From COSY to HESR and EDM Storage Ring

M. Bai on behalf of Institut für Kernphysik,
Forschungszentrum, Juelich

DPG spring meeting, Technische Universität Darmstadt, March 17, 2016

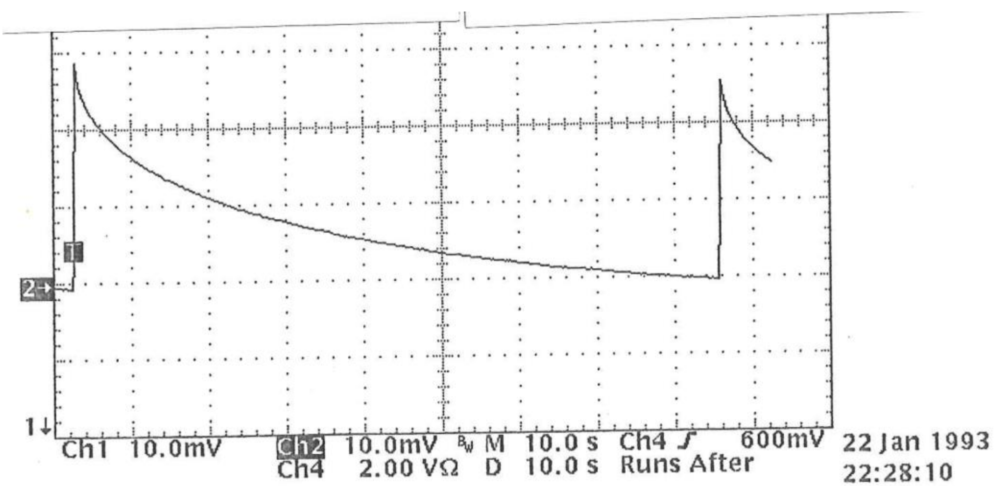
Outline

- The story of COSY
  - Brief introduction
  - Highlights
    - Accelerator
    - Hadron physics
- COSY current status: ideal cradle for challenging projects
  - FAIR contribution: HESR
  - Towards storage ring based EDM search for charged particles
- Future
  - Dedicated storage ring for EDM
  - Platform for multi-disciplinary basic research
- Summary and Outlook

COSY History

- 1968: Institute of Nuclear Physics at FZJ
    - Nuclei investigation with cyclotron (JULIC)
- 1980s: COSY was proposed to provide higher intensity and resolution for nuclear structure experiments using light ion beams from JULIC [**S. A. Martin et al, NIM A236 (1985) 249-255**]
- 1988: COSY foundation, construction started
- 1993: 1st circulating proton beam was achieved at injection

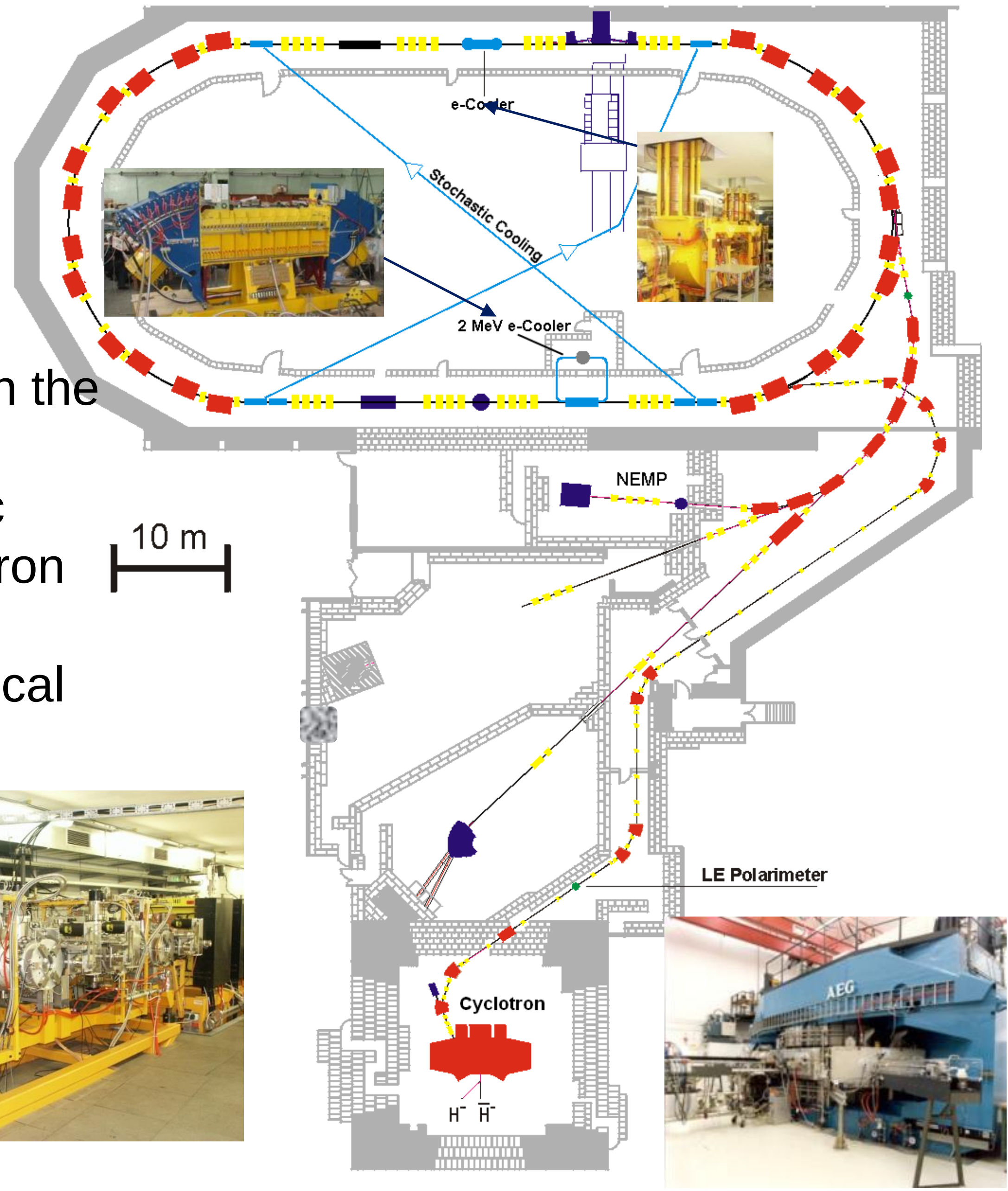
First stored p beam at injection energy

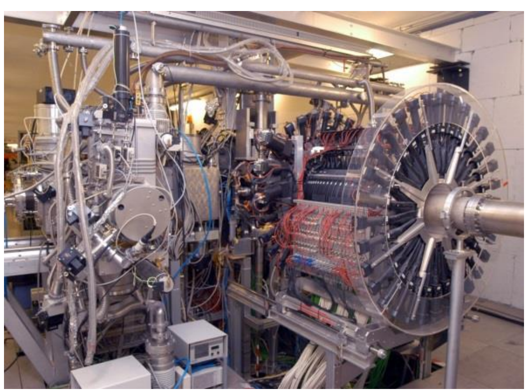


Member of the Helmholtz Association

COoler SYnchrotron

- Circumference: 184 m
- Species: protons, deuterons including polarized beams
- Maximum beam momentum:
  - 3.65 GeV/c
- For experiments with internal target as well as and beams in the extraction beamlines
- Equipped with both stochastic beam cooling as well as electron beam cooling
- Cyclotron also produces medical isotopes for research



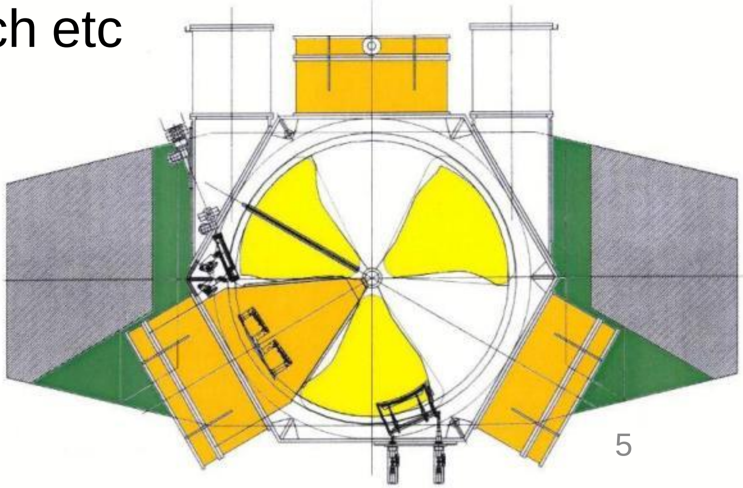


JULIC: COSY injector

- Designed by AEG, 1st beam in 1968
  - Pole diameter: 3.3m/700 Tons iron
  - $<B>_{max}$=1.35 Tesla, B_{hill}=1.97 Tesla
  - 3 ion sources, including polarized ion source
- Together with Big-Karl spectrometer, was the working horse for nuclear physics until COSY
- Upgraded for COSY in 1990
- Still provides excellent service for COSY, as well as nuclear medicine research etc

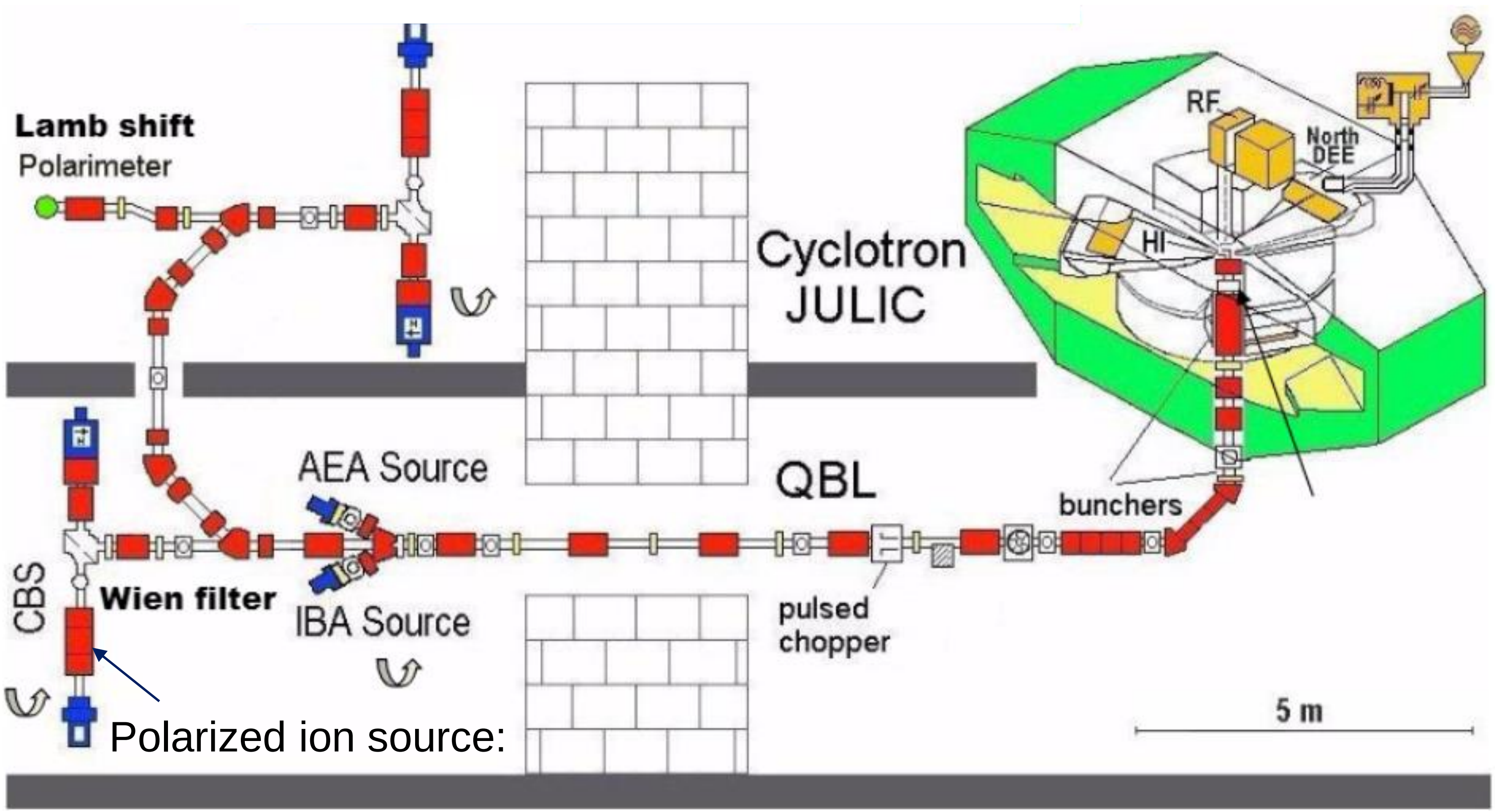
routinely 45 MeV H^- and 75 MeV D^- for COSY with 20 ms stripping injection/cycle

Courtesy of R. Gebel



Highlights of COSY

- Negative polarized H-/D- source
  - 45/35 µA H- / D- output
  - ~92% beam polarization in COSY



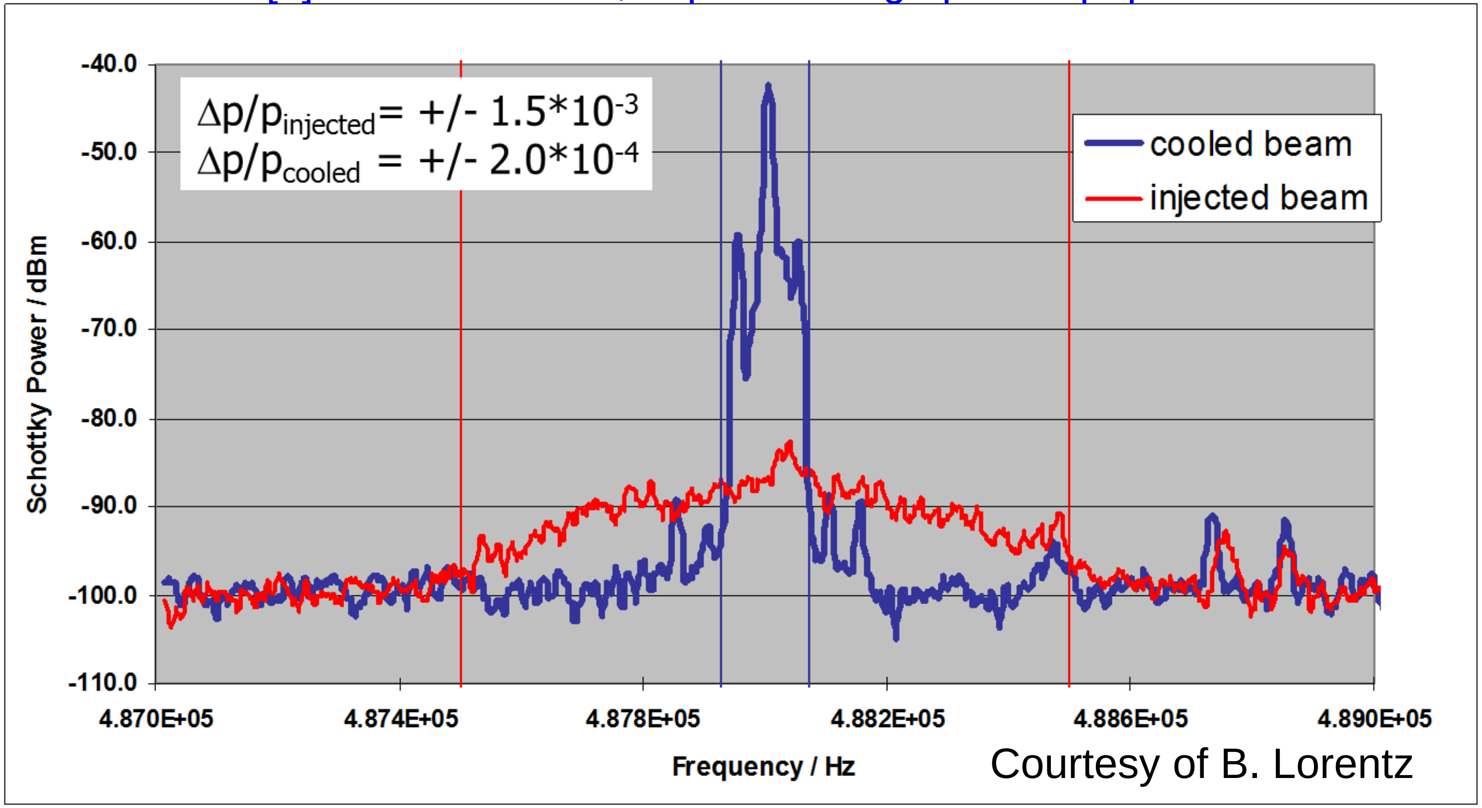
Courtesy of R. Gebel

Highlights of COSY

- Electron cooling

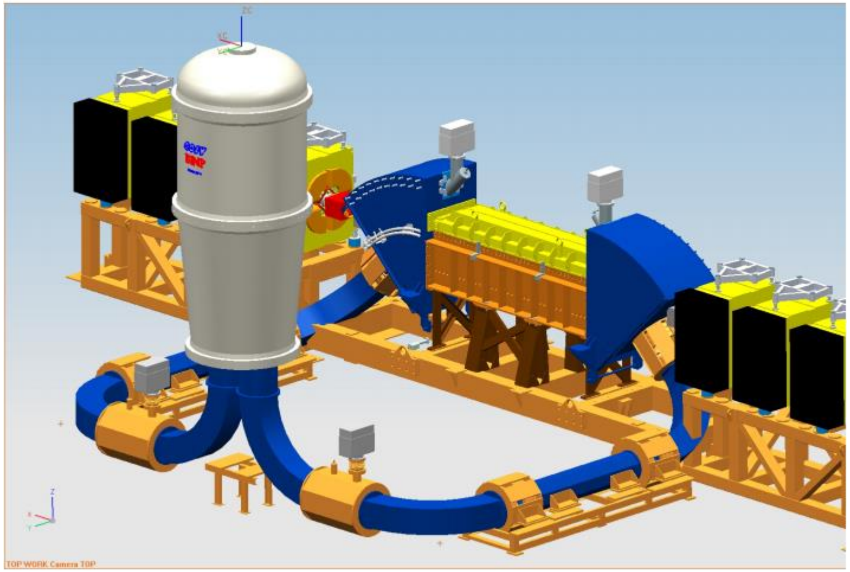
- constructed between 1988 -1993
- 2m long with electron energy from 24.5 -100 keV
- electron beam current: ≤ 4 A
- electron cathode size: 2.54 cm
- was the working horse for internal target experiments: WASA, ANKE, etc

[1] H. J. Stein *et al*, http://arxiv.org/ftp/arxiv/papers/1101/1101.5963.pdf



Highlights of COSY

2 MeV electron cooler development



Design parameters

- Energy range: 0.025 - 2 MeV
- High voltage stability: < 10^{-4}
- Electron current: up to 3 A
- Electron beam diameter: 10 - 30 mm
- Cooling section length: 2.7 m
- Toroid radius: 1 m
- Cooling section solenoid: 0.5 - 2 kG

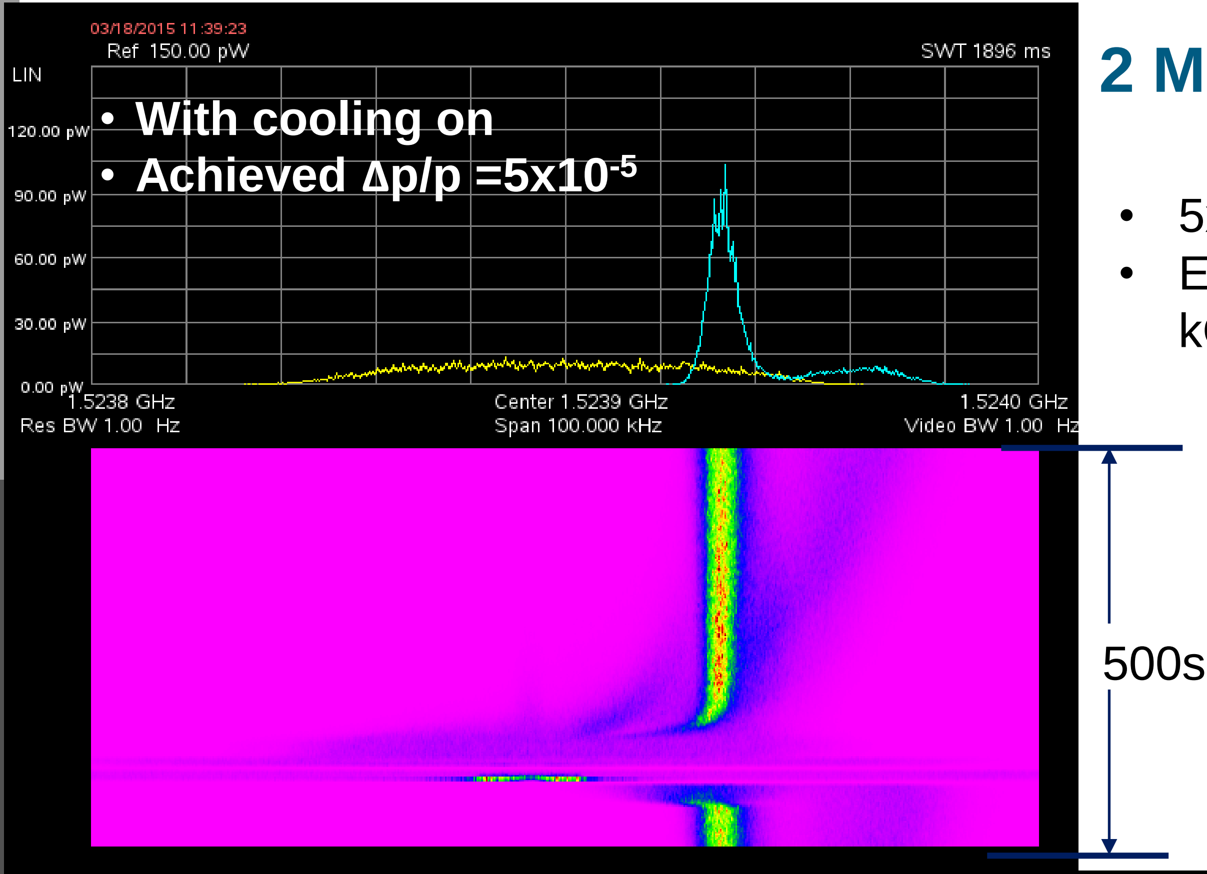
Courtesy of V. Kamerdzhiev

Currently achieved

Proton energy, MeV	Electron energy, MeV	Max. electron current, A
200	0.109	0.5
353	0.192	0.5
580	0.316	0.3
1670	**0.908**	**0.9**

2 MeV electron cooler

- 5×10^8 protons at 1.66 GeV, DC
- Electron current 0.8 A, with 1.3 kG solenoid



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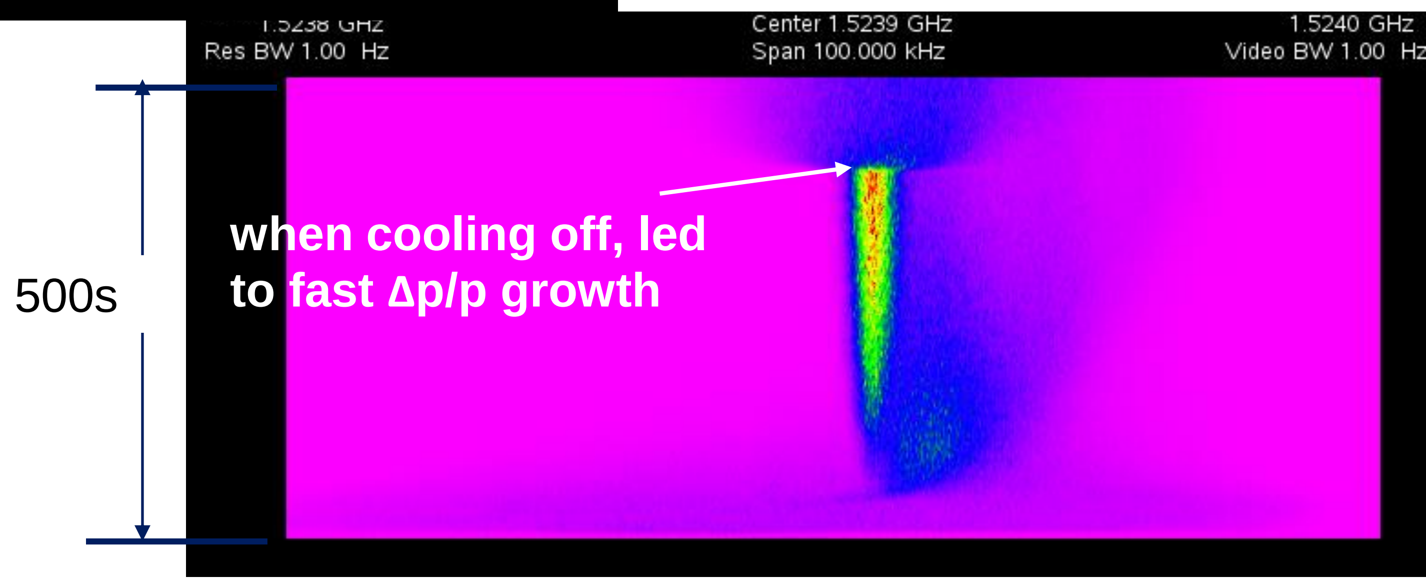
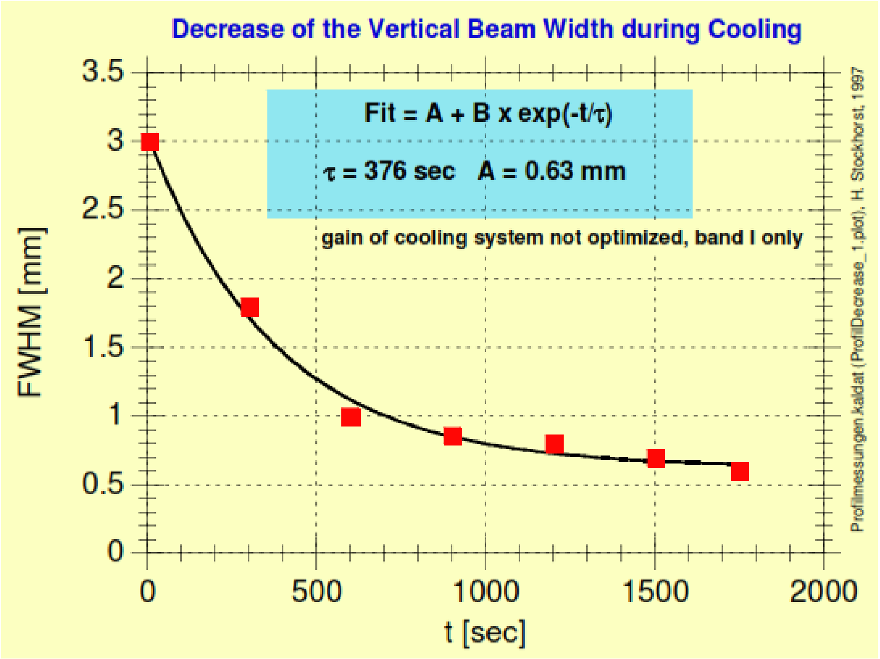


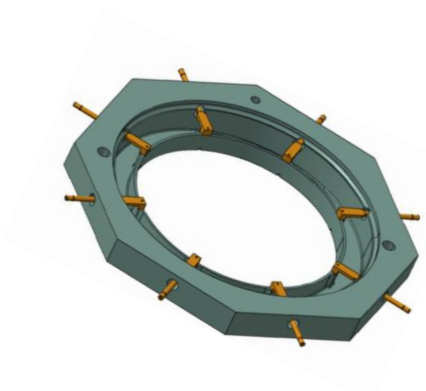
Highlights of COSY

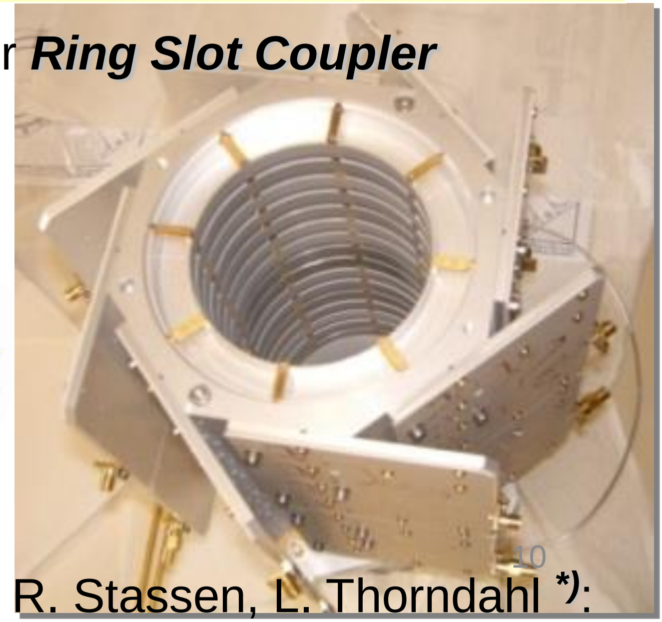
- Stochastic cooling at COSY
  - Transverse betatron cooling
  - Longitudinal cooling using notch filter technique
  - Effective from beam energy 1.5 GeV/c to 3.7 GeV/c
  - Bandwidth: 1-3 GHz



- Stochastic cooling for HESR
  - Novel compact design of pickup/kicker
    - ring-slot coupler
    - bandwidth of 2-4 GHz
    - high sensitivity
    - fixed aperture

Pickup/Kicker ***Ring Slot Coupler***



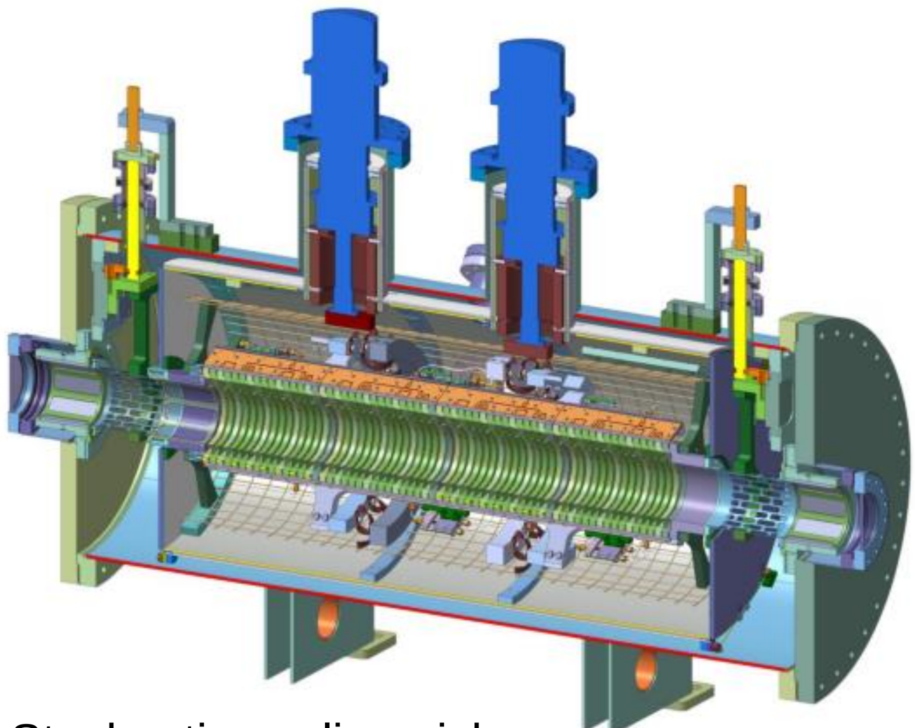


R. Stassen, L. Thorndahl *):

Courtesy of H. Stockhorst

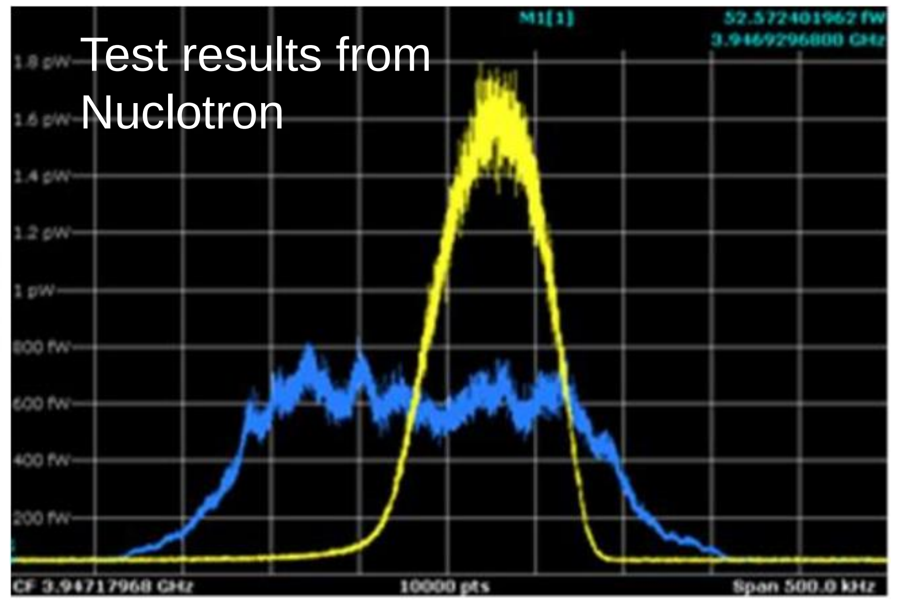
Highlights of COSY

- Was prototyped and tested at COSY and Nuclotron (JINR)
  - 2×10^9 Deuteron beam
  - Beam energy at 3 GeV
  - Cooling time 480 sec



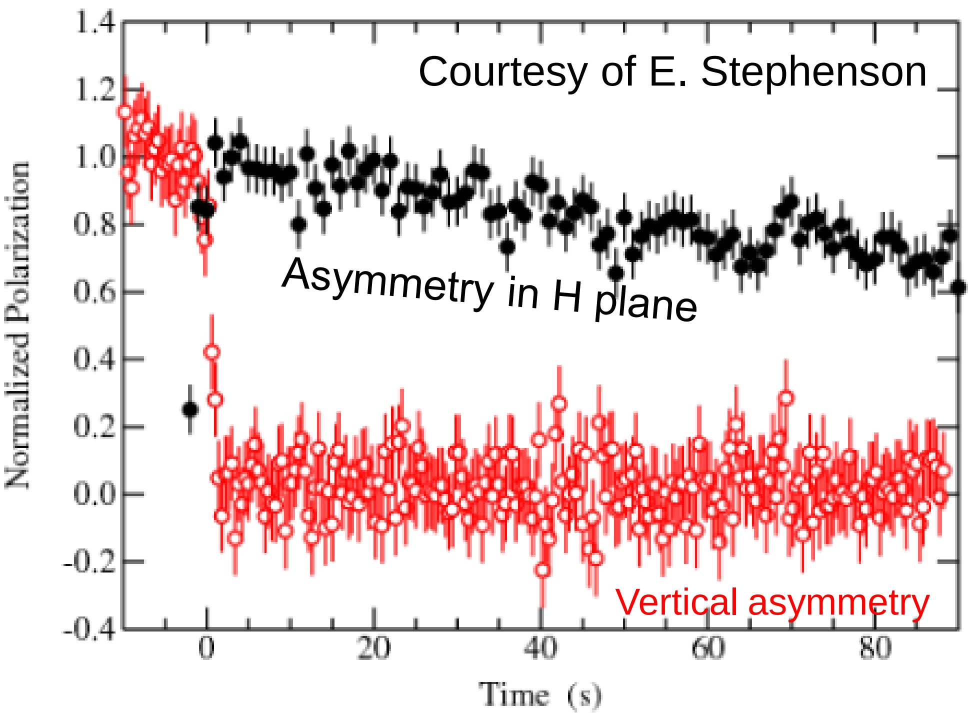
Stochastic cooling pickup

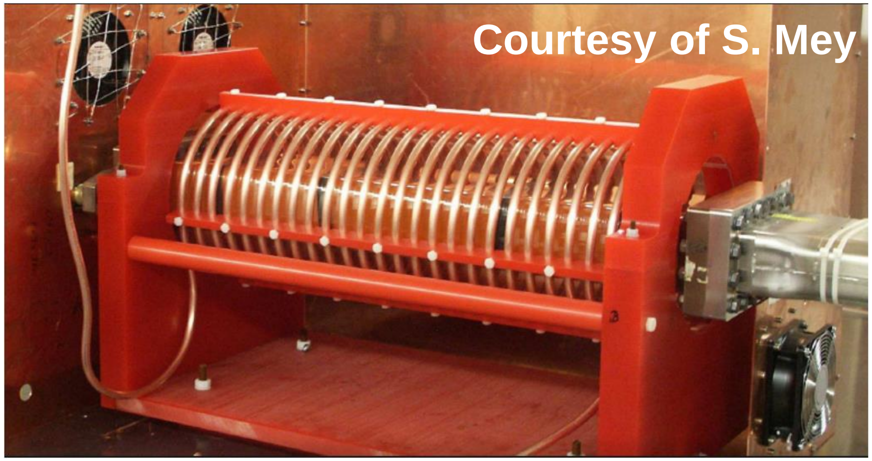
R. Stassen, H. Stockhorst, et al



Highlights of COSY

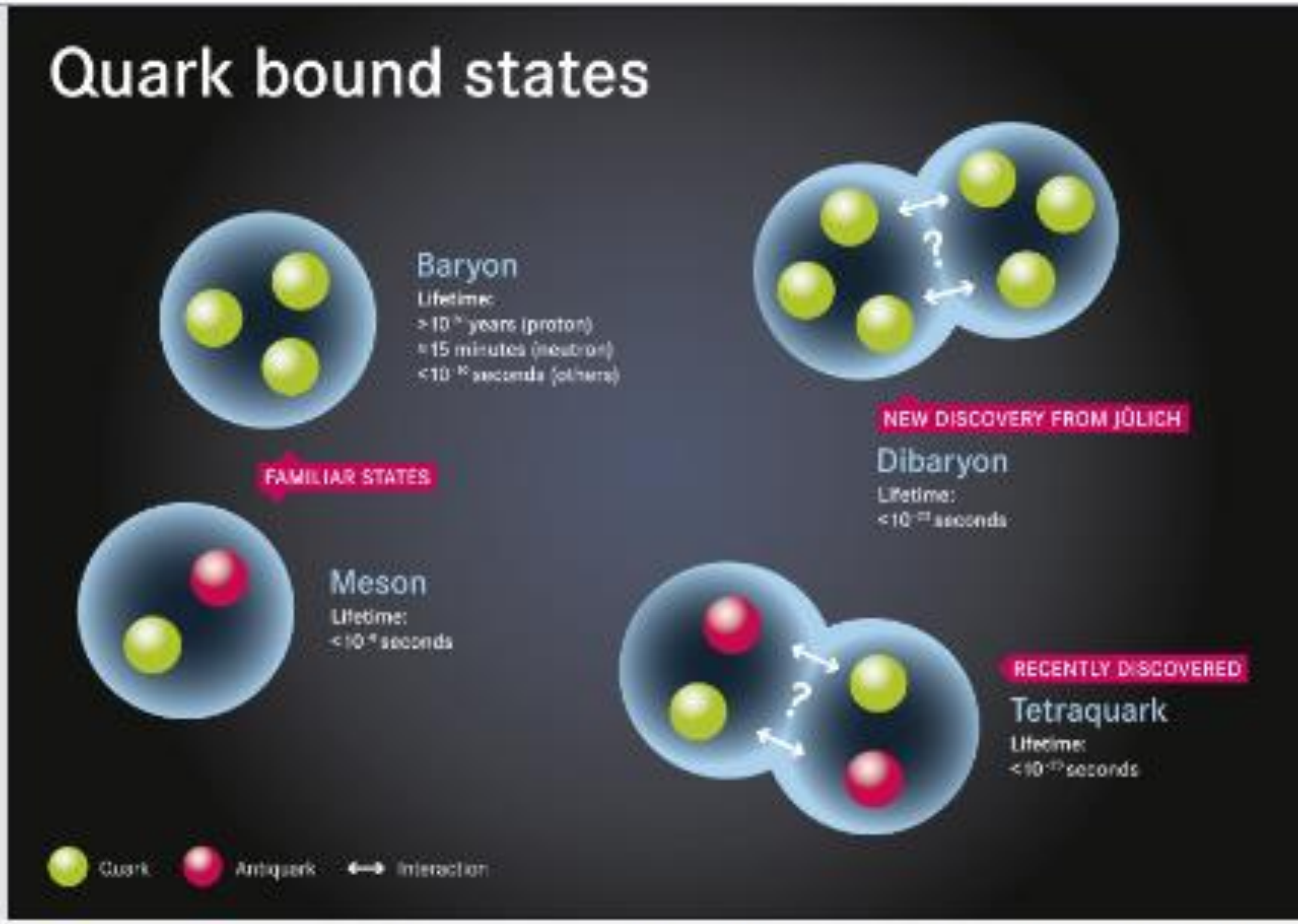
- Polarized beam manipulation
  - RF solenoid to achieve full spin flip, as well as the tool to place spin into horizontal plane





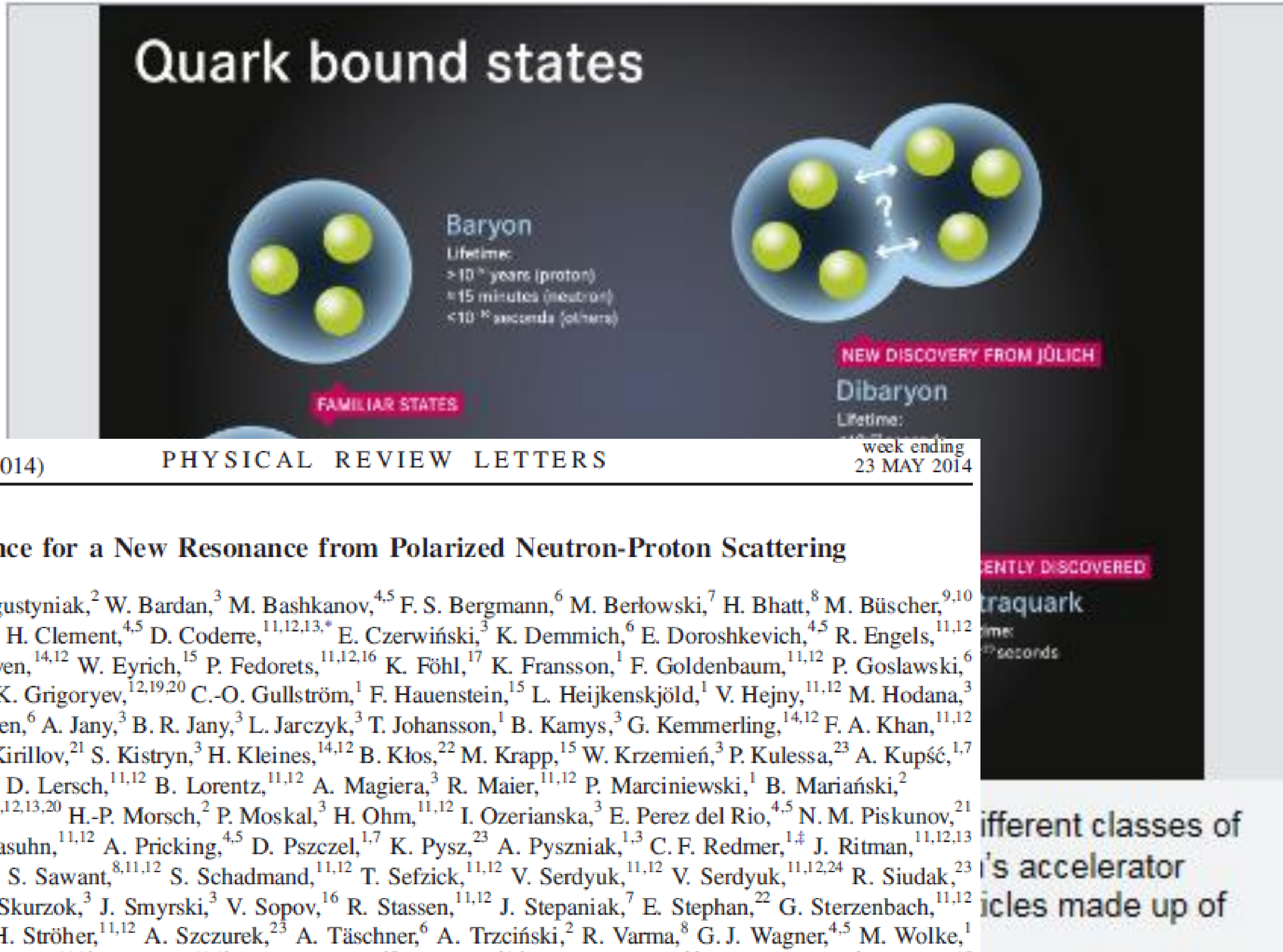
- Effective length: 0.564 m
- # of turns: 25
- Inductance: 40 uH
- Resonant frequency: 425 ~ 1940 kHz
- Maximum field strength: 4.3 T-mm

Highlight of Physics Results of COSY



For a long time, physicists were only able to reliably verify two different classes of hadrons: baryons and mesons. Experiments performed at Jülich's accelerator COSY have now shown that, in fact, another class of exotic particles made up of six quarks exists.

Highlight of Physics Results of COSY

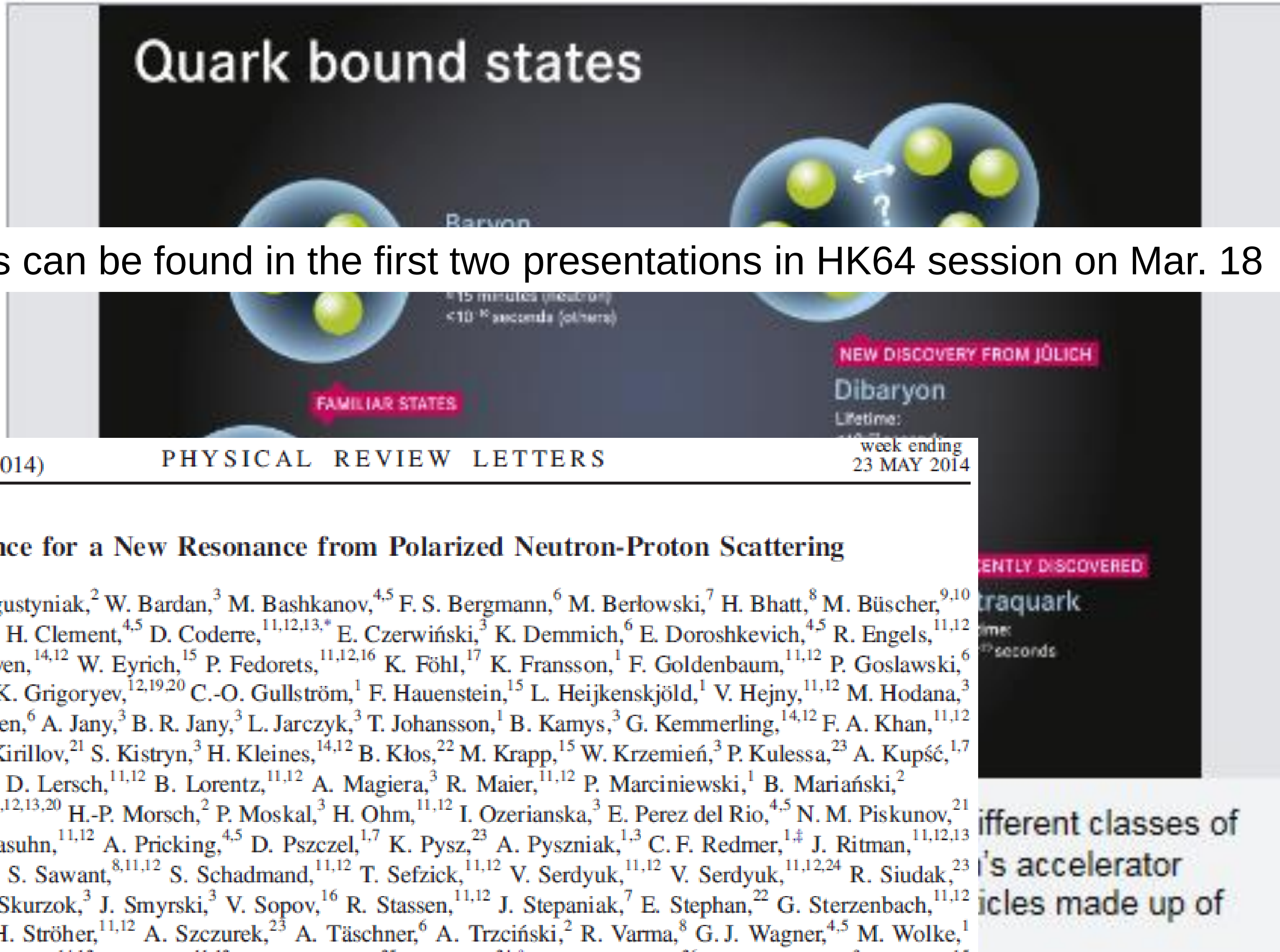


PRL 112, 202301 (2014) PHYSICAL REVIEW LETTERS week ending 23 MAY 2014

Evidence for a New Resonance from Polarized Neutron-Proton Scattering

P. Adlarson,[1] W. Augustyniak,[2] W. Bardan,[3] M. Bashkanov,[4,5] F. S. Bergmann,[6] M. Berłowski,[7] H. Bhatt,[8] M. Büscher,[9,10] H. Calén,[1] I. Ciepał,[3] H. Clement,[4,5] D. Coderre,[11,12,13,*] E. Czerwiński,[3] K. Demmich,[6] E. Doroshkevich,[4,5] R. Engels,[11,12] A. Erven,[14,12] W. Erven,[14,12] W. Eyrich,[15] P. Fedorets,[11,12,16] K. Föhl,[17] K. Fransson,[1] F. Goldenbaum,[11,12] P. Goslawski,[6] A. Goswami,[11,12,18] K. Grigoryev,[12,19,20] C.-O. Gullström,[1] F. Hauenstein,[15] L. Heijkenskjöld,[1] V. Hejny,[11,12] M. Hodana,[3] B. Höistad,[1] N. Hüsken,[6] A. Jany,[3] B. R. Jany,[3] L. Jarczyk,[3] T. Johansson,[1] B. Kamys,[3] G. Kemmerling,[14,12] F. A. Khan,[11,12] A. Khoukaz,[6] D. A. Kirillov,[21] S. Kistryn,[3] H. Kleines,[14,12] B. Kłos,[22] M. Krapp,[15] W. Krzemień,[3] P. Kulessa,[23] A. Kupść,[1,7] K. Lalwani,[8,†] D. Lersch,[11,12] B. Lorentz,[11,12] A. Magiera,[3] R. Maier,[11,12] P. Marciniewski,[1] B. Mariański,[2] M. Mikirtychiants,[11,12,13,20] H.-P. Morsch,[2] P. Moskal,[3] H. Ohm,[11,12] I. Ozerianska,[3] E. Perez del Rio,[4,5] N. M. Piskunov,[21] P. Podkopał,[3] D. Prasuhn,[11,12] A. Pricking,[4,5] D. Pszczel,[1,7] K. Pysz,[23] A. Pyszniak,[1,3] C. F. Redmer,[1,‡] J. Ritman,[11,12,13] A. Roy,[18] Z. Rudy,[3] S. Sawant,[8,11,12] S. Schadmand,[11,12] T. Sefzick,[11,12] V. Serdyuk,[11,12] V. Serdyuk,[11,12,24] R. Siudak,[23] T. Skorodko,[4,5] M. Skurzok,[3] J. Smyrski,[3] V. Sopov,[16] R. Stassen,[11,12] J. Stepaniak,[7] E. Stephan,[22] G. Sterzenbach,[11,12] H. Stockhorst,[11,12] H. Ströher,[11,12] A. Szczurek,[23] A. Täschner,[6] A. Trzciński,[2] R. Varma,[8] G. J. Wagner,[4,5] M. Wolke,[1] A. Wrońska,[3] P. Wüstner,[14,12] P. Wurm,[11,12] A. Yamamoto,[25] L. Yurev,[24,§] J. Zabierowski,[26] M. J. Zieliński,[3] A. Zink,[15] J. Złomańczuk,[1] P. Żuprański,[2] and M. Żurek[11,12]
(WASA-at-COSY Collaboration)

Highlight of Physics Results of COSY



more details can be found in the first two presentations in HK64 session on Mar. 18

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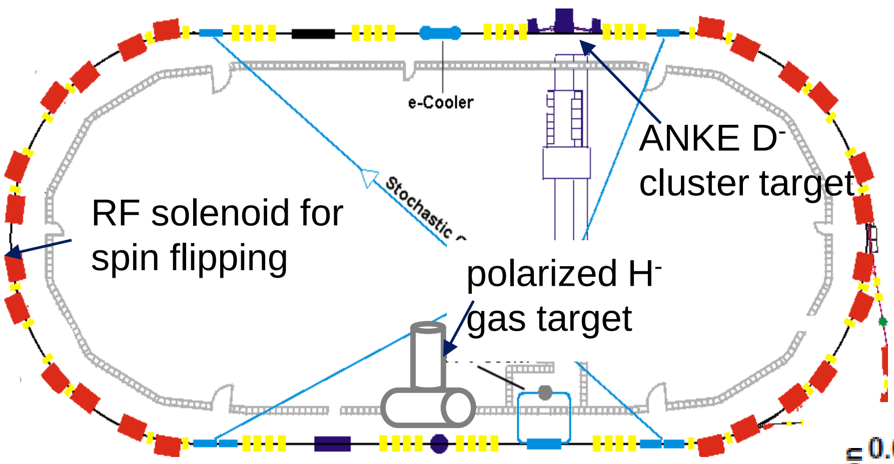
(WASA-at-COSY Collaboration)

Polarization of a Stored Beam by Spin-Filtering

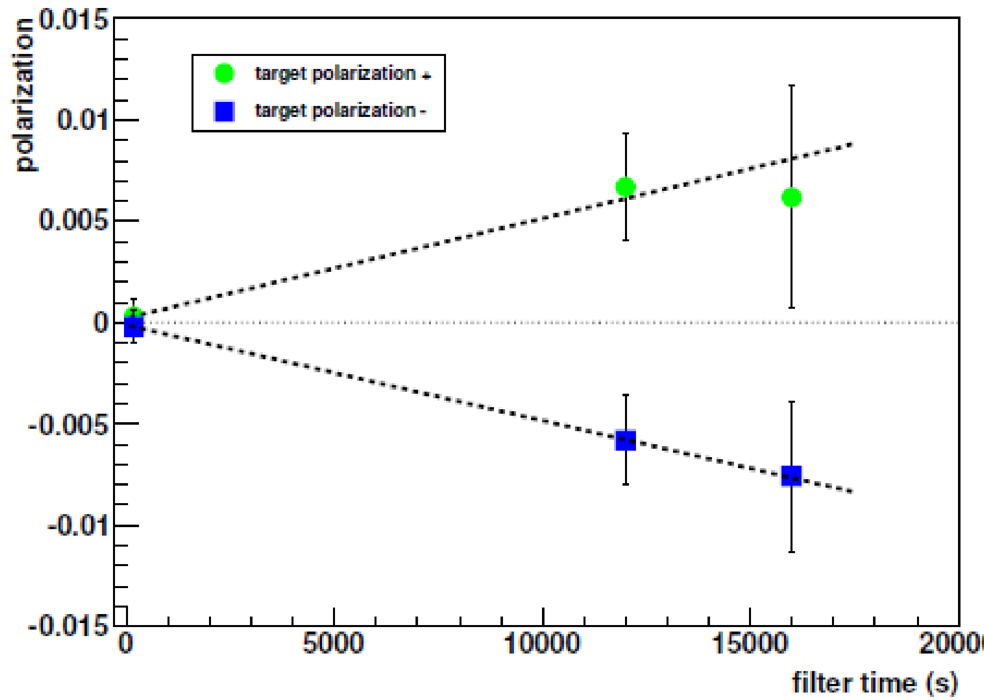
Antiproton-ProtonScattering Experiments with Polarization (PAX)

http://collaborations.fz-juelich.de/ikp/pax/



- Motivation: innovative technique for establishing polarized anti-proton beam
- Proof-of-Principle at COSY to polarize circulating proton beam with a polarized gas target

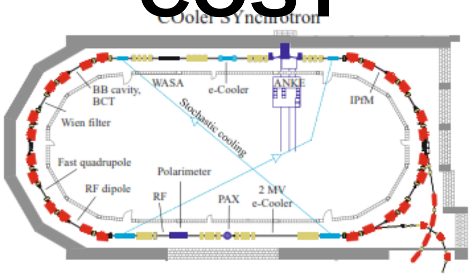
un-polarized protons stack injected in COSY at 45 MeV followed up a quick acceleration to 49.3 MeV



From COSY to HESR

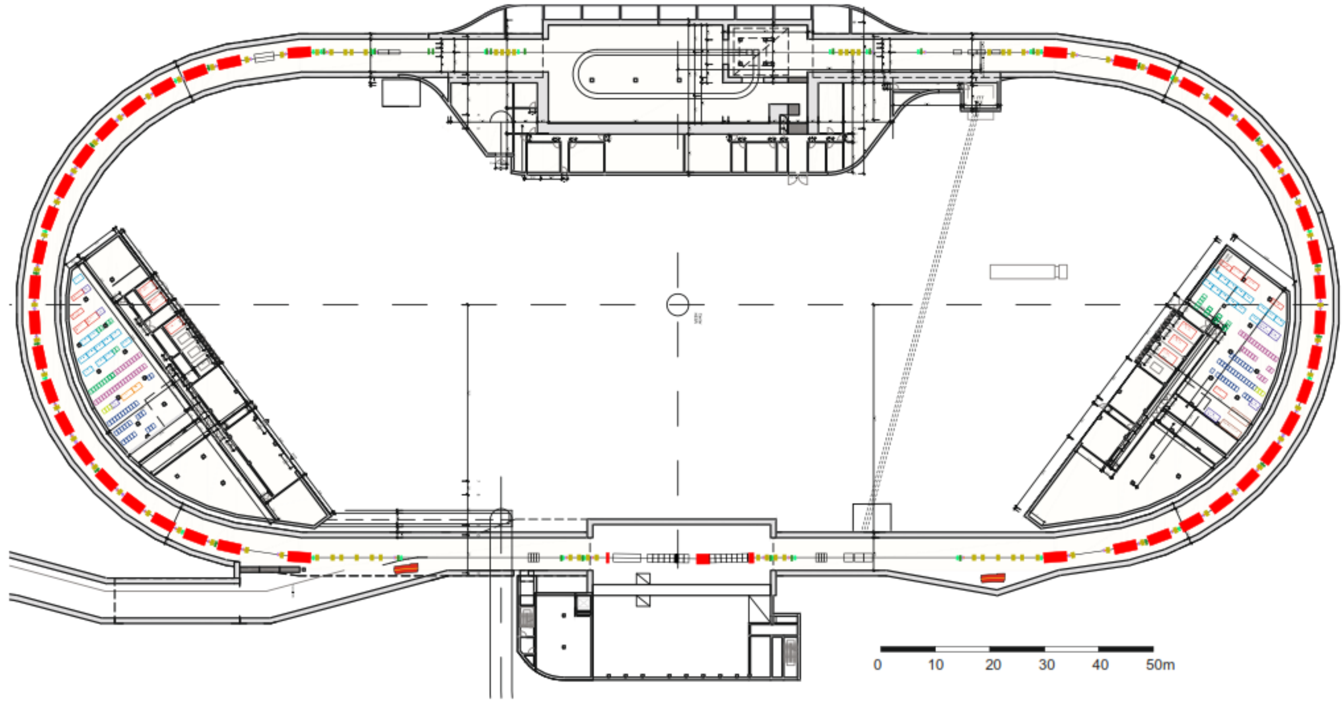
JÜLICH FORSCHUNGSZENTRUM

COSY



Trajectory
Dipoles
Quadrupoles
Sextupoles
SteererH
SteererV
BPM

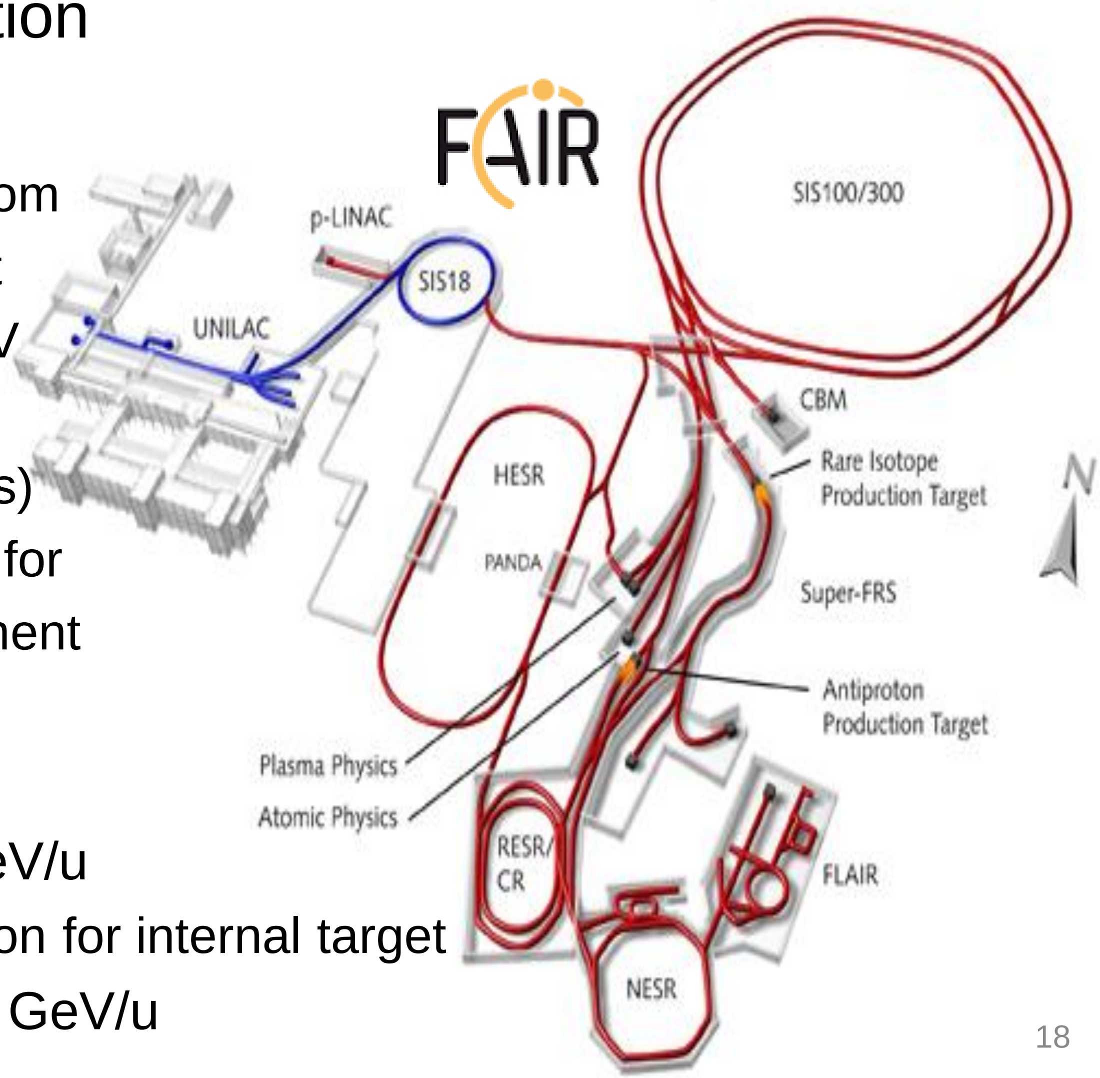
High Energy Storage Ring



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

HESR Challenges

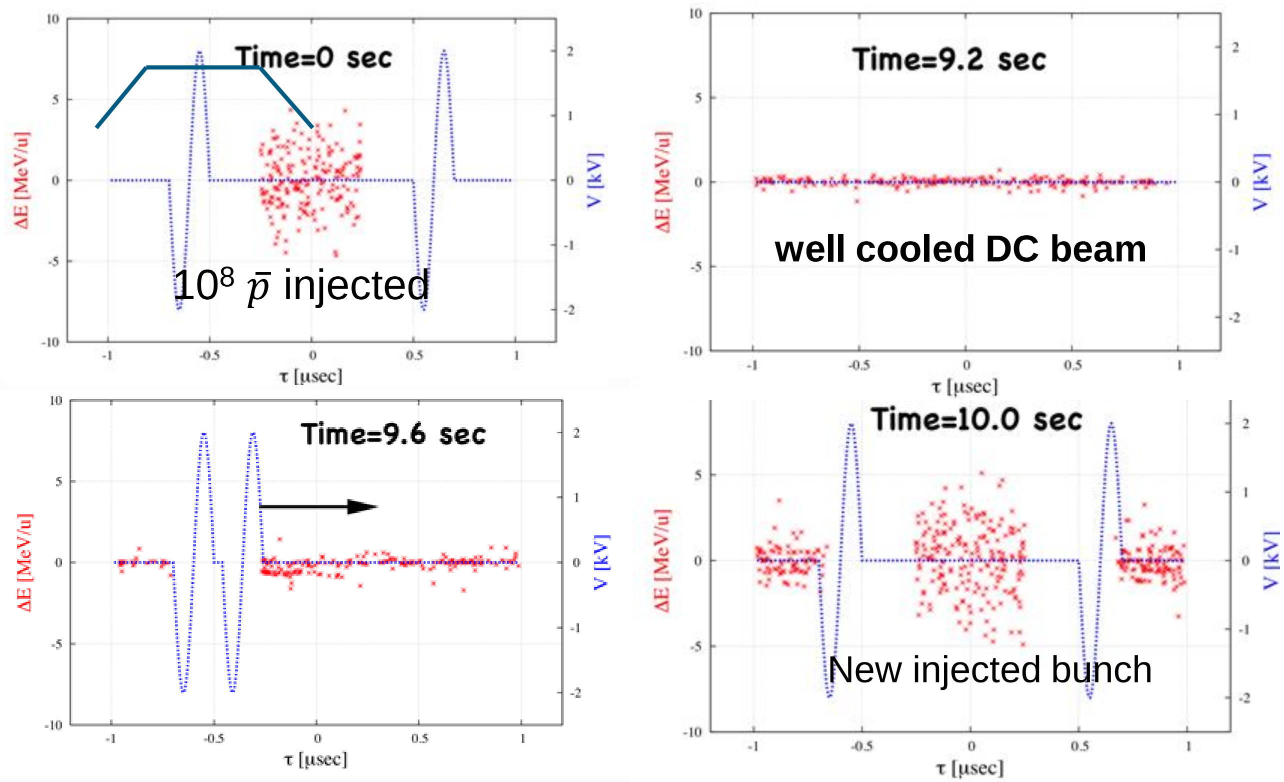
- Design to achieve high resolution and high luminosity for internal target operation
  - Anti-proton
    - Accumulating beam from Collector Ring (CR) at injection energy 3 GeV
    - Deceleration to 1 GeV (cooling at 2 GeV, 25 s)
    - Energy compensation for internal target experiment
  - Heavy ion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



HESR Challenges:
high resolution and high luminosity for internal target operation

- Antiproton accumulation: direct injection from Collector Ring (CR)
  - Longitudinal stack with moving barrier bucket is favored over the conventional radial stacking technique (AD@CERN, FNAL)
    - Save space, and also eliminate the needs of dedicated cooling for injection as well as for stacking
    - PoP was demonstrated in SIS18@GSI [M. Steck et al, Cool’11]

Schmatics of longitudinal stacking:
Simulation by T. Katayama



Courtesy of H. Stockhorst

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

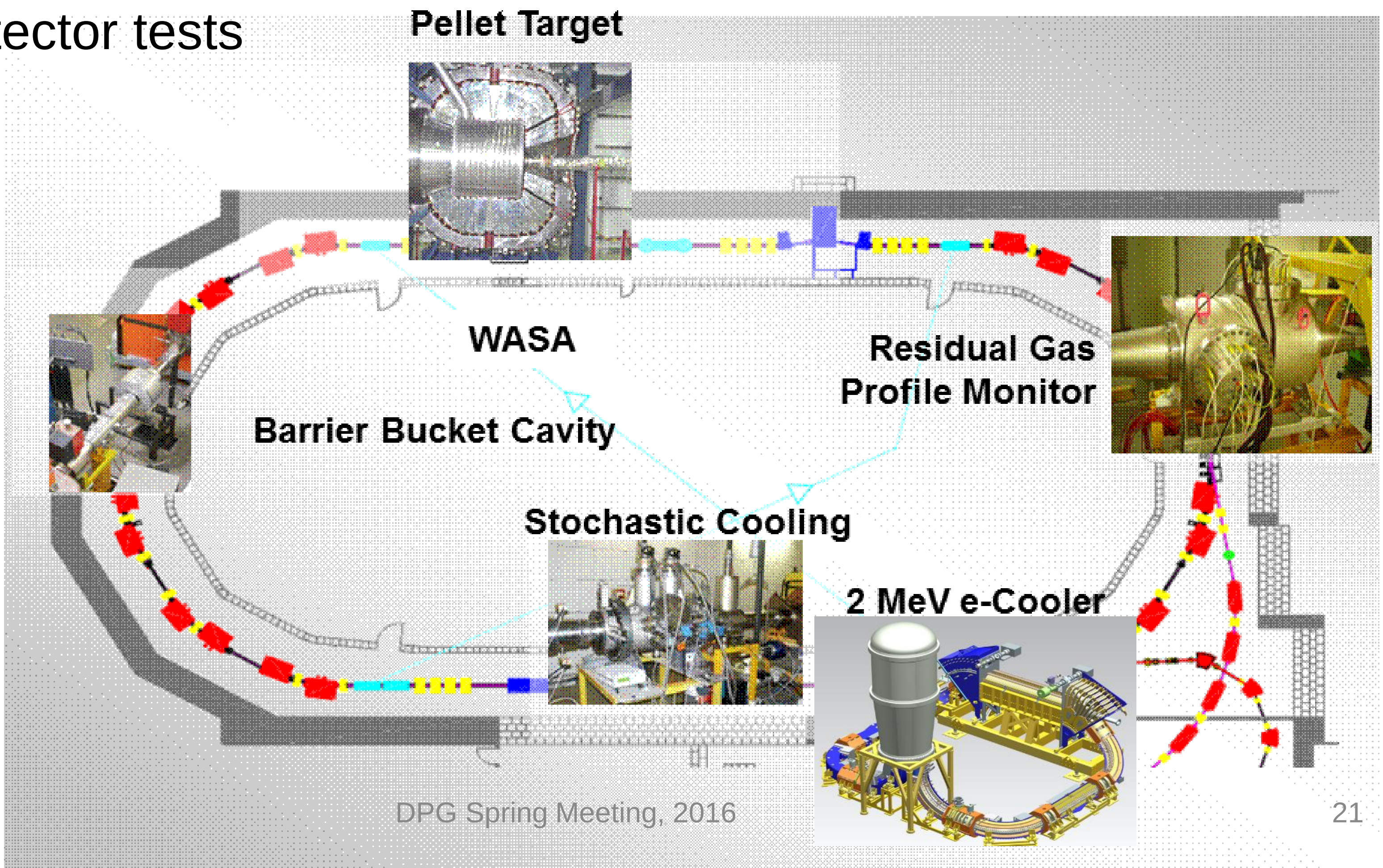
  - High energy electron cooling
    - With conventional un-bunched electron beam cooling, 8 MeV electron beam is required to cover the energy range of HESR

COSY as a test bed for FAIR

- Beam cooling
- Beam instrumentation

  A. Halama, AKBP 12: Beam Diagnostics I, 17. März 2016, 14:15–14:30, S1/05 23

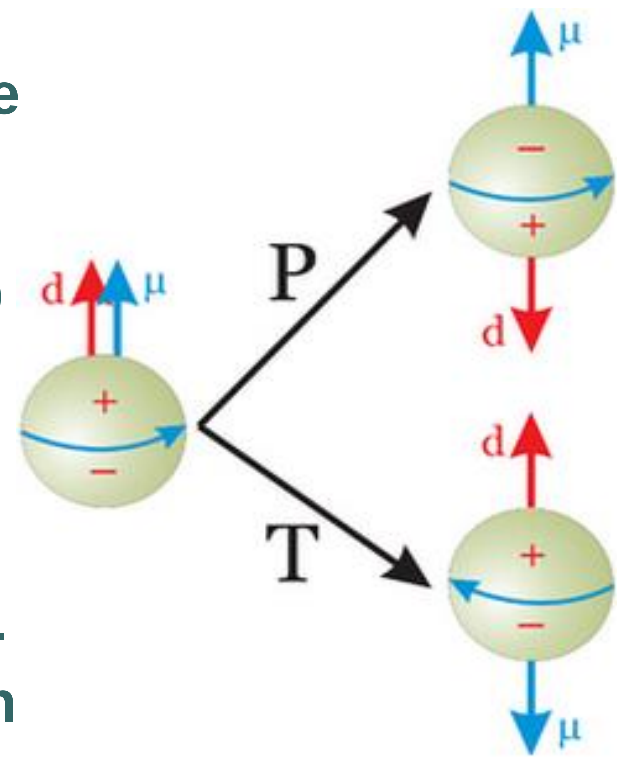
- Detector tests



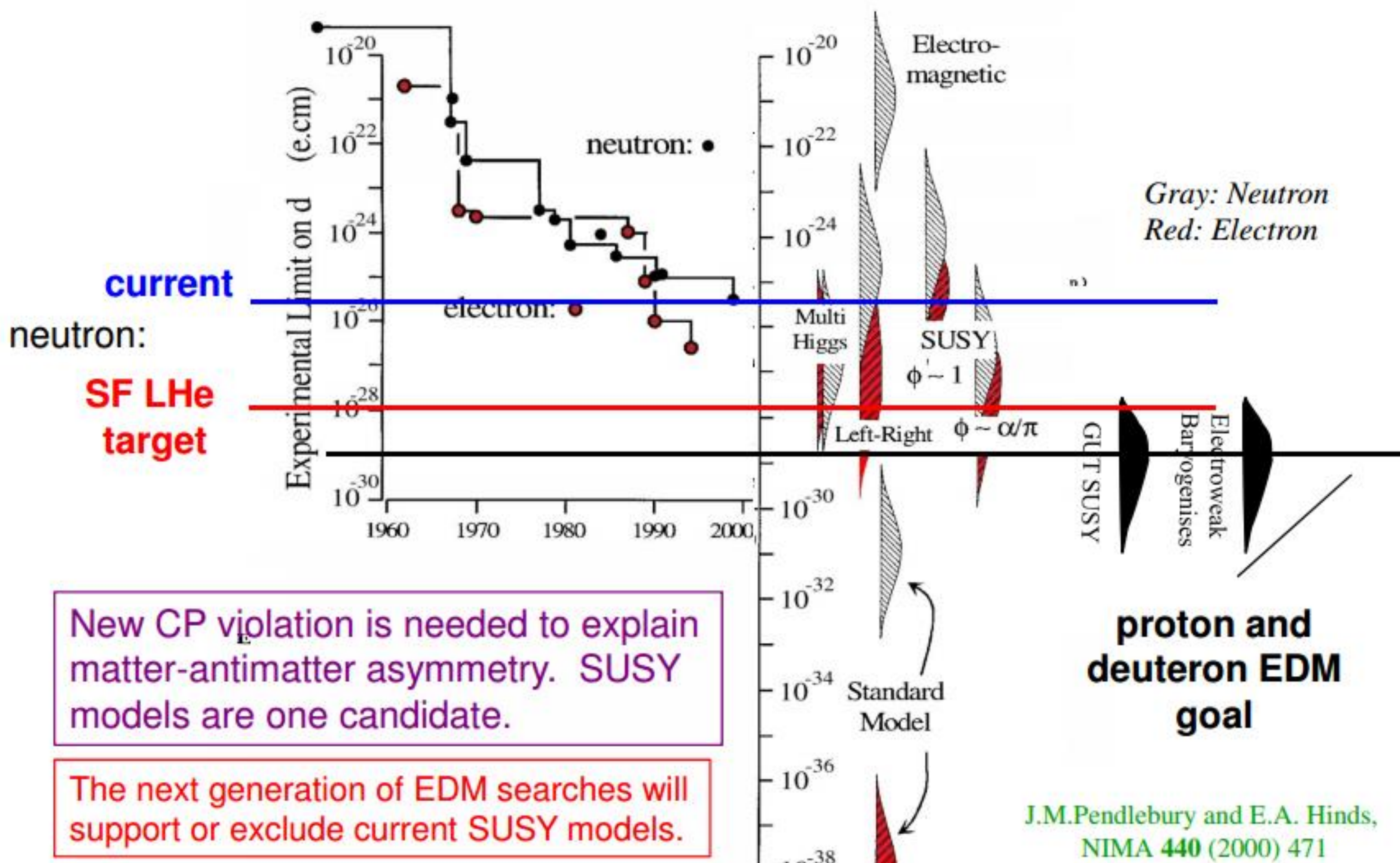
EDM search at COSY

- What is EDM? And Why?

  - **Describes the separation of positive and negative charge inside a particle**
  - **It aligns along the spin axis of the particle, and violates both parity (P) and time reversal (T)**
  - **Hence, significant EDM measurement of fundamental particles is an effective probe of CP-violation, could be the key to explain the asymmetry between matter and antimatter**



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.

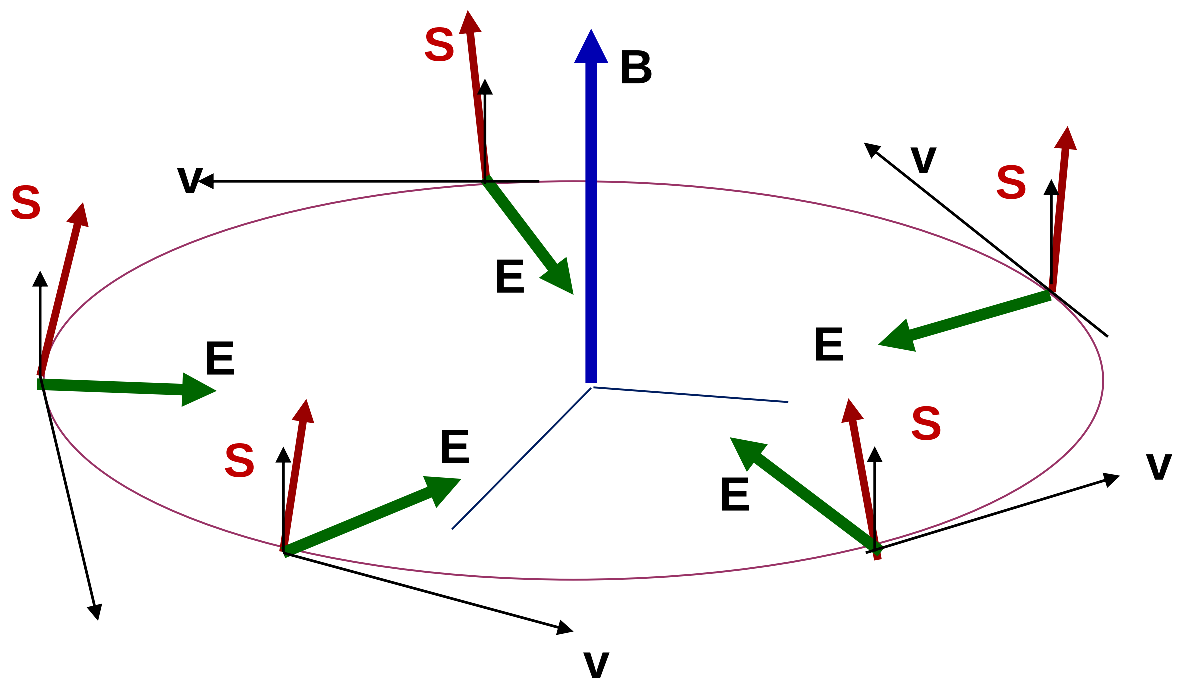
Courtesy of E. Stephenson

Storage ring based EDM search

- Only way to have direct access to charged particle's EDM
  - Spin motion in a planar-circular accelerator

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

Spin tune: # of spin precession in a orbital revolution

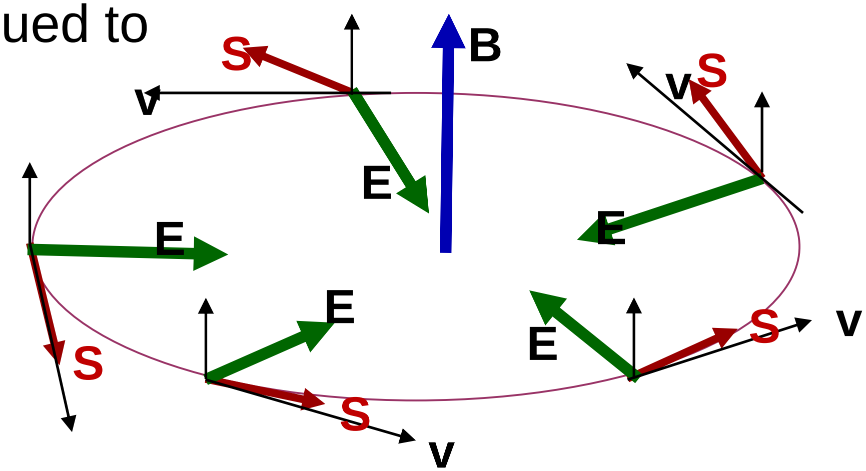


Storage ring based EDM search

- Only way to have direct access to access charged particle's EDM
- Spin frozen method

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

- Null to remove the MDM contribution to spin motion. And then place spin vector along the particle's velocity in the horizontal plane
  - If no EDM, the spin vector is glued to the horizontal plane
  - **Non-zero EDM results in the vertical polarization buildup**

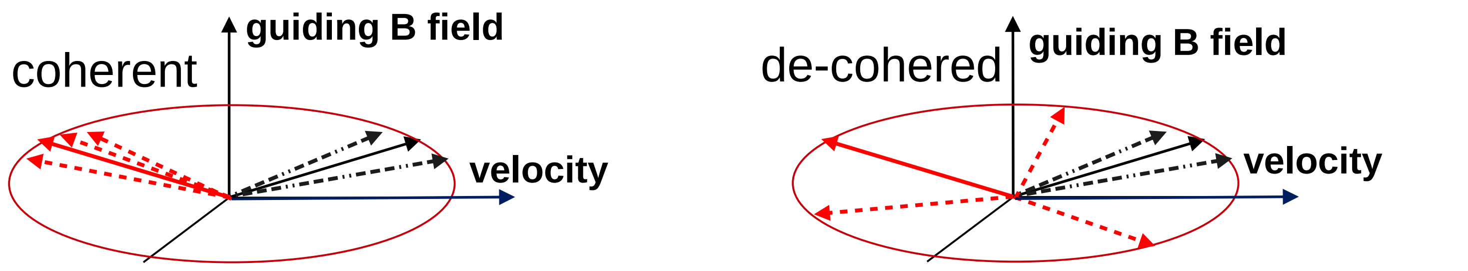


Storage ring based EDM search

- Spin frozen method

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

  - In the absence of systematic errors, vertical spin buildup rate is proportional to the size of the EDM, as well as the strength of the Lorentz force
    - **Spin frozen storage ring: most efficient way!**
  - Long spin coherence time
    - to reach 10^{-29} e-cm measurement within a year $T_{tot}=10^7$ sec, $T_{spin} \geq 1000 sec$ is needed



Storage Ring based EDM challenges

- Long spin coherence time
- Fast polarimeter with high efficiency
  - Measure the spin buildup due to EDM signal
  - Spin manipulation
- 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 signal as radial E field of E_r
    - **Can be mitigated by CW-CCW rotating beams**
  - Requires not only state of the art of quality control of the magnetic/electric fields, but also high precision beam monitoring/control

COSY: a perfect place for EDM development

Long history of polarized beams

- Polarized protons and deuterons

Excellent beam cooling setups for spin manipulations

In house expertise with international collaborations

- **J**uelich **E**lectric **D**ipole moment **I**nvestigation
  - a total of 118 collaborators from

BELARUS, BELGIUM, CHINA, FRANCE, GEORGIA GERMANY ITALY, KOREA, POLAND, RUSSIA, SWEDEN UNITED KINGDOM, USA

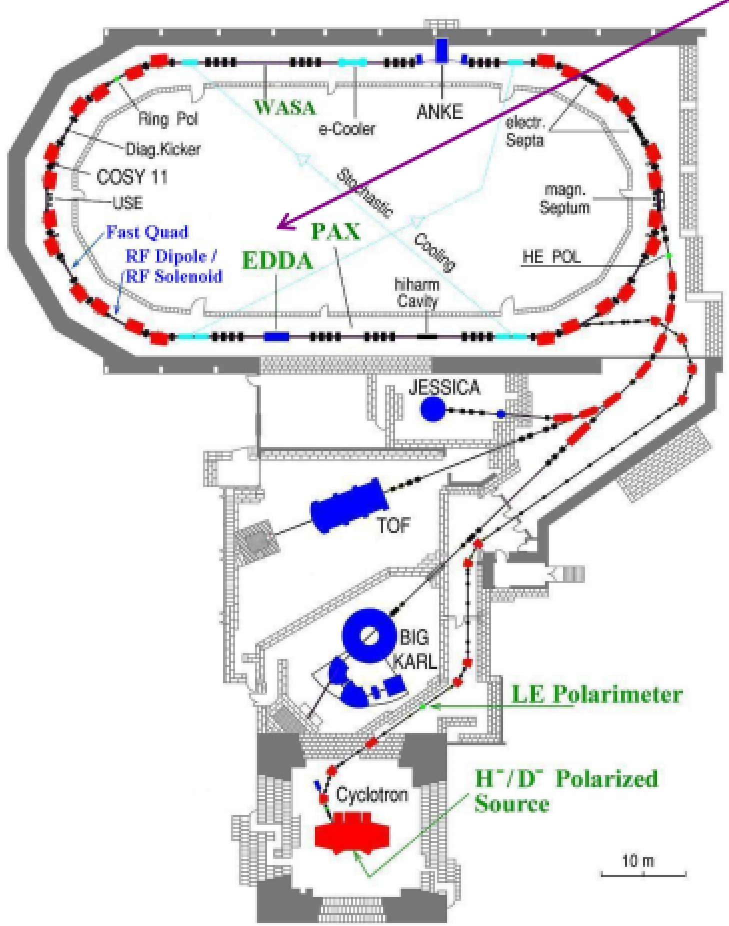
JEDI

EDM @ COSY

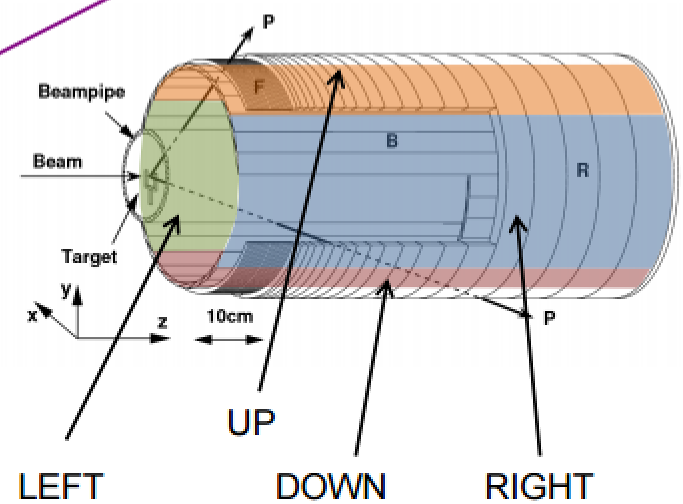
- High efficiency polarimeter
  - Enables the investigation of spin coherence

COSY storage ring

polarized deuterons, 0.97 GeV/c



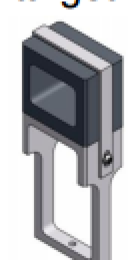
EDDA detector



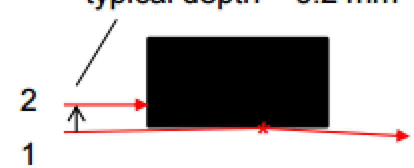
Azimuthal angles yield two asymmetries:

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

17 mm C target



typical depth ~ 0.2 mm

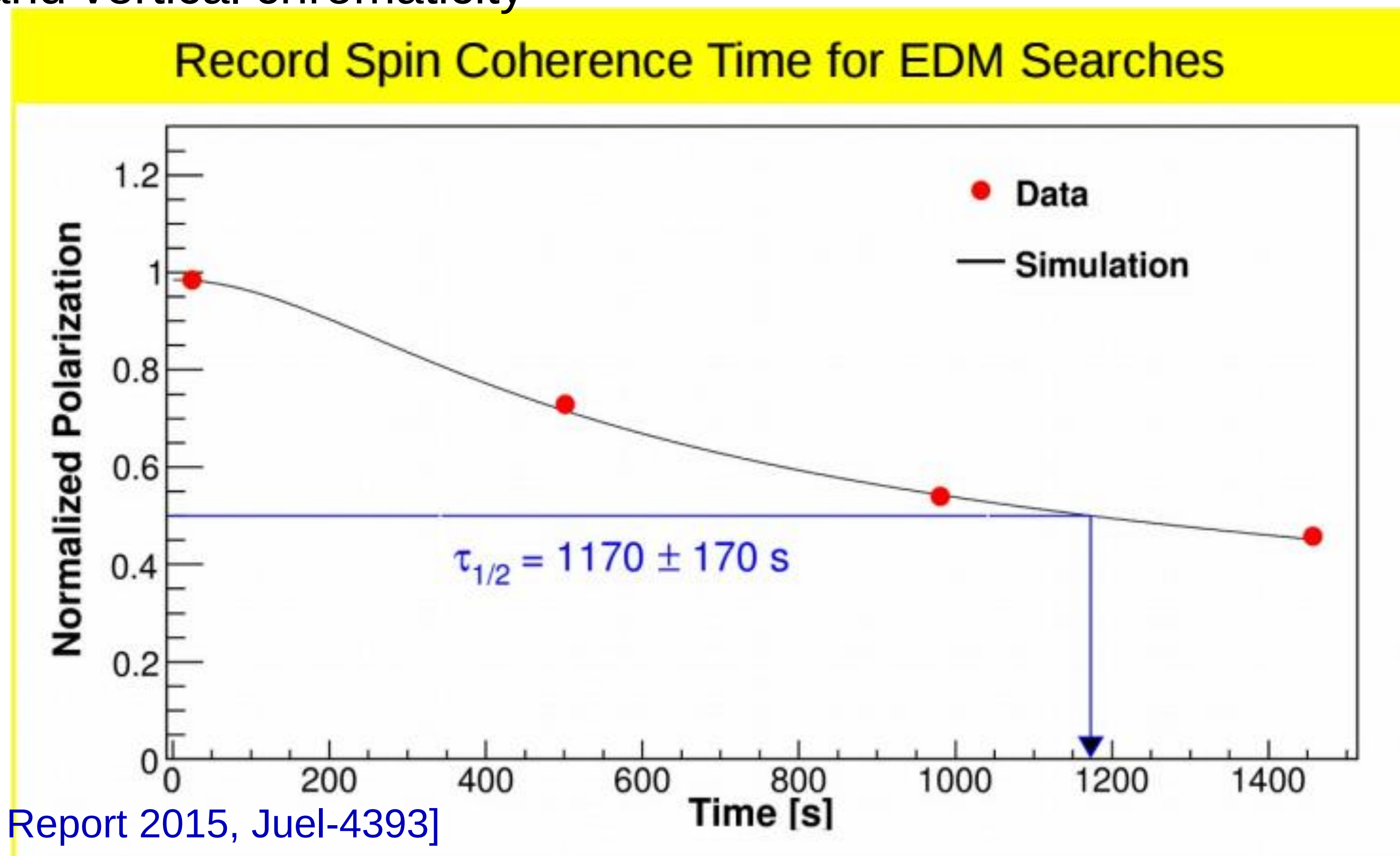


double-hit extraction?: deflect at (1), then oscillate to (2)

Courtesy of E. Stephenson, "Storage Ring Polarimetry", Spin2014

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



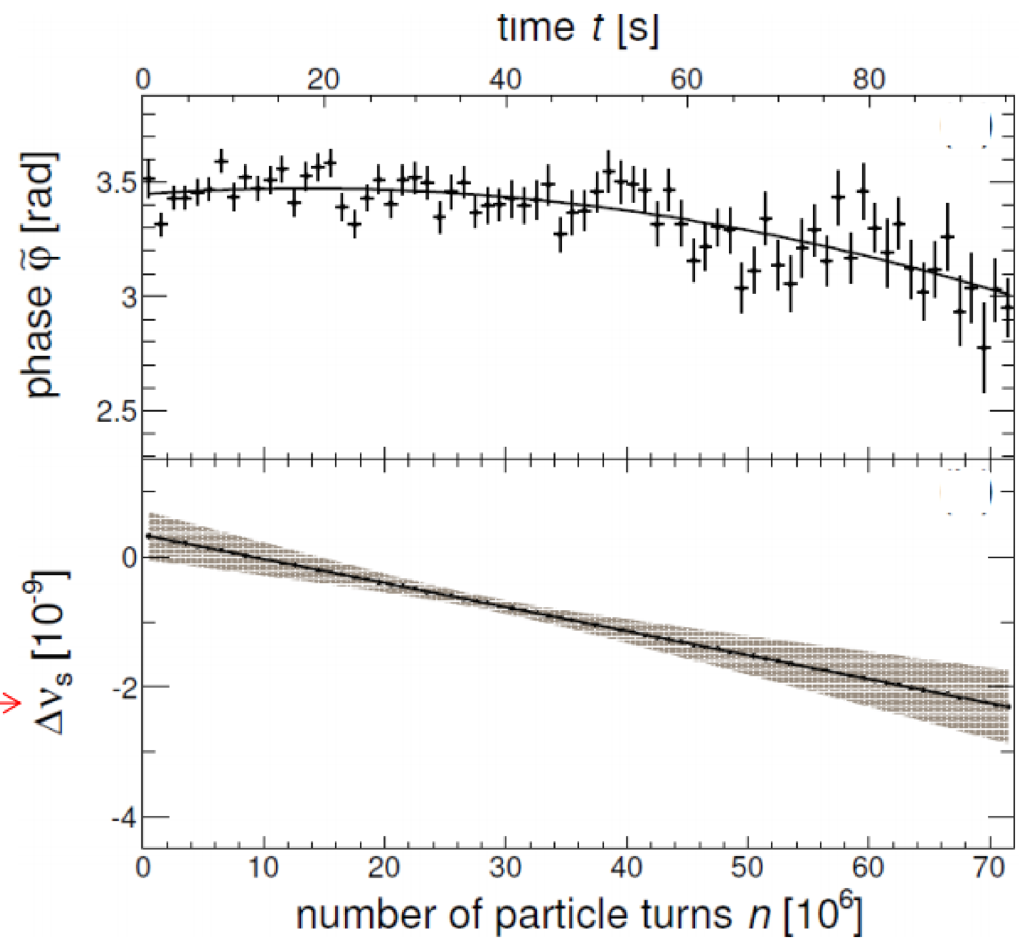
[Annual Report 2015, Juel-4393]

EDM @ COSY

- High precision spin tune measurement

Monitor phase of asymmetry with fixed ν_s in a 100 s cycle.

$$\nu_s(n) = \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\varphi}(n)}{\mathrm{d}n}$$
$$= \nu_s^{\text{fix}} + \Delta\nu_s(n)$$

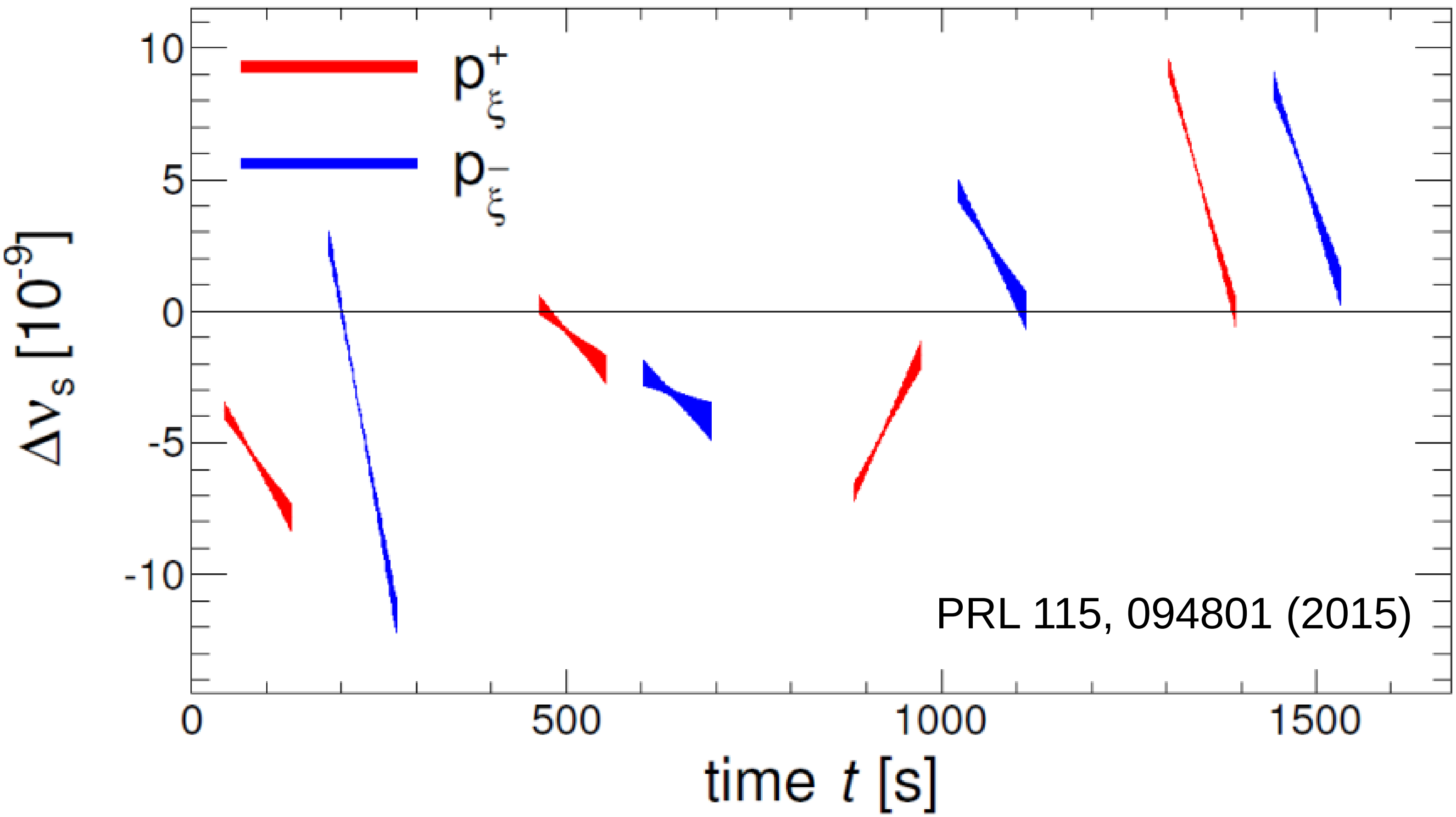


from F. Rathmann, Search for Electric Dipole Moments using Storage Rings

Spin tune ν_s determined to $\approx 10^{-8}$ in 2 s time interval, and in a 100 s cycle at $t \approx 40$ s to $\approx 10^{-10}$ (PRL 115, 094801 (2015)

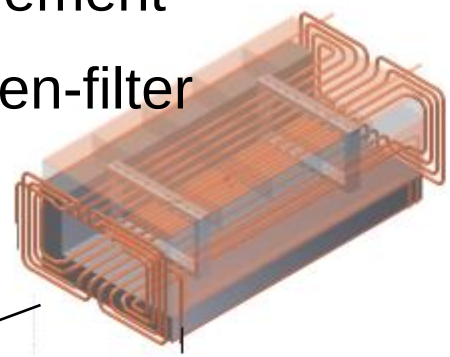
High precision measurement and observation of accelerator stability

- Observed the change of spin tune from cycle to cycle
  - Indication of the machine reproducibility
  - Why the difference between the two spin state?



EDM precursor experiment @ COSY

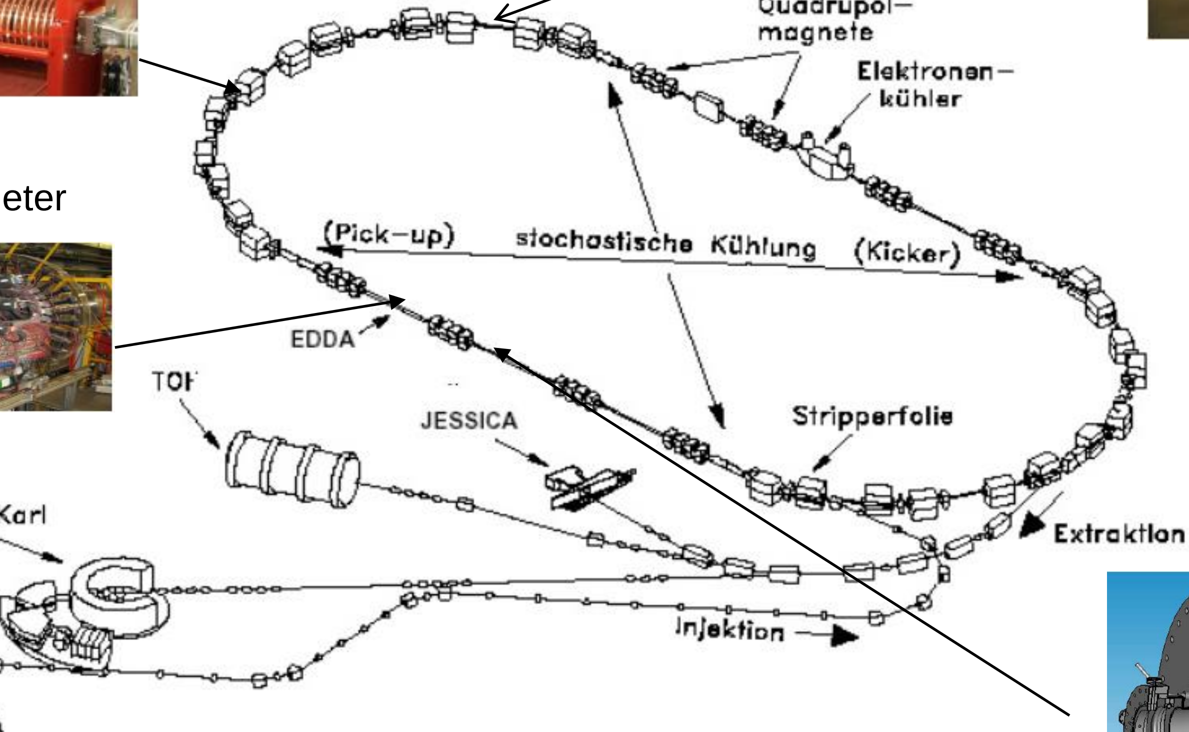
- Direct deuteron EDM measurement
- Partial spin frozen with RF Wien-filter



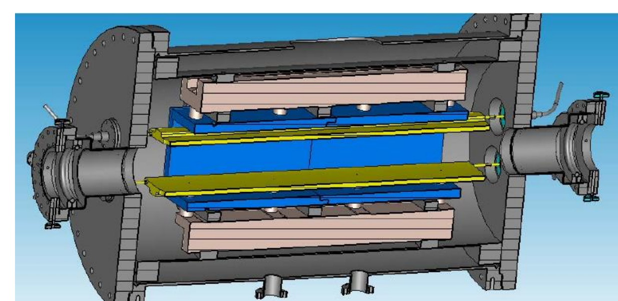
RF wien filter by
S. Mey and R. Gebel

RF solenoid

polarimeter

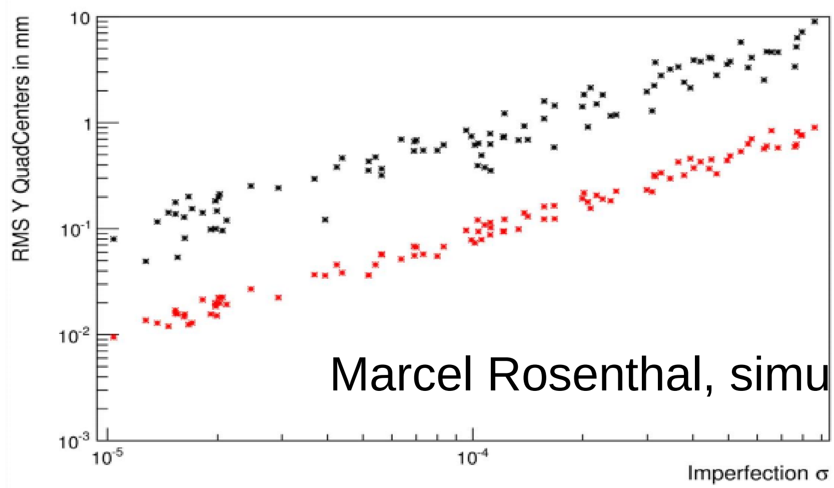


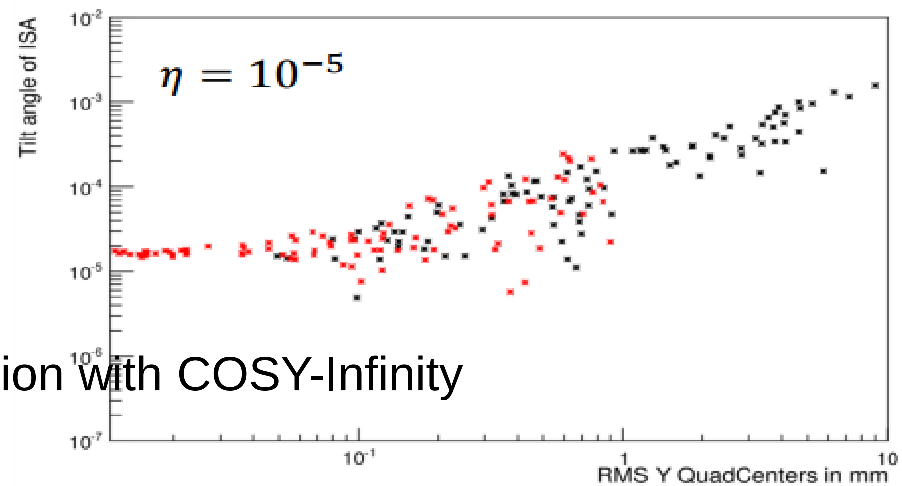
RF wien filter by
J. Slim (RWTH)



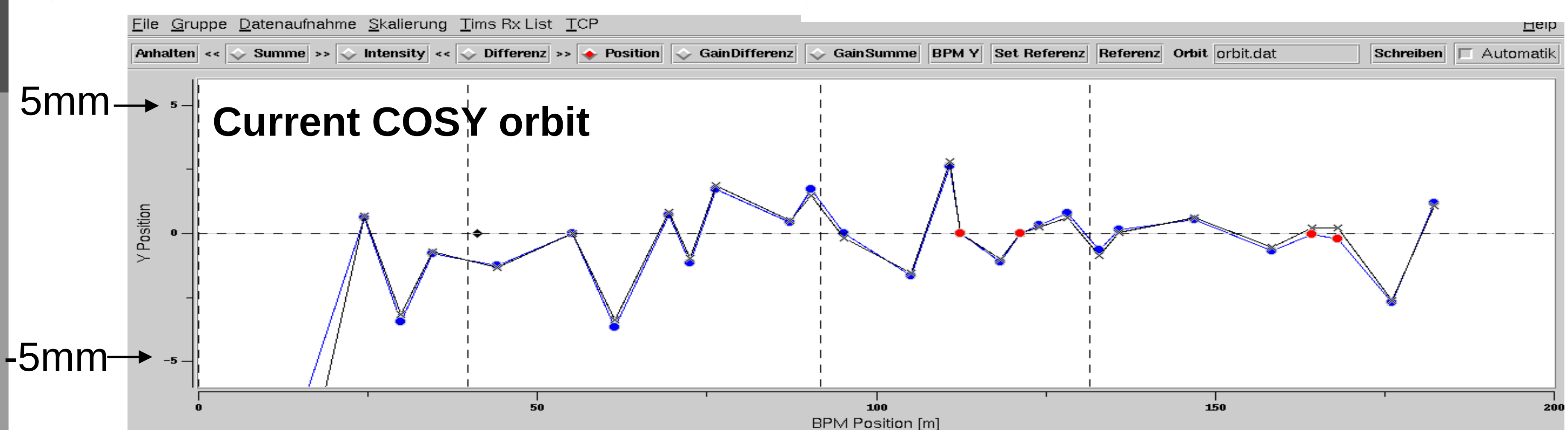
Challenges with precursor

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





Marcel Rosenthal, simulation with COSY-Infinity



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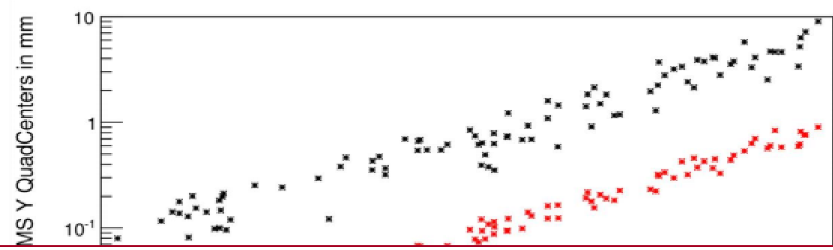
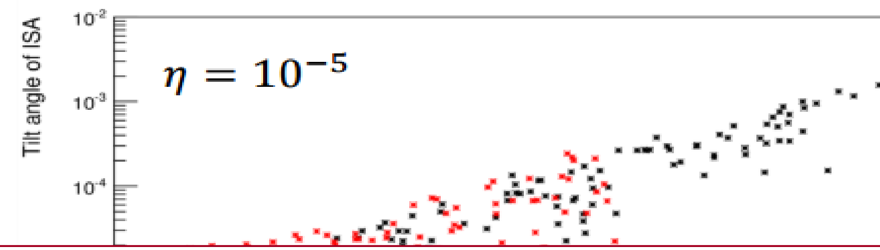
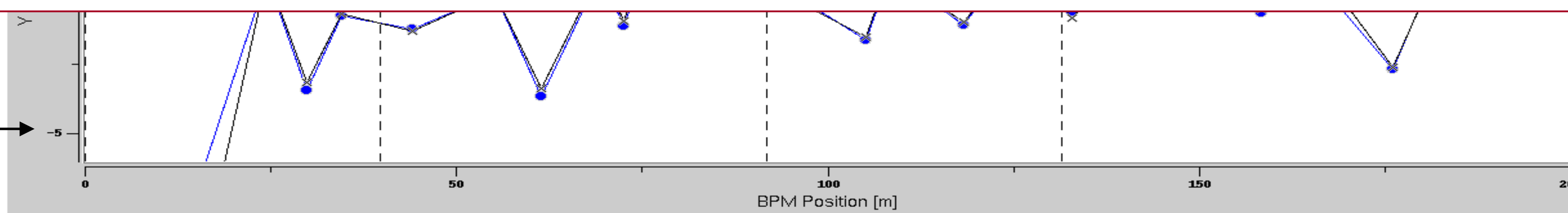




- COSY BPM upgrade are in working progress (C. Boehme, V. Kamerdzhiev)
  - reviewed by BI experts from GSI, CERN and DESY
- Implemented automation of ORM data taking (F. Hinder, M. Simon)
- Implemented ORM based optics measurement (D. Ji [IHEP])
- ORM based COSY online model improvement (C. Weidermann)

-5mm



Member of the Helmholtz Association

Summary

- COSY served nuclear physics as the working horse for over two decades with outstanding physics[1], as well as many excellent PhD students

  [1] C. Wilkin et al, The legacy of the Experimental Hadron Physics program at COSY, EPJ Review, to be submitted

- It has been evolved to a test bed for HESR, and challenging projects like EDM search in a storage ring
- In addition, COSY has become a facility for the precision frontier physics experiments
  - EDM precursor experiment: first direct measurement of deuteron
  - Antiproton-Proton Scattering Experiments with Polarization (PAX)
    - http://collaborations.fz-juelich.de/ikp/pax/
  - Time-Reversal Invariance at COSY (TRIC)
    - https://apps.fz-juelich.de/pax/paxwiki/index.php/Test_of_Time-Reversal_Invariance_at_COSY_(TRIC)

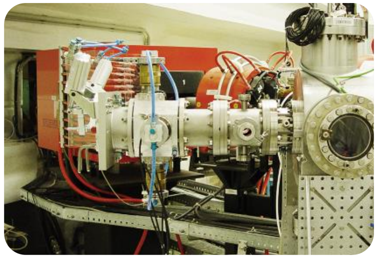
Outlook

- With all the above, we hope we convince you that COSY as a unique machine still has potential for a bright future. (there are many older machines that still serve)
  - Direct charged particle EDM search in a storage ring
  - Ideal test bed for the future success of one of the major scientific cases at FAIR
  - Education of beam physics, and beam manipulation
    - Compare to current operational high energy accelerators, COSY has the beauty of being very accessible to students etc
  - Multi-disciplinary capabilities for basic research in other scientific fields

Extending COSY Capability

- COSY has been a dedicated accelerator for hardon physics till now

- It has demonstrated its versatile operational modes: internal target, energy range, extracted beam. Its full potential still waits to be fully explored
  - Increase average beam current in the extraction beamlines
    - Beam request from INM-5 on radionuclide study at COSY: > 10 nA
  - additional ion species
  - others



INM-5 target station at JULIC, COSY injector

- As one of the few hadron synchrotrons in Germany, it can also benefit the scientific community with its unique features
  - Nuclear medicine research
  - Radiobiology basic research
    - Important for radiotherapy
    - Nasa Space Radiation Lab @ BNL

Outlook

- With all the above, we hope we convince you that COSY as a unique machine still has potential for a bright future. (there are many older machines who still serves)

- In reality, am afraid that COSY's future together with the the physics programs of IKP beyond 2018 are in jeopardy due to the ongoing Strategy Process at FZJ

- We are still fighting for our future at FZJ. Stay tuned!

- We appreciate you in supporting us to reach out to the society about
  - the importance of fundamental research in Germany
  - the long term impact to German physics research including accelerator community