Non Scaling Fixed Field Alternating Gradient Gantries

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NS-FFAG GANTRIES

1. Introduction
   - Motives: reduction of cost by using method - simpler is better
   - Small size for carbon - superconducting combined function magnets
   - Spot scanning, simplify operation, large energy acceptance
   - CYCLOTRON application, TERA LINAC application

2. Basic concept of Non-Scaling FFAG (NS-FFAG)

3. SAD definition

4. NS-FFAG gantry with adjustable fields

5. NS-FFAG gantry with fixed fields

6. Summary
Motivation for the NS-FFAG gantries

Motivation

Reduce a major cost for the hadron therapy

Present solutions use large magnets (carbon ions especially)

Magnetic field is the same for all energies

Carbon $E_k=400$ MeV/u

$B_{\rho} = 6.35 \text{ Tm} \ (\theta = Bl/B_{\rho})$

If: $B=1.6 \text{ T}$ then $\rho \sim 4.0 \text{ m}$

If: $B=3.2 \text{ T}$ then $\rho \sim 2.0 \text{ m}$

Weight of the transport components - 135 tons

Total weight = 630 tons

Length of the rotating part 19 m long.
ACCELERATORS:

- Cyclotron
  *isochronous

- Synchrotron
  *const. closed orbit
  (varying mag. field)

- FFAG
  *varying closed orbit
  (const. mag. field)
Scaling vs. non-scaling FFAG

- Orbit offsets are proportional to the dispersion function:
  \[ \Delta x = D_x \times \frac{\delta p}{p} \]

- To reduce the orbit offsets to ±4 cm range, for momentum range of \( \delta p/p \sim \pm 50\% \) the dispersion function \( D_x \) has to be of the order of:
  \[ D_x \sim 4 \text{ cm} / 0.5 = 8 \text{ cm} \]
Non-scaling FFAG for Muon Acceleration

$$\Delta x = D_x * \delta p/p$$

- Extremely strong focusing with small dispersion function.
- Smaller energy acceptance.
- Tunes vary.
- Orbit offsets are small.
- Magnets are small.

**Design of a nonscaling fixed field alternating gradient accelerator**

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Dejan Trbojevic, May 23, 2011

2nd Workshop on Hadron Beam Therapy of Cancer - Erice 2011
Basic cell of the “triplet” NS-FFAG muon

Orbit for \( \frac{dp}{p} = 33.3\% \)

Orbit for \( \frac{dp}{p} = 0 \)

Orbit for \( \frac{dp}{p} = -33.3\% \)

Angle \( q_f = -0.027 \)

L_qf = 0.58 m

Total Circumference \( C = 328 \) m

Cell length = 4.9697 m

Number of cells \( N = 66 \)

Drift for a cavity

\( \frac{1}{2} L_{cav} = 0.99185 \) m

\( s = \frac{L_{cav}}{2} \)

L_{qd} = 1.5 m

Angle \( q_d = 0.1436 \)
Orbits in the NS-FFAG muon acceleration triplet cell
Scaling FFAG - Non scaling FFAG

**Scaling FFAG properties:**
- Zero chromaticity.
- Orbits parallel for different $\delta p/p$.
- Relatively large circumference.
- Relatively large physical aperture (80 cm – 120 cm).
- RF - large aperture.
- Tunes are fixed for all energies no integer resonance crossing.
- Negative momentum compaction.
- $B = B_0 (r/r_0)^k$ non-linear field.
- Large acceptance.
- Large magnets.
- Very large range in $\Delta p/p = \pm 90\%$

**Non-Scaling FFAG properties:**
- Chromaticity is changing.
- Orbits are not parallel.
- Relatively small circumference.
- Relatively small physical aperture (0.50 cm – 10 cm).
- RF - smaller aperture.
- Tunes move 0.4-0.1 in basic cell resonance crossing for protons.
- Momentum compaction changes.
- $B = B_0 + x G_0$ linear field.
- Smaller acceptance.
- Small magnets.
- Large range in $\Delta p/p = \pm 60\%$.
Possible applications of the NS-FFAG gantries:

- **CYCLOTRON** – energy degrader
  - Spot scanning
  - Multi-leaf collimator

- Slow extraction slow cycling synchrotrons

- Fast cycling synchrotrons

- Linac modules
Possible application of the NS-FFAG Gantries
Possible application of the NS-FFAG Gantries
Possible application of the NS-FFAG Gantries

IDRA design: Riccardo Zennaro
with “LINAC” by Ken Crandall

Replace with NS-FFAG
Possible applications of the NS-FFAG gantries:

- CYCLOTRON – energy degrader
- Fast cycling synchrotrons
- Linac modules
- Spot scanning
- Multi-leaf collimator
- Slow extraction, slow cycling synchrotrons

Replace with NS-FFAG
SAD – SOURCE-TO-AXIS-DISTANCE

The maximum dose to the patient surface relative to the dose in the SOBP increases as the effective source-to-axis distance (SAD) decreases. For a fixed, horizontal beam, large SAD's are easy to achieve; but not for gantry beam lines. A smaller gantry with a physical outer diameter of less than 2 meters may have important cost implications. Such a gantry would require magnetic optics to ensure that the effective source-to-axis distance is large enough to provide adequate skin sparing.
Smaller size proton/carbon gantries with adjustable magnetic fields for each energy

\[ L_d = 30 \text{ cm} \]
\[ B_D = 5.58 \text{ T} \]
\[ G_D = -93.0 \text{ T/m} \]

\[ L_f = 32 \text{ cm}, \]
\[ B_F = 3.665 \text{ T} \]
\[ G_F = 110.0 \text{ T/m} \]

TRIPLET:
\[ KDP1 = 31.0 \text{ T/m} \]
\[ KFP2 = -48.4 \text{ T/m} \]
\[ KDP3 = 31.0 \text{ T/m} \]
MAGNET PROPERTIES

Ld = 30 cm, Lf = 32 cm,
Byd = 5.58 T, Byf = 3.665 T
GF = 110.0 T/m
GD = -93.0 T/m

TRIPLET:
KDP1 = 31.0 T/m
KFP2 = -48.4 T/m
KDP3 = 31.0 T/m
Superconducting carbon ions gantry with energy acceptance $\Delta p/p = \pm 20\%$ 
$(200 \text{ MeV/u} < E_k < 400 \text{ MeV/u})$
Gradients and Magnetic fields

Combined Function magnets:
B\text{f} focusing magnet l=19 cm:
\[ B_{\text{fo}} = 0.625 \text{ T, Gradient} = 200 \text{ T/m,} \]
Maximum field:
\[ B_{\text{d}} = 0.625 + 202.8 \times 9.5 \times 10^{-3} = 2.55 \text{ T} \]
\[ B_{\text{d}} = 0.625 + 202.8 \times (-7.2 \times 10^{-3}) = 1.09 \text{ T} \]

B\text{d} defocusing magnet l=19 cm:
\[ B_{\text{do}} = 5.21 \text{ T, Gradient} = -157.26 \text{ T/m,} \]
Maximum field:
\[ B_{\text{d}} = 4.97 + (-157.3) \times 9.5 \times 10^{-3} = 3.48 \text{ T} \]
\[ B_{\text{d}} = 4.97 + (-157.3) \times (-7.2 \times 10^{-3}) = 6.1 \text{ T} \]
Particle tracking at the end of the gantry
All at once: Fixed field & fixed focusing

Magnification 30 TIMES

- 400 MeV/u
- 200 MeV/u

Dimensions:
- 3.883 m
- 4.166 m
- 1.483 m
- 2.683 m
- 9 mm
- 2 mm

Angles:
- 72°
- 18°
Vasily Morozov - Dejan Trbojevic
NS-FFAG 10 fixed gradients

KBF1 = 212.7332 T/m
KBD1 = -179.260 T/m
KBF2 = 214.650 T/m
KBD2 = -173.543 T/m
KBF3 = 216.805 T/m
KBD3 = -171.042 T/m
KBF4 = 220.030 T/m
KBD4 = -178.477 T/m
KBD5 = -182.891 T/m

KFTRP1 = 25.5 T/m
KDTRP2 = -25.5 T/m
KFTRP3 = 25.5 T/m

KFTRP1 = 25.5 T/m
KDTRP2 = -25.5 T/m
KFTRP3 = 25.5 T/m

LBFTRP = 0.20 m
LBDTRP = 0.34 m
LBFTRP = 0.20 m

BFtr = 1.905 T
BDtr = 0.4035 T
Magnet Properties:

Combined Function magnets:

\( B_f \) focusing magnet \( l=17 \text{ cm} \):
- \( B_{fo}=0.625 \ T \), Gradient \( =212.8 \ T/m \),
- Maximum field:
  \[ B_f=0.403+ 212.8 \times 9.5 \times 10^{-3}=4.33 \ T \]
  \[ B_f=0.403+ 212.8 \times (-5.7 \times 10^{-3})=-0.8 \ T \]

\( B_d \) defocusing magnet \( l=8 \text{ cm} \):
- \( B_{do}= 4.76 \ T \), Gradient-max \( =-174 \ T/m \),
- Maximum field:
  \[ B_d=4.76+(-174) \times 9.5 \times 10^{-3} =3.48 \ T \]
  \[ B_d=4.76+(-174) \times (-2.2 \times 10^{-3})=5.1 \ T \]
Magnet design

In a quadrupole, the coil length limits the fill factor in the cross-section when it becomes less than one fourth of the circumference. We used six spacers (wedges) in the cross-section to make the first six allowed harmonics nearly zero. Once again, a large integral transfer function is obtained since the mid-plane turns span the entire end-to-end coil length. The design has a coil diameter of 200 mm and coil length of 90 mm (less than half the radius). Quad with Coil Length Less Than Coil Radius Sextupole with Coil Length 2/3 Coil Radius We carried out a similar exercise for a 200 mm aperture sextupole having an end-to-end coil length of 66 mm. This is ~1/3 of diameter. We were again able to get a design with low harmonics and a good integral transfer function.

[Image: OPERA3d model of a short length dipole based on the Optimum Integral Design. Coil length is ~175 mm and coil diameter is 200 mm.]
BNL-preliminary combined function magnet design

![Diagram of Direct Wind Combined Function Gantry Magnet]

Even without shielding coil, fringe field < 2 gauss at 3 m.

- \( B_0 = 3.500 \) T
- \( C = 52.6 \) T/m

Field is very linear until close to the coil winding.
AML combined function magnet design

Figure 2. Dipole windings with 50% normal quad amplitude. The turn spacing, $h'$, has been increased due to the conductor impingement effect at the mid-plane.

Figure 3. Diagram of a proposed 4-layer double-helix coil used in a $180^\circ$ beam channel bend.
AML combined function magnet design

<table>
<thead>
<tr>
<th></th>
<th>Dipole</th>
<th>Dipole+quad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil aperture, mm</td>
<td>100</td>
<td>100</td>
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<tr>
<td>Coil current, A</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>Conductor turn spacing, mm</td>
<td>6.400</td>
<td>11.421</td>
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<tr>
<td>Quadrupole amplitude ($e_2$)</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Dipole field, T</td>
<td>-5.124</td>
<td>-3.047</td>
</tr>
<tr>
<td>Quadrupole field @ r=30 mm, T</td>
<td>0.000</td>
<td>-1.385</td>
</tr>
<tr>
<td>Gradient, T/m</td>
<td>0.000</td>
<td>-46.167</td>
</tr>
</tbody>
</table>

A = 4 cm
Reaching the patient with parallel beams

4.16 m
Reaching the patient with parallel beams
Scanning system

\[ \Delta x = 0.028 \times 0.62 = 0.0174 \text{ m} \]
Scanning system

\[ \Delta x = 0.028 \times 0.62 = 0.0174 \text{ m} \]
Scanning system

$\Delta x = 0.028 \times 0.62 = 0.0174 \text{ m}$

4.16 m
Possibility of SAD = ∞
Possibility of $SAD = \infty$
Betatron functions

4.16 m
**NS-FFAG gantry with permanent magnets**

**Halbach PM Dipole Structures:**

\[ B_g = B_r \ln(OD/ID) \]

There is no upper limit for air gap flux density in Halbach dipole structures according to equation.
Permanent Halbach magnet NS-FFAG gantry

BRHO = 1.7372345376900 Tm  ANG=2π/120 = 0.05235987755982988
BYD= 2.0214 T  KF =160.0 T/m  KD= -175.0 T/m
L_{CELL} =0.285081466313463

14 cells-27 cells

r=2.71 m

h_1=2.61 m

h_2=3.172 m

84°

162°
Spot scanning

Triplet combined function magnet properties and settings:

GF-TP1 = 27.1482 T/m
GD-TP2 = -23.967 T/m
GF-TP3 = 37.716 T/m

D22P = 0.9487 m
D31P = 0.2773 m
D32P = 0.0959 m

$\beta_{y_{\text{max}}} = 11.949 \text{ m}$
$\beta_{x_{\text{max}}} = 5.4445 \text{ m}$

$h_2 = 3.00 \text{ m (SAD)}$
$h_2 = 3.172 \text{ m}$

$L_1 = 10 \text{ cm}$
$L_2 = 10 \text{ cm}$
$L_3 = 10 \text{ cm}$

Drf4P = 1.348 m
What is innovative: extreme focusing

\[
\begin{align*}
L_{QF/2} &= 6.05 \text{ cm} \\
L_{QD} &= 9.2 \text{ cm} \\
L_B &= 3.8 \text{ cm} \\
29.7 \text{ cm}
\end{align*}
\]
Particle tracking through the gantry

Particles in $x$ - $y$ phase space at the end of the gantry

Energy range between 68-250 MeV
Matching NS-FFAG gantry with the triplet

Input parameters are:
\[ x_{\text{max}} \] and \[ x_{\text{min}} \] from the arc NS-FFAG
\[ p_{\text{max}}, \ p_{\text{o}}, \ \text{and} \ p_{\text{min}}, \ D, \ \beta_x, \ \beta_y, \]

Unknowns: \[ B_D, \ B_F, \ \Phi_{\text{fo}}, \ \Phi_{\text{do}}, \ \text{and} \ l_0 \]

\[
\rho_{\text{do}} = \frac{p_c}{eB_D}
\]
\[
\rho_{\text{d max}} = \frac{p_{\text{max}}}{eB_D}
\]
\[
\rho_{\text{d min}} = \frac{p_{\text{min}}}{eB_D}
\]
\[
\rho_{\text{f 0}} = \frac{p_c}{eB_F}
\]
\[
\rho_{\text{f max}} = \frac{p_{\text{max}}}{eB_F}
\]
\[
\rho_{\text{f min}} = \frac{p_{\text{min}}}{eB_D}
\]

To be matched to the input parameters of the linac: \[ \beta_x, \ \beta_y, \ \alpha_x, \alpha_y \]
SUMMARY:

1. NS-FFAG gantries provide transfer of carbon ions with $\Delta p/p=\pm20\%$
2. Weight is reduced for one or two orders of magnitude.
3. Size of NS-FFAG the carbon gantry is of PSI proton one.
4. Operation is simplified as the magnetic field is fixed.
5. Scanning system is with SAD~3m.
6. Beam size is adjustable with the triplet magnets.
7. It is possible to transfer in one pass beam with all energies after the multi-leaf collimator.
8. Triplet magnets do not need to be superconducting