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Configurable Field Magnets for a Proton Beam Dynamics R&D Ring

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Abstract

Magnets with many independently-powered coils can provide nearly arbitrary combinations of multipoles up to a certain order. This paper gives examples of field quality in such an "omni-magnet", which is normal-conducting and simulated with Poisson. Since the magnets also have quite large apertures they may be used to make a general-purpose FFAG and synchrotron test ring for beam dynamics studies. This could use the 3MeV H^- beam from the RAL proton Front End Test Stand (FETS) and outline ring parameters are given for that situation.

Extending FETS with a Ring

- **Electron models are not sufficient** for simulating the beam dynamics of H^- stripping injection, must use an ion species.
- **The Front End Test Stand (FETS) at RAL** is a source of H^- ions at 3MeV, ~50mA current and 50Hz repetition rate.
- **FETS already provides** a high-quality beam with significant space charge and a fast/slow beam chopper integral to the design.
- **Using configurable magnets** would allow many synchrotron and FFAG lattices to be tested without having to build a model for each.

Table 1: Parameters of the Proton Omni-Ring

Beam energy	3	MeV
Beam momentum	75.09	MeV/c
Magnet packing factor	40	%
Mean dipole in magnet	0.2	T
Ring diameter	6.262	m
Revolution frequency	1.216	MHz
Example cell structure		
Magnets per ring	24	
Cell length	0.8197	m
Magnet length	0.3279	m
Drift length	0.4918	m

- **Injection line from FETS** should ideally contain multi-axis kickers (and maybe an RF cavity) for injection painting, beam position and profile monitors, beam diluters to vary space charge and toroids.
- **Fast extraction line from ring** should contain diagnostics of the beam profile, halo and possibly emittance of any single turn.

Omni-Magnet

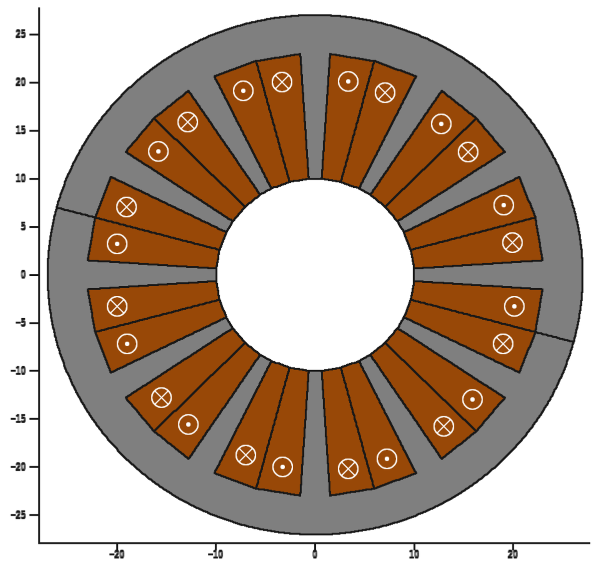
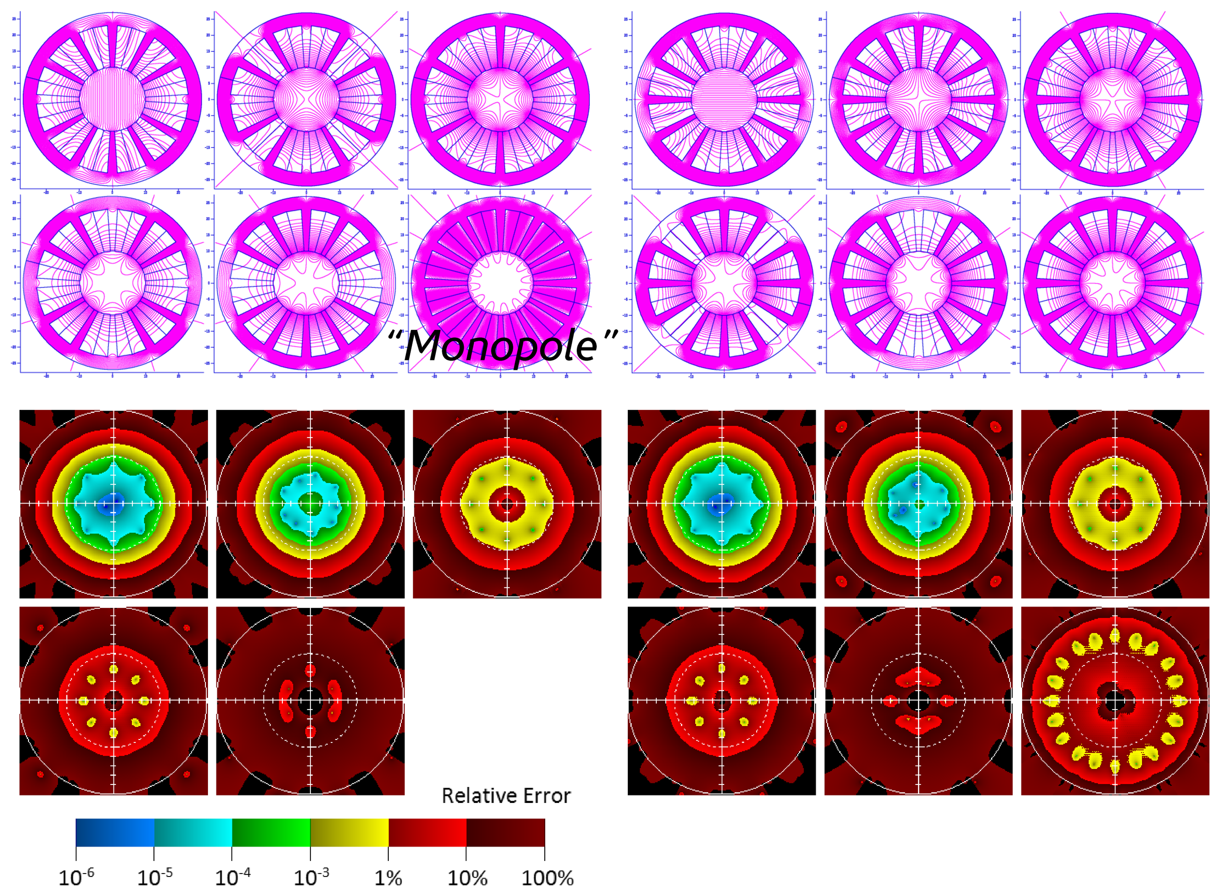


Table 2: Omni-Magnet Multipole Field Strengths

n	**Pole**	**Max j** A/mm²	**Strength** T/m^{n-1}	**Max B in poles** Tesla
1	Dipole	5	0.241558	1.23
2	Quad	2.165	2.21262	1.13
3	Sext	1.667	39.36	1.37
4	Oct	1.083	1032	1.20
5	Deca	1	34800	1.30
n	**Skew**	**Max j**	**Strength**	**Max B in poles**
1	Dipole	5	0.241558	1.23
2	Quad	2.5	2.21136	1.29
3	Sext	1.667	39.38	1.37
4	Oct	1.25	1032	1.38
5	Deca	1	34800	1.30
6	Dodeca	0.833	2892000	1.15

***Above left:** Cross-section of the omni-magnet. The magnet resembles a dodecapole but the current in each coil can be varied independently. The bore radius is 10cm, surrounded by 13cm-long poles and a 4cm-thick iron return yoke for a total radius of 27cm. The poles take up 25% of the angular fraction.*

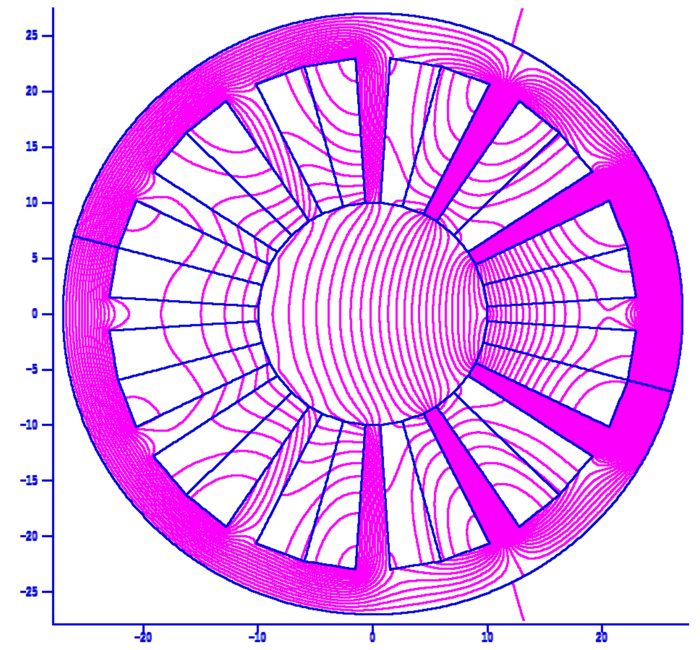
Multipole Fields



***Above:** (top) Fields generated by the omni-magnet in multipole (left) and skew multipole (right) current configurations. The current density in each winding is given by $j = (5A/mm^2)\sin(n\theta)/n$, with sin replaced by cos for skew poles.*

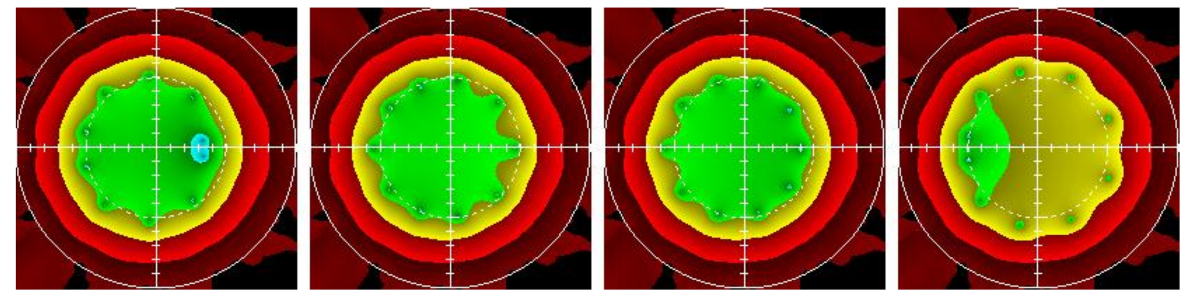
(bottom) Relative errors, defined by $|B-B_{goal}|/|B_{goal}|$, of the corresponding fields in the top row. Each plot shows x,y from −10 to 10cm, including the entire magnet bore. The same colour scale is used throughout this poster.

Scaling FFAG Fields

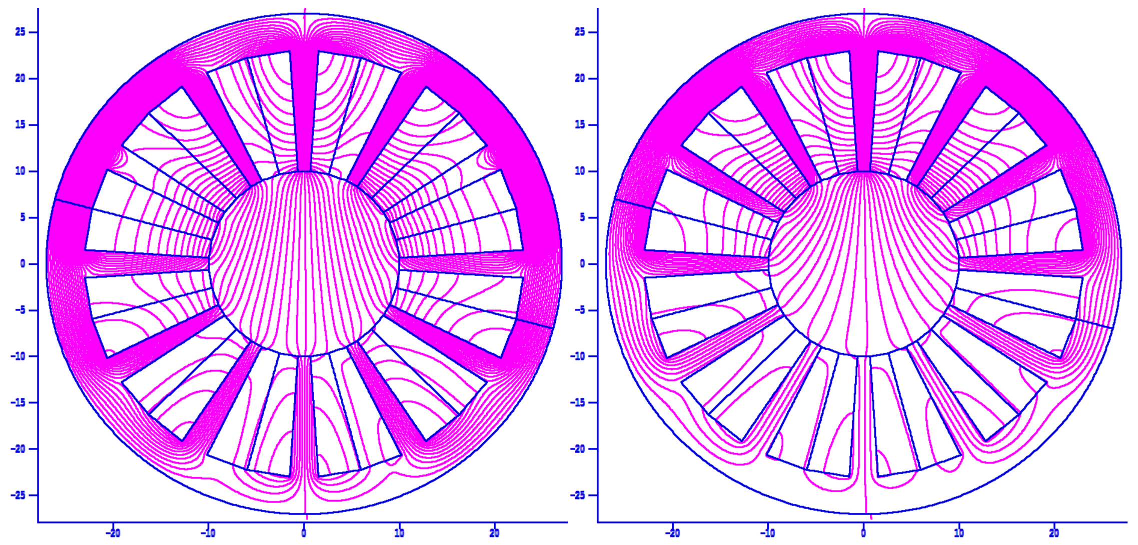


***Left:** Omni-magnet producing a scaling FFAG field by linearly combining multipole current configurations according to the Taylor series of the scaling FFAG field law: $B_y = B_0(r/R_0)^k$ for $y = 0$, where $r = R_0+x$. Here, $B_0 = 0.2T$, $k = 20$ and $R_0 = 3.131m$.*

***Below:** Relative field errors in the k = 20 scaling FFAG for field strengths B_0 = 0.05, 0.1, 0.15 and 0.2T (left to right).*

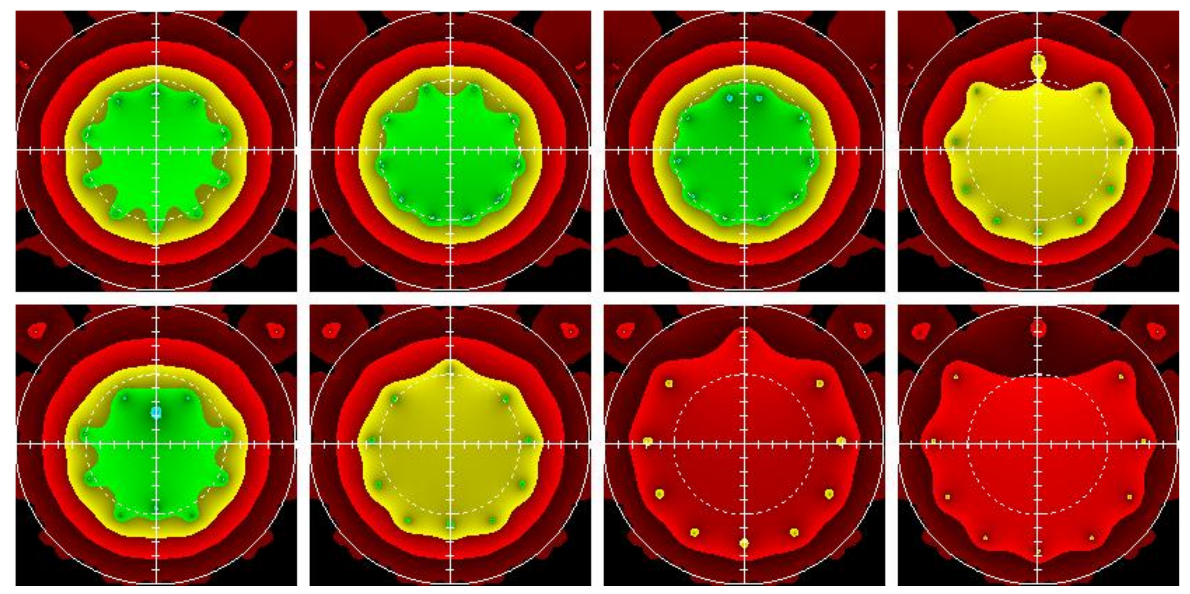


Exponential VFFAG Fields



Above: Fields from the vertical orbit excursion FFAG scaling law ($B_y = B_0e^{ky}$ for $x = 0$) for $k = 5m^{-1}$ (left) and $10m^{-1}$ (right).

Below: Relative error plots for VFFAGs with $k = 5m^{-1}$ (top row) and $10m^{-1}$ (bottom row) for field strengths B_0 = 0.05, 0.1, 0.15 and 0.2T (left to right), saturation occurs towards bottom right.

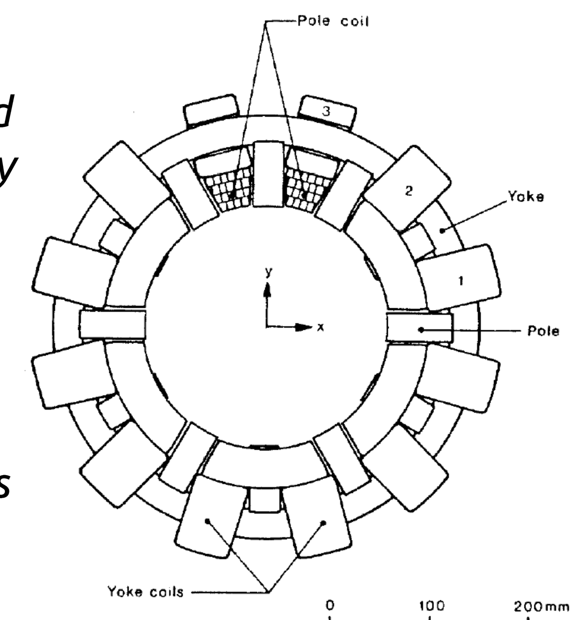


Field Strength Upgrades

The iron poles only take up 25% of the circumference of the magnet bore, so if the iron starts to saturate at 1.4T, the maximum field at the edge of the bore can only be 25% of this (0.35T) since all the flux lines have to bunch together to go through the iron.

Higher field strength may be achieved in future by using thicker or non-tapering poles.

***Right:** The corrector magnets used in the SRS at Daresbury Laboratory (designed by Neil Marks) had a very similar principle to omni-magnets but operated at lower fields. They also have windings around the iron return yoke that may produce low-order multipoles using less current.*

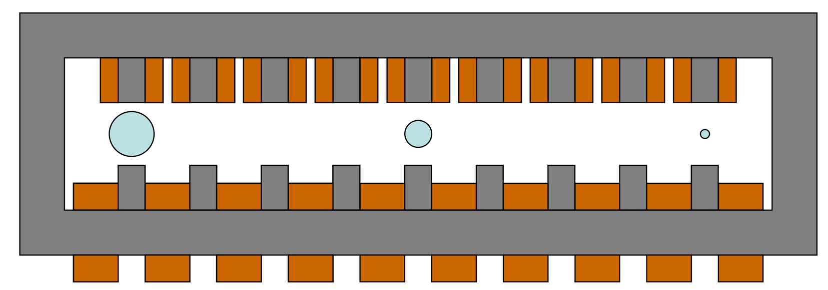


Other Future Work

- **Correction schemes** have not yet been used to fine-tune the currents in these magnets; e.g. the higher-order poles have a small dipole defect that could be subtracted out. This will be necessary in the case of each real magnet as well as in the simulations.
- **Fitting schemes** such as least-squares error fitting of a polynomial can provide better field quality over a finite range than just using the Taylor series at a point.
- **Operating with the iron in saturation** can provide higher pole-tip fields at the expense of non-linear operation. It may be possible with very careful calibration.

Slotted Variant for FFAG Correction

- A "hybrid FFAG" uses superconducting fixed-field magnets for main dipole and quadrupole, PLUS:
- "Omni-Corrector Magnet"



Alternative coil configuration shown on bottom half

- The above iron+copper magnet used for:
  - Static field/tune error correction in DC mode
  - In pulsed/programmable mode (~10kHz bandwidth):
    - Resonance jumping
    - Dynamic aperture improvement
    - [Optional] Resonant extraction

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