DESIGN AND OPTIMIZATION OF A FAST ELECTROSTATIC CHOPPER FOR FLASH PROTON THERAPY RADIOBIOLOGY EXPERIMENTS

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Abstract

FLASH proton therapy has shown the potential to reduce normal-tissue toxicity while maintaining tumor control by delivering radiation in ultra-high dose-rate pulses (>40Gy/s). However, more radiobiology experiments are needed to better understand the subjacent mechanism and optimize its application beam parameters. To explore this regime using the Cyclotron at Centro Nacional de Aceleradores in Seville, we have developed a fast electrostatic chopper for beam length structure manipulation in order to be able to produce short and high intensity pulsed beams. In this paper, we present the design and optimization of this device, intended to generate well-defined beam pulses for radiobiology experiments in the FLASH regime. Electromagnetic simulations were performed with CST Particle Studio to define the electrode geometry, determine the required operating voltage, and carry out tolerance studies for the mechanical design. The designed chopper was integrated into a full TOPAS model of the external cyclotron beamline to evaluate the need of additional subsystems such as slits for bema size control at the entrance of the electrostatic chopper and a collimator to absorb the deflected beam. First studies carried out with this model are also presented.

INTRODUCTION

In recent years, FLASH radiotherapy has emerged as a promising technique capable of reducing normal tissue toxicity while preserving tumor control when radiation is delivered at ultra-high dose rates, typically above 40 Gy/s, although the underlying mechanisms remain under investigation [1]. Experimental studies have explored this effect using electron, photon, and proton beams, with proton FLASH therapy attracting particular interest due to its favorable depth-dose distribution and precise tumor targeting capabilities. Several facilities worldwide have adapted cyclotrons and synchrotrons to investigate this regime; however, limitations in beam delivery systems, especially regarding temporal beam structure and dose-rate control, still hinder systematic radiobiological studies.

In this context, this work presents the technological developments carried out to establish a platform for FLASH proton beam studies at the Centro Nacional de Aceleradores (CNA). The facility operates an IBA Cyclone 18/9 cyclotron capable of accelerating protons and deuterons up to 18 MeV and 9 MeV, respectively, and includes an external research beamline for applied beam physics experiments. This work focuses on the electromagnetic (EM) design and installation of a fast electrostatic chopper for temporal beam shaping, adjustable slits for transverse beam control, and initial TOPAS simulations to evaluate and optimize the system performance.

EM AND MECHANICAL DESIGN

Electrostatic choppers are widely used in accelerator to manipulate the temporal structure of charged particle beams using time-dependent electric fields. By applying synchronized voltage pulses to a pair of electrodes, selected portions of the beam can be transmitted or deflected, enabling the generation of short beam pulses with controlled temporal characteristics. Their fast response, precise timing control, and non-interceptive operation make them well suited for applications requiring flexible beam shaping and high temporal resolution [2]. They consists of two parallel electrode plates installed inside an ultra-high-vacuum (UHV) chamber and separated by a fixed gap. The achievable beam deflection, y(V), depends on the applied voltage, beam energy, and electrode geometry according to:

$$y(V) = \frac{q_p \cdot V \cdot L}{d \cdot m_p \cdot v^2} \cdot \left(D + \frac{L}{2}\right) \tag{1}$$

where q_p and m_p are the proton charge and mass, respectively; V is the applied voltage; L is the electrode lenght, d is the inter-electrode gap; D is the distance from the end of the chopper to the observation point; and v is the proton velocity. In addition, the deflection angle induced by the chopper can also be estimated as:

$$\theta(V) = \frac{q_p \cdot V \cdot L}{d \cdot m_p \cdot v^2} \tag{2}$$

To evaluate the feasibility of the proposed system for its implementation at CNA, the beam deflection downstream of the electrostatic chopper was analytically calculated using Eq. 1 for different operating voltages. The study considered an 18 MeV proton beam, a fixed inter-electrode gap d of 24 mm, a distance D of 1.344 m, and electrode lengths of 300 mm and 350 mm. Figure 1 shows the comparison of the deflection obtained for different operating voltages using

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Eq.(1) and using CST-PS at the chopper exit (M2) and at a distance D downstream (M1). A good agreement between analytical and the 3D EM simulations.

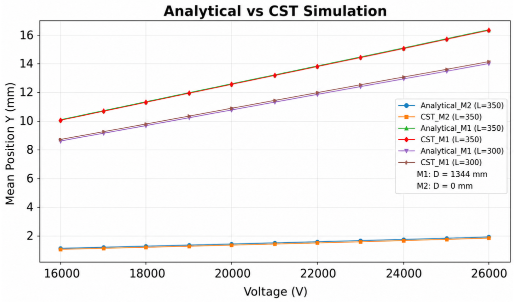

Figure 1: Analytic and CST-PS deflection effect comparison.

To assess the impact of mechanical tolerances on the chopper performance, EM simulations were performed using CST-PS including variations of the inter-electrode gap (d), electrode dimensions (h,L), and horizontal and vertical alignment with respect to the beam axis. Asumming a fixed operating voltage of 26 kV the beam deflection was evaluated from the mean transverse beam position at 1.344 m downstream of the chopper. The results are summarized in Table 1.

Table 1: Mean Position Deflection for Different Parameters.

Parameters	**Range**	$\boldsymbol{\Delta_y}$	$\boldsymbol{\Delta_x}$
d (0.2) [mm]	(23,25)	(0.719,-0.665)	(-0.003,-0.007)
d (0.05) [mm]	(23.9,24.1)	(0.064,-0.065)	(-0.003,0.004)
h [mm]	(39,41)	(-0.009,0.004)	(-0.001,-0.019)
L [mm]	(349,351)	(-0.021,0.018)	(-0.013,-0.012)
x [mm]	(-1,1)	(0.022,-0.008)	(0.003,-0.014)
y [mm]	(-1,1)	(0.008,-0.013)	(-0.032,0.009)
θ_{sym} [rad]	(-1,1)	(-1.13,1.94)	(-0.009,0.002)
θ_{asym} [rad]	(-1,1)	(0.099,-0.05)	(-0.002,0.001)

This study shows that the chopper performance is robust against most geometrical variations, including electrode height, length, and horizontal and vertical alignment. The inter-electrode gap positioning was identified as the most critical parameter. Considering a typical CNA uniform beam at the chopper location of 8 mm radius, a deflection error of 1 mm in the worst direction could imply that about 6 % of the particles pass through without being absorbed at the exit window collimator. Since the system is intended to operate in high-intensity regimes, it is preferable to keep this fraction below 1 %, which can be achieved by maintaining mechanical tolerances below 100 µm as shown in Tab. 1. To ensure electrode positioning, spacing, and parallelism, adjustable ceramic supports were developed together with a dedicated alignment tool based on a calibrated gauge block. This system enabled precise centering of the electrodes within the vacuum chamber and maintained the nominal 24 mm gap with a 50 µm accuracy.

The mechanical design, shown in Fig. 2, was constrained by high-voltage and ultra-high-vacuum (UHV) requirements. To prevent electrical breakdown, minimum clearances of 8.3 mm between high-voltage and grounded components were adopted based on a 3 kV/mm criterion, while a more conservative 25 mm clearance was used for the supports.

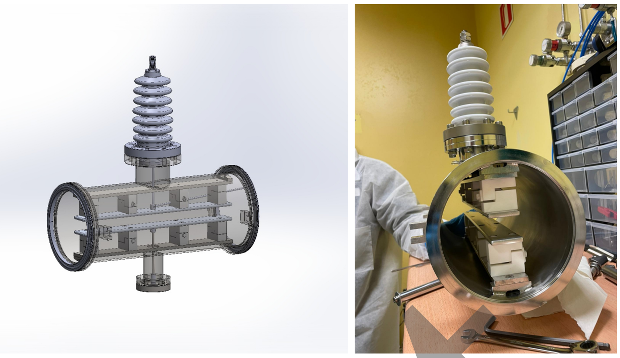

Figure 2: Chopper design (left) and prototype (right).

The UHV chamber was manufactured from AISI 316L stainless steel, whereas the electrodes were made of low-alloy aluminum EN AW-1350 (Al ≥ 99.5 %) to minimize residual activation despite its higher machining difficulty. EM simulations performed with CST PS showed a negligible effect of plate thickness on the electric field distribution Fig. 3; therefore, a 6 mm thickness was selected as an optimal compromise between EM and mechanical requirements.

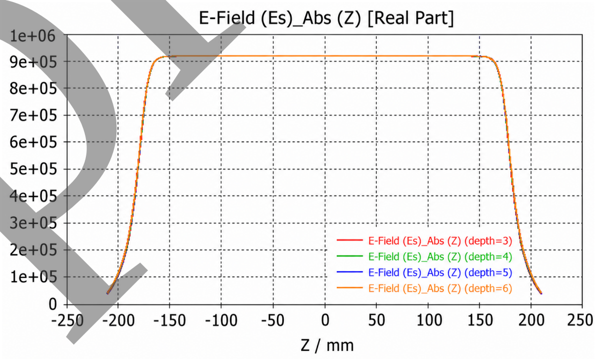

Figure 3: E_z for x=y=0 for different plates thickness.

The power supply was designed to operate the electrostatic chopper with variable-frequency pulsing in a voltage range from 1 kV to 26 kV. The system delivers pulses with rise and fall times below 900 ns, repetition rates between 1 Hz and 1 kHz, and pulse widths ranging from 2.5 µs to continuous DC operation. These capabilities provide flexible control of the beam temporal structure.

CHOPPER AND SLITS INSTALLATION

The electrostatic chopper was fabricated by *Neptury Technology* company and installed at the CNA facility in April 2026. In addition a system of four movable slits was bougth and installed before the chopper in order to protect it and optimize its performance. Figure 4 shows the CNA external beamline with the newly implemented elements indicated.

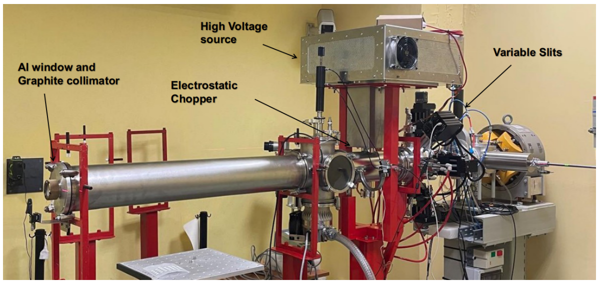

Figure 4: CNA external beamline.

PERFORMANCE OPTIMIZATION

TOPAS Beamline Model

A Monte Carlo model of the experimental CNA beamline has been developed using TOPAS [3]. The beamline is modeled from the last quadrupole to the exit window. A vacuum region was defined inside the stainless-steel beam pipe and the main components were integrated as illustrated in Fig. 5. The model includes an Al collimator, followed by a graphite collimator, the new rectangular adjustable slits for beam size control upstream the electrostatic chopper, and the electrostatic chopper. The latter is represented as a uniform electric field region between the two defined parallel aluminum plates. A final circular graphite collimator and a thin Al window define the beam exit.

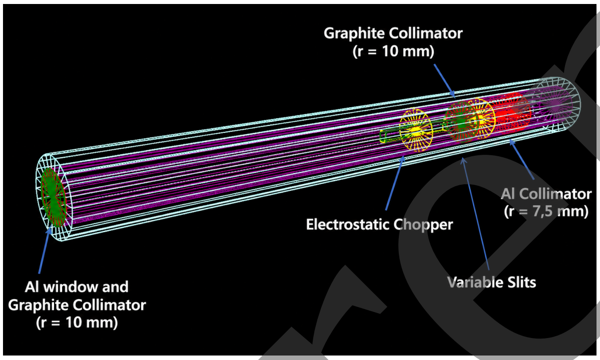

Figure 5: TOPAS beamline.

A first set of simulations was performed using TOPAS with the geometry defined in Fig. 5, assuming an operating voltage of 26 kV and an 18 MeV uniform, parallel proton beam with an 8 mm radius at the entrance [4]. The default TOPAS physics configuration was employed. Parametric sweeps were carried out by varying the side length of the square slits and evaluating the number of particles transmitted through the 20 mm diameter graphite collimator located at the beamline exit. The transmitted particles were quantified using a screen placed downstream of the collimator. The obtained results are summarized in Table 2 for different slits half-lengths.

For the smallest slit aperture ($L/2$=5 mm), the transmitted fraction was almost completely suppressed, with only 0.0034 % of the particles reaching the exit. Increasing the slit half-length to 6 mm raised the transmission to 1.25 %, while apertures of 7 mm and 8 mm resulted in transmissions of 4.72 % and 5.64 %, respectively.

Table 2: Simulation Results for Different Slits Half-lengths

L/2 [mm]	**Beam Transmission [%]**
5	0.0034
6	1.25
7	4.72
8	5.64
Open	5.65

An additional TOPAS simulation with fully open slits was performed to evaluate the spatial beam distribution at the graphite collimator position for an 18 MeV proton beam with a 0.14 MeV energy spread and an operating voltage of 26 kV. The beam centroid was obtained at y = 15.44 mm, in good agreement with the analytical prediction of y = 15.76 mm from Eq. 1. This agreement supports the validity of the simulation model and provides a reliable basis for future optimization studies of the beam intensity delivered to radiobiology samples.

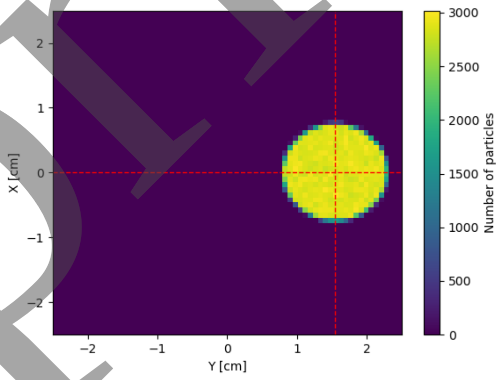

Figure 6: Transverse beam distribution at the collimator.

SUMMARY

A fast electrostatic chopper for FLASH proton radiobiology experiments has been designed, optimized, and installed in the CNA external beamline. The work included analytical calculations for the preliminary dimensioning of the system, followed by electromagnetic simulations performed with CST Studio Suite to optimize the electrode geometry, evaluate the beam deflection performance, and assess the sensitivity to mechanical tolerances. In addition, Monte Carlo simulations using TOPAS were carried out to study the beam transport conditions and optimize the aperture of the slits installed before the chopper to improve its performance. The commissioning of the system with beam is planned in the following months and the optimization studies using the developed TOPAS model will continue to optimize the beam intensity and beam quality for radiobiology studies in the FLASH regime.

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