COMSOL Aided Design of an Extraction Pipe for the Electron Beam from a Plasma Focus Device

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Abstract: The electron beam emitted backward by Plasma Focus devices is being investigated as a radiation source for IORT (Intra-Operative Radiation Therapy) applications. A Plasma Focus device is being developed to this aim. The electron beam is driven through an electron pipe made of stainless steel to impinge on a 50 µm brass foil, where conversion X-rays are generated. Electromagnetic forces in the Plasma Focus device have to be investigated to understand their influence on the electron beam produced by the extraction tube. The AC/DC Module in COMSOL is being used to simulate the electromagnetic field in the extraction tube to determine the optimum material.
Keywords: Plasma Focus, x-rays, electron beam, electromagnetics, AC/DC module.

1. Introduction

In the last few decades, Plasma Focus devices have been used as sources of various particles (electrons, neutrons, x-rays) in different research fields. Their use spans a wide range: microelectronics lithography [1], surface micromachining, pulsed X-ray and neutron source for medical and security inspection applications and materials modification [2], external neutron source for nuclear weapons [3], simulation of nuclear explosions (for the testing of the electronic equipment), short and intense neutron sources for non-contact discovery or inspection of nuclear materials (uranium, plutonium), and many others. A prototype plasma focus named PFMA-3 (Plasma Focus for Medical Applications-3) has been designed and put into operation within the framework of a research project of the Alma Mather Foundation of the University of Bologna. The electron beam emitted backwards (with respect to the macroscopic motion of the plasma sheet, see next section) can be used as an X-ray source in radiation therapy, particularly in IORT applications (IntraOperative Radiation Therapy) [4][5]. To take the next step toward a medical use of the Plasma Focus device, though, it is necessary to optimize the materials composing the extraction tube for the electron beam. At the working frequencies of this device (10^5-10^6Hz), a steel extraction tube prevents the magnetic field produced by the device to modify the trajectory of the electrons; however, metallic materials are barred by electrical safety reasons. On the other hand, plastic materials proved (after experimental tests) completely permeable to the EM field, which deflects the electron beam and makes it impossible to generate X-rays. For this reason, the AC/DC module in Comsol has been used to simulate the electromagnetic field in the extraction tube at different frequencies and with different materials.

2. Theory

A Plasma Focus device is basically composed of two coaxial cylindrical electrodes, closed at one end and open at the other. Between the two electrodes there is a cylinder made of insulating material (often Pirex, even if for the sake of the simulation Delrin has been used). Two possible configurations exist: the Filippov design, in which the axis of the electrodes is directed orthogonally with respect to the macroscopic direction of the plasma, and the Mather design [6], in which the plasma motion direction coincides with the axis of the electrodes (Figure 1)[7].

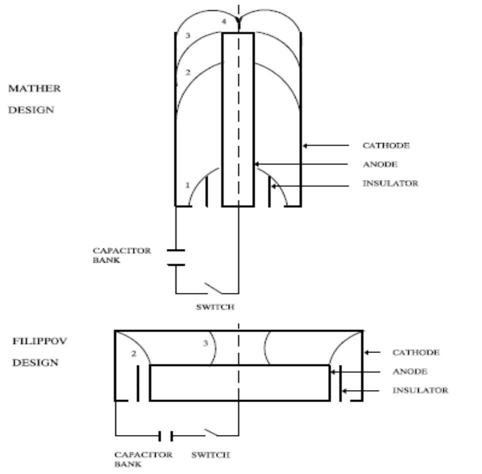

Figure 1. Plasma Focus configurations.

Figure 2. PFMA-3 device.

PFMA-3 (Figure 2) has been built in a Mather-type configuration.
The inner electrode is connected to a capacitor bank by a fast switch, while the outer electrode (built in a squirrel-cage configuration) is electrically grounded through the lower conducting plate. The electrodes and the insulator are contained in a quartz chamber, in which vacuum is made (by a turbo-molecular pump backed by a scroll pump). The vacuum chamber is then filled with a few Pascal of the working gas; usual gases used are Hydrogen, Deuterium, Tritium, Nitrogen, Oxygen and other mixtures; in the specific case of PFMA-3, the working gas is Nitrogen, usually at about 45Pa.
The plasma focus discharge can be divided in three ideal phases: breakdown, axial acceleration and pinch (Figure 3).
When the switch is closed, the electric potential difference between the inner and outer electrodes causes the gas to breakdown and become ionized (phase 1). The gas breakdown creates a low-resistivity path for the current to flow, thus closing the electrical circuit.

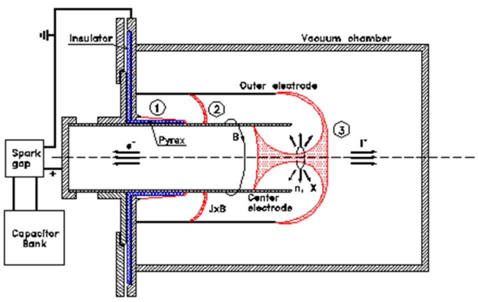

Figure 3. The three phases of a Plasma Focus discharge.

The charged particles produced (electrons and ions) are then pushed towards the open end of the electrodes and accelerated by Lorentz forces; as the plasma sheet reaches the end of the insulator, the magnetic pressure confines it in a parabolic shape (phase 2). When the plasma reaches the open end of the electrodes, it undergoes a quick radial collapse that causes a large increase in temperature and density (phase 3); this phenomenon, called pinch, can reach temperatures over a few tens of keV and ion concentrations of 10^{21} cm^{-3}[8].
In this phase, nuclear reactions of fusion can occur if the working gas is a mixture of D-D, D-T or D-^{3}He, as the neutron yields of various plasma focus devices show [9][10]. Two beams are produced at this stage: an ion beam, in the direction of the macroscopic motion of the plasma along the electrodes, and an electron beam, emitted in the opposite direction, referred to as the "backward" direction; this electron beam flows within the electrodes and is collimated by the extraction tube to impinge on a brass foil producing bremsstrahlung and characteristic X-rays.
Ultimately, MHD instabilities (mainly sausage and kink) disrupt the plasma sheet, opening the electrical circuit and ending the Plasma Focus discharge.

3. Governing equations

As mentioned, the goal of the simulation is to study the distribution of the electromagnetic field in the extraction tube. For this reason, what is to be solved are Maxwell's equations: Gauss's law (3.1), Maxwell-Faraday's law (3.2), Gauss's law for magnetism (3.3) and Ampere's circuital law (3.4).

$$\vec{\nabla} \cdot \vec{\mathbf{D}} = \boldsymbol{\rho} \tag{3.1}$$

$$\vec{\nabla} \times \vec{\mathbf{E}} = -\frac{\partial \vec{\boldsymbol{B}}}{\partial \boldsymbol{t}} \tag{3.2}$$

$$\vec{\nabla} \cdot \vec{\mathbf{B}} = \mathbf{0} \tag{3.3}$$

$$\vec{\nabla} \times \vec{\mathbf{H}} = \vec{\mathbf{J}} + \frac{\partial \vec{\boldsymbol{D}}}{\partial \boldsymbol{t}} \tag{3.4}$$

In addition, to ensure the relationships between the electric field $\vec{E}$ and the electric displacement field $\vec{D}$, between the magnetic flux density $\vec{B}$ and the magnetic field $\vec{H}$, and between the electric field $\vec{E}$ and the electric current density $\vec{J}$, constitutive equations (3.5), (3.6), (3.7) are used.

$$\vec{\mathbf{D}} = \boldsymbol{\varepsilon}_{\mathbf{0}}\vec{\mathbf{E}} + \vec{\mathbf{P}} \tag{3.5}$$

$$\vec{\mathbf{H}} = \frac{\mathbf{1}}{\boldsymbol{\mu}_{\mathbf{0}}}\vec{\mathbf{B}} - \vec{\mathbf{M}} \tag{3.6}$$

$$\vec{\mathbf{E}} = \frac{\mathbf{1}}{\boldsymbol{\sigma}}\vec{\mathbf{J}} \tag{3.7}$$

where $\vec{P}$ is the electric polarization vector, $\vec{M}$ is the magnetization vector, ε_0 is the permittivity of vacuum ($8.854\cdot 10^{-12}$F/m), μ_0 is the permeability of vacuum ($4\pi\cdot 10^{-7}$H/m) and σ is the electrical conductivity of the material.

4. Use of COMSOL Multiphysics

The AC/DC module has been chosen for the study of the magnetic field produced by the Plasma Focus device; the interface used is the "Magnetic and Electric Fields", specifying a frequency domain study with frequencies ranging from 50Hz to 1MHz (50Hz, 1kHz, 100kHz and 1MHz). This choice has been made over the Plasma module due to memory limitations of the machine used for the simulations; hence, to simulate the plasma a copper conductor in contact with both electrodes of the device has been added to the geometry. In fact, with respect to the extraction tube, the plasma acts simply as a conducting medium that closes the electric circuit. In the same vein, the fast switch that ensures the triggering of the plasma discharge has been replaced by a steel plate, since the transient response is not investigated. The capacitor bank has been eliminated from the model, and the tension input has been ensured by a "Terminal" boundary condition (with a 1V tension input) on the two copper pins connected to the upper plate; on the lower plate a "Ground" condition has been added. The software adds by default the boundary conditions of "Magnetic Insulation" and "Ampere's Law and Current Conservation", so no other conditions are required. Figure 4 shows the geometry as built in the COMSOL interface. The materials used in the model are: stainless steel (AISI 304) for the conducting plates; copper for the electrodes, the capacitor pins and for the conducting plate that replaces the plasma; Delrin (whose electrical properties have been inserted manually) for the insulator between the electrodes and between the superior and the inferior conducting plates; air for the volume within the electrodes and in the outer domain.

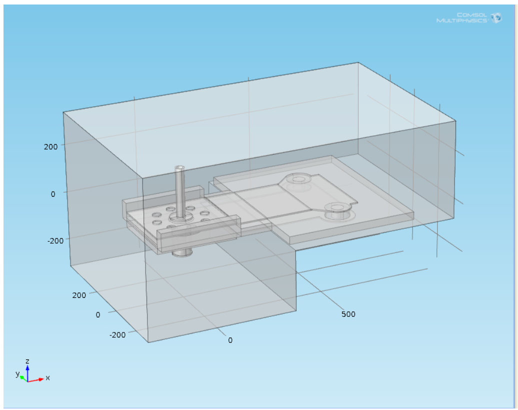

Figure 4. Geometry of the PFMA-3 device in COMSOL

A direct solver has been used to solve the equations, since the numerical problem is ill-conditioned and iterative solvers are unable to reach a converging solution. This could be due to the mesh failing to resolve the skin effect, thus requiring much finer mesh elements; once again, memory limitations of the machine used for the simulations made it impossible to refine the mesh. Another solution to the skin effect problem could have been the Impedance boundary condition; however this would require the inactivation of the metal domains from the physics interface, thus making impossible to study the response of the EM field to the material used for the extraction tube. However, the error introduced neglecting skin effect turned out to be insignificant, and the numerical solution obtained agrees very well with both experimental values and analytical calculations.

5. Results

Plots of the magnetic field vs the z-coordinate have been extracted using the cut line feature; the cut line has been chosen as the axis of the electrodes and of the extraction tube. This

way, the plots show the trend of the magnetic field within the tube (0 to 150mm), thus making it possible to appreciate the possible effects of the EM field on the electron beam at different frequencies.
Figure 5 shows the semi-log cut line plot for the frequencies chosen, when the extraction tube material is stainless steel.
As shown by the figure, the magnetic field intensity in the zone of the electrodes (-100 to 0mm) and of the extraction tube (0 to 150mm) strongly decreases as the frequency rises; furthermore, at the working frequencies (100kHz to 1MHz), the magnetic field norm is nearly zero. It is safe to assume, then, that a steel tube completely shields the electron beam produced by the plasma focus; this is confirmed by experimental tests conducted on PFMA-3.
Figures 6 shows the magnetic field trend when the material used for the extraction tube is instead a plastic one (Delrin).
By looking at the semi-log plot in Figure 6 it becomes clear that plastic materials are completely permeable to EM fields. This renders plastic tubes unusable as the magnetic field would deflect the electron beam away from the brass target.

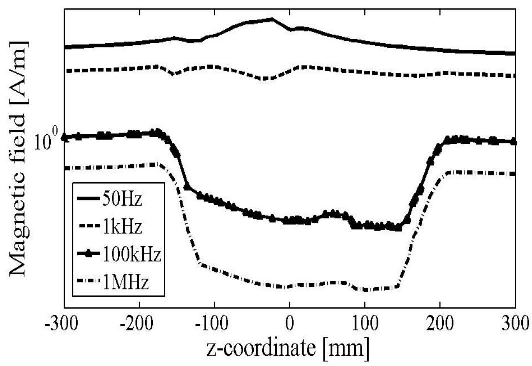

Figure 5. Magnetic field in the extraction tube for different frequencies when the material is steel.

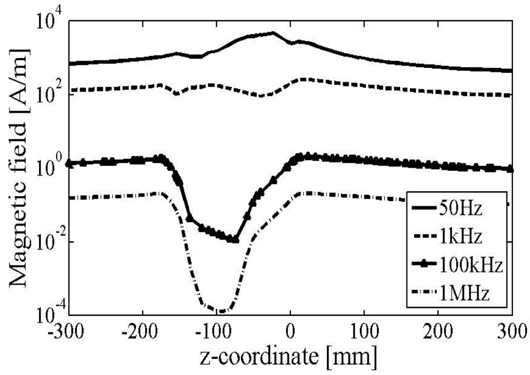

Figure 6. Magnetic field in the extraction tube for different frequencies when the material is Delrin.

6. Design of the extraction tube

Up to this point, the solution found with COMSOL has confirmed the initial hypothesis. So the next step has been to try to simulate an extraction tube made of steel with an external Delrin coating. This way, the tube should maintain the shielding capability against the EM field, and at the same time it should be safe from the electric point of view.
To do so, the extraction tube in the geometry interface has been modified by adding the Delrin coating; no further boundary/initial conditions are required, as the new domain has been added to the default "Magnetic Insulation" and "Ampere's Law and Current Conservation" conditions. Figure 7 shows the modified extraction tube as seen in the geometry interface.

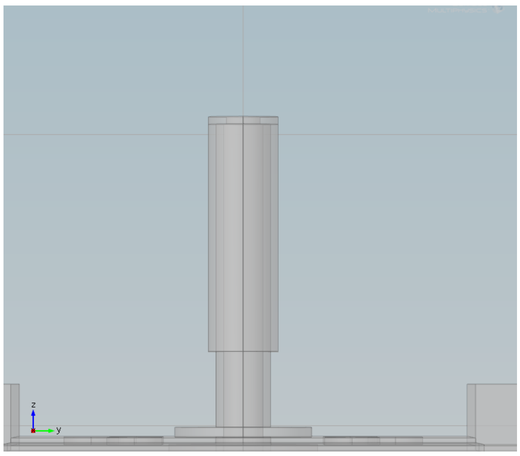

Figure 7. Modified geometry of the extraction tube.

A new solution has been found; as previously, a semi-log plot of the magnetic field norm has been extracted using the cut line feature (Figure 8).
Figure 8 seems to show no differences with the case of the extraction tube made of steel.

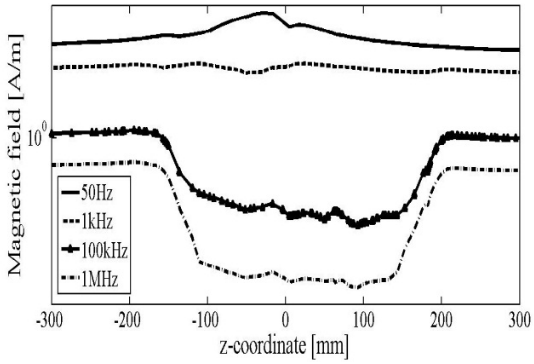

Figure 8. Magnetic field produced by the PFMA-3 device when using a steel tube with a Delrin coating.

As expected, the new extraction tube seems to be completely impermeable to the electromagnetic field, thus preventing it from deflecting the electron beam; on the other hand, the outer surfaces of the tube are made of an insulating medium, providing electrical safety in case of contact with human tissues.
Figure 9, 10 and 11 show the magnetic field energy trend in the extraction tube zone, using a cut plane feature (an xz-cut plane passing through the extraction tube axis is used).

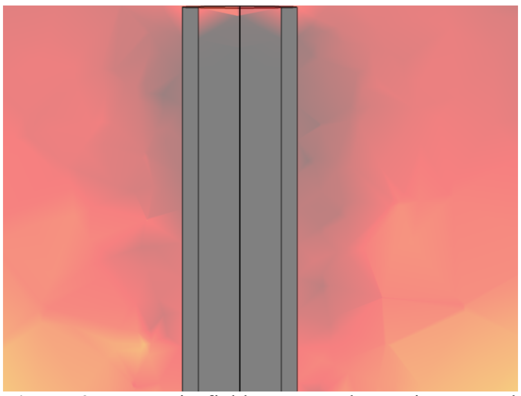

Figure 9. Magnetic field energy when using a steel extraction tube.

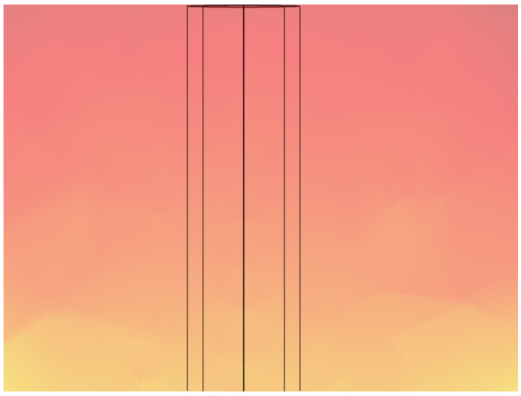

Figure 10. Magnetic field energy when using a Delrin extraction tube.

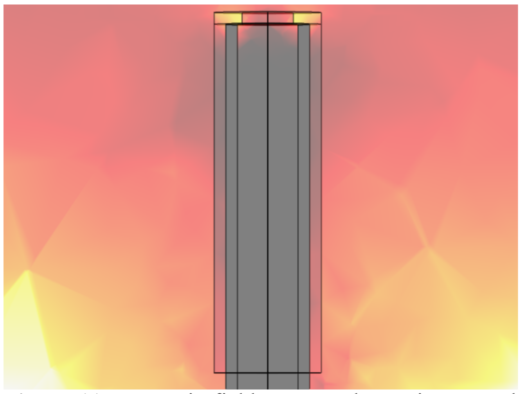

Figure 11. Magnetic field energy when using a steel extraction tube with a Delrin coating.

It is clear that, beside some effects caused by the edges of the geometry, the magnetic field cannot penetrate through the metal walls. Thus, the electron beam's trajectory is unaltered and x-ray production is made possible.

7. Conclusions

The design of the extraction tube of the PFMA-3 device has two constraints: electrical safety reasons ban the use of metallic materials, as the extraction tube is electrically connected to the upper plate; and, insulating materials seem to be completely permeable to the electromagnetic field produced by the device, resulting in undesired deflection of the electron beam. Numerical simulations with COMSOL multiphysics confirmed the initial hypothesis, and helped to find the optimum material configuration for the extraction tube: a steel tube with a Delrin coating. This design solves the electrical safety problem and at the same time ensures negligible deflections of the electrons.

8. References

Software version: COMSOL Multiphysics 4.2a (4.2.1.166)

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