Status and Progress in PIMMS-Family Machines

M. Pullia
on behalf of CNAO and MedAustron accelerator groups

Slow extraction workshop 2019 – Fermilab July 22-24, 2019
PIMMS

- Study hosted at CERN, 1995-1999

- The Proton-Ion Medical Machine Study (PIMMS) was set up following an agreement between Med-AUSTRON (Austria) and the TERA Foundation (Italy) to join their resources in the design of a medical synchrotron that could later be adapted to individual national needs. CERN agreed to host this collaboration inside its PS Division and to contribute to the study. The group has worked in collaboration with GSI (Germany) and was later joined by Onkologie 2000 (Czech Republic).

- Designed keeping in mind that the facility would be operated in a hospital environment
Active systems

Energy variation from the synchrotron

Patient
Target volume

Horizontal scanning
Vertical scanning

Fast
Slow

Field 22
E2

Field 4
E4

Scanning system

Total thickness

Depth [cm]
CNAO and MedAustron

Treatments started in 2011 and 2017 respectively
CNAO and MedAustron: 2 implementations of PIMMS
Sources

2 (3) Supernanogan ECR sources for fast particle change and stable Operation
C$^{4+}$ or H$_3^+$ 8 keV/u
LINAC

Same RFQ+LINAC (GSI design)
400 keV/u RFQ
7 MeV/u LINAC
Synchrotron

Same Synchrotron design (PIMMS)
60 – 250 MeV protons
120-400 MeV/u carbon ions
HEBT

Different HEBT design
Compact vs modular
D = D' ≠ 0

D = D' = 0

2 Superperiods
2 Closed dispersion bumps
1 Dipole Family
3 Quadrupole Families
3 Sextupole Families

<table>
<thead>
<tr>
<th>p inj</th>
<th>p – 60 MeV</th>
<th>p – 250 MeV</th>
<th>C^{6+} inj</th>
<th>C^{6+} – 120 MeV</th>
<th>C^{6+} – 400 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>B_{p} (T m)</td>
<td>0.4</td>
<td>1.1</td>
<td>2.4</td>
<td>0.8</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Treatment execution

Sync

1 s

2-3 min

Extraction magnets

Injection magnets

Extracted beam
Extraction setup at CNAO

Half of the machine lattice

Resonance sextupole
\[ D_x = 0 \text{ m} \]
\[ D_{xx} = 0 \]
\[ \beta_x = 8.78 \text{ m} \]
\[ \beta_z = 3.33 \text{ m} \]

Electrostatic septum (ES)
\[ D_x = 3.94 \text{ m} \]
\[ D_{xx} = -0.63 \]
\[ \beta_x = 16.39 \text{ m} \]
\[ \beta_z = 7.18 \text{ m} \]

Magnetic septum (MS)
\[ D_x = 0 \text{ m} \]
\[ D_{xx} = 0 \]
\[ \beta_x = 8.95 \text{ m} \]
\[ \beta_z = 3.87 \text{ m} \]

Kick becomes a gap of 19.5 mm for MS

\[ \Delta \mu = 229^\circ \]

\[ \Delta \mu = 51^\circ \]

Kick = 2.5 mrad

Figure 3 Extraction configuration
Hardt condition

\[ D_n \cos(\alpha_0 - \Delta \mu) + D'_n \sin(\alpha_0 - \Delta \mu) = -\frac{4\pi}{S} Q' \]
Betatron extraction
Head and tail of extraction

Amplitude

$\Delta p/p$

Head

Tail
Momentum distribution driven into resonance by Betatron core

\[ \sum. \text{En:62.4 MeV, 1}^{\text{st}} \text{Harm} \]

A. De Franco, A. Goetz
Extraction features at CNAO

Betatron core

Empty bucket channelling

Air core quadrupole

RF-KO with new exciter

Beam shaping with Schottky PU

Additional quad winding
Betatron core

\[ \Delta \Phi = 2.46 \text{ Wb} \]

Sensitivity to gap between halves

Magnetic screen needed
Empty bucket channelling


LOW FREQUENCY DUTY FACTOR IMPROVEMENT FOR THE CERN PS SLOW EXTRACTION USING RF PHASE DISPLACEMENT TECHNIQUES

R. Cappi, Ch. Steinbach
CERN, CH-1211 Geneva 23, Switzerland

Fig. 2: Slow extraction spill (50 ms/div.)
Empty bucket

\[ \Delta E \]

Amplitude

Resonance region

Sense of stack acceleration

\( P \)
RF-Channeling spill smoothening

En: 62.4 MeV - $F_{rev}$: 1.33 MHz.
$\Delta F_{ch}$: 15kHz – 1500V
Negligible losses

A. De Franco, C. Schmitzer

Change Spot Sizes!!!
→ Re-commissioning

Max Peak to Mean in a Spill

Same scale
With RF channeling

Spill time structure (50kHz)
Empty Bucket results

Carbon ions

Rms duty factor

Max / average

Protons

Rms duty factor

Max / average

Courtesy of L. Falbo
Air core quadrupole
Air core quad feed forward
Automatic feed forward

Feed forward correction requires repeatability, which was the case in the medium term (one day), but the correction parameters could vary over longer time (week).

In the days following the air core quad feed forward MD, R. Cappi set up a system performing FFT and applying the correction at the following spill.
High Frequency Ripple Injection

Feed forward does not work at CNAO, not even on the very short time scale (1 second). We needed an alternative.

- Ripple with betatron off. Brushing against the resonance
- Ripple with betatron on. Irregular spill with strong modulation
High Frequency Ripple Injection

Inject a large ripple with a frequency higher than the one you are interested in.

The amount of extracted beam depends only on the betatron, thus an apparently more homogeneous spill is obtained.
High Frequency Ripple Injection

Feed forward does not work at CNAO, not even on the very short time scale (1 second)
Effect on the beam at isocenter

Rms/avg full spill

SigmaX

SigmaY

Rms/avg 3000-3500

CMX

CMY

Off 0.6 0.8 0.95 a.u. excitation
RF frequency sweeping HFRI

The same effect can be obtained with every means that can bring
The beam towards and away from the resonance
Empty Sweeping Bucket vs Empty Bucket

Carbon ions

Max / Average

Proton ions

Max / Average

Rms Duty Factor

Rms Duty Factor

Courtesy of L. Falbo
Air core quad with feedback

Feedback start

Signal from a scintillator (qualification monitor in the HEBT)
Ripple compensation

Integration time 100 us (10 kHz data)

100 ms

No compensation

Empty bucket + HFRI

Empty bucket

Empty bucket + ACQ feedback
Different ripple spectra at CNAO and MedAustron
Carbon & proton ripples

1ms sampling frequency. All shift included (also few Machine Dev.)

S. Waid, A. De Franco
Bar of charge
Bar of charge measurement at MedAustron

Use 8 monitors in the long straight section and match Twiss parameters.
Bar of charge at MedAustron

Twiss parameters at EX-01-000-SFX-A from matching HWHM

<table>
<thead>
<tr>
<th>Ex [p mm mrad]</th>
<th>Ey [p mm mrad]</th>
<th>HWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.076</td>
<td>6.270</td>
<td></td>
</tr>
<tr>
<td>Bx</td>
<td>374.22</td>
<td>17.98</td>
</tr>
<tr>
<td>ax</td>
<td>-203.12</td>
<td>9.96</td>
</tr>
<tr>
<td>Gx</td>
<td>110.25</td>
<td>5.57</td>
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</tbody>
</table>

Beam size calculated with matched parameters and beam size measured

<table>
<thead>
<tr>
<th>62 MeV</th>
<th>CalcX</th>
<th>MeasX</th>
<th>CalcY</th>
<th>MeasY</th>
</tr>
</thead>
<tbody>
<tr>
<td>EX-01-000-SFX-A</td>
<td>5.33</td>
<td>5.18</td>
<td>10.62</td>
<td>10.63</td>
</tr>
<tr>
<td>EX-01-001-SFX-A</td>
<td>0.93</td>
<td>0.87</td>
<td>3.34</td>
<td>3.37</td>
</tr>
<tr>
<td>EX-01-002-SFX-A</td>
<td>2.16</td>
<td>2.26</td>
<td>8.05</td>
<td>8.05</td>
</tr>
<tr>
<td>EX-01-003-SFX-A</td>
<td>3.40</td>
<td>3.30</td>
<td>3.21</td>
<td>3.14</td>
</tr>
<tr>
<td>EX-02-000-SFX-A</td>
<td>4.00</td>
<td>3.78</td>
<td>5.71</td>
<td>5.94</td>
</tr>
<tr>
<td>EX-02-001-SFX-A</td>
<td>3.16</td>
<td>3.35</td>
<td>3.21</td>
<td>3.27</td>
</tr>
<tr>
<td>EX-03-000-SFX-A</td>
<td>5.33</td>
<td>5.58</td>
<td>5.71</td>
<td>5.47</td>
</tr>
</tbody>
</table>

Bar of charge (red)
Drawn inside a 5π mm mrad empty ellipse at 8 monitors in the HEBT
Simulated particle distribution at magnetic septum

Particles tracked at first monitor

Dispersive region

Non dispersive region

Courtesy of A. Wastl
Particles tracked at monitor
With measured ellipse and $5\pi$ empty ellipse
HEBT Chopper

Fast turn on/off for the beam

Intrinsically safe

Allows beam qualification
Chopped beam

Acquisition frequency 10 kHz

Beam in room

Beam on chopper dump

200 μs

Dump

To treat. room
Intensity modulation

The number of required particles varies a lot in spots of the same slice. Adapt intensity to spot!
Intensity modulation

Subdivide slice in classes and re-sort in order to treat spots with increasing intensity.
Multi-Energy Extraction

Saved time

1 s

Sync

Saved time

Extraction magnets

Injection magnets

Extracted beam
RFKO kicker in place
RFKO installed
RFKO Commissioning started

VERY preliminary

Bunched RFKO

Debunched RFKO

Work just started and low priority, still low extraction efficiency, many aspects still to be understood and implemented… more to come
Recent news and short future

CNAO
- Experimental room under commissioning
- Single room facility for protons being acquired
- Third source for other ions

MedAustron
- Carbon treatments started
- Gantry installation coming soon
- First rotator
Thank you for your attention

“Physics is like sex: sure, it may give some practical results, but that’s not why we do it. ”

R. Feynmann