INNOVATIONS IN FIXED-FIELD ACCELERATORS: DESIGN AND SIMULATION*

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Abstract

The drive for higher beam power, high duty cycle, and reliable beams at reasonable cost has focused world attention on fixed-field accelerators, notably a broad class of accelerators termed Fixed-field Alternating Gradient accelerators, or FFAGs, (with cyclotrons considered a specific expression or sub-class of FFAGs). Recently, the concept of isochronous orbits has been explored and developed for the most general type of FFAG (termed non-scaling) using powerful new methodologies in fixed-field accelerator design. One application is high-intensity, in particular high-energy (GeV), proton drivers which encounter duty cycle and space-charge limits in the synchrotron and machine size concerns in the weaker-focusing cyclotrons. With isochronous orbits, FFAGs are capable of the high duty cycle, or CW operation, associated with cyclotrons. Further, their strong focusing enables smaller losses, and potential energy variability that are more typical of the synchrotron. With the cyclotron as the current industrial and medical standard, a competing CW FFAG, could potentially have broad impact on research, industrial, and medical accelerators and associated facilities. This paper reports on new advances in FFAG accelerator technology, design, and simulation, and also presents advanced tools developed for all fixed-field accelerators unique to the code COSY INFINITY[1].

INTRODUCTION

The drive for higher beam power, high duty cycle, and reliable beams at reasonable cost has focused world attention on fixed field accelerators, notably a broad class of accelerators termed Fixed-field Alternating Gradient (FFAGs). Cyclotrons can be considered a specific expression or sub-class of FFAGs which employ a predominately constant rather than gradient magnetic field. Recently, the concept of isochronous orbits has been explored and developed for the most general type of FFAG (termed non-scaling) using powerful new methodologies in fixed-field accelerator design. The property of isochronous orbits enables the simplicity of fixed RF and by inference, CW operation. By tailoring a nonlinear radial field profile, the FFAG can remain isochronous, well into the relativistic regime. One application is high-intensity, and, in particular, high-energy (GeV) proton drivers which encounter duty cycle and space-charge limits in the synchrotron and machine size concerns in the weaker-focusing cyclotrons. With isochronous orbits, the machine proposed here has the high average current advantage and duty cycle of the cyclotron in combination with the strong focusing, smaller losses, and potential energy variability that are more typical of the synchrotron. Further, compact high-performance devices like FFAG-type accelerators and cyclotrons often are operated in a regime where space charge effects become significant. The strong focussing attribute, particularly in the vertical of the FFAG, implies some degree of mitigation of space-charge effects and possible stable acceleration of higher currents.

With the cyclotron as the current industrial and medical standard, a competing CW FFAG, could potentially have broad impact on facilities using medical accelerators, proton drivers for neutron production, accelerator-driven nuclear reactors, waste transmutation, and the production of radiopharmaceuticals and open up a range of as-yet unexplored industrial applications. This paper reports on new advances in FFAG accelerator technology, design, and simulation, and also presents advanced tools developed for all fixed-field accelerators unique to the high-order code COSY INFINITY[1].

BACKGROUND

The FFAG concept in acceleration was invented in the 1950s independently in Japan[2], Russia[3] and the U.S[4] (T. Ohkawa[3] in Japan, H.S. Snyder[5] at Brookhaven, and A.A. Kolomenskij[3] in the Soviet Union). The field is weak at the inner radius and strong at the outer radius, thus accommodating all orbits from injection to final energy. Focusing is provided by an alternating body gradient (which alternately focuses in each transverse plane) or through body gradient focusing in one plane (nominally horizontal) and strong gradient-dependent edge focusing in the other (vertical) plane. An extensive discussion of the various FFAG configurations, including derivations of the formulas relating the various accelerator and orbit parameters can be found in the references[6]. The configuration initially proposed was called a radial sector FFAG accelerator. A spiral sector configuration was also invented consisting of magnets twisted in a spiral such that as the radius increases, and the beam crosses the magnet edges, it experiences alternating gradients. With no reverse-bending magnets, the orbit circumference of the spiral-sector scaling FFAG is about twice that for a circular orbit in a uniform field. These machines are the so-called scaling FFAGs (either spiral or radial-sector FFAGs) and are characterized by geometrically similar orbits of increasing radius. Direct application of high-order magnetic fields and edge focusing maintains a constant tune and optical functions during the acceleration cycle and avoids low-order resonances. The

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magnetic field follows the law B ∝ r^k, with r as the radius and k as the constant field index.

The non-scaling FFAG was invented in 1997 (C. Johnstone and F. Mills) and a working lattice published in 1999[7] as a solution for the rapid acceleration of muon beams. The non-scaling FFAG proposed for muon acceleration utilizes simple, combined function magnets like a synchrotron. However, it does not maintain a constant tune and is not suitable for an accelerator with a modest RF system and a slower acceleration cycle.

Recently, innovative solutions were discovered (C. Johnstone, Particle Accelerator Corp.) for non-scaling FFAGs which duplicated the constant tune feature of the scaling FFAG without applying the scaling principle. This new non-scaling FFAG accelerator applied weak and alternating gradient focusing principles (both edge and field-gradient focusing) in a specific configuration to a fixed-field combined-function magnet to stabilize tunes [8]. Note that, stable tunes, however, do not imply isochronous orbits.

Isochronous performance is achievable only at relativistic energies in a synchrotron and predominately nonrelativistic energies in a cyclotron. In a synchrotron, the magnetic field increases proportional to momentum and therefore particles are confined about a laboratory-based reference trajectory independent of energy. Since the path-length is fixed independent of energy, the orbital frequency changes with energy. A frequency change in the accelerating RF is required except at highly-relativistic energies, so swept-frequency RF is unavoidable. In a fixed-field machine, such as a FFAG or cyclotron, the reference orbit moves outward transversely with energy so the orbital path length always changes with energy. At nonrelativistic energies the increase in path length can be scaled with momentum which is directly proportional to velocity thus keeping the orbital frequency constant and the RF frequency fixed (isochronous condition). As the energy becomes increasingly relativistic, the path length must have an increasingly nonlinear dependence on momentum which becomes increasingly difficult to engineer with a predominately dipole field.

As noted above, recently the problem of isochronous orbits has been solved for non scaling FFAG designs in the relativistic energy regime, ~a couple of GeV and below. These isochronous, compact non-scaling FFAGs lattices were discovered by tailoring an arbitrary radial field profile to both constrain tunes and confine orbits to isochronous ones using new advanced accelerator design and modelling tools. Designing and demonstrating performance, particularly for the FFAGs with their complex field profiles and edge contours required new advances in accelerator modelling which will be described in a later section.

DYNAMICS OF FFAGS

Tune is perhaps the most important optical indicator of stable particle motion, since it determines when particles in the beam, executing periodic motion around the accelerator, return to the same transverse position relative to a central, or reference orbit in the machine. In a fixed-field machine such as an FFAG or cyclotron, this reference orbit moves with energy so the tune is controlled through radial and azimuthal variations in the magnetic field as described below.

Three conventional techniques exist for controlling the beam envelope and corresponding tune, or phase advance, in a magnetic field. The first confinement technique is the weak focusing principle used in classical cyclotrons in which changes in path-length through the magnetic field as a function of transverse position focus the beam, but only in the bend plane (which is typically horizontal). Weak focusing by the dipole component of the field in the body of the magnet does not affect the vertical plane.

The second arises from the field falloff at the physical edge of a magnet. A vertically-oriented (horizontally-bending) dipole field presents either a horizontally focusing or defocusing effect or no effect depending on the on the angle through which the beam traverses the fringe field. This edge effect is essentially equivalent to a quadrupole-like element located at each magnet edge: it can be either focusing horizontally and defocusing vertically, or the reverse for a non-normal crossing angle. (A normal entrance angle has no focusing effect.) In a cyclotron, vertical control is established via edge focusing through deliberate radial shaping of the pole-tip combined with a non-normal edge-crossing angle. The use of an edge-crossing angle in a cyclotron for vertical envelope control is normally weaker than focusing from path-length differences in the horizontal plane.

The remaining technique used in synchrotrons involves application of strong-focusing, alternating gradients in consecutive ring magnets. Strong-focusing techniques are capable of focusing equally in both planes with much stronger strengths resulting in larger phase advances, shorter focal lengths, and corresponding higher machine tunes than achievable in weak-focusing machines, i.e. stronger and more versatile envelope control. Contrary to cyclotrons, edge focusing effects are kept deliberately small in large multi-cell synchrotron rings. This term becomes increasingly important for and often causes difficulties in the dynamics of small synchrotron rings.

All three principles are applied in FFAGs—scaling machines specifically require edges plus gradient fields in relatively constant strengths to achieve similar orbits and corresponding constant tunes. In the non-scaling FFAG, the different focusing principles are combined in different and generally varying composition through the acceleration cycle – the varying composition can be exploited to control the machine tune without applying the field scaling law.

In particular, and unlike a cyclotron, the strength of the edge focusing and centripetal terms can be enhanced in the presence of a gradient - importantly their strength can increase with radius and therefore with energy. Understanding the powerful interplay between gradient and the centripetal and edge focusing is critical to understanding the dynamics and potential of the FFAG accelerator.

Thin Lens Formulism

The application of the transverse focusing terms and their inter-dependence can be understood conceptually using the thin-lens approximation. This approximation provides direct insight into the transverse dynamics of both FFAGs and traditional accelerators.

The dynamics of most accelerators can be expressed and understood almost completely in terms of the three "conventional" transverse focusing principles outlined above. To understand the interplay between strong, weak and edge focusing, a simple linear, thin-lens matrix model serves as a guiding example. The approach is most easily rendered using a simple sector magnet matrix, adding a gradient term to the focusing, and then applying an edge angle to the entrance and exit. The following is the first order matrix for a horizontally-focusing sector magnet with a gradient and an edge angle, η.

$$\mathrm{M}=\begin{bmatrix} 1 & 0 \\ -\tan \eta/\rho_0 & 1 \end{bmatrix}\begin{bmatrix} \cos\Theta & \frac{1}{\sqrt{K}}\sin\Theta \\ -\sqrt{K}\sin\Theta & \cos\Theta \end{bmatrix} \qquad (1)$$

where $\Theta=\sqrt{K}l$ and $K=k_0+1/\rho_0^2$ for a C.F. sector magnet. For the edge angle we adopt the sign convention to be: η>0 is outward, or away from the body of the magnet and thus it increases the net horizontal focusing. Reducing to thin lens, the matrices from the center of the gradient magnet through the edge are:

$$\begin{aligned}
&\begin{bmatrix} 1 & 0 \\ -\tan \eta/\rho_F & 1 \end{bmatrix}\begin{bmatrix} 1 & l \\ -Kl & 1 \end{bmatrix} \approx \begin{bmatrix} 1 & 0 \\ -\eta/\rho_F & 1 \end{bmatrix}\begin{bmatrix} 1 & l \\ -Kl & 1 \end{bmatrix} \\
&= \begin{bmatrix} 1 & l \\ -(k_F l + l/\rho_F^2 + \eta/\rho_F) & -\eta l/\rho_F + 1 \end{bmatrix} \\
&\cong \begin{bmatrix} 1 & l \\ -(k_F l + l/\rho_F^2 + \eta/\rho_F) & 1 \end{bmatrix} \qquad (2) \\
&= \begin{bmatrix} 1 & l \\ -(k_F l + \frac{(\vartheta+\eta)}{\rho_F}) & 1 \end{bmatrix} = \begin{bmatrix} 1 & l \\ -1/f_F & 1 \end{bmatrix}
\end{aligned}$$

since $l/\rho_F^2 \cong \vartheta/\rho_F$, where ϑ is the sector bend angle and the length l is the half-magnet length. The edge angle here has been assumed small to allow the tangent function to be approximated. Note that the gradient is not necessarily linear, but this thin lens derivation applies "locally" even in the presence of a nonlinear gradient. For the case of a nonlinear gradient, the local focusing strength (B') is simply evaluated at each orbital location.

From Equation 3 for the focal length, one can immediately see that the sector angle and edge angle term increase the focusing in the horizontal plane for a positive bend angle or dipole component. The choice of dipole component – which, in the presence of a gradient, changes at each reference orbit as a function of energy – has very important consequences. If the dipole component increases with radius, then focusing increases with energy relative to injection. Both the centripetal and edge-angle term add constructively with the strong-focusing. The integrated strength of the strong-focusing term can also increase if a) the edge angle increases the path length through the magnetic field, and/or b) if the gradient itself increases with radius (for a non-constant gradient; i.e. higher or quadrupole). When the integrated strong focusing strength increases as a function of energy, it serves to stabilize the tune. Both planes are not identical, however, for in the vertical only the strong focusing and edge-angle terms contribute to a change in focusing strength.

$$1/f_F = k_F l + \frac{\vartheta}{\rho_F} + \frac{\eta}{\rho_F} \qquad (3)$$

Therefore, in the vertical version of Equation 3, only the gradient, $k_D l$, and the edge term apply so two terms contribute to the vertical machine tune. The following summarizes tune and envelope control in conventional accelerators.

- *Centripetal* (Cyclotrons + FFAGs) :
  - Bend plane only, horizontally defocusing or focusing
  - Strength ∝ θ/ρ (bend angle/bend radius of dipole field component on reference orbit);
- *Edge focusing* (Cyclotrons + FFAGs) :
  - Horizontally focusing / vertically defocusing, vice versa, or no focusing,
  - Strength ∝ tan η/ρ , or ~ η/ρ for a small edge-crossing angle (edge crossing angle/bend radius of dipole field component at entrance to magnet;
- *Gradient focusing* (Synchrotrons + FFAGs) :
  - Body field components > dipole:
  $B=a+bx+cx^2+dx^3+\ldots\quad B'=b+2cx+3dx^2+\ldots$
  - Constant gradient*:* Synchrotrons, linear-field non-scaling FFAGs (muon FFAGs)
  - Scaled nonlinear field*,* gradient increases with *r* or energy: Scaling FFAGs,
  - Arbitrary nonlinear field, gradient increases with *r* or energy: nonlinear, non-scaling FFAGs.

FFAG DESIGN PRINCIPLES

In a scaling FFAG, the field-scaling law predetermines that the reference beam trajectories remain parallel implying that much of the optics remain constant with energy – in particular the tunes remain fixed. The non-scaling FFAG relaxes this condition and aims only for stable beam during acceleration. If the acceleration is quick, then tune variations can be tolerated. If the acceleration is slow the tune must be more controlled (although some tune variation can be accommodated or compensated for if the acceleration cycle is slow enough)

Non-scaling in its simplest terms implies nonparallel reference orbits in a FFAG. Although parallelism automatically implies constant tune (through fixed number of betatron oscillations), it is not a necessary condition. In the non-scaling FFAG, the different focusing terms can be varied independently to control tune and further optimize machine parameters. This last point is very important for FFAGs because it allows the field, orbit location, and important machine parameters such as tune, footprint, and aperture to be more independent and strongly controlled than in cyclotron.

The constant + linear-gradient field case serves as an instructive example. Interestingly, this case remains a valid “local” interpretation of FFAG dynamics even in the presence of a strongly nonlinear global field. The local “quadrupole” strength parameter, *k,* is simply the derivative of the field profile evaluated at the reference orbit for a specific energy. Even in the case of only linear gradient field profiles, a sextupole component [9] arises when the quadrupole body field is combined with an edge angle. The presence of higher-order field components contributes still higher nonlinear terms in combination with an edge angle. Therefore, even in the linear case, the dynamics do not obey linear optics. However, a local interpretation in terms of linear optics and dynamics remains valid and is critical to designing and understanding compact FFAG accelerators.

FFAG Lattice Design

FFAG lattices are completely periodic, like a cyclotron. Periodicity permits closed geometry and repetitive, adiabatic optical solutions over a tremendous range in momentum. However, the strong-focusing does allow stable, “long” straights to be integrated into the base unit cell. (Specialized utility insertions are under development but are nontrivial to properly match over the large dynamical momentum range of the FFAG.).

All lattices are simple, single lens structures based on the FODO cell. The maximum and minimum beam envelopes alternate between opposing planes – even in the so-called doublet and triplet FFAGs. Single lens structures are optically stable over a large range in momentum; there are no telescope-based FFAGs with any significant dynamical range.

FFAGs utilize short cells to achieve short focal lengths. The stronger the focusing and the shorter the focal length; the more adiabatic the optical functions, and the larger the stable momentum range. FFAG designs exploit combined function magnets to minimize unit cell length and optimize dynamic range. Long straights are inserted at points of reflection symmetry in the lattice (at points where the derivatives of optics functions are zero) thereby causing little disruption to the periodic optics.

Progression of the Non-scaling FFAG Design

Initial non-scaling FFAG lattices (EMMA project)[10] utilized a linear fields/constant gradient and rectangular magnets. However, it does not maintain a constant tune and is not suitable for an accelerator with a modest RF system and therefore a slower acceleration cycle. .

With tune is the strongest indicator of stable particle motion, constraining the machine tune can be sufficient to design a stable machine. In all fixed-field accelerators, the FFAG or the cyclotron, the reference orbit moves with energy. Using this property, tune can be controlled in a linear or nonlinear gradient FFAG by shaping the edges of the magnets.

All three focusing terms are impacted by the edge contour and their interaction can be used to manipulate the machine tune in the horizontal. Two terms, gradient and edge focusing, are available for tune control in the vertical. For example, use of a gradient plus an edge angle on a linear-gradient magnet enhances not only the integrated strong-focusing strength, but also weak (centripetal), and edge focusing as a function of radius (and therefore energy). Further, in a non-scaling FFAG, contributions from the different strength terms can vary with radial position and can also be independent in the F and D magnets. In a non-scaling FFAG the edge crossing angle often changes with energy resulting in non-similar orbits. This increase in strength of all the terms tracks the increase in momentum and stabilizes the tune. The result is a dramatic increase in the momentum reach of the machine, from 2-3 to a factor of 6 utilizing a simple edge contour on a constant-gradient magnet. Figures 1 and 2 below indicate the improvement in tune control in a constant-gradient non-scaling FFAG through application of a simple linear edge contour.

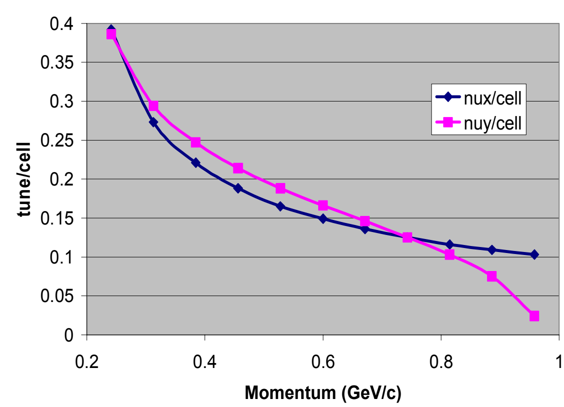

Figure 1: Variation of tune in a linear gradient, large acceptance non-scaling FFAG for rapid acceleration.

Completely stable tunes, and compact machines in footprint and aperture, however, required higher-order, field profiles tailored to reach the advanced specifications. An arbitrary field expansion has been exceptionally successful in controlling both tunes and physical attributes of a machine. An order of magnitude increase has been achieved in momentum range relative to the initial non-scaling concept (an acceleration range of a factor of 44 has been achieved in one ultra-compact nonlinear design). Even in predominately nonlinear fields, the strong focusing permits adjustment of cell tunes to produce a large dynamic acceptance and surprisingly linear performance (elliptical phase space portraits).

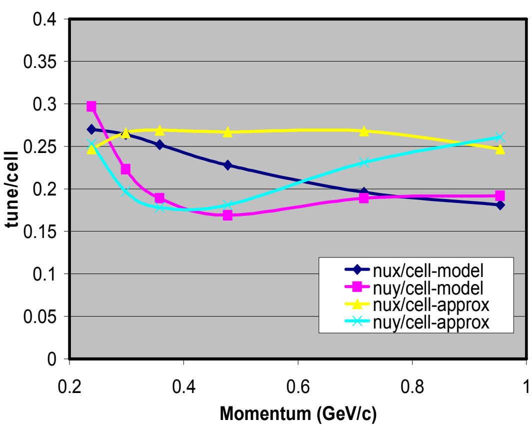

Figure 2: A constant gradient nonscaling FFAG with an edge contour to stabilize tune.

Further, isochronous orbits have been achieved in a non-scaling FFAG by applying both a nonlinear gradient and edge contour. Isochronous implies CW operation and simple rf systems.

Isochronous orbits are proportional to velocity. However, the orbital path length of a particular momentum follows the B field and thus is not necessarily proportional to velocity. At relativistic energies, momentum is an increasingly nonlinear function of velocity. Therefore, the integrated B field must be a nonlinear function of radius proportional to the relativistic velocity. A nonlinear field expansion combined with an appropriate edge angle can constrain the orbit at each momentum to be proportional to velocity and simultaneously control the tune. Unlike the cyclotron which relies on a dipole field and is therefore limited in adapting path length to match relativistic velocities, the non-scaling FFAG can maintain isochronous orbits well into strongly relativistic energy regimes as shown in Figure 3. Further, the nonlinear gradient required to achieve this decreasing change in path length with increasing momentum at relativistic energies has the advantage of providing increasing focusing in both transverse planes as a function of energy.

ISOCHRONOUS FFAG DESIGN

In general, conventional accelerator codes provide too-little flexibility in field description and are limited to low order in the dynamics; as such they cannot adequately formulate and predict FFAG accelerators, especially in the presence of the strong nonlinearities from edge contours and fields along with other high-order effects.

Powerful new methodologies in accelerator design and simulation have been pioneered using control theory and optimizers in advanced design scripts with final simulation in COSY INFINITY[1]. COSY INFINITY now has a full complement of sophisticated simulation tools to fully and accurately describe both conventional accelerators and the FFAG's complex electromagnetic fields. Specifically, new tools were developed for the study and analysis of synchrotron, cyclotron, and FFAG dynamics based on transfer map techniques unique to the code COSY INFINITY. With these new tools, closed orbits, transverse amplitude dependencies, and dynamic aperture are determined inclusive of full nonlinear fields and kinematics to arbitrary order. 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 3D field data from a magnet design code or actual components, respectively. These new advanced tools fulfil a critical need in advanced accelerator design.

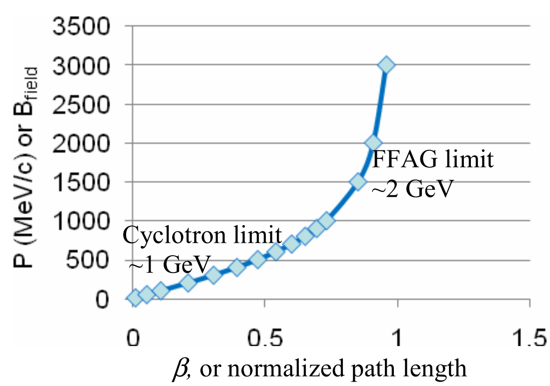

Figure 3: Momentum dependence (∝ <B> field) on velocity (or path length) to maintain isochronous condition.

High-energy Isochronous FFAG Example

The concept of isochronous orbits has been tested on a preliminary 0.25-1 GeV nonscaling FFAG designed using the new methodologies and optimizers described above.. Two options are available to extend this initial effort to a complete accelerator system: a) a two-ring system, both isochronous, with the lower energy one H^- or b) a single ring with a high-order field profile which reaches 5T at extraction to increase compactness and energy range. Use of H^- in the lower energy ring permits CW injection into the higher-energy ring through charge-changing (stripping) methods.

The design is initiated using sophisticated scripts with approximate starting machine parameters then imported into the advanced accelerator simulation code of COSY INFINITY. The ring layout and 3D field profile is given in Figure 4 and Table I gives general parameters with tracking results in Figure 5. Figure 6 shows corresponding results achieved by Craddock, et.al. [13] using the cyclotron COSY. The level of isochronous behaviour is ±3% in this preliminary design.

Table 1: General Parameters of an initial 0. 250 – 1 GeV non-scaling, isochronous FFAG lattice design.

Parameter	*250 MeV*	*585 MeV*	*1000 MeV*
Avg. Rad. (m)	3.419	4.307	5.030
Cell ν_{x}/ ν_y Ring ν_{x}/ ν_y (2π rad)	0.380/ 0.237 1.520/ 0.948	0.400/ 0.149 1.600/ 0.596	0.383/ 0.242 1.532/ 0.968
Field F/ D (T)	1.62/ -0.14	2.06/ -0.31	2.35/ -0.42
Mag. Length F D (m)	1.17/ 0.38	1.59/ 0.79	1.94/ 1.14

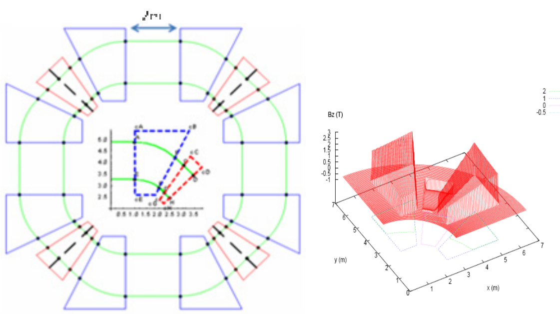

Figure 4: Ring layout and 3D field profile from COSY.

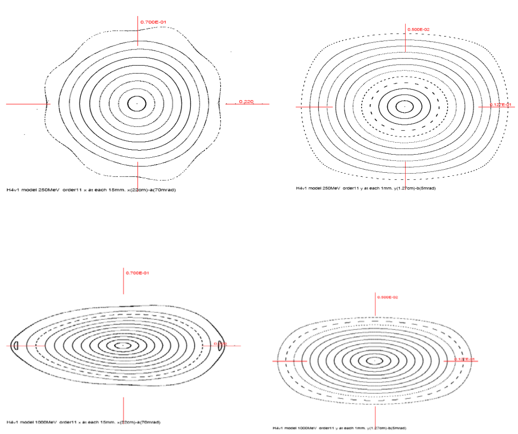

Figure 5: Tracking profiles at injection (top) and extraction (right) in horiz. (left, 1.5 mm steps) and vert. (right, 1mm steps)

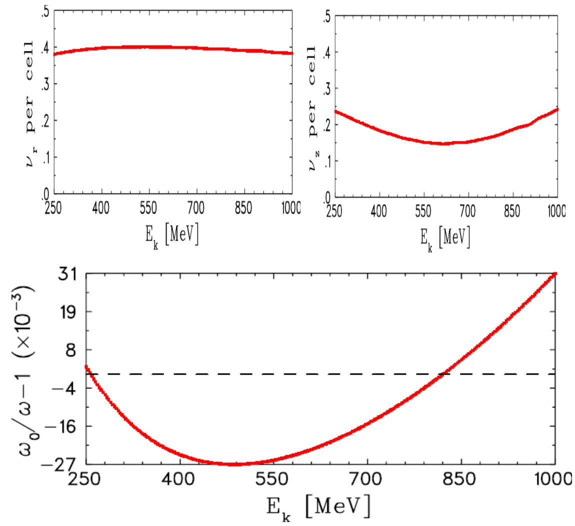

Figure 6: Results using the cyclotron code CYCLOPs {13].

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