Particle Therapy with the
Varian / ACCEL
250 MeV
S.C. Proton Cyclotron

1st Workshop HADRON BEAM THERAPY OF CANCER
ERICE – SICILY, 24 APRIL - 1 MAY 2009

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References: M.J. Schippers (PSI)
ACCEL History towards Accelerators for Medical Applications

- **Fab first**
- **Start SC Magnet Tech**
  - Accelerator Designs
  - HERA Quads, DetectorMagnets

- **Layout of PTS Foundation of ACCEL**
  - MGH Boston (Cycl.+Syn.)

- **SERSE Hexapole Reevaluate**
- **PTS Options**
- **Contracts** *PSI Cyclotron*
  - PSI&RPTC *Assembly of RPTC*
  - LHC Main Quads


→ Year
Site for Cyclotron Assembly

400 LHC SC-Quadrupoles CERN
Order Volume
~50Mio.$
System Overview / Cyclotron D&D

- in 2001 started from the `93 NSCL “Proposal for a manufacturing Prototype superconducting Cyclotron for advanced Cancer Treatment” with no in-house cyclotron expertise at that time, only experiences in (nearly) all different technologies needed (s/c magnets, RF, Linacs, ...)

- Extensive use of 3D-FEM codes for magnetic, electrostatic, RF, heat load calculations, no mock-ups

- Close collaborations with various experts of different institutions:
... some design parameters and customer specifications ...

- **Beam**
  - Energy: 250 MeV
  - Emittance of extracted beam: \( \leq \frac{3\pi}{5\pi} \) mm mrad
  - Momentum spread \( \Delta p/p \): \( \pm 0.2\% \)
  - Extraction efficiency: > 80%
  - Fast intensity modulation: \( \frac{\Delta I}{I} > 90\% \) in 100 \( \mu \)s (beam switch off) with 1 kHz max. repetition rate

- **Iron yoke**
  - Outer diameter: 3.2 m
  - Weight: 90 t

- **Magnet**
  - Central field: 2.4 T
  - Max. field at the coil: < 4 T
  - Operating current: 160 A
  - Rated power cryocoolers: 40 kW

- **RF-System**
  - Frequency: 72.8 MHz (2\(^{nd}\) harmonic)
  - Number of Dees: 4
  - Voltage Source to Puller / @ extraction radius: 80 kV / 130 kV
  - RF-Power: \(~120\ kW\)
System Overview / Design Goals

**Purpose:** medical cyclotron serving as the source for proton therapy

**Features...**

- extensive, detailed modeling to optimize the system (RF, electrostatics, magnetics, neutron heating, mech. stress analysis, tracking...)
- superconducting
- magnet trimming: only trim rods at two radii, (centering, extraction bump) + main coil, no trom coils
- two adjustable (radius and width) slits with current read out
- vertical deflector
- two extraction deflectors with moderate voltages
- internal cold cathode ion source

...serve design goals:

- reliability, reduced need and effort for maintenance
- large, constant gap, compact, high extraction efficiency, low activation, low dose for maintenance personnel, fast morning startup
- simple, not heat load, passive, reliable
- Beam control and valuable fast beam diagnostics for (QA)
- Fast control of beam current, needed for adv. scanning
- Reliable, low maintenance effort
- simple, proven design, designed after Harper Medical Cyclotron

Erice 2009
Magnet Technology for a Medical Proton Cyclotron: Advantages by using Superconducting Magnet Coils:

No Ohmic losses

- Less Rated Power needed and reduced Electrical Consumption: (40 kW for Cryo-system instead of >200 kW power supply)
- No heat introduced into iron yoke
- Machine will stay powered overnight → reduces time to switch on the machine in the morning

Reduced size and weight (less activated material)

- Superconducting: 90 t and 3 m diameter

Make use of achievable high fields in larger volume to increase gap size over full radius

- Reduced Non-Linearities
- Improved Extraction Efficiency >80% meaning less activation)
250 MeV Superconducting Proton Cyclotron

System Overview

- LHe-Supply Vessel w/4 Cryocoolers
- Compressors: 4x for cryocoolers, 2x for shield coolers
- Shield Cooler (2x)
View of 3D-TOSCA Modell
Design: Magnet

- First magnetic design with saturated iron approximation codes; Fast iteration steps
- Refinement of magnetic design with TOSCA 3D model using saturated iron approximation to determine the changes for hill shape etc.
Factory Tests: Magnetic Performance

TOSCA Model + Corrections

First Average Field, Measured

Final Average Field, Measured
Manufacturing: cold mass and coils
Mounting of cryostat into lower yoke
First successful Ramping of PSI Cyclotron Magnet, 12/2003
Performance

Cryogenic System / cooling capacity

Calc. of heat load in cold mass per 100 nA stopped:

- PSI (Atchison) : 0.4-0.6 W
- KVI (Beijers, Brandenburg) : 0.3 W
- ACCEL : 0.58 W

Calculation of heat load induced by neutrons produced by dumping protons into beam probe

$\Delta = 0.9 \text{ W} @ 250 \text{ nA}$

$P_{\text{Heater}} = 3.7 \text{ W}$

$p_{\text{He}} = 1040 \text{ mbar}$

0.36 W / 100 nA stopped beam
or 1.8 W / 500 nA

Acceptance test performed with only 3 of 4 cold heads in operation.

$\Rightarrow$ comfortable margin
Factory Tests: Cryogenics

- Design current (160A) exceeded without any quench
- Large amount (> 4 W) of redundant cooling power
- Superconductor with high stability margin:
  Quench @ quench heater power > 4 W

Proven conservative cryogenic design
Commissioning / Verification

Isochronism: Smith – Garren measurement

Smith-Garren:
• Variation of main coil current

Goal:
• Verification of magnetic field shimming
• Verification of energy gain per turn

Result:
• excellent agreement between phase curve derived from measured field maps and Smith-Garren measurement
The 250 MeV Proton Cyclotron at ACCEL for cryogenic and magnetic factory tests
Installation of the Cyclotron at RPTC
Commissioning

Status PSI Cyclotron Sept. 04 (~ Tokyo-Conference)
System Overview

Time line PSI - Project

- Δt=10 months
  Contract RPTC: spring 2002
- Δt=2 months
  Commissioning start at RPTC: Feb. 05
- Δt=2.5 weeks
  First beam at RPTC: Apr 19th

Contract:
- Apr. 01
- Dec. 04
- Apr. 1st, 05
- Dec. 05
- Mar. 06
- Oct. 06
- Feb. 07

Learning curve

Start commissioning
First beam
Acceptance test phase
End of test phase
Start of PROSCAN Integration
1st Patient

Cyclotron Conferences:
- East Lansing ‘01
- Tokyo ‘04
- Giardini Naxos ‘07

Now: cyclotron routinely run by operators
Design: RF-Structures

- RF-Design
  - Started with simple models for estimations/rough and fast optimization steps (e.g. acc. gap)
  - Detailed 3D-Models of one sector (Microwave Studio, O(10⁶) nodes)
  - Simple 3D-Models full geometry (Microwave Studio)
  - Detailed full 3D-Model (using 3D-CAD data, Omega 3P)

Separate talk 18B3, H. Fitze, PSI
Cyclotron Inner Region E-Fields, First proton turns

Extensive 3D-Computations performed to optimize pattern of electrical fields
Design: RF-Structures

• Central Region:
  • Started with electrostatic and rough model (Relax 3D)
  • Refinement of electrostatic design with TOSCA 3D
    Exchange of data between 3D-CAD and TOSCA for iterations,
goals: Optimizing focusing, minimize electric fields, etc.

3D-CAD 3D E-Static TOSCA Model

Good agreement: calculated and measured mode separation,
Needed RF power = 110 kW
(120 kW deduced from calculations + experience),
extensive use of accurate and detailed modelling
paid off: No problem with high electric fields in the
inner region (200 kV/cm)
Commissioning

RF System

• Good agreement: calculated and measured mode separation

• Needed power 110 kW (120 kW deduced from calculations + experience)

• extensive use of accurate and detailed modelling paid off: No problem with high electric fields in the inner region (200 kV/cm)

• number of spark events within specs  ➔ talk M. Schippers (MOXCR04, Cyclotron Conf. 2007)

• Contact fingers in RF amplifier and Dee 3 exchanged
Simulation Results

- **Mode Separation:**
  - Desired mode is mode $1$ (push-pull mode) at $72.8$ MHz
  - Sufficient distance to mode $2$?
  - Excitation of higher order modes by harmonics?

- **Tuning**
  - Resonance tuning: moving all 8 shorting plates identical
  - Field balance tuning: moving each shorting plate individually
Simulation Results

• Gap-Voltage distribution
  – Voltage minimum at stem position
  – Results used for beam dynamic calculations

• Design of Contact Springs
  – Calculation of maximum current at contact spring position
  – Verification of contact spring design
Commissioning

RF System

Spread in DEE voltages reduced from $\Delta=20\text{kV}$ to $\Delta=2\text{kV}$ with a X-ray detector.

- number of RF trips strongly reduced
- problem with contact fingers eliminated

![Graph showing fitted Dee voltage vs. RF power](attachment:graph.png)

**BEFORE**

Before modification, the spread in DEE voltages was significant, with a large variance in the fitted Dee voltage across different RF powers.

**AFTER**

After implementing the X-ray detector, the spread in DEE voltages was greatly reduced, with a much smaller variance in the fitted Dee voltage.

![Image of contact fingers before modification](attachment:before_modification.png)

![Image of contact fingers after modification](attachment:after_modification.png)
Commissioning / RF System

- Model is fitted to determine Dee voltage
- Online fitting
- "side development"

- Small low resolution X-ray detector
- Collimation from iron
- Easy calibration and exchange
RF-Stems, RF-Amplifier
Animation of Cyclotron Acceleration
System Performance Overview

**Purpose:**
medical cyclotron serving as the source for proton therapy

**Design Goals:**
- High reliability
- Low activation
- Easy maintenance
- Suitable for advanced scanning techniques
- Fast morning start-up
- Easy to use
First Steps: Beam Centering and Beam Control
Performance

Ion Source

- Acceptable beam quality for “simple” raster scanning at PSI (Gantry 1) and RPTC

- Now: clear evidence that ion source is capable of providing adequate beam quality for 2D-fast scanning

Beam Current Measurements at RPTC:

- Before: stability typically 30%
- After: stability better 10%, reproducible

Recently: After applying changes to the geometry of plasma chamber

Fulfills requirements for PSI - Gantry 2 and RPTC
Commissioning / Beam Optimization

Beam centering

- beam measured with shadow finger probe on platform in inner region (commissioning probe)
- centering optimized with magnetic ‘Trim Rods’

Bad Centering

Good Centering
Intensity modulation

1. Ion Source
   For slow variations

2. Vertical deflectors plates
   Variations up to 10kHz

First results:

- Saw-tooth voltage →
- Vertical beam profile visible
- Vertical position on external monitor is stable
- **Max intensity** set by: Ion source + phase slits

Roles of deflector plate:
- **decrease drift** of intensity
- **set requested** intensity within 5%

Febr. 2007: start program to reach spec=> best: $\sigma = 3\%$
(see poster)

Courtesy of M. Schippers, PSI
Commissioning

Diagnostics

• Radial probe viewer

• Radial probe integral head

• Foils

• Profile monitors

+ Special developments:
  • Commissioning probe
  • X-ray detector
  • Phase probe (automation)
Beam on/off and stability

Necessary for fast dynamic scanning (Gantry-2)

Acceptance tests:
- repetition rate 1 kHz ✔
- beam off < 50 μsec ✔
- intensity stability σ<5% —
  (for Gantry-1 and München: ✔)

Vertical deflector in cycl. Center
-beam on/off

On/off by means of Vertical deflector

Beam intensity

-0.6-0.7-0.8 ms

40 μs
Extraction from cyclotron

Electrostatic extraction elements

80% (ACCEL / Varian)

Courtesy of M. Schippers, PSI
Commissioning / beam optimization

Extraction efficiency

- one of the most important parameters / design goals
- low activation allows efficient maintenance → high up-time
- specified: > 80%
- difficult to measure… ➔ M. Schippers (MOXCR04)

Now:

routine at PSI: 85% , tuned by operators
at RPTC: 80% , tuned by operators
not being explored further
>80% extraction efficiency: Low dose to service staff

24 h after beam off, June 2007
(extracted beam integral 72 μA.h):

- on pole, closed cap: 400 μSv/h (40 mrem/h)
- mid plane, open pole cap: 250 μSv/h (25 mrem/h)

Courtesy of M. Schippers, PSI
Electrostatic extraction elements

Extraction efficiency

Retrof R=30cm

R=30 cm: 100%

Routinely: 80-83%

Simulations of probe efficiency

Measurement of current on probe: Extr eff = 80.6%
Performance

Automation / daily work:

- switch on the beam from overnight shutdown:
  - two button process on control system panel
    - beam within 8 min
  - isochronism is maintained by an automated phase control loop
    - beam within spec and machine ready for daily QA-checks within 10 min ( = additional 2 min )

- perform calibration (beam current) and daily QA checks
Performance

Automation:

Transition Overnight Shutdown -> Beam On

- $I_{Mag} = 158A$
- $I_{Mag} = f(Irontemp)$
- $PRF = 85kW$
- $U_{VD} = 3.5kV$
- $H_2$-flow = 1.4sccm
- $I_{EDx} = 50kV$
- $IS_{arc} = 250mA$
- $PRF = 110kW$
- $t=0min$
- $t=1min$
- $t=6min$
- $t=8min$
- $t=10min$
- $I_{beam}$ within spec

1 – calibration phase measurement
2 – automatic phase control loop

• no operators routinely required (PSI specification): very close
Performance

Maintenance

• relevant maintenance operations so far for “internal components” since 2005:

  • Ion Source: every 2 weeks, exchange/cleaning of chimney and cathode, breaking of cyclotron vacuum not necessary
  • RF-Window (cleaning)
  • Jacking-System of the pole cap (greasing)
  • vertical deflector (exchange, RPTC only)
  • Regular maintenance of cold heads and shield coolers
  • extraction deflectors: one set of deflectors and HV feed throughs installed for more than one year at PSI, similar at RPTC
Contents

- Introduction
  - ACCEL History
  - Why Particle Therapy?

- System Technology
  - Cyclotron versus Synchrotron
  - Magnet Technology: Advantage of Superconductivity
  - The ACCEL 250 MeV Cyclotron - Overview

- Performance
  - Ion Source (Animation!)
  - RF-System
  - Activation / Maintenance
  - Automation / daily work
  - Reliability

- Proton Therapy Facility and Application
  - Scanning Requirements, Workflow, (New) Layouts,

- Conclusions
System Overview

Varian/ACCEL Cyclotron installed at:

- **Paul Scherrer Institut (PSI)**, Villigen, Switzerland
  - dedicated cyclotron (COMET) for the **PSI PROSCAN** project
  - intensification of R&D on proton therapy like
    - intensity modulated proton therapy (IMPT)
    - faster treatment, repainting of large volumes, etc.

- **Rinecker Proton Therapy Center (RPTC)**
  - Munich, Germany
  - As part of the delivery of complete proton therapy system
  - identical to the PSI cyclotron
Proton Therapy Facilities beam/patient paths
Proton Therapy Facility RPTC, Munich

I. S.C. cyclotron

II. Energy Selection System/ Beam Transfer Line

III. Gantry Rooms

Eye Treatment Room

~90 m
~15 m
Carbon wedge degrader
238-70 MeV
5 mm $\Delta$Range in 50 ms

Beam-energy adjustment

Degrader unit

Steerer (Kicker)
Commissioning / Verification

Energy verification

- Specified: 250 +1 -4 MeV
- PSI: 249.6 MeV
- RPTC: 250.2 MeV

Emittance verification

horizontal (π mm mrad)    vertical (π mm mrad)

Specified (95% of particles): 3.0    5.0
PSI: 3.0    4.7
Energy measurement

Ion chamber in water tank to measure proton range

Range in water => E=250.4(1) MeV
Product Offering – Turn Key Proton Therapy Facility

- SC Cyclotron
- Beam Transfer Line (Energy Selection Section w/ Degrader)
- Gantry for 360° Irradiation
- Scanning Nozzle
- Patient Couch
- Patient Position Verification
- Integrated Software Package (TP, TCS, PIS, etc.)
- Building Interfacing
Conclusions

• PSI cyclotron has been commissioned successfully and has been accepted

• design and calculations were verified

• design goals fulfilled, in particular performance and reliability fulfill high demands on medical devices

• PSI cyclotron is fully operational, patient treatment has started

• RPTC patient treatment has started March ‘09
Perspectives:

Industrialization of Fabrication of PT-Equipment, especially of sc Cyclotrons!

Expansion to Ion Therapy?

Expansion into smaller Synchro-Cyclotrons?
Thank you for your attention!