FFAG Simulations in COSY

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FFAG09

Sept 23, 2009

Fermilab

Simulation Challenges

New accelerator prototypes are often simulated with conventional tracking codes,

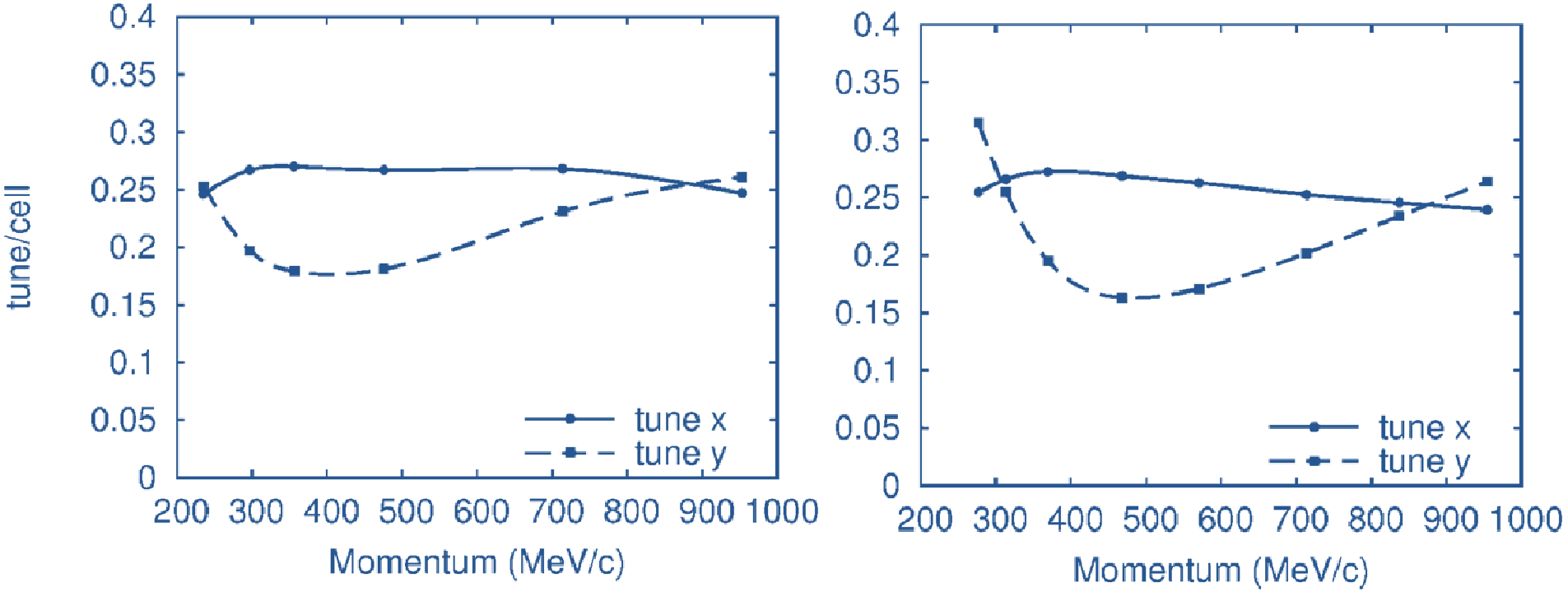
- *these codes do not provide much flexibility in the field description and are limited to low order in the dynamics.*
- *This limitation is inadequate to demonstrate performance in the presence of strong nonlinearities due to edge fields and other high-order effects appear.*
- *This is particularly true for the FFAGs where edge crossing and strong bends, or "small-ring" effects can dominate the optics. In the muon FFAGs, the large beam emittances preclude the use of codes which do not include kinematical (or angle) effects in the Hamiltonian. which implies that codes which fully describe the kinematics are necessary .*

The current number of supported design and optimization codes that can adequately describe the complex field and magnet contours for both the scaling and nonscaling FFAG variants is limited to the cyclotron code CYCLOPS [1], and the field-map code ZGOUBI [2], and recently COSY INFINITY[3]

1. R Baartman et al. CYCLOPS. Technical report.
2. F. Meot. The ray-tracing code ZGOUBI. Nuclear Instruments and Methods A, 427:353–356, 1999 and F. Lemuet and F. Meot. Developments in the ray-tracing code ZGOUBI for 6-d mul-titurn tracking in FFAG rings, 2005.
3. M. Berz and K. Makino. COSY INFINITY Version 9.0 beam physics manual. Technical Report MSUHEP-060804, Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, 2006. See also http://cosyinfinity.org.

The early design: linear nonscaling FFAG
ZGOUBI Results: comparison with MAD

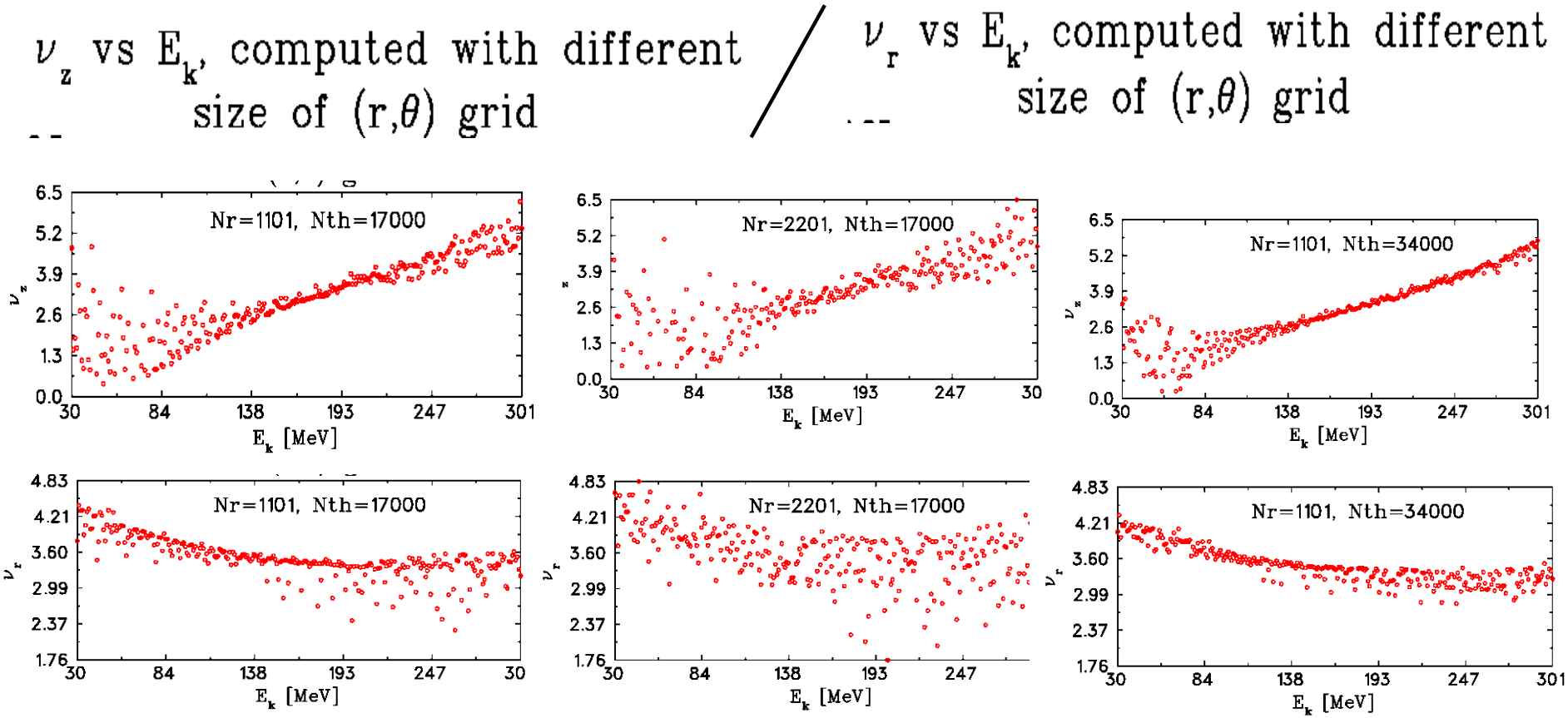
Considerable effort was expended in ZGOUBI (T. Yokoi) to model both the edge contour and a hard edge in order to compare with an equivalent hard-edge MAD model. (The parameters of the Enge function were adjusted to emulate a sharp fall-off.) The final tune dependence in the figure reflects repetitive tuning of the edge angle.



Tune dependence of the nonscaling, linear-field FFAG in the code MAD (left) and ZGOUBI (right) for a single cell of a 14-cell ring. Significant adjustment of edges and Enge-function parameters were required to achieve even approximate agreement with the intended design described by hard-edge and analytical approximations.

Linear Nonscaling Field – early Cyclops results

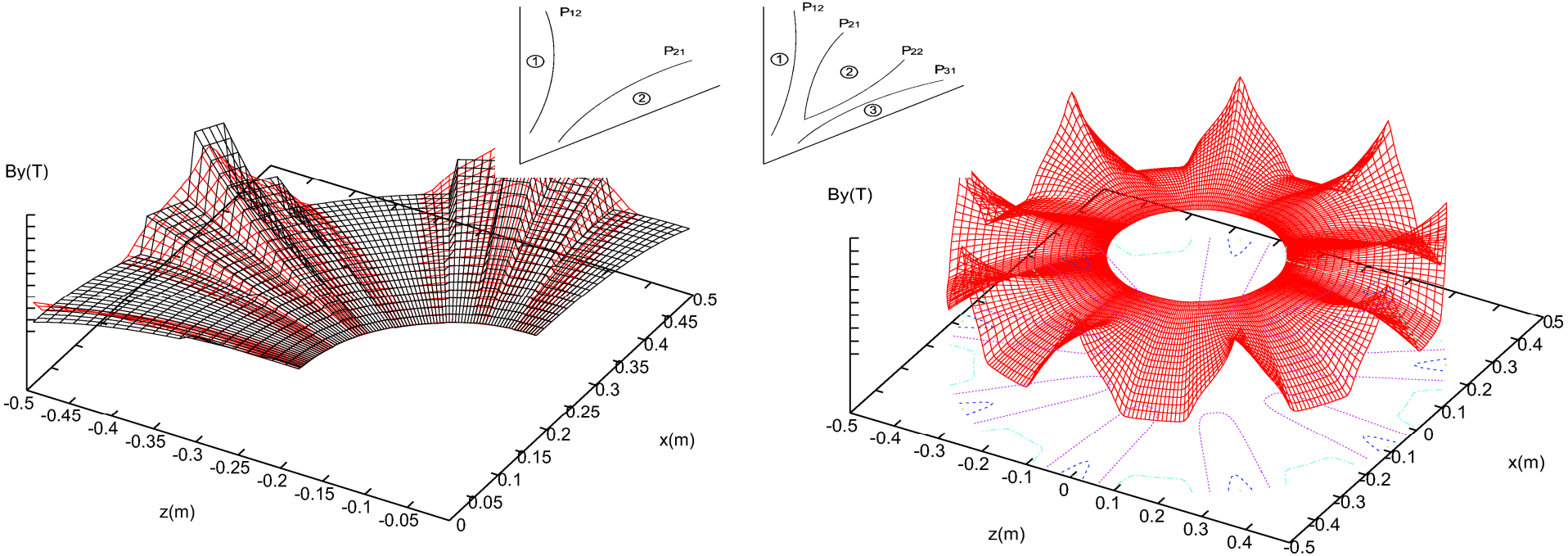
Results were dependent on the integration step size across such an edge with figures below showing results for different mesh sizes.



The Nonlinear Nonscaling Simulation in COSY INFINITY

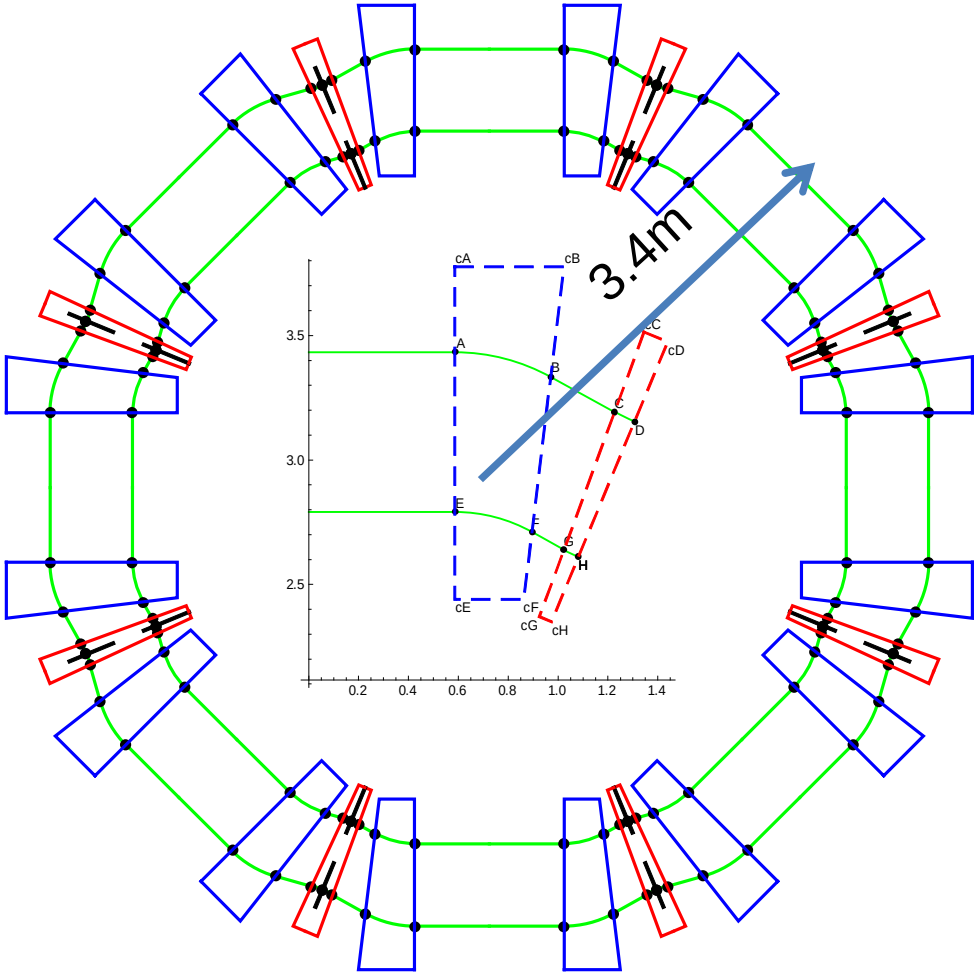
- Most conventional accelerator codes provide too-little flexibility in field description and are limited to low order in the dynamics, new tools were developed for the study and analysis of FFAG dynamics based on transfer map techniques unique to the code COSY INFINITY.
- Various methods of describing 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.

HARD EDGE Arbitrary shapes, field content, contours **FULL FRINGE FIELDS**



A 30-250 MeV Proton FFAG for Hadron Therapy

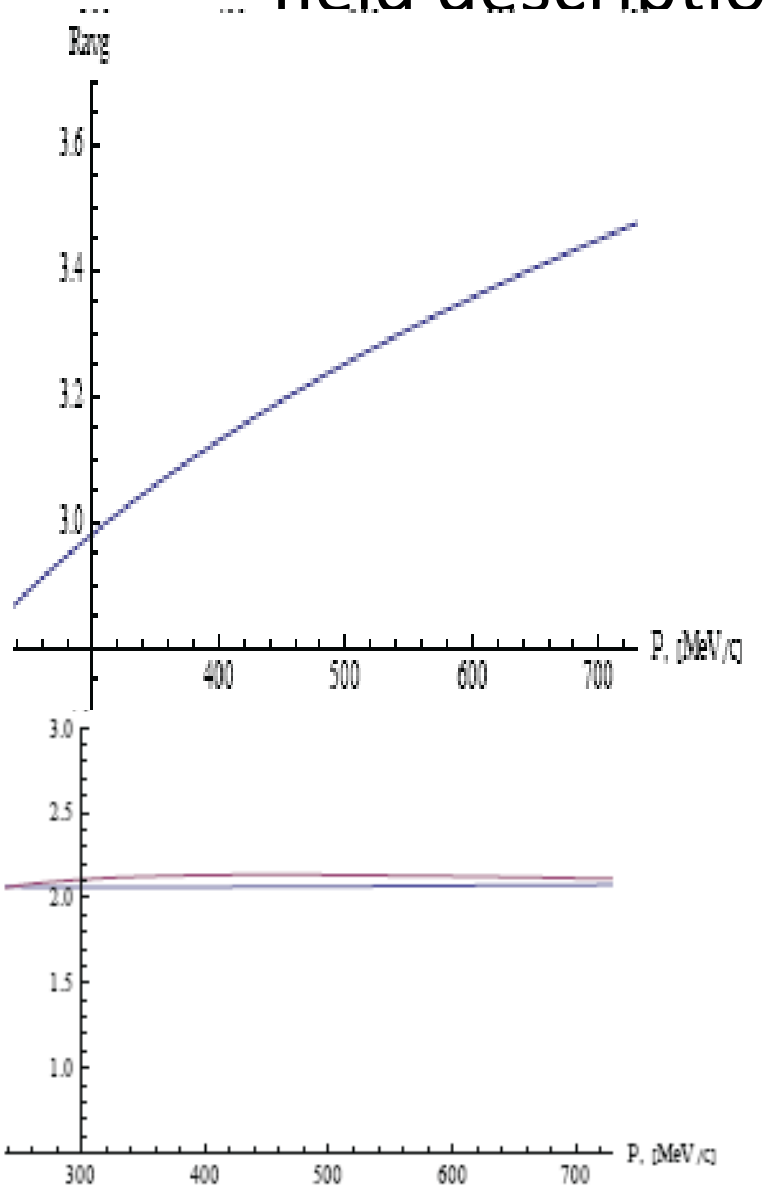
Mathematica® initial parameters imported into **COSY INFINITY to generate a full field description** - compared with TOSCA design

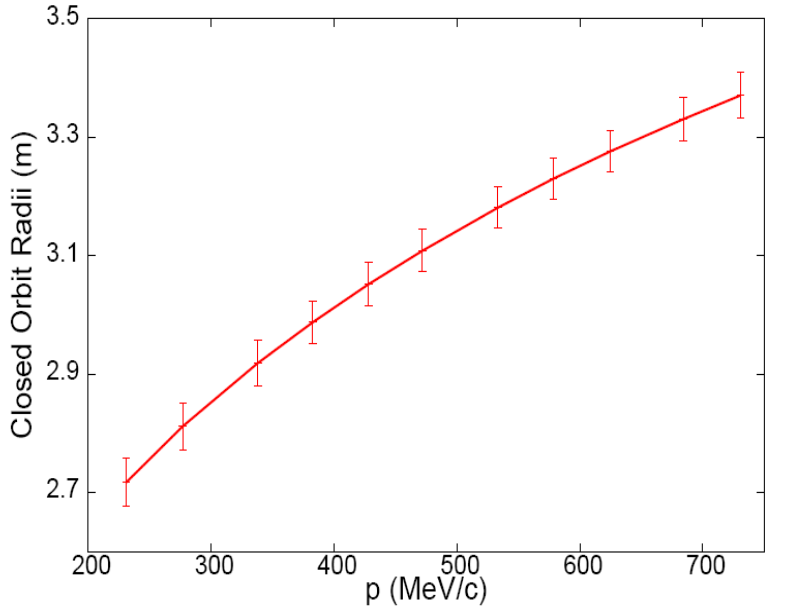


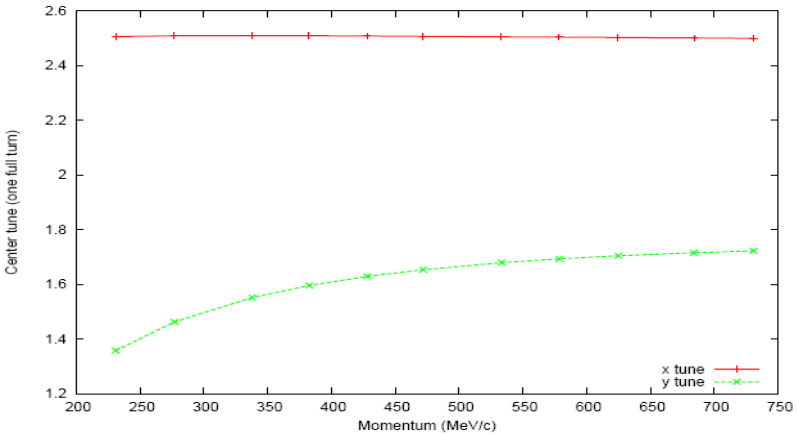
- No cells: 8 (FDF)
- Injection: Ravg = 2.75 m
- Extraction: Ravg = 3.39 m
- B_{peak} F/D 3.1 / -3.4 T
- Long straight 1.17 m
- Wedge Magnets
  - F injection/extraction 0.65 – 0.80 m
  - Dinjection/extraction 0.13 – 0.18 m
- $\Delta\nu_x$ <0.01
- $\Delta\nu_y$ 0.20
- Reduced with COSY to
- $\Delta\nu_x$ <0.01
- $\Delta\nu_y$ 0.15

B field expansion – up to octupole

Comparing *Mathematica*® initial parameters with a full field description in **COSY INFINITY**

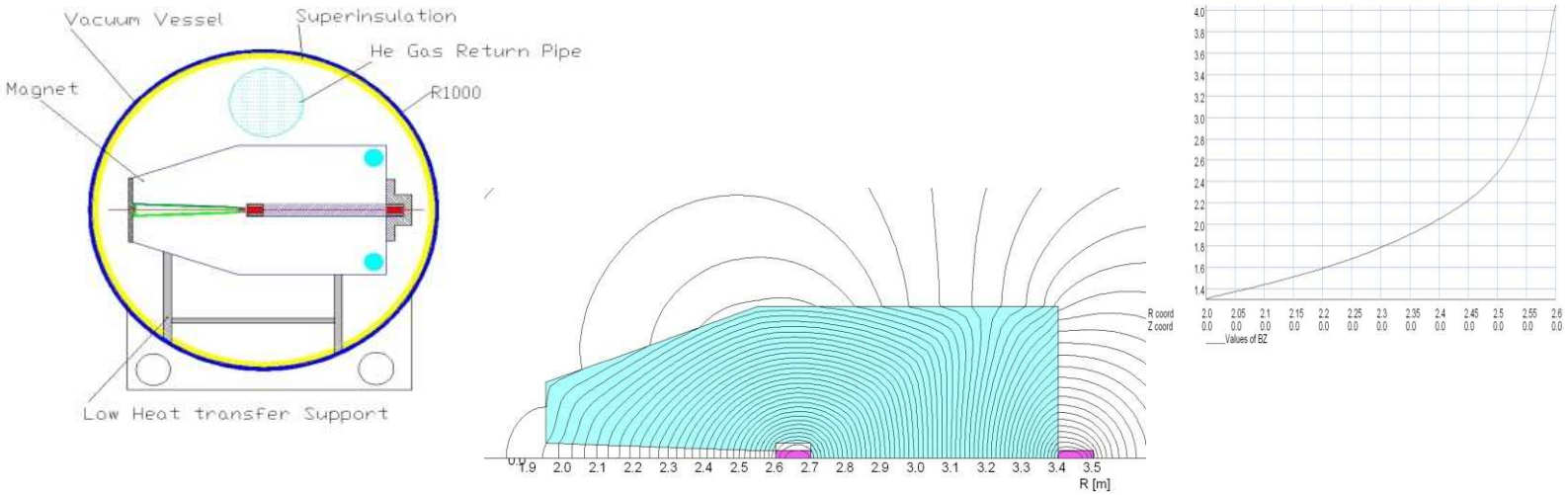




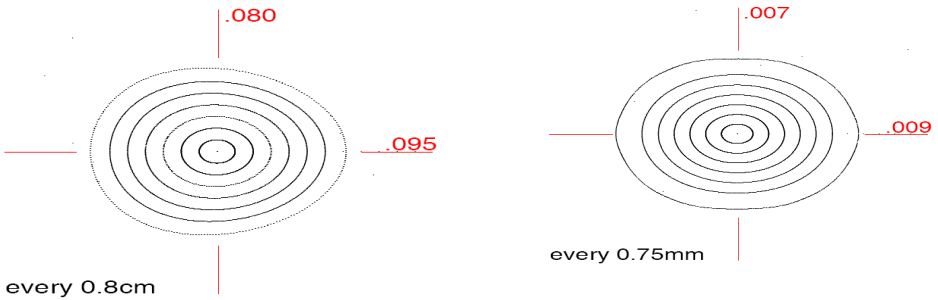


Radial dependence is surprisingly well reproduced but strong tune splitting horz/vert from Enge function representation of fringe fields

Magnet Design and Tracking Studies

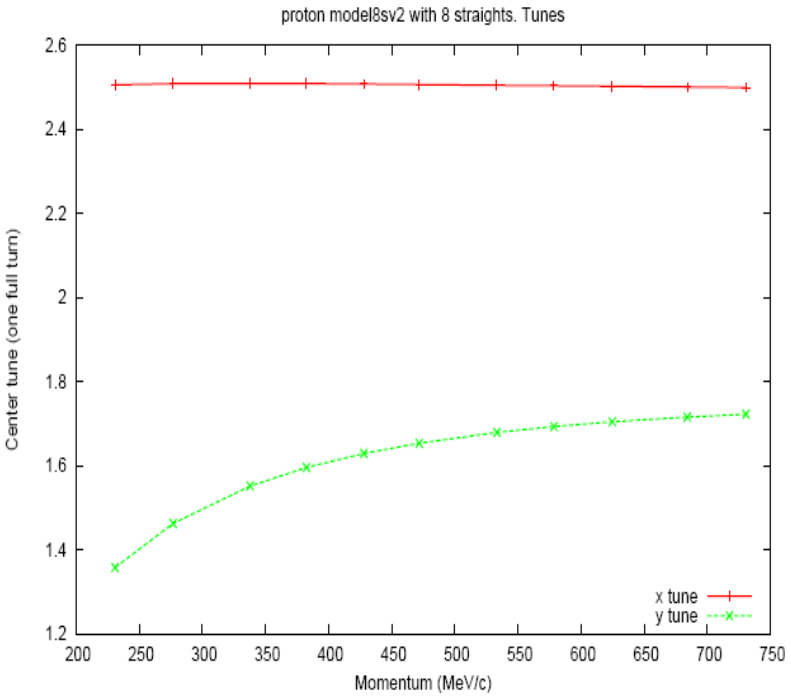


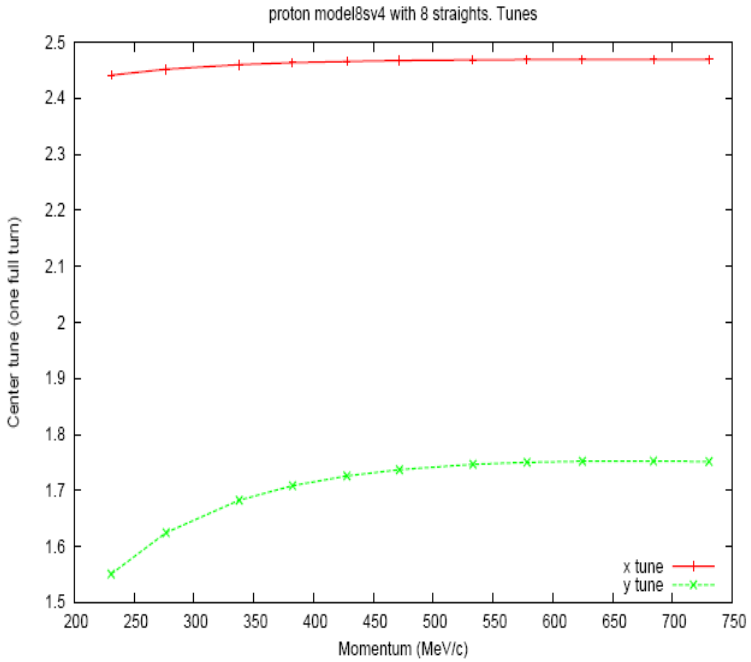
TOSCA magnet and field designs



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

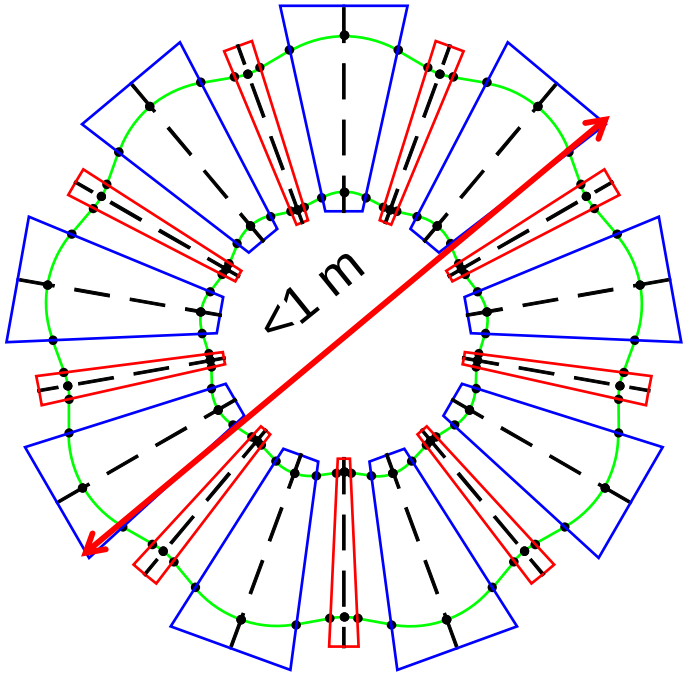
Further tune refinement in COSY

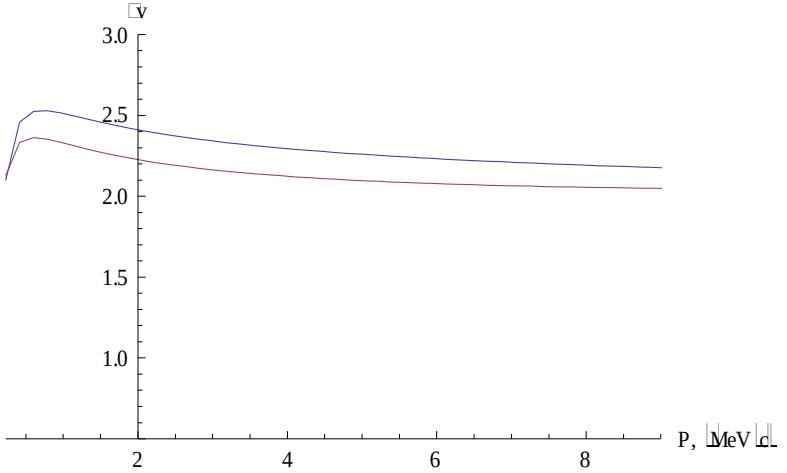




Manipulation of gap profile in COSY to adjust tune profile

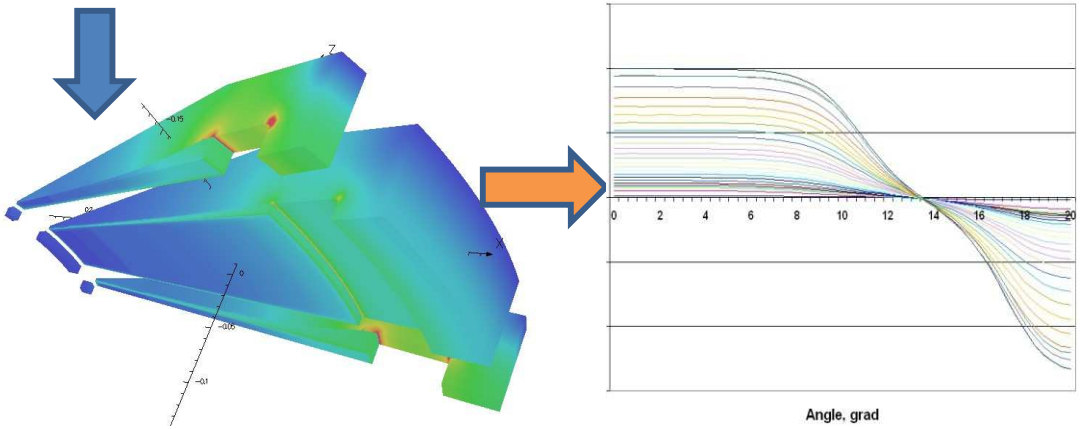
Jewel in the Crown: 50 keV to 9 MeV Compact Electron Accelerator

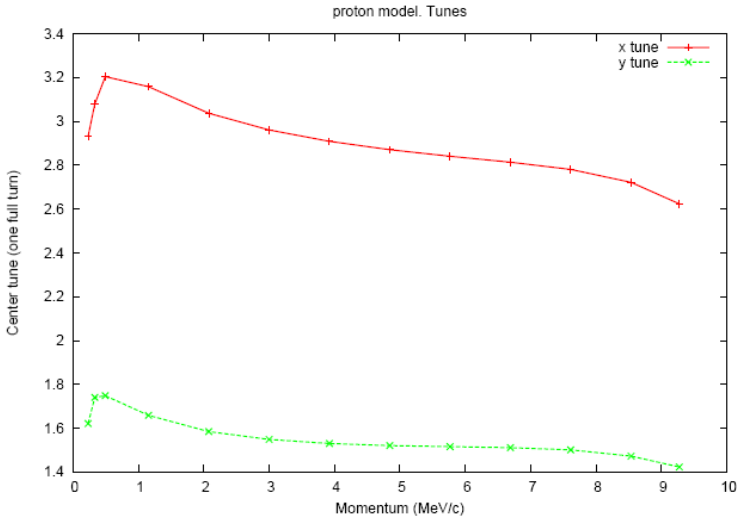




COMPARISON Tune Results:
hard edge vs. extendedfFringe field

Mathematica® Full 9-MeV ring with injection and extraction orbits displayed.

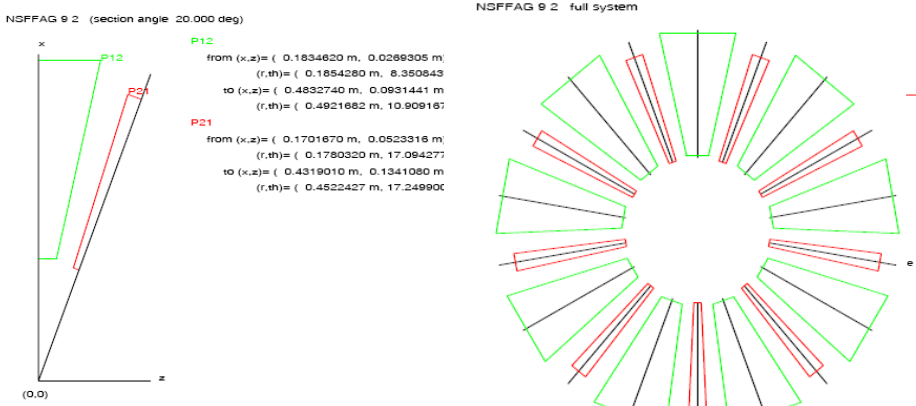


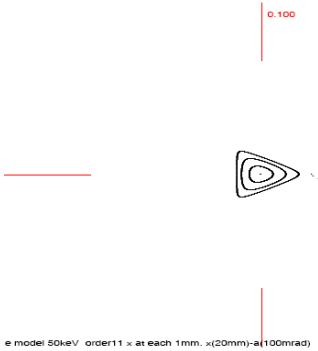


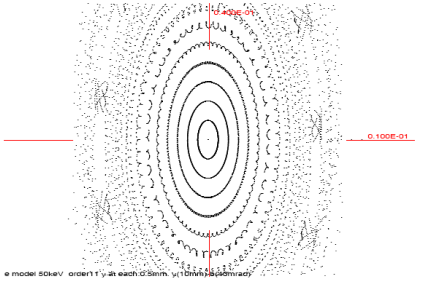
TOSCA Magnet Design and Field profiles.

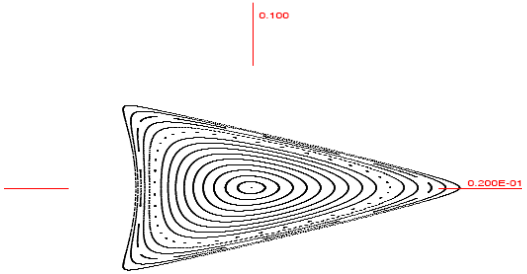
COSY INFINITY Tune Results

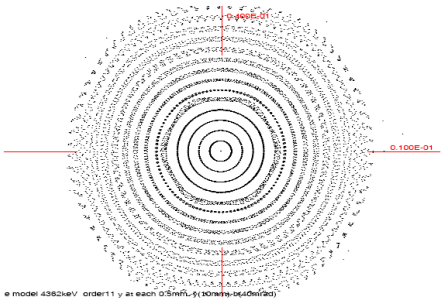
COSY Results: Electron Ring

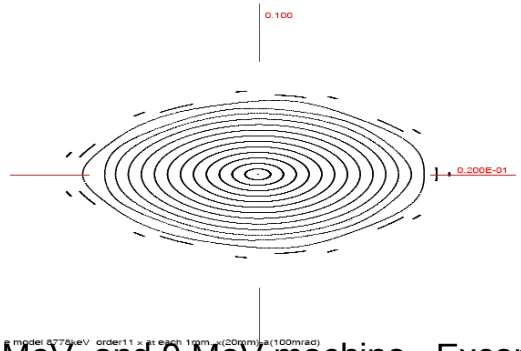


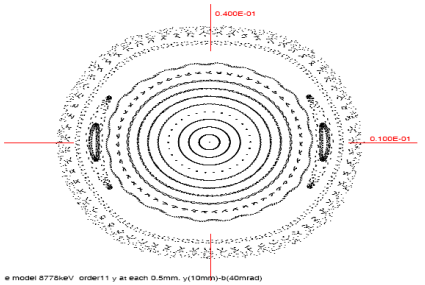


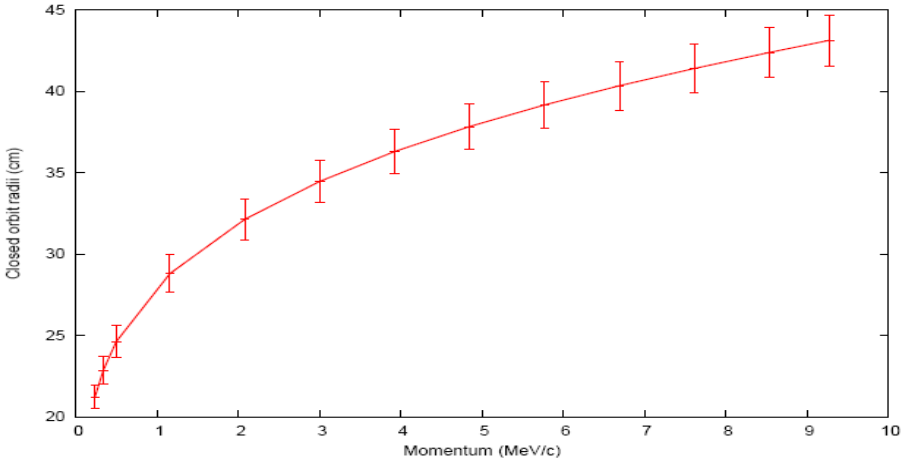












COSY results and tracking at 3 energies: 50 keV, 4.4 MeV, and 9 MeV machine. Except for the tune change required at horizontal injection, the DA is very large.

Much Work to Do

- Agreement between codes: hard-edge benchmark
- Fringe-field modeling
- Import of TOSCA field maps
- Optimization tools in advanced codes