Toward polarized antiprotons:
Machine development for spin-filtering experiments at COSY

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Motivation

- The PAX collaboration proposed to investigate Drell Yan processes in scattering of polarized proton - antiproton beams at the HESR (FAIR).

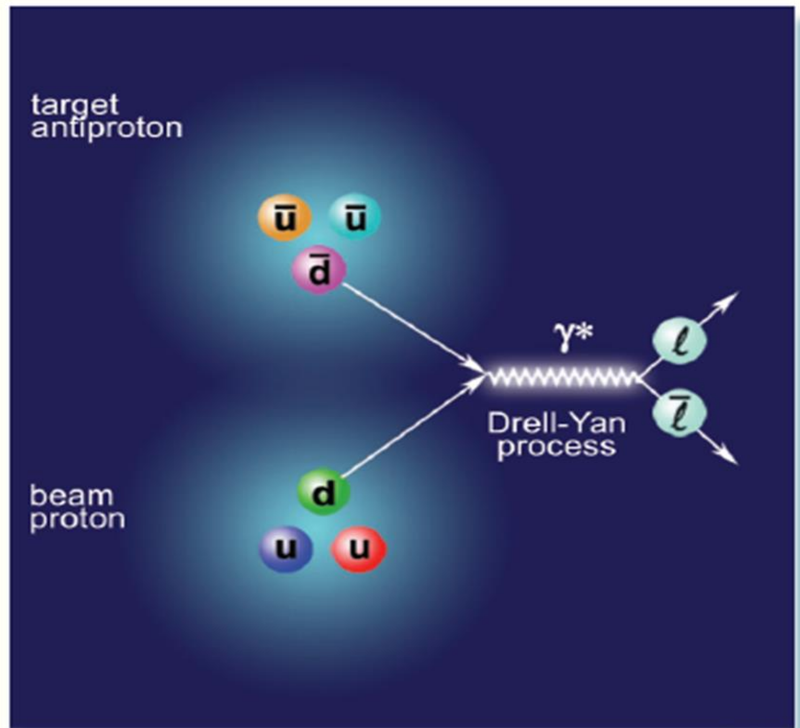
- Annihilation of valence quark with an antivalence quark allows direct access to: transversity, ….

$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2)\, h_1^{\bar{q}}(x_2, M^2)}{\sum_q e_q^2\, q(x_1, M^2)\, \bar{q}(x_2, M^2)}$$

- <u>Requirements:</u>

  Polarized proton beam ✓

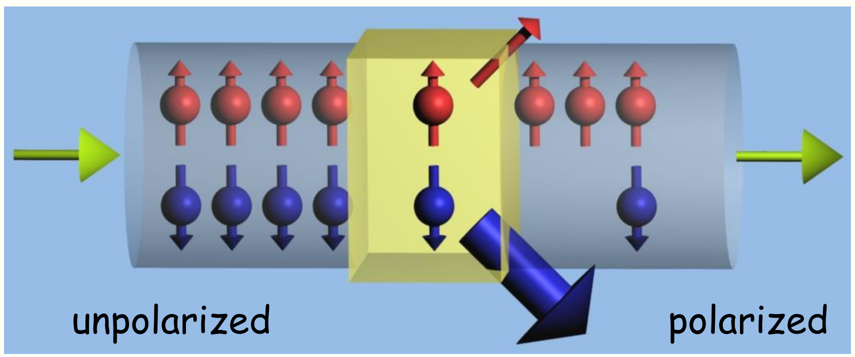
  Polarized antiproton beam ✗



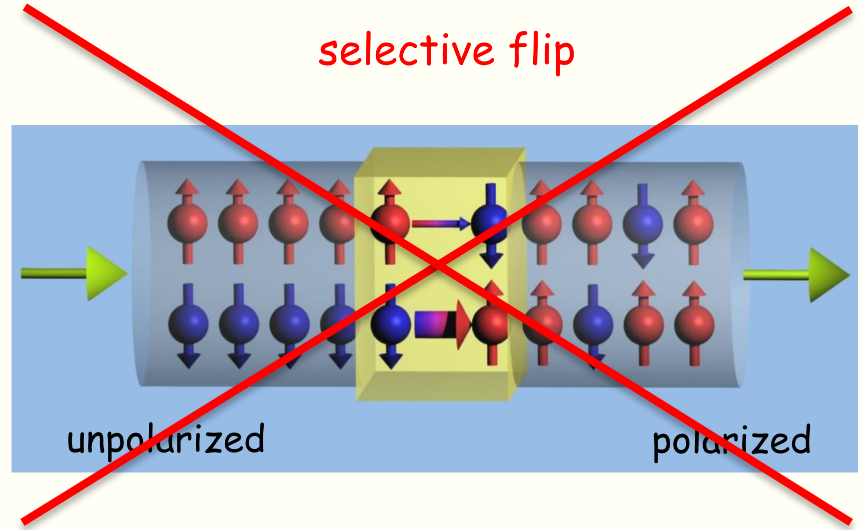
How to Polarize Antiprotons?

- Spin-1/2 particles: 2 states

selective removal



selective flip



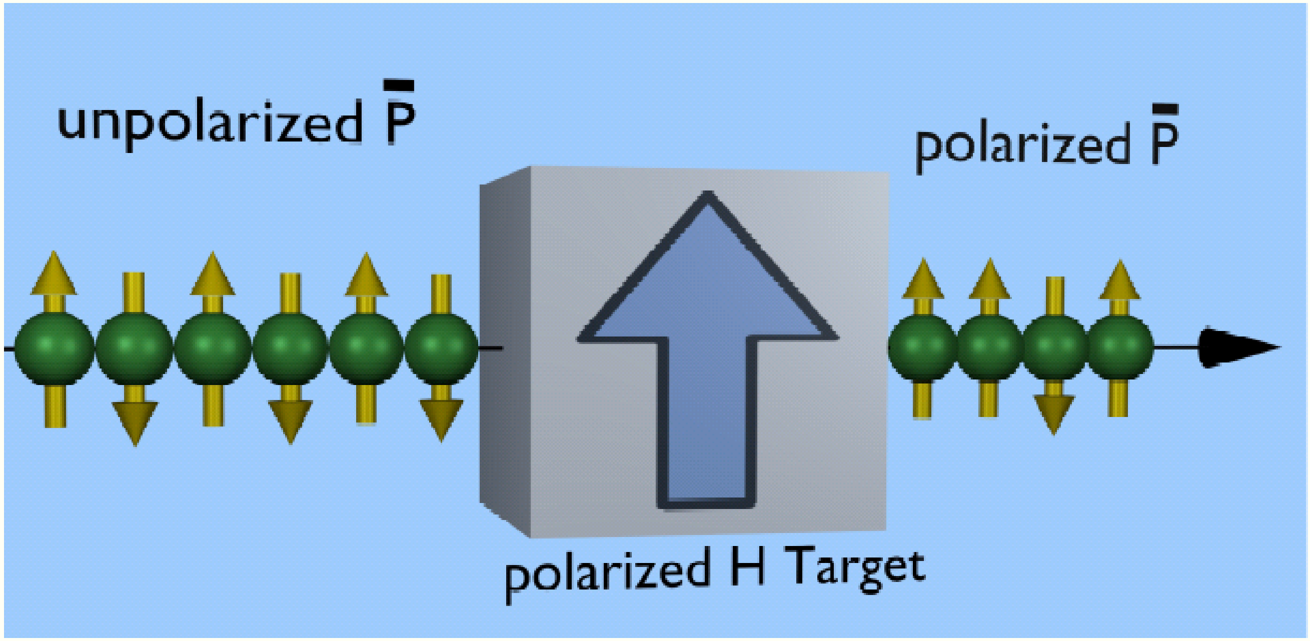
- Selective removal reduces beam intensity – *Selective flip does not affect intensity*
- but at COSY we demonstrated that
- $e^+ \bar{p}$ spin-flip cross-section is too low to use selective flip

D. Oellers. et al., Phys. Lett. B 674 (2009) 269.
D. Oellers. et al., Nucl. Instrum. Meth. A 759, 6 (2014).

$\sigma_\parallel < 8.0 * 10^6$ b
$\sigma_\perp < 5.5 * 10^6$ b

Spin-filtering

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

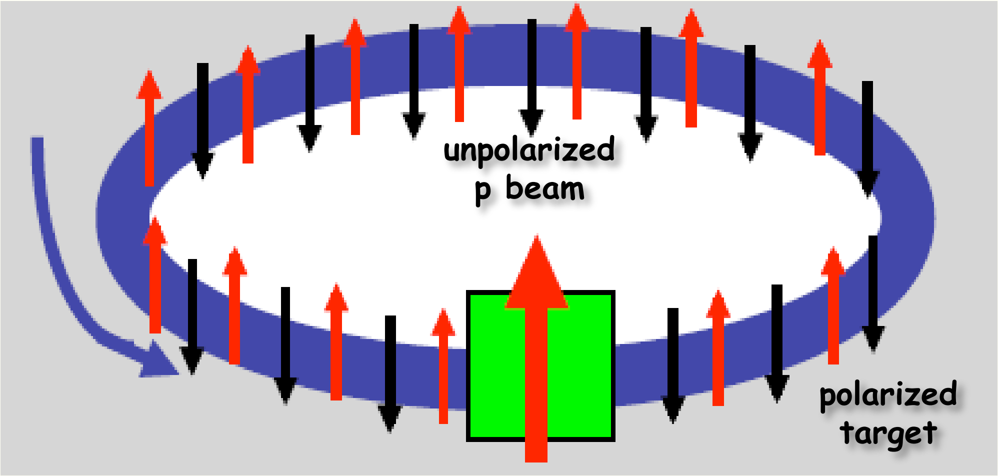


Spin-filtering

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

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

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



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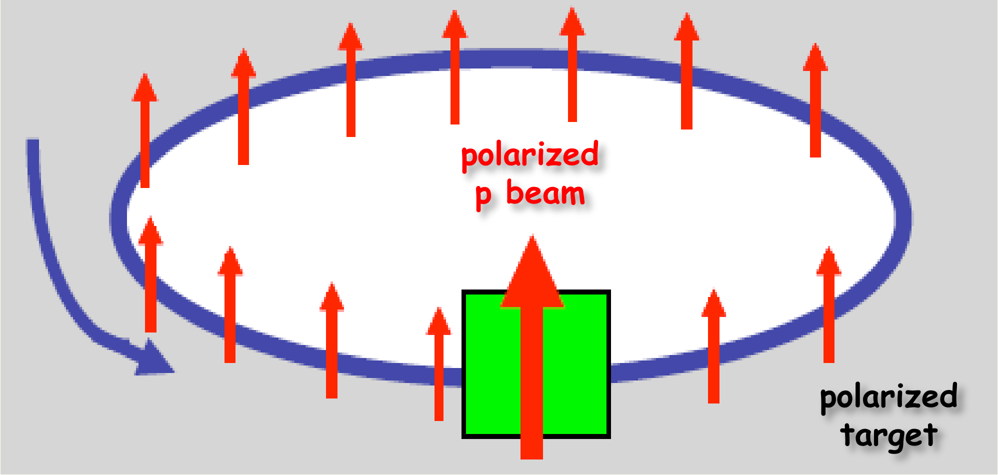
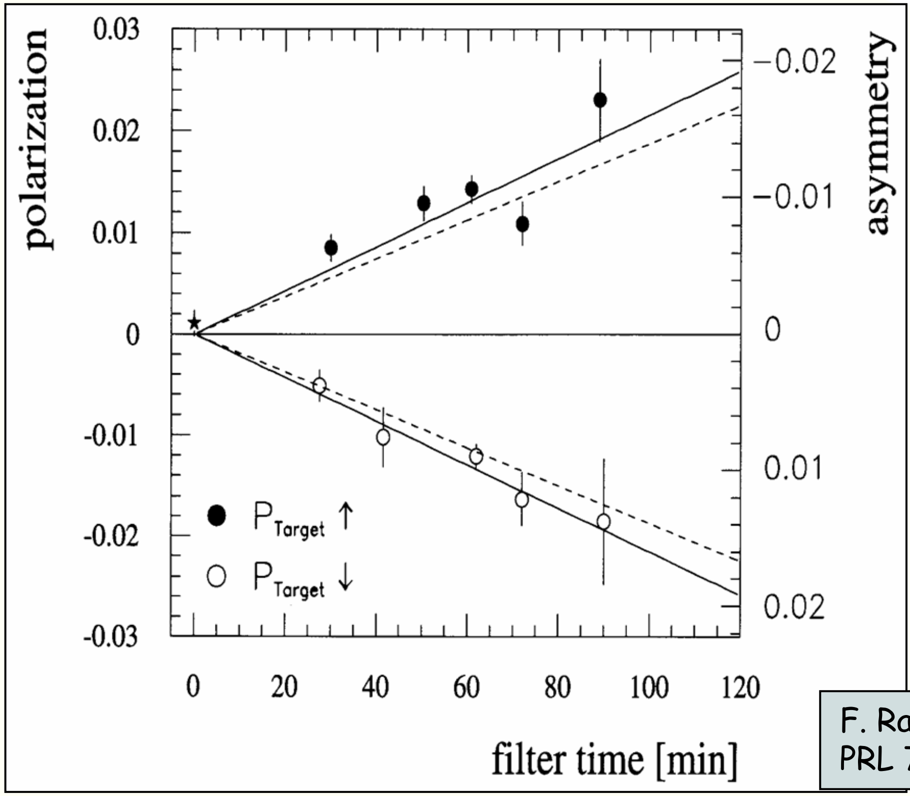


1992: Filter Test at TSR with protons



F. Rathmann. et al., PRL 71, 1379 (1993)

Spin filtering works for protons

PAX submitted new proposal to find out how well does spin filtering work for antiprotons

Measurement of the Spin-Dependence of the pp Interaction at the AD Ring

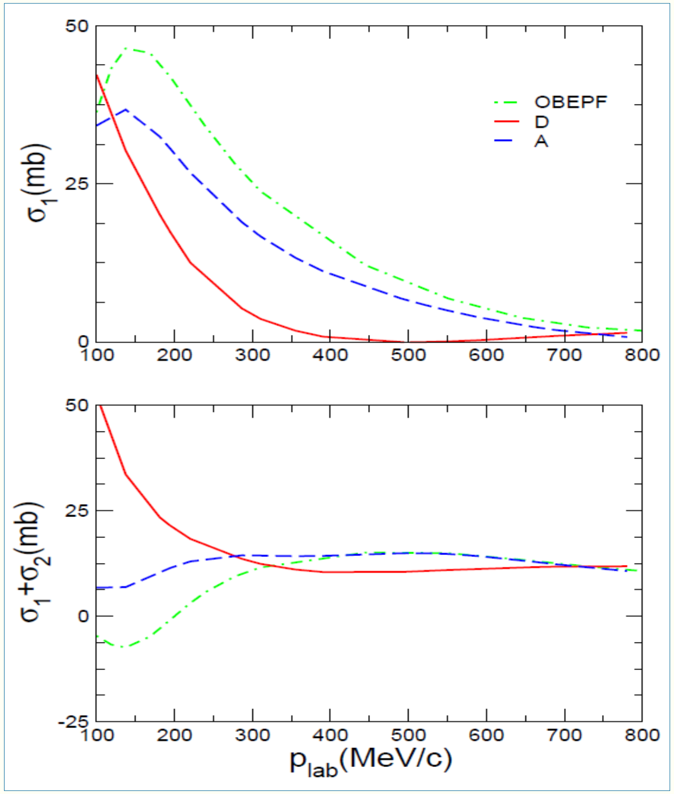
(CERN-SPSC-2009-012 / SPSC-P-337)

Spin-dependence of the pbar-p interaction

Model A: T. Hippchen et al., Phys. Rev. C 44, 1323 (1991).

Model OBEPF: J. Haidenbauer, K. Holinde, A.W. Thomas, Phys. Rev. C 45, 952 (1992).

Model D: V. Mull, K. Holinde, Phys. Rev. C 51, 2360 (1995).



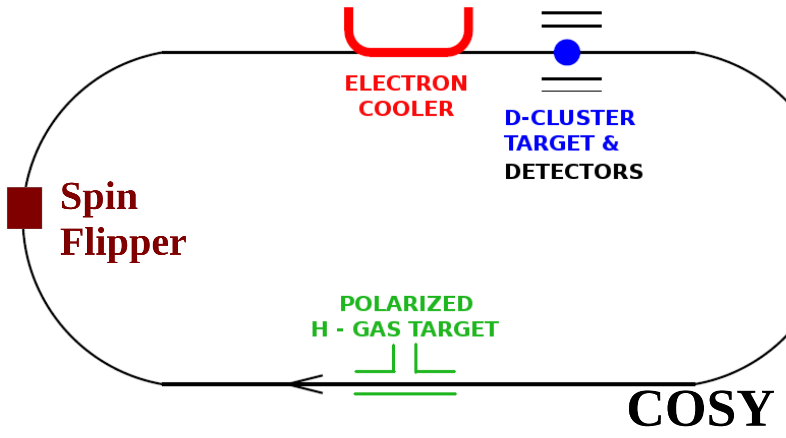
Oct. 2009 SPS Committee:

… Taking into account the timeline and constraints of the various projects concerned, the SPSC **encourages the PAX Collaboration to first perform their spin filtering measurements at COSY**…

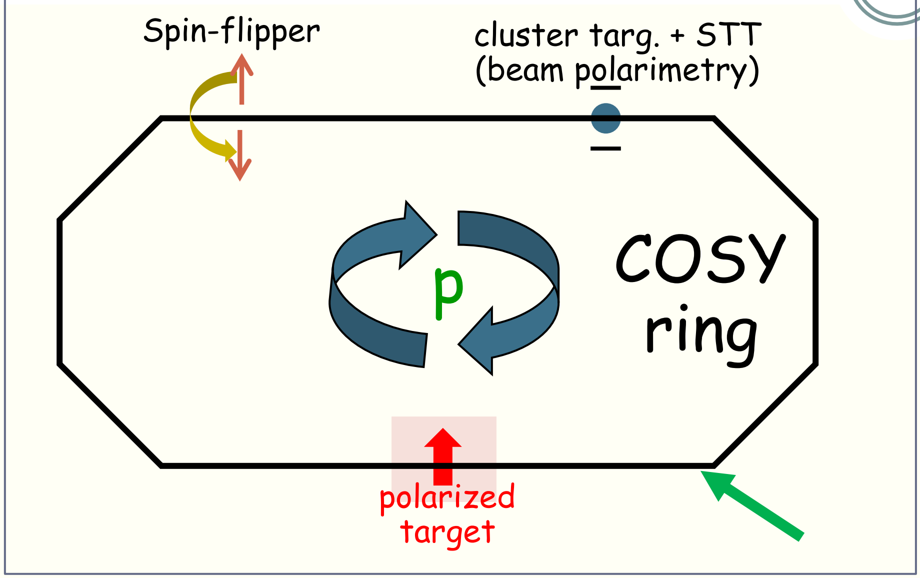
Spin Filtering at COSY

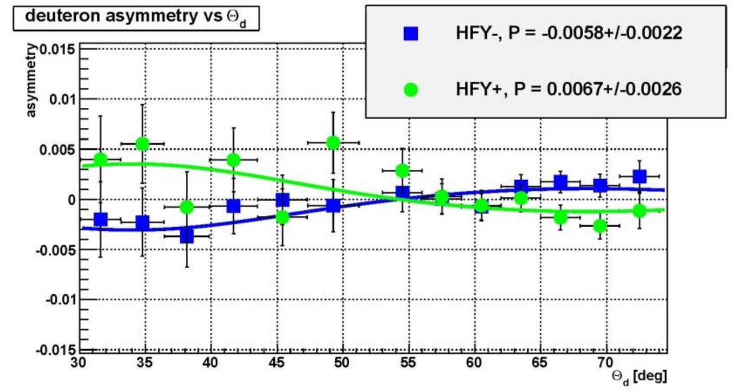
Spin filtering with protons to confirm understanding of the process and to commission the experimental setup

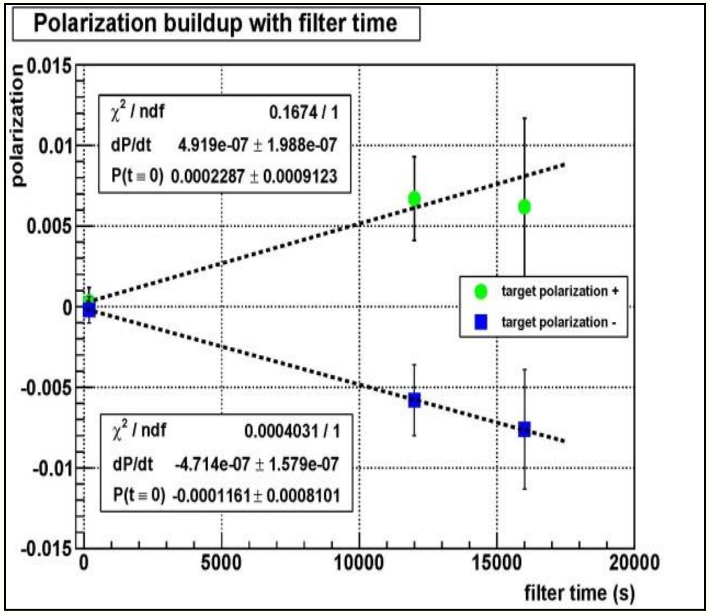
- Length: 183.4 m
- Injection energy: 45 MeV
- Electron cooling for long lifetimes up to 600 MeV/c (p)



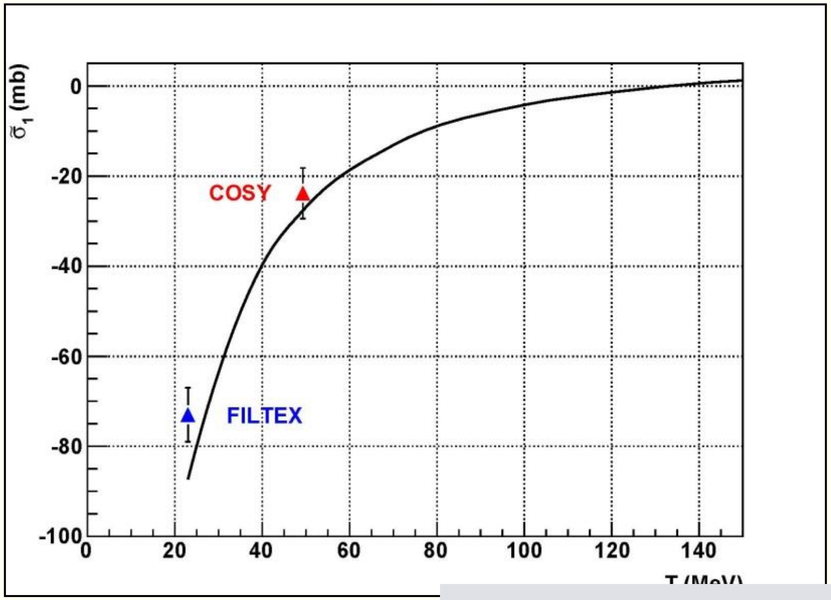
Spin-filtering cycle







Spin-filtering: result



W. Augustyniak et al., Physi. Lett. B 712 (2012) 64

- Milestone for the field
  - Confirms understanding of spin-filtering as a viable method to polarize a stored beam.
  - Confirms complete control of the systematics of the experiment.

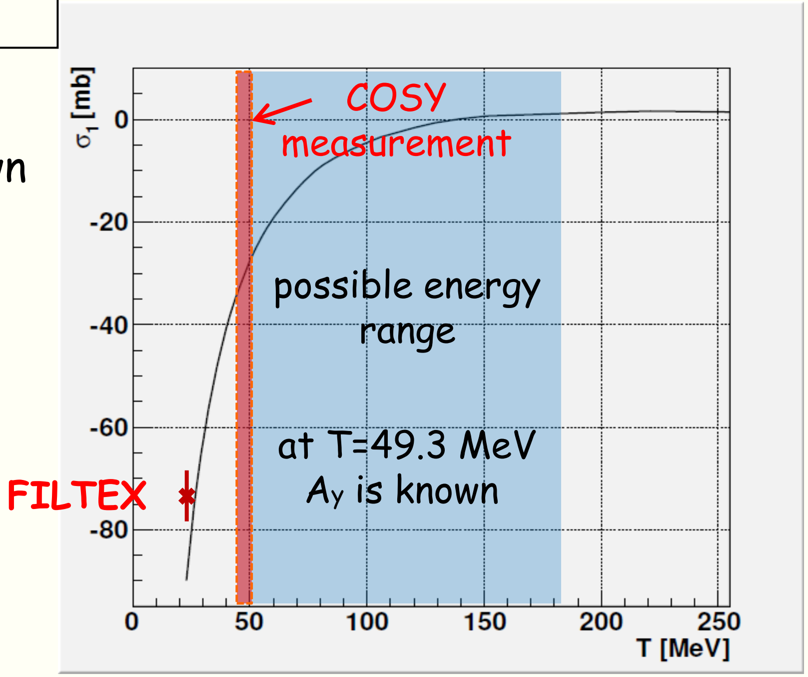
Mar. 2012 SPS Committee:

… many positive developments have occurred at the AD, leading to an updated program for the coming years ….We consider that PAX is **now** incompatible with this program.

Comments: I

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

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



FILTEX

F. Rathmann. et al., PRL 71, 1379 (1993)

Comments: II

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

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

Comments: III

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

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

Comments: IV

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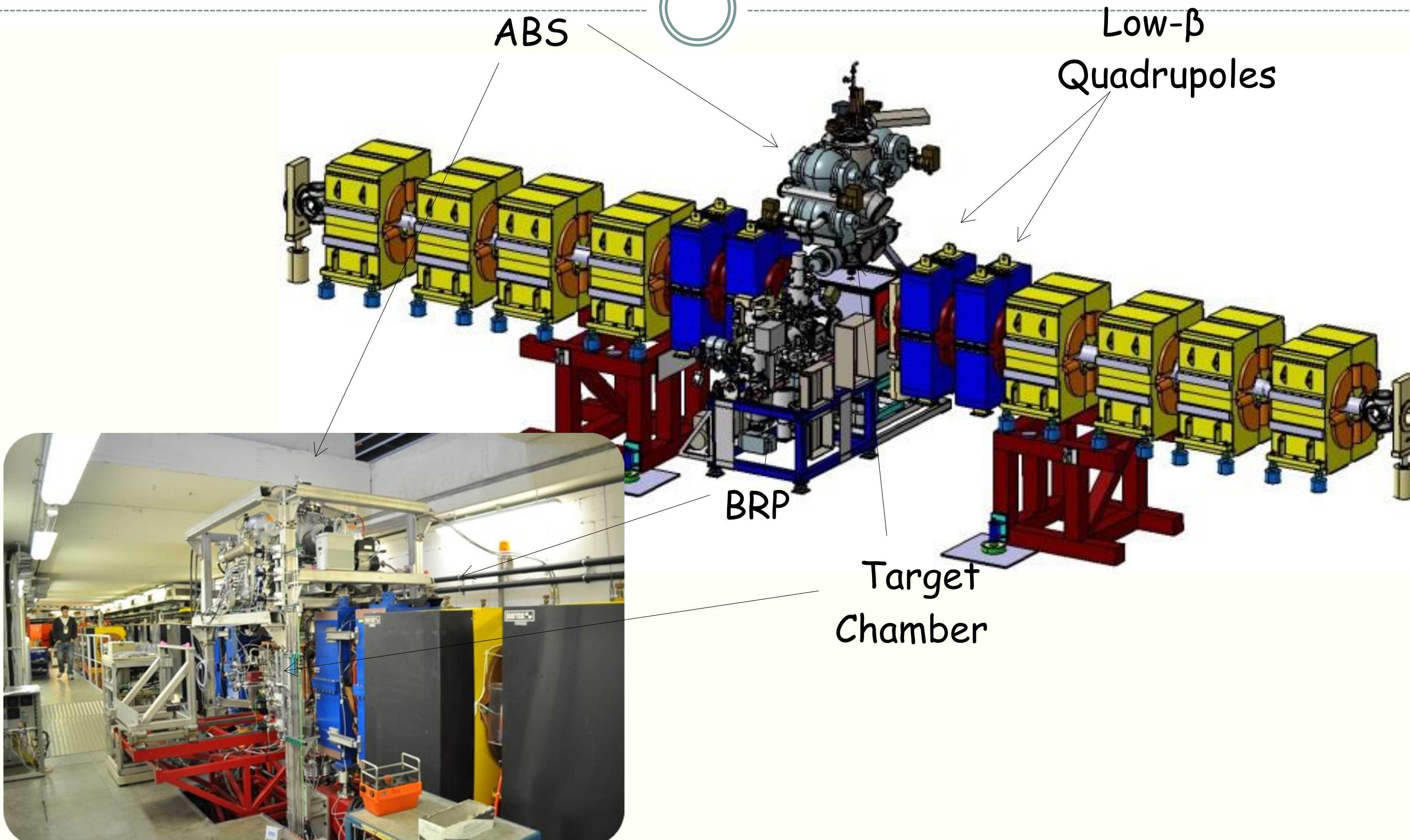
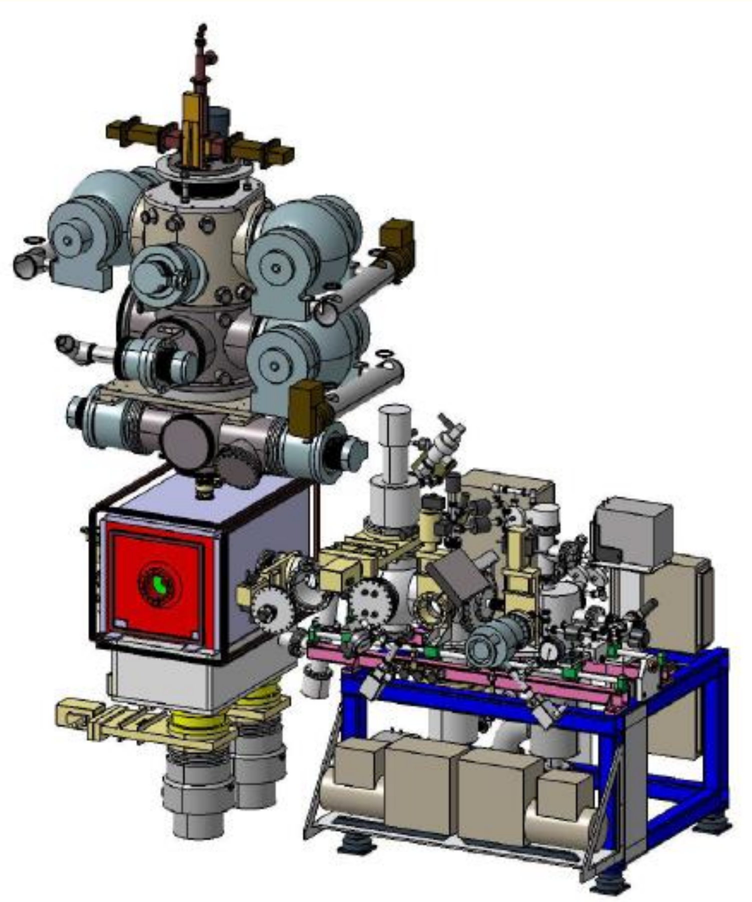
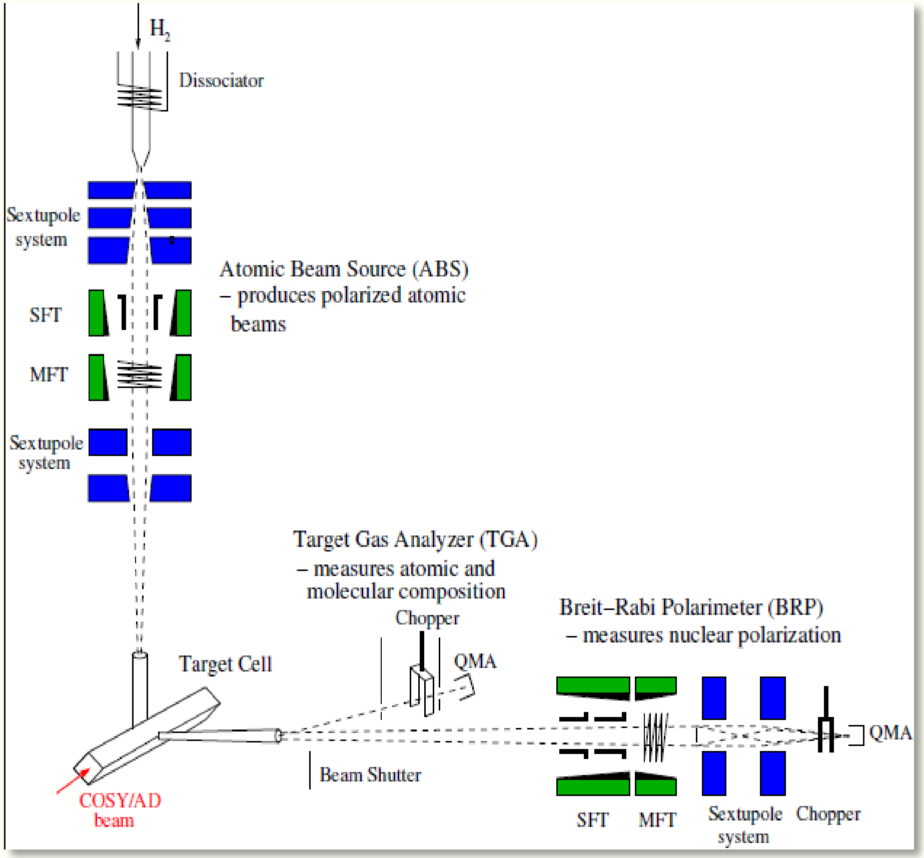
   - small kinetic energy
2. Maximum revolution frequency
   - large kinetic energy
   - short accelerator
3. Maximum target polarization and density
   - high dense polarized gas target (Atomic Beam Source)
   - storage cell
4. Maximum filtering time
   - long beam lifetime (UHV, good beam preparation,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

Experimental setup and commissioning



Atomic Beam Source

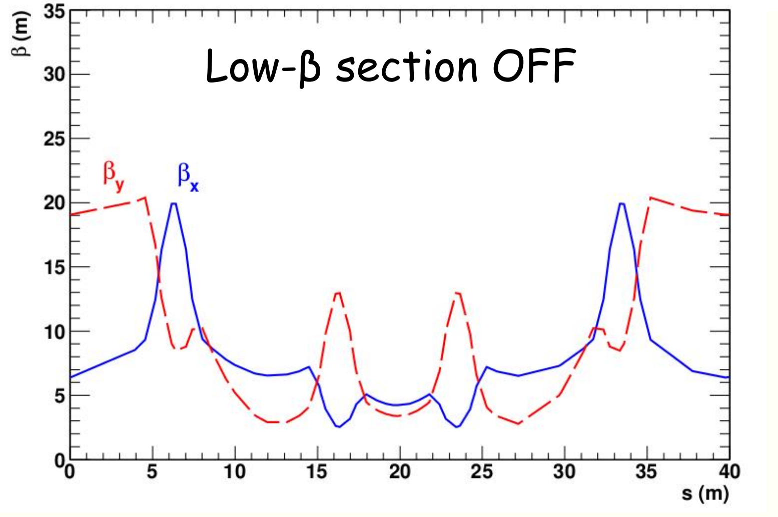




Low-β section

$$t \;\mu\; q_{acc}^{2} \;\mu\; \frac{1}{b^{2}}$$

- Significant reduction of the machine acceptance due to storage cell (d = 9.6 mm, l = 400 mm)
- Solution: low-β section



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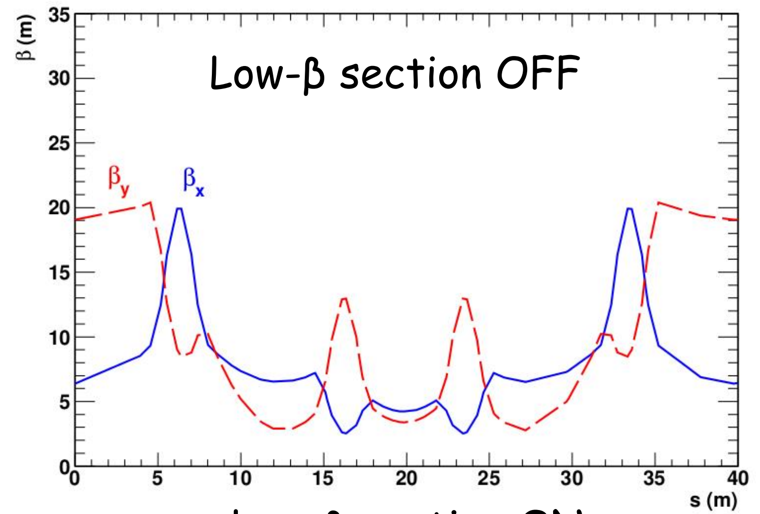
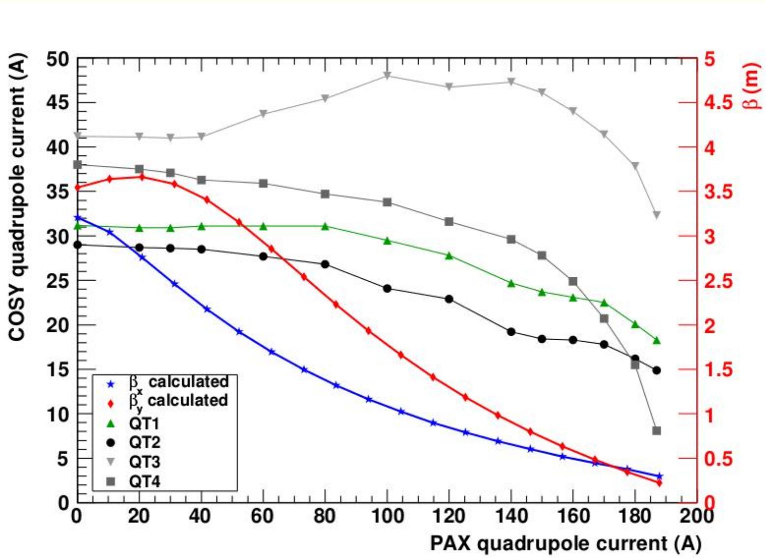
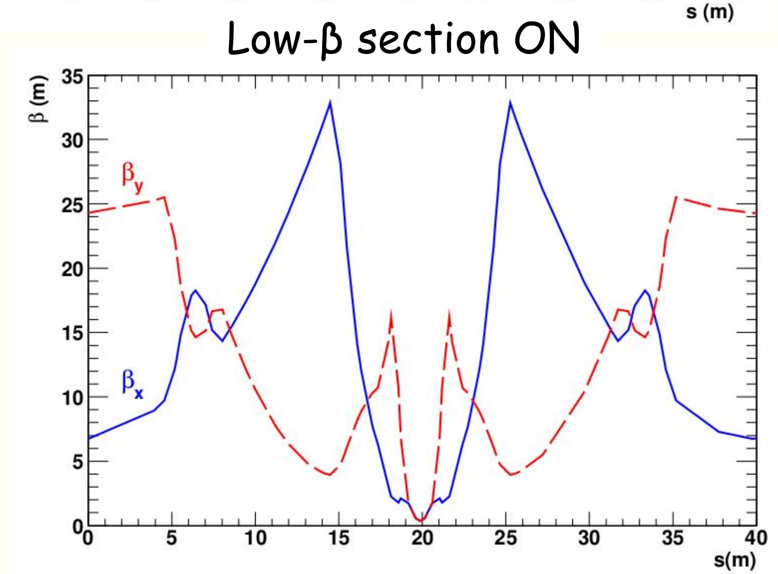






Vacuum system: I

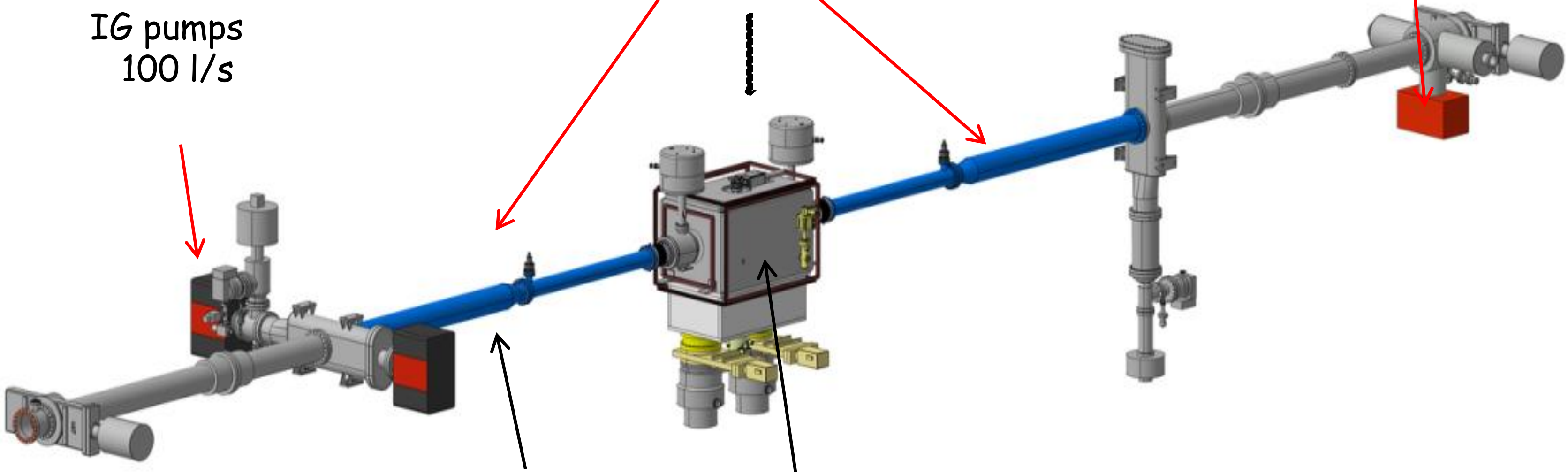
PAX vacuum section

$3 \times 10^{16} \frac{atoms}{s}$

NEG coated
beam pipes
(each 5000 l/s)

IG pumps
100 l/s

IG pumps
100 l/s



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

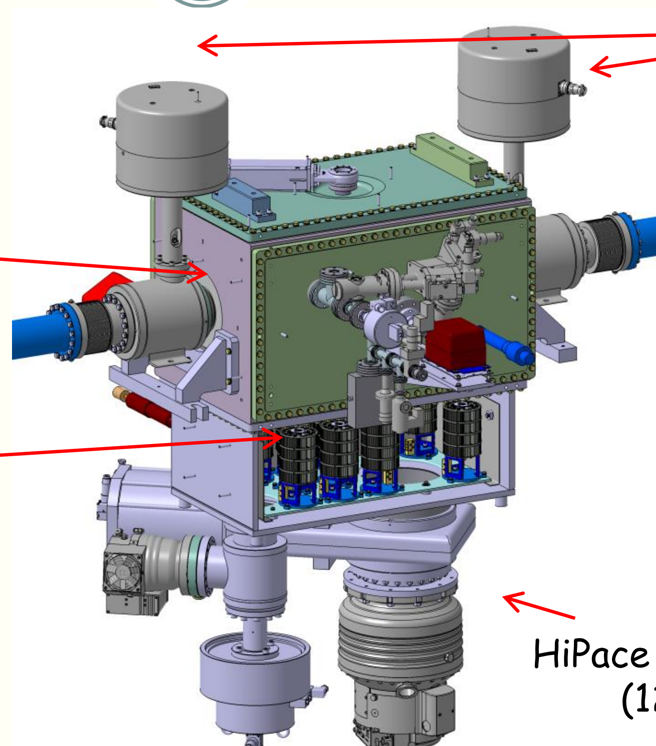
Vacuum system: II

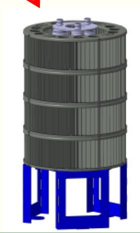
PAX target chamber

Fast shutters
(<15 ms)

Flow limiters
(d = 19 mm, l = 80 mm)

SAES getter pump
(each 1900 l/s)





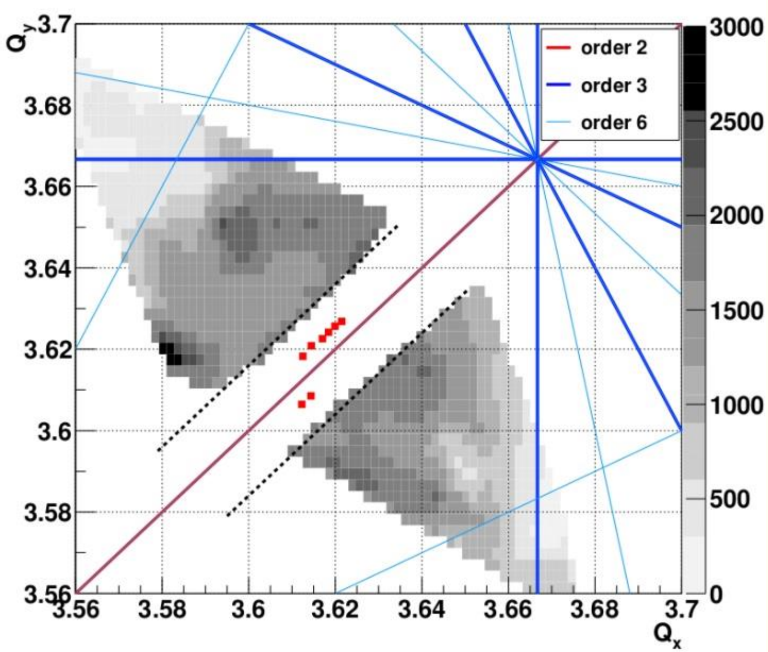
HiPace 1800 turbo
(1200 l/s)

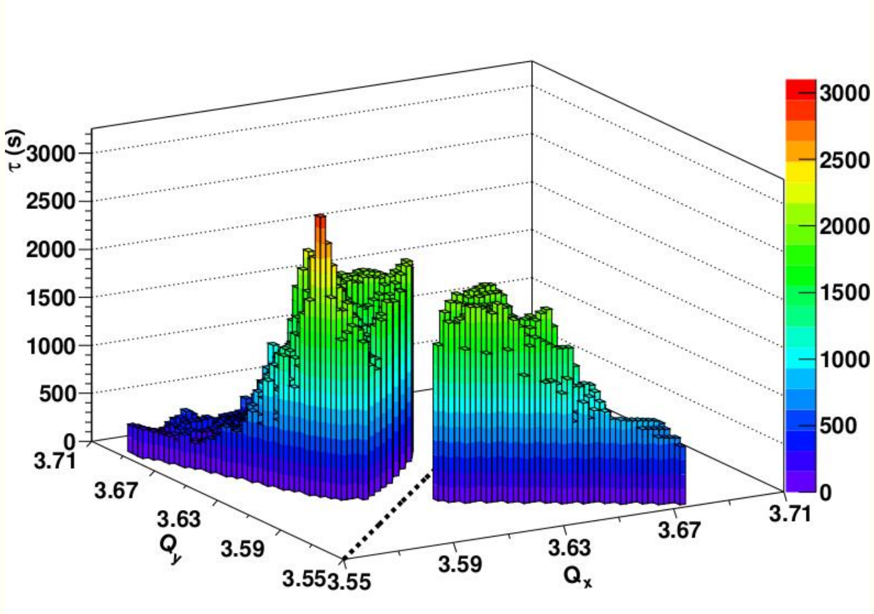
Beam losses due to	τ(s)
single-scattering in storage cell	48500
gas load elsewhere in the low-β section	47500
machine vacuum alone	12000

24000s (combined: single-scattering in storage cell + gas load elsewhere in the low-β section)

Identification of optimal working point

- Search for optimal betatron tune by varying currents in quads ± 3%
- Beam lifetime increaseas by decreasing tune spin: $\Delta Q_{split}=|Q_x-Q_y|$
- Difference resonance not reachable due to coupling of betatron motion
- Improvement by sextupole or orbit corrections





R.Cappi, E. Métral, D. Möhl, in Proceedings of the 18th International Conference, HEACC 2001, Tsukuba, Japan, CERN-PS-2001-010-AE.

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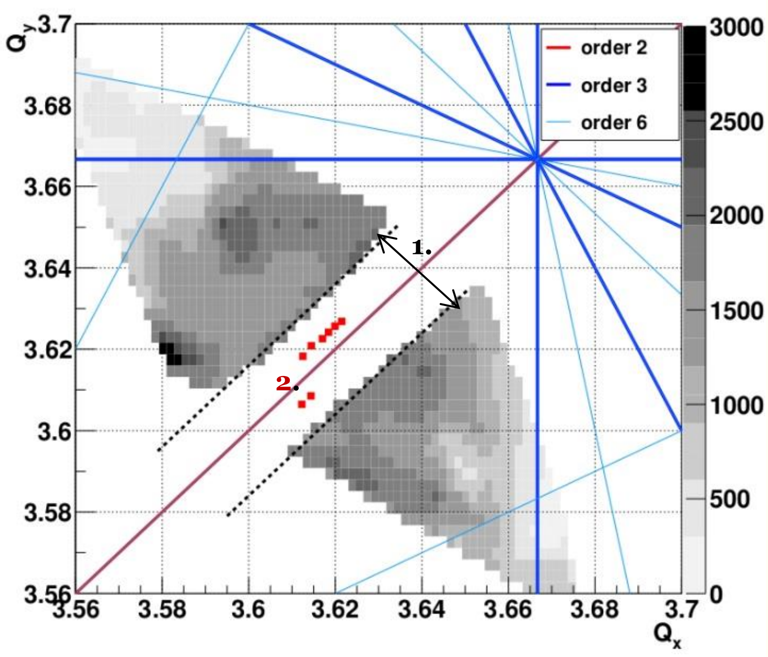


1. ΔQ_{split} = 0.014
2. ΔQ_{split} = 0.006 (sextupoles)
3. ΔQ_{split} = 0.008 (orbit correction)

R.Cappi, E. Métral, D. Möhl,
Proceedings of the 18th International Conference, HEACC 2001, Tsukuba, Japan, CERN-PS-2001-010-AE.

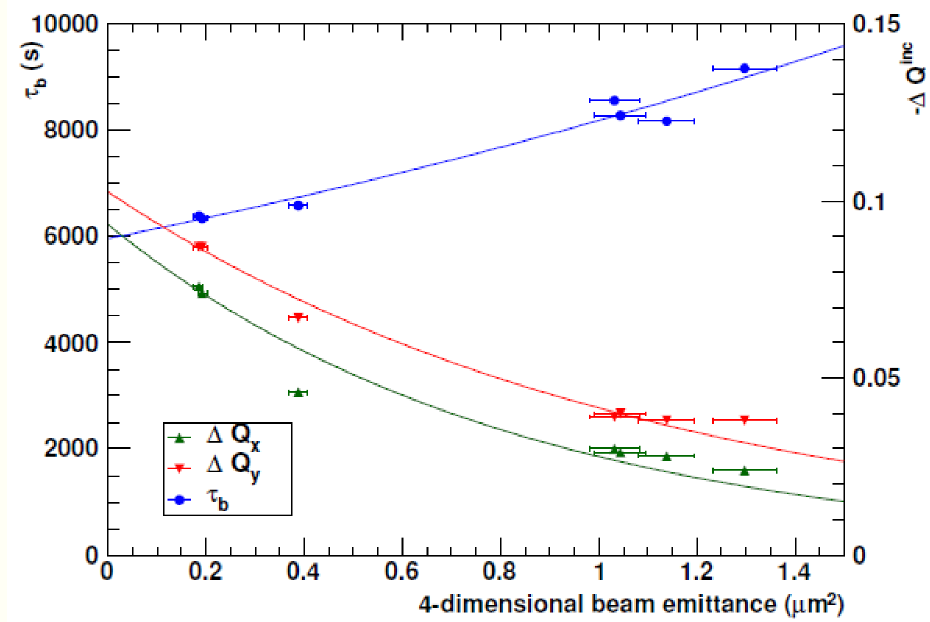
Space charge effects

- Measure beam lifetime as function of space charge
- Variation of beam emittance for constant intensity
- Tilt of e-beam with respect to p-beam changes cooling performance

- Beam lifetime increases with decreasing space charge
- Betatron amplitude-dependent detuning („tune spread")

Maximal incoherent tune shift given by:

$$\Delta Q_{x,y}^{inc} = -\frac{r_0 \cdot N}{\pi \beta_L^2 \gamma_L^3} \cdot \frac{F_{x,y} G}{B_f} \cdot \frac{1}{\varepsilon_{x,y} + \sqrt{\varepsilon_x \cdot \varepsilon_y}}$$



K. Schindl, *Space Charge, CERN Accelerator School, Zeuthen, Germany, September 15-26, 305 (2003).*

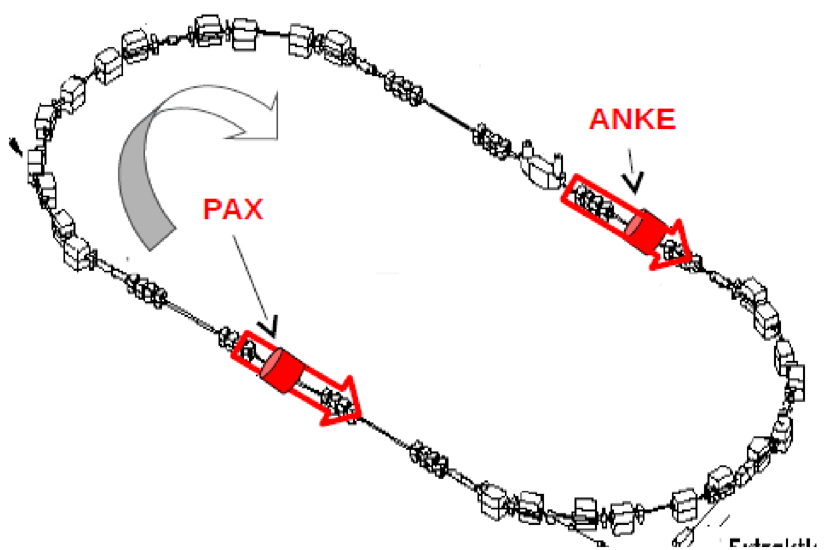
Future plans

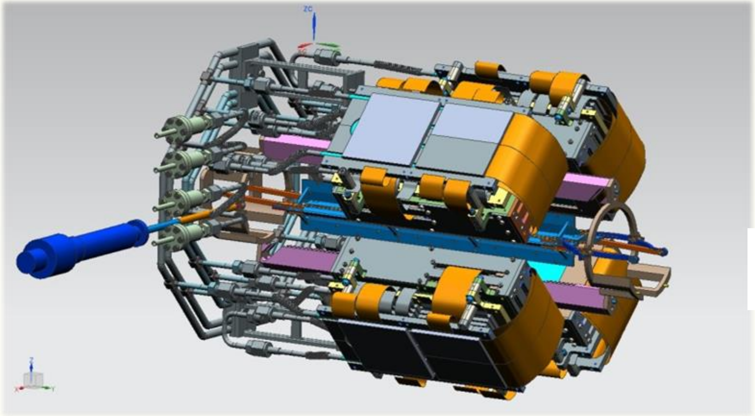
Waiting for CERN ... (or construction of FAIR facility)

Longitudinal spin-filtering test at COSY

Superconducting 2.1 Tm at ANKE place

Longitudinal polarization at PAX place





Longitudinal beam polarimeter in preparation

(➔ G. Ciullo 24.10)

Summary

Status:

- Successfull spin filtering measruement at COSY on transverse polarized target.
- Excellent agreement with theoretical predictions for protons
- Development of a protocol for spin-filtering tests
- Eccellent performance for the COSY ring (precision machine)

Future plans at COSY

- Spin filtering with protons and a longitudinally polarized gas target at COSY at $T_p =$ 130 MeV ($\vec{p}\vec{p}$ scattering)

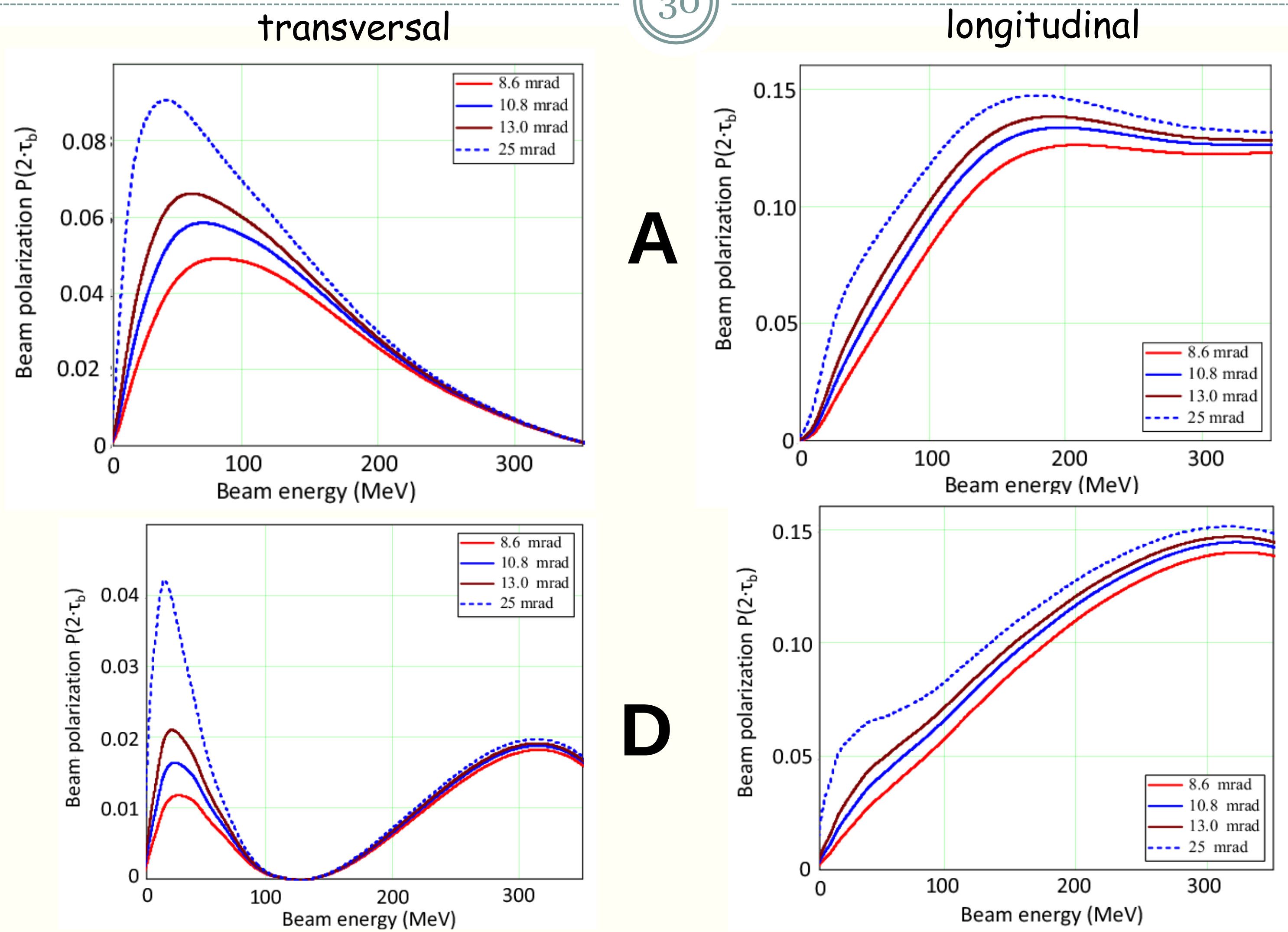
Still pending:

- Spin-filtering experiments at AD (or FAIR) (transv. and long. polarization)

Thank you!

Additional Slides

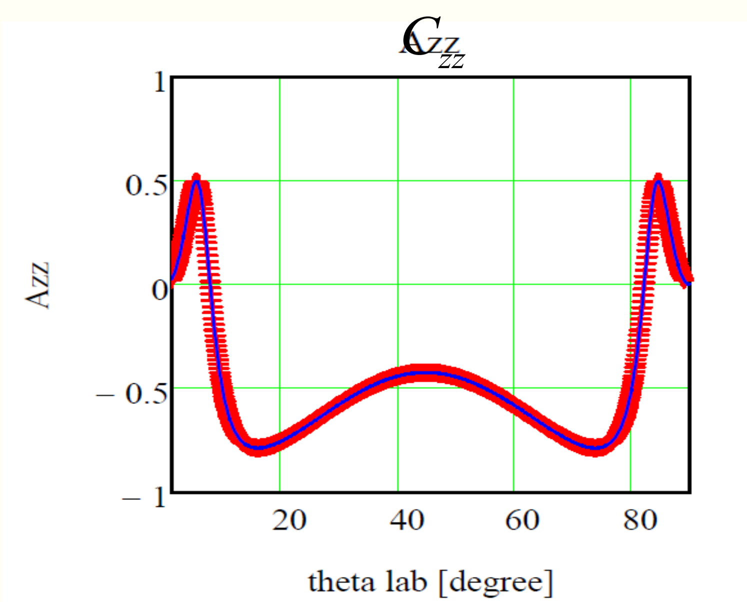
Expected Polarizations for pbar

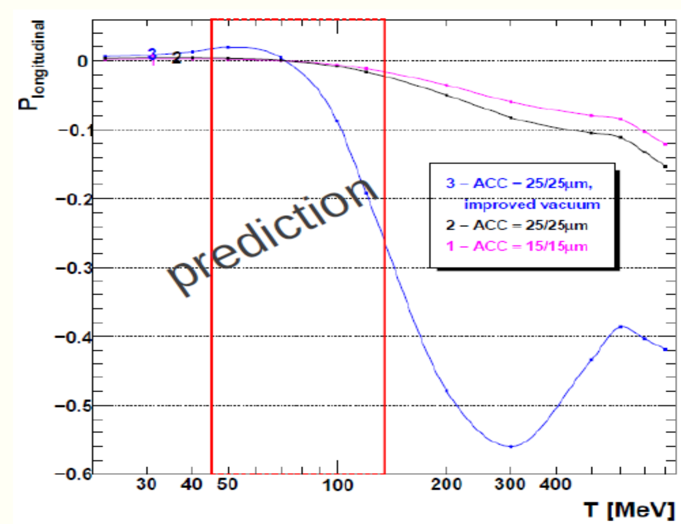


Spin Filtering with Longitudinal Polarization

- Buildup of longitudinal beam polarization due to repeated interactionwith a longitudinally polarized hydrogen target
- T_p 45 - 130 MeV kinetic proton energy
- Detector: Measurement of longitudinal beam polarization using elastic scattering
  - Measurement duringfilteringwith hydrogen targetpossible
  - Spin correlationcoefficient (~ 0.5)
  - Nobackground

$$\frac{ds}{dW} = \frac{ds_0}{dW}(1 + C_{zz} P_z Q_z)$$



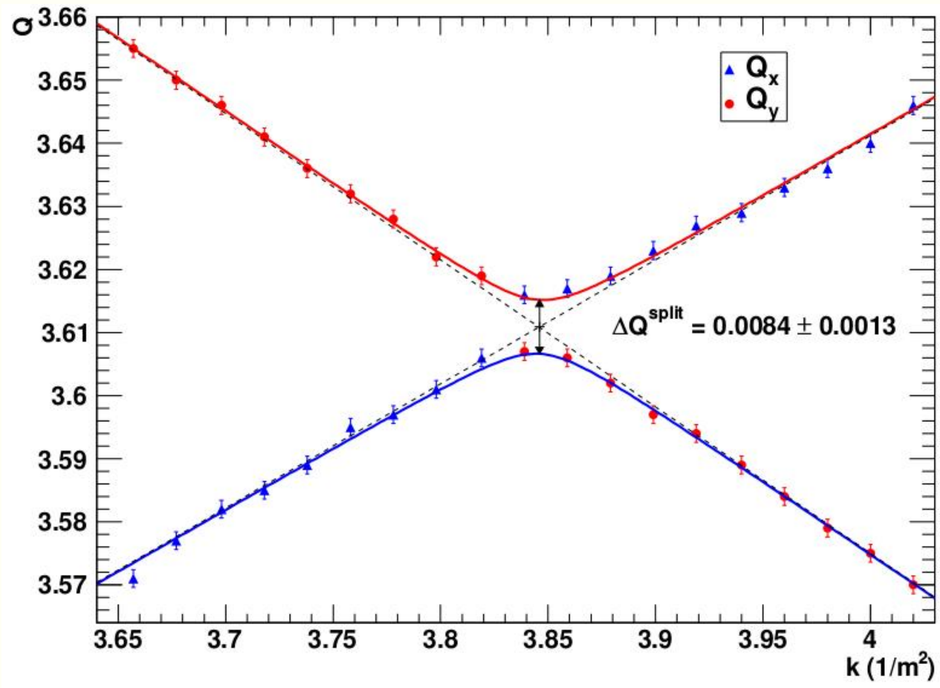


Low-β section: II

Measurement of β-function

$$\beta_{x,y} = \frac{4\pi}{l}\left|\frac{\Delta Q_{x,y}}{\Delta k}\right|$$

- Measure tune change as function of quadrupole strength
- PAX magnets are powered pairwise



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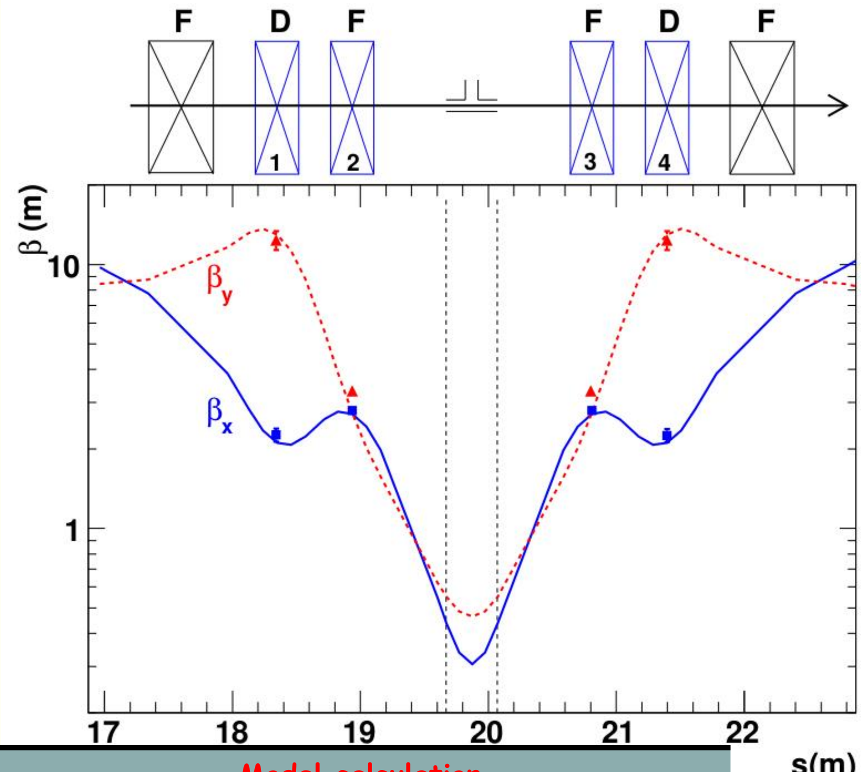

	Measurement		Model calculation		
	PAX 1	PAX 2	PAX 1	PAX 2	center
β_x (m)	2.31±0.13	2.80±0.04	2.11	2.71	0.31
β_y (m)	12.41±1.01	3.31±0.05	12.99	2.74	0.46

Orbit Correction

- Corrections of deviations from ideal orbit
- Closed orbit correction scheme based on orbit response matrix (ORM)

$$u(s) = R^u_{s,i} \times \theta_u(s) \quad \text{with} \quad R^u_{s,i} = \sqrt{\beta_{u,i} \cdot \beta_{u,s}}\,\frac{\cos\left(\pi Q_u - \varphi_{u,s\to i}\right)}{2\sin\left(\pi Q_u\right)}$$

- χ^2 minimization to determine correction angle kicks θ_u