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FORSCHUNGSZENTRUM

Performance and Perspectives of Hadron Storage Rings

8th International Conference on Nuclear Physics at Storage Rings - STORI'11, Frascati

October 12, 2011 | Andreas Lehrach

Outline

Facility for **A**ntiproton and **I**on **R**esearch FAIR

High-**E**nergy **S**torage **R**ing HESR

Status Start Version and Upgrade Options

Cooler **S**ynchrotron COSY

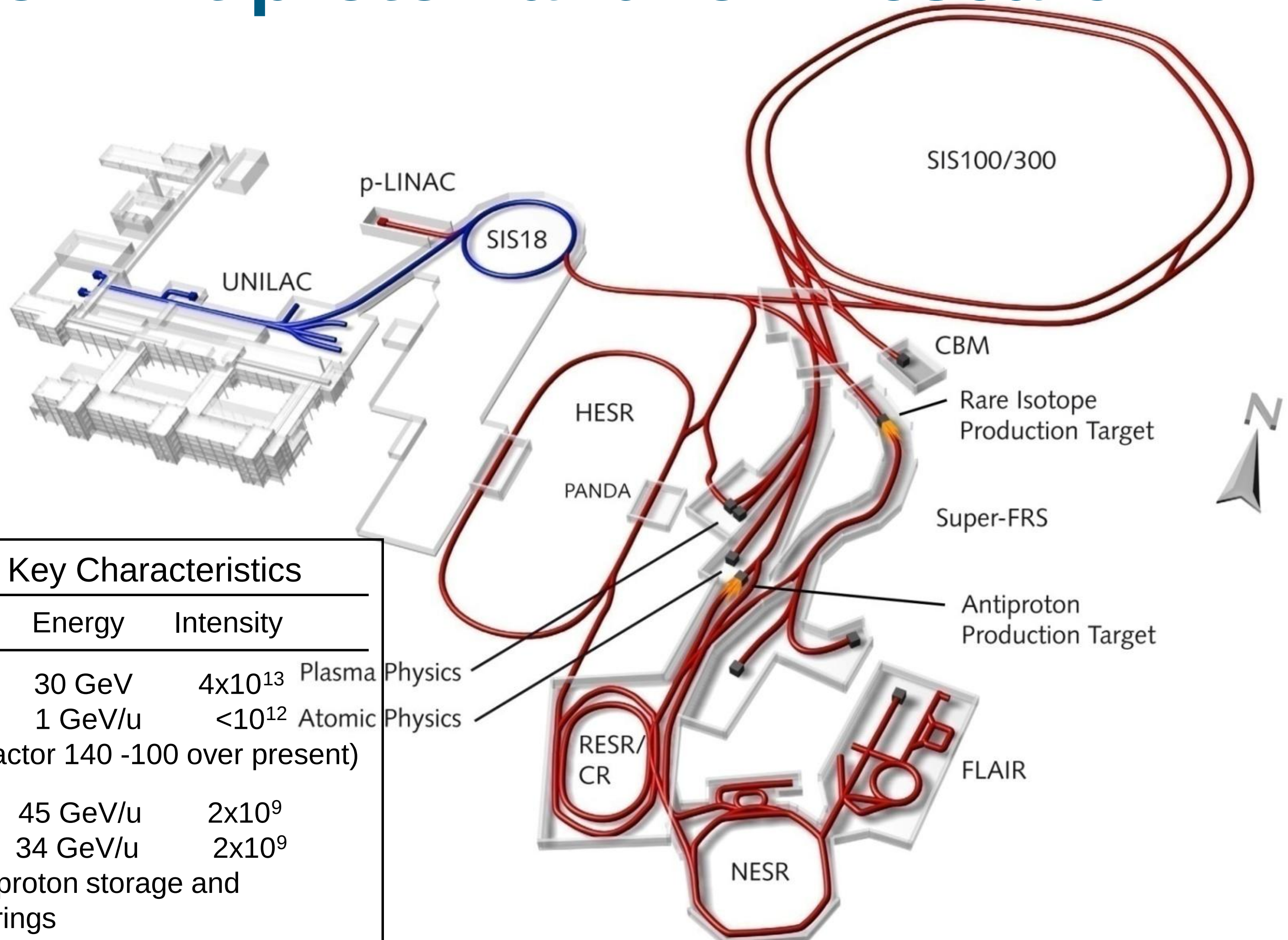
Upgrade Program

Electric **D**ipole **M**oment **S**torage **R**ing

Current Activities and Perspectives

Summary / Outlook

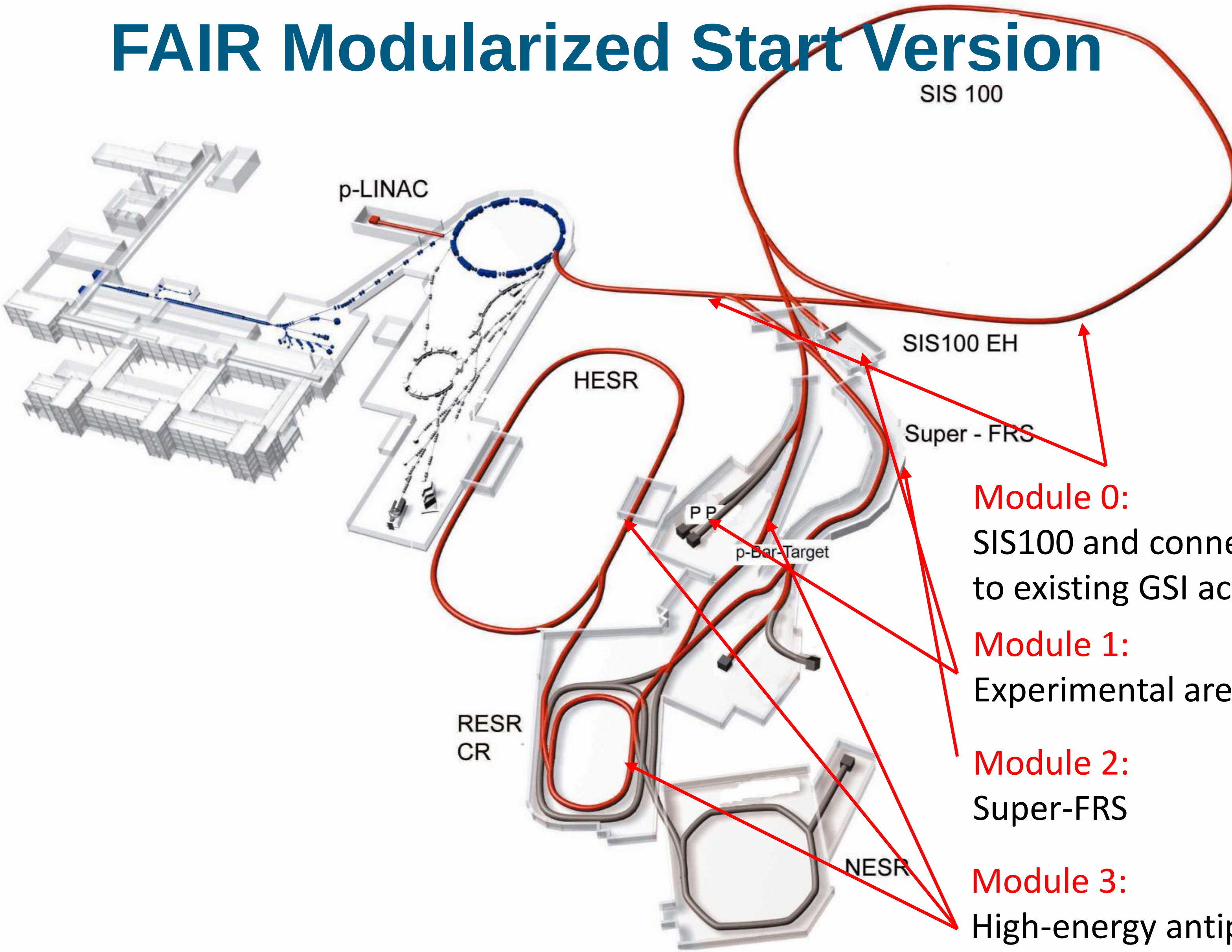
FAIR
Facility for Antiproton and Ion Research



Accelerator Components & Key Characteristics

Ring/Device	Beam	Energy	Intensity
SIS100 (100Tm)	protons	30 GeV	4×10^{13}
	^{238}U	1 GeV/u	$<10^{12}$
	(intensity factor 140 -100 over present)		
SIS300 (300Tm)	^{40}Ar	45 GeV/u	2×10^{9}
	^{238}U	34 GeV/u	2×10^{9}
CR/RESR/NESR	ion and antiproton storage and experiment rings		
HESR	antiprotons	14 GeV	$\sim 10^{11}$
SuperFRS	rare-isotope beams	1 GeV/u	$<10^{9}$

FAIR Modularized Start Version



Module 0:
SIS100 and connection to existing GSI accel.

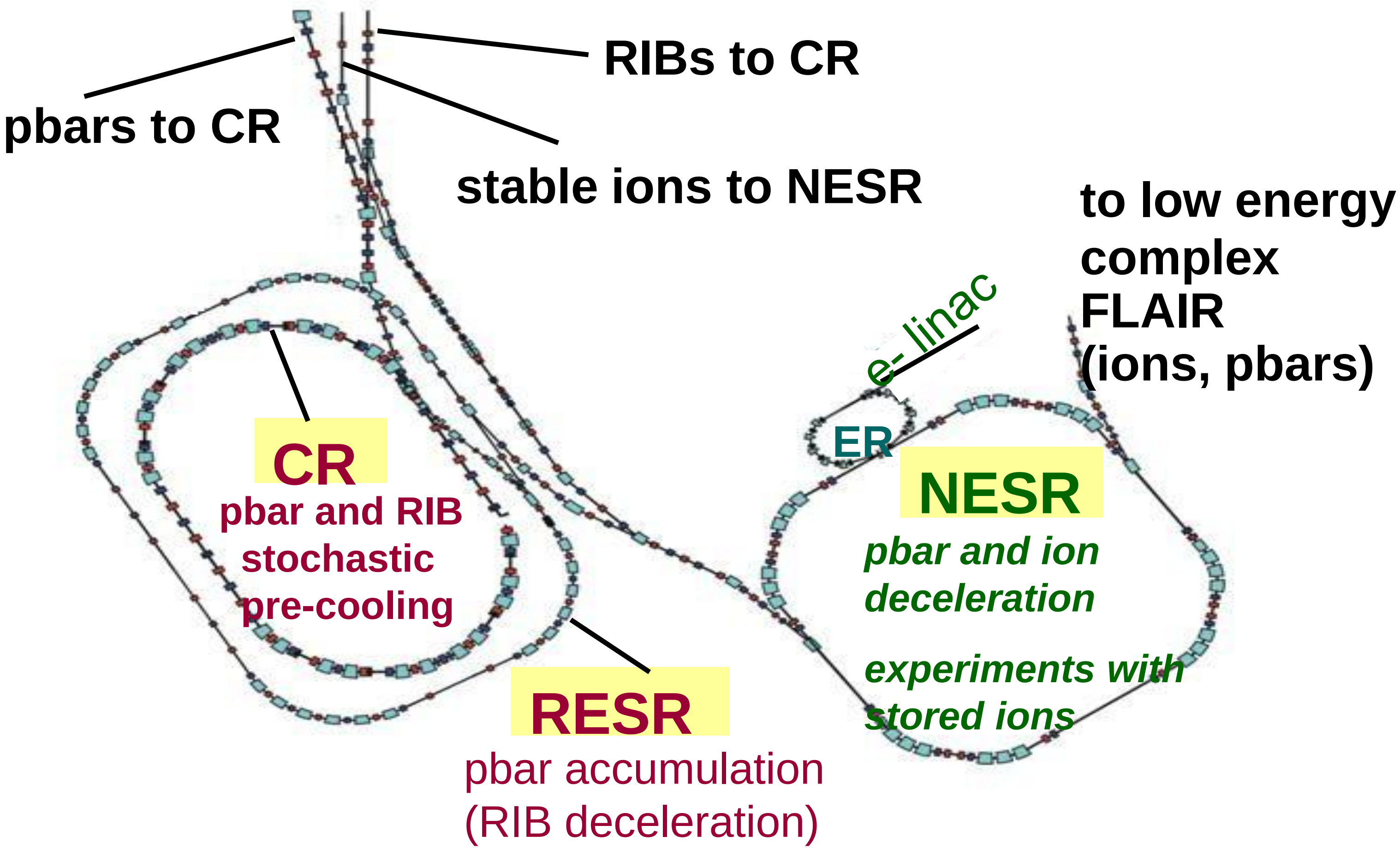
Module 1:
Experimental areas

Module 2:
Super-FRS

Module 3:
High-energy antiprotons (p-linac, pbar-target, CR, HESR)

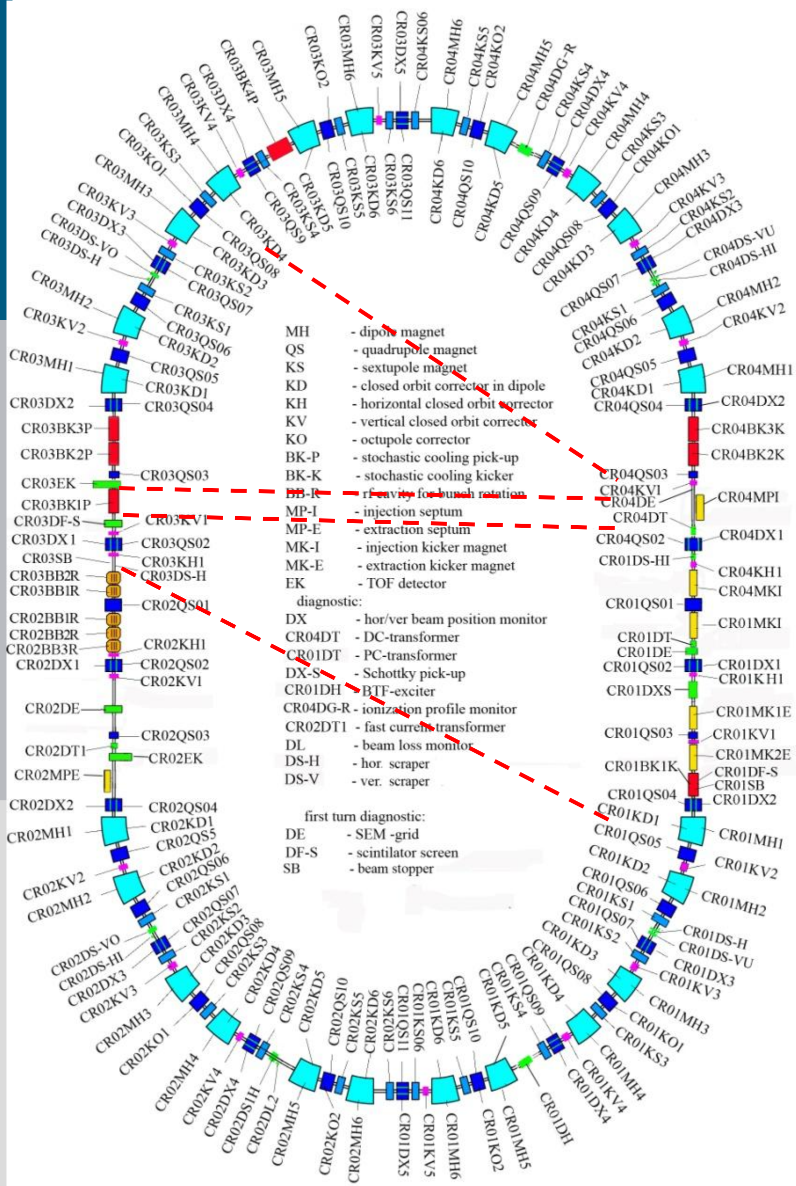
Courtesy: S. Richter (GSI)

FAIR 13 Tm Storage Rings



Courtesy: M. Steck (GSI)

Collector Ring CR



circumference 221.5 m
magnetic bending power 13 Tm
large acceptance $\varepsilon_{x,y}$ = 240 (200) mm mrad
$\Delta p/p = \pm$ 3.0 (1.5) %

fast stochastic cooling (1-2 GHz) of antiprotons (10 s) and rare-isotope beams (1.5 s)

- *fast bunch rotation at h=1 (U_{rf} =200 kV)*
- *adiabatic debunching*
- *optimized ring lattice (slip factor) for proper mixing*
- *large acceptance magnet system*

additional feature:
isochronous mass measurements of rare isotope beams

option: upgrade of rf system to 400 kV and stochastic cooling to 1-4 GHz

Talk by S. Litvinov (GSI)

Experimental Requirements

PANDA (Strong Interaction Studies with Antiprotons):

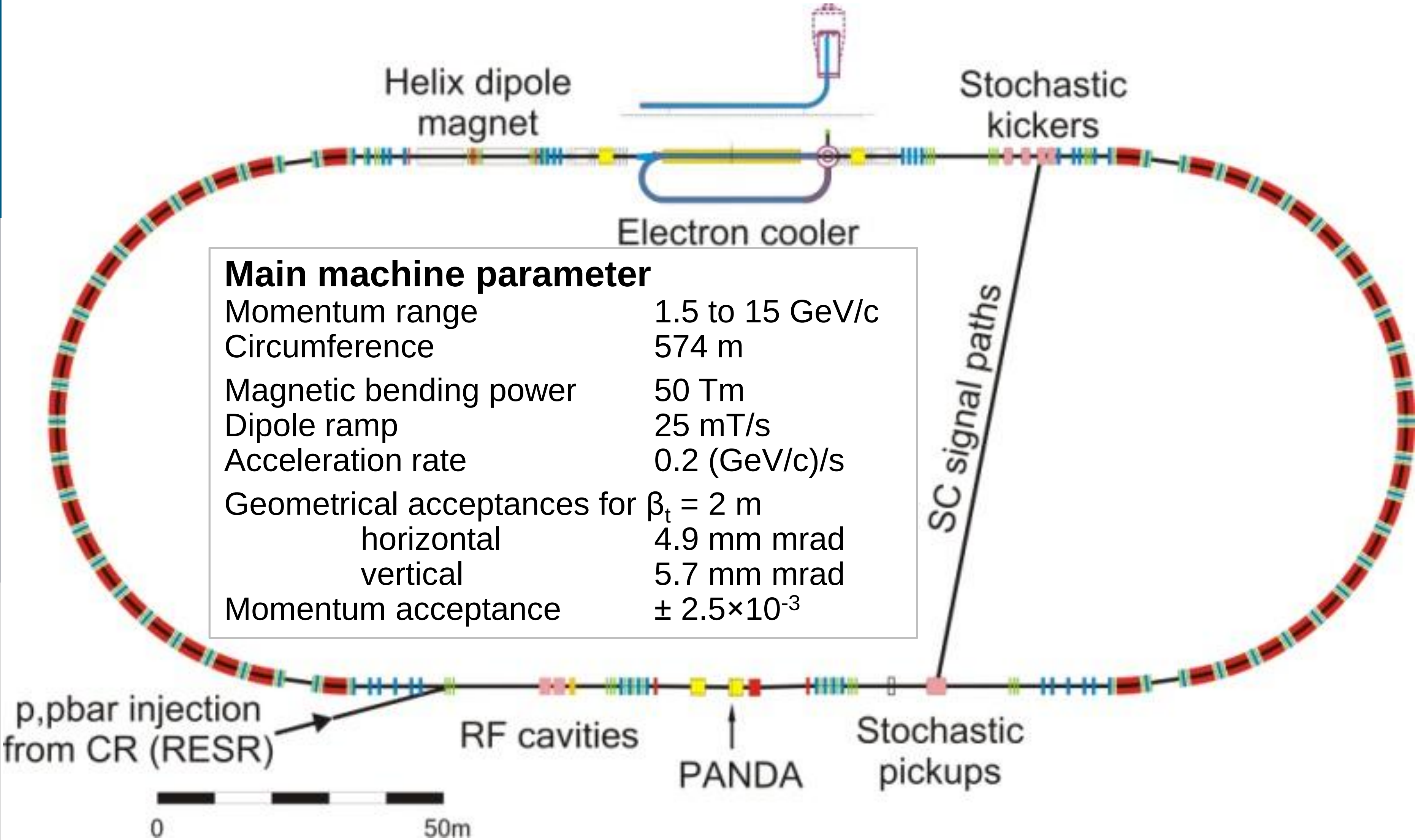
Momentum range: 1.5 to 15 GeV/c (Antiprotons)

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



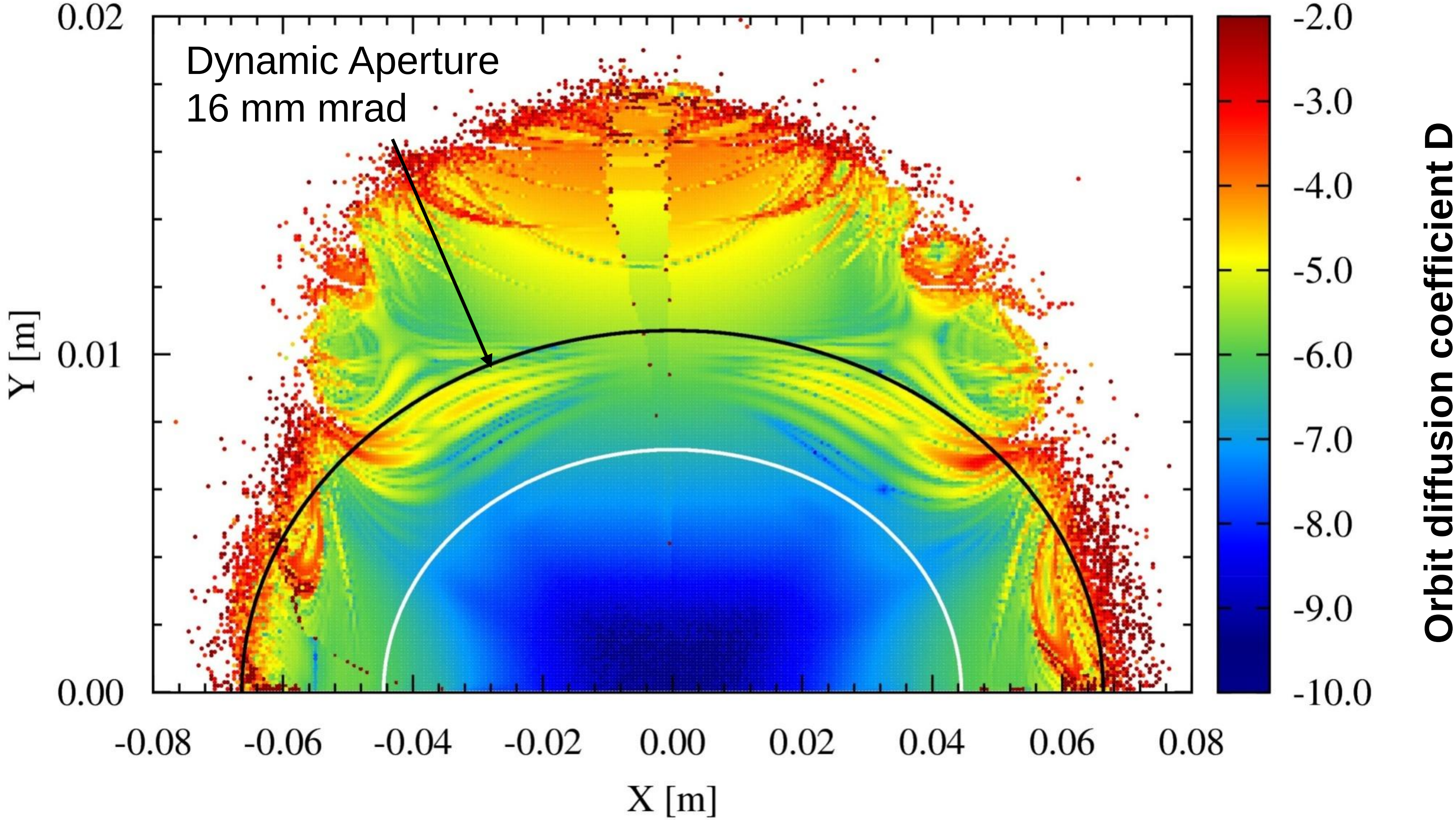
Main machine parameter

Momentum range	1.5 to 15 GeV/c
Circumference	574 m
Magnetic bending power	50 Tm
Dipole ramp	25 mT/s
Acceleration rate	0.2 (GeV/c)/s
Geometrical acceptances for β_t = 2 m	
horizontal	4.9 mm mrad
vertical	5.7 mm mrad
Momentum acceptance	$\pm 2.5\times10^{-3}$

Beam Dynamics Simulations

- **Beam Accumulation:** stochastic cooling and barrier bucket cavity
  (Jülich stochastic cooling code)
- Closed-orbit correction: steering concept
  (MAD-X)
- **Dynamic aperture calculations:** optimization of beam stability and ring acceptance
  (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 code)

Dynamic Aperture



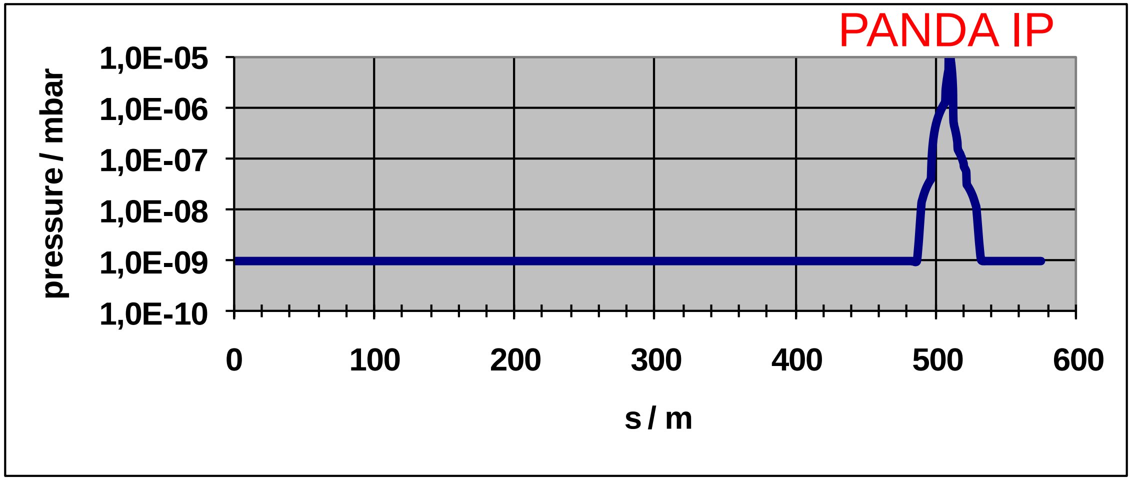
Orbit diffusion coefficient (e.g. after 1000 and 2000 turns):

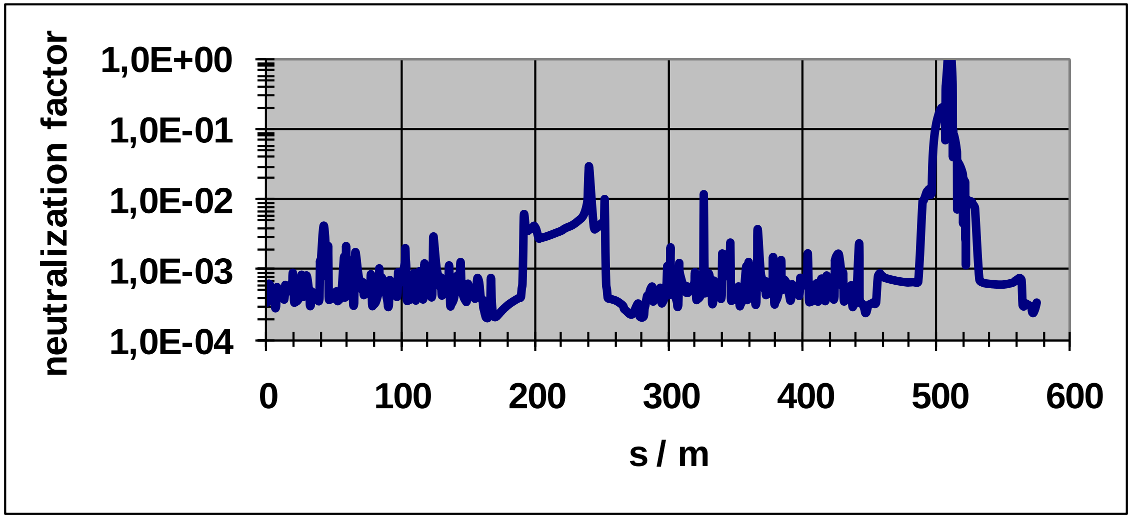
$$D = \log_{10}\left[\sqrt{\left(Q_x^{(2)} - Q_x^{(1)}\right)^2 + \left(Q_y^{(2)} - Q_y^{(1)}\right)^2}\right]$$

D ≤ -7 longterm stable

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

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

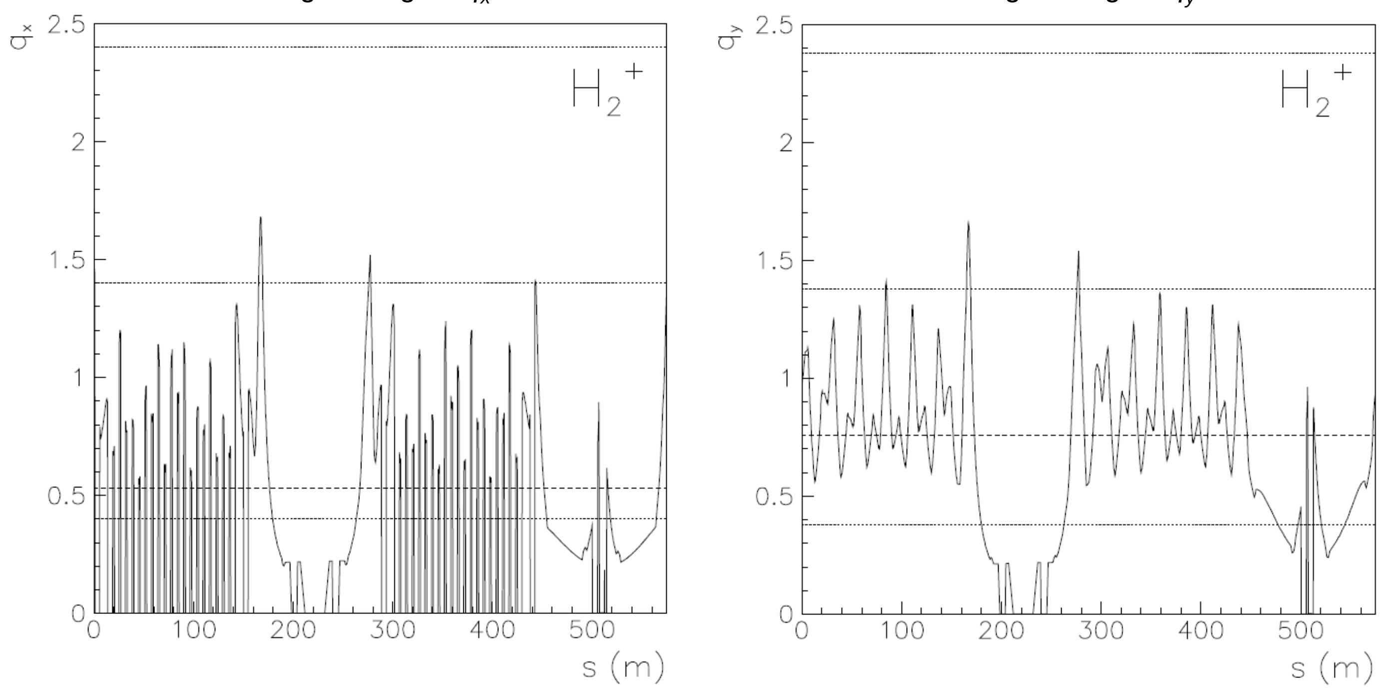
Resonance frequencies: $(8 - Q_x) = 0.4005$ and $(8 - Q_y) = 0.3784$,
$(9 - Q_x) = 1.4005$ and $(9 - Q_y) = 1.3784$
$(10 - Q_x) = 2.4005$ and $(10 - Q_y) = 2.3784$

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

horizontal — vertical

Dotted lines: $(8 - Q_x)$, $(9 - Q_x)$ and $(10 - Q_x)$
Dashed line: ring-averaged $q_x^{rms} = 0.533$

Dotted lines: $(8 - Q_y)$, $(9 - Q_y)$ and $(10 - Q_y)$
Dashed line: ring-averaged $q_y^{rms} = 0.759$



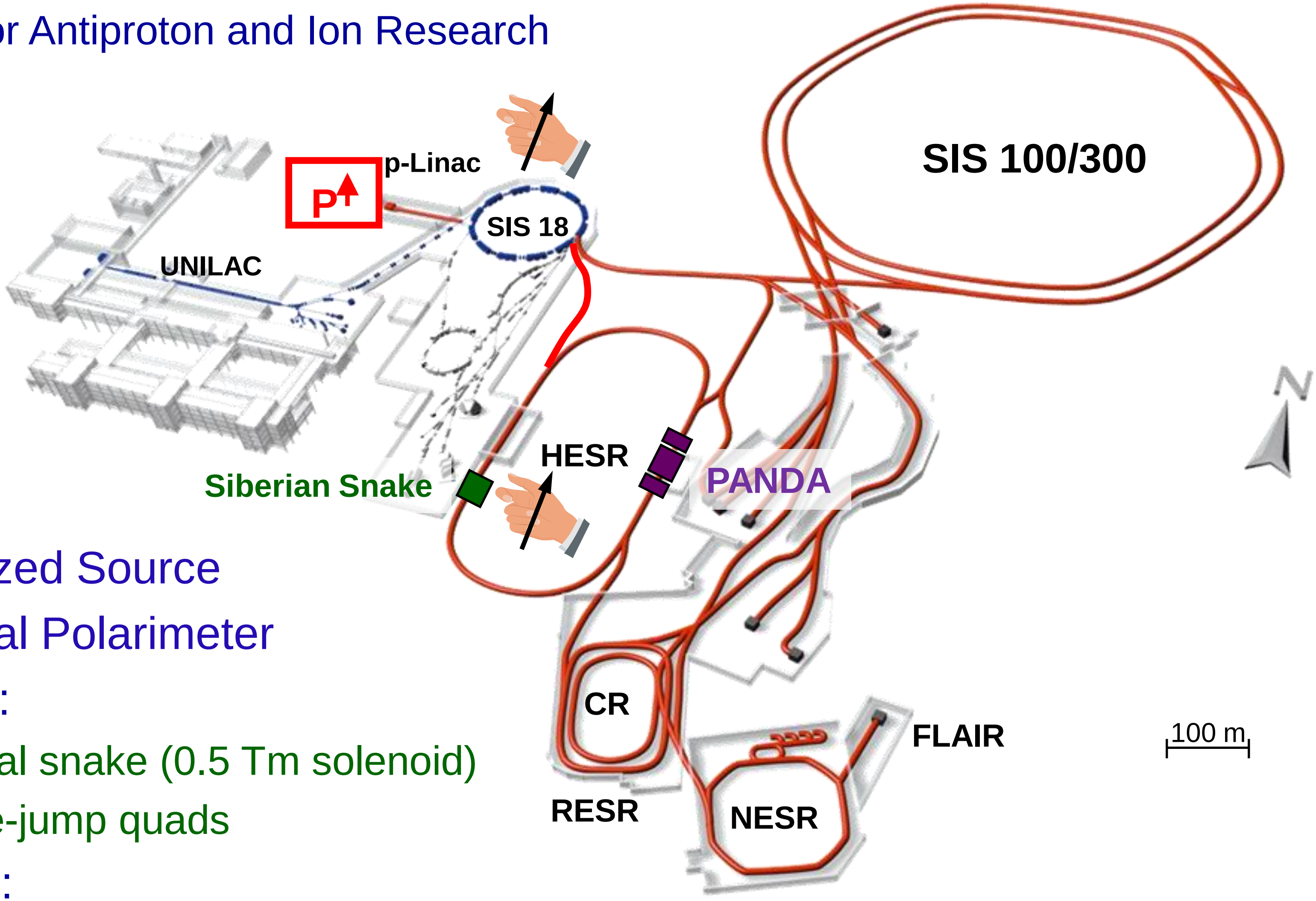
$N_{\bar{p}} = 1.0 \cdot 10^{11}$

$p_{\bar{p}} = \mathbf{15.0\ GeV/c}$

F. Hinterberger, Ion Trapping in the HESR ring (in preparation)

Polarized Beams at FAIR

Facility for Antiproton and Ion Research



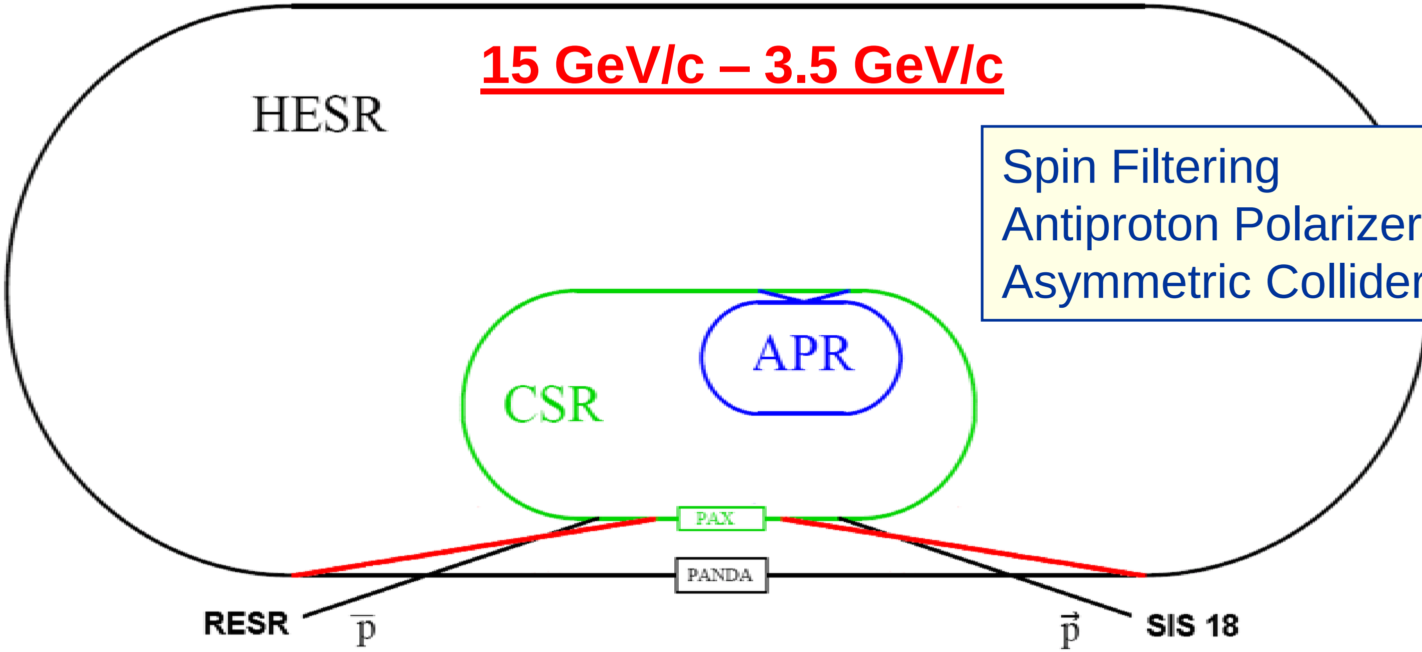
- Polarized Source
- Several Polarimeter
- SIS18:

3% partial snake (0.5 Tm solenoid) and tune-jump quads

- HESR:

Siberian Snake

Polarized Proton-Antiprotons Collider



Spin Filtering
Antiproton Polarizer (APR)
Asymmetric Collider

- Luminosity (baseline): $L = 1.2 \cdot 10^{31}$ cm^{-2}s^{-1}

β_{IP} [m] = 0.1 m, $\Delta Q_{sc} \geq 0.02$, $E_{ecooler}$ = 8.2 MeV, $I_{ecooler}$ = 1 A

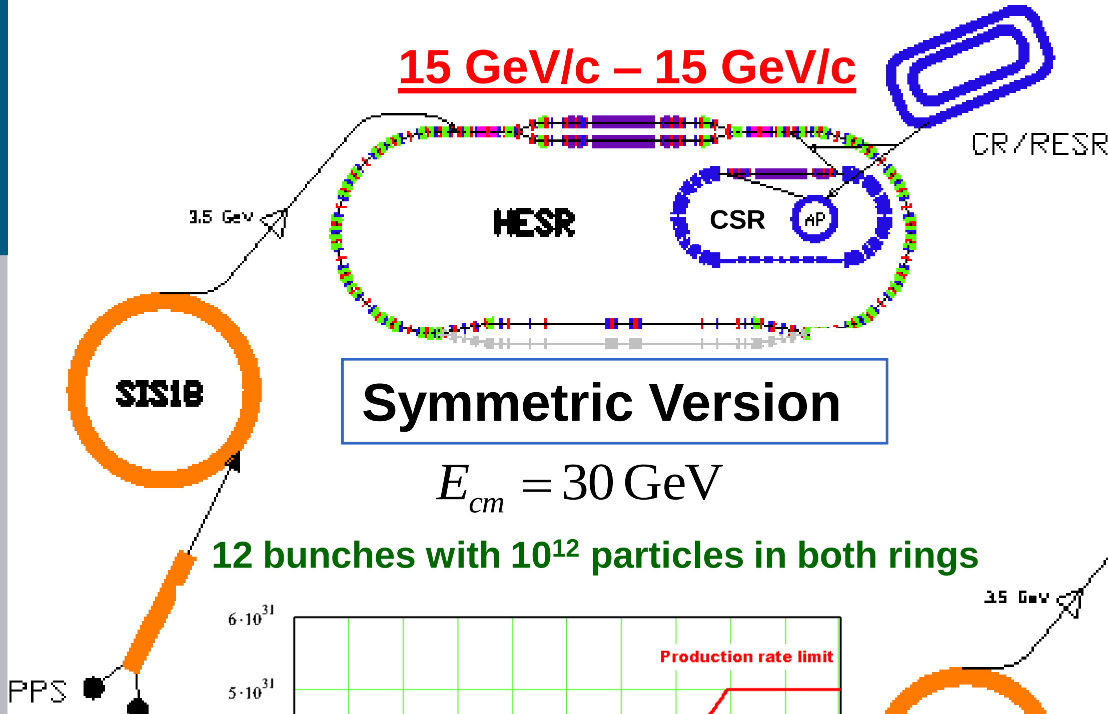
Upgrade of the planned electron cooler needed

Proposal by PAX collaboration, spokespersons: F. Rathmann (FZ Jülich), P. Lenisa (Ferrara)
178 Collaborators, 36 institutions (15 EU, 21 NON-EU)

Polarized Proton-Antiproton Collider

"Conceptual Design for a Polarized Proton-Antiproton Collider Facility at GSI" by F. Bradamante, I. Koop, A. Otboev, V. Parkhomchuk, V. Reva, P. Shatunov, Yu. M. Shatunov

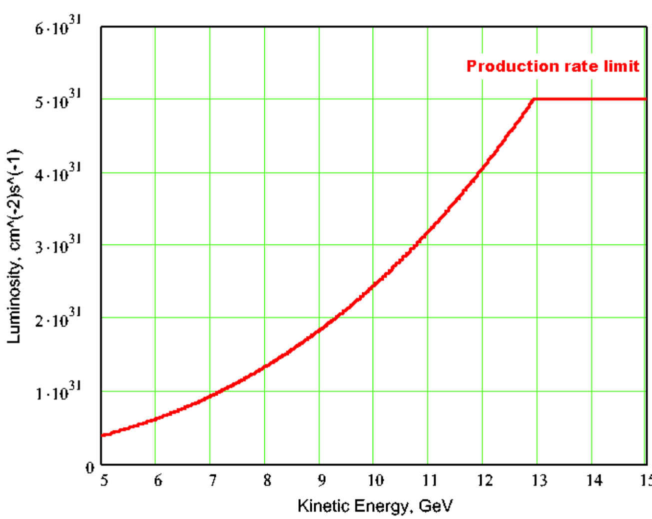
15 GeV/c – 15 GeV/c



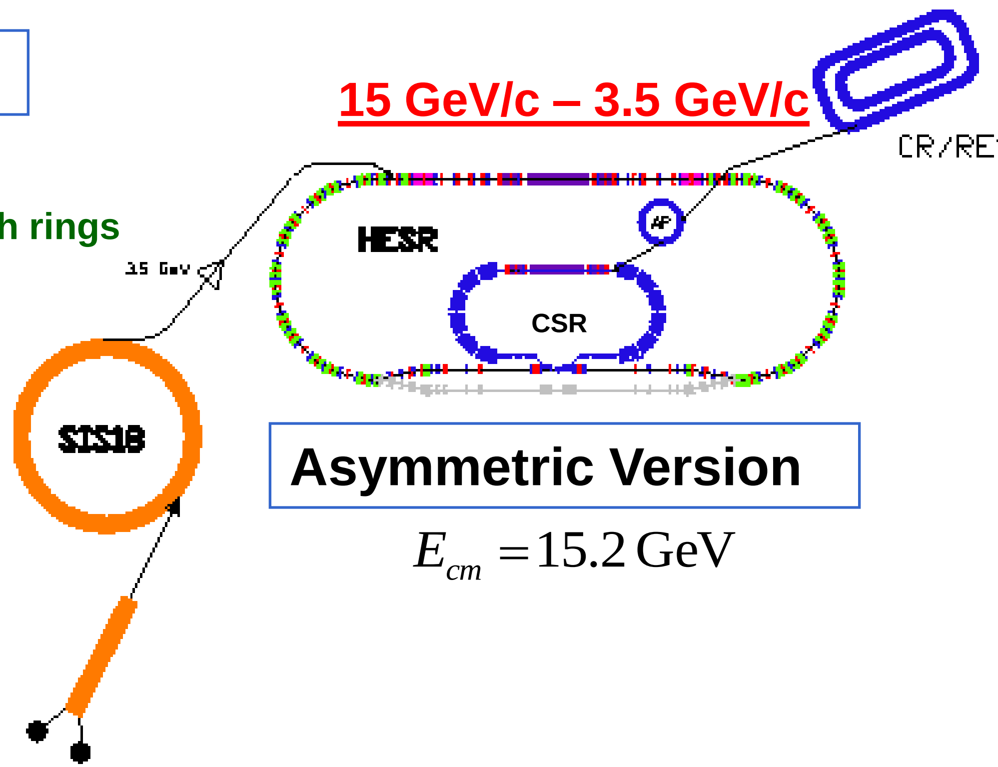
Symmetric Version

$$E_{cm} = 30\,\text{GeV}$$

12 bunches with 10^{12} particles in both rings



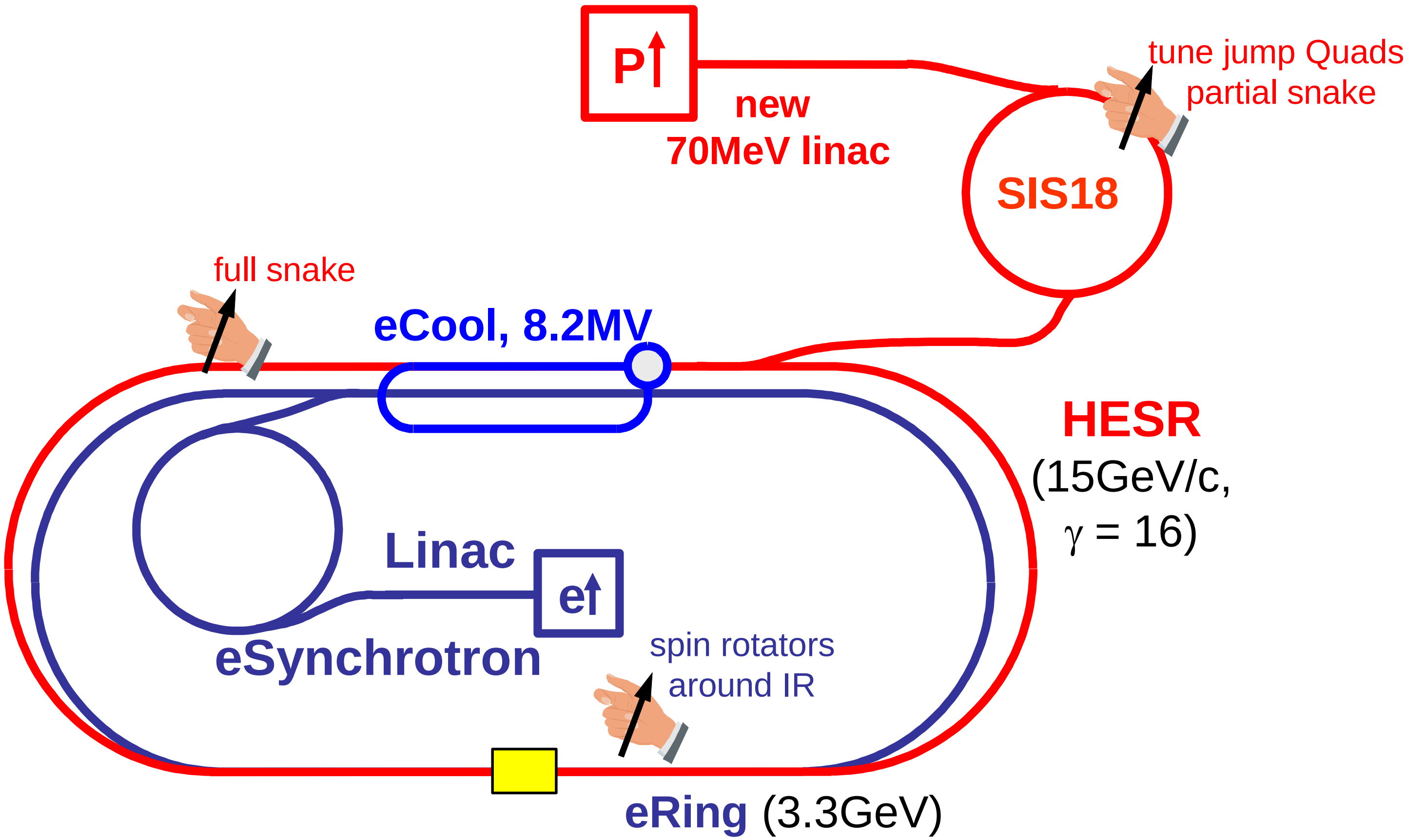
15 GeV/c – 3.5 GeV/c



Asymmetric Version

$$E_{cm} = 15.2\,\text{GeV}$$

Polarized Electron-Nucleon Collider ENC



Accelerator Working Group:

Luminosity ENC

- 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

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

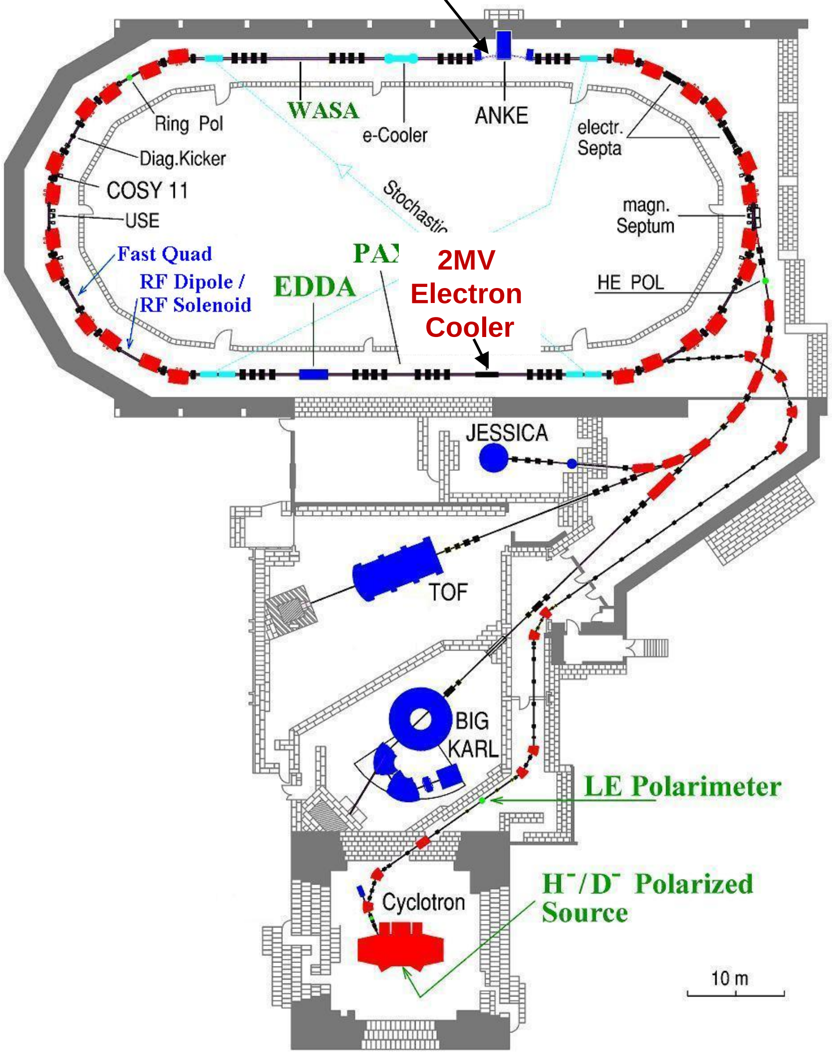
  β_{IP} [m] = 0.1 m, $\Delta Q_{sc} \geq 0.1$, $E_{ecooler}$ = 8.2 MeV, $I_{ecooler}$ = 3 A

  Modifications of the IP concept required

- 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, $I_{ecooler} \leq 1$ A

Cooler Synchrotron COSY



Ions: (pol. & unpol.) p and d

Momentum: 300/600 to 3700 MeV/c for p/d, respectively

Circumference of the ring: 184 m

Electron Cooling:

Beam Accumulation at Injection

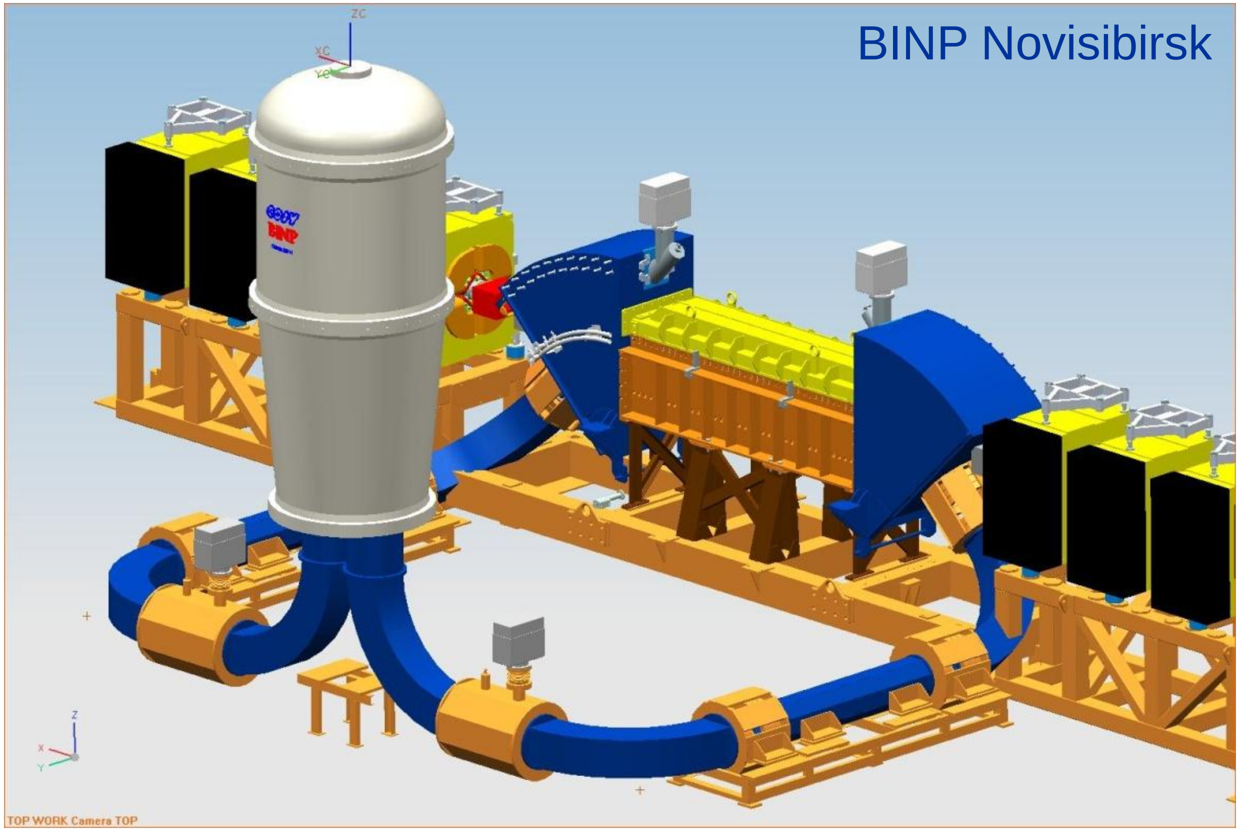
Stochastic Cooling:

Counteracting beam-target interacting and intra-beam scattering

Targets:

- Internal: solid, cluster, atomic beam
- External: solid, liquid

New 2 MV Electron Cooler at COSY



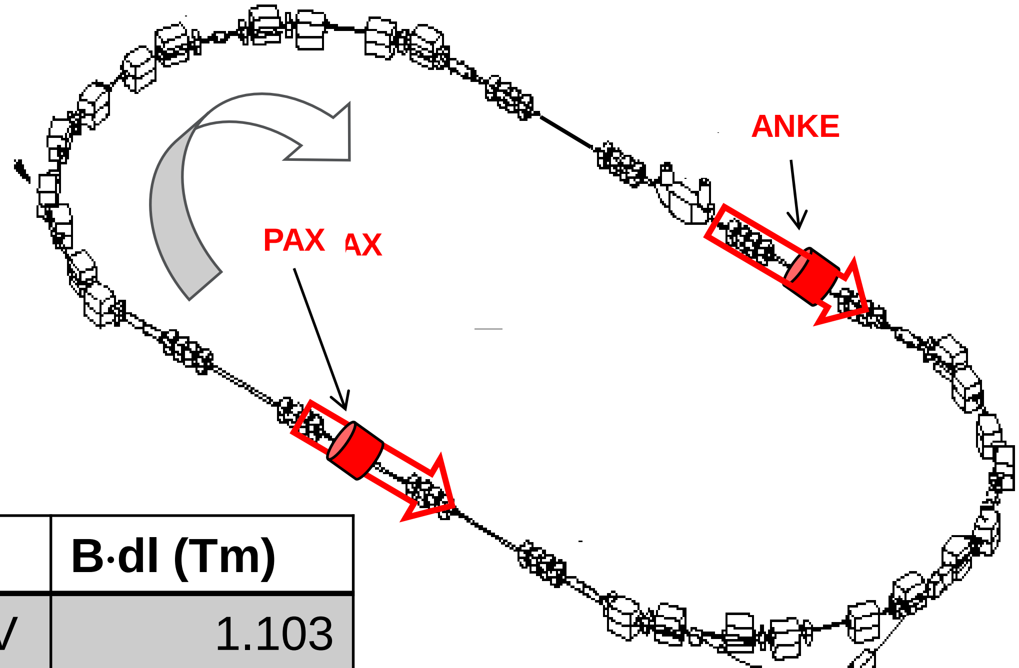
- Energy Range: 0.025 ... 2 MeV
- High Voltage Stability: $< 10^{-4}$
- Electron Current: 0.1 ... 3 A
- Electron Beam Diameter: 10 ... 30 mm
- Cooling section length: 2.694 m
- Magnetic field (cooling section): 0.5 ... 2 kG

Installation at COSY in the winter shutdown 2011/12

Courtesy: J. Dietrich (FZJ)

Siberian Snake for COSY

- Should allow for flexible use at two locations
- Fast ramping <30s
- Integral long. field >4.7 T m
- Cryogen-free system
- Magnet ordered (Cryogenic)



	B·dl (Tm)
COSY Injection Energy 45 MeV	1.103
$pn \rightarrow \{pp\}_s \pi^-$ at 353 MeV	3.329
PAX at COSY 140 MeV	1.994
PAX at AD 500 MeV	4.090
T_{max} at COSY 2.88 GeV	13.887

Installation at COSY end of 2012

Magnetic Moment and Electric Dipole Moment

Particle	Magnetic Moment	Current EDM limit
Proton	1.410 606 662 (37) · 10^{-26} J T^{-1}	< $7.9 \cdot 10^{-25}$ e·cm
Neutron	-0.966 236 41 (23) · 10^{-26} J T^{-1}	< $1.6 \cdot 10^{-26}$ e·cm
Deuteron	0.433 073 465 (11) · 10^{-26} J T^{-1}	
Helium-3	-1.074 552 982 (30) · 10^{-26} J T^{-1}*	

* Shielded value for Helium-3: difference for proton (shielded / unshielded) would be ~$2 \cdot 10^{-31}$ J T^{-1}

Standard Model prediction:

$$\left| d_N^{SM} \right| < 10^{-32}\, \mathrm{e} \cdot \mathrm{cm}\,,\; N = n, p$$

Frozen Spin Method (FSM)

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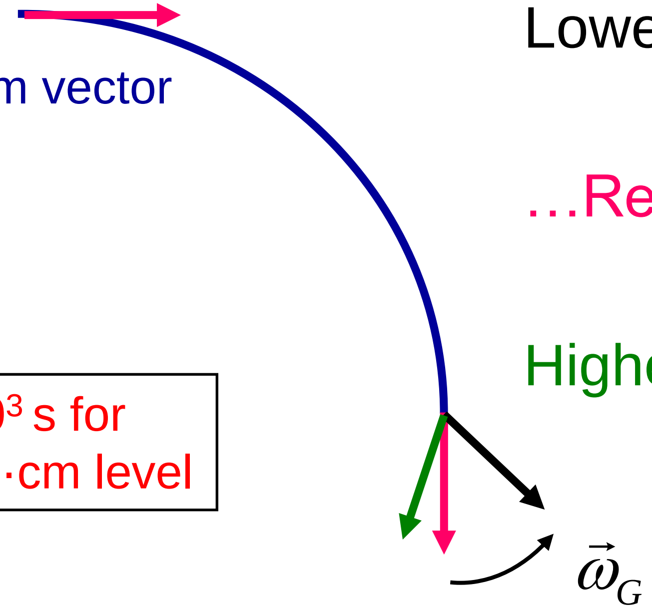


Spin coherence time: 10^3 s for measurement on 10^{-29} e·cm level

For $\vec{\beta}\cdot\vec{B}=\vec{\beta}\cdot\vec{E}=0$, the spin precession (magnetic moment) relative to the momentum direction is given by

$$\vec{\omega}_G=\frac{e}{m}\left[G\cdot\vec{B}+\left(\frac{1}{\gamma^2-1}-G\right)\frac{\vec{\beta}\times\vec{E}}{c}\right],\qquad G=\frac{g-2}{2}$$

Systematic Effects

Dominant systematic error: non-zero average value for the vertical component of the electric field $\langle E_V \rangle \equiv \langle \vec{E} \cdot \vec{B} \rangle / B \neq 0$

$$\omega_{E_V} \cong \frac{\mu \langle E_V \rangle}{\beta c \gamma^2}$$

Radial precession

The ratio of the spin precession (due to the vertical electric field) to the EDM spin precession

$$R \cong \frac{G\mu}{d\beta} \frac{\langle E_V \rangle}{E_R}$$

Needs to be minimized

The EDM signal is a difference for CW and CCW beams.
The precession ω_{E_V} , *relative to ω_{edm}, changes sign when we inject* the beam clock-wise (CW) vs. counter-clockwise (CCW).

Without this symmetry $\langle E_V \rangle / E_R \leq 3 \cdot 10^{-14}$ would be required for an EDM systematic error of 10^{-27} e · cm.

R&D Brookhaven Proposal

A Magic Proton Ring for 10^{-29} e·cm

Clock-wise (CW) & Counter-clock-wise (CCW) storage

Magic momentum for protons: p = 700.74 MeV/c

Ring circumference: ~240m

R&D Activity	Goal	Test
Internal Polarimeter	Spin as a function of time Systematic errors < 1 ppm	EDM at COSY
	Full-scale polarimeter	EDM at COSY
Spin Coherence Time	~10^3 s	EDM at COSY
Beam Position Monitor	Resolution 10 nm, 1 Hz BW 64 BPMs, 10^7 s measurement time → 1 pm (stat.) relative position (CW-CCW)	BNL RHIC IP
E-field Deflector	~17 MV/m for 2 cm plate separation	BNL

Courtesy: Storage Ring EDM Collaboration
21 Institutions, 80 Collaborators
http://www.bnl.gov/edm

Deuteron EDM Proposal

Deuteron momentum: p = 1 GeV/c,

Ring parameter: R_B = 8.4 m, <R> ~ 10 m, C = 85m

Deflectors: E_R = -12 MV/m (radial), B_V = 0.48 T (vertical)

- 2004 BNL proposal: single ring

  CW and CCW consecutive beam injections

  Limiting error: time-dependent part of the average vertical electric field over the entire ring

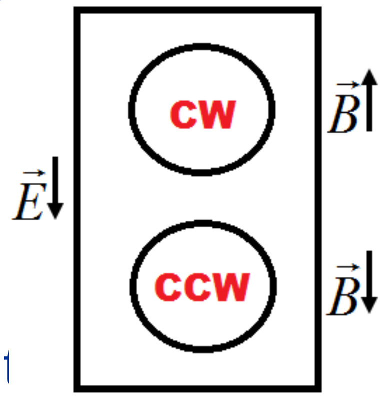
  → sensitivity $\sim 10^{-27}$ e · cm for one year measurement

- 2008 BNL proposal: double ring

  CW and CCW simultaneously

  2-in-1 magnet design with common E-field plates

  → sensitivity $\sim 10^{-29}$ e · cm for one year measurement



See http://www.bnl.gov/edm

Systematic Effects for Deuteron EDM

CW/CCW procedure with consecutive beam injections will not perfectly cancel systematic errors:

1. CW/CCW runs are taken at different times (separated by 10^3s)

   → Field stability, ground motion, temperature stability

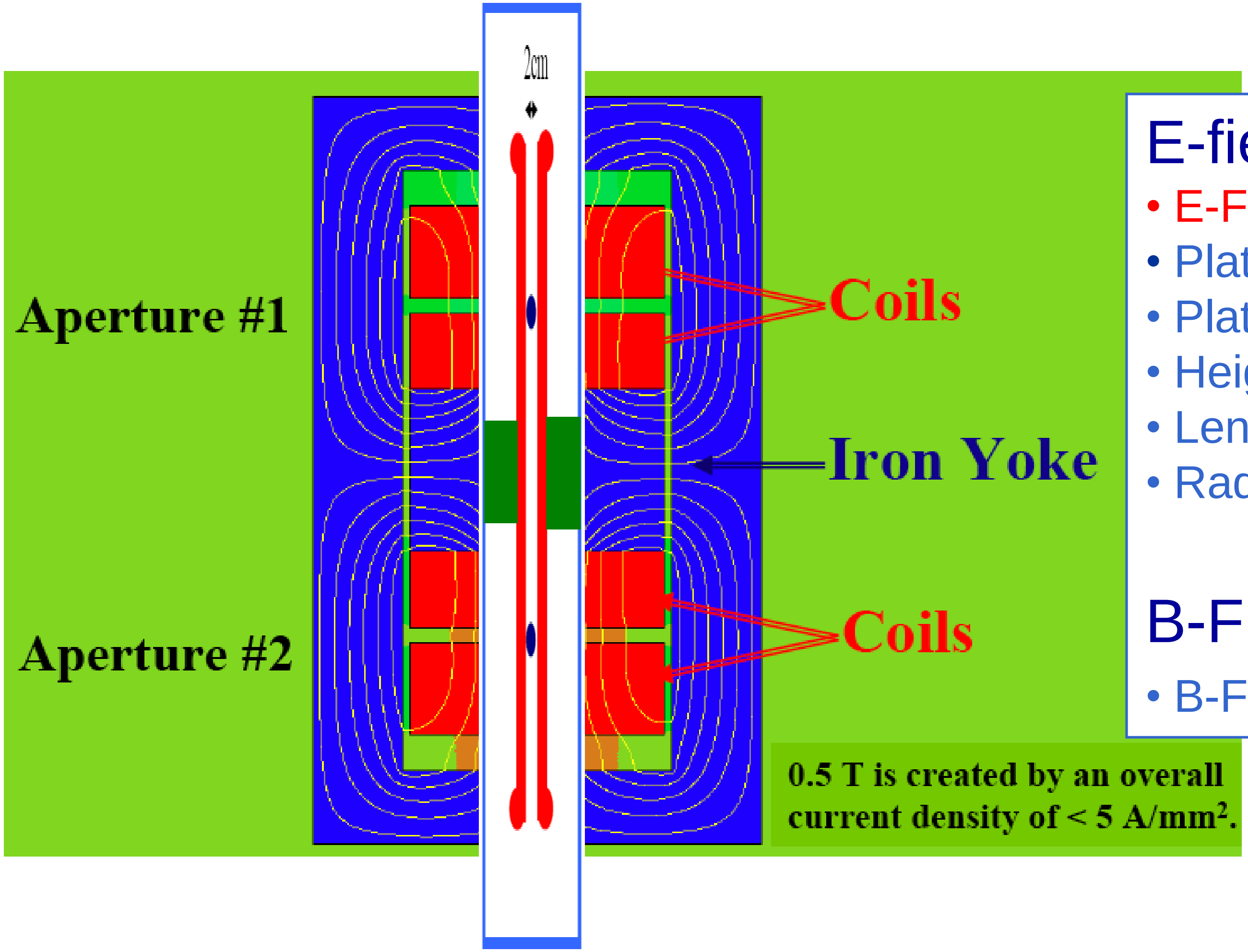
2. Spatial extent of the beam will be different for CW/CCW
3. Systematic change in E_V when magnetic field is reversed
4. Magnetic field does not reverse perfectly for CW/CCW

Measures:

→ Control the E-plate alignment and B-fields as a function of time
→ Install active feedback system
→ Measure beam position and profile

Common Coil Design for EDM

Preliminary magnetic design with water-cooled copper coils and iron shield by BNL



E-field Plates

- E-Field gradient: 120 kV/cm
- Plates 2 cm apart
- Plate thickness:1.5 cm
- Height: 40-60 cm
- Length: 3.3 m/ea
- Radius of curvature: 8.5 m

B-Field Coils

- B-Field: 0.52 T

Courtesy: R. Gupta, B. Morse (BNL)

EDM with E- and B-Fields

„all-in-one“ storage ring

Protons: p_p = 0.701 GeV/c
E_R = 16.8 MV/m, B_V = 0 T

Deuterons: p_d = 1.0 GeV/c
E_R = -4.0 MV/m, B_V = 0.16 T

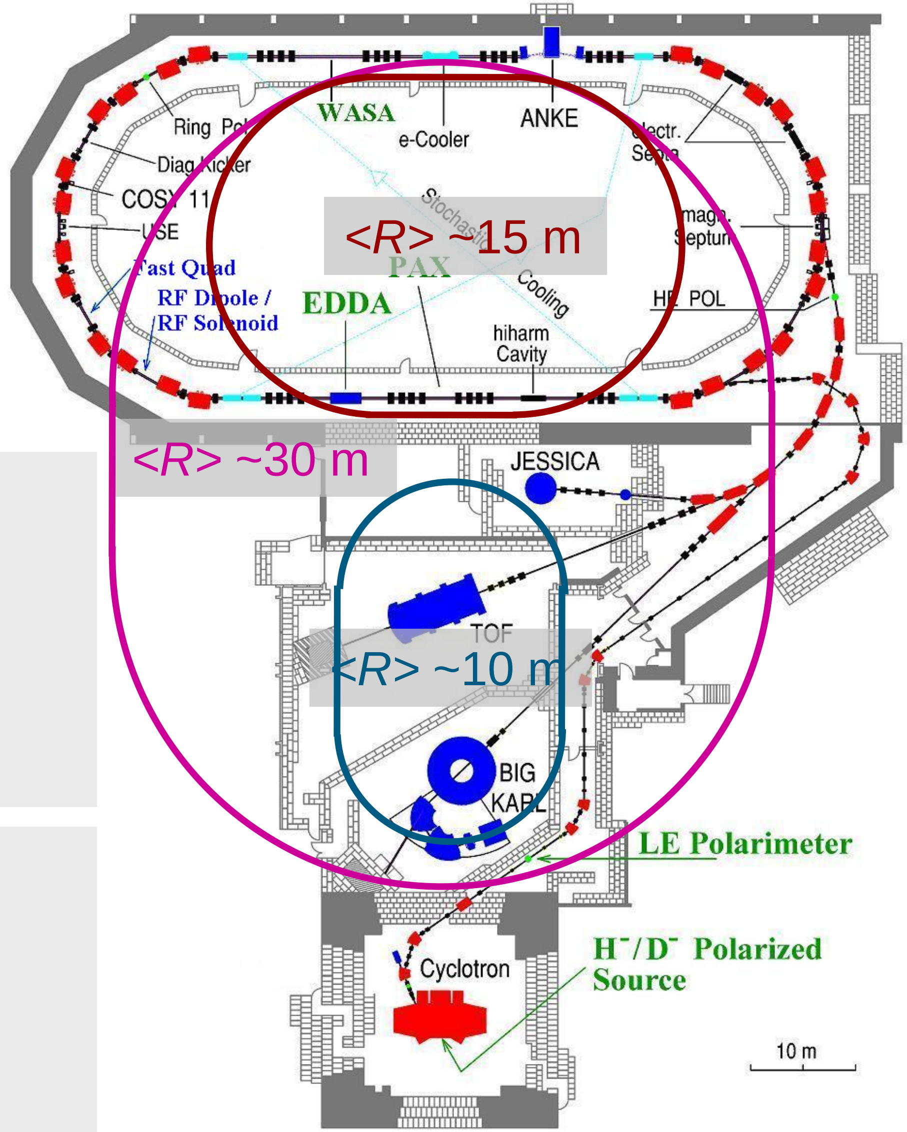
Helium-3: $p_{^3He}$ = 1.285 GeV/c
E_R = 17.0 MV/m, B_V = -0.05 T

„all-in-one“ storage ring

Protons: p_p = 0.527 GeV/c
Deuterons: p_d = 1.0 GeV/c
Helium-3: $p_{^3He}$ = 0.946 GeV/c
$E_R \leq$ 17 MV/m, $B_V \leq$ 0.31 T

„all-in-one“ storage ring

Protons: p_p = 0.435 GeV/c
Deuterons: p_d = 1.0 GeV/c
Helium-3: $p_{^3He}$ = 0.765 GeV/c
$E_R \leq$ 17 MV/m, B_V < 0.5 T



List of R&D Activities (Accelerator)

Beam and Spin Simulations

COSY Infinity Code: Beam and spin tracking for EDM storage ring

Prototype E-B Deflectors

ARD (Accelerator Research and Development) proposal to the HGF)

Layout: Field calculations to optimize the coil and conductor plate
Design: Mechanical design of the deflector
Prototype: Development of a deflector prototype
Test bench: Study field quality and stability
Test with beam in COSY

Prototype BPM (BNL for CW-CCW beams)
Prototype BPM for single beams at Jülich?

Summary / Outlook

FAIR / HESR

Start Version

- Status of Start Version
- Beam Dynamics for HESR

HESR Upgrade Options

Polarized proton-antiproton or electron-nucleon collider

- Progress in high-energy electron cooling
- Timeline with respect to PANDA

Electric Dipole Moment

Light-Ion EDM Storage Ring (“all-in-one” or dedicated)

- Upgrade of COSY
- Precursor experiment at COSY (Talk by F. Rathmann)
- R&D effort for E-B field deflectors and BPMs
- Advanced beam and spin tracking