Bunch Compressor for intense Proton Beams


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FRANZ: Requirement at the Target

- $N_{\text{bunch}} = 9$
- $\Delta T = 50-100\,\text{ns} \Rightarrow \Delta T_{\text{rms}} \approx 1\,\text{ns}$
- $A_{\text{beam at target}} < 3\times 3\,\text{cm}^2$
- $I_{\text{per pulse}} \approx 8\,\text{A}$
- $\Delta W < \pm 5\%$

175 MHz-DTL
rep. rate = 250 kHz
$E \sim 2.0\,\text{MeV}$
$I = 150\,\text{mA}$

Makro Bunch
Mikro Bunch
Realistic particle distribution after the LINAC

Beam size $r_0 \approx 1\text{cm}$

**Average current over one RF-period:** $I = 150\text{mA}$

Center energy of the Bunch: $W = 2\text{MeV}$

Velocity/speed of light: $\beta = 0.065$

**Charge per micro bunch:** $Q_{\text{bunch}} = 0.85\text{nC}$

Number of protons per Bunch: $N_{\text{proton}} = 5.3 \cdot 10^9$

Path length (1. traj.): $L \approx 4\text{m}$

Electric field on the surface of the bunch: $E_0 = 76.4\text{kV/m}$

Acceleration (proton on surface): $a = 7.4 \cdot 10^{15}\text{m/s}^2$

Potential Energy (proton on surface): $W_{\text{pot}} = 763.9\text{eV}$

Max. velocity due to space charge forces: $v_{\text{max}} = 3.8 \cdot 10^5\text{m/s}$

$\Rightarrow$ max. Beam size after $4\text{m}$ drift: $r_1 \approx 5\text{cm}$

LORASR (IH): $I = 150\text{mA}$

$$e_{\text{exp.}}^{x,y} = 1.42[\pi\cdot\text{mm}\cdot\text{mrad}]$$

$$e_{\text{exp.}}^{x,y} = 1.44[\pi\cdot\text{mm}\cdot\text{mrad}]$$

$$e_{\text{exp.}}^{x,y} = 423.99[\pi\cdot\text{keV}\cdot\text{deg}]$$

Significant
Space charge forces!
Mobley-Buncher: (μA-Proton beams)

**Kicker**
- Separation of the micro bunches

**Bending system (1 Dipole)**
- “weak” focusing
- path length differences
- longitudinal compression

Negligible energy spread (RF-deflector)
Mobley-Buncher: (µA-Proton beams)

*Kicker*
→ Separation of the micro bunches

*Bending system (1 Dipole)*
→ “weak” focusing
→ path length differences
→ longitudinal compression

**Improvements for 150mA Proton beams:**

*2 main dipoles (Gradient)*
→ more parameters for beam dynamics

*2 auxiliary dipoles (homogeneous)*
→ linear separation of the trajectories
→ momentum exchange in trans. plane

*2 rebuncher cavities*
→ longitudinal Beam dynamics
Bunch Compressor: Improvements for 150mA Proton beams

**Components:**

- **Kicker:** $f = 5\text{MHz}$, $U_{\text{max}} = 250\text{kV}$; $P \approx 15\text{kW}$
- Homogeneous dipoles: $B_1 = -515.0\text{mT}$
- Dipoles with gradient: $B_2 = 551.9 \pm 98.4\text{mT}$
- Multi-Aperture-Rebuncher: $U_{\text{eff}} = 100-140\text{kV}$, $P \approx 15\text{kW}$
- Broad-Gap-Rebuncher: $U_{\text{eff}} = 120\text{kV}$, $P \approx 10\text{kW}$

THX @ Y. Nie & H. Podlech
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@87.5MHz

Multi-Aperture-Rebuncher

©D. Noll

@175MHz

Broad-Gap-Rebuncher

©D. Noll
Bunch Compressor: Envelopes(95%) – bunch(1)

LORASR

quadrupoles triplets

IH + CH  dip1  dip2

Multi-aperture Rebuncher: (87.5 MHz, 100 kV)
reb2: (87.5 MHz, 120 kV)
Bunch Compressor: projections at the target

Bunch(1)  
Bunch(5)  
Rebuncher(2)  
Rebuncher(2)

<table>
<thead>
<tr>
<th></th>
<th>Bunch(1)</th>
<th>Bunch(5)</th>
<th>Rebuncher(2)</th>
<th>Rebuncher(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$ [MHz]</td>
<td>87.5</td>
<td>175.0</td>
<td>87.5</td>
<td>175.0</td>
</tr>
<tr>
<td>$U_{\text{eff}}$ [kV]</td>
<td>120</td>
<td>60</td>
<td>120</td>
<td>60</td>
</tr>
<tr>
<td>$\varepsilon_{x,rms}$ [π mm mrad]</td>
<td>2.354</td>
<td>2.932</td>
<td>2.011</td>
<td>2.798</td>
</tr>
<tr>
<td>$\varepsilon_{y,rms}$ [π mm mrad]</td>
<td>1.654</td>
<td>1.752</td>
<td>1.583</td>
<td>1.638</td>
</tr>
<tr>
<td>$\varepsilon_{z,rms}$ [π keV ns]</td>
<td>7.656</td>
<td>8.865</td>
<td>6.848</td>
<td>9.043</td>
</tr>
</tbody>
</table>

$\bullet N_{\text{bunch}} = 9$

$\bullet \Delta T = 50-100\,\text{ns} \implies \Delta T \approx 1\,\text{ns}$

$\bullet A_{\text{(beam at target)}} < 3 \times 3 \, \text{cm}^2$

$\bullet I_{\text{(per pulse)}} \approx 8\,\text{A}$

$\bullet \Delta W < \pm 5\%$
Bunch Compressor: Merging Scenario

- single bunch beam dynamics => realistic distributions
- Bunch-bunch-interaction in front of the target
- Particle in Cell: full space charge forces

L = 35 cm
I = 9x150 mA
N_{\text{particle}} ≈ 90 k
N_{\text{grid}} = 100x100x100
ΔX_{\text{stepsize}} = 1 mm
Δt_{\text{calc+plot}} ≈ 50 s

<transp.:merge>:
- Particle in Cell (PIC)
- dynamic lattice
- finite differences
- Poisson solver

Projections at target

Merge
Bunch Compressor: Merging - Projections at the target

- Requirements: \((\Delta W/W)_{\text{rms}} < \pm 5\%\) ✓ \(\Delta T_{\text{rms}} < 1\text{ns}\) ✓ \(A < 3\times3\text{cm}^2\) ✓
Bunch Compressor: Conclusion & Outlook

• Improvement of the **Mobley bunch compressor for high current applications**: Several µA beam current => 150mA per micro bunch

• Additional dipoles => transverse beam dynamics

• Rebuncher cavities => longitudinal beam dynamics

• Single **Bunch beam dynamics** + merging scenario => fulfills the requirements

• first step for technical realization of the bunch Compressor

• **Kicker**: design studies + numerical studies + **measurements at scaled model**
  => Results in good agreement with analytical and numerical estimations

• **Dipoles**: numerical studies with CST:EMS
  => Realistic field distributions <=> **beam dynamics**
  => Technical realization of the hardwares

• **Cavities**: feasible design with CST:MWS
  => optimization of the power consumptions
Thank you for your attention.

on behalf of:


_IAP, Goethe University Frankfurt_

acknowledgment:

Y. Nie, H. Podlech, A. Schempp, S. Schmidt

_IAP, Goethe University Frankfurt_

LINAC-AG http://linac.physik.uni-frankfurt.de
AG-Schempp http://iaprfq.physik.uni-frankfurt.de
NNP-AG http://nnp.physik.uni-frankfurt.de

DFG http://www.dfg.de
HIC for FAIR http://hicforfair.de
Bunch Compressor: geometrical parameters

\[ B_1 = -0.51497 \text{[T]} \]
\[ \alpha_{\text{max}} = 25.69 \text{[deg]} \]
\[ < \alpha > = 3.21 \text{[deg]} \]
Mobley Type Bunch Compressor

Components:

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<table>
<thead>
<tr>
<th>Dipole(1)</th>
<th>Dipole(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_1/\text{[mT]} )</td>
<td>515</td>
</tr>
<tr>
<td>( g/\text{[mm]} )</td>
<td>60</td>
</tr>
<tr>
<td>( N \cdot I/\text{[A]} )</td>
<td>10420</td>
</tr>
<tr>
<td>( A_{\text{coil}}/\text{[mm}^2\text{]} )</td>
<td>50×150</td>
</tr>
<tr>
<td>( A_{\text{wind}}/\text{[mm}^2\text{]} )</td>
<td>7×7</td>
</tr>
<tr>
<td>( N )</td>
<td>153</td>
</tr>
<tr>
<td>( I/\text{[A]} )</td>
<td>68</td>
</tr>
</tbody>
</table>
Bunch Compressor: Bunch(1) at the target

- reb2: 87.5 MHz
- reb2: 175.0 MHz

Graphs showing data points and curves for x/p, y/p, dW/keV, dt/µs, and x-y/µm with respect to z/cm.
Bunch Compressor: Bunch(5) at the target
Bunch Compressor: Bunch(9) at the target

![Graphs showing bunch compressor performance.](image-url)
Center motion significantly changed by large fringing field.

paraxial approach over estimate the emittance growth in transverse plane.

bigger emittance growth in long. plane with realistic fields.

field enhancement nearby the edges due to saturation

Insufficiently described by first order matrix formalism.
<table>
<thead>
<tr>
<th></th>
<th>Analytical</th>
<th>MWS</th>
<th>Measured (Powermeter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Inductance</td>
<td>µH</td>
<td>12.9</td>
<td>12.3</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>12.5</td>
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<tr>
<td>Effective Capacitance</td>
<td>pF</td>
<td>23.8</td>
<td>31.1</td>
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<tr>
<td></td>
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<td>Frequency</td>
<td>MHz</td>
<td>9.09</td>
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<tr>
<td>Intrinsic Quality Factor</td>
<td></td>
<td>2986</td>
<td>3058</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1772</td>
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<tr>
<td>Shunt impedance</td>
<td>MΩ</td>
<td>4.4</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.8</td>
</tr>
</tbody>
</table>

- Good agreement for the Inductance
- Stray Capacitance underestimated => higher frequency
- ~ 60% of the calculated intrinsic quality factor can be reached
- Measurements with network analyzer give comparable results
- Analytic formulas are good enough for “first shot” estimations
- big loops (~ 120×62mm²) are needed for critical coupling
  => mechanical problems + RF-properties of the loop
- alternative coupling methods (capacitive, galvanic) have to be investigated
Bunch Compressor: field along the first trajectory at preliminary dipole design

- large fringing field
- Connected fringing field region

=> Effects of fringing fields on beam dynamics?
field enhancement at the edges due to saturation effects
The complete effect of the fringing field is applied in one instantaneous kick in the transverse planes:

\[
x' = x_0' + k_x(\phi, \rho_0) \cdot x_0
\]

\[
y' = y_0' + k_y(\phi, \frac{g}{\rho_0}, K) \cdot y_0
\]

**Parameters of the first dipole:**
- Fringing field Integral \( K \) = 1.034
- Edge angle \( \phi_{\text{entrance}} \) = -25.01 [deg]
- Edge angle \( \phi_{\text{exit}} \) = 29.31 [deg]
- Magnetic field \( B_0 \) = 515.0 [mT]
- Gap \( g \) = 60.0 [mm]

Comparison with realistic field distribution:
- 0mA: real field dist. vs. matrix
- 150mA: real field dist. vs. matrix
- real field dist.: 0mA vs. 150mA