Measuring the Proton's Polarizabilities at MAMI

Garth Huber

UNIVERSITY OF REGINA

Physics Department Seminar, October 7, 2011.

Particle Data Group: Baryon Listings

$\boxed{p}$ $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

p MASS (MeV)

VALUE (MeV)
938.272013±0.000023

p MAGNETIC MOMENT

VALUE (μ_N)
2.792847356±0.000000023

Valence quarks: uud

p CHARGE RADIUS

VALUE (fm)
0.8768±0.0069

p ELECTRIC DIPOLE MOMENT

VALUE (10^{-23} e cm)
< 0.54

p ELECTRIC POLARIZABILITY α_p

VALUE (10^{-4} fm^3)	*DC*
12.0 ±0.6 OUR AVERAGE	

p MAGNETIC POLARIZABILITY β_p

VALUE (10^{-4} fm^3)	*D*
1.9 ±0.5 OUR AVERAGE	

p MEAN LIFE

LIMIT (years)	*PARTICLE*
$>5.8 \times 10^{29}$	***n***
$>2.1 \times 10^{29}$	***p***

p DECAY MODES

Response to a deformation force

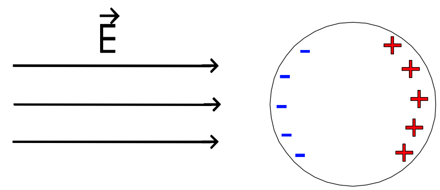
What is a Polarizability?

A measure of response of system to a quasi-static field.

e.g. Electric Polarizability α_E

Applied E induces EDM

$$\vec{p} = \alpha_E \vec{E}$$



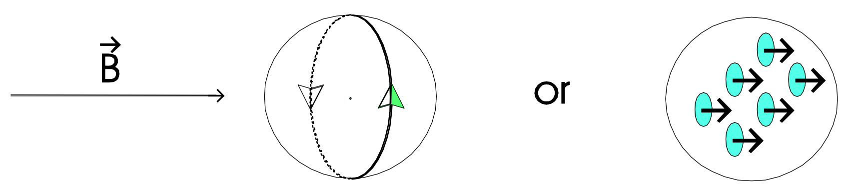
with energy density

$$u_E = -\frac{1}{2}\alpha_E \vec{E}^2$$

Similarly, applied H induces MDM

$$\vec{m} = \beta_E \vec{H}$$

$$u_M = -\frac{1}{2}\beta_M \vec{H}^2$$



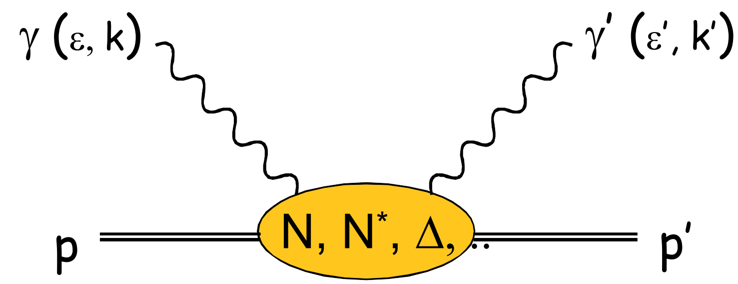
Diamagnetism

$\beta_{dia} < 0$

Paramagnetism

$\beta_{para} > 0$

Nucleon Scalar Polarizabilities



Low energy outgoing photon plays role of applied E.M. dipole field

Nucleon response: POLARIZABILITIES

Nucleon Polarizabilities of interest to many fields:

- In astrophysics, they determine neutron star properties.
- In atomic physics, they yield an appreciable correction to Lamb shift and hyperfine structure.
- In hadronic physics, they are fundamental observables of nucleon structure.

How to measure Proton Scalar Polarizabilities

- **Accessed via Compton scattering of Real Photons**

$$\gamma + N \rightarrow \gamma + N$$

- **2^{nd} and higher order terms describe polarizabilities and evidence of proton's internal structure.**

$$H_{eff}^{(2)} = \frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2$$

- **Compton scattering angular distribution**

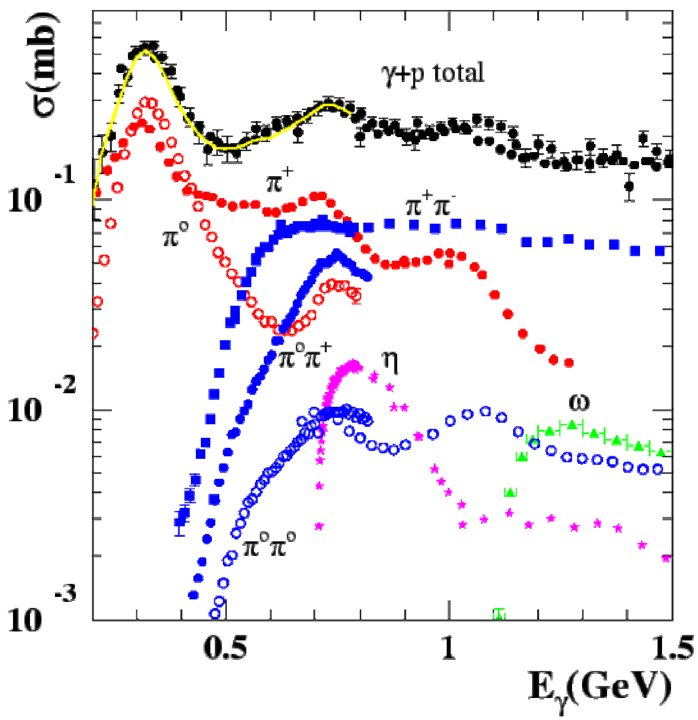
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{m^2}\left(\frac{\omega'}{\omega}\right)^2 \left(\frac{1}{2}\left(1+\cos^2\theta\right) - \frac{m\omega\omega'}{\alpha}\left[\begin{array}{c} \frac{\alpha_{E1}+\beta_{M1}}{2}\left(1+\cos\theta\right)^2 \\ +\frac{\alpha_{E1}-\beta_{M1}}{2}\left(1-\cos\theta\right)^2 \\ +\ldots \end{array} \right] \right)$$

Polarizabilities from Real Compton Scattering

1. Total inclusive photoabsorption cross section:

$$\alpha_{E1} + \beta_{M1} = \frac{1}{2\pi^2} \int_{\upsilon_{thr}}^{\infty} \frac{d\upsilon}{\upsilon^2} \sigma_{abs}(\upsilon)$$

Baldin Sum Rule (1960)

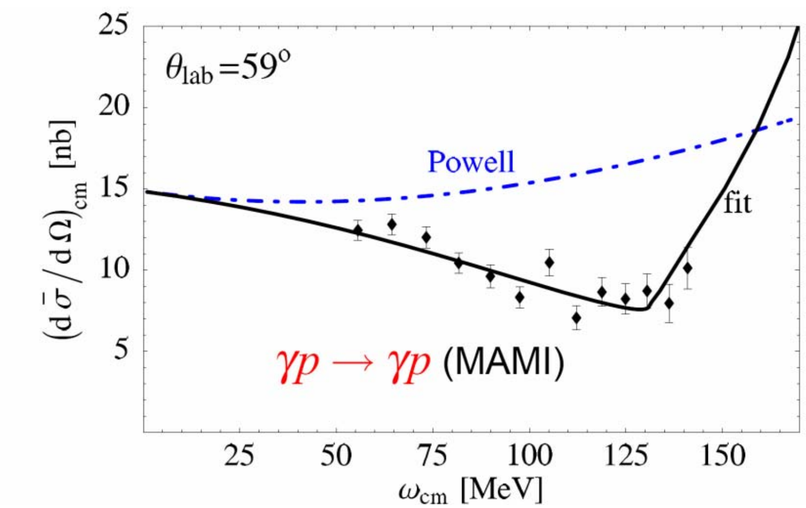


Sum Rule is model independent
→ but a model is needed to evaluate integral beyond experimental data.

$$\alpha_{E1} + \beta_{M1} = (13.8 \pm 0.4) \cdot 10^{-4} \ \text{fm}^3$$

Polarizabilities from Real Compton Scattering

2. Compton scattering angular distribution vs energy (ν)



Olmos de Leon et al., EPJ A10 (2001)

Powell cross section: photon scattering off a pointlike nucleon with anomalous magnetic moment.

Disperson relation analysis used to extract α-β from the data.

$$\alpha_{E1} - \beta_{M1} = (10.5 \pm 0.9) \cdot 10^{-4}\ \text{fm}^3$$

Global average of Scalar Polarizability Data

- Electric polarizability α_{E1} well constrained by experimental data.
- Magnetic polarizability β_{M1} less certain.
  - Diamagnetism is important in the nucleon, but uncertainty ~25%.
  - Experimental value about 2x smaller than value obtained from Chiral Perturbation Theory.

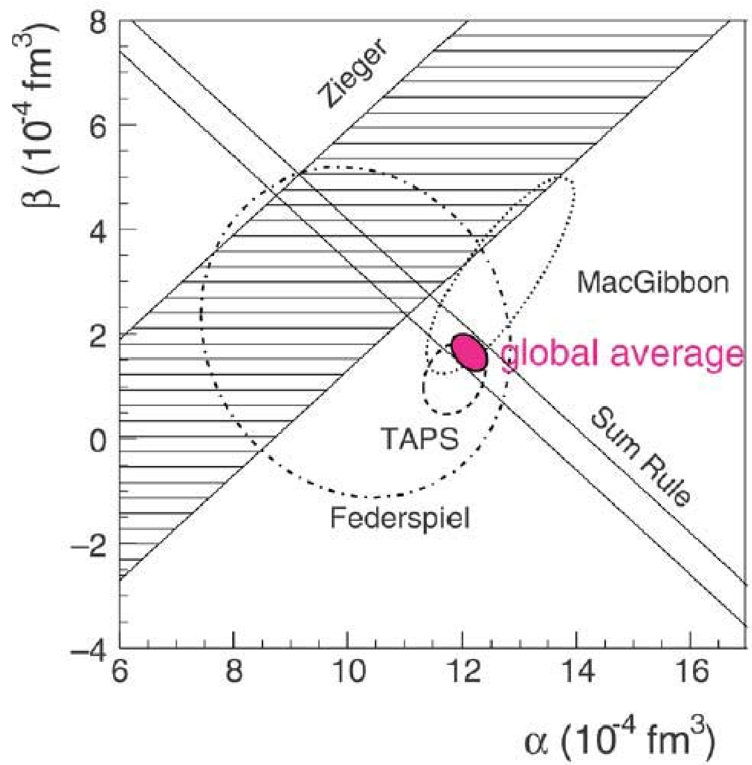


Fig. 6. Error contour plot in the ($\bar{\alpha}$-$\bar{\beta}$)-plane of the experiments in table 3 (last column) for which the errors are taken as the statistical ones only. The contours correspond to the values $\chi^2_{\min}+1$ of the individual fits. Also shown are the sum rule constraint and the value $\bar{\alpha}-\bar{\beta}$ as follows from the experiment by Zieger *et al.* [28]. The thick solid line shows the result of the global fit, eq. (22).

Olmos de Leon et al., EPJ A10 (2001)

A simple picture of what the results mean

Experimental values (PDG2010):

α_{E1}=(12.0±0.6)x10^{-4} fm^3 β_{M1}=(1.9±0.5)x10^{-4} fm^3

- Size of α_{E1} measures "stiffness" of system to electric deformation.

For ^{1}H atom, well known calculation yields

$$\alpha_E^H = \frac{9}{2} a_B^3 = \frac{27}{8\pi}\text{Vol}$$

While for proton $\alpha_E^p \cong 3\times 10^{-4}\,\text{Vol}$

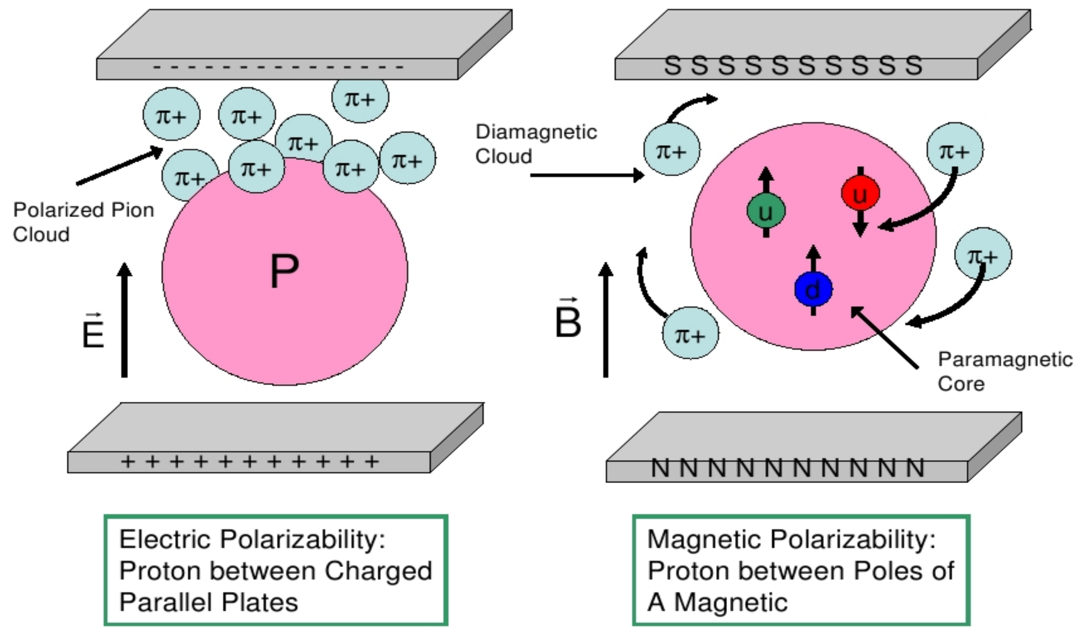
- Apparently, the proton is very "stiff".

- Simple estimate shows why: $$\frac{\alpha_E^p}{\alpha_E^H} \approx \frac{E_{bind}^H}{E_{bind}^p} \approx \frac{\alpha_{EM}^2}{\alpha_{Strong}^2} \approx 10^{-4}$$

More detailed explanation

- **Need to take into account that the proton is surrounded by a virtual meson cloud in order to quantitatively understand the observed α_{E1}, β_{M1} polarizabilities.**

- p(J=½)→Δ(J=3/2) dipole transition makes very strong paramagnetic contribution to $\beta_M \sim 10^{-3}$ fm^3.
- Partially offset by strong diamagnetic component from meson cloud.



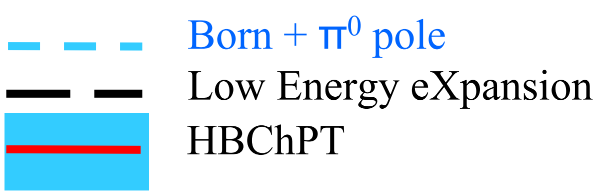
B. Holstein, MAMI and Beyond Conference, 2008.

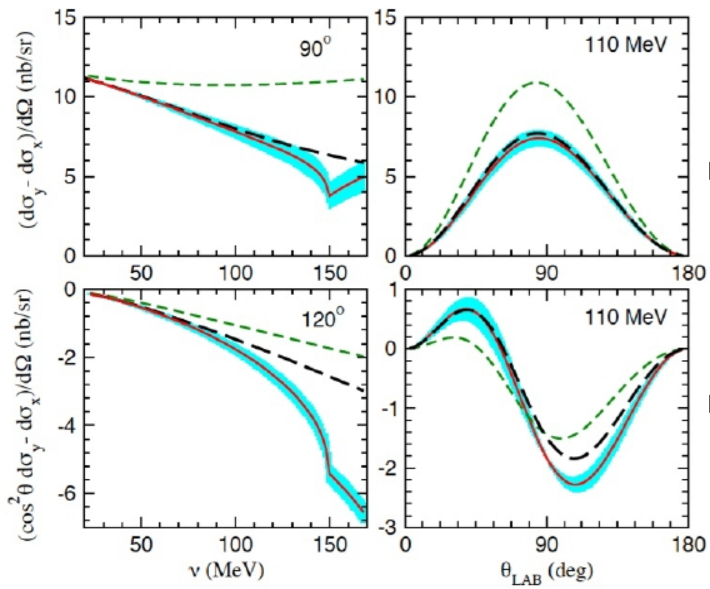
How to obtain more accurate values of α_{E1}, β_{M1}

- 2x discrepancy in β_{M1} between experiment and theory has motivated a new generation of experiments.
- Combinations of cross sections with linearly polarized photons → leading order contribution from α and β

$$\frac{d\sigma^{\parallel}}{d\Omega} = \frac{d\sigma^{\parallel}_{Powell}}{d\Omega} - \frac{e^2}{2\pi m_p}\left(\frac{\upsilon'}{\upsilon}\right)^2 \upsilon\upsilon'\left(\alpha_E \cos\theta^2 + \beta_M \cos\theta\right) + O\left(\upsilon^3\right)$$

$$\frac{d\sigma^{\perp}}{d\Omega} = \frac{d\sigma^{\perp}_{Powell}}{d\Omega} - \frac{e^2}{2\pi m_p}\left(\frac{\upsilon'}{\upsilon}\right)^2 \upsilon\upsilon'\left(\alpha_E + \beta_M \cos\theta\right) + O\left(\upsilon^3\right)$$





→ α_{E1}

→ β_{M1}

- Measurement from 120-200 MeV is proposed for MAMI.

[Lensky, Pascalutsa, EPJC (2010)]

Proton Spin (Vector) Polarizabilities

If include spin, next term in Hamiltonian:

$$H_{eff}^{(3)} = -\frac{1}{2}\left[\begin{array}{l}\gamma_{E1E1}\vec{\sigma}\cdot\vec{E}\times\dot{\vec{E}}+\gamma_{M1M1}\vec{\sigma}\cdot\vec{H}\times\dot{\vec{H}} \\ +2\gamma_{E1M2}H_{ij}\sigma_i E_j - 2\gamma_{M1E2}E_{ij}\sigma_i H_j\end{array}\right]$$

involves one field derivative wrt either time or space $\dot{\vec{E}} = \partial_t \vec{E}, \quad E_{ij} = \frac{1}{2}\left(\nabla_i E_j + \nabla_j E_i\right)$

e.g. γ_{M1E2} excited by electric quadrupole (E2) radiation
and decays by magnetic dipole (M1) radiation

- "Stiffness" of proton spin against E.M.-induced deformations relative to the spin axis.
  - Defines the frequency of proton's spin precession induced by variable E.M. fields.

Linear combinations of Spin Polarizabilities

One can extract the spin polarizabilities using knowledge of α, β, the linear combinations γ_0,γ_π, and Subtracted Dispersion Relations.

Backward Spin Polarizability
(unpolarized Compton scattering)

$$\gamma_\pi = \gamma_{E1E1} + \gamma_{M1M1} - \gamma_{E1M2} + \gamma_{M1E2}$$

$$\gamma_\pi = (-38.7 \pm 1.8) \cdot 10^{-4}\ \mathrm{fm}^4$$

TAPS, LARA, SENECA
Schumacher, Prog. Part. Nucl. Phys. 55(2005)

Forward Spin Polarizability
(polarized beam and target)

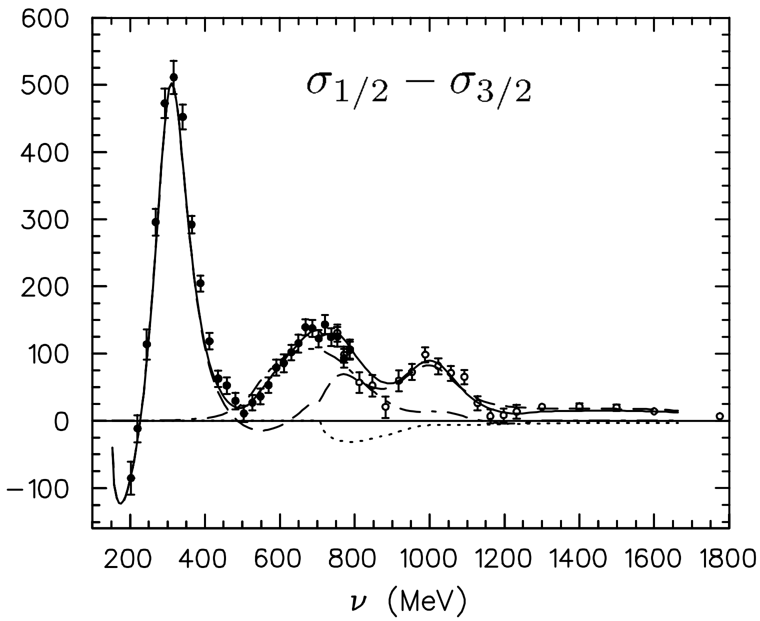
$$\gamma_0 = -\gamma_{E1E1} - \gamma_{M1M1} - \gamma_{E1M2} - \gamma_{M1E2}$$

$$\gamma_0 = \frac{1}{4\pi^2}\int_{\nu_{thr}}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{\nu^3}\, d\nu$$

$$\gamma_0 = -(1.00 \pm 0.08 \pm 0.10) \times 10^{-4}\ \mathrm{fm}^4$$

GDH Coll. (MAMI & ELSA)

Ahrens et al., PRL87 (2001)
Dutz et al. PRL91 (2003)



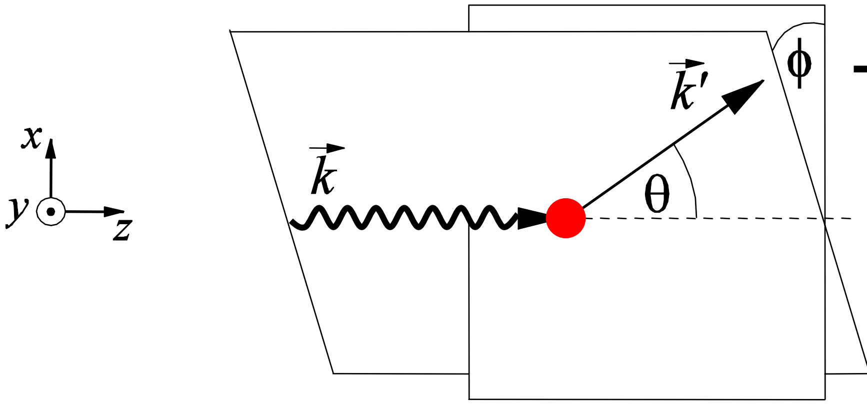
Dr. Garth Huber, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.

Better way to extract Spin Polarizabilities

- Spin polarizabilities appear in the effective interaction Hamiltonian at third order in photon energy
  - **It is in the Δ resonance region (Eγ=200-300 MeV)** where their effect becomes significant.

- In this energy region, it is possible to accurately measure polarization asymmetries using a variety of polarized beam and target combinations
  - **All four spin polarizabilities can be independently extracted from these asymmetries.**

Asymmetries with Linearly Polarized γ



azimuthal angle between the scattering plane and the photon polarization vector

- ϕ = 0 and unpolarized target $\rightarrow$ Σ_3
- ϕ = 0 and transversely polarized target in the y direction $\rightarrow$ Σ_{3y}
- ϕ = 45^o and longitudinally pol. target $\rightarrow$ Σ_{1z}
- ϕ = 45^o and transv. pol. target in the x direction $\rightarrow$ Σ_{1x}

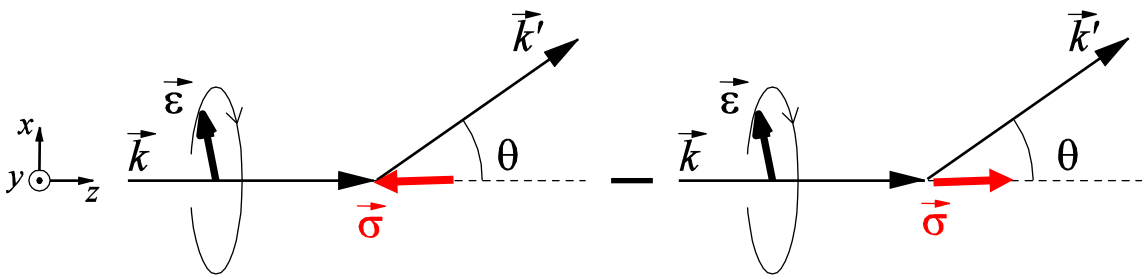
$$\Sigma_3 = \frac{\sigma^{||} - \sigma^{\perp}}{\sigma^{||} + \sigma^{\perp}}$$

Asymmetry is measured with linearly polarized photons, parallel and perpendicular to the scattering plane, and unpolarized target.

Double Spin Asymmetries w/ Circularly Polarized γ

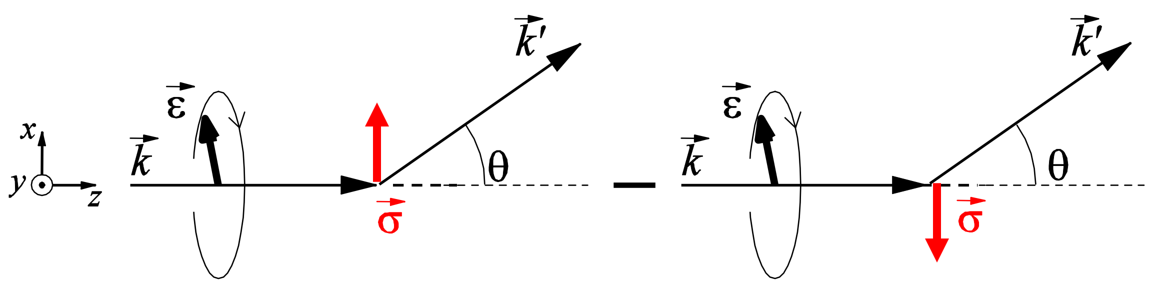
- Longitudinal asymmetry

$$\Sigma_{2z} = \left[\frac{\left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\uparrow} - \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\downarrow}}{Sum} \right]_{h=\pm 1}$$



- Transverse asymmetry

$$\Sigma_{2x} = \left[\frac{\left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\rightarrow} - \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\leftarrow}}{Sum} \right]_{h=\pm 1}$$



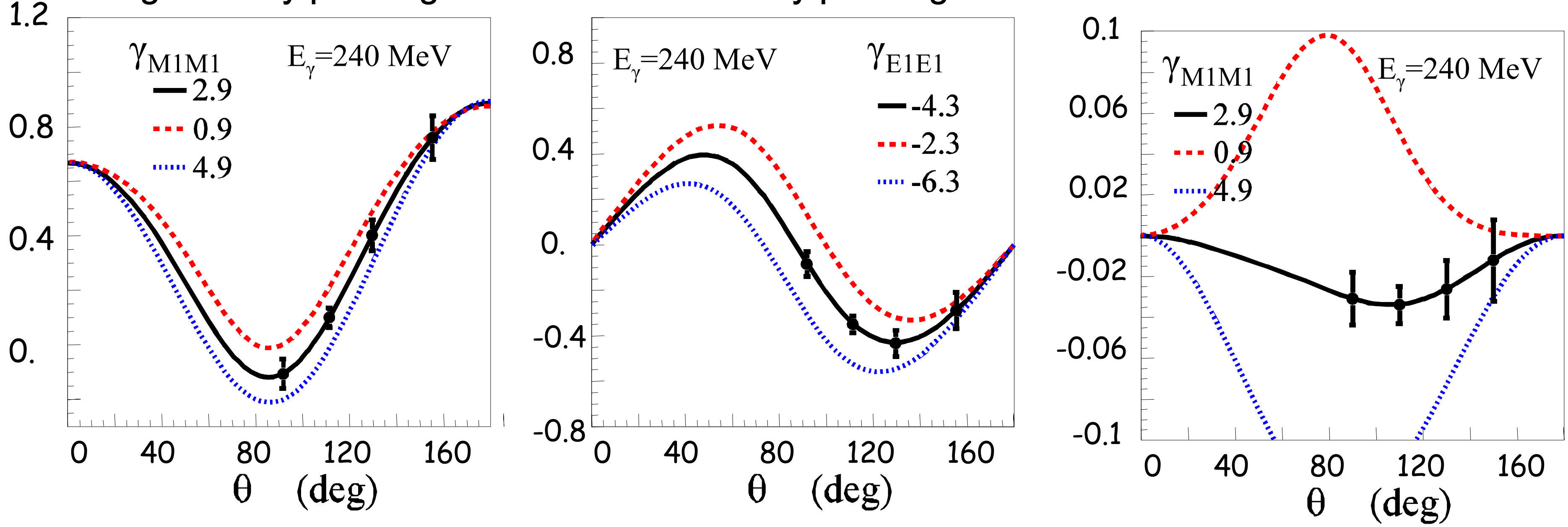
Sensitivity to Spin Polarizabilities

	Polarization			
Polarization Asymmetry	**Beam**	**Target**	**E_γ Range (MeV)**	**Spin Polarizability**
Σ_{2z}	Circular	Longitudinal	200-300	γ_{M1M1}
Σ_{2x}		Transverse	200-300	γ_{E1E1}
Σ_{3}	Linear	None	200-300	γ_{M1M1}
Σ_{3y}		Transverse	200-300	γ_{E1E1}
Σ_{1z}		Longitudinal	200-300	Both
Σ_{1x}		Transverse	150-250	Both

Spin Polarizabilities from Double and single polarization experiments at MAMI

(proposal A2/11-2009-contact person D. Hornidge)

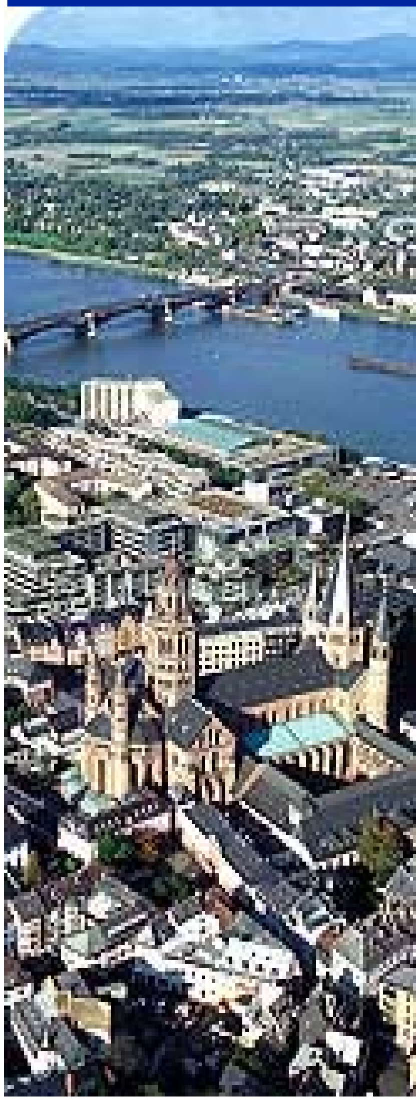
circularly pol. photons longitudinally pol. target | circularly pol. photons transversely pol. target | beam asymmetry



- leading spin polarizabilities are treated as free parameters
- α and β are fixed to central exp. value
- higher-order polarizabilities are fixed by subtracted dispersion relations based on pion-photoproduction multipoles

B. Pasquini, D. Drechsel, M. Vanderhaeghen, Phys. Rev. C **76** 015203 (2007)

Mainz Microtron MAMI



Major facility upgrade:

- Upgraded accelerator.
- Upgraded detectors.
- New frozen spin target.

"Ultimate" polarized observables laboratory:

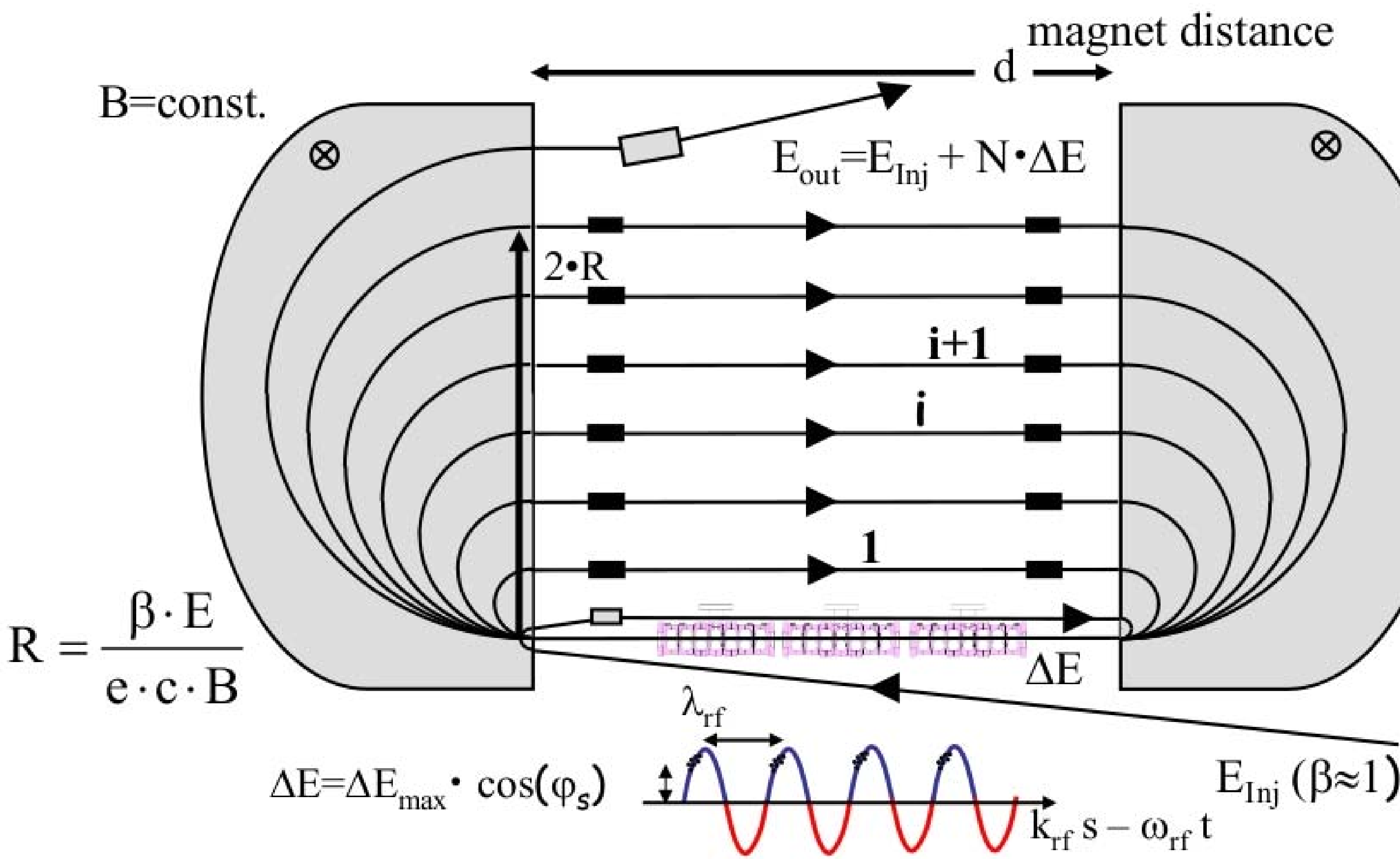
→ polarized beam.

→ polarized target.

→ recoil polarization.

Nearly 4π Detector Coverage.

Race Track Microtron Concept

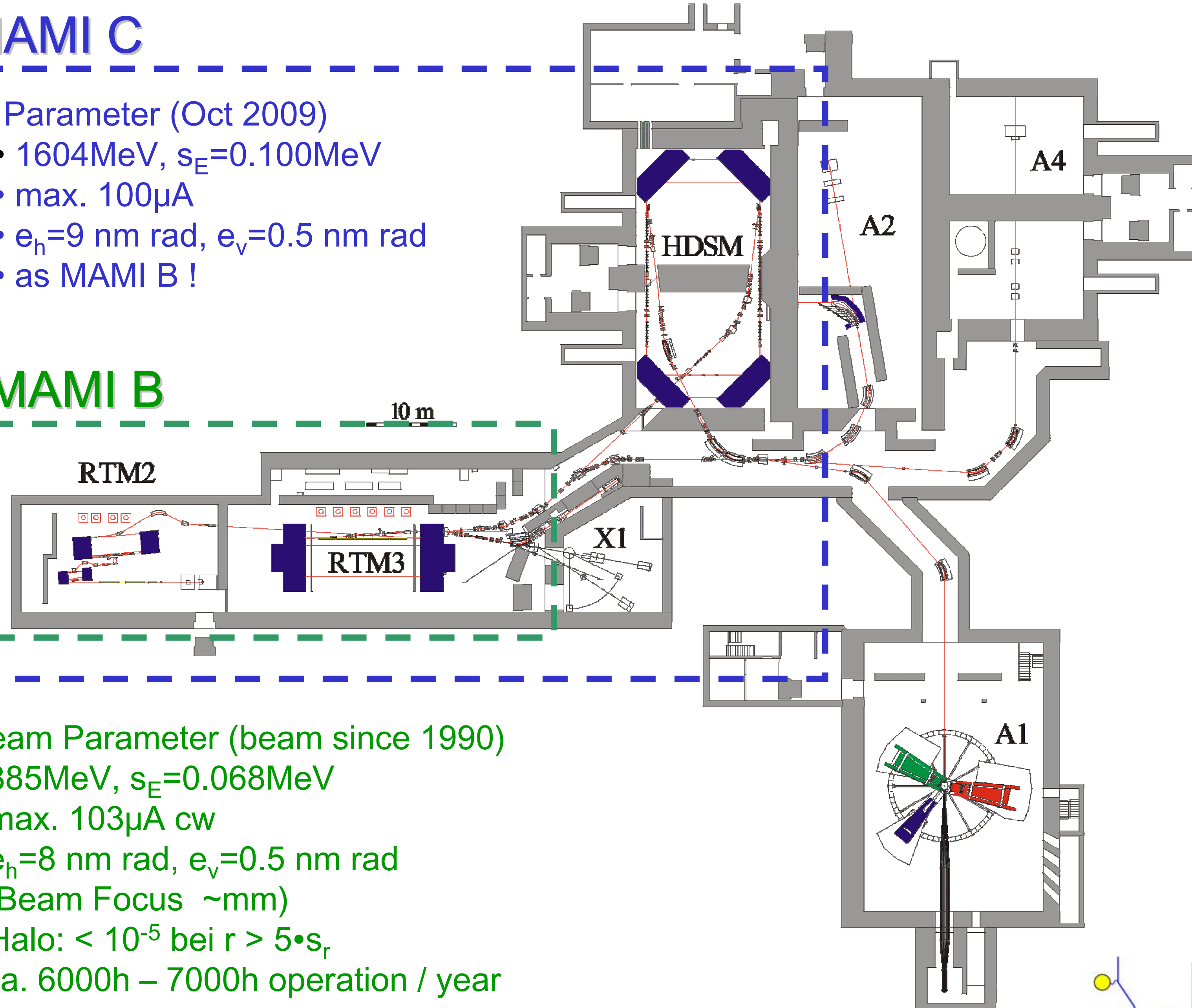


- 2 m long, 25 kW Hf, 18 MeV acceleration
- Need 1km Linac to get 800 MeV
- Solution → multiple passes! → Race Track Microtron (RTM)

MAMI C

Parameter (Oct 2009)
- 1604MeV, s_E=0.100MeV
- max. 100µA
- e_h=9 nm rad, e_v=0.5 nm rad
- as MAMI B !

MAMI B



Beam Parameter (beam since 1990)
- 885MeV, s_E=0.068MeV
- max. 103µA cw
- e_h=8 nm rad, e_v=0.5 nm rad
  (Beam Focus ~mm)
- Halo: < 10^{-5} bei r > $5 \cdot s_r$
- ca. 6000h – 7000h operation / year

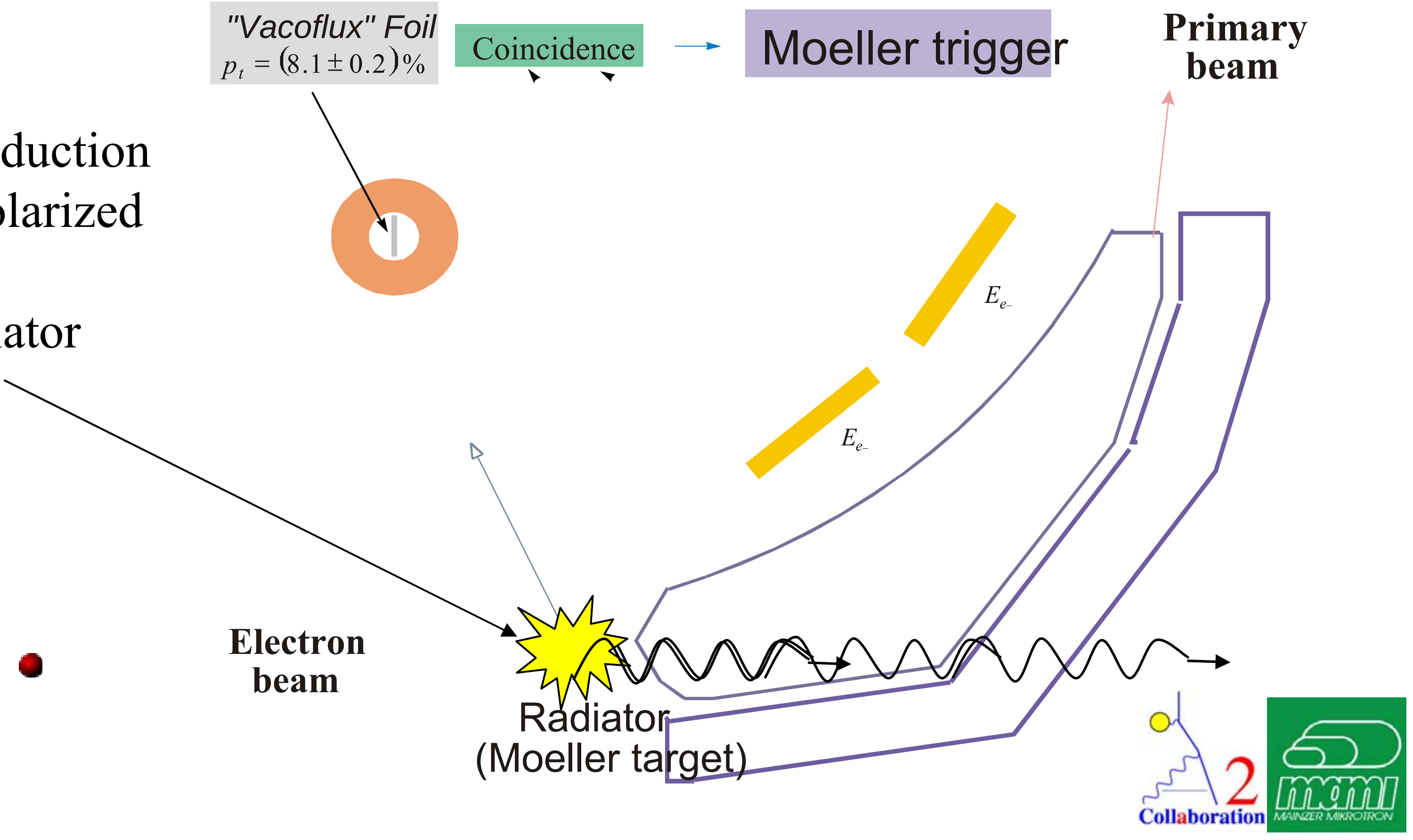
A2 Tagging system (Glasgow,Mainz)

1. Production and energy measurement of Bremsstrahlung photons

2. Determination of the degree of polarization of the electron beam (Moeller Polarimeter); Circularly pol. photons

$$A = \frac{N^+ - N^-}{N^+ + N^-} = a\vec{p}_t \vec{p}_b \cos(z)$$

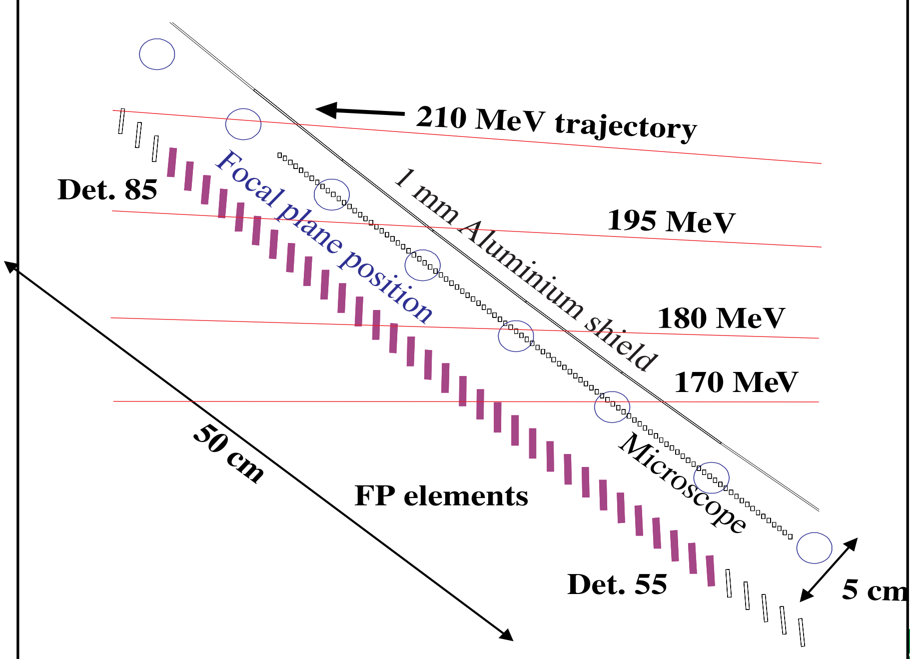
3. Coherent production of linearly polarized photons on a diamond radiator



A2 Tagger Detectors and Tagger Microscope

Energy resolution of our standard tagger ladder (352 plastics) **4 MeV per Channel**.

- **96 Plastic Scintillator** Fibers (3x2 mm).
- 1/3 Overlap of the fibers with its neighbor.
  Overlap region defines the Microscope channel ***μch* (191 channels)**.
- Energy resolution: **0.3 MeV per microscope channel (*μch*)**.
- Microscope Tagger is positioned in the electron energy range of the reaction threshold,
  e.g. Beam energy E_0=883 MeV corresponds to a **photon energy range from 674 MeV to 730 MeV**
  (*η-threshold* ~707 MeV).

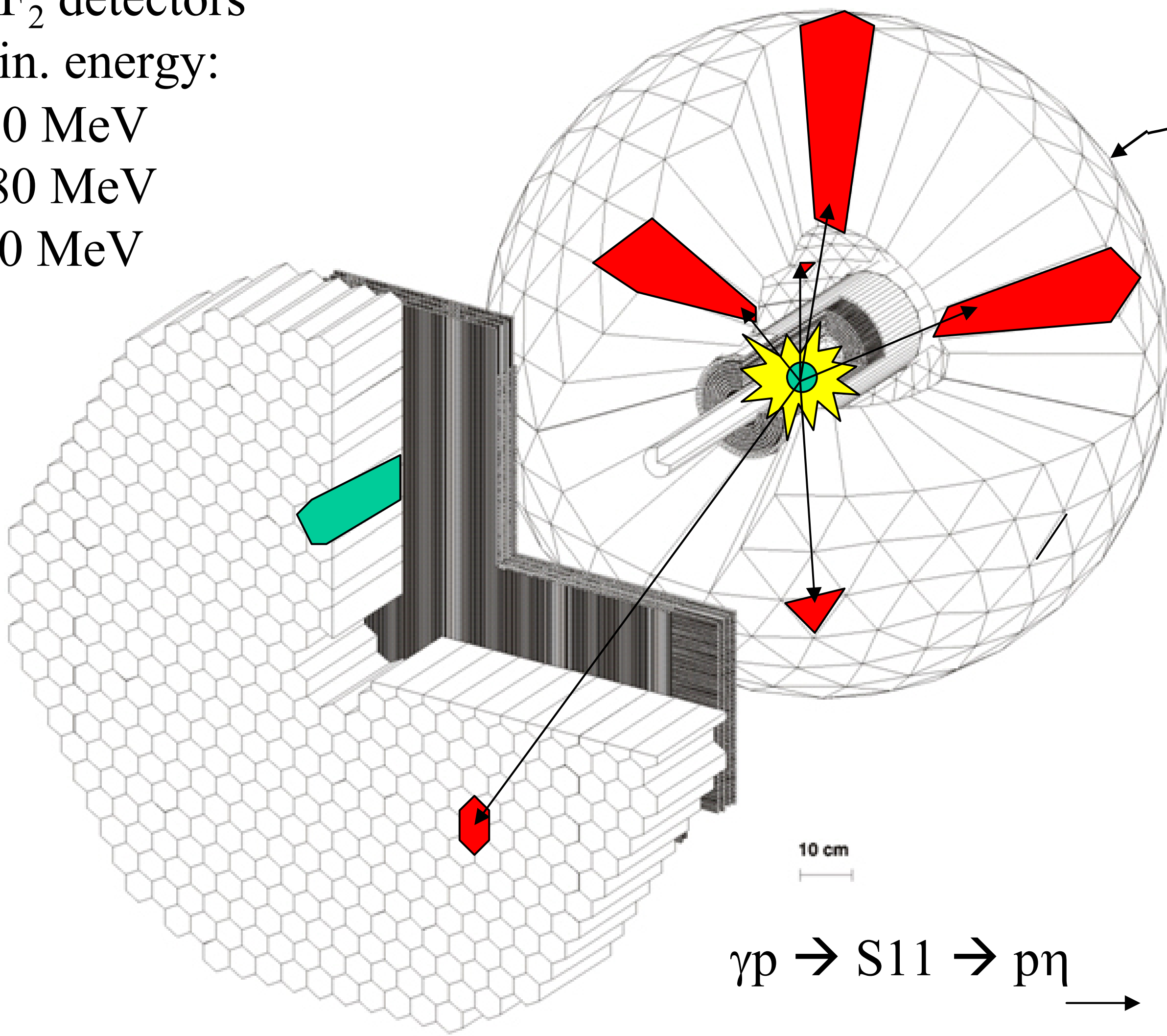


Collaboration MAINZER MIKROTRON

4π photon Spectrometer @ MAMI

TAPS:
510 BaF_2 detectors
Max. kin. energy:
π^{+-} : 180 MeV
K^{+-} : 280 MeV
P : 360 MeV

Crystal Ball:
672 NaJ detectors
Max. kin. energy:
μ^{+-} : 233MeV
π^{+-} : 240 MeV
K^{+-} : 341 MeV
P : 425 MeV



Vertex detector:
2 Cylindr. MWPCs
480 wires, 320stripes

PID detector:
24 thin plastic detectors

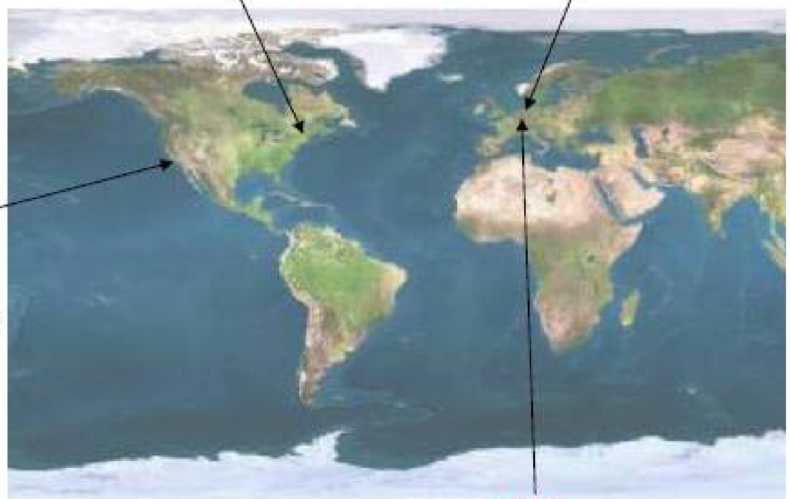
$\gamma p \rightarrow S11 \rightarrow p\eta$
$\rightarrow \pi^0\pi^0\pi^0$
$\rightarrow \gamma\gamma\gamma\gamma\gamma\gamma$

Crystal Ball Detector Arrival at Frankfurt Airport

1996-2002
BNL-AGS
(E_{cm} = 1.2 – 1.53 GeV)
$N^*, \Delta, \Lambda^*, \Sigma$,
η decays, medium. mod

1982-1986
DORIS
(Ecm = 9 -10 GeV)
Y spectroscopy
radiative Υ decays

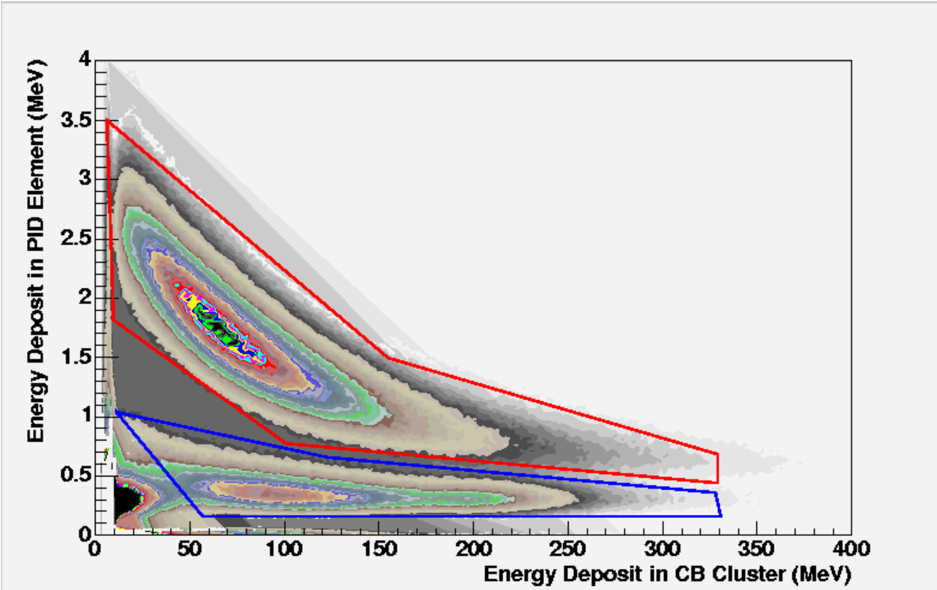
1976
Conceived
1978 -1981
SPEAR
(E_{cm} = 3 - 7 GeV)
ψ, ψ' spectroscopy
radiative ϕ decays
τ decays
D decays,
$\gamma\gamma \rightarrow \gamma\gamma$,
η, η', f

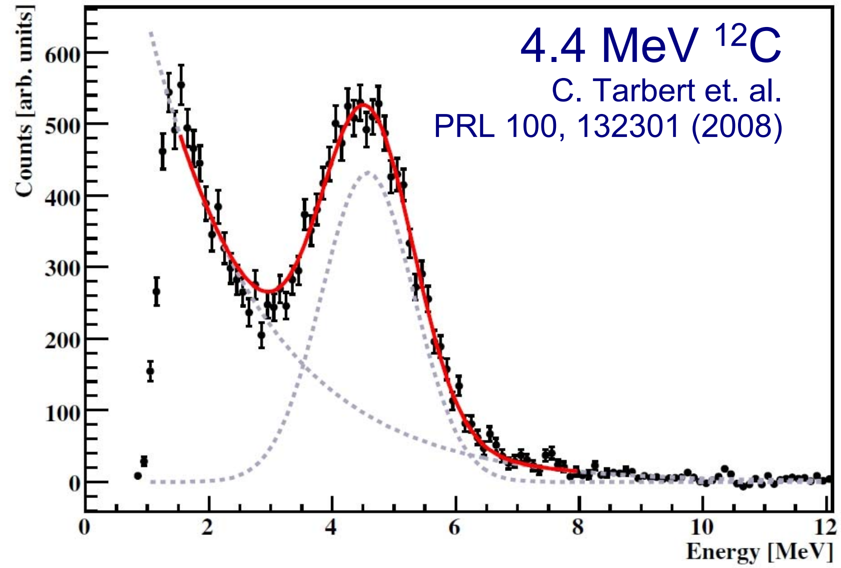


2002
MAMI
(E_{cm} = 1.2 -1.9 GeV)

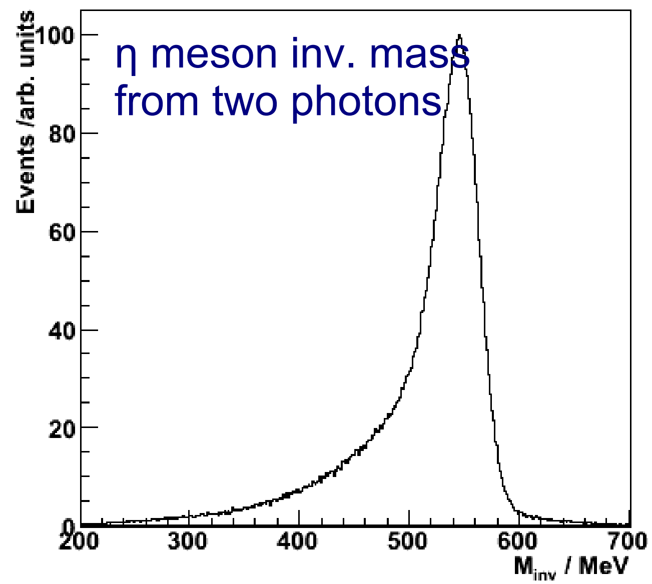
- Accurate separation of final states → good detector resolution.
- Sensitivity to small σ processes → 4π detector acceptance, large γ flux.
- Access to polarization observables → polarized beam, target, recoil.

Crystal Ball: Particle Calorimetry and Identification



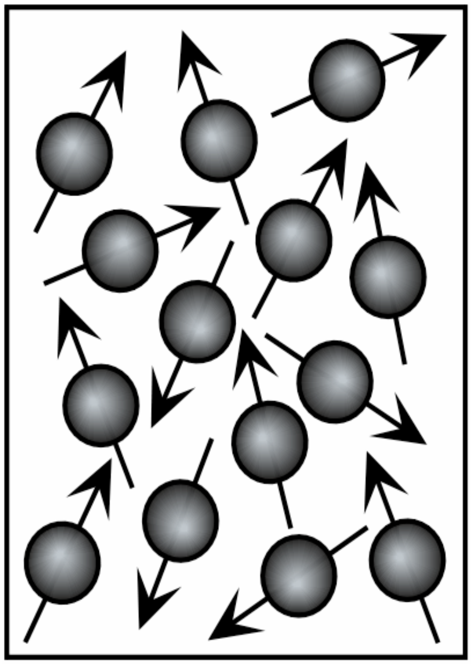


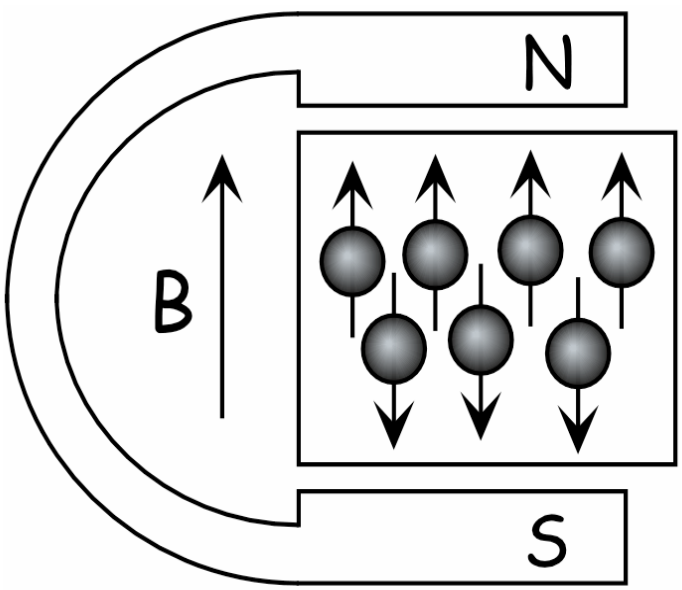
- Wide energy range with good resolution
- Energy resolution: $\Delta E/E = 0.020 \cdot E[\mathrm{GeV}]^{0.36}$
- Angular resolution: σ_θ = 2-3° $\sigma_\varphi=\sigma_\theta/\sin(\theta)$
- MWPC → Charged particle tracking
- ΔE (PID) / E (CB) locus → particle id.
- High photon & neutron efficiency



Polarized Solid Target

Polarization = Orientation of Spins in a magnetic field





$$P = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}$$

P=100% is not so easy to realize: Complicated interplay between

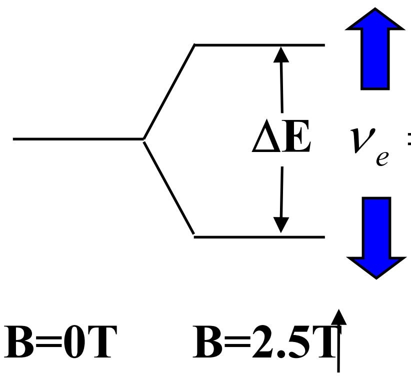
Polarizing force ~ magnetic field **B**

and

Depolarizing force ~ thermal motion of spins (temperature **T** – relaxation)

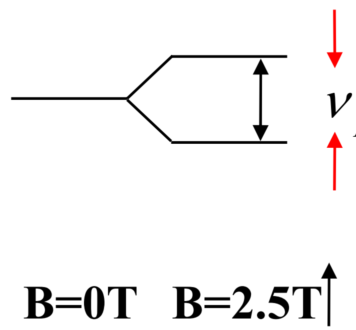
Physics of solid Pol. Targets:

Magnetic moment in magnetic field: $E = -\vec{\mu} \cdot \vec{B} = -g\mu_o mB$



$\nu_e = \frac{\Delta E}{h} = 70GHz$

electron



$\nu_p = 106MHz$

proton

Thermal equilibrium
Boltzmann distribution

$$\frac{N(E+\Delta E)}{N(E)} = e^{-\frac{\Delta E}{kT}}$$

Spin1/2 $$P = \frac{N_+ - N_-}{N_+ + N_-} = \tanh\frac{\mu B}{kT}$$

T=1K B=5T ⇨ **P_e=99.76%** **P_p=0.51%**

Trick: Transfer of the high electron polarization to the nucleon via μ-wave irradiation (DNP)

Model: Solid State Effect (SSE)

$$H = H_{SZ} + H_{IZ} + H_{IS} + H_{II} + H_{SS}$$

H_{SZ}: $g_e \mu_e \sum_k B S_k$

H_{IZ}: $g_p \mu_p \sum_j B I_j$

H_{II}: **small** $\frac{g_e \mu_e}{g_p \mu_p} \approx 660$

H_{SS}: **small distance e-big (~r^{-3})**

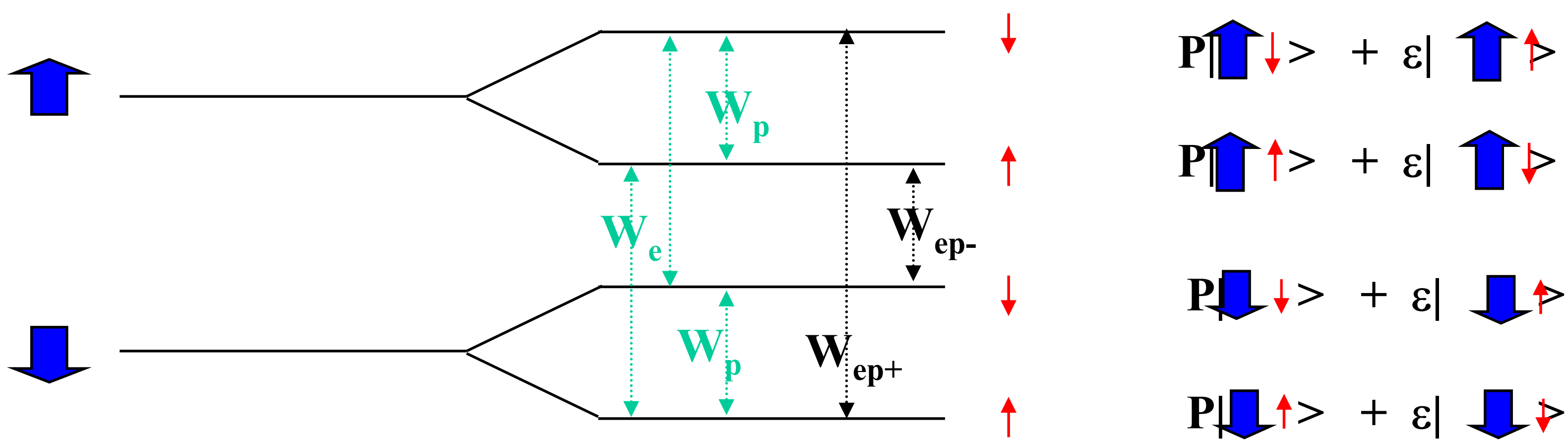
Zeemann

e Dipole-p Dipole : $H_{IS} = g_e \mu_e g_p \mu_p \sum_{i,k} r_{ik}^{-3} \left[I_i \cdot S_k - \frac{3(I_i r_{ik})(S_k r_{ik})}{r_{ik}^2} \right]$

Mixing of the energy levels

$$\varepsilon \approx \frac{B_l}{B} \approx 10^{-2}$$

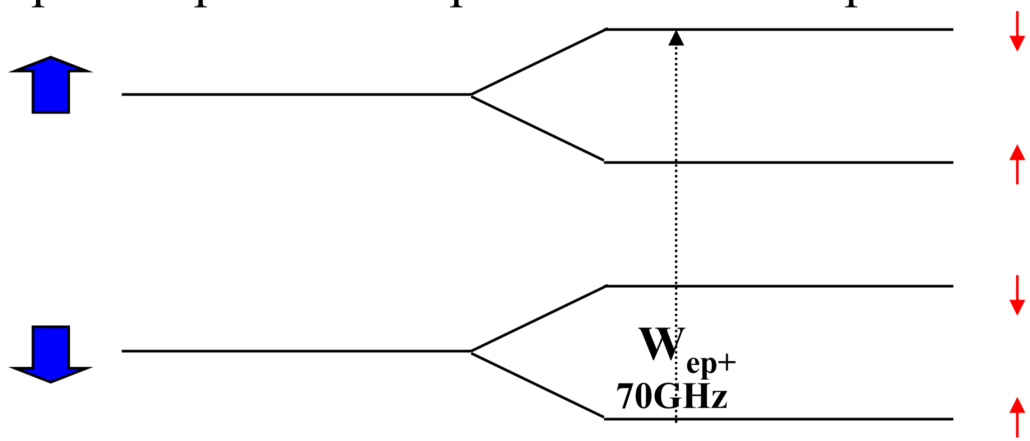
$$B_l \propto \frac{\mu_e S_k}{r^3}$$



Magnetic Dipole transition allows Spin flip (Δm=+-1) of electrons or protons.
Probability to pump forbidden transitions W_{ep+} or W_{ep-} ~ ε^2

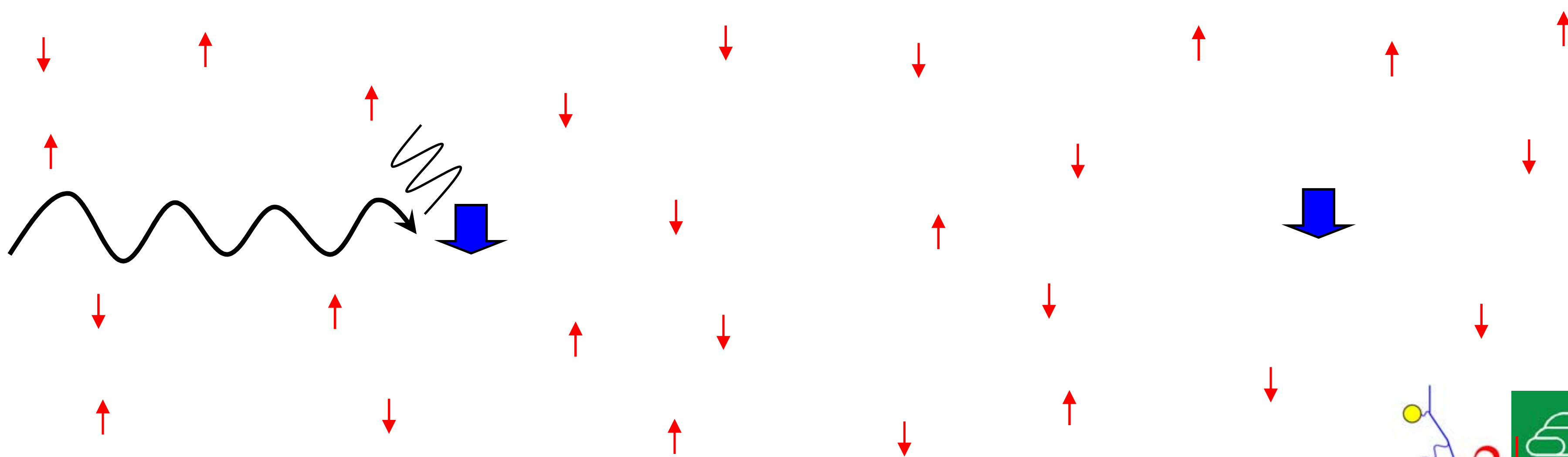
Target material is doped with free electrons (Butanol)

Zeeman Dipole-Dipole-IA couples electrons and protons

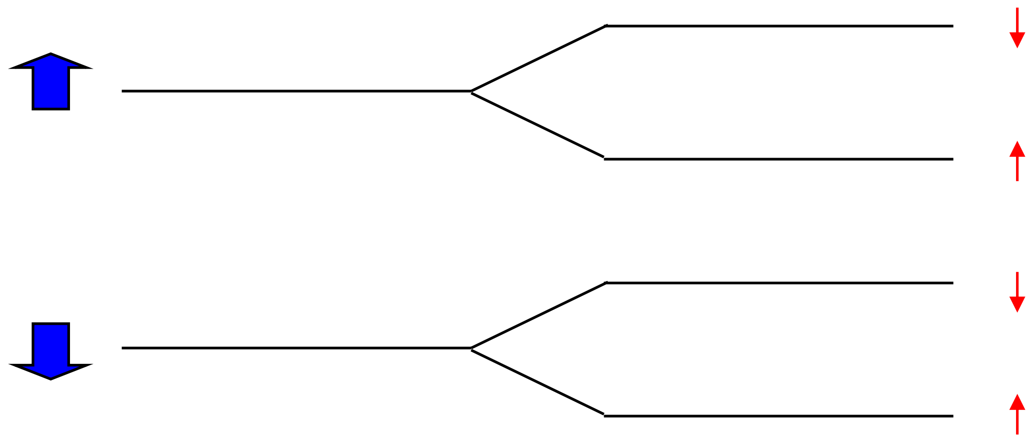


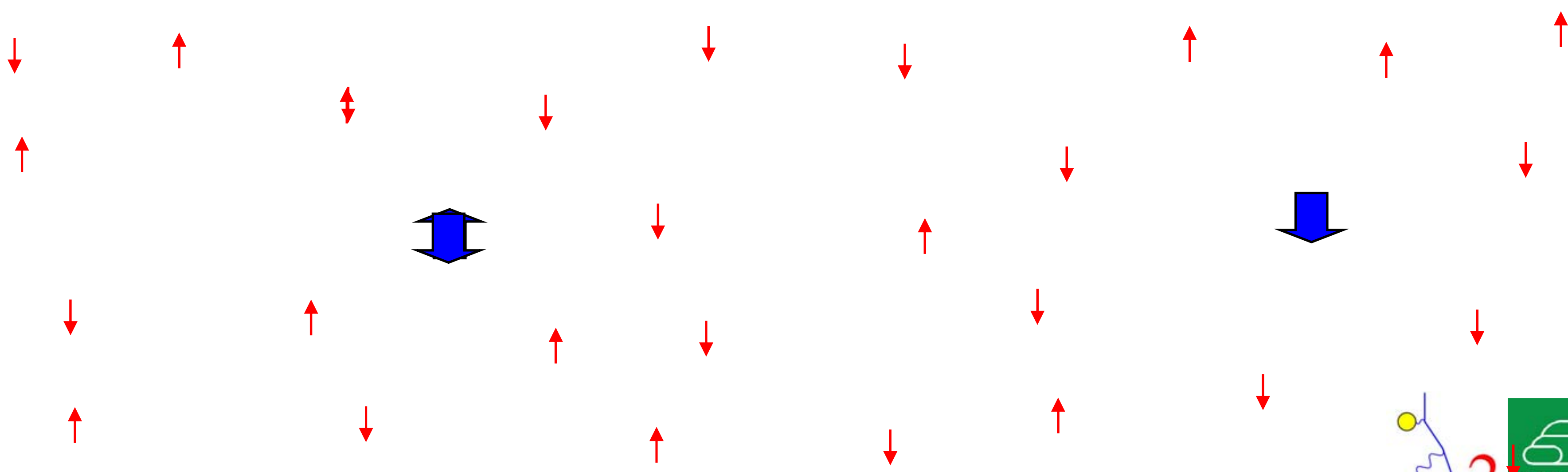
Transfer of the high electron polarization to the protons

via μ-wave irradiation

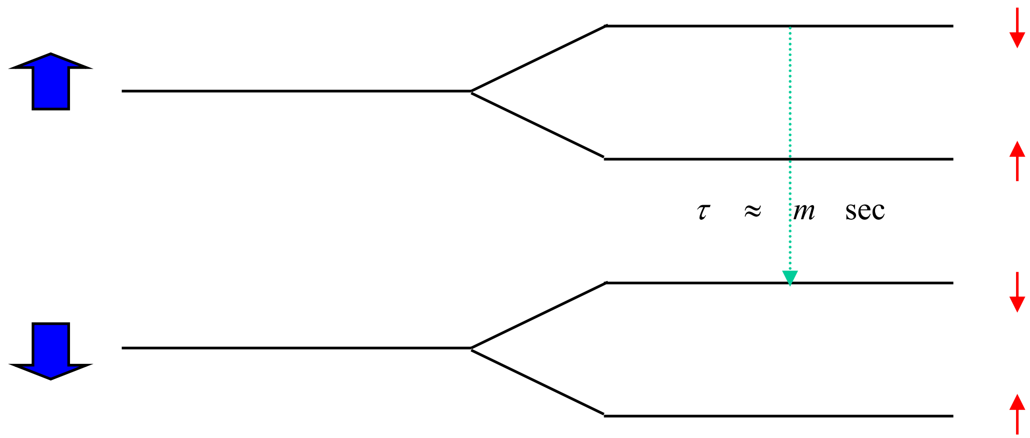


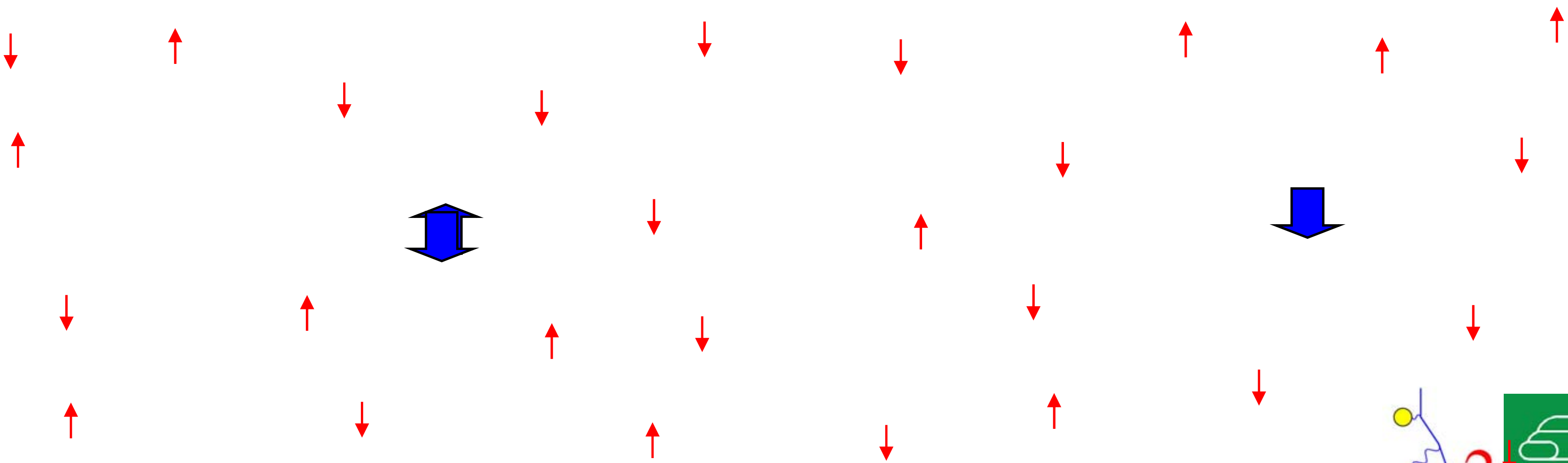
•**Simultaneous spinflip of electrons and protons**



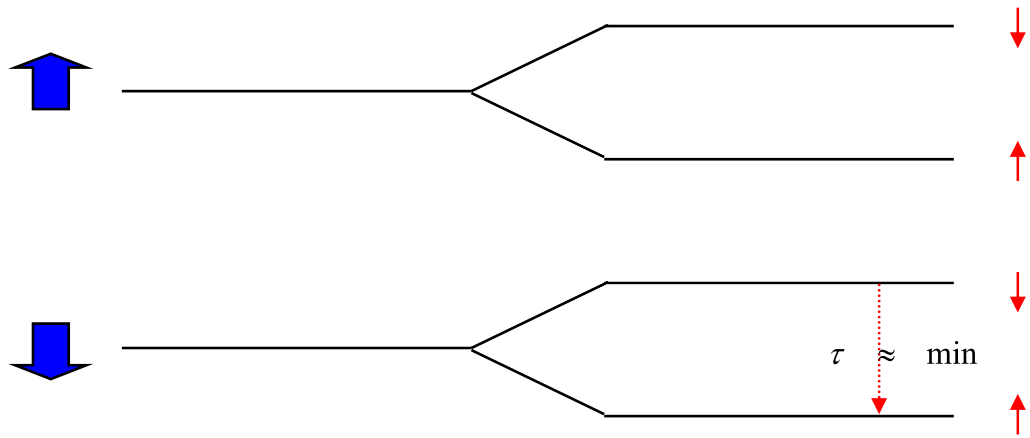


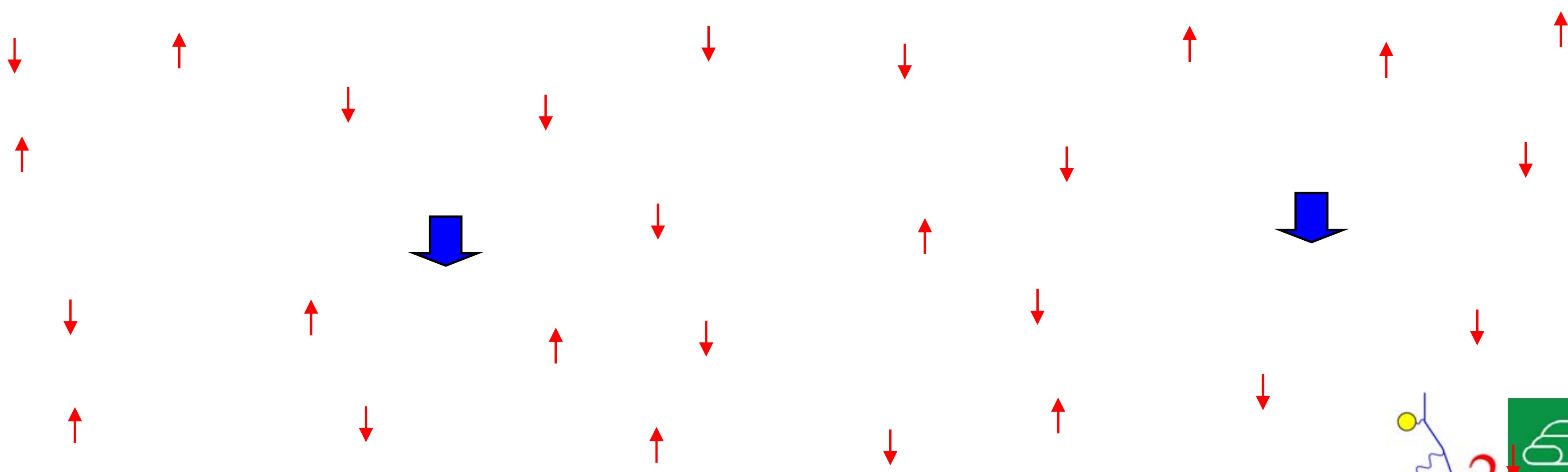
•**Fast spin-lattice-relaxation of the electrons**



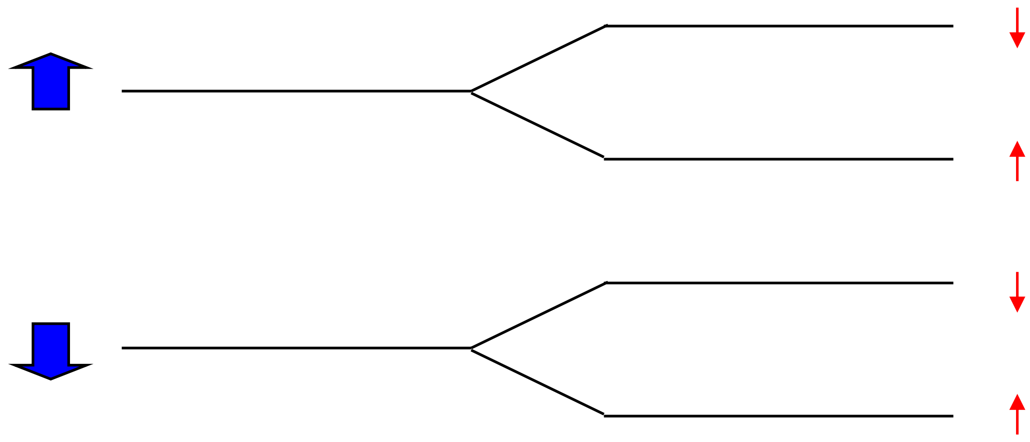


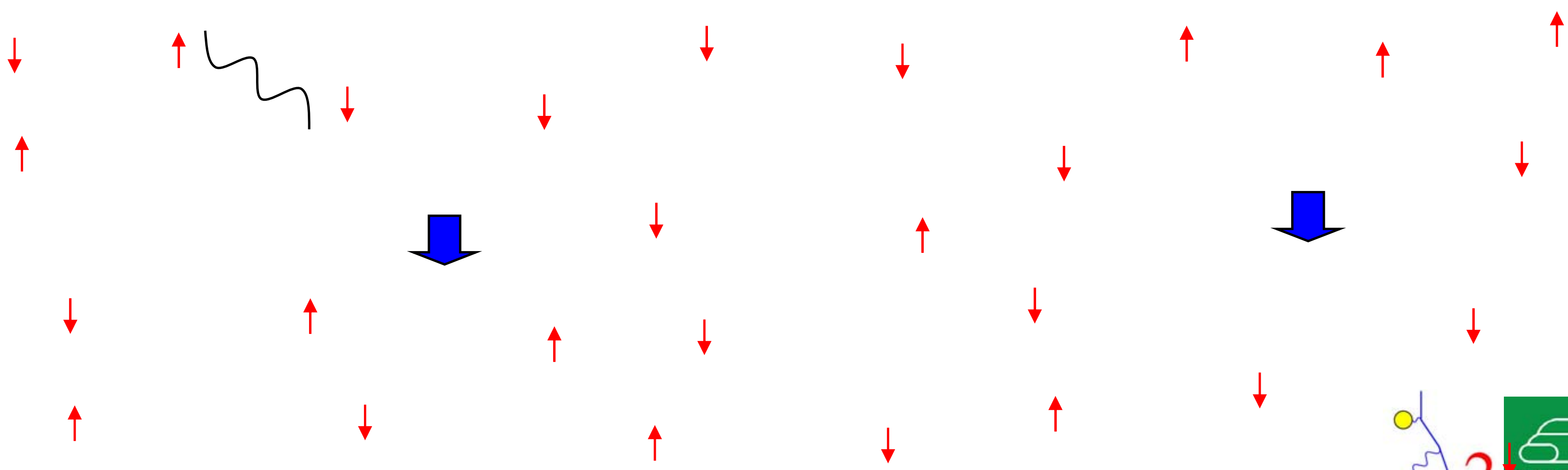
•**Long relaxation time of the protons**



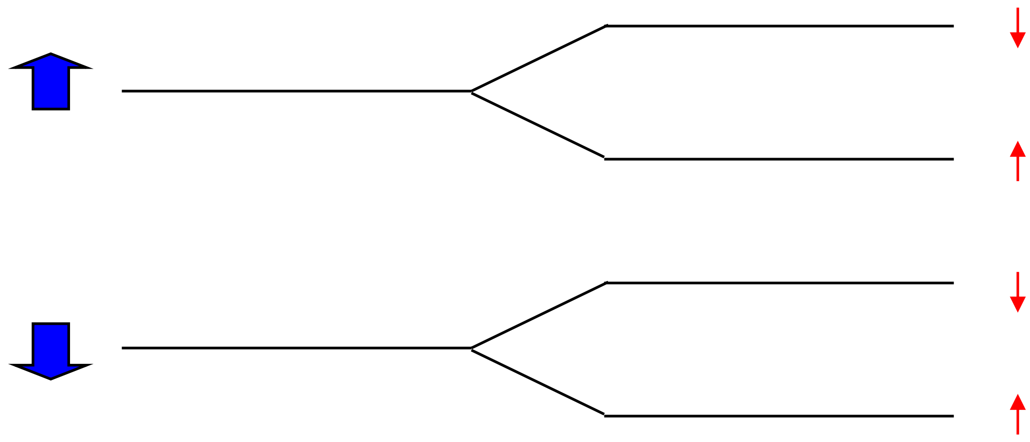


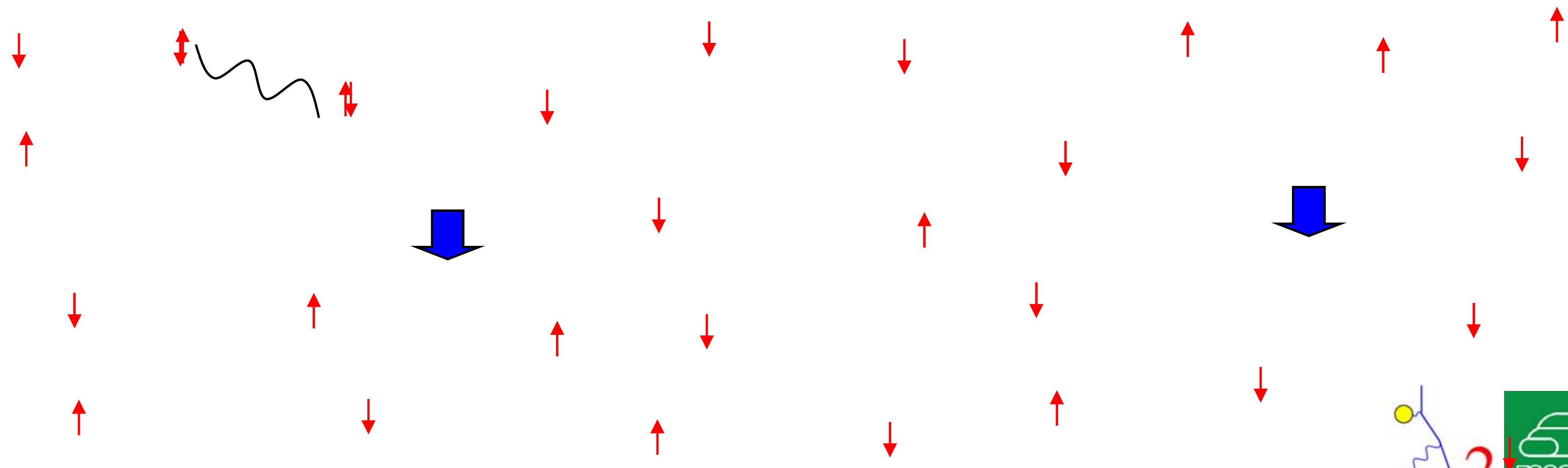
•**Dipole-Dipole-WW of the protons**





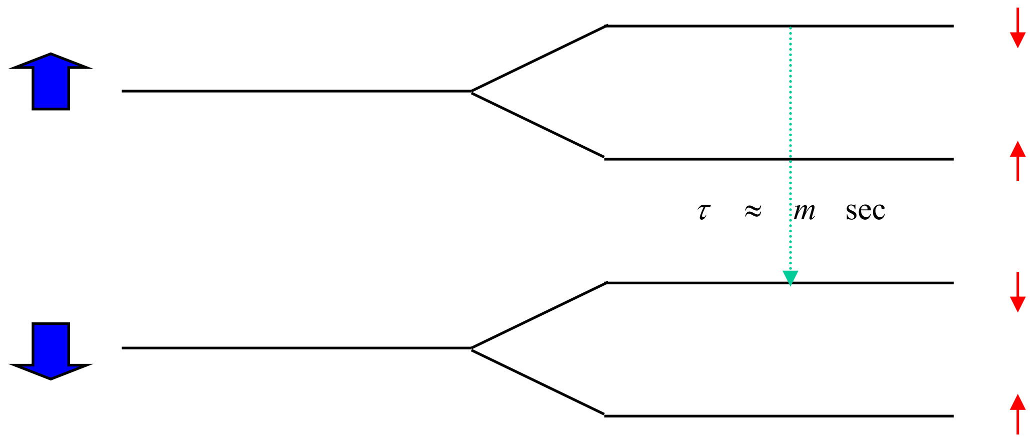
Spin diffusion homogeneously spreads the proton polarization

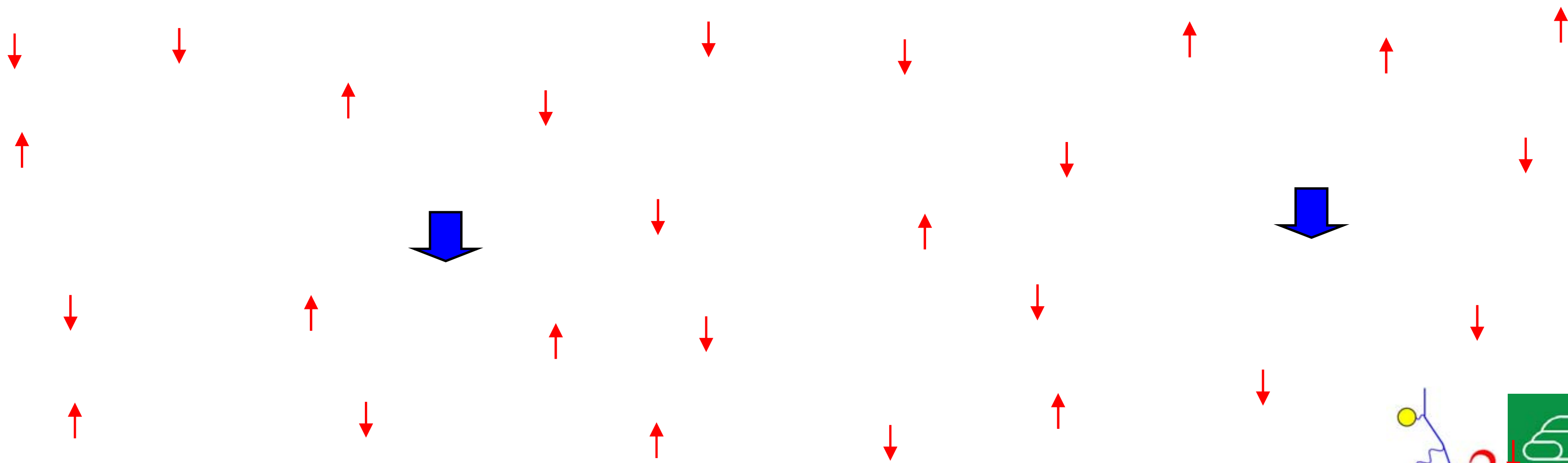


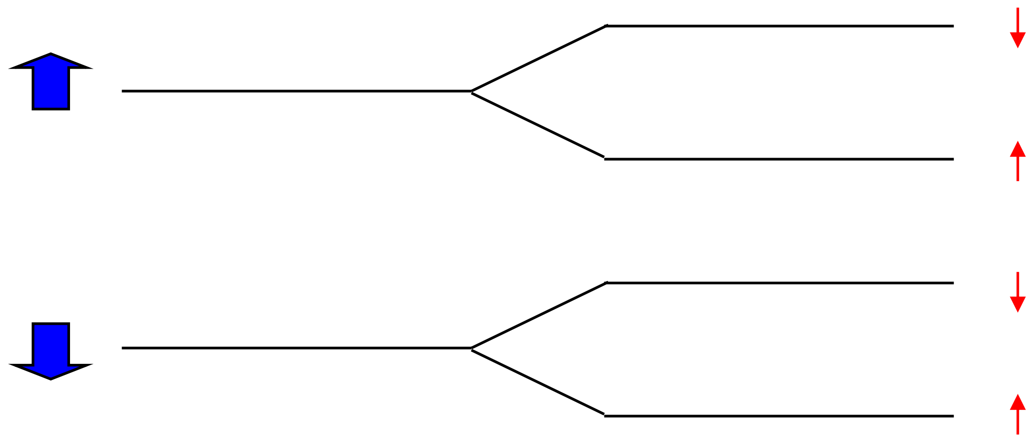


Collaboration

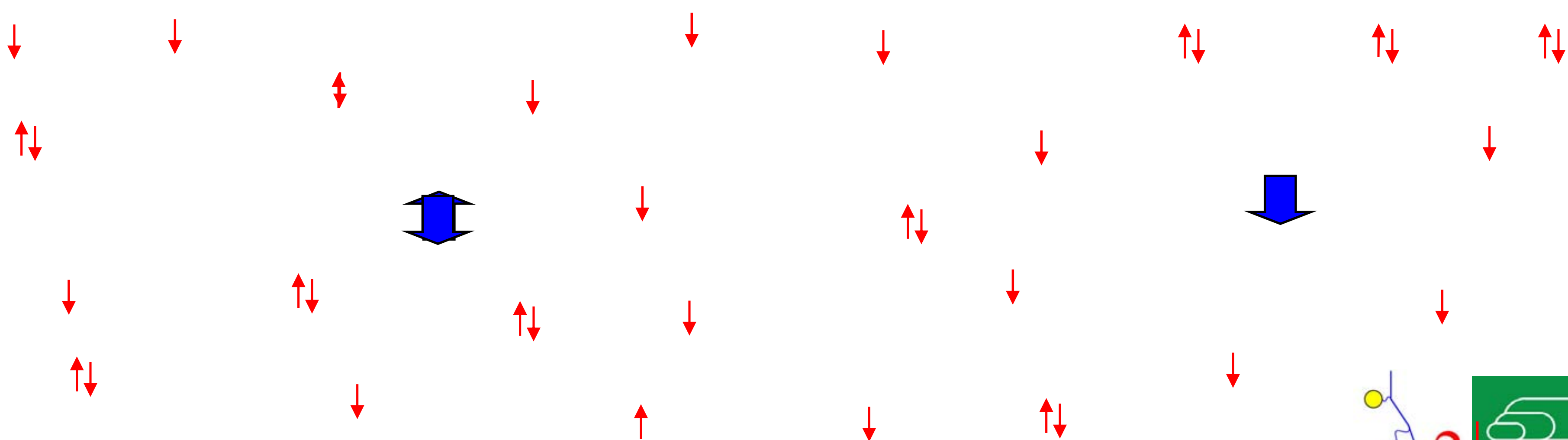
Electrons are ready for the next simultaneous spinflip







P ~ 95%

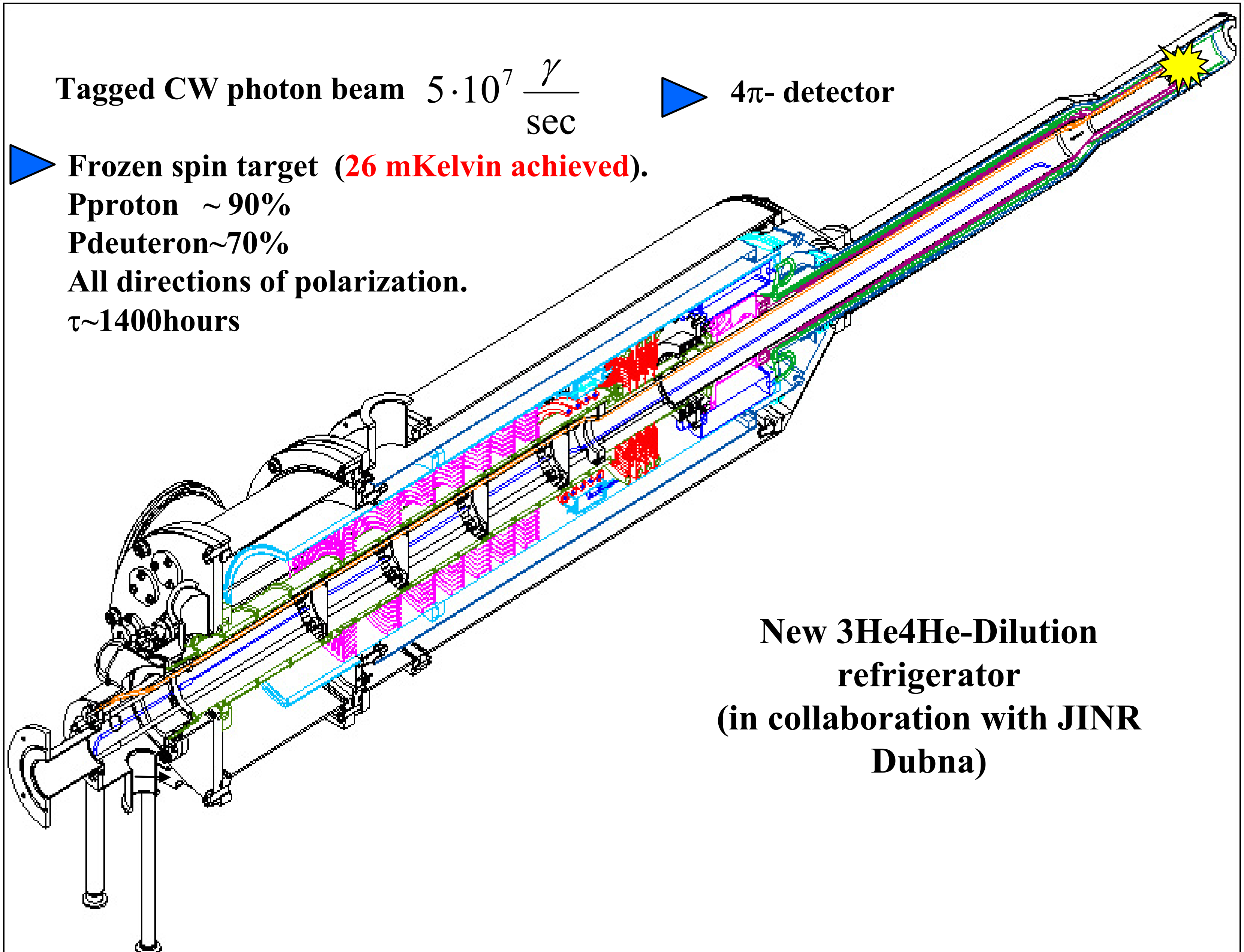


Polarized Target for Crystal Ball

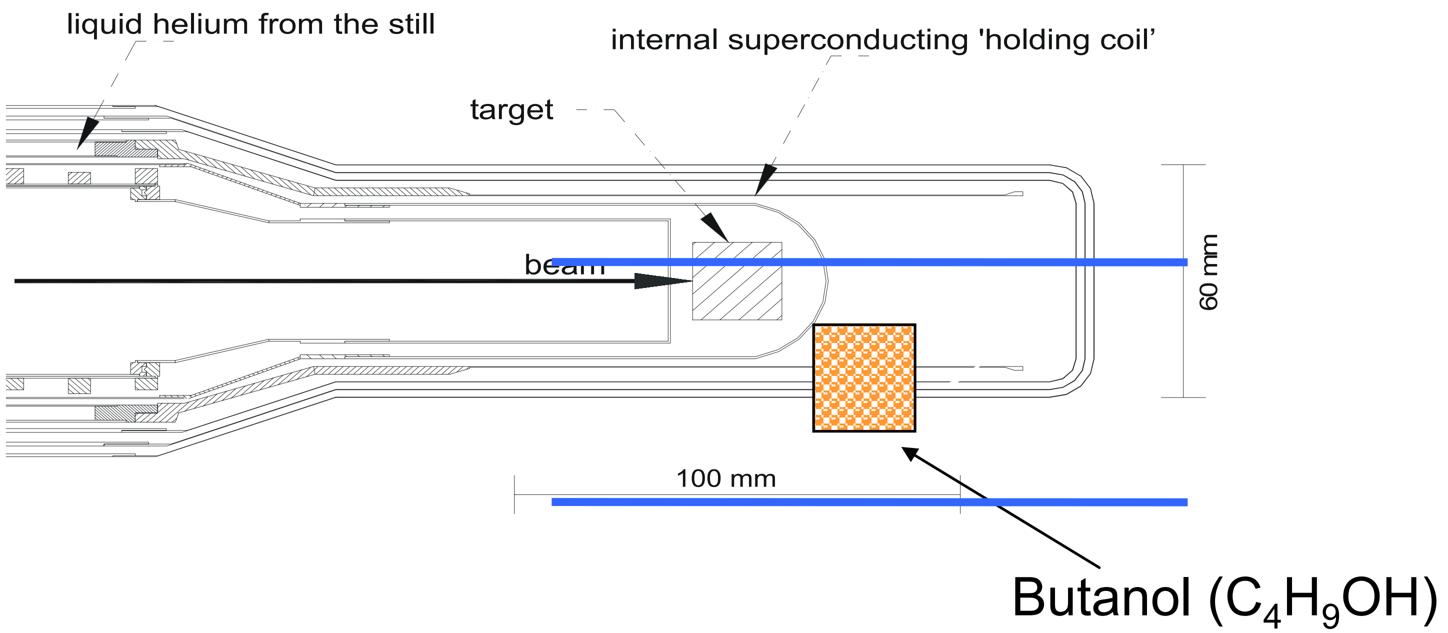
Tagged CW photon beam $5 \cdot 10^7 \frac{\gamma}{\sec}$

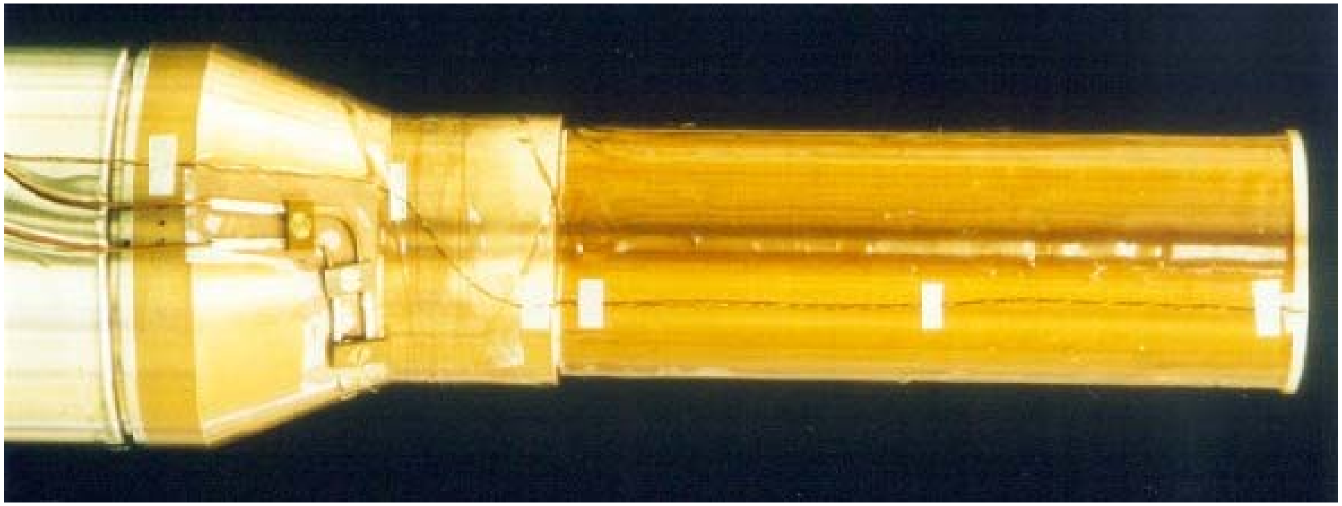
- 4π- detector

- Frozen spin target (26 mKelvin achieved).
  Pproton ~ 90%
  Pdeuteron~70%
  All directions of polarization.
  τ~1400hours



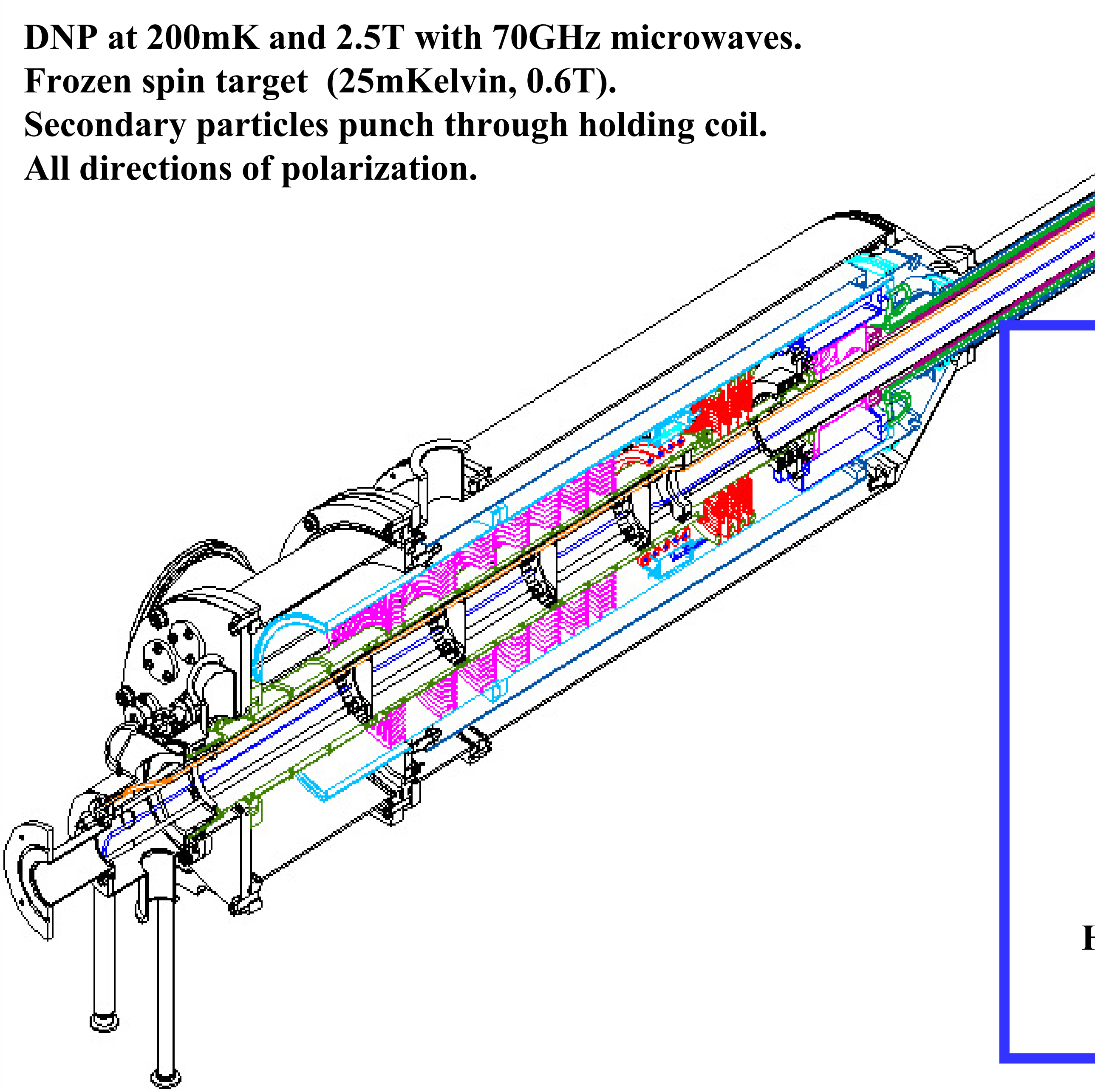
New 3He4He-Dilution refrigerator
(in collaboration with JINR Dubna)


liquid helium from the still
internal superconducting 'holding coil'
target
beam
60 mm
100 mm
Butanol (C_4H_9OH)



Magnet Technology

DNP at 200mK and 2.5T with 70GHz microwaves.
Frozen spin target (25mKelvin, 0.6T).
Secondary particles punch through holding coil.
All directions of polarization.



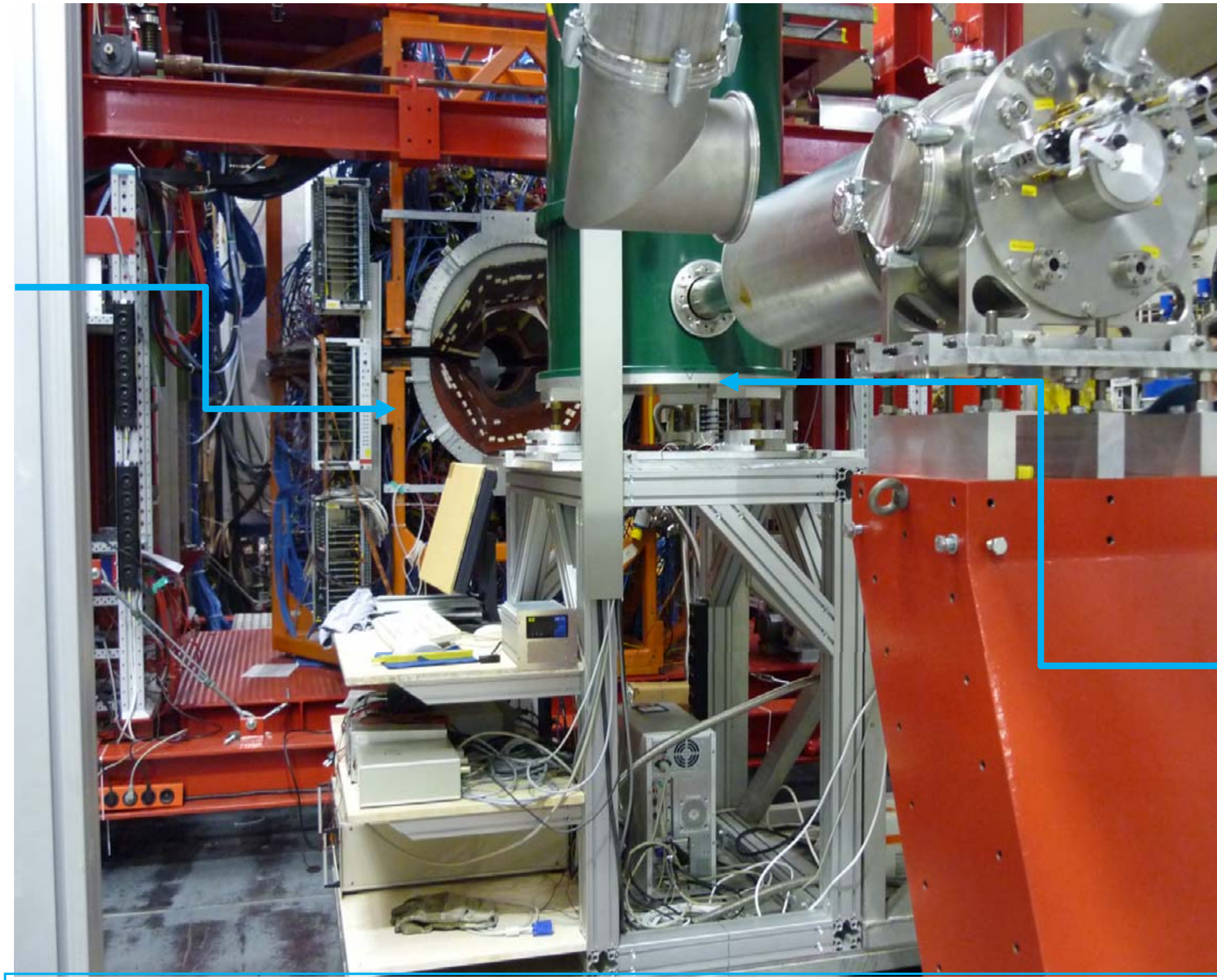
Transverse (Saddle coil)

Longitudinal (Solenoid)

Holding Field (1.2K, 0.6T)

Setup in the A2 – Tagger Hall

Movable Crystal Ball 4π-Photon Detector

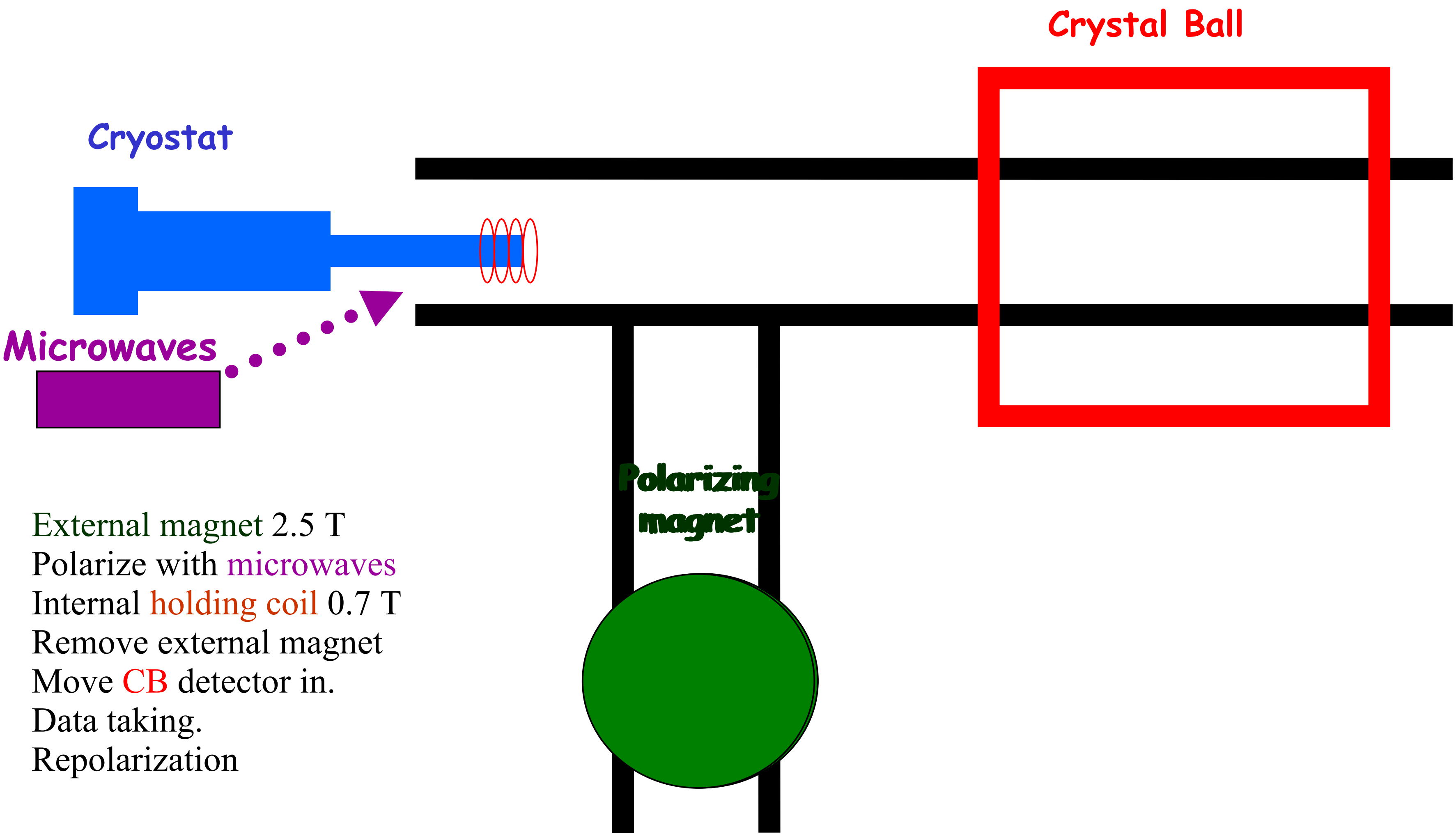


Cryostat

Movable 2.5Tesla Polarizing Magnet

First Beam with Transverse Polarization started December, 2009.
In 2010 we had more than 2000 hours beam on this target.

Frozen Spin Target Waltz



1. External magnet 2.5 T
2. Polarize with microwaves
3. Internal holding coil 0.7 T
4. Remove external magnet
5. Move CB detector in.
6. Data taking.
7. Repolarization

Collaboration 2
mami
MAINZER MIKROTRON

Plans and Prospects

- Short term goal: new extraction of α_{E1}, β_{M1} using linearly polarized beam and unpolarized target.
  - New technique promises to resolve large discrepancy between theory and experiment for magnetic polarizability.
- **Completion of all three asymmetry measurements** Σ_3, Σ_{2z}, Σ_{2x} will allow all four spin polarizabilities to be extracted independently with very small statistical and systematic errors.
  - A powerful technique that takes advantage of the different effects the individual spin polarizabilities have on the energy and angular dependences of the asymmetries.
  - Circularly polarized photon data was taken in concert with a transversely polarized target in the summer of 2010. We are optimistic to complete the remaining measurements by 2014.

Acknowledgements

The following kindly provided slides which were helpful in the preparation of this talk:

COLLABORATORS

- Evie Downie
- Dave Hornidge
- Andreas Thomas

THEORISTS

- Barry Holstein
- Vladimir Pascalutsa
- Barbara Pasquini