Electromagnetic modeling of the extraction region of the ISIS H^- ion source

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The ISIS Penning surface plasma source, which routinely produces 35 mA of H^- ions during a 200 μs pulse at 50 Hz for uninterrupted periods of up to 50 days, is regarded as one of the leading operational sources in the world. The ISIS source should provide an excellent starting point for a development program to produce H^- ion sources with performances exceeding those achieved today, which will be a key requirement for the next generation of high power proton accelerators. One goal is to produce 60 mA of H^- ions from the source without large departures from the optimum conditions for source lifetime or increased emittance. As the ISIS source operates in the space-charge limited mode it is predicted that an increase in extraction potential from 17 to 25 kV should be sufficient to achieve this, and a suitable pulsed power supply for the ion source extraction electrode has been manufactured. An understanding of how extract geometry changes affect beam transport is essential for operation at higher extraction potential. An examination has been undertaken of the electromagnetic fields in the extract electrode region using MAFIA finite element analysis software. The effects of changing the extraction potential, gap, and electrode geometry are described. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1695614]

I. INTRODUCTION

The design of the ISIS H^- ion source has previously been described in detail.[1] One critical aspect of this design is the optics of beam transport from the ion source aperture through the 17 kV extraction region and then a 90° sector magnet with a bending radius of 80 mm and a field index of $n=1$. The extraction electrode and sector magnet are housed inside a cold box which is held at the extraction potential. The sector magnet is intended to remove any electrons from the H^- beam, and also focus the beam profile from 0.6×10 mm at the ion source aperture to ≈10×10 mm at the cold box exit. However, it has been suspected for some time that steering and focusing are compromised by inadequate termination of sector magnet fringe fields,[2] and suboptimal extraction geometry.

To allow a better understanding of the factors affecting the beam optics in this region a MAFIA[3] finite element analysis (FEA) model has been developed (Fig. 1).

II. FINITE ELEMENT ANALYSIS

MAFIA employs a finite integration technique to solve for electromagnetic fields. This has an advantage over finite difference techniques in that the time taken to calculate the fields increases linearly (rather than as a power) with the number of elements. The downside of the finite integration technique is that the model must be discretized onto a regular mesh, unlike finite difference techniques which can have an irregular tetrahedral mesh. This has important consequences when trying to model a problem with both large and small features. The accuracy of the result from any FEA is dependent upon the element size local to the result.

In the FEA model in Fig. 1 the extract electrode is very small compared to the rest of the model. It is essential that the fields in this region are calculated accurately and hence a high mesh density is required. Available computing resources prevent a high mesh density from being used throughout the model, so great care is taken to optimize the regular grid, while keeping the elements small enough around the extract regions and pole pieces. The mesh density is increased until the results converge and a 1 GB problem size (limited by the computer RAM available) is reached. In the present model

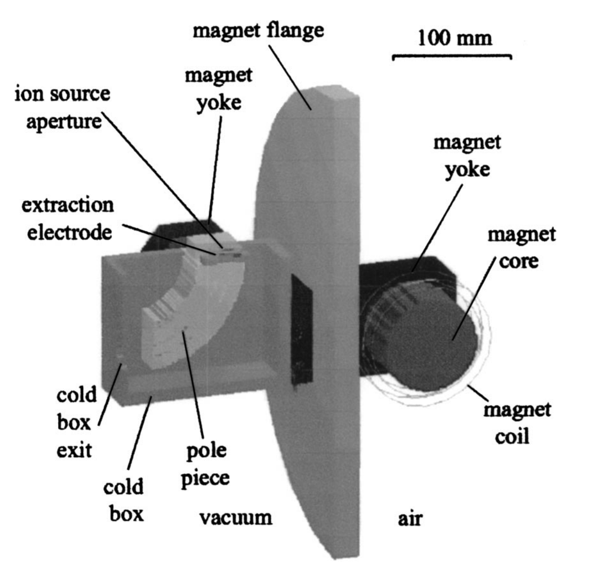

FIG. 1. MAFIA model of the ISIS ion source extraction region and 90° sector magnet.

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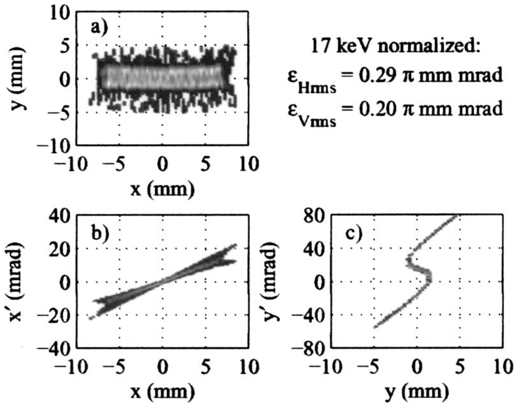

FIG. 2. (a) Position, (b) horizontal emittance, and (c) vertical emittance from the MAFIA model using the standard ISIS design.

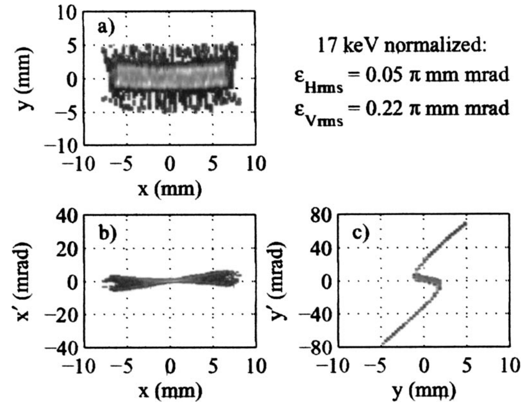

FIG. 4. As Fig. 2, but including optimized "maximag" tube insert.

density of mesh elements varies from 1×10^{3} to $2\times10^{13}\ \mathrm{m}^{-3}$.

After the electromagnetic fields have been calculated particles representing the H^{-} ions are run through the model. 10 000 particles are emitted from the ion source aperture plate with uniform thermal energy, orthogonal to the aperture plate and with a random uniform spatial distribution. MAFIA uses a time stepping particle in cell code to calculate the particle positions after one time step. The time step is reduced until the particle trajectories converge to a solution. 20 000 5 ps time steps are used to ensure accurate results. Horizontal and vertical emittance monitors are set up in MAFIA at the cold box exit to monitor the particles.

III. RESULTS

In the standard ISIS design the only attempt to deal with fringe effects at the end of the sector magnet is to cut off the pole pieces 14 mm back from the full 90° bend. The MAFIA results for this design are shown in Fig. 2. It is obvious that the beam profile is asymmetric, the beam is strongly divergent in the horizontal plane, and there is severe aberration in the focusing in vertical plane.

In addition, when it is steered to be on center in the vertical plane, the beam is angled upwards by ≈15 mrad as a result of bending in the magnet fringe field. It has previously been suggested that this effect can be overcome by the insertion of a tube of high permeability material into the fringe field region.[2] This approach has been investigated further to include the effects of extraction and optimized to produce the design shown in Fig. 3, where "maximag" magnet steel has been used for the insert. The optimal design has the pole pieces cut off 3 mm back from the full 90° bend, and a "maximag" tube (internal diameter 30 mm, wall thickness 5 mm) extending from 3 mm in front of the 90° plane to flush with the cold box exit. The results are shown in Fig. 4. There is a large reduction in divergence in the horizontal plane, and the vertical emittance now shows the beam to be both on center and parallel to the axis. However, there is still an asymmetric beam profile and evidence of aberration in the focusing in the vertical plane.

The standard ISIS extraction geometry is illustrated in Fig. 5. MAFIA has been used to investigate the effect of terminating this electrode so that rather than being open ended it becomes a slit with dimensions proportional to those of the ion source aperture. The results are shown in Fig. 6. It is clear that termination of the electrode produces a beneficial effect. The beam profile has now become symmetric, and the

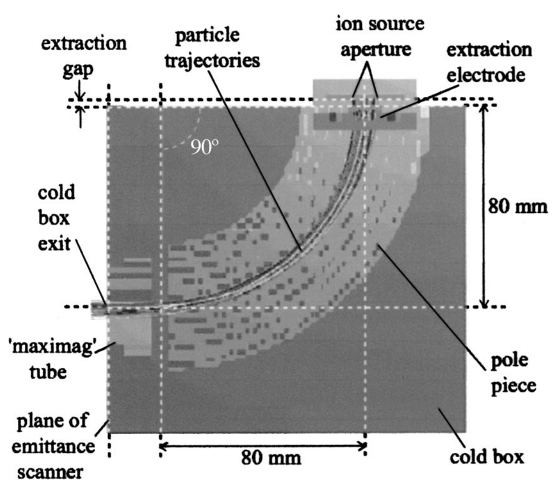

FIG. 3. Cross section through the center of the cold box in the MAFIA model showing particle trajectories and "maximag" insert.

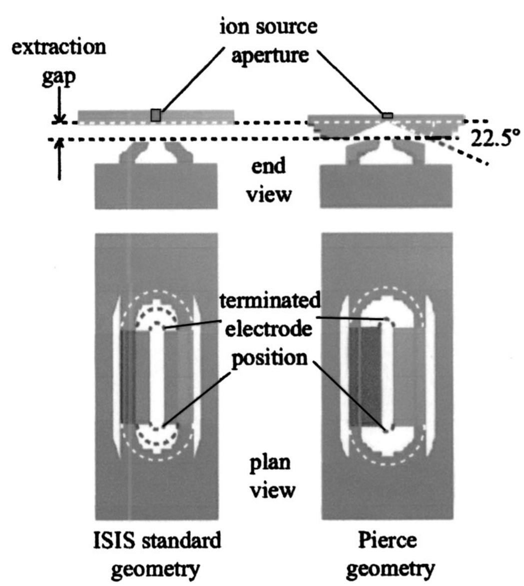

FIG. 5. Extraction electrode geometries taken from the MAFIA model.

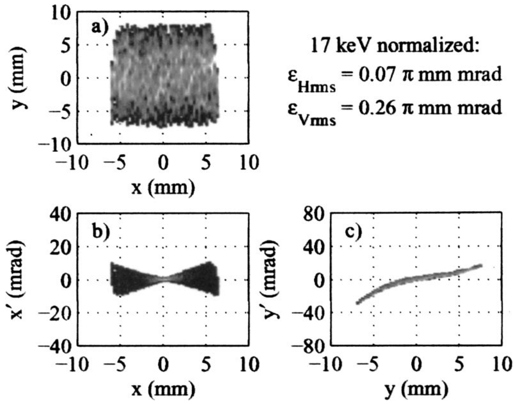

FIG. 6. As Fig. 2, but including terminated standard electrode and optimized ''maximag'' tube insert.

aberration in focusing has disappeared from the vertical plane.

If the standard ISIS extraction geometry is replaced by a Pierce geometry,[4] as in Fig. 5, which has also been appropriately terminated the effect is as shown in Fig. 7. The effect of the Pierce geometry is to focus the beam towards the origin in both planes. This produces a particularly marked effect on the vertical emittance value, as the beam becomes virtually parallel to the axis at all points.

All the above simulations have also been run at 25 kV extraction potential, with only very minor degradation of the performance of the optics, which indicates that these designs should remain valid if the extraction potential is increased in an attempt to produce 60 mA from the ISIS ion source. Increasing the extraction gap from the ISIS standard of 2.3 mm produces a small improvement in the beam optics, but it must be remembered that the extracted beam current (I_B) is expected to be related to the extraction voltage (V) and extraction gap (d) by

$$I_B = \frac{V^{3/2}}{d^2}, \quad (1)$$

and hence any increase in extraction gap will offset the effect of increasing the extraction potential.

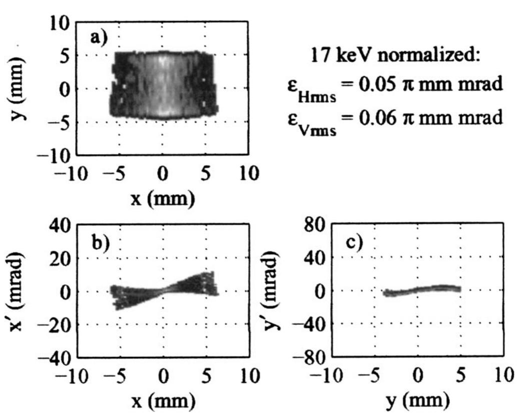

FIG. 7. As Fig. 2, but including terminated Pierce geometry electrode and optimized ''maximag'' tube insert.

IV. FUTURE WORK

Optimization of the beam optics in the extraction region using MAFIA has demonstrated that careful attention to the details of the system can produce dramatic changes in performance. A comparison of Fig. 2 with Fig. 7 shows that the addition of the correct ''maximag'' insert and a terminated Pierce geometry extraction electrode makes the difference between a badly aberrated, asymmetric beam (which of course would appear to be what is presently being used on ISIS) and a much higher quality beam. It also appears that the predicted emittance values of $\varepsilon_{H\mathrm{rms}}=0.29$ and $\varepsilon_{V\mathrm{rms}}=0.20\ \pi$ mm mrad for the present design could be reduced to $\varepsilon_{H\mathrm{rms}}=0.05$ and $\varepsilon_{V\mathrm{rms}}=0.06\ \pi$ mm mrad. These changes will be incorporated into the experimental apparatus on the ion source development rig at RAL[5,6] in the near future to observe how they effect the real H^- ion beam. While it is appreciated that the effects predicted by MAFIA are idealized and therefore may be somewhat exaggerated, it is expected that this work will have a significant impact on improving the ISIS ion source.

ACKNOWLEDGMENTS

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