Mitglied der Helmholtz-Gemeinschaft

Spin Filtering at COSY

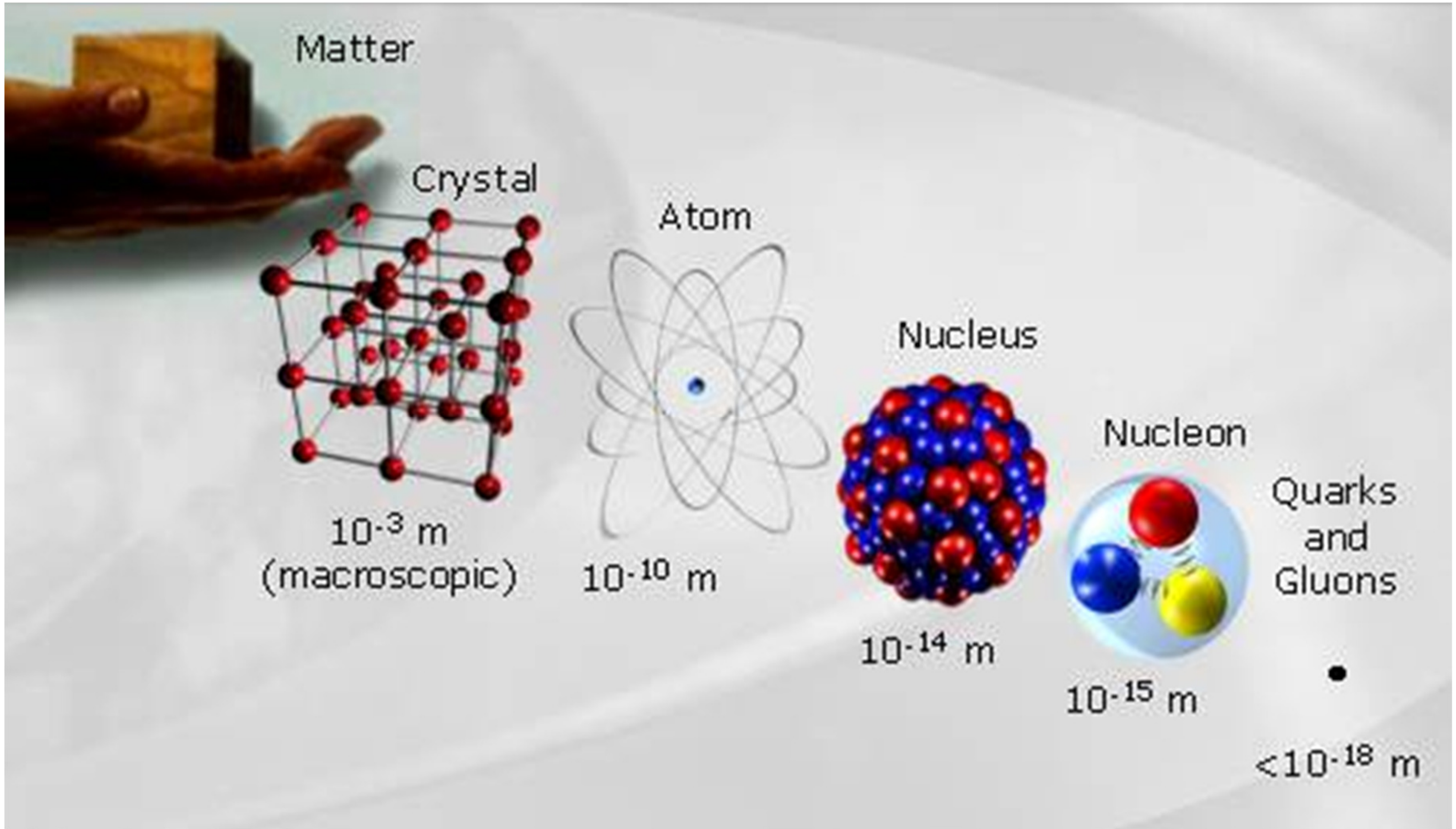
Technical Challenges

9. August 2012 | Christian Weidemann

Outline

- **Motivation**
- **Spin-Filtering Experiment**
  - **Idea**
  - **Cooler Synchrotron/Jülich**
- **Technical Challenges**
  - **High Density Polarized Gas Target**
  - **Maximum Beam Lifetimes**
  - **Beam Polarization Determination**
- **Summary**

Motivation



Matter
Crystal
Atom
Nucleus
Nucleon
Quarks and Gluons
10-3 m (macroscopic)
10-10 m
10-14 m
10-15 m
<10-18 m

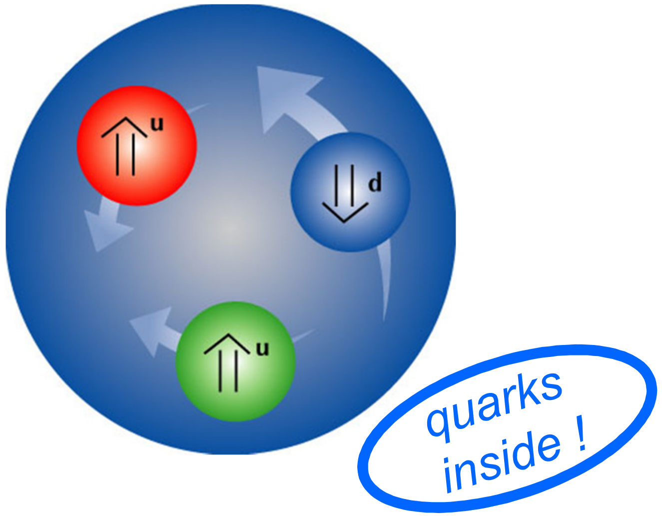
Polarized Antiproton eXperiments

Motivation

- **The proton consists of 2 ‘up’ und 1 ‘down’ Quark**

- **Proton charge:**
$$\underset{\text{up}}{\frac{2}{3}}+\underset{\text{up}}{\frac{2}{3}}+\underset{\text{down}}{\left(-\frac{1}{3}\right)}=1$$

- **Proton spin:**
$$\frac{1}{2}+\frac{1}{2}+\left(-\frac{1}{2}\right)=\frac{1}{2}$$

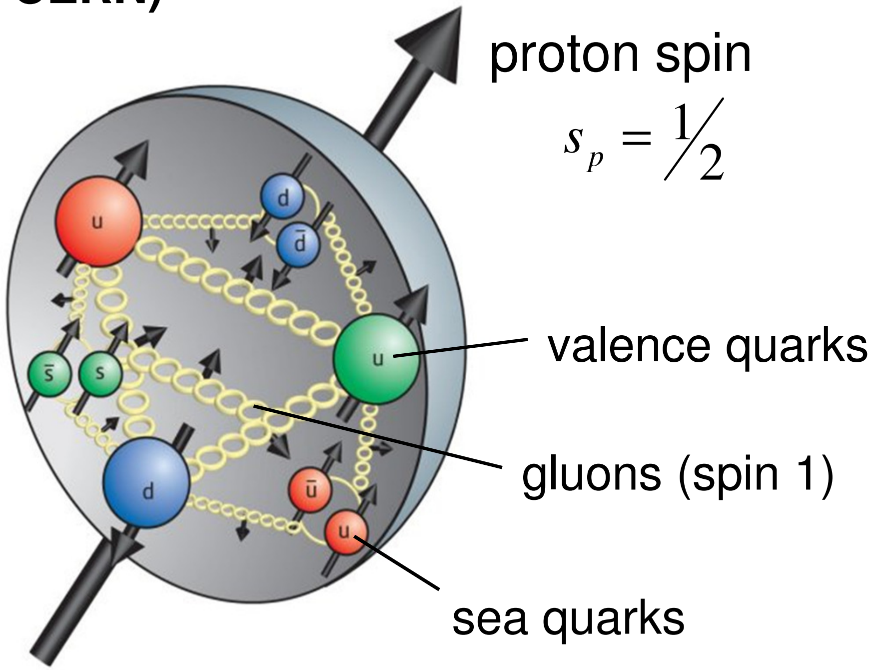


- **Experiments in 1988 at CERN (EMC):**
  “The valence quarks intrinsic spin contributes by only 25-30% to the proton spin”

Motivation

Polarized Antiproton eXperiments

- **Gluon contribution is to small (STAR at RHIC and COMPASS at CERN)**
- **Contribution of sea quark polarization is consistent with zero (HERMES at DESY)**



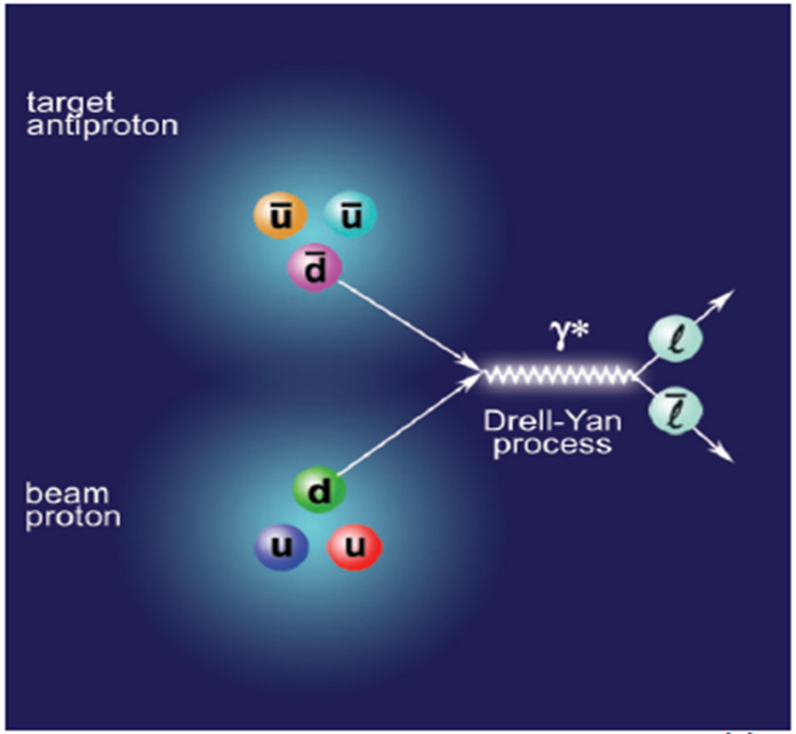
- **Where does the nucleon spin come from ?**

Motivation

Polarized Antiproton eXperiments

- **The PAX collaboration wants to study so called Drell-Yan processes in scattering of polarized proton (p) and antiproton (pbar) beams at the HESR (FAIR)**

- **Annhilation of valence quark with an antivalence quark is needed!**



- **<u>Requirements:</u>**

  Polarized proton beam

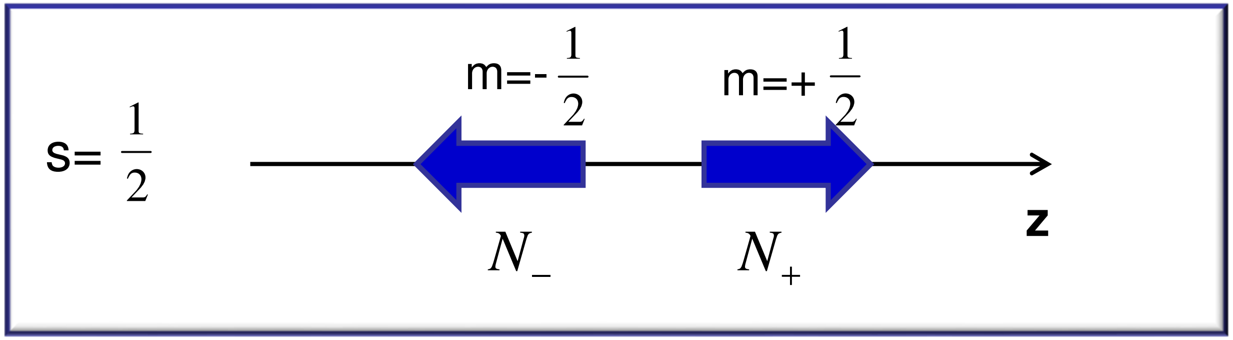
  Polarized antiproton beam

Basics: Polarization

Spin s: 2s+1 possible orientations along quantization axis z

- **spin ½ → 2 orientations**
- **spin 1 → 3 orientations**

magnetic quantum number m=s$_z$ (z-component in units of $\hbar$)



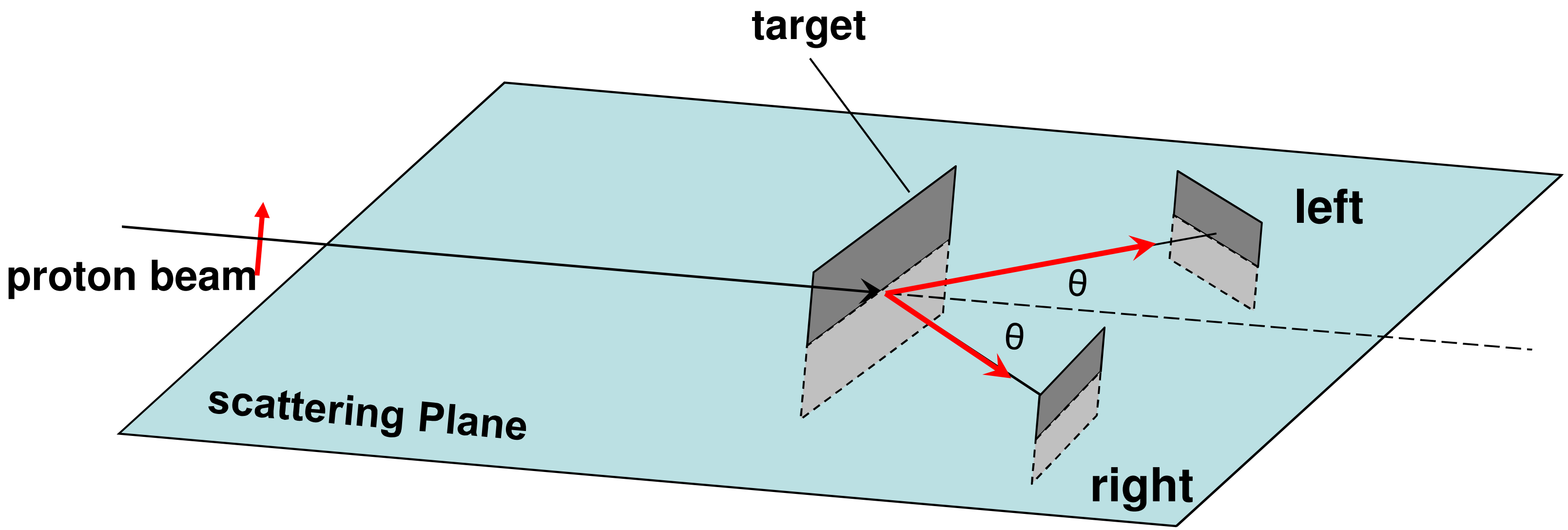
intensity

$$I = N_- + N_+$$

polarization

$$\boxed{P_z = \frac{N_+ - N_-}{N_+ + N_-}}$$

Basics: Polarization Determination



Experiment measures "asymmetry"

$$\varepsilon = P_y \cdot A_y = \frac{N_L - N_R}{N_L + N_R}$$

analyzing power $A_y(\theta,E)$

beam polarization

How to polarize antiprotons?

Polarized Antiproton eXperiments

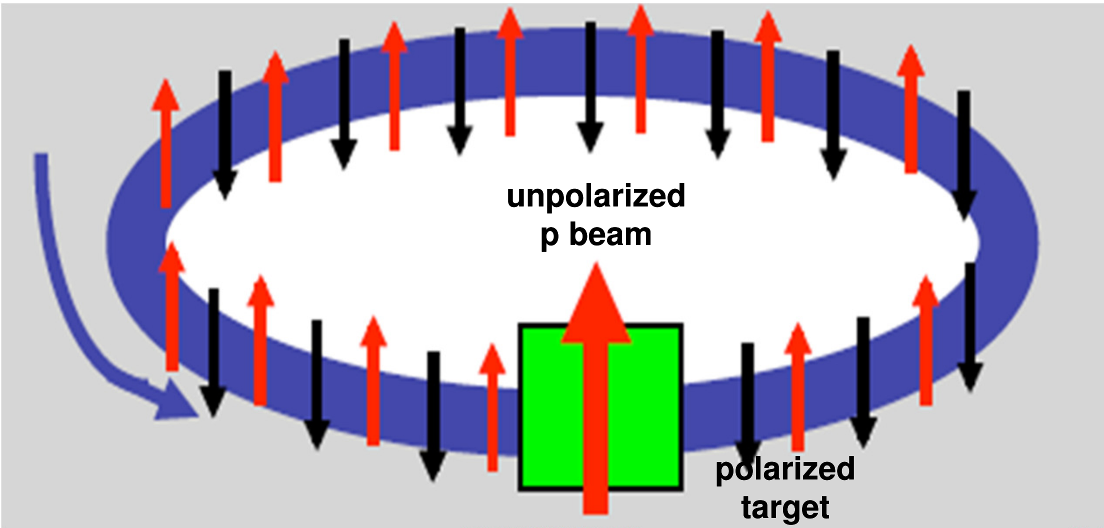
Spin Filtering

Polarization build-up of a circulating particle beam by interaction with a polarized gas target

$$\sigma_{tot} = \sigma_0 + \sigma_1(\vec{P}\cdot\vec{Q}) + \sigma_2(\vec{P}\cdot\hat{k})(\vec{Q}\cdot\hat{k})$$

P…beam particle spin orientation
Q…target particle spin orientation
k || beam direction

$$P(t) = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \tanh\left(\frac{t}{\tau_1}\right) \approx t\cdot\tilde{\sigma}_1\cdot Q\cdot d_t\cdot f$$



Spin Filtering

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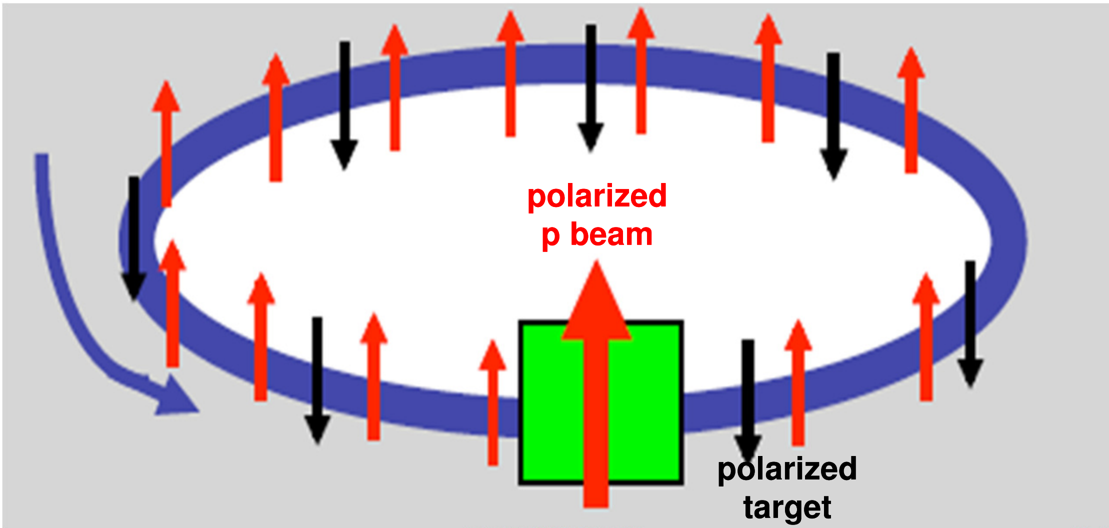

Polarized Antiproton eXperiments

Spin Filtering

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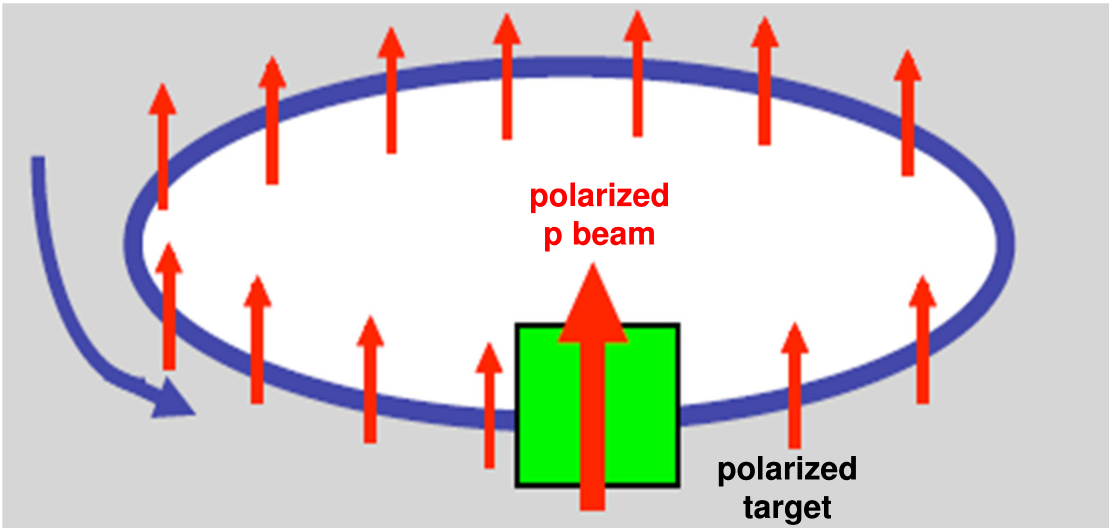
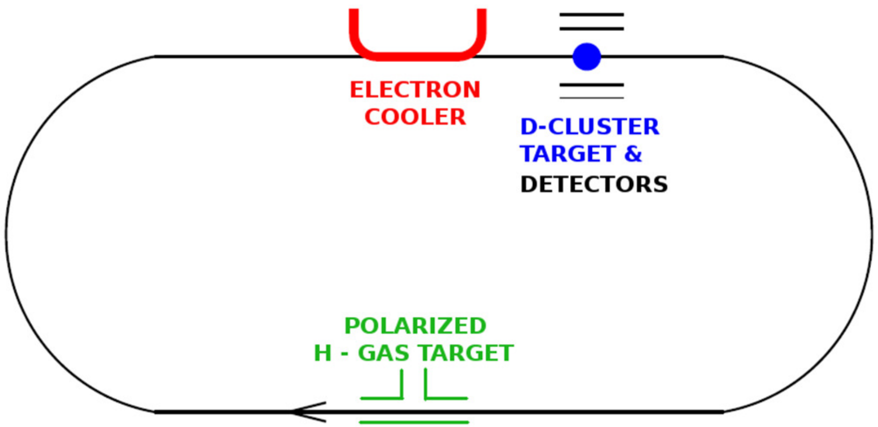


Spin Filtering at COSY

Polarized Antiproton eXperiments

Spin filtering with protons for better understanding of the underlying processes and commissioning of the experimental setup

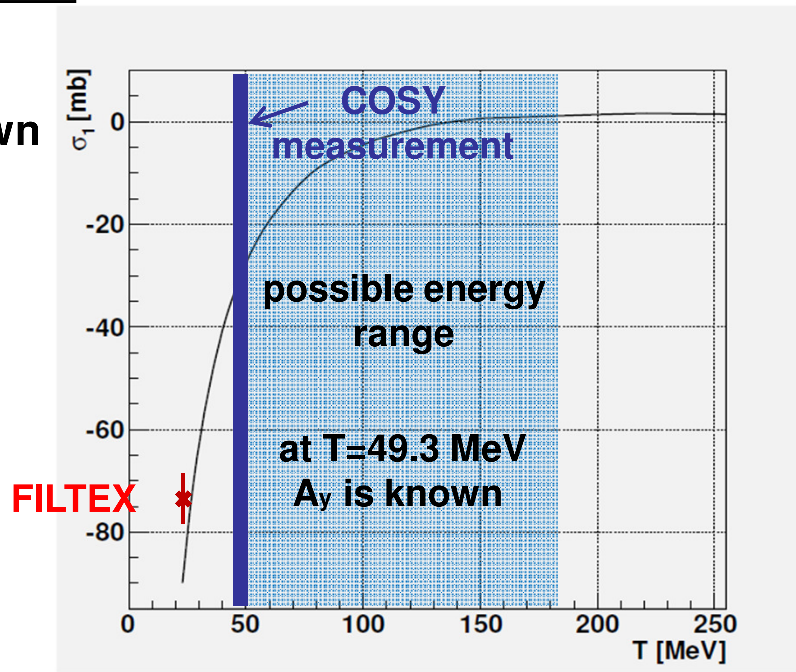
- **length: 183.4 m**
- **injection energy: 45 MeV**
- **electron cooling for long lifetimes up to 600 MeV/c (p)**



Optimize Spin Filtering

$$P(t)=\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}=\tanh\left(\frac{t}{\tau_1}\right)\approx \tilde{\sigma}_1 \cdot f \cdot Q \cdot d_t \cdot t$$

1. **Maximum polarizing cross section**
   - **small kinetic energy, where the analyzing power is known**



Optimize Spin Filtering

Polarized Antiproton eXperiments

$$P(t)=\frac{N_{\uparrow}-N_{\downarrow}}{N_{\uparrow}+N_{\downarrow}}=\tanh\left(\frac{t}{\tau_1}\right)\approx\tilde{\sigma}_1\cdot f\cdot Q\cdot d_t\cdot t$$

1. **Maximum polarizing cross section**
   - **small kinetic energy**
2. **Maximum revolution frequency**
   - **large kinetic energy (compromise between 1. & 2. needed)**
   - **short accelerator (we use COSY)**

Optimize Spin Filtering

Polarized Antiproton eXperiments

$$P(t) = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \tanh\left(\frac{t}{\tau_1}\right) \approx \tilde{\sigma}_1 \cdot f \cdot Q \cdot d_t \cdot t$$

1. **Maximum polarizing cross section**
   - **small kinetic energy**
2. **Maximum revolution frequency**
   - **large kinetic energy**
   - **short accelerator**
3. **Maximum target polarization and density**
   - **high density polarized gas target (Atomic Beam Source)**
   - **storage cell**

Optimize Spin Filtering

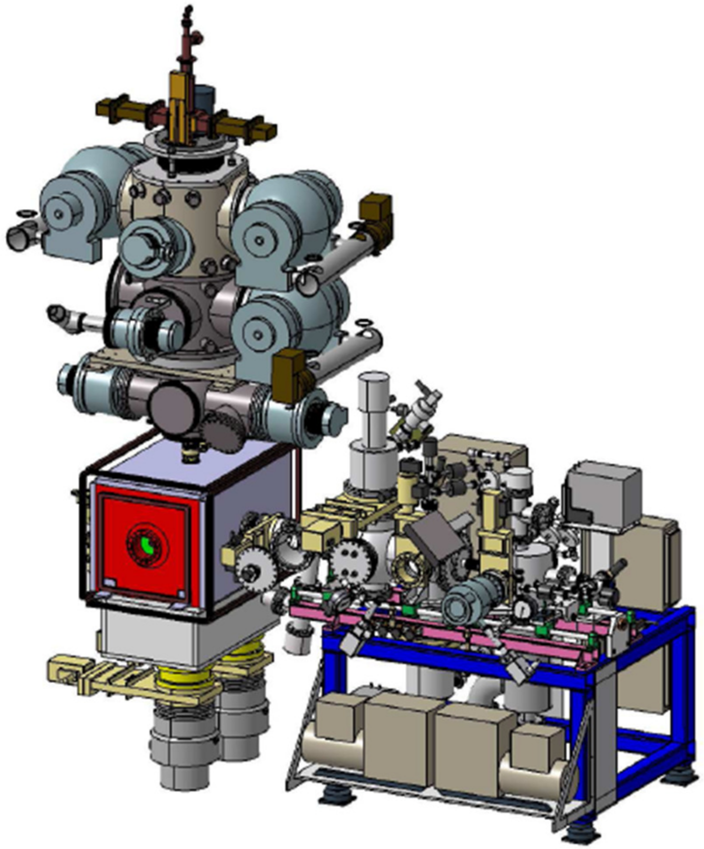
Polarized Antiproton eXperiments

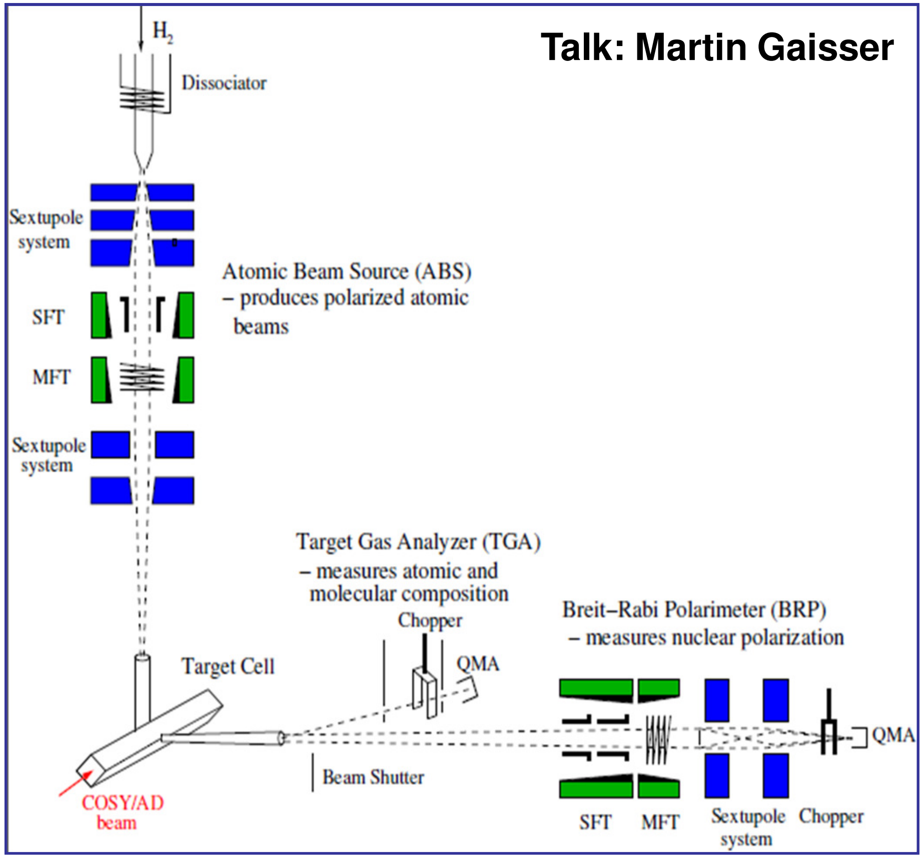
$$P(t) = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \tanh\left(\frac{t}{\tau_1}\right) \approx \tilde{\sigma}_1 \cdot f \cdot Q \cdot d_t \cdot t$$

1. **Maximum polarizing cross section**
   - **small kinetic energy**
2. **Maximum revolution frequency**
   - **large kinetic energy**
   - **short accelerator**
3. **Maximum target polarization and density**
   - **high density polarized gas target (Atomic Beam Source)**
   - **storage cell**
4. **Maximum filtering time**
   - **long beam lifetime (UHV, good beam preparation, etc.)**

High Density Polarized Gas Target

Polarized Gas Target

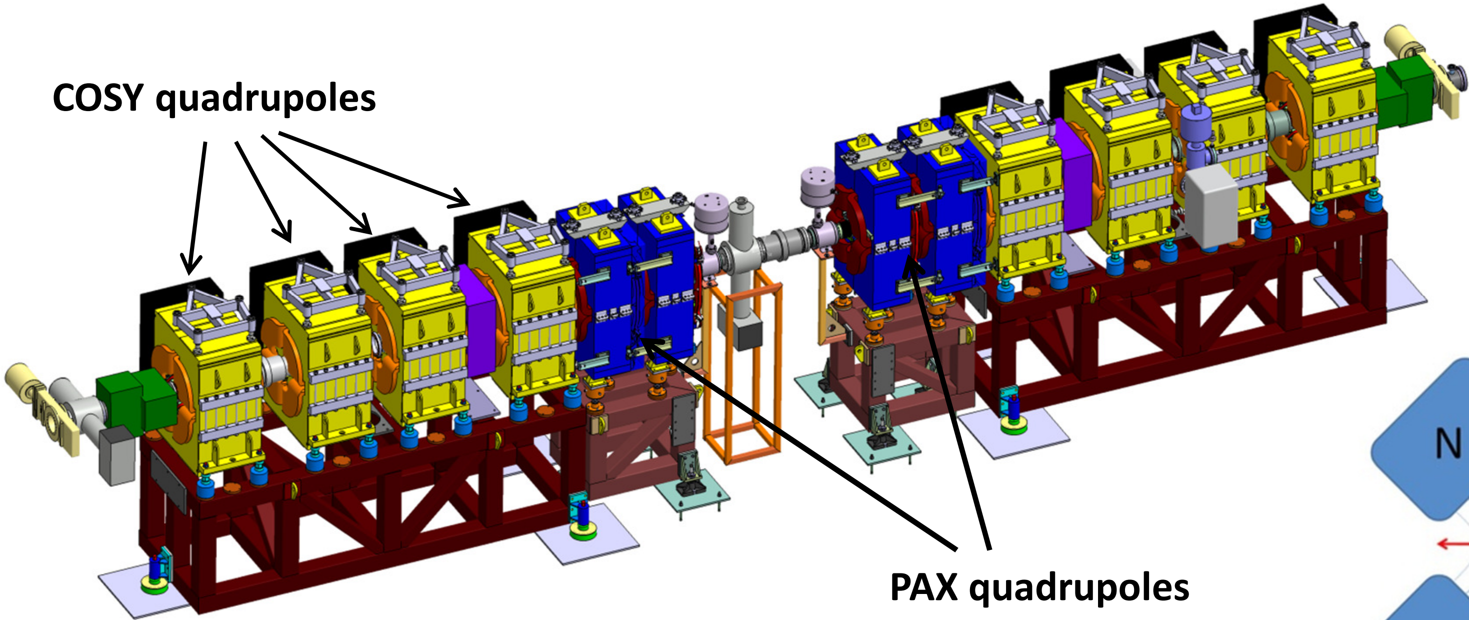


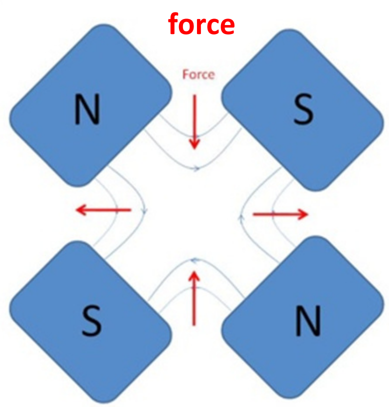


- **Storage cell increases the dwell time of the target gas atoms within the area of the beam and thus increases the target areal density**

„Low-β“ Section

- Storage cell dimensions are 10x 10 mm with 400mm length
- The COSY beam has to be squeezed to fit through the cell without losses
- Additional quadrupole magnets have to be installed





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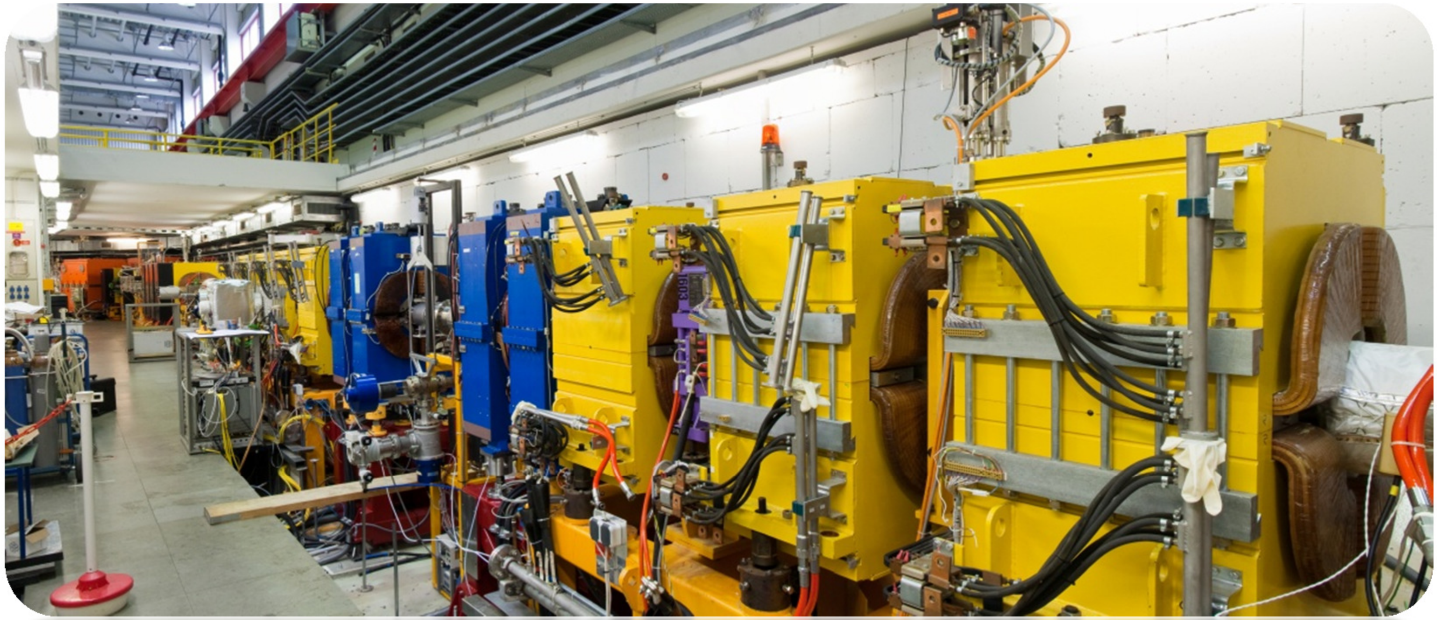
„Low-β“ Section

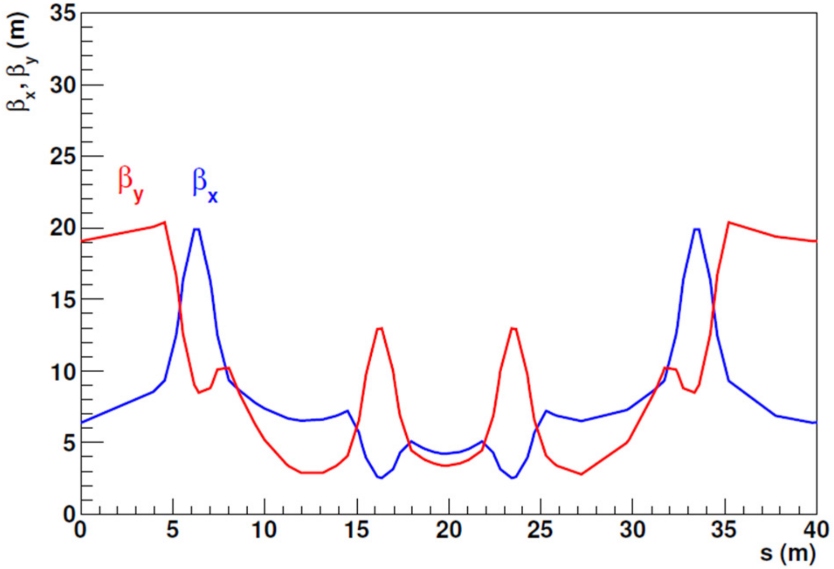


„Low-β“ Section

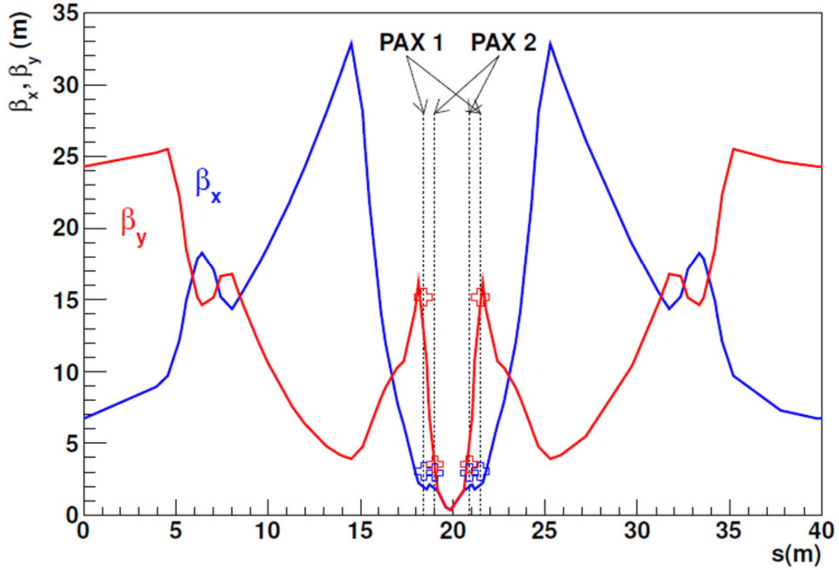
- **The beam size is given in terms of standard deviations as:**

$$\boxed{\sigma(s) = \sqrt{\varepsilon \cdot \beta(s)}}$$

PAX OFF **Low-β section off**



PAX ON **Low-β section on**



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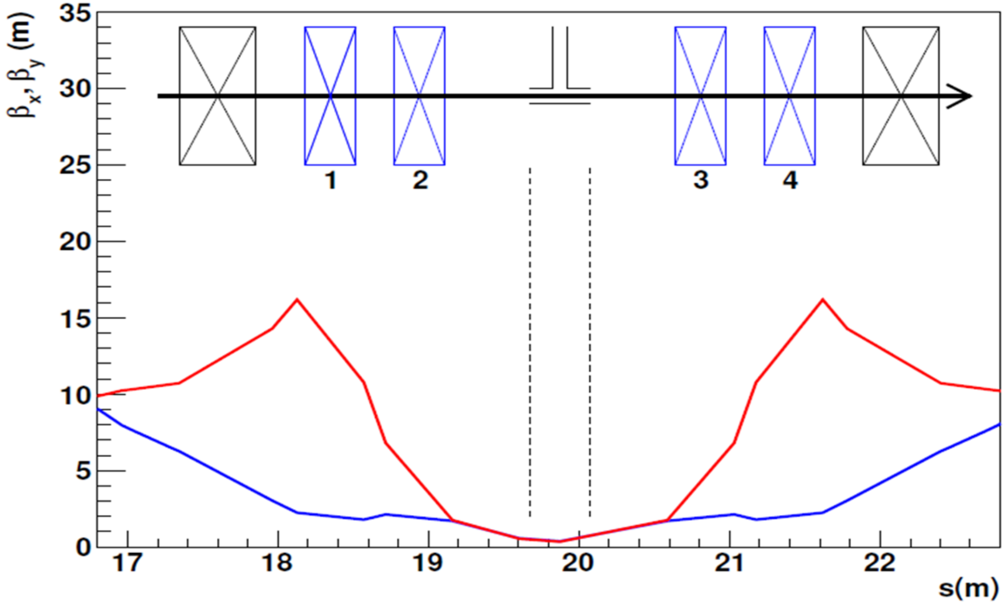
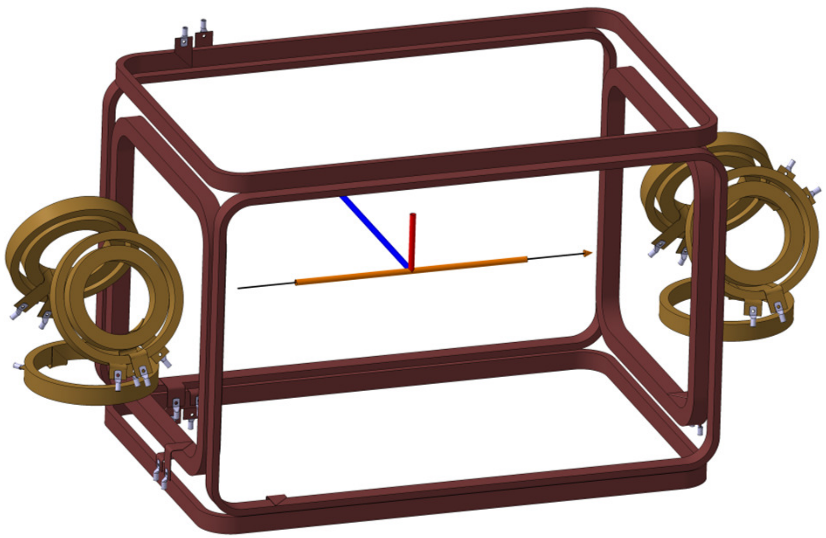


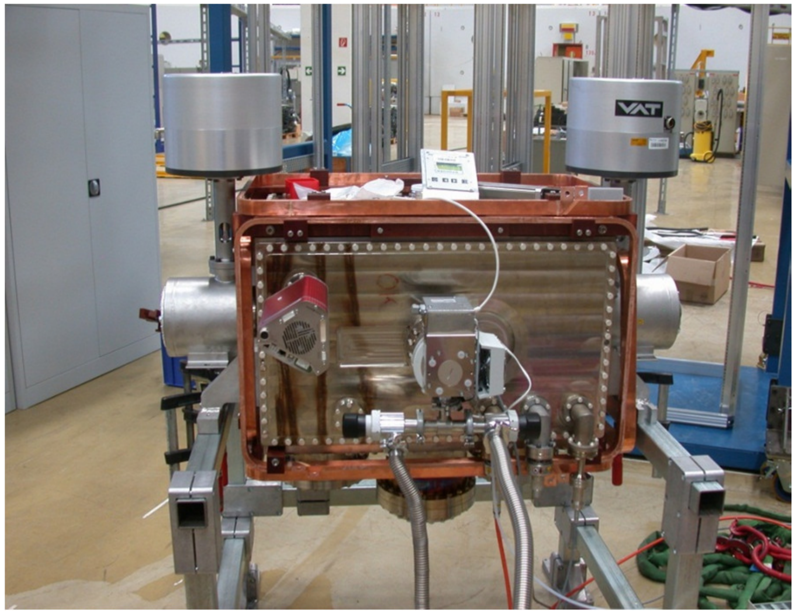
- **Beam sizes of 2σ = 1.2 mm can be reached**

Target Holding Field System

- **The target holding field system provides magnetic guide fields in the order of 1 mT in x-, y-, and z-direction**
- **Switching of polarization within 10 ms**
- **Compensation coils avoid influences on the beam axis**



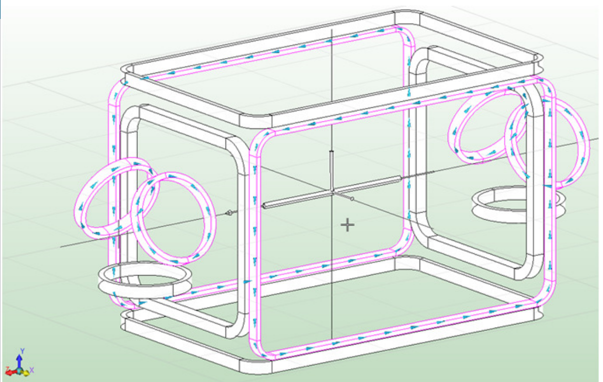
IKP & ZAT

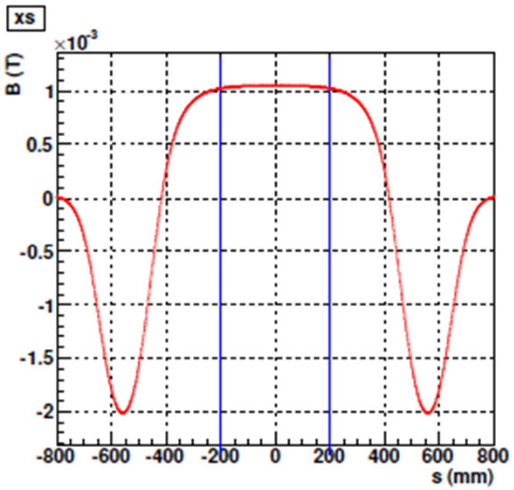


Target Holding Field System

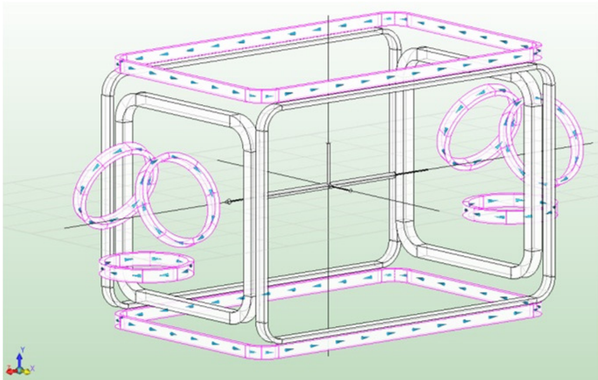
Polarized Antiproton eXperiments

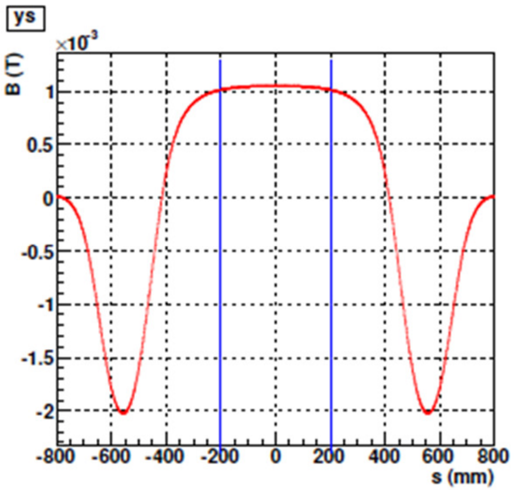
x-direction



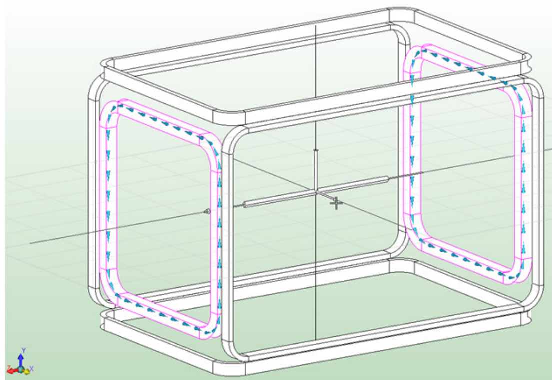


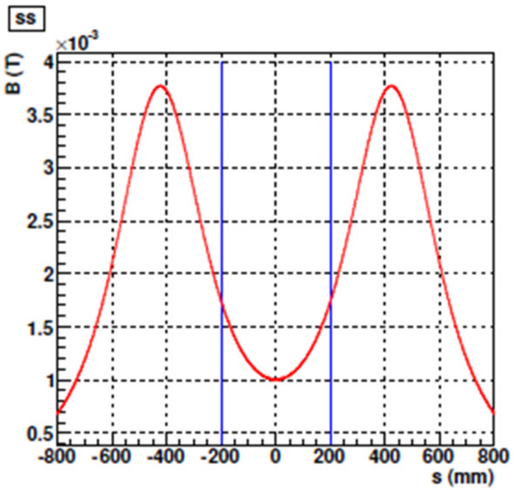
y-direction





z-direction





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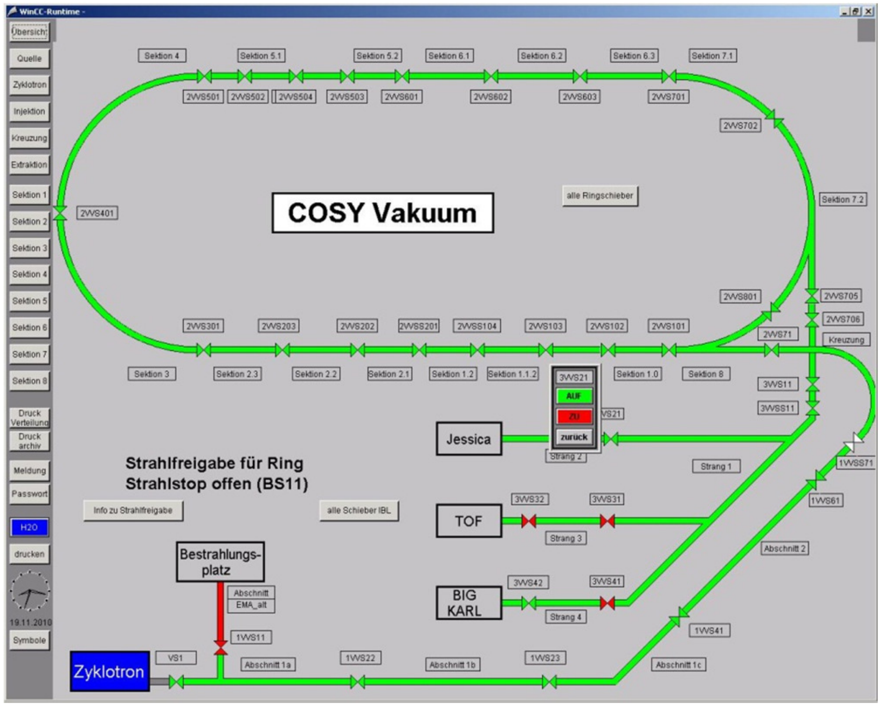
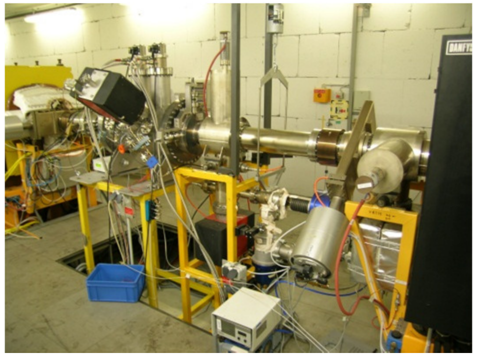
Maximum Beam Lifetime

COSY Ultra-high Vacuum System

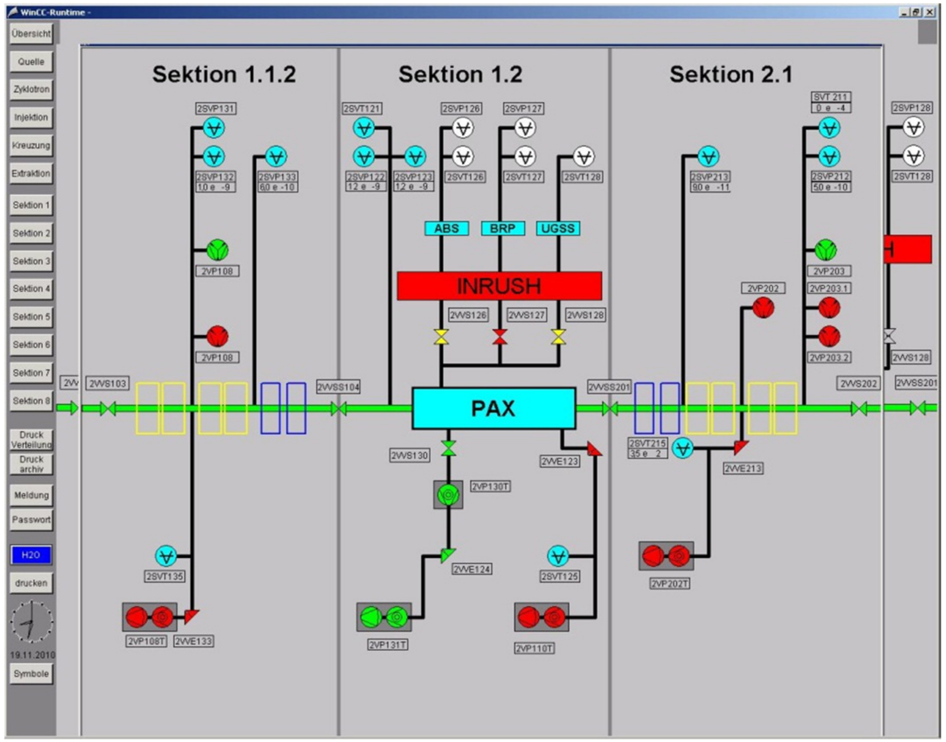
COSY UHV equipment and control system





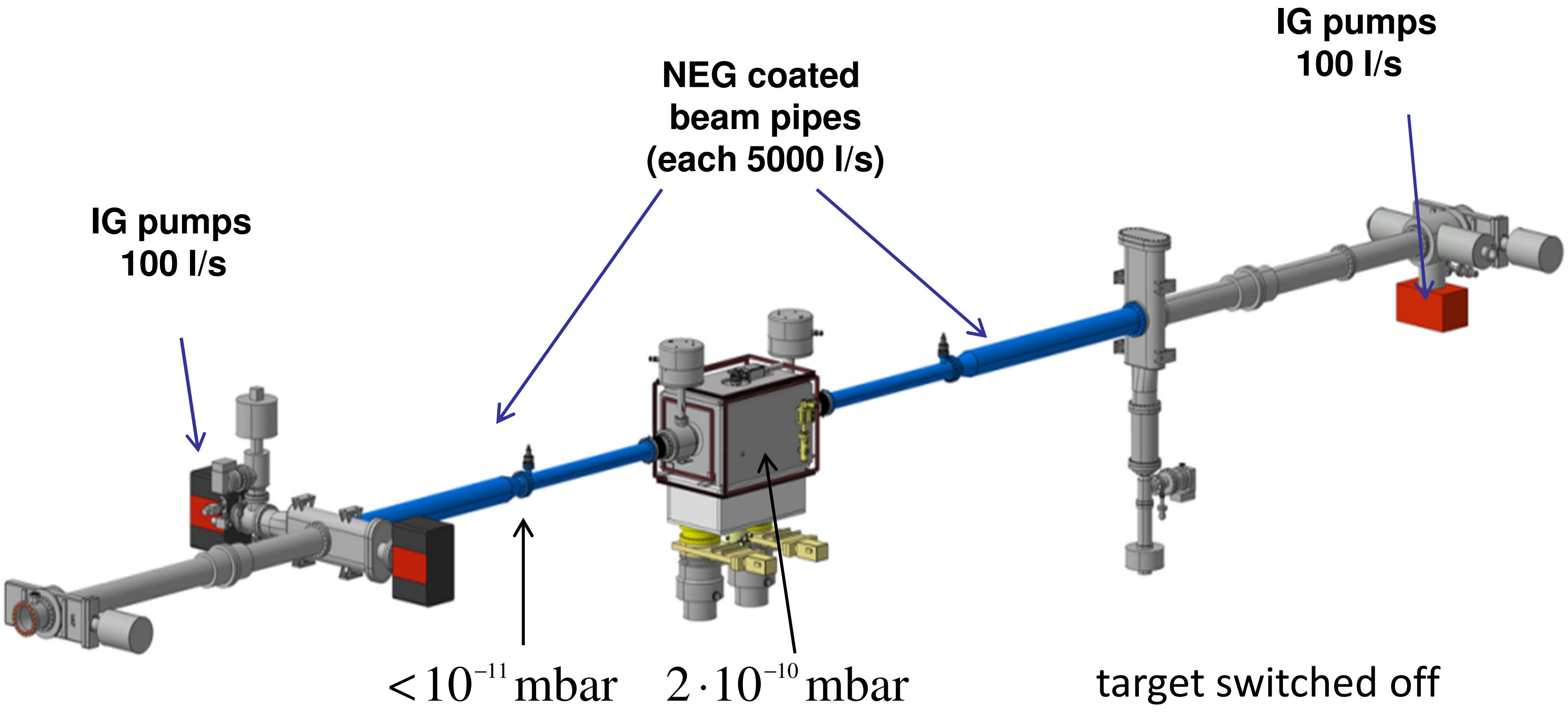
COSY Ultra-high Vacuum System

COSY Vacuum control per section



PAX Ultra-high Vacuum System

PAX vacuum section



PAX Ultra-high Vacuum System

Polarized Antiproton eXperiments

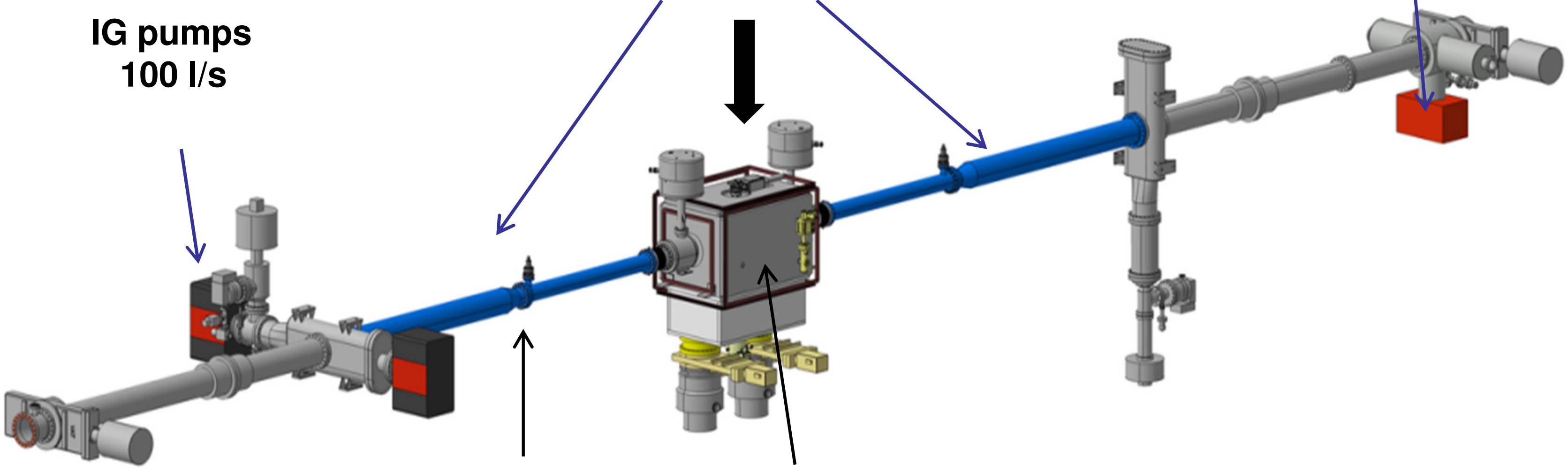
PAX vacuum section

$3 \cdot 10^{16}\,\mathrm{H/s}$

NEG coated beam pipes (each 5000 l/s)

IG pumps 100 l/s

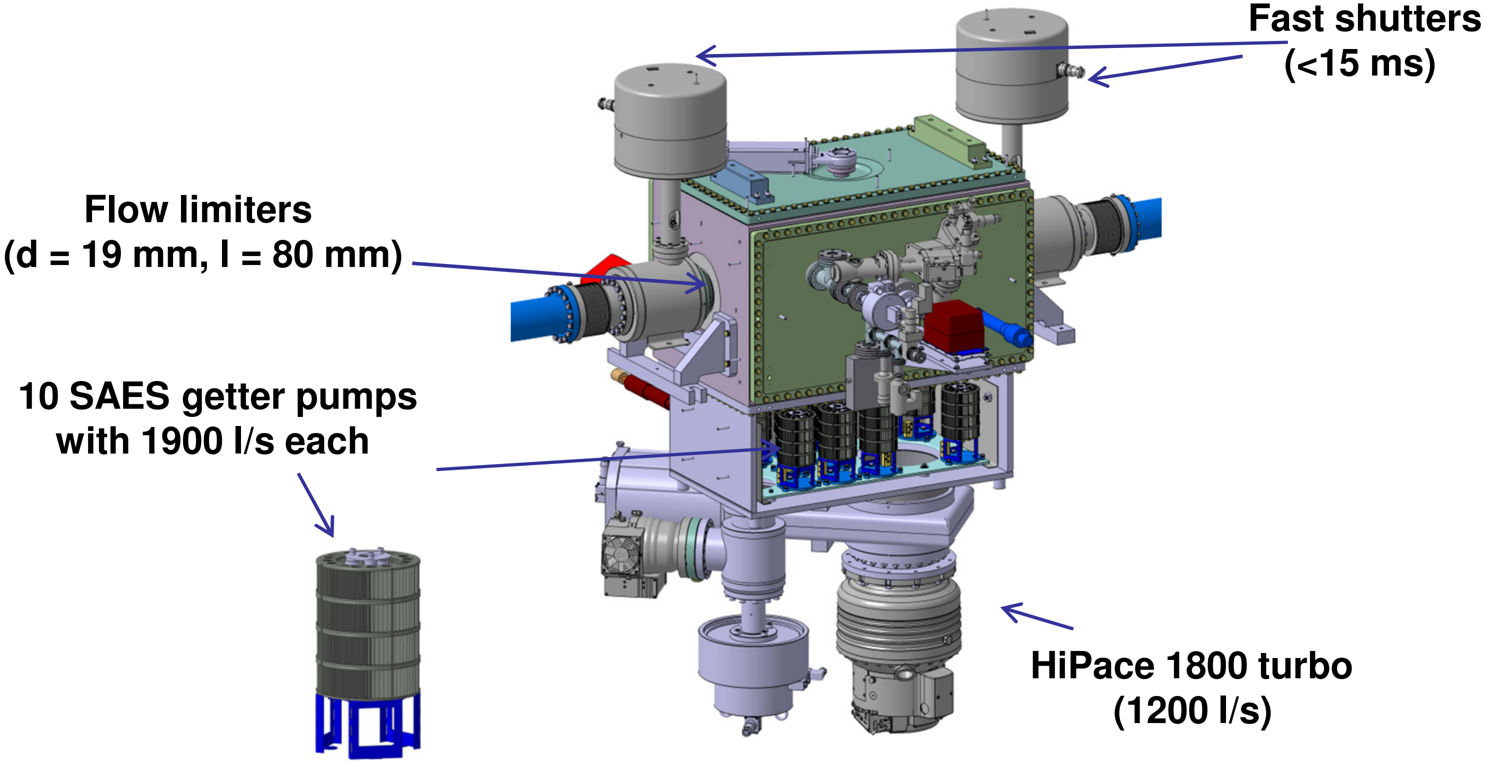
IG pumps 100 l/s



$< 10^{-11}\,\mathrm{mbar}$	$2 \cdot 10^{-10}\,\mathrm{mbar}$	target switched off
$< 10^{-9}\,\mathrm{mbar}$	$< 10^{-7}\,\mathrm{mbar}$	target switched on

PAX Ultra-high Vacuum System

PAX target chamber



PAX Ultra-high Vacuum System

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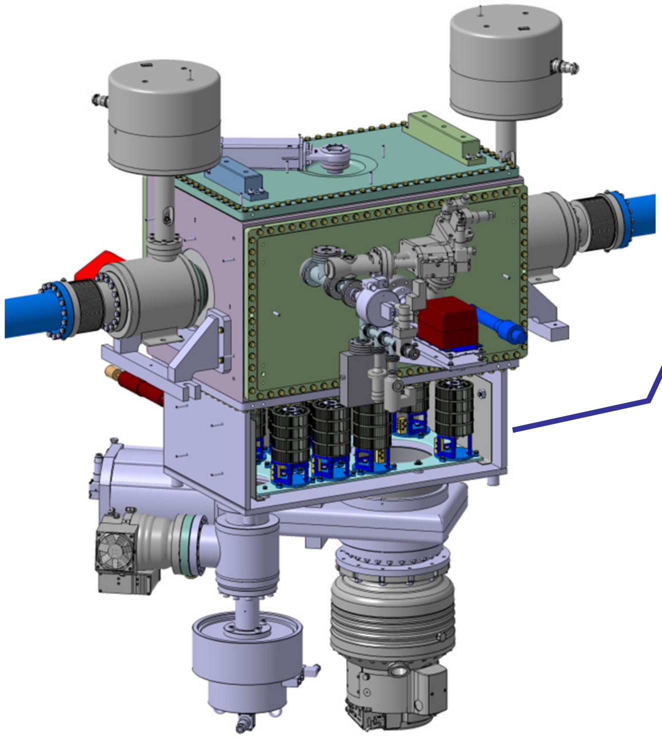
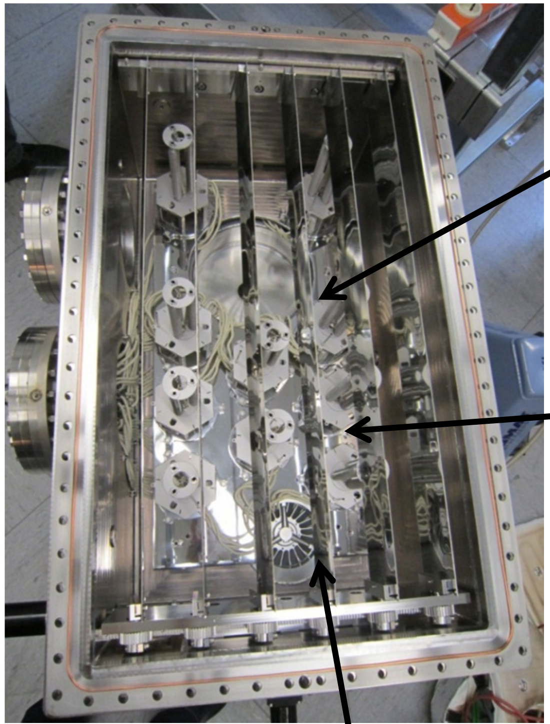
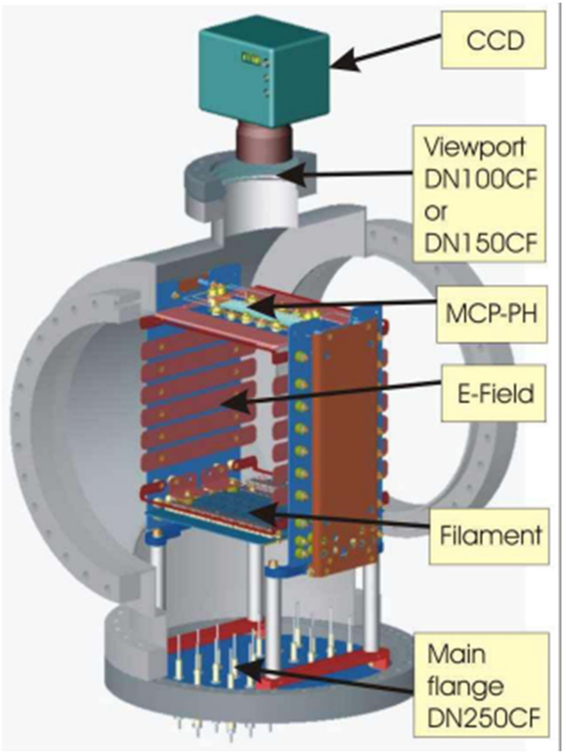


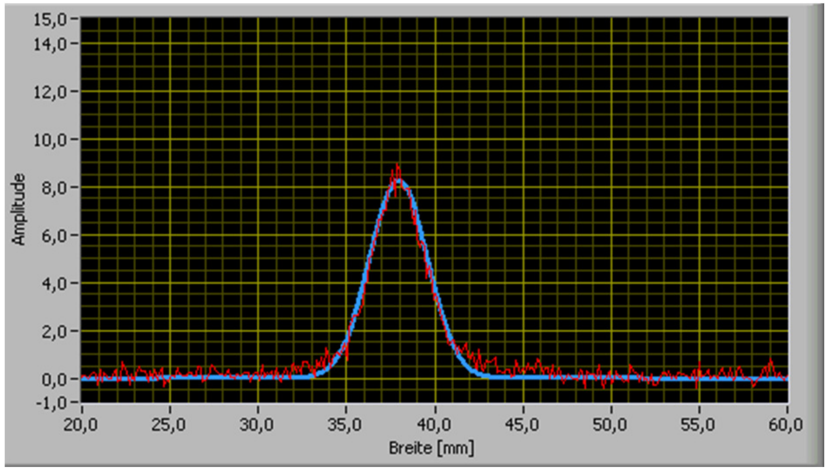


Orbit Correction

- **Measurement of beam positions and the beam size along the accelerator using an ionisation profile monitors**



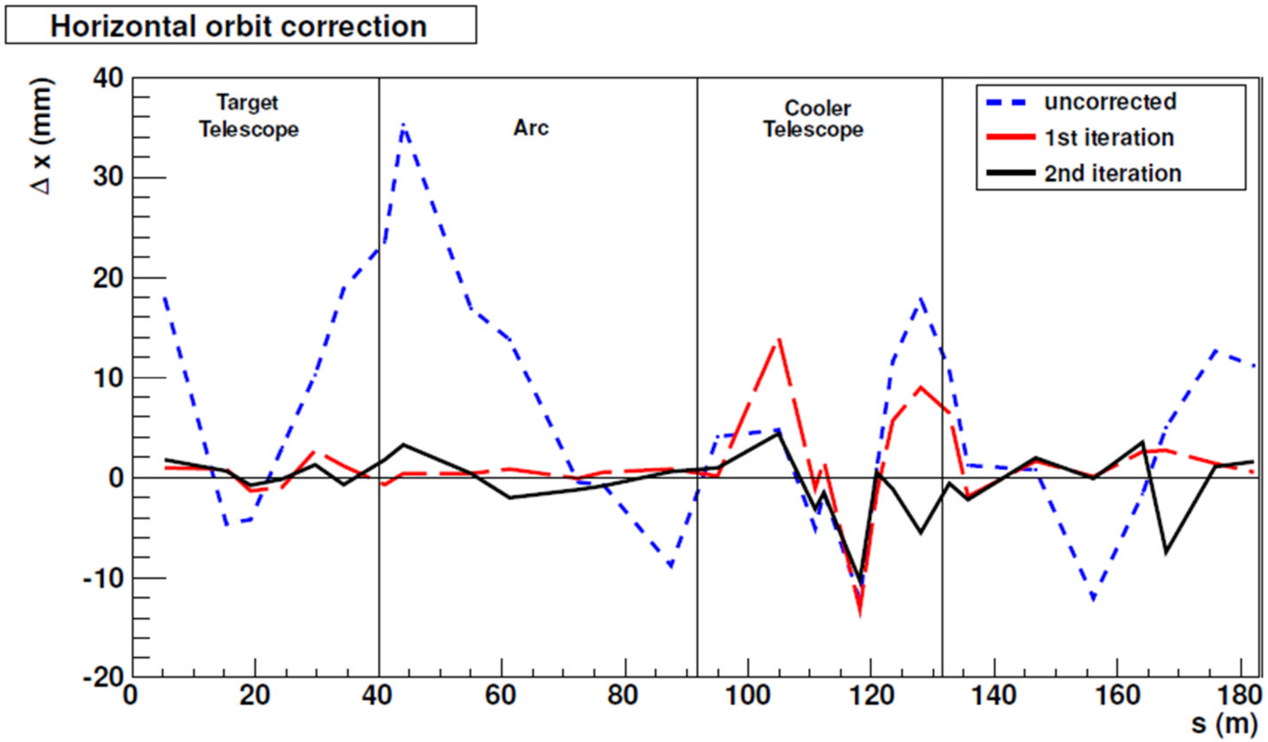
GSI



Particle distribution in x-direction

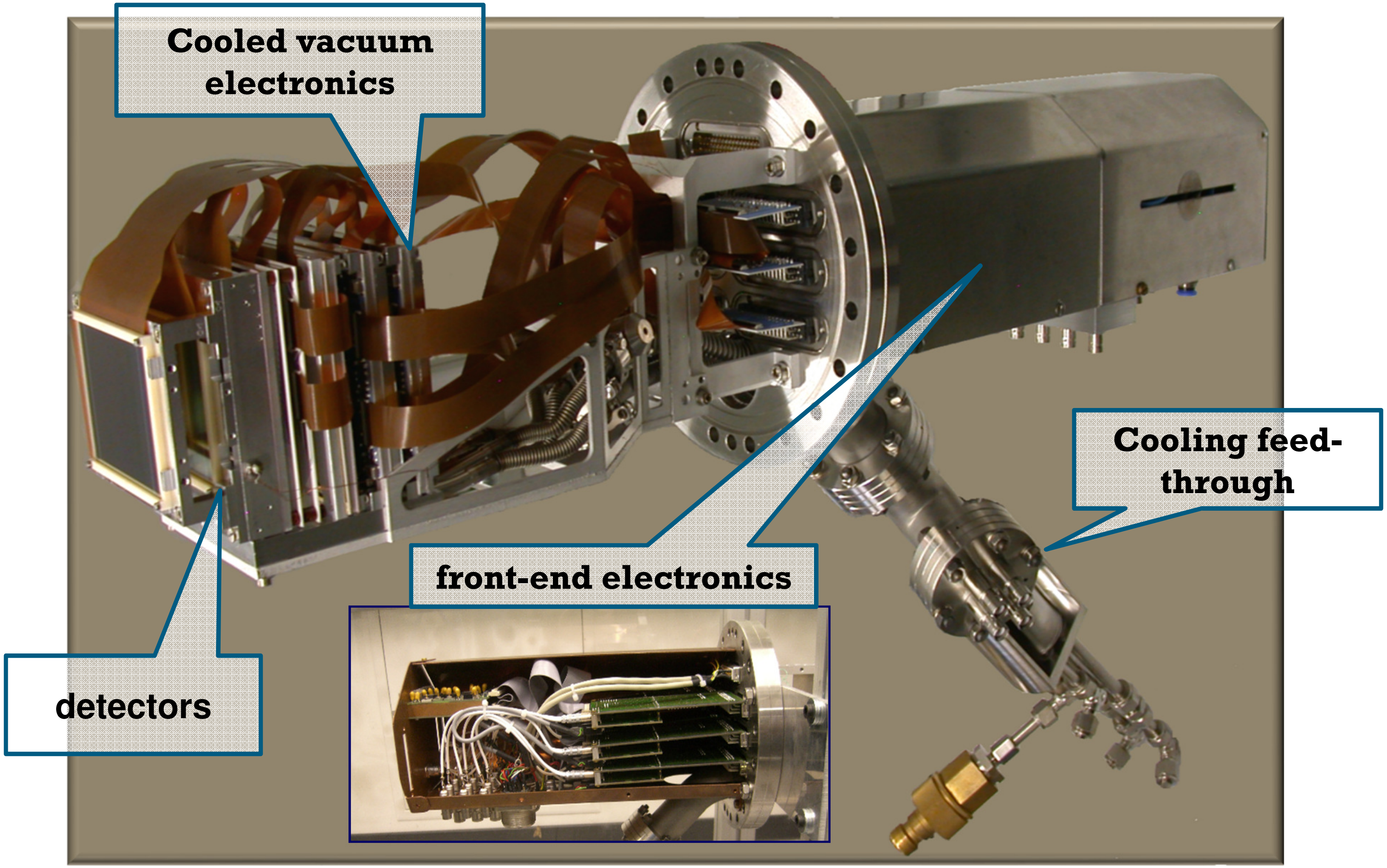
Orbit Correction

- **Measurement of beam positions and the beam size along the accelerator using an ionisation profile monitors**
- **Optimize deviation of beam from nominal orbit in an iterative process**



Beam Polarization Measurement

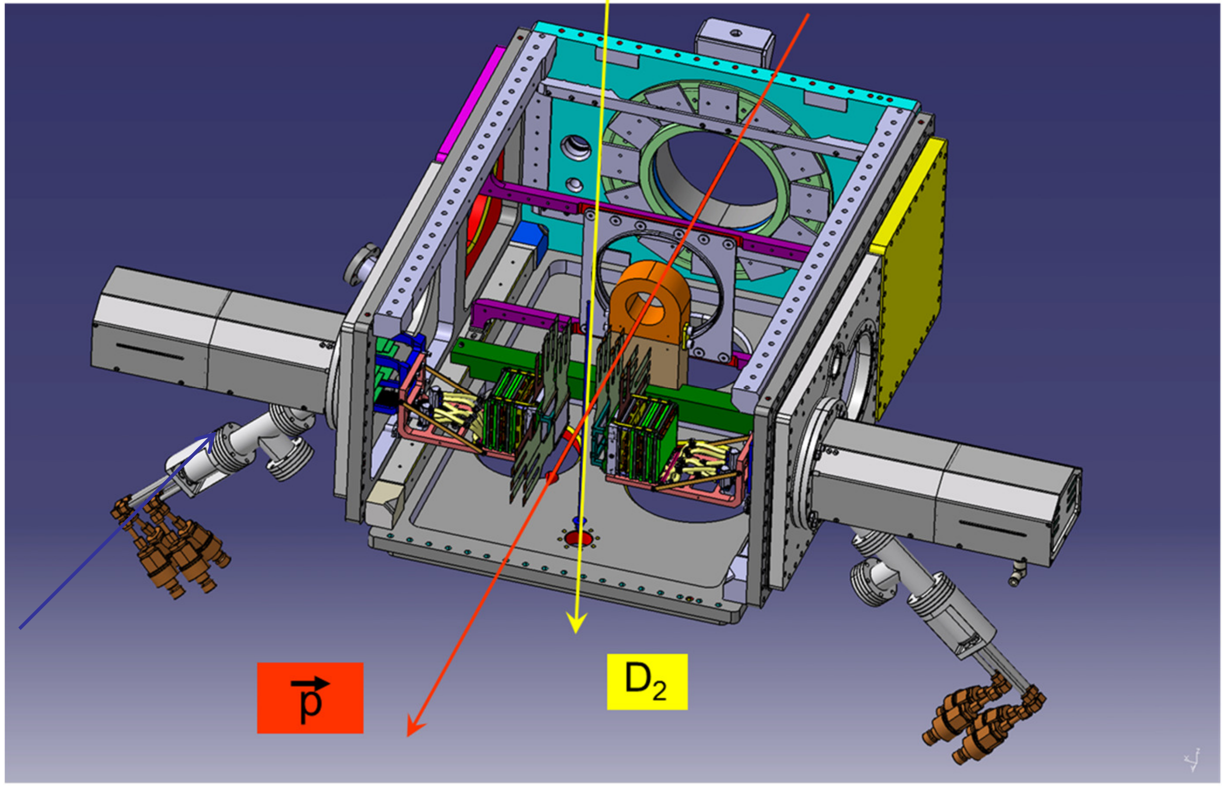
Beam Polarization Measurement



Talk: R. Schleichert

Beam Polarization Measurement

- **Measurement of L-R asymmetry in elastic pd scattering**
- **2 Silicon Tracking Telescopes left and right of the beam target overlap region**
- **Deuterium cluster target ($1 \cdot 10^{14}\,\mathrm{atoms/cm^2}$)**



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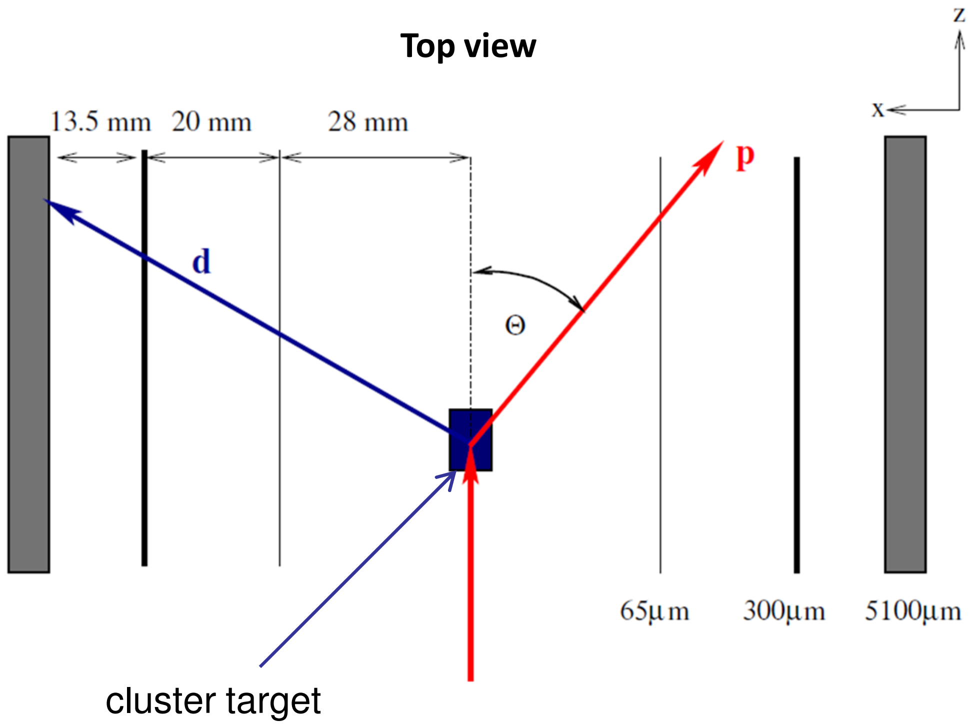
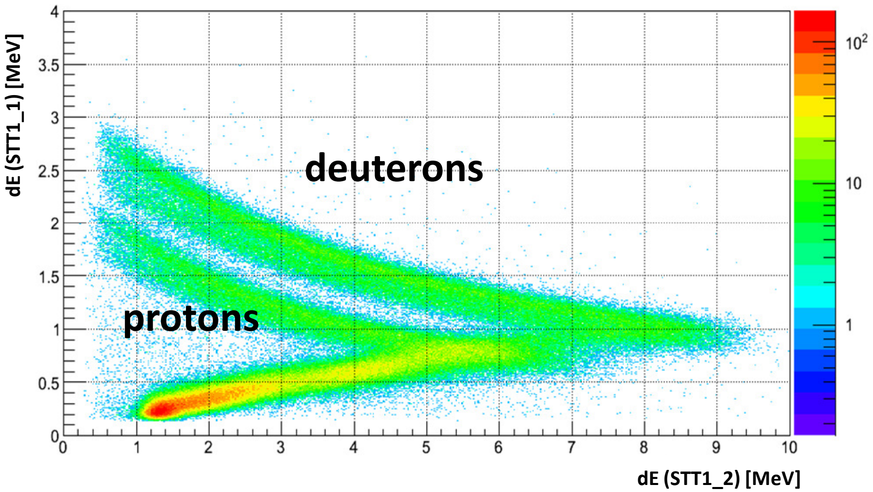


Detectors measure E, Θ, φ

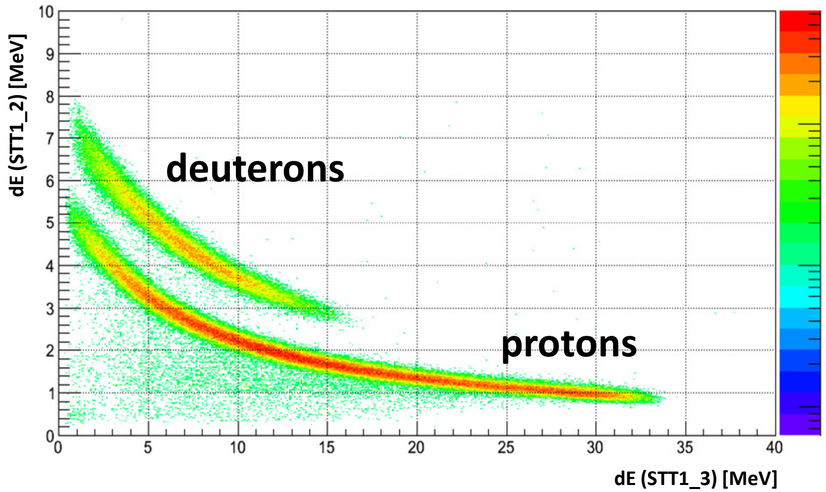
- **particle identification**
- **selection of elastic scattering events**

Beam Polarization Measurement

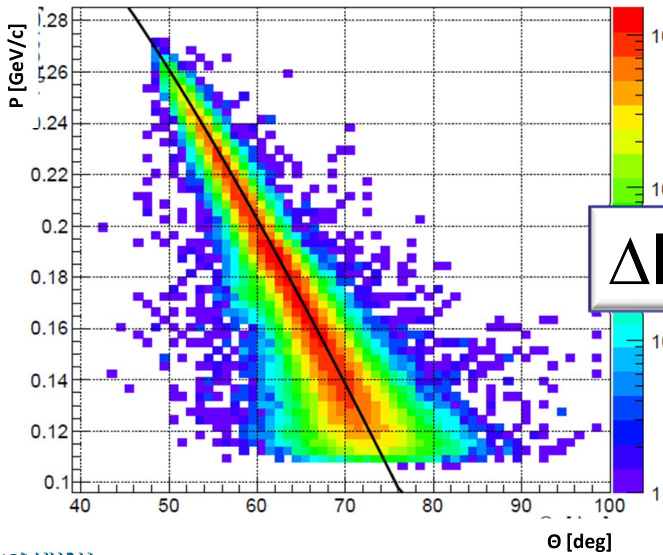
Energy loss in 1. vs 2. layer



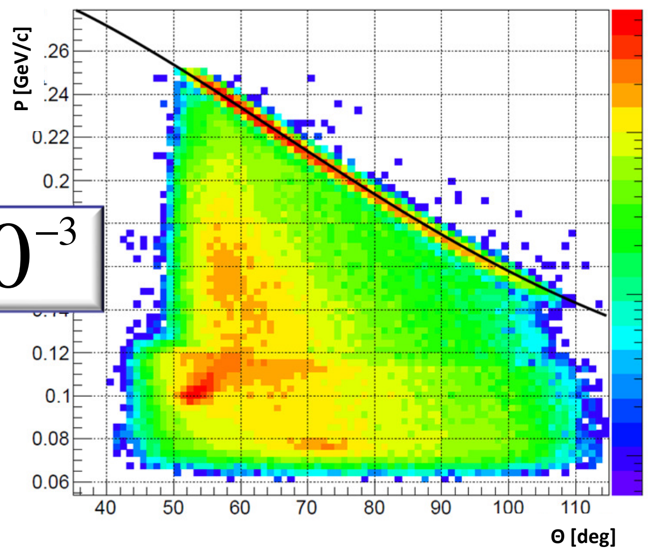
Energy loss in 2. vs 3. layer



Deuteron momentum vs. scattering angle



Proton momentum vs. scattering angle

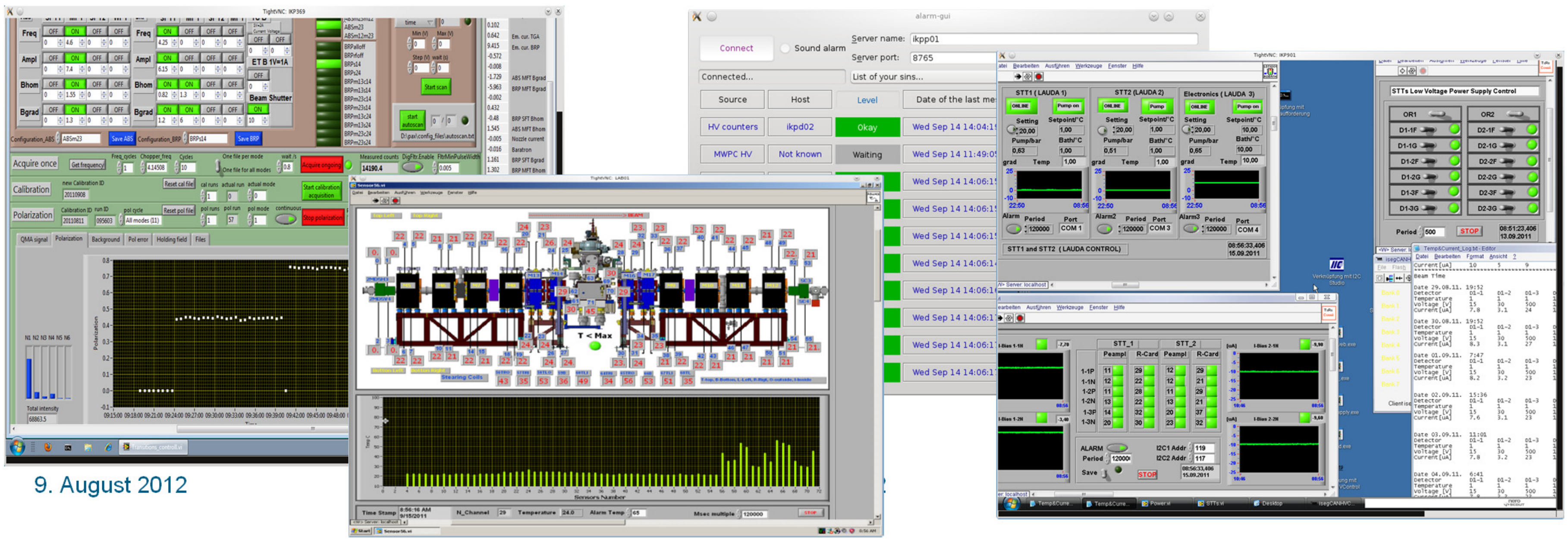


$$\Delta \mathbf{P} = 1 \cdot 10^{-3}$$

Summary

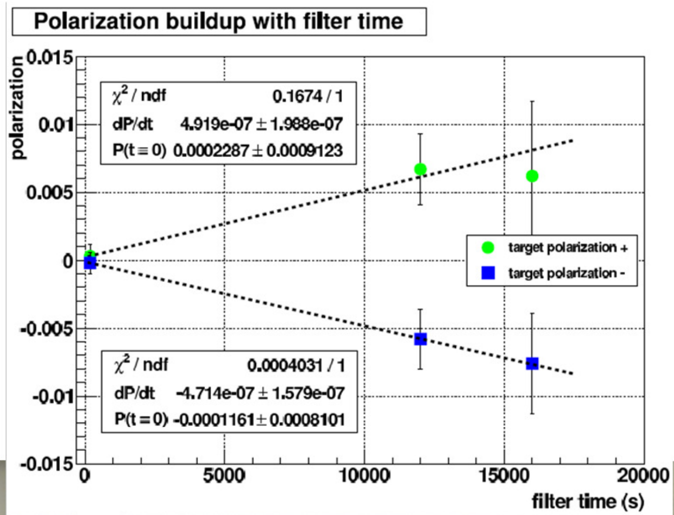
- **Very good understanding of the spin-filtering method and how to optimize the experiment**
- **Beam development procedure: improvement from 500s to 8000s**
- **Successful commissioning and usage of the experimental equipment of several subsystems:**

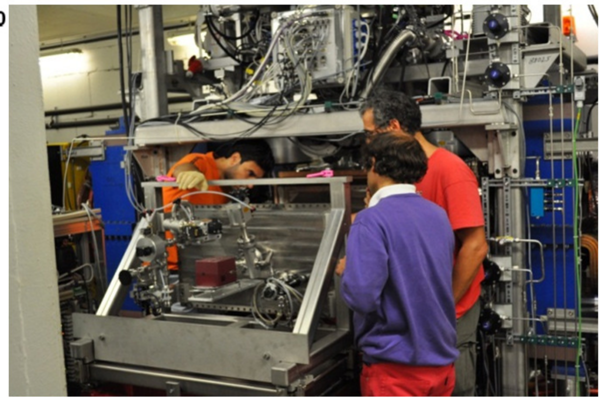
  Atomic Beam Source, Breit-Rabi Polarimeter, Silicon Tracking Telescopes, Temperature Control, Pressure Readout, Data Acquisition, Vacuum System, Flow Limiter, …



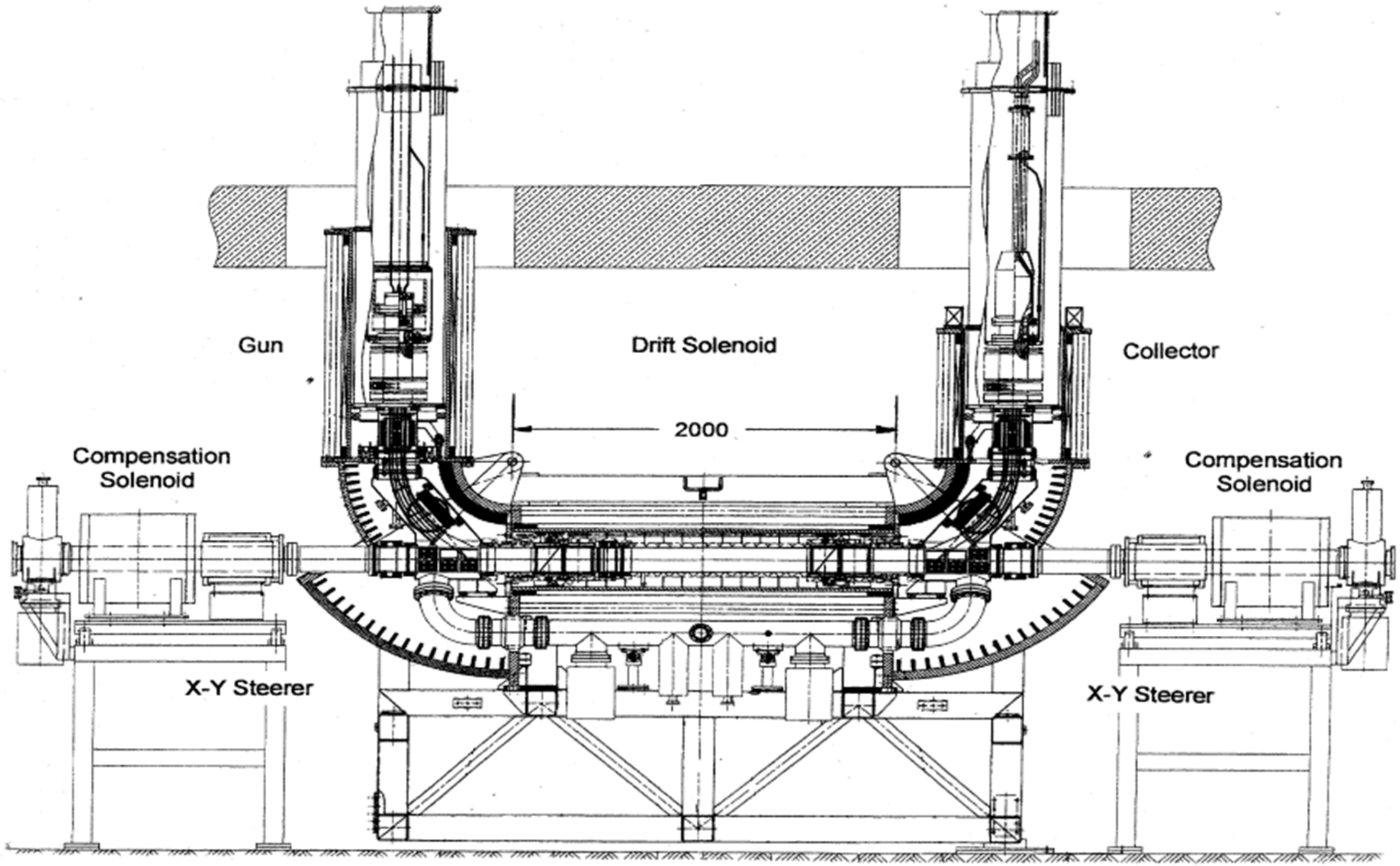
Summary

- **Successful spin-filtering experiments with measurement of the polarizing cross section at COSY!**



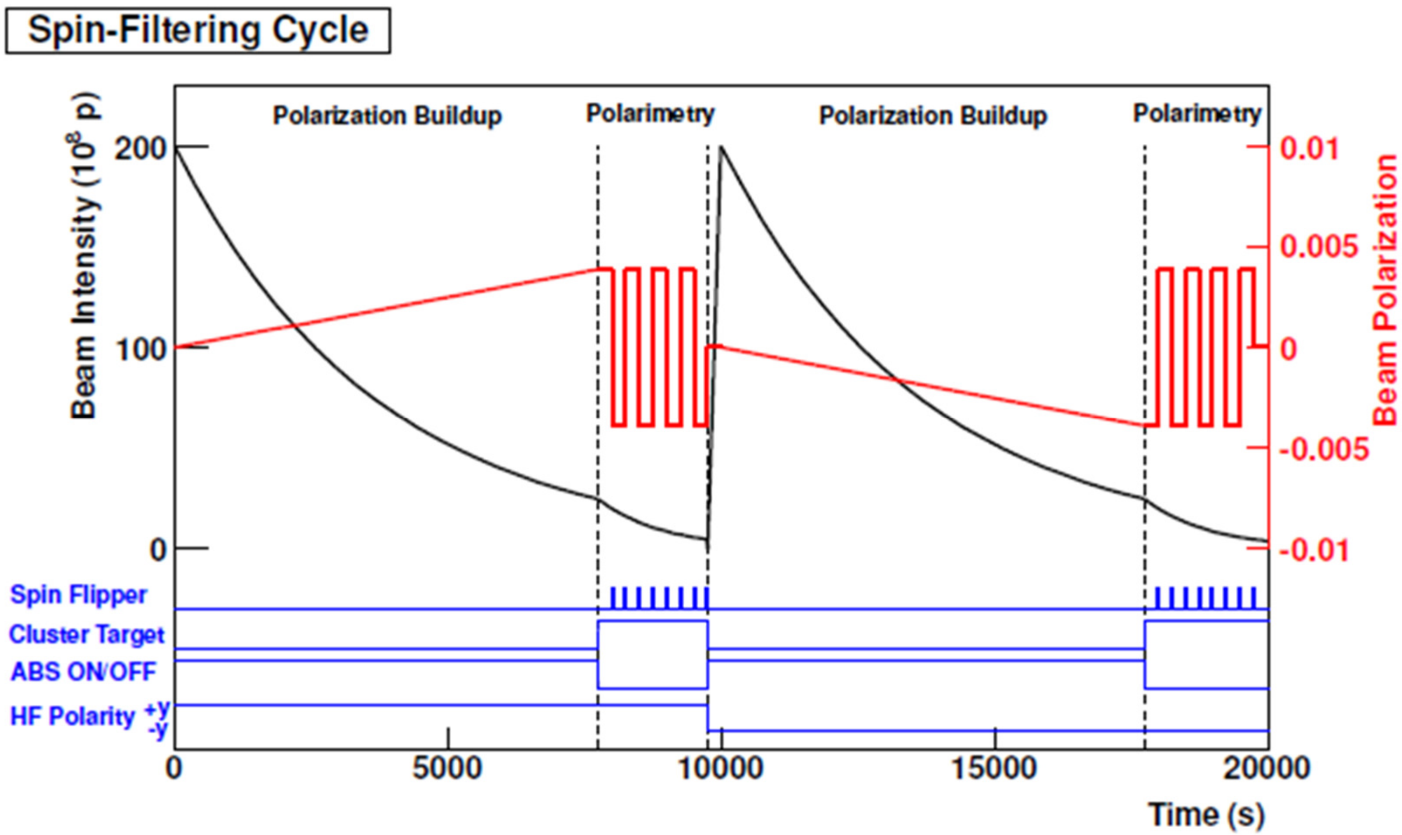


Additional slides

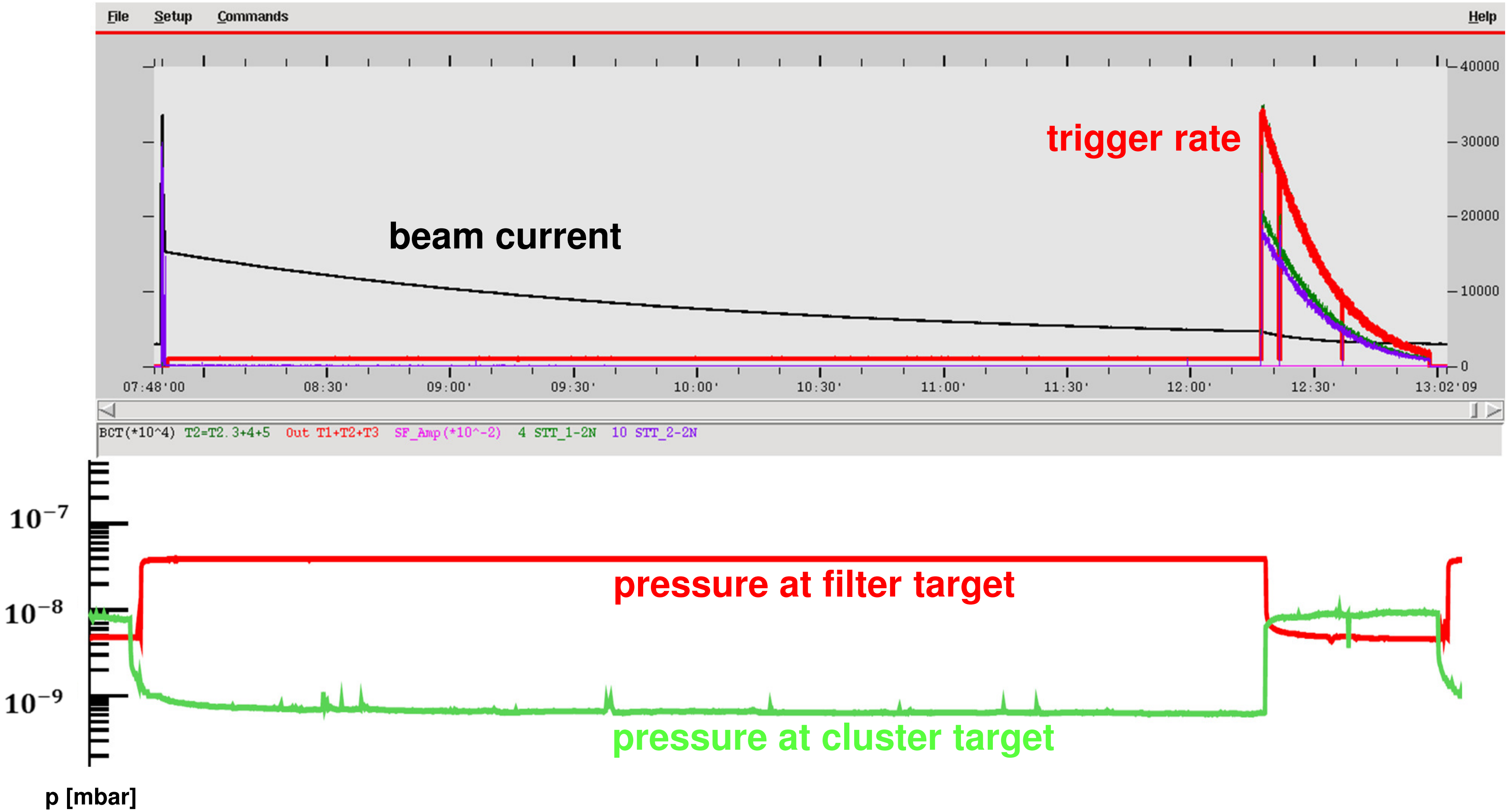

Gun
Drift Solenoid
Collector
2000
Compensation Solenoid
Compensation Solenoid
X-Y Steerer
X-Y Steerer

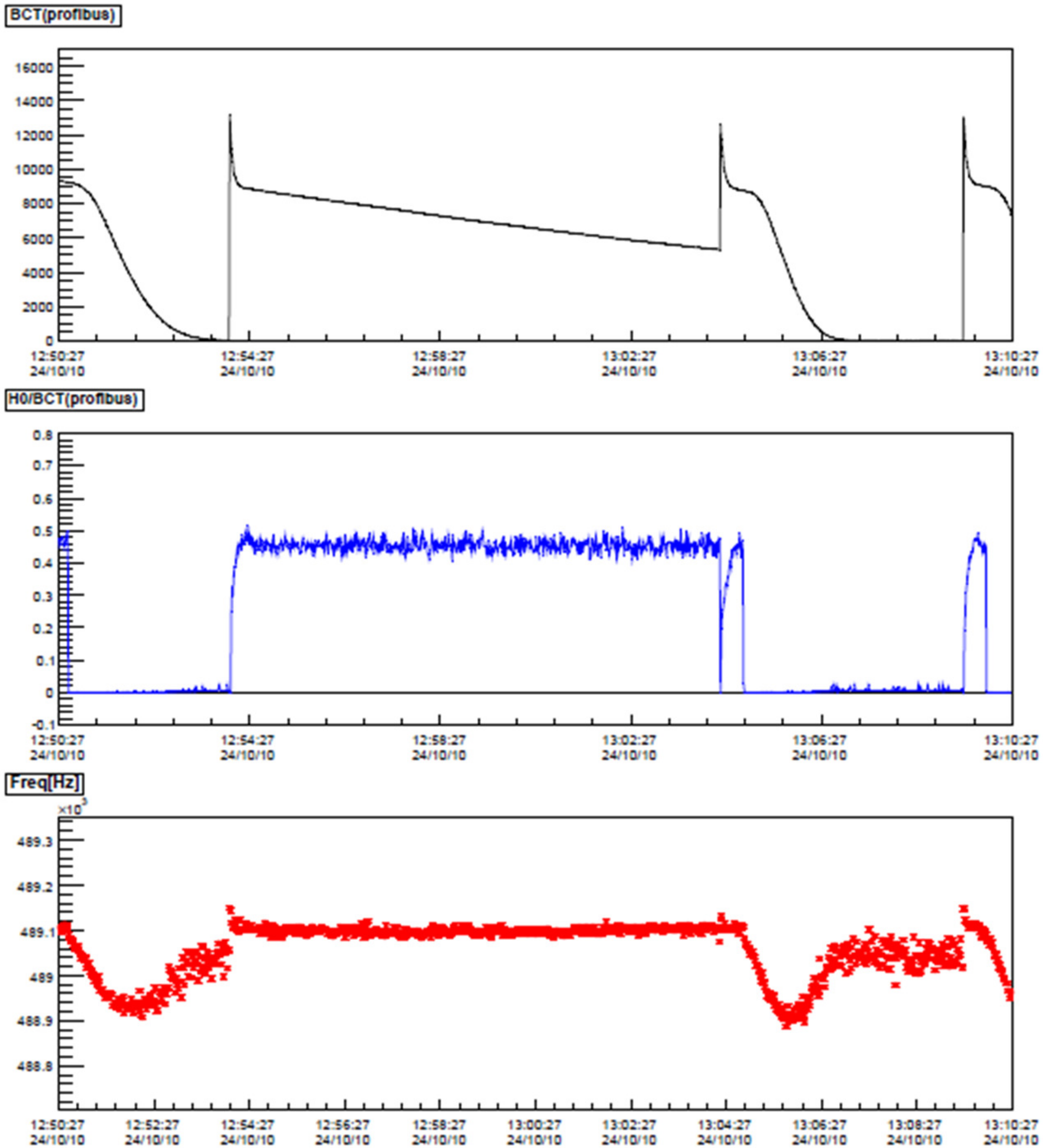
Spin-filter Cycle

- **A cycle consist of two subcycles with reversed target polarization**



Spin-filter Cycle





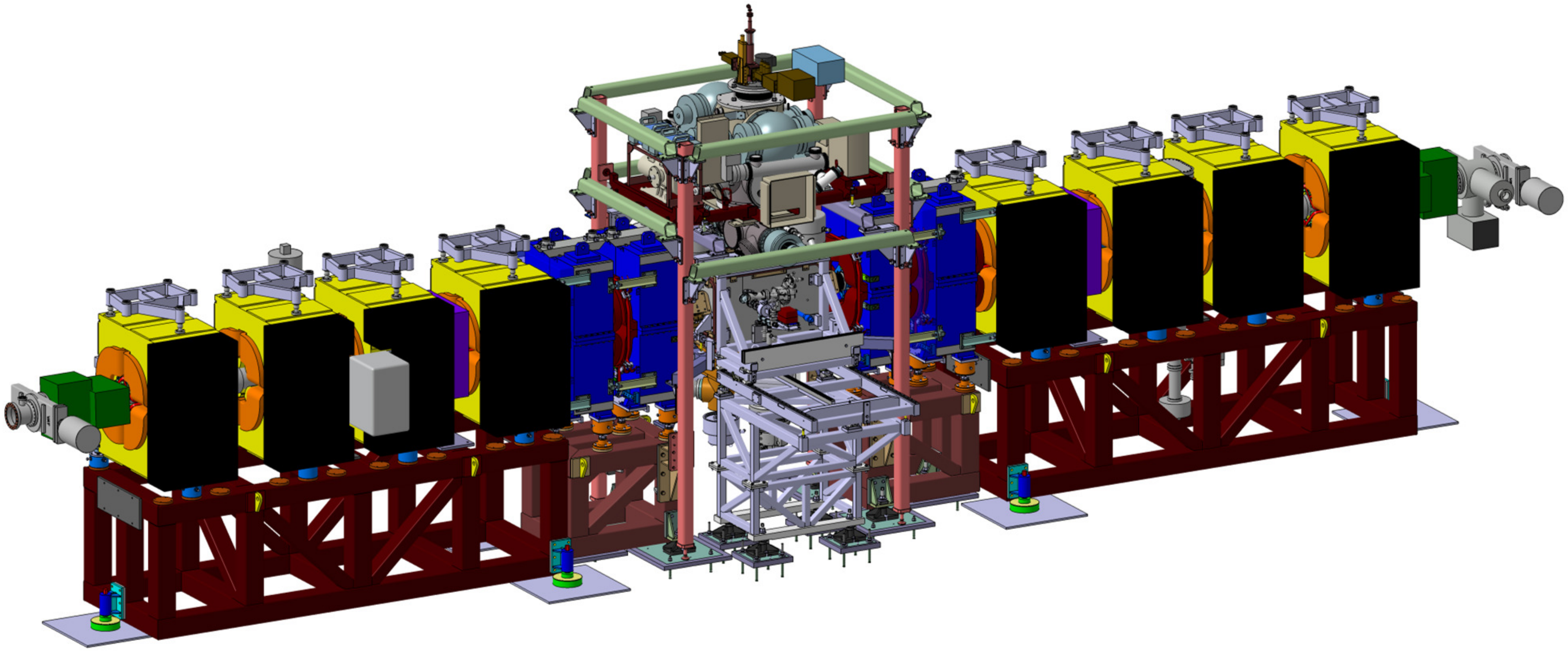
Polarized Antiproton eXperiments

Beam current

Beam Cooling

Revolution frequency

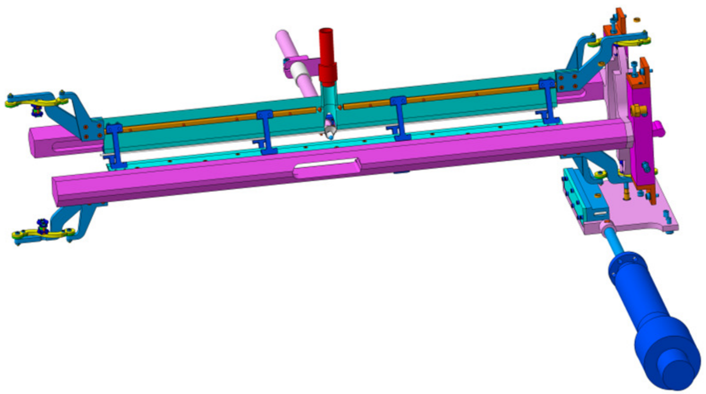
PAX Target Section



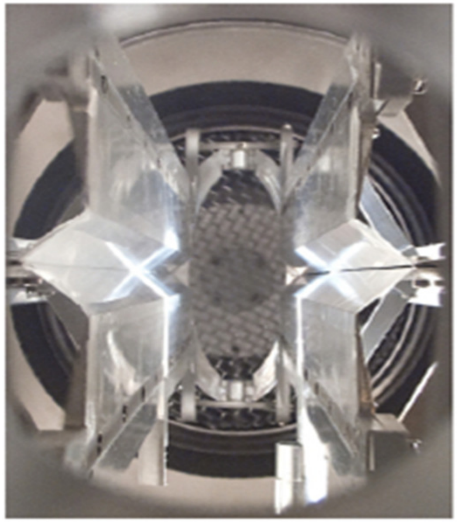
Storage Cell

- **Storage cell increases the dwell time of the target gas atoms within the area of the beam and thus increases the target areal density**

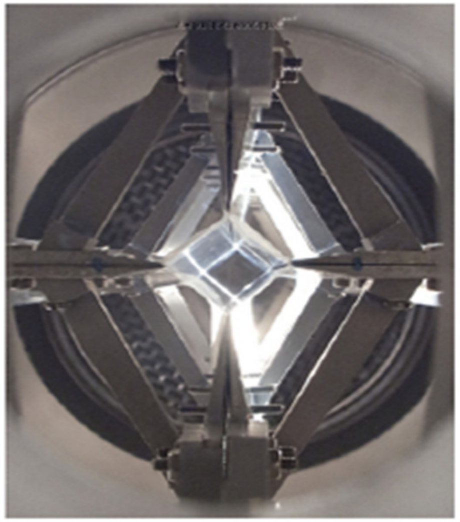
length: 400 mm
area: 10x10 mm



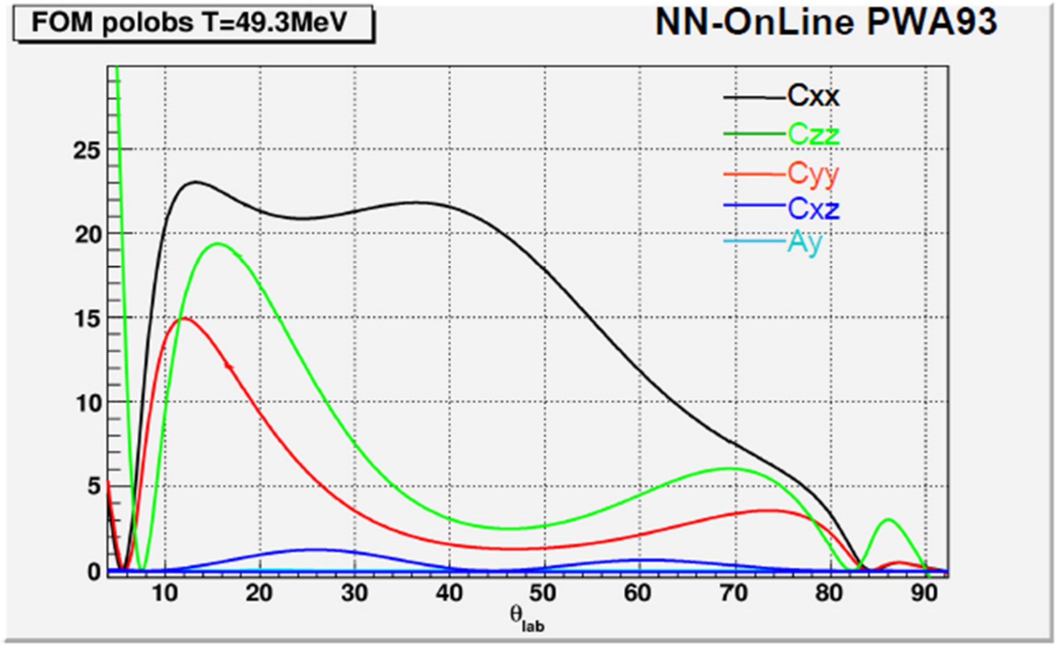
open



closed



Polarization Measurement Using $\vec{p}\vec{p}$ Elastic Scattering



$$
\begin{aligned}
X = \sigma/\sigma_0 = 1 + A_y &\left[(P_y + Q_y)\cos\phi - (P_x + Q_x)\sin\phi\right] \\
&+ C_{xx}\left[P_x Q_x \cos^2\phi + \boxed{P_y Q_y \sin^2\phi} + (P_x Q_y + P_y Q_x)\sin\phi\cos\phi\right] \\
&+ C_{yy}\left[P_x Q_x \sin^2\phi + \boxed{P_y Q_y \cos^2\phi} - (P_x Q_y + P_y Q_x)\sin\phi\cos\phi\right] \\
&+ C_{xz}\left[(P_x Q_z + P_z Q_x)\cos\phi + (P_y Q_z + P_z Q_y)\sin\phi\right] \\
&+ C_{zz} P_z Q_z
\end{aligned}
$$

Beam Polarization Measurement

Polarized Antiproton eXperiments

Events in left $L_{\uparrow,\downarrow}$ and right $R_{\uparrow,\downarrow}$ detector

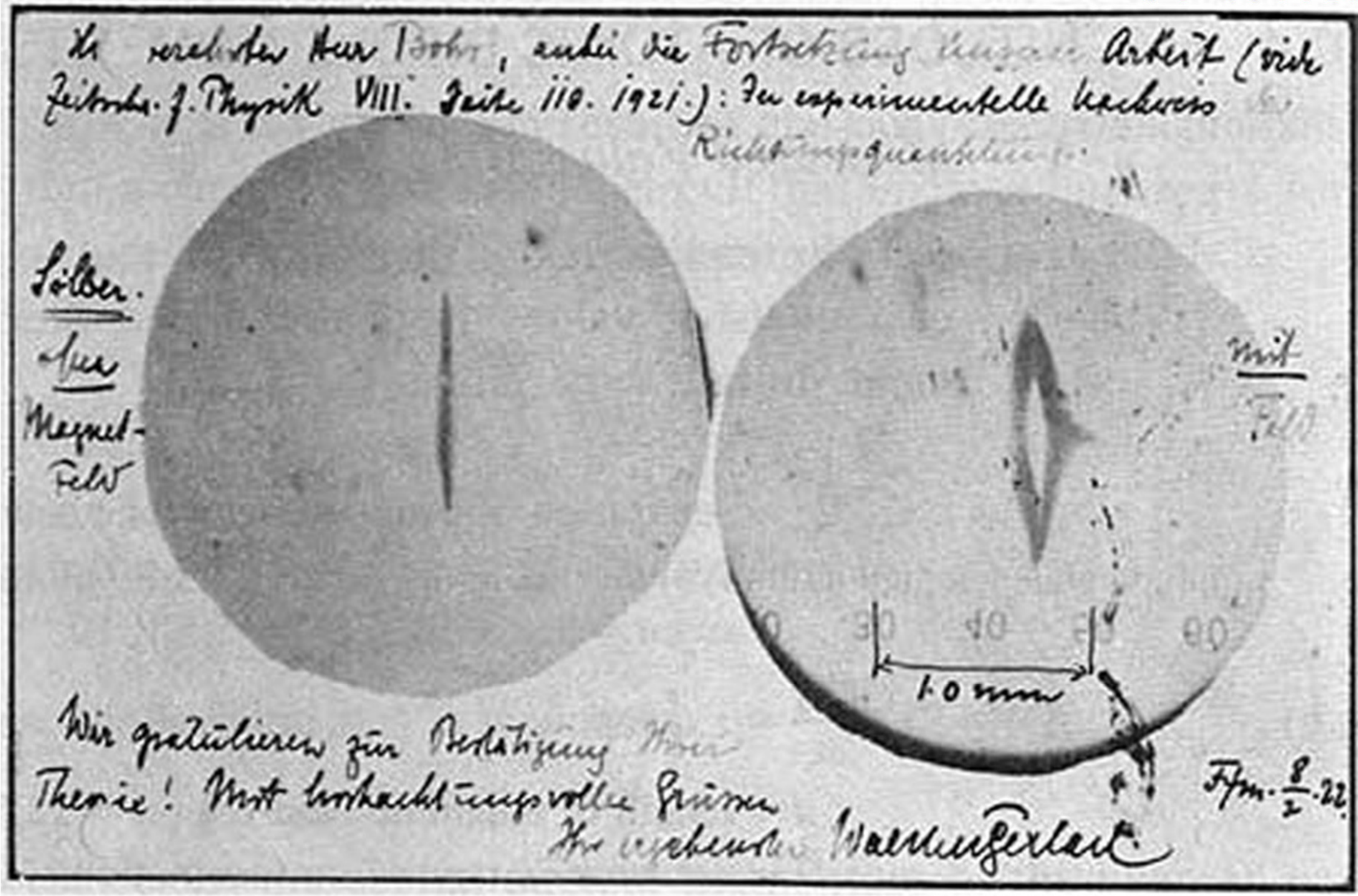
$$\delta = \frac{\sqrt{L_\uparrow \cdot R_\downarrow}}{\sqrt{L_\downarrow \cdot R_\uparrow}} = \cancel{\frac{\sqrt{\mathcal{L}_\uparrow \cdot \mathcal{L}_\downarrow \cdot \Omega_L \cdot \Omega_R \cdot E_L \cdot E_R} \cdot \frac{d\sigma}{d\Omega}}{\sqrt{\mathcal{L}_\uparrow \cdot \mathcal{L}_\downarrow \cdot \Omega_L \cdot \Omega_R \cdot E_L \cdot E_R} \cdot \frac{d\sigma}{d\Omega}}} \cdot \frac{1 + PA_y(\theta)}{1 - PA_y(\theta)}$$

$$\boxed{\epsilon = \frac{\delta - 1}{\delta + 1} = PA_y(\theta)}$$

$$\boxed{P = \frac{\epsilon}{A_y(\theta)}}$$

Figure of Merit:

$$FOM = A_y^2 \cdot \frac{d\sigma}{d\Omega}$$



Gerlach's postcard, dated 8 February 1922, to Niels Bohr. It shows a photograph of the beam splitting, with the message, in translation: "Attached [is] the experimental proof of directional quantization. We congratulate [you] on the confirmation of your theory." (Physics Today December 2003)