Beam Physics for the HESR

11. May 2012 | Andreas Lehrach
Outline

Introduction

FAIR Facility
HESR & Experimental Requirements

Beam Dynamics

Beam Injection and Accumulation
Closed Orbit Correction
Dynamic Aperture
Luminosity Estimates
Beam Equilibria

Summary / Outlook
Facility for Antiproton and Ion Research

Linac: 70MeV protons, 70mA, ≤4Hz
SIS 18: 5·10^{12} protons/cycle
SIS 100: 4·10^{13} protons/cycle

29GeV protons
bunch compressed to 50nsec

Production target: 2·10^8 antiprotons/cycle
3% momentum spread

CR: bunch rotation and stochastic cooling at 3.8GeV/c, 10s

RESR: accumulation at 3.8GeV/c
# Experimental Requirements

**PANDA (Strong Interaction Studies with Antiprotons):**

Momentum range: 1.5 to 15 GeV/c (Antiprotons)

| Effective target thickness (pellets) | 4·10^{15} cm^{-2} |
| Beam radius at target (rms)          | 0.3 mm             |
| Momentum range                       | “High Luminosity Mode” |
| Number of antiprotons                | 1.5 – 15 GeV/c |
| Peak luminosity                      | 2·10^{32} cm^{-2}s^{-1} |
| Momentum resolution (rms)            | \Delta p/p = 1·10^{-4} |
|                                     | “High Resolution Mode” |
|                                     | 1.5 - 8.9 GeV/c |
|                                     | 2·10^{31} cm^{-2}s^{-1} |
|                                     | \Delta p/p \leq 4·10^{-5} |

Electron and stochastic cooling, thick internal (pellet) targets
HESR Layout

Circumference: 574 m
Momentum (energy) range: 1.5 to 15 GeV/c (0.8-14.1 GeV)
Acceleration rate 0.2 (GeV/c)/s
Ion Optics

Betatron amplitude at PANDA:
\[ \beta_{x,y} = 1 - 15 \text{ m} \]

Betatron amplitude at electron cooler:
\[ \beta_{x,y} = 25 - 200 \text{ m} \]

Transition energy:
\[ \gamma_{tr} = 6.2 - 15 (30) \]

Low dispersion in straights
Beam Dynamics Simulations

- Beam injection and accumulation: steering concept
  (Simulation codes by T. Katayama and H. Stockhorst)

- Dynamic aperture calculations and closed-orbit correction: steering and multipole correction concept
  (MAD-X, SIMBAD based on ORBIT)

- Beam losses at internal targets / luminosity estimations:
  particle losses (hadronic, single Coulomb, energy straggling, single intra-beam)
  (Analytic formulas)

- Beam-cooling / beam-target interaction / intra-beam scattering: beam equilibria
  (BetaCool, MOCAC, PTARGET, Jülich stochastic cooling code)

- Ring impedance: RF cavities, kicker etc.
  (SIMBAD based on ORBIT)

- Trapped ions: discontinuity of vacuum chamber, clearing electrodes
  (Analytic codes)
Antiproton Accumulation with Barrier Buckets and Stochastic Cooling

Barrier Bucket Cavity to create a **time gap where the new batch is injected**. The gap separates the injected and already accumulated beam in azimuth or time.

Parameters for Beam Stacking

**CR beam:**

- relative momentum spread $5 \times 10^{-4}$ (rms)
- bunch length less than time gap 500 ns
- $10^8$ anti-protons injected into HESR every 10 s

**Kicker & BB parameter:**

- Kicker rise/fall time 50 ns
- Kicker pulse flat top length 500 ns
- Barrier peak voltage 2 kV
- Barrier frequency 5 MHz
Stochastic Cooling System

- Cooling Bandwidth (2 – 4) GHz
- Pickup and Kicker Structures: Circular Slot Type Couplers*
- Aperture 90 mm
- Length per cell 12.5 mm
- 88 pickup cells
- Total length: 1100 mm
- Zero dispersion at pickup and kicker
- Noise temperature pickup plus equivalent amplifier noise: 40 K

Advantages:
- Covers full aperture
- Used as pickup: Longitudinal, horizontal and vertical plane simultaneously
- High sensitivity

- Momentum range 1.5 GeV/c to 15 GeV/c
- Above 3.8 GeV/c: Filter Cooling
- Below 3.8 GeV/c: TOF Cooling
Accumulation with Moving Barriers

- Injection of $10^8$ anti-protons from the CR every 10 s

T. Katayama and H. Stockhorst
Accumulation efficiency reaches 100 % after 1000 s
- Gain must be reduced during accumulation to reduce heating by Schottky noise
- $10^{10}$ antiprotons have been accumulated after 1000 s

The momentum acceptance of the cooling system in the HESR requires a CR beam with momentum spread less than $p/p = 5 \times 10^{-4}$ (rms)

T. Katayama and H. Stockhorst
Closed-Orbit Correction

Assumed errors

| Positioning error of all elements | Gaussian |
| Angle / mrad | $\sigma=0.1$ |
| Position / mm | $\sigma=0.1$ |
| BPM accuracy | Gaussian |
| Resolution | $\sigma=0.1$ |
| Electr. offset / mm | $\sigma=0.1$ |

Goal:
Max. closed-orbit below 5mm
Strength of correction dipoles below 1 mrad

Results (1000 different seeds for positioning errors):
Number of correction dipoles: 36 (48)
Number of BPMs: 64
Closed-orbit (max.): 4.9 mm
Closed-orbit (max. rms): 1.9 mm

Closed orbit bumps: at the injection, cooling devices, and target point, 1 mrad correction strength additionally

Dynamic Aperture

Correction scheme:
24 horizontale + 28 vertikale Sextupoles in arcs

Tune Diagram (2D)

Resonance condition: \( m, n, p \rightarrow m \cdot Q_x + n \cdot Q_y = p \)

1) Skew Sextupole: 2,1,23
2) Octupole: 2,2,31
3) Skew Octupole: 3,1,31
4) Octupole: 4,0,31;
5) 12-pole: 4,2,47
Dynamic Aperture (Design Working Point)

Orbit diffusion coefficient (e.g. after 1000 and 2000 turns):

\[
D = \log_{10} \left[ \sqrt{(Q_x^{(2)} - Q_x^{(1)})^2 + (Q_y^{(2)} - Q_y^{(1)})^2} \right]
\]
Dynamic Aperture (Optimized)

- Optimized working point and compensation of multipoles
- Dynamic Aperture: 16 mm mrad

Orbit diffusion coefficient $D$
Magnet Requirements

• integrierte Multipole components (units of \(10^{-4}\)) on reference radius \(r_0 = 33\) mm over entire field range

**Dipole:** 0.17 T to 1.7 T
• \(|b_3| < 5\)
• \(|b_5| < 1\)

**Quadrupole:** 0 to 20 T/m (25 T/m)
• \(|b_6| < 0.5\)
• \(|b_{10}| < 0.05\)

**Sextupole:** 0 to 45 T/m² (90 T/m²)
• \(|b_9| < 0.2\)
• \(|b_{15}| < 0.01\)

All other multipole components:
\(|b_n| < 0.1\)
Dipole Layout

- Good field region (GFR)

<table>
<thead>
<tr>
<th>Field</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17 T</td>
<td>35 mm</td>
</tr>
<tr>
<td>0.42 T</td>
<td>35 mm</td>
</tr>
<tr>
<td>1.0 T</td>
<td>25 mm</td>
</tr>
<tr>
<td>1.7 T</td>
<td>21 mm</td>
</tr>
</tbody>
</table>

Integral multipole component
- $|b_3| \leq 5$
- $|b_5| \leq 1$
- $|b_n| \leq 0.1$, $n = 2,4,6,7,8,9,10$

- First Design
  Optimization at 1 T $b_3 < 10$ at 1.7 T
- New Design:
  Optimization at injection 0.42 T (3 GeV)
  $b_3 < 3.5$ bei 1.7 T

Number          44
Magnetic length  4.2 m
Deflection angle 8.182°
Max B-field      1.7 T
Min B-field      0.17 T
Aperture         100 mm

Helmut Soltner, FZJ
Quadrupole/Sextupole Layout

<table>
<thead>
<tr>
<th>Gradient [T/m]</th>
<th>GFR [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>40</td>
</tr>
<tr>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>20</td>
<td>21</td>
</tr>
<tr>
<td>25</td>
<td>21</td>
</tr>
</tbody>
</table>

Integral multipole component
• \(|b6| \leq 0.5\)
• \(|b10| \leq 0.05\)

<table>
<thead>
<tr>
<th>Sextupolstärke [T/m²]</th>
<th>GFR [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>12</td>
<td>40</td>
</tr>
<tr>
<td>27</td>
<td>25</td>
</tr>
<tr>
<td>45</td>
<td>21</td>
</tr>
</tbody>
</table>

Integral multipole component
• \(|b9| \leq 0.2\)
• \(|b15| \leq 0.01\)

Helmut Soltner, FZJ
Luminosity Considerations (Full FAIR version)

Antiproton production rate: \(2 \cdot 10^7 / \text{s}\)
Pellet target: \(n_t = 4 \cdot 10^{15} \text{ cm}^{-2}\)
Transverse beam emittance: 1mm.mrad
Longitudinal ring acceptance: \(\Delta p/p = \pm 10^{-3}\)
Betatron amplitude at PANDA: 1m
Circulating antiprotons: \(10^{11}\)

<table>
<thead>
<tr>
<th>Scattering Process</th>
<th>1.5 GeV/c</th>
<th>9 GeV/c</th>
<th>15 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic Interaction</td>
<td>(1.8 \cdot 10^{-4})</td>
<td>(1.2 \cdot 10^{-4})</td>
<td>(1.1 \cdot 10^{-4})</td>
</tr>
<tr>
<td>Single Coulomb</td>
<td>(2.9 \cdot 10^{-4})</td>
<td>(6.8 \cdot 10^{-6})</td>
<td>(2.4 \cdot 10^{-6})</td>
</tr>
<tr>
<td>Energy Straggling</td>
<td>(1.3 \cdot 10^{-4})</td>
<td>(4.1 \cdot 10^{-5})</td>
<td>(2.8 \cdot 10^{-5})</td>
</tr>
<tr>
<td>Touschek (Single IBS)</td>
<td>(4.9 \cdot 10^{-5})</td>
<td>(2.3 \cdot 10^{-7})</td>
<td>(4.9 \cdot 10^{-8})</td>
</tr>
<tr>
<td>Total relative loss rate</td>
<td>(6.5 \cdot 10^{-4})</td>
<td>(1.7 \cdot 10^{-4})</td>
<td>(1.4 \cdot 10^{-4})</td>
</tr>
<tr>
<td>(1/e\ Beam lifetime / s)</td>
<td>(~ 1540)</td>
<td>(~ 6000)</td>
<td>(~ 7100)</td>
</tr>
</tbody>
</table>

Cycle averaged luminosity
- Momentum 1.5 GeV/c: \(0.3 – 0.7 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}\)
- Momentum: 15 GeV/c: \(1.5 – 1.6 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}\)

(Production rate: \(1 – 2 \cdot 10^7 / \text{s}\))

A. Lehrach et al., NIMA 561 (2006)
O. Boine-Frankenheim et al., 560 (2006)
F. Hinterberger, Jül-4206 (2006)
Cycle Averaged Luminosity (Full FAIR version)

Cycle averaged luminosity
- Production rate $1 \cdot 10^7$ /s (1.5 – 15 GeV/c): $0.34 \cdot 1.5 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$
- Production rate $2 \cdot 10^7$ /s (1.5 – 15 GeV/c): $0.67 \cdot 1.6 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$

$\bar{L} = L_0 \frac{\tau [1 - e^{-\frac{t_{exp}}{\tau}}]}{t_{exp} + t_{prep}}$

$L_0 = n_p n_t f_{rev}, n_p = 10^{11}$

A. Lehrach et al., NIMA 561 (2006)
Cooled Beam Equilibria

Beam cooling, beam-target interactions, intra-beam scattering

rms relative momentum spread $\sigma_p/p$

Electron cooled beams

- **HR mode:** $7.9 \cdot 10^{-6}$ (1.5 GeV/c) to $2.7 \cdot 10^{-5}$ (8.9 GeV/c), and $1 \cdot 10^{-4}$ (15 GeV/c)
- **HL mode:** $<10^{-4}$

Stochastic cooled beams

- **HR mode:** $5.1 \cdot 10^{-5}$ (3.8 GeV/c), $5.4 \cdot 10^{-5}$ (8.9 GeV/c), and $3.9 \cdot 10^{-5}$ (15 GeV/c)
- **HL mode:** $\sim 10^{-4}$

Transverse stochastic cooling can be adjusted independently


Expected Pressure Distribution and Neutralization Factor

The mean time for residual gas ions in the antiproton beam $T_c$ (clearing time) in relation to the time of ion production $T_p$:

$$\eta = \frac{T_c}{T_p}$$

Average distance of clearing electrodes of 10 m, with a clearing voltage of 200 V.

→ Emittance Growth
→ Incoherent Tune Shift
→ Beam Instabilities
Coherent Beam Instabilities

Resonance frequencies: \((8 - Q_x) = 0.4005\) and \((8 - Q_y) = 0.3784\), \((9 - Q_x) = 1.4005\) and \((9 - Q_y) = 1.3784\)

Bounce frequencies of transverse \(H^+_2\) ion oscillations represented as tune numbers \(q_{x,y}\)

Estimates for beam instabilities

Measures for Trapped Ions

• Trapped Ions may cause full neutralization within $\leq 7$ s.
• Discrete Clearing Electrodes every 10 m and near potential minima.
• Continuous Clearing Electrodes near PANDA target.
• PANDA Solenoid suppresses transverse coherent oscillations
  Note: The ions can be extracted in the longitudinal direction.
• Vacuum $10^{-10}$ mbar
• Beakout system prepared
• Cluster-jet target
• Resonant beam shaking, feed-back system
Summary / Outlook

- Beam injection and accumulation
  up to $10^{10}$ particles in 1000s with promised CR beam parameter

- Closed orbit correction:
  steering concept completed

- Dynamic aperture:
  chromaticity correction and dynamic aperture calculations completed

- Luminosity estimates:
  studies finished, sufficient antiproton production rate needed for low momenta

- Beam equilibrium:
  experimental requirements can be fulfilled with electron and stochastic cooling

- Longitudinal impedance:
  moderate for $\Delta p/p < 4 \cdot 10^{-5}$ and $10^{11}$ particles

- Trapped ions:
  Beam instabilities, strip electrodes in PANDA region, report available