Beam-Dynamics Simulation for the High-Energy Storage Ring

A. Lehrach, FZ Jülich

Introduction

FAIR Layout
HESR Reference Design

Beam Dynamics Studies
Closed-Orbit Correction
Beam Equilibria
Luminosity Considerations
Impedances

Conclusion / Outlook

HESR-Consortium: FZJ, GSI, TSL, and Univ. of Bonn and Dortmund
Antiproton production

Linac: 50 MeV protons
SIS18: $5 \times 10^{12}$ protons / cycle
SIS100: $2-2.5 \times 10^{13}$ protons / cycle
26 GeV protons
bunch compressed to 50nsec

Production target: antiprotons
3% momentum spread

CR: bunch rotation and stochastic cooling at 3.8 GeV/c
RESR: accumulation at 3.8 GeV/c

Production rate: $2 \times 10^7$/s ($7 \times 10^{10}$/h)
High-Energy Storage Ring (HESR)

Momentum: 1.5 – 15 GeV/c
Arcs: 6-fold symmetry, with dispersion suppression and imaginary gamma transition
Straights: Cooler and target section
Ring circumference: 574 m.
## Experimental Requirements

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

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

<table>
<thead>
<tr>
<th></th>
<th>“High Resolution Mode”</th>
<th>“High Luminosity Mode”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum range</td>
<td>Up to 8.9 GeV/c</td>
<td>Full momentum range</td>
</tr>
<tr>
<td>Number of circulating particles</td>
<td>$10^{10}$</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td>Target thickness (Hydrogen Pellets)</td>
<td>$4 \cdot 10^{15}$ cm$^{-2}$</td>
<td>$4 \cdot 10^{15}$ cm$^{-2}$</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$2 \cdot 10^{31}$ cm$^{-2}$s$^{-1}$</td>
<td>$2 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Beam emittance (rms, norm.)</td>
<td>1 mm mrad</td>
<td>1 mm mrad</td>
</tr>
<tr>
<td>Momentum resolution</td>
<td>$\Delta p/p_{\text{rms}} = 10^{-5}$</td>
<td>$\Delta p/p_{\text{rms}} = 10^{-4}$</td>
</tr>
<tr>
<td>Beam Cooling</td>
<td>Electron Cooling (8.9 GeV/c)</td>
<td>Stochastic Cooling (&gt;3.8 GeV/c)</td>
</tr>
</tbody>
</table>
Beam Dynamics Issues

- **RF requirements**
  - injection scheme, acceleration, clearing gap → RF requirements (ORBIT)

- **Closed-orbit correction**
  - positioning errors of magnets → steering concept (MAD-X)

- **Dynamic aperture**
  - field quality of magnets → multipole corrector concept
  - effect of the electron beam and other non-linear fields (MAD-X, PTC(?))

- **Beam-cooling / beam-target interaction / intrabeam scattering**
  - beam heating → beam cooling
    - (BetaCool, MOCAC, PTARGET, Analytic code)

- **Beam losses at internal targets / luminosity estimations**
  - particle losses → ring acceptance
  - cycle description → average luminosity
    - (Analytic formulas)

- **Impedance**
  - RF cavities, kicker / pick-ups → low impedance design, feedback
    - (SIMBAD based on ORBIT)
Closed-Orbit Correction

10 closed-orbits

Positioning error  |  Gaussian | Uniform
--- | --- | ---
Angle / mrad  | 0.55 | 1.1
Position / mm  | 0.5 | 1.0
BPM accuracy  | Gaussian
Scaling  | 0.1
Offset / mm  | 0.1

Gaussian distribution truncated at 2.5 σ

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

Method: Ideal orbit response matrix

Normal: \( S = R \cdot \Theta \)
Inverted: \( \Theta = R^{-1} \cdot S \)

\[
R_{kb} = \frac{\cos(\frac{\mu}{2} - \phi_{bk})}{2 \sin \frac{\mu}{2} \sqrt{\beta_b \beta_k}}
\]
Closed-Orbit Correction

Simple Concept: BPM and correcting dipole near each quadrupole
⇒ 108 correction dipoles and BPMs

Results: 24 uni-directional correction dipole per plan in arcs = 48
8 bi-directional ones in straights

About 100 corrected closed-orbits for each case

<table>
<thead>
<tr>
<th>32 BPMs per arc</th>
<th>24 BPMs per arc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max: Gaussian: 2.91 mm</td>
<td>Gaussian: 7.15 mm</td>
</tr>
<tr>
<td>Max: Uniform: 3.38 mm</td>
<td>Uniform: 6.65 mm</td>
</tr>
<tr>
<td>Mean: Gaussian: (2.37 ± 0.46) mm</td>
<td>Mean: Gaussian: (5.59 ± 1.22) mm</td>
</tr>
<tr>
<td>Mean: Uniform: (2.70 ± 0.43) mm</td>
<td>Mean: Uniform: (5.74 ± 0.63) mm</td>
</tr>
<tr>
<td>Max: Gaussian: 4.67 mm</td>
<td>Max: Gaussian: 5.96 mm</td>
</tr>
<tr>
<td>Max: Uniform: 5.48 mm</td>
<td>Max: Uniform: 7.27 mm</td>
</tr>
<tr>
<td>Mean: Gaussian: (3.36 ± 0.77) mm</td>
<td>Mean: Gaussian: (4.88 ± 1.04) mm</td>
</tr>
<tr>
<td>Mean: Uniform: (3.72 ± 0.83) mm</td>
<td>Mean: Uniform: (5.23 ± 0.99) mm</td>
</tr>
<tr>
<td>Max: Gaussian: (0.93 ± 0.09) mm</td>
<td>Max: Gaussian: (1.07 ± 0.14) mm</td>
</tr>
<tr>
<td>Max: Uniform: (1.06 ± 0.10) mm</td>
<td>Max: Uniform: (1.34 ± 0.16) mm</td>
</tr>
<tr>
<td>Mean: Gaussian: (1.08 ± 0.18) mm</td>
<td>Mean: Gaussian: (1.26 mm)</td>
</tr>
<tr>
<td>Mean: Uniform: (1.17 mm)</td>
<td>Mean: Uniform: (1.38 mm)</td>
</tr>
<tr>
<td>Mean: Gaussian: (0.87 ± 0.16) mm</td>
<td>Mean: Gaussian: (1.01 ± 0.20) mm</td>
</tr>
<tr>
<td>Mean: Uniform: (0.96 ± 0.16) mm</td>
<td>Mean: Uniform: (1.11 ± 0.17) mm</td>
</tr>
</tbody>
</table>

- Closed orbit bumps at the injection, cooling devices, and target point: 1 mrad correction strength additionally
- Closed orbit correction at electron cooler: 29 mrad at injection energy
- Investigation of failed BPMs

Courtesy: D.M. Welsch (FZ Jülich)
INTAS Project
Advanced Beam Dynamics in Storage Rings

Tasks:
- Physics models for beam cooling equilibria
- Development and benchmarking of simulation tools
- Instabilities and impedances
- Trapped particle studies
- Experiments at (CELSIUS), COSY and ESR
- Full HESR/NESR simulations

Participating institutes (team leaders):
- GSI Darmstadt (O. Boine-F.)
- FZ Jülich (A. Lehrach)
- ITEP Moscow (P. Zenkevich)
- JINR Dubna (I.N. Meshkov)
- Univ. Kiev (I. Kadenko)
- TSL Uppsala (V. Ziemann)
- TU Darmstadt (Th. Weiland)

Workshops and reports

Workshops:
I. General project meeting meetings, Kiev: 28.5.2004 - 29.5.2004
Meeting on Beam-target interaction, Uppsala 29.6.2004
II. General project meeting meetings, Dubna: 24.3.2005 - 25.3.2005
Meeting on internal target effects: Darmstadt, 3.6.2005
III. General project meeting meetings, Jülich, 20.10.2005 - 21.10.2005

Final report + several papers

Project duration: April 2004 to March 2006
Pellet target

- HESR: Target will be switched on after injection and cooling/IBS equilibrium
- Transverse heating is required to ensure 1 mm spot size on the target

Formation of frozen hydrogen pellets

Pellet speed 60 m/s

\( H_2 (\rho = 0.08 \text{ g/cm}^3) \)

20000 pellets/s

\( d = 30-50 \mu \text{m} \)

\( <n> = 4 \times 10^{15} \text{ cm}^{-2} \)
Electron Cooling Force

Parkhomchuk model (*particle frame):

\[ F^* (\vec{v}^*) = -KL_C \frac{\vec{v}^*}{((\vec{v}^*)^2 + (v_{eff}^*)^2)^{3/2}} \]

Effective Coulomb log:

\[ L_C = \ln \left( \frac{b_\perp + \rho_{max}}{b_\perp} \right) \approx 10 \]

Cooling rate:

\[ \tau_0^{-1} = \frac{4\pi Z^2 r_p r_e n_e c \eta_c L_e}{A \gamma_0^2} \frac{c^3}{(v_{eff}^*)^3} \]

Longitudinal force (momentum spread \( \delta \)):

\[ F_{\parallel}^e = \tau_0^{-1} \delta \frac{\delta_{eff}^3}{(\delta_{eff}^2 - \delta^2)^{3/2}} \]

Measurements at CELSIUS indicates an accuracy of the longitudinal Parkhomchuk force within a factor of 2
Electron Cooling

Electron Cooler:
- \( L = 30 \text{ m} \)
- \( I_e = 0.2 \text{ A} \)
- \( v_{\text{eff}} = 2\cdot10^4 \text{ m/s} \)
- \( \beta_c = 100 \text{ m} \)

Beam:
- \( 10^{10} \) particles
- Target:
  - Pellet Stream
  - \( d_t = 4\cdot10^{15} \text{ cm}^{-2} \)
  - \( \beta_t = 1 \text{ m} \)

Equilibrium beam parameters

Results agree very well with BetaCool simulations

Fixed transverse emittance

Beam-target overlap has to be further studied!

O. Boine-Frankenheim et al., NIMA 560 (2006)
Based on the Fokker-Planck equation the beam equilibria are:

Transverse cooling:

\[ \varepsilon_{eq,rms} = \frac{1}{4\sqrt{2\pi}} \frac{N f_0^2 \beta_t}{|\eta| \delta_{rms} W f_c} \theta_{loss}^2 \]

Longitudinal cooling

\[ \delta_{eq,rms} = \frac{4}{5} \left( \frac{3}{32} \frac{N f_0^2}{|\eta| W f_c} \delta_{loss}^2 \right)^{1/3} \]

\[ \eta = 1 / \gamma^2 - 1 / \gamma_{tr}^2 \]

Stochastic Cooler:

W = 2-4 GHz
quarter-wave loop pickups and kickers
notch-filter cooling
\[ \gamma_{tr} = 6.5i \]
above 3.8 GeV/c

Target:
Pellet Stream
\[ d_i = 4 \cdot 10^{15} \text{ cm}^{-2} \]
\[ \beta_t = 1 \text{ m} \]

Transverse cooling can be applied independently!

Courtesy: H. Stockhorst (FZ Jülich)
Production Rate and Maximum Luminosity

Antiproton production rate:

\[ \dot{N}_{\bar{p}} = 2 \cdot 10^7 / s \]

\[ \Rightarrow \] Maximum luminosity:

\[ L_{\text{max}} = \frac{\dot{N}_{\bar{p}}}{\sigma_{\text{total}}} \]

\[ \sigma_{\text{tot}} = 100 \text{ to } 50 \text{ mbarn} : \text{total hadronic cross section} \]

\[ \Rightarrow L_{\text{max}} = 2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1} \]

Relative particle loss rate:

\[ (\tau_{\text{loss}}^{-1}) = f_{\text{rev}} n_t \sigma_{\text{total}} \]

At low energies: Single Coulomb scattering at target out of the ring transverse acceptance
Energy straggling at target out of the longitudinal ring acceptance
Single IBS scattering (Touschek loss rate) for small beam emittance

PDG: http://pdg.lbl.gov/xsect/contents.html
Beam Loss Rates

- Hadronic Interaction

\[(\tau_{loss})_H^t = f_{rev} n_t \sigma_{pp}^{\text{total}}\]

- Single Coulomb scattering out of the acceptance

\[(\tau_{loss,\perp})_C^t = f_{rev} \frac{4\pi Z_i^2 Z_f^2 r_i^2 n_t}{\beta_0^4 \gamma_0^2 \theta_{eff}^2}, \theta_{eff} = \sqrt{\frac{\varepsilon_i}{\beta_t}}\]

- Energy straggling out of the acceptance

\[(\tau_{loss,\parallel})_S^t = f_{rev} \int_{\varepsilon_{eff}}^{\varepsilon_{max}} w(\varepsilon) d\varepsilon = f_{rev} \varepsilon_{max} \left\{ \frac{1}{\varepsilon_{eff}} - \frac{1}{\varepsilon_{max}} - \frac{\beta_0^2}{\varepsilon_{max}} \ln \frac{\varepsilon_{max}}{\varepsilon_{eff}} \right\}\]

- Single IBS scattering (Touschek loss rate)

\[(\tau_{loss})_{IBS}^t = \frac{1}{T_0} \frac{D_{IBS}^\parallel}{L_C \delta_{eff}^2}, D_{IBS}^\parallel = \frac{\Lambda_{IBS}^\parallel}{\varepsilon_{\perp}^{3/2}}\]

\[\varepsilon_t = 1 \text{ mm mrad}, \delta_{eff} = -\varepsilon_{eff}/(\beta_0^2 E_\theta) = 10^{-3}\]
### Luminosity Considerations

**Example:** Pellet target: \( n_t = 4 \cdot 10^{15} \text{ cm}^{-2} \)

Total hadronic cross section (1.5, 9, 15 GeV/c) : \( \sigma = 100, 60, 50 \text{ mbarn} \)

Revolution frequency: \( f_c = 443, 519, 521 \text{ kHz} \)

<table>
<thead>
<tr>
<th>Scattering Process</th>
<th>( 1.5 \text{ GeV/c} )</th>
<th>( 9 \text{ GeV/c} )</th>
<th>( 15 \text{ 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 (( \varepsilon = 1 \text{ mm mrad} ))</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 (( \Delta p_{\text{max}}/p = \pm 10^{-3} ))</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 (( \varepsilon = 1 \text{ mm mrad} ))</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 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>( \sim 1540 )</td>
<td>( \sim 6000 )</td>
<td>( \sim 7100 )</td>
</tr>
<tr>
<td>Maximum Luminosity / ( 10^{32} \text{ cm}^{-2} \text{s}^{-1} )</td>
<td>( 0.82 )</td>
<td>( 3.22 )</td>
<td>( 3.93 )</td>
</tr>
</tbody>
</table>

O. Boine-Frankenheim et al., NIMA 560 (2006)
A. Lehrach et al., NIMA 561 (2006)
F. Hinterberger, Jül-4206 (2006)
Average Luminosity

\[ L = L_0 \frac{\tau}{t_{\text{exp}} + t_{\text{prep}}} \]

where:
- \( L_0 \): initial luminosity
- \( \tau \): beam lifetime
- \( t_{\text{exp}} \): experimental time
- \( t_{\text{prep}} \): beam preparation time
- \( n_p \): number of particle
- \( n_t \): target density
- \( f_{\text{rev}} \): revolution frequency

HESR Nominal Cycle

for different cycle times (beam preparation time + experimental time)!
**Longitudinal Impedance**

10000 macros, $10^{11}$ particle charges, 128 long. bins, initial long. distribution: 360°, $\Delta p/p = 10^{-3}$ to $10^{-6}$ (rms)

\[ Z_n = \sqrt{\text{Re}(Z_n)^2 + \text{Im}(Z_n)^2} \]
\[ \chi_n = \arctan \frac{\text{Im}(Z_n)}{\text{Re}(Z_n)} \]

Energy kick on the i-th macro:

\[ \delta(\Delta E)^{Li}_i = I_n |Z_n| \cos(\phi_i + \phi_n + \chi_n), \Delta E = E_i - E_s \]
Super Computer JUMP

Parameter IBM p690-Clusters Jump, FZ Jülich

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>41</td>
</tr>
<tr>
<td>Processors per node</td>
<td>32</td>
</tr>
<tr>
<td>Processors total</td>
<td>1312</td>
</tr>
<tr>
<td>Overall Peak Performance</td>
<td>8.9 TFLOPS</td>
</tr>
<tr>
<td>Memory per node</td>
<td>128 GByte</td>
</tr>
<tr>
<td>Total memory</td>
<td>5 TByte</td>
</tr>
<tr>
<td>Storage capacity</td>
<td>50 TByte</td>
</tr>
<tr>
<td>Operating system</td>
<td>AIX 5.1</td>
</tr>
<tr>
<td>Users</td>
<td>ca. 450</td>
</tr>
</tbody>
</table>

4 CPU hours on 2 nodes (32 processors per node), full 3D simulation:

1000000 macros $\rightarrow$ 3740 turns
10000 macros $\rightarrow$ 36900 turns
1000 macros $\rightarrow$ 364000 turns

$\rightarrow$ Study 3D long term stability with many macro particles
Summary & Outlook

- **RF gymnastics:**
  system parameter determined, beam losses studies to be done

- **Closed orbit correction:**
  steering concept finished

- **Dynamic aperture:**
  calculated field maps for HESR magnets and non-linear field of electron cooler beam used soon

- **Beam equilibrium calculations:**
  different codes available and utilized for electron and stochastic cooling

- **Beam losses and cycle description:**
  studies finished, sufficient antiproton production rate needed
  especially low momenta
  ring acceptance should be increased (curved magnets)

- **Longitudinal impedance**
  $\frac{\Delta p}{p} > 3 \cdot 10^{-5}$ seems possible for long. impedance in the range of $100 \Omega$!

⇒ **Main tool for beam dynamics studies:** MAD-X, Different Codes for Beam Cooling
Design Study EU-FP6: DIRAC Secondary Beams
HESR4: Beam Dynamics and Collective Effects

- **Task 1:** Detailed beam accumulation studies
  - barrier bucket manipulations
- **Task 2:** Beam cooling and kinetic equilibrium
  - Code benchmarking
  - 3D beam distribution in the HESR
- **Task 3:** Collective instabilities and impedances
  - Accurate impedance budgets
  - Impedance calculations and models

**Partners:**
- GSI Darmstadt
  - High current beam physics group
  - Contact: O. Boine-Frankenheim
- FZ Jülich
  - IKP, COSY group
  - Contact: A. Lehrach
- Uppsala University, Sweden
  - The Svedberg Laboratory
  - Contact: V. Ziemann

**Results and achievements**

- Employment: Aug. ‘05 Scientist for HESR beam dynamics simulations hired at GSI.
- Publications: Analysis of the HESR luminosities using realistic machine cycles.
  - Kinetic study of longitudinal beam cooling equilibrium and beam loss
- Ongoing studies: 3D kinetic studies (beam cooling equilibrium and beam loss); beam stability and impedance budget

**Project duration: 2005 to 2008**