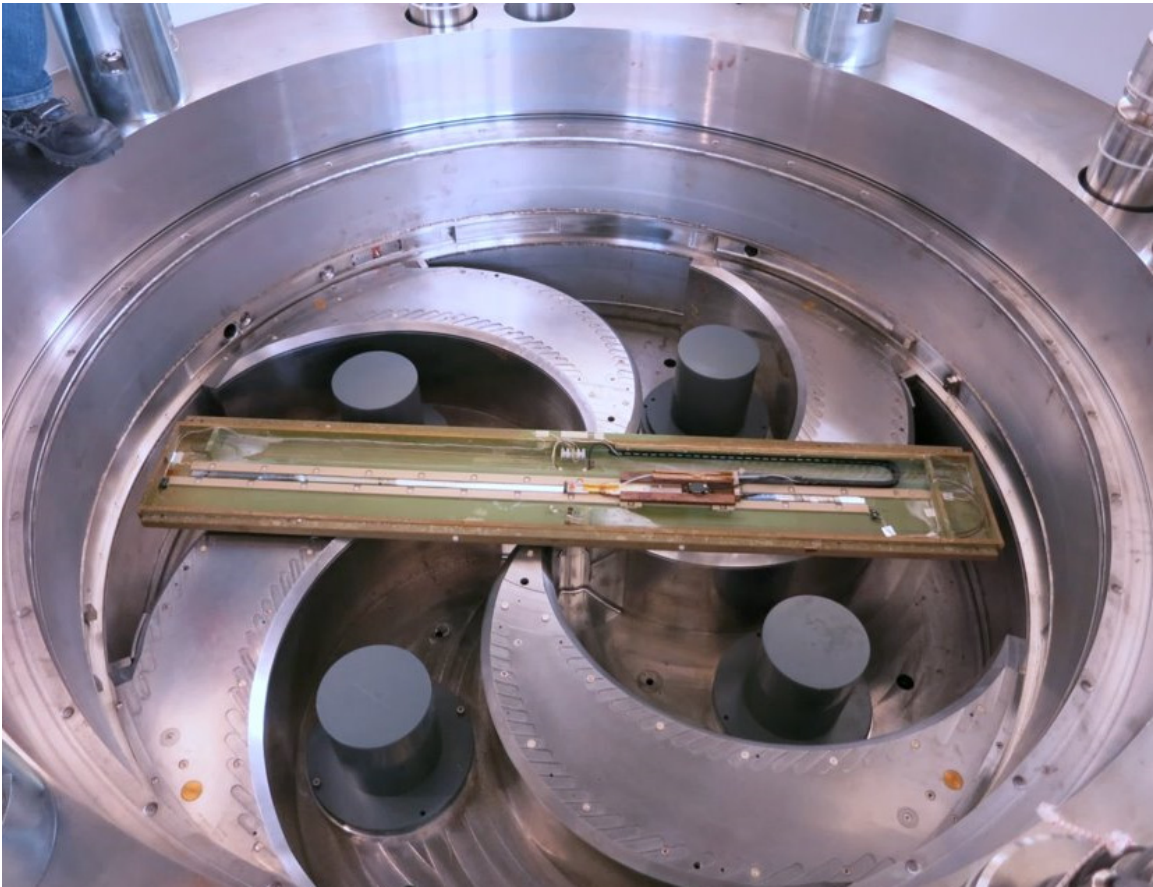
Decision for AC226 in Dec 2018

- Transfer of S23 cyclotron into first of its kind (FOIK) AC226 machine
- In parallel beam dynamics studies for 226 MeV (vs. baseline results for AC250 simulations)
- Strong collaboration between engineering and operations teams
- 1st quarter 2019: field mapping and shimming of FOIK AC226 conducted



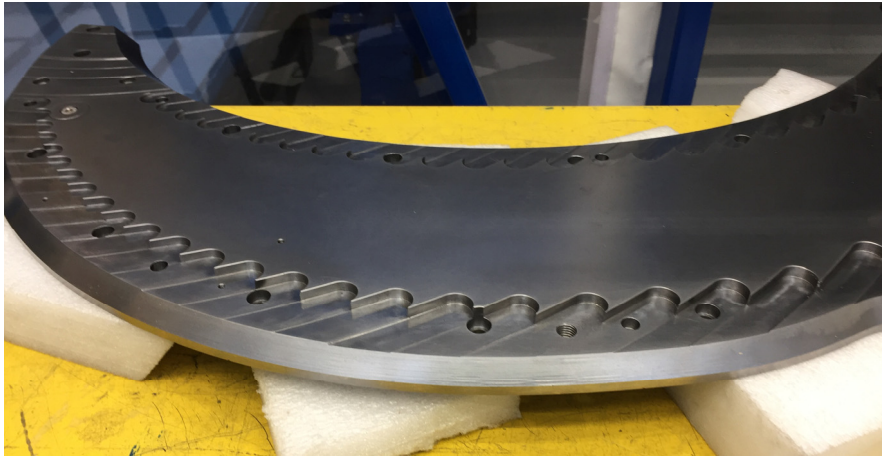
Magnetic field mapping FOIK AC226

Basis for radial coil alignment, shimming and tracking computations

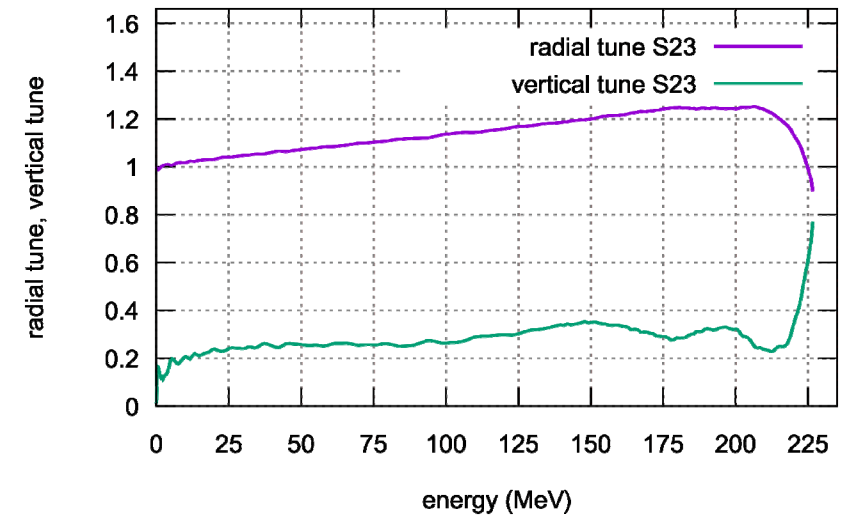
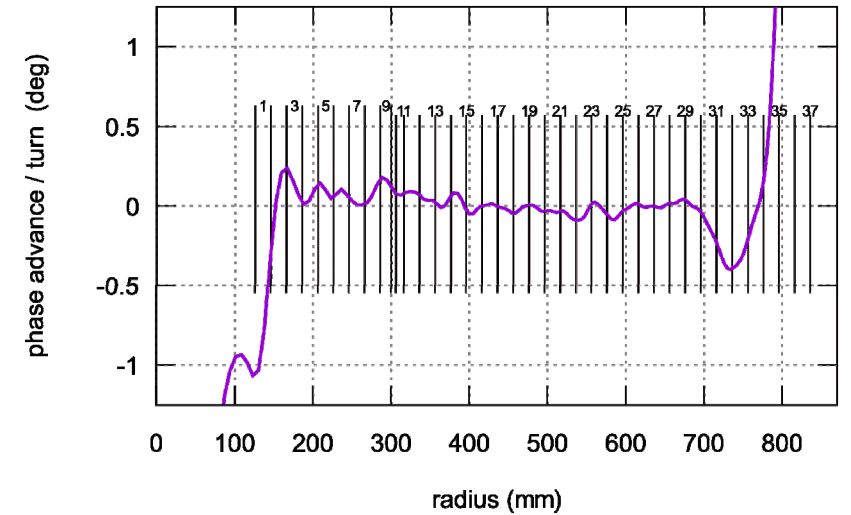


Magnetic shimming FOIK AC226

Use of eight shim plates with radial stripes



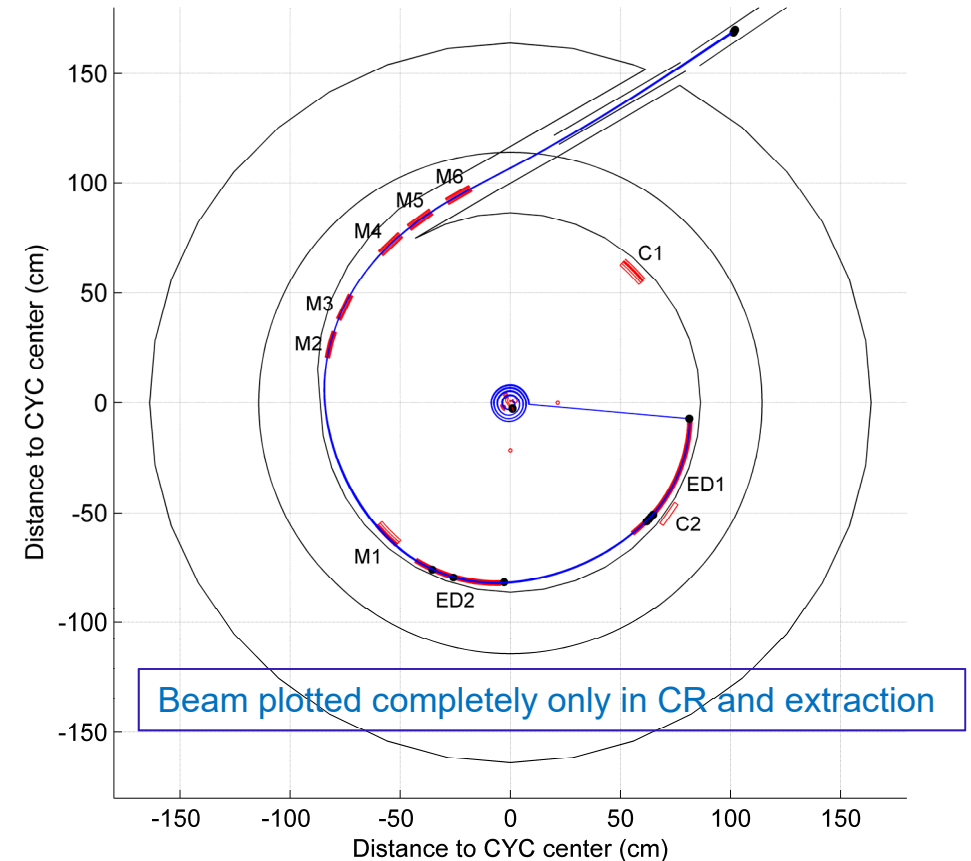
- Iterative process: pre-machining plus two steps of field mapping, computation, machining, verification
- Milling depth up to 10 mm, for AC250 maximum 4 mm
- Similar or better results for isochronism and beam focusing as compared to AC250



Orbit tracking computations for AC226

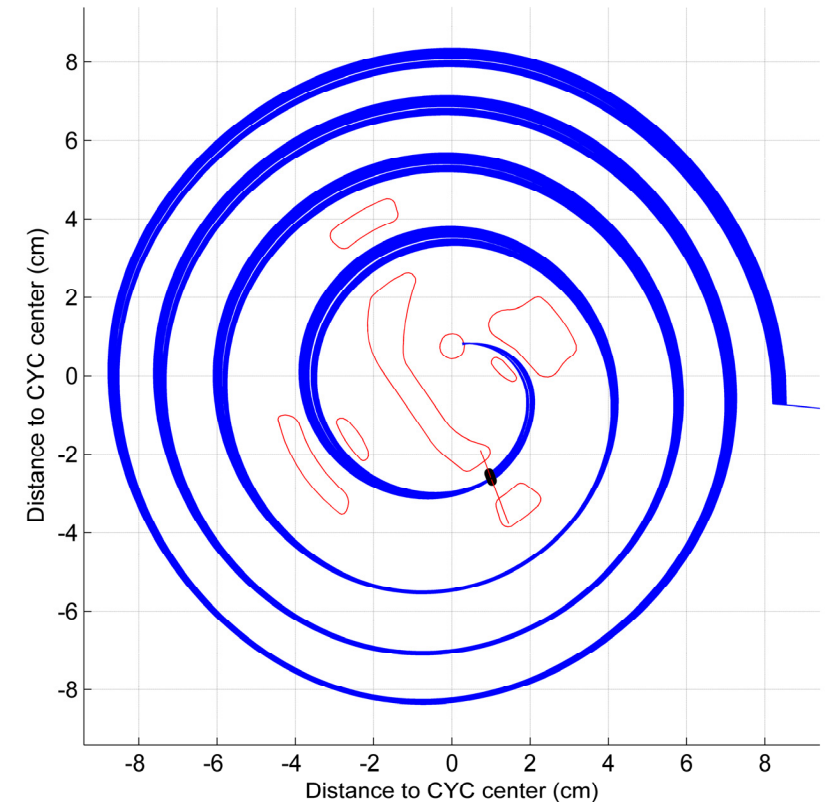
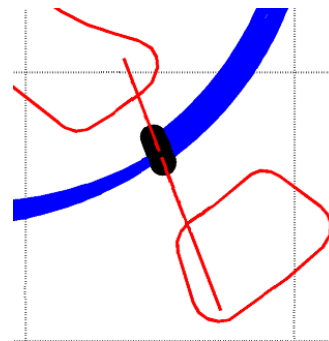
Approach: measured magnetic field maps, multi-particle start-to-end simulations

- Cyctrack: tracking code by ACCEL (derived from NSCL codes), used also for shimming calculations
- Particle tracking from chimney of ion source, through central region (CR), and in extraction channel
- Fixed (phase) slit (FS) used in CR
- Consider complete extraction model:
 - two electrostatic deflectors (ED1, ED2)
 - six passive magnetic elements (M1 – M6)
 - two compensation bars (C1, C2)
 - extension of measured field data (up to $R = 83$ cm) using simulated magnetic field maps with TOSCA



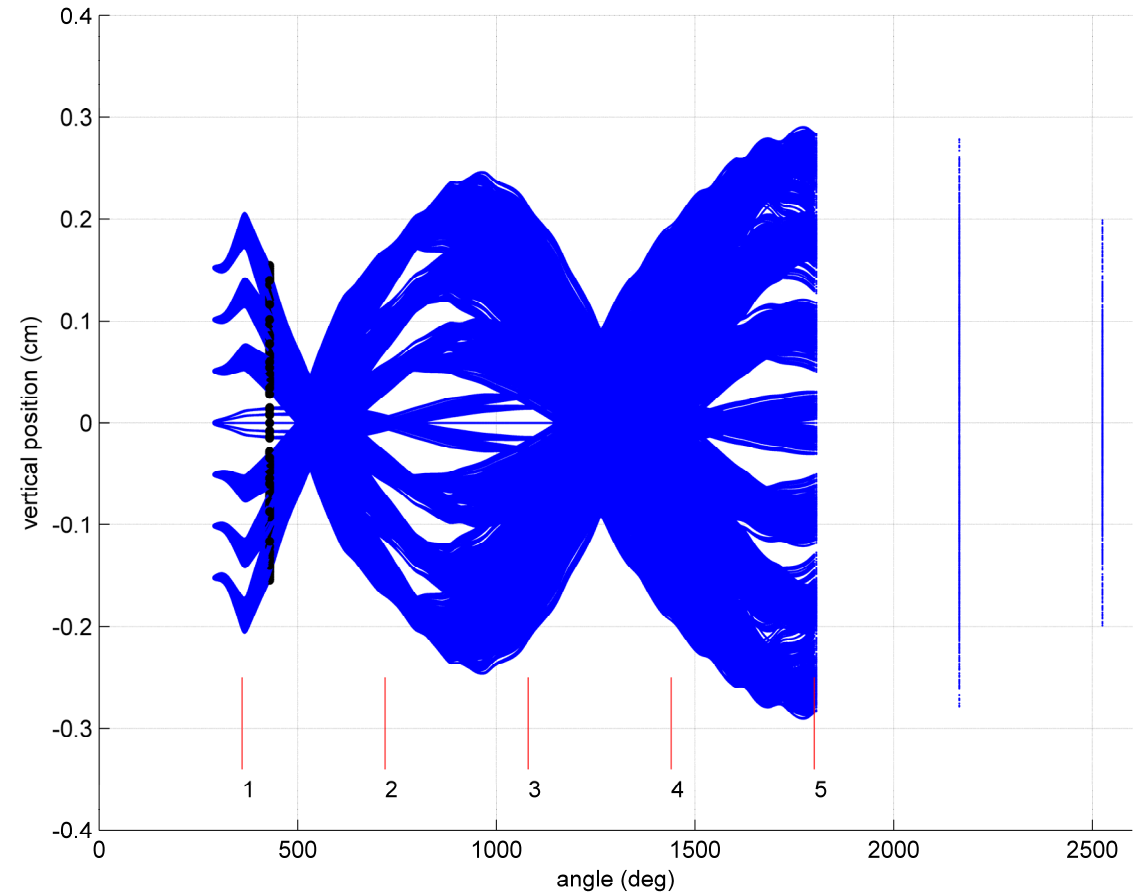
AC226 central region (CR) tracking – horizontal plane

- 6125 protons from IS chimney opening
- Starting phases: [226°, 227°, ..., 231°] for complete radial overlap of FS in dee 2
- Optimized width and radial position of FS for good compromise between intensity output and turn separation (at higher radii)
- No HW changes of CR for AC226 required



AC226 central region (CR) tracking – vertical

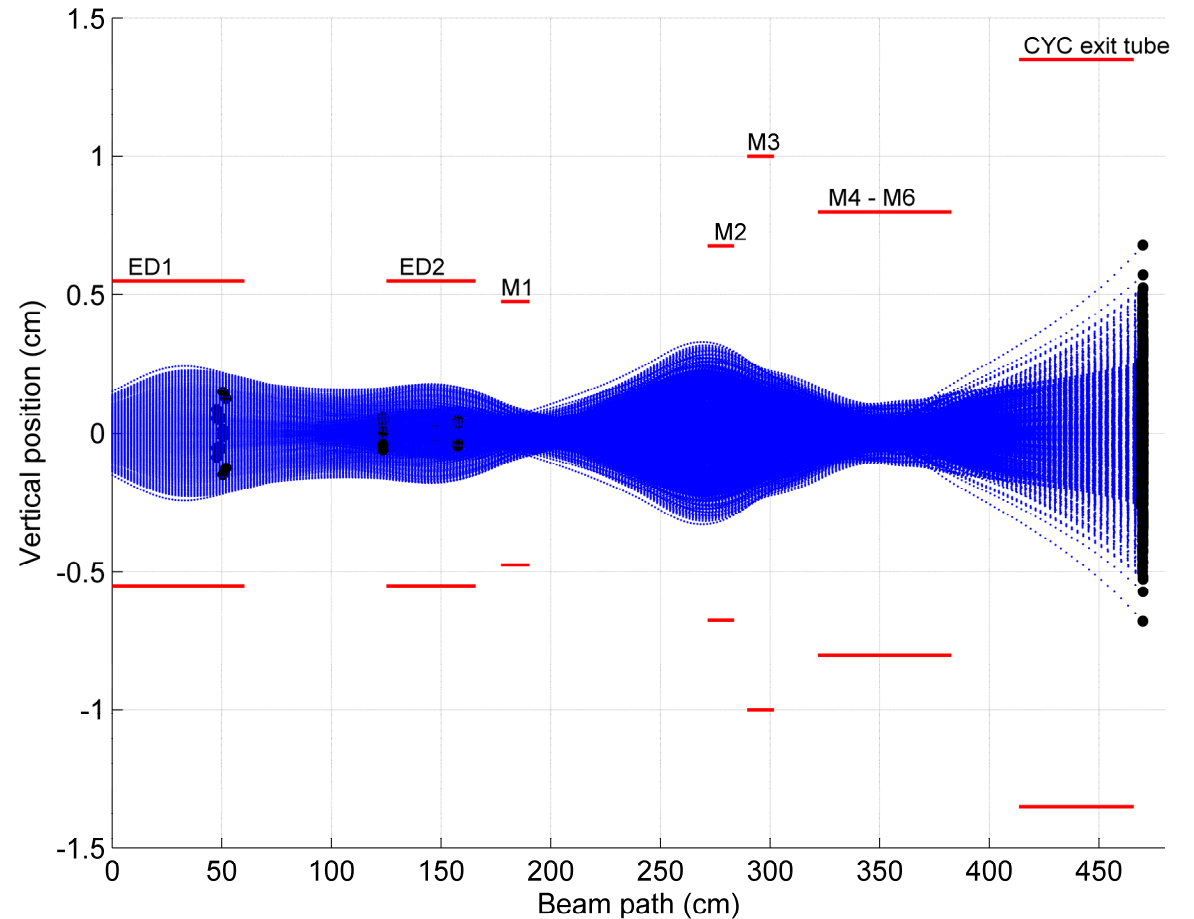
- Vertical starting conditions represent chimney opening of ± 0.15 cm
- Good vertical focusing in CR
- Further beam dynamics studies planned regarding vertical misalignments of CR components



AC226 beam extraction tracking – vertical

Continuation of CR tracking into cyclotron extraction channel

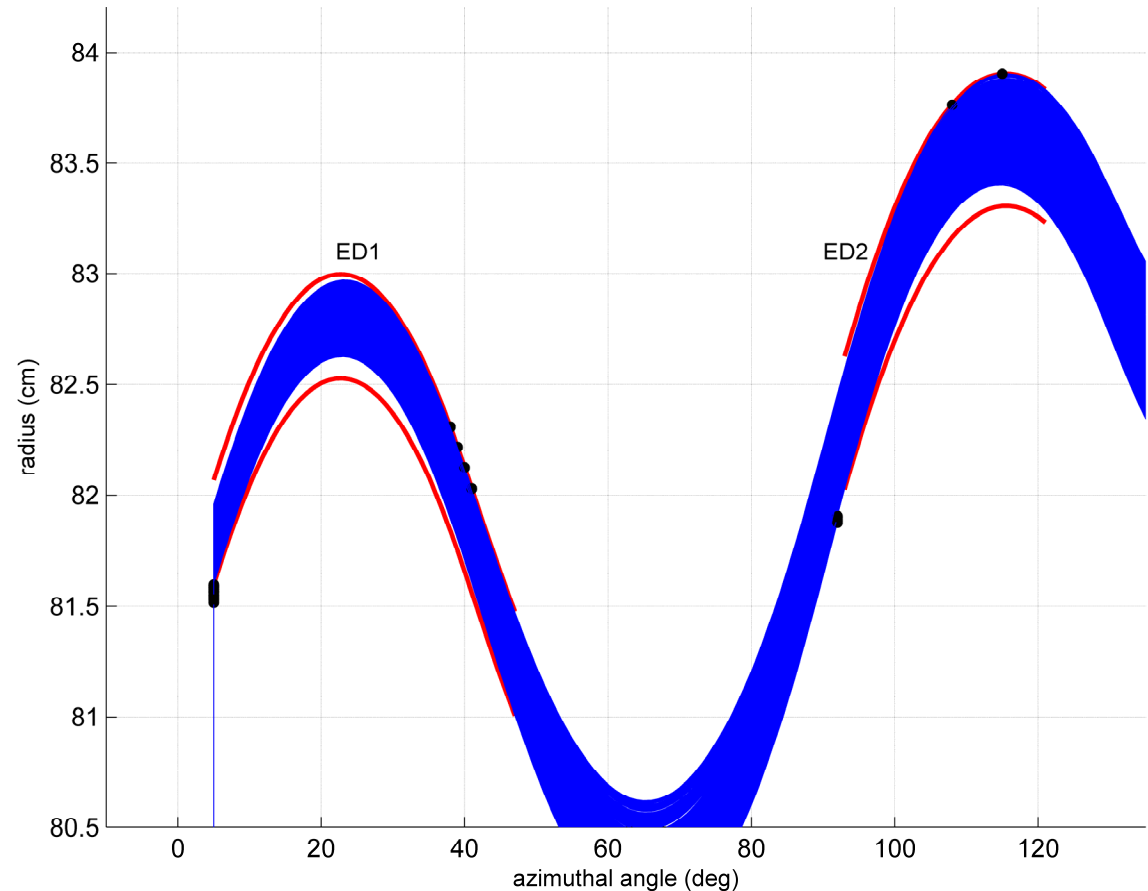
- Minor particle losses in ED1 & ED2, no losses in M1 – M6
- Vertical beam width comparable to results from AC250 tracking simulations and beam commissioning
- Vertical width (1σ) of extracted beam: ± 0.20 cm



AC226 beam extraction tracking – horizontal

Overall extraction efficiencies (EE) in the range of 70% to 85%

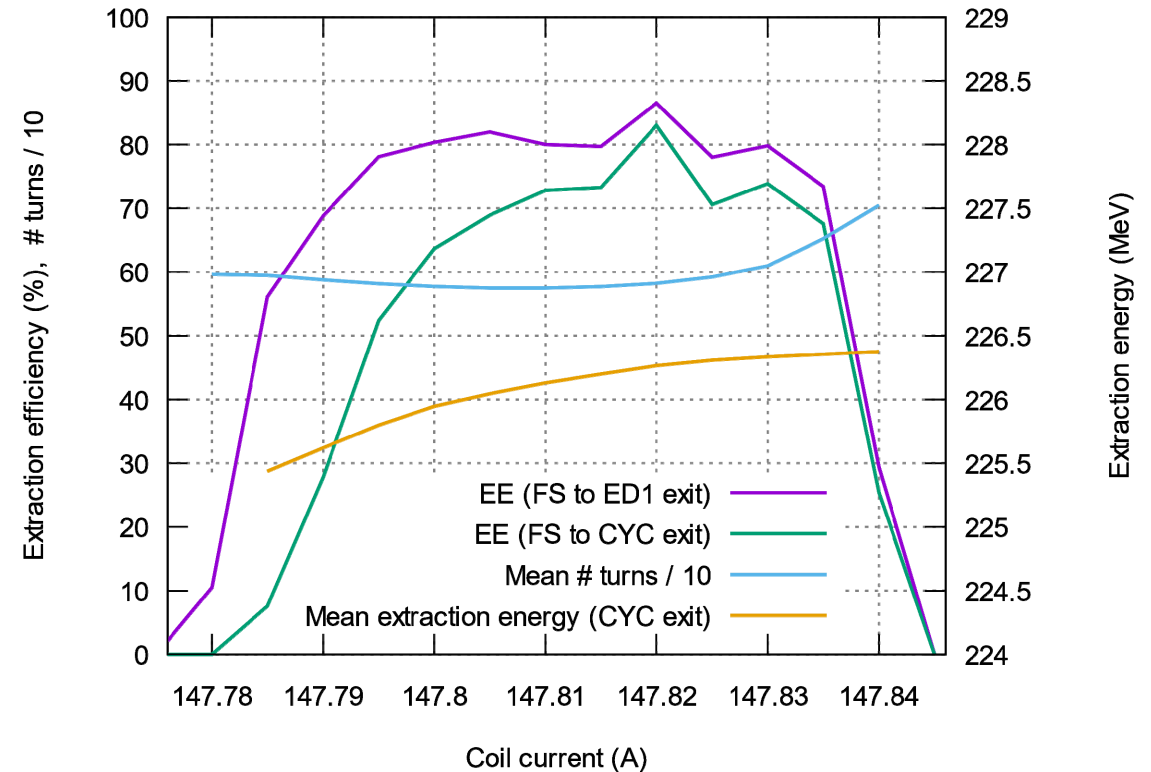
- Overall EE calculated as #protons extracted, divided by #protons passed FS
- ED1 & ED2 are bottlenecks: septum edges and radial aperture (defined by distance of septum to cathode)
- E-fields increased by up to 20% as compared to AC250 settings (absolute values for AC226 of up to 110 kV/cm)
- Compensation of $v_r = 0.95$, whereas only 0.74 for AC250



AC226 extraction efficiency, energy and stability

Extraction tracking computation to find stable cyclotron working point (I_{coil})

- Overall EE (green line) higher than 70% for main coil current changes within a range of 25 mA
- Number of turns (blue line) at minimum value of 580
- At highest overall EE of 83%, energy averaged over all extracted protons (#2131) is (226.3 ± 0.1) MeV
- EE (FS to ED1 exit, purple line) shows potential for further optimization (ED2, M1 - M6)

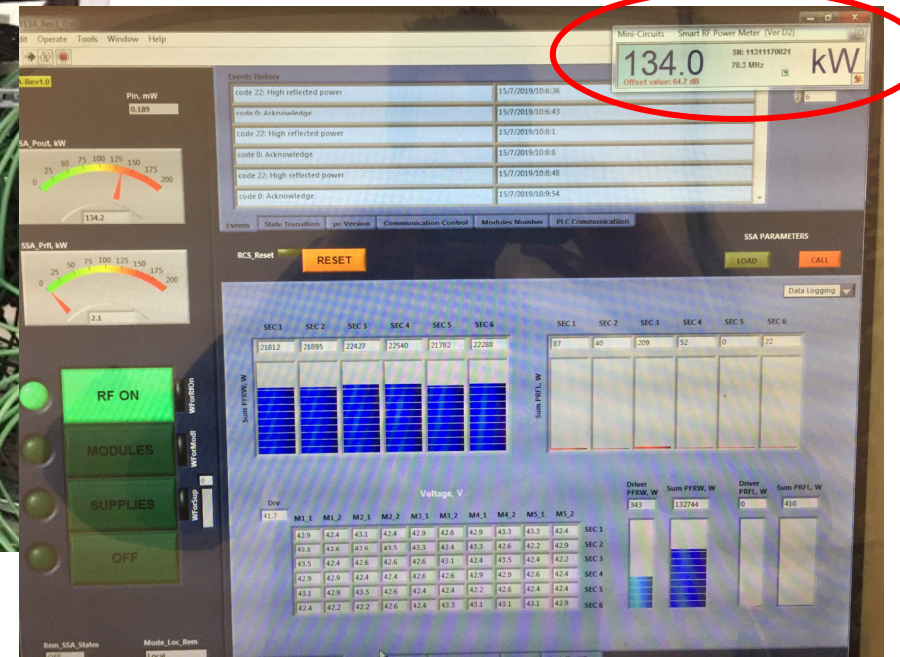


Status FOIK AC226: amplifier adaption by Cryoelectra

Same RF amplification modules, new 60-way RF splitter and combiner



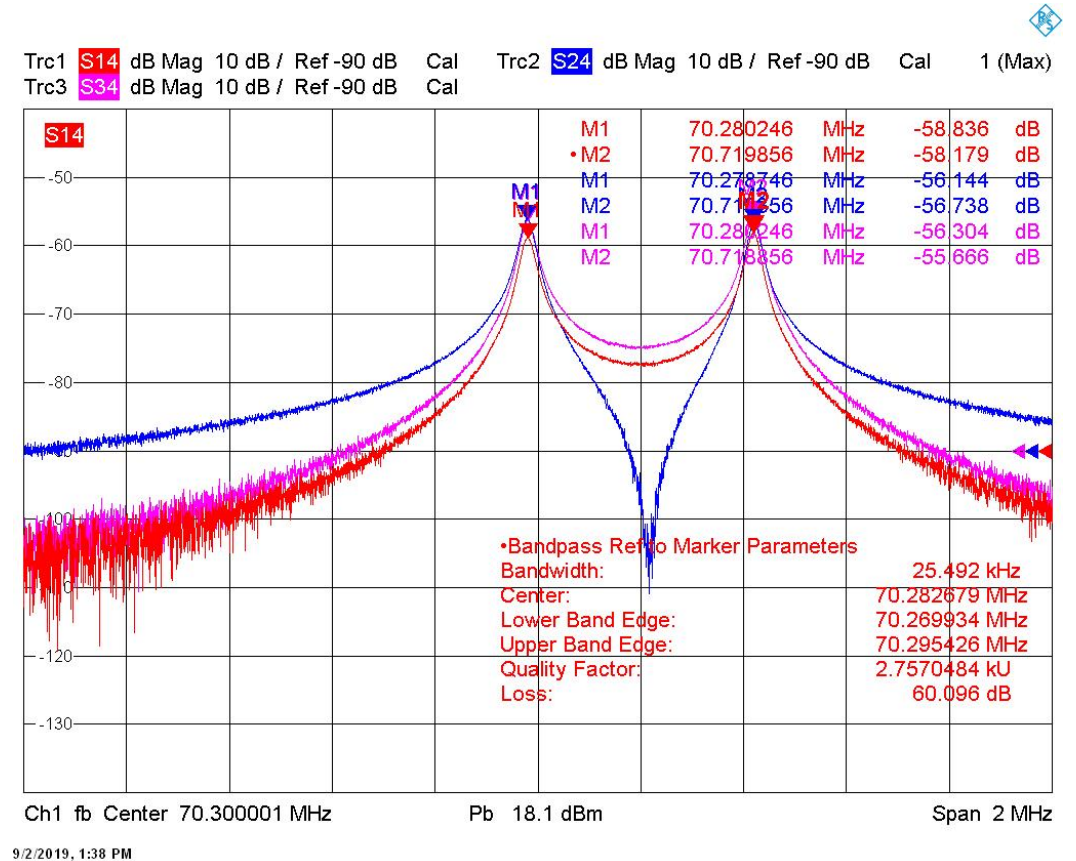
July 2019: rework of existing “old” 312C amplifier in factory to new model 313A, successful high power test at 70.3 MHz on water-load



Status FOIK AC226: RF conditioning ongoing

Installation of RF structures, further CYC subcomponents, installation into factory test-cell completed in August 2019

- RF Cavity system of FOIK tuned to acceleration mode of 70.28 MHz based on low power RF mode measurements
- RF conditioning currently in progress towards nominal RF power of 115 kW
- Start of beam commissioning planned for next week



Conclusion

- VPS performed a program to reduced the cyclotron beam energy to 226 MeV on a short timeline
- Magnetic shimming for 226 MeV successfully conducted for FOIK AC226 machine
- Results of AC226 tracking simulations (central region and extraction) show:
 - No cyclotron hardware changes required (besides adapted shimming), allowing a smooth integration into cyclotron series production
 - At least similar or even better performance compared to AC250 expected
- Successful adaption and high power test of RF amplifier to 70.3 MHz
- FOIK AC226 completely manufactured and installed into test-cell, RF conditioning in progress
- FOIK AC226 beam commissioning will start next week

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Thank you very much for your attention!