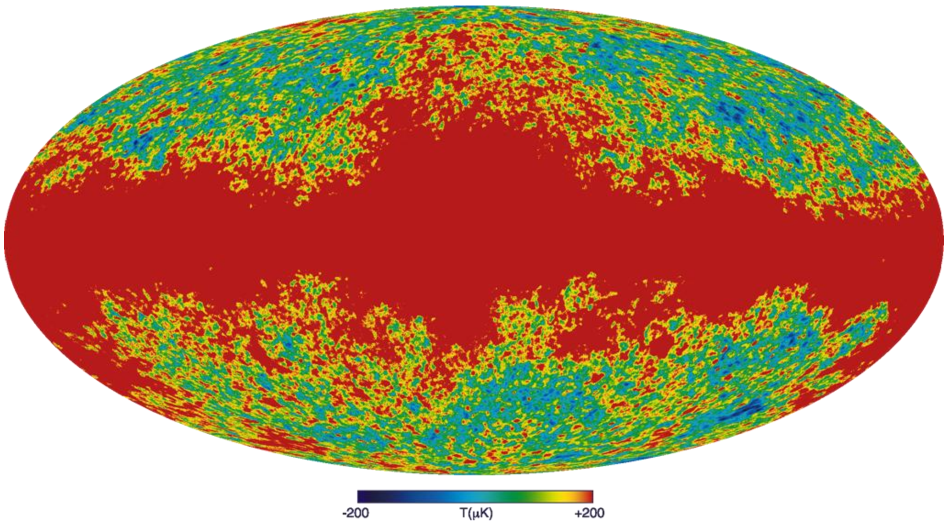
Baryon Asymmetry of the Universe



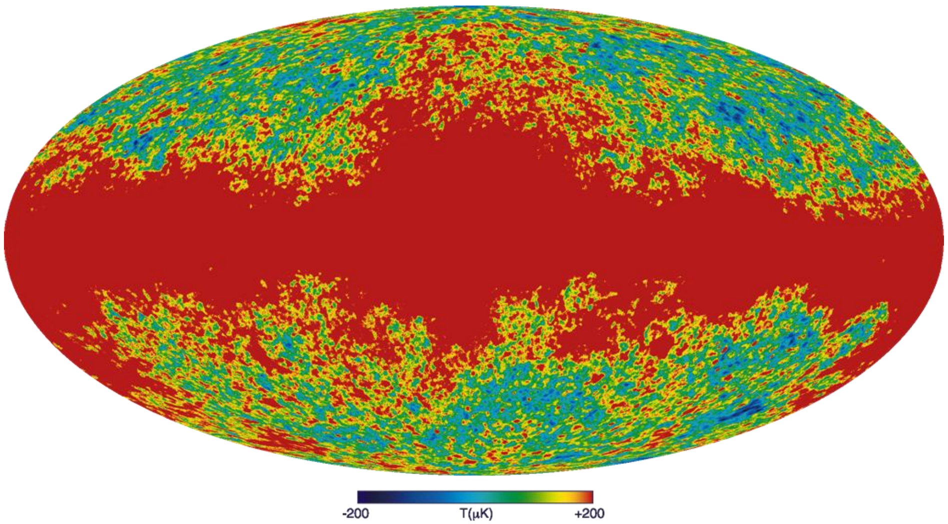
Observed: $(n_B - n_{\bar{B}}) / n_\gamma = 6 \cdot 10^{-10}$

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

WMAP+COBE, 2003

Why ?

Baryon Asymmetry of the Universe



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

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

WMAP+COBE, 2003

8 orders of magnitude are missing!

Three conditions (*A.Sakharov JETP Lett.* ***5***,*24*)

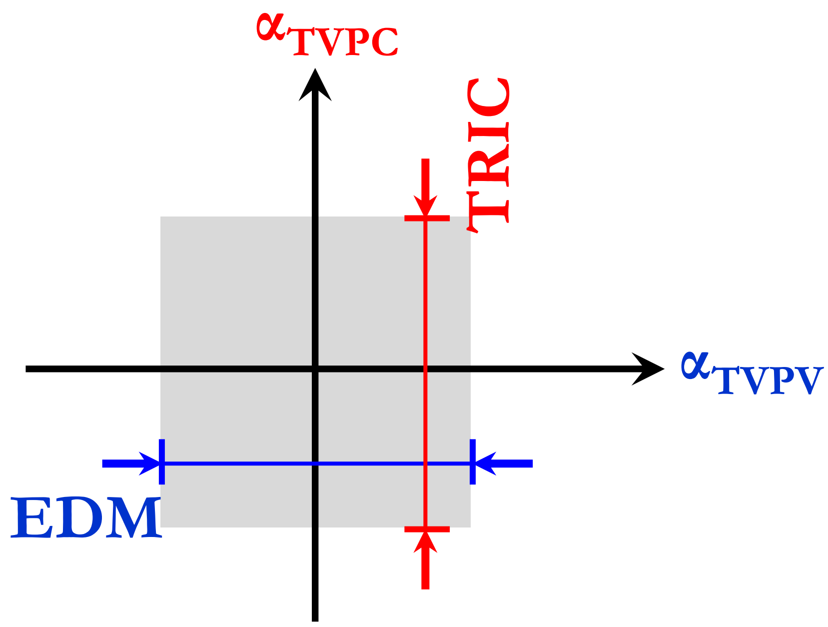
- Baryon number conservation is violated
- Violation of CP ↔ T Violation (since TPC holds)
- A non thermalized system

Consider T violation (with and without P conservation):

$$L = L_{SM} + \alpha_{\mathrm{TVPV}} L_{\mathrm{TVPV}} + \alpha_{\mathrm{TVPC}} L_{\mathrm{TVPC}} + \ldots$$

EDM

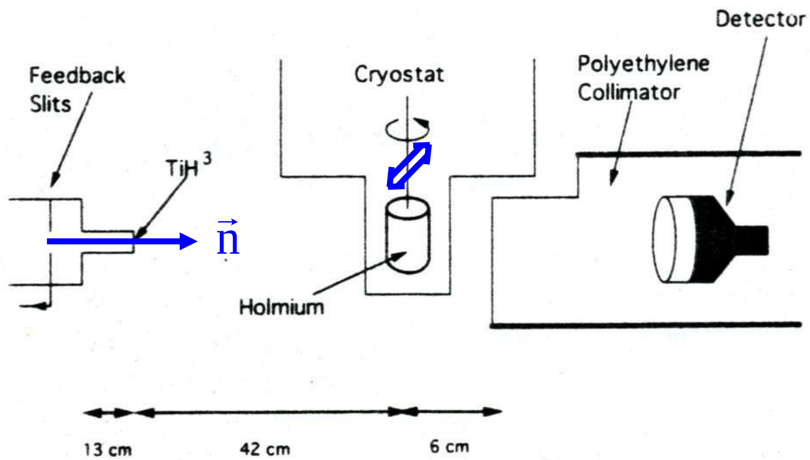
TRIC



EDM and TRIC probe different extensions of the SM

5.9 MeV Neutron Transmission Experiment through ^{165}Ho

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

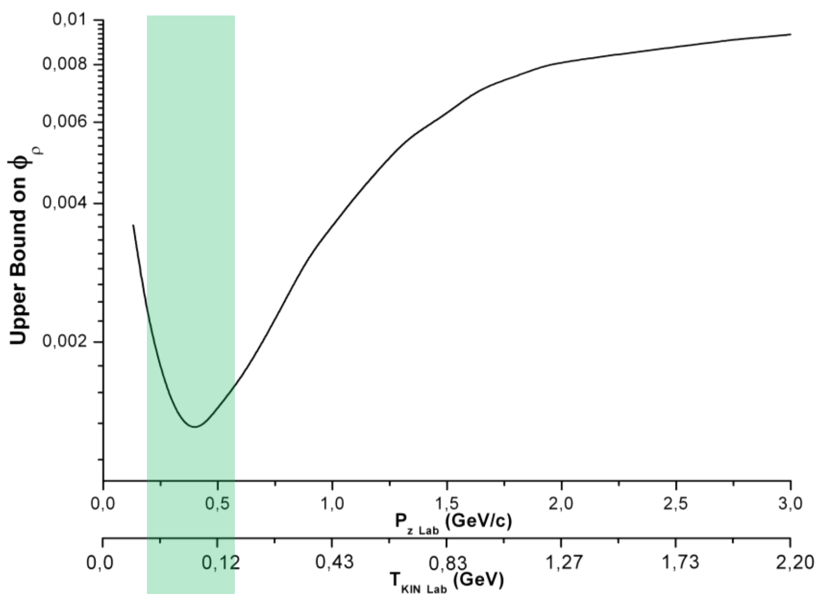


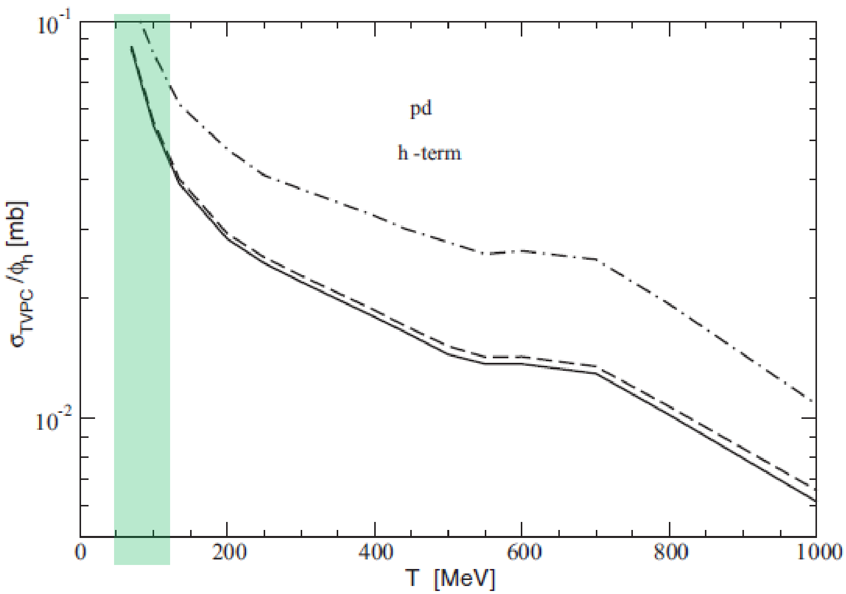
J.E.Koster et al., Phys. Rev. C ***49*** *(1994) 710*

- 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 **Spin½ – Spin1** system, i.e. $\vec{p}$ - $\vec{d}$ scattering at COSY (as an internal experiment)

Beam Energy for TRIC





M. Beyer NPA 560 (1993) 895

Yu. Uzikov PRC 92 (2015) 014002

Two independent theoretical calculations suggest to perform TRIC below 200 MeV

The Time Reversal Invariance Experiment at COSY (TRIC)

What are the Goals for TRIC ?

- (Most) accurately probe TRI (T-odd, P-even) in nuclear matter
- Dynamics independent;
  especially: Not sensitive to Final State Interaction (FSI)
- Only dependent on the structure of the reaction matrix as determined by general conservation laws „True test of TRI“
- Simple reaction (Two particles in → two particles out)

True TRI Null-Test

What is the Goal for TRIC ?

But:

There is no such TRI Null-Test for any reaction in atomic nuclear or elementary physics

*F.Arash, M.J. Moravcsik and G.R. Goldstein, Phys.Rev.Lett. **54** (1985) 2649*
*M.Simonius, Phys. Rev. Lett. **78** (1997) 4161*

Loophole: **Proof holds for bilinear observables only.**

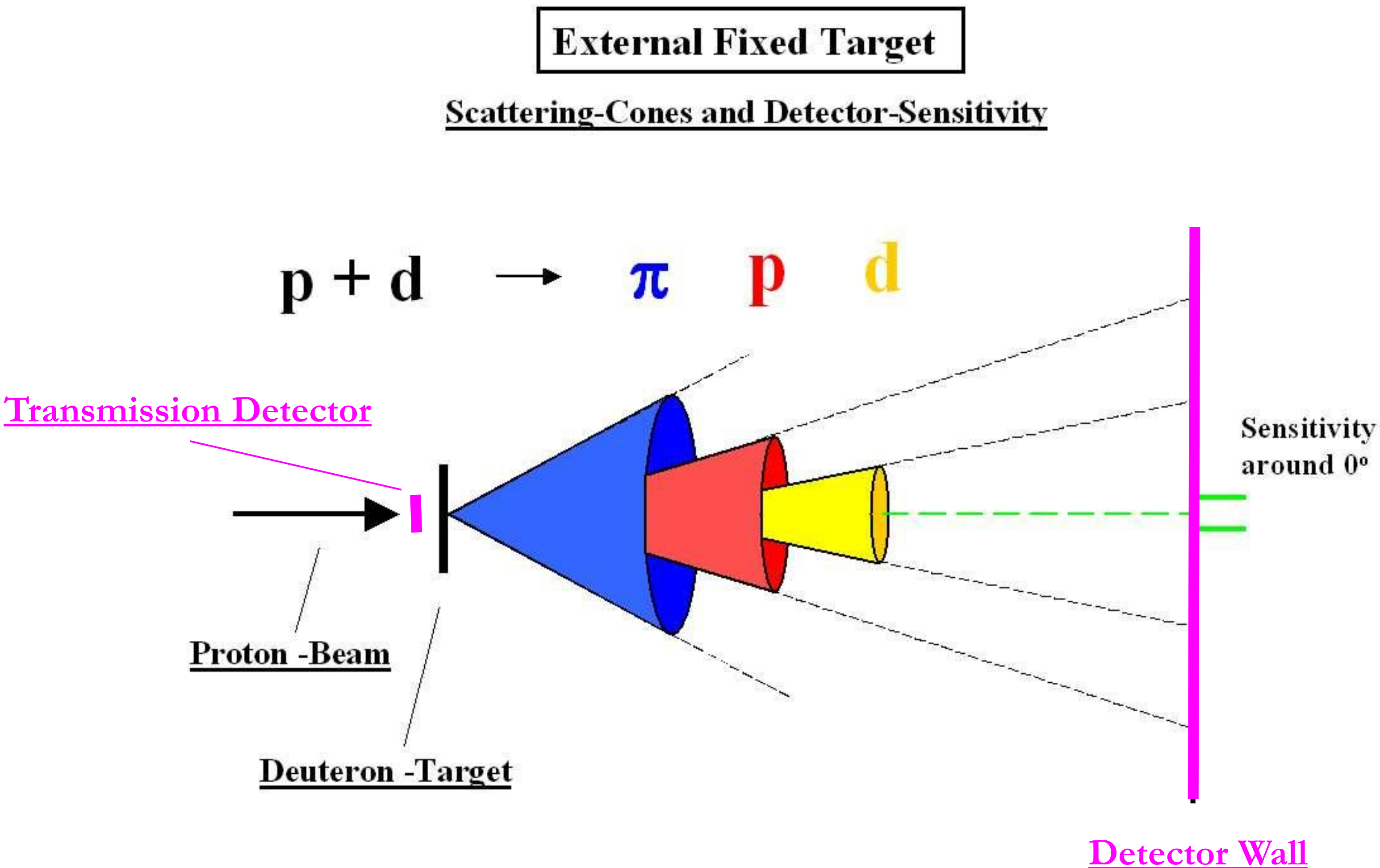
H.E. Conzett, „7th Int. Conf. on „Pol. Phen. Nucl. Phys.“, Paris (1990) 2D

Measure forward scattering amplitude and thus total cross sections via the Optical Theorem

$\boxed{\text{Measure total } A_{y,xz} \text{ in } \vec{p}-\vec{d} \text{ scattering}}$

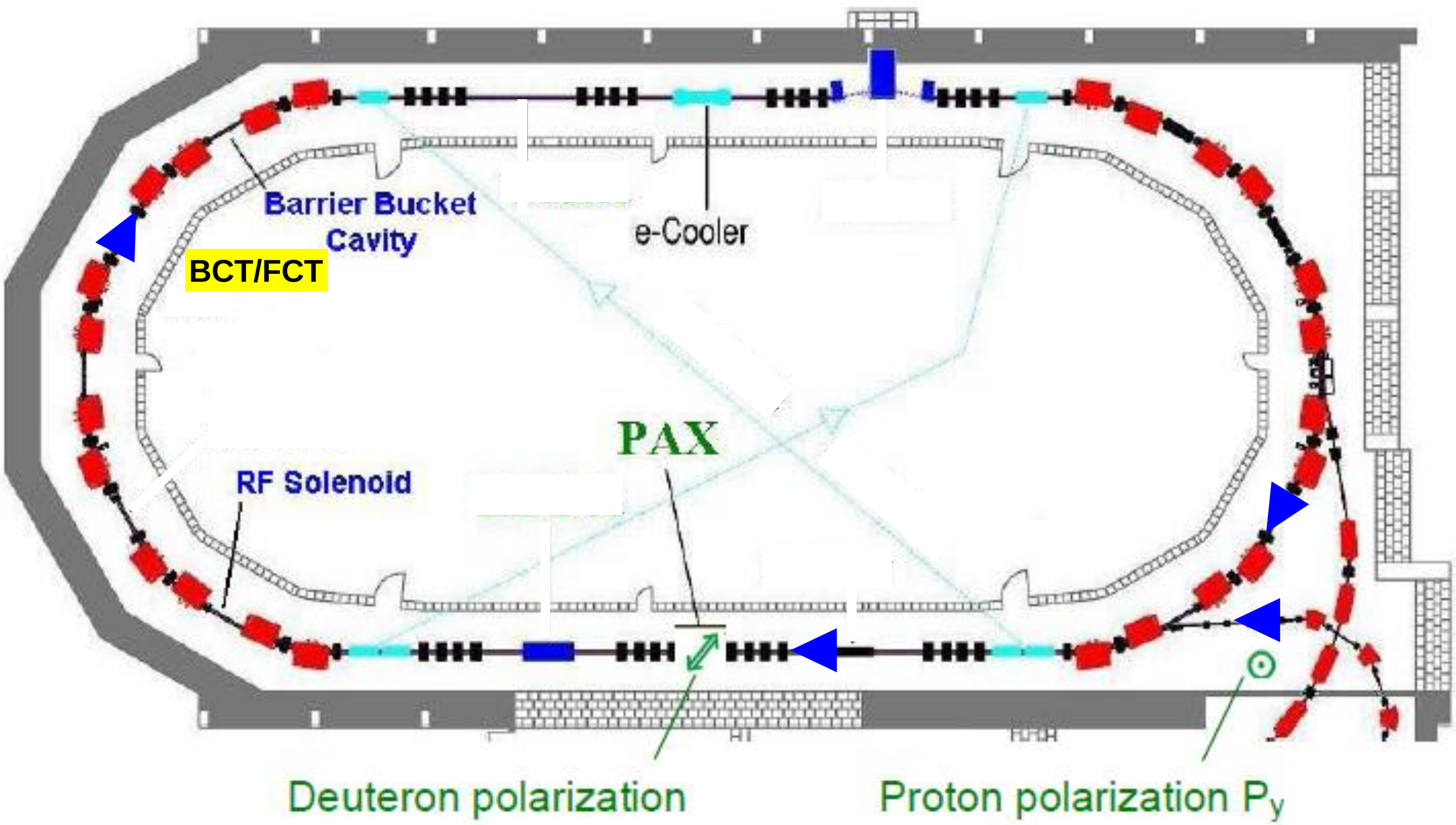
The Time Reversal Invariance Experiment at COSY (TRIC)

The Experimental Setup



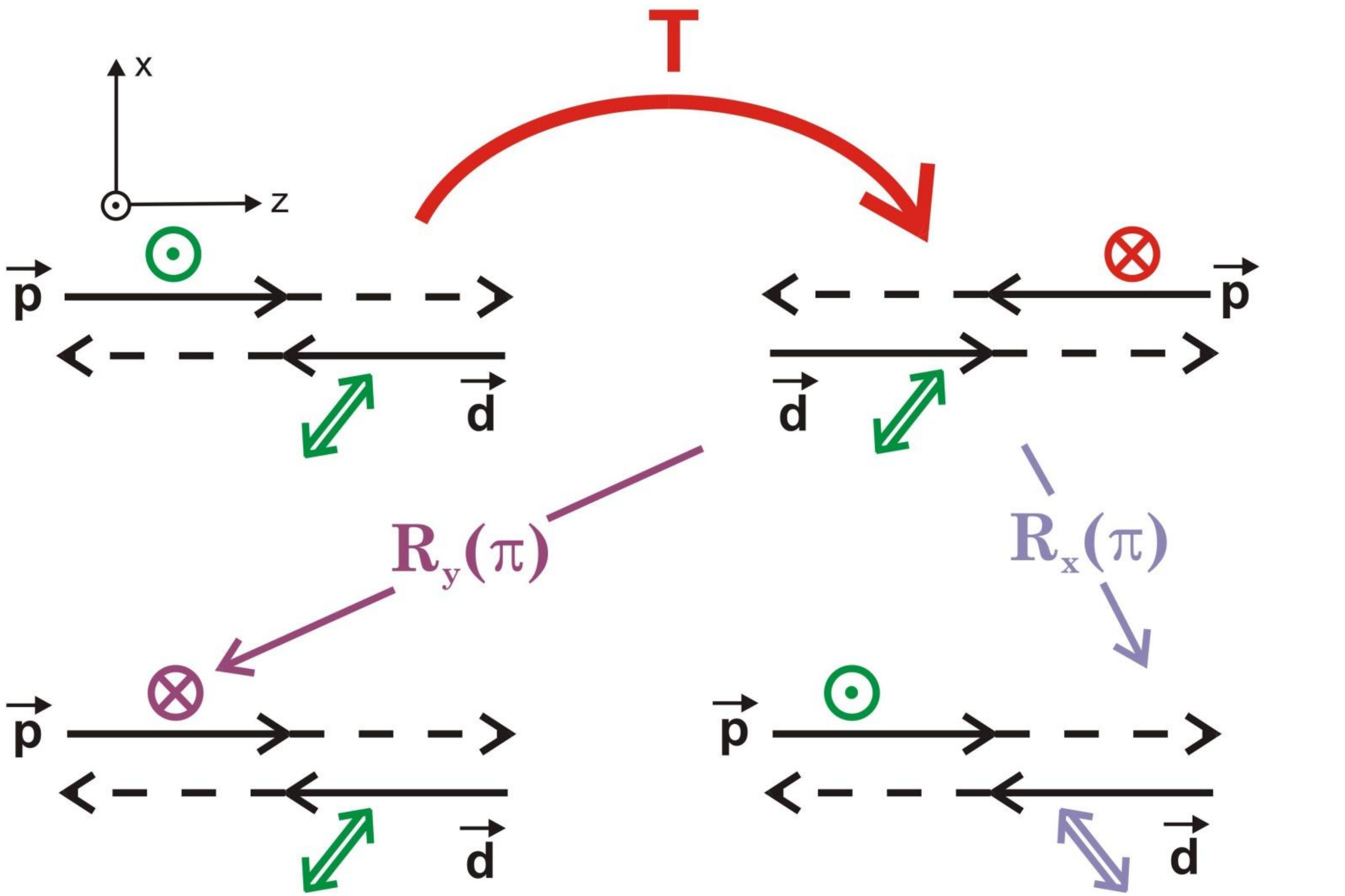
The Time Reversal Invariance Experiment at COSY (TRIC)

The Experimental Setup



The Principle Idea of the Experimental Setup

The Principle of the Time Reversal Invariance test at COSY (TRIC)



Principal Error Analysis

TRIC

Involved Spins: ½ + 1 → ½ + 1

$I_{0,0}$	$A_{0,X}$	$A_{0,Y}$	$A_{0,Z}$
$A_{X,0}$	$A_{X,X}$	$A_{X,Y}$	$A_{X,Z}$
$A_{Y,0}$	$A_{Y,X}$	$A_{Y,Y}$	$A_{Y,Z}$
$A_{Z,0}$	$A_{Z,X}$	$A_{Z,Y}$	$A_{Z,Z}$

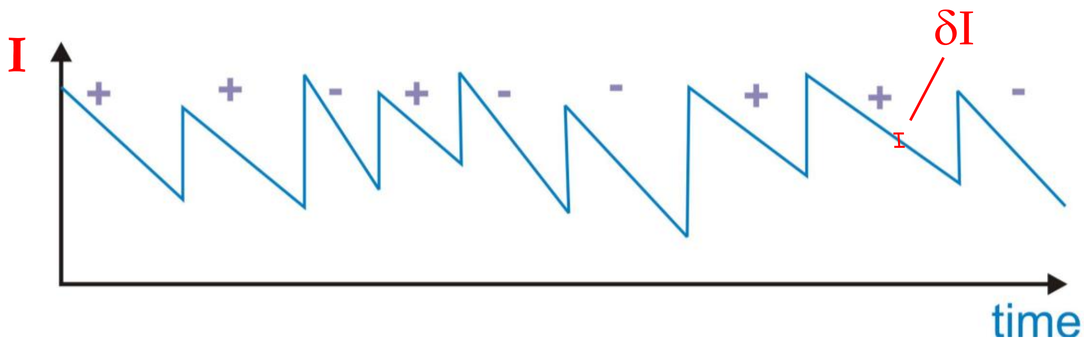
$A_{0,XX}$	$A_{0,YY}$	$A_{0,ZZ}$	$A_{0,XY}$	$A_{0,YZ}$	$A_{0,XZ}$
$A_{X,XX}$	$A_{X,YY}$	$A_{X,ZZ}$	$A_{X,XY}$	$A_{X,YZ}$	$A_{X,XZ}$
$A_{Y,XX}$	$A_{Y,YY}$	$A_{Y,ZZ}$	$A_{Y,XY}$	$A_{Y,YZ}$	$A_{Y,XZ}$
$A_{Z,XX}$	$A_{Z,YY}$	$A_{Z,ZZ}$	$A_{Z,XY}$	$A_{Z,YZ}$	$A_{Z,XZ}$

Line cancels because of : Protonspinflip
p_x, p_z negligible for protons

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

The Time Reversal Invariance Experiment at COSY (TRIC)

Some Experimental Details



$$\delta A_{y,xz}^{meas} \propto \frac{\sqrt{\Delta t}}{h\sqrt{H}}\,\delta I$$

with: Δt is the time interval between two consecutive current measurements on a slope [s]

h is the spin flip period of the target [h]

H is the total measuring time [h]

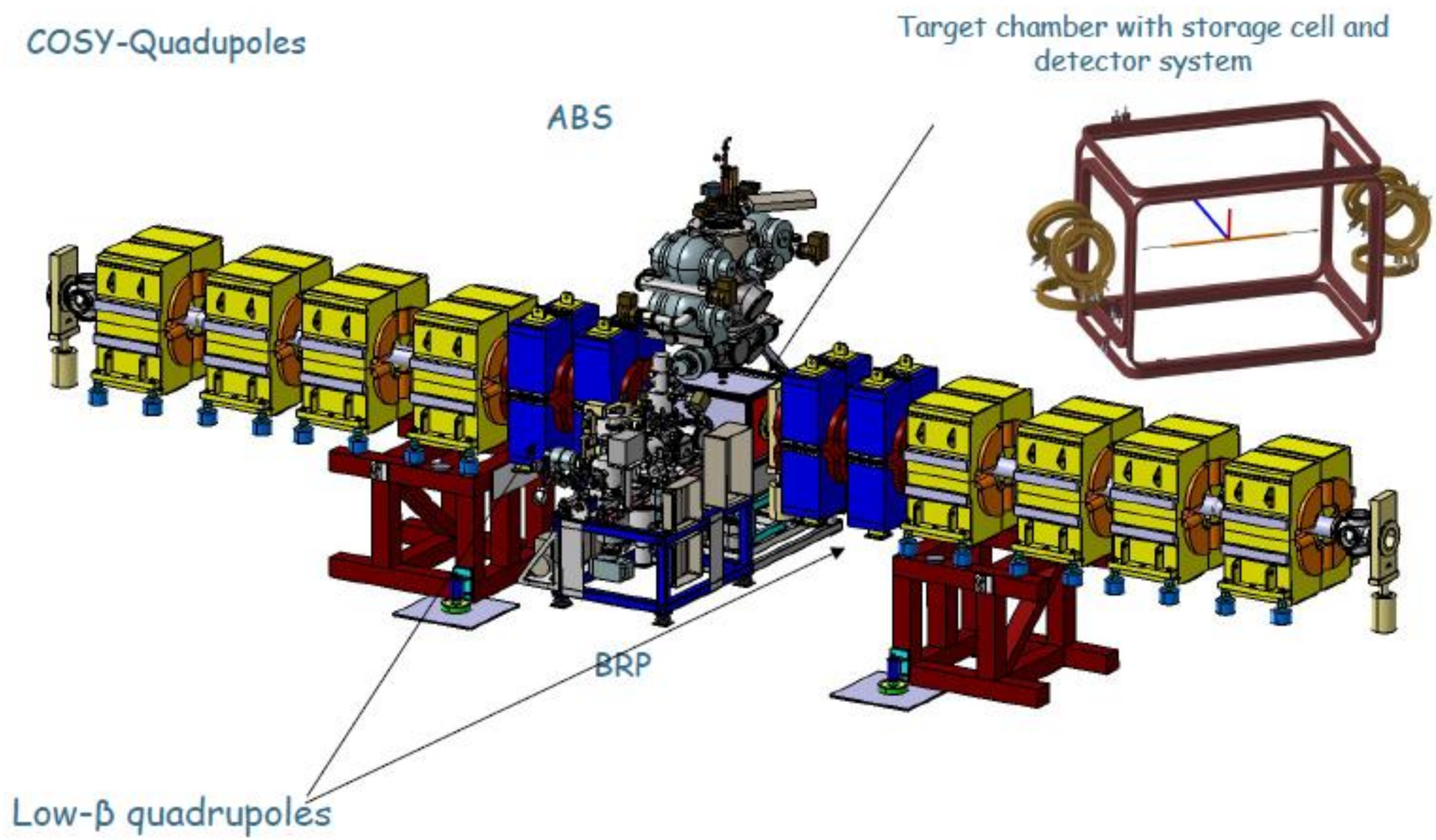
δI is the error of the current measurement in the interval Δt [A]

When are these accuracies equal ? $\delta A_{y,xz}^{meas} = \delta A_{y,xz}^{shot}$

$$h_{min} \propto \delta I$$

The Time Reversal Invariance Experiment at COSY (TRIC)

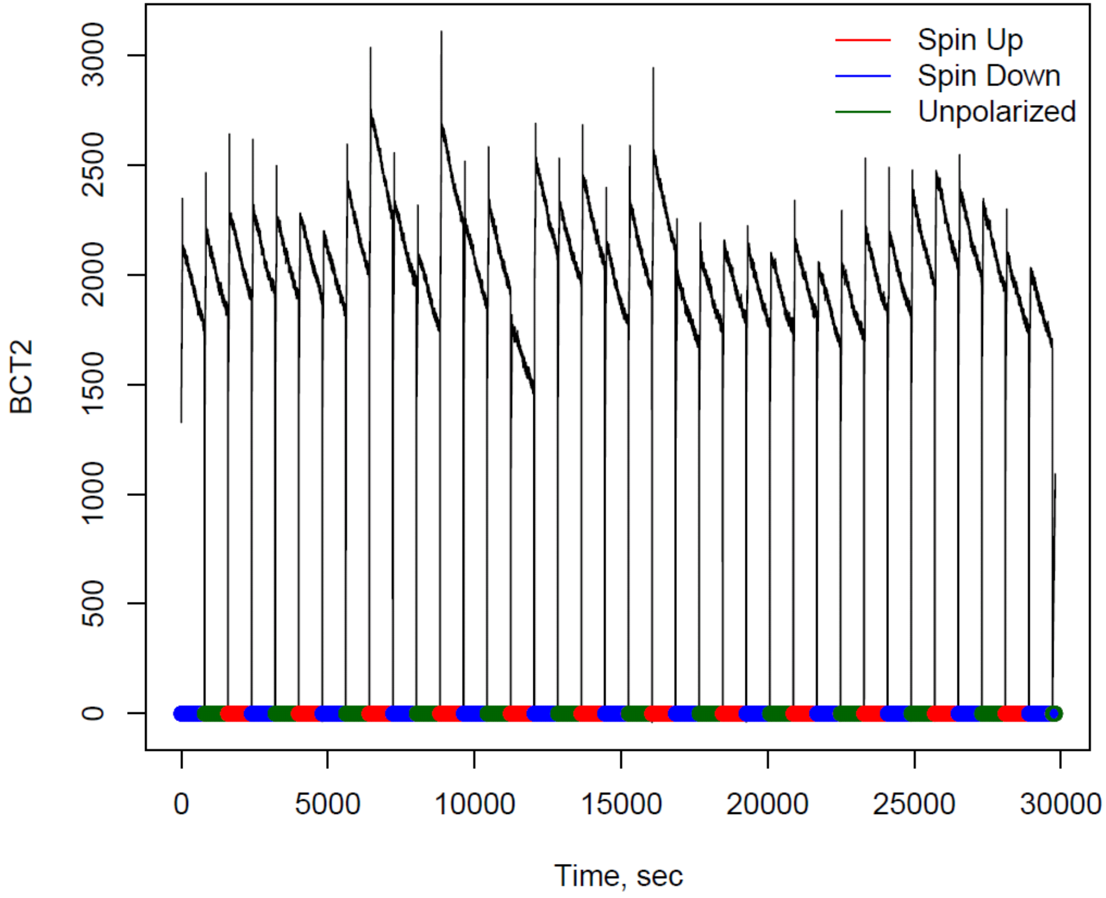
Some Experimental Details



P. Lenisa and F. Rathmann CERN-SPSC-2012-013/SPSC-SR-099

First Test of the Novel Measurement Method

BCT-response run



Preliminary result:

$$A_{y,y}(\vec{p}-\vec{d}) = 0.06 \pm 0.09$$

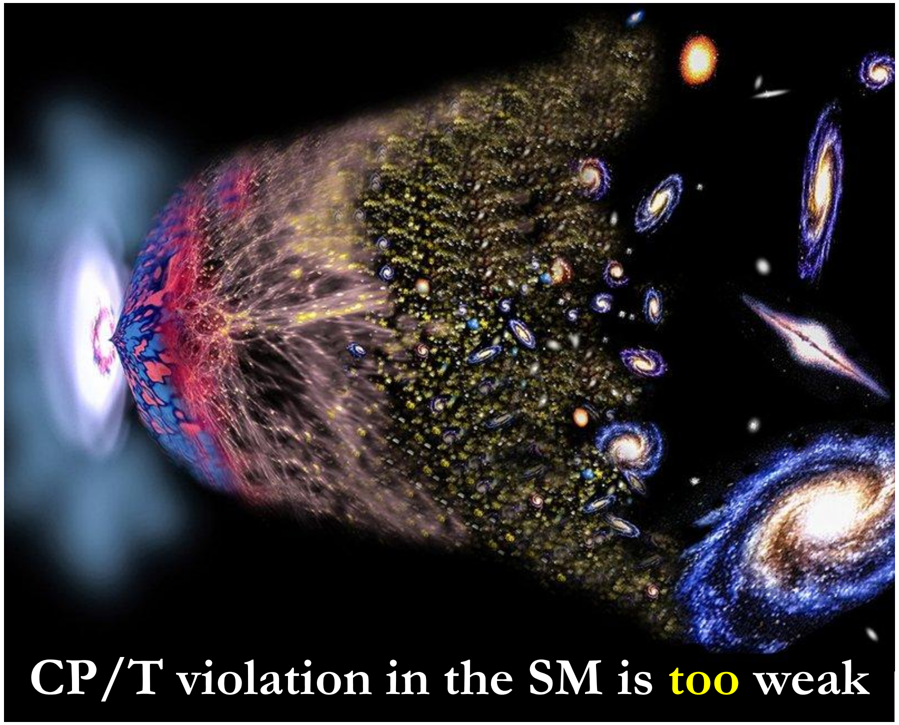
Summary

- **TRIC probes physics beyound the SM**
- **The TRIC experiment at COSY constitutes a precision transmission T-odd, P-even True TRI Null-Test**
- **For the TRIC experiment COSY serves as accelerator, ideal forward spectrometer and detector**
- **COSY is ready for the TRIC experiment**

Thank You

CP/T Violation in Early Universe

Big Bang **Time** → **Today**



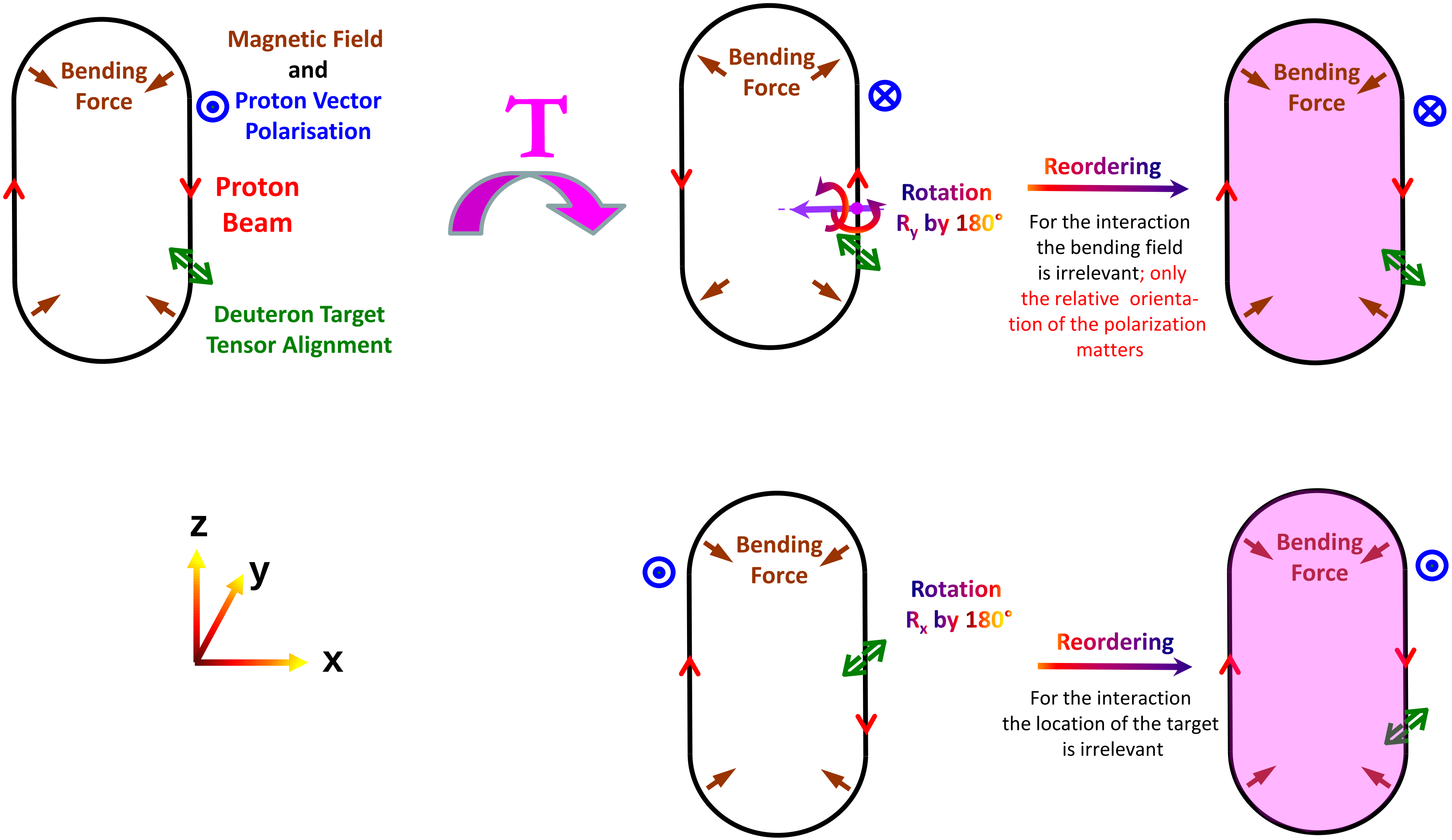
Matter & Antimatter

Matter Only !

New CP/T violation beyond the SM must exist !

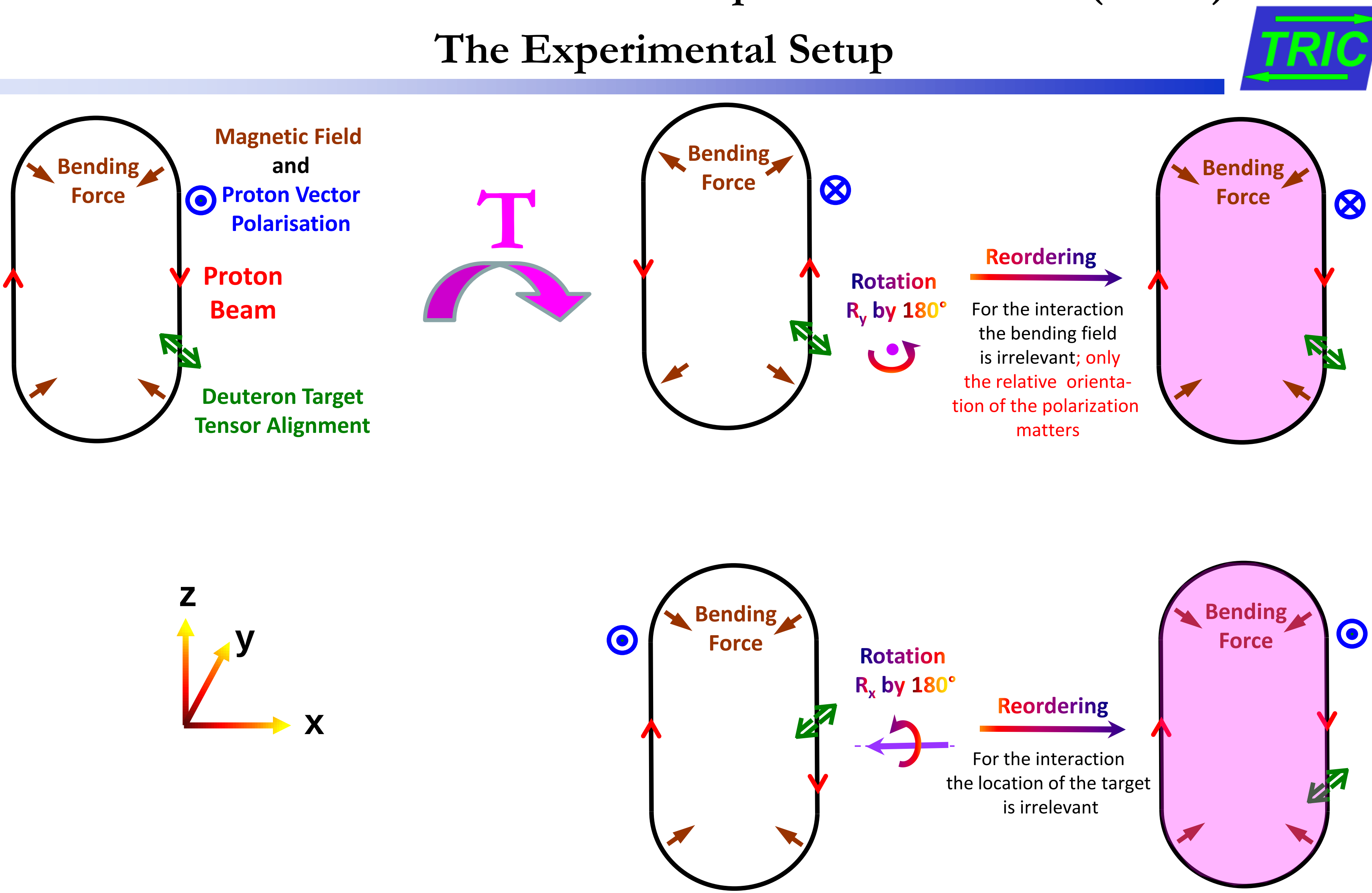
The Time Reversal Invariance Experiment at COSY (TRIC)

The Experimental Setup



The Time Reversal Invariance Experiment at COSY (TRIC)

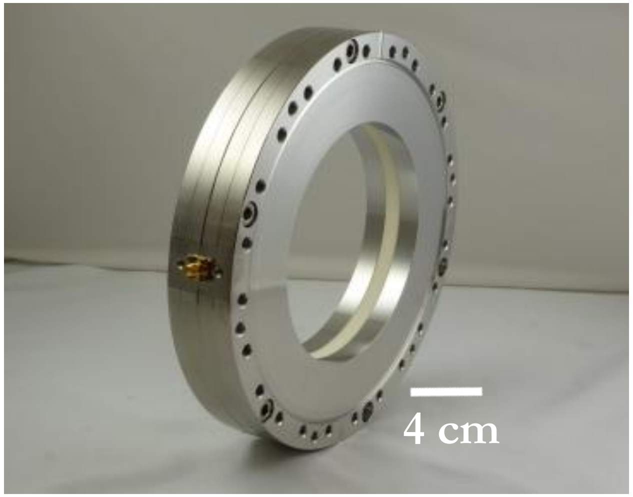
The Experimental Setup



Some Experimental Details

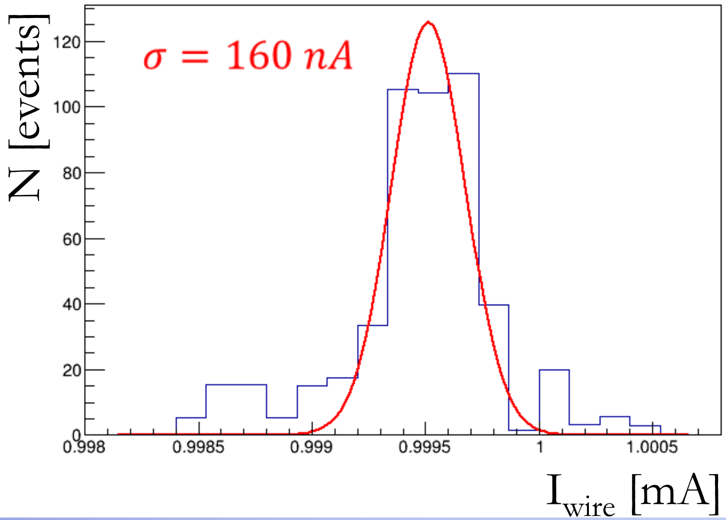
Fast Current Transformer (FCT):

- Commercial device (Bergoz)
- Sensor for bunched beam



Readout Electronics:

- Lock-In-Amplifiers
- High resolution ADC



- With the **FCT** we can detect **down to 40 000 protons** stored in COSY

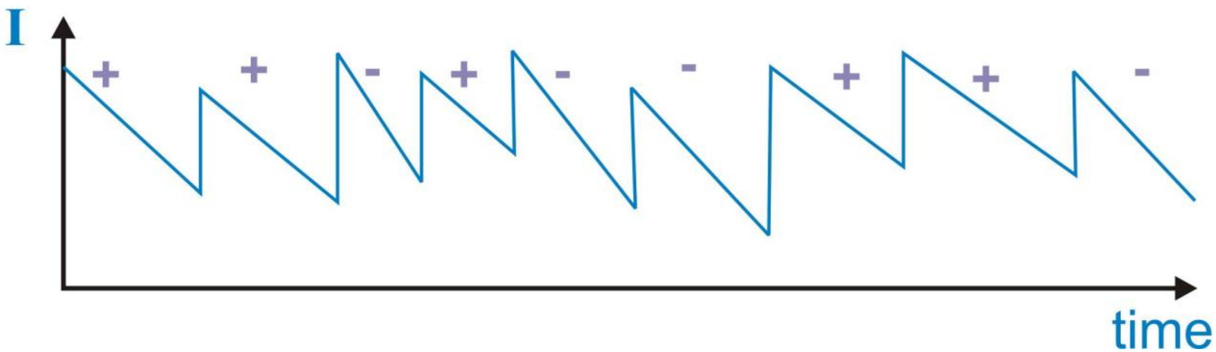
The Experimental Setup

The total pol. correlation $A_{y,\,xz}$ is measured via the forward scatt. amplitude $\mathcal{F}(0)$

$$\sigma_{tot} = \frac{4\pi}{k}\, Im\, F(0) \quad \rightarrow \quad \frac{4\pi}{k}\, Im\, tr(\rho\, \mathcal{F}(0))$$

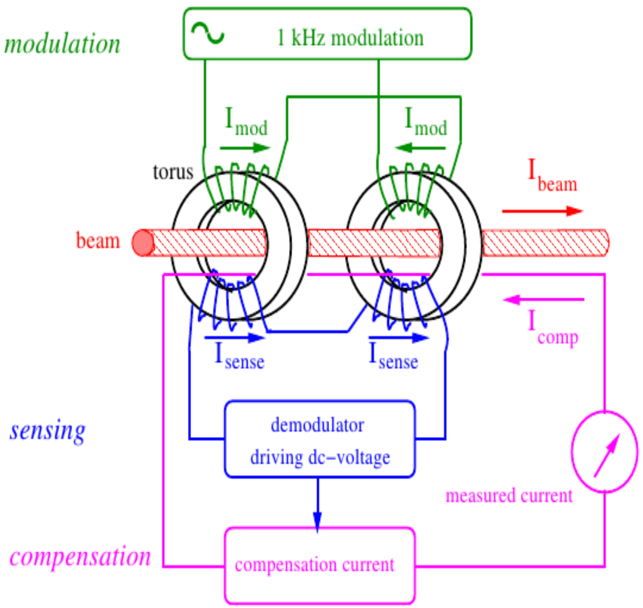
$F(0)$ - Forward scatt. amplitude for unpolarized particles
ρ - Density matrix
$\mathcal{F}(0)$ - Forward scatt. amplitude (matrix) for polarized particles

$A_{y,\,xz}$ is proportional to the relative difference of the current slopes of the circulating proton beam with respect to the chosen polarization configuration (+/-) of the proton beam and deuteron target.

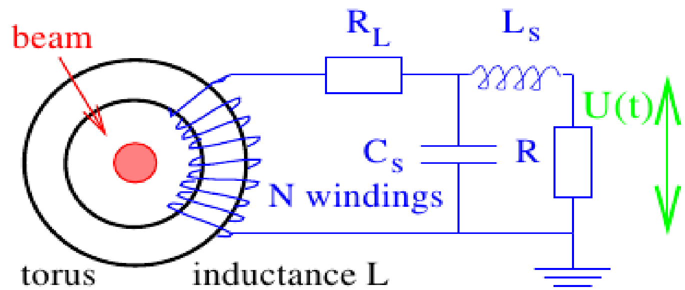


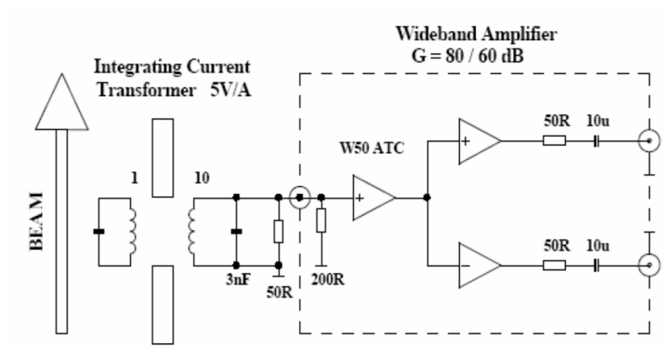
The Time Reversal Invariance Experiment at COSY (TRIC)

DC transformer

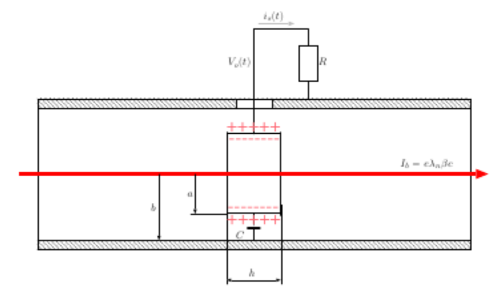


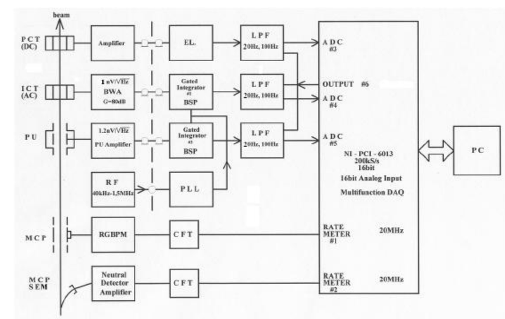
AC transformer





Capacitive pick up





1) COSY BCT σ_I=0.5μA/√Hz

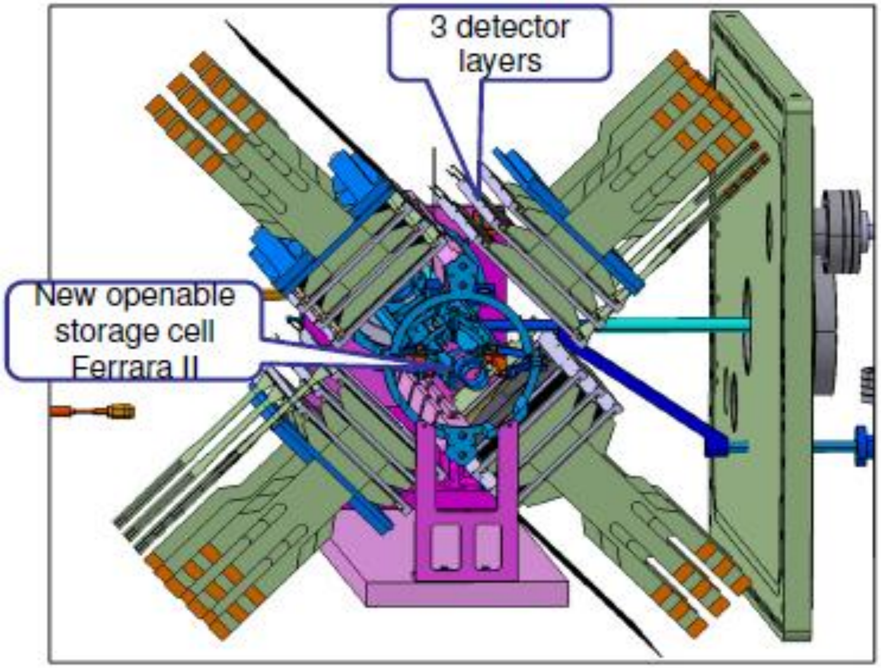
2) NPCT Bergoz σ_I=0.3μA/√Hz

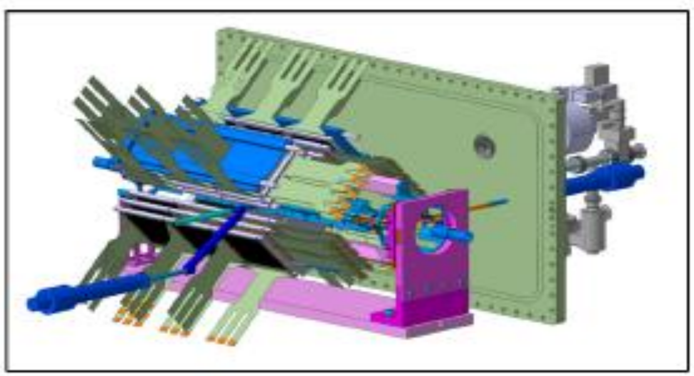
3) CCC GSI σ_I=0.25nA/√Hz

4) ICT Bergoz σ_I=1nA/√Hz

5) ICT Bergoz/CRYRING σ_I=0.1nA/√Hz

The Time Reversal Invariance Experiment at COSY (TRIC)

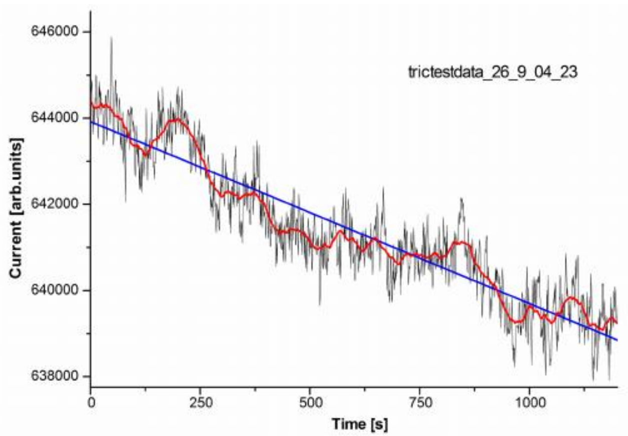


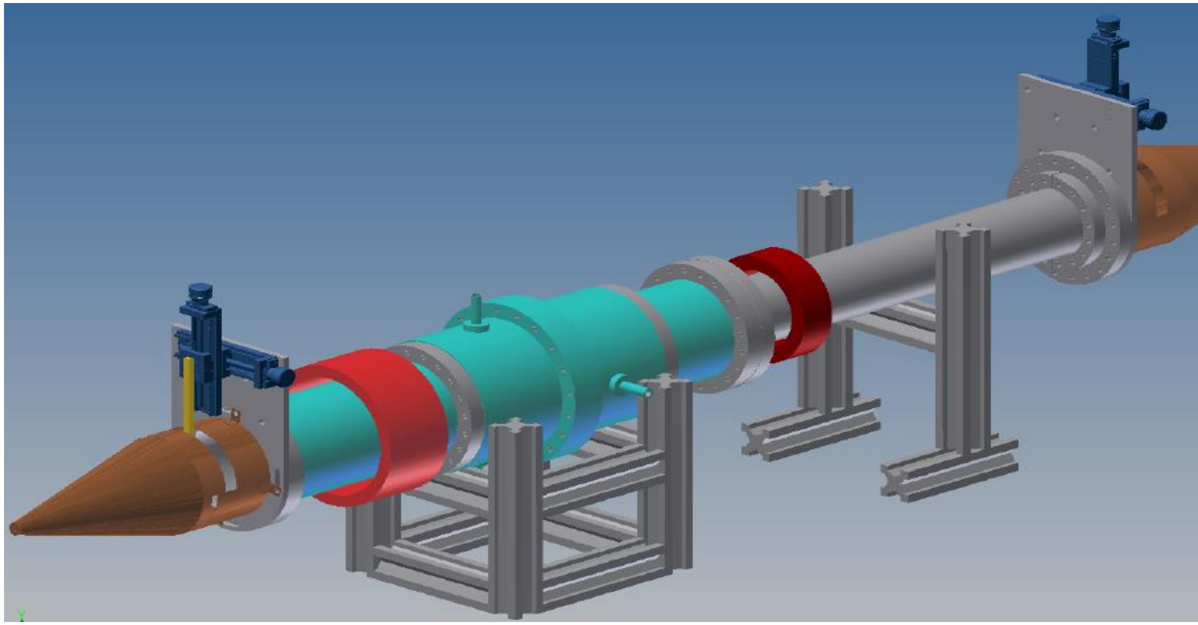


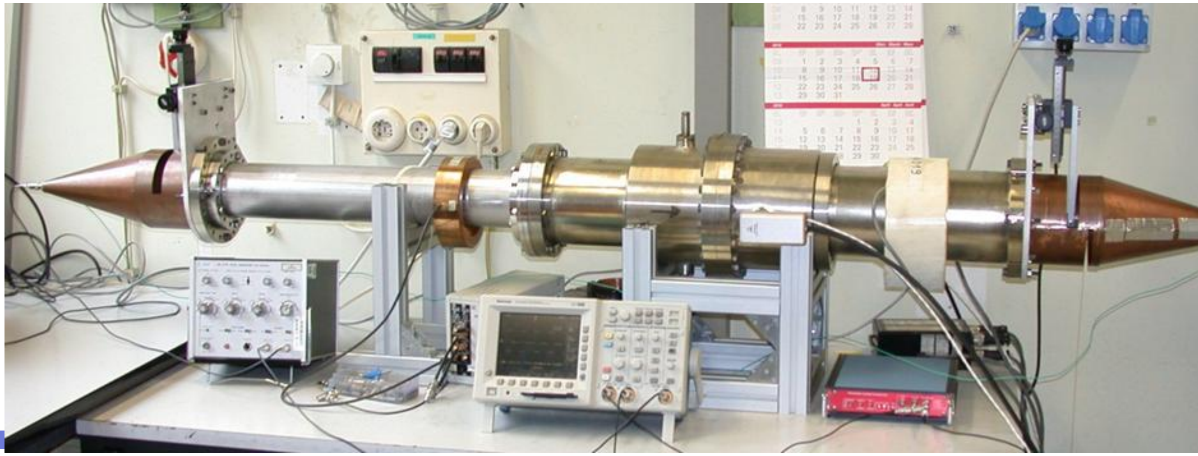
In 2014 at the PAX target place will be available:

- Atomic Beam Source and Breit-Rabi Polarimeter will be capable to operate with deuterium
- Opennable storage-cell for highly polarized target density
- Holding field system to preserve and flip the target polarization during a measurement cycle
- φ - symmetric multipurpose PAX detector for beam and target polarimetry

The Time Reversal Invariance Experiment at COSY (TRIC)

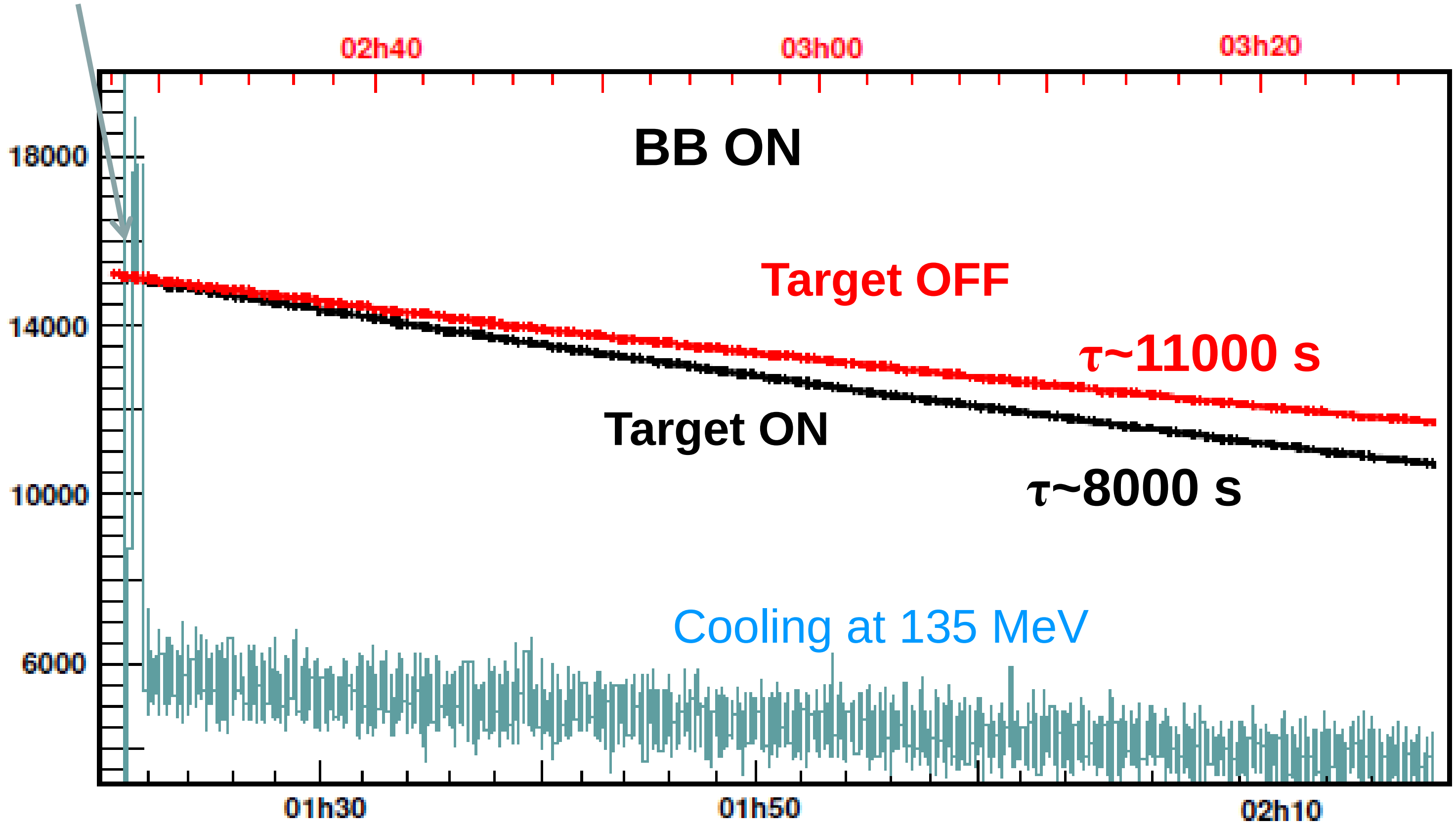






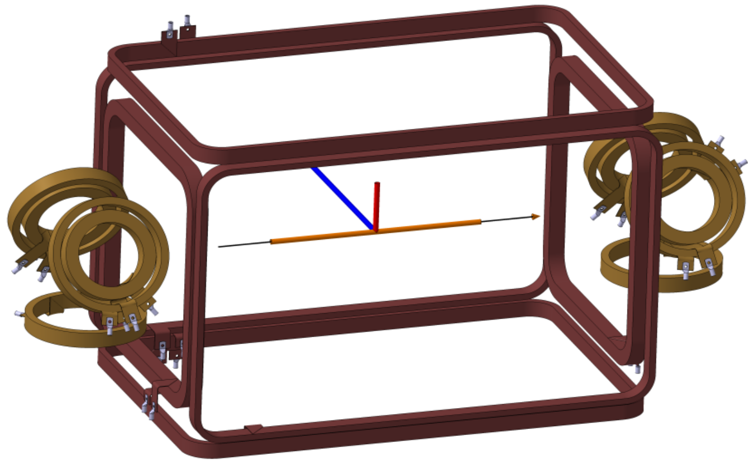
The Time Reversal Invariance Experiment at COSY (TRIC)

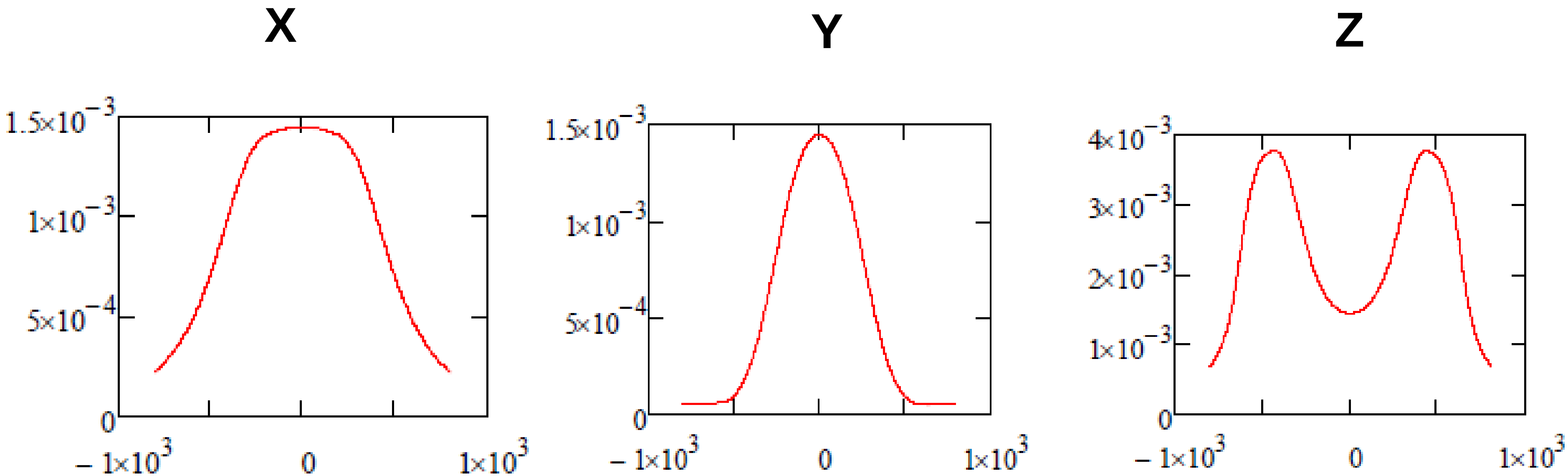
Injection, cooling at Inj., Acceleration



COSY can provide as with a beam through the PAX storage cell

The Time Reversal Invariance Experiment at COSY (TRIC)





Concerning FSI :

Reading the Optical Theorem carefully: $\frac{4\pi}{k} \operatorname{Im} F^{el}(0°) = \sigma_{tot}^{el} + \sigma_{tot}^{inel}$

Has been proven by R.M. Ryndin

(proceeding of 3rd LNPI Winter School, *Test of T-invariance in strong interactions*),

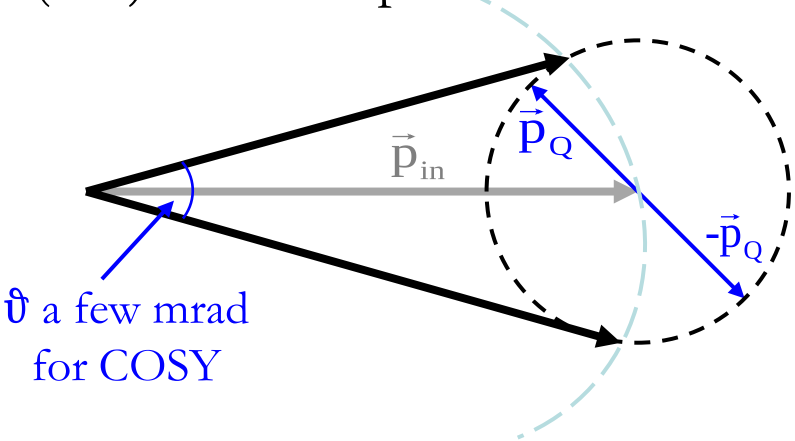
the idea of the proof can be found in: *V. Gudkov and Young-Ho Song, arXiv:1110.1279vl [nucl-th] 6Oct 2011*

Unitarity $\longrightarrow$ Optical Theorem $\longrightarrow$ $F_i(0°) = F_f(0°)$ $\longrightarrow$ Unitarity

Final State Interaction

$$\frac{4\pi}{k}\,\mathrm{Im}\,F^{el}(0°) = \sigma^{el}_{tot} + \sigma^{inel}_{tot}$$

For all inelastic processes the following conditions have to be fulfilled by the (FSI) scattered particles in order to be transported by COSY:



i) The e/m has to be that of a proton to 10^{-4}

ii) The momentum p has to match to at least 10^{-4}

iii) The scattering angle ϑ must not exceed a few mrad

The phase space is considered to be virtually Zero

The Time Reversal Invariance Experiment at COSY (TRIC)

TRI and Parity Tests

TRIC

$\gamma - \gamma$	correlation in ^{57}Fe	$\bar{\alpha}_{\not T} \leq 5\cdot 10^{-6}$	
Detailed Bal.	in p + ^{27}Al ↔ ^{4}He + ^{24}Mg	$\bar{\alpha}_{\not T} \leq 10^{-3}$	
P – A	in $\vec{p}$ - p scattering	$\bar{g}_{\not T} \leq 3\cdot 10^{-2}$	
Neutron EDM		$\bar{g}_{\not T \not P} \leq 10^{-11}$	$\bar{g}_{\rho \not T} \leq 1.5\cdot 10^{-3}$
Atomic EDM	in ^{199}Hg		$\bar{g}_{\rho \not T} \leq 1\cdot 10^{-2}$
CSB	ΔA for $\vec{n}$ - p and $\vec{p}$ - n scatt.		$\bar{g}_{\rho \not T} \leq 6.7\cdot 10^{-3}$
$\vec{n}$ - transm.	through $^{165}\vec{\mathrm{Ho}}$	$\bar{g}_{\not T} \leq 2.8\cdot 10^{-4}$	$\bar{g}_{\rho \not T} \leq 2.3\cdot 10^{-2}$

Null-tests

A_L in $\vec{p}$ - p scattering (δA ~ $2\cdot 10^{-8}$)

$A_{y,xz}$ in $\vec{p}$ - $\vec{d}$ scattering (potentially **0.1** $\cdot\ \bar{g}_{\rho \not T}$ of $^{165}\vec{\mathrm{Ho}}$)

$\bar{\alpha}_{\not T}$ Strength of eff. T-violating N-core potential

$\bar{g}_{\not T / \not T \not P}$ Strength of T-violating / TP-violating NN potential

$\bar{g}_{\rho \not T}$ Strength of T-violating ρ-MN coupling constant

Parity Violation

Why can A_z be measured to the 10^{-7} level ?

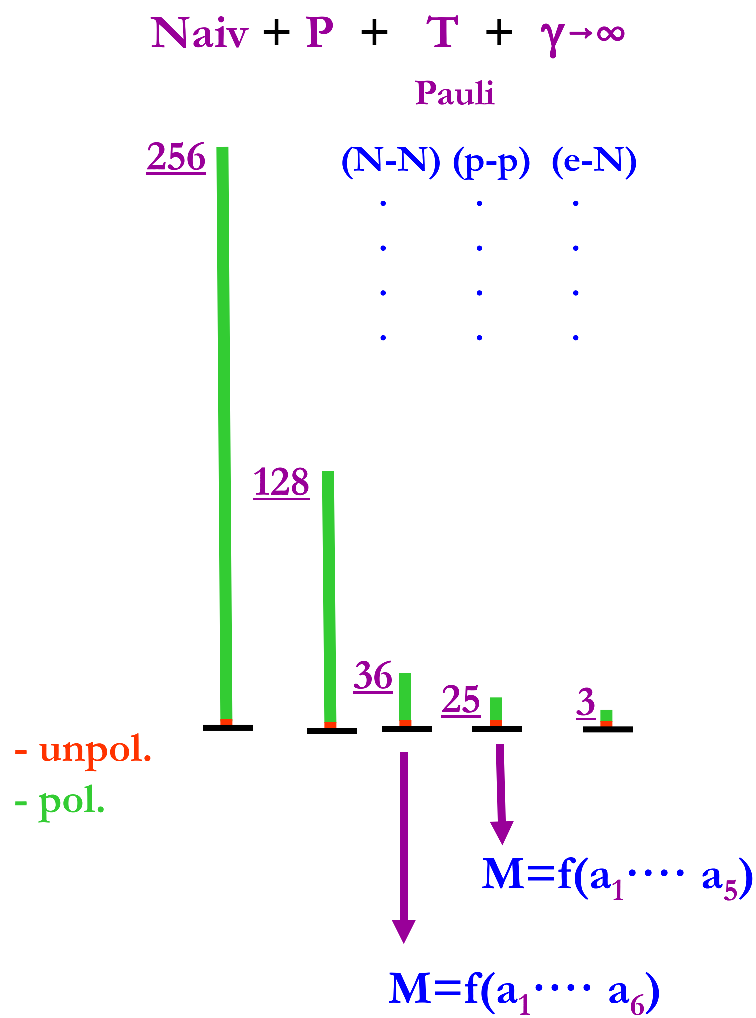
- A_z measurement is a **Null-Experiment.**
- **Signature** of A_z is **unique** compared to other observables.
- As A_z is a polarization observable, it is a **relative measurement**.

In addition:

- **Reduce sensitivities** to errors by proper set-up/alignment.
- Reduce „error amplitudes“ by **feedback control**.
- **Correct** for remaining errors.
- Convince yourself by measurement, that error contributions thought to be negligible, are negligible.
- Is the reduced χ^2 after all corrections close to **1** ?

Parity Violation

Number of Spin½ + Spin½ Observables



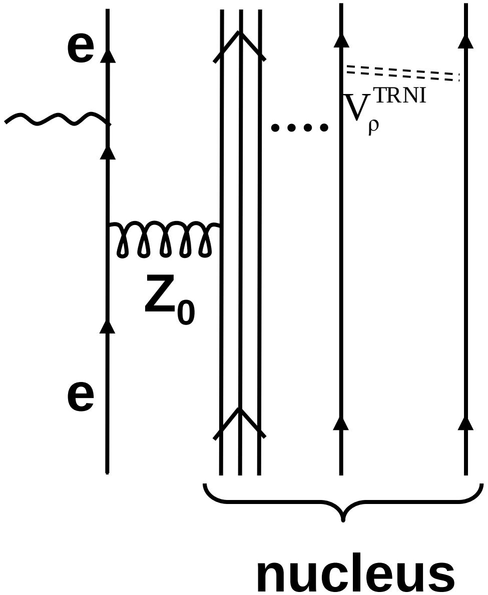
Example:

$$\sigma_0 = \sum_i a_i a_i^*$$

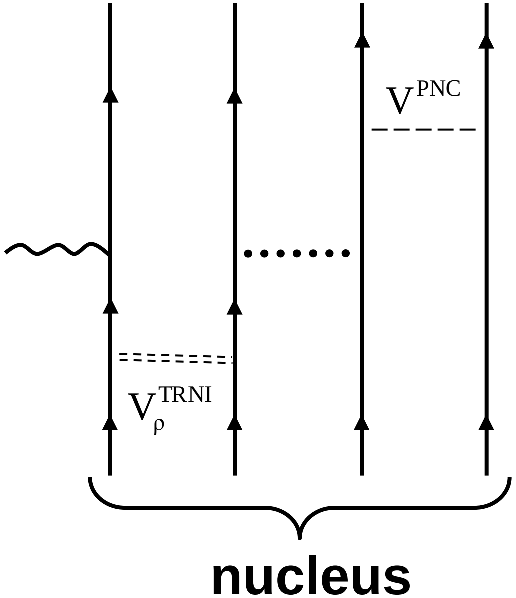
$$\sigma_{pol} = \sum_{i,j} \pm a_i a_j^*$$

The Time Reversal Invariance Experiment at COSY (TRIC)
Defining the Goal for TRIC

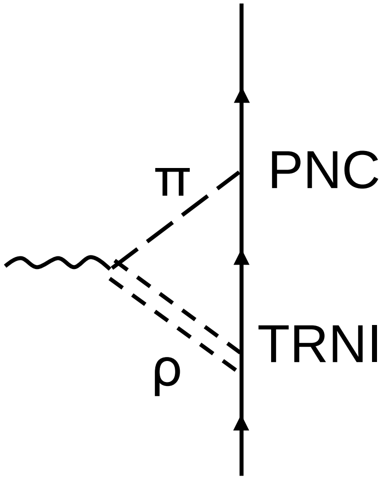
The atomic EDM



The nuclear EDM



The nucleon EDM



W.C.Haxton. Antje Höring and M.J. Musolf, Phys.Rev. ***D50*** *(1994) 3422*

Defining the Goal for TRIC

EDM of an elementary particle :

Observable : $\vec{\sigma} \cdot \vec{E}$

P-odd/T-odd experiment

Upper limit from n-EDM

Prediction: Deduced Strength for **P-even/T-odd** : $\bar{g}_{\rho \cancel{T}} < 1.5 \cdot 10^{-3}$

W.C.Haxton. Antje Höring and M.J. Musolf, Phys.Rev. ***D50*** *(1994) 3422*

Experiment: From $A_5 = 8.6 \pm 7.7 \cdot 10^{-6}$ gives: $\bar{g}_{\rho \cancel{T}} : 2.3 \pm 2.1 \cdot 10^{-2}$

P.R. Huffmann et al., Phys.Rev. ***C55*** *(1997) 2684*

The Time Reversal Invariance Experiment at COSY (TRIC)

Some Experimental Details

- The error in the TRI sensitive observable $A_{y,xz}$ depends on :
  i) The accuracy with which the current of circulating protons are measured

  ii)The number of turns of the proton beam through the target

$$\Delta T_{y,xz} = \frac{T^{+} - T^{-}}{T^{+} + T^{-}} = \frac{\exp-(\chi^{+}) - \exp-(\chi^{-})}{\exp-(\chi^{+}) + \exp-(\chi^{-})}$$

with: T^{+} -Transmission factor for the proton-deuteron spin-configuration with $P_y \cdot P_{xz} > 0$

T^{-} -Transmission factor for the time reversed situation, i.e. $P_y \cdot P_{xz} < 0$

$\chi^{+/-}$ -Is the product of the factors $(\sigma_{tot} \cdot \varrho d \cdot n)$ with respect to the proton-deuteron spin-alignment

$$\boxed{\Delta T_{y,xz} = -\sigma_o \, \varrho d \, n \, P_y \, P_{xz} \, A_{y,xz} =: - S \, A_{y,xz}}$$

with: S - Is the sensitivity of the experiment with respect to $A_{y,xz}$

n - Number of turns the beam takes through the target

Outline

- **Why** is this experiment interesting ?
- **What** do we measure ?
- **How** do we measure ?
- **Some Tricks of TRIC**
- **Summary**