POLARIZATION AND ELECTRIC DIPOLE MOMENTS – THE GRAND PICTURE

Kurt Aulenbacher,
Institut für Kernphysik,
Johannes Gutenberg-Universität Mainz

From EuCARD-2 XBEAM to ARIES APEC, Valencia, Spain

February,14, 2017

OUTLINE

- What did we learn from XBEAM WP-5.5 “Polarization” ?

→ Polarization in upcoming accelerator projects

→ The role of polarization measurement

→ Electric Dipole Moments

Polarization at the low energy scale („small“ accelerators)

- **Discovery** (strong CP and T violation)
- **Precision** experiments (weak P violation) with small scale accelerators

EUCARD-2 workshop "Search for the electron EDM in an electrostatic storage ring"
10-11 September 2015
Mainz
https://indico.mitp.uni-mainz.de/event/38/

Polarization at the high energy scale... (future BIG projects).

EUCARD-2 workshop "Spin optimization at Lepton accelerators"
12-13 February 2014
Mainz
https://indico.mitp.uni-mainz.de/event/18/

EuCARD-2 XPOL workshop on "Polarization Issues in Future High Energy Circular Colliders"
16 April 2016
Rome
https://indico.mitp.uni-mainz.de/event/62/

Polarization at the high energy scale...

(future BIG projects).

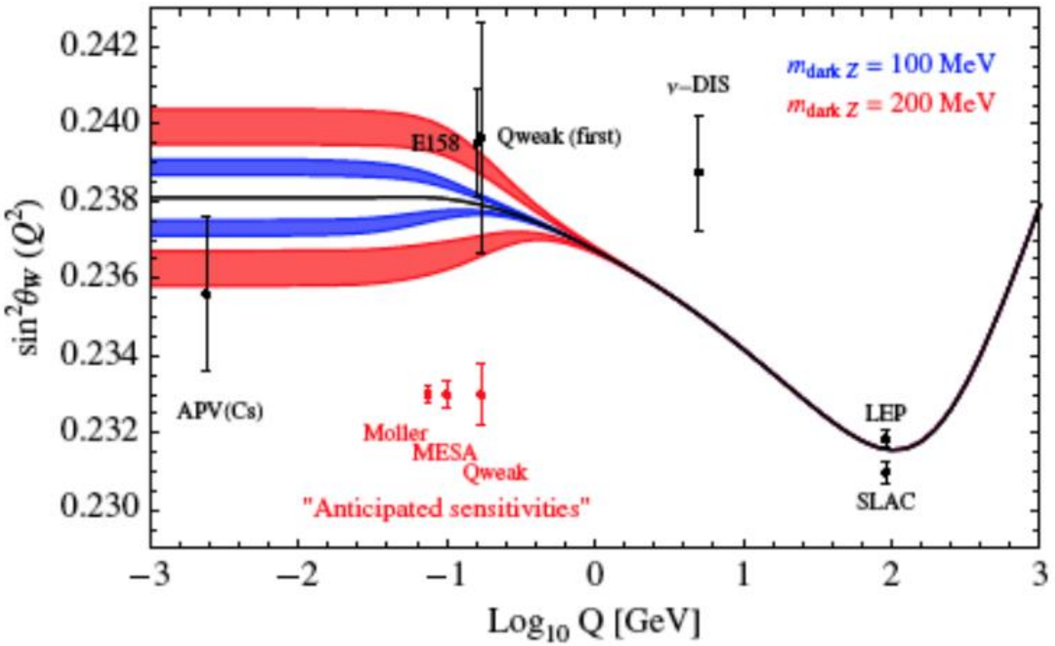
- Precision measurements at the ILC
  1. Polarized positron source technologically challenging
  2. Polarization measurement via Compton backscattering promising (ΔP/P ~0.1%)
- Precision beam parameters at the FCC-(ee)
  -absolute energy calibration (by resonant depolarization) order ΔE/E ~ 10-6
- High energy pol. proton beam at the fcc-hh is not completely impossible (would increase circumference by „only“ a few %)
- Fixed Target pol. at LHC or FCC-hh is possible
- LHeC collider arrangement (linac-ring) is feasible with polarized electron beam

Observables in future accelerator spin physics

- Storage ring: EDM (~~CP~~ „JEDI“)
  - Aiming at discovery of an effect
  - FCC-ee: Precision energy calibration for resonance
- Linac : Parity violating electron scattering , e.g. At JLAB, SLAC or MESA, ILC: Precision measurements
  - -neutron skins (PREX, ...) (program ongoing→ JLAB & MESA)
  - weak charge (E166, QWEAK, program ongoing → Moller, P2)
  - elctroweak production and precision measurements at ILC e.g. 350 GeV (tt-threshold)

Observables in NEAR and MEDIUM FUTURE
future accelerator spin physics

- LINAC example : Parity violating electron scattering
  - accurate measurement of electro weak mixing angle „$\sin^2\theta_W$“



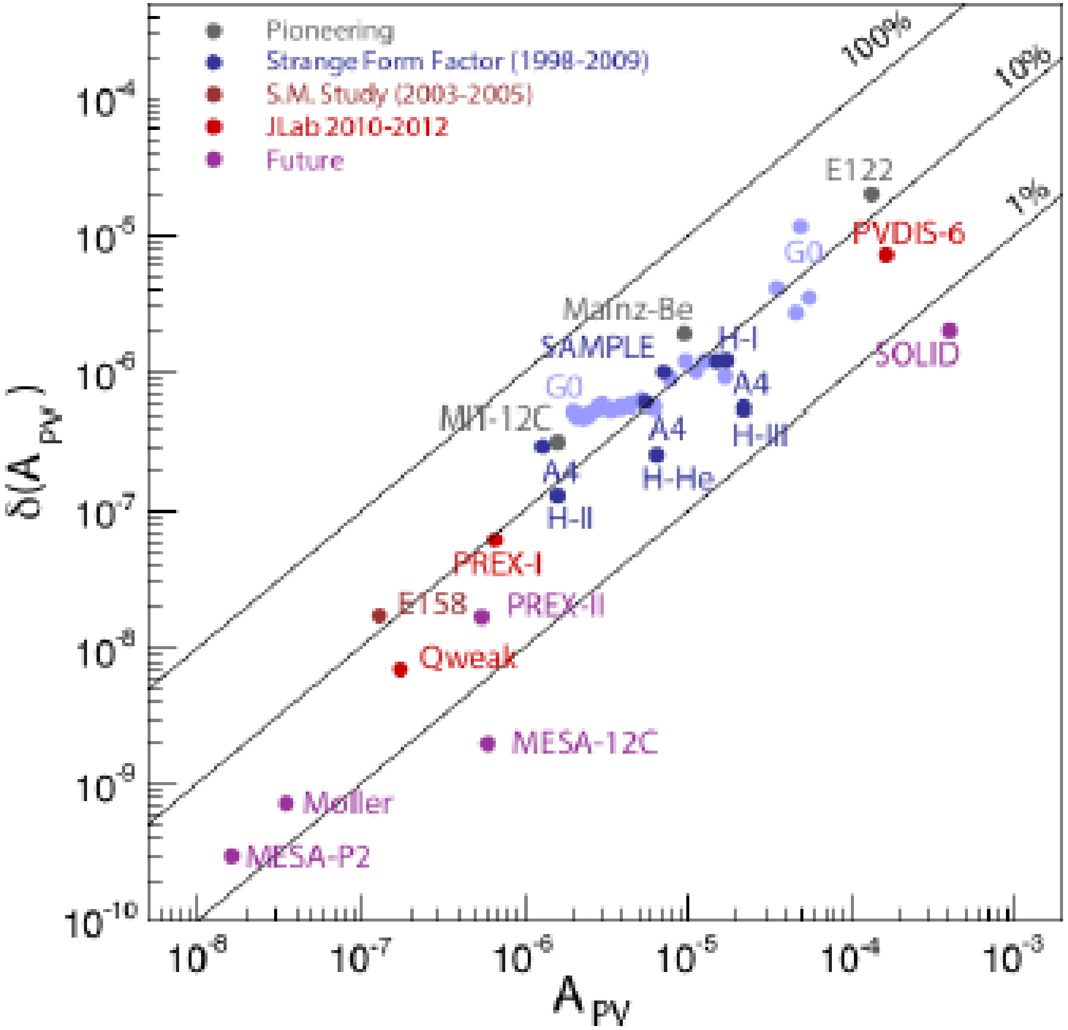
Influence of
„dark Z boson“
which also contributes
to muon anomalous
magnetic moment..

F. Maas, PAVI2014 conf.

„Elastic electron scattering on proton measures 1-4sin$^2\Theta_W$ → small asymmetry , high sensitivity

- Supressing hadronic contributions favours low momentum transfer and low beam energy

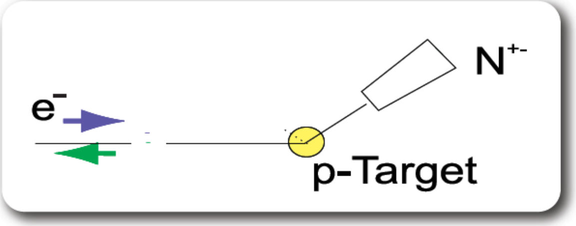
Challenge: low signal, high accuracy

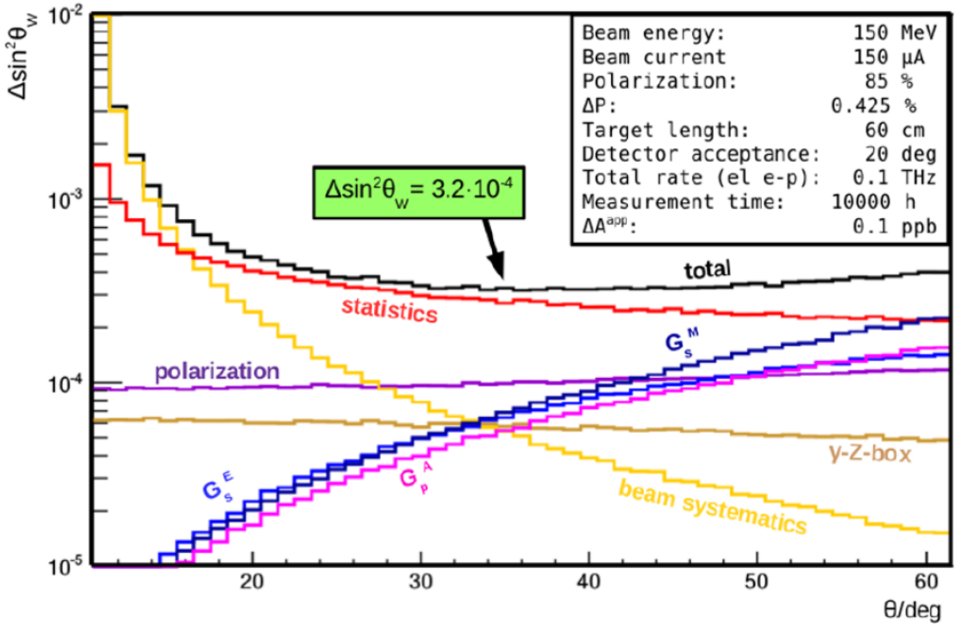


S. Baunack
PAVI 2016

The P2 Experiment at MESA

-basic demands





150 µA Beamcurrent , 60cm lq. H2, Beampol: 85%.
10000 h Data-taking (~13-15000 h Runtime)
High accuracy polarization measurement (ΔP/P=0.5% !!)
Extremely high demands on control of HC-fluctuations!

- Good option at energies > a few GeV is Laser-Compton backscattering with Potential error $\sim 10^{-3}$
- Two independent methods seem to be required anyway: Hydro Möller & Double scattering

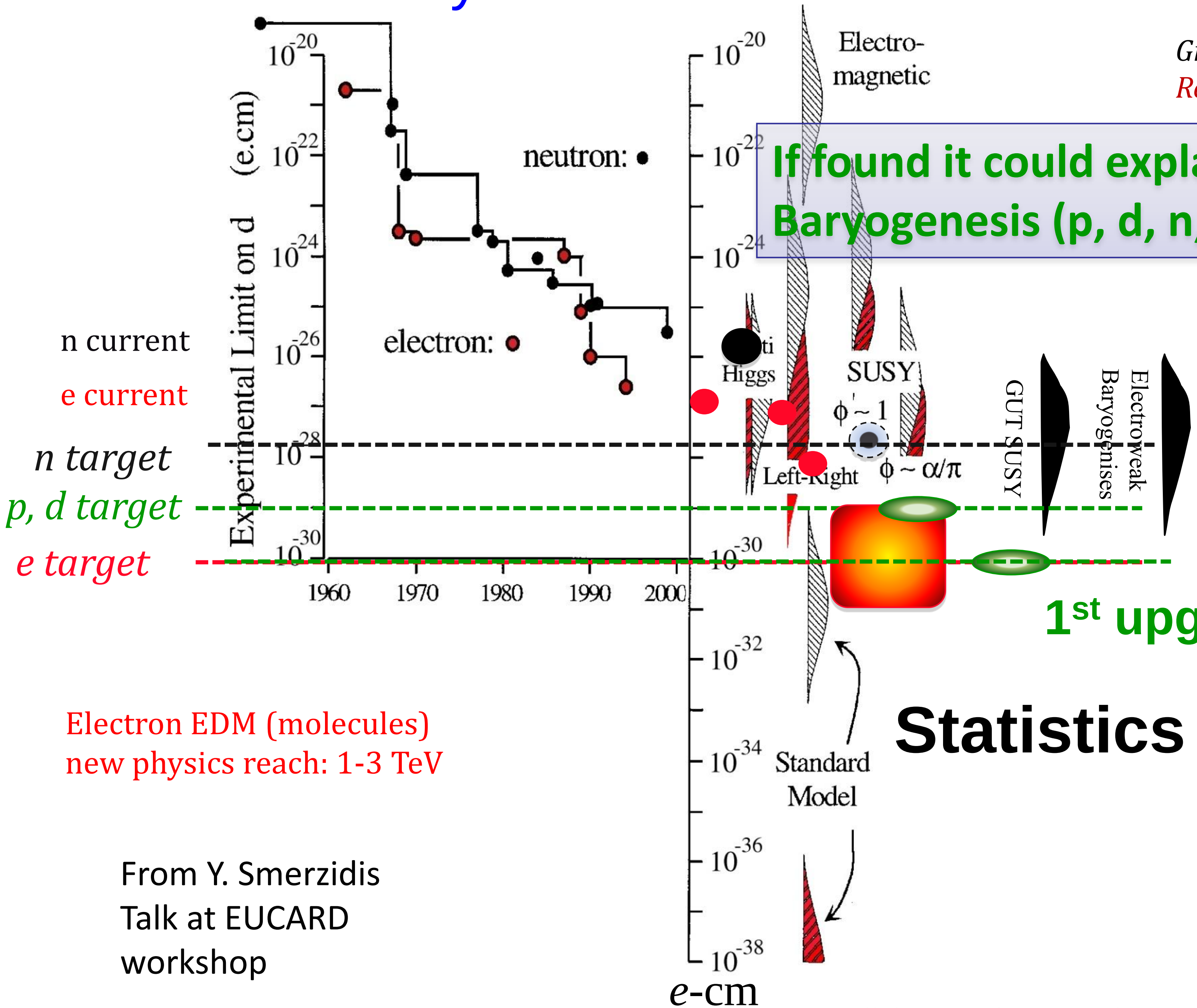
F. Maas PAVI2014 conf.

Observables in NEAR and MEDIUM FUTURE
future accelerator spin physics

- Storage ring example: Jülich Electric Dipole Moment Investigations EDM (~~CP~~ „JEDI“) - Aiming at discovery of effect in „electrostatic storage ring“

Why is this important?

Sensitivity to Rule on Several New Models



Gray: Neutron

Red: Electron

If found it could explain Baryogenesis (p, d, n, ^{3}He)

n current

e current

n target

p, d target

e target

1st upgrade

Statistics limited

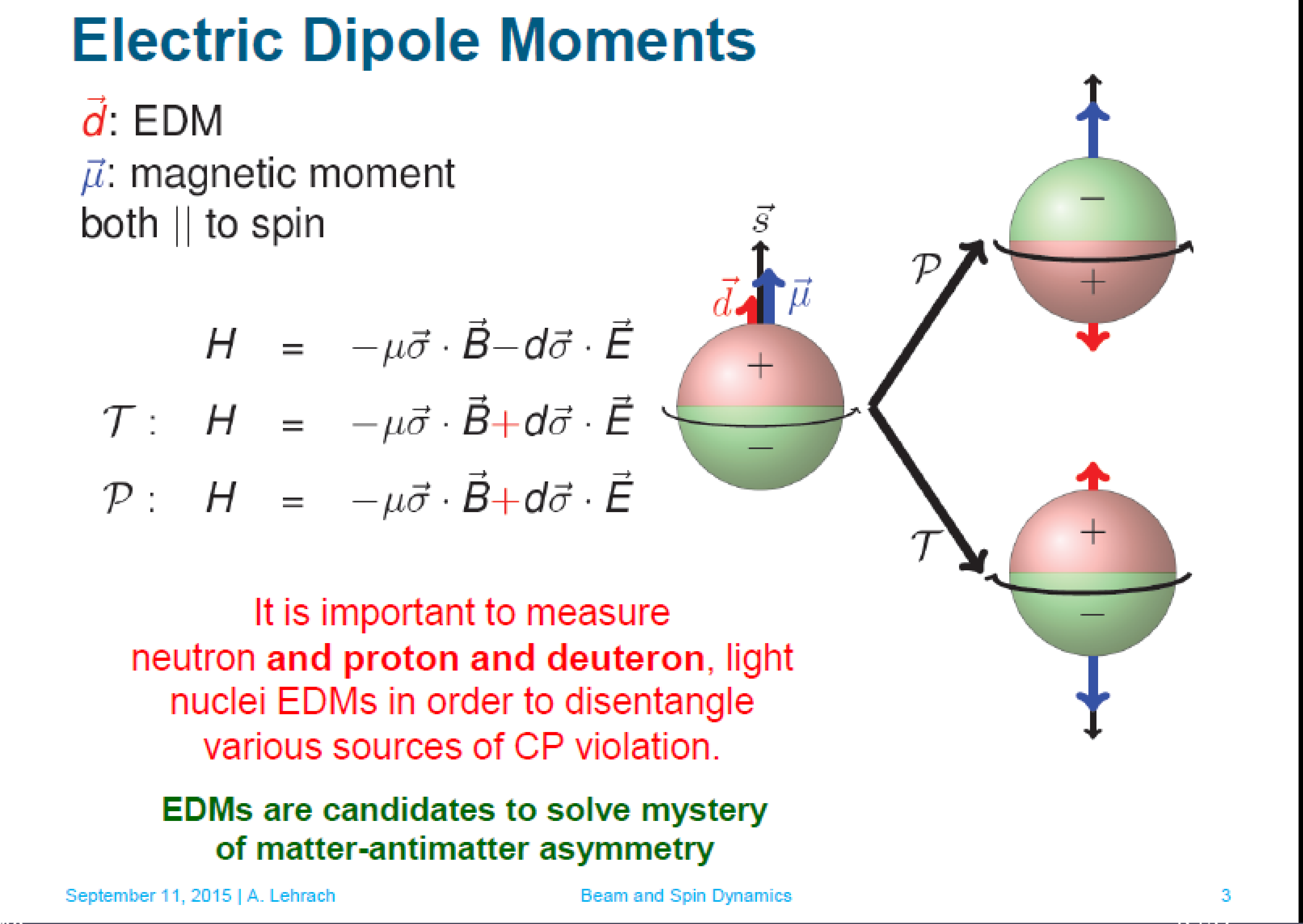
Electron EDM (molecules)
new physics reach: 1-3 TeV

From Y. Smerzidis
Talk at EUCARD
workshop

J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

Observables in NEAR and MEDIUM FUTURE
future accelerator spin physics

From A. Lehrachs talk at the EUCARD-2 workshop



Electric Dipole Moments

$\vec{d}$: EDM
$\vec{\mu}$: magnetic moment
both || to spin

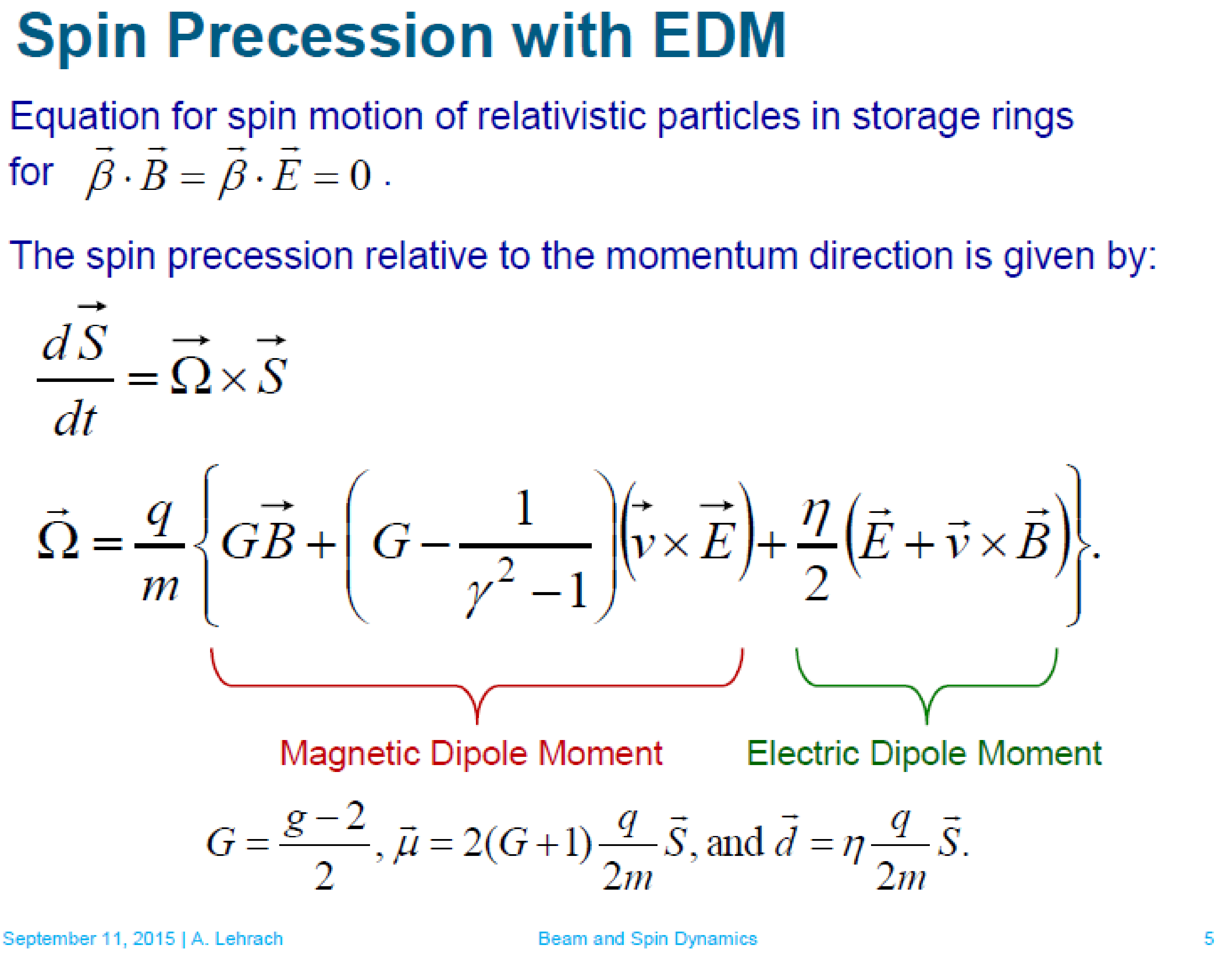
$$\begin{aligned} H &= -\mu\vec{\sigma}\cdot\vec{B} - d\vec{\sigma}\cdot\vec{E} \\ \mathcal{T}: \quad H &= -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E} \\ \mathcal{P}: \quad H &= -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E} \end{aligned}$$

It is important to measure neutron **and proton and deuteron**, light nuclei EDMs in order to disentangle various sources of CP violation.

EDMs are candidates to solve mystery of matter-antimatter asymmetry

Observables in NEAR and MEDIUM FUTURE
future accelerator spin physics

From A. Lehrachs talk at the EUCARD-2 workshop



Spin Precession with EDM

Equation for spin motion of relativistic particles in storage rings for $\vec{\beta} \cdot \vec{B} = \vec{\beta} \cdot \vec{E} = 0$.

The spin precession relative to the momentum direction is given by:

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

$$\vec{\Omega} = \frac{q}{m}\left\{ \underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\left(\vec{v} \times \vec{E}\right)}_{\text{Magnetic Dipole Moment}} + \underbrace{\frac{\eta}{2}\left(\vec{E} + \vec{v} \times \vec{B}\right)}_{\text{Electric Dipole Moment}} \right\}.$$

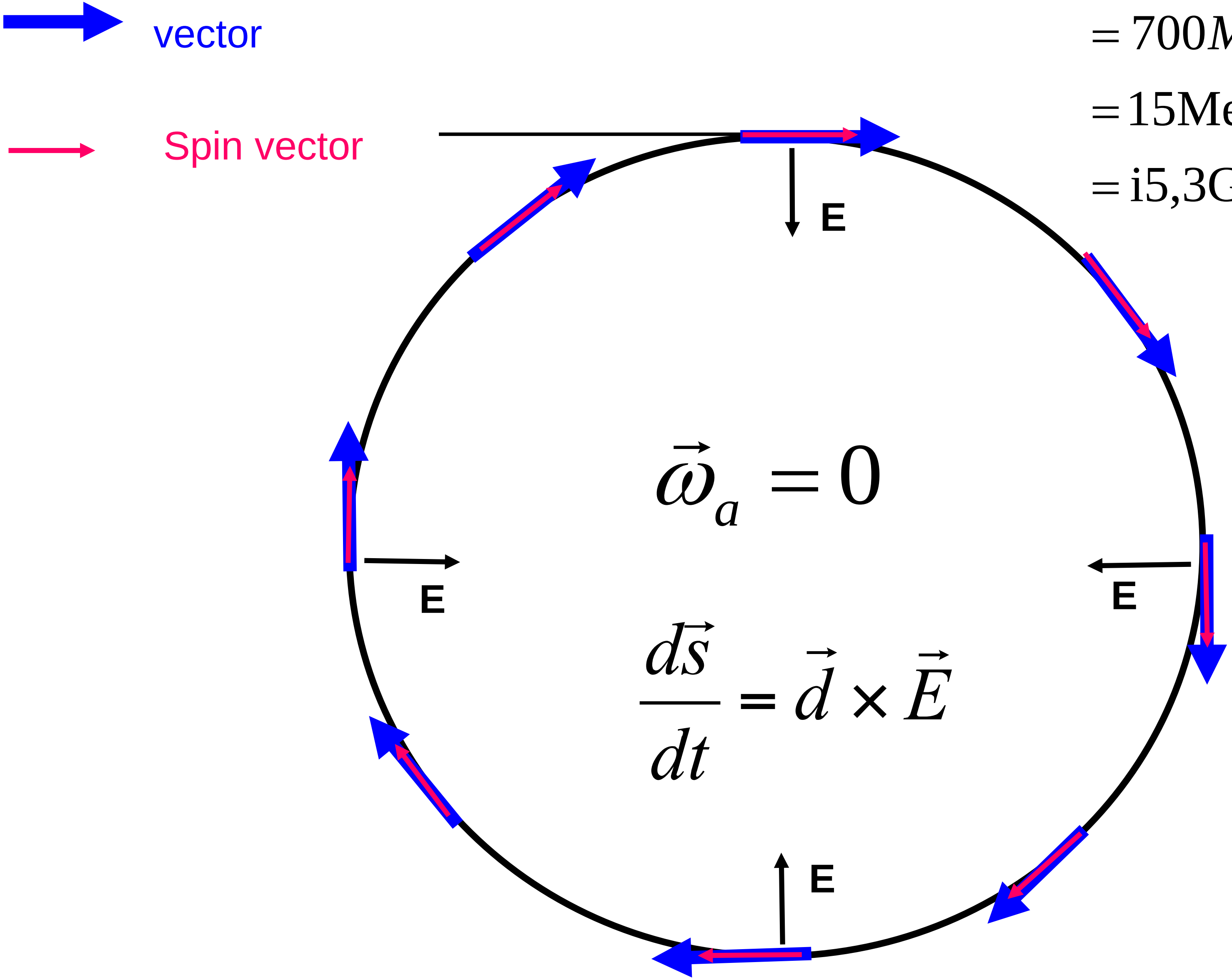
$$G = \frac{g-2}{2}, \vec{\mu} = 2(G+1)\frac{q}{2m}\vec{S}, \text{and } \vec{d} = \eta\frac{q}{2m}\vec{S}.$$

$$p_{freeze} = \frac{m}{\sqrt{G}}$$

$$= 700 MeV/c \quad \text{(Proton)}$$

$$= \text{15MeV/c (Elektron)}$$

$$= \text{i5,3GeV/c (Deuteron)}$$



$$\vec{\omega}_a = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

Observables in NEAR and MEDIUM FUTURE future accelerator spin physics

- stat. Sensitivity for EDM detection

$$Sens = \frac{1}{\sigma_{EDM}} > 1$$

$$Sens \propto P_{beam} \sqrt{I_{stored} * t_{dec} * t_{\exp}}\, \varepsilon \Longrightarrow$$

t_{dec} = decoherence time of beam polarization (>> fill time)

$$\Rightarrow t_{\exp} \approx N_{Fill} t_{dec} \Rightarrow Sens = P_{beam} t_{dec} \varepsilon \sqrt{I_{stored} * N_{Fill}} \quad (*)$$

$\varepsilon \propto S \sqrt{\frac{I_{Scat}}{I_{Beam}}}$: Statistical Quality factor of Polarization analysis:

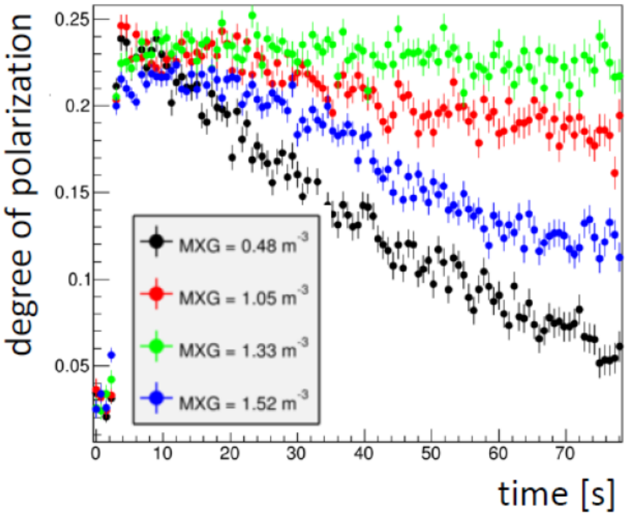
S is called the analyzing power

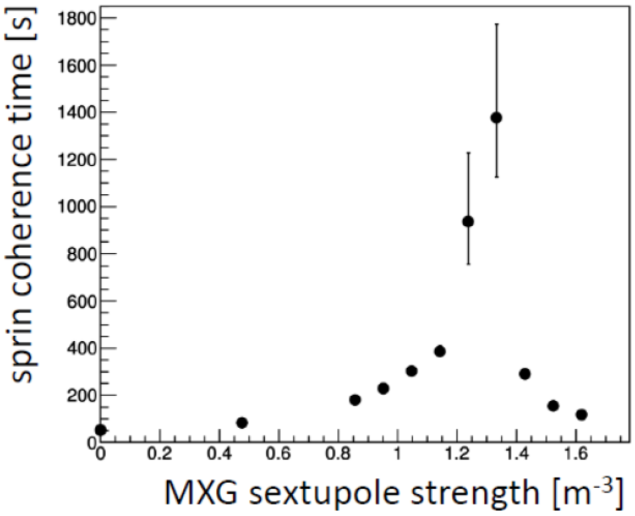
(*) many challenges of spin physics unitied in one formula!

Spin coherence time at COSY

10^9 polarized deuterons at 970 MeV/c, bunched and electron cooled

adjust three arc sextupoles to increase spin coherence time





→ Long SCT for adjusted transverse beam chromaticities

Poster by Greta *Guidoboni* (UNIFE, Ferrara) at IPAC 2015: THPF146
Spin Coherence Time Lengthening of a Polarized Deuteron Beam with Sextupole Fields

A. Lehrach, FZJ

Signals and systematic errors in ....

- EDM (~~CP~~ „JEDI“)

  - spurious polarization occurs

$$P_{y,obs} = P_{y,EDM} + P_{y,imperfect}$$

  - $P_{y,imperfect}$ are caused by , e.g., horiz B-field

- PV electron scattering

  - „false Asymmetries“

$$A_{\exp} = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow} = A_{true} + \sum_{p} Slope_{p}(x_{p}^{\uparrow} - x_{p}^{\downarrow})$$

$$Slope_{p} = \text{Sensitivity of cross section wrt to beam parameter p}$$

$$(x_{p}^{\uparrow} - x_{p}^{\downarrow}) = \text{helicity correlated fluctuation of parameter p, e.g. beam current}$$

Signals and systematic errors in ....

Spurious effects are far too large !

- Example: estimation for EDM precursor experiment at COSY (non optimized, magnetic ring)

“Rotations of the RF Wien filter by 0.1 mrad or normally distributed vertical shifts of the quadrupoles with y = 0.1mm introduced signals mimicking a deuteron EDM of about 5 · 10−19 e cm” (PhD thesis Rosenthal, Aachen, 2016)

- Example: PV

The Helicity correlated Intensity variation is given by:

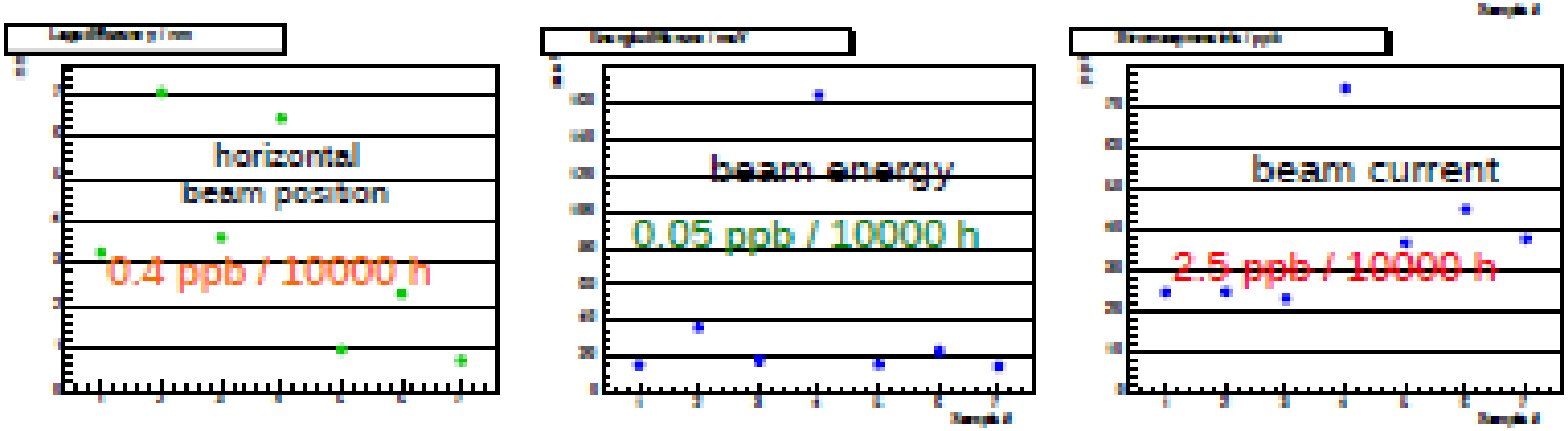
$$A_{\exp} = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow} = A_{true} + \sum_{p\neq I} Slope_p (x_p^{\uparrow} - x_p^{\downarrow}) + \underbrace{\frac{I\uparrow - I\downarrow}{I\uparrow + I\downarrow}}_{A_I}$$

$$\mathrm{A_I} \approx \mathrm{P_{LIN}}\varepsilon_{ISR}\cos(\theta_{Comp}) \;\; \mathrm{P_{LIN}} = \text{Linear Polarization Amplitude}, \varepsilon_{\mathrm{ISR}} = \text{Dichroizity of Photcathode}$$

$$P_{LIN} \approx \varepsilon_{ISR} \approx 0.03, \cos(\theta_{Comp}) \approx 0.001 \Rightarrow A_I \approx 1ppm$$

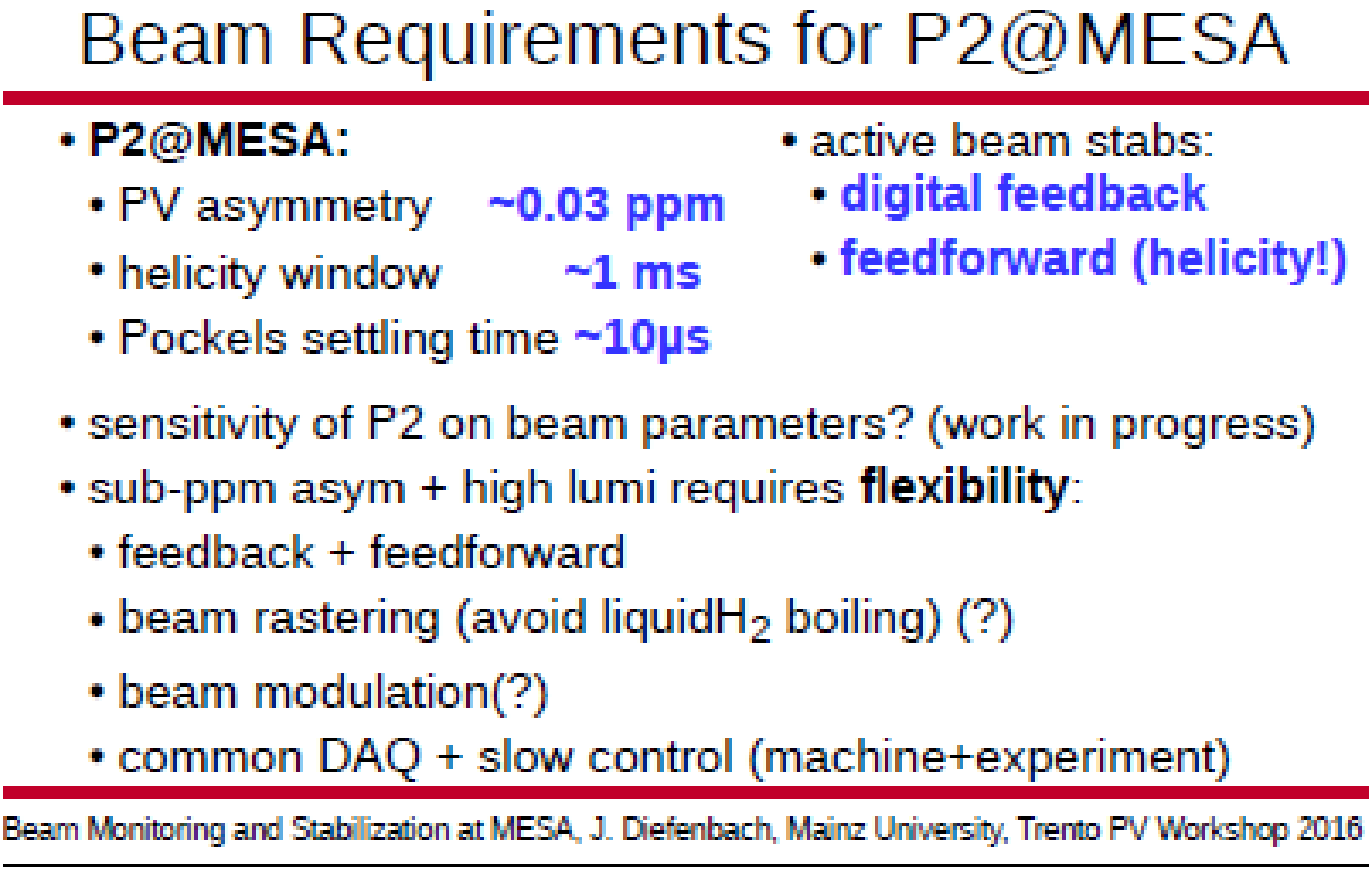
Beam Requirements for P2@MESA

Extrapolation from A4 @210MeV to 10 000h P2:



- beam energy: good!
- beam position: too large!
- beam current: way to large!
- *all uncertainties together must not exceed 0.1 ppb for P2*

Beam Monitoring and Stabilization at MESA, J. Diefenbach, Mainz University, Trento PV Workshop 2016



Beam Requirements for P2@MESA

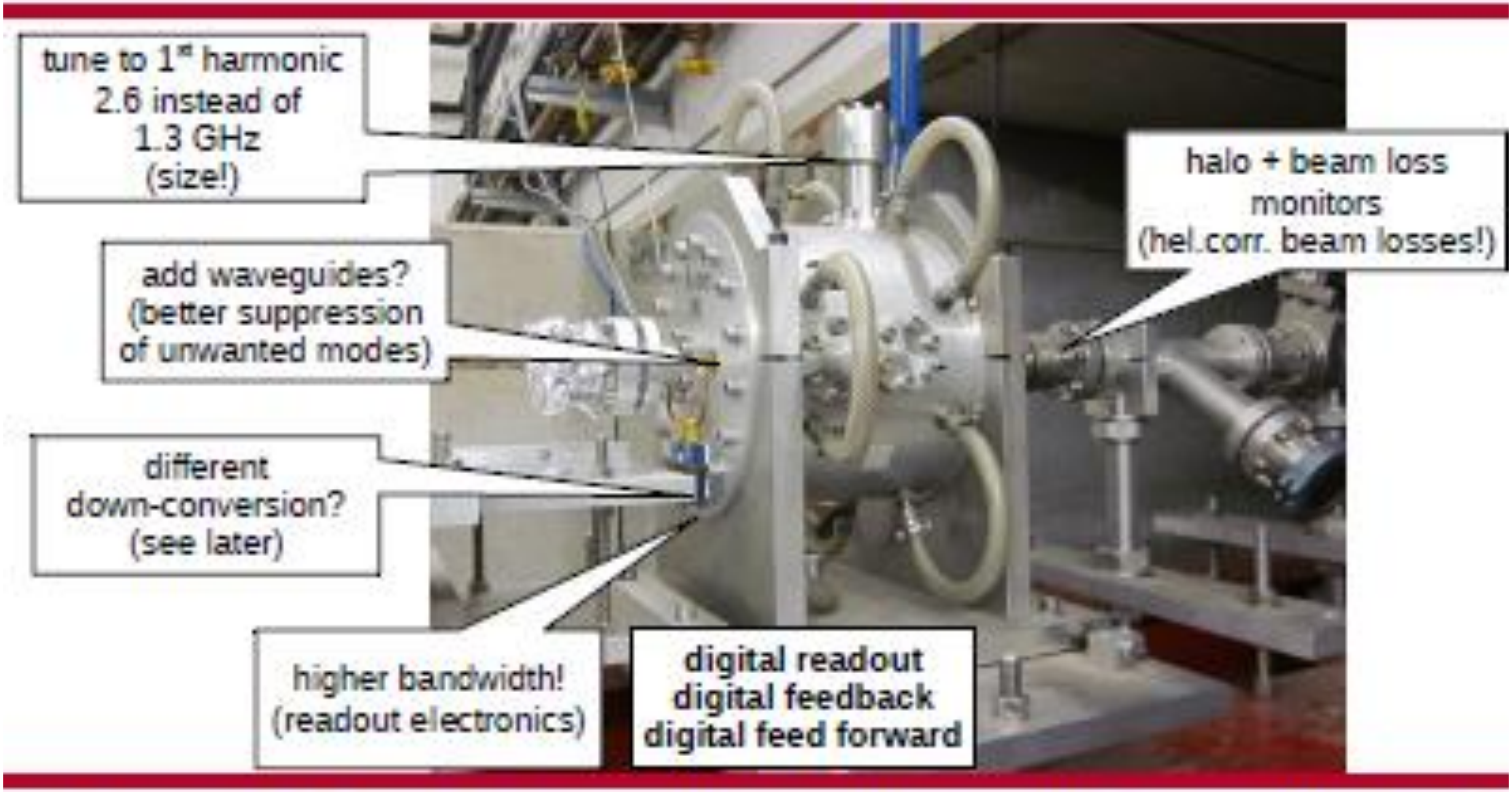
- **P2@MESA:**
  - PV asymmetry **~0.03 ppm**
  - helicity window **~1 ms**
  - Pockels settling time **~10µs**

- active beam stabs:
  - **digital feedback**
  - **feedforward (helicity!)**

- sensitivity of P2 on beam parameters? (work in progress)
- sub-ppm asym + high lumi requires **flexibility**:
  - feedback + feedforward
  - beam rastering (avoid liquidH_2 boiling) (?)
  - beam modulation(?)
  - common DAQ + slow control (machine+experiment)

Beam Monitoring and Stabilization at MESA, J. Diefenbach, Mainz University, Trento PV Workshop 2016

Possible Improvements



tune to 1st harmonic
2.6 instead of
1.3 GHz
(size!)

add waveguides?
(better suppression
of unwanted modes)

different
down-conversion?
(see later)

higher bandwidth!
(readout electronics)

digital readout
digital feedback
digital feed forward

halo + beam loss
monitors
(hel.corr. beam losses!)

Beam Monitoring and Stabilization at MESA, J. Diefenbach, Mainz University, Trento PV Workshop 2016

Summary

- BIG projects: requirements well defined
- Mostly feasible, somewhat challenging (pol positron production, energy calibration in fcc-ee)
- Small and feasible projects in near future: good playground for „extreme beam control“ („identical orbits, helicity correlated fluctuations)

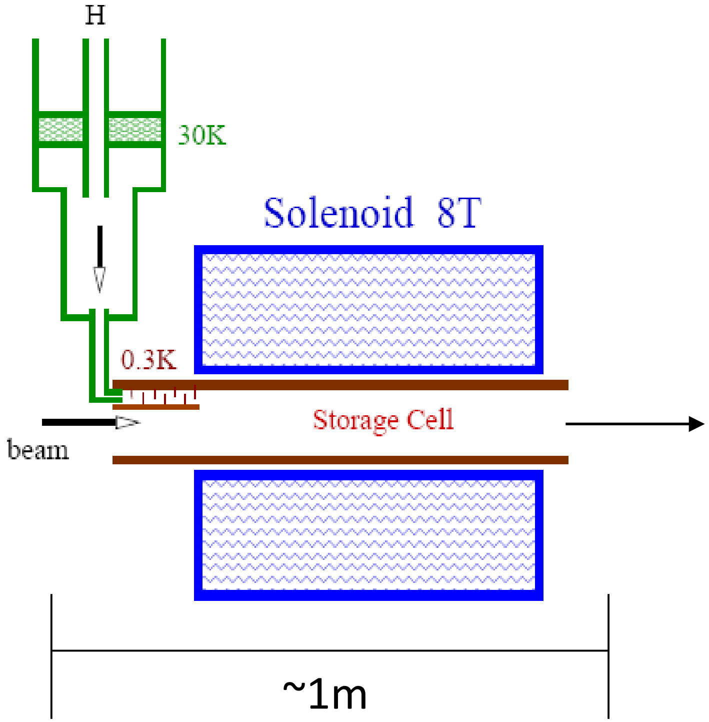
Progress is realized under demand!

→ Small projects needed while /if waiting for the larger ones

Thank you for your attention!

The Hydro Möller proposal

Chudakov&Luppov, Proceedings IEEE Trans. Nucl. Sc. **51**, 1533 (2004)



+ measurement is non-invasive and
+ provides sufficient statistical accuracy at the beam current level of the PV experiment

„Prototype“ of atomic trap was donated by UVA/Don Crabb
→ Template for cryostate development

A completely polarised electron target

H_1: $\vec{\mu} \approx \vec{\mu_e}$;
H_2: opposite electron spins

Magnetic field B splits H_1 ground state

Low energy

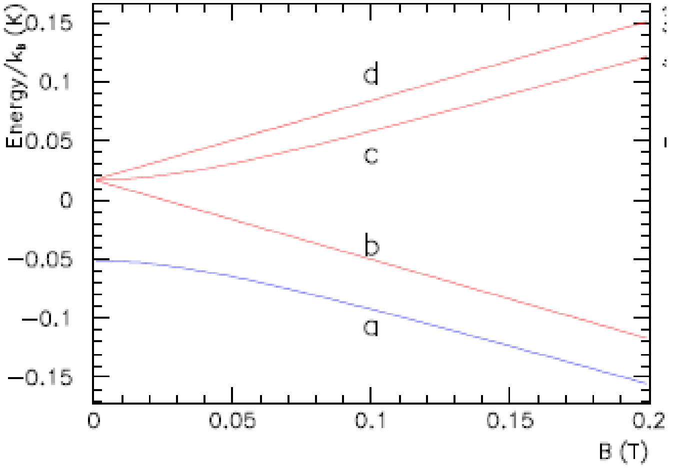
$|b\rangle = |\downarrow ⤈\rangle$

$|a\rangle = |\downarrow ⤉\rangle \cdot \cos\theta - |\uparrow ⤈\rangle \cdot \sin\theta$

High energy

$|d\rangle = |\uparrow ⤉\rangle$

$|c\rangle = |\uparrow ⤈\rangle \cdot \cos\theta + |\downarrow ⤉\rangle \cdot \sin\theta$



H_1 in B = 8T at T = 300 mK at thermodynamical equilibrium:

$$n_+/n_- = exp(-2\mu B/kT) \approx 3 \cdot 10^{-16}$$

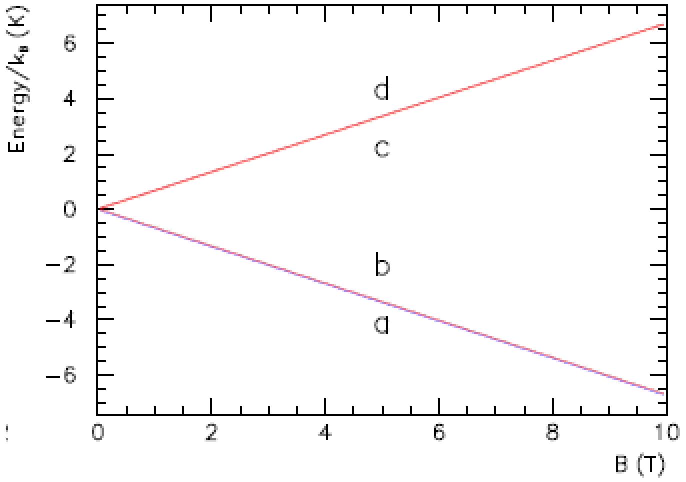
Mixing angle $\tan 2\theta \approx 0.05/B(T)$

At B =8T $\sin\theta \approx 0.3\%$

Mixture $\sim$53% of $|a>$ and $\sim$47% of $|b>$:

$\mathcal{P}_e \sim 1 - \delta, \qquad \delta \sim 10^{-5}$,

$\mathcal{P}_p \sim\ - 0.06$ (recombination $\Rightarrow \sim$80%)

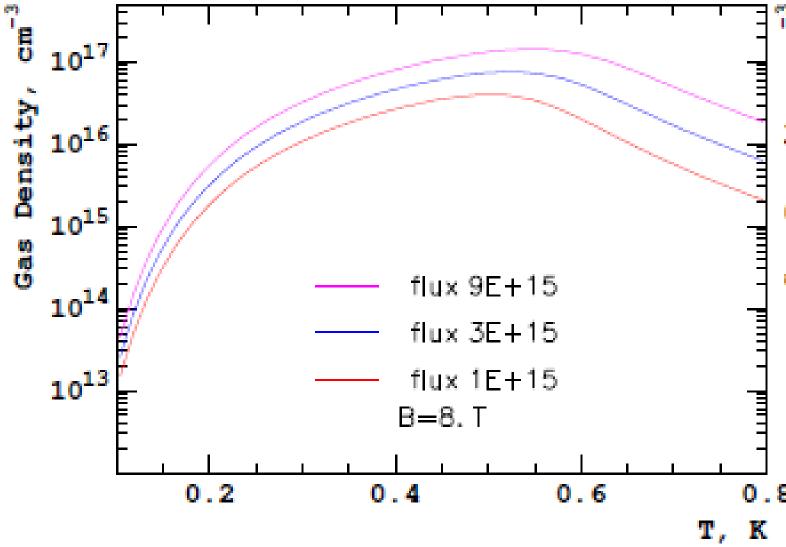


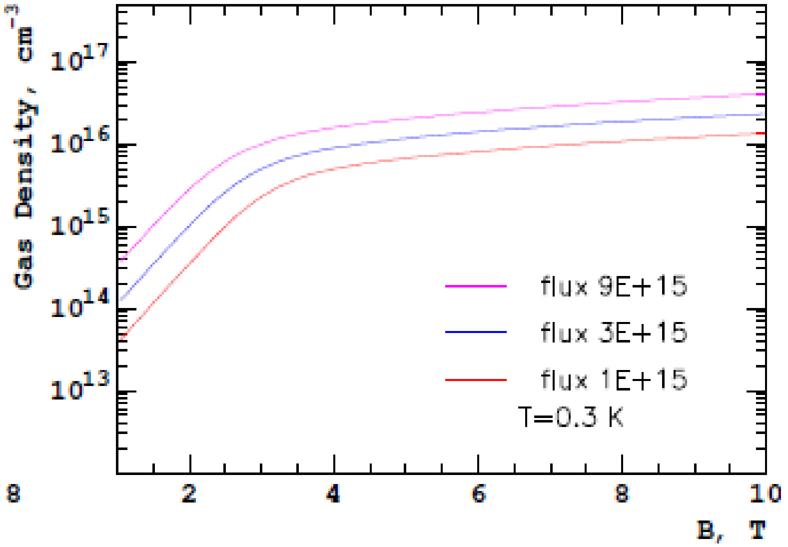
A completely polarised electron target

Gas Lifetime in the Cell

Loss of hydrogen atoms from the cell due to:

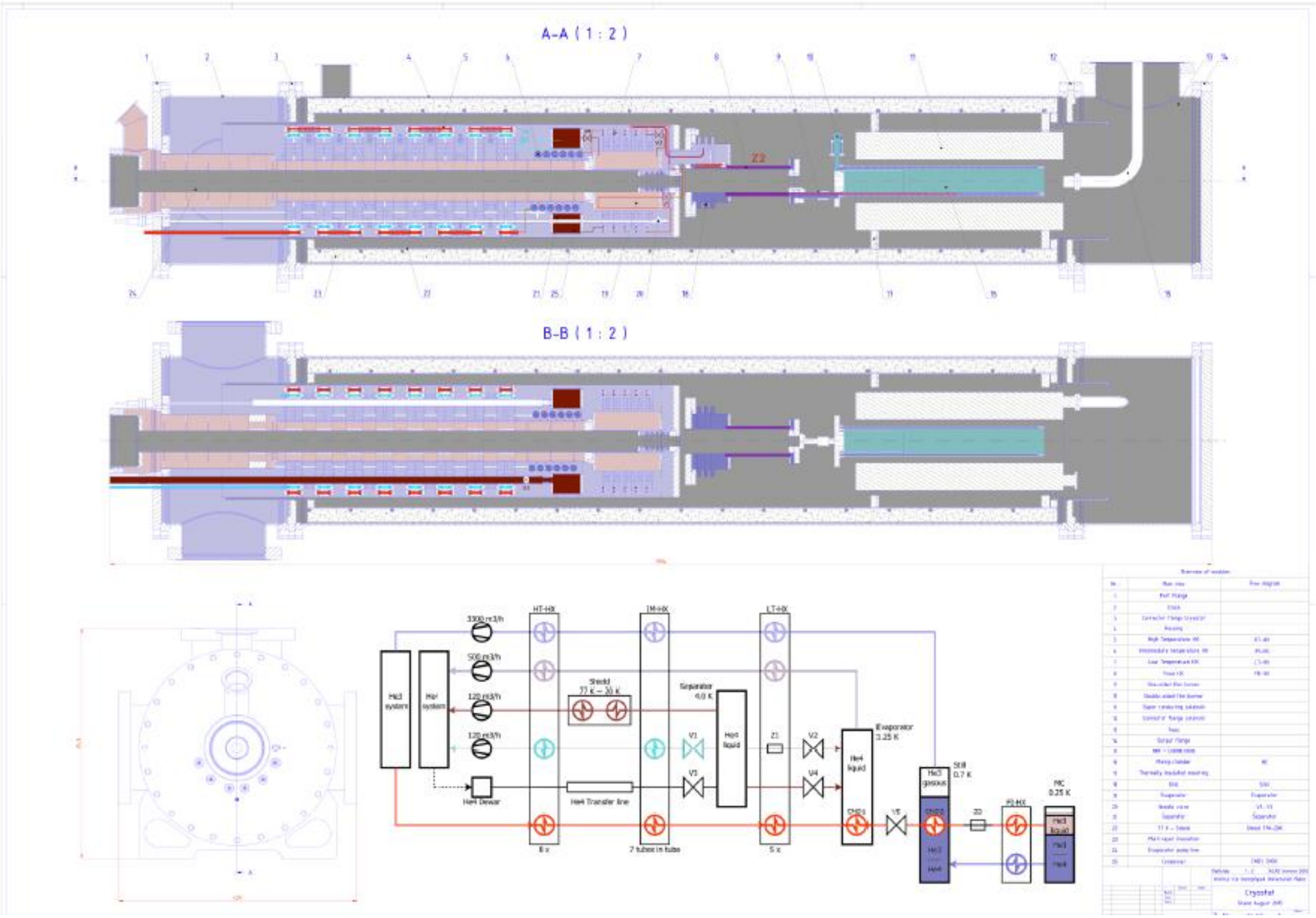
- Thermal escape through the magnetic field gradient → dominates at T > 0.55 K
- Recombination in the gas volume → negligible up to densities of ~ 10^{17} cm^{-3}
- Recombination in the cell surface → constant feeding the cell with atomic hydrogen





Requires powerful dilution refrigerator….

Draft of cryostat design for P2-Hydro-Möller (V. Tioukine with lots of help from Dubna, CERN, JLAB)

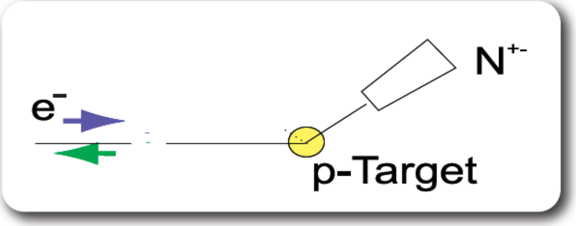


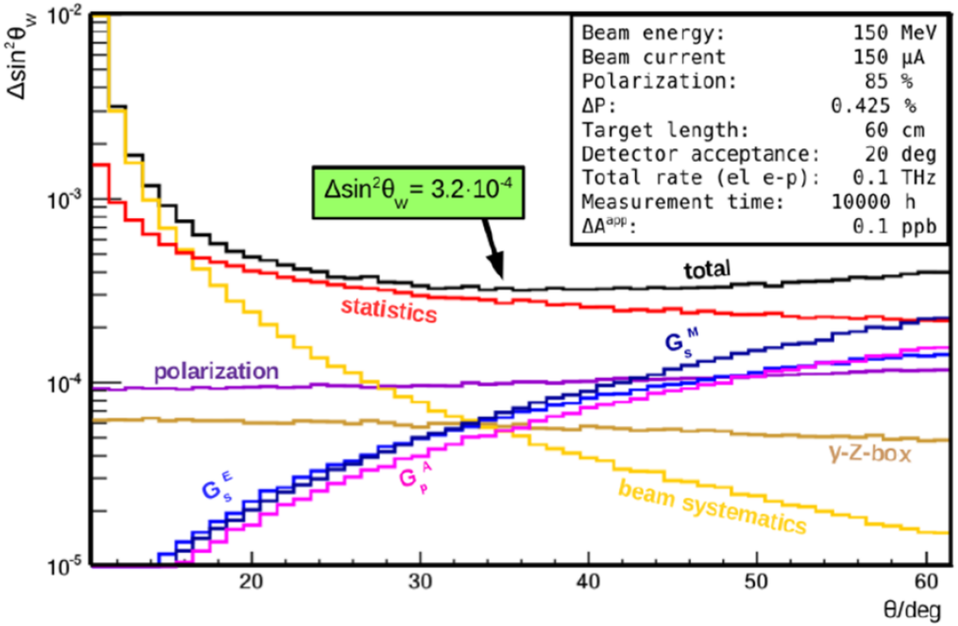
Status Hydro Möller

- Challenge: Functionality can only be tested when trap is working!
- Detailled cryostat design accomplished
- Will build 4K precooling stage from available funding
- ~200 k€ for remainig cryostat parts and magnet
- Substantial amount of 3He needed : 50-100 cm^3 lq. (~200k€ ??)
- Pumping stages for the precooling and the mixing circuit (~300k€ ??)
- No detection system designed yet!
- Full design report needed for funding request

The P2 Experiment at MESA

-basic demands





```
Beam energy:            150 MeV
Beam current            150 µA
Polarization:            85 %
ΔP:                   0.425 %
Target length:           60 cm
Detector acceptance:     20 deg
Total rate (el e-p):    0.1 THz
Measurement time:     10000 h
ΔA^app:                 0.1 ppb
```

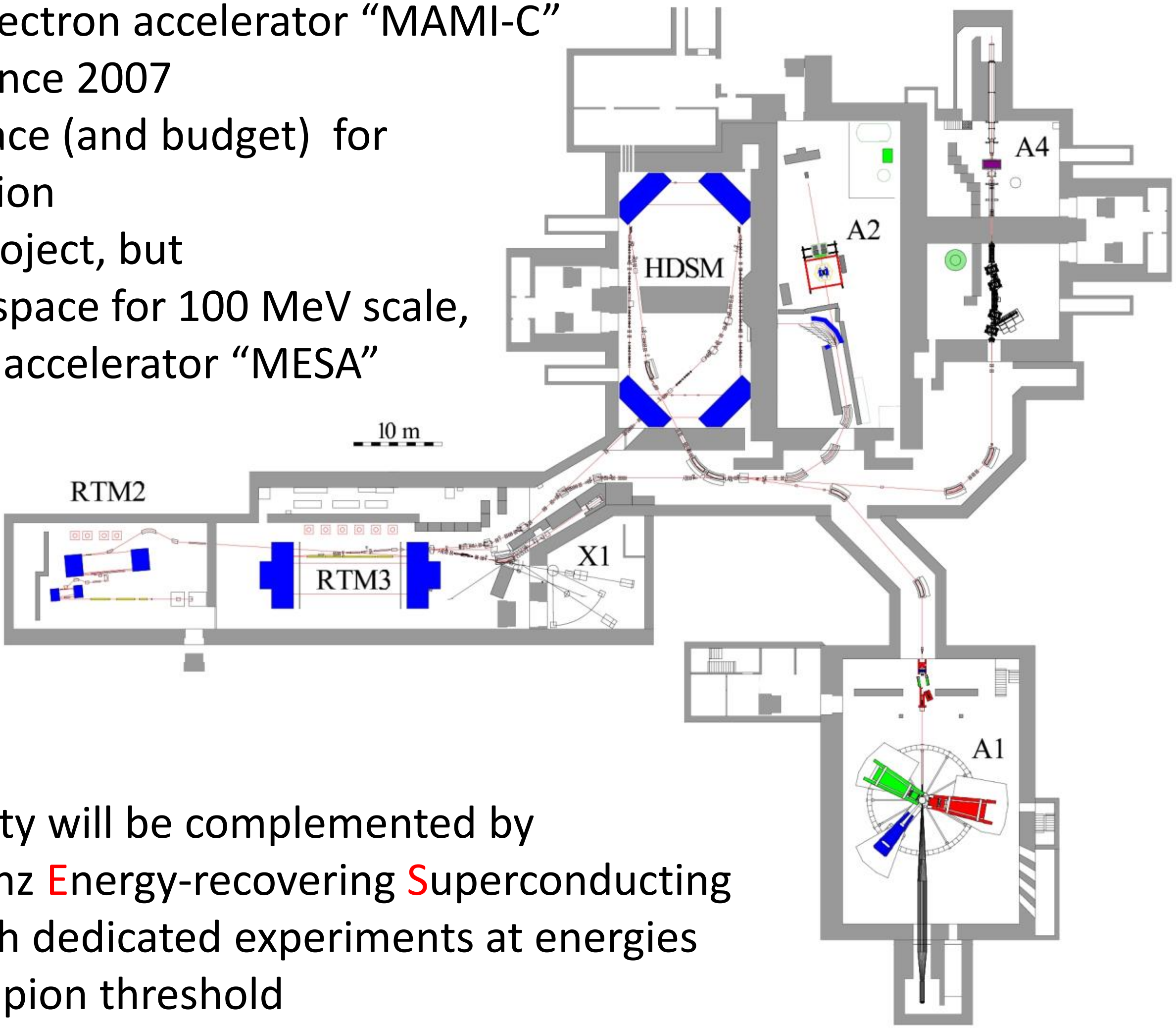
150 µA Beamcurrent , 60cm lq. H2, Beampol: 85%.
10000 h Data-taking (~13-15000 h Runtime)
High accuracy polarization measurement (ΔP/P=0.5% **!!**)
Extremely high demands on control of HC-fluctuations!

→ ~4000h/Year Runtime
→ Accelerator must be optimized for reliability& stability
→ Count rate several hundred Gigahertz→ Integrating detector + spectrometer

F. Maas PAVI2014 conf.

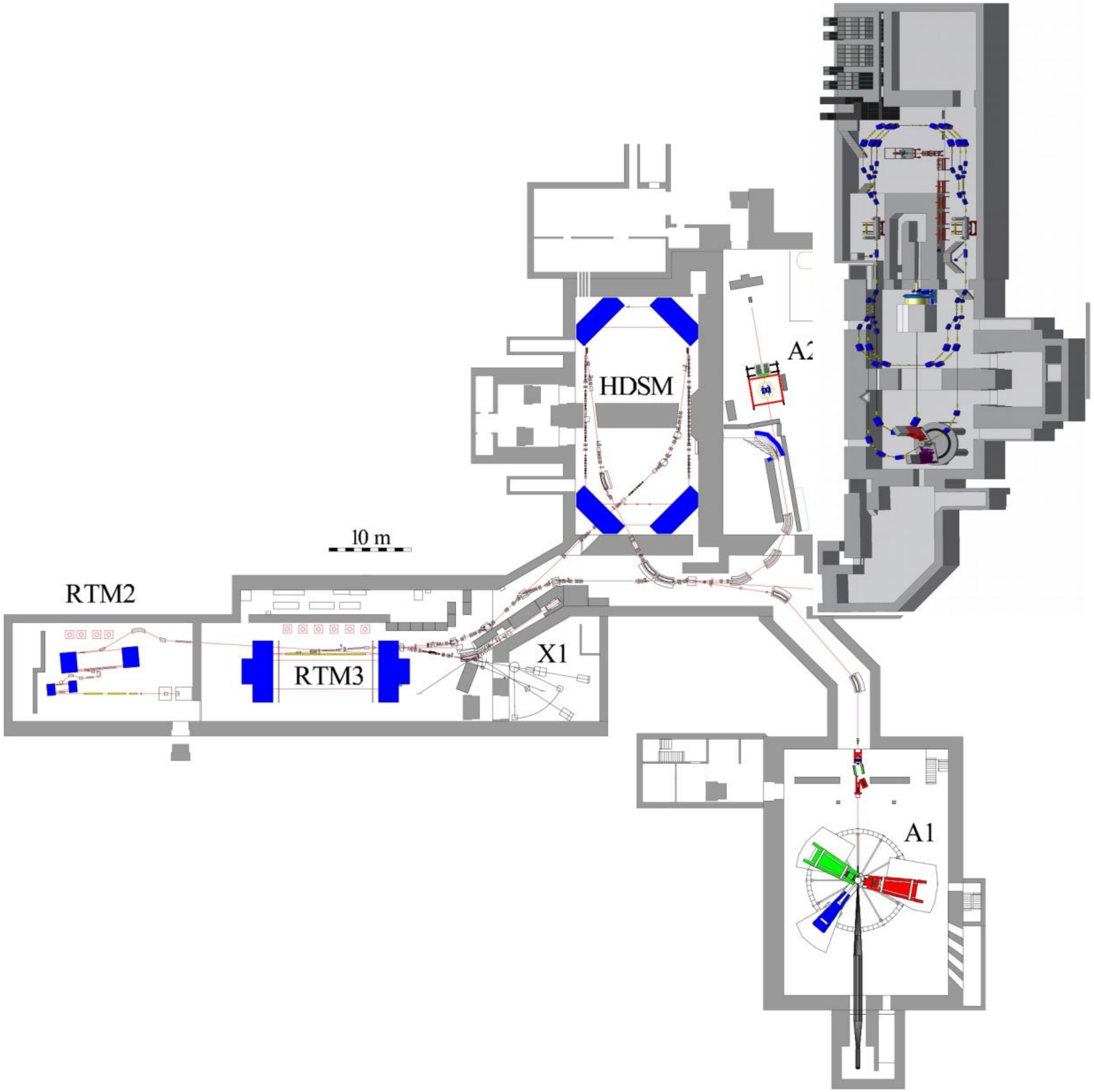
Expanding the MAMI facility by "MESA"

- 1.6 GeV c.w. electron accelerator "MAMI-C" in operation since 2007
- Insufficient space (and budget) for further extension
- no MAMI D project, but use available space for 100 MeV scale, high intensity accelerator "MESA"

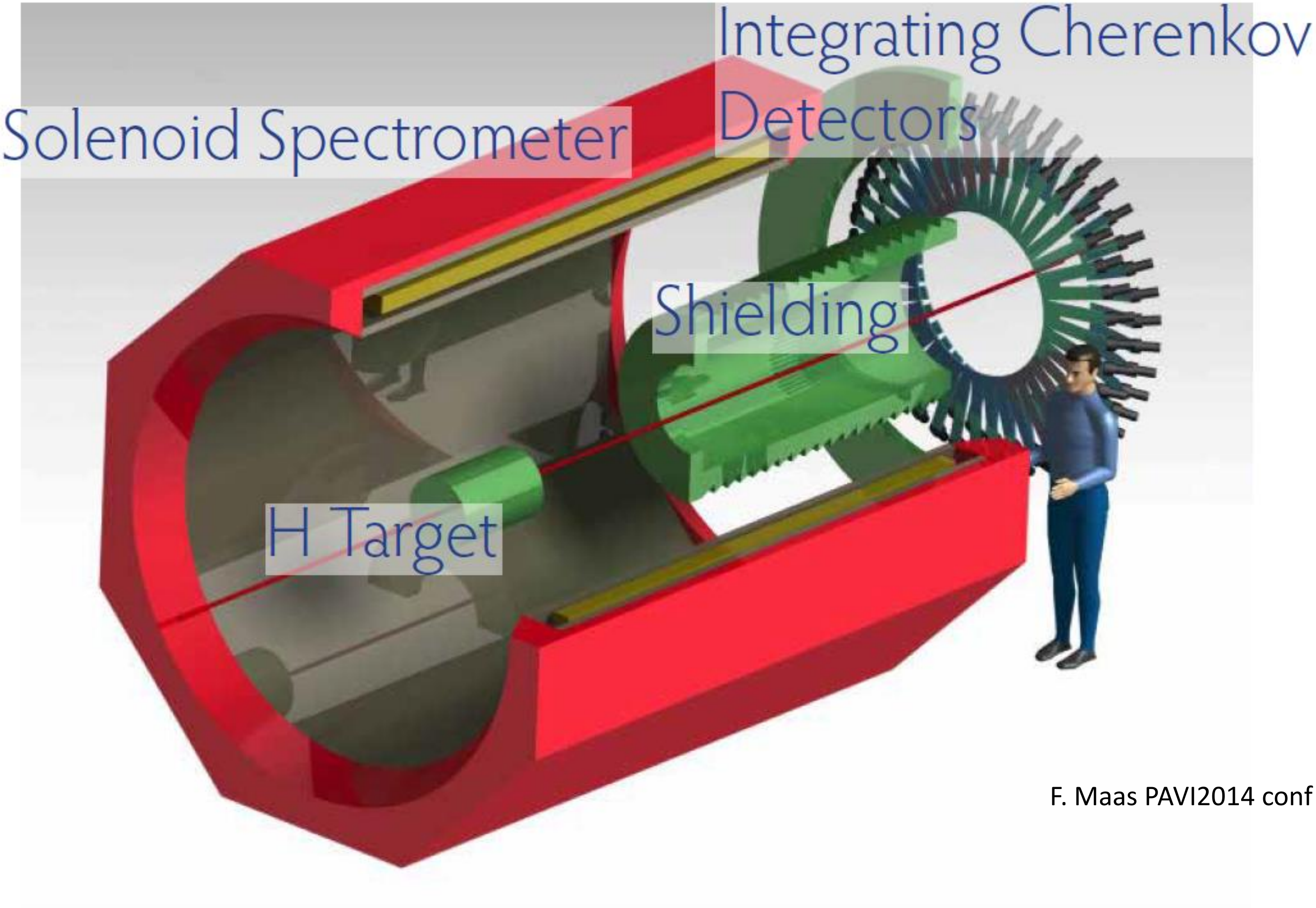


The MAMI facility will be complemented by MESA, the Mainz Energy-recovering Superconducting Accelerator, with dedicated experiments at energies below or at the pion threshold

Expanding the MAMI facility by “MESA”



The P2 Experiment at MESA
- detector

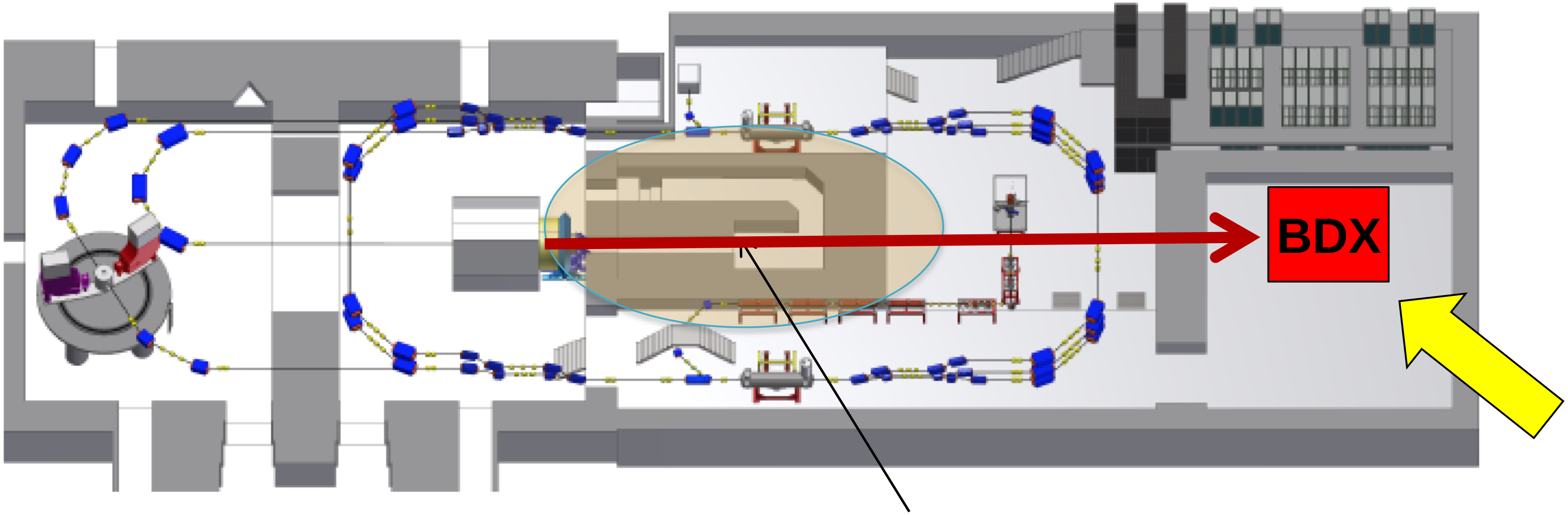


F. Maas PAVI2014 conf.

The P2 Experiment at MESA

Beam Dump Experiment (BDX) @ MESA

Electron Scattering on Beam Dump → Collimated pair of Dark Matter particles !



This existing beam dump is going to be the P2 beam dump

10,000 hours @ 150 µA

→ 10^{23} electrons on target (EOT)

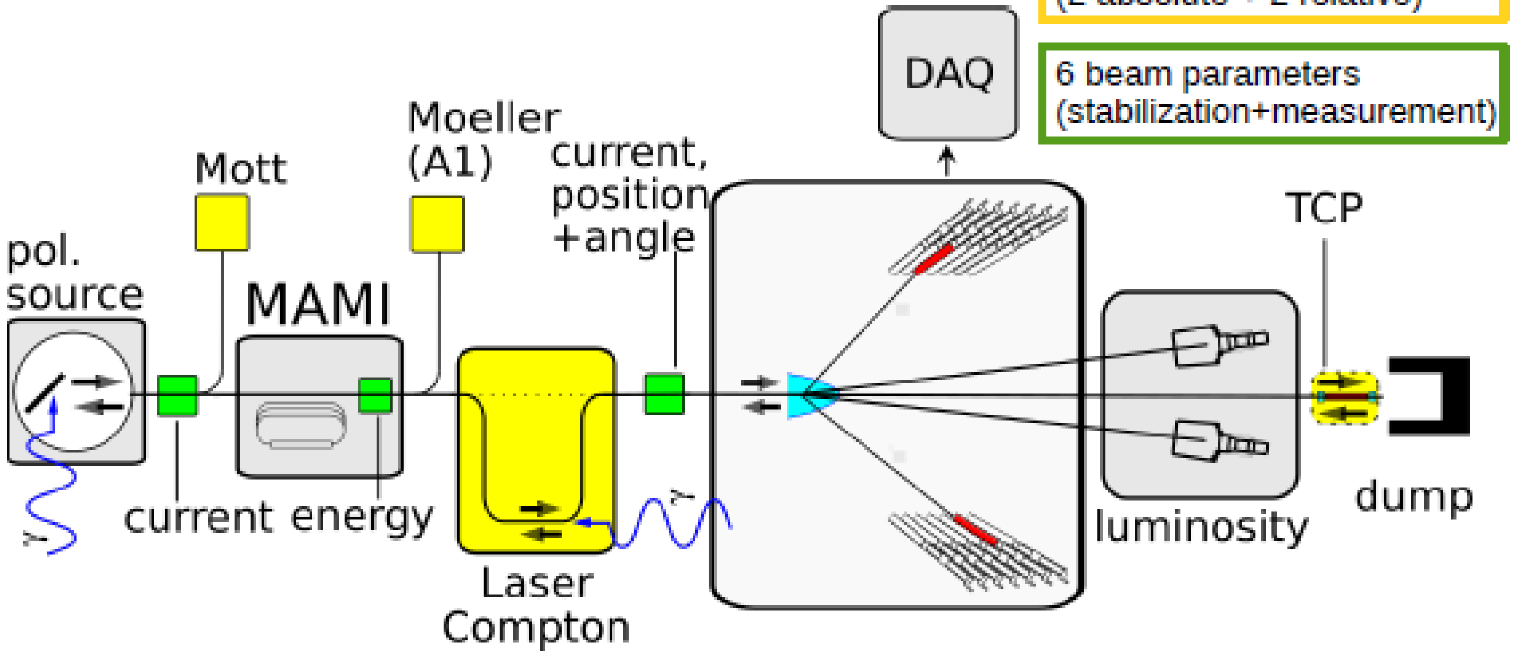
The P2 Experiment at MESA:

False asymmetry control

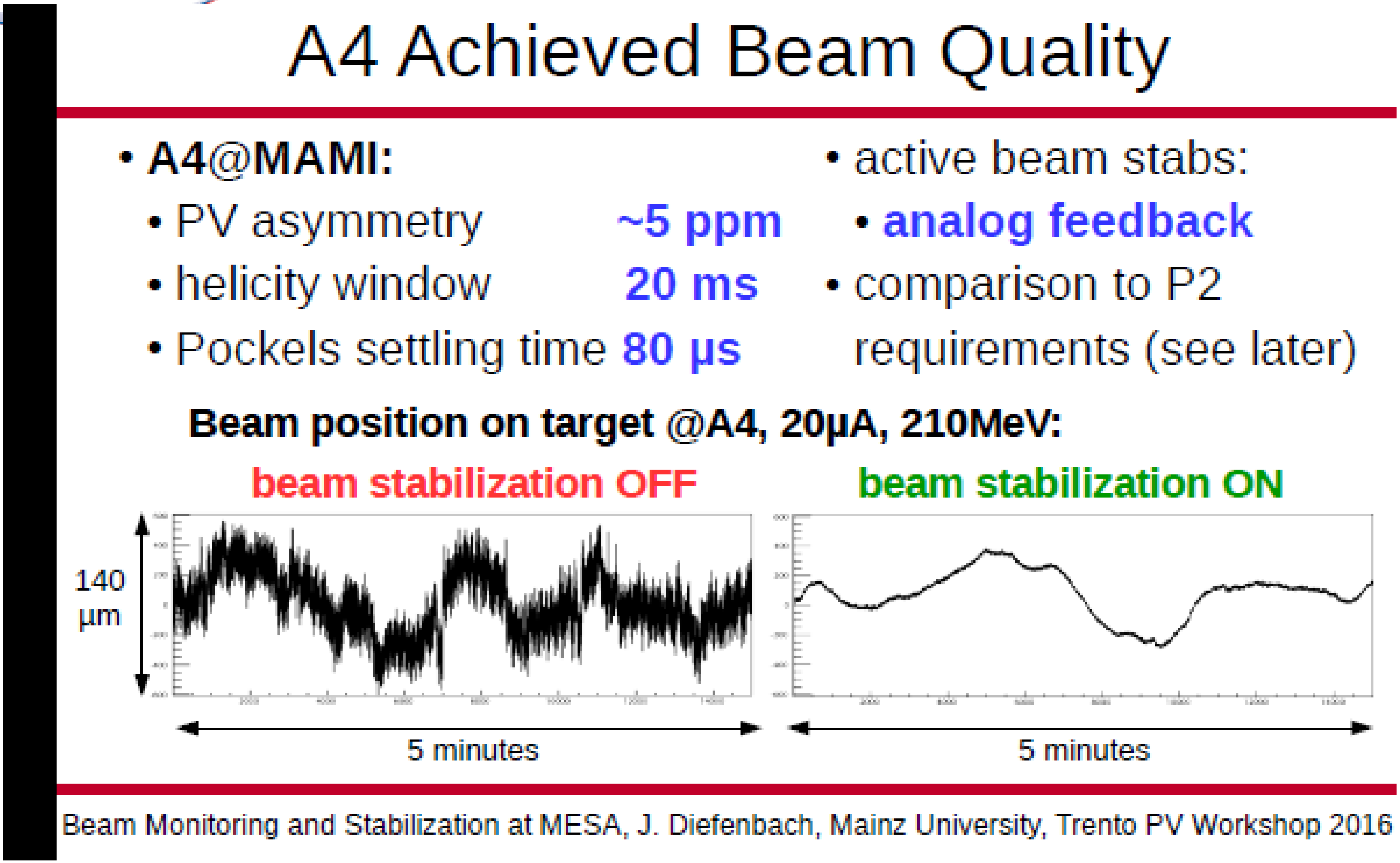
A4 Experiment at MAMI – Overview

4 polarimeters
(2 absolute + 2 relative)

6 beam parameters
(stabilization+measurement)



eam Monitoring and Stabilization at MESA, J. Diefenbach, Mainz University, Trento PV Workshop 2016



A4 Achieved Beam Quality

- **A4@MAMI:**
  - PV asymmetry **~5 ppm**
  - helicity window **20 ms**
  - Pockels settling time **80 µs**
- active beam stabs:
  - **analog feedback**
- comparison to P2 requirements (see later)

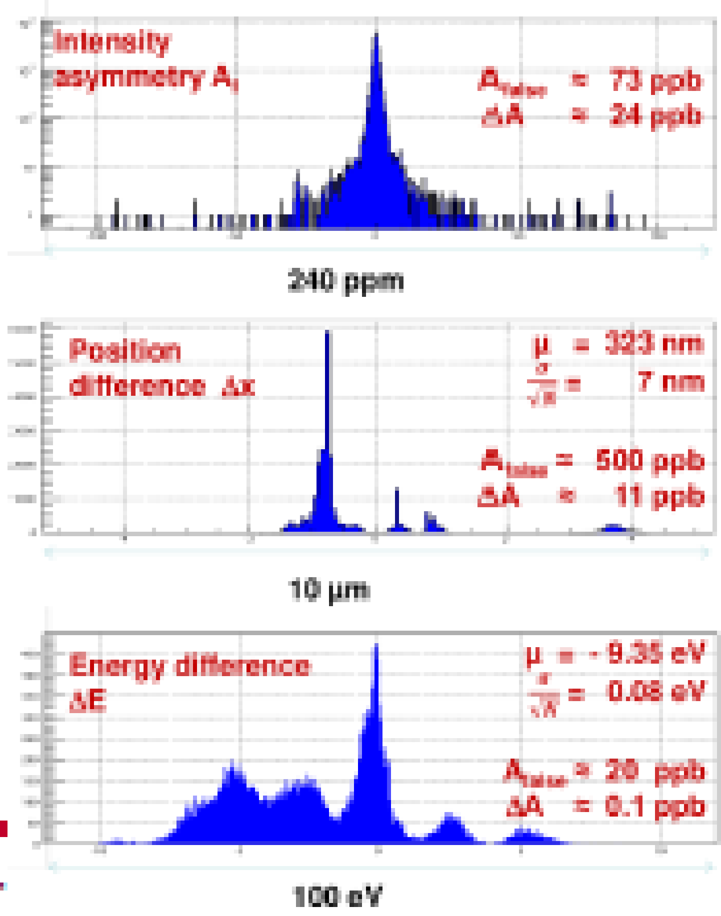
Beam position on target @A4, 20µA, 210MeV:

Beam Monitoring and Stabilization at MESA, J. Diefenbach, Mainz University, Trento PV Workshop 2016

A4 Achieved Beam Quality

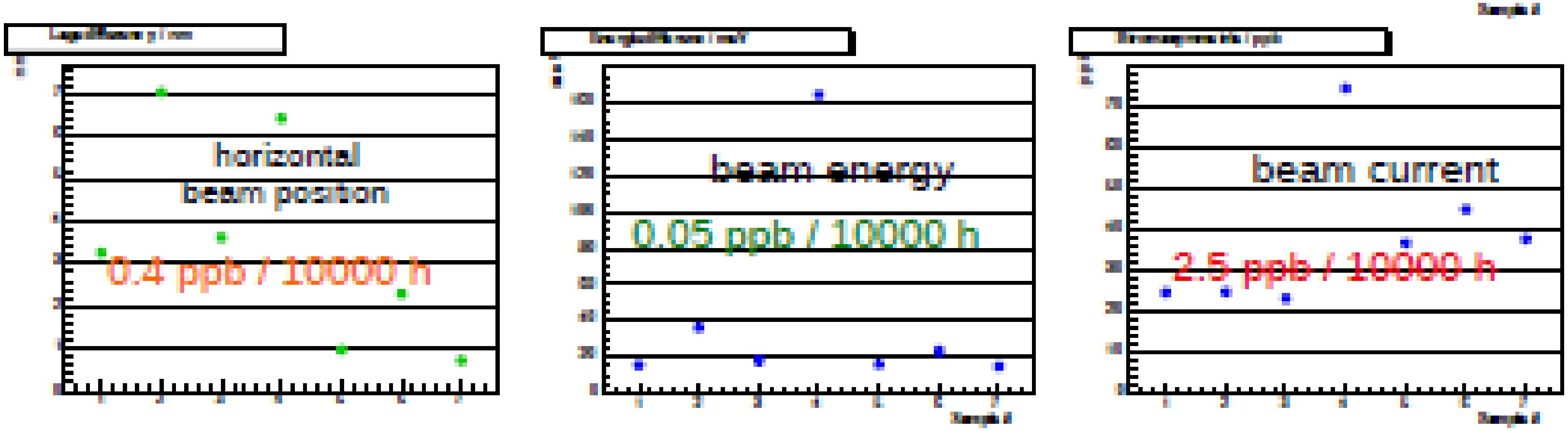
- measure beam parameters
- determine sensitivity for each parameter
- apply correction to result
  - **differences for helicity states**

- uncertainty in differences means systematic uncertainty in result
  - A4 210MeV 2300h of beam: max. 24 ppb vs. A_{PV}~5 ppm



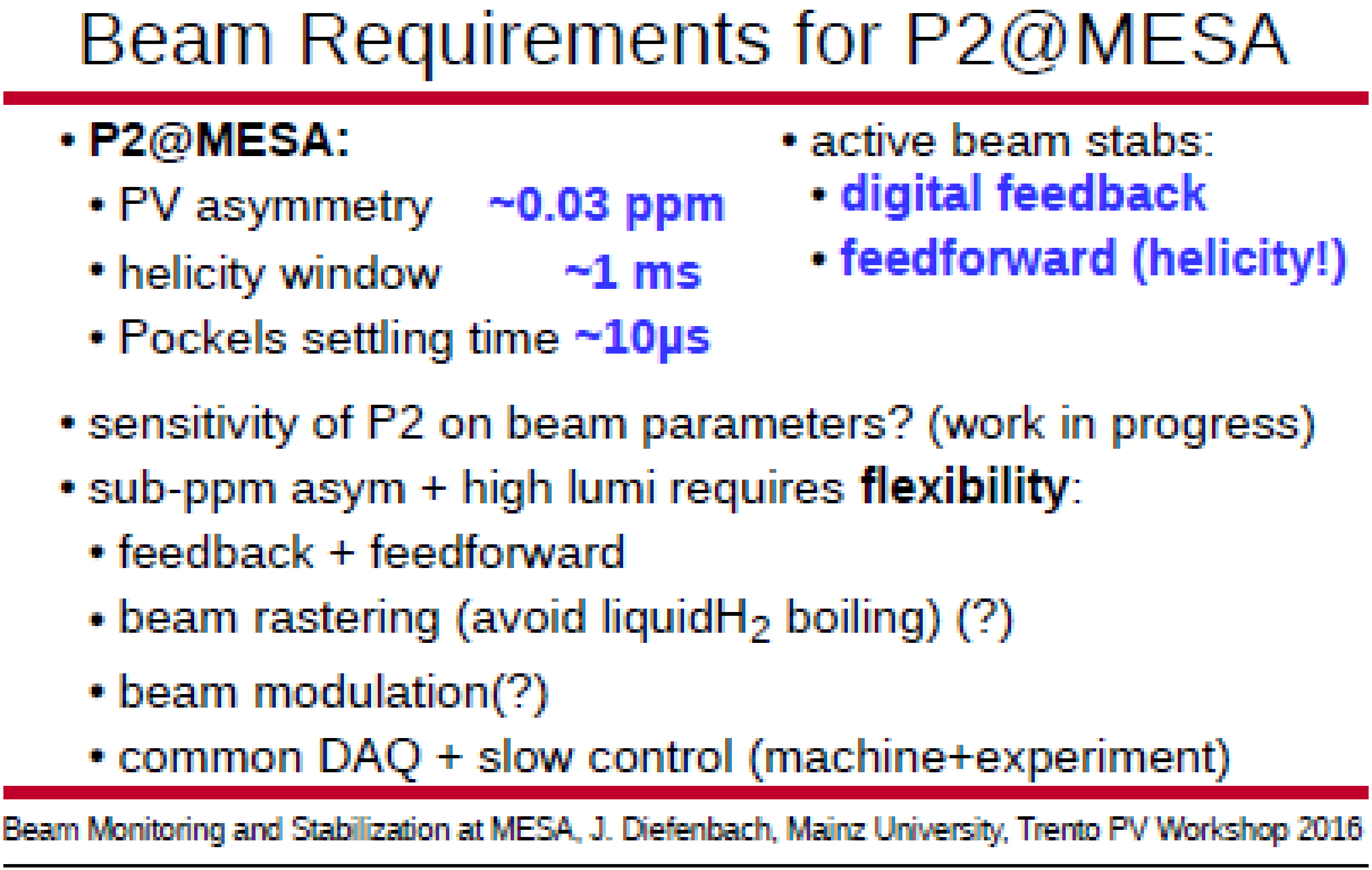
Beam Requirements for P2@MESA

Extrapolation from A4 @210MeV to 10 000h P2:



- beam energy: good!
- beam position: too large!
- beam current: way to large!
- *all uncertainties together must not exceed 0.1 ppb for P2*

Beam Monitoring and Stabilization at MESA, J. Diefenbach, Mainz University, Trento PV Workshop 2016

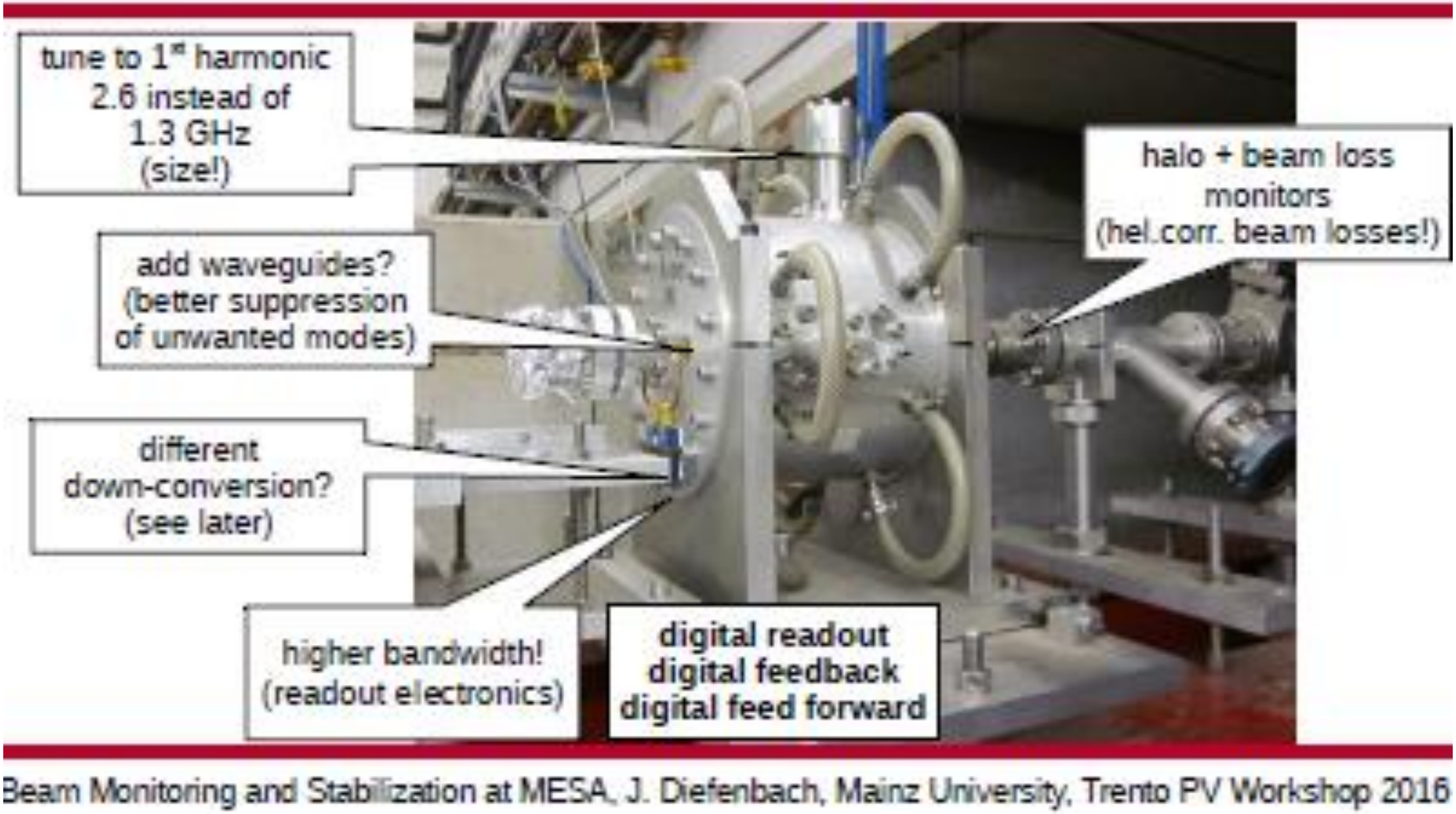


Beam Requirements for P2@MESA

- **P2@MESA:**
  - PV asymmetry **~0.03 ppm**
  - helicity window **~1 ms**
  - Pockels settling time **~10µs**
- active beam stabs:
  - **digital feedback**
  - **feedforward (helicity!)**
- sensitivity of P2 on beam parameters? (work in progress)
- sub-ppm asym + high lumi requires **flexibility**:
  - feedback + feedforward
  - beam rastering (avoid liquidH_2 boiling) (?)
  - beam modulation(?)
  - common DAQ + slow control (machine+experiment)

Beam Monitoring and Stabilization at MESA, J. Diefenbach, Mainz University, Trento PV Workshop 2016

Possible Improvements



tune to 1st harmonic
2.6 instead of
1.3 GHz
(size!)

add waveguides?
(better suppression
of unwanted modes)

different
down-conversion?
(see later)

higher bandwidth!
(readout electronics)

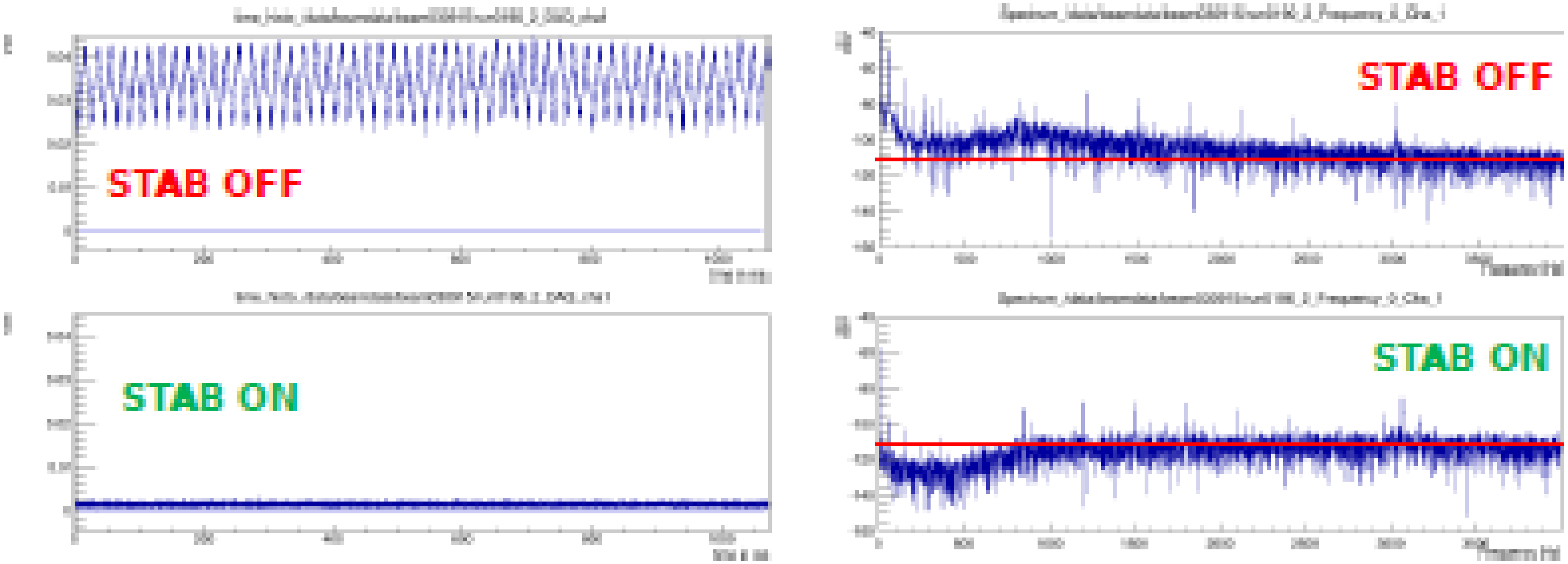
digital readout
digital feedback
digital feed forward

halo + beam loss
monitors
(hel.corr. beam losses!)

Beam Monitoring and Stabilization at MESA, J. Diefenbach, Mainz University, Trento PV Workshop 2016

First digital beam stabilization tests for P2 with 180MeV@MAMI

- using RedPitaya internal PID blocks (used only PI)!
- not yet optimized transfer functions!



- -50dB @50Hz, -50 dB @100Hz, -20dB @1000Hz
(A4/MAMI: -40dB@50Hz)

PhD thesis Ruth Herbertz

Beam Monitoring and Stabilization at MESA, J. Diefenbach, Mainz University, Trento PV Workshop 2016

The role of Polarization measurement - accuracy and efficiency

Storage ring experiment : efficiency matters!

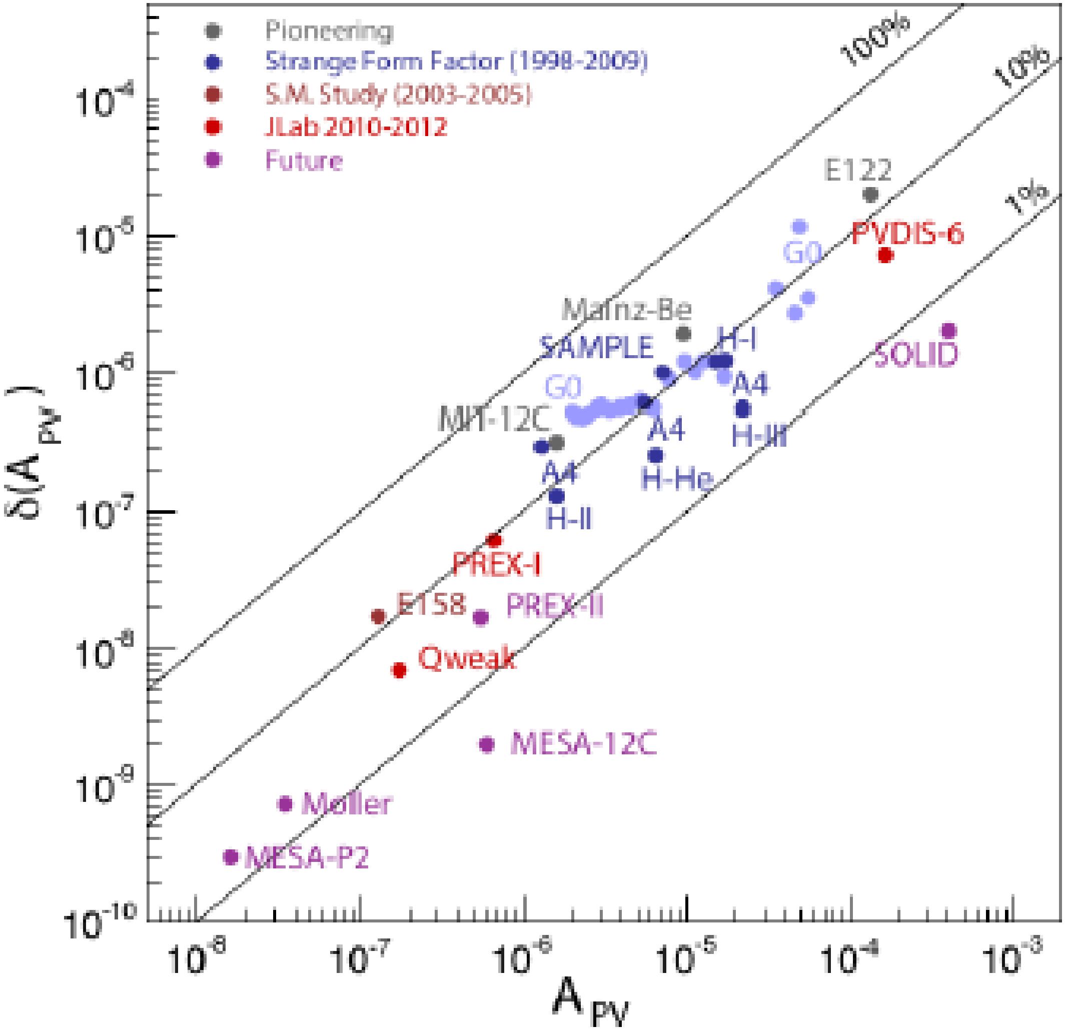
$$Sens = \frac{1}{\sigma_{EDM}} \propto P_{beam}\sqrt{I_{stored} * t_{dec} * t_{\exp}}\,\varepsilon = P_{beam} t_{Dec}\sqrt{I_{stored} * N_{Fill}}\,\varepsilon$$

t_{dec} = decoherence time of beam polarization (>> fill time)

ε = EDM: Statistical Quality factor of Polarization analysis:

- Strong interaction polarization analysis by single spin asymmetry is at least two orders of magnitude more ffective than electromagnetic – disadvantage for lepton EDM rings!
- Possibility to use Stern Gerlach forces in superconicting cavity (R. Talman) to detect spin precession non invasively would reverse this argument... (new idea, not tested in practice)

The role of Polarization measurement - accuracy and efficiency



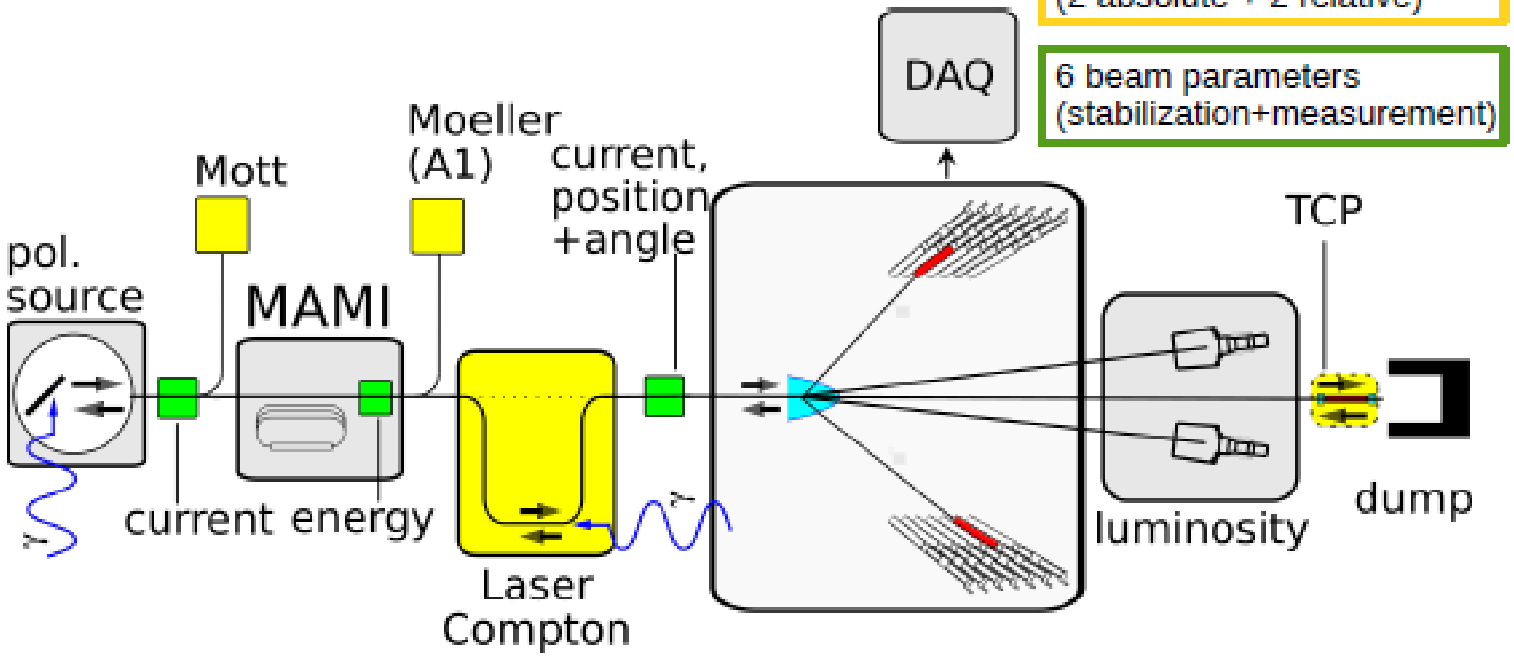
$$A_{PHYS} \propto P_{Beam}$$

$\Rightarrow \frac{\Delta P}{P}$ contributes to to systematic error,

in particular if $\frac{\Delta A}{A}$ is small

S. Baunack
PAVI 2016

A4 Experiment at MAMI – Overview



4 polarimeters
(2 absolute + 2 relative)

6 beam parameters
(stabilization+measurement)

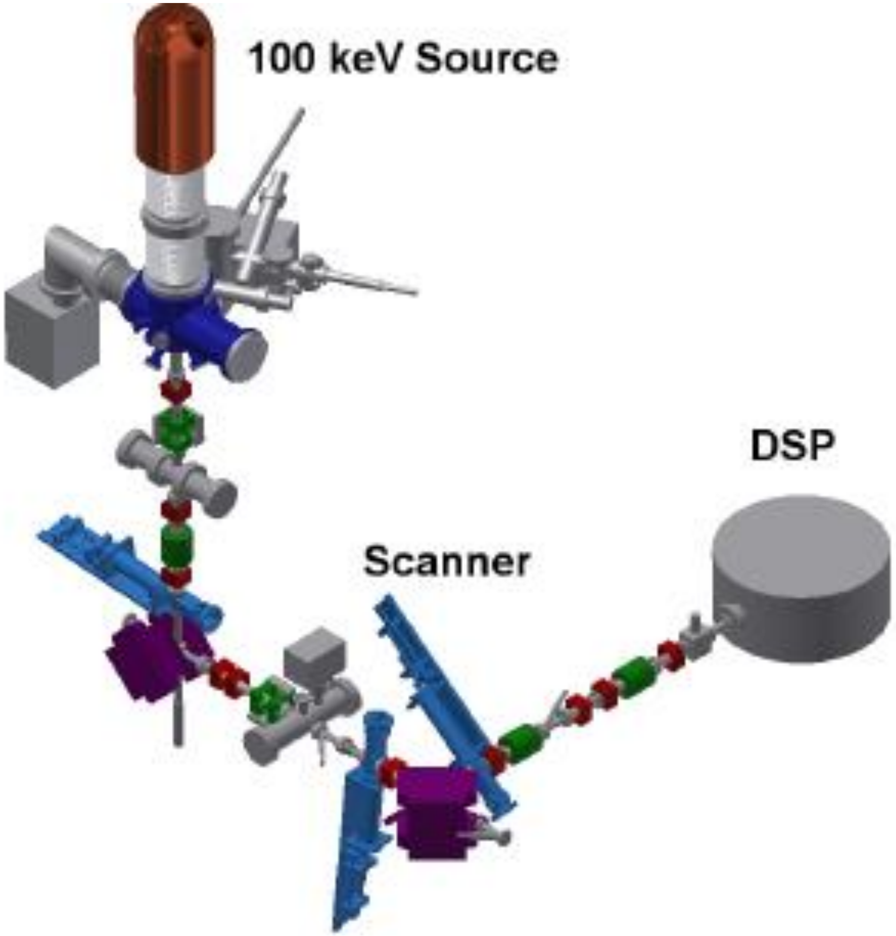
eam Monitoring and Stabilization at MESA, J. Diefenbach, Mainz University, Trento PV Workshop 2016

The role of Polarization measurement - accuracy and efficiency

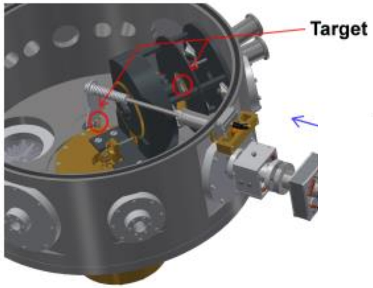
At lepton energies >> 1GeV : Laser Compton Scattering is a useful tool,
- can achieve Accuacies well below 1% (SLAC,JLAB)

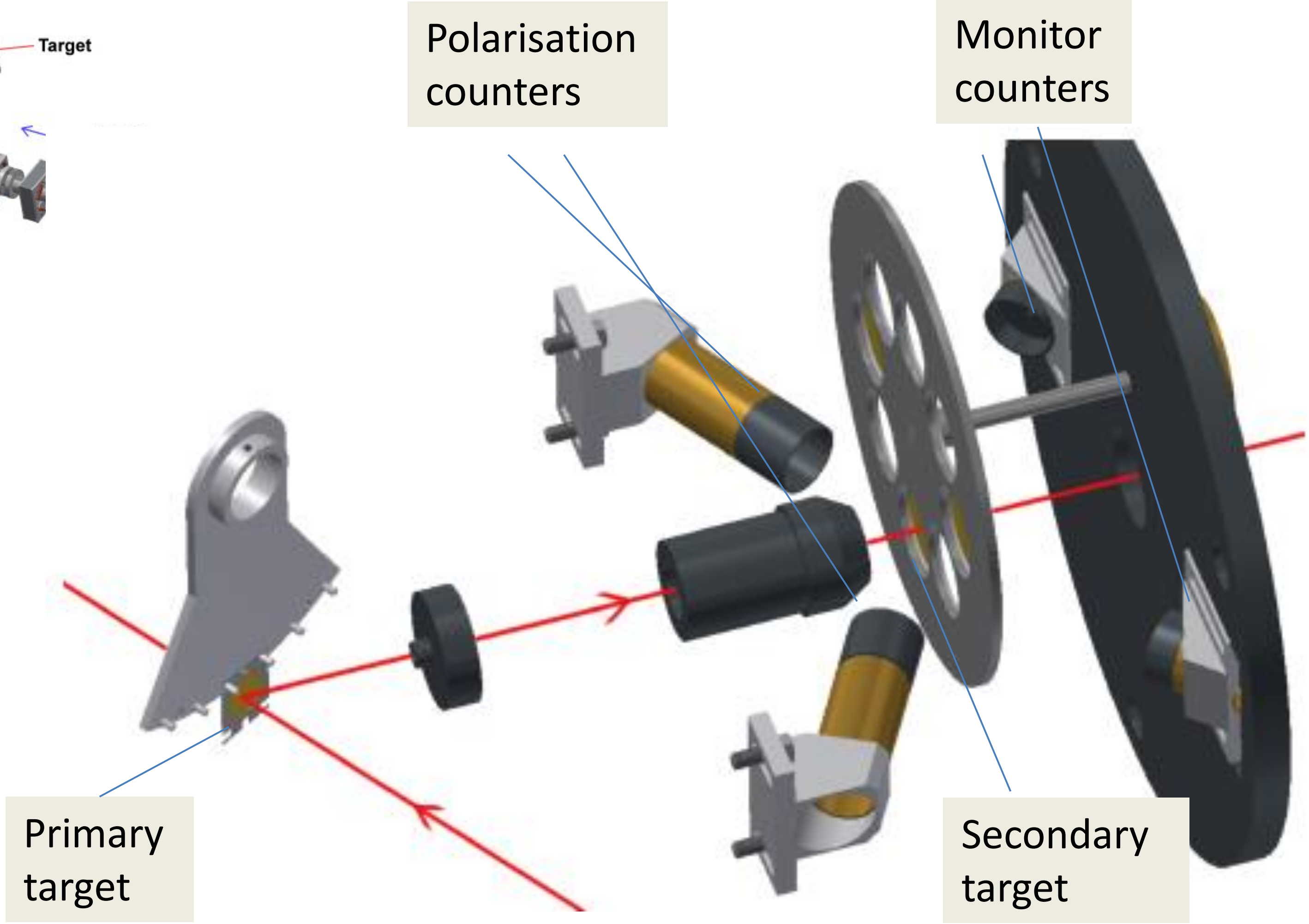
- Experiments with enrgies below 1GeV require improvement of new techniques
- Standard Möller or Mott ca be improved to below 1%
- New techniques for P2: „Hydro-Möller“ and Double scattering Mott may achieve <0.5%.

Present set-up of DSP at PKA2



Inside the scattering chamber...




Polarisation counters

Monitor counters

Primary target

Secondary target

Double scattering (Kesslers Method)

After scattering of unpolarized beam :

$P_{sc} = S_{eff}$

(Equality of polarizing and Analyzing Power :)

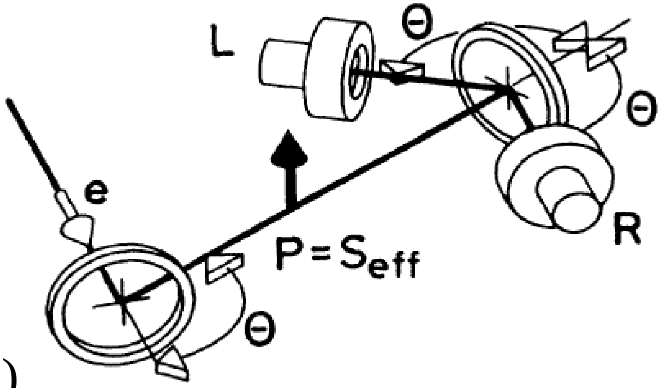
After second "identical" scattering process

$A_{exp} = S^2_{eff}$

with great effort to elliminate

apparative asymmetries and to provide 'identical' scattering)

the claimed accuracy in S_{eff} is $< 0.3\%$!



A. Gellrich and J.Kessler
PRA 43 204 (1991)

Kessler/HopsterAbraham/Kessler Method

$$1.)\ \text{measurement: Pol beam on second target}$$

$$A_1 = S_{eff} P_0$$

$$2.)\ \text{with 'auxiliary target': } S_T; +P_0$$

$$A_2 = P_T S_{eff} = \frac{S_T + \alpha P_0}{1 + S_T P_0} S_{eff}$$

$$\alpha = \text{Depolarization factor for first Target}$$

$$3.\text{with 'auxiliary target': } S_T; -P_0$$

$$A_3 = P_T S_{eff} = \frac{S_T - \alpha P_0}{1 - S_T P_0} S_{eff}$$

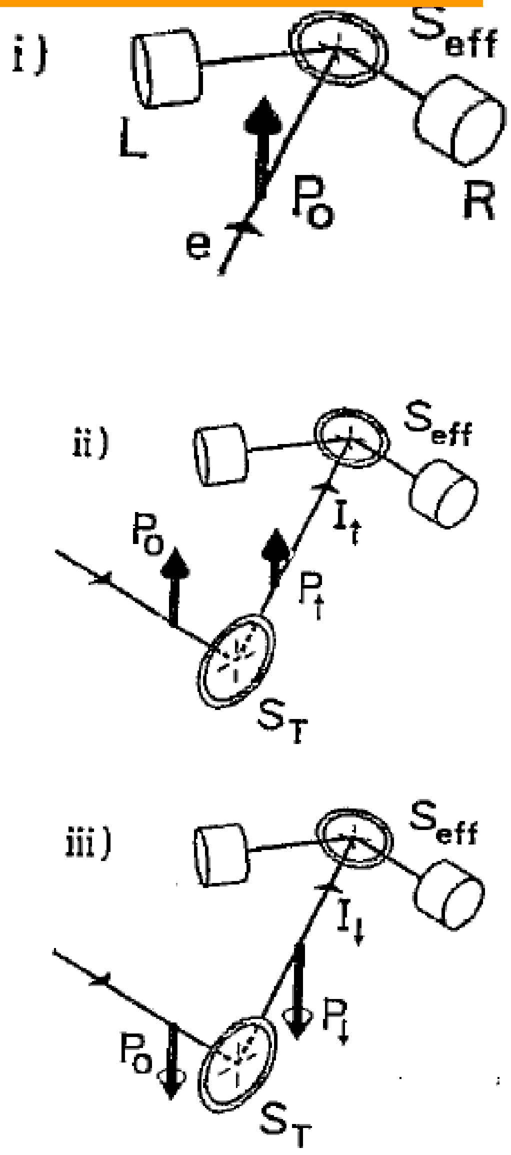
$$4.\ \text{unpolarized beam on aux. target}$$

$$A_4 = S_T S_{eff}$$

$$5.\ \text{Scattering asymmetry from auxiliary target}$$

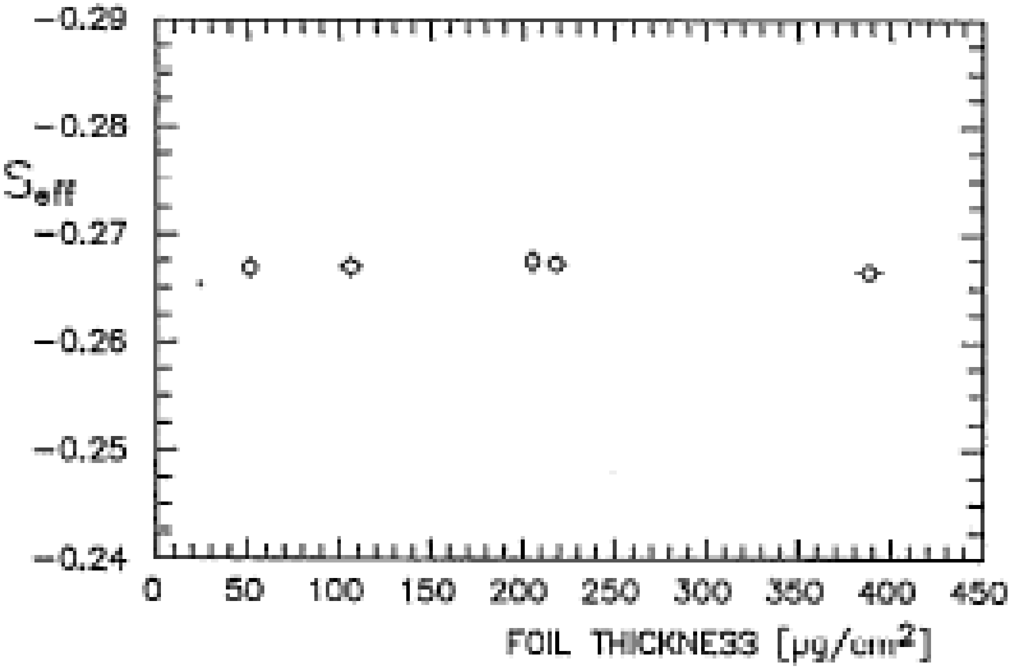
$$A_5 = P_0 S_T$$

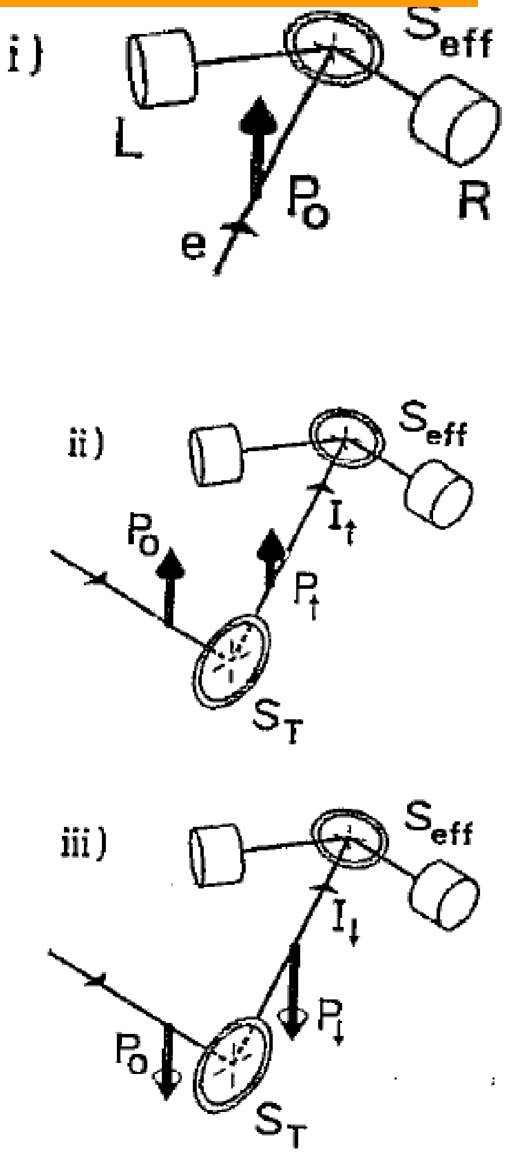
5 equations with four unknowns→
consistency check for apparative asymmetries!
→ Results achieved by Kessler were consistent <0.3%



S. Mayer et al
Rev. Sci. Instrum. 64 952 (1993)

Kessler/HopsterAbraham/Kessler Method

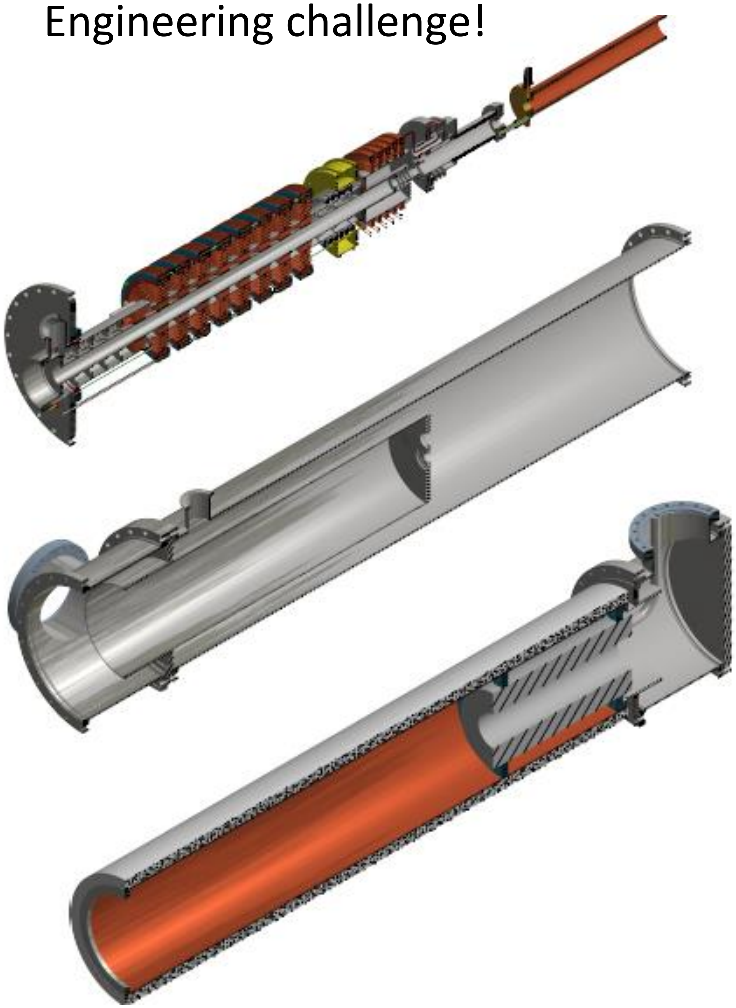




5 equations with four unknowns→
consistency check for apparative asymmetries!
→ Results achieved by Kessler were consistent <0.4%

S. Mayer et al
Rev. Sci. Instrum. 64 952 (1993)

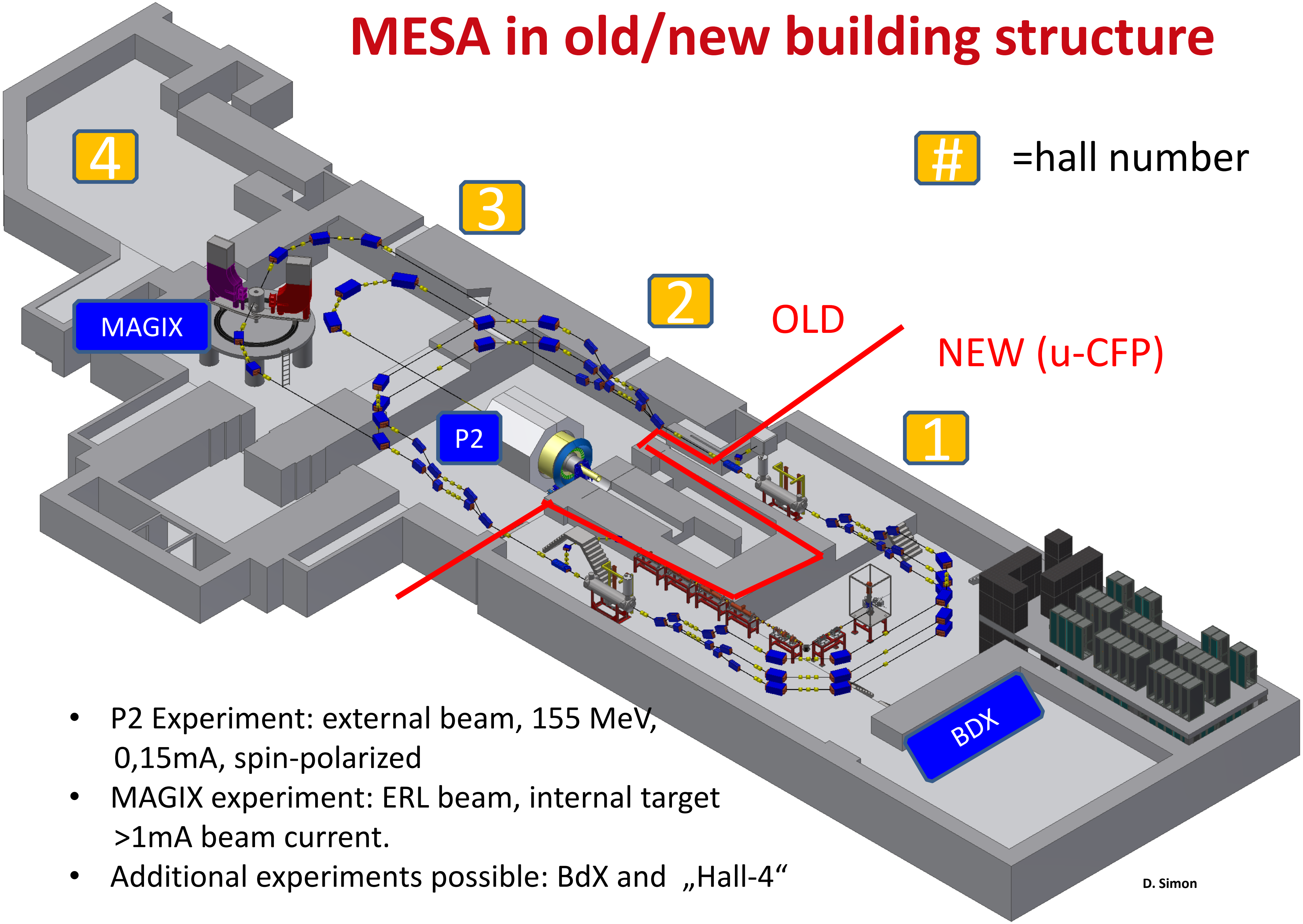
2 m long cryostat
Engineering challenge!



- Dilution Cryostat – Mixing He3 in He4
- $P_{cooling} \sim 60.0\,\mathrm{mW}$ at $T_{mc} = 0.25\,\mathrm{K}$ and $\dot{n}_{He3} = 22.5\,\frac{\mathrm{mmol}}{\mathrm{s}}$
- $P_{precooling} \sim 150.0\,\mathrm{W}$
- Insert (up)
- Housing (middle)
- Magnet and MLI (down)

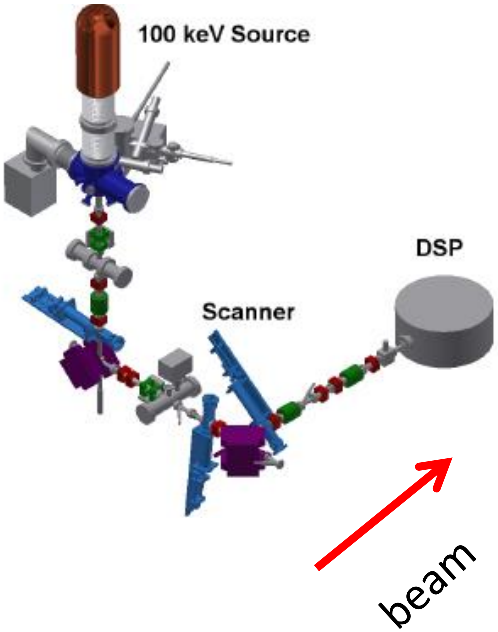
Supplementary transparencies

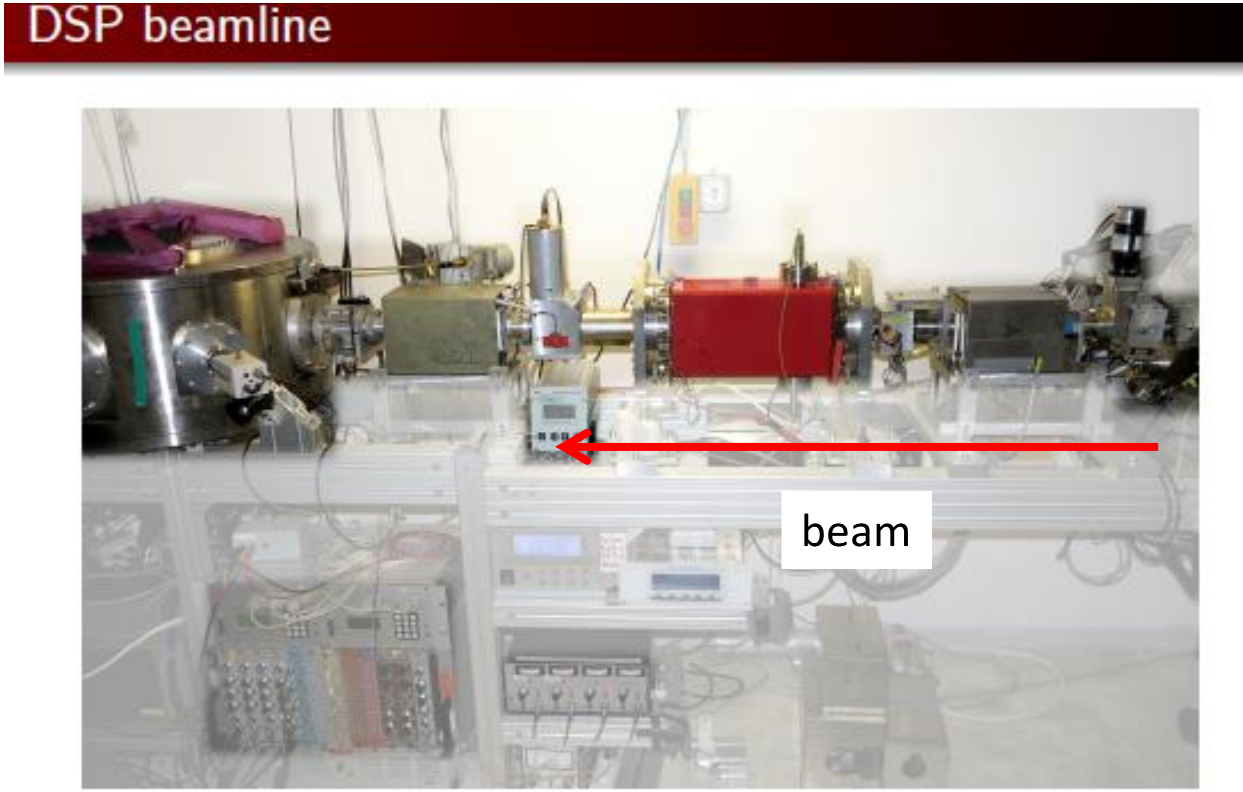
MESA in old/new building structure



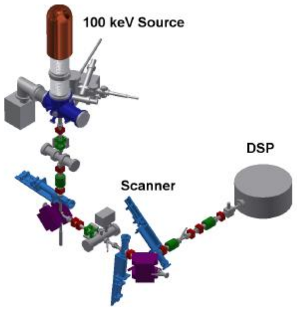
- P2 Experiment: external beam, 155 MeV, 0,15mA, spin-polarized
- MAGIX experiment: ERL beam, internal target >1mA beam current.
- Additional experiments possible: BdX and „Hall-4“

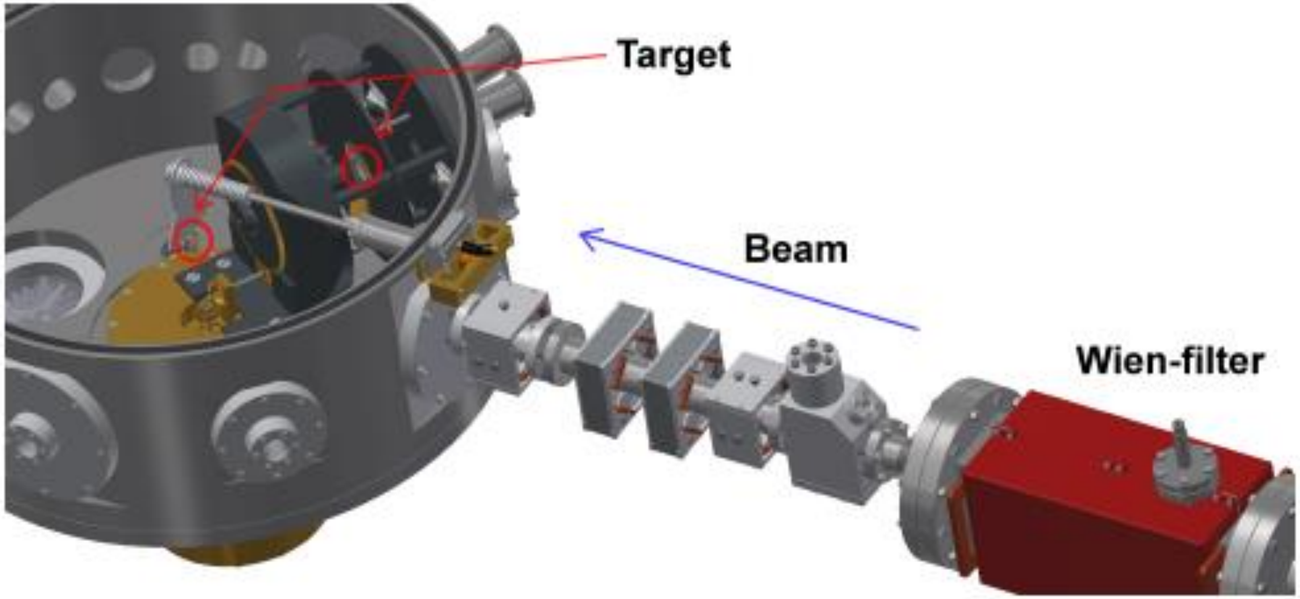
Present set-up of DSP at PKA2




DSP beamline

Present set-up of DSP at PKA2

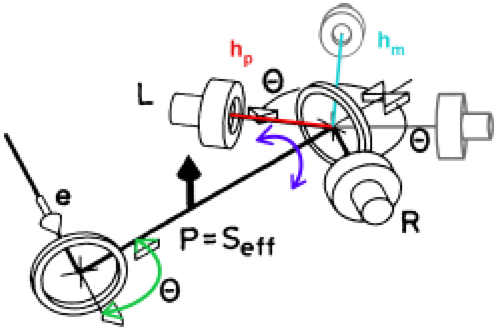


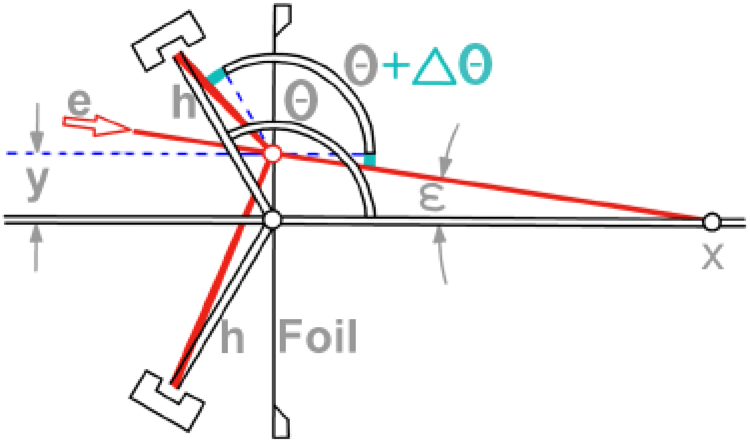


Elimination of apparative asymmetries (when spin cannot be flipped)

- Rotating counters to eliminate efficienciy differences
- Monitor counters to measure false asymmetries (solid angles, scattering angle)

Caveat: a zero asymmetry of monitor countors may be result of compensation between changes of solid angle and scattering angle due to misalignement!





Gellrich, Jost, Kessler: Rev. Sci. Instrum. 61, 3399 (1990)

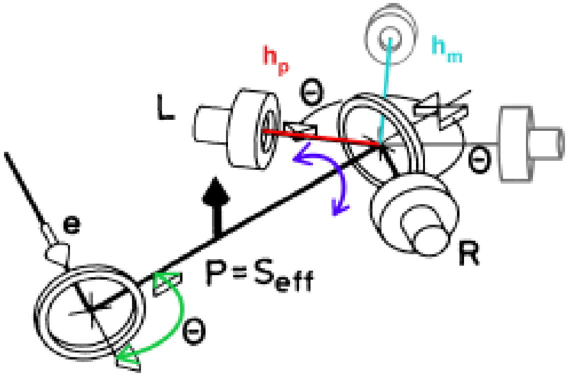
Elimination of apparative asymmetries (when spin cannot be flipped)

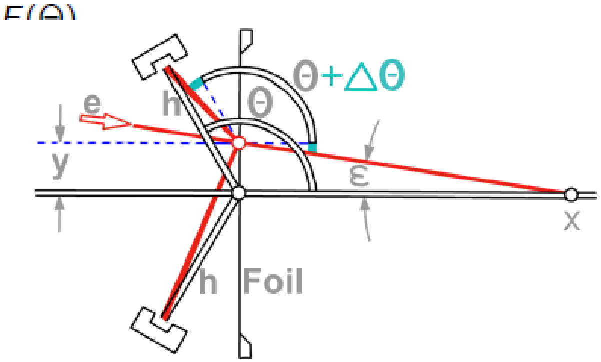
- It can be shown that the false asymmetry of the MONITOR counters is proportional to the false asymmetry measured in the POLARISATION counters IF AND ONLY IF

$$\frac{h_m}{h_p} = \frac{\cos\Theta_m - 2\left[E(\Theta_m)\right]^{-1}\sin\Theta_m}{\cos\Theta_p - 2\left[E(\Theta_p)\right]^{-1}\sin\Theta_p}$$

$$E(\Theta) = \frac{1}{I(\Theta)}\frac{\partial I}{\partial\Theta}$$

(Rev. Sci. Instrum. 61(11) 1990 p.3399)





Gellrich, Jost, Kessler: Rev. Sci. Instrum. 61, 3399 (1990)

The Hydro Möller-general remarks

- „internal target“ with complete (>99.99%)electronic polarization
- Thin target → online capability
- But thick enough to prvide frequent polarization measurements
- Expected accuracy ΔP/P <0.5%
- Technologically demanding

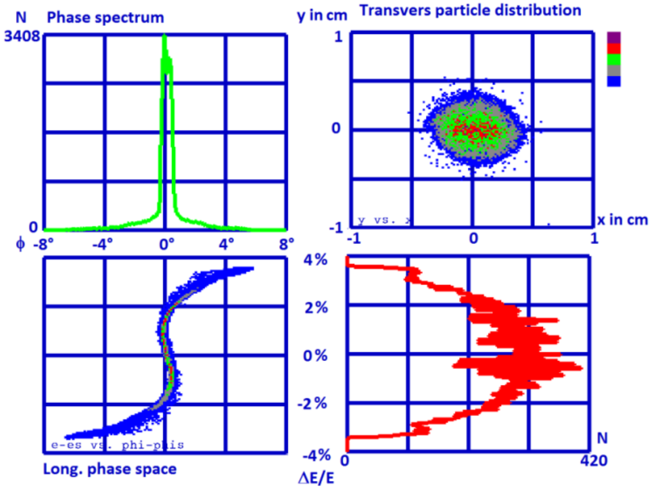
Full Assembly of MELBA planed until early 2017

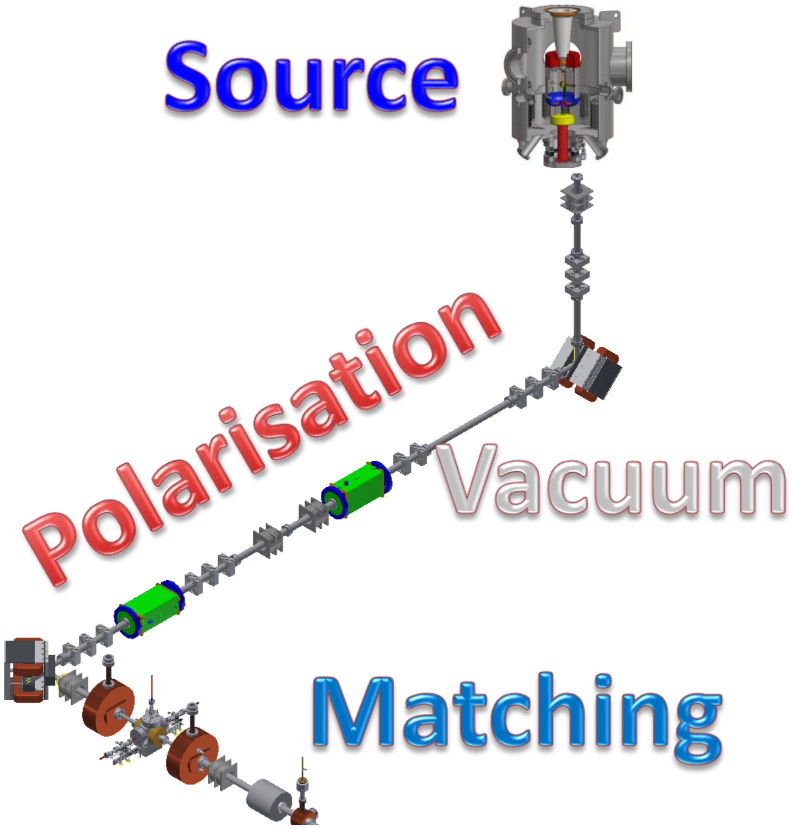
„Start to end“ Simulation predicts for 100keV beam:

-Compatibility with spin rotation

- Sufficient beam quality
  for injection into MAMBO
  with 1pC bunches (=1,3mA)

At the end of MELBA:





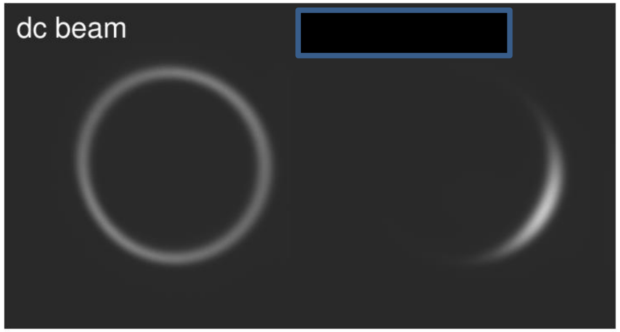
C. Matrejcek

$\frac{\Delta E}{E}_{RMS}$ in %	$\Delta\phi_{RMS}$ in °	$\epsilon_{z,RMS}$ in °keV
1.7	1.3	1.576

α_x	β_x in m	$\epsilon_{x,RMS,n}$ in µm	α_x	β_x in m	$\epsilon_{y,RMS,n}$ in µm
16.5	4.6	0.419	12.2	3.7	0.386

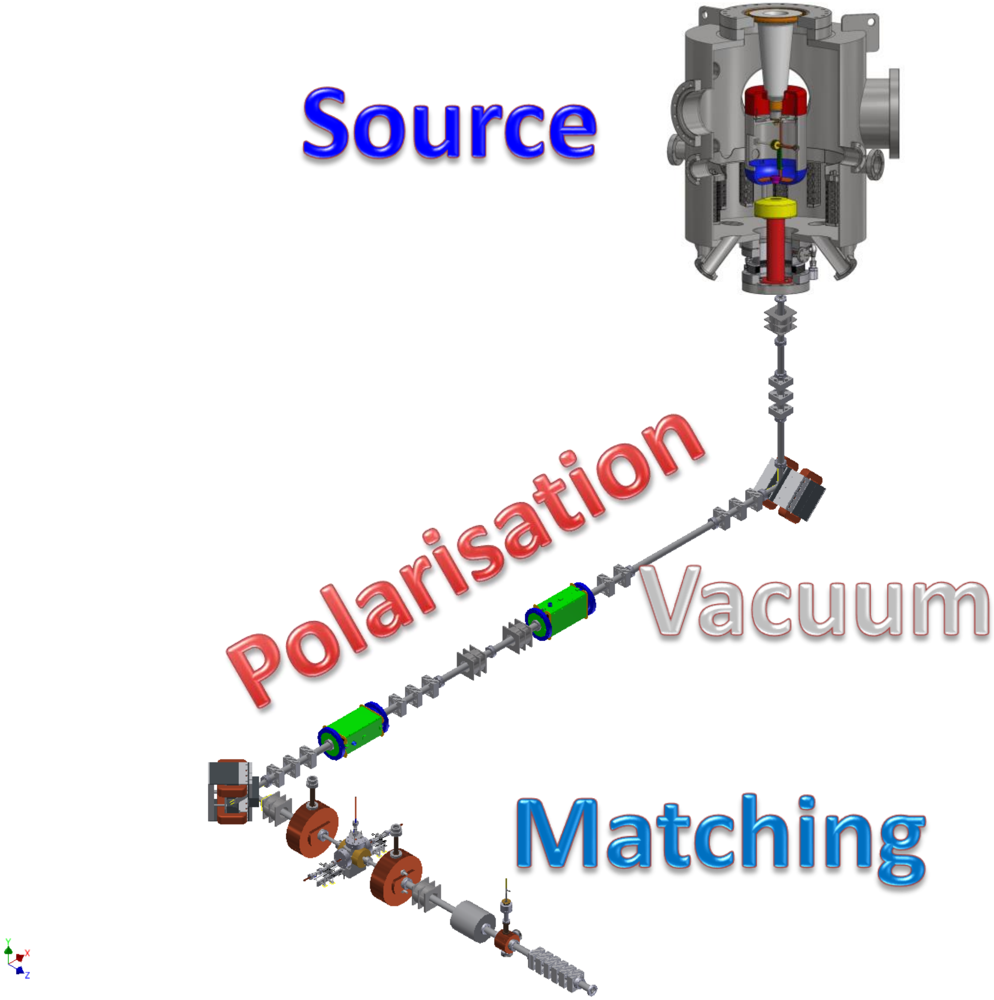
Assembly of MELBA (MEsa Low Energy Beam Apparatus) in 2016

Blue ray disc laser and longitudinal diagnostics already tested….



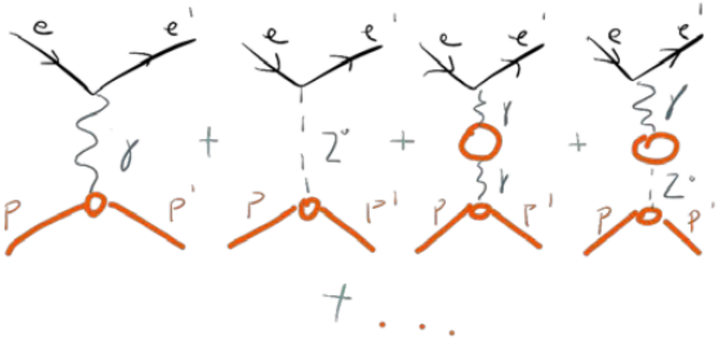
I. Alexander

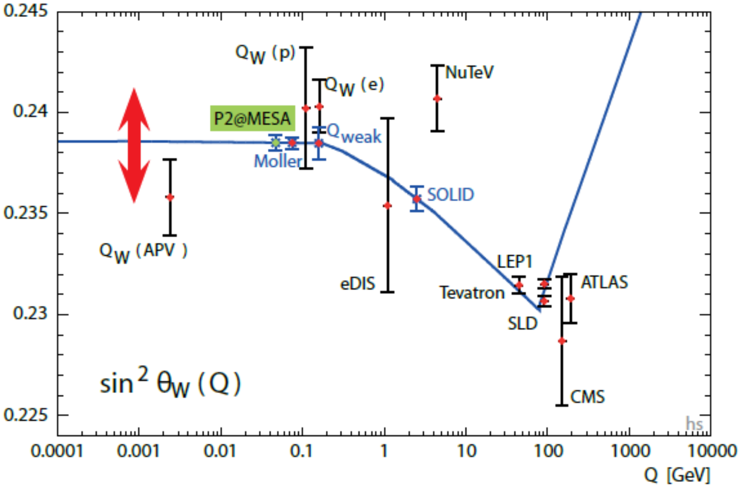
Longitudinal diagnostics at Bunch charges corresponding to > 1mA average current

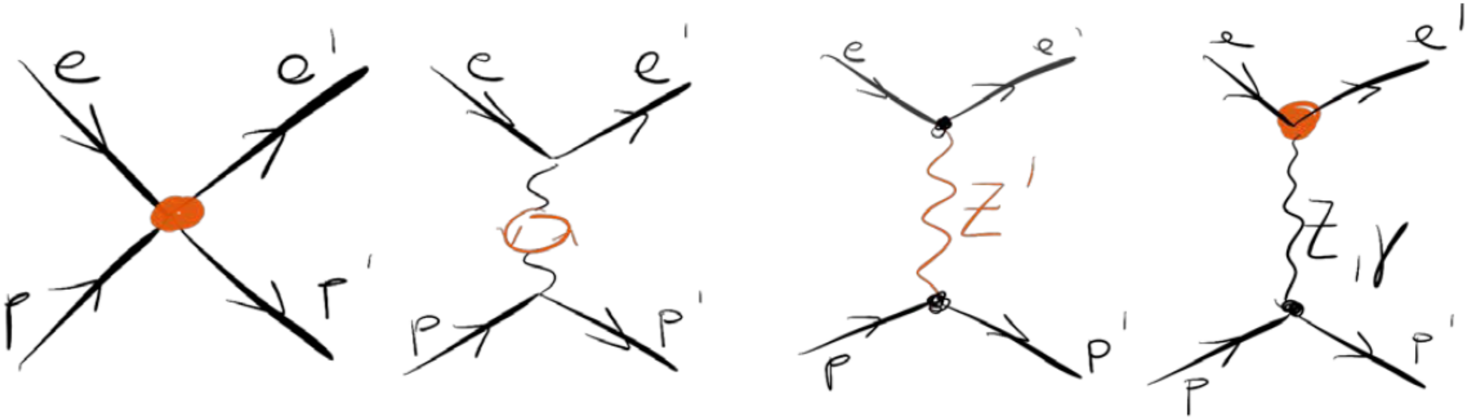


The P2 experiment at MESA

New Physics in the running

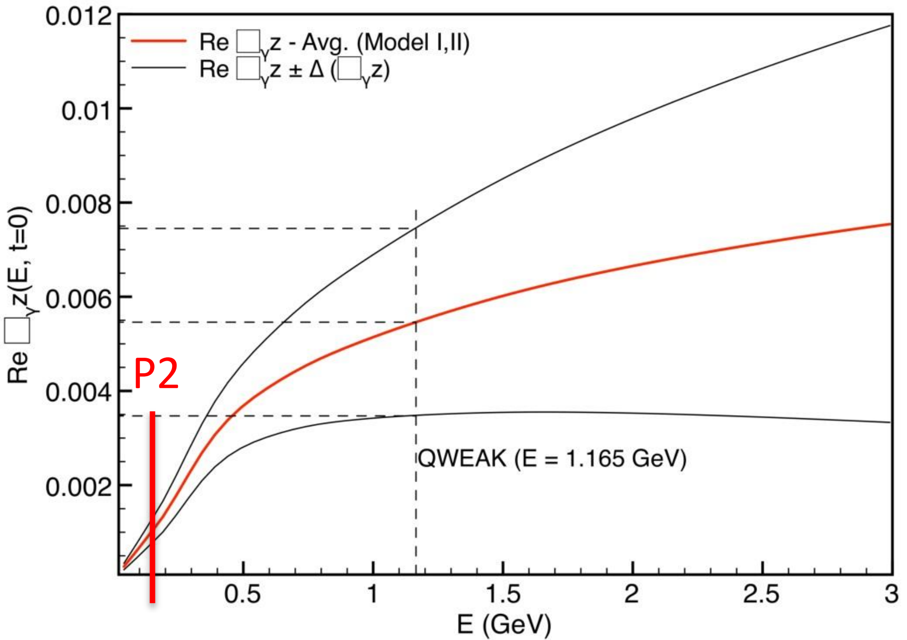






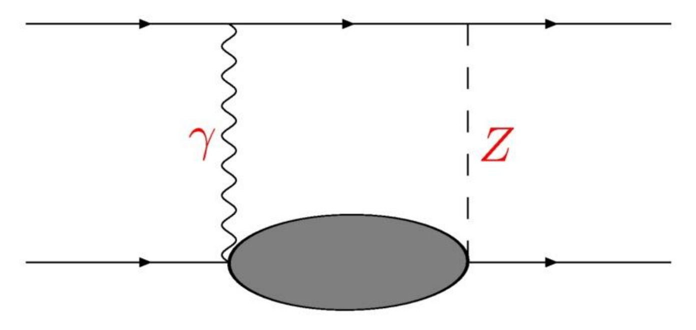
N. Berger

- γZ box graph contributions obtained by modelling hadronic effects:



[Gorchstein, Horowitz & Ramsey-Musolf 2011]

- Hadronic uncertainties suppressed at lower energies
- Low beam energy experiment: **P2 @ MESA**

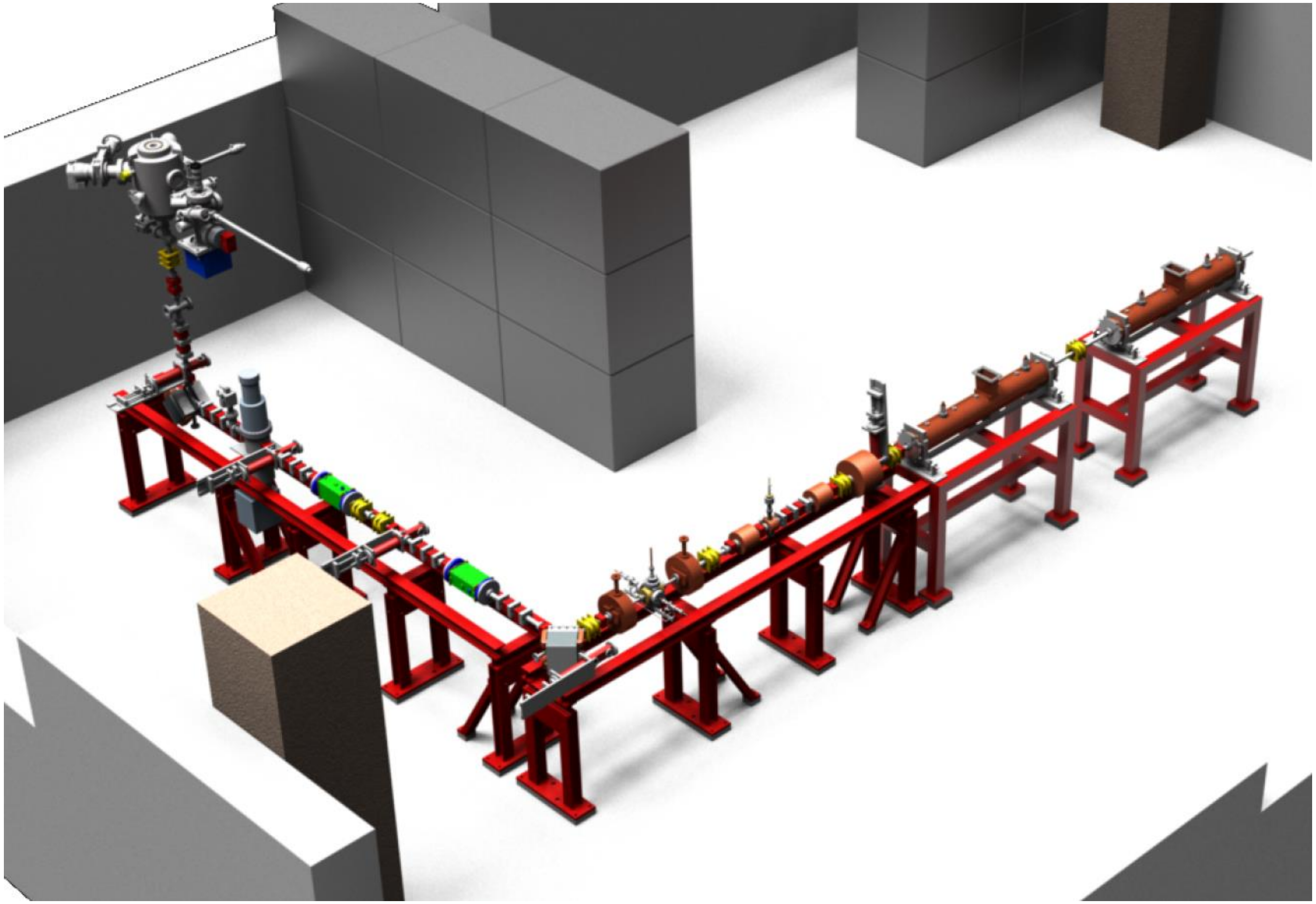


Dominant theoretical uncertainty:

γZ box graphs, $\boxdot_{\gamma Z}$

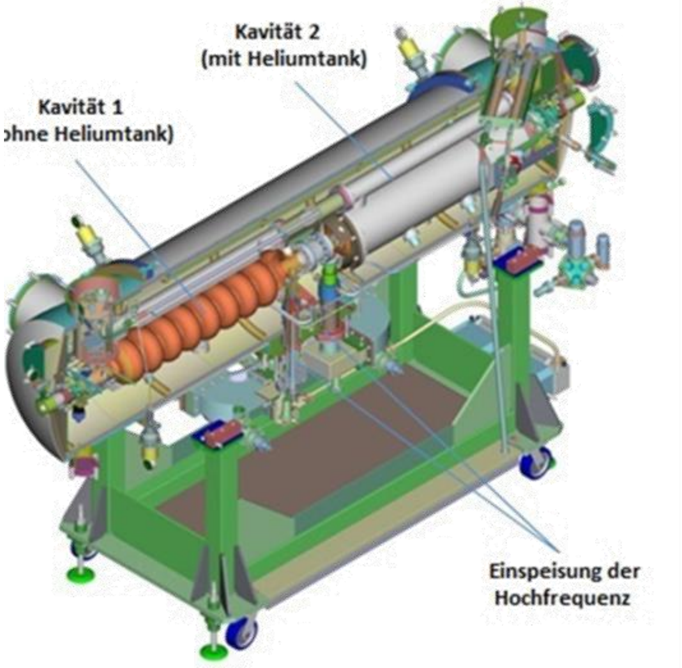
Sensitive to hadronic effects

Beam test of MELBA and “50%” MAMBO planed until end 2018

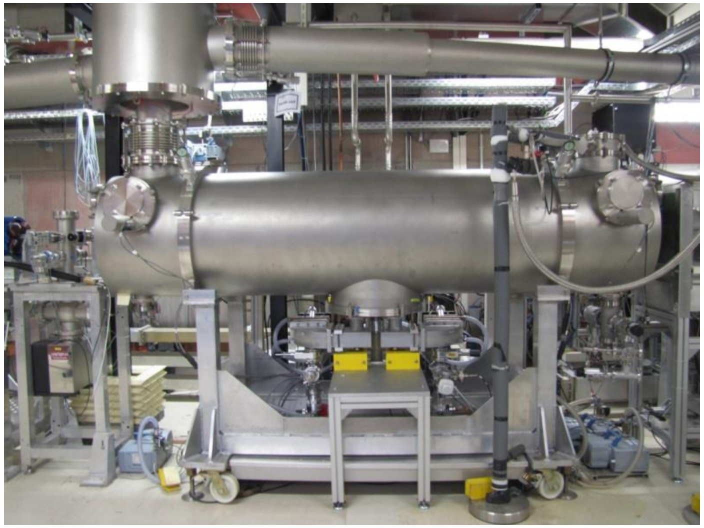


- First two sections of MAMBO will be installed. →2.5 MeV „full relativistic“ beam
- 1300 MHz Rf power generated by **solid state amplifiers** with up to 80kW c.w.
- Beam current >1mA can be tested

MEEK (Mesa Elbe Enhanced Kryomodules)



J. Teichert et al. NIMA 557 (2006) 239

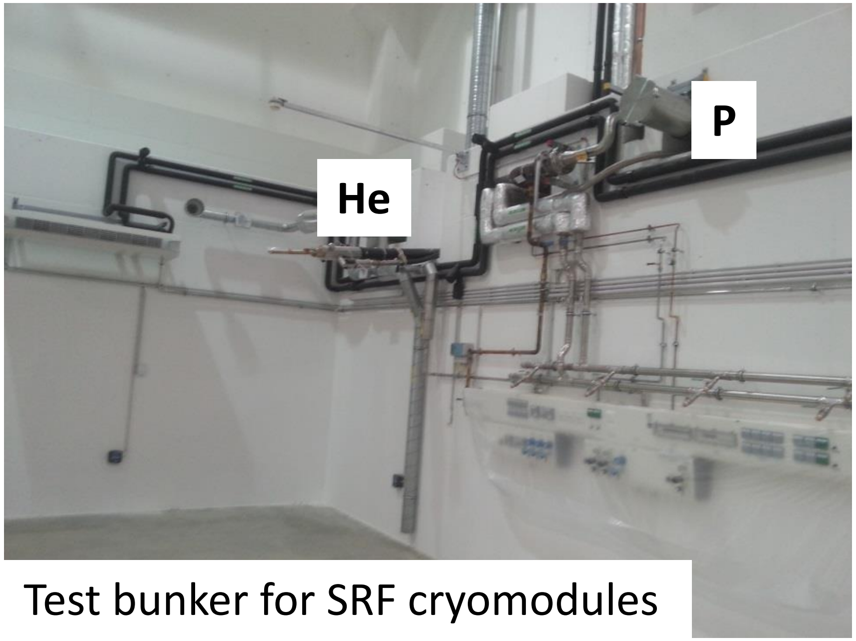


Installation at ELBE

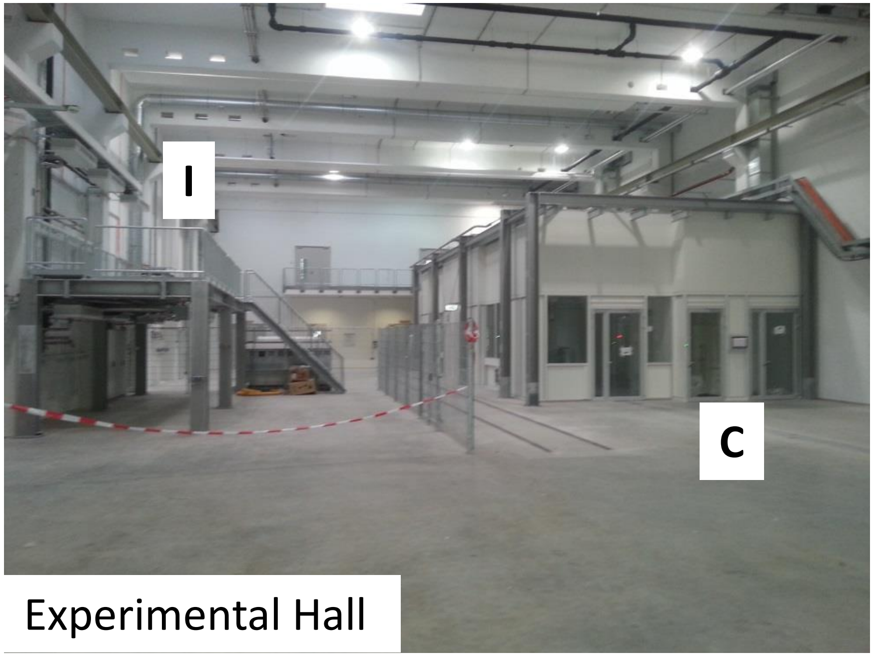
- Design Gradient 13MV/m at Q_0 =1.5*$10^{10.}$
- 2 Cryomodules with four cavities will yield 50MeV energy gain/turn
- „Enhancements“: -faster tuner and improved HOM capabilities for higher current
- Under fabrication at RI Instruments Bergisch Gladbach
- Delivery date for the two modules and April/June 2017
- Performance tests at new „HIM experimental hall“

MEEK Cryomodules -preparing for the test phase

„Helmholtz Institut Mainz“ (HIM) will by ready for operation this summer….



Test bunker for SRF cryomodules

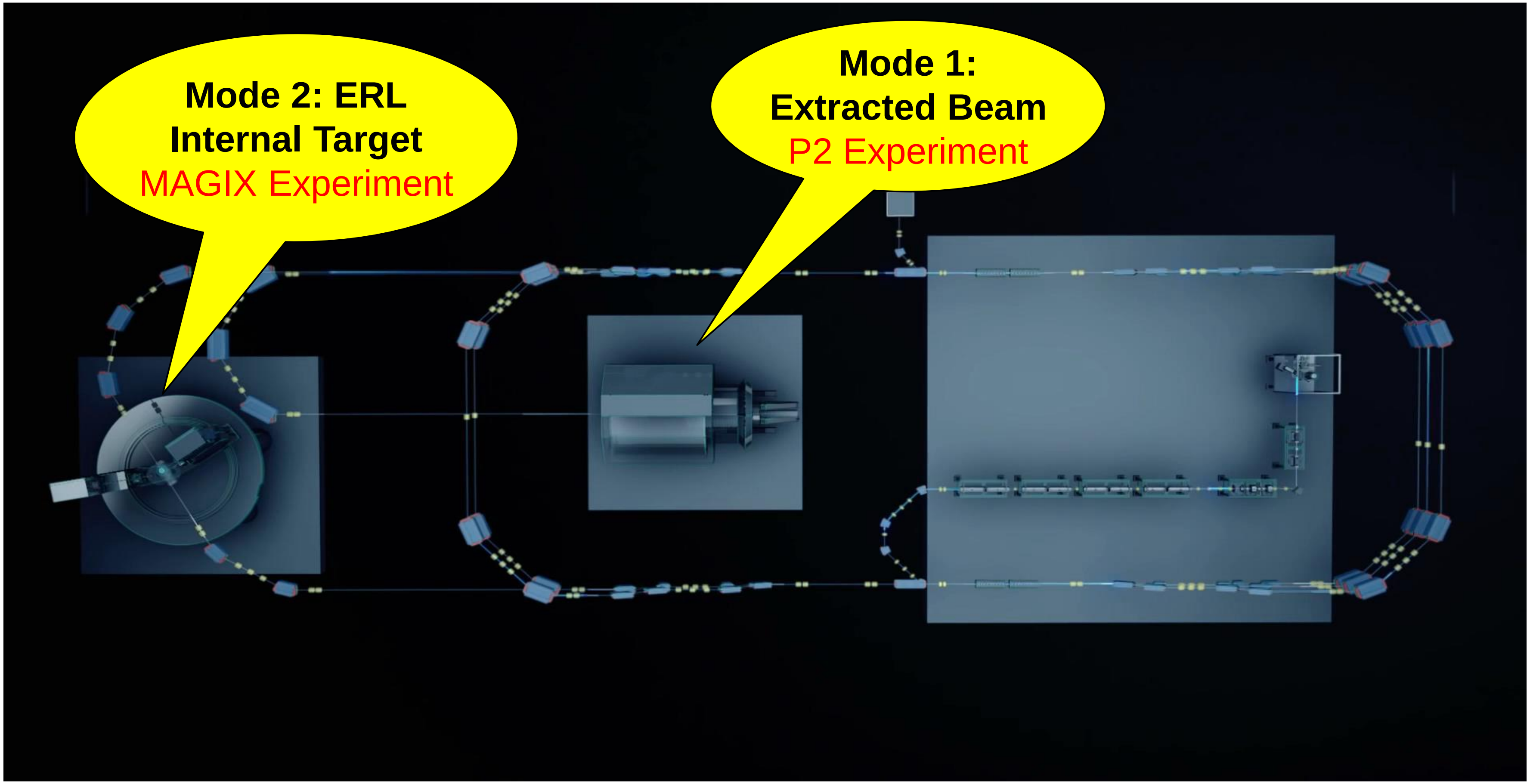


Experimental Hall

01 June 2016

He: Lq. Helium supply line from liquifier in nuclear physics institute: >50l/hour through 220 m long pipe demonstrated. **P:** 4g/s pump stage at 16mbar is presently being ordered.
I: Instrumenttion platform, **C**: Clean room for cryomodule maintenance

Experiments at MESA



Mode 2: ERL

Mode 2: ERL
Internal Target
MAGIX Experiment

Mode 1:
Extracted Beam
P2 Experiment

http://www.prisma.uni-mainz.de/1795.php#imagefilm

Highlights and roadmap from EuCARD-2 XPOL

Kurt Aulenbacher

Content XPOL

Deliverables: One workshop per year

So far three workshops took place:

-12-30 participants..

General remark: Spin at accelerators is a “fundamental” science issue.

- particle physics meets accelerator people..perhaps more directly than in other cases…

-But: Almost no applied Physics yet

(→small community!)

XPOL workshop
Spin optimization at Lepton accelerators
(Mainz, February, 12-13 2014)

23 Participants: -national research centers (DESY,BNL)
& - Many german universities (Bonn, Heidelberg, Munich, Mainz,)
Highlights: high energy circular proton machines, polarized positron source , “Spin at work” (in linear collider)

XPOL workshop
Spin optimization at Lepton accelerators

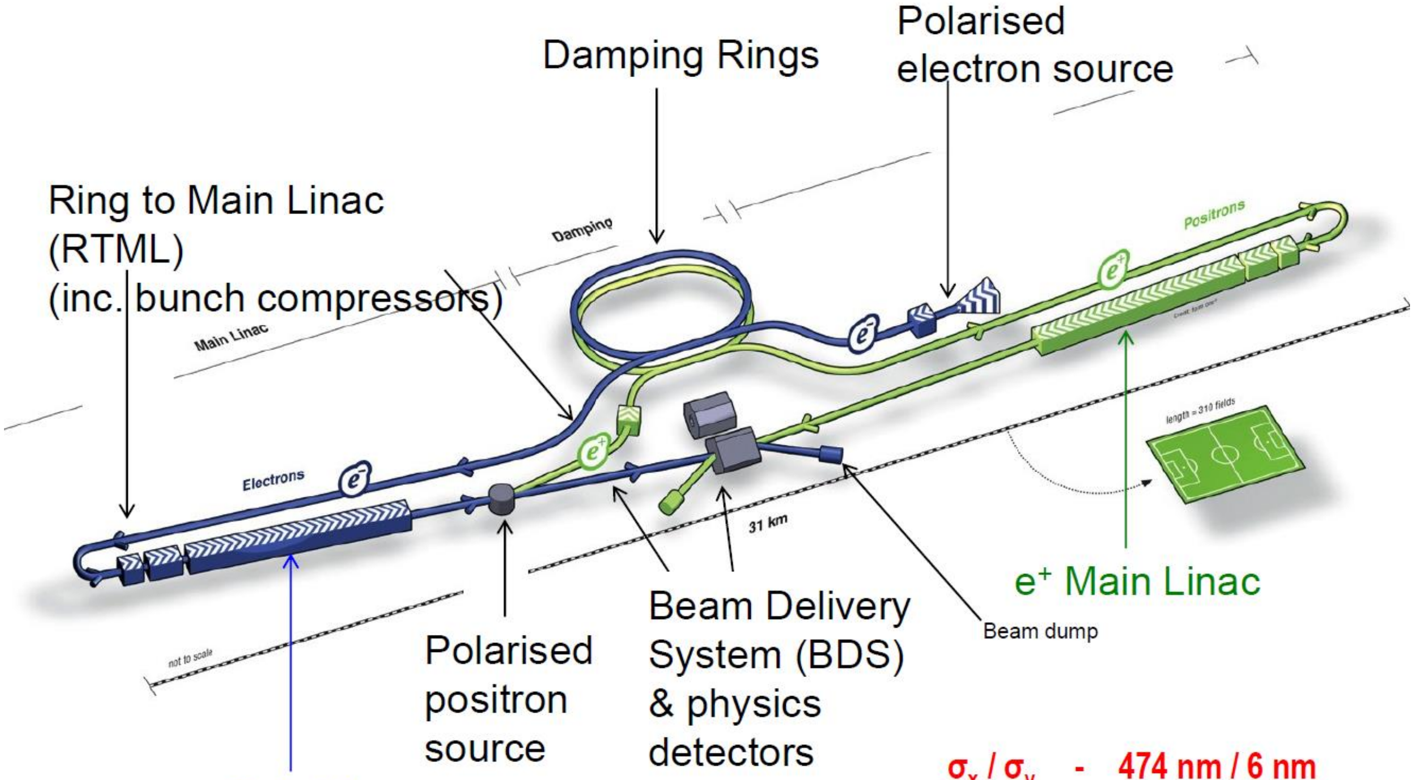
(Mainz, February, 12-13 2014)

23 Participants: -national research centers (DESY,BNL)

& - Many german universities (Bonn, Heidelberg, Munich, Mainz,)

Highlights: high energy circular proton machines, polarized positron source , “Spin at work” (in linear collider)

ILC Machine Overview



Damping Rings

Polarised electron source

Ring to Main Linac (RTML) (inc. bunch compressors)

e⁺ Main Linac

Beam dump

Polarised positron source

Beam Delivery System (BDS) & physics detectors

e⁻ Main Linac

σ_x / σ_y - 474 nm / 6 nm

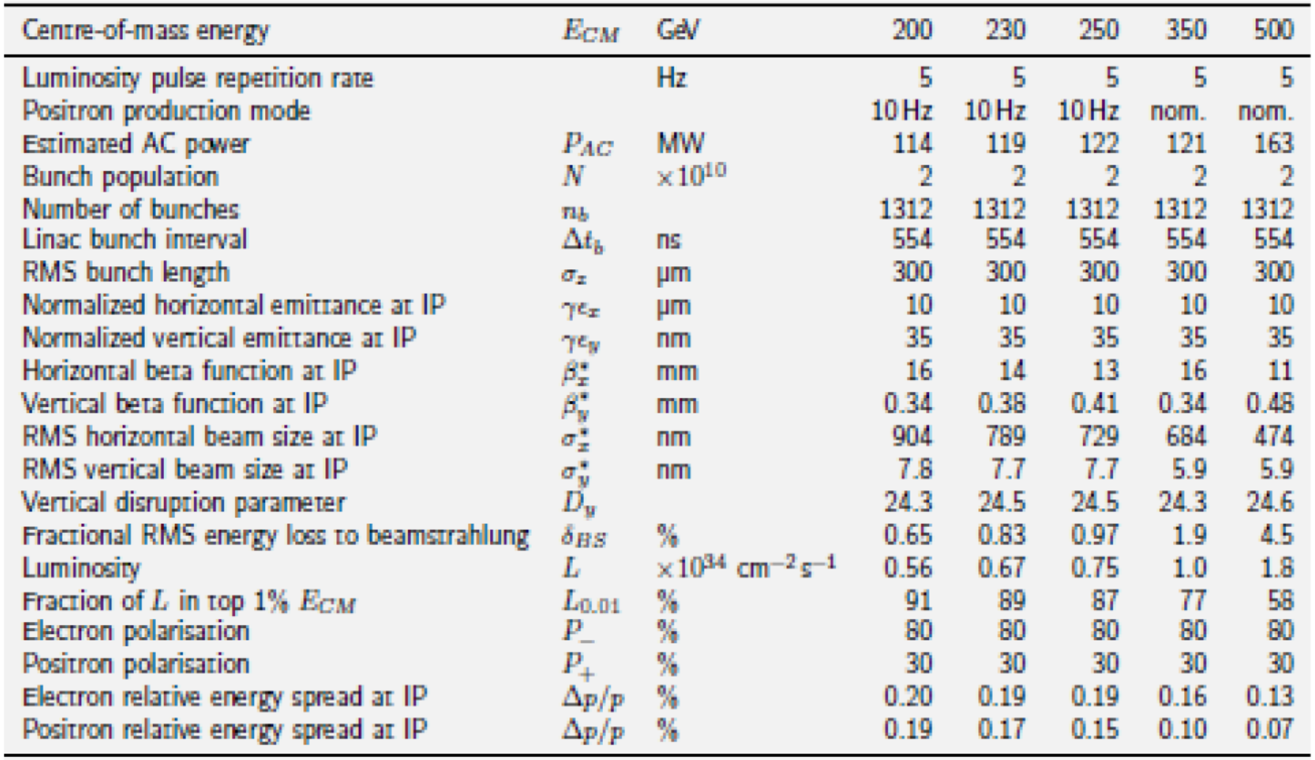
Luminosity - 2×10^{34} cm^{-2}s^{-1}

Polarisation (e-/e+) - 80% / 30%

not to scale

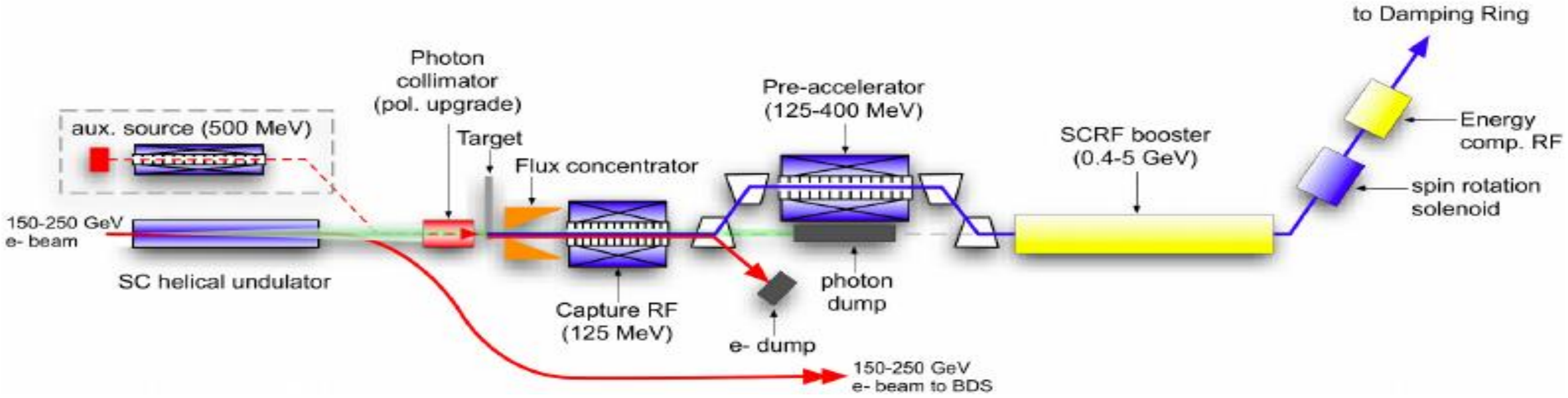
.C Scheme | © www.form-one.de

ILC Parameters



Centre-of-mass energy	E_{CM}	GeV	200	230	250	350	500
Luminosity pulse repetition rate		Hz	5	5	5	5	5
Positron production mode			10 Hz	10 Hz	10 Hz	nom.	nom.
Estimated AC power	P_{AC}	MW	114	119	122	121	163
Bunch population	N	$\times 10^{10}$	2	2	2	2	2
Number of bunches	n_b		1312	1312	1312	1312	1312
Linac bunch interval	Δt_b	ns	554	554	554	554	554
RMS bunch length	σ_z	μm	300	300	300	300	300
Normalized horizontal emittance at IP	$\gamma\epsilon_x$	μm	10	10	10	10	10
Normalized vertical emittance at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
Horizontal beta function at IP	β_x^*	mm	16	14	13	16	11
Vertical beta function at IP	β_y^*	mm	0.34	0.38	0.41	0.34	0.48
RMS horizontal beam size at IP	σ_x^*	nm	904	789	729	684	474
RMS vertical beam size at IP	σ_y^*	nm	7.8	7.7	7.7	5.9	5.9
Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6
Fractional RMS energy loss to beamstrahlung	δ_{BS}	%	0.65	0.83	0.97	1.9	4.5
Luminosity	L	$\times 10^{34}$ $\mathrm{cm^{-2}\,s^{-1}}$	0.56	0.67	0.75	1.0	1.8
Fraction of L in top 1% E_{CM}	$L_{0.01}$	%	91	89	87	77	58
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30
Electron relative energy spread at IP	$\Delta p/p$	%	0.20	0.19	0.19	0.16	0.13
Positron relative energy spread at IP	$\Delta p/p$	%	0.19	0.17	0.15	0.10	0.07

(Polarized) Positron
Bunch population not
Completely safe…



Positron source is located at the end of the electron linac

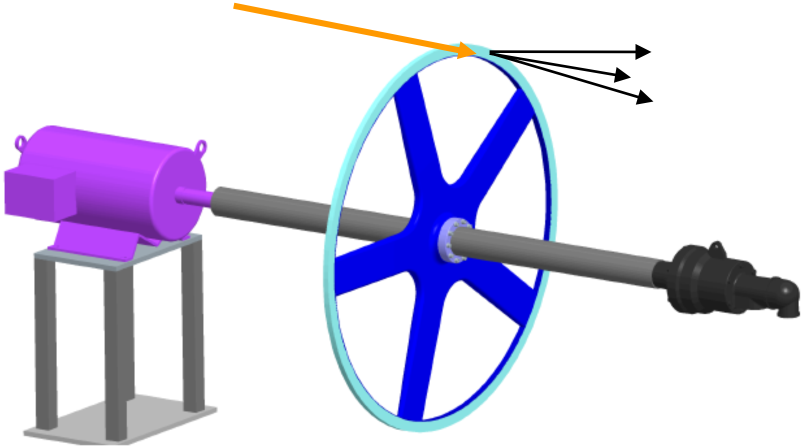
- **required positron yield Y = 1.5 e+/e-**

- Superconducting helical undulator – 231m maximum active length
  → positron beam is polarized
- Photon-Collimator to increase e+ pol
  - Removes part of photon beam with lower polarization
- e+ Production Target, 400m downstream the undulator
- Positron Capture: OMD (Optical Matching Device)
  - Pulsed flux concentrator

Positron Target

Material: Titanium alloy Ti-6%Al-4%V
Thickness: 0.4 X_0 (1.4 cm)
Incident photon spot size on target: $\sigma \sim 2$ mm (rms) (Ee- = 150GeV)
~ 1.2 mm (Ee- = 250GeV)
Power deposition in target: TDR 5-7% (~4kW)
small beam size ⬄ high peak energy density
→spinning wheel to avoid damage due to high energy deposition density

- 2000 r.p.m. (100m/s)
- Diameter: 1m
- Wheel is in vacuum
- water-cooled



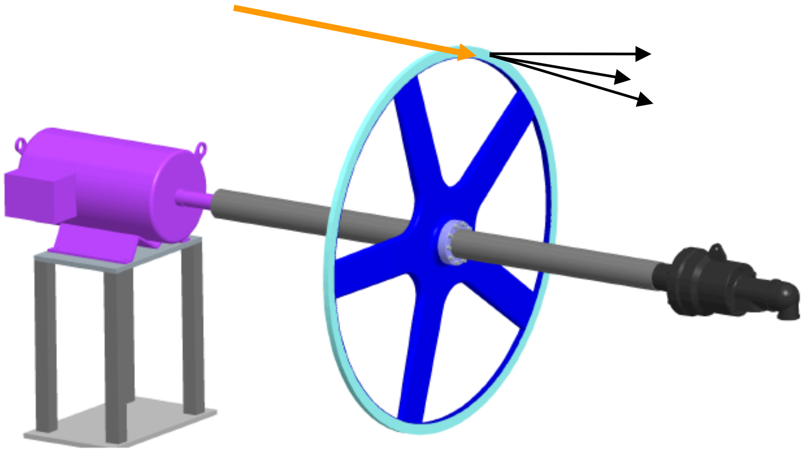
Potential problems

- Stress waves due to cyclic heat load ⬄ target lifetime
- High peak energy deposition
- Eddy currents
- rotating vacuum seals to be confirmed suitable (design and prototyping is ~ongoing)

Positron Target

„EUCARD SPIN-OFF“: POSITAR Experiment

„MIMIC“ impact of photon beam by ionization loss due to focussed electron beam at several MeV. High repetition rate possible at c.w. electron accelerators.
→ 1 day of operation at MAMI mimicks 1 year operation at the ILC.
(first experiment on Titanium alloy 2/2016)



XPOL workshop
Search for the electron EDM in an electrostatic storage ring.
Mainz, September 10-11 2015

Participants: 27 Particle physics meets storage ring! (No collider!)
US (BNL, CORNELL), Korea (CAPP), Germany (COSY-Jülich), Italy (Ferrara), Russia (Dubna),
Highlights: Spin coherence, non-invasive effective polarimetry, Particle physics without collisions!

Electric Dipole Moment=EDM

EDM‘s imply CP-violation (bigger than present standard model)

→ So far only effective experiments with NEUTRAL (composite) systems (exception: neutron)

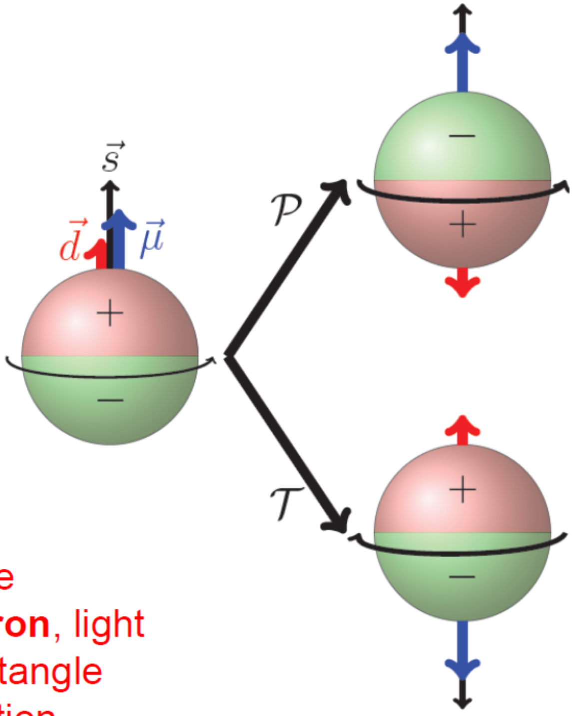
→ Storage rings allow for measurement on truely elementary systems (p, e, μ,...)

→ Electric

Electric Dipole Moments

$\vec{d}$: EDM
$\vec{\mu}$: magnetic moment
both || to spin

$$
\begin{aligned}
H &= -\mu\vec{\sigma}\cdot\vec{B} - d\vec{\sigma}\cdot\vec{E} \\
\mathcal{T}: \quad H &= -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E} \\
\mathcal{P}: \quad H &= -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}
\end{aligned}
$$

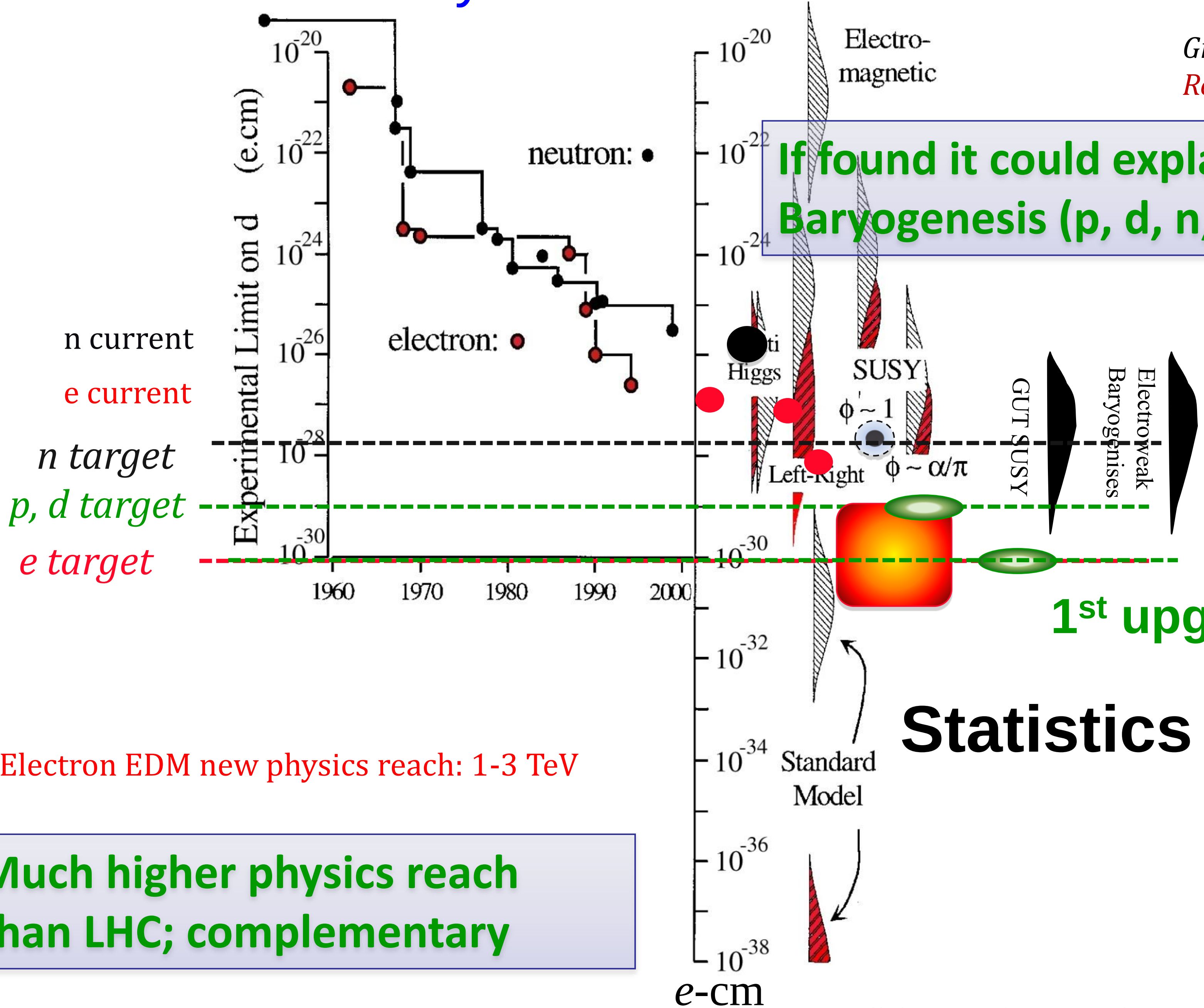


It is important to measure neutron **and proton and deuteron**, light nuclei EDMs in order to disentangle various sources of CP violation.

EDMs are candidates to solve mystery of matter-antimatter asymmetry

Assuming CPT is invariant,
this implies that
CP is violated too…

Sensitivity to Rule on Several New Models



Gray: Neutron

Red: Electron

If found it could explain Baryogenesis (p, d, n, ^{3}He)

1st upgrade

Statistics limited

Electron EDM new physics reach: 1-3 TeV

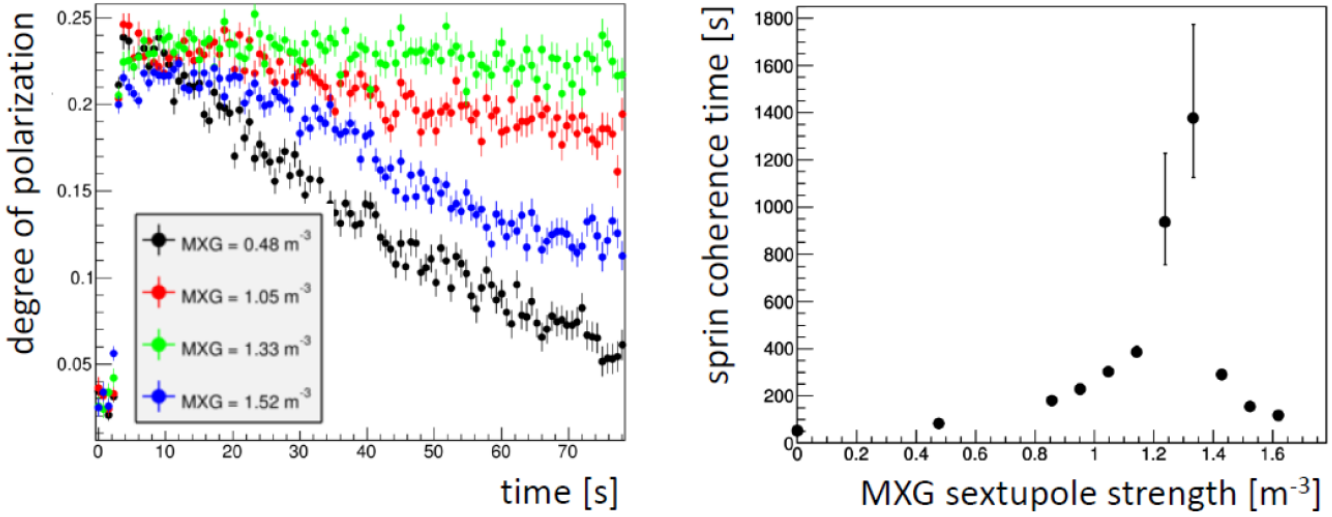
Much higher physics reach than LHC; complementary

J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

Spin coherence time at COSY

10^9 polarized deuterons at 970 MeV/c, bunched and electron cooled

adjust three arc sextupoles to increase spin coherence time



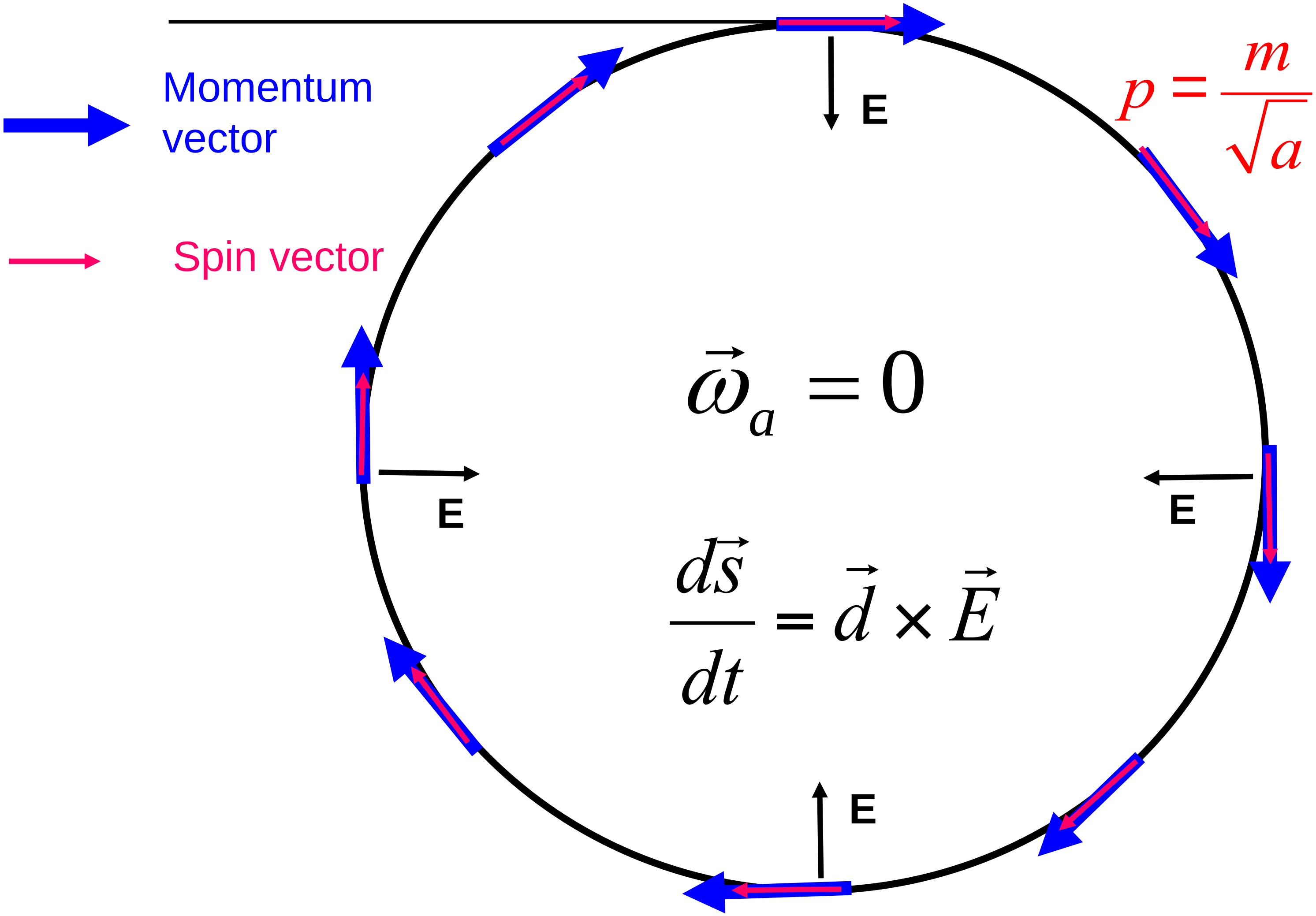
→ Long SCT for adjusted transverse beam chromaticities

Poster by Greta *Guidoboni* (UNIFE, Ferrara) at IPAC 2015: THPF146
Spin Coherence Time Lengthening of a Polarized Deuteron Beam with Sextupole Fields

A. Lehrach, FZJ

at the magic momentum

$$p = \frac{m}{\sqrt{a}} = 0.7\ \mathrm{GeV/c}$$



$$\vec{\omega}_a = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

Signal can be mimicked by radial magnetic fields
→ eliminate those by all electric ring operaqting at „magic“ momentum („frozen spin“ points always in direction of motion)

$$p = \frac{m_0 c}{\sqrt{a}}$$

$$a_{el} = 1/800 \Rightarrow p_e = 14{,}8\ \mathrm{MeV/c}$$

$$\mathrm{a_p} = 1.79 \Rightarrow p_p = 747 MeV / c$$

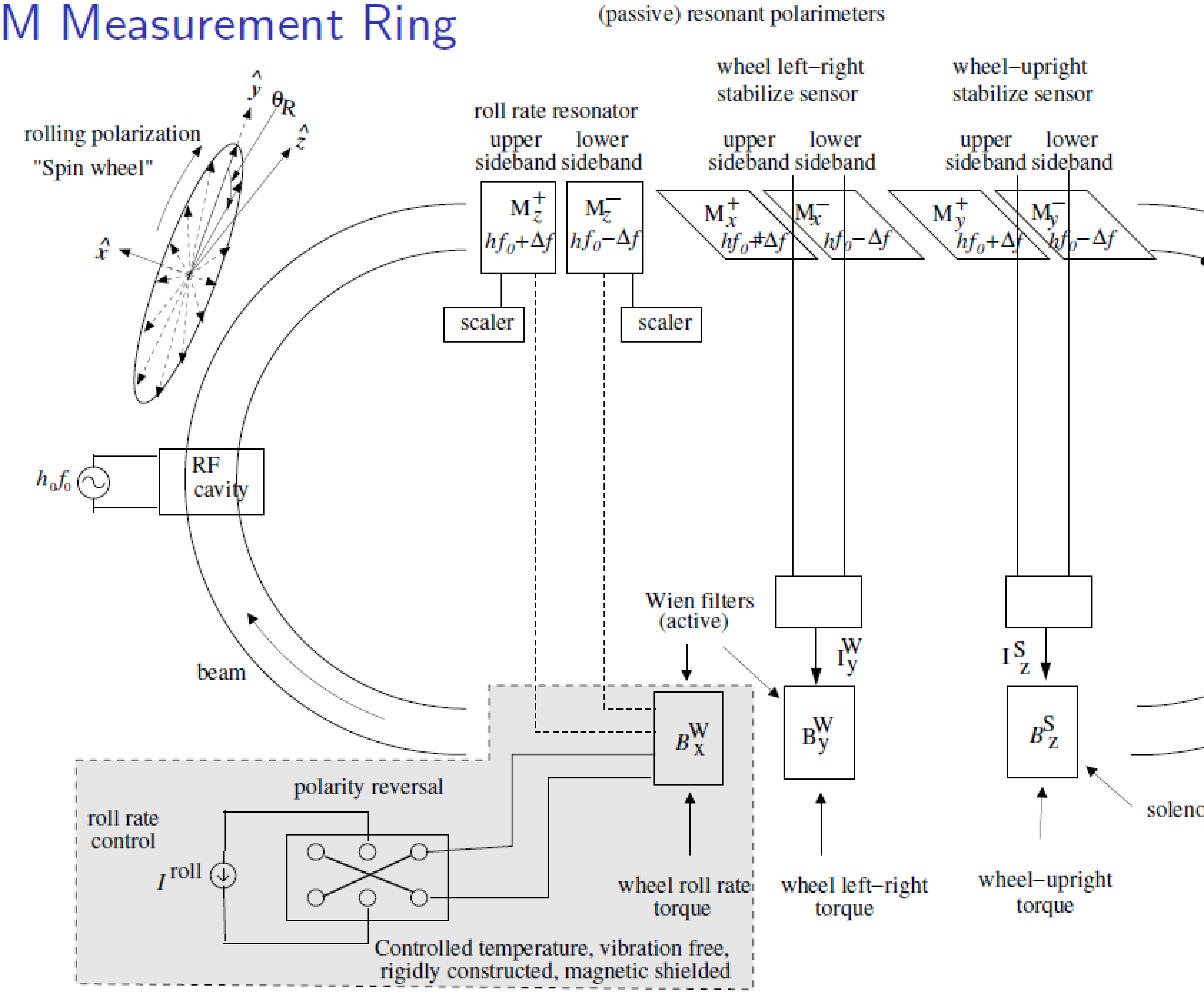
$$a_D = -0.14 \Rightarrow ?$$

Hadrons promise easier success, but require much more expensive ring

Problem with electron: efficiency of Polarimetry.

Way out: Transfre from intensity to frequency measurement (Talman)

9 EDM Measurement Ring



XPOL workshop

Polarization issues in future high energy circular colliders
Rome, April 16 2015

14 Particpants
(China, Germany, Japan,
Switzerland, Russia, US,)

Small, but extremely intense meeting with vivid Discussions…

Highlights: Vertical polarization In fcc-ee → energy calibration (Ginafelice, Hillert, Koop,

Fcc-hh: polarization not hopeless (Ptytsin) internal Target also (Lenisa)

Again ,polarimetry is the key…

Sokolov-Ternov polarization

Beam get vertically polarized in the vertical guiding field of the ring

$$P_\infty = 92.3\% \qquad \tau_p^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e\gamma^5\hbar}{m_0C}\oint\frac{ds}{|\rho|^3}$$

For FCC-e^+e^- with $\rho \simeq$ 10424 m, fixed by the maximum attainable dipole field for the hh case, it is

E (GeV)	U_0 (MeV)	σ_E/E (%)	τ_{pol} (h)
45	35	0.038	256
80	349	0.067	14

Next XPOL workshop End of 2016

New venues in polarimetry

Beam Polarimetry is the key issue for several project in acclerator based research

- fcc-ee energy calibration

- eEDM determination („Resonant polarimter“)
-
- Highly accurate polarimeters for precision observables
  (Hydro Moller completely polarized internal target, double scattering,)