Advanced Simulation and Optimization Tools for Dynamic Aperture of Non-Scaling FFAGs and Related Accelerators

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FFAG Renaissance

- Concept suggested in the 1950's, never progressed toward building a proton machine
- Progress in magnet and rf design technology
- Since 1999 there is a dramatic rise in interest: race for higher repetition rates and larger acceptances
- 8 scaling machines operating, more being built
- New non-scaling concepts are actively studied and improved:
  - EMMA
  - PAMELA
  - FFAG for IDS-NF
  - ...and more

Scaling vs non-scaling

- First FFAGs were scaling (spiral or radial-sector): 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.
- Many of the newer designs are non-scaling: relaxed optical parameters aiming only for stable acceleration, tune is not constant
  - Linear, for fast acceleration, where resonance crossing is not an issue
  - Non-linear tune-stabilized designs (two examples will follow)

FFAG applications

- Cancer therapy
- Industrial irradiation
- Driving subcritical reactors
- Boosting high-energy proton intensity
- Producing neutrinos

- Synchrotrons: low duty cycle and become quite large for light ions
- Cyclotrons: higher losses and no energy variability

Simulation codes and issues

- ZGOUBI
- CYCLOPS
- COSY Infinity

- Mesh integration = mesh size/integration step
- Edge focusing + fringe field = careful account for both
- Lack of out-of-plane expansion order
- Multiple reference orbits
- Magnetic field changes along the reference orbit

FFAG magnet in COSY

- Supports magnetic field change along the reference orbit
- Allows for superposition of arbitrary multipoles with arbitrary offsets
- Magnetic fields are calculated in the lab coordinates to support multiple reference orbits at different energies
- Fringe fields are carefully taken into account via Enge function or direct input from magnet design codes such as TOSCA

Field calculation demonstration

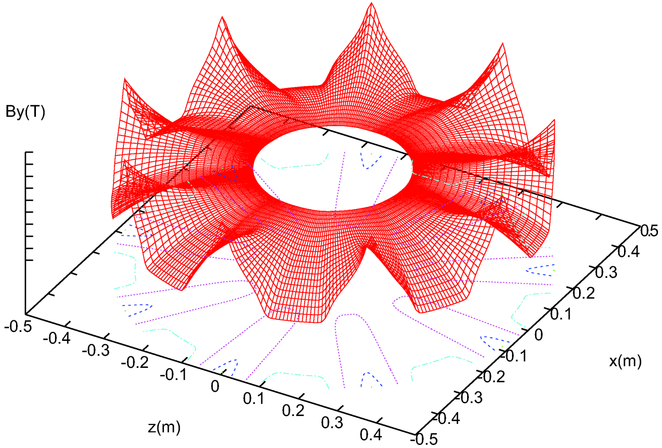


Figure: Sample 3d field profile

Field calculation demonstration

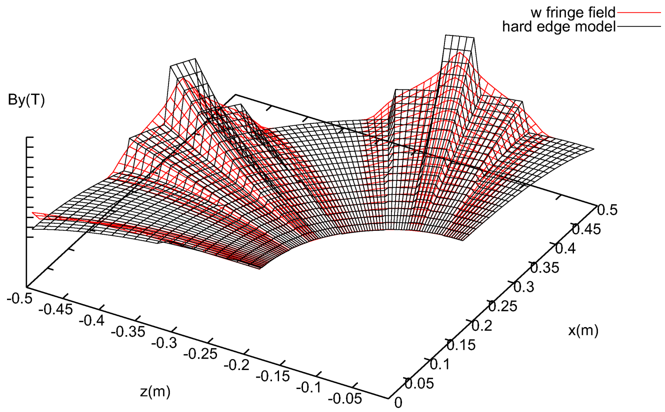


Figure: Hard edge vs Enge function fringe field

Field calculation demonstration

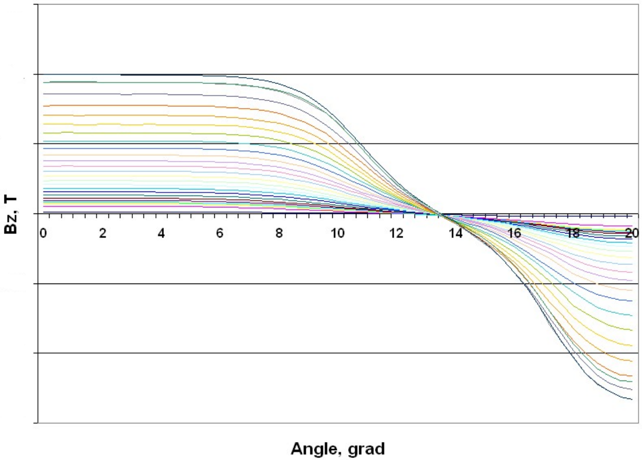
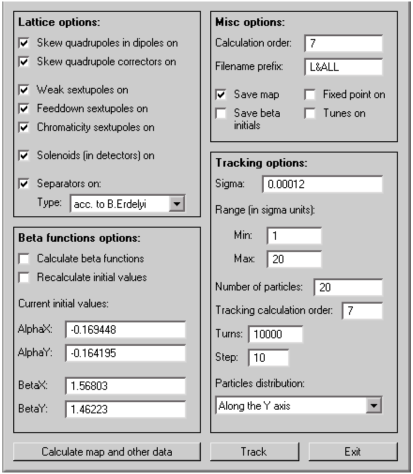


Figure: Azimuthal field profile

Software tools development – design tools

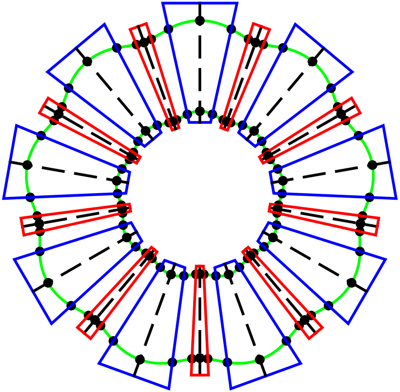
- New simulation tools:
  - Preliminary simulation + optimization tools in Mathematica: these procedures allowed extensive exploration of all important machine parameters, confirming optimization and a robust starting point for advanced simulations.
  - Parameter export to COSY Infinity (automatic).
  - COSY Infinity FFAG magnet simulation tools + local/global optimization tools.

Software tools development – machine tuning tools



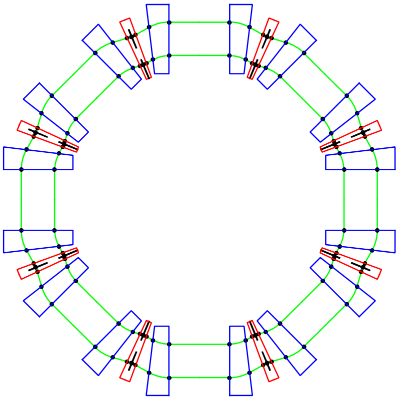
- Work in progress:
  - User interface for straightforward design, optimization and visualization

8-cell FODO proton machine simulation results



- 8-cell proton machine, injection energy at 0.2 MeV, extraction energy at 269 MeV.
- Potential uses: proton driver.

8-cell triplet proton machine simulation results



- 8-cell proton machine with 1.2 m straights, injection energy at 30 MeV, extraction energy at 269 MeV.
- Potential uses: proton therapy machine.

Tune variation, orbit radius

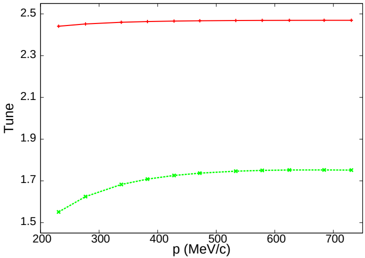


Figure: Tune variation: red–horizontal, green–vertical, full ring tunes

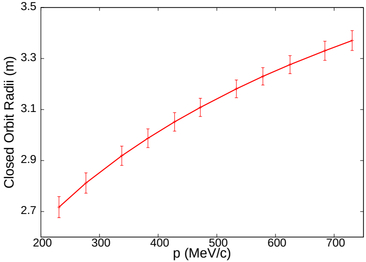


Figure: Mean orbit radius and its variation

Dynamic aperture

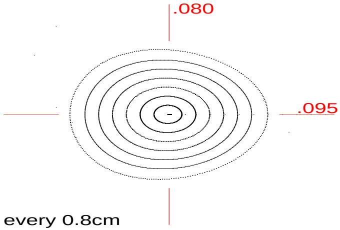


Figure: Particle tracking, $(x - p_x)$

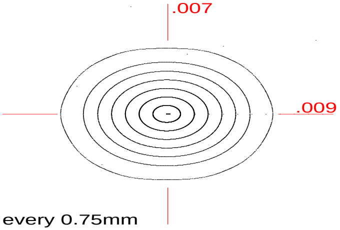


Figure: Particle tracking, $(y - p_y)$

Summary

- A set of new tools have been developed in Mathematica and COSY Infinity to efficiently design and optimize FFAG machines, and minimize the number of by-hand operations and iterations.
- Two lattices for proton non-scaling FFAGs were proposed, and their performance analyzed using the newly introduced tools.
- One of the proposed proton machines can be utilized as a proton driver, another one—as a medical machine for cancer therapy.