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Acceleration in Vertical Orbit Excursion FFAGs with Edge Focussing

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Abstract

FFAGs with vertical orbit excursion (VFFAGs) provide a promising alternative design for rings with fixed-field superconducting magnets. They have a vertical magnetic field component that increases with height in the vertical aperture, yielding a skew quadrupole focussing structure. Edge focussing can provide an alternating gradient within each magnet, thus reducing the ring circumference. Like spiral scaling horizontal FFAGs (but not non-scaling ones) the machine has fixed tunes and no intrinsic limitation on momentum range. Rings to accelerate the 800MeV beam from the ISIS proton synchrotron are investigated, in terms of both magnet field geometry and longitudinal behaviour during acceleration with space charge. The 12GeV ring produces an output power of at least 2.18MW.

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;

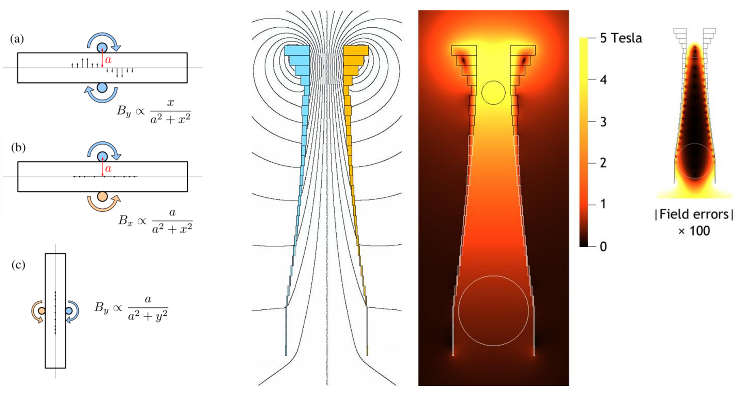
• **Non-scaling** FFAGs can have negative gradients in positive bends (thus smaller) but optics and usually tunes change with energy;

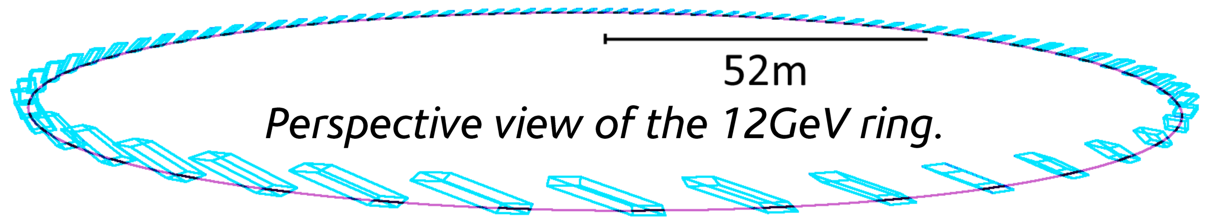
• **Spiral scaling** FFAGs use edges to give alternating gradients while only having positive bends. E.g. the RACCAM medical accelerator.

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.



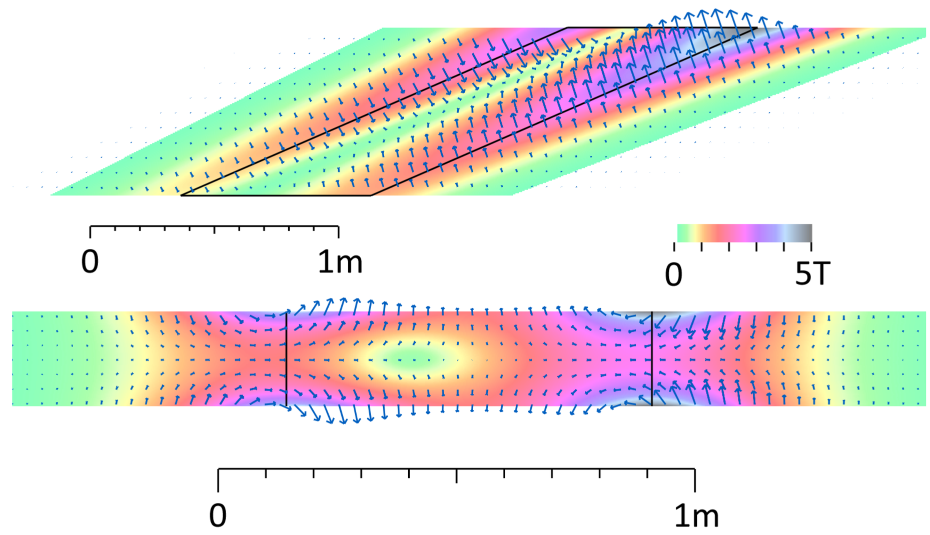


Perspective view of the 12GeV ring.

Table 1: VFFAG Proton Accelerator Ring Parameters

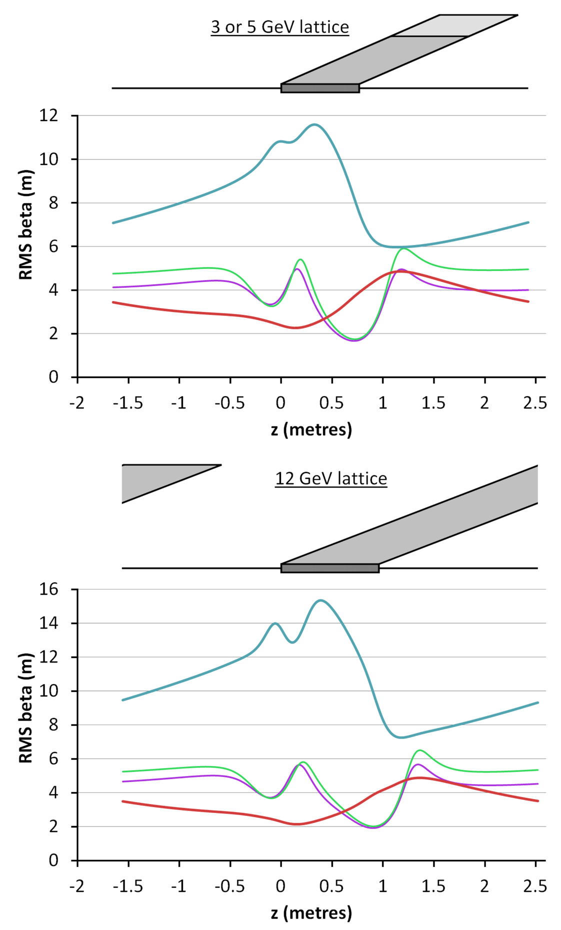
$E_{k,\mathrm{inj}}$	800 MeV		
$E_{k,\mathrm{ext}}$	3 GeV	5 GeV	12 GeV
Mean radius	52 m (2×ISIS)		
RF harmonic	$h = 8$		
Superperiods	80 (superperiod is one cell)		
Cell length	4.0841 m		
Drift length	3.3174 m		3.1257 m
Magnet Parameters			
Magnet length	0.7667 m		0.9584 m
B_0	0.5 T		0.4 T
k	2.05 m^{-1}		2.23 m^{-1}
$\tau = \tan\theta_{\mathrm{edge}}$	2.3		2.6
θ_{edge}	66.50°		68.96°
Fringe length	$f = 0.3\,\mathrm{m}$ 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

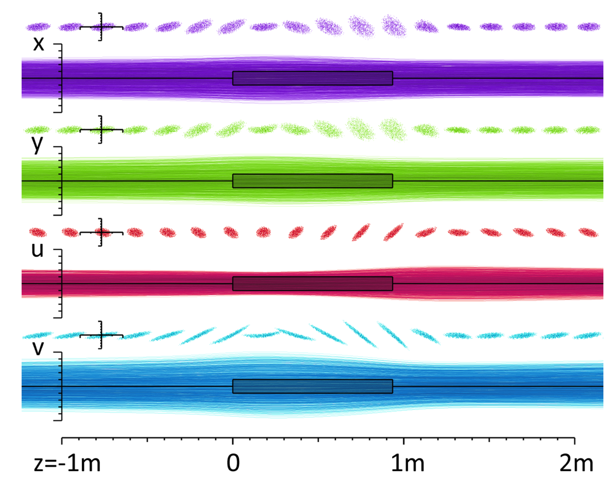
VFFAG Magnetic Field

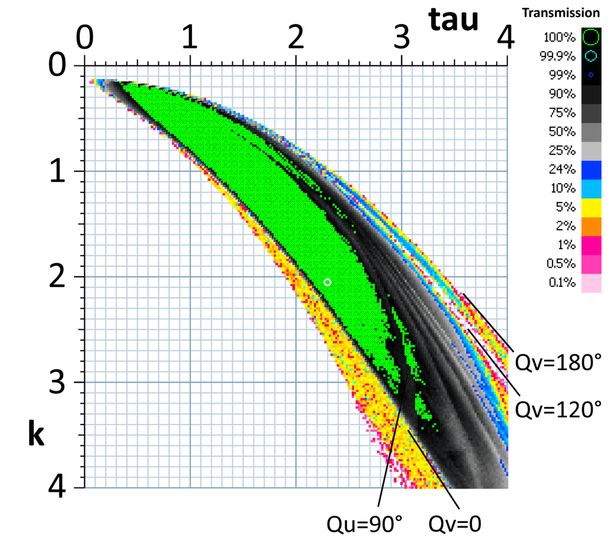


Above: Cross-section of the 5GeV ring magnet's field in ZY (top) and ZX (bottom) planes. The beam travels left to right and the orbit moves upwards on the top picture with increasing energy.

Optics and Dynamic Aperture





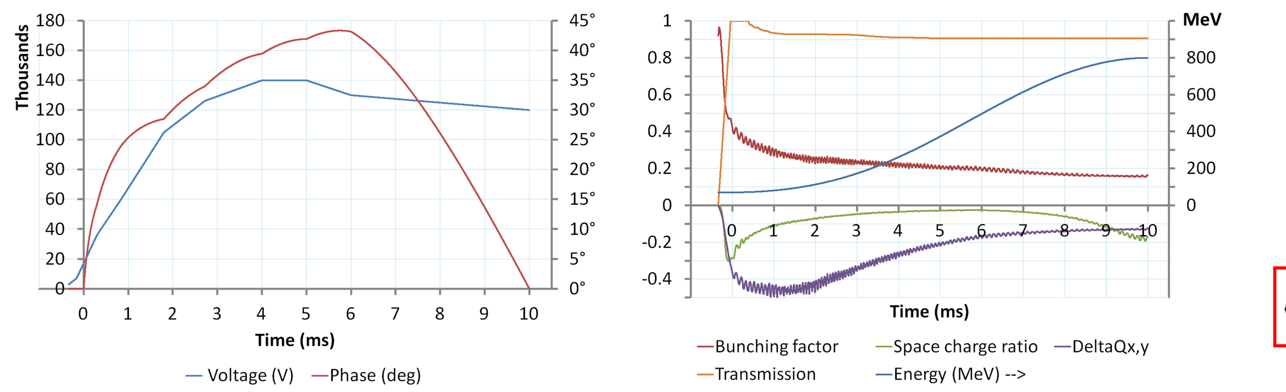


Above: (left) Beta functions in the two lattices, in non-skew and skew coordinates. Magnet size is to scale in z and y. Skew coordinates are defined as: $u = (x+y)/\sqrt{2}$ and $v = (y-x)/\sqrt{2}$

(top right) 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.

(bottom right) 150mm.mrad waterbag proton beam transmission as a function of τ and k, with lines of increased loss on cell tune resonances labelled. The 3 or 5GeV ring design is circled.

Longitudinal ISIS Simulation



Above: To obtain an input distribution for the VFFAG (and as a check), 1D simulations were first run on ISIS starting from the linac injection at 70.44MeV. (left) ISIS first harmonic RF program. (right) Bunching factor, transmission and intensity-dependent effects in the ISIS first harmonic simulation.

Longitudinal VFFAG Simulation

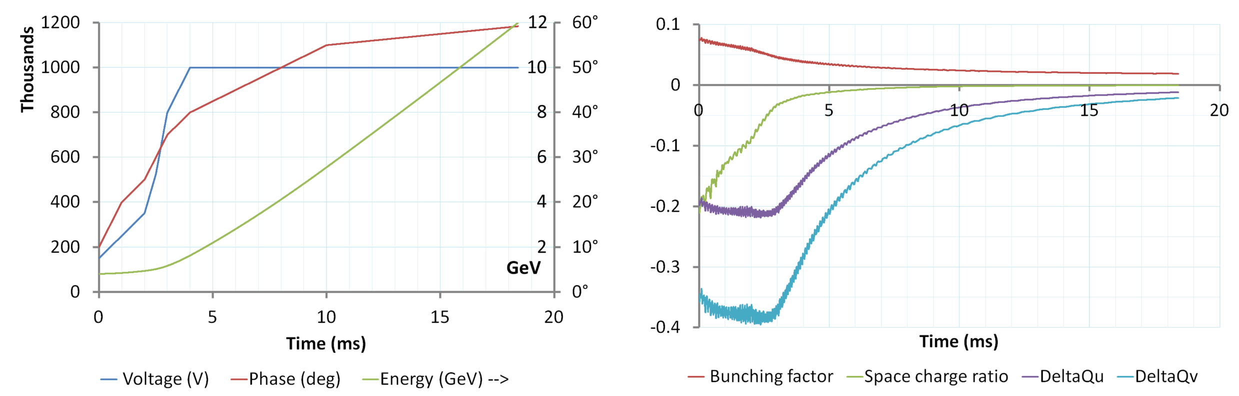


Table 2: Longitudinal parameters for the 12 GeV VFFAG. Peak voltage per turn and phase are linearly interpolated from the times given.

RF harmonic	$h = 8$
RF frequency	6.179–7.321 MHz
Cycle duration	18.41 ms
Rep. rate	50 Hz

Time (ms)	Voltage (kV)	Phase
0	150	10°
1	250	20°
2	350	25°
2.5	525	30°
3	800	35°
4	1000	40°
10	1000	55°
18.41 (extract)	*1000*	*59.21°*
20	1000	60°

Above: *(left) RF program for the 12GeV VFFAG.*
(right) Intensity dependent effects in the VFFAG.
Below: *(left) Bunch length decreases to 1.64ns RMS, suitable for a neutrino factory proton driver.*
(right) Reciprocal increase in bunch energy spread.

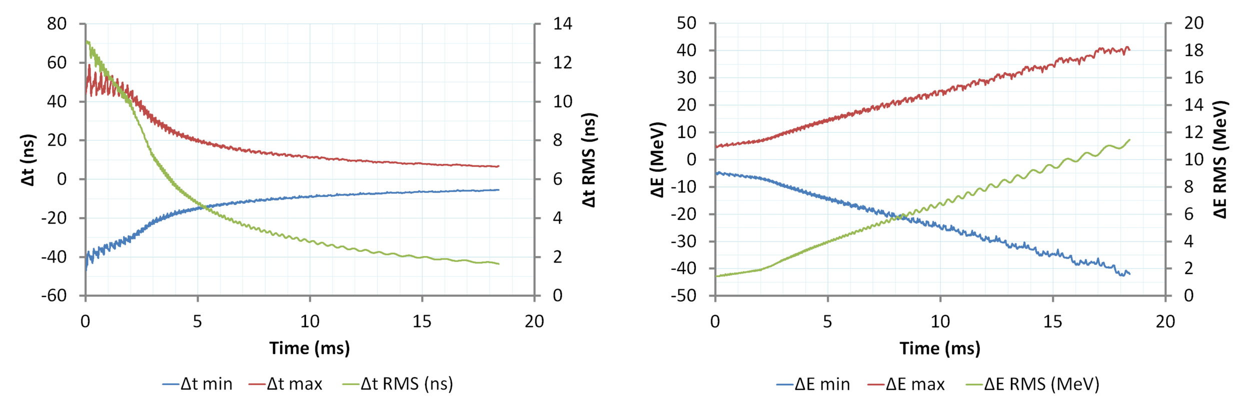


Table 3: Intensity-dependent parameters for the ISIS single harmonic and 12 GeV VFFAG simulations run in series, for different numbers of protons injected into ISIS.

ISIS Protons In	2.50e13	2.75e13	3.00e13
ISIS μA in	200.3	220.3	240.3
ISIS transmission	90.54%	87.95%	85.98%
ISIS protons out	2.26e13	2.42e13	2.58e13
ISIS μA out	181.3	193.7	206.6
ISIS power (kW)	145	155	165
VFFAG transmission		100%	
VFFAG power (MW)	2.18	2.32	2.48
ISIS Peak Intensities			
Bunching factor	0.154	0.150	0.151
Space charge ratio	-0.301	-0.305	-0.311
$\Delta Q_{x,y}$	-0.499	-0.544	-0.580
VFFAG Peak Intensities			
Bunching factor	0.0188	0.0190	0.0190
Space charge ratio	-0.211	-0.257	-0.278
ΔQ_u	-0.219	-0.240	-0.254
ΔQ_v	-0.395	-0.434	-0.458

Bunching factor: $\langle\rho_{1\mathrm{D}}\rangle / \rho_{1\mathrm{D}}^{\mathrm{peak}}$

Space charge ratio: $V_{\mathrm{sc}}/V_{\mathrm{rf}}$, $\Delta Q_s/Q_s$

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