ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-FRA03

ENERGY REDUCTION OF VARIAN'S ProBeam 250 MeV CYCLOTRON TO 226 MeV

A. Roth, E. Akcöltekin, O. Boldt, F. Klarner, H. Röcken, T. Stephani, J. C. Wittschen
VARIAN Medical Systems Particle Therapy GmbH, Troisdorf, Germany

Abstract

With its superconducting 250 MeV isochronous proton cyclotron AC250, Varian uses a powerful accelerator for the ProBeam particle therapy systems. However, data from clinical operation has shown that the vast majority of treatments is only making use of proton ranges of less than 30 cm WET (water equivalent thickness), i.e. beam energy of 218 MeV at the patient. This led to a decision at Varian in Dec 2018 to conduct a redesign program with the goal to reduce extraction energy of the ProBeam cyclotron to 226 MeV. We present beam dynamics simulations for the AC226 beam acceleration and extraction. They actually show that only a reduced main coil current and adapted magnetic shimming process, as well as a slightly lower RF frequency is needed for re-tune. Furthermore, results indicate that a similar performance as compared to the AC250 can be expected. A first of its kind (FOIK) AC226 cyclotron is built by seamless integration into Varian's production process. The magnetic field measurement and shimming is completed, in-house RF and beam commissioning is planned for autumn 2019. We report on the status of the FOIK machine.

ProBeam CYCLOTRON

Varian's Proton Solutions (VPS) business unit provides with its superconducting isochronous proton cyclotron AC250 a powerful accelerator for the ProBeam proton therapy platform. With a fixed extraction energy of 250 MeV and extracted beam currents of up to 800 nA, this cyclotron drives proton therapy centers worldwide, many of them already in clinical operation, others currently in an installation and commissioning phase.

Design details of this cyclotron and factory testing including RF and beam commissioning were already reported in [1, 2]. The current status of VPS cyclotron series production is presented in [3].

ENERGY REDUCTION TO 226 MeV

Motivation

During the last decade, analysis of clinical cases has shown that the vast majority of treatments is only making use of proton ranges of less than 30 cm WET (water equivalent thickness), which corresponds to a beam energy of 218 MeV at the patient. Taking into account energy losses and necessary energy degradation of a few MeV from cyclotron exit to gantry isocenter, the corresponding beam extraction energy is 226 MeV. Consequently, the current 250 MeV ProBeam cyclotron is somewhat overdesigned in terms of beam energy, leading to potentially higher building cost for the customer, esp. due to more stringent shielding requirements.

Furthermore, in either case an energy degrader installed behind the cyclotron extraction must be used which lowers the beam energy by moving graphite wedges into the beam path. The energy degradation also leads to significant, needless reduction of beam intensity. This effect can be minimized when the cyclotron generates a lower energy beam already by design, which then results in a lower requirement for the extracted beam current to be provided by the cyclotron.

Therefore, VPS decided in December 2018 to redesign the ProBeam AC250 cyclotron for 226 MeV extraction.

Basic Concept

To achieve a fast integration of the new AC226 machine in VPS's ongoing production, the changes must be as limited as possible. VPS therefore decided not to change the extraction radius of the cyclotron of 816 mm (radius of the septum of the first extraction deflector ED1). Then the extraction of 226 MeV protons requires a lower magnetic field[1] B_{extr} of 2.82 T at 816 mm. Accordingly, the magnetic field[2] B_0 at the cyclotron center needs to be reduced and determines a slightly lower revolution frequency which finally results in change of the 2nd harmonic RF frequency f_{RF} from 72.8 MHz to 70.3 MHz. Since the RF acceleration voltage (roughly 80 kV in the center) is not changed, the mean number of turns until the protons reach extraction radius is decreased to about 580. A comparison of relevant cyclotron parameters for 226 MeV and 250 MeV machines is summarized in Table 1.

Table 1: ProBeam Cyclotron Key Parameters 226 MeV vs. 250 MeV

Parameter	226 MeV	250 MeV
R_{extr}	816 mm	816 mm
B_{extr}	2.82 T	2.98 T
$^2B_0$	2.27 T	2.35 T
I_{coil}	~148 A	~162 A
f_{RF}	70.3 MHz	72.8 MHz
# turns	~580	~650

In practice, adaption and isochronism of the shape of the averaged magnetic field from cyclotron center to extraction can be achieved by reducing the excitation current I_{coil} of the superconducting main coil and by a proper modification of the magnetic shimming of the iron poles.

[1] Azimuthally averaged magnetic field.
[2] $B_0 = B_{\text{extr}} / \gamma$.

22nd Int. Conf. on Cyclotrons and their Applications Cyclotrons2019, Cape Town, South Africa JACoW Publishing
ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-FRA03

In order to operate the AC226 cyclotron at the lower RF frequency, an adaption of the high-power RF amplifier is needed which is designed according to VPS's specifications by the Cryoelectra GmbH, Germany. The bandwidths of the digital LLRF and the cavity system (four spiral-shaped dees) are large enough so that both systems did not require a design change. The eight stems with movable shorting plates of the cavity system provide sufficient tuning range to shift the resonance frequency of the accelerating mode to 70.3 MHz.

Implementation into Series Production

End of 2018, VPS decided to transfer the S23 cyclotron (23rd cyclotron of VPS's production series) – which at that time was ready for magnetic field mapping in the factory – into the first AC226 machine. In the first quarter of 2019, the field mapping and shimming for 226 MeV were conducted. This first of its kind (FOIK) AC226 machine marked the starting point for a seamless adaption of VPS's cyclotron manufacturing. Simultaneously, a comprehensive beam dynamics simulation program was conducted and showed that smooth integration in the series production without major design changes is possible.

MAGNETIC SHIMMING PROCESS

The field of the FOIK has been measured with VPS's standard magnetic field mapping machine using a search coil, voltage integration, and absolute calibration by NRM measurements. Based on these field data, the phase advance per turn as well as the radial (ν_r) and vertical (ν_z) betatron frequencies were determined by equilibrium orbit computations up to 226 MeV. Required changes of the magnetic field shape to ensure isochronism as well as radial and vertical beam focusing were determined and transferred to precision machining of the shim plates[3]. The complete process for the FOIK consisted of one pre-machining step and two iterative steps of field mapping, computation, machining, and verification measurements. The final verification is presented in Figure 1 and Figure 2 and shows similar or even better results for isochronism and focusing properties as compared to the AC250 cyclotrons.

BEAM DYNAMICS SIMULATIONS

The shimming and equilibrium orbits computations presented above, and following beam dynamics simulations were conducted with the particle tracking software CYCTRACK, an in-house developed code of ACCEL[4], derived in parts from the NSCL tracking codes Z3CYCLONE and SPRGAP [4]. Based on electrical field maps existing for the 250 MeV cyclotrons and measured magnetic field maps from FOIK field mapping, tracking computations were performed starting from the chimney opening of the internal ion source (IS) up to the target energy of 226 MeV and through the extraction channel. Starting conditions of the protons at the chimney were varied over a complete set of horizontal and vertical positions and angles as well as starting phases[5], representing a realistic beam of a few thousand particles.

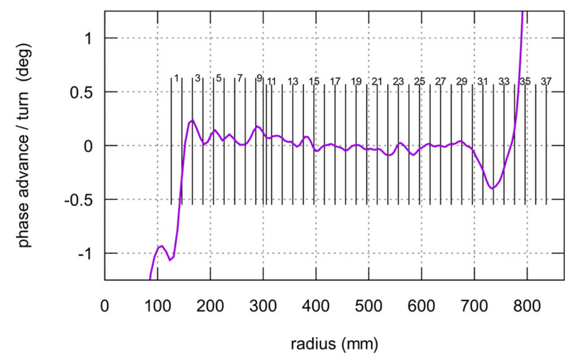

Figure 1: Phase advance per turn vs. cyclotron radius after completion of AC226 shimming. #1 - #37 indicate radial positions of the milling stripes on the shim plates.

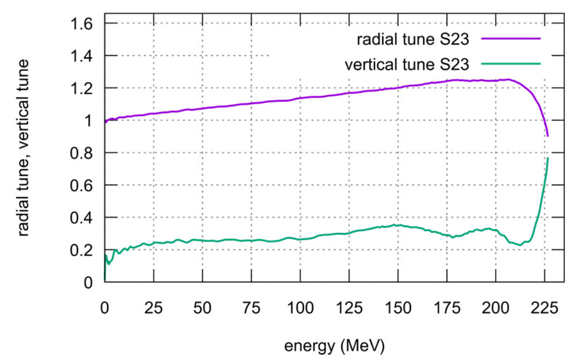

Figure 2: Tunes (ν_r and ν_z in units of revolution frequency) vs. beam energy for AC226. The vertical focusing for energies larger than 10 MeV exceeds 0.2 (for AC250 it was only 0.15).

Central Region Simulations

Figure 3 shows a tracking simulation in the horizontal plane of the central region (CR) with 6125 particles started at the IS. After transit through the puller nose of dee 1, the beam has to pass the first fixed (phase) slit (FS) in dee 2 nose. Starting phases at the IS were varied from 226° to 231° in one-degree steps which ensured that the beam was radially covering the complete FS. Radial position and width of the FS were optimized for a central passage through the subsequent dee noses and for a good compromise between beam intensity output from the FS and clear turn separation at higher radii[6]. Compared to the FS usually used for the AC250 beam commissioning, its radial position was shifted by about 1 mm outside for these tracking computations to take the slightly larger radius of the beam into account.

Based on the presented results which are supported by further simulations also for the vertical phase space and

[3] Iron plates mounted on top of each magnet hill allowing to remove material for magnetic shimming along 37 dedicated stripes at the hill edges.
[4] ACCEL Instruments GmbH, acquired by Varian in 2007.

[5] Starting phase is defined as phase in degrees with respect to the phase of the RF field.
[6] Turn separation at higher radii is essential to achieve a sufficient dynamic range for setting the cyclotron beam current for clinical applications via adjustable slits positioned at 20 cm radius.

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-FRA03

compared to similar simulations for the AC250 machine, e.g. [5], it was concluded that no hardware changes in the CR for AC226 are needed.

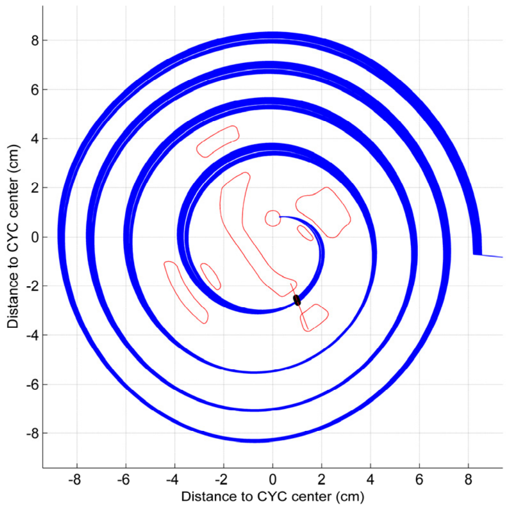

Figure 3: Tracking simulations in horizontal midplane of the CR with RF dee noses (red contours): 60% of the protons started at IS are stopped at FS edges (black dots) within dee 2 nose, protons passing the FS are accelerated further without any beam loss.

Beam Extraction Studies

The extraction path of the ProBeam cyclotron comprises two electrostatic deflectors (ED1, ED2) and six passive magnetic elements (combined dipoles/quadrupoles, M1 – M6) guiding the beam into the exit tube. Using eight adjustable trim rods (TR) positioned close to the $\nu_r = 1$ resonance, a 1st harmonic magnetic field bump is created for separation of the accelerated beam into ED1.

To extend the available magnetic field data from FOIK field mapping also along the extraction path, magnetic field maps computed for a complete cyclotron model with the TOSCA software package were patched to the measured data. On that base, detailed studies of the beam extraction have been conducted. As an example, in Figure 4 the continuation of the CR tracking simulation presented in Figure 3 is shown along the extraction path and in vertical phase space. The extracted beam is characterized by no particle losses in M1 to M6 and only minor losses at or within the EDs, by a mean energy of (226.2 ± 0.1) MeV, and by a vertical beam width (1σ) of ±2 mm.

By optimization of hardware settings and operational parameters in the simulation like main coil current, TR settings, ED field strengths, positions of EDs and magnetic elements, overall extraction efficiencies[7] (EE) in the range of 70% to 85% could be finally calculated.

During these studies, it turned out that to obtain such high EEs it was required to increase the electrical fields of the EDs by up to 20% as compared to the AC250 settings, resulting in absolute values of up to 110 kV/cm for AC226. The higher deflection field is required to compensate the stronger radial beam focusing of $\nu_r = 0.95$ at extraction energy, whereas ν_r is 0.74 in case of AC250.

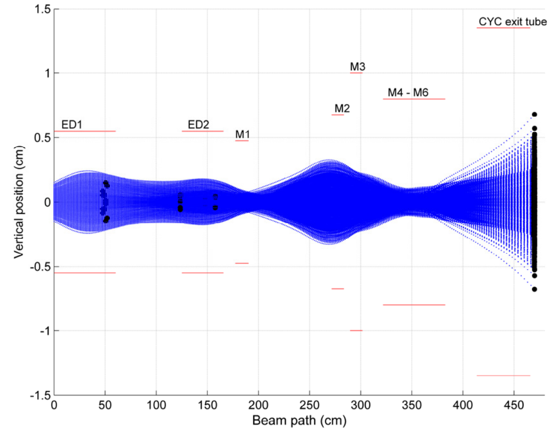

Figure 4: AC226 extraction: vertical proton position vs. beam path in the extraction channel. Aperture of EDs and M1-M6 are shown by red lines. Black dots indicate protons extracted or stopped at ED1 or ED2 (protons stopped by the septum edge of ED1 at position 0 cm are not marked).

Extraction Energy

During beam commissioning, measurement of overall EE in dependence of main coil current is a standard method to determine the working point and stability of the cyclotron which is especially important for clinical operation. Consequently, several sets of extraction tracking computations for different coil currents were performed. In addition to EE calculations, the mean energy of the extracted beam was determined with the goal to tune the cyclotron by optimization of the RF frequency to the target extraction energy of (226.0 ± 0.5) MeV.

In Figure 5, the overall EEs (FS to CYC exit, green curve) obtained from tracking computations for main coil currents between 147.77 A and 147.85 A and for an optimized RF frequency of 70.2803 MHz are shown. Within a coil current range of 25 mA an overall EE larger than 70% could be achieved while the mean number of turns reached a minimum value of around 580. Based on the number of protons reaching the exit of ED1, a second EE value (FS to ED1 exit) was calculated (purple curve in Figure 5). This EE is higher than the overall EE, showing that further optimization of settings and element positions, e.g. of ED2 and M1 - M6, could result in even higher overall EEs. For the highest overall EE of 83% at a coil current of 147.82 A, the extraction energy averaged over all extracted protons (#2131) is (226.3 ± 0.1) MeV.

STATUS FOIK AC226

The beam dynamics simulations for the AC226 cyclotron show a similar or even better performance as compared to simulation results obtained for AC250. No design changes in addition to the modified magnetic shimming for 226 MeV had to be implemented into the FOIK, and the regular manufacturing process (installation of RF structure and further subcomponents, transport and installation into factory test-cell) was completed in August 2019.

[7]The overall extraction efficiency is calculated by #protons extracted out of the CYC (CYC exit), divided by #protons passed the FS.

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-FRA03

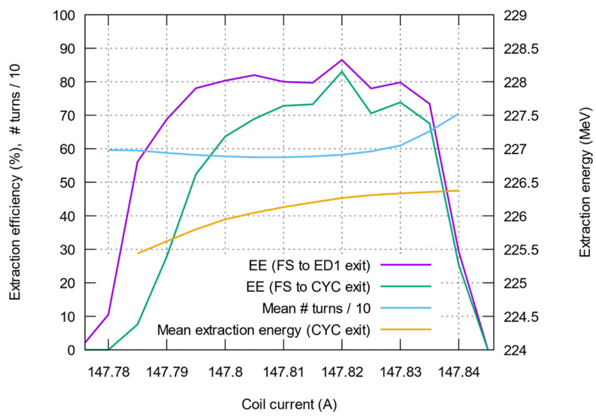

Figure 5: EE simulations for different main coil currents and optimized RF frequency of 70.2803 MHz to tune AC226 close to an extraction energy of 226 MeV. Optimum working point is around 147.82 A.

Adaption of RF Amplifier

In July 2019, Cryoelectra GmbH finalized the adaption of their existing high power, solid-state 72.8 MHz RF amplifier (model 312C) using newly designed splitter and combiner units for 70.3 MHz. This new RF amplifier (313A) is operating with the same RF power amplification modules than used for 312C amplifier. The 313A was successfully tested up to an RF output power of more than 130 kW on a water load in VPS's factory.

RF and Beam Commissioning

In September 2019, the RF commissioning process of the FOIK AC226 was started. Figure 6 shows a low power mode measurement via the coaxial RF line and dee pick-ups using a network analyzer. Positions of the eight shorting plates in the stems were adjusted to achieve a uniform balance of the electric fields and to tune the resonance frequency of the desired push-pull mode (1st mode) close to the RF frequency of 70.28 MHz.

With the 313A amplifier in operation, the cavity system of the FOIK is currently conditioned. After reaching stable RF operation at the nominal power of 115 kW, the AC226 beam commissioning will start. An integral part of the beam commissioning will be the verification of key specifications, e.g. overall EE and final beam energy. To determine the beam energy, a water phantom is currently installed in the test cell allowing Bragg peak range measurements.

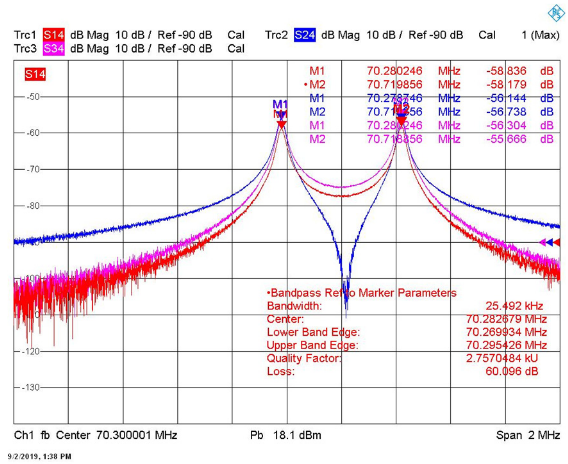

Figure 6: Mode measurement of FOIK AC226 cyclotron under vacuum using pick-up signals from dee 1 (red curve), dee 2 (blue curve) and dee 3 (magenta curve): 1st mode (push-pull mode) tuned to 70.28 MHz and same level as 3rd mode (pull-pull mode), while 2nd mode is suppressed.

CONCLUSION

On a short timeline, VPS realized a re-design program to reduce the energy of the ProBeam cyclotron to 226 MeV. Detailed tracking simulations for AC226 indicate that a similar performance as for the AC250 machine can be expected. Only ten months after the project kick-off RF commissioning of the FOIK started and the first extraction of 226 MeV beam is planned for October 2019.

ACKNOWLEDGEMENT

We thank Christian Baumgarten (PSI, Switzerland) for fruitful discussions and remarks.

REFERENCES

[1] A. E. Geisler *et al.*, "Commissioning of the accel 250 MeV proton cyclotron", in *Proc. 18th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'07)*, Italy, Oct. 2007, pp. 9-14.

[2] H. Röcken *et al.*, "Progress at Varian's superconducting cyclotrons: A base for the ProBeam platform", in *Proc. 20th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'13)*, Vancouver, Canada, Sep. 2013, pp. 55-57.

[3] O. Boldt *et al.*, "Manufacturing and commissioning of cyclotrons in a series production at Varian", presented at the 22nd Int. Conf. on Cyclotrons and their Applications (Cyclotrons'19), Cape Town, South Africa, Sep. 2019, paper TUP017, this conference.

[4] MSU NSCL Accelerator Group: Z3CYCLONE Instruction Manual, Version 4.0, Michigan State University, East Lansing, 2 March 1993.

[5] C. Baumgarten *et al.*, "A beam profile measurement in the ACCEL 250 MeV medical proton cyclotron", *Nucl. Instrum. Methods Phys. Res., Sect. A,* vol. 569, pp. 706-712, Dec. 2006. doi:10.1016/j.nima.2006.09.077