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Vertical Orbit Excursion FFAG Accelerators with Edge Focussing

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Abstract

FFAGs with vertical orbit excursion (VFFAGs) provide a promising alternative design for the magnets in fixed-field machines. They have a vertical magnetic field component that increases with height in the vertical aperture, yielding a skew quadrupole focussing structure. The end fields of such magnets with edge angles provide an alternating gradient without the need for reverse bends, thus reducing the machine circumference. Similarly to spiral scaling horizontal FFAGs (but unlike non-scaling versions), the machine has fixed tunes and no intrinsic limitation on momentum range. Rings capable of boosting the 800MeV beam from the ISIS proton synchrotron (ε_{geom} = 150mm.mrad) to 3, 5 and 12GeV using superconducting magnets are presented, the latter corresponding to 2.5MW beam power.

Options for a Multi-GeV Ring

• **Ramping field** synchrotron provides fixed tunes and small beam aperture but at 50Hz operation needs normal-conducting magnets;

• **Fixed field** FFAG allows superconducting magnets and does not need time for magnets to ramp down but needs wide slot aperture.

Synchrotron options are being investigated by others in ISIS. Within FFAGs there is a second decision:

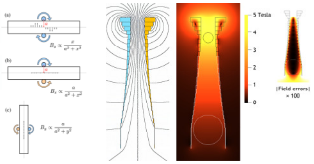
• **Scaling** FFAGs have fixed tunes and optics at all energies by construction but negative gradients require reverse bends;

• **Non-scaling** FFAGs can have negative gradients in positive bends (thus smaller) but optics and usually tunes change with energy;

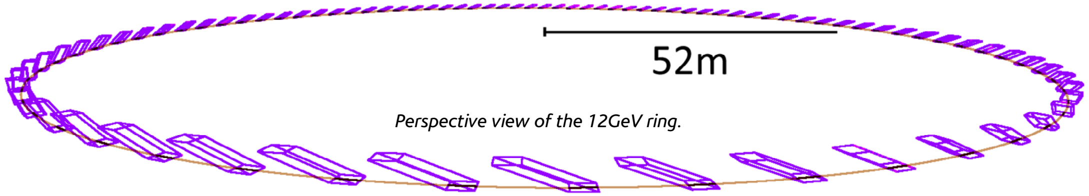
• **Spiral scaling** FFAGs use edges to give alternating gradients while only having positive bends. E.g. the RACCAM medical accelerator.

Finally, the orbit can move either **horizontally** (conventional FFAG) or **vertically** (VFFAG) with energy. The scaling law for horizontal machines is $B \sim r^k$ and for VFFAGs it is $B \sim e^{ky}$.

This work investigates a spiral scaling VFFAG.

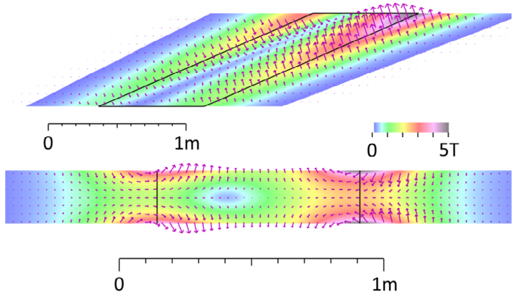


Right: *VFFAG magnets can be made as a slot with opposing current windings on each side.*



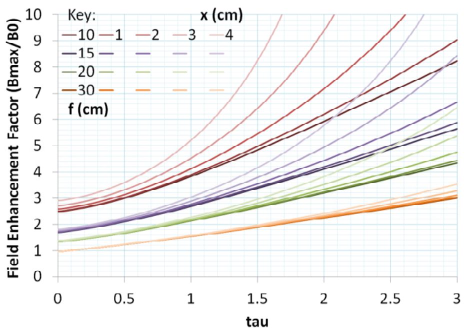
Perspective view of the 12GeV ring.

VFFAG Magnetic Fields

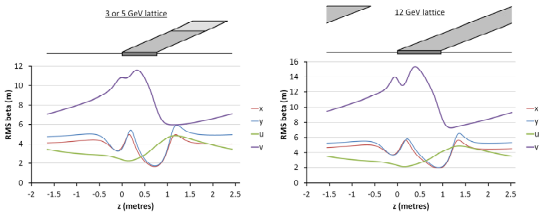


Above: *Cross-section of the 5GeV ring magnet's field in ZY (top) and ZX (bottom) planes.*

Below: *Magnet end-field enhancement as a function of τ, fringe length (f) and distance from mid-plane (x) from 0 to 4cm, in the 3 or 5GeV magnet design with k = 2.05m^{-1}.*



Optics



Above: *Beta functions in the two lattices, in non-skew and skew coordinates. Magnet size is to scale in z and y. Skew coordinates are defined as:* $u = (x+y)/\sqrt{2}$ and $v = (y-x)/\sqrt{2}$

Below: *Phase space and beam evolution through the 12GeV ring cell at injection energy. Transverse scale is ±5cm and x', y', u', v' ranges are ±20mrad.*

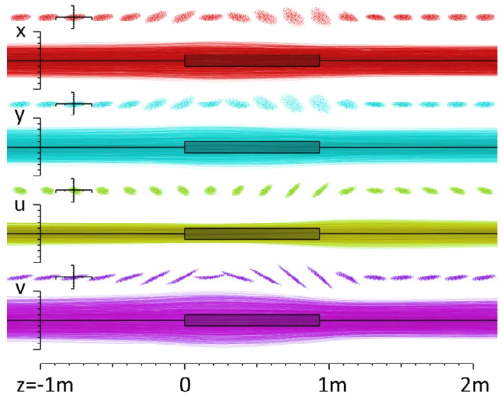
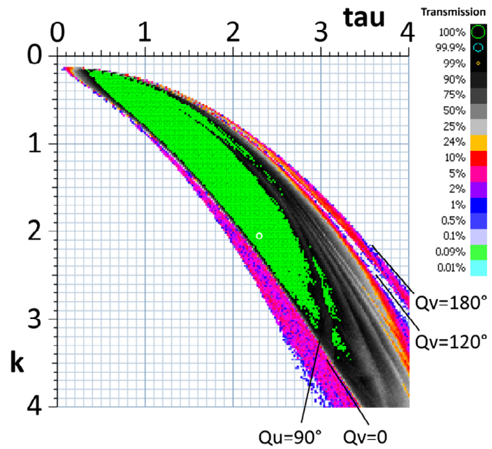


Table 1: VFFAG Proton Accelerator Ring Parameters

	3 GeV	5 GeV	12 GeV
$E_{k,\mathrm{inj}}$	800 MeV		
$E_{k,\mathrm{ext}}$	3 GeV	5 GeV	12 GeV
Mean radius	52 m (2×ISIS)		
RF harmonic	$h = 8$		
Superperiods	80 (superperiod is one cell)		
Cell length	4.0841 m		
Drift length	3.3174 m		3.1257 m
Magnet Parameters			
Magnet length	0.7667 m		0.9584 m
B_0	0.5 T		0.4 T
k	2.05 m^{-1}		2.23 m^{-1}
$\tau = \tan\theta_{\mathrm{edge}}$	2.3		2.6
θ_{edge}	66.50°		68.96°
Fringe length	$f = 0.3$ m in $B \propto \frac{1}{2} + \frac{1}{2}\tanh(z/f)$		
B_{ext}	1.3069 T	2.0036 T	3.5274 T
$B_{\mathrm{fringe}}/B_{\mathrm{body}}$	$2.7251_{x=4\,\mathrm{cm}}$		$2.6399_{x=2\,\mathrm{cm}}$
$B_{\max}$	3.5615 T	5.4600 T	9.3119 T
Beam Optics			
$y_{\mathrm{ext}} - y_{\mathrm{inj}}$	0.4687 m	0.6771 m	0.9762 m
μ_u (per cell)	71.11°		71.33°
μ_v	28.68°		19.65°
Q_u (ring)	15.802		15.851
Q_v	6.373		4.367



Above: *Proton beam transmission as a function of τ and k, with lines of increased loss corresponding to cell tune resonances labelled. The 3 or 5GeV ring design is circled. At this point,*

$$\frac{\partial Q_{u,v}}{\partial k} = \begin{bmatrix} -8.49 \\ -94.46 \end{bmatrix} \quad \text{and} \quad \frac{\partial Q_{u,v}}{\partial \tau} = \begin{bmatrix} 39.92 \\ 119.82 \end{bmatrix}$$

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