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Electrostatic design and beam transport for a folded tandem electrostatic quadrupole accelerator facility for accelerator-based boron neutron capture therapy

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ABSTRACT

Within the frame of an ongoing project to develop a folded Tandem-Electrostatic-Quadrupole (TESQ) accelerator facility for Accelerator-Based Boron Neutron Capture Therapy (AB-BNCT), we discuss here the electrostatic design of the machine, including the accelerator tubes with electrostatic quadrupoles and the simulations for the transport and acceleration of a high intensity beam.

1. Introduction

Within the frame of an ongoing project to develop a folded Tandem-Electrostatic-Quadrupole (TESQ) accelerator facility (Kreiner et al., 2007, 2008, 2009, 2010a, 2010b) for Accelerator-Based Boron Neutron Capture Therapy (AB-BNCT), we discuss here the electrostatic design of the machine (Hellborg, 2005; Lee, 2004) including the accelerator tubes with quadrupoles and the simulations for the transport and acceleration of the 30 mA proton beam.

The overall geometry of the accelerator column and of the acceleration and focusing tubes, to comply with the maximum electrostatic field values adopted for a safe operation, were calculated with simulation codes using the finite integral method.

The transport of the intense proton beam through the accelerator (Reiser, 2008) has been simulated using codes that take into account self consistently the effect of space charge.

2. Simulation method

The electrostatic fields have been calculated using CST STUDIO SUITE™ (2010). This software is a general-purpose electromagnetic simulator based on the Finite Integration Technique (FIT).

This numerical method provides a universal spatial discretization scheme applicable to various electromagnetic problems ranging from static field calculations to high frequency applications in time or frequency domain. Unlike most numerical methods, FIT discretizes the integral form of Maxwell's equations rather than the differential one.

The CST Particle Studio® Particle Tracking Solver calculates the effect of electromagnetic fields on the movement of charged particles. The Gun Iteration Solver alternately performs electromagnetic calculations of space charge effects and particle tracking calculations. Based on a previous particle tracking run, the corresponding electric space charge caused by the particles is calculated. Then the electric field caused by the space charge is calculated and considered for the next particle tracking iteration. This iteration is repeated until convergence is reached.

3. Results

In the following section we discuss the results we have obtained for the electrostatic design of the accelerator structure (in its two versions of 600 kV and 1.2 MV terminal voltage), accelerator tubes with the electrostatic quadrupoles as well as the results we have obtained for the simulations of the transport and acceleration of the 30 mA proton beam.

3.1. Accelerator structure

The accelerator structure has been designed as a right cylinder of 2.5 m diameter, crowned at its upper end by a high-voltage dome. The column consists of a series of stacked cylindrical boxes (35 cm in height), surrounded by semi-toroidal surfaces, which

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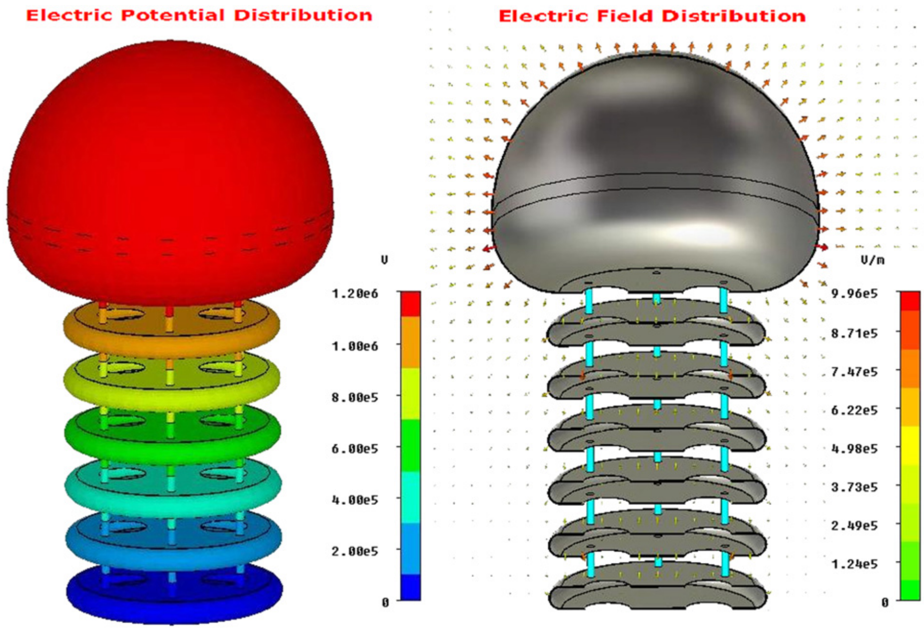

Fig. 1. Electric potential and field distributions of the 1.2 MV electrostatic accelerator.

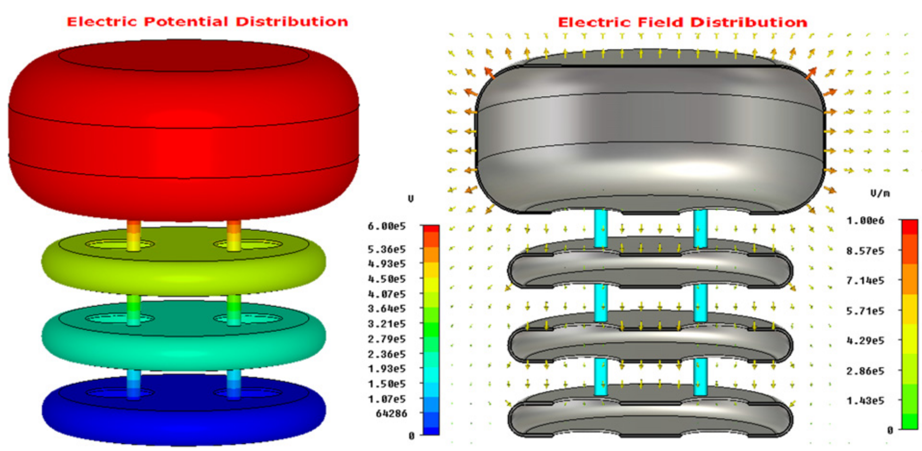

Fig. 2. Electric potential and field distributions of the 600 kV prototype.

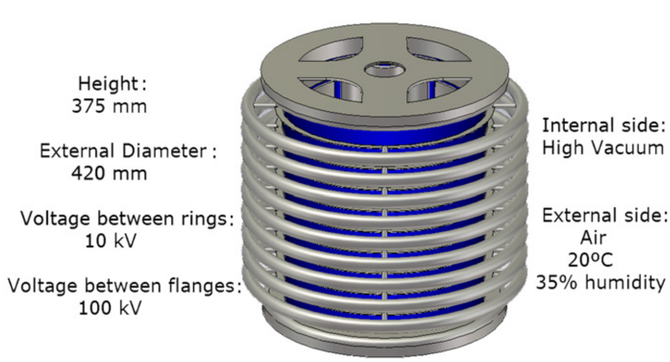

Fig. 3. Accelerator tube with the electrostatic quadrupoles. Full size view.

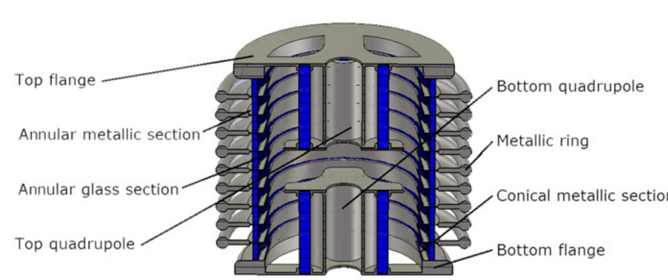

Fig. 4. Accelerator tube with the electrostatic quadrupoles. Cross section view.

are separated by 200 kV voltage and 40 cm air gaps (a total of 4 to reach 600 kV and 7 to reach 1.2 MV, see Figs. 1 and 2).

This column houses the up- and downgoing acceleration tubes with the quadrupoles inside.

The electric fields have been calculated paying special attention to avoid sharp edges and points to limit the fields to safe values.

The criteria have been to limit the fields on metal surfaces in air to values not exceeding from 10 kV/cm (see Figs. 1 and 2) to 5 kV/cm at the interfaces between insulators and air (the room which will house the machine will have controlled temperature and humidity about 20 °C and 35%, respectively).

The distance to the wall (a cylindrical grounded Faraday cage) is also optimized in order to keep the electric field at its minimum value. The required distance from the box column central axis is 3.5 m. The height from ground to roof turns out to be about 10 m for the 1.2 MV accelerator, while 6 m is enough for the 600 kV prototype.

3.2. Accelerator tubes with the electrostatic quadrupoles

The accelerator tubes consist of 10 annular borosilicate glass pieces (outer diameter of 30 cm, thickness of 0.9 cm and height of 3.15 cm) separated by and bonded to annular metallic pieces (2 flanges and 9 electrodes).

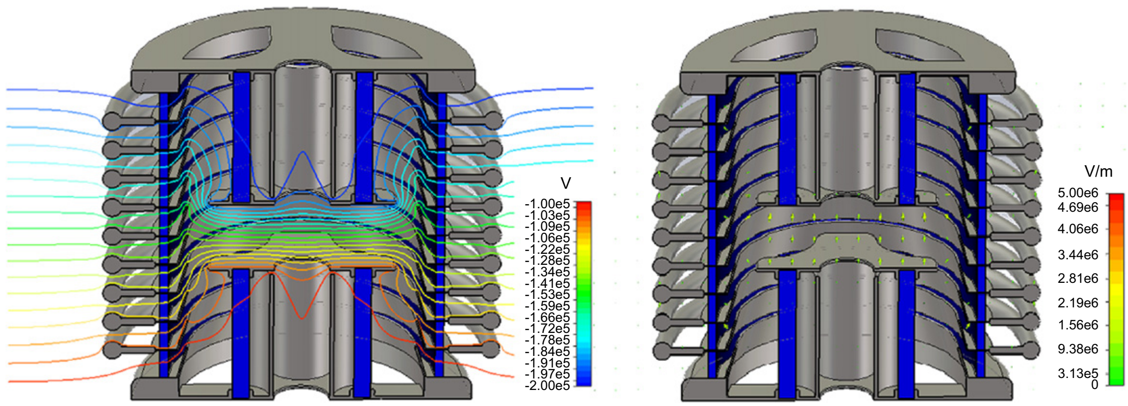

Fig. 5. Electric potential and field distributions in the longitudinal mid-plane of the accelerator tube with electrostatic quadrupoles.

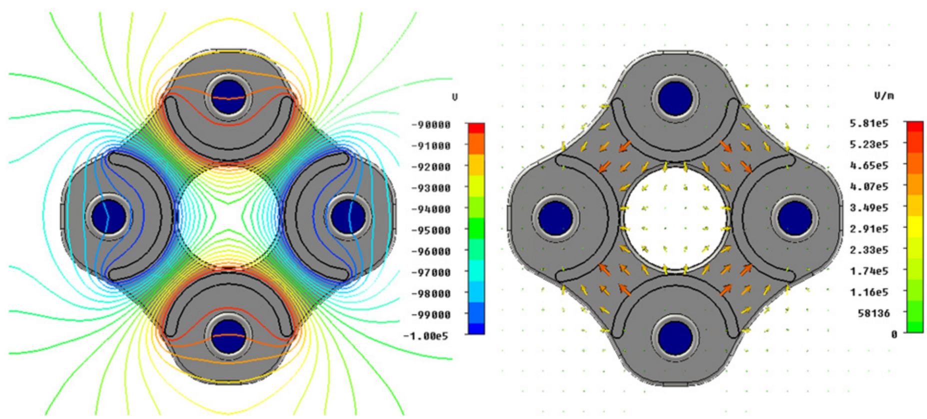

Fig. 6. Electric potential and field distributions in the transverse mid-plane of the accelerator tube with electrostatic quadrupoles.

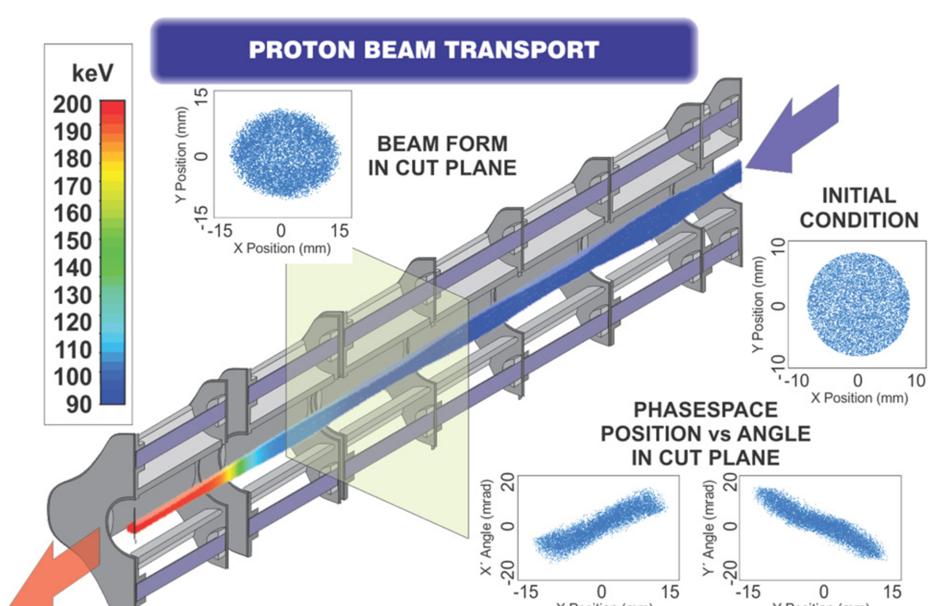

Fig. 7. Beam transport through the matching section and the first acceleration gap.

The electrostatic quadrupoles are made of semi-cylindrical rounded-edge aluminum pieces that are held in place by conducting supports fixed to the flanges. Each tube section is 37.5 cm high (see Figs. 3 and 4).

Inside each tube, there are conical metal pieces, one per electrode, to shield the glass insulators from direct view of the beam. On the outside they are terminated as rings to limit the maximum field at the sharp edges.

The total voltage across two tube sections, located between the mid-planes of two consecutive boxes, is designed to be 200 kV. While the voltage between poles for each quadrupole is 10 kV, the voltage between poles of consecutive quadrupoles (accelerating gaps) is 80 kV.

The electric fields are limited to 5 kV/cm on the insulator–air interfaces, to 8 kV/cm on the insulator–vacuum interfaces and to 50 kV/cm on the metal surfaces in vacuum (see Figs. 5 and 6).

3.3. Simulation of the beam transport

The 30 mA proton beam transport and acceleration has been simulated by solving the Poisson–Lorentz equations self consistently.

The beam propagation is done by taking into account applied and self generated fields, the latter being dependent on the evolution of the beam itself. This is accomplished by the following procedure: first the Laplace equation is solved and particles are propagated throughout the structure without considering the space charge forces, the positions at each time step are stored and a density function is created then the Poisson equation is solved considering the geometry and its density function, electric fields are calculated and particles are propagated once again, a new density function is then created, and the process is repeated until convergence is reached.

The proton beam provided by the ion source is assumed to have a current of 30 mA, 0.4 mm mrad of normalized emittance (for x and y), 10 mm of radius and an energy of 100 keV.

The matching section is composed of 5 electrostatic quadrupoles (see Fig. 7) and it is designed to shape the beam in a way that presents the minimum variation of its envelopes and the lowest maximum excursion to be further transportable through the chain of quadrupole doublets and accelerating gaps, which form the accelerator tubes (see Fig. 8).

Fig. 9 shows the X and Y envelopes through the matching section and the first accelerating gap (from an energy of 100 keV up to 200 keV). Under these conditions the beam can be safely transported to the high voltage terminal with small oscillations of its envelopes.

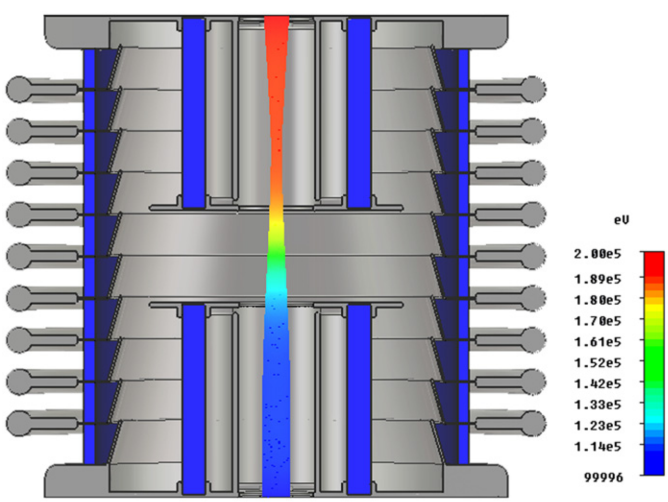

Fig. 8. Beam transport through the accelerator tube with the electrostatic quadrupoles.

4. Conclusions

The simulation of the electrostatic fields of the machine (in its two versions of 600 kV and 1.2 MV terminal voltage) and its enclosing Faraday cage has been completed, limiting the maximum electric field in air and on metal surfaces to 10 kV/cm. This value is considered safe since the accelerator will work at 20 °C and 35% humidity level.

The electric fields for the accelerator tube with the electrostatic quadrupoles are limited to 5 kV/cm on the insulator–air interfaces, to 8 kV/cm on the insulator–vacuum interfaces and to 50 kV/cm on the metal surfaces in vacuum.

The results of the simulations including the space charge effect show that it is possible to guide and accelerate a 30 mA beam confined to a radius of 10 mm through the accelerator with small oscillations of its envelopes.

Acknowledgments

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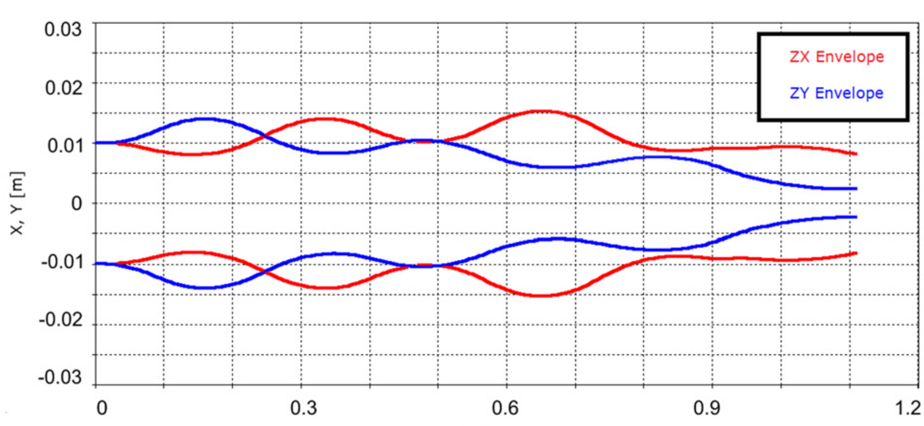

Fig. 9. Beam transport: X and Y envelopes.

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