From RHIC to COSY, an Adventurous Journey

Mei Bai

GSI, Universität Bonn

Forschungszentrum, Jülich, Brookhaven National Lab

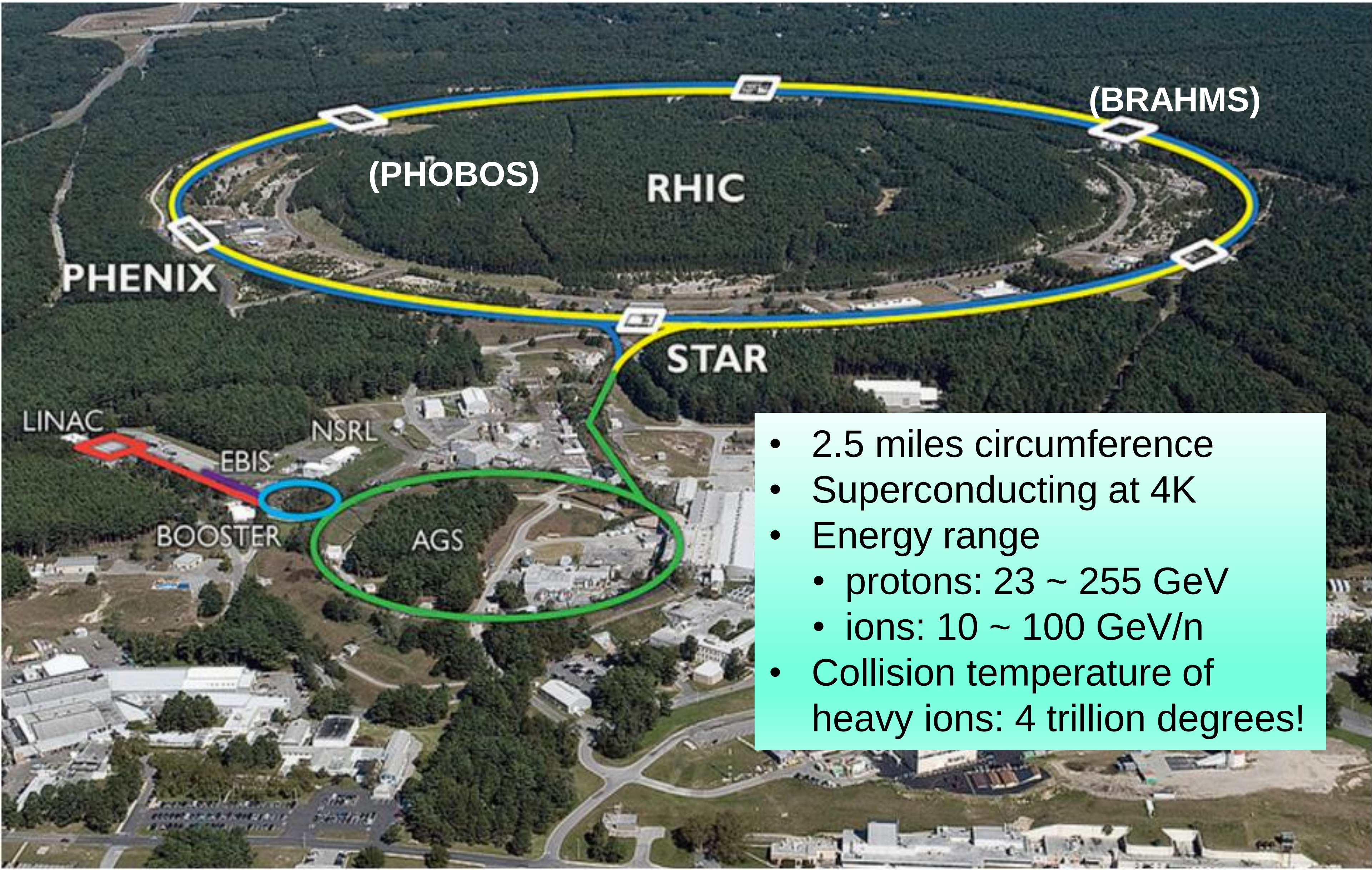
Outline

- Introduction
  - What is RHIC, its physics and it operation?
  - What is COSY, its physics legacy, status?

- What I have learned?
  - from RHIC
  - from COSY
    - ❖ Current status and challenges
    - ❖ Future plans
      - ➢ High Energy Storage Ring (HESR)

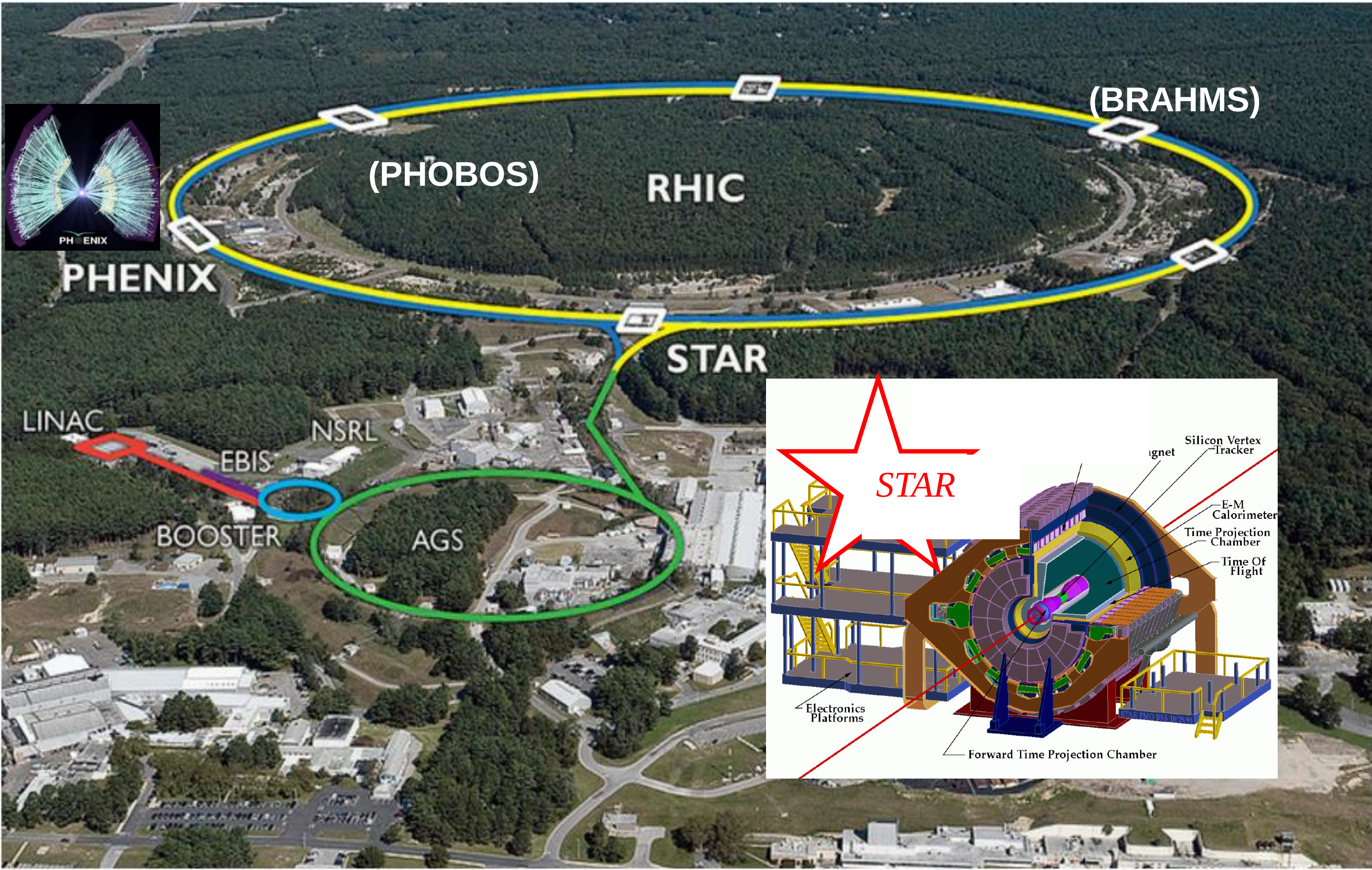
- Summary

The Atom Smasher on the Island!



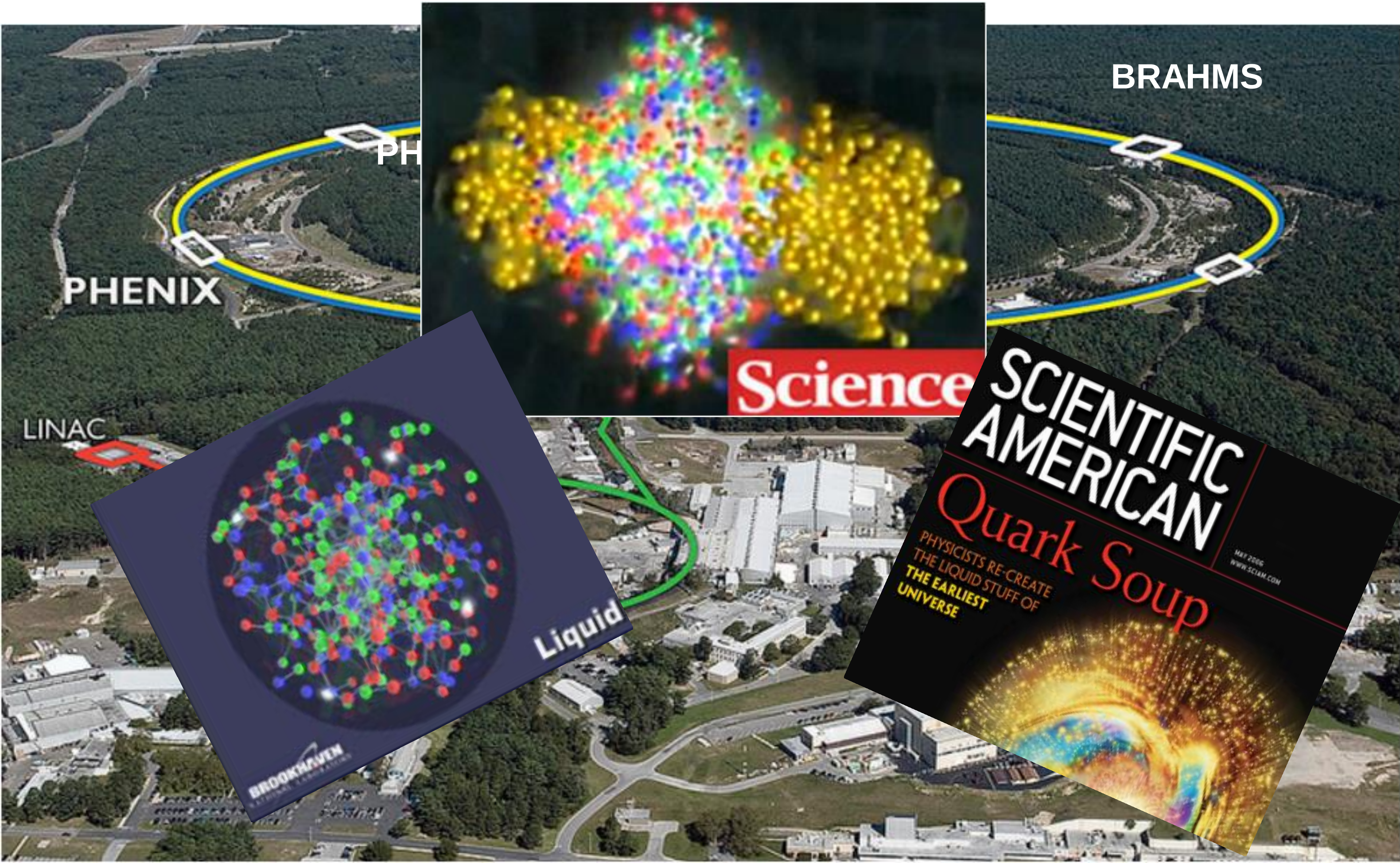
- 2.5 miles circumference
- Superconducting at 4K
- Energy range
  - protons: 23 ~ 255 GeV
  - ions: 10 ~ 100 GeV/n
- Collision temperature of heavy ions: 4 trillion degrees!

The Atom Smasher on the Island!



A Discovery Machine!

The "perfect" Liquid



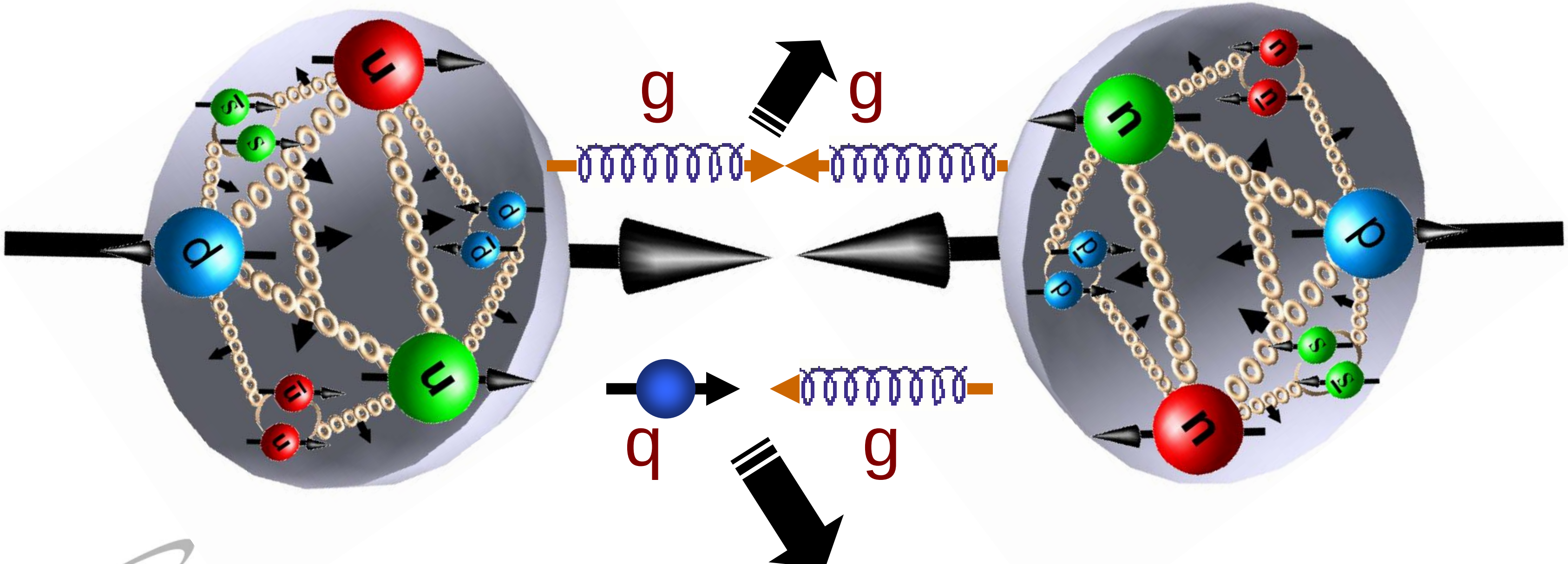
RHIC: the world only high energy

Polarized proton collider

Understand the proton spin structure

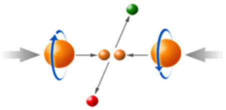
$$S=\frac{1}{2}=\frac{1}{2}\Delta\Sigma+\Delta g+L_q+L_g$$

gluon spin contribution



quark/antiquark spin contribution

A Versatile Collider



Collisions of a variety of ion species

Species	Collision beam energy[GeV/n]	Avg. store luminosity[$10^{28}cm^{-2}s^{-1}$]
Au-Au	3.8/4.6/5.8/7.3/10/14/19.5/32/65/100	$1.25x10^{-4}$/$1.2x10^{-5}$/$1.5x10^{-3}$/$2x10^{-3}$/$2x10^{-4}$ /$4x10^{-3}$/0.012/0.013/0.03/$1.7x10^{-3}$/0.87
d-Au	10/20/31/100	0.87/2.35/9.35/50
Cu-Cu	11/31/100	$5x10^{-3}$/0.08/0.8
U-U	96.4	0.056
Cu-Au	100	1.0
h-Au	104-100	10
$P^{\uparrow}$-Au	103-97,	45
$P^{\uparrow}$-Al	103-98	400
$P^{\uparrow}$ - $P^{\uparrow}$	11.3/31/100/205/250/255	0.6/100/6300/1500/9000/16000

BROOKHAVEN NATIONAL LABORATORY

http://www.rhichome.bnl.gov/RHIC/Runs/

JÜLICH FORSCHUNGSZENTRUM

Brief History of RHIC

1989: RHIC design

1991: construction started

1996: AGStRHIC transfer line commission

1997: first sextant test

1999: Engineering test, first circulating Au beam

2000: first Au-Au collision at 100 GeV/u!

2003: d-Au collision

2005: Cu-Cu collision

2002: first polarized proton collision at 100 GeV

2009: first polarized proton collision at 250 GeV

BROOKHAVEN NATIONAL LABORATORY

GSI

JÜLICH FORSCHUNGSZENTRUM

What matters for Collider Operation?

- **Luminosity! Luminosity!**

  # of collisions per unit area and per unit time

- For the case of head-on collisions

# of particles from beam 1 in collision

# of particles from beam 2 in collision

$$L = f\frac{N_1 N_2}{A}$$

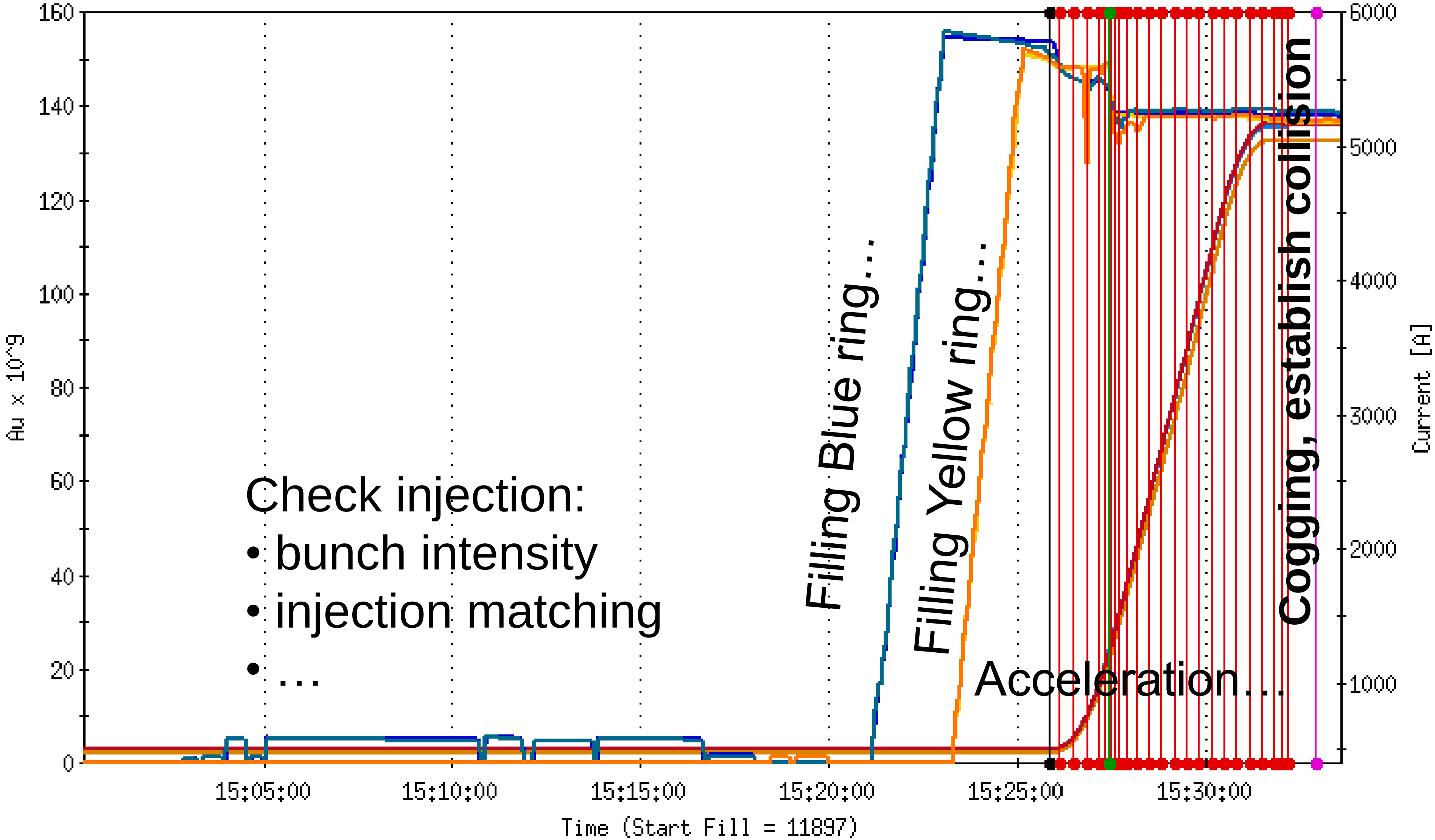
Frequency of collision

Area of collision, ie the product of beam size

- Ways to increase the peak luminosity
  - Increase # of particles in each beam, ie bunch intensity
  - Increase # of bunches
  - Make each bunch more bright, ie shrink the size of the bunch at collision pt

RHIC Operation:

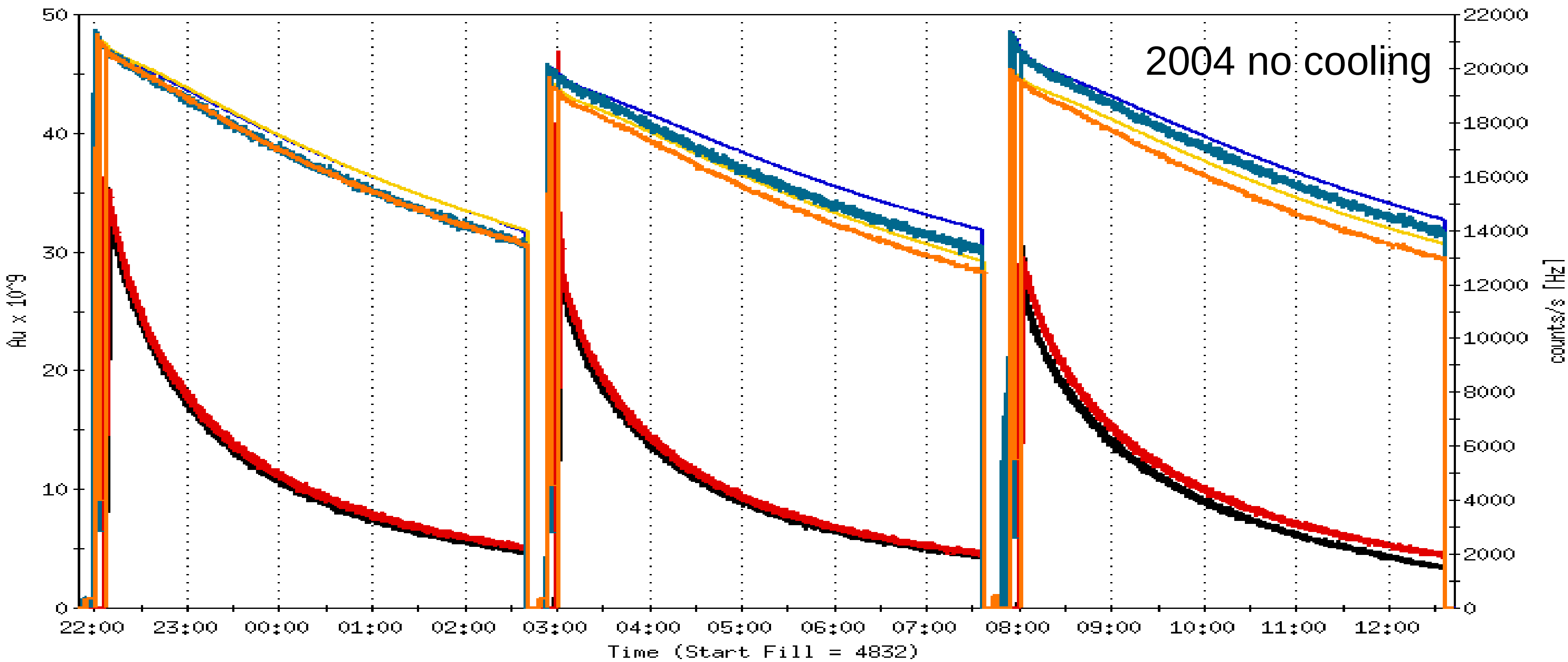
A Typical RHIC Store



Challenges in RHIC Heavy Ion Luminosity

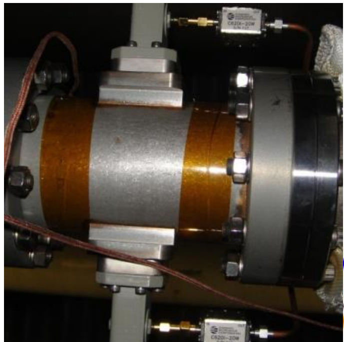
Intra-beam scattering

- Couloumb interaction between charged particles
- Leads to debunching and transverse emittance growth, i.e. longer bunch length and larger transverse beam size



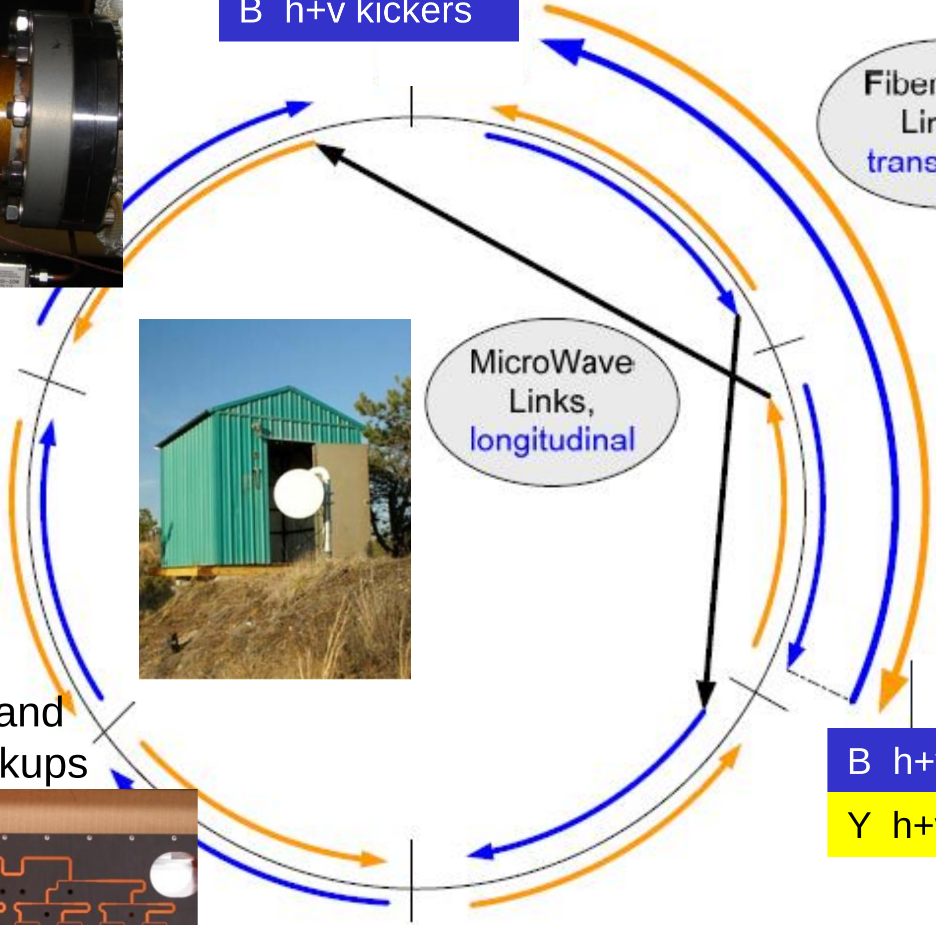
Full 3D Stochastic Cooling at RHIC

longitudinal pickup

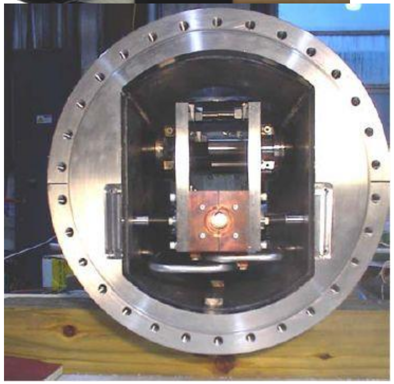


Y h+v pickups

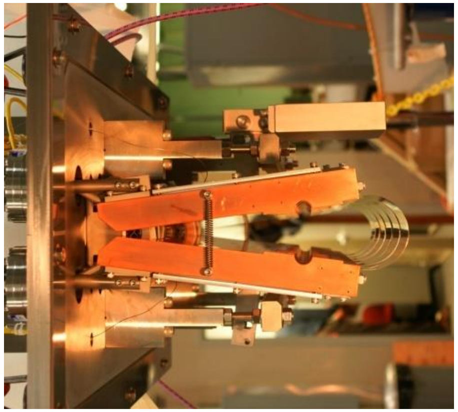
B h+v kickers



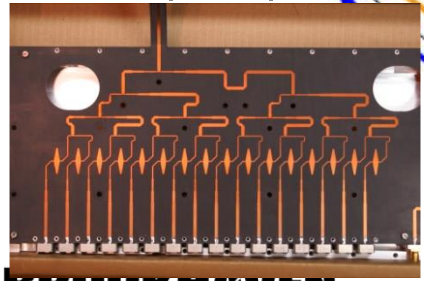
longitudinal kicker (closed)



horizontal kicker (open)



horizontal and vertical pickups



B h+v pickups

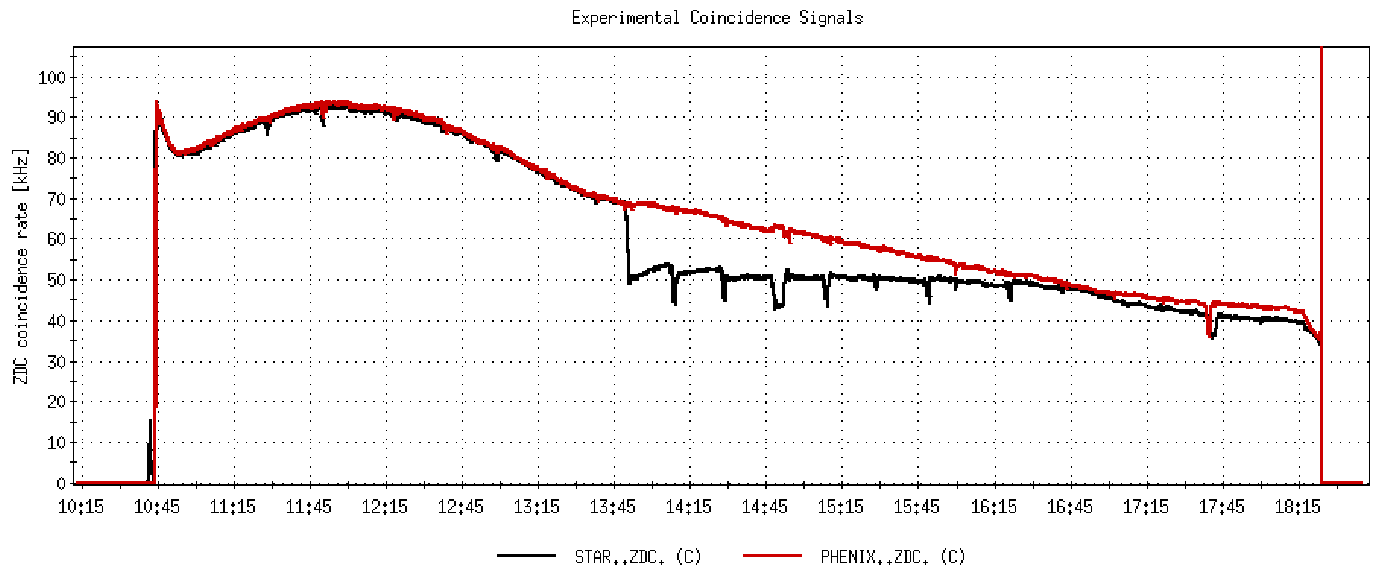
Y h+v kickers

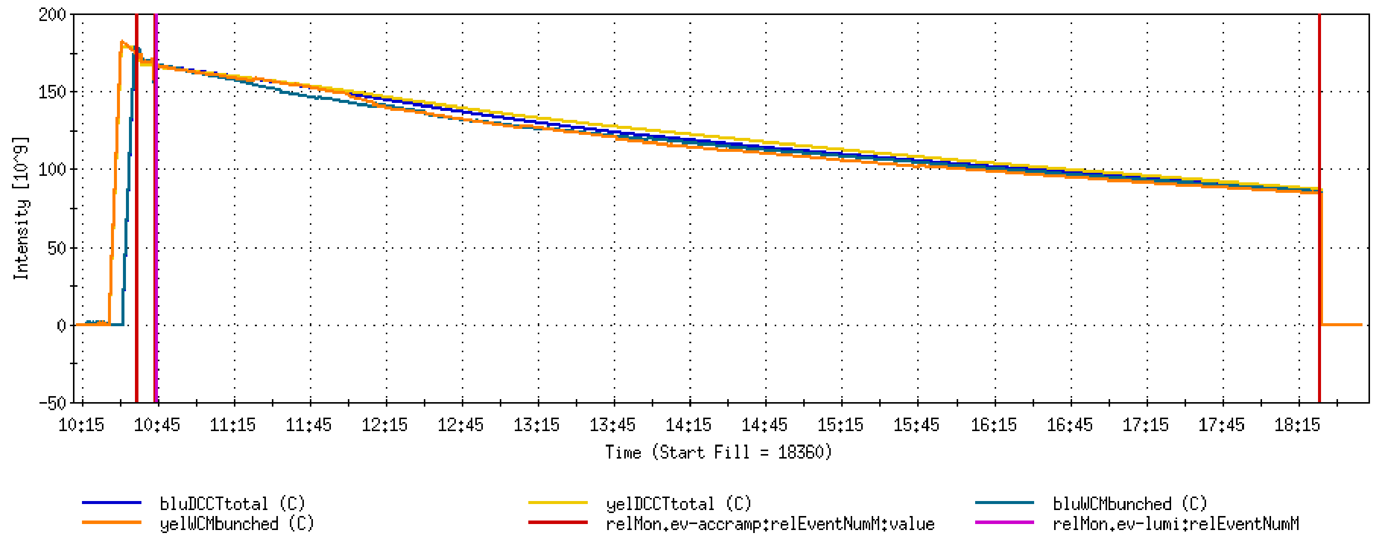
vertical kicker (closed)

5-9 GHz, cooling time ~1 h

M. Brennan, M. Blaskiewicz, K. Mernick

Heavy Ion Store w. Stochastic Cooling



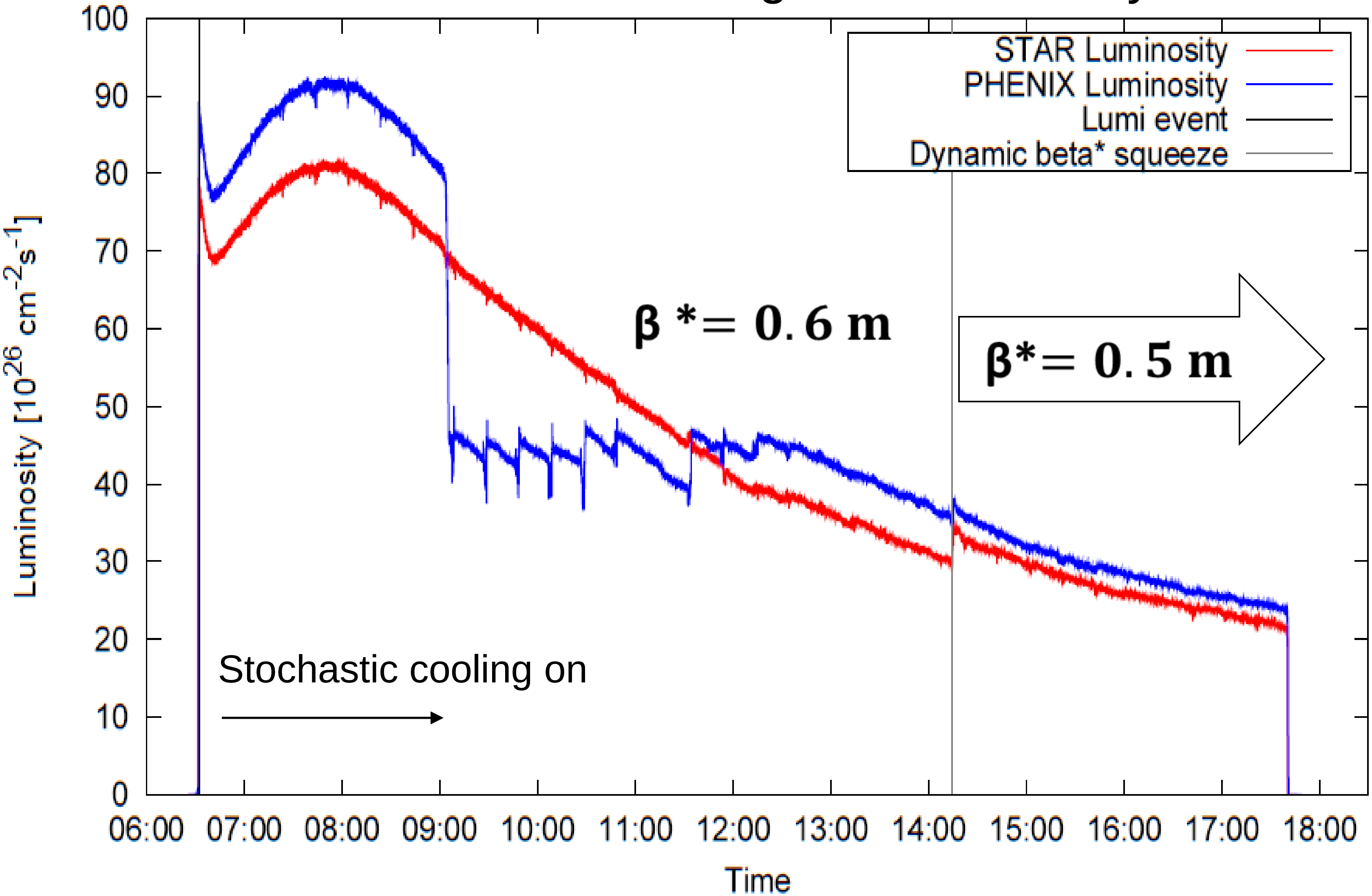


BROOKHAVEN NATIONAL LABORATORY

JÜLICH FORSCHUNGSZENTRUM

Dynamic Beta Squeeze

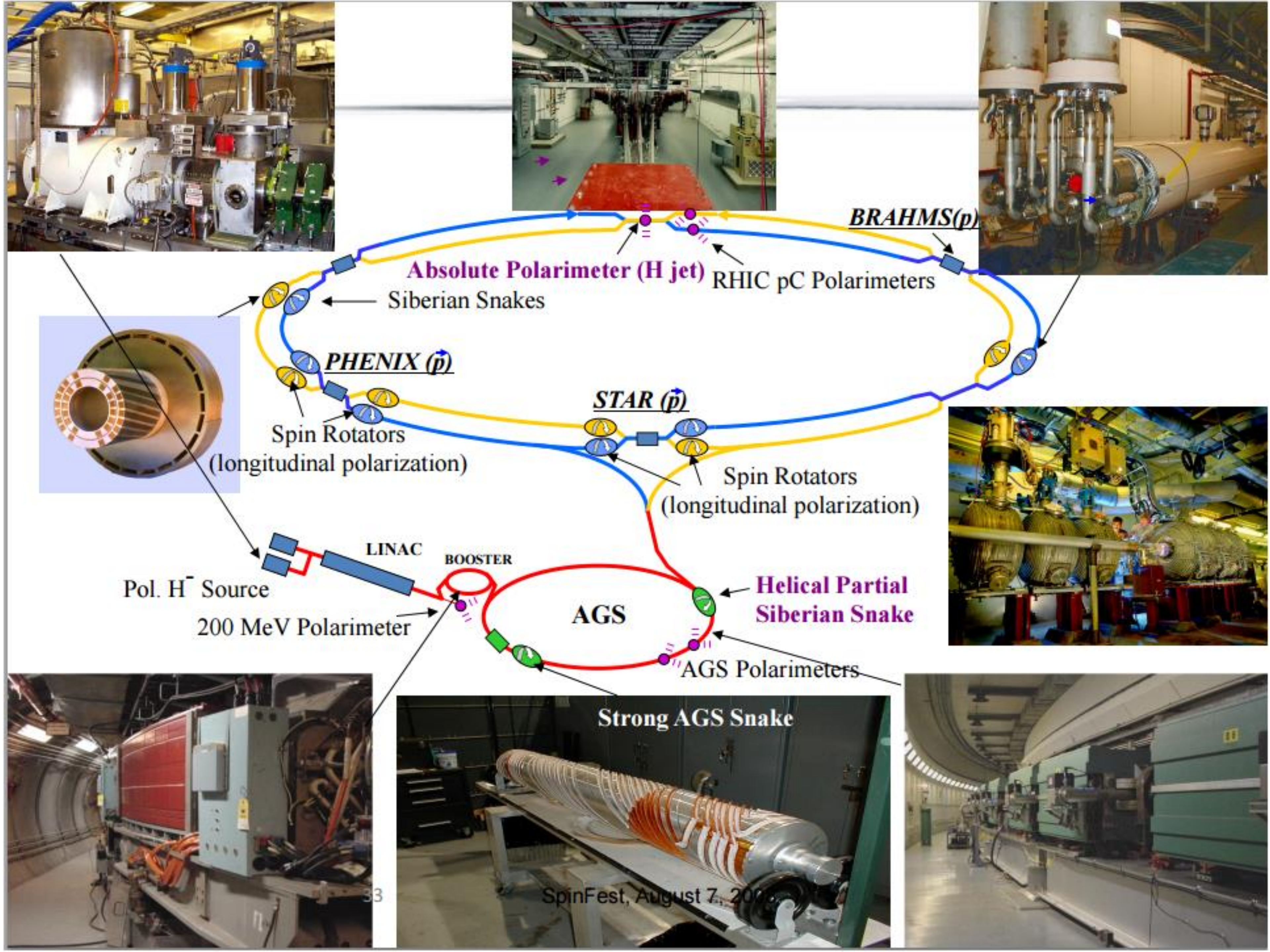
To maximize the integrated luminosity



G. Robert-Demolaize, M. Bai, A. Marusic, et al.

NATIONAL LABORATORY

JÜLICH FORSCHUNGSZENTRUM


Absolute Polarimeter (H jet)
RHIC pC Polarimeters
BRAHMS(p)
Siberian Snakes
PHENIX (p)
STAR (p)
Spin Rotators
(longitudinal polarization)
Spin Rotators
(longitudinal polarization)
LINAC
BOOSTER
Pol. H⁻ Source
200 MeV Polarimeter
AGS
Helical Partial
Siberian Snake
AGS Polarimeters
Strong AGS Snake

Spin motion in a circular accelerator

Thomas BMT Equation: (1927, 1959)

L. H. Thomas, Phil. Mag. 3, 1 (1927); V. Bargmann, L. Michel, V. L. Telegdi, Phys, Rev. Lett. 2, 435 (1959)

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times \left[(1+G\gamma)\vec{B}_T + (1+G)\vec{B}_L + \left(G\gamma + \frac{\gamma}{\gamma+1}\right)\frac{\vec{E}\times\vec{\beta}}{c}\right]$$

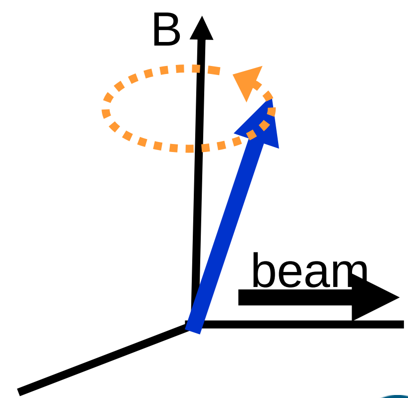
Spin vector in particle's rest frame

Magnetic field perpendicular to the particle's velocity

Magnetic field along the direction of the particle's velocity

- G is the anomalous g- factor, for proton, G=1.7928474
- **γ:** Lorenz factor

Spin tune Q_s: number of precessions in one orbital revolution: $Q_s = G\gamma$



BROOKHAVEN NATIONAL LABORATORY

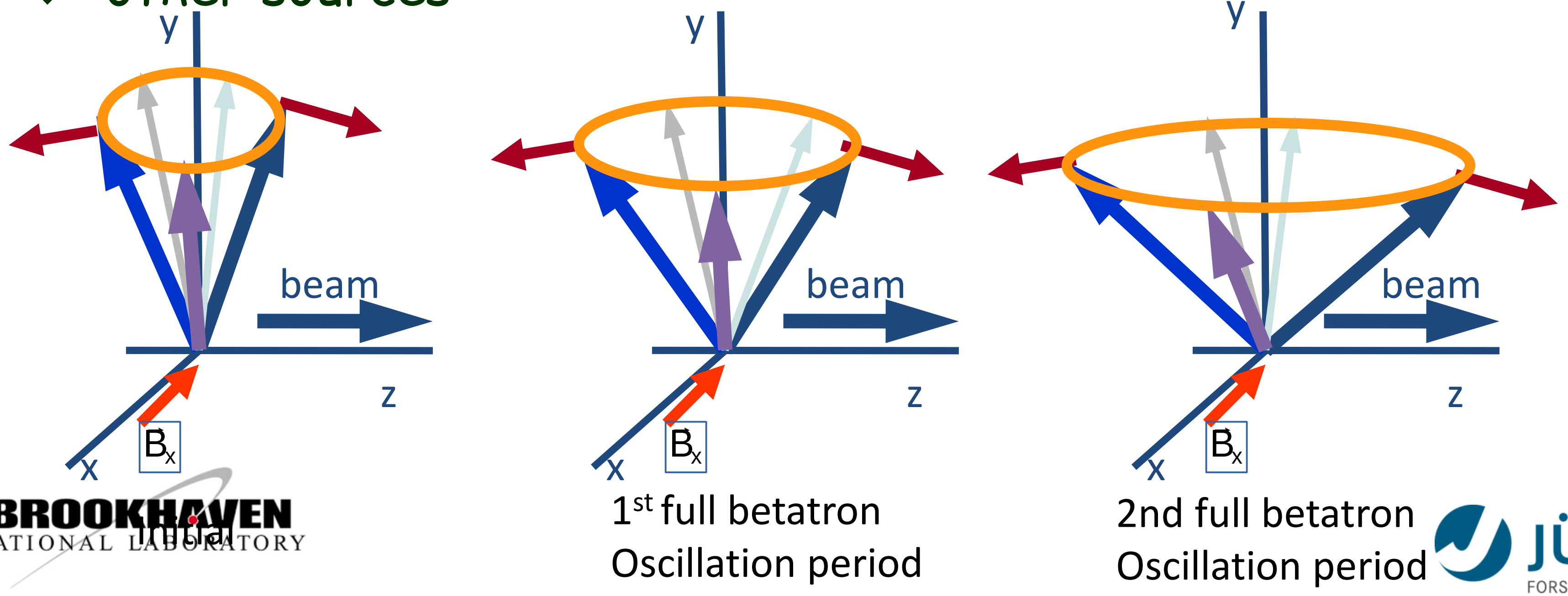
GSI

JÜLICH FORSCHUNGSZENTRUM

Depolarizing mechanism in a synchrotron

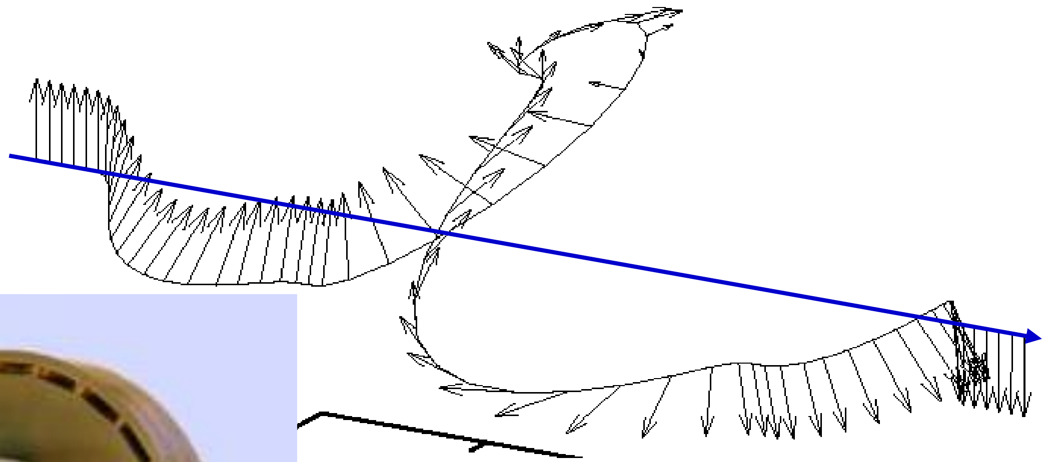
Horizontal field kicks the spin vector away from its vertical direction, and can lead to polarization loss

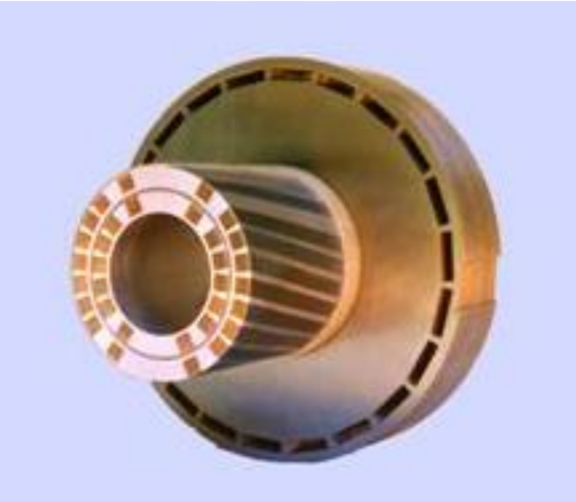
- dipole errors, misaligned qadrupoles, imperfect orbits
  - imperfection resonance: **$G\gamma = k$, k is an integer**
- betatron oscillations
  - intrinsic resonance: **$G\gamma = kP \pm Q_y$**
- other multipole magnetic fields
- other sources



Full Siberian Snake

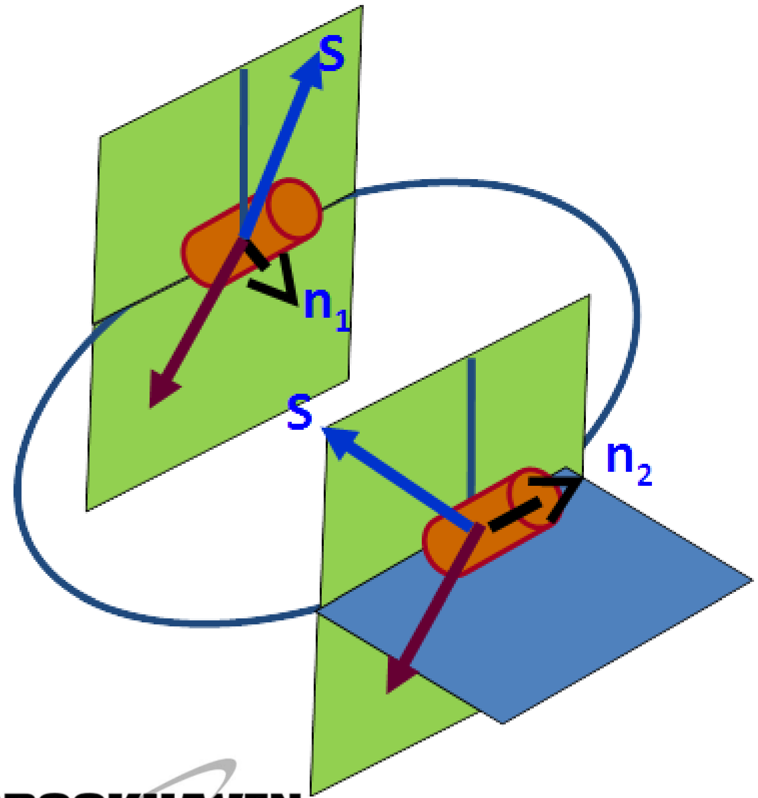
- A magnetic device to rotate spin vector by 180°
- Invented by Derbenev and Kondratanko in 1970s [*Polarization kinematics of particles in storage rings, Ya.S. Derbenev, A.M. Kondratenko* (Novosibirsk, IYF) . Jun 1973. Published in Sov.Phys.JETP 37:968-973,1973, Zh.Eksp.Teor.Fiz 64:1918-1929]
- Keep the spin tune independent of energy

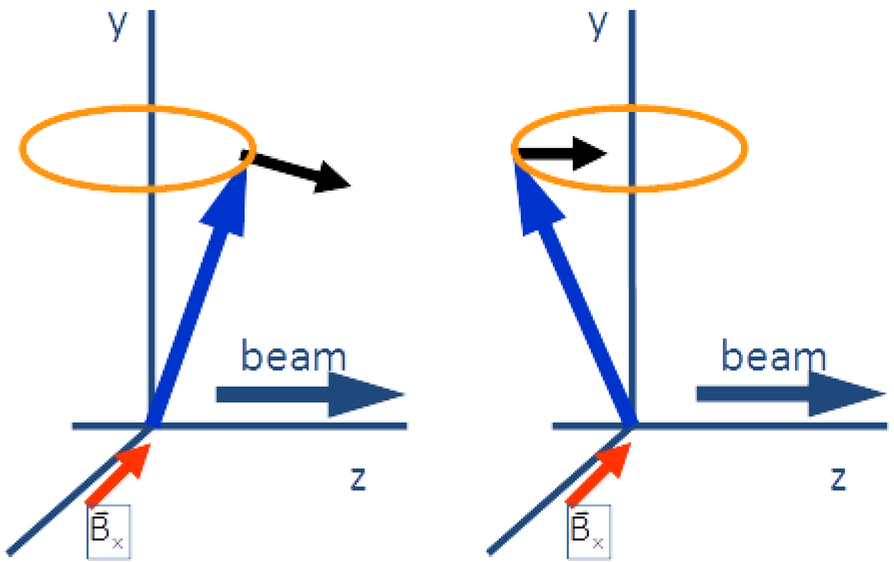




Dual Snake Set-up

- ❑Use one or a group of snakes to make the spin tune to be at ½
- ❑Break the coherent build-up of the perturbations on the spin vector





BROOKHAVEN NATIONAL LABORATORY

GSI

JÜLICH FORSCHUNGSZENTRUM

Snake Depolarization Resonance

- **Condition**

- S. Y. Lee, Tepikian, Phys. Rev. Lett. 56 (1986) 1635
- S. R. Mane, NIM in Phys. Res. A. 587 (2008) 188-212

$$mQ_y = Q_s + k$$

- **even order resonance**
  - Disappears in the two snake case if the closed orbit is perfect
- **odd order resonance**
  - Driven by the intrinsic spin resonances

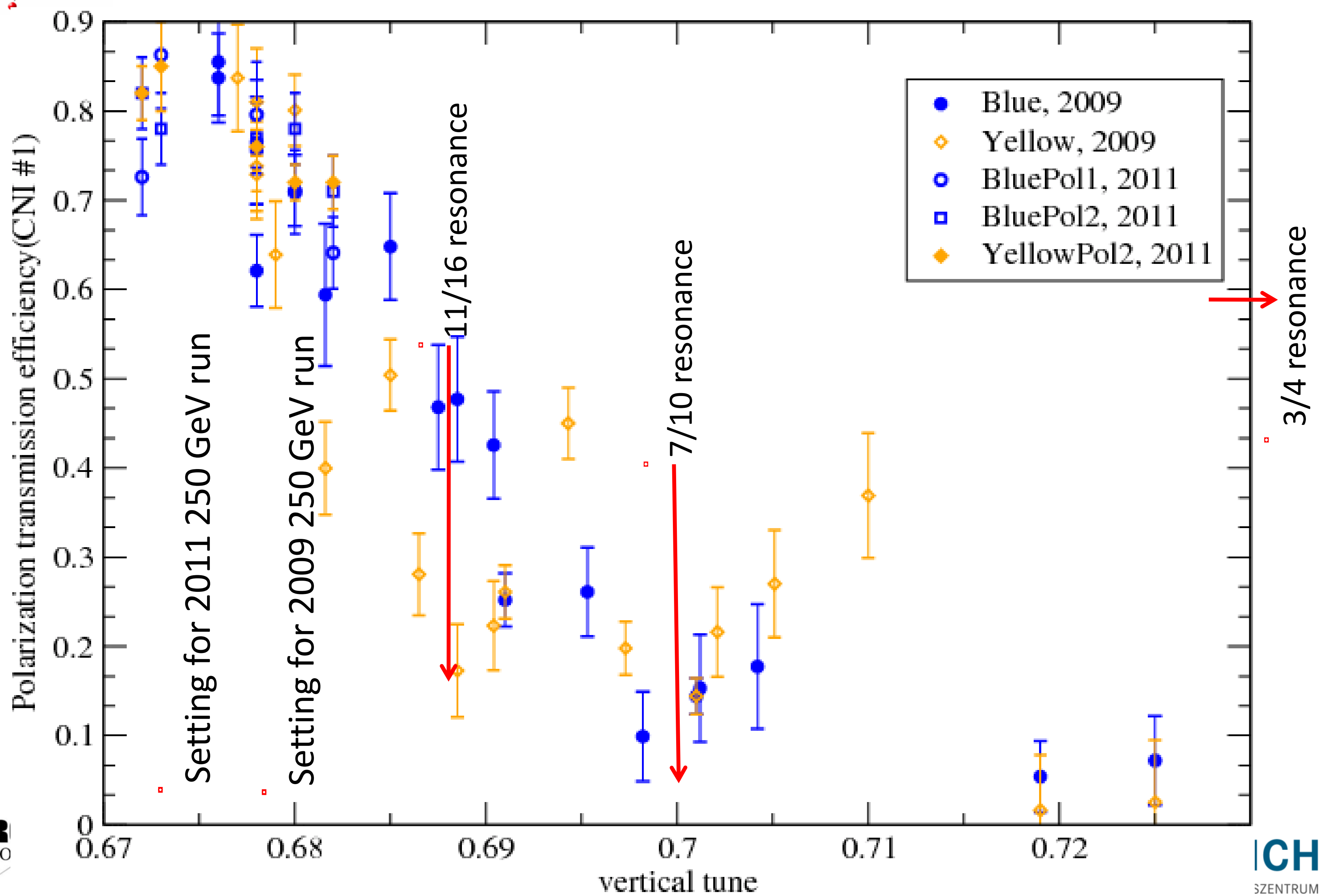
- Adequate number of snakes

$$N_{snk} > 4\left|\varepsilon_{k,\max}\right| \qquad Q_s = \sum_{k=1}^{N_{snk}} (-1)^k \phi_k$$

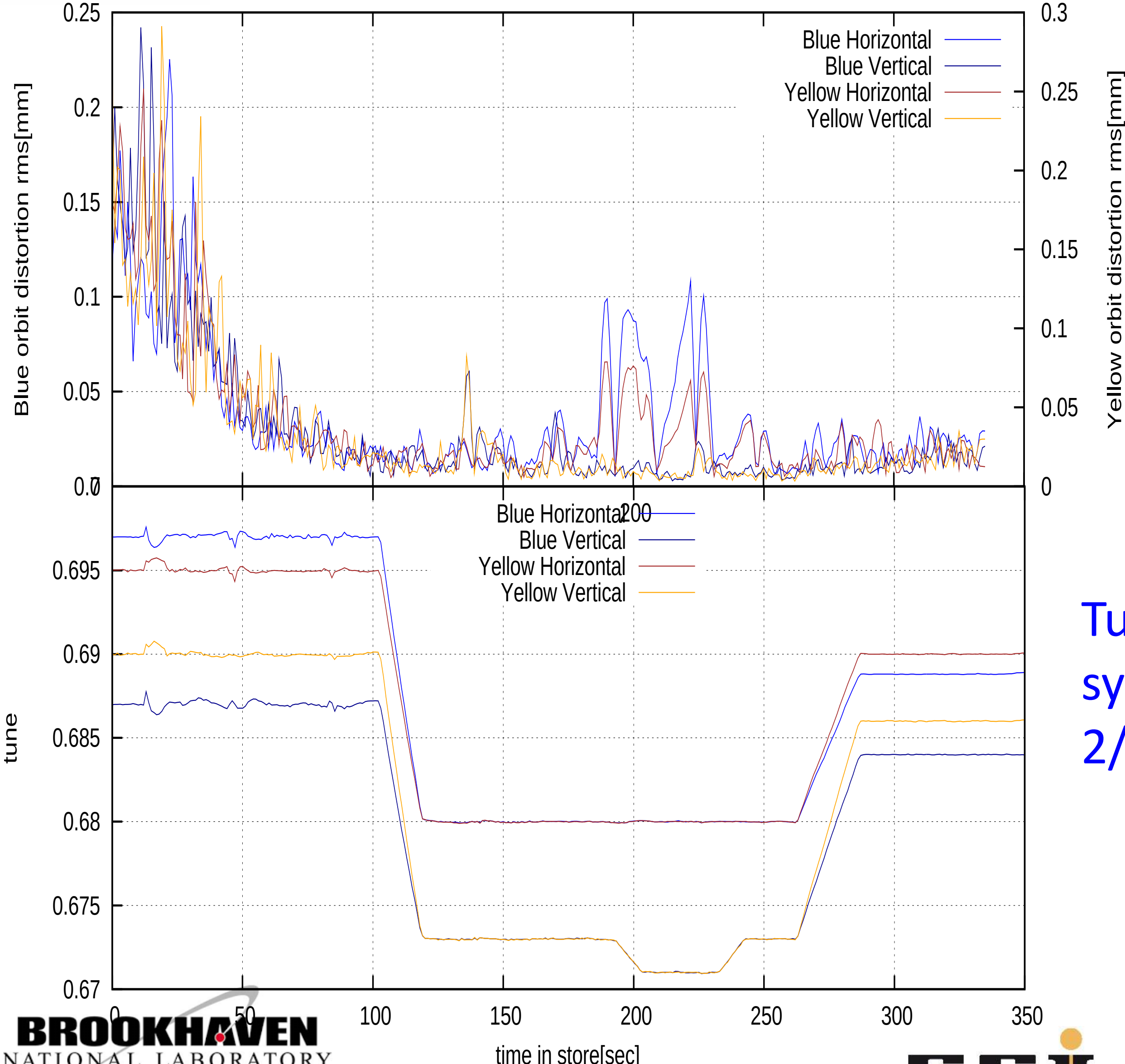
ϕ_k is the snake axis relative to the beam direction

BROOKHAVEN NATIONAL LABORATORY GSI JÜLICH FORSCHUNGSZENTRUM

Snake resonance observed in RHIC



Precise Beam Control



Orbit feedback system: rms orbit distortion less than 0.1mm

Tune/coupling feedback system: acceleration close to 2/3 orbital resonance

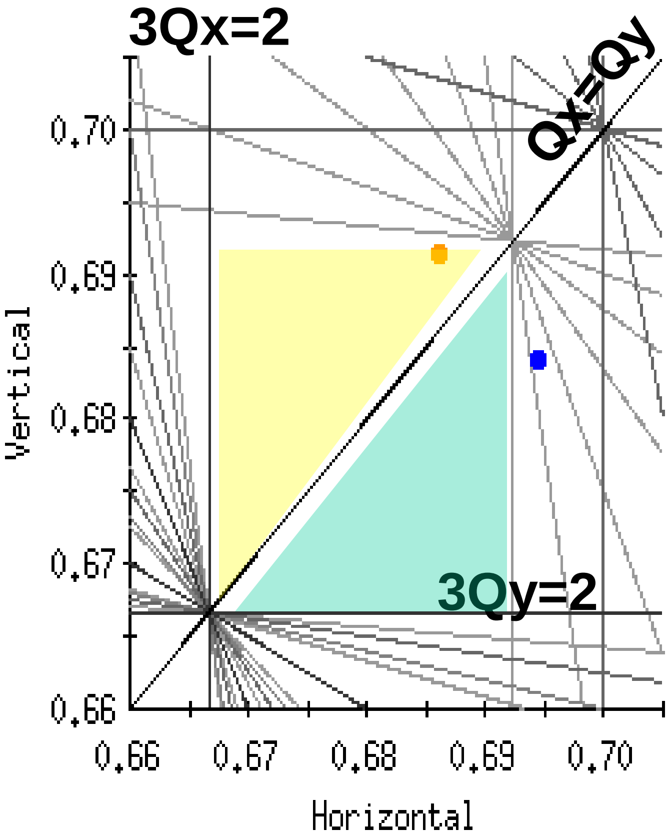
BROOKHAVEN NATIONAL LABORATORY

GSI

JÜLICH FORSCHUNGSZENTRUM

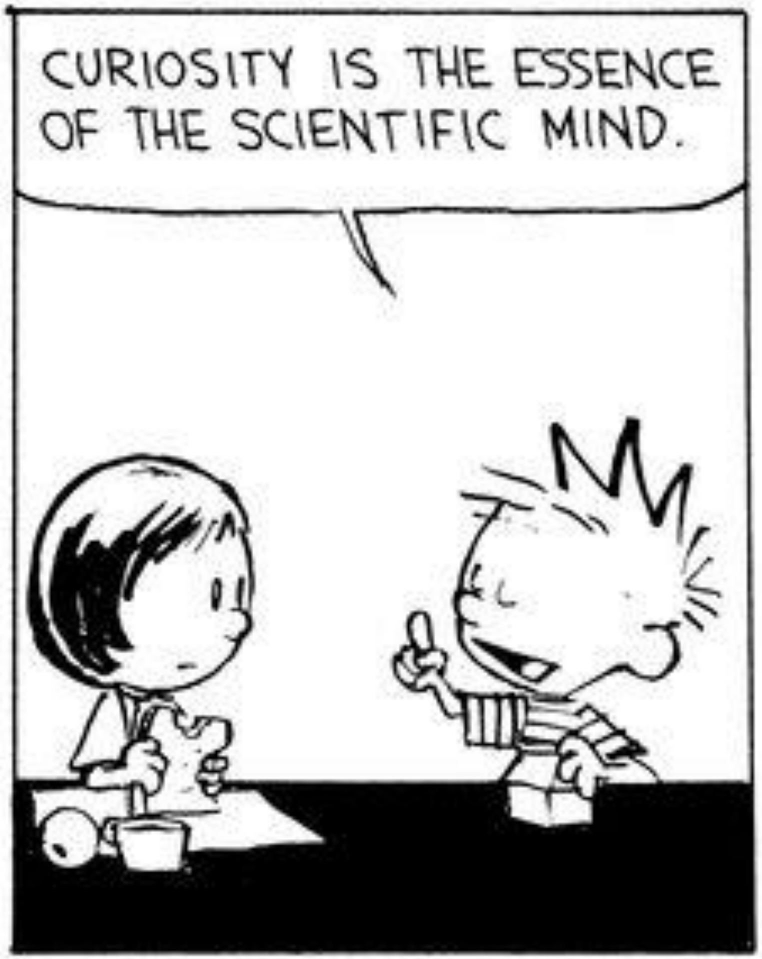
other challenges with p↑ collider

- Luminosity limit
  - Beam-beam
    - coherent tune shift
    - Incoherent tune spread
    - E-lens: W. Fischer, Y. Luo, et al
      - Successfully Implemented in 2015
    - Near-integer working point
- Polarization lifetime
- Spin flipping
  - Has been demonstrated at RHIC injection energy very recently!



BROOKHAVEN NATIONAL LABORATORY
GSI
JÜLICH FORSCHUNGSZENTRUM

being a scientist …



BROOKHAVEN NATIONAL LABORATORY

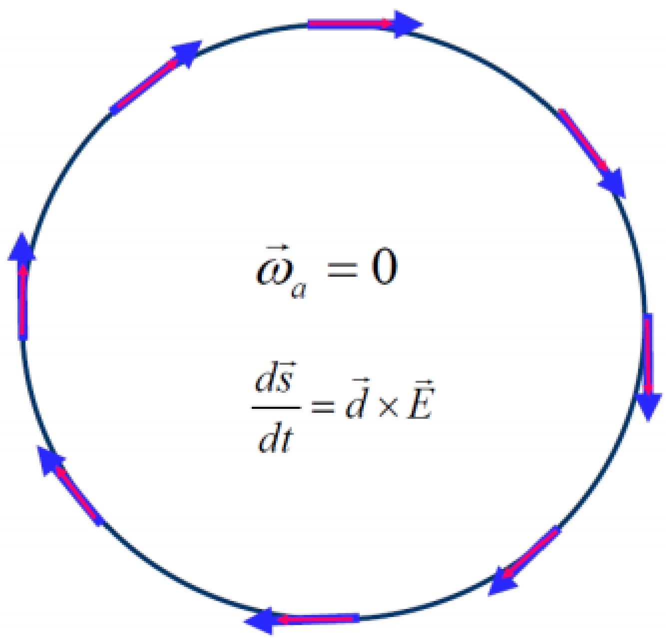
GSI

JÜLICH FORSCHUNGSZENTRUM

Hadron Electric Dipole Moment in a Storage Ring

A Proposal to Measure the Proton Electric Dipole Moment with 10^{-29} *e*·cm Sensitivity

by the Storage Ring EDM Collaboration



https://www.bnl.gov/edm/

October 2011

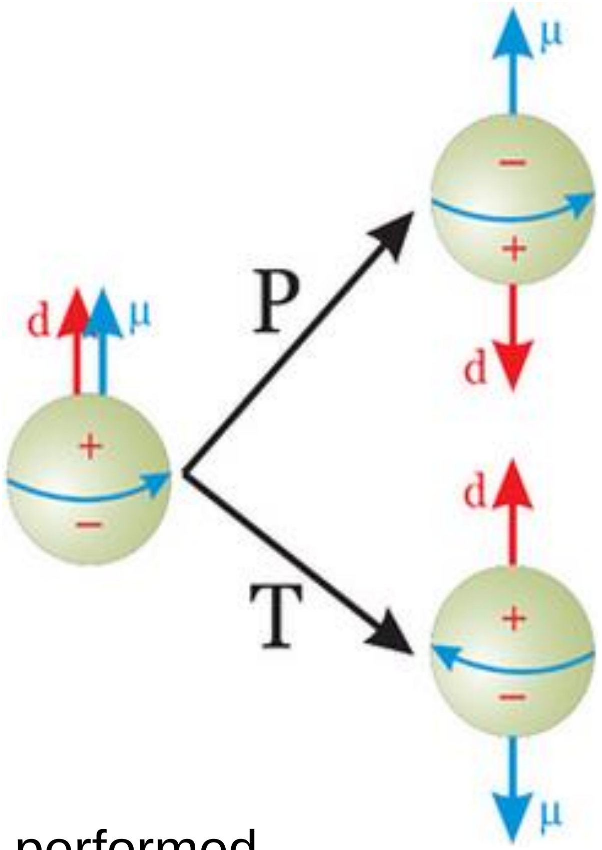
BROOKHAVEN NATIONAL LABORATORY

GSI

JÜLICH FORSCHUNGSZENTRUM

Why search for Electric Dipole Moment?

- Like the MDM, EDM is a vector-like intrinsic property of particles aligning along the spin axis. Non-EDM violates both Parity and Time reversal, an excellent probe for CP-violation
  - SM expects EDM on the order of 10^{-38} e-cm, too weak to explain the asymmetry between matter and anti-matter
  - New physics is needed!



- 1st EDM search of neutron started in 1951 by Smith, Purcell and Ramsey

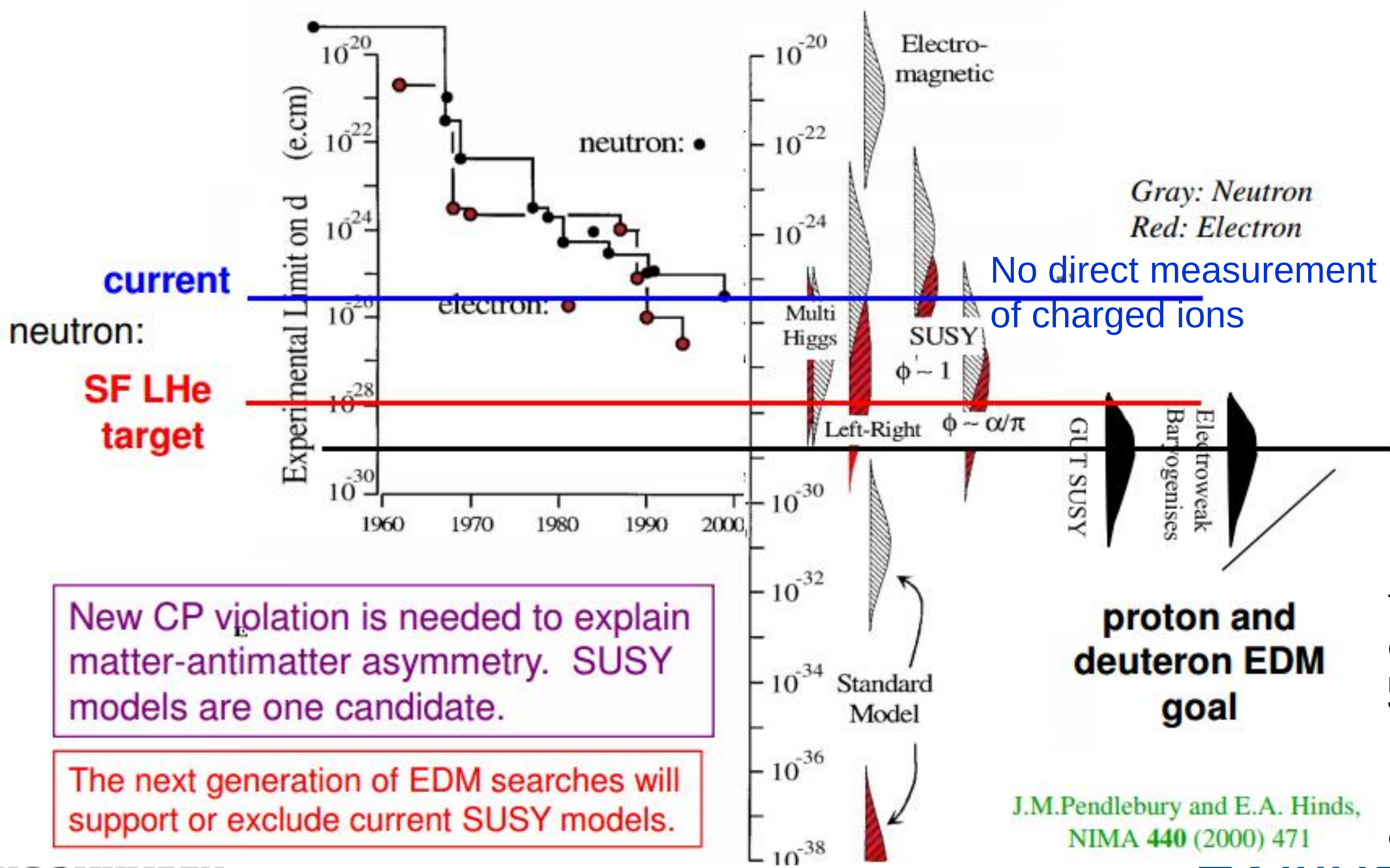
- Currently, direct charged ion EDM hasn't yet been performed

BROOKHAVEN NATIONAL LABORATORY

GSI

JÜLICH FORSCHUNGSZENTRUM

Status of EDM search



Courtesy of E. Stephenson

New CP violation is needed to explain matter-antimatter asymmetry. SUSY models are one candidate.

The next generation of EDM searches will support or exclude current SUSY models.

Storage ring based EDM search

- One way to have direct access to charged ions' EDM

Spin motion in a planar-circular accelerator with electrostatic deflectors

$$\frac{d\vec{S}}{dt} = \frac{e}{m}\vec{S} \times \left[\left(\frac{1}{\gamma} + G\right)\vec{B}_T + \frac{1}{\gamma}(1+G)\vec{B}_L + \left(G + \frac{1}{\gamma+1}\right)\frac{\vec{E}\times\vec{\beta}}{c} + \frac{\boldsymbol{\eta}}{\mathbf{2c}}\left(\vec{\boldsymbol{E}} + \vec{\boldsymbol{\beta}} \times \vec{\boldsymbol{B}}\right) \right]$$

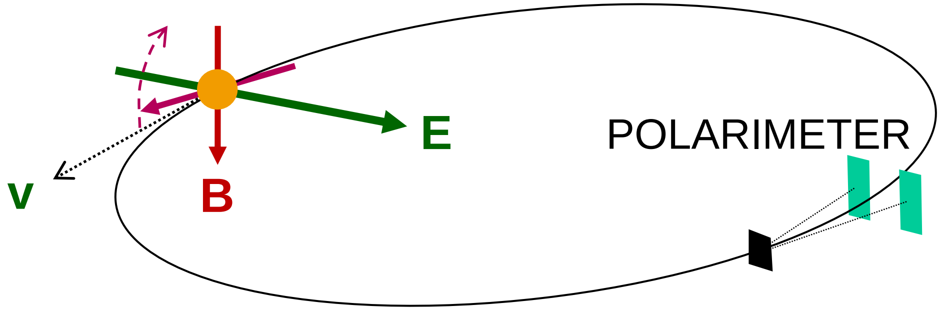
- Null to remove the magnetic dipole moment contribution to spin motion. And then place spin vector along the particle's velocity in the horizontal plane. In the absence of EDM, the spin vector shall stay in the horizontal plane
  - **Spin frozen method**

Storage ring based EDM search

- Spin frozen method

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times [\boldsymbol{d}(\vec{\boldsymbol{E}} + \vec{\boldsymbol{\beta}} \times \vec{\boldsymbol{B}})]$$

- In a full spin frozen storage ring, the observation of slow polarization buildup in the vertical plane is directly due to **Non-zero EDM, and the buildup rate is the measure of the size of the EDM**



courtesy of E. Stephenson

Full Spin Frozen storage ring is the most effective way!

BROOKHAVEN NATIONAL LABORATORY GSI JÜLICH FORSCHUNGSZENTRUM

To freeze spin

For proton, G=1.793 and a electrostatic storage ring at magic momentum

p= $m/\sqrt{G} = 0.7007\ GeV/c$

For deuteron, G = -0.14

$$E = \frac{G\gamma cp}{1 + G\beta^2\gamma^2} B$$

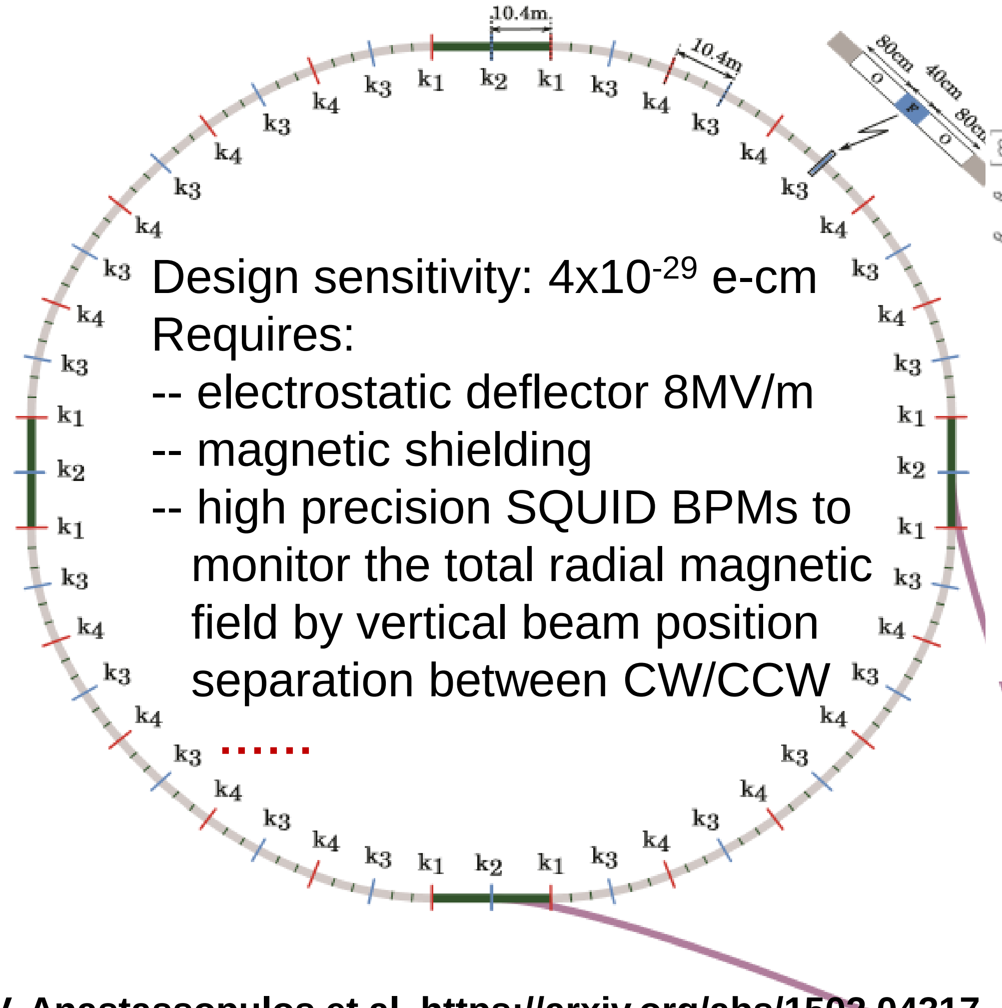
	Bending radius[m]	Deflector E field strength	Deflector B field strength	CW/CCW same orbit/time
pEDM	52.3	8.017 MV/m	--	yes
dEDM	52.3	2.3 MV/m	0.07 Tesla	no
dEDM	26.4	4.54 MV/m	0.153 Tesla	no
pEDM	26.4	15 MV/m	--	yes

Key: high field electrostatic deflector

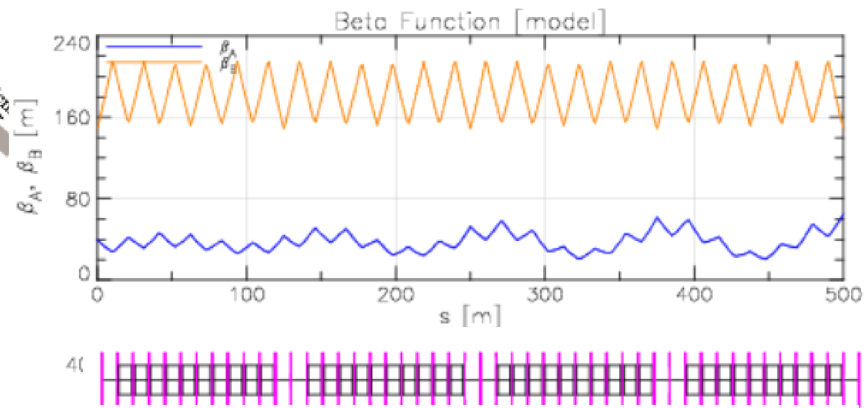
Key: ExB deflector

pEDM storage ring

Pure Electrostatic Storage Ring for proton EDM



Design sensitivity: 4×10^{-29} e-cm
Requires:
-- electrostatic deflector 8MV/m
-- magnetic shielding
-- high precision SQUID BPMs to monitor the total radial magnetic field by vertical beam position separation between CW/CCW
......



Bending radius	52.3 m
circumference	500 m
Electrode spacing	3 cm
Deflector shape	cylindrical
Harmonic, RF[MHz]	100, 35.878
Q_x, Q_y	2.42, 0.44
ε_x , ε_y [mm-mrad]	17, 3.2
maximum $\frac{dp}{p}$	4.6×10^{-4}
Dispersion, max [m]	30 m

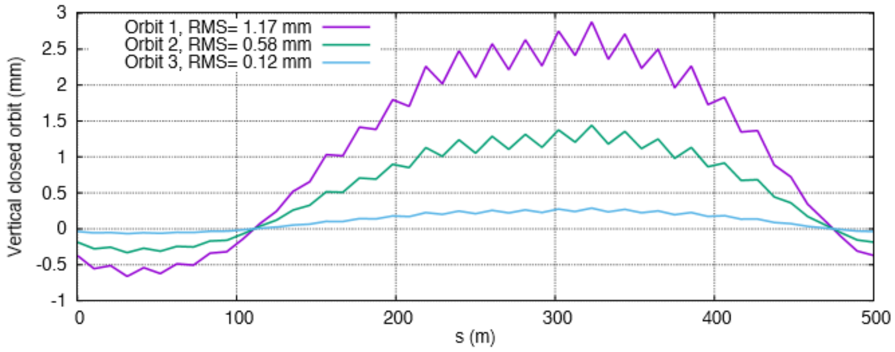
V. Anastassopulos et al, https://arxiv.org/abs/1502.04317

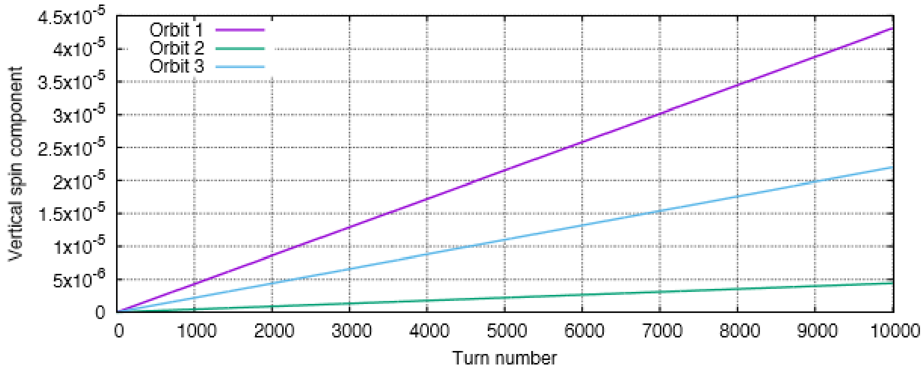
BROOKHAVEN NATIONAL LABORATORY GSI JÜLICH FORSCHUNGSZENTRUM

Full spin transparent storage ring

- A typical storage ring has to have quadrupoles. Spin frozen condition for deflector and for quadrupole is difference
- Off-center orbit in quadrupole makes beam encounter electric or magnetic fields that result in vertical spin buildup not from EDM, aka geometric effect. For an all-electrostatic pEDM ring [1], the amount of spin precession in one turn is given by [2]

$$\psi = (G\gamma + \frac{\gamma}{\gamma+1}) \sum_{i=1}^{N} b_{1e,i} y_i \frac{\beta_{\parallel,i}}{c} \frac{L_i}{B\rho},$$





[1] V. Anastassopulos et al, arXiv:1502.04317, 2016
[2] M. Bai, Y. Dutheil, D. Sagan, **arXiv:1611.04992, 2016**

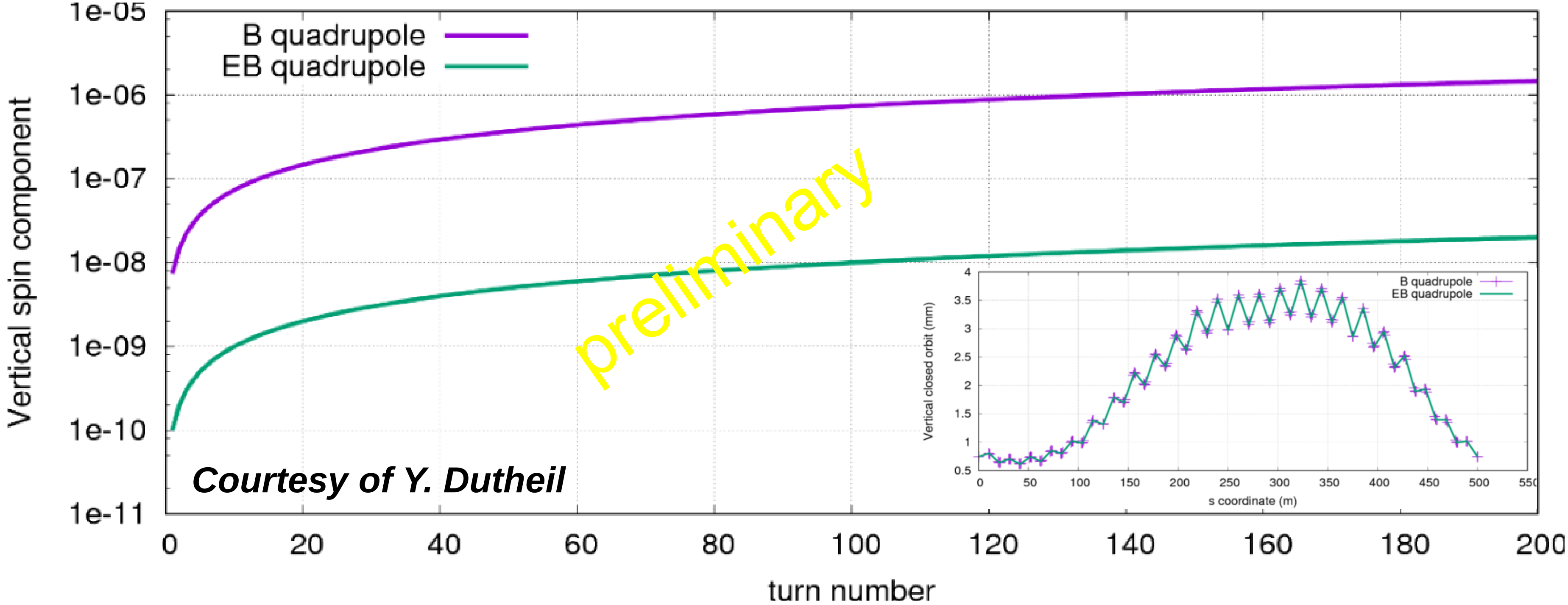
BROOKHAVEN NATIONAL LABORATORY

JÜLICH FORSCHUNGSZENTRUM

Full spin transparent storage ring

- For a EDM storage ring with EB deflectors, such an effect can be significantly reduced by employing spin transparent quadrupoles where

$$\vec{B} \cdot \vec{E} = 0.$$



M. Bai, Y. Dutheil, D. Sagan, **arXiv:1611.04992, 2016**

Storage Ring based EDM search challenges

- Long spin coherence time
  - 1000 sec spin coherence time for reaching 10^{-29} e-cm in one year (10^{27} sec)

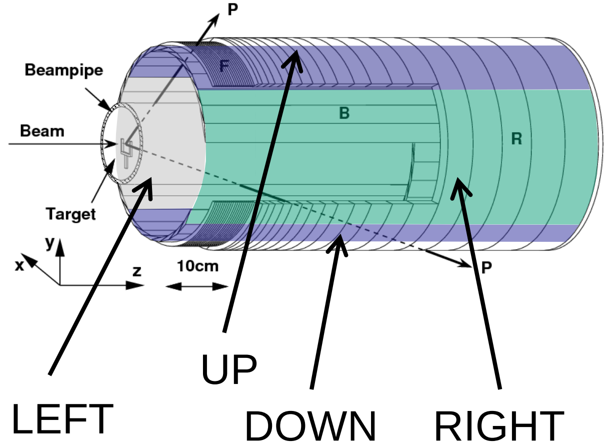
- High efficient polarimeter
- Monitor/mitigate systematic fake EDM signals due to various sources of un-wanted fields
  - A radial magnetic field of $B_r = \frac{d}{\mu} E_r$ produces the same vertical spin buildup signal due to the magnetic dipole moment
    - **Can be mitigated by CW and CCW beams**
  - Requires not only state of the art quality control of the magnetic and electric fields, but also high precision beam monitoring and control

BROOKHAVEN NATIONAL LABORATORY GSI JÜLICH FORSCHUNGSZENTRUM

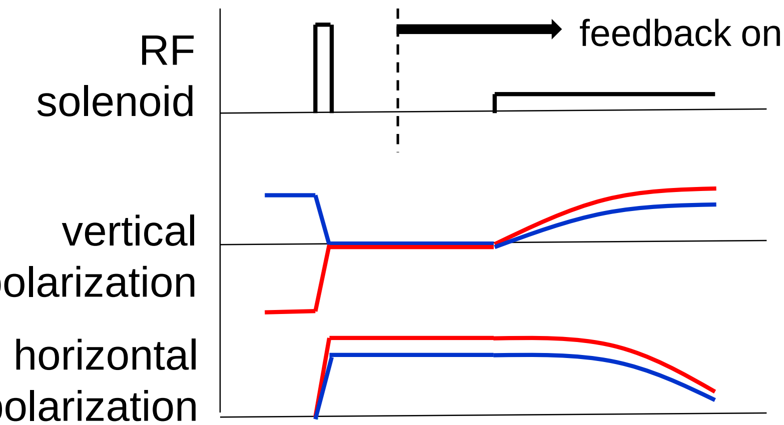
EDM @ COSY

Fast polarimeter@COSY that enabled spin coherence time investigation

EDDA detector



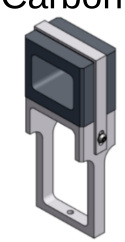
Real time feedback to control the spin phase at the polarimeter was demonstrated in the latest JEDI beam time at COSY



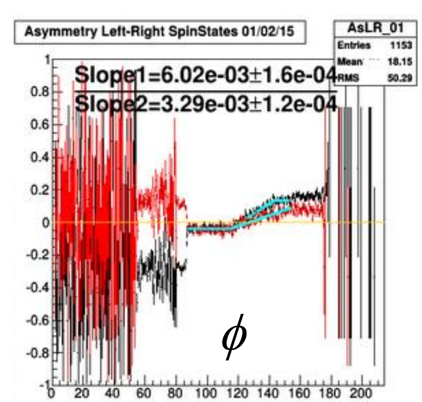
Azimuthal angles yield two asymmetries:

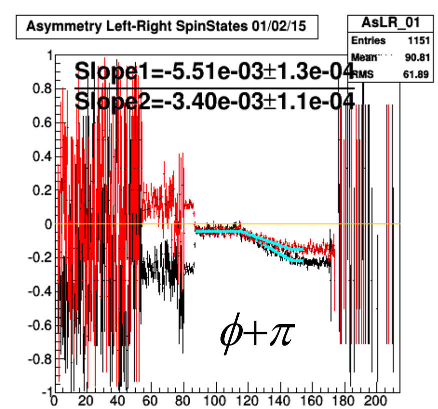
$$\varepsilon_{EDM} = \frac{L-R}{L+R} \qquad \varepsilon_{g-2} = \frac{D-U}{D+U}$$

17 mm Carbon target



double-hit extraction?:
deflect at (1), then oscillate to (2)

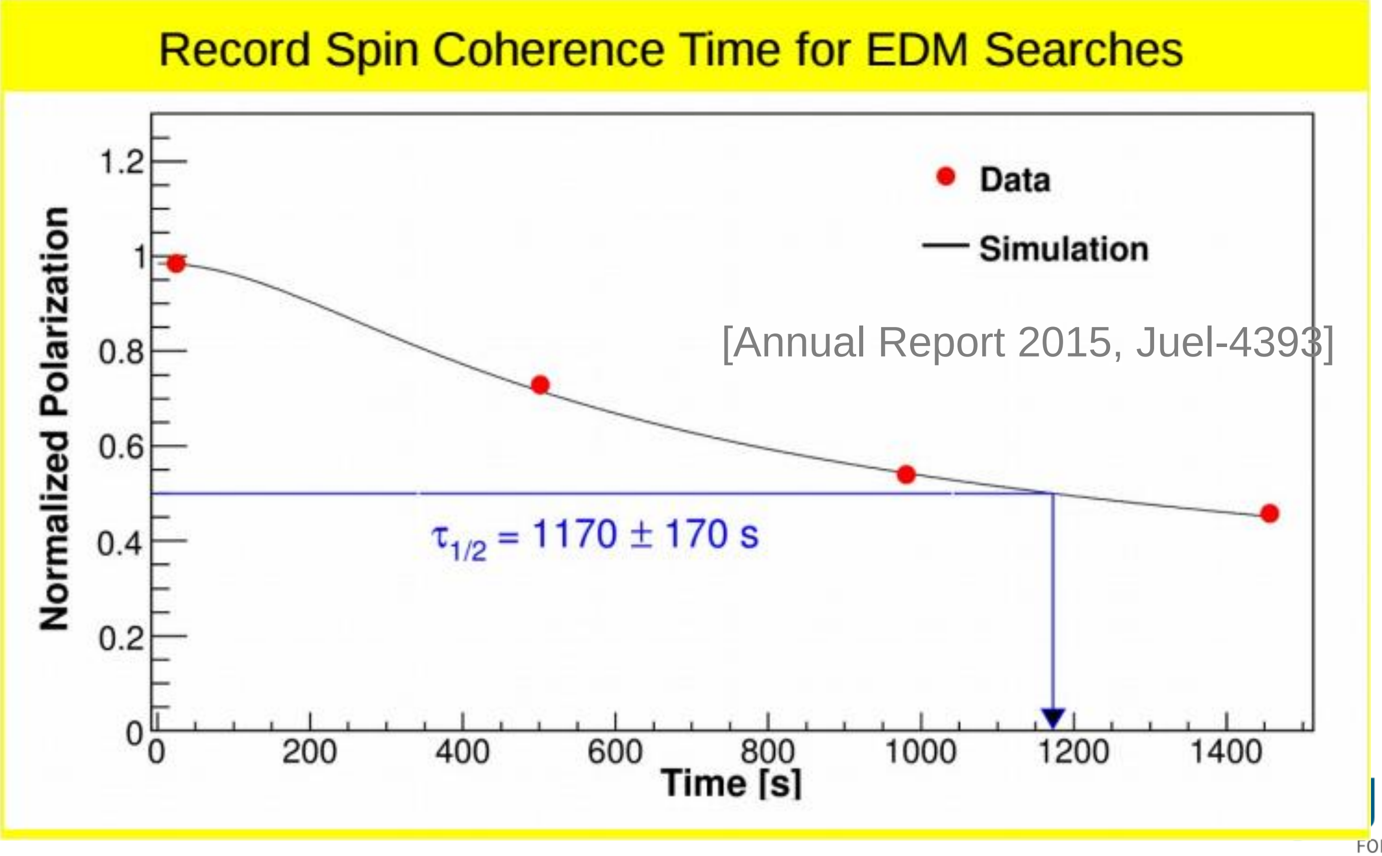




Courtesy of E. Stephenson

EDM @ COSY

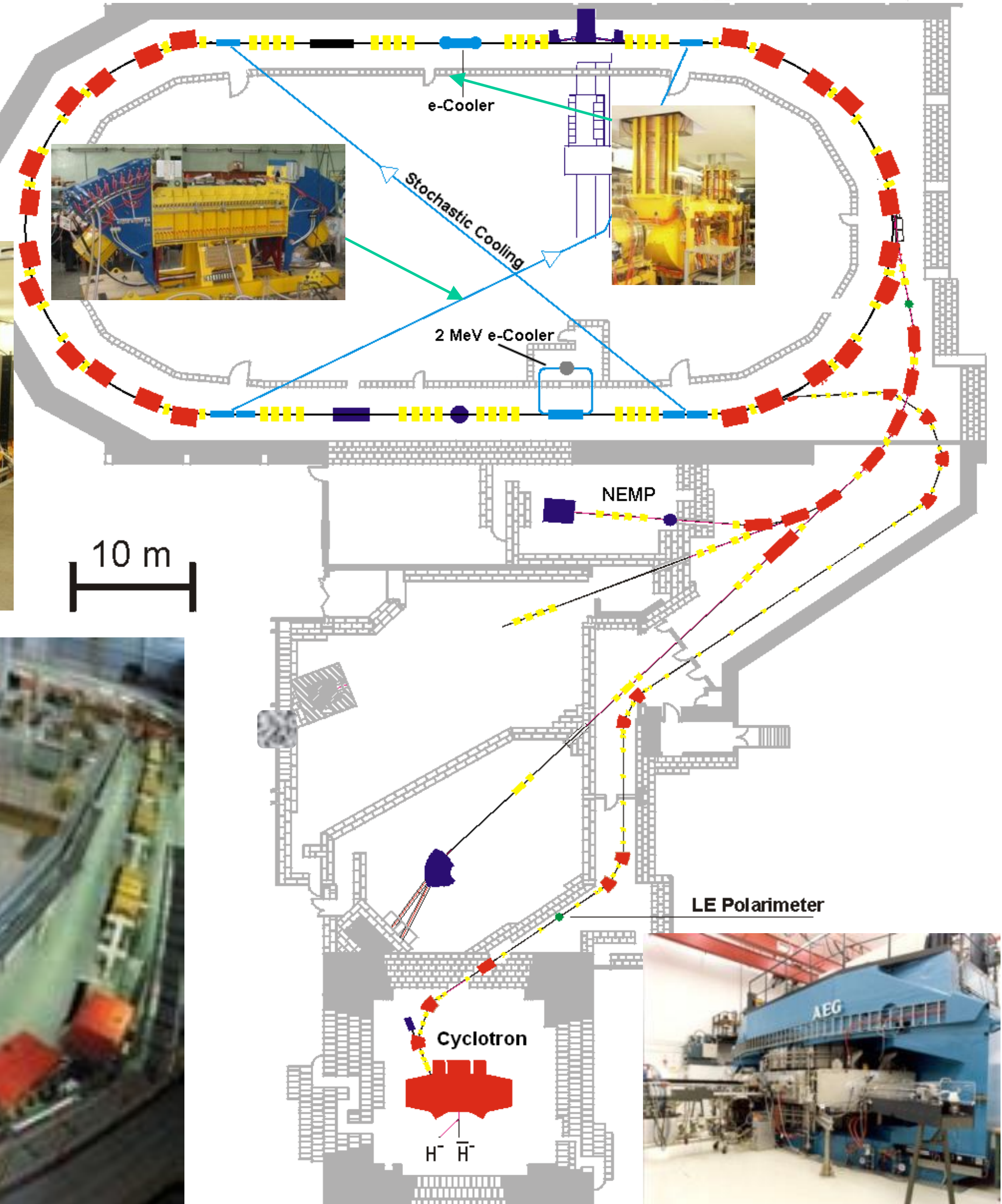
- Achieved long spin coherence time with deuteron beams
  - Beam momentum: ~970 MeV/c. Beam intensity: ~10^9
  - pre-cooled with COSY 100 keV e-cooler for ~75 sec
  - All sextupole (3 families) were adjusted to minimize both horizontal and vertical chromaticity



[Annual Report 2015, Juel-4393]

Cooler SYnchrotron

- Circumference: 184 m
- Species: protons, deuterons including polarized beams



Uniqueness of COSY

- Light ion beams with wide range of energy
  - Currently, COSY can provide proton and deuteron
    - between energy of 45MeV/75MeV to ~2GeV
    - Intensity at injection: <= 10^11 protons
    - Intensity at higher energy: <0.7^11 protons

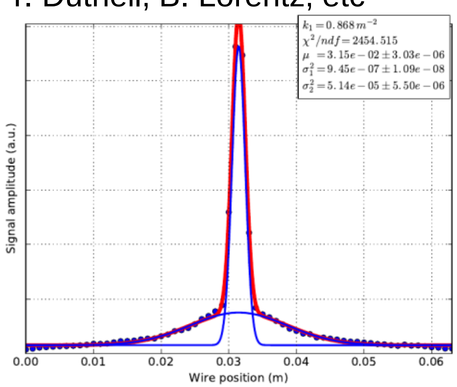
- Sophisticate beam cooling
  - Allows internal target operation
  - High brightness beam

- Extraction beam available in three of its beamlines

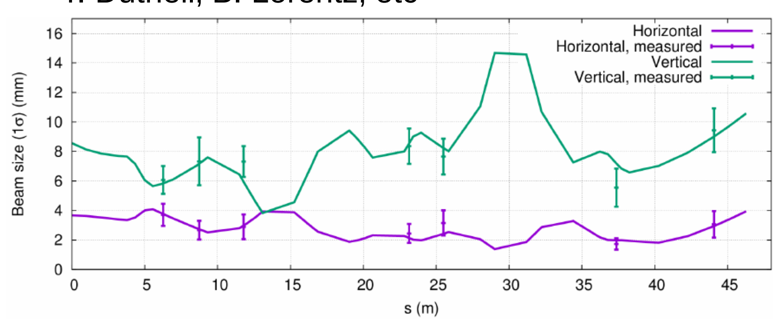
For a collider guy with zero German

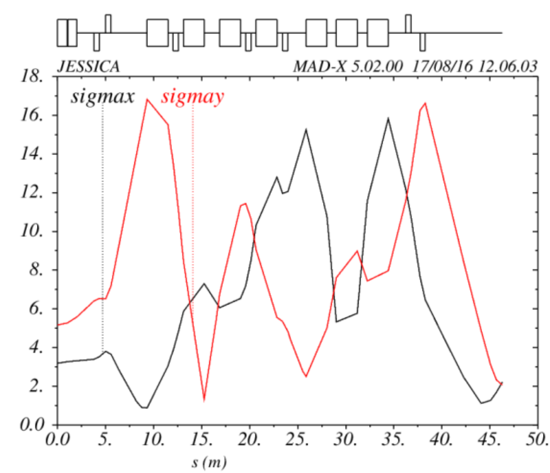
- Alles in Deutsch!!!
  - Survived, but not without a lot of embarrassing stories!
- Have to first remember particles can be non-relativistic!
  - This was embarrassing
- Have to deal with injection and extraction!
  - But this was fun!
  - Complains about the beam size at one of the beam lines, JESSICA
    - Default model shows flipping the polarity of Q15 can significantly reduce the optics run-away. This was confirmed during the latest run.
    - Further modeling shows having independent power supplies for Q13 and Q14 may allow to further reduce beam size

Y. Dutheil, B. Lorentz, etc



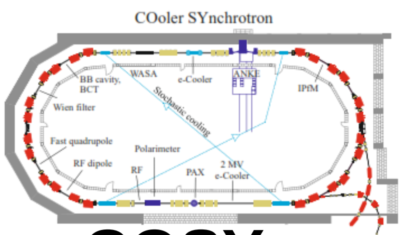
Y. Dutheil, B. Lorentz, etc



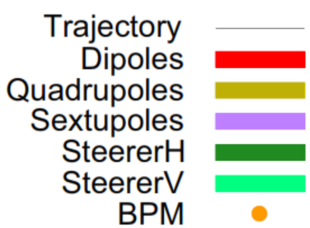


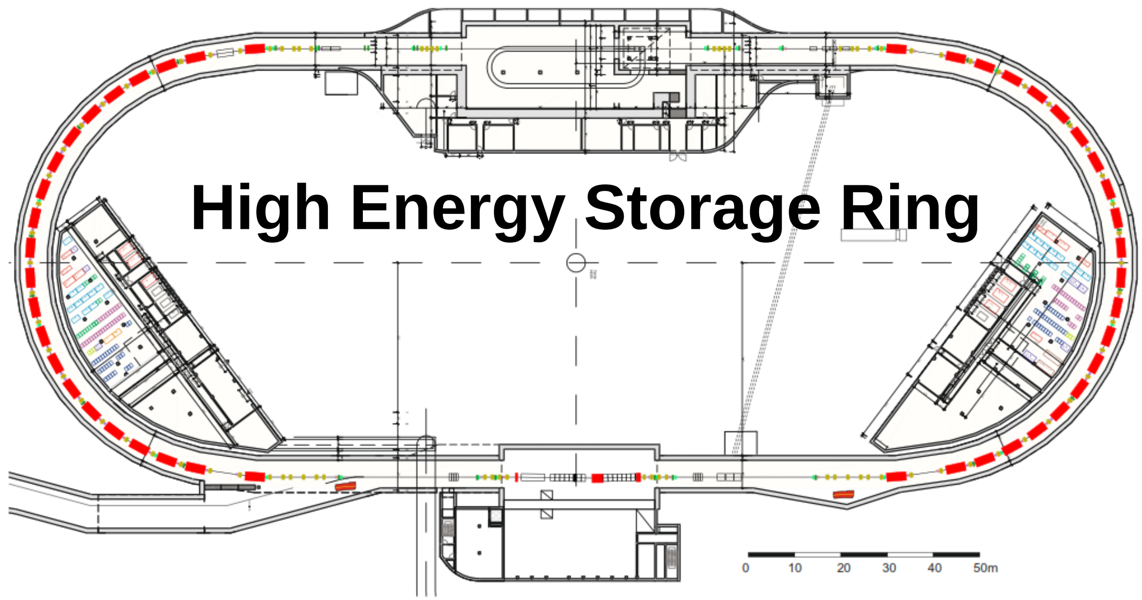
Current Operation Challenges

- **EDM precursor experiment at COSY**
  - Measure deuteron EDM using an RF wien filter
- **As test bed for FAIR**



COSY

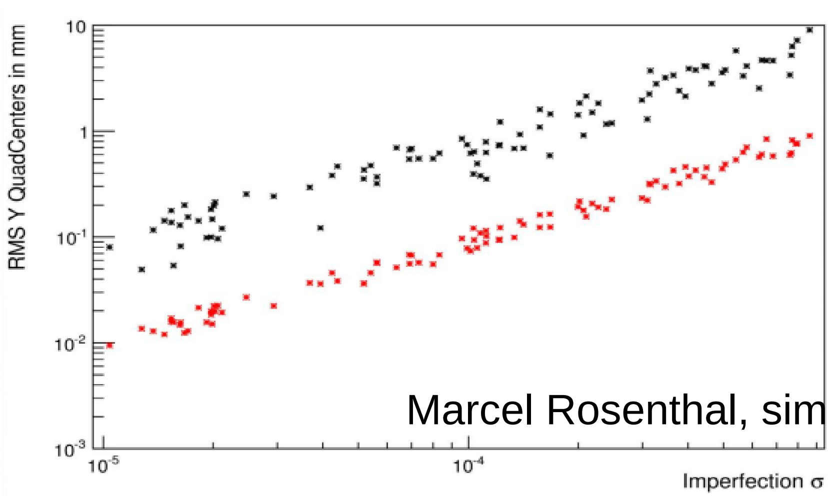


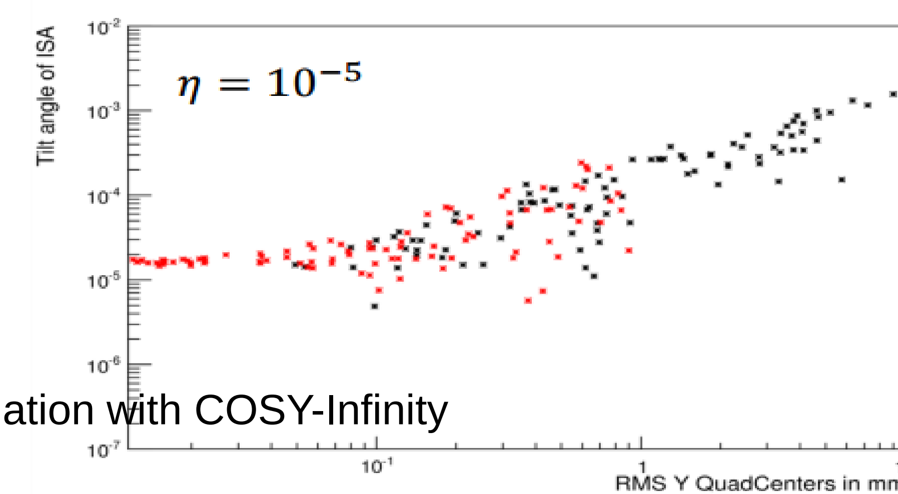


	Circumference	Energy range	Species
COSY	184m	0.3 ~ 3.7 GeV/c	Proton/deuteron
HESR	575m	1.5 ~ 15 GeV/c	Antiproton, heavy ion

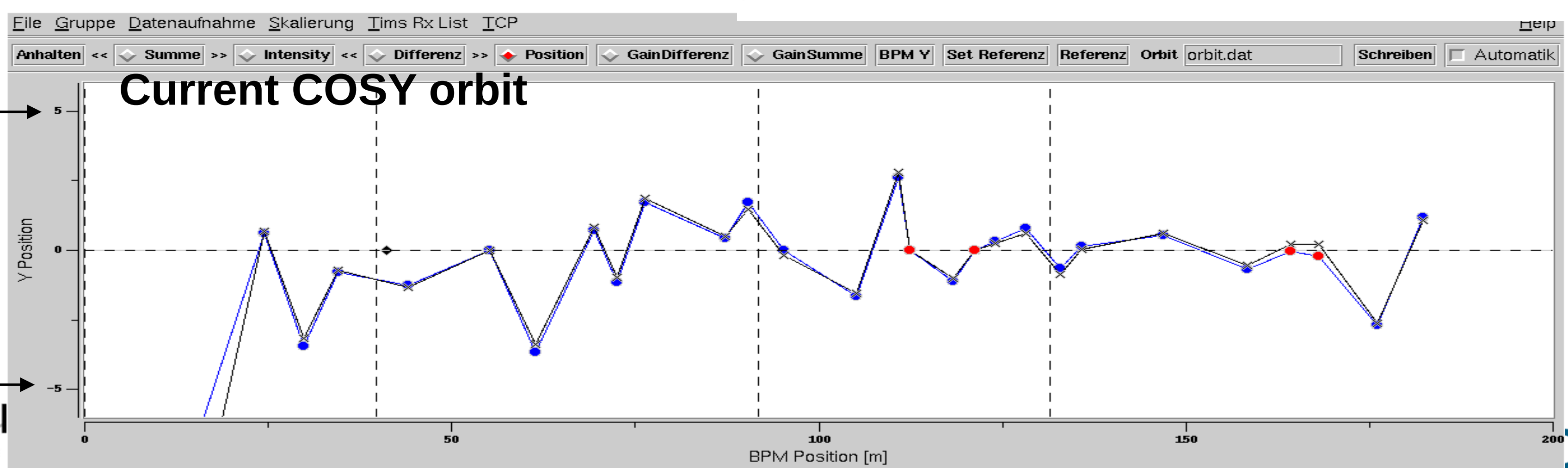
Challenges with precursor

Imperfection of the machine tilts stable spin direction away from vertical. Excluding other systematics, rms c.o ~ 100 μm puts the precision limit ~ 5×10^{-18} e-cm



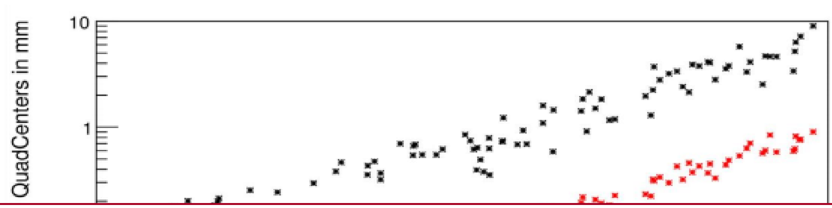


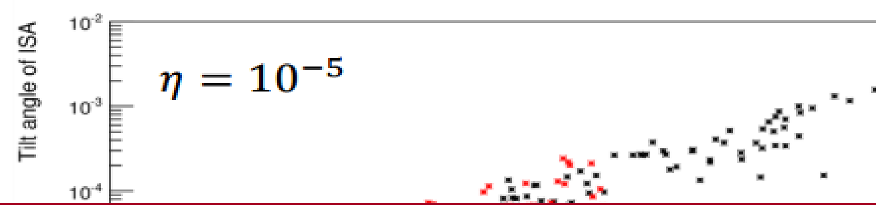
Marcel Rosenthal, simulation with COSY-Infinity



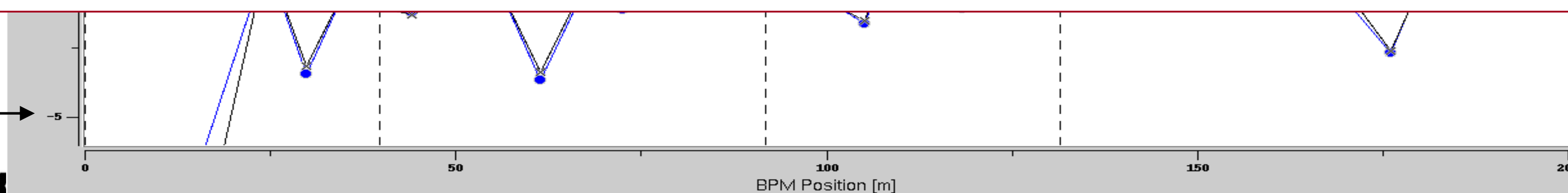
Challenges with precursor

Imperfection of the machine tilts stable spin direction away from vertical. Excluding other systematics, rms c.o ~ 100 μm puts the precision limit ~ 5×10^{-18} e-cm



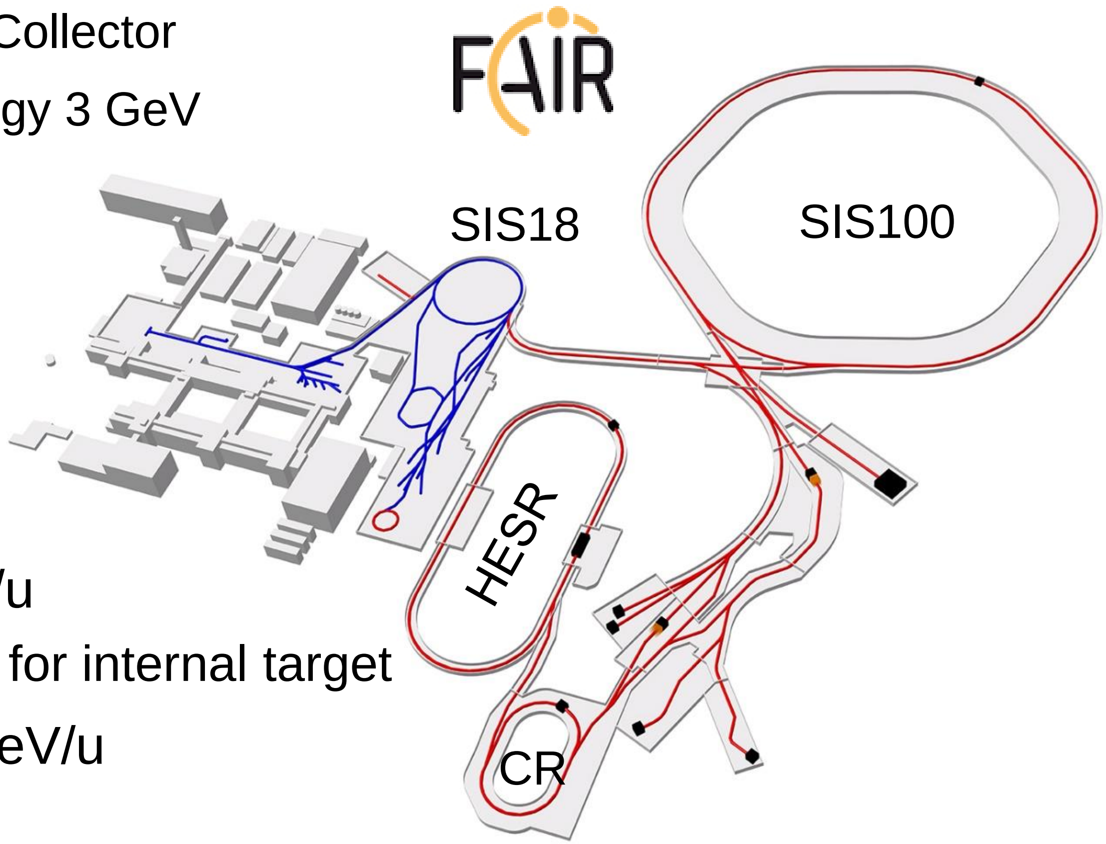


- Implemented automation of ORM data taking (F. Hinder, M. Simon)
- Implemented ORM based optics measurement (D. Ji [IHEP])
- COSY BPM upgrade are in working progress
  - In collaboration with cosyLab
  - Very recently demonstrated orbit feedback. Operation in progress
- ORM based COSY online model improvement (working progress)



HESR Challenges

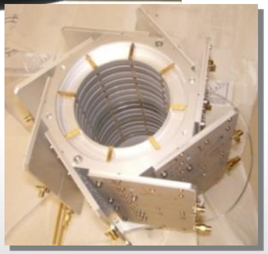
- Design to achieve high resolution and high luminosity for internal target operation
  - Anti-proton
    - Accumulating beam from Collector Ring (CR) at injection energy 3 GeV
    - Deceleration to 1 GeV (cooling at 2 GeV, 25 s)
    - Energy compensation for internal target experiment
  - Heavy ion
    - Injection at 740 MeV/u
    - Energy compensation for internal target experiment up to 5 GeV/u



HESR Challenges

- Beam cooling
  - Stochastic cooling
    - Needs to cover entire energy range
    - compact design and large bandwidth
      - 2-4 GHz first
      - 4-6 GHz 2nd if necessary
    - High sensitivity with fixed aperture

HESR SC kicker tank

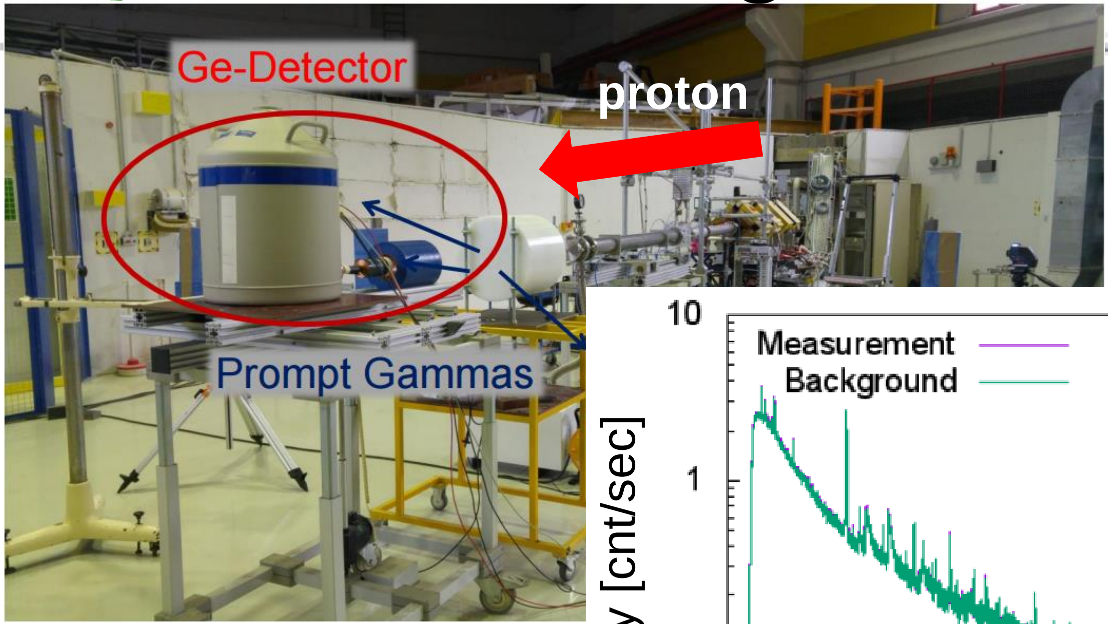


- High energy electron cooling
  - With conventional un-bunched electron beam cooling, 8 MeV electron beam is required to cover the energy range of HESR

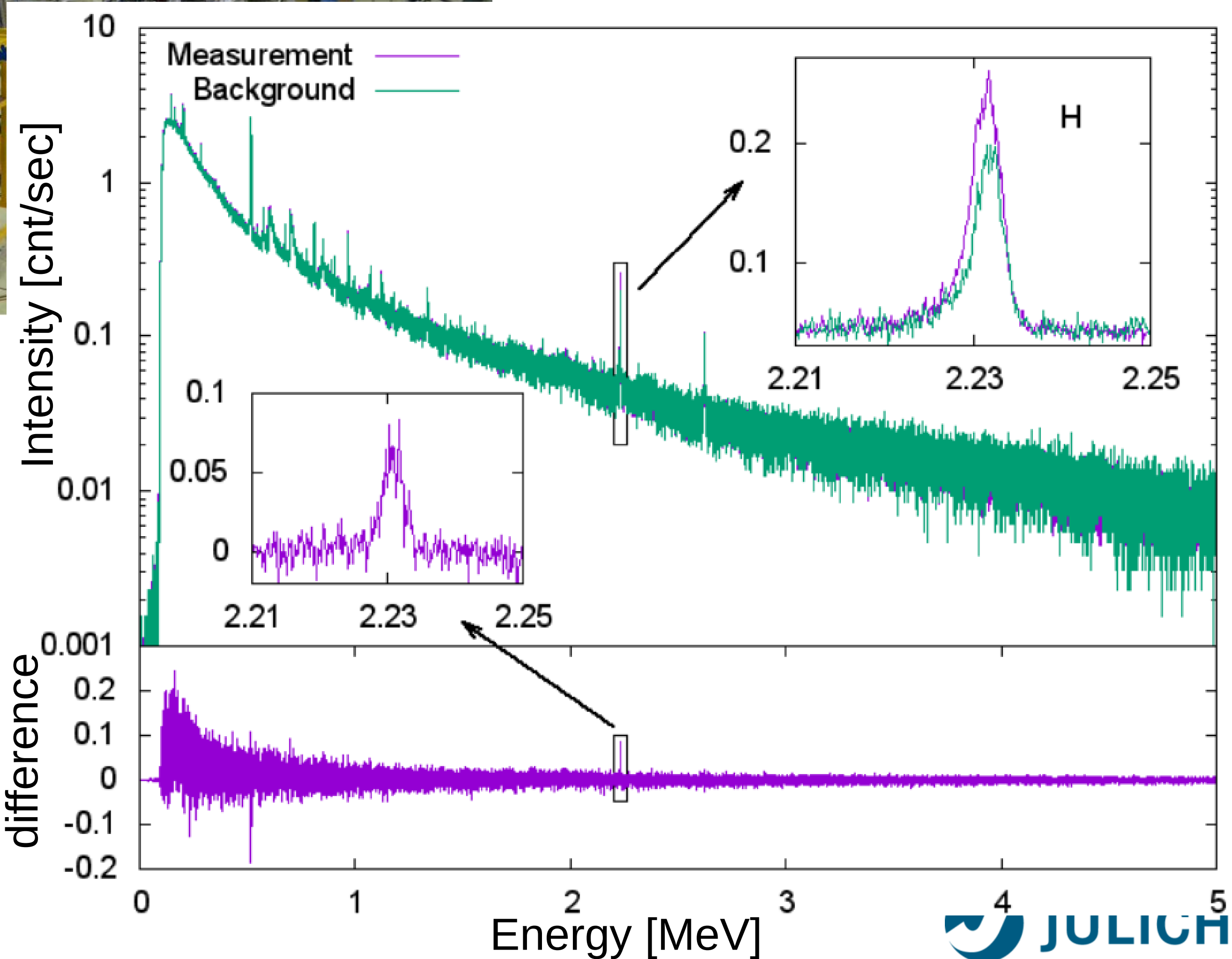
Current Operation Challenges

- **EDM precursor experiment at COSY**
  - Measure deuteron EDM using an RF wien filter
- **As test bed for FAIR**
  - Detector R&D
  - Accelerator R&D: beam cooling, beam instrumentation, etc
- **Expanding COSY capability for multidisciplinary science research**
  - Nuclear medicine, irradiation study, HBS development
  - High extraction beam current
    - **1 nA 100 MeV proton extracted at BigKarl beamline**
  - Various beam requirements
    - Beam energies including low energies
    - Beam size and distributions

Proton beam for High Brillian n Source@BigKarl



- 100 MeV protons extracted
- Degraded to 40 MeV



COSY beam proposal to validate neutron production for the development of high-brilliant neutron source targets:

- Paul Zakalek, etc from JCNS

BROOKHAVEN NATIONAL LABORATORY

JÜLICH FORSCHUNGSZENTRUM

Summary

- The opportunity of growing up together with RHIC gave me the rich experience with high energy collider R&D and operation. And, COSY operation allows me to expand my knowledge
- It is very valuable for an accelerator physicist to stay with live machine operation
- For an user facility, depending on the user community, there are differences between the operation modes. But, there are still a lot of overlaps
  - Reliability
    - planning: spares for critical devices, systematic upgrades, continuation of expertise, etc
    - adapt new technologies: automation etc
  - Continuous R&D

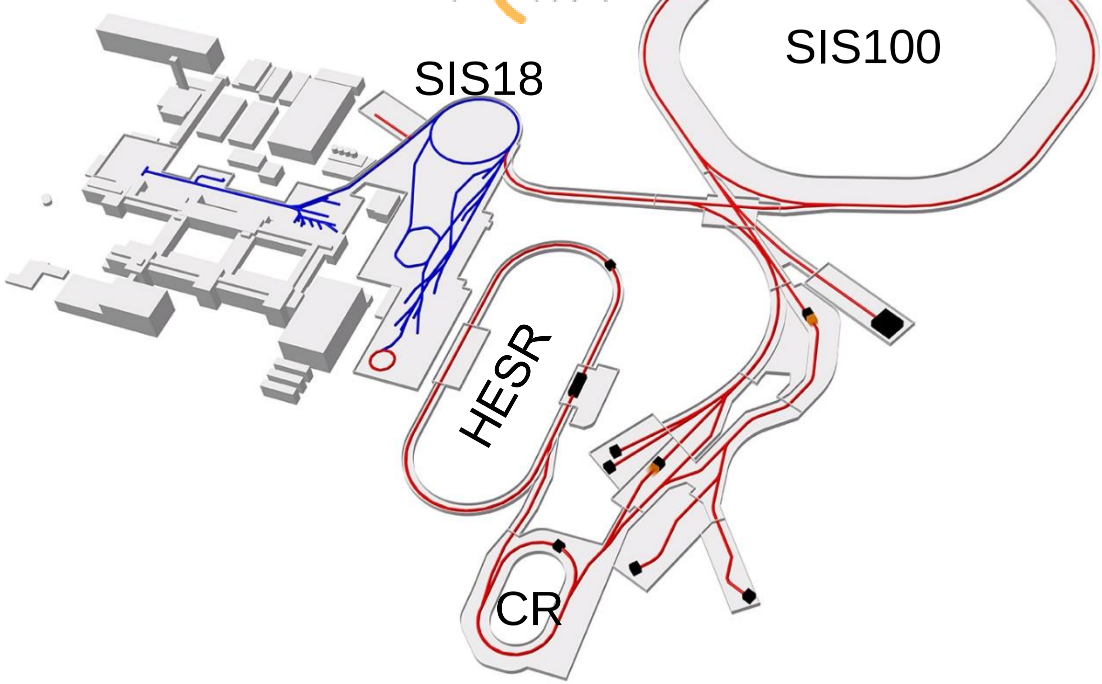
BROOKHAVEN NATIONAL LABORATORY

GSI

JÜLICH FORSCHUNGSZENTRUM

Outlook

- Freshly joined GSI/FAIR barely 3 days ago
- Look forward to the new challenges in the area of multi-user high intensity beam operation for world-class science
- Also, look forward to work with the colleagues to advance the research and development in the field of Accelerator Sci&Tech



BROOKHAVEN NATIONAL LABORATORY

JÜLICH FORSCHUNGSZENTRUM

ACCELERATOR SEMINAR

Prof. John Cary

TechX, Boulder USA

Thursday, 11th May at 4 p.m.

KBW lecture hall

Planckstraße 1, 64291 Darmstadt

"Structure Preserving Integration of Charged Particles in Electromagnetic Fields"

... will follow ...