Beam Dynamics Layout of the FAIR Proton Injector

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The FAIR Proton Injector: Overview and Requirements
Comparison between different currents
Alternative solutions for the beam dynamics layout
Loss and Random Error Studies
Conclusions & Milestones
People
FAIR: Facility for Antiproton and Ion Research

GSI Today

FAIR

7\cdot10^{10} \text{ cooled pbar / hour}
**Injection of protons into SIS18**
- Acceleration to 2 GeV
- Injection into SIS100

- Impact on target \(\Rightarrow\) hot pbars
- Stoch. pbar cooling in CR
- Injection into in RESR

**Stoch. pbar cooling in CR**

**Injection into HESR**
- Acceleration to 14.5 GeV
- or
- Deceleration in NESR to 30 MeV
- Extraction to low energy pbar experiments
The client of the p-linac is SIS18.

Number of protons that can be put into SIS18 is limited to
\[ N_{SIS} = 4.305 \cdot 10^{13} \cdot \beta^2 \gamma^3 \], i.e. depends on energy.

Number of SIS18 turns during injection depends on phase space areas.

Injection energy → duration → current → emittance \( \varepsilon \) are coupled by

\[ B_n := \frac{I}{(\beta \gamma) \varepsilon_{tot}} = 63.6 \, \text{mA} \, \mu\text{m} \cdot \frac{(\beta \gamma)^2}{\eta_{MTI}} \]

\( \eta_{MTI} \rightarrow 60\% \) (good empiric value)

Energy remains to be chosen.
Parameters for Proton Linac

final rate of cooled pbar depends on injector energy:

\[ B_n = 63.6 \frac{\text{mA}}{\mu\text{m}} \cdot \frac{(\beta\gamma)^2}{\eta_{MTI}} \rightarrow 16.5 \text{ mA / } \mu\text{m} \rightarrow \]

- \( I = 35 \text{ mA} \)  Required for Operation  RF Cavity DESIGN up to 70 mA
- \( \beta\gamma_x = 2.1 \mu\text{m} \)  RFQ Optimised for 45 mA
The choice of the operating frequency is a compromise between the demands of

- High frequency in order to optimize the RF Efficiency

\[ ZT^2 \propto \sqrt{f} \]

- Low frequency to minimize the RF defocusing effect on the beam at low energy

\[ \Delta p_r \propto \frac{f}{(\beta \gamma)^2} \]

and the availability of commercial RF feeder (klystrons, tubes, IOT's.....)

For a Multi MeV machine the best choice is to base the machine in the 300-400 MHz range which satisfies all those requirements

\[ F = 325,244 \text{ MHz} \text{, i.e} \ 9 \times 36.13 \text{ MHz (GSI HSI-Unilac)} \]
Cross-Bar H-mode DTL (CH-DTL) represents the extension of well established Interdigital Linac for low-medium $\beta$ velocity profile. Its geometry is particularly suited for efficient cooling and allows the construction of high duty cycle and superconducting linacs.

$H_{211}$

R.T and S.C. CH
E < 150 AMeV
150<f<3000 MHz
DTL: Rf-coupled Crossed-bar H-Cavities

H-Mode cavities in combination with the KONUS Beam Dynamics ⇒ Highest Shunt Impedance

- reduce number of klystrons
- reduce place requirements
- profit from 3 MW klystron development
- avoid use of magic T's
- reduce cost for rf-equipment

ALVAREZ (LINAC4)
Linac will be mounted on rails and each module is directly connected with the next one.
• ECR proton source & LEBT
• RFQ (4-rod)
• 6 Pairs of Coupled CH-DTL
• 2 Bunchers
• 14 Magnetic Triplet
• 4.9 MW of beam loading (peak), 710 W (average)
• 11 MW of total rf-power (peak), 1600 W (average)
• 41 beam diagnostic devices
RFQ-Output distributions

- **45 mA**
  - RMS $\varepsilon_{\text{norm}} X-X'$ mm mrad: 0.262
  - RMS $\varepsilon_{\text{norm}} Y-Y'$ mm mrad: 0.26
  - RMS $\varepsilon_{\text{norm}} \Delta \Phi - \Delta W$ keV/ns: 1.292

- **70 mA**
  - RMS $\varepsilon_{\text{norm}} X-X'$ mm mrad: 0.362
  - RMS $\varepsilon_{\text{norm}} Y-Y'$ mm mrad: 0.357
  - RMS $\varepsilon_{\text{norm}} \Delta \Phi - \Delta W$ keV/ns: 1.58
45 mA

- RMS $\varepsilon_{\text{norm}}^{X-X'}$ mm mrad: 0.383
- RMS $\varepsilon_{\text{norm}}^{Y-Y'}$ mm mrad: 0.409
- RMS $\varepsilon_{\text{norm}}^{\Delta \Phi - \Delta W}$ keV/ ns: 2.09

70 mA

- RMS $\varepsilon_{\text{norm}}^{X-X'}$ mm mrad: 0.657
- RMS $\varepsilon_{\text{norm}}^{Y-Y'}$ mm mrad: 0.650
- RMS $\varepsilon_{\text{norm}}^{\Delta \Phi - \Delta W}$ keV/ ns: 2.82

Relative RMS Increase doesn't depend on the input current!
Alternative Layout

**USE of KONUS ⇒ Long section without triplet**

- 3 Pairs of Coupled CH-DTL's followed by 3 longer standard CH-DTL's
  - 11 magnetic triplet required instead of 14
  - Simplified RF and Mechanical Design
  - A rebuncher needed after the diagnostics section

**OUTPUT for I= 45 mA**

<table>
<thead>
<tr>
<th>RMS $\varepsilon_{\text{norm}}$</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X-X'$ mm mrad</td>
<td>0.41</td>
</tr>
<tr>
<td>$Y-Y'$ mm mrad</td>
<td>0.45</td>
</tr>
<tr>
<td>$\Delta \Phi- \Delta W$ keV/ ns</td>
<td>1.95</td>
</tr>
</tbody>
</table>
1. Singles errors are applied to fix the tolerances for fabrication errors and power oscillation. Single errors includes:

- Transversal Quadrupole translations: $\Delta X, \Delta Y \leq \pm 0.1 \text{ mm}$
- 3D Quadrupole Translations: $\Delta \Phi_x, \Delta \Phi_y \leq \pm 1 \text{ mrad}, \Delta \Phi_z \leq 5 \text{ mrad}$
- Single Gap Voltage Errors: $\pm 1\%$
- Phase Oscillations: $\leq \pm 1^\circ$
- Voltage Oscillations: $\leq \pm 1\%$
- Errors follow a gaussian distributions cut at $2 \sigma$

**Single error tolerances doesn't depend on the current**

2. All the sources of error are combined to evaluate the effect in terms of beam losses and RMS emittance degradation.

3. In case 1 and 2, 1000 runs are performed with a 100 000 particles RFQ-Output Distribution.
12 CCH

RMS Degradation 45 mA

6 CCH + 3 CH-DTL
Average Transmission

Minor Losses distributed all along the machine

Steering correction not included

Critical point is represented by the last long CH-DTL
The GSI Proton injector will be the first linac based on coupled H-Mode cavities in combination with the KONUS Beam Dynamics

Two designs are under discussions and they are comparable in terms of beam quality

Error Studies indicated that both designs are robust enough against fabrication errors and power supplies oscillations

Tolerances are comparable with the ones of other High Intensity linacs such as LINAC 4 or SNS

Fabrication of the first RF Cavity (Coupled CH 3 and 4) in preparation

Express of Interest declared by Germany, France, Russia and India

Construction starts in 2010

Commissioning in 2013
University of Frankfurt, GSI
• CH-cavity design
• RFQ design
• DTL beam dynamics

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CEA/Saclay
• Proton source & LEBT

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GSI Darmstadt
• Magnets, Power converters, RF-sources
• Proton source, Diagnostics, UHV, Civil constr.,
• Controls, Coordination

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