Compact, Achromatic Non-scaling FFAG Accelerators for Muon Acceleration and Cancer Therapy

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DPF Meeting

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Detroit, MI

7/30/2009

New Directions in Accelerators: FFAGs: (Fixed-field Alternating Gradient)

- *Accelerators are playing increasingly important roles in science, technology, and medicine, with demands for higher beam currents, duty factors, and precision beam control, all in the context of affordable and reliable technology.*
- *This drive has generated world-wide interest in FFAGs. FFAGs have the high repetition rates characteristic of cyclotrons, yet they embody the advantages of the synchrotron: variable energy with low losses, and a more compact footprint and higher energy reach.*
- *With the best features of the cyclotron and synchrotron combined, the FFAG accelerators represent new directions in accelerator science and are presently under international development.*

The International FFAG Collaboration: International Accelerator Laboratories

U.S.

Fermilab

Brookhaven National Lab

Lawrence Berkeley National Laboratory

University of California: L.A., Riverside

Michigan State University

Canada

TRIUMF

University of British Columbia

Switzerland

CERN

France

LPS

Grenoble

U.K.

Daresbury Laboratory.

Manchester, Liverpool, Leeds, and

Lancaster and Oxford University

Imperial College

Rutherford Appleton Laboratory

John Adams Institute, Oxford

Birmingham University

Clatterbridge Centre for Oncology

Beatson Oncology Centre

Gray Cancer Center

Japan

KEK

Kyoto University (KURRI)

Osaka University

FFAG09 is @Fermilab, Sept. 21-25th HEP, medical, and Accelerator-driven Subcritical Reactor sessions are planned and accelerator comparisons: everyone is welcome!

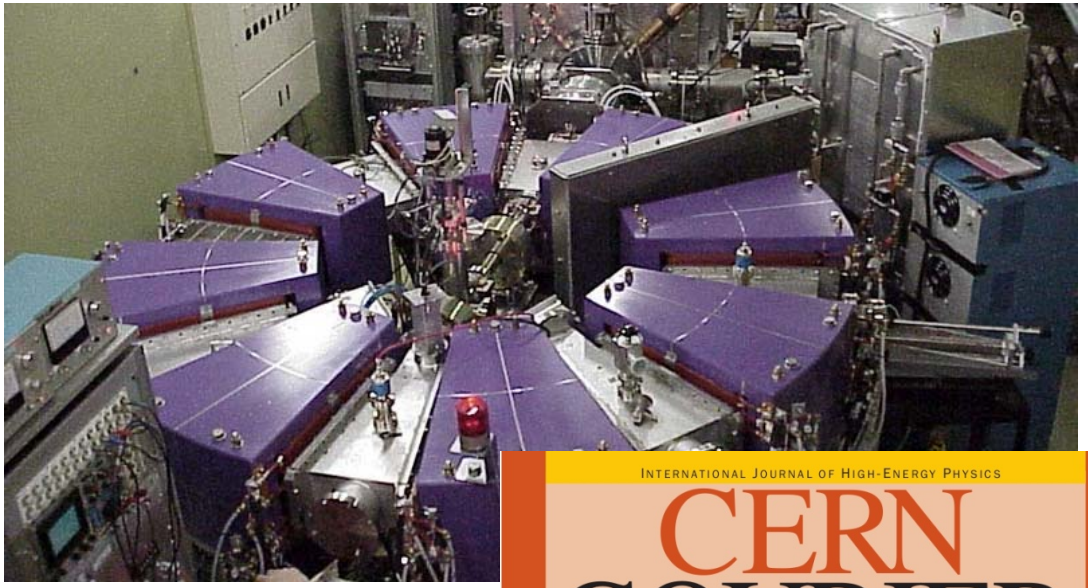
Abstract

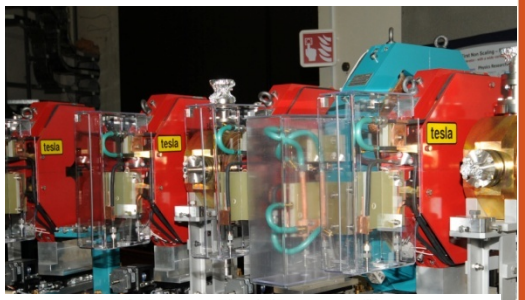
- *A new concept in non-scaling FFAGs has been invented in which the machinetune is stable over an extended acceleration cycle, a factor of a 3-6, ormore, Up to 44! has been successfully achieved in momentum.*
- *Fermilab Research Association (FRA) has elected to patent this concept and a strong collaborative design effort to optimize, simulate, and demonstrate the technical feasibility of this accelerator approach is underway to be followed by an engineering design.*
- *Sophisticatedsimulation tools within the advanced accelerator simulation code, COSY INFINITY, have been developed to fully and accurately describe the FFAG'scomplex electromagnetic fields - including realistic edge-field effects and high-order dynamics.*
- *Predicted performance showed the promised tune stability, and a sustainable slow acceleration rate by a modest acceleration system. The new nonscaling variant retains important features of thesynchrotron: smaller radial aperture, variable energy, and kicker and resonant extraction, yet has the high current advantage of the cyclotron.*

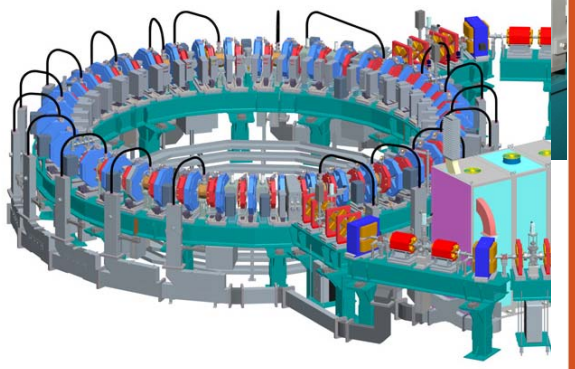
Understanding FFAGs and their Variations

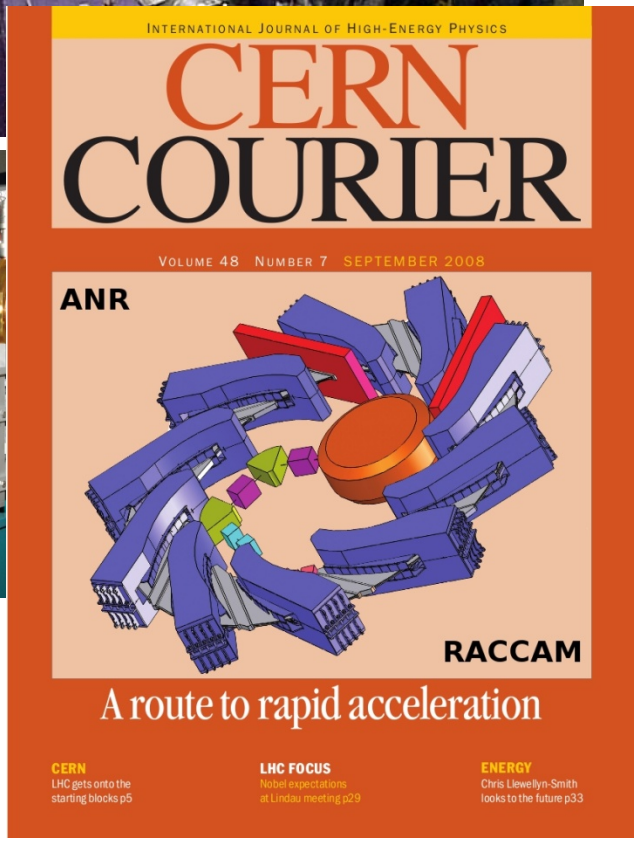
Scaling FFAGs (spiral or radial-sector) are characterized by geometrically similar orbits of increasing radius, imposing a constant tune. Magnetic field follows the law $B \propto r^k$, with r as the radius, and k as the constant field index.

Linear-field, nonscaling FFAGs. Proposed and developed for High Energy Physics (Neutrino Factories and Muon Colliders), relaxing optical parameters and aiming only for stable acceleration. In general they are not suitable fo an accelerator with a modest acceleration system and accelerate over a factor of 2-3 range in momentum.









Recent Accelerator Lattice Design and Optimization

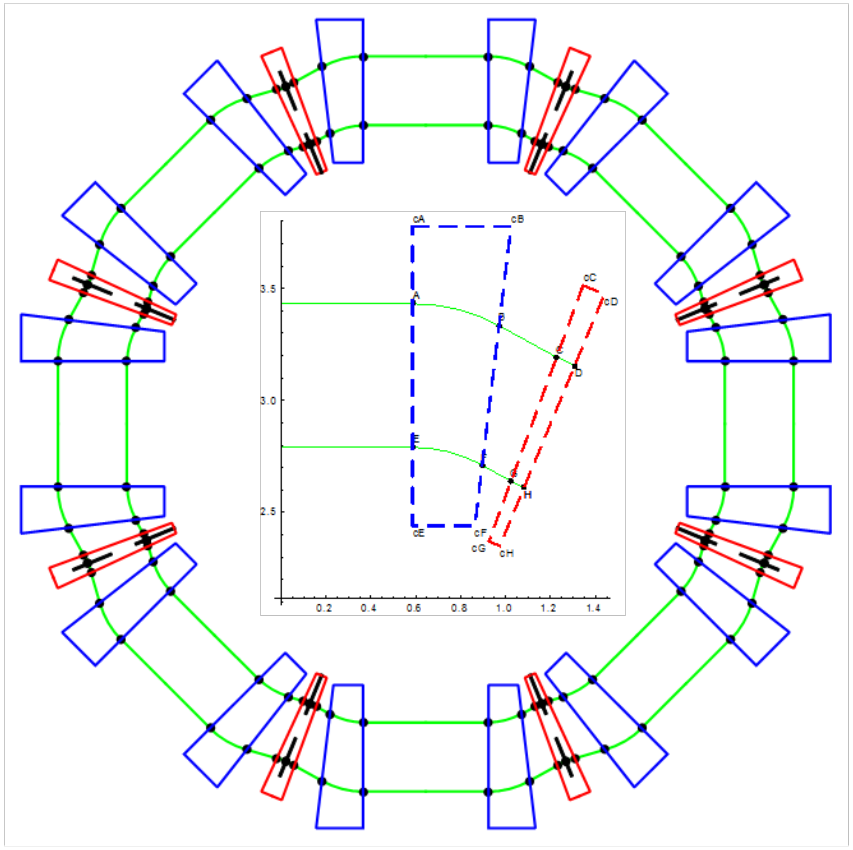
- **Nonlinear nonscaling FFAG** The radial sector has been generalized , allowing independent, unconstrained field and edge profiles between two combined-function magnets to stabilize the machine tune over an expanded acceleration range: 3 to >6. Further, a powerful new methodology was pioneered for FFAG optics design using control theory and native optimizers in *Mathematica*® to develop executable design scripts. These procedures allowed global exploration of all important machine parameters. The *Mathematica*® scripts use simple, hard edge linear matrices. Full evaluation required new advanced simulation tools not existing in current accelerator codes. Such tools have been developed and implemented in COSY INFINITY to describe the exact complex field and edge profiles to optimize and accurately predict machine performance

Details of Nonlinear Nonscaling Concept

- A non-scaling approach to slow acceleration was proposed in which the constant tune feature of the scaling FFAGs was successfully combined with the simplicity of the linear-field, non-scaling FFAG components. Weak, alternating gradient focusing principles (both edge and quadrupole focusing) are applied in a specific configuration to a fixed-field (DC) combined-function magnet to stabilize tunes.
- This new concept was generalized and extended beyond the initial, simple linear-field invention, primarily through incorporation of higher, unconstrained field expansions to advantageously impact additional machine parameters such as footprint. This approach can be considered a generalized version of the radial-sector FFAG.

The Nonlinear Nonscaling Design Approach

- A powerful new methodology was pioneered for FFAG optics design using control theory and native optimizers in *Mathematica*® to develop executable design scripts. These procedures allowed global exploration of all important machine parameters specific to this FFAG approach, confirming optimization and a robust starting point for advanced simulations.

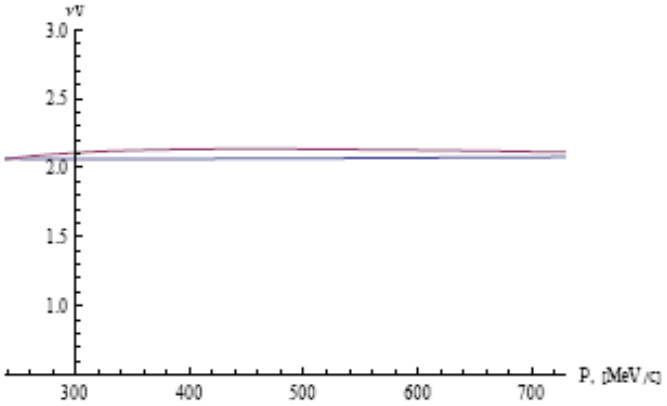


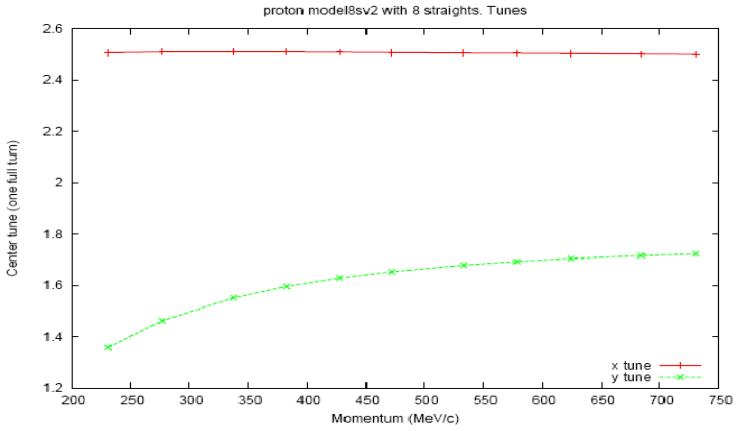
Example of *Mathematica*® parameter output with full ring and half- cell layout shown

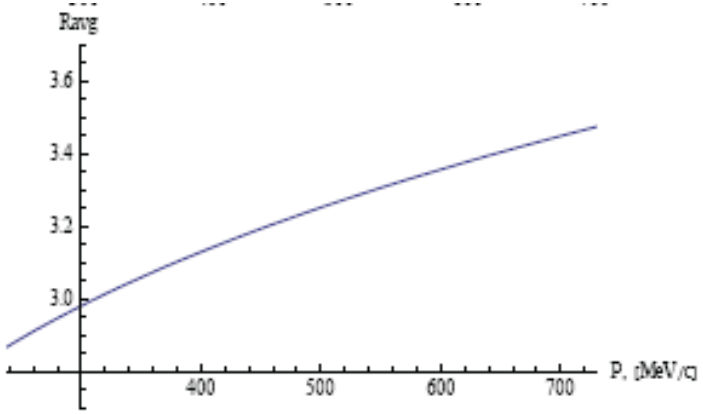
The Nonlinear Nonscaling Simulation in COSY INFINITY

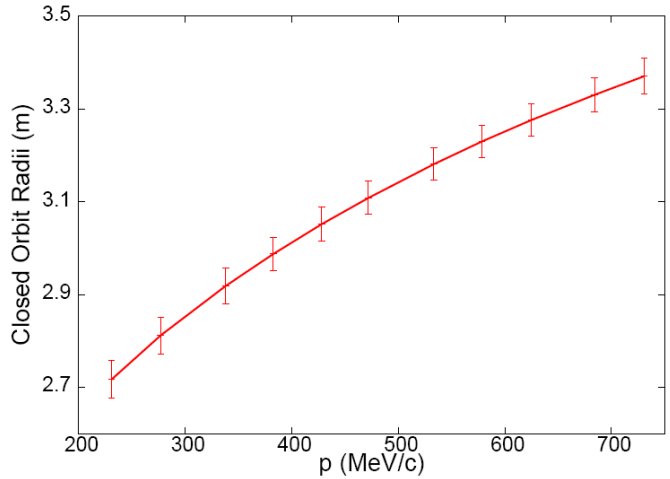
- As conventional accelerator codes provide too-little flexibility in field description and are limited to low order in the dynamics, new tools were developed for the study and analysis of FFAG dynamics based on transfer map techniques unique to the code COSY INFINITY.
- Various methods of describing complex fields and components are now supported including representation in radius-dependent Fourier modes, complex magnet edge contours, as well as the capability to interject calculated or measured field data from a magnet design code or actual components.

Mathematica® initial parameters compared with COSY INFINITY and full field description







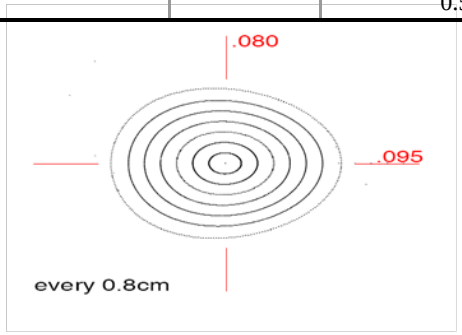


Large tune shift is due to the fringe field vs. the hard-edge model

COSY INFINITY results and DA

General Parameters of the triplet 30-250 MeV nonscaling FFAG design.

Parameter	Unit	Injection	Extraction
Energy Range	MeV	30	250
Tune/cell (ν_x / ν_y) Ring tune (ν_x / ν_y)	2π-rad	0.31 / 0.16 2.51/1.28	0.31 / 0.21 2.51/1.66
Average Radius	m	2.75	3.39
No. cells		8	
Long Straight	m	1.17	1.17
Peak Field F D	T	 1.21 -1.37	 3.13 -3.41
Magnet Lengths F D	m	 0.646 0.129	 0.803 0.176
Apertures F D	m	 0.63 0.55	



General Parameters of the triplet 30-250 MeV nonscaling FFAG design after tune optimization in COSY – only tune variations are affected.

Parameter	Unit	Injection	Extraction
Energy Range	MeV	30	250
Tune/cell (ν_x / ν_y) Ring tune (ν_x / ν_y)	2π-rad	0.31 / 0.22 2.48/1.75	0.31 / 0.19 2.48/1.55
Average Radius	m	2.75	3.39
No. cells		8	
Long Straight	m	1.17	1.17
Peak Field F D	T	 1.21 -1.37	 3.13 -3.41
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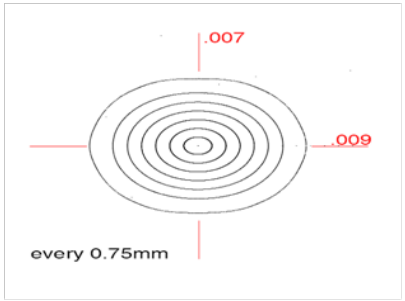
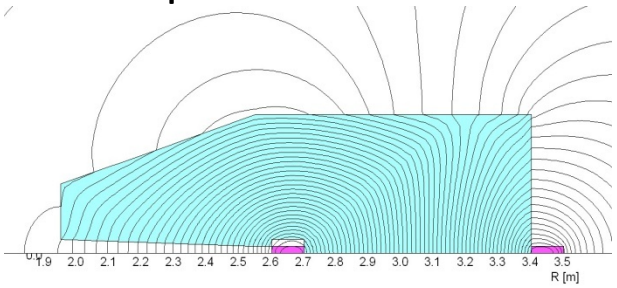
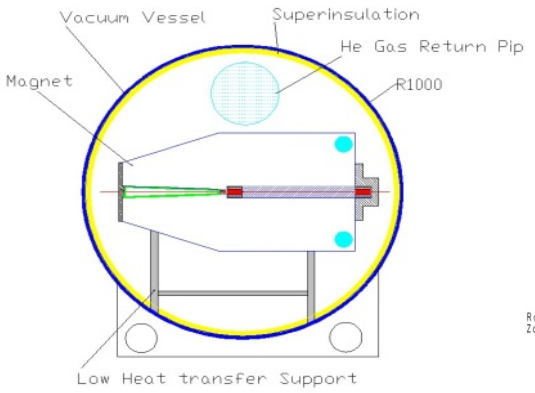


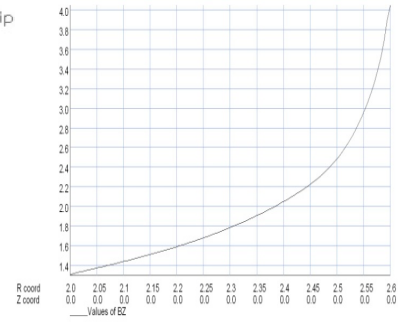
Dynamic aperture a midpoint, 112 MeV., horizontal (left), vertical (right) DA at all energies for both planes is extremely large.

Hardware Concepts for a Nonlinear Nonscaling FFAG

- An innovative new approach to a combined-function 4T magnet is under design based conventional NbTi superconducting magnet technologyand construction techniques.







- Preliminary rf parameters have been investigated and, given the frequency sweep required, it has been concluded that a normal conducting rf system is the only option. Moreover, the properties of available microwave ferrites for cavity tuning imply a frequency below 50 MHz. With a small vertical aperture of only a few cm, the RF leakage from the large horizontal aperture is acceptably small if the device operates below 500 MHz. The large magnet apertures therefore do not present a serious technical issue in terms of an rf structure.

Summary of Work on a New Nonlinear Nonscaling FFAG

- FFAG designs are advancing rapidly internationally, particularly for medical and HEP applications
- The first demonstration of Accelerator Driven Subcritical Reactor was performed this year at KURRI using the FFAG.
- Embedded rings for multi-ion cancer therapy are an exciting new reasearch area.