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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

Facility for Antiproton and Ion Research (FAIR)

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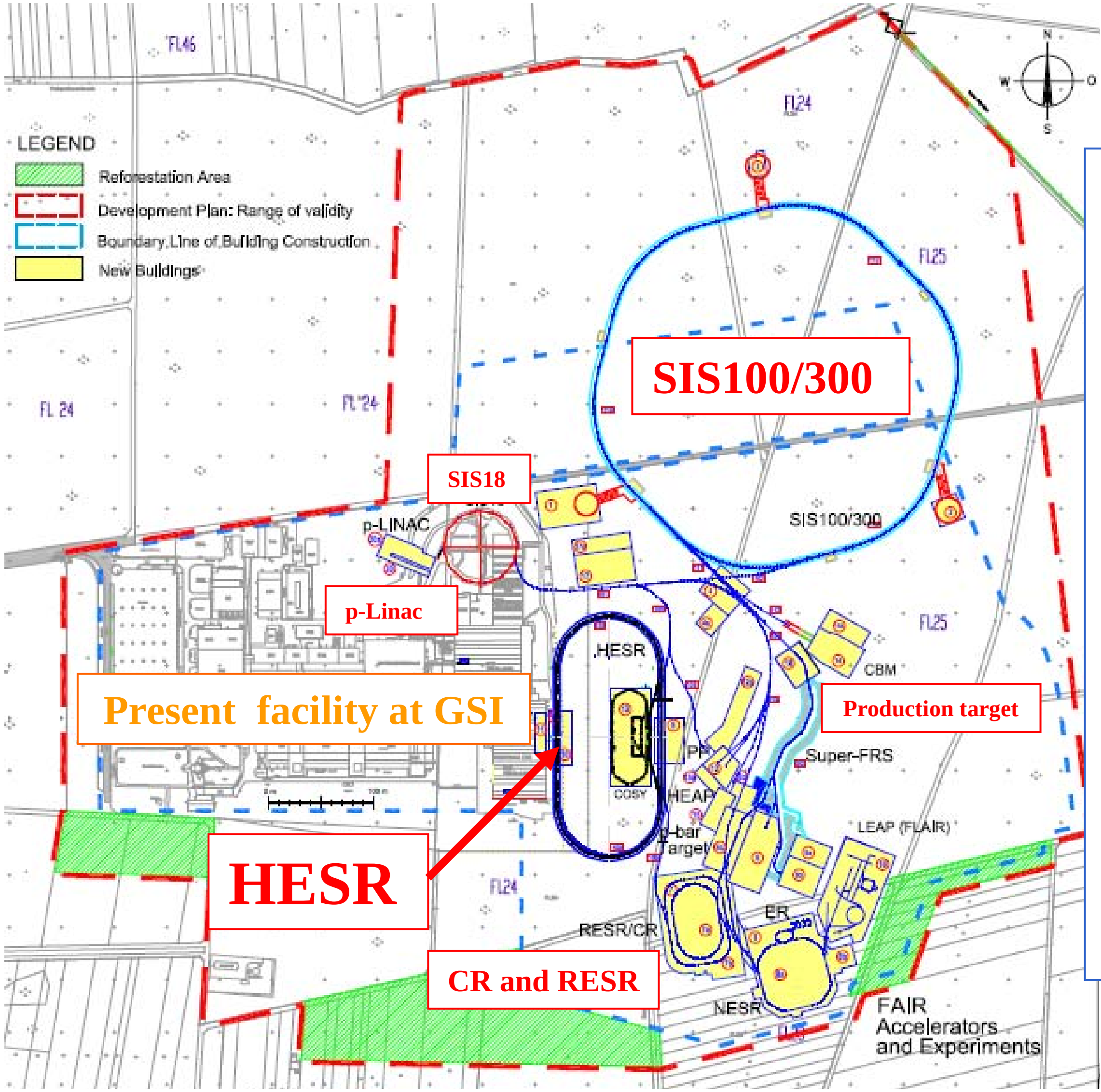
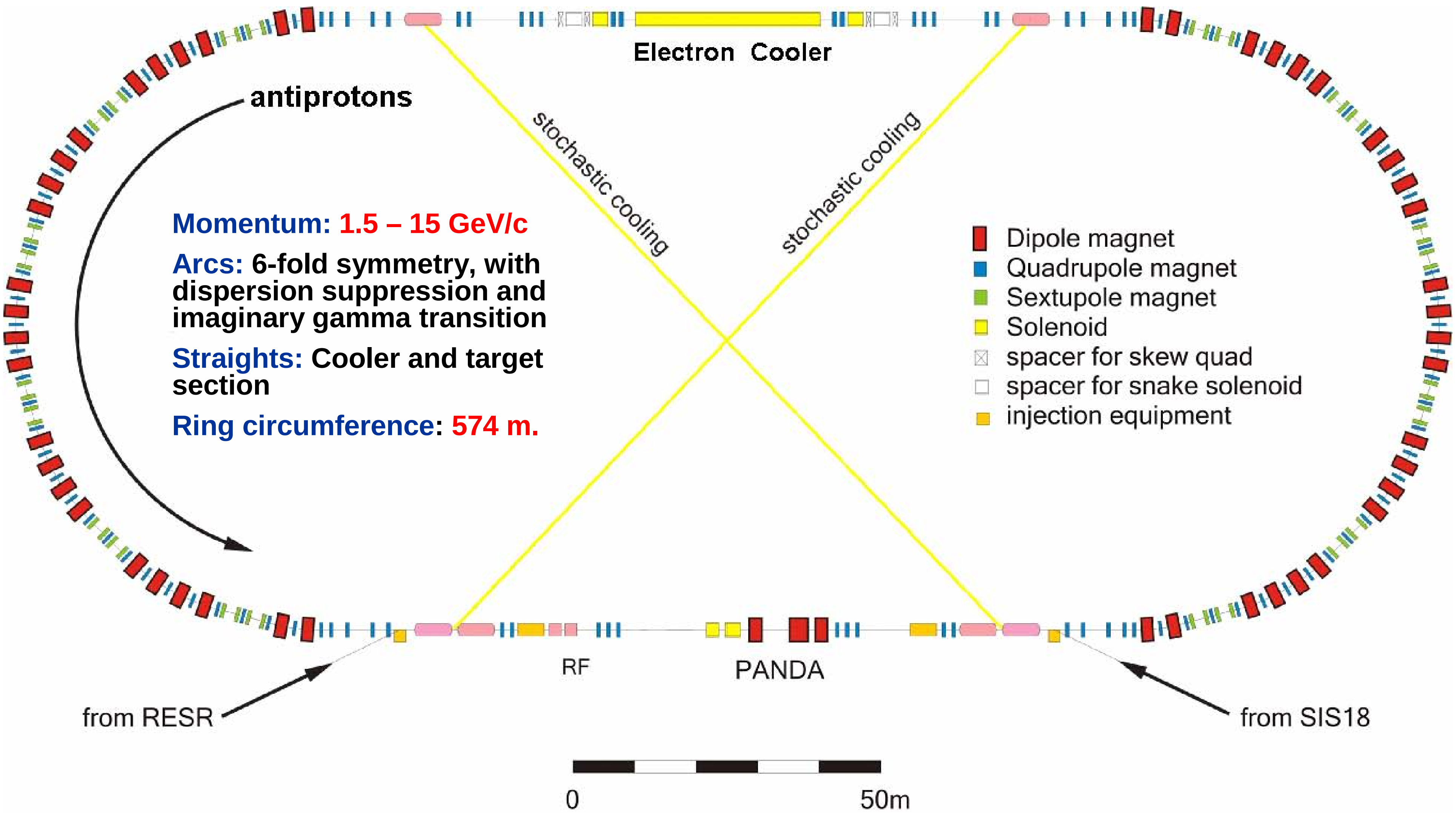


Antiproton production

- **Linac:** 50 MeV protons
- **SIS18:** $5\cdot10^{12}$ protons / cycle
- **SIS100:** $2\text{-}2.5\cdot10^{13}$ 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

$\overline{p}$ **production rate: $2\cdot10^{7}$/s ($7\cdot10^{10}$/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

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PANDA (Strong Interaction Studies with Antiprotons):

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

	"High Resolution Mode"	"High Luminosity Mode"
Momentum range	Up to 8.9 GeV/c	Full momentum range
Number of circulating particles	10^{10}	10^{11}
Target thickness (Hydrogen Pellets)	$4 \cdot 10^{15}$ cm^{-2}	$4 \cdot 10^{15}$ cm^{-2}
Peak luminosity	$2 \cdot 10^{31}$ cm^{-2}s^{-1}	$2 \cdot 10^{32}$ cm^{-2}s^{-1}
Beam emittance (rms, norm.)	1 mm mrad	1 mm mrad
Momentum resolution	$\Delta p/p_{rms} = 10^{-5}$	$\Delta p/p_{rms} = 10^{-4}$
Beam Cooling	Electron Cooling (8.9 GeV/c)	Stochastic Cooling (>3.8 GeV/c)

Beam Dynamics Issues

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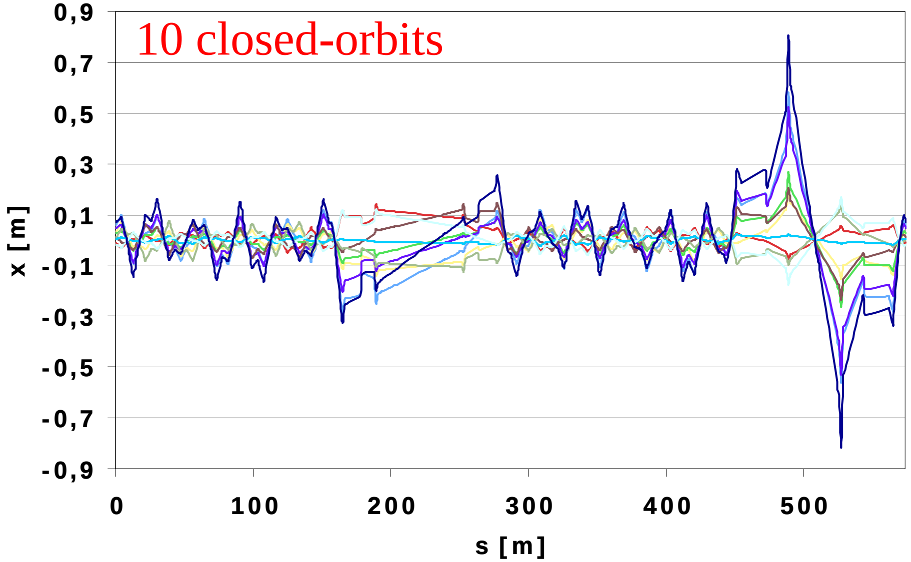
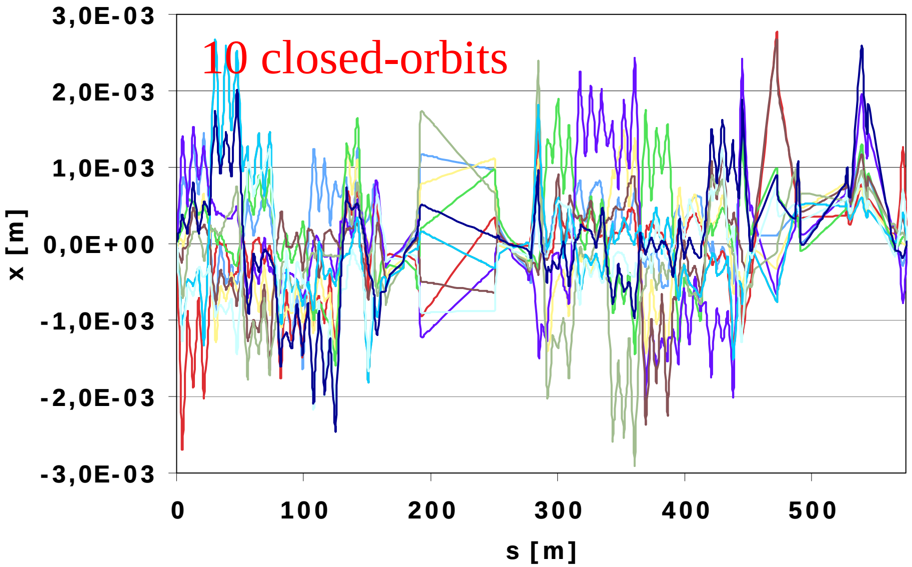
- **RF requirements**
  injection scheme, acceleration, clearing gap → RF requirements
  (ORBIT)
- **Closed-orbit correction**
  positioning errors of magnets → steering concept
  (MAD-X)
- **Dynamic aperture**
  field quality of magnets → multipole corrector concept
  effect of the electron beam and 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





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

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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
} **56**

About 100 corrected closed-orbits for each case

		32 BPMs per arc		24 BPMs per arc	
		Gaussian	**Uniform**	**Gaussian**	**Uniform**
X	**Max:**	2.91 mm	3.38 mm	7.15 mm	6.65 mm
	Mean:	(2.37 ± 0.46) mm	(2.70 ± 0.43) mm	(5.59 ± 1.22) mm	(5.74 ± 0.63) mm
Y	**Max:**	4.67 mm	5.48 mm	5.96 mm	7.27 mm
	Mean:	(3.36 ± 0.77) mm	(3.72 ± 0.83) mm	(4.88 ± 1.04) mm	(5.23 ± 0.99) mm
X (RMS)	**Max:**	0.93 mm	1.06 mm	1.38 mm	1.63 mm
	Mean:	(0.73 ± 0.09) mm	(0.88 ± 0.10) mm	(1.07 ± 0.14) mm	(1.34 ± 0.16) mm
Y (RMS)	**Max:**	1.08 mm	1.17 mm	1.26 mm	1.38 mm
	Mean:	(0.87 ± 0.18) mm	(0.96 ± 0.16) mm	(1.01 ± 0.20) mm	(1.11 ± 0.17) mm

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

Courtesy: D.M. Welsch (FZ Jülich)

INTAS Project
Advanced Beam Dynamics in Storage Rings

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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

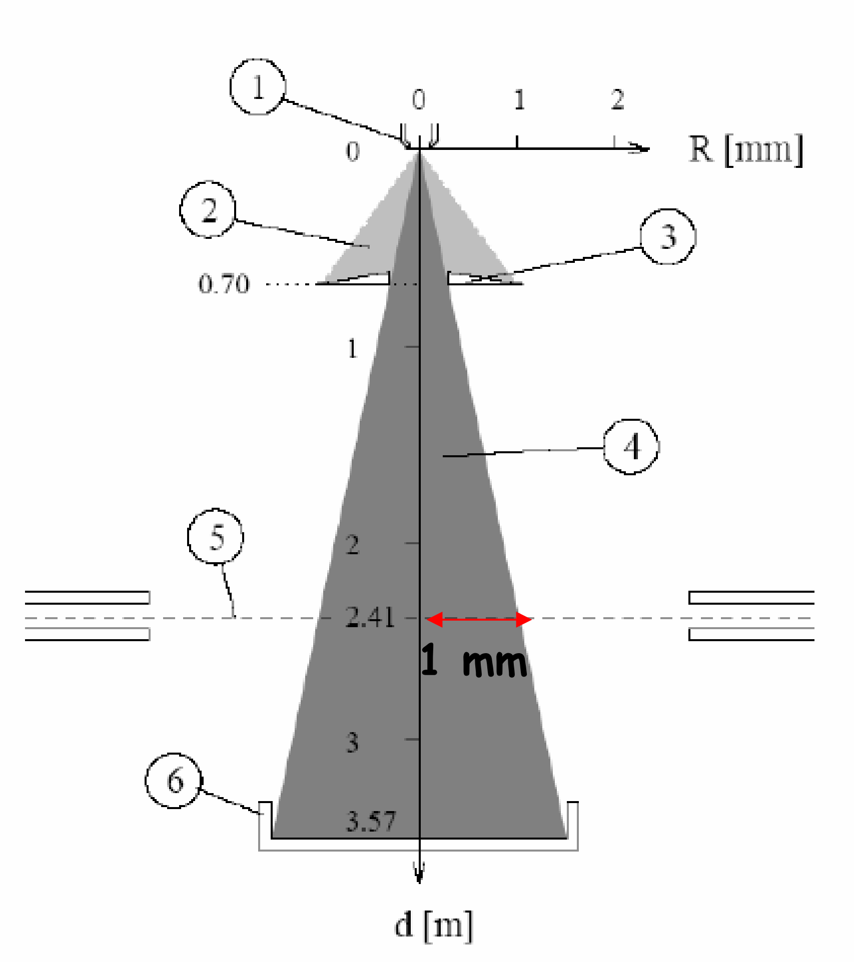
Workshops:

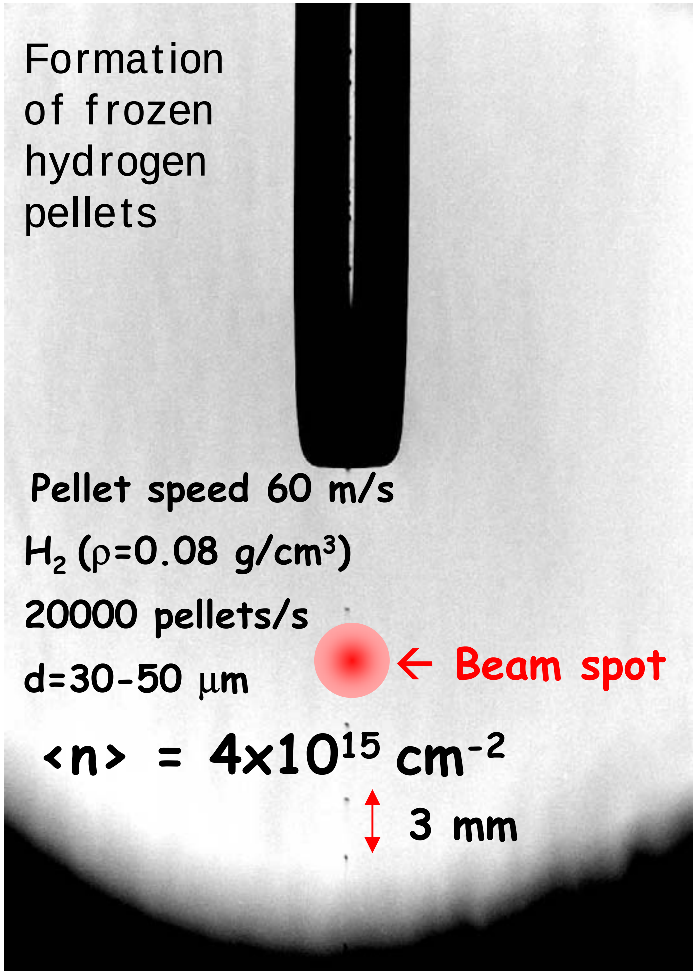
I. General project meeting meetings, Kiev: 28.5.2004 - 29.5.2004
Meeting on Beam-target interaction, Uppsala 29.6.2004
II. General project meeting meetings, Dubna: 24.3.2005 - 25.3.2005
Meeting on internal target effects: Darmstadt, 3.6.2005
III. General project meeting meetings, Jülich, 20.10.2005 -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

Electron Cooling Force

Parkhomchuk model (*particle frame):

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

Effective Coulomb log:

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

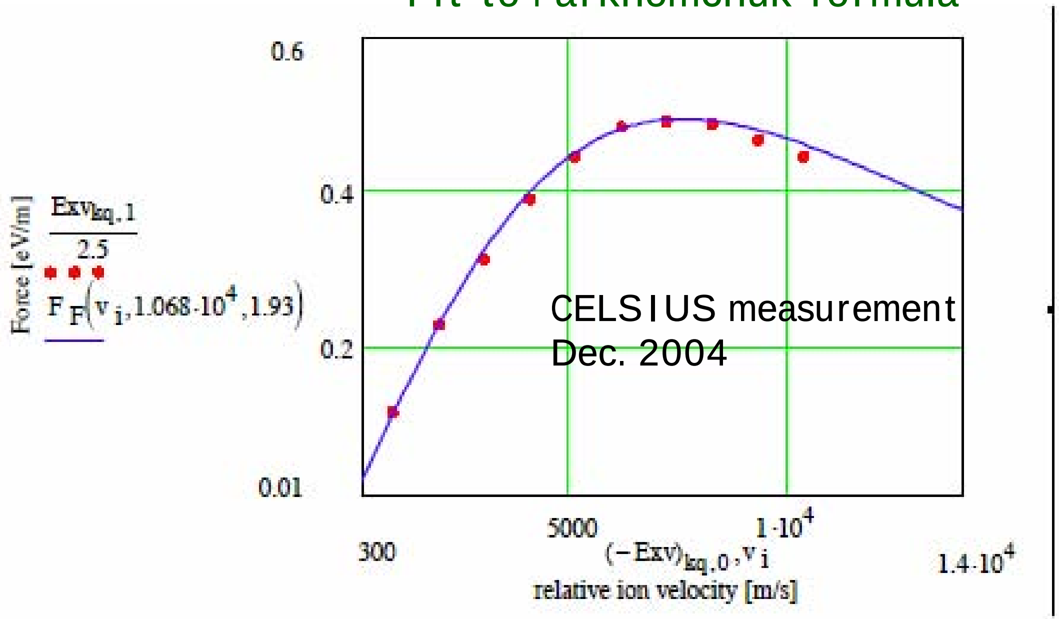
Cooling rate:

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

Longitudinal force (momentum spread δ):

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

Fit to Parkhomchuk formula



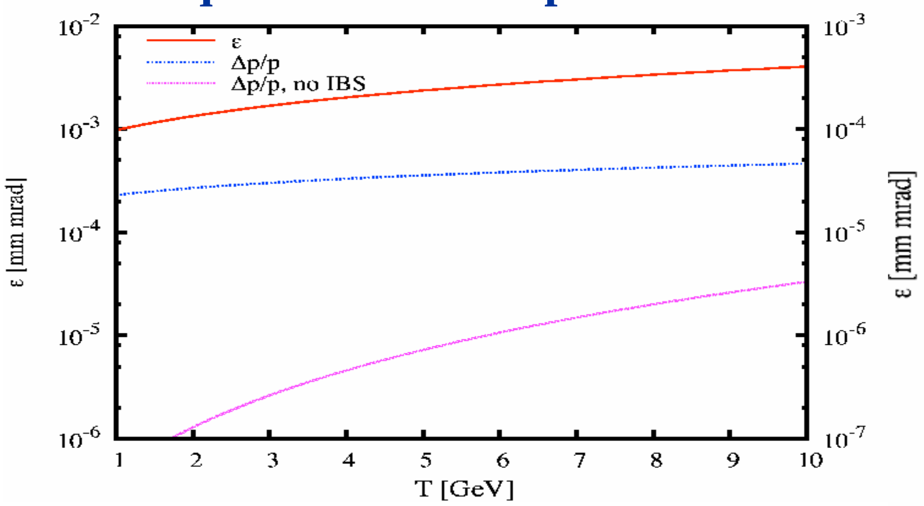
$$v_{eff}^* \approx 10^4 \text{ m/s}$$

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

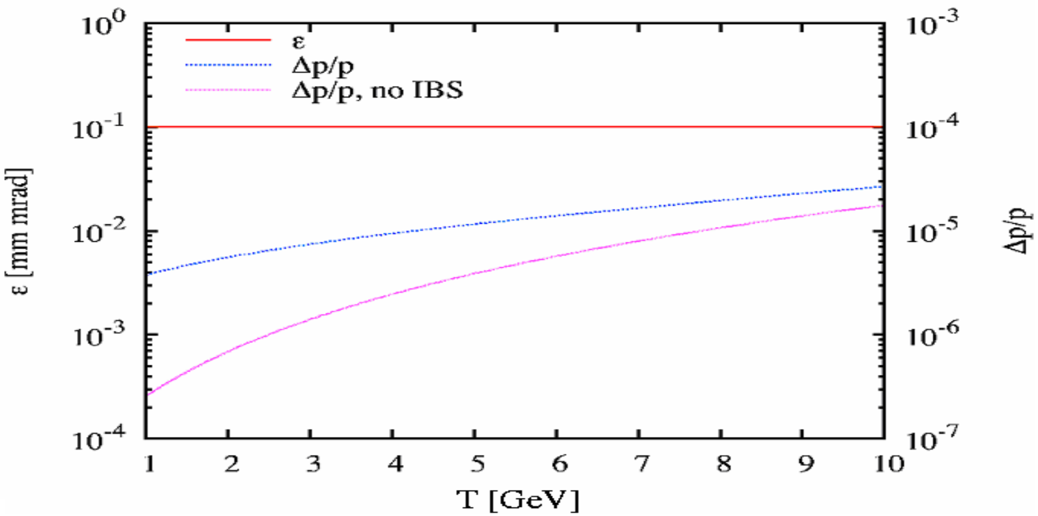
Electron Cooling

Results agree very well
with BetaCool simulations

Equilibrium beam parameters



Fixed transverse emittance



Electron Cooler:
L = 30 m
I_e = 0.2 A
$v_{eff} = 2 \cdot 10^4$ m/s
β_c = 100 m

Beam:
10^{10} particles
Target:
Pellet Stream
$d_t = 4 \cdot 10^{15}$ cm^{-2}
β_t = 1 m

Beam-target overlap has
to be further studied!

O. Boine-Frankenheim et al., NIMA 560 (2006)

Stochastic Cooling

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Based on the Fokker-Planck equation the beam equilibria are:

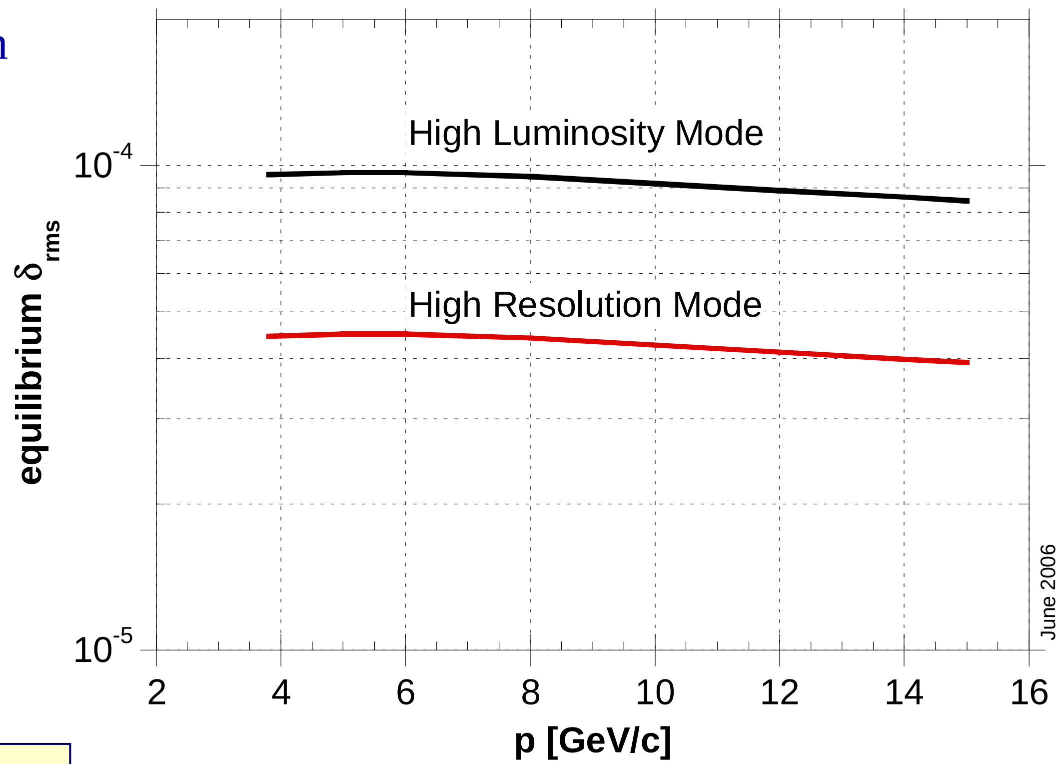
Transverse cooling:

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

Longitudinal cooling

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

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



Stochastic Cooler:
W = 2-4 GHZ
quarter-wave loop pickups and kickers
notch-filter cooling
γ_{tr}=6.5i
above 3.8 GeV/c

Target:
Pellet Stream
$d_t = 4\cdot10^{15}$ cm^{-2}
β_t = 1 m

Transverse cooling can be applied independently!

Courtesy: H. Stockhorst (FZ Jülich)

Production Rate and Maximum Luminosity

Antiproton production rate:

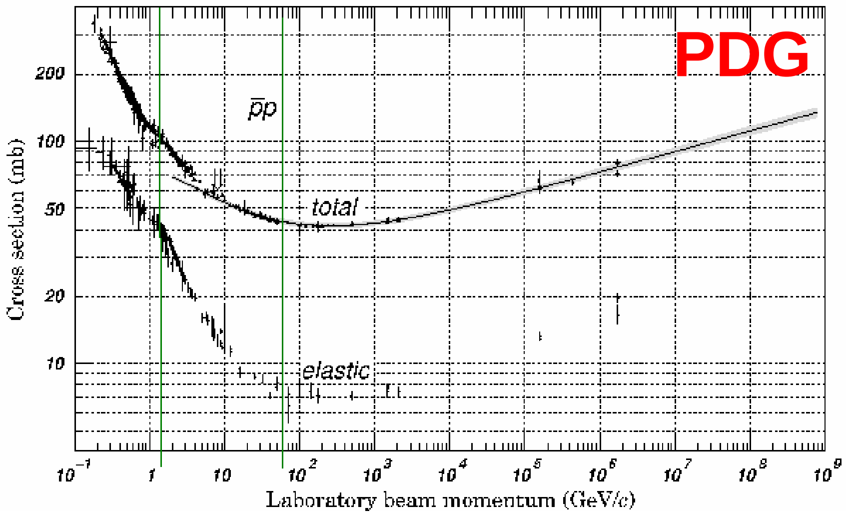
$$\dot{N}_{\bar{p}} = 2 \cdot 10^7 / s$$

→ Maximum luminosity:

$$L_{max} = \frac{\dot{N}_{\bar{p}}}{\sigma_{total}}$$

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

$\Rightarrow L_{max} = 2 \text{ to } 5 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$



Cross section for $p - \bar{p}$ collisions

http://pdg.lbl.gov/xsect/contents.html

Relative particle loss rate: $(\tau_{loss}^{-1}) = f_{rev} n_t \sigma_{total}$

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

Beam Loss Rates

- **Hadronic Interaction**

$$(\tau_{loss}^{-1})_H^t = f_{rev} n_t \sigma_{p\bar{p}}^{total}$$

- **Single Coulomb scattering out of the acceptance**

$$(\tau_{loss,\perp}^{-1})_C^t = f_{rev} \frac{4\pi Z_t^2 Z_i^2 r_i^2 n_t}{\beta_0^4 \gamma_0^2 \theta_{eff}^2}, \theta_{eff} = \sqrt{\frac{\varepsilon_t}{\beta_t}}$$

- **Energy straggling out of the acceptance**

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

- **Single IBS scattering (Touschek loss rate)**

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

ε_t = 1 mm mrad, $\delta_{eff} = -\varepsilon_{eff}/(\beta_0^2 E_0) = 10^{-3}$

Luminosity Considerations

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Example: Pellet target: $n_t=4\cdot10^{15}$ cm^{-2}

Total hadronic cross section (1.5, 9, 15 GeV/c) : σ=100, 60, 50 mbarn

Revolution frequency: f_c=443, 519, 521 kHz

Relative Loss Rate $(\tau_{loss}^{-1})/s^{-1}$			
Scattering Process	1.5GeV/c	9 GeV/c	15 GeV/c
Hadronic Interaction	$1.8\cdot10^{-4}$	$1.2\cdot10^{-4}$	$1.1\cdot10^{-4}$
Single Coulomb (ε=1mm mrad)	$2.9\cdot10^{-4}$	$6.8\cdot10^{-6}$	$2.4\cdot10^{-6}$
Energy Straggling ($\Delta p_{max}/p=\pm10^{-3}$)	$1.3\cdot10^{-4}$	$4.1\cdot10^{-5}$	$2.8\cdot10^{-5}$
Touschek (ε=1mm mrad)	$4.9\cdot10^{-5}$	$2.3\cdot10^{-7}$	$4.9\cdot10^{-8}$
Total loss rate	$6.5\cdot10^{-4}$	$1.7\cdot10^{-4}$	$1.4\cdot10^{-4}$
1/e Beam lifetime / s	~ 1540	~ 6000	~ 7100
Maximum Luminosity / 10^{32} cm^{-2} s^{-1}	0.82	3.22	3.93

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

Average Luminosity

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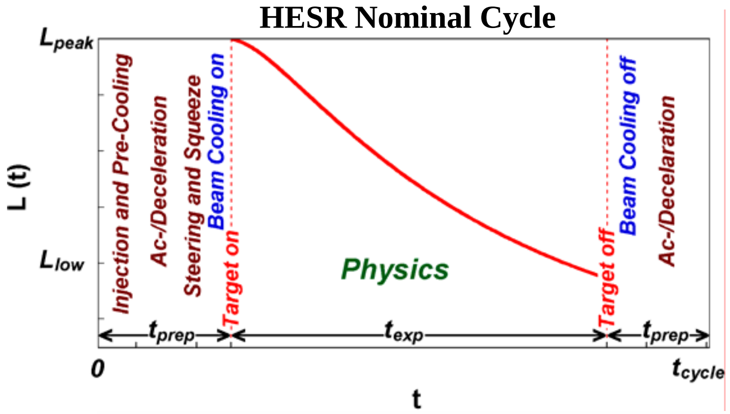
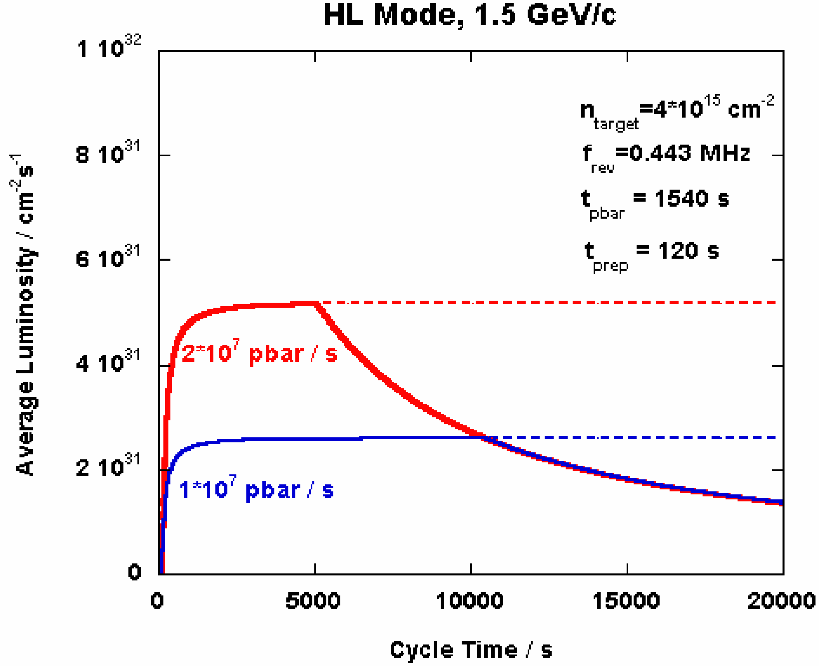
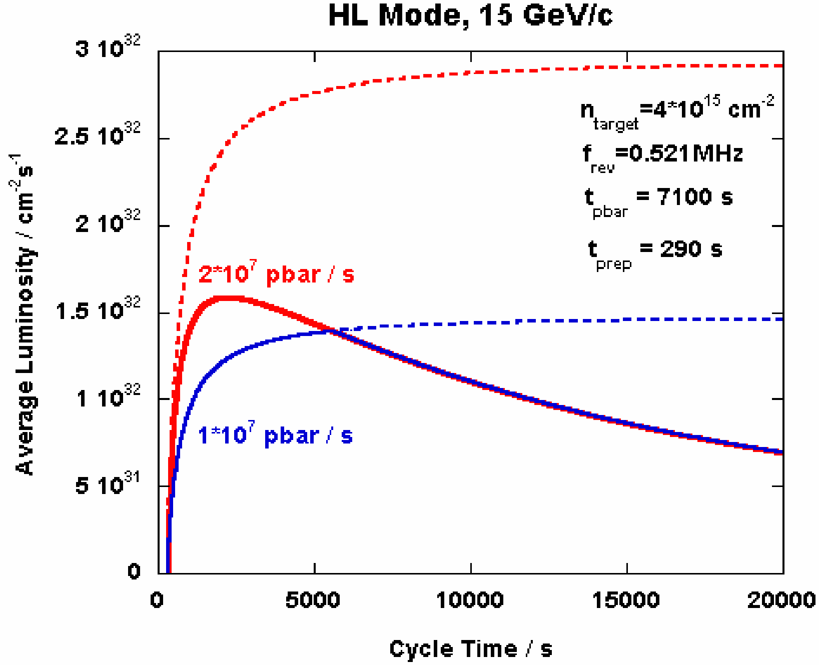


$$\bar{L} = L_0 \frac{\tau[1-e^{-\frac{t_{exp}}{\tau}}]}{t_{exp}+t_{prep}}$$

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

L_0: initial luminosity
τ: beam lifetime
t_{exp}: experimental time
t_{prep}: beam preparation time
n_p: number of particle
n_t: target density
f_{rev}: revolution frequency





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

Longitudinal Impedance

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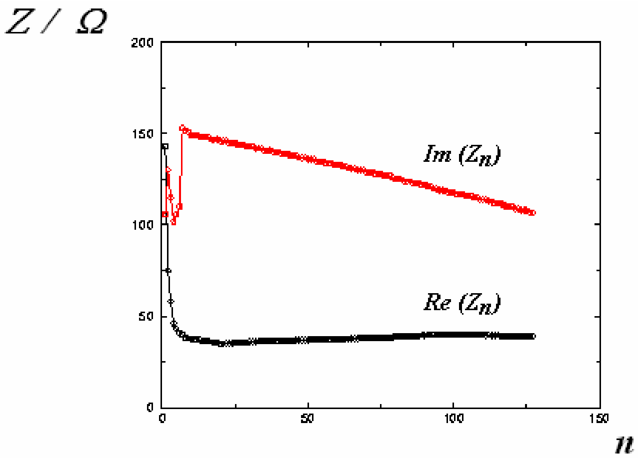
10000 macros, 10^{11} particle charges, 128 long. bins, initial long. distribution: 360°, $\Delta p/p = 10^{-3}$ to 10^{-6} (rms)

In Collaboration with A.U. Luccio et al. (BNL)



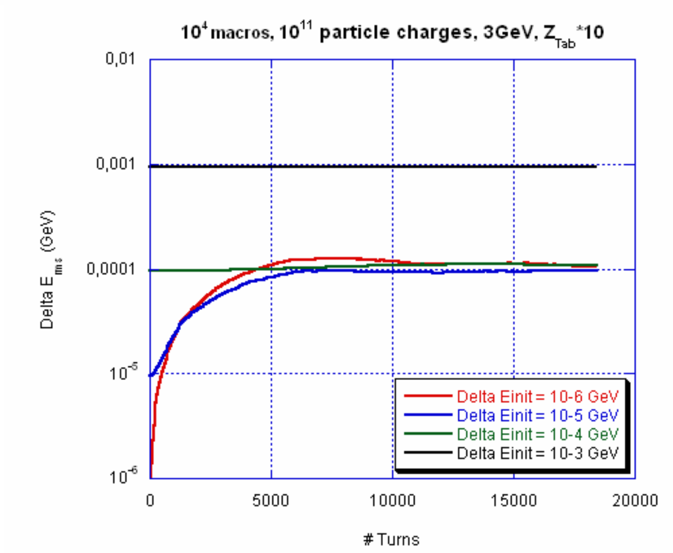
$$\begin{cases} Z_n = \sqrt{\mathrm{Re}(Z_n)^2 + \mathrm{Im}(Z_n)^2} \\ \chi_n = \arctan \dfrac{\mathrm{Im}(Z_n)}{\mathrm{Re}(Z_n)} \end{cases}$$

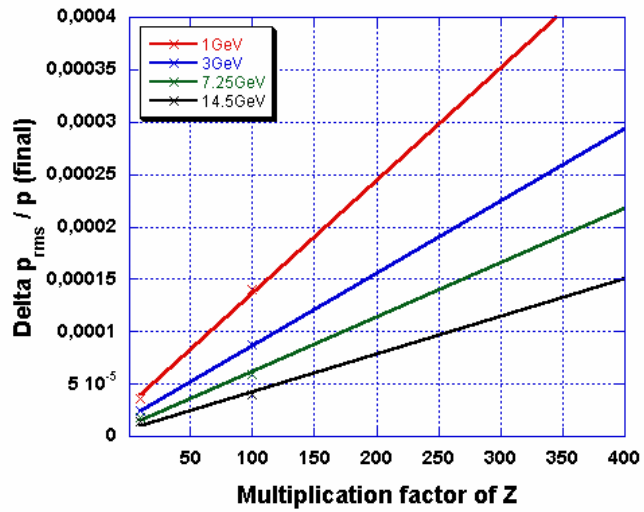
I_n, ϕ_n : Fourier spectrum of the beam

ϕ_i : Phase of the individual particle

Energy kick on the i-th macro:

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





Super Computer JUMP

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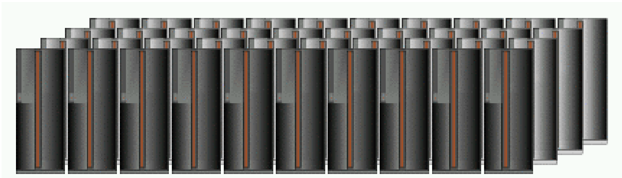
John von Neumann
Institut für Computing



Parameter IBM p690-Clusters Jump, FZ Jülich	
Nodes	41
Processors per node	32
Processors total	1312
Overall Peak Performance	8,9 TFLOPS
Memory per node	128 GByte
Total memory	5 TByte
Storage capacity	50 TByte
Operating system	AIX 5.1
Users	ca. 450

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

100000 macros → 3740 turns

10000 macros → 36900 turns

1000 macros → 364000 turns

→ 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**

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

→ **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

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- **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