JÜLICH
FORSCHUNGSZENTRUM

The ENC@FAIR Accelerator Project

September 27-29, 2009 | Andreas Lehrach

Accelerator Working Group

K. Aulenbacher, D. Barber, O. Boldt, R. Heine, W. Hillert,
A.Jankowiak, A. Lehrach, Chr. Montag, P. Schnizer, T. Weis

Content

Introduction

FAIR accelerator facility
HESR layout and experimental requirements
Modifications for ENC@FAIR

Beam Dynamics

Beam equilibria and luminosities

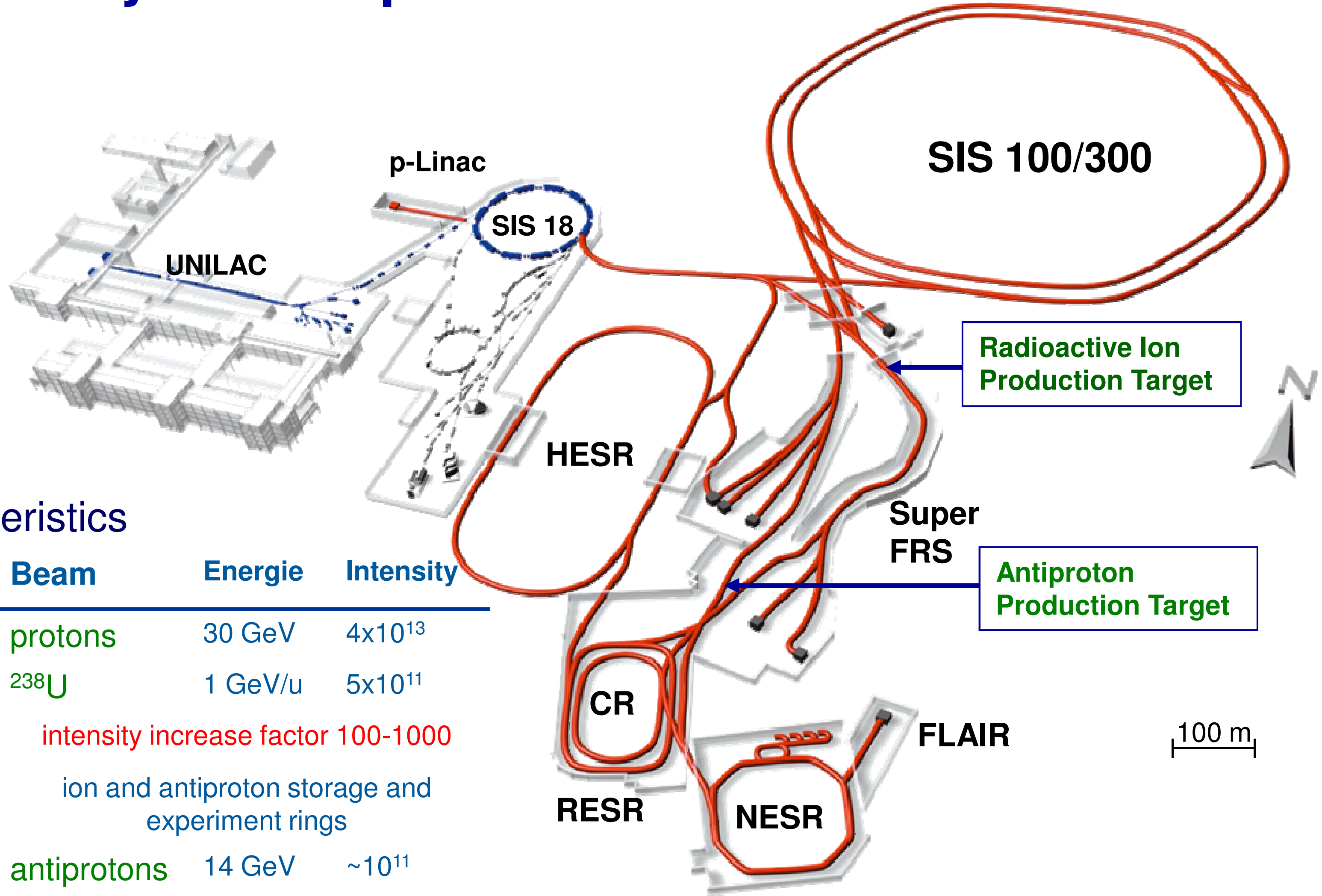
Spin Dynamics

Spin resonances in SIS18 and HESR
Measures for polarized beams

Summary

List of Major Tasks and Extensions

FAIR
Facility for Antiproton and Ion Research

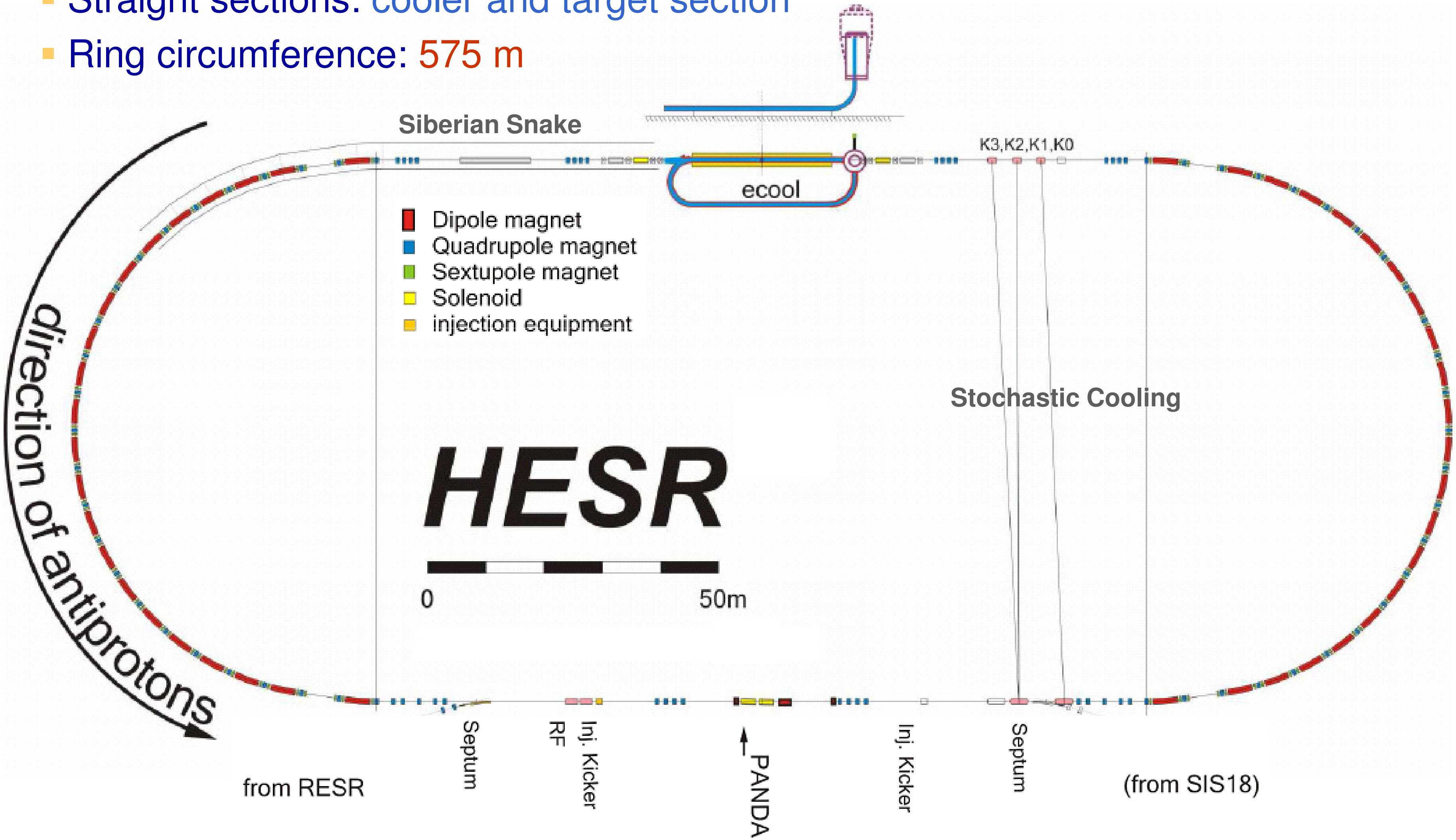


Beam characteristics

Ring/Device	Beam	Energie	Intensity
SIS100	protons	30 GeV	$4x10^{13}$
	^{238}U	1 GeV/u	$5x10^{11}$
	intensity increase factor 100-1000		
CR/RESR/NESR	ion and antiproton storage and experiment rings		
HESR	antiprotons	14 GeV	$\sim10^{11}$
Super-FRS	rare-isotope beams	1 GeV/u	$<10^{9}$

HESR Layout

- Momentum range: 1.5 – 15 GeV/c
- Straight sections: cooler and target section
- Ring circumference: 575 m



HESR 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 on target (rms):	**0.3 mm**

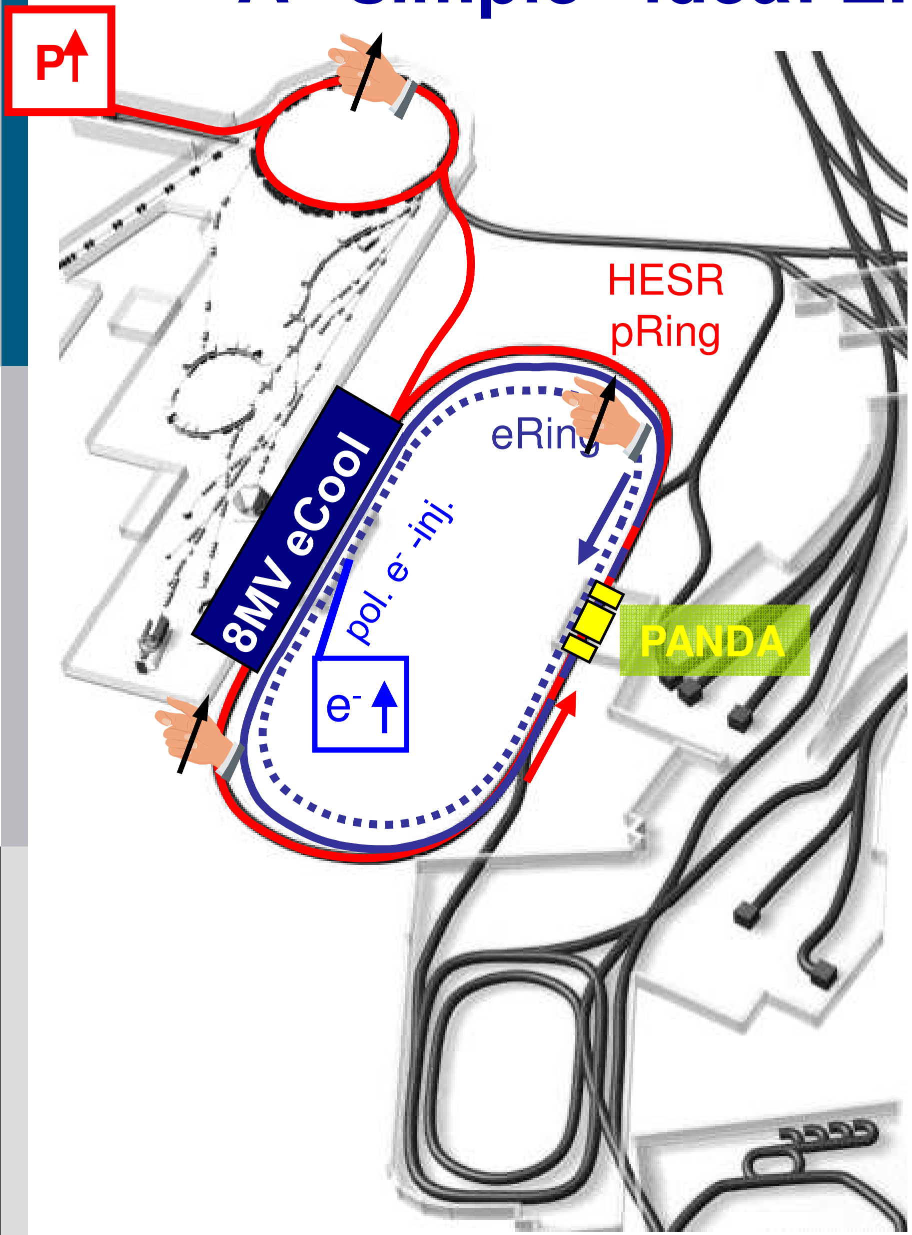
	High Luminosity (HL)	High Resolution (HR)
Momentum range	1.5 – 15 GeV/c	1.5 – 8.9 GeV/c
Number of antiprotons	10^{11}	10^{10}
Peak luminosity	$2 \cdot 10^{32}$ cm^{-2}s^{-1}	$2 \cdot 10^{31}$ cm^{-2}s^{-1}
Rel. momentum spread (rms)	$1 \cdot 10^{-4}$	$\leq 4 \cdot 10^{-5}$

Electron and stochastic cooling

Thick internal (pellet) targets

Cavities for acceleration and barrier bucket (h=1 … 20)

A "simple" idea: ENC@FAIR



idea emerged 08/2008

L > 10^{32} $cm^{-2}s^{-1}$

$s^{1/2}$ > 10GeV
(3.3GeV/c e^- ↔ 15GeV/c p)

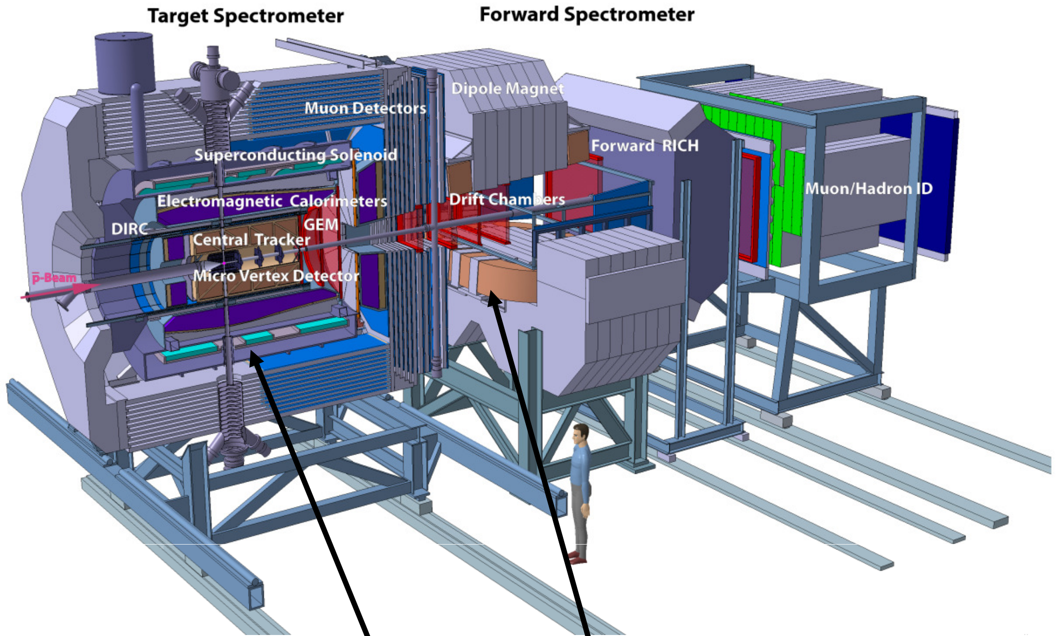
polarized e^- (> 80%)
↔
polarized p / d (> 80%)
(transversal + longitudinal)

using the PANDA detector
as much as possible

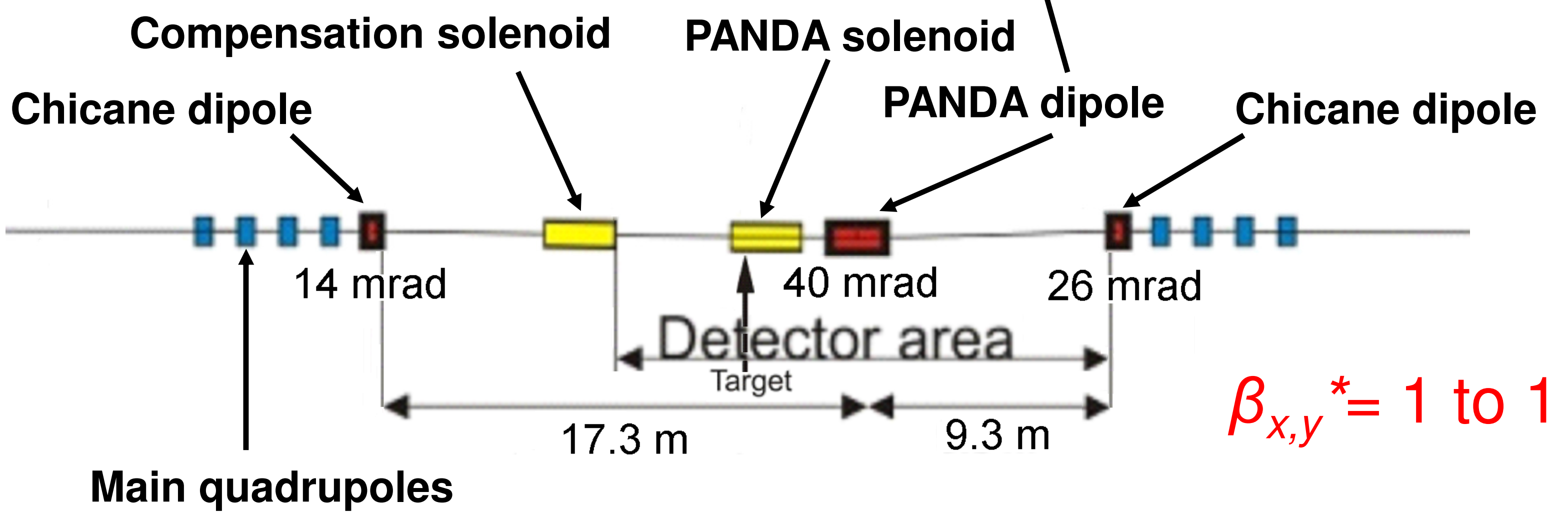
double polarized
Electron Nucleon Collider
Luminosity: 8 × HERA (unpol.)

Experiment Section

PANDA detector



Magnet system



$\beta_{x,y}^{*}$= 1 to 10m

IP Requirements

Requirements for Kick-Off Meeting IR Design, 09/09/09 Jülich:

- Acceptance angles in proton direction:

  0° to 5°: detection and momentum resolution of protons in forward direction

  25° to 155°: particle detection in target spectrometer

  175° to 180°: detection of small-angle scattered electron

- Preserve PANDA geometry and PANDA central detector, other than inner tracker (30 cm diameter, 1.5m long)

- $\beta_{x,y}^* \leq 0.3$m for high luminosity

- Aperture radii: $6\sigma_p + 0.01$m for protons, $10\sigma_e + 0.01$m for electrons

IP Concept

Beam separation:

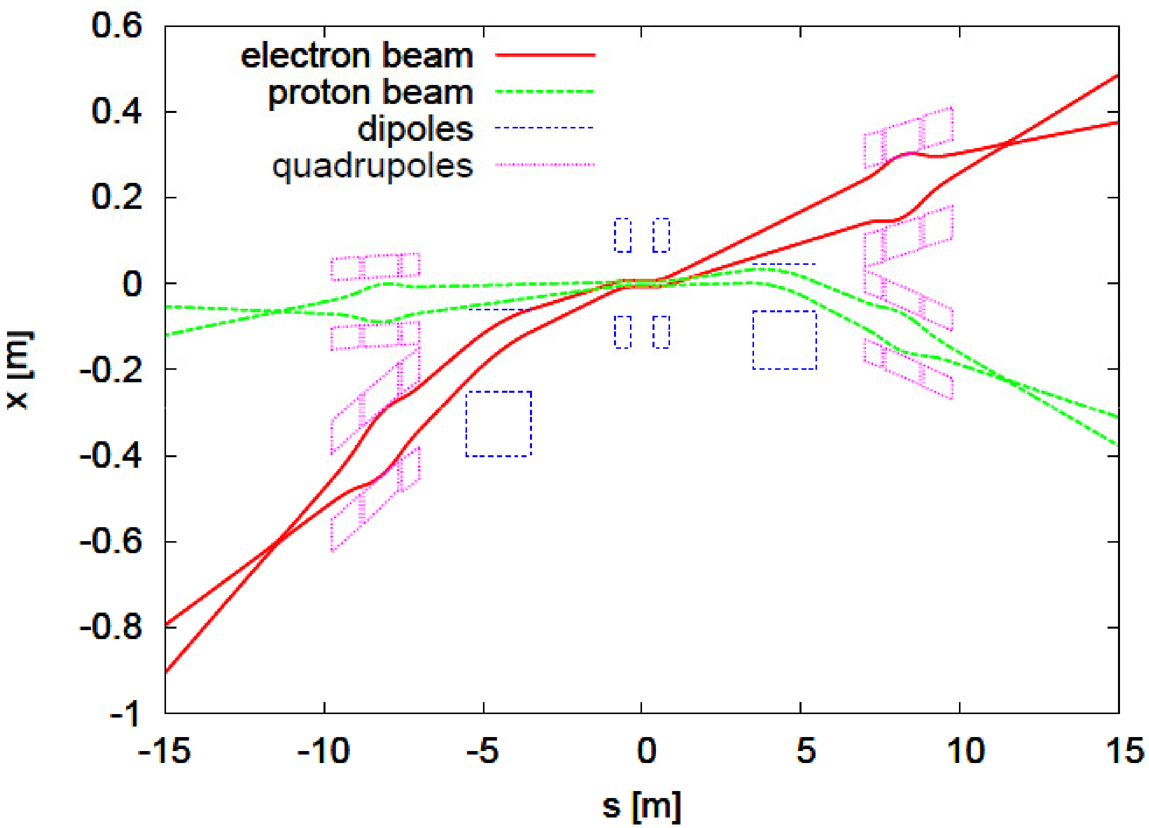
- Replace inner tracker with two dipoles, $B = 0.6$T; $l = 0.5$m
- Inside PANDA dipole, shield electron beam pipe by an iron pipe
- $B = 1$T PANDA dipole increases separation by bending the proton beam
- On opposite side, increase separation by $B = 0.2$T; $l = 2$m electron dipole

Beam focusing:

- Superconducting quadrupole triplets for each beam
  ~50 T/m for protons and 10 T/m for electrons
- Side-by-side in common cryostat for both triplets
- Quadrupole entrance at s = ±7m (1m behind the PANDA dipole)

IP Layout

Top view



Sufficient separation at s = 1.44m for 200 bunches

$\beta_{x,y}{}^{*}$= 0.3m

Chr. Montag, BNL

IP Beam Properties

Chromaticity: $\zeta_{x,y} = \Delta Q_{x,y}/(\Delta p/p)$

- HESR with PANDA with $\beta_{x,y}^{*}$= 1m: ~ -15 (IP triplet: ~ -5, E-Cooler triplet: ~ -2)

Presently correction system with 52 sextupoles in four families can handle ~ -20

- ENC with $\beta_{x,y}^{*}$= 0.3m: ~ -40 (IP triplet:~ -30)

→ Add additional sextupole magnets and sextupole families are needed

- ENC with $\beta_{x,y}^{*}$= 0.1m: beta function roughly a factor of three larger in triplets compared to $\beta_{x,y}^{*}$= 0.3m

  more than a factor of three larger chromaticity
  more beam separation needed
  reduced machine acceptance

→ Quadrupole entrance would have to be moved to $s \leq \pm 3.5$m

HESR Electron Cooler

Momentum range (Antiprotons): 1.5 – 8.9 GeV/c

Electron energy: 0.45 – 4.5 MeV

Electron current: 0 - 1 A

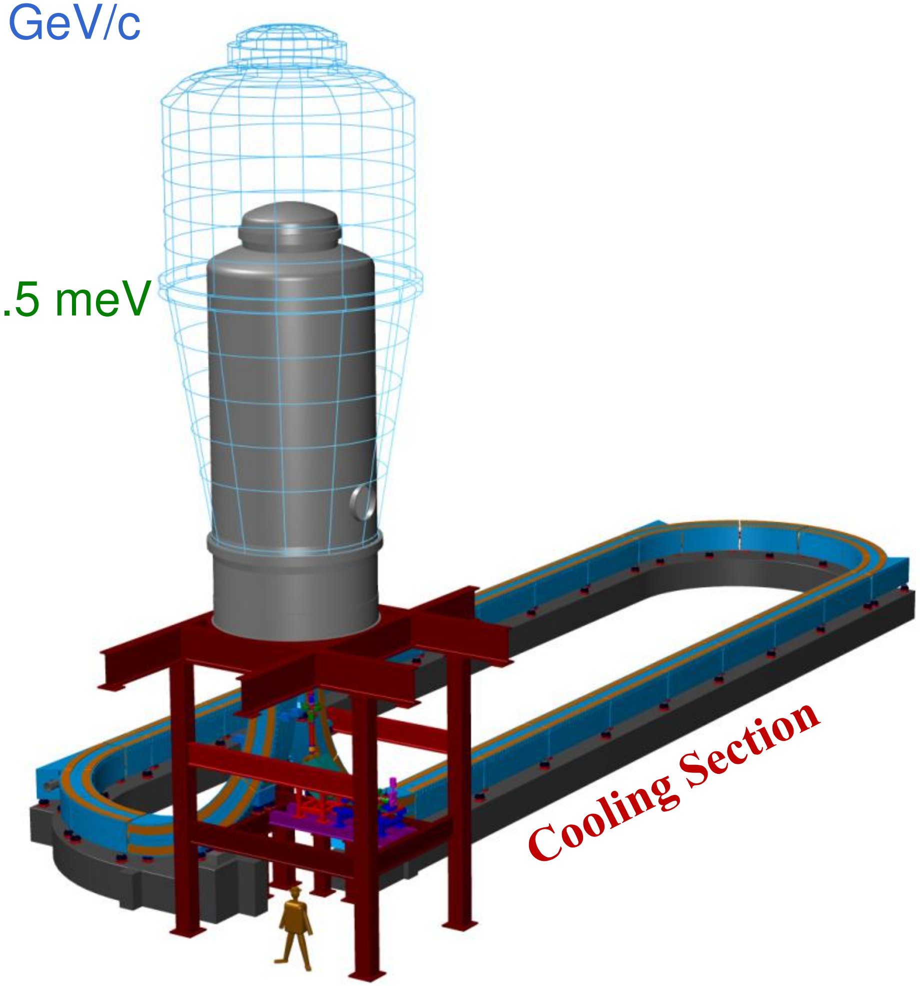
Electron radius: 5 mm

Temperature of electron beam (t,l): 1eV, 0.5 meV

Magnetic field (cooling section): 0.2 T

Field qualtiy (rms): $B_r/B < 10^{-5}$ rad

Length of cooling section: L_{eff} = 24 **m**



The Svedberg Laboratory
Uppsala University

Beam Equilibria and Luminosities

JÜLICH FORSCHUNGSZENTRUM

Baseline design (protons)

e-Cooler parameter: E=8.2 MeV, I=3 A, B=0.2T, T_T=1eV, T_L=0.5meV, $B_r/B < 10^{-5}$, L=24m
RF parameter: f=52 MHz, U=300 kV

<table>
<tr><th></th><th>HESR / 15GeV p</th><th>eRing / 3GeV</th></tr>
<tr><td>L [ring circumference, m]</td><td colspan="2">~ 575</td></tr>
<tr><td>ε^{norm} / ε^{geo} [mm mrad, rms]</td><td colspan="2">≤ 2.1 / ≤ 0.13</td></tr>
<tr><td>Δp/p (rms)</td><td>~ $4 \cdot 10^{-4}$</td><td></td></tr>
<tr><td>β_{IP} [m]</td><td colspan="2">0.3</td></tr>
<tr><td>r_{IP} [mm, rms]</td><td colspan="2">≤ 0.2</td></tr>
<tr><td>l (bunch length) [m]</td><td>0.27 - 0.35</td><td>0.1</td></tr>
<tr><td>n (particle / bunch)</td><td>$5.4 \cdot 10^{10}$</td><td>$23 \cdot 10^{10}$</td></tr>
<tr><td>h (number of bunches)</td><td>100</td><td>100</td></tr>
<tr><td>f_{coll} (collision freq) [MHz]</td><td colspan="2">~ 52</td></tr>
<tr><td>l_{coll} (bunch distance) [m]</td><td colspan="2">~ 5.76</td></tr>
<tr><td>ΔQ_{sc} (space charge)</td><td>≥ 0.05</td><td></td></tr>
<tr><td>ξ (beam-beam parameter)</td><td>0.014</td><td>0.015</td></tr>
<tr><td>L (luminosity) [$cm^{-2}s^{-1}$]</td><td colspan="2">~ $2 \cdot 10^{32}$</td></tr>
</table>

BetaCool program
JINR Dubna

Beam Equilibria and Luminosities

Advanced design (protons)

e-Cooler parameter: E=8.2 MeV, I=3 A, B=0.2T, T_T=1eV, T_L=0.5meV, $B_r/B < 10^{-5}$, L=24m
RF parameter: f=104 MHz, U=300 kV

	HESR / 15GeV p	eRing / 3GeV
L [ring circumference, m]	~ 575	
ε^{norm} / ε^{geo} [mm mrad, rms]	≤ 2.3 / ≤ 0.14	
Δp/p (rms)	~ $4 \cdot 10^{-4}$	
β_{IP} [m]	0.1	
r_{IP} [mm, rms]	≤ 0.1	
l (bunch length) [m]	0.19 - 0.25	0.1
n (particle / bunch)	$3.6 \cdot 10^{10}$	$23 \cdot 10^{10}$
h (number of bunches)	200	200
f_{coll} (collision freq) [MHz]	~ 104	
l_{coll} (bunch distance) [m]	~ 2.88	
ΔQ_{sc} (space charge)	≥ 0.1	
ξ (beam-beam parameter)	0.014	0.01
L (luminosity) [$cm^{-2}s^{-1}$]	~ $6 \cdot 10^{32}$	

BetaCool program
JINR Dubna

Beam Equlibria Protons vs. Deuterons

Analytic formula for 15 GeV/c beams:
Cooling rate (electron cooling) ~ $1/(A^*gamma^2)$
→Factor of two larger for deuterons
Heating rate (IBS) ~ $1/(A^2{}^*beta^4{}^*gamma)$
→Approx. factor of two smaller for deuterons

Beam equilibria of deuterons roughly a factor of three smaller
ε^{geo} ~ 0.12 mm mrad (rms) for protons
→ ε^{geo} ~ 0.04 mm mrad (rms) for deuterons

Relative momentum spread also much smaller:
$\Delta p/p$ (rms) ~ 4^*10^{-4} (rms) for protons
→ $\Delta p/p$ (rms) ~ 2^*10^{-4} (rms) deuterons and half bunch length

Luminosity could be much higher with same number of particles
or cooling force can be reduced significantly
But space charge limit has to be considered

→ Reduce Electron Current of the Cooler for Deuterons: $I_{ecooler} < 1$ A

Beam Equilibria and Luminosities

JÜLICH FORSCHUNGSZENTRUM

Baseline design (deuteron)

e-Cooler parameter: E=4.1 MeV, I=0.5 A, B=0.2T, T_T=1eV, T_L=0.5meV, $B_r/B < 10^{-5}$, L=24m
RF parameter: f=89 MHz, U=300 kV

	HESR / 15GeV d	eRing / 3GeV
L [ring circumference, m]	~ 576	
ε^{norm} / ε^{geo} [mm mrad, rms]	≤ 2.4 / ≤ 0.15	
Δp/p (rms)	~ $2.4 \cdot 10^{-4}$	
β_{IP} [m]	0.1	
r_{IP} [mm, rms]	≤ 0.1	
l (bunch length) [m]	0.17 – 0.19	0.1
n (particle / bunch)	$1.1 \cdot 10^{10}$	$23 \cdot 10^{10}$
h (number of bunches)	173	172
f_{coll} (collision freq) [MHz]	~ 89.3	
l_{coll} (bunch distance) [m]	~ 3.3	
ΔQ_{sc} (space charge)	≥ 0.1	
ξ (beam-beam parameter)	0.014	0.030
L (luminosity) [$cm^{-2}s^{-1}$]	~ $1.8 \cdot 10^{32}$	

BetaCool program
JINR Dubna

Beam Preparation

Goal: 3.6-5.4·10^{12} polarized protons / deuterons in 100-200 bunches

Injection:

2·10^{11} pol. Protons / deuterons per cycle from SIS18
→ approx. 20 injections and bunch compression in h=2 cavity
Pre-cooling?

Acceleration:

h=1 resp. h=2 system to 15 GeV/c

Beam preparation:

beam cooling to equilibrium and
„adiabatic " bunching in h=100-200 system

Problem: Cooling time to equilibrium

Cooling Time to Equilibrium

Cooling time for 200 bunches:

At 3.8 GeV/c: 200s
At 15 GeV/c: 250000s with same initial long. and transv. emittances
With factor of four smaller initial emittance:100000s (27h!)

Cooling time for one or two bunches:

At 15 GeV/c: 40000-50000s
With factor of four smaller initial emittance: 800-2000s

Cooling time for unbunched beam:

At 15 GeV/c: 35000s
With factor of 4 smaller initial emittance: 1000s

→ Low initial emittance (pre-cooling) and cooling of unbunched beams at 15 GeV/c

Pre-cooling at lower momentum could be limited by space charge

Spin Dynamics in Circular Accelerators

JÜLICH FORSCHUNGSZENTRUM

Thomas-BMT Equation (Thomas [1927], Bargmann, Michel, Telegdi [1959]):

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\,\vec{S}\ x\ [(1+\gamma G)\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel}]$$

Lab system

Number of spin rotations per turns: $\nu_p = \gamma G$

$$G = \frac{g-2}{2},\ G_p = 1.7928473,\ G_{\bar{p}} = 1.800,\ G_d = -0.142987$$

Imperfection resonance:

$$\gamma G = k$$

k: integer

Field and positioning errors of magnets

Resonance strength ~ y_{rms}

→ **Vertical closed orbit correction**

→ **Partial Snake**

Intrinsic resonance:

$$\gamma G = (kP \pm Q_y)$$

P: Super-periodicity

Q_y: Vertical tune

Vertical focusing fields

Resonance strength ~$\sqrt{\varepsilon_y}$

→ **Vertical tune jump**

→ **Vertical coherent betatron oscillation**

Methods for Polarization Preservation

- < 5 GeV: Conventional methods

  → Correcting dipoles
  → Tune-jump quadrupoles

  ZGS, COSY, ELSA, …

- 5 - 10 GeV: Adiabatic spin-flip

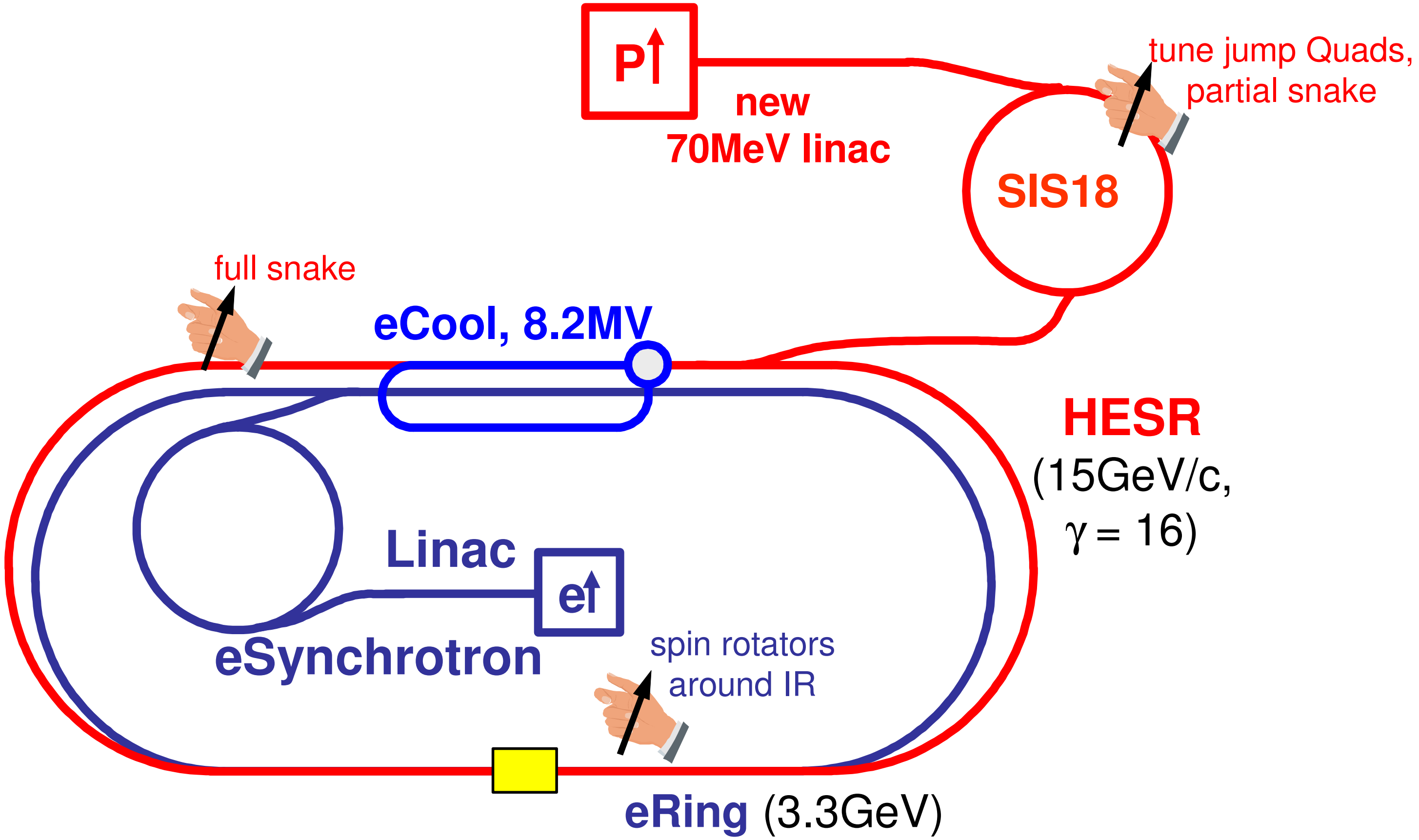
  → Partial snake
  → AC dipole

  AGS

- > 10 GeV: Full Siberian snake

  RHIC

Preliminary Scheme for ENC at FAIR



Scheme of the ENC@FAIR for electron-proton collisions

Contribution to the Particle Accelerator Conference, Vancouver, 2009

Proton Spin Resonances in SIS18

Acceleration to HESR injection: 369 MeV/c (70 MeV) – 3.8 GeV/c (3.0 GeV)

- Imperfection: 6

  2 (464 MeV/c) , 3 (1.26 GeV/c), 4 (1.87 GeV/c),
  5 (2.44 GeV/c), 6 (3.00 GeV/c), 7 (3.51 GeV/c)

  Correction: Acceleration rate 1 GeV/c per 0.05s
  → 3% partial snake (0.5 Tm solenoid)

- Intrinsic (P=12, Qy=3.28): 1

  0+ (1.44 GeV/c)
  12- (4.47 GeV/c)

  Correction: Depending on beam emittance
  20 mm mrad (norm.): $\varepsilon_R = 3\cdot10^{-3}$ → AC dipole
  1 mm mrad (norm.): $\varepsilon_R < 10^{-3}$ → Tune-jump quadrupole

Proton Spin Resonances in HESR

- Imperfection: 25

  4, 5, 6, ... , 28

  Strong: 8, 16, 24

- Intrinsic (P=1, Q_y=7.61): 50

  21-, 22-, ... , 45-

  -3+, -4+, ..., 11+

  Strong: 0+, 44-

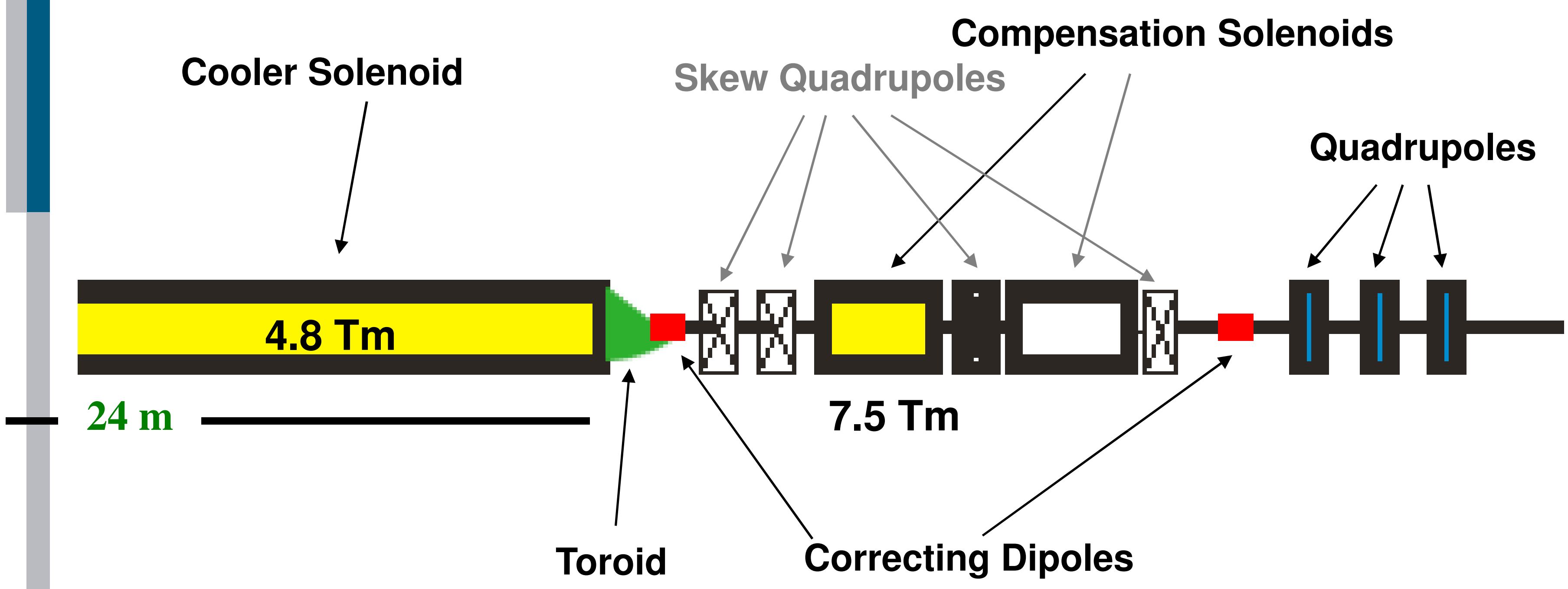
- Coupling: 50

  21-, 22-, ... , 45-

  -3+, -4+, ..., 11+

Correction: Full Siberian Snake

Magent System of the Electron Cooler



Integral magnetic field : ~20Tm

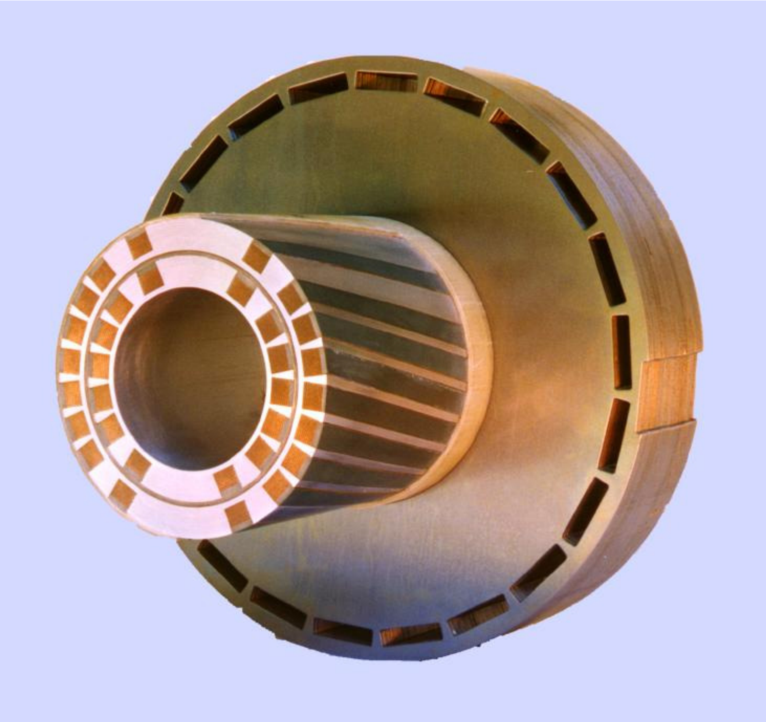
Required for full Siberian snake: 60 Tm
(Proc. of SPIN 2004)

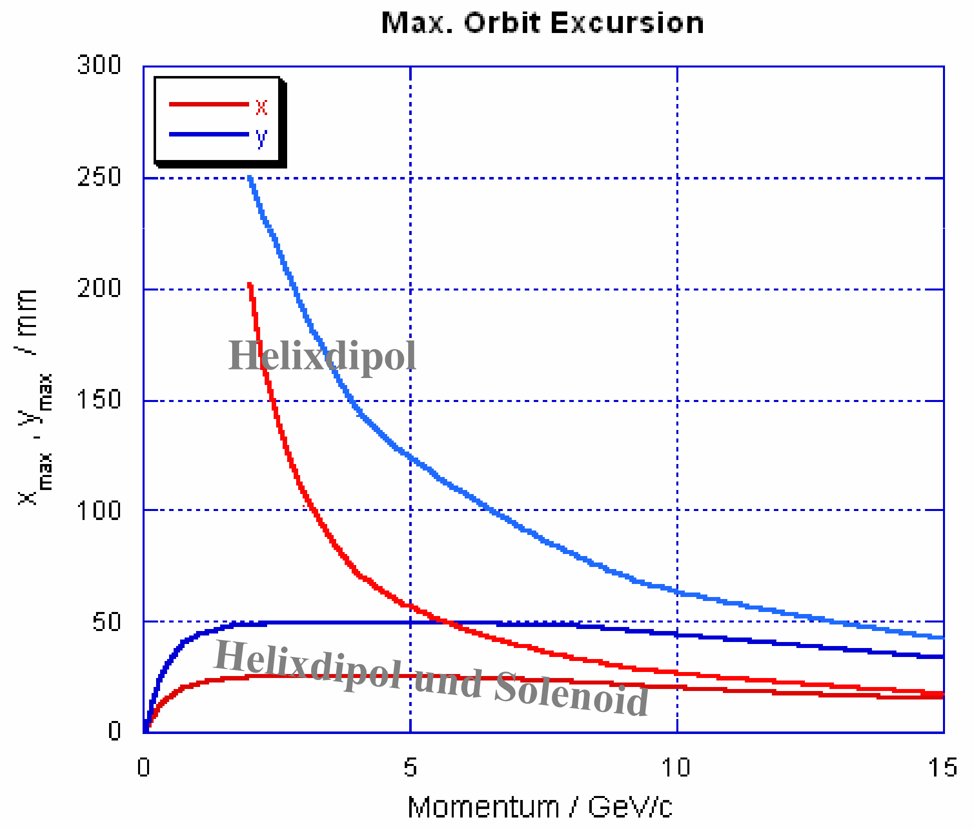
In Collaboration with Y.M. Shatunov et al. (BINP Novosibirsk)

Siberian Snake for HESR

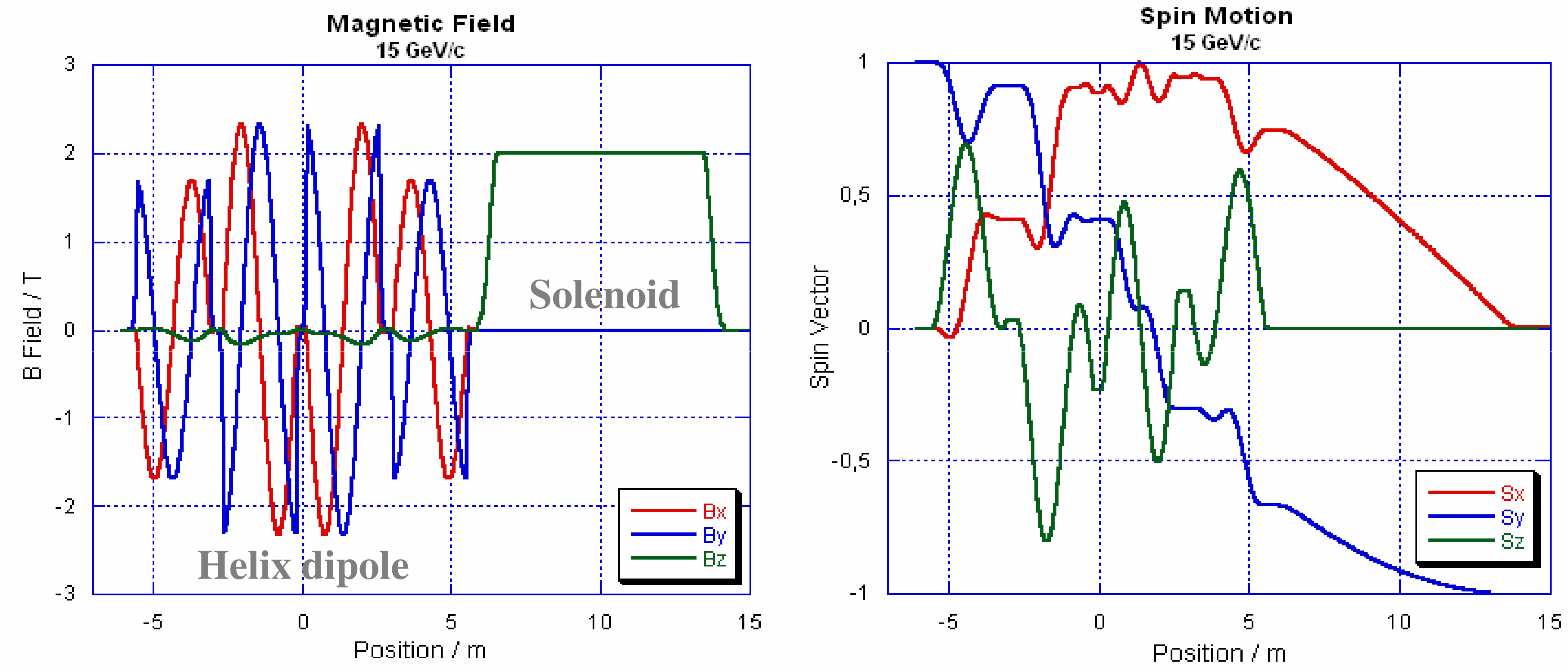
RHIC Helix dipole snake

4 superconducting helix: 4T, 2 m length
with almost 360° twist of conductors





Siberian Snake for HESR



HESR: 4 helix dipole (2.5 T) and 15 Tm solenoid

In Collaboration with A.U. Luccio, BNL

Polarized Protons vs. Deuterons

Polarization states:	(2S+1) → 3 states for Spin 1
Vector polarization:	$P_z = (n_+ - n_-) / (n_+ + n_- + n_0)$ $P_z^{max} = \pm 1$
Tensor polarization:	$P_{zz} = (1 - 3n_0) / (n_+ + n_- + n_0)$ $P_{zz}^{max} = 1, -2$
Gyromagnetic anomaly:	$G_p / G_d = -12.6$
Spin tune:	$\gamma_p G_p / \gamma_d G_d = -25.2$
Spin resonance strength:	13 (low energies) to 25 (high energies) times weaker 25 times further apart
Strength of spin resonances:	same for vector and tensor polarization
Siberian snake:	much stronger magnetic fields

Deuteron Spin Resonances

- SIS18: 0

  No imperfection resonance

  No intrinsic resonance

  One weak gradient error resonance 3- (3.16 GeV/c)

  No Correction needed

- HESR: 3

  Imperfection resonance: –1 (13.0 GeV/c)

  Intrinsic resonances: –8+ (4.76 GeV/c), 7- (7.78 GeV/c)

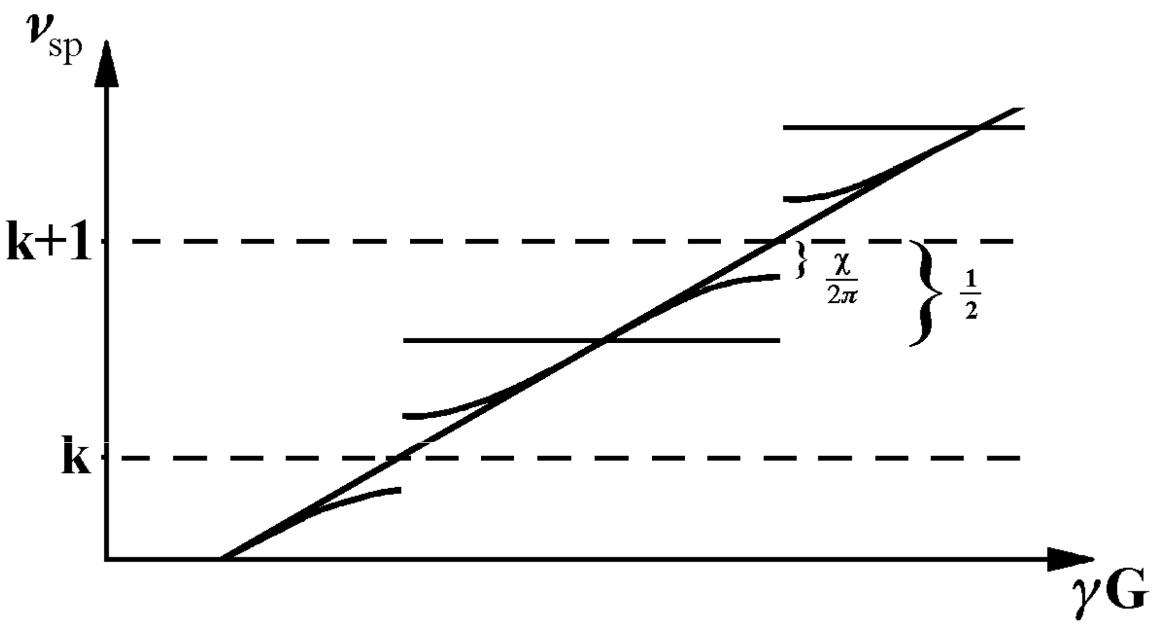
  Two weak coupling resonances

  Correction: Partial snake, tune-jump quads

  No longitudinal polarized beam!

Partial Snake for HESR

Spin Tune with Partial Snake

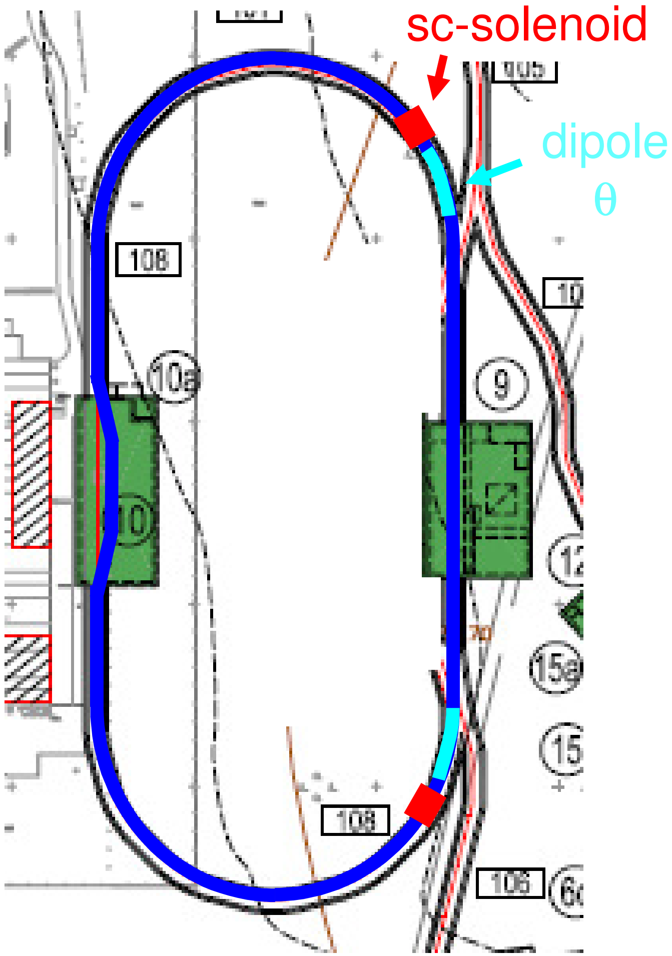


- Full Siberian snake for protons
- ONLY 20% partial snake for deuterons

Move working point close to integer → $.90 < Q_{frac} < .10$

like in the AGS

Polarization Preservation in Electron Ring



- electron spin must be vertical in arcs, otherwise $\tau_{depol} < 20\text{min}$ (D. Barbers / DESY)

- sc solenoids and last bending for longitudinal spin direction at IP

spin dynamics requirements:

$\gamma \bullet a = n + ½$ (a=0.0011596)

and

$\Delta\phi_{spin} = \gamma \bullet a \bullet \theta$ ($\Delta\phi_{spin}$=90°)

1) γ=6467→E=3.305GeV, $\gamma \cdot a$=7.5 and θ=12.00°

2) γ=5605→E=2.864GeV, $\gamma \cdot a$=6.5 and θ=13.85°

(-44% SR-power)

Lattice design under consideration

Extension for Polarized Beams

- Polarized ion and electron sources
- p/d acceleration via p-Linac or UNILAC
- Several polarimeter

- Systems for spin preservation

Electrons

→ correction system for polarized injector

→ polarization preservation and preparation in electron ring

Protons

→ correction system for SIS18

(space available?, 2 times 0.5 m needed)

→ Full Siberian snake for HESR

(space reserved)

Deuterons

→ Partial snake and tune-jump quads for HESR

No longitudinal polarized beam

Summary

- Protons (baseline) : $L = 2 \cdot 10^{32}\ cm^{-2}s^{-1}$

  β_{IP} [m] = 0.3 m, $\Delta Q_{sc} \geq 0.05$, $E_{ecooler} = 8.2$ MeV, $I_{ecooler} = 3$ A

  Upgrade of the planned electron cooler needed

- Deuterons (baseline): $L = 1.8 \cdot 10^{32}\ cm^{-2}s^{-1}$

  β_{IP} [m] = 0.1 m, $\Delta Q_{sc} \geq 0.1$, $E_{ecooler} = 4.1$ MeV, $I_{ecooler} = <1$ A

  Modifications of the IP concept required

- Protons (advanced): $L = 6 \cdot 10^{32}\ cm^{-2}s^{-1}$

  β_{IP} [m] = 0.1 m, $\Delta Q_{sc} \geq 0.1$, $E_{ecooler} = 8.2$ MeV, $I_{ecooler} = 3$ A

Major Tasks and Extensions

Beam dynamics simulations:

- Lattice for electron ring
- Accumulation, acceleration and bunching process in HESR
- Ion-optics at IP / detector integration / Crab crossing
- Chromaticity correction
- Beam – beam effect in low energy e-n collider
- Space charge for protons / deuterons

Hardware extensions and modifications:

- Polarized electron injector and ring
- Modification of the interaction region
- Extension of the electron cooler
- Additional 52 - 104 MHz, 300 kV cavity required