

# A 250 HZ AC SCAN MAGNET FOR HIGH-POWER RADIOISOTOPE PRODUCTION AND BNCT APPLICATIONS\*

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## Abstract

This paper describes the proto-type magnet measurement results for a compact (212 mm effective length) yet large gap (97 mm) ambient air-cooled laminated AC scan magnet. A large aperture is essential for machine safety in radioisotope production, and Boron Neutron Capture Therapy (BNCT) applications with steady-state beam power up to 50 kW [1]. Rose shim and Purcell filter techniques are examined for improved transverse field flatness. The measured magnetic field and frequency response curves through a range from (250 Gauss, 70 Hertz) to (25 Gauss, 250 Hertz) are given for the case of an air-gap, SS316 beampipe, and SS316 bellows. Measured transverse and longitudinal magnetic field curves are also given. A model of the frequency response of the magnet was created and validated against measured data. The model simplifies power supply selection and maps effects of system natural frequency on the magnetic field. Tests were conducted with and without a resistor in parallel with the magnet coils. Lastly, an algorithm for a flat-topped square raster scanned beam intensity distribution is given.

## FIELD MEASUREMENTS & IMPROVEMENTS

D-Pace has developed an AC Scan Magnet for high-power (tens of kW) single-pass beamlines for radioisotope production and BNCT applications. For these applications a short device is required (350 mm insertion length, and 212 mm magnetic effective length) with a large gap (97 mm), so excess space is provided transverse to beams up to 40 mm in diameter to provide clearance between the beam extents and the beam pipe. For high power beams, a small percentage of beamspill would melt beam pipe walls in a catastrophic manner. A good-field region transverse to the beam is achieved with our nominal design where the field is flat to within  $\pm 1\%$  within  $\pm 20$  mm of the beam axis, refer to Figure 1.

Modelling of Rose shims and Purcell filters with Infolytica's Gemini code, as illustrated in Figure 2, resulted in a magnetic field flat to within  $\pm 0.25\%$  within  $\pm 20$  mm of the beam axis. The modelling of several shim and filter designs were undertaken, and the results shown here were the best achieved for a 97 mm gap.

Figures 3 & 4 illustrate the measurement of the magnetic field for the case of (a) an air-gap, (b) 1.6 mm wall SS316 beam tube, and (c) 0.4 mm wall SS316 formed bellows. These measurements were undertaken to determine any degradation to magnetic field resulting from eddy currents in the SS316 tube or bellows material.

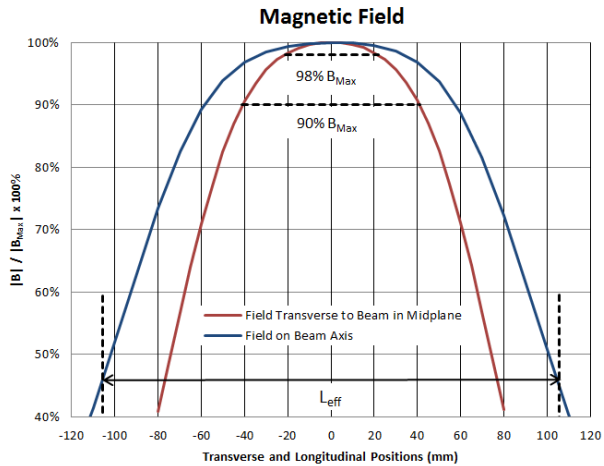


Figure 1: Measured normalized magnetic field transverse to the beam axis, and along the beam axis.

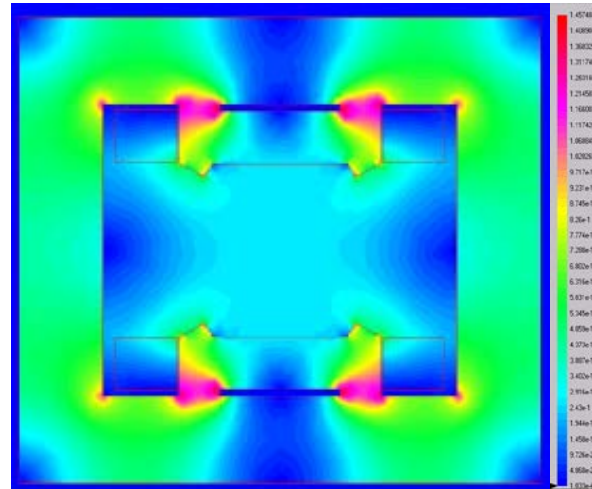


Figure 2: Magnetic field in Tesla. Each Rose shim is a triangle with base 20 mm in horizontal plane and height 8 mm at a point  $\frac{3}{4}$  along the base. Each Purcell filter is an absence of C1010 material, centred at the pole base, 4 mm in height by 72 mm in width.



Figure 3: AC Scan Magnet Field Measurements.

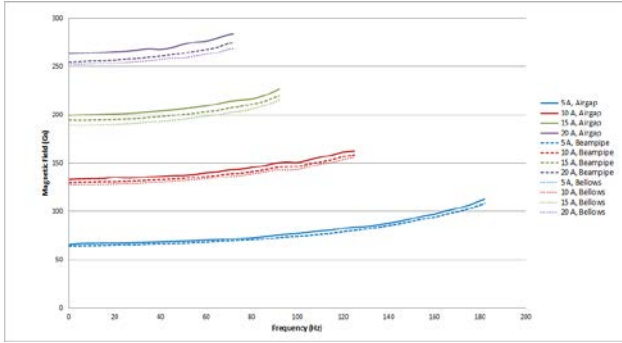


Figure 4: Magnetic field measurements as a function of frequency at centre of magnet gap for the case of (a) air-gap, (b) 1.6 mm wall SS316 wall beam-tube, (c) 0.4 mm wall SS316 roll-formed bellows.

For the case of alternating current magnet performance measurements with the Kepco BOP 50-20 GL Power Supply with 55  $\mu\text{F}$  internal shunt capacitance and no damping shunt resistor for purely sinusoidal beam scanning, Figure 5 shows the magnetic field measurements made at the magnet air-gap centre (no SS316 tube nor SS316 bellows), which range from >250 Gauss through 0 - 70 Hertz, >125 Gauss through 0 - 120 Hertz, and >25 Gauss through 0 - 250 Hertz.

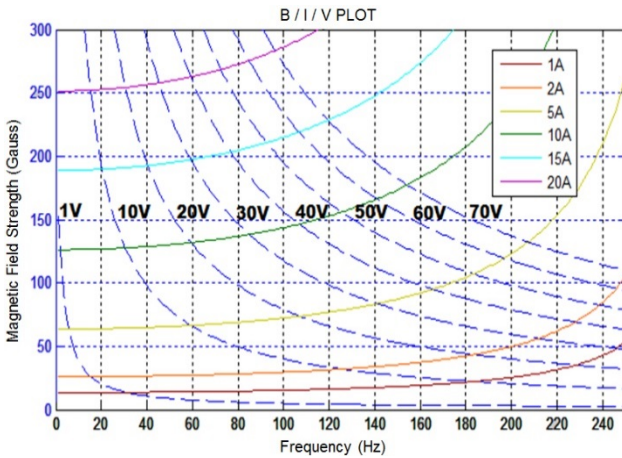


Figure 5: Magnetic field as a function of frequency for power supply sinusoidal peak current values up to  $\pm 20$  Amps and, for the case of the KEPKO BOP 50-20 GL power supply, a maximum of  $\pm 50$  Volts.

## BEAM SCANNING

Using two AC scan magnets one oriented for deflections in the horizontal plane, the other for deflections in the vertical plane can provide effective two-dimensional beam scanning using purely sinusoidal input currents direct from the power supply without additional damping circuits for the case of circular beam scans or Lissajous figures. Better flat-topping of the beam intensity distribution on target can be achieved by raster scanning using non-sinusoidal input currents to the magnets.

## Sinusoidal Scanning

Two-dimensional beam scanning using sinusoidal input currents of identical frequency for one horizontal AC scan magnet, and one vertical AC scan magnet yields a circular or elliptical beam scan pattern. If each magnet is excited with a current of different frequency, then roughly square or rectangular Lissajous beam patterns can be produced.

Consider the following example for the case of circular beam scanning. A 2.5 MeV proton beam is deflected by an angle of 23 milli-radians by a 250 Gauss peak magnetic field (since the magnetic effective length is 212 mm) for the case of a peak 70 Hz sinusoidal input current to each AC magnet of just under  $\pm 20$  Amps, and peak voltages just under  $\pm 50$  V according to Figure 5. At a target distance of 3 metres downstream, a circular beam scan radius of 69.5 mm is achieved (the upstream and downstream magnets have slightly different peak currents to compensate for the 350 mm difference in drift distance to the target position from each magnet). If the DC beam spot size is small relative to the beam scan radius a toroidal intensity distribution results, and if the DC beam spot size is large enough a disc pattern is achieved.

## Raster Scanning

For improved flat-topping of a charged particle beam's intensity distribution, raster scanning can be utilized. To achieve a square and flat-topped intensity distribution downstream of a pair of AC Scan Magnets, for example, requires a magnetic field varying in time as a triangular waveform in one of the magnets, and a stair-case pattern in the other, as shown in Figure 6. However, such non-sinusoidal waveforms contain a range of high frequency components. Such waveforms produced by a frequency generator and then faithfully amplified and delivered as input current signals by the power supplies to the magnets do not yield a 1:1 correspondence in the currents flowing through the magnets, nor a 1:1 correspondence in the magnetic field waveforms due to resonant behaviour. A damping circuit, Figure 7, eliminates the resonant behaviour. Figure 8 shows non-resonant magnet current gain (Magnet Current/Input Current) resulting from the damping circuit.



Figure 6: Blue staircase function (10 Hertz) fed to one AC Scan Magnet for vertical component of beam raster scanning, and red triangular waveform (50 Hertz) fed to the other AC Scan Magnet for the horizontal component of beam raster scanning component.

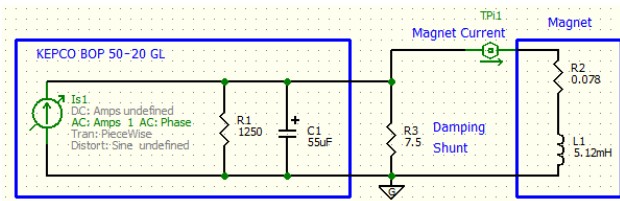


Figure 7: Damping circuit with resistances in  $\Omega$ .

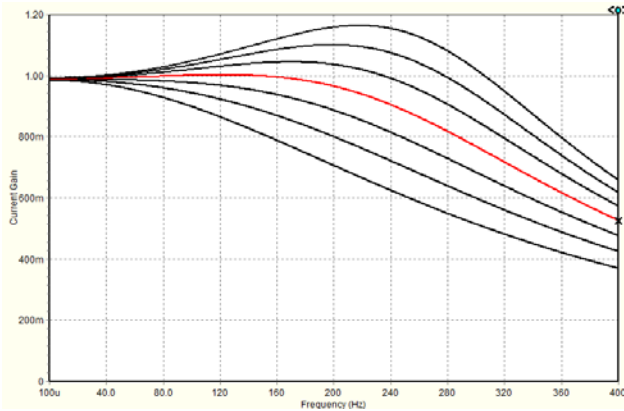


Figure 8: Magnet current gain (1:1 correspondence to magnetic field) as a function of frequency for damping resistances ranging from  $5\Omega$  (bottom) to  $10\Omega$  (top).

Figure 9 illustrates a 325 keV Argon 1+ DC Gaussian beam intensity distribution of nominal 16 mm diameter ( $\sigma_x = \sigma_y = 4$  mm) delivered from a Pantech ECR ion source, which required intensity flat-topping at a target position 2.61 metres distant from the downstream magnet centre. In this scenario, the horizontal and vertical waveforms employed in Figure 6 were used to deflect the DC Gaussian beam intensity distribution in Figure 9 to successfully achieve the flat-topped beam intensity distribution shown in Figure 10.

The intensity distribution in Figure 10 is flat-topped to within  $\pm 10\%$  at the target location. The flatness achieved can be made better or worse depending on the DC beam size being scanned (this can be adjusted by upstream focusing), and the number of steps taken (in this case we used 8 steps), and the spacing between each scanned beam path. This can all be modelled ahead of time, and a solution that is suitable for the application can be chosen.

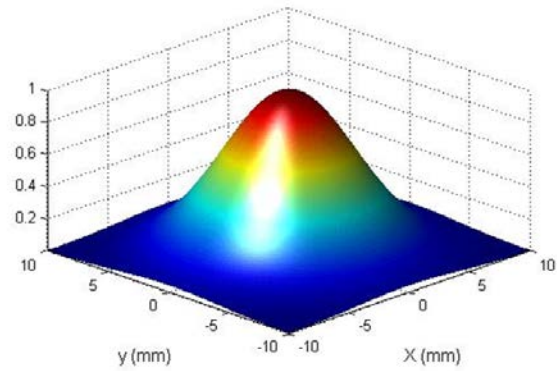


Figure 9: Gaussian distribution 325 keV, Ar+ beam.

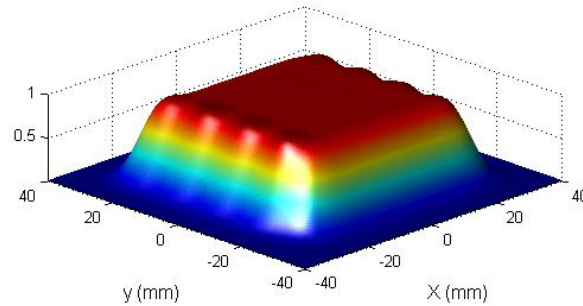


Figure 10: Resultant raster scanned 325 keV Argon 1+ beam with flat-topped intensity distribution (to within  $\pm 10\%$ ) attained on a 60 mm by 60 mm square.

## CONCLUSION

A compact (350 mm insertion length) AC Scan magnet with improved field flatness of  $\pm 0.25\%$  in a 40 mm diameter good-field region functions with a large 97 mm gap for plenty of excess space between high-power beams (up to 40 mm in diameter) and the walls of the vacuum tubing. Furthermore, it operates effectively with peak magnetic field of 250 Gauss in a range 0 – 70 Hertz, and 25 Gauss in a range 0 – 250 Hertz for the case of sinusoidal waveforms. Performance is not significantly affected by SS316 beampipe nor bellows. Through utilization of a damping circuit, resonant behaviour is avoided, and non-sinusoidal raster scanning can be properly implemented for flat-topping beam intensity distributions on target for spreading beam power over a large area in a uniform manner.

## ACKNOWLEDGMENT

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## REFERENCES

- [1] M.P. et al., "A specialized High-Power (50 kW) Proton Beamline for BNCT," NAPAC'13, Pasadena, October, p. 116 (2013);