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HISKP

JÜLICH
FORSCHUNGSZENTRUM

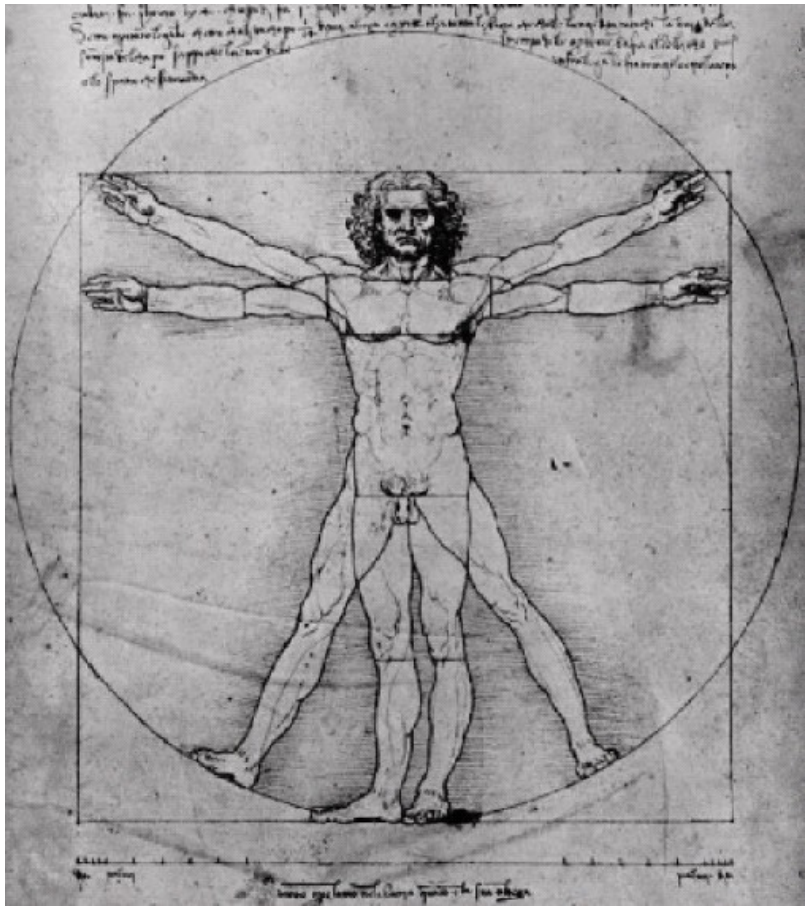
Time-Reversal Invariance Experiment at COSY

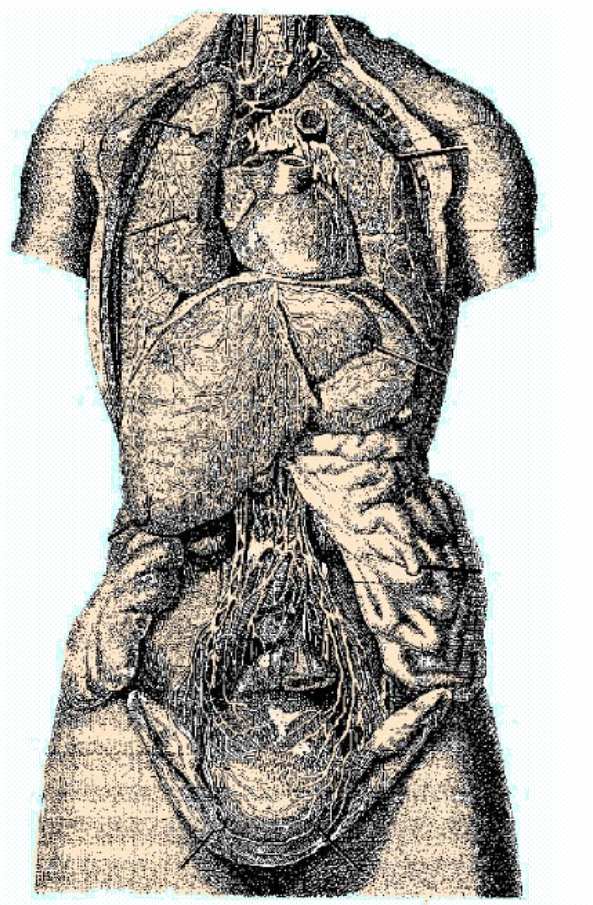
7th of August 2012 | Yury Valdau

Symmetries in nature

Symmetry is widely distributed in nature

Symmetries around us





Men is almost left-right symmetric but only from outside

Symmetries in physics

The Noether theorem:

For every continuous symmetry of the laws of physics there exists a conservation law and vice versa. (1915)

Emmi Noether
(1882-1932)

Symmetry = Conservation Law

Laws of physics are independent of:

Origin of time axis ⇒ Energy conservation

Origin of spacial axis ⇒ Momentum conservation

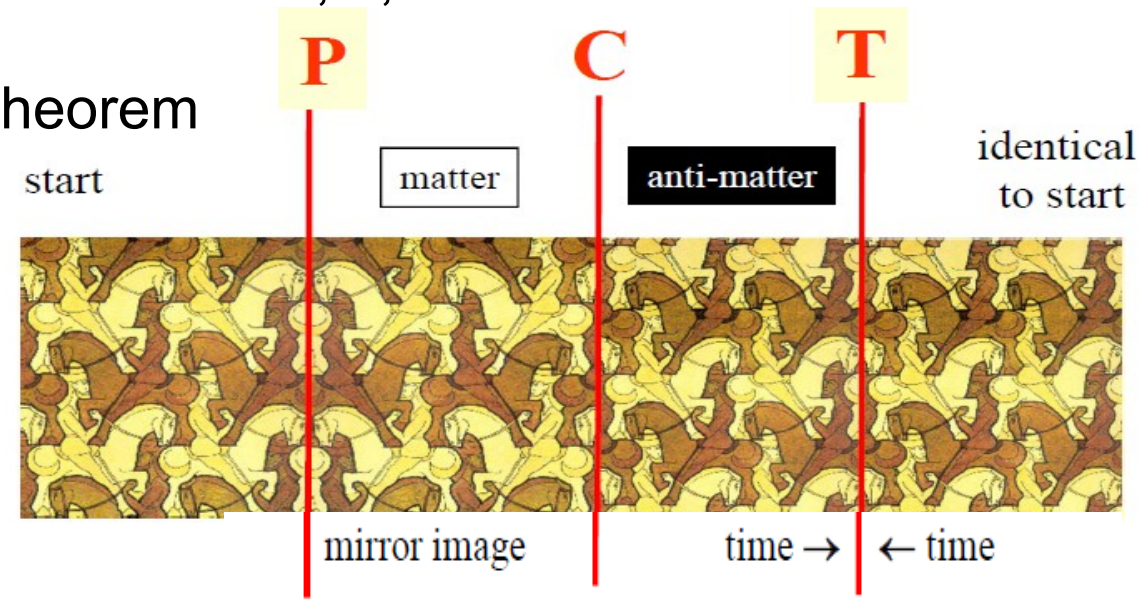
Orientation of spacial axis ⇒ Angular momentum conservation

What is symmetry?

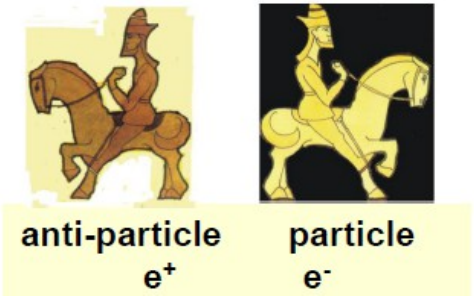
"An object is called *symmetric*, if one can do something with it, without, at the end, when one is finished with the procedure, having changed it."

Three discrete symmetries are fundamental in the standard model C, P, and T

CPT theorem

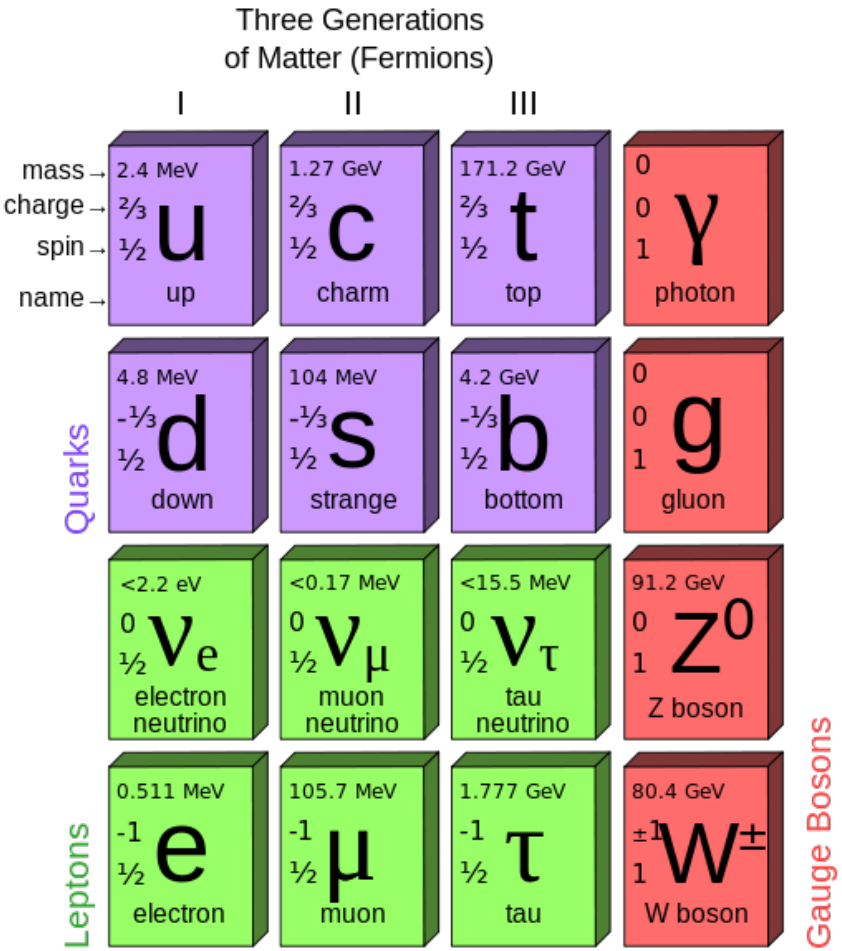


R.P. Feynman: (1918-1988)

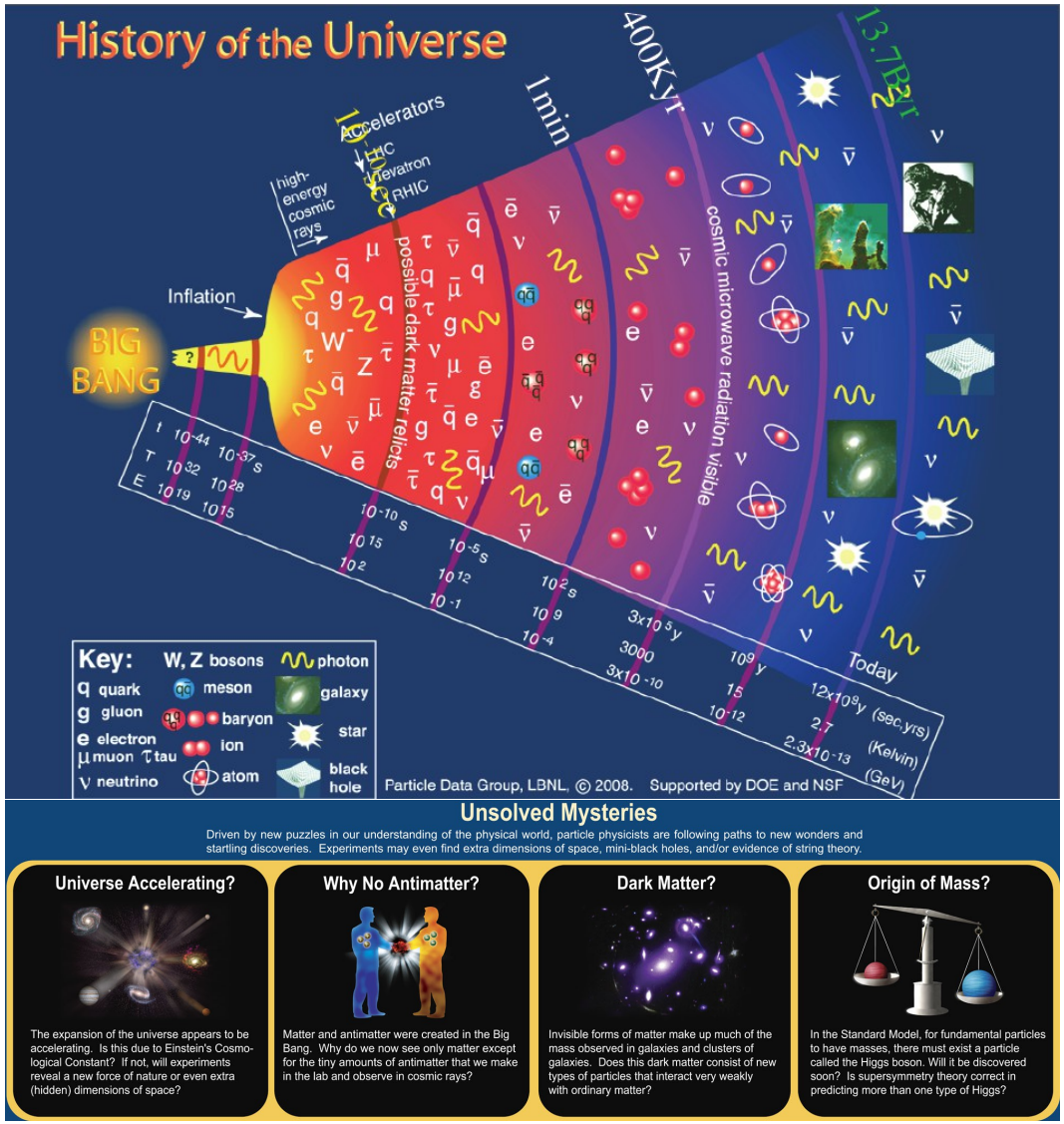


Picture from M.C. Escher

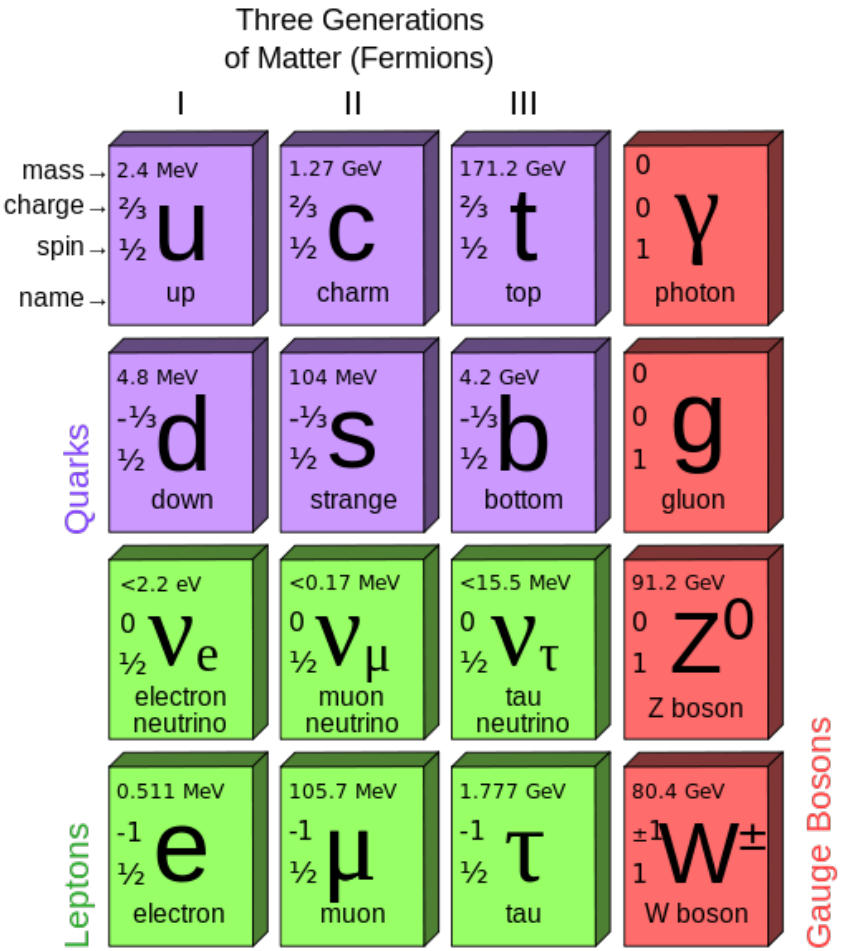
Standard Model



http://pdg.lbl.gov



Standard Model



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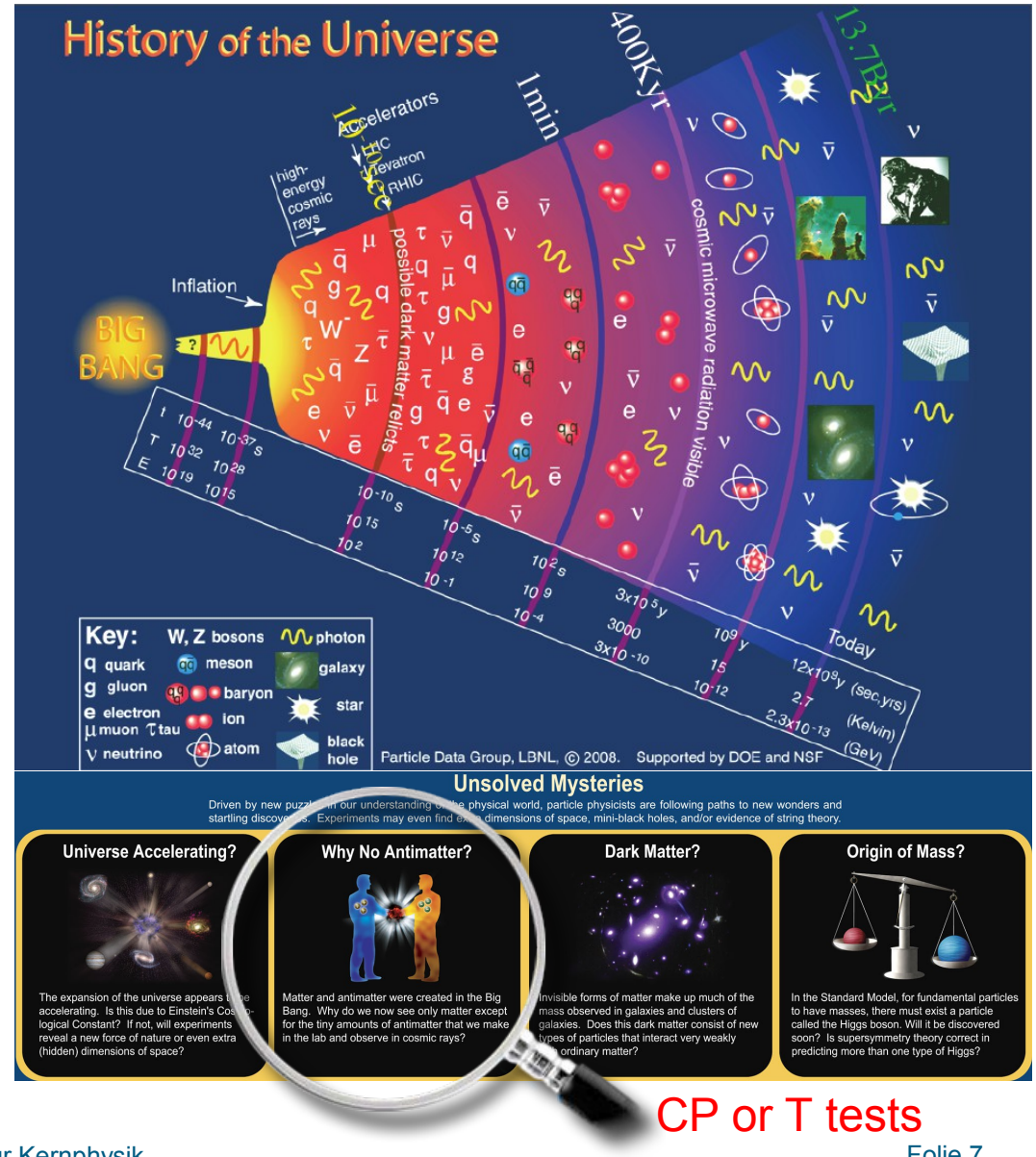
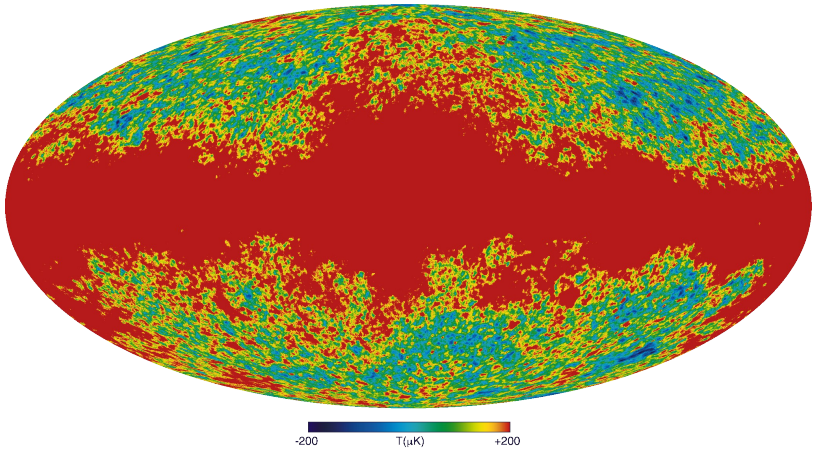


CP or T tests

Symmetries in nature

CPT is strictly conserved in all interactions

CP is violated in the electro-weak interaction



BUT:

CP violation in the SM is not sufficient to explain a Baryon Asymmetry in the Universe!

Observed : $(n_B-n_{\bar{B}})/n_\gamma = 6 \cdot 10^{-10}$

SM Expected: $(n_B-n_{\bar{B}})/n_\gamma \sim 10^{-18}$

Wilkinson Microwave Anisotropy Probe and Cosmic Background Explorer, 2003

Experiments:

Measurements of the EDM tests T and P symmetries (T-odd and P-odd)

In this proposal we are discussing a genuine test of T symmetry (T-odd P-even)

Status of T symmetry tests

- CP violation was observed in decays of K^0 (1964) and B (2001) mesons
- In order to compare different observables, testing fundamental symmetry, they are usually recalculated in to the strength of T-odd potential

T-invariance

Reaction	Result	Symmetry	Reference	
EDM of n	$g_{PT}<10^{-11}$	PT	PR43(1978)409	
	$g_T<10^{-4}$	T	PRD63(2001) 076007	
γ-γ in ^{57}Fe	$\alpha_T<10^{-4}$	T	PRC53(1996)2546	
P-A in pp	$g_T<10^{-2}$	T	PR119(1960)352	
$p^{27}Al \rightarrow {}^{4}He+{}^{24}Mg$	$\alpha_T \approx g_T<10^{-3}$	T	PRL51(1983)355	
A_5 in $n^{165}Ho$	$\alpha_T<7.1*10^{-4}$	T	PRC55(1997)2684	⟸ Current upper limit
	$A_5=8.6*10^{-5}$			
$\vec{p}\vec{d}$ $A_{y,xz}(\Delta\sim10^{-6})$	$\alpha_T<10^{-6}$	T	This experiment	⟸ This experiment

g-strength of T-odd NN potential

α-strength of an effective T-odd N-core potential

Null test of Time-Reversal Invariance

Theorem:
"It is impossible to construct, in any reaction in atomic, nuclear, or particle physics, a null experiment that would unambiguously test the validity of time-reversal invariance independently of dynamic assumptions"

F. Arash, M. J. Moravcsik, and G. R. Goldstein PRL 54 (1985) 2649

This means:
There is no Null-Experiment for a reaction with two particles in and two particles out.

Alternative:
Since the total cross section asymmetry is non-bilinearly related to a T-odd amplitude in forward scattering, a measurements of the total cross section allows to perform a null test of TRI

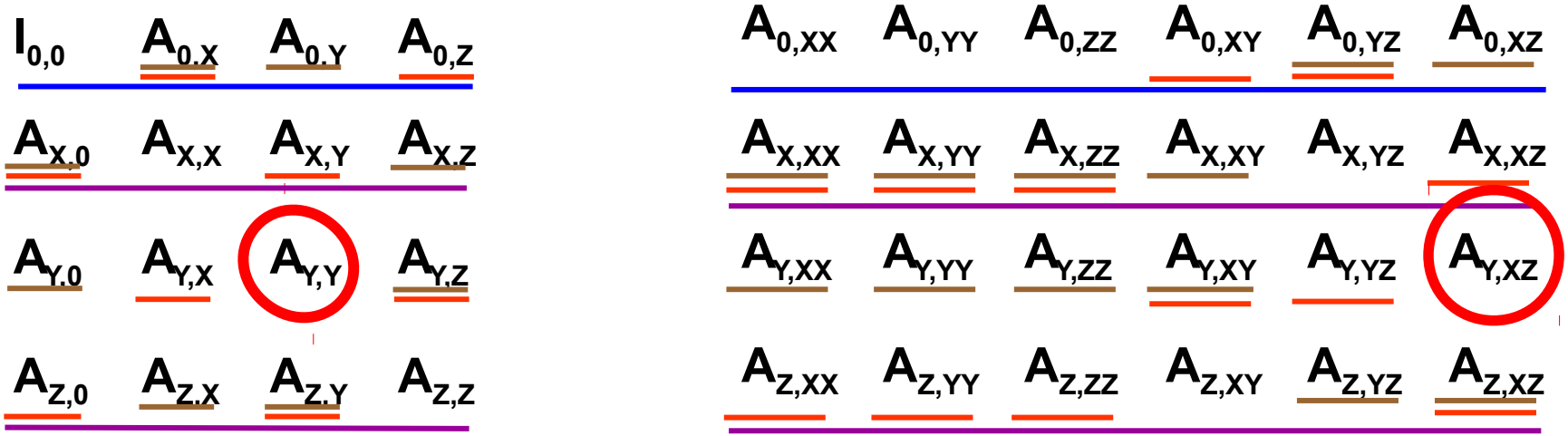
Method:
In the forward direction total cross section can be measure via the optical theorem

$$\sigma_{tot} = 4\pi/k \cdot \mathrm{Im}(F(0))$$

H. E. Conzett, PRC 48 (1993) 423

Observable selection

$\vec{1/2} + \vec{1} \rightarrow \vec{1/2} + \vec{1}$



Line cancels because of: Proton spin flip

p_x, p_z negligible for protons

D. Eversheim, COSY-Proposal #22

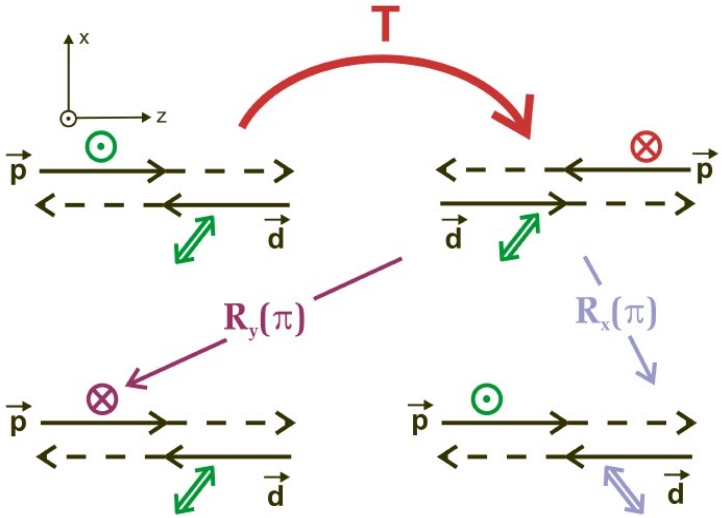
Quantity cancels because of: ~~R~~ ~~P~~

Thus: $A_{y,xz}$ is true null observable

$A_{y,y}$ is probably small, but has to be determined

Time Reversal Invariance test at COSY

$$\vec{1/2}+\vec{1}\rightarrow\vec{1/2}+\vec{1}$$



$\sigma_{tot}=\sigma(1+A_{y,xz}p_y p_{xz})+\sigma_{rest\ gas}$

Since:

$A_{y,x}$ and $A_{y,yz}<10^{-7}$ (from P violation)

$\sigma_{rest\ gas}$ does not depend on beam polarisation

Thus:

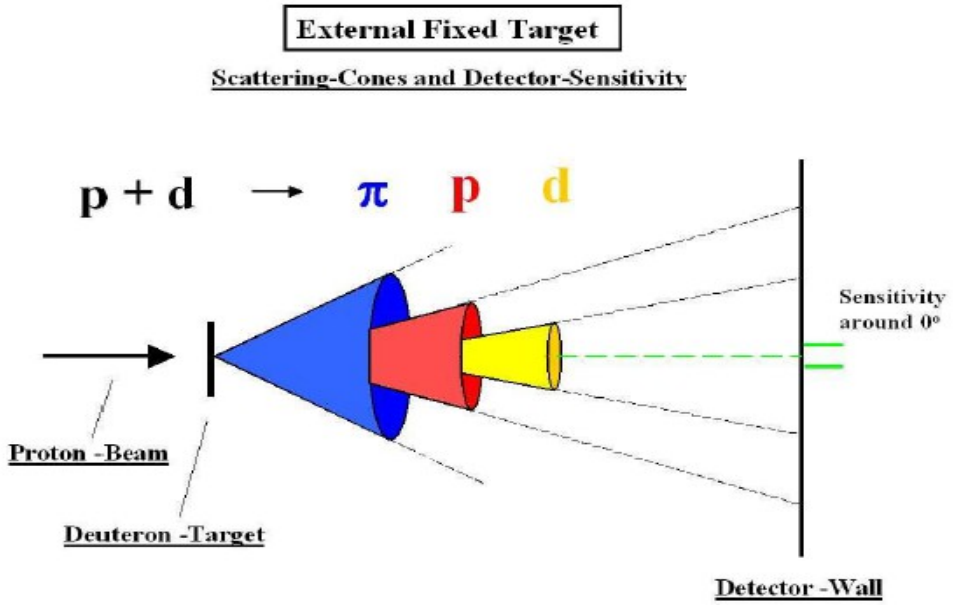
Total cross section measurement in pd scattering in this combination of beam and target polarisations is true T-odd null observable

But how to measure total cross section?

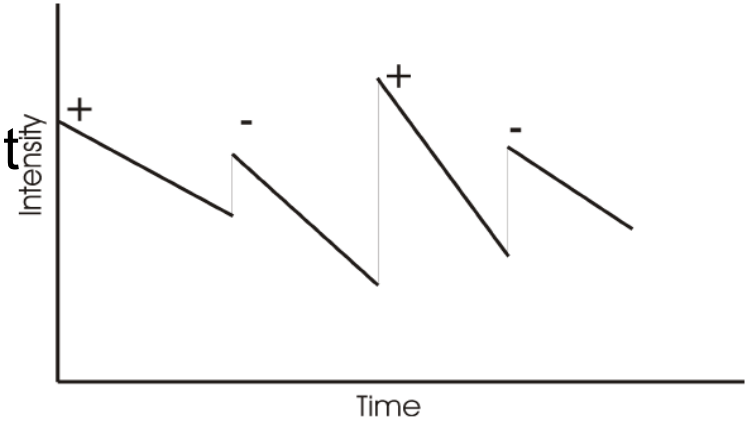
Measurement method

One can either:
build a complicated detector system to **detect all the particle scattered from the beam**, and still use approximation for the zero degree

Optical theorem:
$\sigma_{tot}=4\pi/k \cdot Im(F(0))$



Alternative is:
Perform a transmission experiement – detect particles **which remain in the beam after interaction with the target**

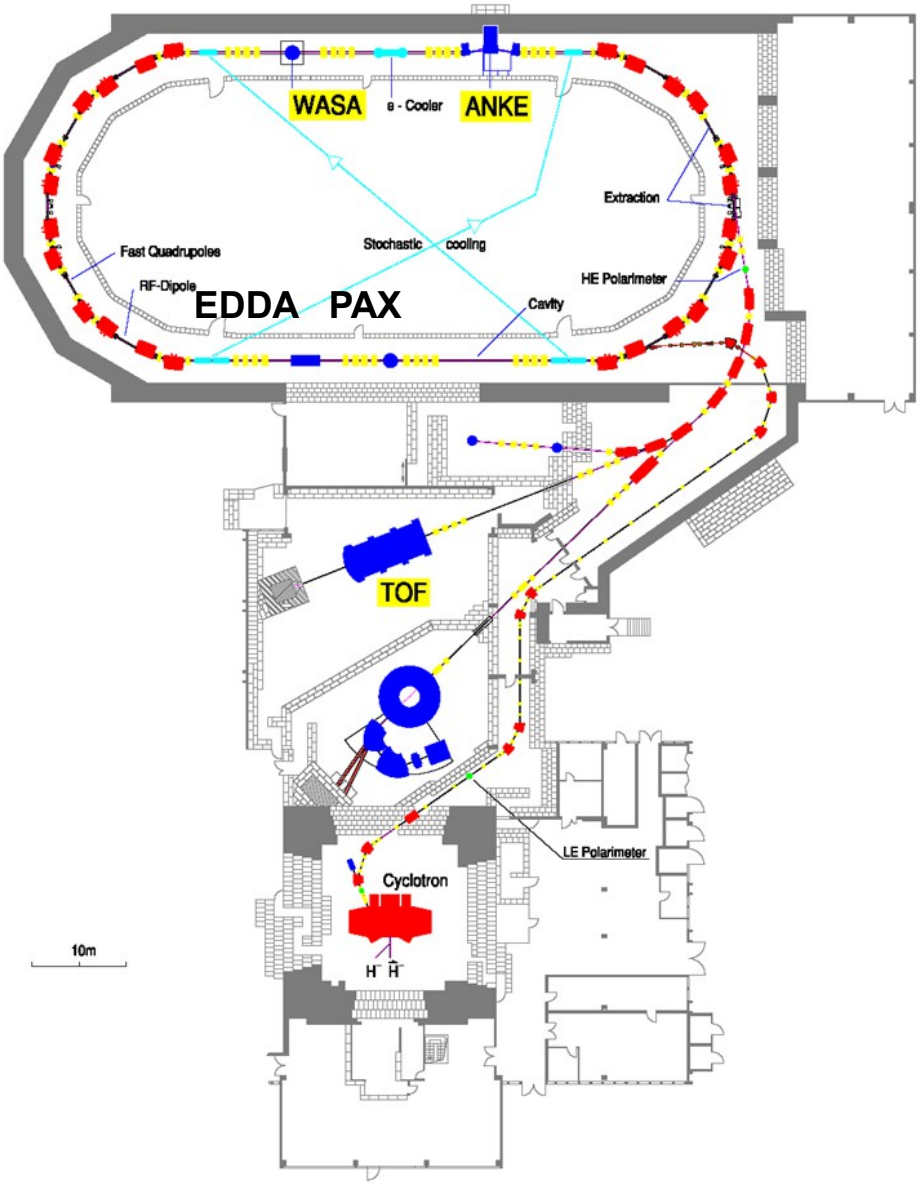


COSY

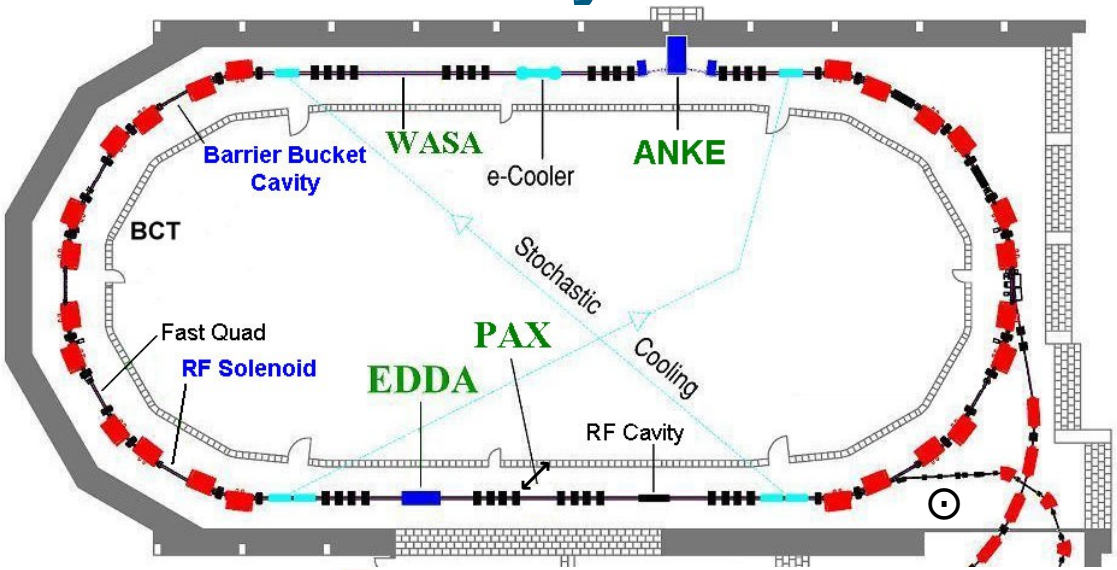
Polarised and unpolarised:
p,d

Maximal momentum:
3.7 GeV/c

Stochastic and electron cooling

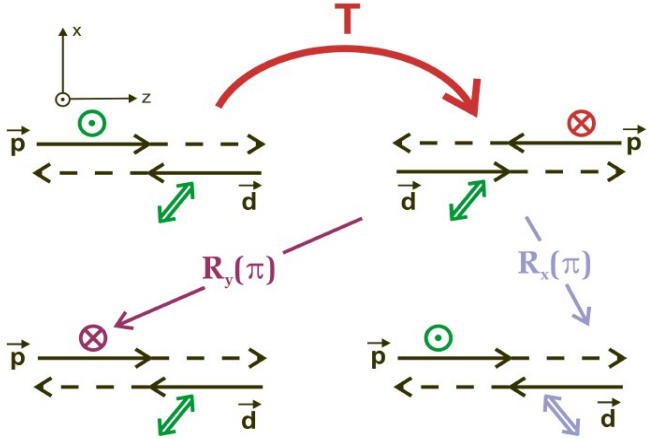


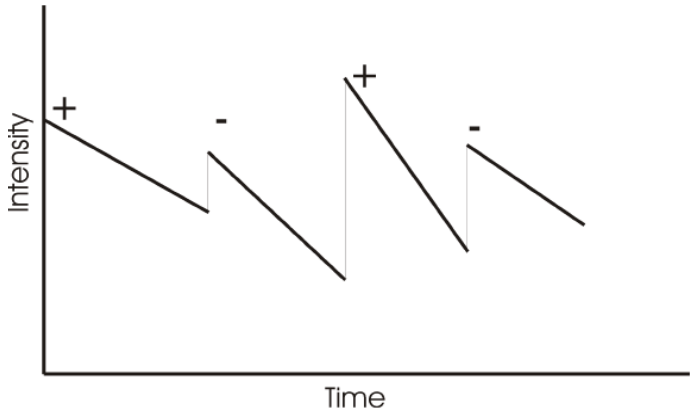
Method to study TRI at COSY

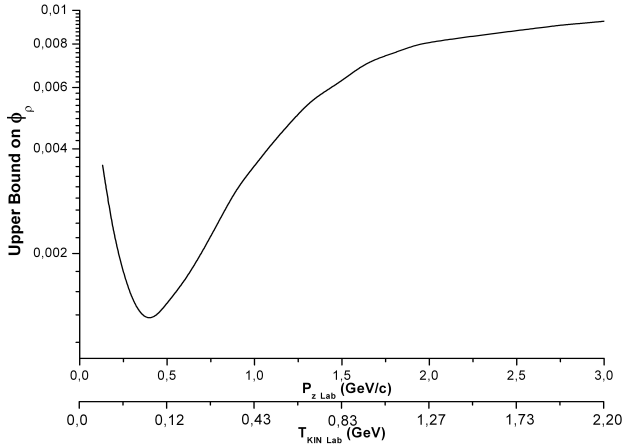


One needs:

- Stable COSY beam conditions at T_p~500 MeV/c
- Long beam life time
- Control COSY rest gas
- High resolution BCT
- Precision DAQ system
- Measure beam and target polarisations





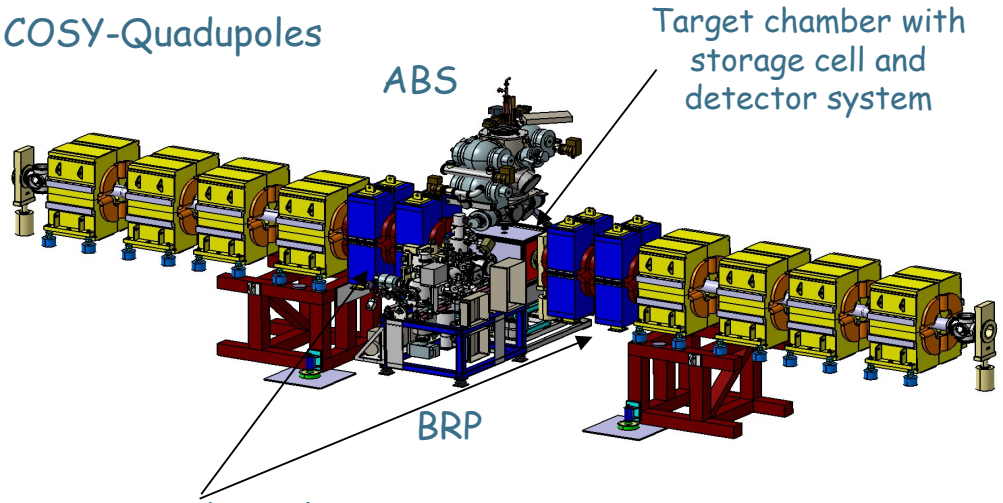


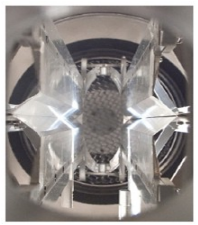
M. Beyer NPA 560 (1993) 895

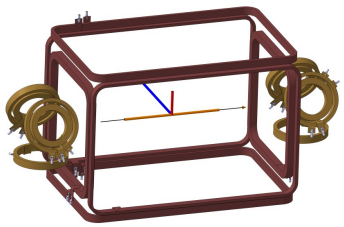
Four tasks for TRI experiment

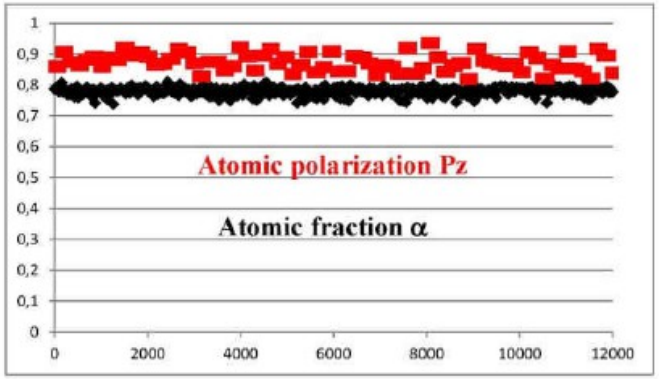
- Target (high thickness deuterium target with openable storage cell and holding field system)
- Polarimetry of the beam and target (detector?, polarimeter for the target, …)
- Beam current measurement (precission, stability, DAQ, …)
- Beam (high polarisation; life time, polarisation life time, low betta, e-cooler, ...)

PAX installation

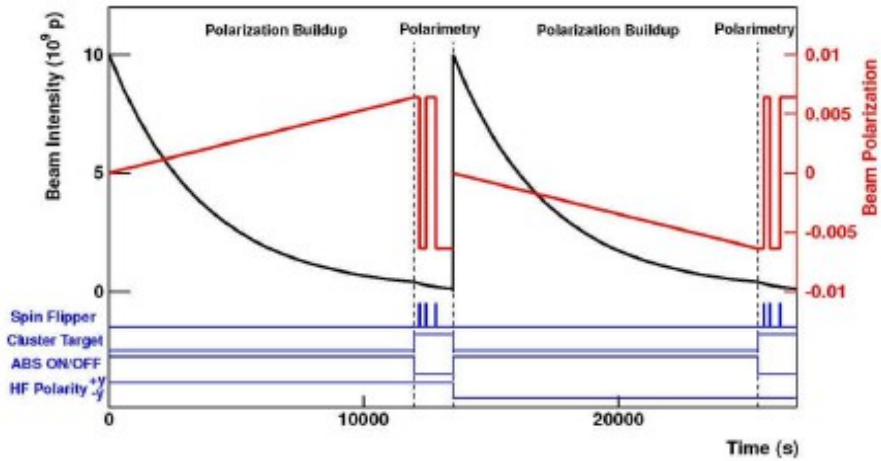








P. Lenisa and F. Rathmann CERN SPS reports



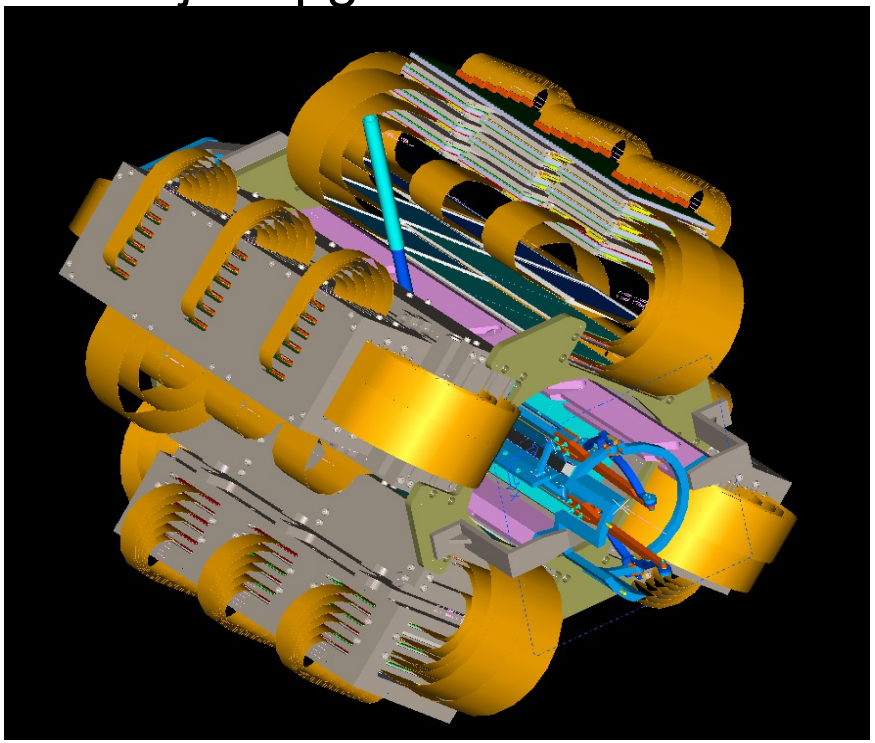
- ✔ Beam life time of ~8000s at injection energy
- ✔ Polarisation life time of >10^5 s at injection energy
- ✔ ABS with polarised H^0 gas
- ✔ Breit-Rabi polarimeter
- ✔ Openable storage cell
- ✔ Holding field system

PAX plans

In Christmas 2012 PAX target chamber with ABS and Breit-Rabi polarimeter will be taken out from COSY for major upgrade

In 2014 at the PAX target place should be available:

- Openable storage-cell
- PAX multi-purpose detector
- Atomic Beam Source and Breit-Rabi will be prepared to operate with deuterium



One of the designs of PAX multipurpose detectors

Four tasks for TRI experiment

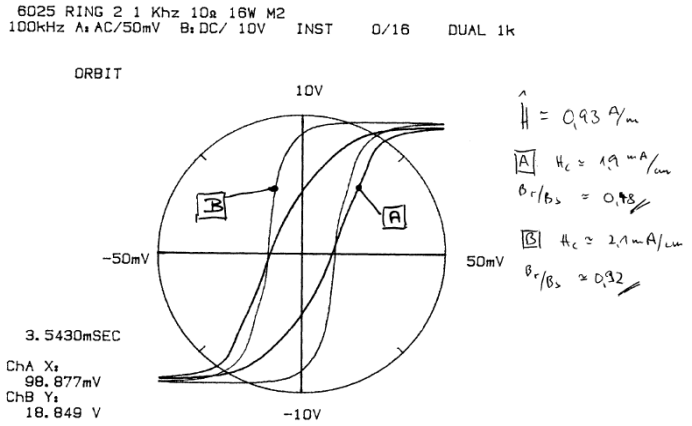
- Target (high thickness deuterium target with openable storage cell and holding field system)
- Polarimetry of the beam and target (detector?, polarimeter for the target, …)
- Beam current measurement (precission, stability, DAQ, …)
- Beam (high polarisation; life time, polarisation life time, low betta, e-cooler, ...)

Available at PAX in 2014

?

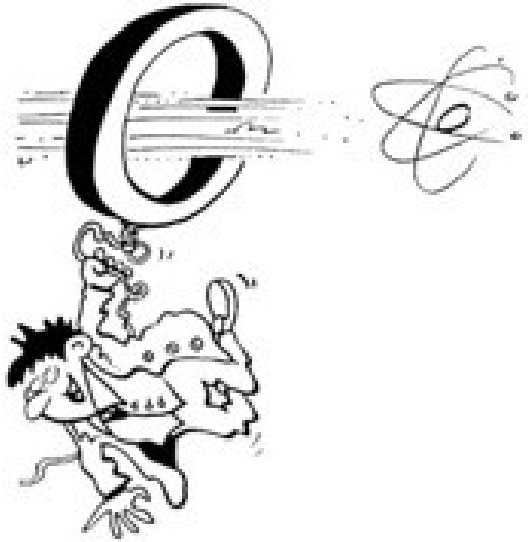
Beam current measurement in storage ring

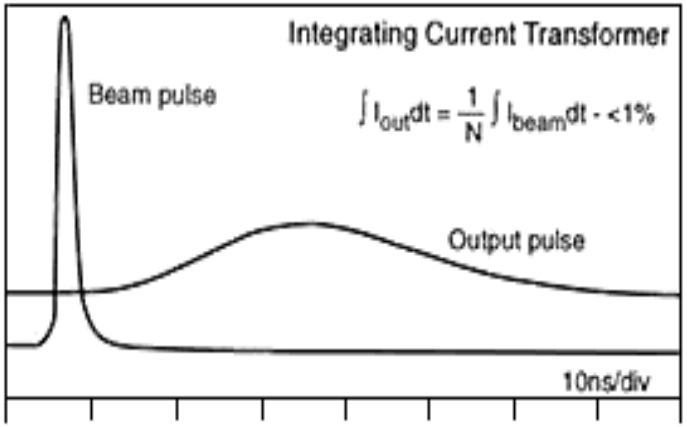
DC current



H. G. Reeg: B-H measurements, Vitrovac 6025F

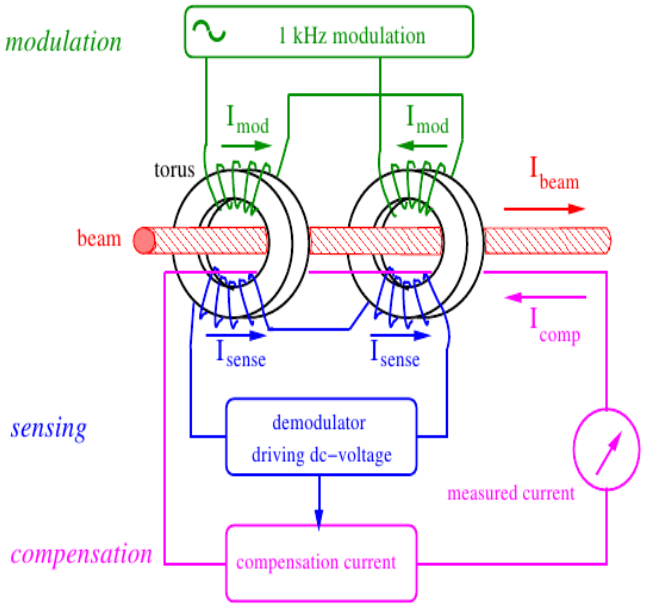
AC current





Types of BCTs

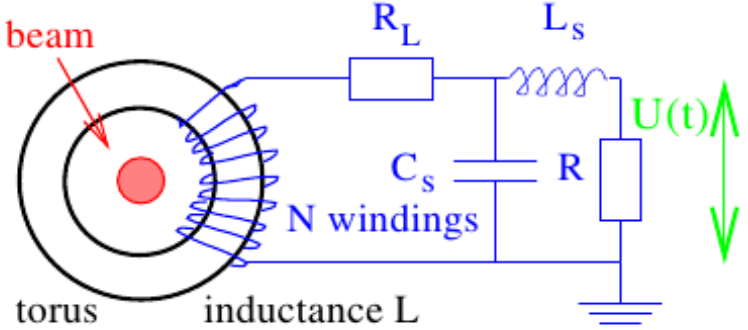
DC transformer

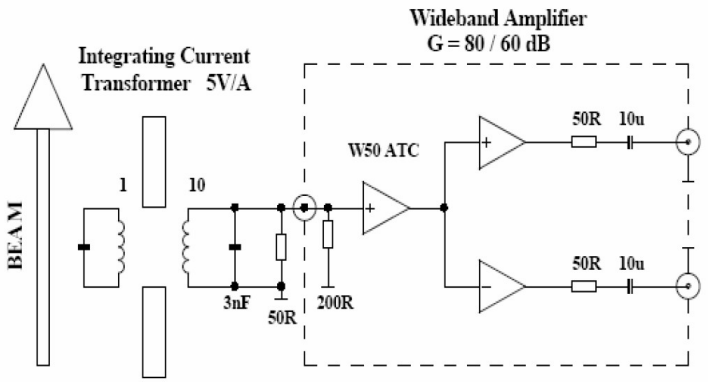


1) COSY BCT σ_I=0.5μA/√Hz
2) NPCT Bergoz σ_I=0.3μA/√Hz
3) CCC GSI σ_I=0.25nA/√Hz

DC or bunched beams

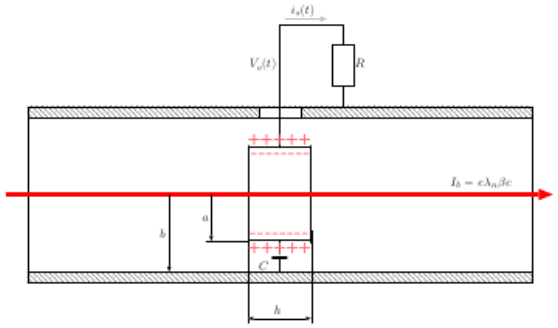
AC transformer

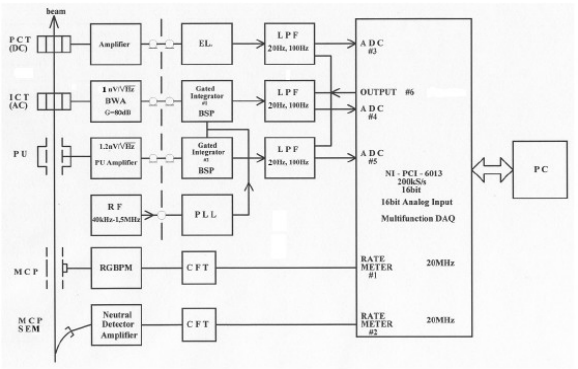




4) ICT Bergoz σ_I=1nA/√Hz

Capacitive pick up





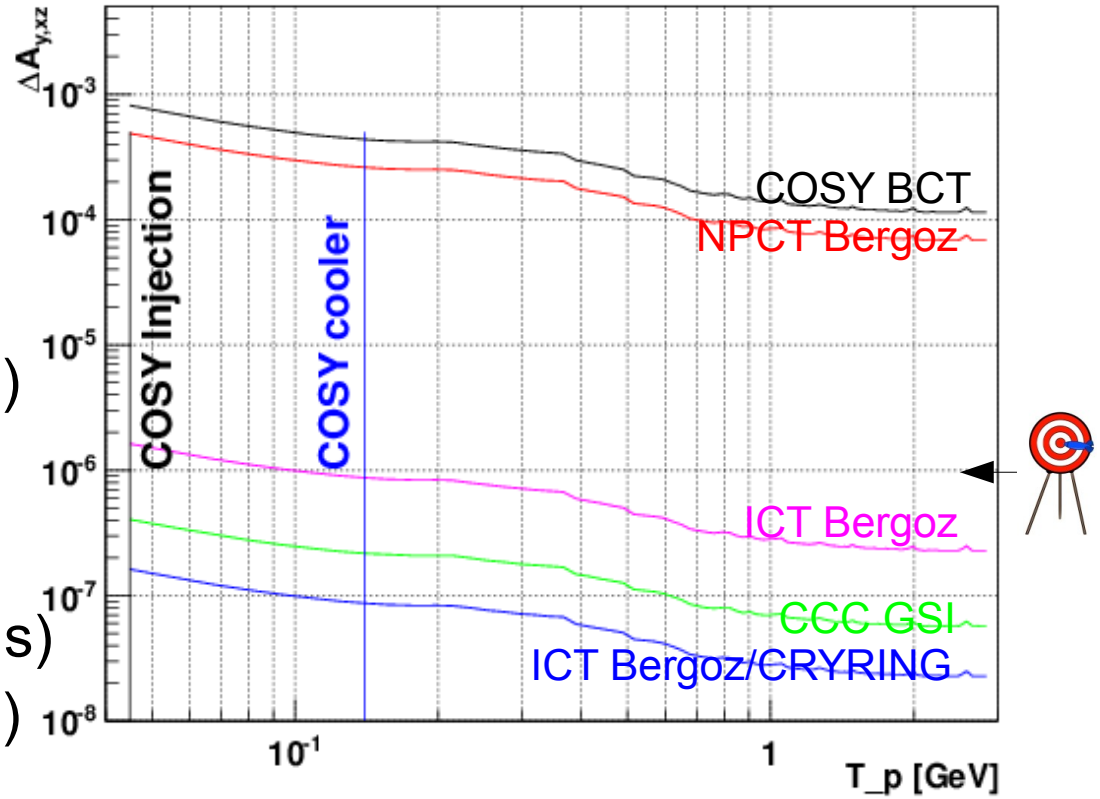
5) ICT Bergoz/CRYRING
σ_I=0.1nA/√Hz

Bunched beam only

BCT sensitivities

$$\delta A_{y,xz} = \frac{8*10^{-6}}{\rho d p_y p_{xz} \sigma_{tot}} \times \frac{\sqrt{t}}{h\sqrt{H}} \times \frac{\sigma_+}{v I_0}$$

N_p =3*10^9 protons in the ring
ρd – target density (8*10^{13} atoms/cm^2)
$p_y p_{xz}$ – target and beam polarisation
h – spin flip time (10 min)
t – measurement integration time (1 s)
H – total measurement time (30 days)



BCT conclusions

- Sensitivity of conventional DC beam measurements is not sufficient to perform TRI test
- It is possible to reach the desired precision using the ICT and a bunched COSY beam
  - Dedicated beam development is needed (long life time for bunched beam, ...)
  - Readout scheme for ICT must be developed
  - ICT must be impemented to COSY
- Using capacitive pick-up (BPM) it is possible improve sensitivity even further (CRYRING method)

Four tasks for TRI experiment

- Target (high thickness deuterium target with openable storage cell and holding field system)
- Polarimetry of the beam and target (detector?, polarimeter for the target, …)
- Beam current measurement (precission, stability, DAQ, …)
- Beam (high polarisation; life time, polarisation life time, low betta, e-cooler, ...)

Available at PAX in 2014

Possible with bunched beam

?

TRIC BD Plan (10.09.12-08.10.12)

Using experience we have got during PAX filtering beam-time we are going to prepare a beam for the TRIC experiment in Autumn this year!

1) Injection and acceleration to 135 MeV (unp. Beam) with PAX quads on
2) Setup E-cooler at 75 kV
3) Orbit correction, tune map measurements
4) Life-time optimisation
5) Beam position with frames, acceptance with frames
6) Storage cell on the beam axis, intensity and life time optimization
7) ABS is on
8) Switch to polarised beam, intensity and beam life-time optimization, crossing the resonance
9) Fixed cell installation
10) ...

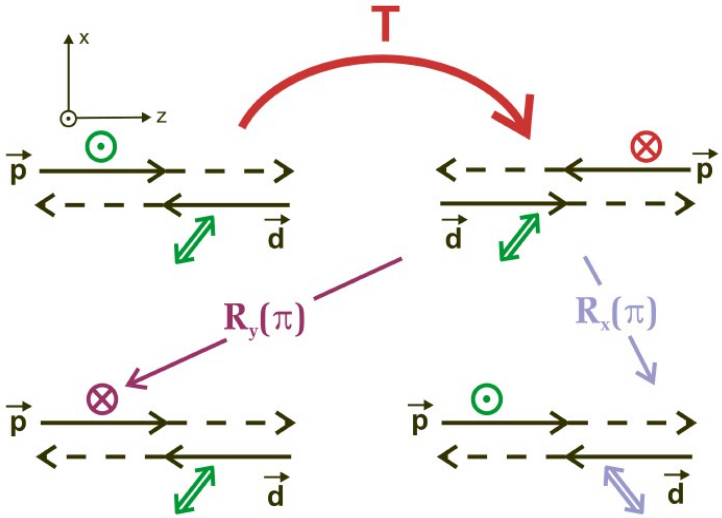
Conclutions&Outlook

- Using proposed method it is possible to improve limit on T-odd P-even interaction by one order of magnitude
- COSY and PAX installation are very well suited for such an experiment
- Experience in preparation and use of high intensity polarised proton beams should be gained during dedicated beam time in autumn this year
- High precision beam current measurement system must be developed and installed at COSY by the end of 2014

Thank you!

Time Reversal Invariance test at COSY

$$\vec{1/2}+\vec{1}\rightarrow\vec{1/2}+\vec{1}$$



$\sigma_{tot}=\sigma(1+A_{y,xz}p_y p_{xz})+\sigma_{rest\ gas}$

Since:

$A_{y,x}$ **and** $A_{y,yz}<10^{-7}$**(from P violation)**

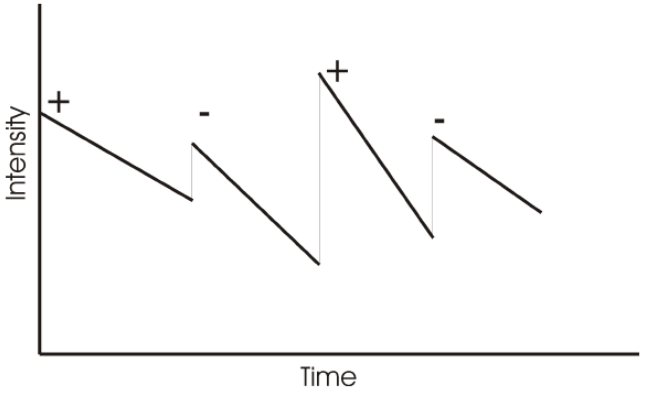
$\sigma_{rest\ gas}$ **does not depend on beam polarisation**

We want to use COSY as an ideal zero degree spectrometer!

$$A_{y,xz}=\frac{1}{2}\frac{1}{\sigma_0 \rho d}\frac{1}{P_x P_{yz}}\frac{1}{N}\left[\frac{dI^+}{I_0^+}+\frac{dI^-}{I_0}\right]$$

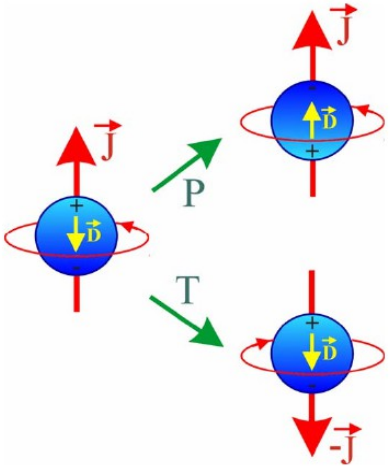
$A_{y,xz}$ – time reversal parity conserving null observable

D. Eversheim, COSY-Proposal #22

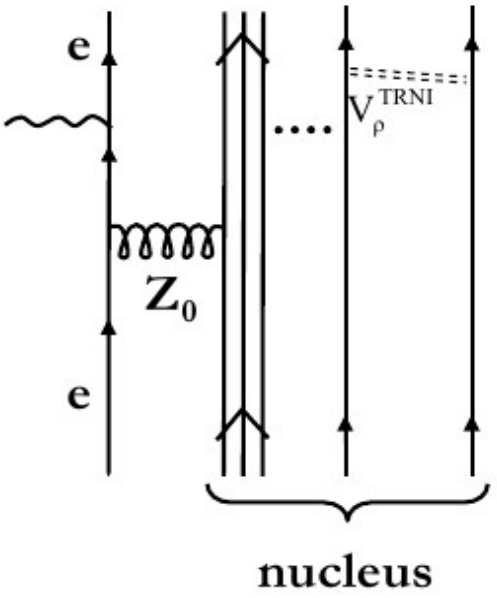


EDM

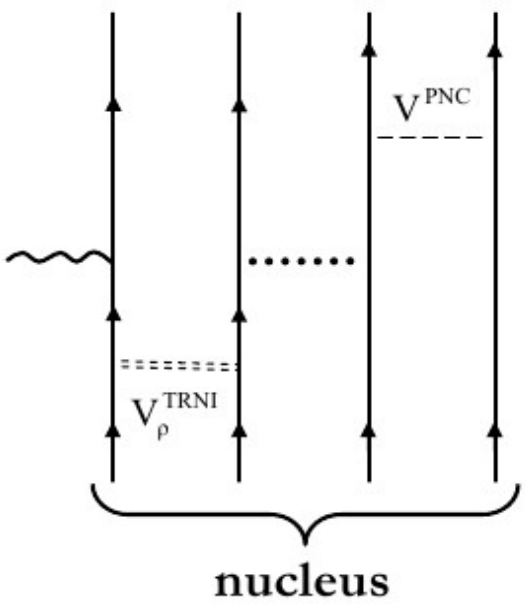
EDM violates:
Parity
Time reversal
CP conservation
(if CPT conserved)



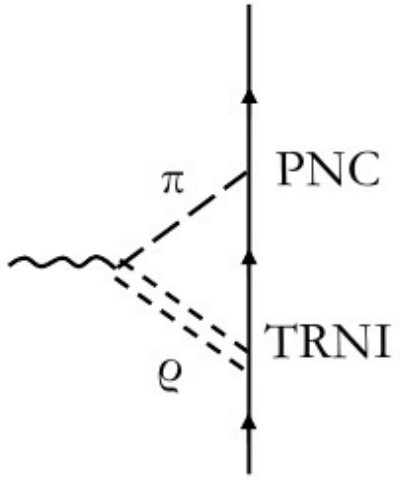
The atomic EDM



The nuclear EDM



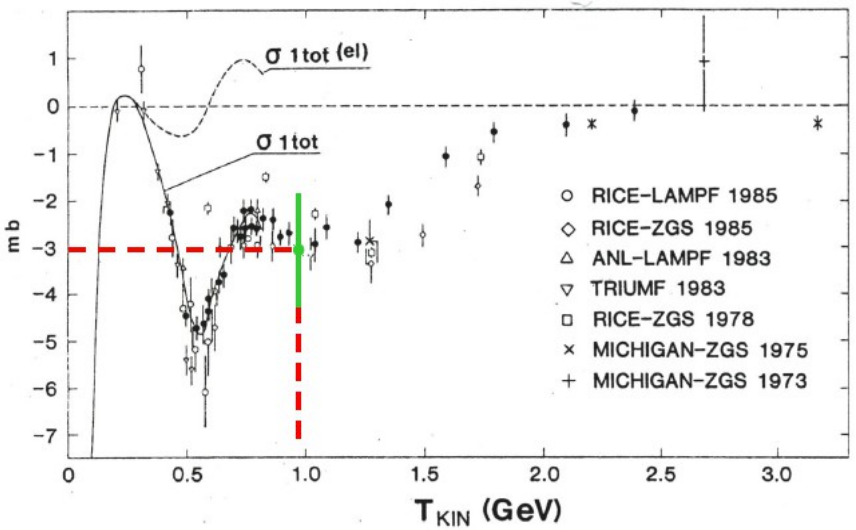
The nucleon EDM

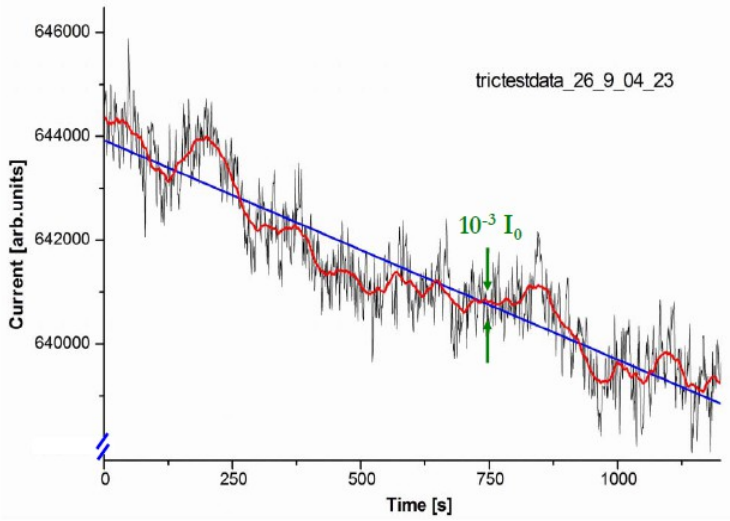


Agenda for this beam request

- Polarised proton beam with at least 80% polarisation
- Acceleration with low-β section up to 135 MeV
- e-cooling at 75 kV(normal operation 70 kV/designed value 100kV)
- Beam intensity not less then $3*10^9$ with storage cell installed in PAX low-β section
- Bunched beam life-time studies
- Bunched beam polarisation life time
- Polarimetry scheme using EDDA and LEP should be tested
- Double polarised total cross section measurements, using existing COSY-BCT, should be performed

Results of feasibilitv test in 2004 (COSY-Proposal #22)





✔ Measurement of total cross section using only beam current is possible

✔ Obtained value of total cross section $\sigma_{1tot} = \sigma A_{y,y} \approx -3.2$ mb is in agreement with world data

✗ Beam life-time was not stable during beam-time

✗ Factor 5 in polarised beam intensity was missing

✗ One order in polarised target thickness was missing

✗ One order in BCT resolution was missing

We can do better with PAX

D. Eversheim, Hyperfine Interact 193 (2009) 335.

Full program for the TRI

- Preparations and studies of polarised bunched beam parameters (2 Weeks) — 2012
- Measurements of A_{yy} in double polarised pd scattering using PAX installation and comissioning of high precission bunched beam current measurements system (~5 Weeks) — 2014
- Measurements of A_{yxz} to the precission of 10^{-6} (~5 Weeks) — 2015

…

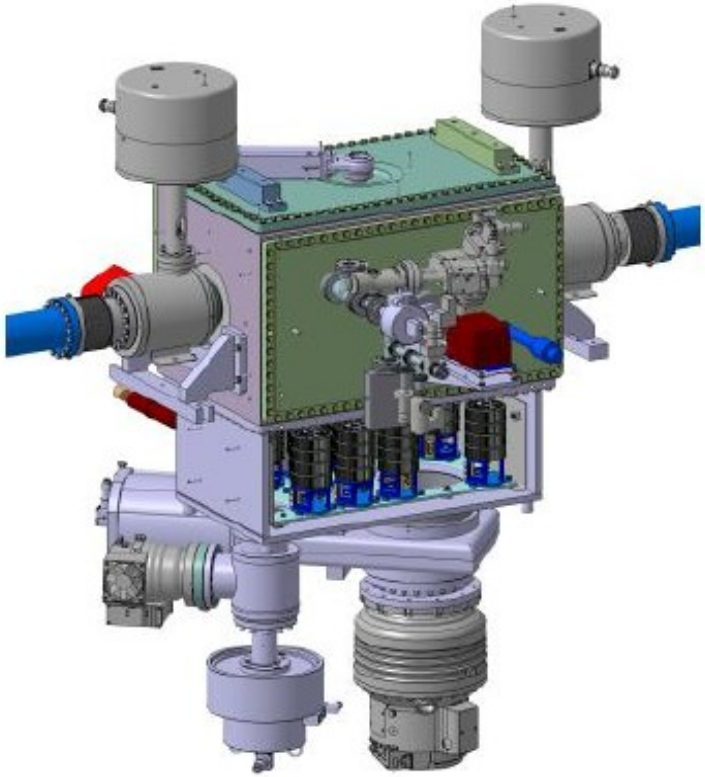
- Measurements of A_{yxz} to the precission of 10^{-7} using CRYRING technique (~5 Weeks) — ?

This experiment

- Prepare e-cooled bunched polarised proton beam at 135 MeV with PAX
- Study polarisation loss due to the resonance crossing using EDDA
- Measure beam and polarisation life time using EDDA
- Optimize beam parameters
- Measure double polarised pp cross section using COSY BCT and PAX polarised gas target

PAX Vacuum

PAX filtering at 45 MeV:
τ_B>8000 s
τ_{pol}>100000 s

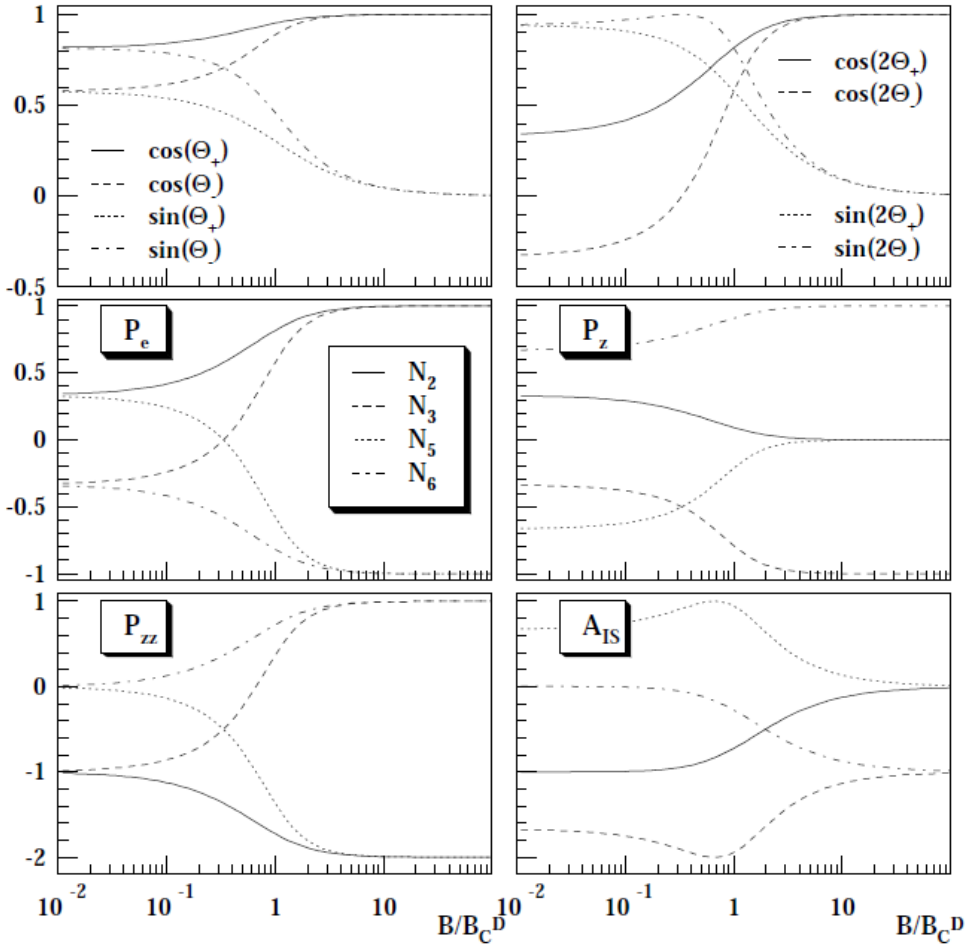


- The new NEG pumping system is installed under the PAX chamber (12000 l/s)
- Pressure in target chamber with $3*10^{16}$ H atoms/s stays below 10^{-8} mbar
- COSY neigboring sections are also equipped with NEG coating
- Almost no effect on the beam life-time due PAX ABS with single H hyperfine state

P. Lenisa and F. Rathmann CERN SPS reports

Target

- PAX ABS with current configuration of holding field system can provide desired type of polarised target
- Two states N_2 and N_3 (P_z=0, P_{zz}=1) can be used together providing a polarised gas target with ρd=6-10*10^{13} atoms/cm²



Picture from PhD thesis of Christian Baumgarten

Beam current measurement

- COSY BCT is in operation and can be used for the experiment. No majour modifications are allowed since it is a working tool for the COSY operation
- VFT can easily be implemented in to the ANKE(already done during PAX beam time) and EDDA DAQ
- New BCT and readout system will only be ready in 2014
  - Prepare a test station in the lab
  - Investigate possibilities of ICT and BCT
  - Consult with BERGOZ
  - Prepare system for installation at COSY

Polarimetry

- Target polarimetry at PAX can be done using BRP with 5% precission
- Beam polarimetry above 1.2 GeV/c (0.585 GeV) can be done using EDDA
- Beam polarimetry can be done at ANKE using two STT
- In 2014, then PAX detector system is in place, beam and target polarimetry can be done at PAX place using data from PRC 74 (2006) 064003

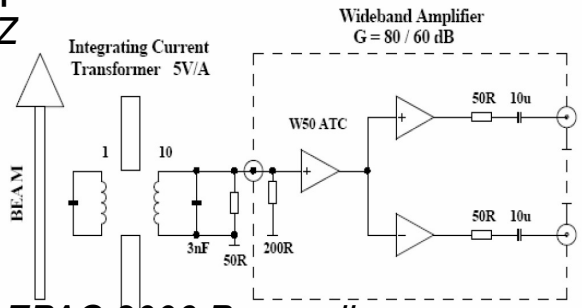
Possible BCT update

New Parametric Current Transformer from BERGOZ δI<0.3μμA/√Hz

New Parametric Current Transformer, User Manual, BERGOZ

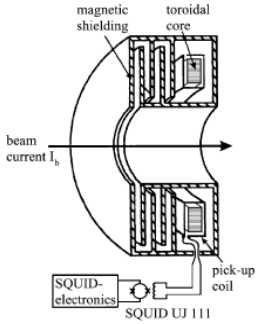
Integrating Current Transformer from BERGOZ δI<1μnA/√Hz

Integrating Current Transformer, User Manual, BERGOZ



Bunched beam current can be measured up to 0.1 nA/√Hz precision using Integrating Current Transformer from BERGOZ and the sum signal from capacitive pick-up

A. Paal et al., EPAC 2006 Proceedings



Cryogenic Current Comparator, read out by low-temperature super-conducting quantum interference device provide resolution up to 0.25 nA/√Hz (Prototyp build for FAIR GSI)

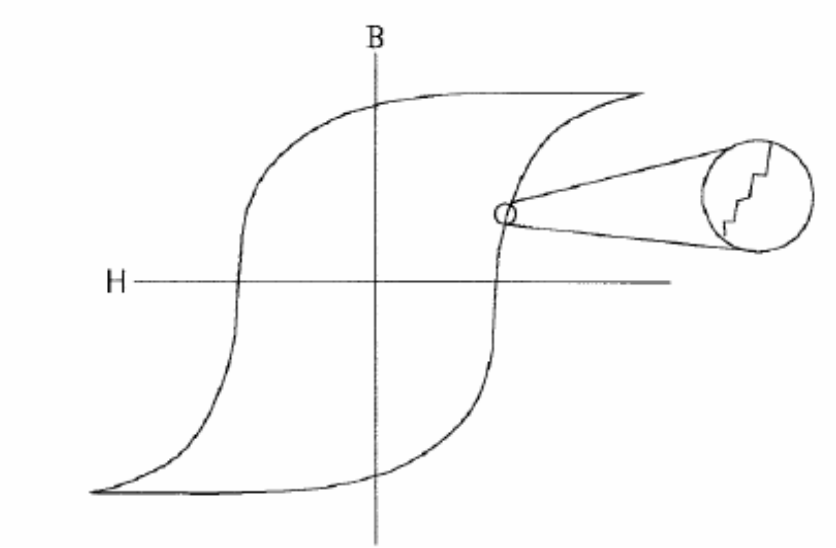
A. Steppke, IEEE Trans. Appl. Superc. (2009)

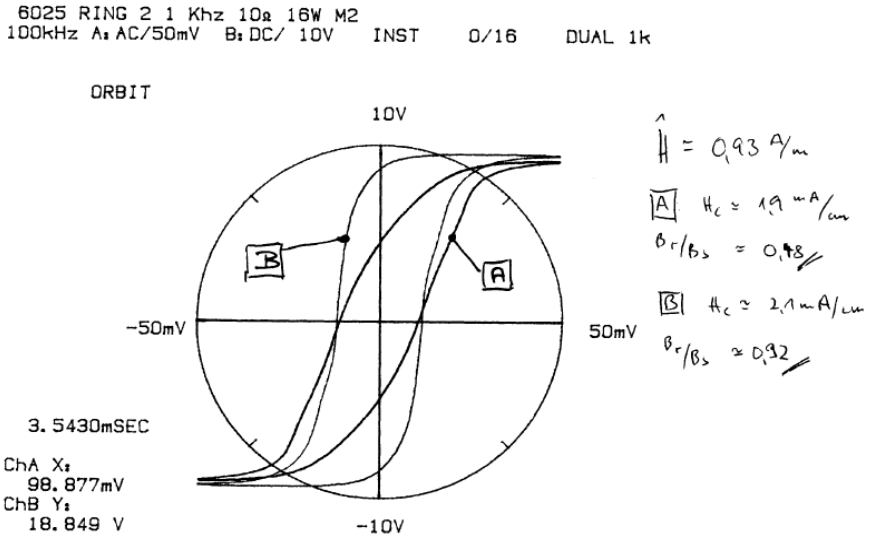
Improvement of ICT up to 1 pC in bunch is possible

M. Werner Highlights and Annual report, Accelerator 2011, p 49

Limits on DC BCT sensitivity

B-H granularity correspond to the magnetic domain size i.e. Barkhausen noise





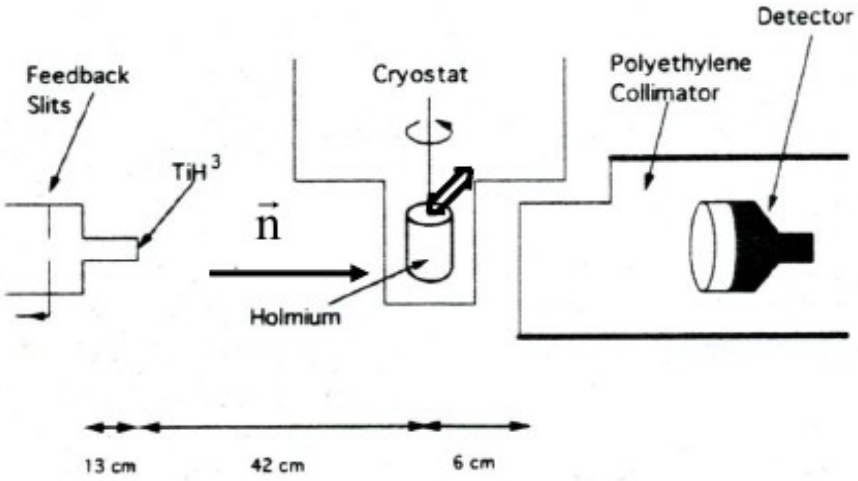
H. G. Reeg: B-H measurements, Vitrovac 6025F

Vitrovac ordered with the same specification at different time (technology did not change)

5.9 MeV Neutron Transmission Experiment through ^{165}Ho

Observable : $\vec{p}\cdot(\vec{\sigma}_1\times\vec{\sigma}_2)(\vec{p}\cdot\vec{\sigma}_2)$

Result : $g_{\varrho T}$: 2,3 • 10^{-2}



*J.E.Koster et al., Phys. Rev. C **49** (1994) 710*

- Since the tensor polarization in ^{165}Ho is generated by one valence nucleon, the effect is diluted by the other 164 nucleons
- Therefore:
  Restrict experiment to most simple Spin1-Spin½ system, i.e. $\vec{p}$ - $\vec{d}$ scattering at COSY (as an internal experiment)

Experiment

External Fixed Target

Scattering-Cones and Detector-Sensitivity