From RHIC to COSY, an Adventurous Journey

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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!

(BRAHMS)

(PhOBOS)

RHIC

(PhENIX)

LINAC

EBIS

NSRL

BOOSTER

AGS

STAR

STAR

Electronics Platforms

Forward Time Projection Chamber

Silicon Vertex Tracker

E-M Calorimeter

Time Projection Chamber

Time Of Flight

ignet
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**

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

http://www.rhichome.bnl.gov/RHIC/Runs/
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
What matters for Collider Operation?

- **Luminosity! Luminosity!**
  
  # of collisions per unit area and per unit time

- For the case of head-on collisions
  
  \[ L = f \frac{N_1 N_2}{A} \]

  Frequency of collision

  Area of collision, i.e., the product of beam size

- Ways to increase the peak luminosity
  
  - Increase # of particles in each beam, i.e., bunch intensity
  - Increase # of bunches
  
  - Make each bunch more bright, i.e., shrink the size of the bunch at collision
RHIC Operation:

A Typical RHIC Store

Check injection:
- bunch intensity
- injection matching
- ...

Filling Blue ring...
Filling Yellow ring...
Cogging, establish collision
Acceleration...
Challenges in RHIC Heavy Ion Luminosity

Intra-beam scattering

Coulomb interaction between charged particles

Leads to debunching and transverse emittance growth, i.e. longer bunch length and larger transverse beam size

2004 no cooling
Full 3D Stochastic Cooling at RHIC

5-9 GHz, cooling time ~1 h

M. Brennan, M. Blaskiewicz, K. Mernick
Heavy Ion Store w. Stochastic Cooling

![Experimental Coincidence Signals](chart1.png)

![Intensity Changes](chart2.png)
Dynamic Beta Squeeze

To maximize the integrated luminosity

\[ \beta^* = 0.6 \text{ m} \]
\[ \beta^* = 0.5 \text{ m} \]

Stochastic cooling on

Spin motion in a circular accelerator

Thomas BMT Equation: (1927, 1959)

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

Spin vector in particle’s rest frame

- G is the anomalous g-factor, for proton, G=1.7928474
- \(\gamma\): Lorenz factor

Spin tune \(Q_s\): number of precessions in one orbital revolution: \(Q_s = G\)

Magnetic field perpendicular to the particle’s velocity

Magnetic field along the direction of the particle’s velocity

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 quadrupoles, 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

Initial beam

$1^{st}$ full betatron Oscillation period

$2^{nd}$ full betatron Oscillation period
Full Siberian Snake

- A magnetic device to rotate spin vector by 180°
- Keep the spin tune independent of energy
Use one or a group of snakes to make the spin tune to be at $\frac{1}{2}$

Break the coherent build-up of the perturbations on the spin vector
Snake Depolarization Resonance

- **Condition**

\[ mQ_y = Q_s + k \]

- **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**

\[ N_{snk} > 4 \left| k, \max \right| Q_s = \sum_{k=1}^{N_{snk}} ( -1 )^k \]

\( k \) is the snake axis relative to the beam direction

Snake resonance observed in RHIC

3/4 resonance

Setting for 2009 250 GeV run
Setting for 2011 250 GeV run

Polarization transmission efficiency (CNI #1) vs. vertical tune

Blue, 2009
Yellow, 2009
BluePol1, 2011
BluePol2, 2011
YellowPol2, 2011
Precise Beam Control

Orbit feedback system: rms orbit distortion less than 0.1mm

Tune/coupling feedback system: acceleration close to 2/3 orbital resonance
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!
CURIOSITY IS THE ESSENCE OF THE SCIENTIFIC MIND.
A Proposal to Measure the Proton Electric Dipole Moment with $10^{-29}\, e\cdot cm$

Sensitivity

by the Storage Ring EDM Collaboration

October 2011

https://www.bnl.gov/edm/
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
Status of EDM search

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.

No direct measurement of charged ions
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

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

- 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

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

• 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

Full Spin Frozen storage ring is the most effective way!
To freeze spin

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

\[
p = \frac{m}{\sqrt{G}} = 0.7007 \text{ GeV/c}
\]

For deuteron, \( G = -0.14 \)

\[
E = \frac{G \gamma c p}{1 + G \beta^2 \gamma^2} B
\]

<table>
<thead>
<tr>
<th>Bending radius [m]</th>
<th>Deflector E field strength</th>
<th>Deflector B field strength</th>
<th>CW/CCW same orbit/time</th>
</tr>
</thead>
<tbody>
<tr>
<td>pEDM 52.3</td>
<td>8.017 MV/m</td>
<td>--</td>
<td>yes</td>
</tr>
<tr>
<td>dEDM 52.3</td>
<td>2.3 MV/m</td>
<td>0.07 Tesla</td>
<td>no</td>
</tr>
<tr>
<td>dEDM 26.4</td>
<td>4.54 MV/m</td>
<td>0.153 Tesla</td>
<td>no</td>
</tr>
<tr>
<td>pEDM 26.4</td>
<td>15 MV/m</td>
<td>--</td>
<td>yes</td>
</tr>
</tbody>
</table>

Key: high field electrostatic deflector
Key: ExB deflector
Pure Electrostatic Storage Ring for proton EDM

Design sensitivity: $4 \times 10^{-29}$ 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
$\varepsilon_x, \varepsilon_y$ [mm-mrad] 17, 3.2
Maximum $\frac{dp}{p}$ 4.6$ \times 10^{-4}$
Dispersion, max [m] 30 m

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]

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

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

\[ \vec{B} \cdot \vec{E} = 0. \]

![Graph showing spin component over turn number](image)

** Courtesy of Y. Dutheil **

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
Azimuthal angles yield two asymmetries: 

\[ \varepsilon_{EDM} = \frac{L-R}{L+R} \quad \varepsilon_{g-2} = \frac{D-U}{D+U} \]

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

EDDA detector

- LEFT
- DOWN
- RIGHT

17 mm Carbon target

typical depth \(\sim 0.2\) mm

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

Record Spin Coherence Time for EDM Searches

$\tau_{1/2} = 1170 \pm 170$ s

[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: $\leq 10^{11}$ 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 runaway. 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
Current Operation Challenges

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

<table>
<thead>
<tr>
<th></th>
<th>Circumference</th>
<th>Energy range</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>COSY</td>
<td>184m</td>
<td>0.3 ~ 3.7 GeV/c</td>
<td>Proton/deuteron</td>
</tr>
<tr>
<td>HESR</td>
<td>575m</td>
<td>1.5 ~ 15 GeV/c</td>
<td>Antiproton, heavy ion</td>
</tr>
</tbody>
</table>
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 ~ 5x10^{-18} e-cm
Challenges with precursor

Imperfection of the machine tilts stable spin direction away from vertical. Excluding other systematics, rms c.o ~ 100 \( \mu \)m puts the precision limit ~ \( 5 \times 10^{-18} \) 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
  - 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 Brilliant 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
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
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
ACCELERATOR SEMINAR

Prof. John Cary
TechX, Boulder USA

Thursday, 11th May at 4 p.m.

Klew lecture hall
Planckstraße 1, 64291 Darmstadt

“Structure Preserving Integration of Charged Particles in Electromagnetic Fields”

... will follow ...