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JÜLICH FORSCHUNGSZENTRUM

Beam Physics for the HESR

11. May 2012 | Andreas Lehrach

Outline

Introduction

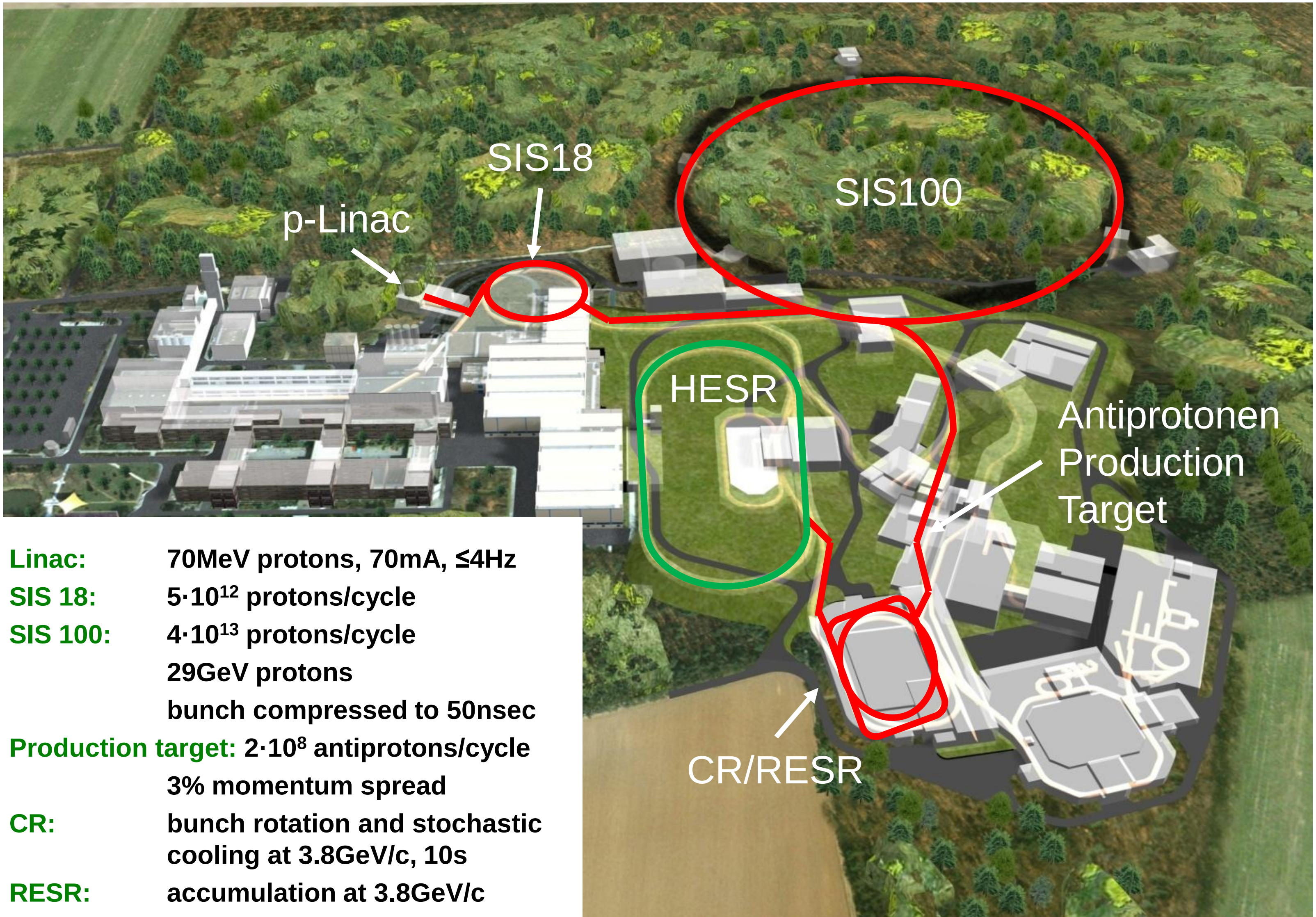
FAIR Facility
HESR & Experimental Requirements

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:	**$5 \cdot 10^{12}$ protons/cycle**
SIS 100:	**$4 \cdot 10^{13}$ protons/cycle**
	29GeV protons
	bunch compressed to 50nsec
Production target:	**$2 \cdot 10^{8}$ 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): $4 \cdot 10^{15}$ cm^{-2}
Beam radius at target (rms): 0.3 mm

	"High Luminosity Mode"	"High Resolution Mode"
Momentum range	1.5 – 15 GeV/c	1.5 - 8.9 GeV/c
Number of antiprotons	10^{11}	10^{10}
Peak luminosity	$2 \cdot 10^{32}$ cm^{-2}s^{-1}	$2 \cdot 10^{31}$ cm^{-2}s^{-1}
Momentum resolution (rms)	$\Delta p/p = 1 \cdot 10^{-4}$	$\Delta p/p \leq 4 \cdot 10^{-5}$

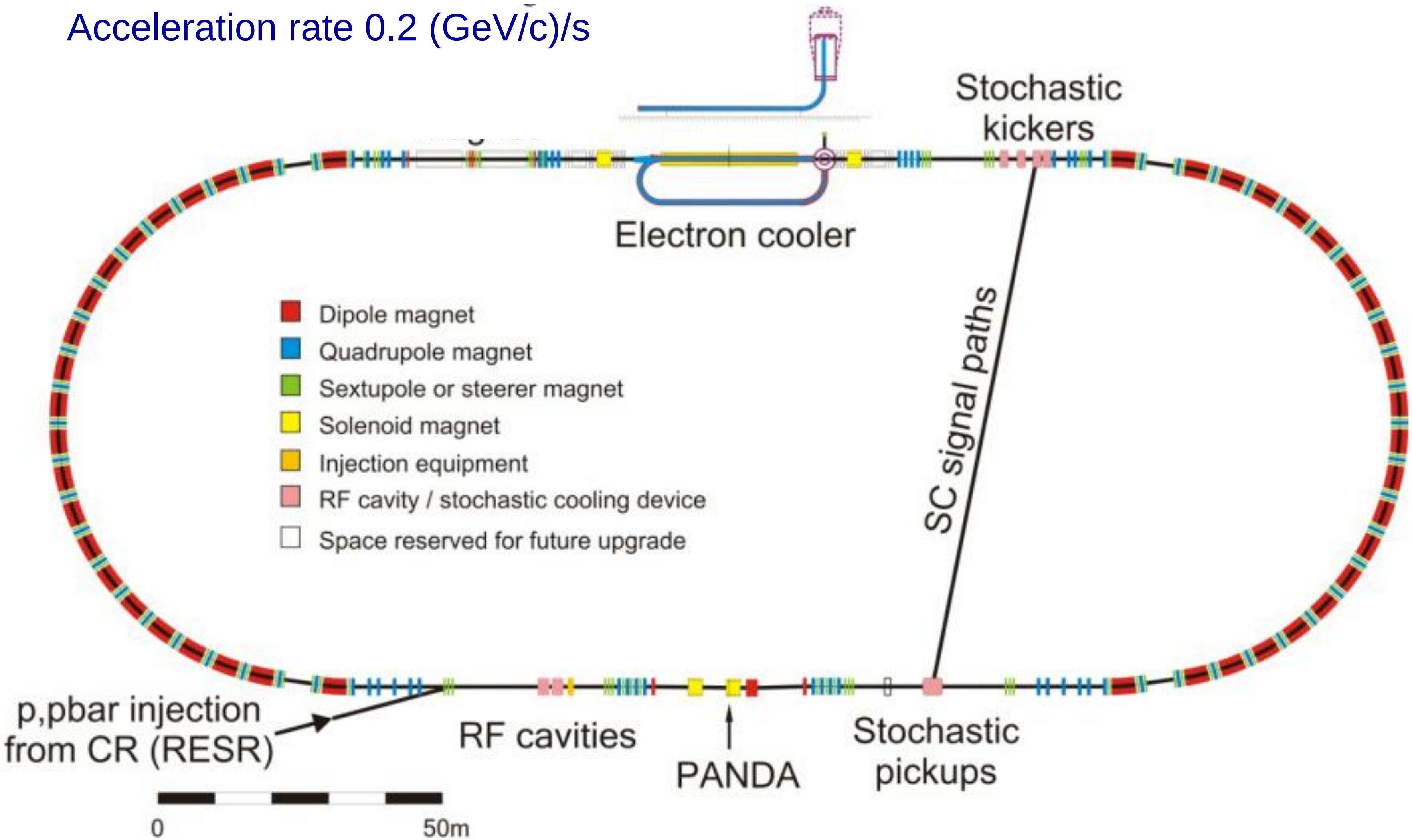
Electron and stochastic cooling, thick internal (pellet) targets

HESR Layout

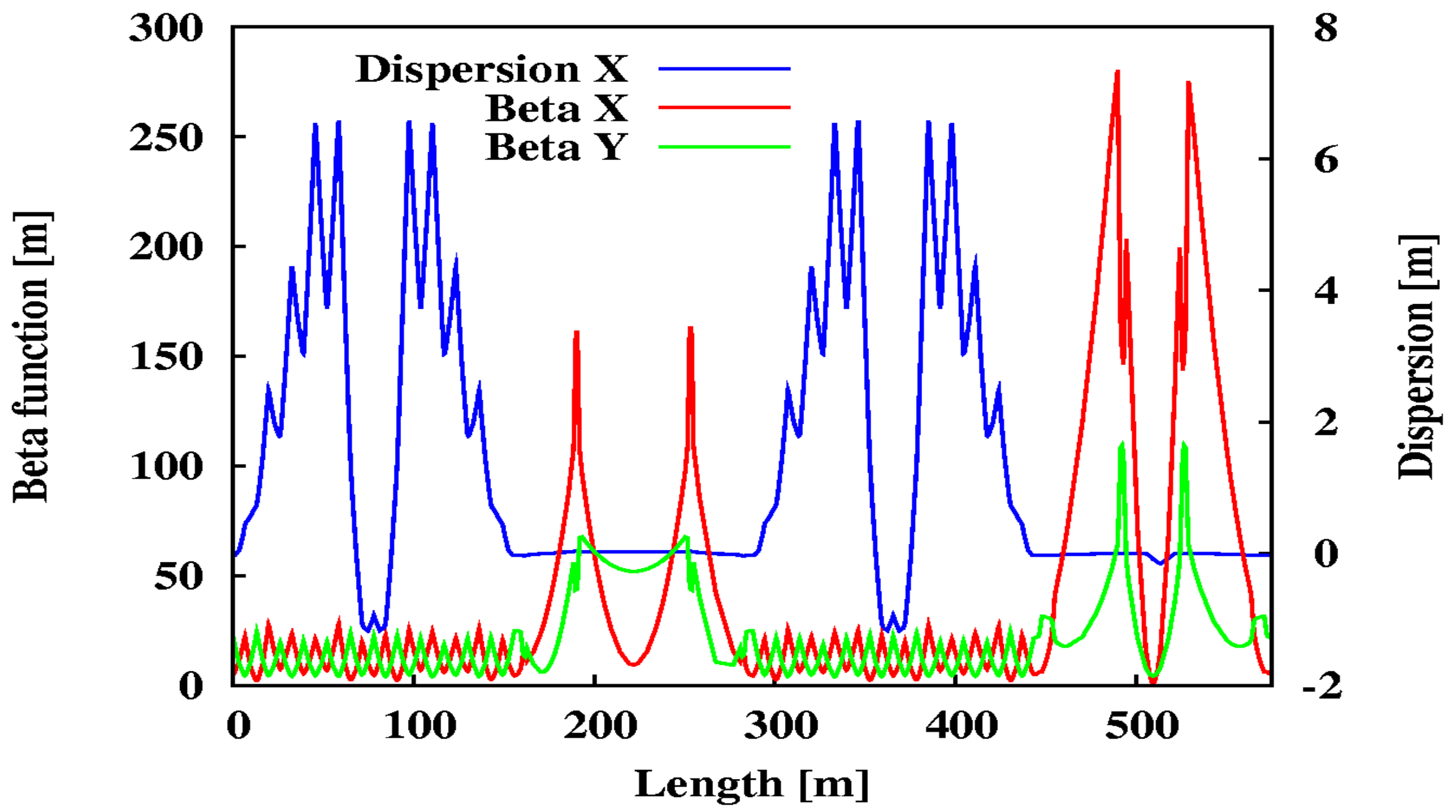
Circumference: 574 m

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 m
Betatron amplitude at electron cooler: $\beta_{x,y}$ = 25 – 200 m
Transition energy: γ_{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:

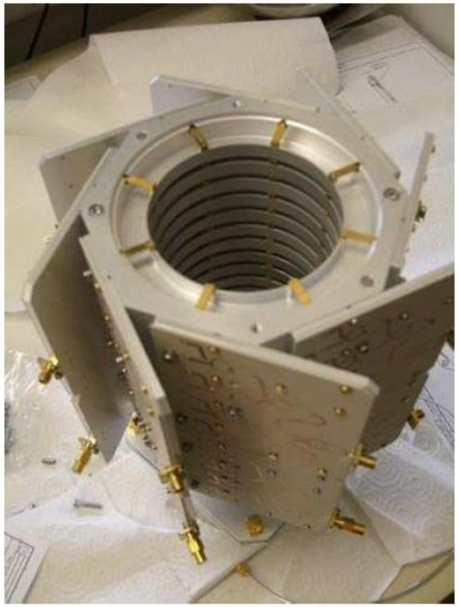
- relative momentum spread 5 x 10^{-4} (rms)
- bunch length less than time gap 500 ns
- 10^{8} anti-protons injected into HESR every 10 s

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



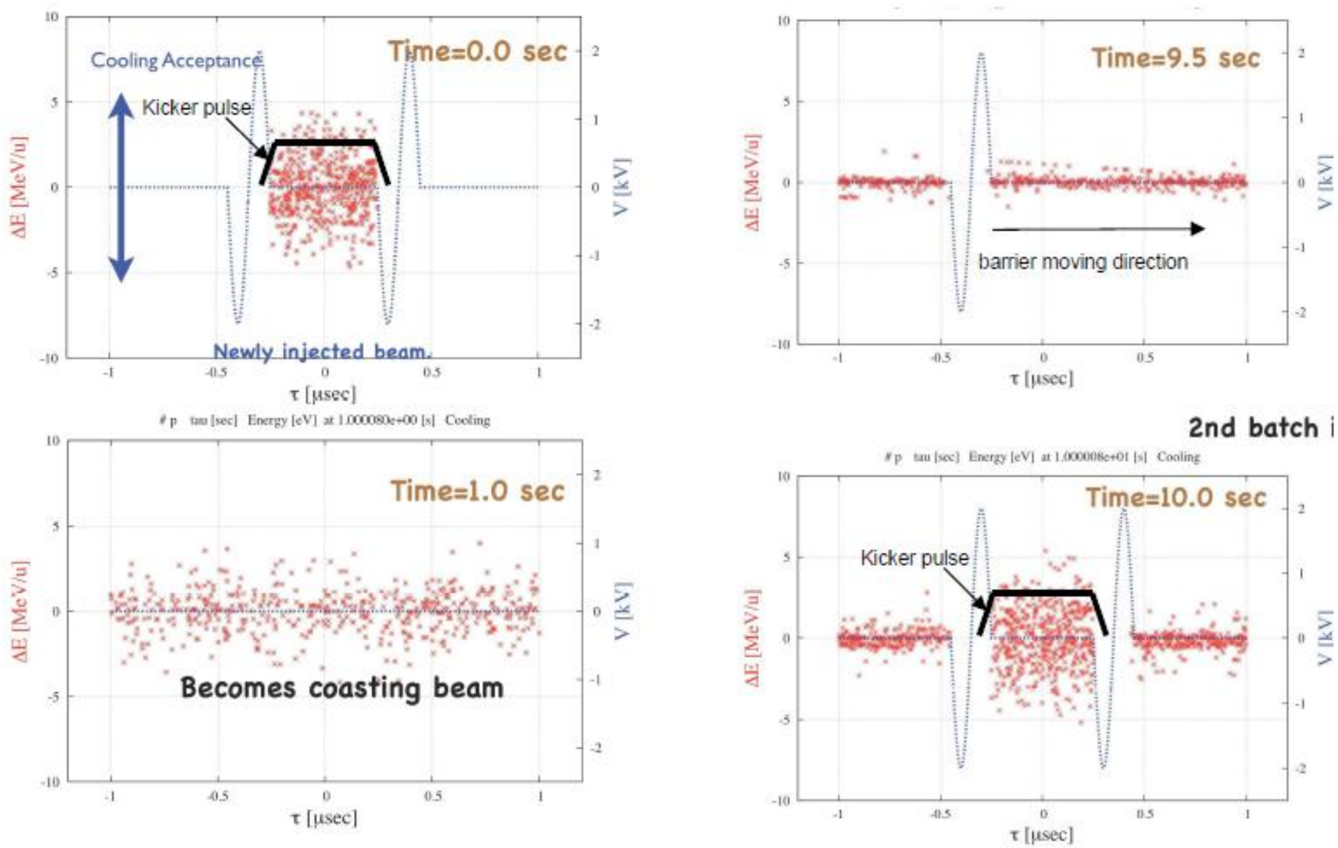
Advantages:

- 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

R. Stassen, FZJ

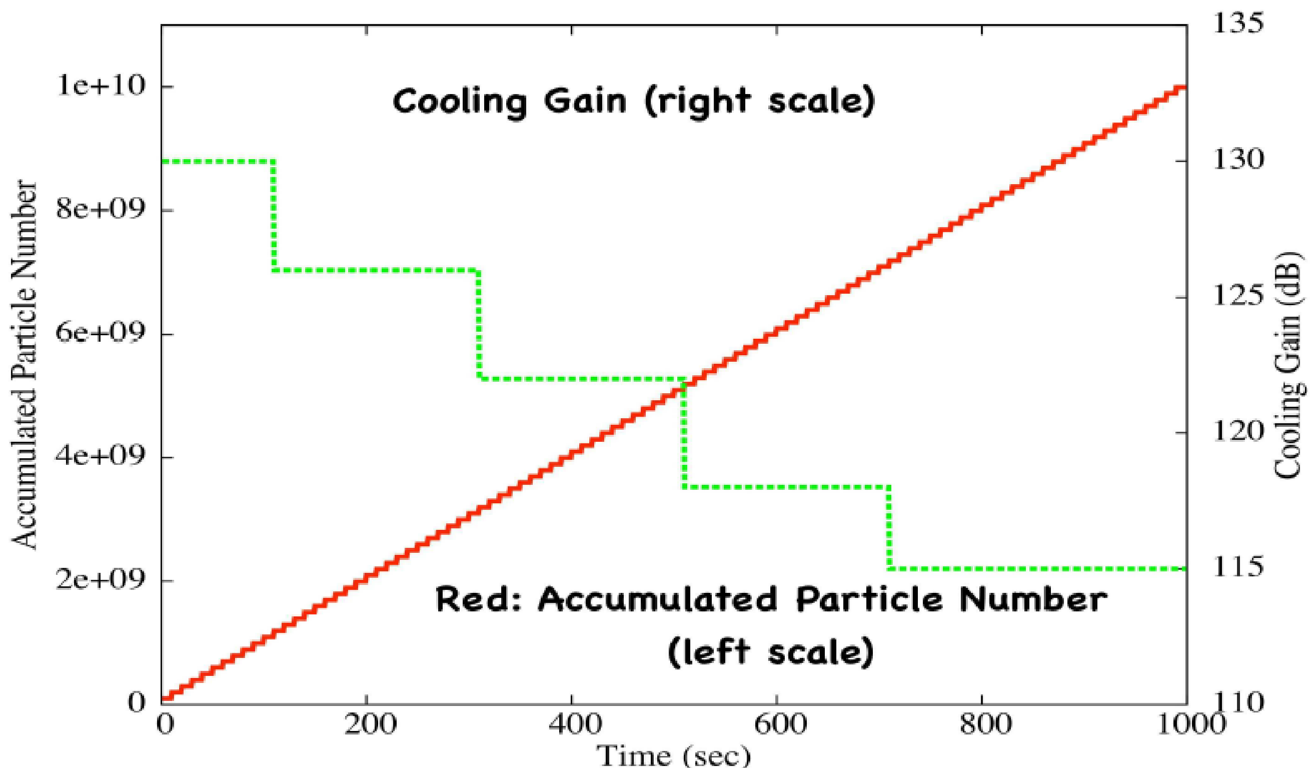
Accumulation with Moving Barriers



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

T. Katayama and H. Stockhorst

Accumulation Efficiency Moving Barrier Bucket



▪ *see: MAC, GSI Feb. 2010*

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

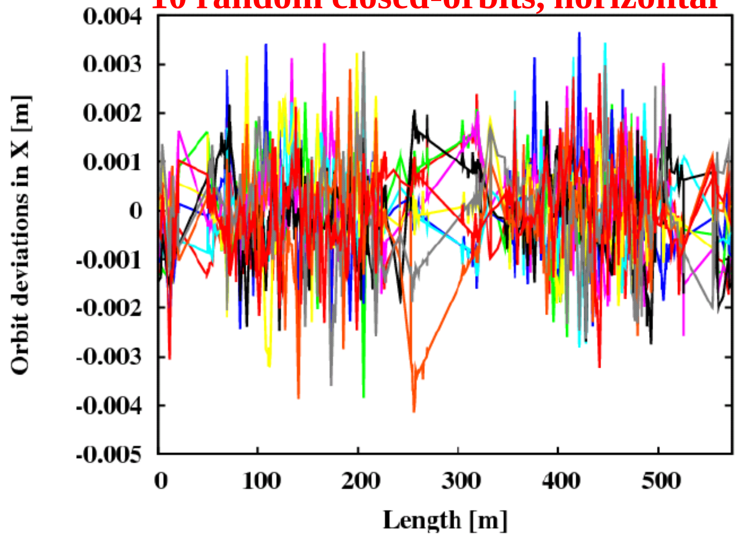
The momentum acceptance of the cooling system in the HESR requires a CR beam with momentum spread less than p/p = 5×10^{-4} (rms)

T. Katayama and H. Stockhorst

Closed-Orbit Correction

Assumed errors

Positioning error of all elements	Gaussian
Angle / mrad	σ=0.1
Position / mm	σ= 0.1
BPM accuracy	Gaussian
Resolution	σ= 0.1
Electr. offset / mm	σ= 0.1



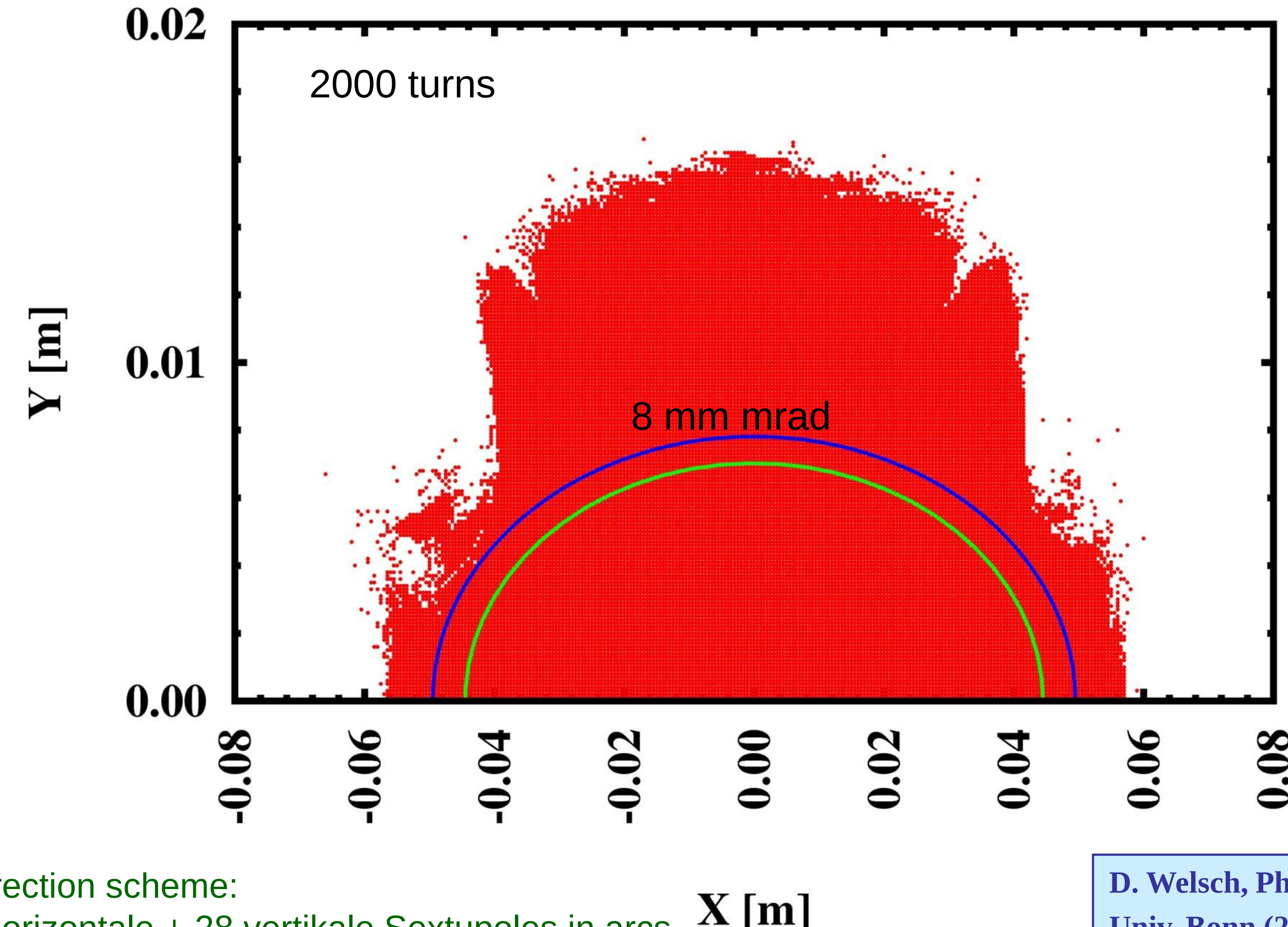
Goal:
Max. closed-orbit below 5mm
Strength of correction dipoles below 1 mrad

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

D. Welsch, Diploma thesis, Univ. Bonn (2006)

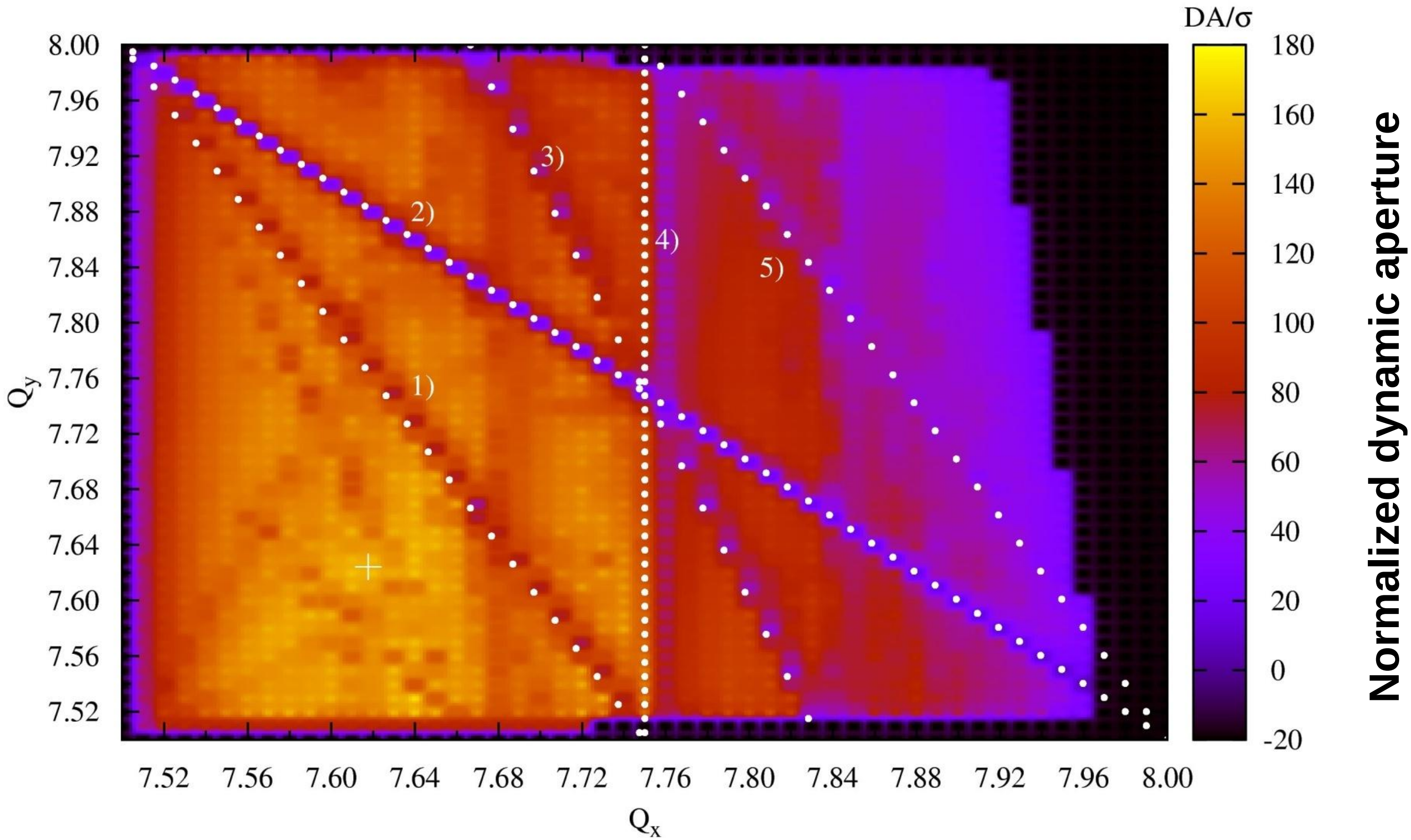
Dynamic Aperture



Correction scheme:
24 horizontale + 28 vertikale Sextupoles in arcs

D. Welsch, PhD thesis, Univ. Bonn (2010)

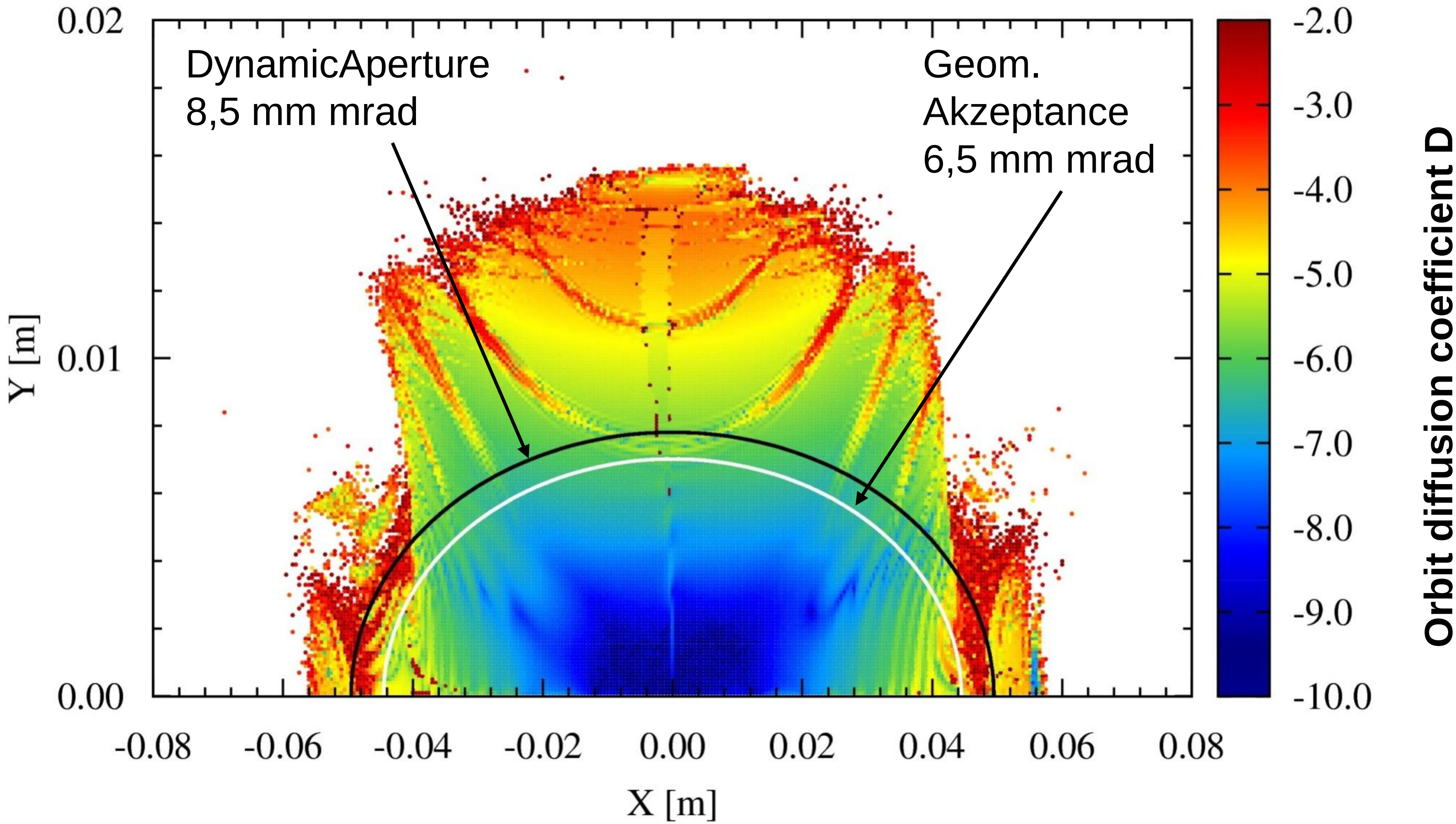
Tune Diagram (2D)



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

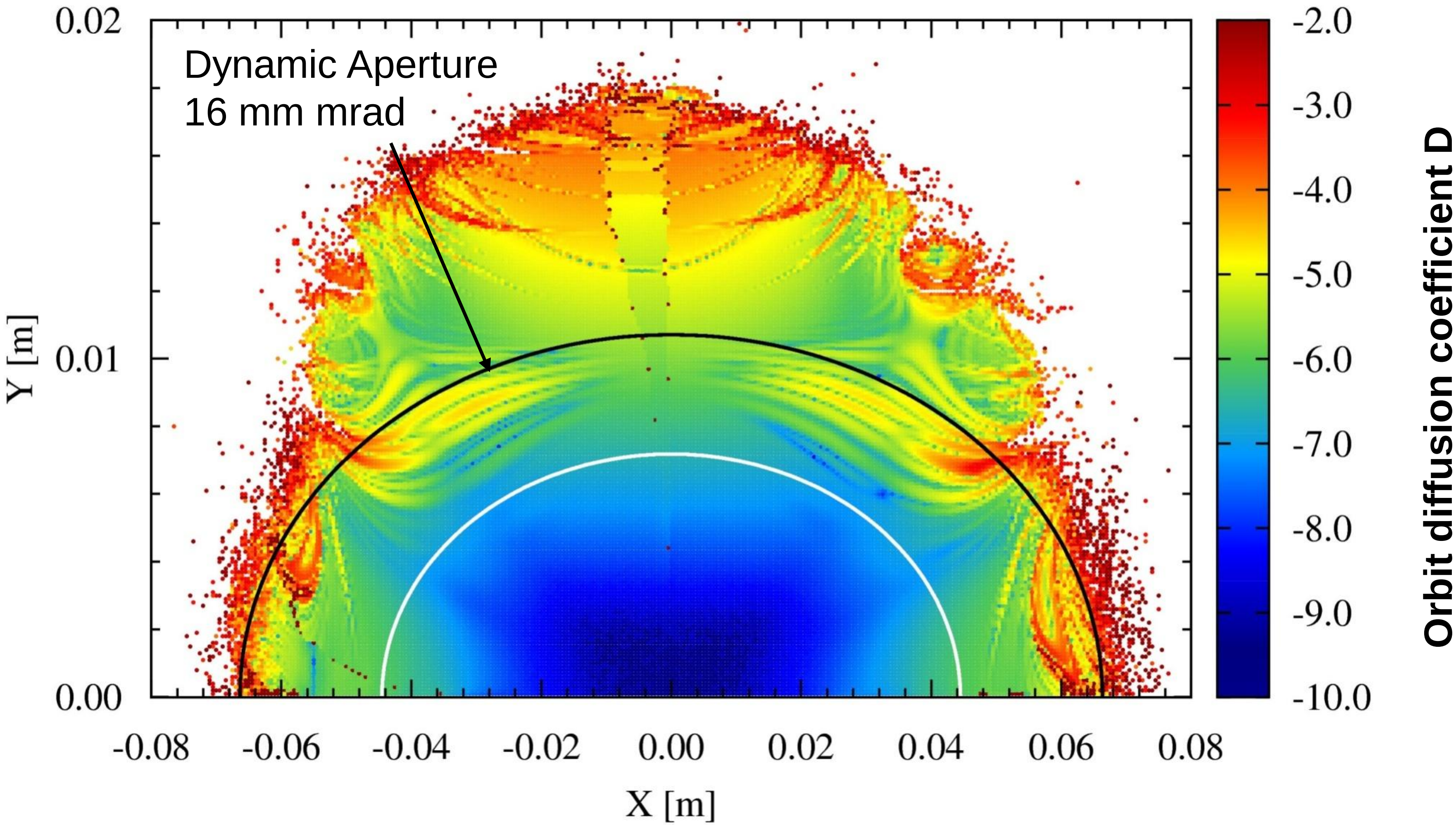
Dynamic Aperture (Design Working Point)



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

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

Dynamic Aperture (Optimized)



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

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

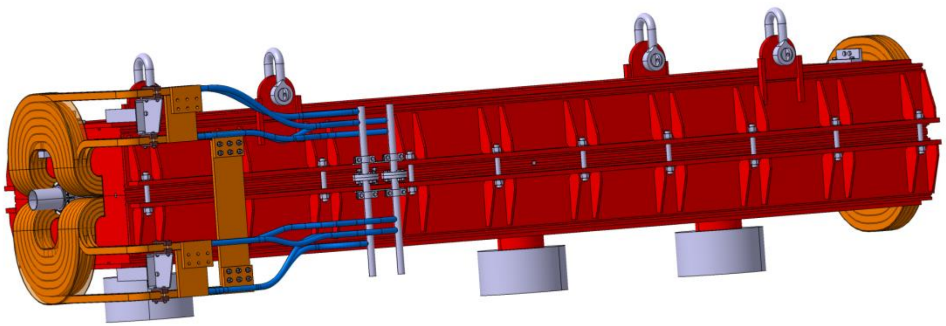
- $|b_3| < 5$
- $|b_5| < 1$
- **Quadrupole:** 0 to 20 T/m (25 T/m)
- |b6| < 0.5
- |b10| < 0.05

Sextupole: 0 to 45 T/m^2 (90 T/m^2)

- |b9| < 0.2
- |b15| < 0.01

All other multipole components: $|b_n| < 0.1$

Dipole Layout



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

- <u>First Design</u>

Optimization at 1 T b_3 < 10 at 1.7 T

- <u>New Design:</u>

Optimization at injection 0.42 T (3 GeV)

- b_3 < 3.5 bei 1.7 T

- Good field region (GFR)

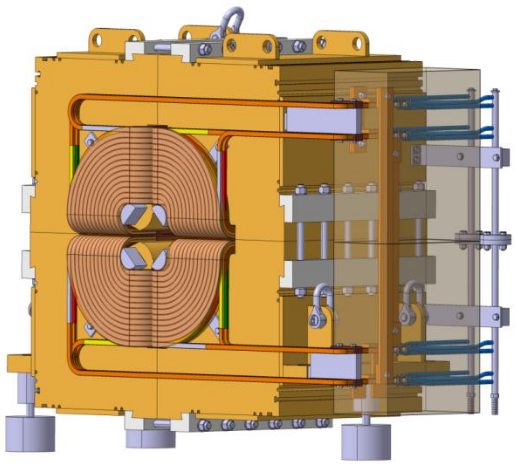
0.17 T	35 mm
0.42 T	35 mm
1.0 T	25 mm
1.7 T	21 mm

Integral multipole component

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

Helmut Soltner, FZJ

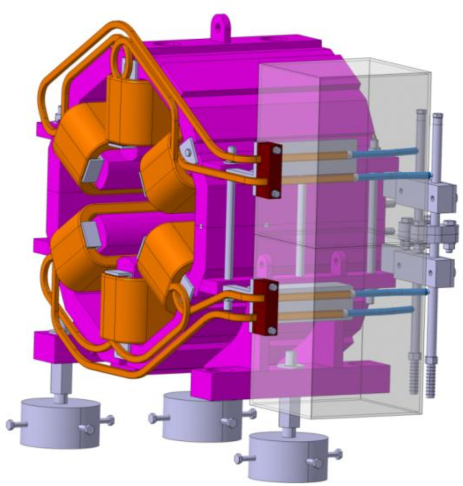
Quadrupole/Sextupole Layout



Number	84
Magnetic length	0.6 m
Iron length (arc)	0.58 m
Max gradient	20 T/m
Aperture	100 mm

Gradient [T/m]	GFR [mm]
2	40
7	40
15	25
20	21
25	21

Integral multipole component
- $|b6| \leq 0.5$
- $|b10| \leq 0.05$



Number	52 in arcs
Magnetic length	0.3 m
Max d^2B/dx^2	42.5 T/m^2
Aperture	135 mm
allow insertion of BMPs	

Sextupolstärke [T/m^2]	GFR [mm]
5	40
12	40
27	25
45	21

Integral multipole component
- $|b9| \leq 0.2$
- $|b15| \leq 0.01$

Helmut Soltner, FZJ

Luminosity Considerations (Full FAIR version)

Antiproton production rate:	$2\cdot10^7$ /s
Pellet target:	$n_t=4\cdot10^{15}$ cm^{-2}
Transverse beam emittance:	1mm·mrad
Longitudinal ring acceptance:	$\Delta p/p = \pm10^{-3}$
Betatron amplitude at PANDA:	1m
Circulating antiprotons:	10^{11}

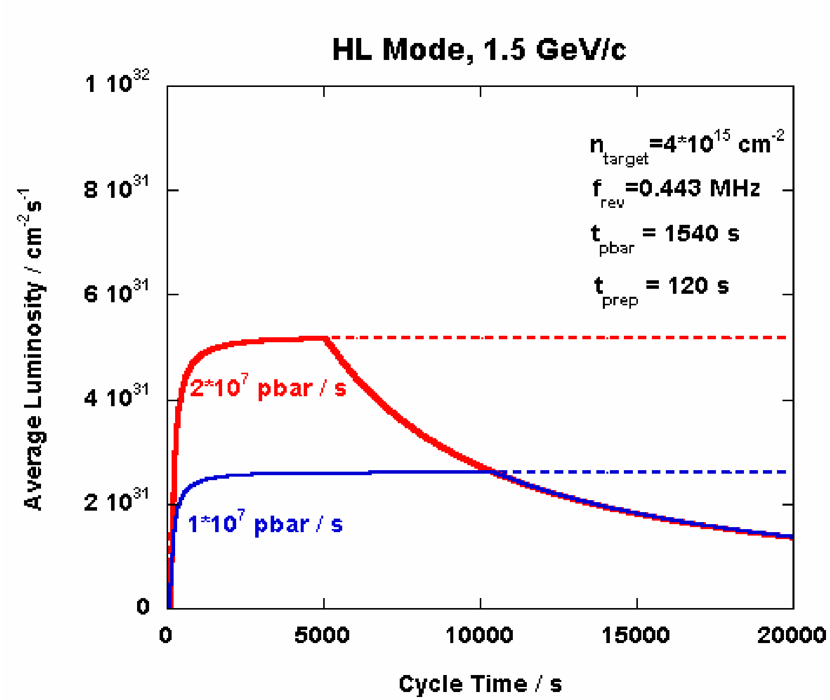
	Relative Loss Rate $(\tau_{loss}^{-1})/s^{-1}$		
Scattering Process	**1.5 GeV/c**	**9 GeV/c**	**15 GeV/c**
Hadronic Interaction	$1.8\cdot10^{-4}$	$1.2\cdot10^{-4}$	$1.1\cdot10^{-4}$
Single Coulomb	$2.9\cdot10^{-4}$	$6.8\cdot10^{-6}$	$2.4\cdot10^{-6}$
Energy Straggling	$1.3\cdot10^{-4}$	$4.1\cdot10^{-5}$	$2.8\cdot10^{-5}$
Touschek (Single IBS)	$4.9\cdot10^{-5}$	$2.3\cdot10^{-7}$	$4.9\cdot10^{-8}$
Total relatve loss rate	$6.5\cdot10^{-4}$	$1.7\cdot10^{-4}$	$1.4\cdot10^{-4}$
1/e Beam lifetime / s	~ 1540	~ 6000	~ 7100

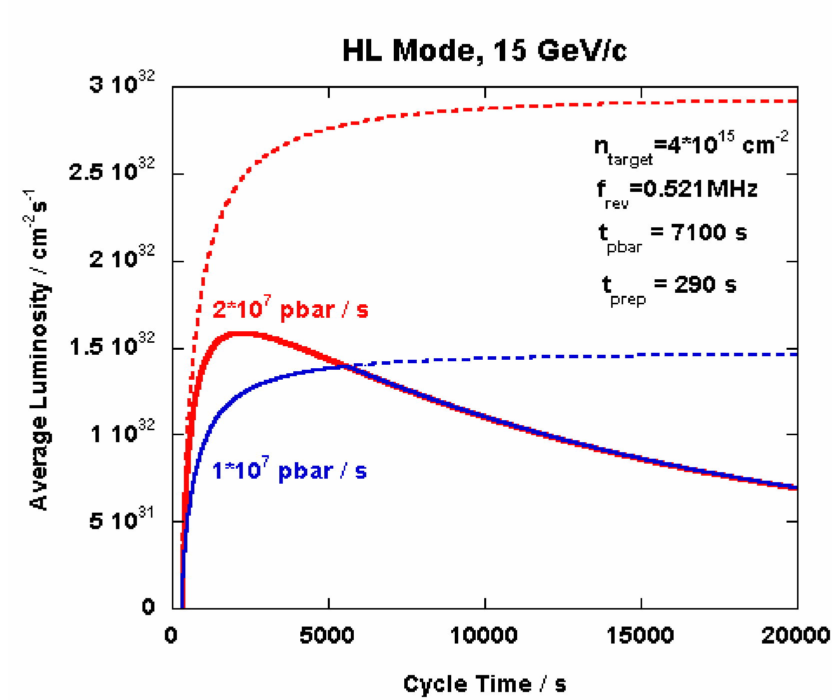
Cycle averaged luminosity
- Momentum 1.5 GeV/c: $0.3 – 0.7\cdot10^{32}$ $cm^{-2}s^{-1}$
- Momentum: 15 GeV/c: $1.5 – 1.6\cdot10^{32}$ $cm^{-2}s^{-1}$

(Production rate: $1 – 2\cdot10^7$ /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 - $1.5 \cdot 10^{32}$ $cm^{-2}s^{-1}$
- Production rate $2 \cdot 10^7$ /s (1.5 – 15 GeV/c): 0.67 - $1.6 \cdot 10^{32}$ $cm^{-2}s^{-1}$

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

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

A. Lehrach et al., NIMA 561 (2006)

Cooled Beam Equilibria

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

rms relative momentum spread σ_p/p

Electron cooled beams

- HR mode: $7.9\cdot10^{-6}$ (1.5 GeV/c) to $2.7\cdot10^{-5}$ (8.9 GeV/c), and $1\cdot10^{-4}$ (15 GeV/c)
- HL mode: $<10^{-4}$

D. Reistad et al:, Proc. of the Workshop on Beam Cooling and Related Topics COOL2007, MOA2C05, 44 (2007)
O. Boine-Frankenheim et al., A 560 (2006) 245–255

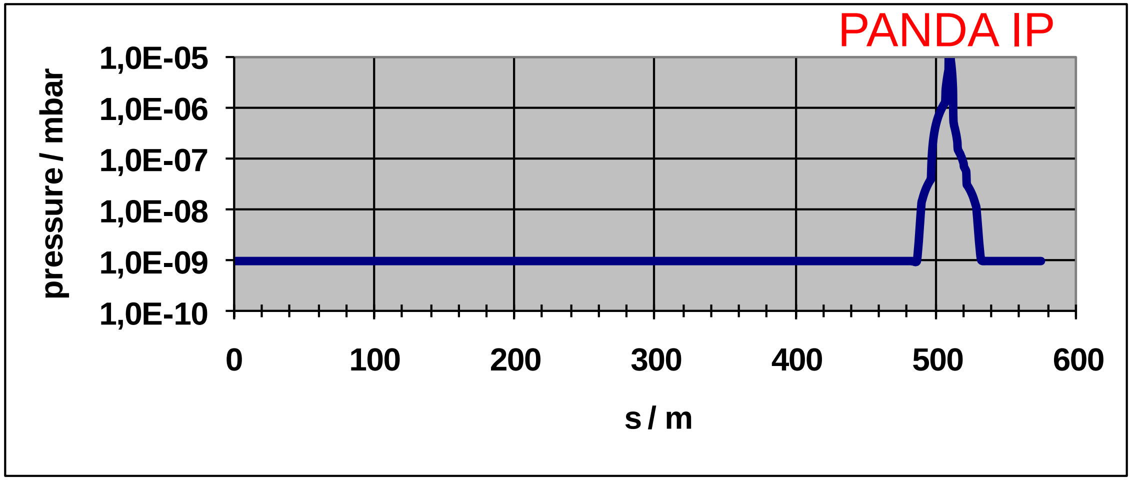
Stochastic cooled beams

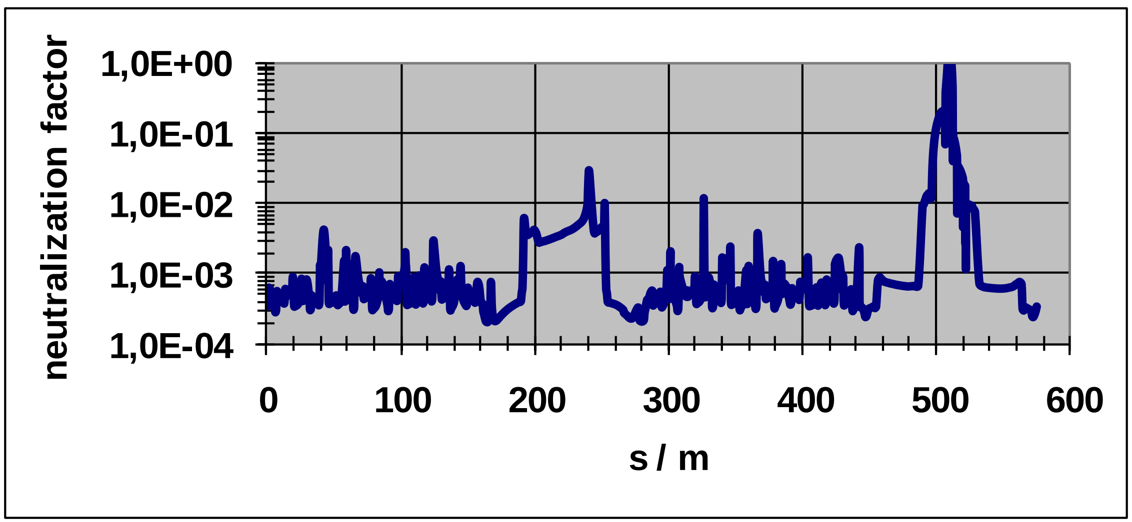
- HR mode: $5.1\cdot10^{-5}$ (3.8 GeV/c), $5.4\cdot10^{-5}$ (8.9 GeV/c), and $3.9\cdot10^{-5}$ (15 GeV/c)
- HL mode: $\sim10^{-4}$

Transverse stochastic cooling can be adjusted independently

H. Stockhorst et al., Proc. of the European Accelerator Conference EPAC2008, THPP055, 3491 (2008).

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:

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

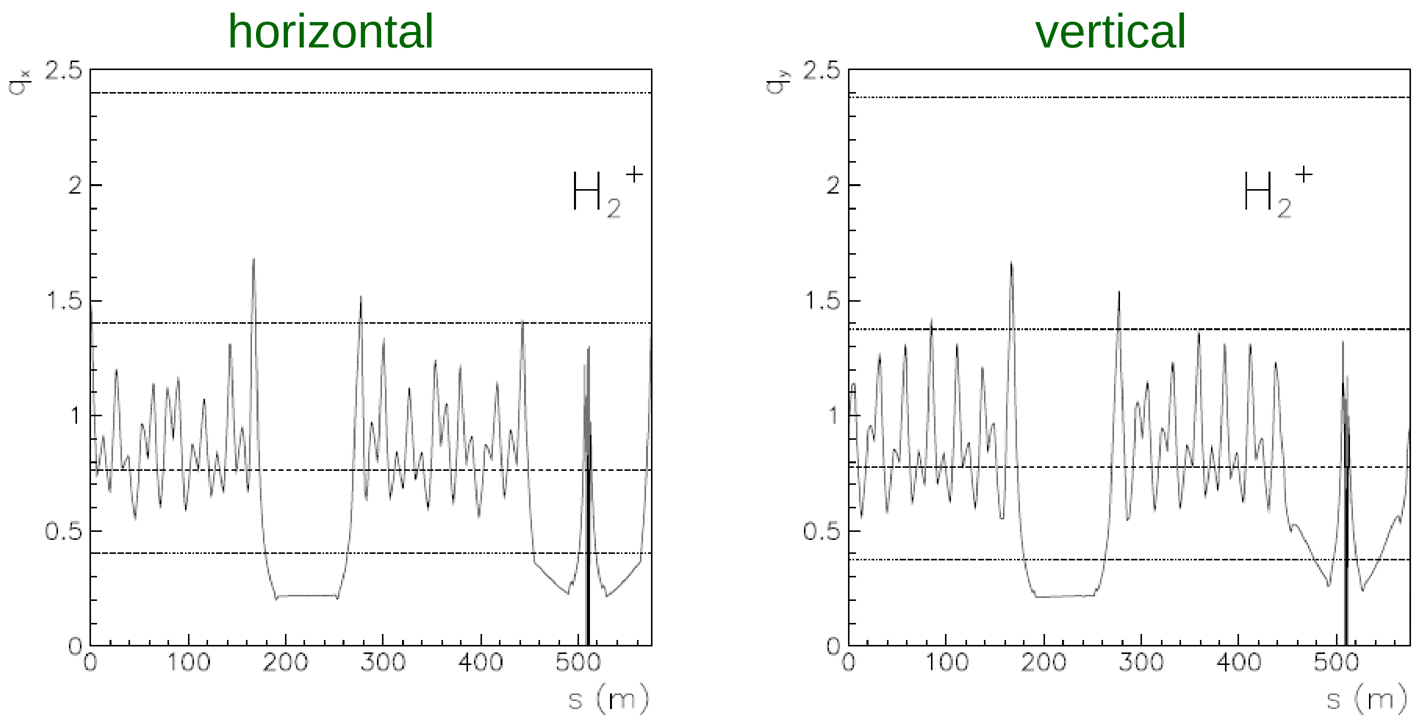
Average distance of clearing electrodes of 10 m, with a clearing voltage of 200 V

→ 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 $q_{x,y}$



Beam momentum
p = 15 GeV/c

Estimates for beam instabilities

F. Hinterberger, Ion Trapping in the High-Energy Storage Ring HESR, JÜL-Report 4343 (2011)

Measures for Trapped Ions

- Trapped Ions may cause full neutralization within ≤ 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