Beam Response to Extreme Operating Conditions

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Outline

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• Morning Beam Performance Check
  – Long-Term Beam Behaviour

• Machine Stress Test
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  – Room Air Response
  – Beam Response

• Conclusion
HIT Key Facts

- Ion beam **therapy facility** of the university clinics in Heidelberg, Germany
- **First patient:** Nov. 2009; ~700 pts. per year; 5000\(^{th}\) pt.: Aug ’18
- **Ions:** therapy: p, C; experiments: O, He (therapy expected end of 2019)
- **Energies:** p: 48... 221 MeV / u, C: 89... 430 MeV / u; E-index: E1-E255
- **3 treatment rooms** (2 fixed beam, 1 iso-centric carbon-gantry)  
  + 1 experimental room
- **3D raster scanning** with position feedback control  
  - Beam **position accuracy** at iso-centre (controlled):  
    ±0.5 mm (soft), ±1.0 mm (sharp)
- **5 s extraction spill, dynamic intensity control** (DIC)
- Synchrotron dipoles with **dynamic field control**
A Typical Day at HIT

6 treatment days per week, 24/7 shift operation

Plan Verification
(Bio)physics Experiments or Beam Maintenance
Quality-assurance
Patient Treatment

24
12
Morning Beam Performance Check: Beam Diagnostics Locations

LINAC-protocol:
- currents / transmission
- stripper efficiency
- energy (7 MeV / u)

Profile Grids
(M1DG1, M1DG4/5)

MWPCs
(B1/2DG3G)

MWPC
(B3DG3G)

MWPC
(G3DG5G)

BPMs
(S#DX#)

BPM: Beam Position Monitor
MWPC: Multi-Wire Proportional Chamber
Morning Beam Performance Check:
Beam Position (hor. / vert.) on 1. HEBT-MWPC

Energy as Index

Hor. Position

Vert. Position

+5 mm  
-5 mm  
+5 mm  
-5 mm
HEBT-MWPC Long-Term Position Variation Proton Beam, First Half Year 2018

- Tuning
- Tuning (2x)
- Maintenance
- p-Tuning
- Standby Op (Test)
- Shutdown
- Standby Op (Easter)
- C Tuning (max. E)
- Shutdown
- Holding Op (C, max. E)
- Stress Test
- Standby Op (Whitsun)
- Maintenance

Graph showing H1D3G Avg. Position (mm) with dates from Jan 01 to Jun 25, indicating various maintenance and operational periods.
District Cooling: Cooling Power

District Cooling
forward
return

Magnet Coils, ...
forward
return

Cooling Power
HEBT MWPC Long-Term Position Variation Proton Beam, First Half Year 2018

Diagram showing position variation of a proton beam with data points for horizontal and vertical positions. The dates range from January 1 to June 25, with markers for maintenance periods and limit lines.
Correlation Between Hor. HEBT-Position and Cooling Power
CURVE-FITTING METHODS
AND THE MESSAGES THEY SEND

LINEAR
"HEY, I DID A REGRESSION."

QUADRATIC
"I WANTED A CURVED LINE, SO I MADE ONE WITH MATH."

LOGARITHMIC
"LOOK, IT'S TAPERING OFF!"

EXPONENTIAL
"LOOK, IT'S GROWING WITHOUT A SLOPE."

LOESS
"I'M SOPHISTICATED, NOT LIKE those simple LINEAR things."

LINEAR, NO SLOPE
"I'M MAKING A SCATTER PLOT BUT IT'S NOT LIFELIKE."
Correlation Between Hor. HEBT-Position and Cooling Power

Pearson (linear) correlation coefficient $r$:

Interpretation:

- $|r| = 0$: no correlation
- $|r| = 1$: complete correlation

$r = 0.97$
Synchrotron Beam Position Monitors
Proton Beam, First Half Year 2018

Estimation:

Synchrotron bending radius: \( R_0 = 4.4 \text{ m} \)
Max. radial position change: \( \Delta r_{\text{max}} = 2.4 \text{ mm} \)
Magnetic beam rigidity: \( B\rho = \text{const.} \)

\[ \Rightarrow \Delta B \approx 5 \cdot 10^{-4} B_0 \]
What is normal, what is extreme operation?

Cooling Power

Normal:
- Average cooling power: 380 kW

Extreme:
- Average cooling power: 1696 kW
- high: 1696 kW
- low: 221 kW
Energy Distribution

Executed therapy cycles (all ion species) from 2018-07-30 to 2018-08-05 (week 31)

Most frequent energies:
- C: 192,13 MeV/u (E61)
- p: 98,27 MeV/u (E55)
Machine Stress Test Shift Programme

11:00 p.m.: Taking over priority from medical physicist (QA); recording of reference beam position at synchrotron extraction and MEBT beam positions for proton beam

11:10 p.m.: Start heating phase: running Carbon, highest energy (430.1 MeV/u), to Gantry

00:00 a.m. - 03:00 a.m.: 6× (every 30 minutes) recording of proton beam positions

03:00 a.m.: End of heating phase: stopping of operation, idle

03:30 a.m. - 06:00 a.m.: 6× (every 30 minutes) recording of proton beam positions

06:00 a.m.: Daily beam performance tests

07:00 p.m.: Begin early shift, maintenance
Cooling Water Temperature Response

Cooling System

Machine Cooling

Return Temperatures

Forward Temperatures

Cooling System

Machine Cooling

Return Temperatures

Forward Temperatures
Room Temperature Response

Data Logger:

- PS room, front
- PS room, back
- PS room, PS sync dipole
- PS underfloor
- Storage, cable shaft

- Sync S2MU1
- Sync S5MU1
- Sync room, south wall
- LINAC
Beam Response: HEBT, 1. MWPC

Position:

Width:
Beam Response: MEBT

1. Profile Grid: (M1DG1)

2. Profile Grid: (M1DG4)

3. Profile Grid: (M1DG5)
LINAC Energy
Phase Probe Measurement
Correlation Between Hor. Position and PS Room Underfloor

Pearson (linear) correlation coefficient:
- all data: $r = 0.90$
- upper branch: $r = 0.97$
- lower branch: $r = 0.95$
Conclusion: Summary of Machine Stress Test

Cooling water:
• In equilibrium, the forward temperature is kept constant by ±0.2 K
• If perturbed, temperature remains within ±1 K

Room Temperature:
• The highest temperature rise of 2 K is found in the power supply room
• In the synchrotron room, the temperature goes up by max. 0.5 K

Beam:
• No beam response in the MEBT
• The *horizontal position* in the HEBT changes by 3 mm
• The *vertical width* varies by 10%

Correlations:
• Beam parameters and room temperature are strongly correlated
Conclusion: Correlation vs. Causality

• **Symptom control:**
  – Learned how to do holding operation (carbon operation, $E_{\text{min}}$, beam dump)
  – Changed beam optics in HEBT (less sensitive to beam variations)

• **Possible root causes for correlations:**
  – Expansion of magnets, *but* longer yoke and higher gap should compensate
  – static/dynamic field control:
    • Hall-probes, *but* they are temperature compensated within $\pm 3$ K
    • Pick-up coil / integrator?
  – Investigations are still ongoing
  – Comments are welcome!