Non-Scaling Fixed-Field Proton Accelerator with Constant Tunes

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Abstract

Recent studies by Dejan Trbojevic have confirmed that Non-Scaling Fixed Field Accelerators (NS-FFAs) can have their tune dependence on momentum flattened by adding nonlinear components to the magnet fields, although not necessarily for an unlimited momentum range. This paper presents such a cell suitable for the proposed 3–12 MeV FETS-FFA proton R&D ring at RAL.

The nonlinear magnetic field components are found automatically using an optimiser and settings covering a ring tune range of one unit in both planes independently are attainable. A fully configurable magnet with multiple windings across its horizontal aperture has been designed in 2D using Poisson, which can produce the required nonlinear fields without exceeding 5 A/mm² current density.

Introduction

The ISIS-II project plans to use a fixed-field accelerator (FFA) to increase the proton beam power driving the neutron source at RAL to ≥1.25 MW from its present ~200 kW.

A prototype FFA using the 3 MeV proton beam from the Front End Test Stand (FETS) at RAL is being designed to test beam dynamics under realistic space charge levels and machine errors. This R&D ring is called FETS-FFA.

Near-constant ring tunes are desirable for accelerating beams with high space charge levels to avoid resonances. Scaling FFAs guarantee this via a scaling law, but are less magnetically efficient because they always include a reverse bend. In this paper, an efficient non-scaling FFA solution with a fixed tune is found for FETS-FFA.

By adding higher-order multipoles to a linear non-scaling FFA cell, the sextupoles can cancel the first tune derivative dQ/dE, the octupoles can cancel d²Q/dE² and so on. This eventually leads to a very flat tune dependence, at least over a finite energy range.

Requirements

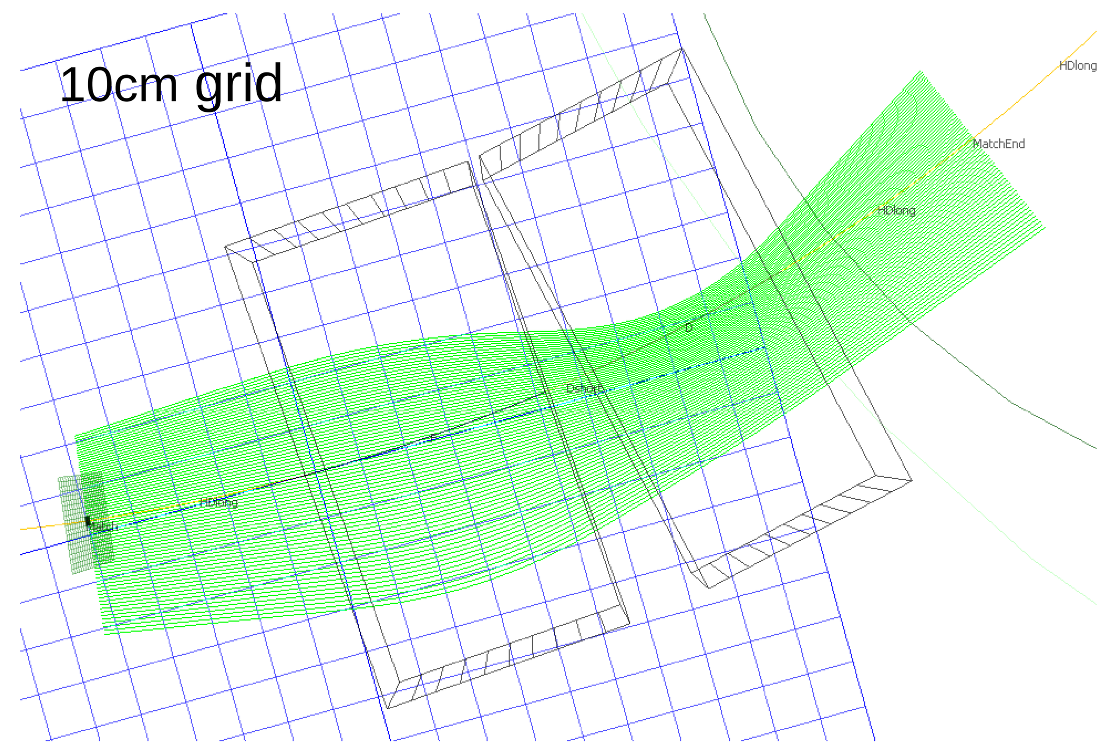
Table 1: FETS-FFA Fixed-Tune Cell Requirements

Parameter	Value	Unit
Species	Proton	
Kinetic energy	3–12	MeV
Average radius	4	m
Long drift length	1	m
Tune variation	<0.01	per ring
	<0.001	per cell
Tune tunability range	1	per ring
Dynamic aperture	1250	mm.mrad (geom.)

Algorithm Nested Loops

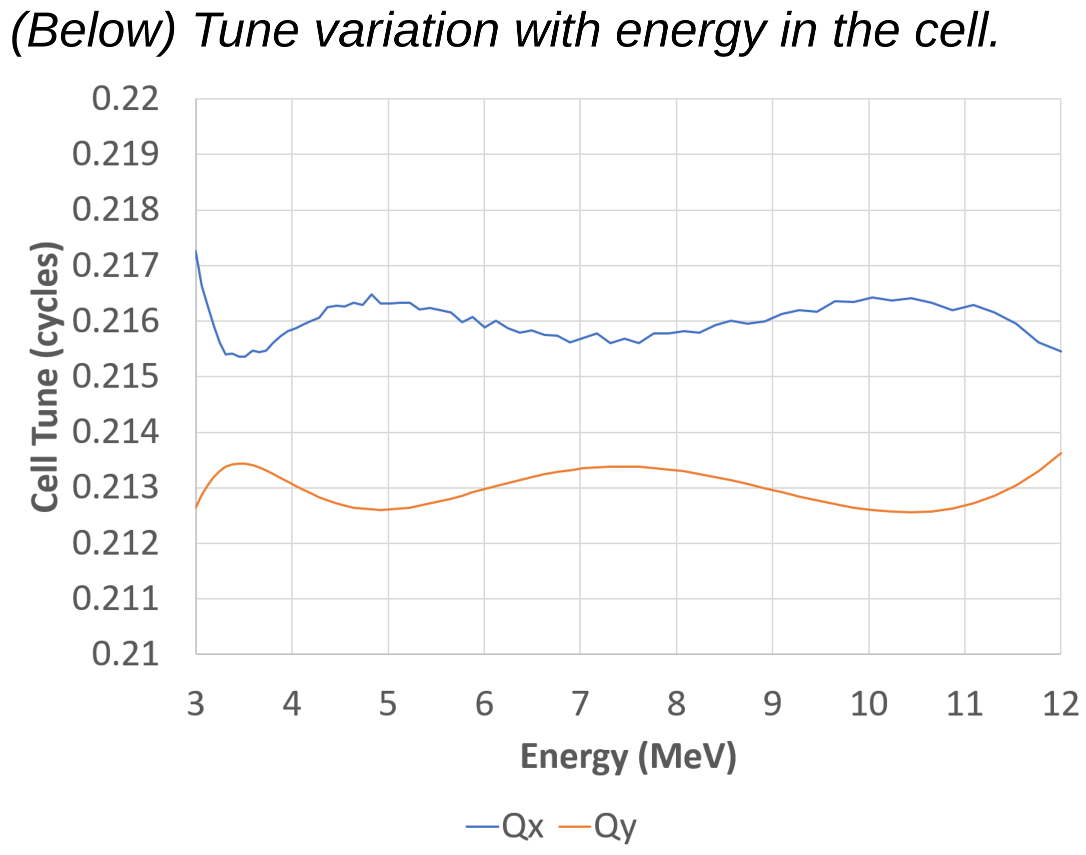
0. Runge-Kutta 4th order tracking step.
1. **Loop** timesteps to get trajectory in cell.
2. **Finite difference** initial position and angle to get transfer matrix (also gives tunes if orbit is closed).
3. **Optimise** (Newton) to find closed orbit.
4. **Loop** over all FFA energies.
5. **Finite difference** magnet parameters to get response matrix of tune functions to multipole changes.
6. **Optimise** (Levenberg–Marquardt) to make lattice tune functions constant with energy.

Fixed-Tune Cell



(Above) Closed orbit range in the Q_x=0.216, Q_y=0.213 cell, from 3–12 MeV (top to bottom).

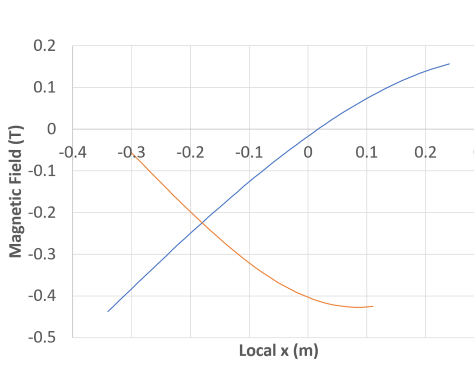
(Below) Tune variation with energy in the cell.



The cell lattice including multipole components for each magnet is shown below (left), with the fields plotted as a function of transverse position (right).

Table 2: Lattice Cell for $Q_x = 0.216$, $Q_y = 0.213$

Element	F	OS	D	OL	Unit
Length	0.5253	0.1	0.4691	1	m
Angle	0.1313	0.025	0.1173	0.25	rad
Fringe σ	0.06		0.06		m
B_0	-0.0169		-0.4034		T
B_1	1.0107		-0.5520		T/m
B_2	-0.9416		3.0345		T/m²
B_3	-0.9379		2.6260		T/m³
B_4	-0.5760		-5.0536		T/m⁴
B_5	-0.6331		-8.1518		T/m⁵



Adjustment of 1 in ring tune (0.0833 in cell tune) is required for R&D purposes. The table below shows fixed-tune cells from the algorithm for all four "corners" of the adjustment range.

Table 3: Adjusted Tune Designs Summary

Cell Q_x	Cell Q_y	Max tune error	Max field (T)	Orbit range (m)
0.216	0.213	0.00126	0.4310	0.573
0.2083	0.2083	0.00074	0.5204	0.641
0.2083	0.2917	0.00185	0.6128	0.688
0.2917	0.2083	0.00168	0.4466	0.389
0.2917	0.2917	0.00037	0.4004	0.381

Mid-Plane Field Model

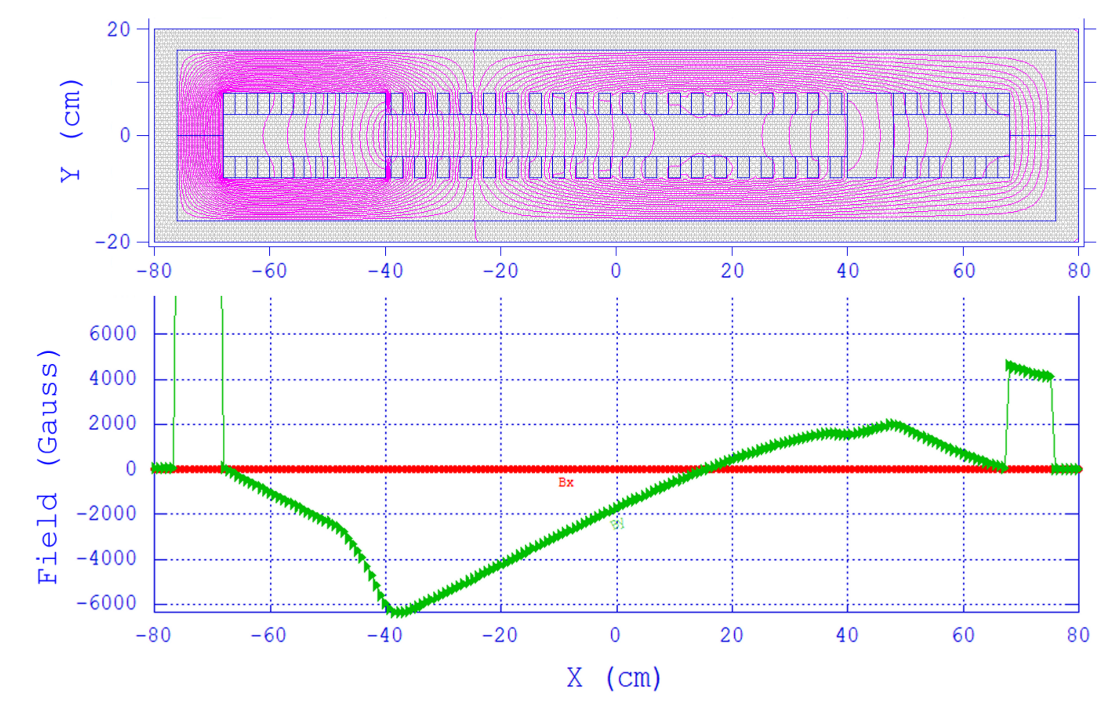
The field at y=0 in the magnets is defined by:

$$B_y(x,0,z) = \Phi\left(\frac{z}{\sigma}\right)\Phi\left(\frac{L-z}{\sigma}\right)\sum_{n=0}^{5} B_n x^n$$

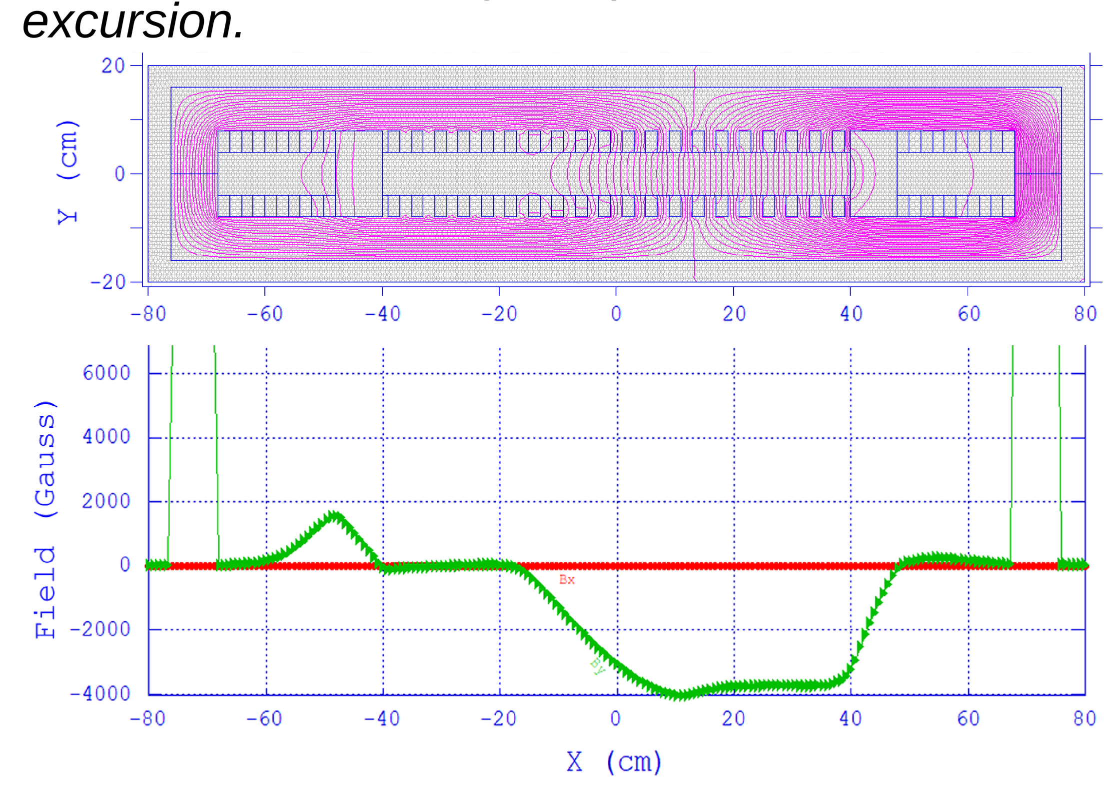
$$\Phi(z) = \tfrac{1}{2} + \tfrac{1}{2}\mathrm{erf}(z/\sqrt{2})$$

Horizontal Omni-Magnets

Tune adjustment in FETS-FFA requires independently adjusting all multipoles of each magnet: an unusual requirement. A magnet with many embedded pole-face coils was designed to provide universal field adjustment capability.



Field lines (top) and mid-plane field (bottom) for the F magnet of the Q_x=0.2083, Q_y=0.2917 cell, which has the largest peak field and orbit excursion.



Field lines and mid-plane field for the D magnet of the Q_x=0.2917, Q_y=0.2917 cell, which has the smallest orbit excursion. Field is only produced in a fraction of the aperture.

Table 4: Magnet Performance Summary

Cell Q_x	Cell Q_y	Magnet	Max current density (A/mm²)	Max B_y error (Gauss)	Max field (T)	Orbit range (m)
0.216	0.213	F	2.372	1.88	0.4224	0.573
		D	4.256	2.32	0.4270	0.400
0.2083	0.2083	F	2.090	2.25	0.5201	0.641
		D	3.111	1.98	0.3921	0.460
0.2083	0.2917	F	3.056	3.31	0.6126	0.688
		D	2.955	2.31	0.4260	0.471
0.2917	0.2083	F	3.073	2.23	0.4418	0.389
		D	3.189	1.89	0.3370	0.247
0.2917	0.2917	F	3.480	2.50	0.3883	0.381
		D	3.944	2.58	0.4035	0.224

Table 5: Horizontal Omni-Magnet Geometry

Parameter	Value	Unit
Full aperture	80 × 8	cm W×H
Main coil size	8 × 16	cm W×H
Winding size	2 × 4	cm W×H
Winding pitch	4	cm
Number of windings	20 top, 20 bottom	
Back yoke thickness	8	cm
Full magnet size	152 × 32	cm W×H

Conclusion

Non-scaling FFA cells with tunes fixed to ~10^{-3} level have been found for the FETS-FFA project.

- Found by an automated algorithm.
- Dynamic aperture of 400 mm.mrad (geom.)
- Magnetic fields below 0.62 T on the beams, compared to >1 T in the scaling FFA.

Very promising machine type for applications with many turns and high space charge levels where resonances must be avoided.