A Next Step in Proton Therapy: Boosting to 350 MeV for Therapy and Radiography Applications

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Current limitations in proton therapy:

- Where is the tumour? → imaging
- What is the range? → radiography (PET, prompt γ, …)
- Sharpen the dose distribution: → high energy
Proton radiography

Note:
Higher energy gives sharper images

U.Scheider and E.Pedroni

Proton range radiograph

( Simulated proton radiograph from:
Jao Seco, Nick Depauw, Marta Dias, MGH )
Proton radiography

**TERA - AQUA PRR SYSTEM**


In construction:
- Larger area: 30x30 cm²
- 48 scintillators
- Faster readout

10x10 cm² Area

*U. Amaldi et al, Nucl. Instr. and Meth. A629(2011)337*
Proton radiography

Proton tomography

Schulte et al., Med Phys 32 (2005) 1035

- 0.16 mGy
- 1.6 mGy
  - Directly measures proton stopping power
  - Very low dose to patient
  - Many beam directions needed
  => high energy needed
- 3.1 mGy
  => gantry needed
Depth dose curve, 350 MeV protons

- Shoot-through technique
- Stereotactic treatment
- At small target volumes, the integral dose to NT is not worse than of photons (work in progress)
Therapy applications:

- (stereo tactic) treatment of small lesions (few cc)
- sharpen edge of dose distrib.
Upgrade for high energy

230 or 250 MeV cyclotron
energy selection
beam transport and switch yard
Linac based on existing TERA design of CCL linac
Gradient: 25 MV/m
=> 100 MeV needs effectively 7 m

Gantry with 20% stronger field

230 or 250 MeV
treatment rooms (gantry or fixed horizontal line)

7m Linac

350 MeV
Boosting to 350 MeV at PSI

ImPulse project PSI:

Linac for boosting from 250 to 350 MeV

In collaboration with TERA

250 MeV cyclotron

Linac location if gantry-3 accepts 350 MeV
Linac 250-350 MeV

4 independent units of 25 MeV

RF pro unit: 3 GHz, 10 MW (peak), 120 kVA
Linac 250-350 MeV

**Linear Booster concept from TERA:**

4 independent units of 25 MeV:

Per unit:

- 3 Tanks
- Bridge coupler
- Focusing in between tanks
**Coupled Cavity Linac**

1 tank:
- Normal conducting copper
- Standing wave
- $\pi/2$ mode
- 3 GHz: strong E field possible

Beam coupling cavities

Accelerating Cavities (12)
Feasibility of proton acceleration (62 → 72 MeV) at 3 GHz in 1.3 m CCL has been demonstrated.

Used acceleration field:
\[ E_0 = 27.5 \text{ MV/m} \]

Needed peak power: 55 kW/cell

LIBO = LInac BOoster
3 GHz Test Cavity to find max $E_0$

- Single accelerating cell
- H-coupled to waveguide

$\Rightarrow E_0 > 45$ MV/m

At:
1 MW / cell peak and max $E_{surface}$ 175 MV/m

Garlaschë, Degiovanni, Verdu A, Bonomi (TERA)
Maximize the acceleration effectiveness:

Effective shunt Impedance:

$$Z_{TT} = \frac{E_0^2 T^2}{P/L}$$

Minimize power losses

Minimize the $E_{\text{max}}$ (break down)

Adapt cavity cell-length per tank to particle speed:

$$L = \beta c/2f \quad \beta: 0.61 \rightarrow 0.71$$

Optimize the geometry using LINAC–code from TERA
LINAC pulses: 200 Hz

LINAC RF: 3 GHz

CYCL. RF: 72 MHz

Proton intensity:
Some frequencies

- 0.8 ns proton pulse from cyclotron
- 0.3 ns LINAC RF

20% of protons arrive at right phase for acceleration in linac
Beam chopping in cyclotron

99.9% of Cyclotron beam is **not used** between the 200 Hz RF pulses

- Proton source
- Vertical Deflector plate
  - 5 µs pulses
  - Ramping time < 1-2 µs
  - Pulse at 200 Hz
Choice of synchronous phase

-15°
-25°

low transm.  ΔE ±0.5%
high transm.  ΔE ±1.5%

Simulations with LINAC code (TERA):

sync. phase: -25°

ΔE/E = ±1.5%

- OK. for High energy therapy
- Beam analysis needed for proton-radiography
- (analysis needed anyway to remove <300 MeV)
Results of simulations

- Longitudinal acceptance at 350 MeV: 25-30%

- Transverse acceptance (4 mm bore radius): $9.2\pi \text{ mm.mrad}$
  
  Typ. beam emittance: $3 - 4\pi \text{ mm.mrad}$

- Energy Acceptance: $250 \pm 4 \text{ MeV}$
  
  Energy spread and max deviation of cyclotron: $1 \text{ MeV}$

=>$\text{Total transmission from cyclotron exit to linac exit:}$

  If cyclotron CW: 0.02 %

  If cyclotron is pulsed: 15 %

1 $\mu$A from cyclotron in 200 Hz pulses of 5 µs:

  **Radiography:** tomogr. 10 lit. needs $10^9-10^{10}$ protons => takes 3-30 sec

  **Therapy:** 10 Gy in 10 cm$^3$ needs $10^{12}$ protons => takes 100 sec

Includes 3x higher losses in Analysis
Conclusion

Study for facility upgrade with booster 250 → 350 MeV:

- **7m long**, 3 GHz (S-band) CCL, 40 MW peak
- **Enough beam intensity** for radiography and special therapies
- **Fits** in standard facilities

250→275 MeV test unit is planned at PSI:
- Total length 1.5 m in existing beam line
- Energy measurement
Thank you!
Quadrupoles

Transverse defocusing:

Compact
Easy to operate

Permanent Qpoles:
Alignment?
Irradiation damage?
25 MeV test unit (1th unit of 100 MeV linac)

Due to the short size of the linac there is no time to bunch the beam, and the energy spectrum, shown in figure 5.23, is almost continues with a maximum energy of 275 MeV.
99.9% of Cyclotron beam is not used between the 200 Hz RF pulses
=> to reduce activation cyclotron beam must be chopped