ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEA001

OPAL SIMULATION ON THE BEAM TRANSMISSION IN THE CENTRAL REGION OF THE MEDICAL CYCLOTRON COMET AT PAUL SCHERRER INSTITUTE

H. Zhang†, Ch. Baumgarten, P. Frey, M. Hartmann, R. Kan, M. Kostezer, A. Mülhaupt, M. Schippers, A. Schmidt, J. Snuverink, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

Abstract

The use of the medical cyclotron COMET for FLASH proton therapy requires a high beam transmission from the ion source through the central region apertures. This paper first presents a model of the COMET cyclotron featuring a rotatable ion source, a movable puller, and an adjustable first fixed slit (FFS), implemented with the OPAL framework. The electromagnetic field is individually created to match each specific configuration. The beam optics parameters, especially beam position and beam size upon approaching and after passing FFS, have been studied in detail. The OPAL simulations demonstrate that an optimal configuration of the ion source, the puller and the FFS is key to achieve a high beam transmission. An experimental test gave a 2.8 times higher intensity within COMET cyclotron with the modifications derived on the basis of the simulations: a 0.57 mm shift of puller and a 5.6° rotation of ion source. The simulations indicate that, with these modifications, the beam can still be centered and accelerated to the extraction energy of 250 MeV. Next step is to investigate the influence of such modifications upon the acceleration and the extraction, again with an iterative approach combining simulations and experiments.

INTRODUCTION

The compact superconducting cyclotron COMET delivers a 250 MeV beam for proton therapy at PSI [1-2]. The central region of the cyclotron, consisting of the ion source, the puller and the first fixed slit (FFS) as shown in Fig. 1, has been under investigation and development throughout the stages of design, commissioning, and routine operation [3-7]. It was recently reported that the beam transmission from the ion source passing through the FFS could be increased up to 60% after a puller shift of 0.56 mm towards the centre [8]. A high FFS transmission is an important step towards extracting beam of high intensity desirable for FLASH proton therapy as well as for patient treatment in a shorter treatment time in order to mitigate problems of organ motion during the treatment. Simulation may lead to a quantitative understanding on the factors correlated with FFS transmission, and to explore improvement potential. OPAL, a parallel open source tool developed at PSI for charged-particle optics in accelerators and beam lines [9], is suited not only for high intensity machines like PSI Ring Cyclotron operating up to 2.4 mA, but also for the medical cyclotron COMET extracting a beam well below 1 µA [6].

† hui.zhang@psi.ch

OPAL SIMULATION

Model of Central Region of COMET Cyclotron

As shown in Fig. 1, three key components in the central region, namely the chimney of the ion source, the puller, and the FFS, are approximated with multiple rectangular pieces, the only form to specify a collimator inside a cyclotron for OPAL simulation. In OPAL input, the chimney may be rotated around its axis, and the puller may be shifted towards the centre. We considered rotation angles θ in the order of a few degrees and displacements s in the sub-millimetre range. Furthermore, the position of the FFS may be shifted while its aperture may be varied. In practice, it is rather cumbersome to adjust the position of the real FFS. However, an FFS with an aperture of 0.16 mm, 0.18 mm, or 0.2 mm, has been applied for routine patient treatment. An FFS of 0.2 mm aperture is mostly used for both simulation and operation. In OPAL the model of COMET cyclotron is a mirror image of the real machine.

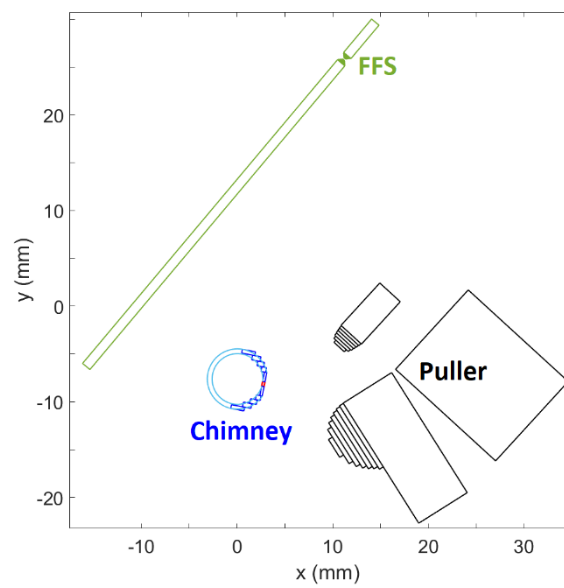

Figure 1: OPAL model for central region of COMET.

Field Maps for Particle Tracking

OPAL features particle tracking through multiple field maps, 2D and 3D, electric and magnetic, static and time varying, separated and overlapped, which is essential for the simulation of the central region of COMET cyclotron. Figure 2 shows the static magnetic field map in the median plane, while Fig. 3 shows the magnitude of the E component of the RF field in the median plane.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEA001

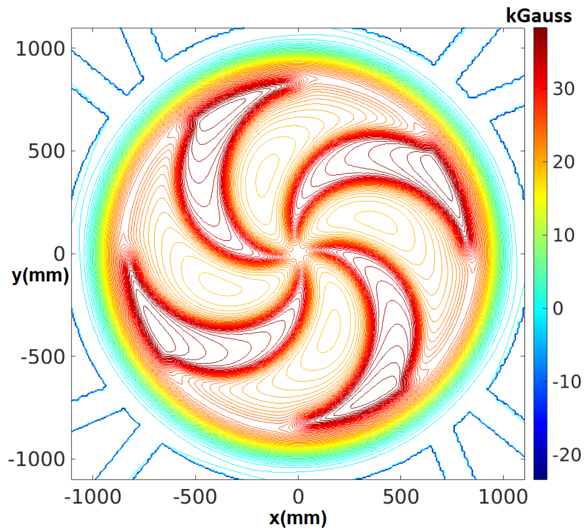

Figure 2: Map of static magnetic field in median plane.

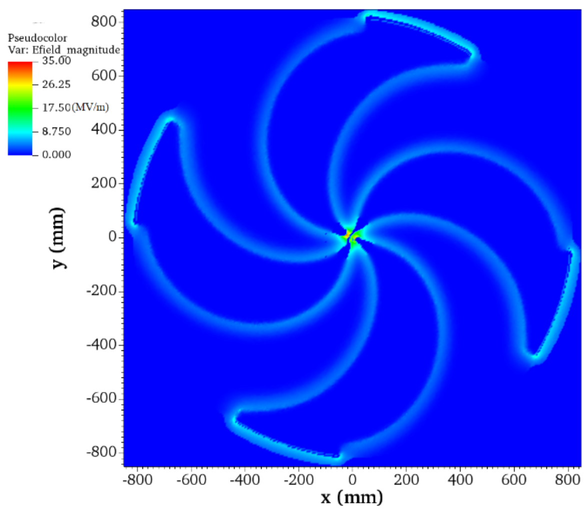

Figure 3: Map of E-magnitude of RF field.

Start Position for Particle Tracking

The so-called reference particle starts from the centre of a zero potential surface at the chimney opening, which is determined with the finite element (FE) method applying the program ANSYS. The peak voltage V_0 of the puller is approximately 80 kV [10], and the voltage V of the puller varies with the time t according to

$$V = -V_0 cos(\omega t + \phi_0), \qquad (1)$$

where $\omega = 2\pi f$ and f = 72.61 MHz for OPAL simulation.

The zero potential surface and the electrostatic field in the central region is individually calculated for a specific configuration defined by the parameters (θ, s, ϕ_0). V = $-80\cos(\phi_0)$ kV is applied at the puller which is the most central part of Dee 1, as well as on Dee 3 which is opposite to Dee 1. V = $+80\cos(\phi_0)$ kV is applied on Dee 2 and Dee 4 which are at 180° RF-phase with respect to Dee 1 and Dee 3. The FFS lies entirely within Dee 2 having little influence on the field calculation. ϕ_0 is the initial RF phase when the tracking starts at t = 0, and must be in the range between -90° and 0°, so that the protons can be pulled out of the chimney and be further accelerated to the FFS.

Figure 4 shows zero potential lines in the median plane corresponding to ϕ_0 = -80°, -60°, -40°, -20° and 0° for the original configuration. Figure 5 shows the E-field map between the chimney and the puller in the median plane for the configuration of 5.6° chimney rotation and 0.57 mm puller shift.

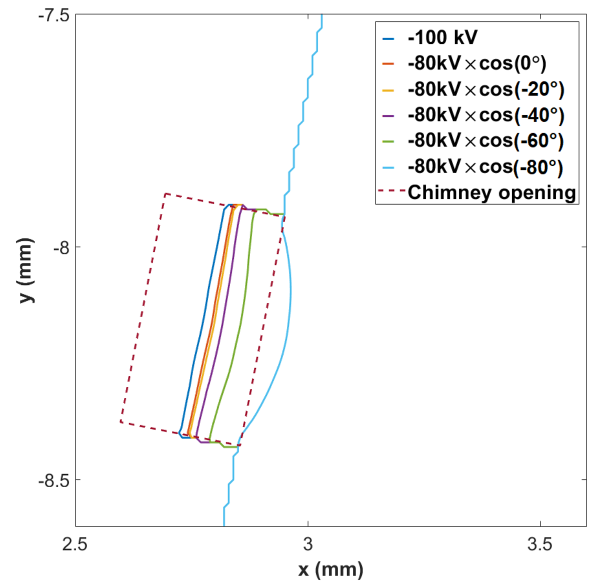

Figure 4: Zero potential lines in chimney opening for different puller voltages (i.e. RF phases).

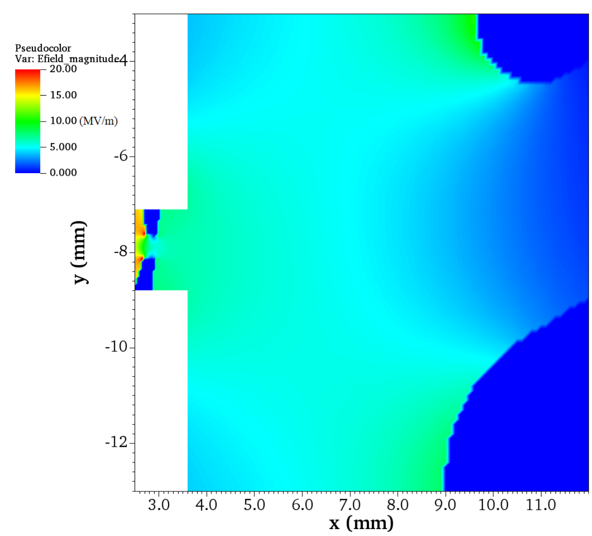

Figure 5: Map of E field in the median plane between chimney (left) and puller (right), (θ, s, ϕ_0. V_0) = (5.6°, 0.57 mm, -60°, 80 kV).

Initial Conditions for Particle Tracking

The initial energy and the initial momentum of the reference particle is set to 1 eV and 43319 eV/c, respectively [4]. The opening of the chimney is 0.5 mm wide (horizontal direction x) and 3 mm high (vertical direction z). 10000 protons are generated from a Gaussian distribution with σ_x = 0.083 mm, σ_y = 0, σ_z = 0.5 mm, and $\sigma_{px} = \sigma_{py} = \sigma_{pz}$ = 30631 eV/c. y is basically the longitudinal direction and parallel to the direction of the reference particle at t = 0.

23rd Int. Conf. Cyclotrons Appl. CYCLOTRONS2022, Beijing, China JACoW Publishing
ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEA001

Beam upon Reaching FFS

Beam position and shape upon reaching the FFS are dependent on θ, s, ϕ_0 and V_0. Figure 6 shows the particle distribution on the front surface of the FFS plate for ϕ_0 from −85° to −25° in 5° step, while (θ, s) = (0, 0). A photo of the FFS with irradiation trace is inserted on the top left corner of the figure.

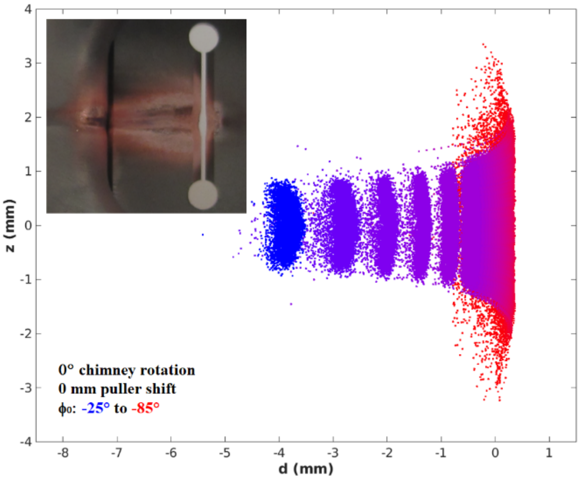

Figure 6: Proton distribution on the front of FFS.

In order to quantify the beam position and size upon reaching the FFS, an axis is defined by the intersection of the FFS front surface and the median plane. The axis points outwards and the origin is the projection of the centre of the FFS aperture on the axis. The average position d measured on the axis and its RMS σ_d can be derived for chosen ϕ_0 and V_0. In Fig. 7, d and σ_d are plotted against ϕ_0 for two configurations (θ, s) = (0, 0) and (θ, s) = (5.6°, 0.57 mm), while V_0 = 79.6 kV. The FFS of 0.2 mm aperture is at its original position, and marked by two dashed green lines on the plot.

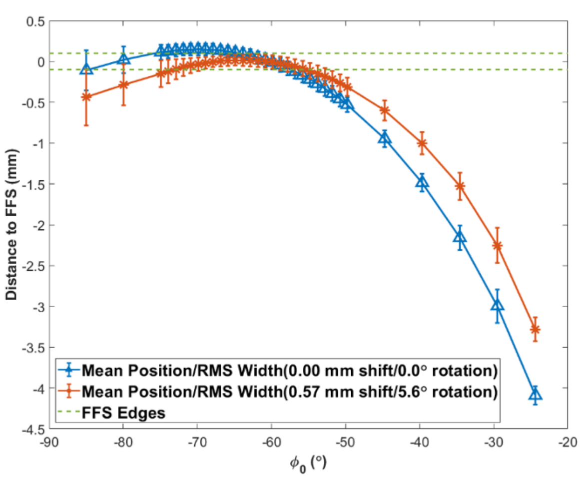

Figure 7: Beam position and size upon reaching FFS.

Transmission Passing FFS

For chosen (θ, s, ϕ_0, V_0), the number of protons passing through the FFS can be readily derived from particle tracking. In Fig. 8 this is plotted against ϕ_0 for (θ, s) = (0, 0) and (5.6°, 0.57 mm), while V_0 = 79.6 kV and a FFS of 0.2 mm aperture is at its original position. The total FFS transmission may be calculated by an integration over ϕ_0, equivalent to an integration over time. The ratio of the integrated FFS transmissions for the above two configurations is around 1.72.

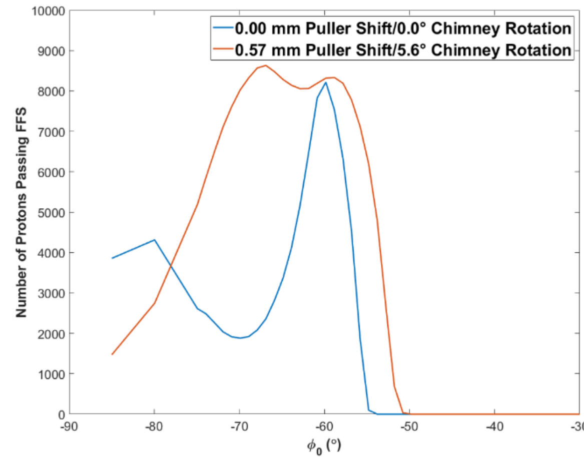

Figure 8: Protons passing FFS with respect to ϕ_0.

The integrated FFS transmission from OPAL simulation may be plotted against V_0, as shown in Fig. 9 for (θ, s) = (0, 0) and (5.6°, 0.57 mm), respectively. In general, the integrated FFS transmission is practically zero if V_0 is so low that the proton is not sufficiently accelerated to reach the FFS aperture. When V_0 increases, the FFS transmission increases and peaks at a certain value V_0. However, the FFS transmission starts to decrease when V_0 is increased further, as the protons are accelerated to a radius higher than the FFS aperture.

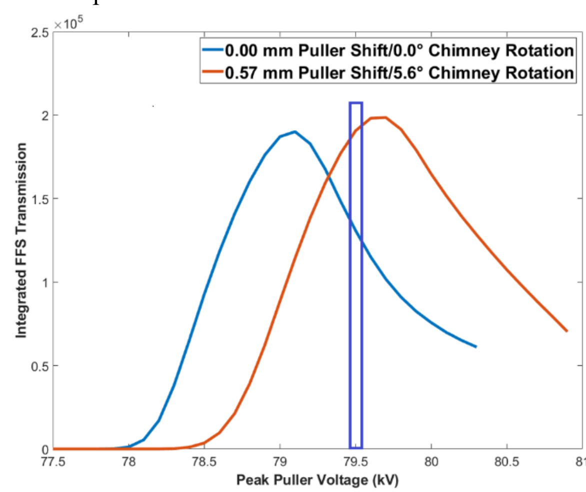

Figure 9: Integrated FFS transmission with respect to V_0.

EXPERIMENT

In order to catch the proton beam passing the FFS, the radial probe is moved to the inner most position, that is 310 mm to the machine centre [1, 7], and the beam path between the FFS and the radial probe is completely cleared out. With a FFS of 0.16 mm aperture a beam current of 368 nA was detected with the radial probe. Then the puller was shifted 0.57 mm towards the centre and the chimney was rotated 5.6° clockwise (anticlockwise in simulation).

This modification was performed in parallel with the installation of a new FFS of 0.2 mm aperture as required by the following patient treatment. Subsequently 1310 nA were collected at the radial probe, while the arc current and voltage of the cold cathode ion source were kept unchanged [7]. This corresponds to improvement of the FFS transmission by a factor of 2.8.

Furthermore, the beam current on the radial probe was measured as a function of the RF voltage after reducing the arc current from 80 mA to 50 mA. Figure 10 shows the plot of the beam current RMJ:IST1:2 in nano-Ampere against CMJLL:SOLA:2 in Volt, which is the average of voltages on pickups inside the Dees, and is 8.4 V during normal operation. A comparison between the measurement and the simulation suggests that CMJLL:SOLA:2 = 8.4 V corresponds to a voltage V_0 around 79.6 kV [7]. This is in good agreement with the X-ray spectral measurement [10].

Figure 10 shows that the FFS transmission is almost at the peak when the Dees are running at the operation point, which implicates that the new configuration is almost optimal for the FFS transmission.

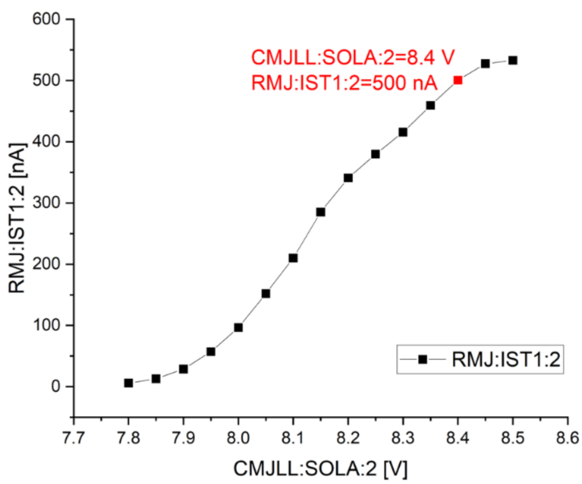

Figure 10: Beam intensity collected by the radial probe against the average of voltages on pickups in the Dees.

DISCUSSION AND CONCLUSION

It is a simplification to assume a constant V_0 over the puller. Nevertheless, it is a normally used and accepted method to investigate the central region of a cyclotron with an electrostatic approach [3-4]. There also seems to be evidence that the plasma boundary bulges out of the chimney aperture when a negative electrostatic voltage on the puller is approaching zero [3]. Therefore we not only take the zero potential surface as the plasma boundary, but further assume the oscillation of the plasma boundary with RF frequency.

It might be reasonable to assume that the reference particle starts from the centre of the zero potential surface, that its initial direction is perpendicular to the zero potential surface, and that the initial energy is around 1 eV. Nevertheless, the initial distribution is likely not Gaussian. Moreover, the proton beam current is likely not constant but rather dependent on many factors like the puller voltage [3].

In spite of the uncertainties of the initial conditions for particle tracking, the OPAL simulation still delivered results that were comparable with experimental observations. The beam distribution from particle tracking agrees well with the image of irradiation trace on the front surface of the FFS. Both simulation and measurement demonstrate that the FFS transmission may be significantly improved by a 5.6° chimney rotation combined with a 0.57 mm puller shift.

Our results show that the reference orbit can still be centred with this modification of the central region. The configuration may be further optimized to achieve even higher FFS transmission. In future work we will verify whether the beam of higher intensity inside the cyclotron can be extracted out of the cyclotron with sufficiently high efficiency, again with an iterative approach combining simulations and experiments.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. O. Boldt from Varian Medical Systems for communicating their results and experience, L. Stingelin for providing the RF map, and M. Schneider for support on the experiment with RF.

REFERENCES

[1] A. E. Geisler *et al.*, “Commissioning of the ACCEL 250 MeV proton cyclotron”, in *Proc. Cyclotrons’07*, Giardini Naxos, Italy, Oct. 2007, pp. 9-14.

[2] J. M. Schippers *et al.*, “The SC cyclotron and beam lines of PSI’s new proton therapy facility PROSCAN”, *Nucl. Instrum. Methods Phys. Res. Sect. B,* vol. 261, pp. 773-776, 2007. doi:10.1016/j.nimb.2007.04.052

[3] J. R. Schubert, “Extending the feasibility boundary of the isochronous cyclotron”, Ph.D. thesis, Michigan State University, East Lansing, USA, 1997.

[4] Ch. 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, 2006. doi:10.1016/j.nima.2006.09.077

[5] J. M. Schippers *et al.*, “Beam intensity stability of a 250 MeV SC cyclotron equipped with an internal cold-cathode ion source”, in *Proc. Cyclotrons’07*, Giardini Naxos, Italy, Oct. 2007, pp. 300-302.

[6] H. Zhang *et al.*, “OPAL simulation for PSI medical cyclotron COMET”, presented at the 38th European Cyclotron Progress Meeting (ECPM’12), Paul Scherrer Institut, Villigen, Switzerland, May 2012, unpublished.

[7] M. Hartmann, “Beam dynamics in the central region of the COMET cyclotron”, Master thesis, EPFL, Lausanne, Switzerland, 2020.

[8] O. Boldt, Varian Medical Systems Particle Therapy GmbH, private communication, Feb. 2020.

[9] A. Adelmann *et al.*, “The OPAL Framework (Object Oriented Parallel Accelerator Library) Version 2.4.0 User’s Reference Manual”, Oct. 2021. https://gitlab.psi.ch/OPAL/src/-/wikis/home

[10] J. H. Timmer *et al.*, “Dee voltage calibration for the ACCEL proton therapy cyclotron”, in *Proc. ICAP’06*, Chamonix, France, Oct. 2006, pp. 102-105.