Fan Blade Construction of 3HMS

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ABSTRACT

This paper describes a novel and counter-intuitive construction topology for the new Hyperbolic Helical Horn Mass Spectrometer (3HMS) [1], a.k.a. the "Ion Centrifuge". Normally, the deflection grids are defined as sheets following a hyperbolic curve. This works fine but has the drawbacks of costly fabrication, high capacitive loading, and poor vacuum. The orthogonal fan blade grid design proposed below single-handedly solves all these issues.

BACKGROUND

The original proposal for 3HMS [1] specified hyperbolic surface sheets for the deflection electrodes. Cylindrically symmetric, the sheet is split into four or eight sections and driven by sine and cosine waveforms. Mathematically this is very simple and produces a very well defined ion trajectory. However, fabrication of the assembly can prove to be costly, requiring precision 3-axis machining and polishing. Figure 1 is a schematic of a 3HMS housed within vacuum chamber.

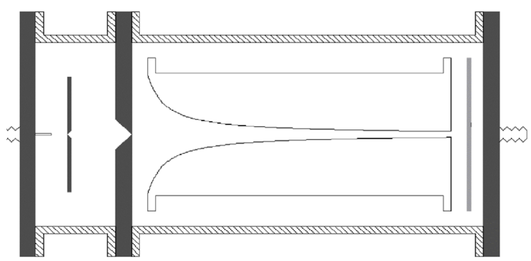

Fig. 1. 3HMS schematic with ionization chamber.

Figure 2 is a 3D plot of an actual 3HMS prototype showing the positioning of the horn-shaped deflection grids.

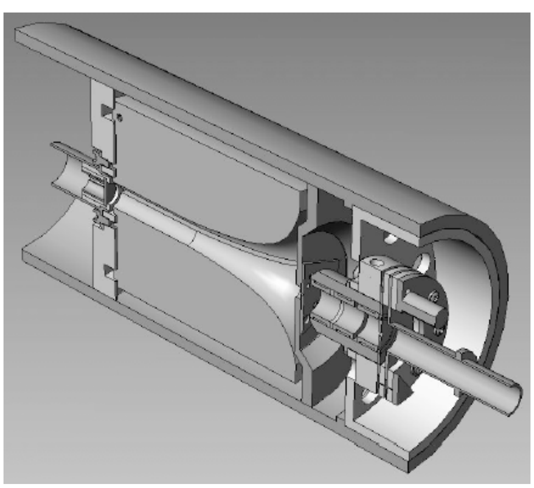

Fig. 2. Cutaway construction of original 3HMS prototype.

FAN BLADES

The proposed alternative is the so-called "fan blade" construction, inspired by the Asian bamboo folding fan. Instead of using hyperbolic surfaces, blades are aligned in an orthogonal fashion to replicate the same shape. It can be shown that the resultant electric field, which is the prime concern here, exhibits a nearly identical constitution.

Figure 3 shows the end-on view of fan blade construction. The path of ion is into the paper. If an infinite number of blades are used, the inner surface becomes an exact replica of the hyperbolic sheet surface of the prior art (Figure 2). The invention is to limit the number of blades to a minimum, yet still maintain electric field integrity.

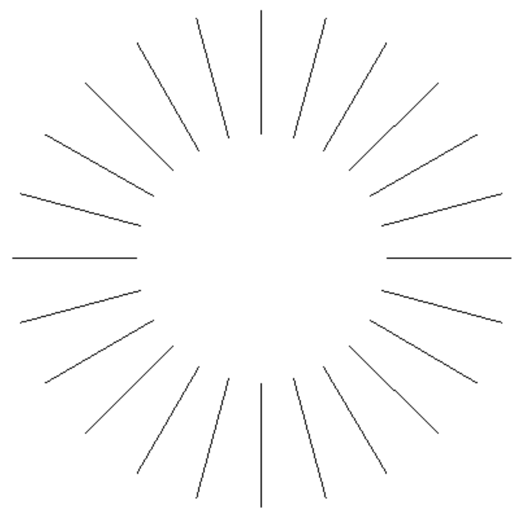

Fig. 3. Longitudinal view of fan blades.

Figure 4 shows the side view. Note the inner surface follows the exact hyperbolic equation as specified in the 3HMS design parameters. The thickness and height of the blades is variable. Fabrication costs are greatly reduced, as a blade can be easily stamped or cut from a sheet of metal stock with great accuracy. No other machining or polishing is necessary.

Fig. 4. Side view of fan blade construction.

Field simulations of a 24-pole arrangement (Figure 5) illustrate near-perfect field isopotential lines. Of significance is the linearity of the field near the center, where the ion trajectory is initiated. Resonant ions will remain in the center half-radius (by definition) as the forces of deflection and inertia are in equilibrium.

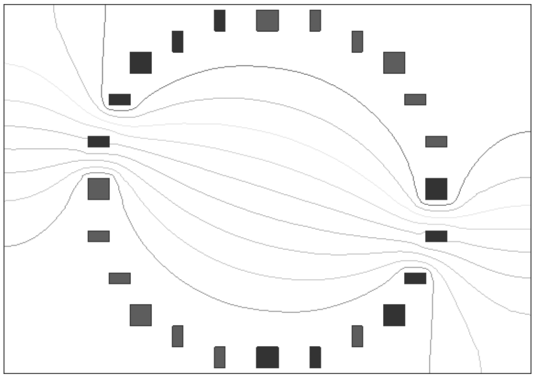

Fig 5. 24-pole electric field simulation.

For optimum field contours, it is important that the blades be relatively close together, such that the radius becomes a far field. Too few blades and the field distortions become considerable and problematic. This can be seen in a simulation of a parallel plate capacitor made from spaced wires. In Figure 6 the distance *d* is less than the spacing *s*, leading to a disfigured field.

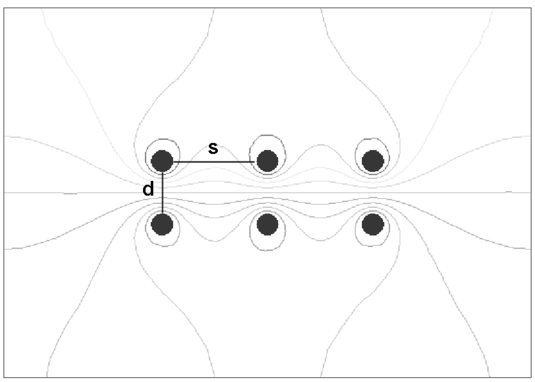

Fig 6. Field simulation of incorrectly spaced grids.

Figure 7 meets the requirement of $d >> s$, resulting in a uniform field. It is this general policy that forces a 3HMS to have either a large number of blades or an ion radius limited to the central field only. More blades will yield less distortion, but also greater complexity and cost.

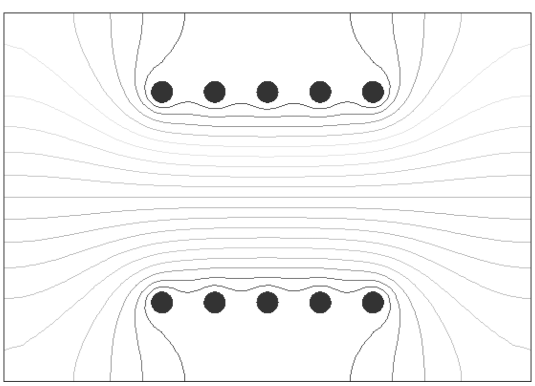

Fig. 7. Field simulation of properly spaced grids.

The optimum number of blades will be determined by a compromise between system cost and desired performance. This paper uses the example of 24 blades only to demonstrate concept. In fact, the performance of a 12-blade or possibly even an 8-blade may be entirely adequate.

DIGITAL DRIVE

In a related paper [3] the prospect of square wave or digital waveforms is proposed. Square waves are much easier to produce than sine waves when the frequency has to be swept over a broad range, as in the 3HMS. There is also a corresponding decrease in circuit cost. The use of fan blade construction permits a square wave or incrementally rotated drive waveform. By having 24 blades, the field can be stepped in 15-degree increments. The result is a parabolic piecewise approximation of a helical ion trajectory. The greater the number of blades, the more perfect this approximation is.

FIELD FLEXIBILITY

The use of many blades also allows the unusual ability to select a particular field shape. Depending on how many blades are charged in parallel, the field shape can change from convex to concave. This is seen in Figures 8 and 9. Ideally, perfect linearity is desirable, but it may be found that the concave field has the additional characteristic of being slightly self-correcting, keeping the ion positioned along the alignment of field rotation.

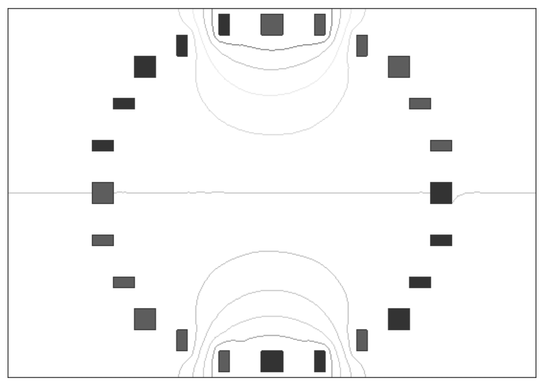

Fig 8. Convex field.

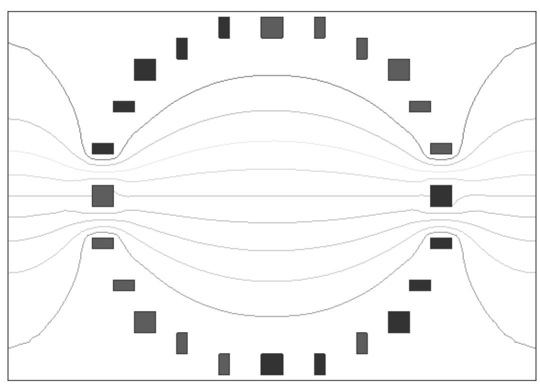

Fig. 9. Concave field.

Resolution of a 3HMS is limited by a number of factors: focusing, mechanical and electrical precision, and by the approximation accuracy of field rotation. The latter limitation is eliminated through the use of a sufficient number of blades.

CAPACITANCE

The 3HMS electric field must be swept over a frequency range to produce a spectrum. The amplifiers that produce the voltage drive to the deflection grids must be capable of driving the load. In this application, the loading is purely capacitive, with power dissipation defined by

$$P = C \cdot f \cdot V^2$$

where C is capacitance, f is frequency, and V is the drive voltage. Reducing the capacitive load is essential in reducing amplifier power output and maximizing performance. The capacitance of each deflection grid is relative to other grids and the outer grounded vacuum housing. A simple parallel plate approximation is given by

$$C = \frac{\varepsilon \cdot A}{d}.$$

Capacitance is proportional to surface area A and inversely proportional to distance d. The construction shown in Figure 2 violates both these principles. The electrodes are extremely close to each other with large surface areas. The area facing the outer housing is even worse. Basically, this makes for a very large parallel plate capacitance.

The fan blade construction is inherently far superior in this respect. Since the blades are thin, they maintain a good distance from adjacent blades, except near the exit aperture. If the blade profile is kept small, this capacitance is reduced even more. Most significantly, is the virtual elimination of capacitance to the vacuum housing, as the blade surfaces are orthogonal.

VACUUM

Mass spectrometers require a good vacuum to operate in. The prior art construction is severely enclosed with very little room for molecules to escape. Hence, there will be a slight pressure buildup within the 3HMS. A skeletal structure is greatly preferred, as molecules are not trapped and can be easily whisked away. The fan blades offer this in spades.

SUMMARY

This paper described a novel construction method for the deflection grids used in a 3HMS. Benefits include lower fabrication costs, easier methods of electrical drive, lower capacitance, and improved vacuum environment. In short, cost is greatly reduced and performance increased.

REFERENCES

1. "Hyperbolic Horn Helical Mass Spectrometer (3HMS)", Hagerman, 2005.
2. "Image Plane of 3HMS", Hagerman, 2005.
3. "Digital Drive of 3HMS", Hagerman, 2006.
4. "Rotating Field Mass and Velocity Analyzer", Patent 5,726,448, Smith, 1997.