New Accelerator Technologies for Particle Therapy

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Outline

• Requirements for particle therapy
• Current available accelerator concepts
• New accelerator concepts:
  – FFAG
  – Downscale existing technology
  – Dielectric wall acceleration
  – Wake field acceleration
Particle Therapy: Requirements

Example:

- Protons and carbon ions
- Maximum range: 33 cm
- Field size: 30x30 cm
- Scanning beam
- 2 Gy fraction in less than 1 minute
- Energy change in less than 2 seconds
- proton gantry and a horizontal line for C-12
Translation of Requirements:

The accelerator physicist:

- Two ion sources...
- Max energy 250-270 MeV for protons 400 MeV/u for C-12
- Scanning magnets
  Which scanning system, what FWHM of beam?
- I beam = xxx nA

- Adaption of range:
  - Synchrotron : per acc. cycle
  - Cyclotron : range shifter
Additional Operation Requirements

- Accurate beam positioning
- Stable beam intensity
- Safety (e.g. spill abortion system)

..and some additional Options:
- Sync patient motion with beam?
- Fast switching between ion species?
- PET monitoring?
General requirements

- 1000 patients/yr (throughput)
- Reliability
- Easy to operate
- Certified for patient treatment
Financial issues

• Price of accelerator facility: say, 100 M€
  – 1/3 concrete
  – 1/3 accelerator
  – 1/3 diagnostics

• Compact layout: *Smaller is cheaper*

• *But it may be limited what actually is being saved... “...less than 20 % if new accelerator concept is developed.”* (!?)
Current available concepts

CYCLOTRONS
- Isochronous cyclotron (dB/dr ≠ 0)
- Synchrocyclotron (df/dt ≠ 0)

SYNCHROTRONS
- Strong focusing
- Weak focusing
- Rapid cyling

FFAG

NEW TECHNOLOGIES
- Wakefield acceleration
- Dielectric wall
Typical Proton Cyclotron Facility

RPTC-1, Munich, Germany
Varian/Accel

250 MeV protons
PMRC, Tsukuba, Japan (Hitachi)

- 250 MeV
- 23.3 m circumference
- 0.5 Hz, 7 nA -> 2 Gy/min
FFAG

Fixed-Field Alternating-Gradient (FFAG)
CYCLOTRON
• Isochronous cyclotron
  \[
  \frac{dr}{dt} > 0 \\
  \frac{df}{dt} = 0 \ (not \ sync.cycl) \\
  \frac{dB}{dt} = 0 \\
  \frac{dB}{dr} > 0
  \]

SYNCHROTRON
• Fixed closed orbit
  \[
  \frac{dr}{dt} = 0 \\
  \frac{df}{dt} > 0 \\
  \frac{dB}{dt} > 0
  \]

FFAG
• Var. closed orbit
  \[
  \frac{dr}{dt} > 0 \\
  \frac{df}{dt} > 0 \\
  \frac{dB}{dt} = 0 \\
  \frac{dB}{dr} > 0\]
Disadvantage for high proton/carbon energies. Fix: “Non-scaling FFAG”.

Yoshiharu Mori, KEK.
**FFAG Bending Magnet**

- Synchrotron: fixed orbit, varying B-field
- Cyclotron: $\frac{dB}{dt} = 0$ ($\frac{dB}{dr}$ is 0 for the synchrocyclotron), varying orbit
- FFAG: fixed B-field, like cyclotron, orbit increases with Energy, but is closed.

*Yoshiharu Mori, KEK.*
History and Current Status of FFAGs

- First electron FFAG 1953 (MURA)
  - 400 keV electrons
- Long break, due to lack of technology:
  - New RF cavity: (no ferrite)
    250 Hz with 1.5-4.6 MHz sweeps
  - Magnet design:
    3D design F/D magnets,
    zero chromacity
- First proton FFAG 2000 (KEK)
  - 500 keV protons
- Non-scaling FFAG
  - Breaks $B(r)=B(r/R_0)^k$
- Proton/carbon ion therapy FFAG is under construction: PAMELA
  http://www.conform.ac.uk

C. Ohkawa and Y. Mori
150 MeV Proton Scaling-FFAG

Yoshiharu Mori, KEK.

Focusing using alternating gradients.
Proton FFAG Accelerator

2006 @ KEK, Tsukuba, Japan.

- Cyclotron for injection
- 150 MeV
- 100 Hz
- 90 % Extraction efficiency

Yoshiharu Mori, KEK.
Non-scaling FFAG for Particle Therapy

- Non-scaling FFAG
  - Breaks $B(r) = B(r/R_0)^k$
- Fast cycling: perhaps up to 1 kHz ---> high currents
- Fixed magnetic field: eases operation, similar to cyclotron.
- FFAGs can also accelerate heavier ions
- Variable beam energy extraction (cyclotron are monoenergetic)
- Compact ring, easy accessible -> easy maintenance.
- Multiple extraction points possible
- High efficiency -> low activation of structure
- **Not cheaper/smaller but faster and stronger**
Downscale existing technology
Reducing size of CYCLOTRON based facilities
Reducing Size of Cyclotron Based Facilities

- Superconducting cyclotron itself cannot be made much smaller than 1-2 meters Ø
- Entire facility is tried to be scaled down via innovative gantry designs.

Varian

StillRiver
MONARCH 250
COMPACT PROTON THERAPY

StillRiver SYSTEMS

Has not received FDA 510k clearance
Secondary neutrons?

250 MeV protons, 31.8 mrad divergence

Fluence per primary [cm$^{-2}$]

Depth [cm]

- Red: Neutrons
- Black: All protons
- Blue: Primary protons
Secondary neutrons?

Carbon range shifter

Neutron fluence map

Water target
Reducing size of SYNCHROTRON based facilities
Decrease size, Russian way
Reducing size of synchrotrons?

- Russian technology
- Bought by “ProTom”
- Small, simple, inexpensive

- But is it really small?

Loma Linda, Ca.
Table-top synchrotron, BINP, Novosibirsk

- Down-scale all known components to technical limits
- 1.6 m x 1.6 m

Fig. 1 - Schematic design of the proton synchrotron
Table-top synchrotron, BINP, Novosibirsk

- Circumference = 6.4 meter
- $E_{\text{max}} = 200$ MeV
- Injection at 12 MeV
- RF 7.42 - 26.5 MHz
- Sweep 3.5 msec
- $B = 4$ T, iron free magnets

Status

- Many-turn injection was shown
- Beam stored 2 orders magnitude lower than projected
- No RF
- No extraction
- 1 MW cooling at 10 Hz?
- **Project abandoned**

(Thanks to Vladimir A. Vostrikov, BINP)
Decrease size, Russian way
Table-top synchrotron, BINP, Novosibirsk

- Project restarted with more “realistic” parameters, with Japanese group KEK/NIRS
  - $E_{\text{max}} = 200$ MeV
  - $E_{\text{inj}} = 2$ MeV
  - $<10$ Hz repetition
  - RF 1.7 – 15.0 Mhz
  - 11.3 m circumference

- Carbon version
  - $E_{\text{max}}$ 200 MeV/u
  - $<10$ Hz repetition
  - 24.2 m circumference

- *Abandoned for unknown reasons after ~ 1 year.*

Figure 1: Magnet configuration for a superperiod of the proton (right half) and carbon ion ring (left half).
Dielectric Wall Accelerator (DWA)

“Proton acceleration at the fifth at the cost, and the size of a X-ray machine”
Proton ThomoTherapy.
**High Gradient Insulator (HGI)**

Closely spaced conductors inhibit the breakdown process. **Conventional Insulator**

- Emitted electrons repeatedly bombard surface

**High Gradient Insulator**

- Emitted electrons repelled from surface

HGI structure forms a periodic electrostatic focusing system for low energy electrons.


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**Surface breakdown field stress (MV/M) vs. Pulsewidth**

- HGI: sandwich layered structure, layers are less than mm thick
- Achieved 100 MV/meter

\[
y = 104.27x^{-0.2003}
\]

\[
y = 23.36x^{0.2592}
\]

(Yu-Jiuan Chen, LLNL)
Blumlein Pulse Generator

http://pulsedpower.eu
Blumlein Pulse Generator

(Yu-Jiuan Chen, LLNL)
(Yu-Jiuan Chen, LLNL)
• Flash X-ray radiography

3 MV/m gradient (600 kV) across stack and HGI’s with 1 kA electron beam load

(Yu-Jiuan Chen, LLNL)
DWA - Traveling Wave Acceleration

Charged Blumleins

HGI: shorter pulse $\rightarrow$ higher achievable gradient.

(Yu-Jiuan Chen, LLNL)
• Focusing before acceleration.
• Space charge - acceleration time is short.

(Yu-Jiuan Chen, LLNL)
DWA - Status: Proton Injector

- F.A.S.T. concept:
  - First Article System Test

- “easy disassembly to repair failed components at modest cost”

- Acceleration pulse is only 3 ns, protons must therefore be at 200 keV before injection into F.A.S.T.

(Caporaso et al., LLNL)
DWA Status - F.A.S.T.

- Have demonstrated accelerated electron beam through 7 Blumleins
- Energy?

- Proton beam through one Blumlein,
- demonstrated acceleration and deceleration of protons.
- Energy?

(Caporaso et al., LLNL)
Wakefield acceleration / Laser acceleration
• Idea first conceived 1979 by T. Tajima and J.M. Dawson, UCLA
• Use electric field from intense laser light for electron acceleration
  – But no lasers readily available with required intensity, since amplification optics break down
  – Chirped pulse amplification: expand laser pulse in spectra and or time domain, amplify and bundle again.
    Can reach TW in e.g 20 J over 600 femto seconds.
  – Reach 100 GV/m (RF is in the 10 MV-50MV range)
  – Have shown 1 GeV electron acceleration
Laser acceleration
Gradients achieved: 10 – 100 GeV/m easily
But delta E / E = 100 %
2004, breakthrough: using gas jets, % level energy spread.
Gas must be ionized, then heated
  - Can be done with two laser pulses, but laser heating is inefficient at low densities
  - Leemans et al use a capillary discharge waveguide
  - Guides laser, reduces energy spread
  - 40 TW peak laser pulse
Wakefield acceleration
Wakefield acceleration
Protons

- 60 MeV protons
- 100 MeV flourine ions
- 225 MeV (2 MeV/u) Palladium ions
- Carbon ions a few MeV/u dE/E = 17 %
- Recently Schnell and Wilkens (PMB 54, 2009) show using a spectrum of energies to effectively build a SOBP.
Things to Worry About

• Medical equipment certification
• “Heidelberg Ion (HIT) facility has the smallest possible size which still fulfills requested parameters AND reliability AND reproducibility, needed for certification”.

• “Build new accelerator on ship, do treatment in international waters.” (Inspired by Prof. O. Jäkel).