Polarized Beams

a powerful tool for particle physics

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Electron Stretcher Accelerator

ELSA

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Why? → Physics with polarized protons/deuterons and electrons

How? → a) Beam generation (sources of polarized protons and electrons)

→ b) Beam acceleration (crossing of depolarizing resonances)

→ c) Spin management, energy calibration

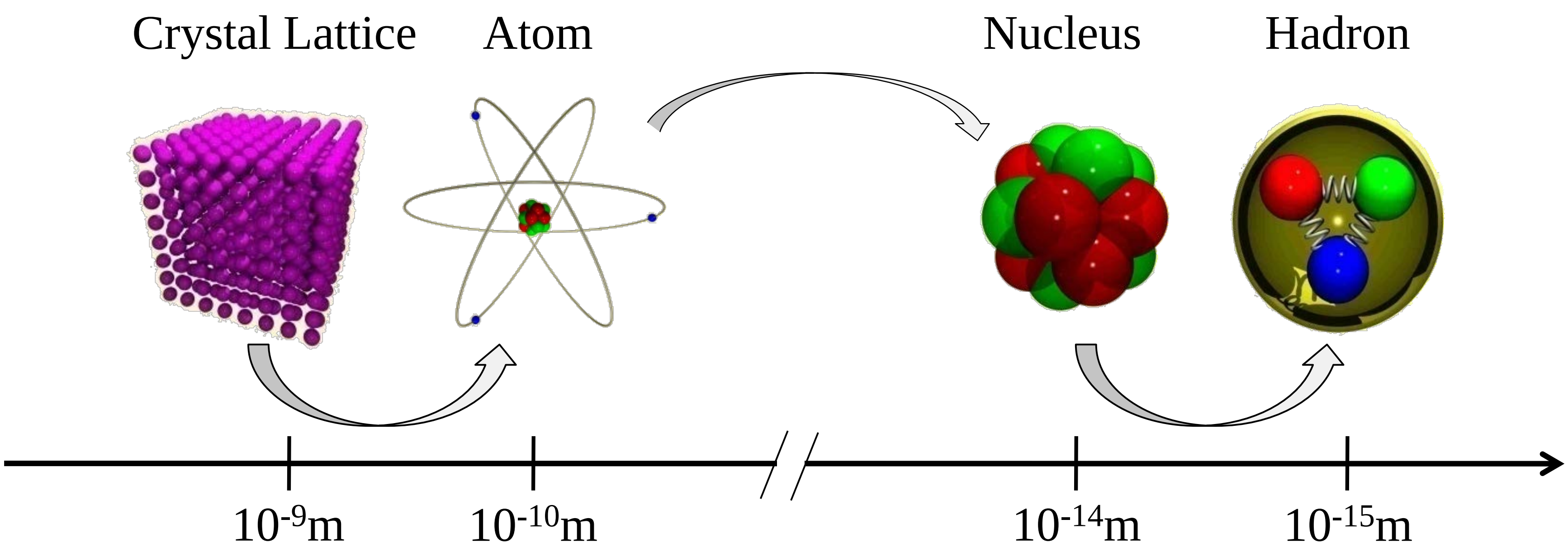
Coming? → Polarized antiparticles, new projects

Why?

Matter and Forces

Electromagnetic Interaction

Strong Interaction



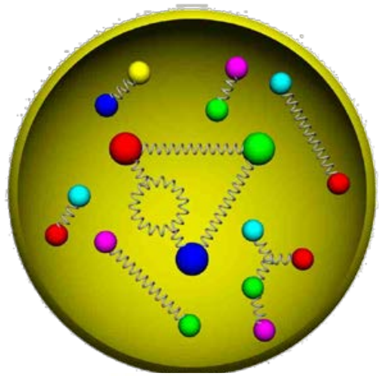
„Nanometer"

„Femtometer"

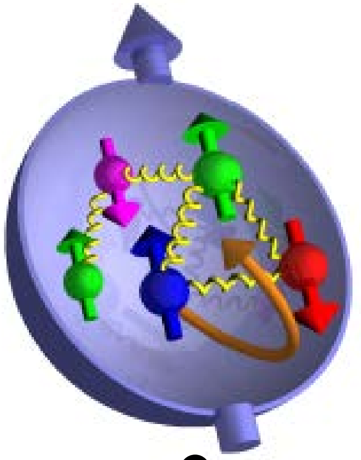
Nucleons:

Made from quarks and gluons, bound by strong interaction.

Many open questions, e.g.:



- **What generates the mass of the nucleon** and its excitations (resonances)?
  - small contribution of the quark masses!

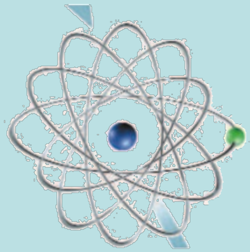


- **Spin-Structure of the nucleon**? contributions to the nucleon spin?
  - spin of the quarks
  - spin of the gluons
  - angular momentum (quarks, gluons)

Polarized beams (and polarized targets) required!

Baryon - Spectroscopy

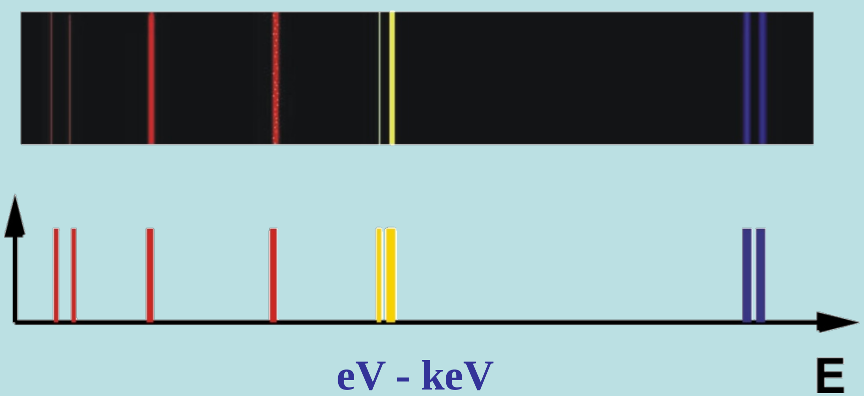
Atomic Physics



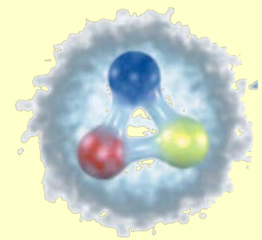
Atom: 10^{-10} m

Excitation with Photons:

Line Spectrum



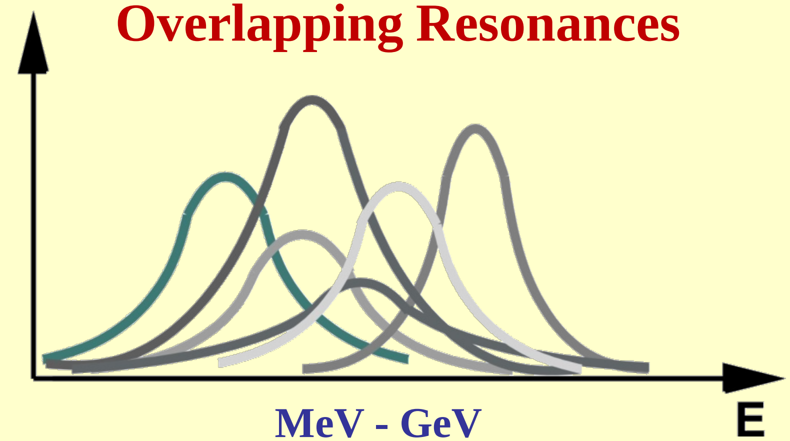
Hadron Physics



Hadron: 10^{-15} m

Excitation with Photons:

Overlapping Resonances



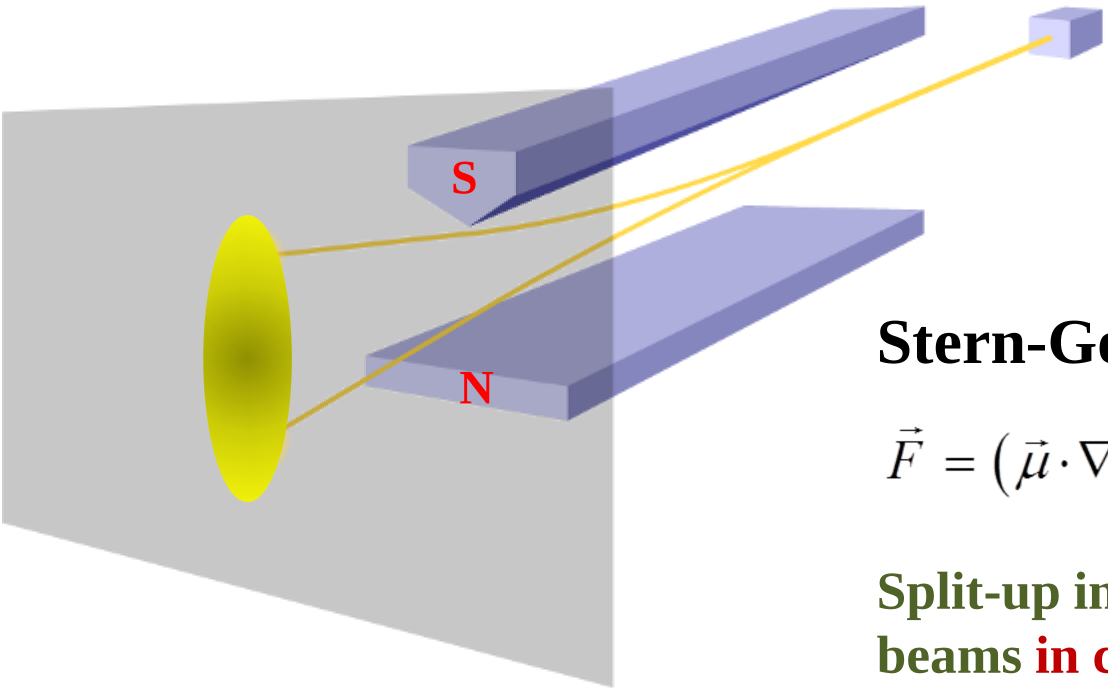
Linewidth from $\Delta E \cdot \Delta t \geq \hbar$

→ **Double Polarization Experiments**

How?

a) Sources for polarized particles

Spin Filtering?



Stern-Gerlach Experiment:

$$\vec{F} = (\vec{\mu} \cdot \nabla)\vec{B} \quad \rightarrow \quad F_z = \mu \cdot \frac{\partial B_z}{\partial z}$$

Split-up into different separated beams in case of neutral atoms

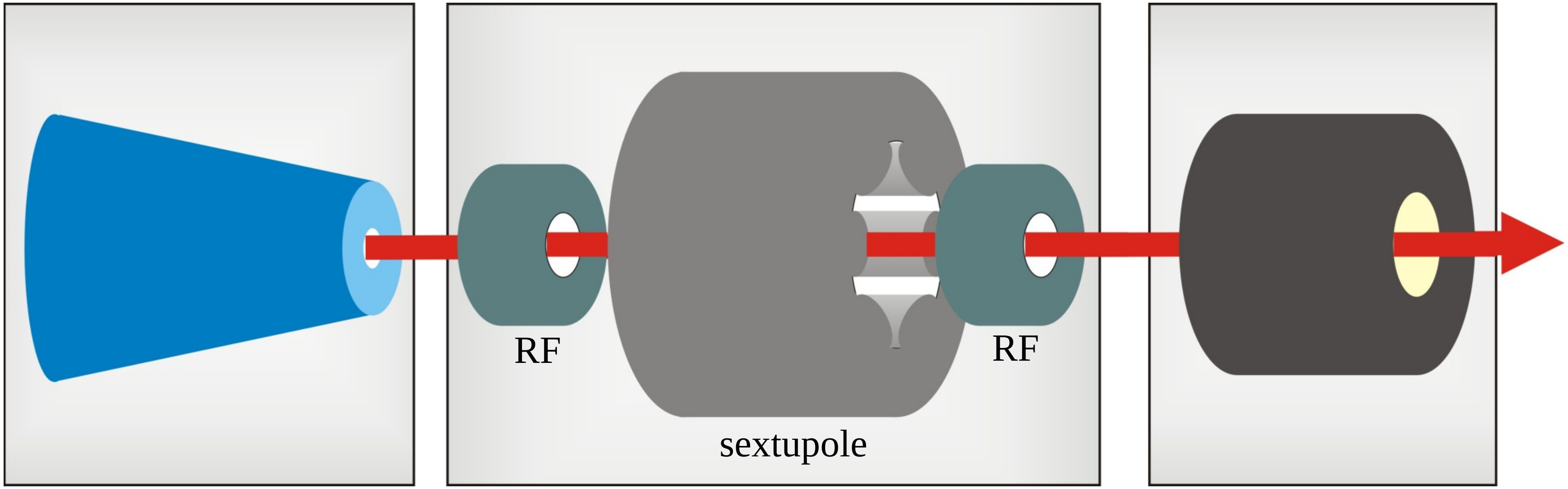
Charged particles (e^-, p^+): $\vec{F} = \frac{q}{m} \cdot \left(\vec{p} \times \vec{B}\right)$ and $\Delta x \cdot \Delta p_x > \hbar$

but:

Polarized Protons

Functional Principle:

Atomic Beam | **Beam Separation** | **Ionization**



dissociator
LN_2-cooled nozzle
→ thermalized H atoms

6-pole fields & RF-transitions
act as „Stern-Gerlach“-polarizer
pol-enhancement by RF-pumping

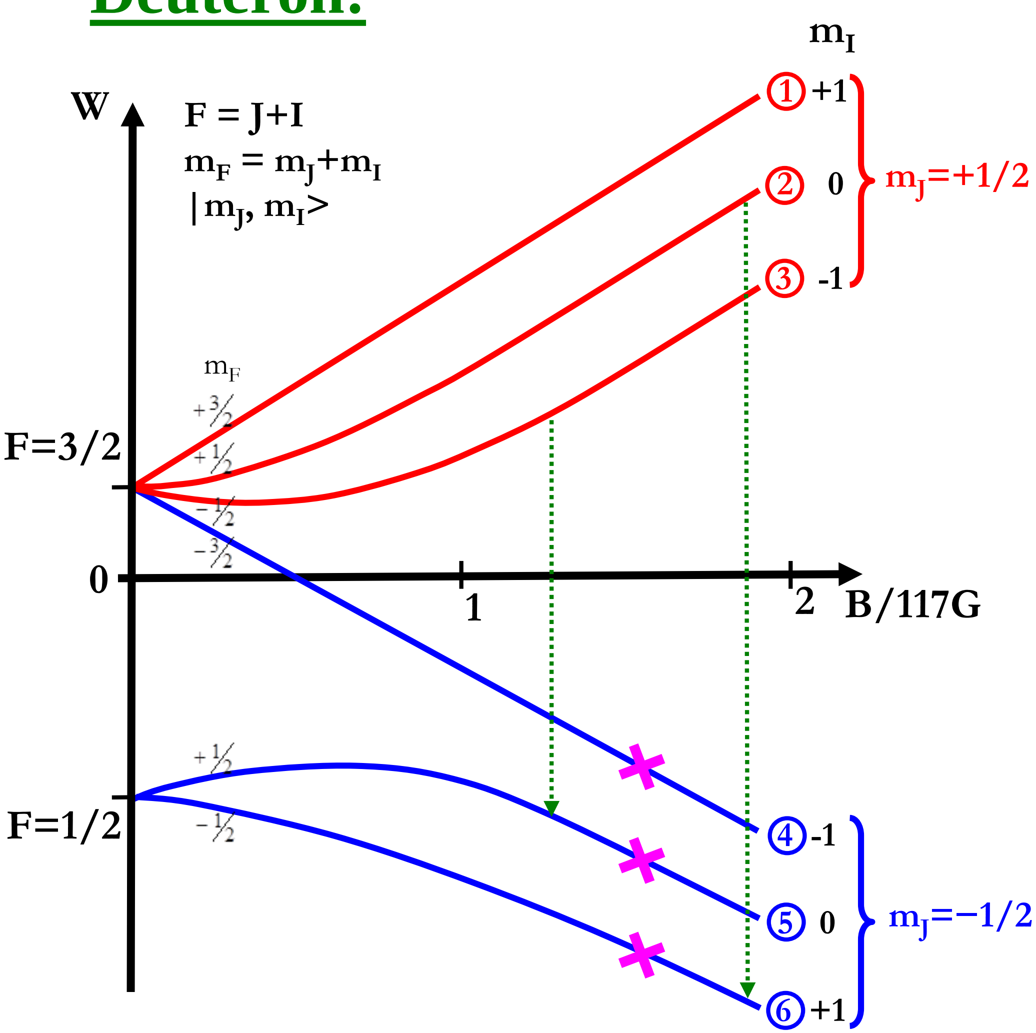
Penning ionizer
e-removal and acceleration

Haeberli (review), 1967

Polarization Scheme

slow (≈ 3 meV) atomic beams

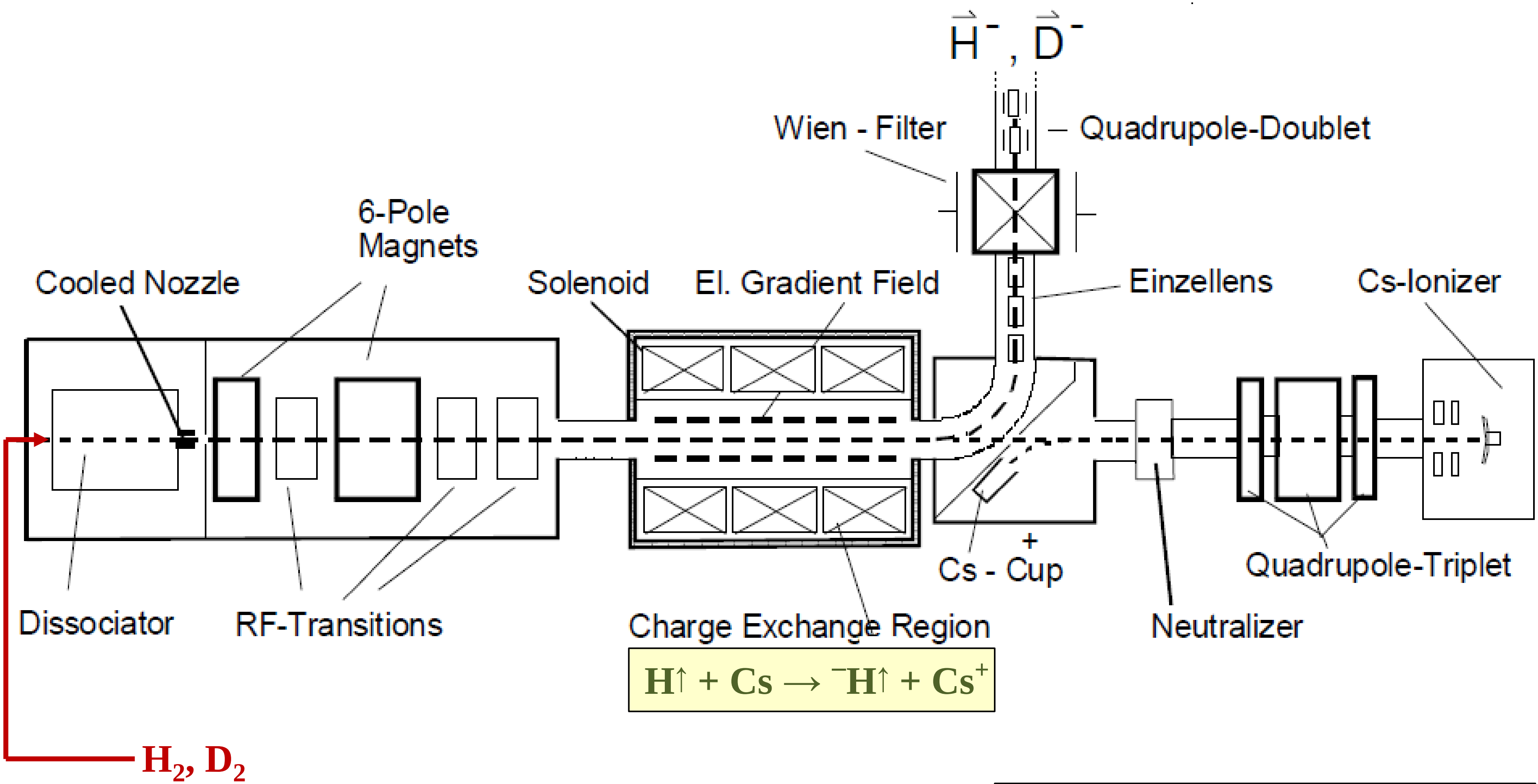
Deuteron:



→ 6-Pole | RF-Trans. (3→5) | 6-Pole | RF-Trans. (2→6)

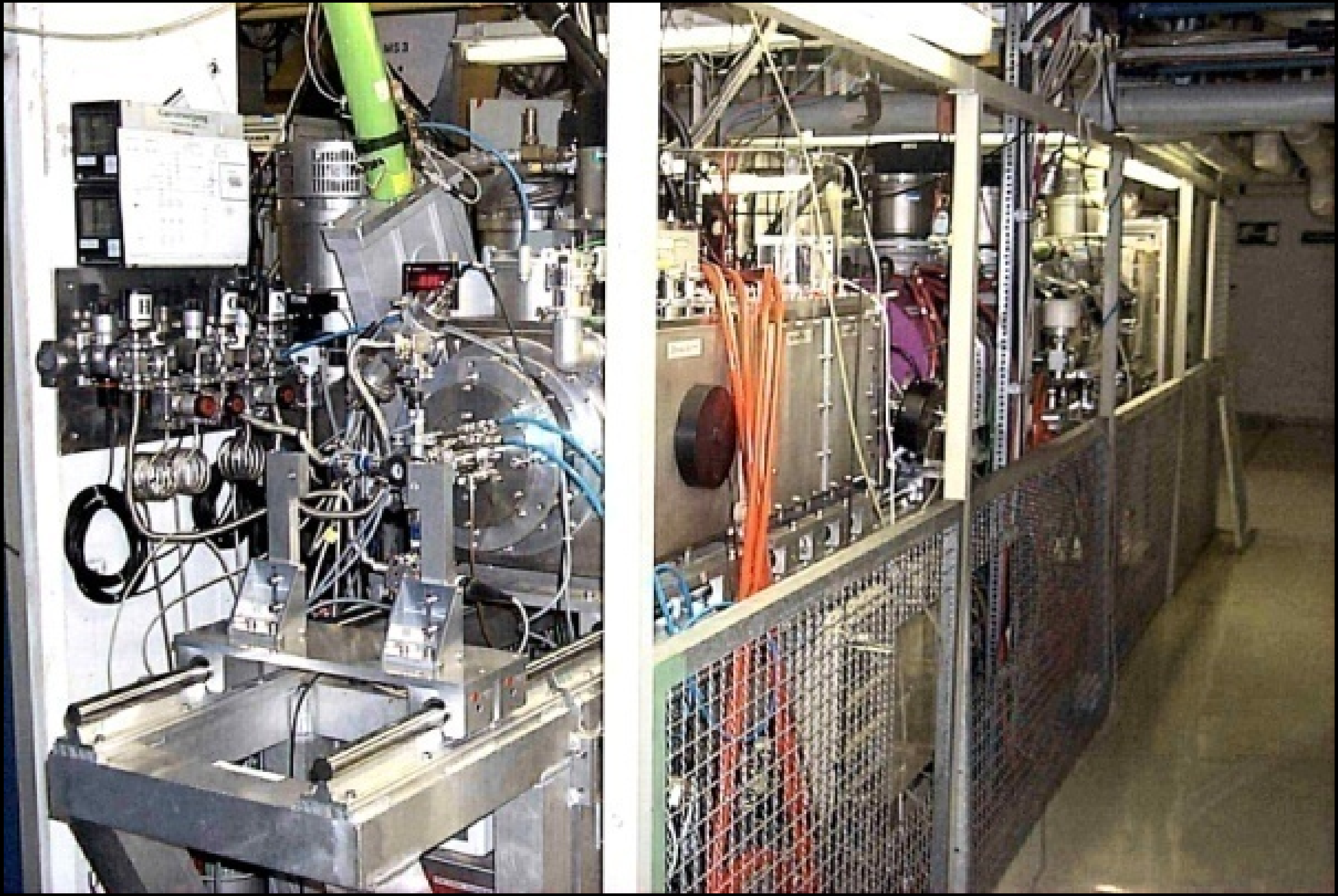
State No.	Unpolar.	Electron Polar. (1st 6-Pole)	RF-Trans. (3→5)	2nd 6-Pole	RF-Trans. (2→6)
①					
②					
③					
④					
⑤					
⑥					
P_Z			1/3	1/2	1
$P_Z^2 \cdot I_r$			1/9	1/6	2/3
P_{ZZ}			-1	-1/2	1
$P_{ZZ}^2 \cdot I_r$			1	1/6	2/3

Polarized H^{-} -Atoms



CBS @ FZJ, © D. Eversheim

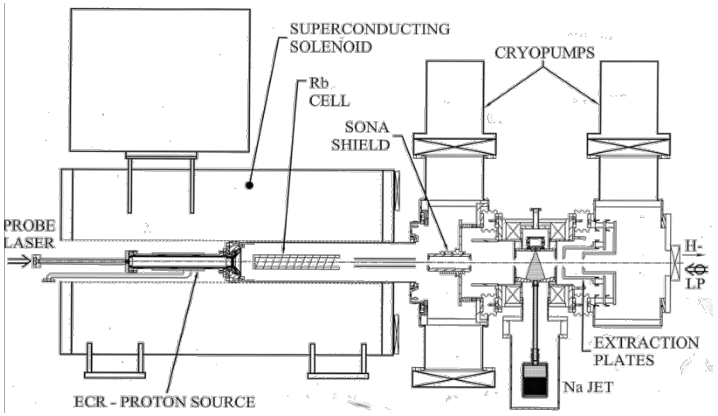
COSY CBS Source



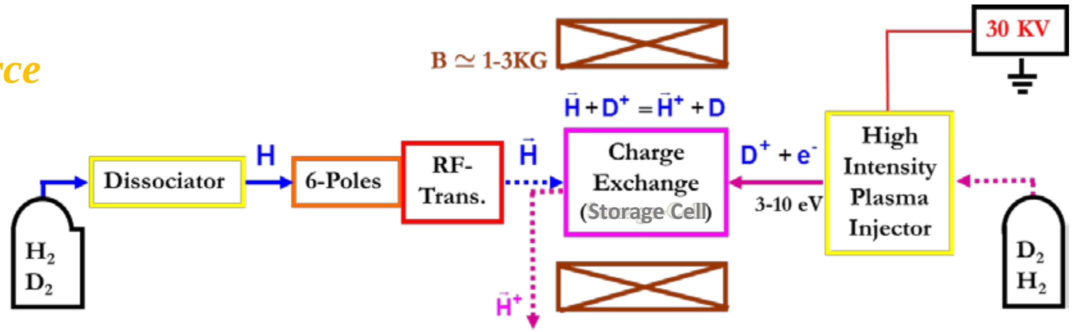
High Intensities

Other types of sources in operation, e.g.:

- **OPPIS (BNL)**
  Optically Pumped Polarized Ion Source
  based on polarization transfer:
  $H^{+} + Rb\uparrow \rightarrow H\uparrow + Rb^{+}$

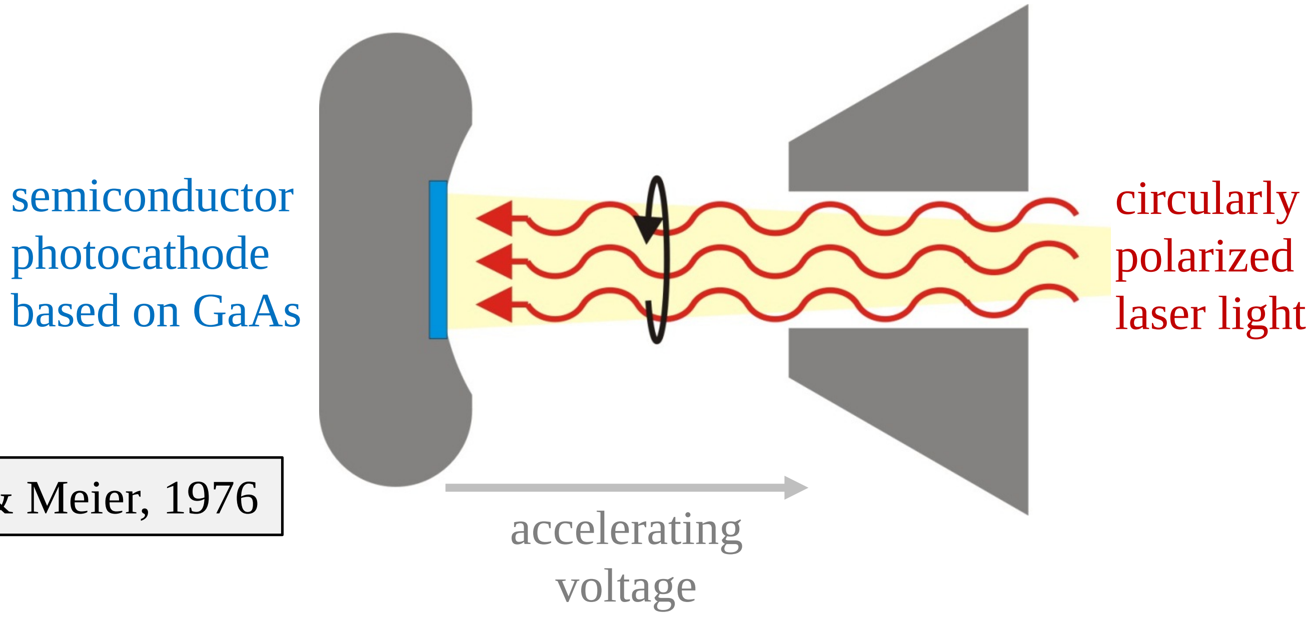


- **CIPIOS (FZJ)**
  Cooler Injector Polarized Ion Source
  based on spin filtering and
  RF transitions
  ionization:
  $H\uparrow + D^{+} \rightarrow {}^{+}H\uparrow + D$



Polarized Electrons

Functional Principle:



Pierce & Meier, 1976

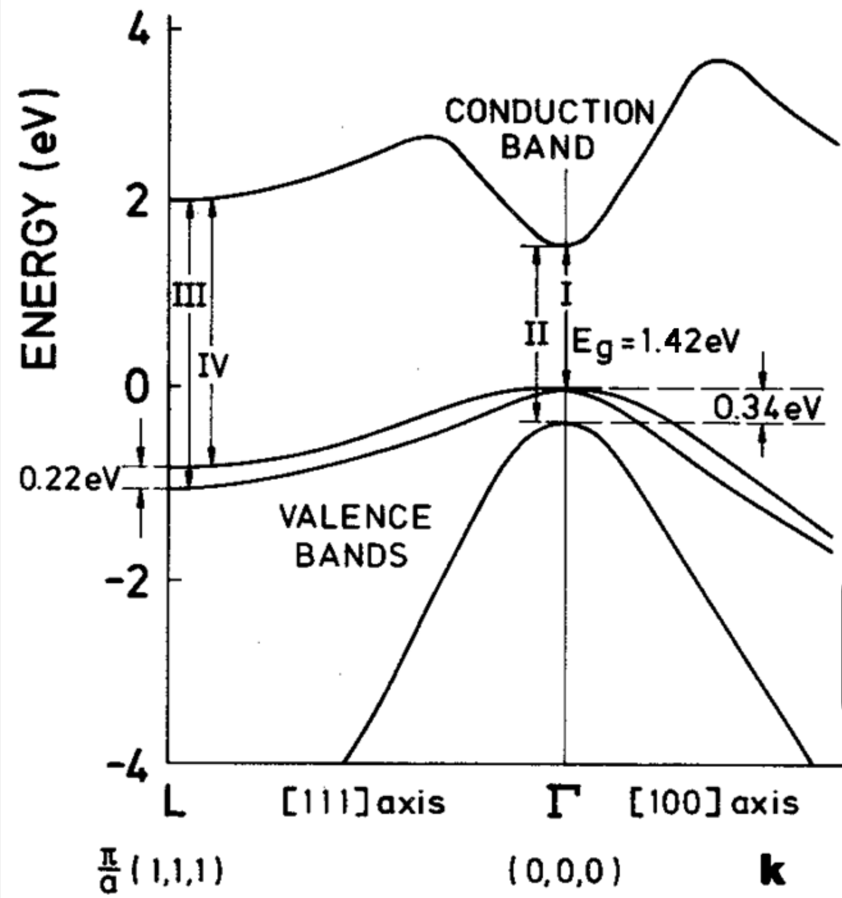
Photoelectron emission from GaAs

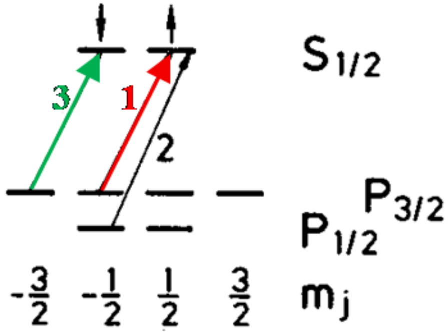
polarization transfer from laser photons to emitted electrons

Polarized Electrons

Optical Pumping:

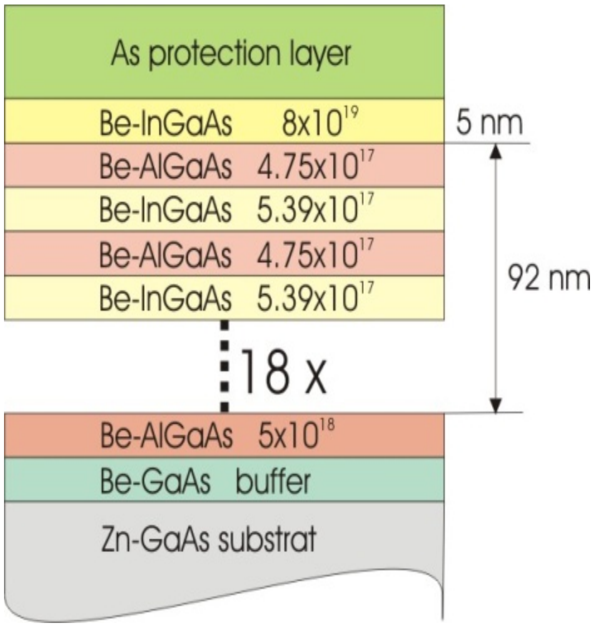
GaAs





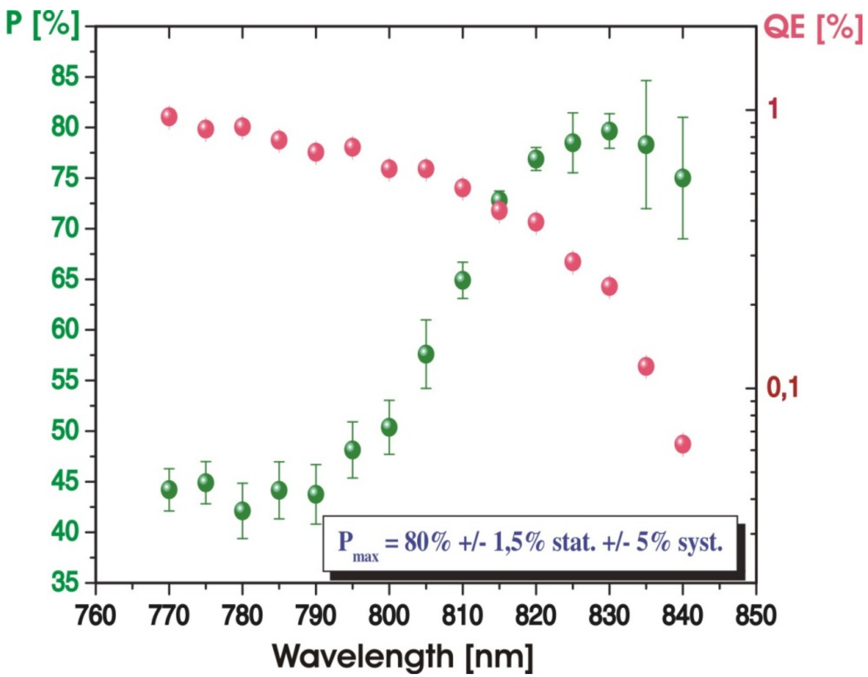
$$P_{max} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \frac{1-3}{1+3} = -0,5$$

Polarized Electrons



Be-InGaAs/AlGaAs Superlattice

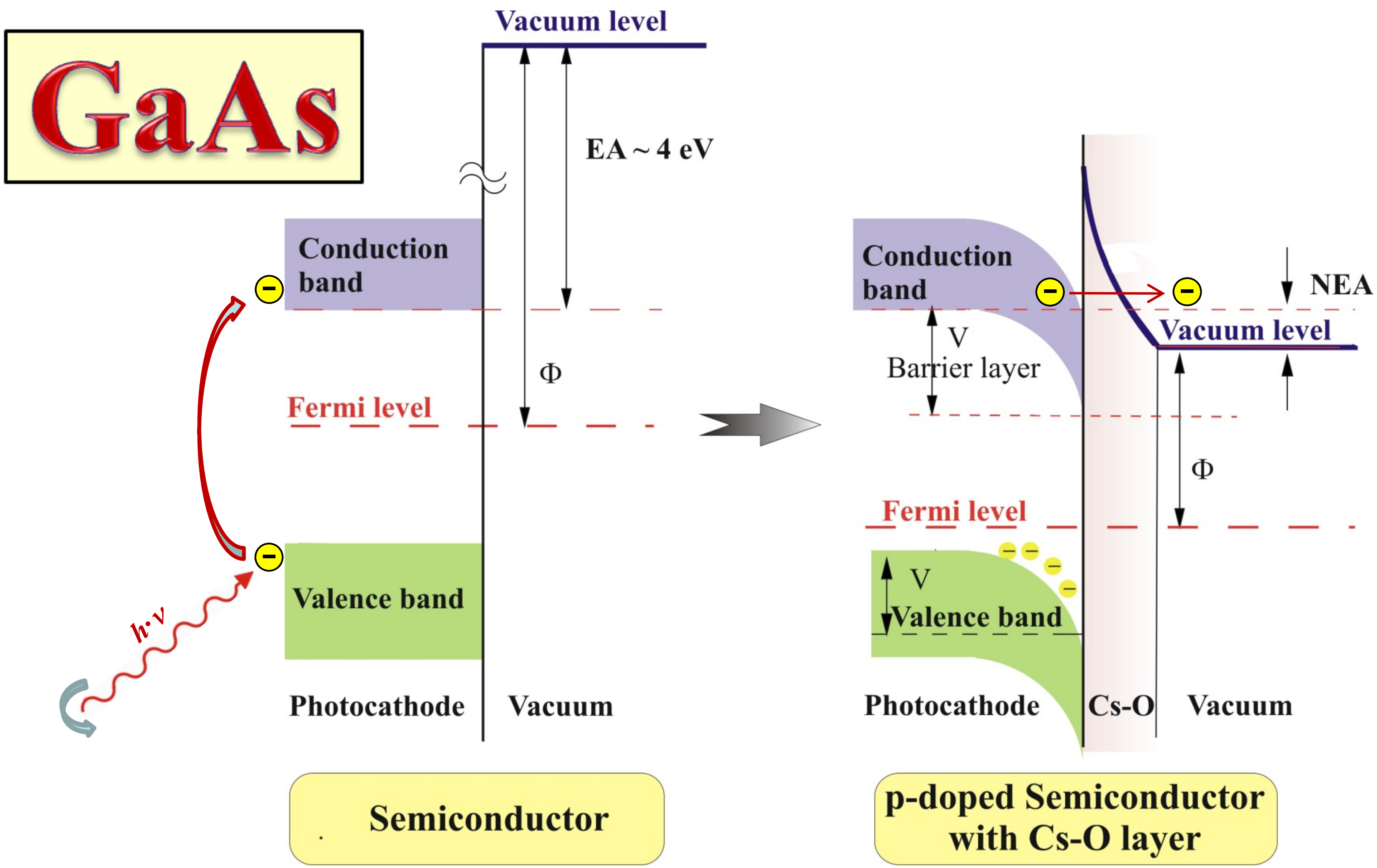
Polarization



Removal of the degeneracy:

- local distortions of the lattice (strain)
- multilayer structures (superlattice)

Generation of Polarized Electrons



Operation, heat cleaning and activation in extreme UHV

Lifetime 1000 h ↔ P (H_2O, CO_2) < 10^{-13} mbar

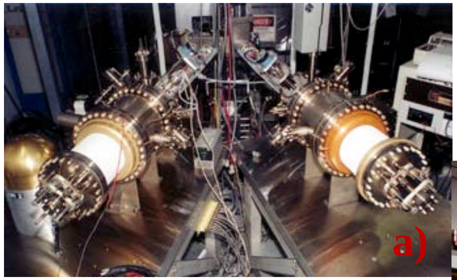
Polarized e⁻-Sources Worldwide

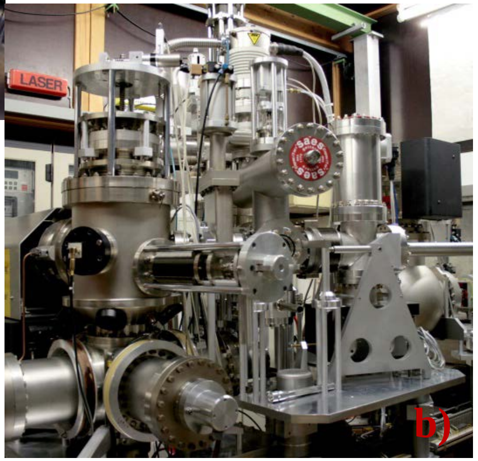
- **CEBAF (Jefferson Lab, a)**
  E = 100 keV, P > 80%, I = 200 μA (cw)

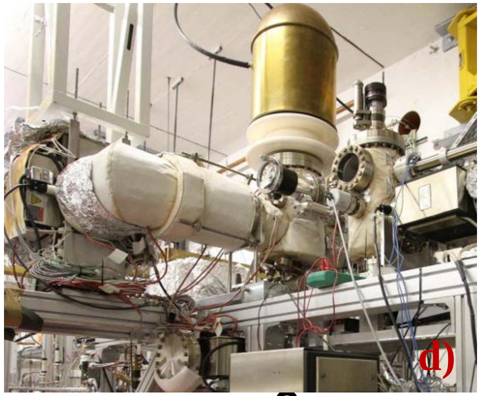
- **Bonn (ELSA, b)**
  E = 48 keV, P > 80%, I = 100 mA (1μs)

- **Mainz (MAMI, c)**
  E = 100 keV, P > 80%, I < 40 μA (cw)

- **Darmstadt (S-DALINAC, d)**
  E = 100 keV, P > 80%, I = 60 μA (cw)







Challenge: **long photocathode lifetime ↔ ultimate vacuum required**

How?

b) Acceleration of polarized particles

Facilities with Polarized Beams

Protons:

- **COSY** / Jülich (E < 2.4 GeV)
- **Saturne II** / Saclay (E < 3 GeV)
- **KEK PS** / Tsukuba (E < 7 GeV)
- **ZGS** / Argonne (E < 12 GeV)
- **AGS** / Brookhaven (E < 22 GeV)
- **RHIC** / Brookhaven (E < 250 GeV)
- …

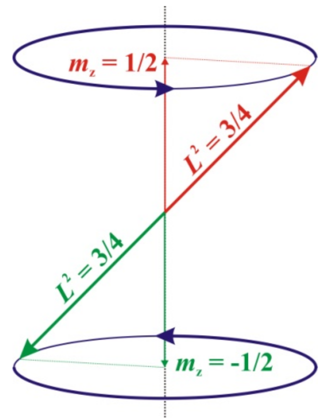
Electrons:

- **SDALINAC** / Darmstadt (E < 130 MeV)
- **AMPS** / Nikhef (E < 0.9 GeV)
- **SHR** / MIT-Bates (E < 1 GeV)
- **MAMI** / Mainz (E < 1.6 GeV)
- **ELSA** / Bonn (E < 3.2 GeV)
- **SPEAR** / SLAC (E < 3.7 GeV)
- **DORIS** / DESY (E < 5 GeV)
- **CEBAF** / Jlab (E < 6 GeV)
- **PETRA** / DESY (E < 18 GeV)
- **HERA** / DESY (E = 27.5 GeV)
- **SLC** / SLAC (E < 46 GeV)
- …

Polarization

- **Spin ½: Electrons, Protons, …**

$$L = \tfrac{1}{2} \rightarrow m = \begin{cases} +\tfrac{1}{2} \\ -\tfrac{1}{2} \end{cases}$$

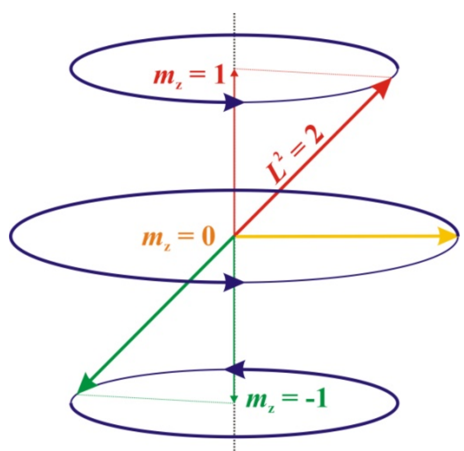


$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

Vector Polarization

- **Spin 1: Deuterons, …**

$$L = 1 \rightarrow m = \begin{cases} +1 \\ 0 \\ -1 \end{cases}$$



in addition:

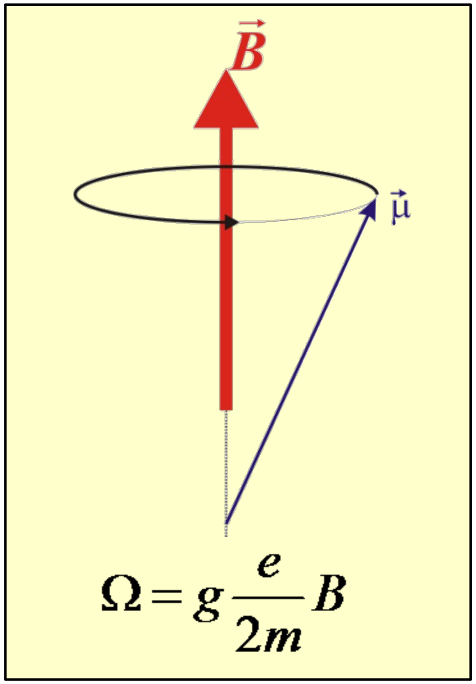
$$P = 1 - \frac{3N_0}{N_\uparrow + N_0 + N_\downarrow}$$

Tensor Polarization

Spin-Precession

Spin ↔ Magnetic Moment:

$$\vec{\mu} = g\frac{e}{2m}\cdot\vec{S}$$



Spins in Magnetic Fields:

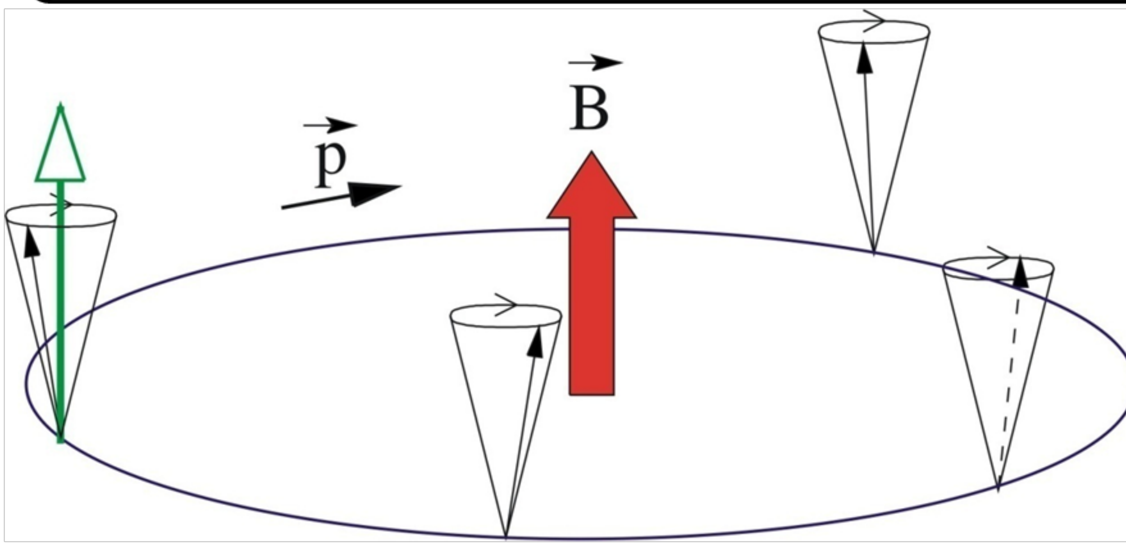
$$\frac{d\vec{S}}{dt} = \vec{\mu}\times\vec{B}$$

Landé-Factor and Gyromagnetic Anomaly:

- Electrons: $a = ½\,(g - 2) = 1{,}15967\cdot 10^{-3}$
- Protons: $a = ½\,(g - 2) = 1{,}792843$
- Deuterons: $a = ½\,(g - 2) = -0{,}142987$

Spin-Precession

Spin-Tune: $Q_{Sp} = \gamma a, \quad a = \frac{g-2}{2}$

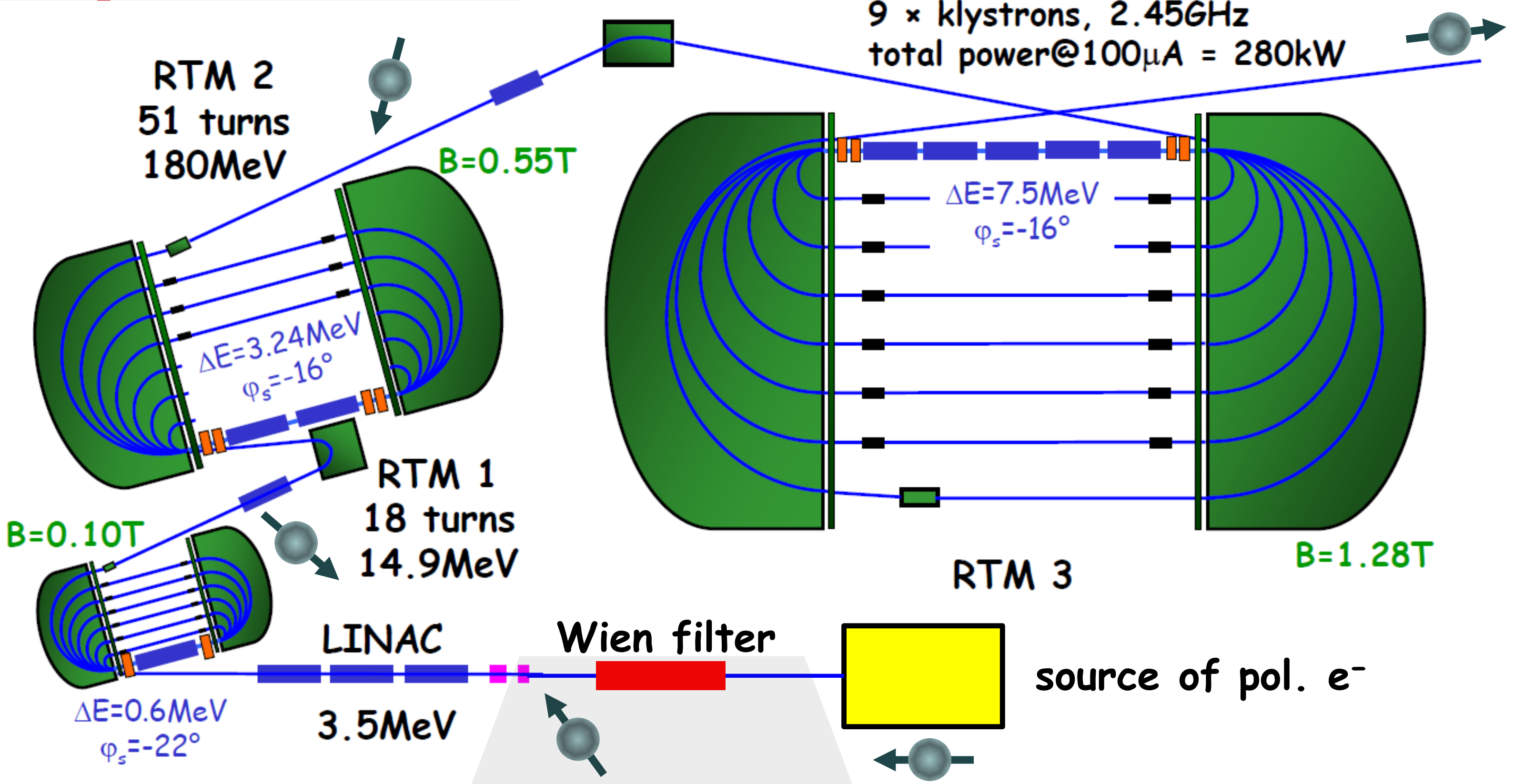


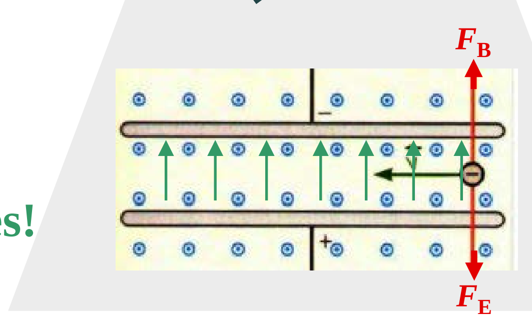
$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} \qquad \vec{\Omega}^* = -\frac{e}{m_0}(1+a)\cdot\vec{B}$$

$$\vec{\Omega}_{BMT} = -\frac{e}{m_0\gamma}\left\{(1+a\gamma)\cdot\vec{B}_\perp + (1+a)\cdot\vec{B}_\parallel - \left(a + \frac{1}{\gamma+1}\right)\cdot\gamma\vec{\beta}\times\frac{\vec{E}}{c}\right\}$$

LINACs and Recirculators

Example: MAMI / Mainz

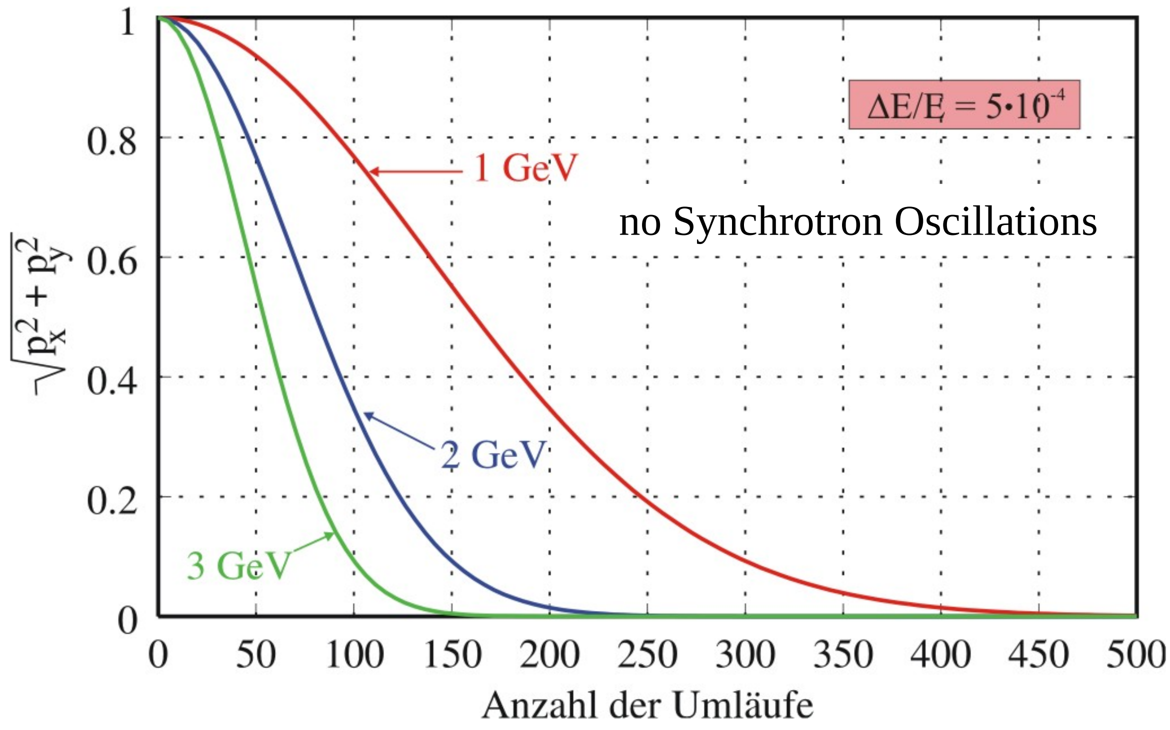




$$\vec{E}\perp\vec{B},\quad E/B=\mathrm{v},\qquad \phi_{Spin}=\frac{eB_{\perp}}{\gamma^2 m_0}\cdot\frac{\beta c}{L}$$

✓ for „moderate“ energies!

Spin-Precession in Circular Acc.



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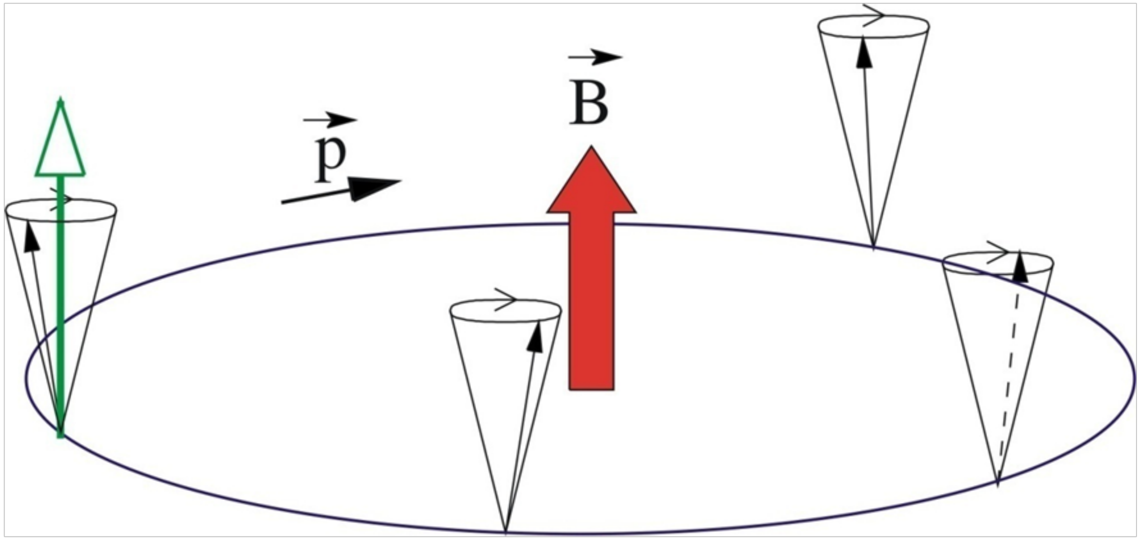
$$\vec{\Omega}_{BMT} = -\frac{e}{m_0\gamma}\left\{(1+a\gamma)\cdot\vec{B}_\perp + (1+a)\cdot\vec{B}_\parallel - \left(a+\frac{1}{\gamma+1}\right)\cdot\gamma\vec{\beta}\times\frac{\vec{E}}{c}\right\}$$

Spin-Precession in Circular Acc.

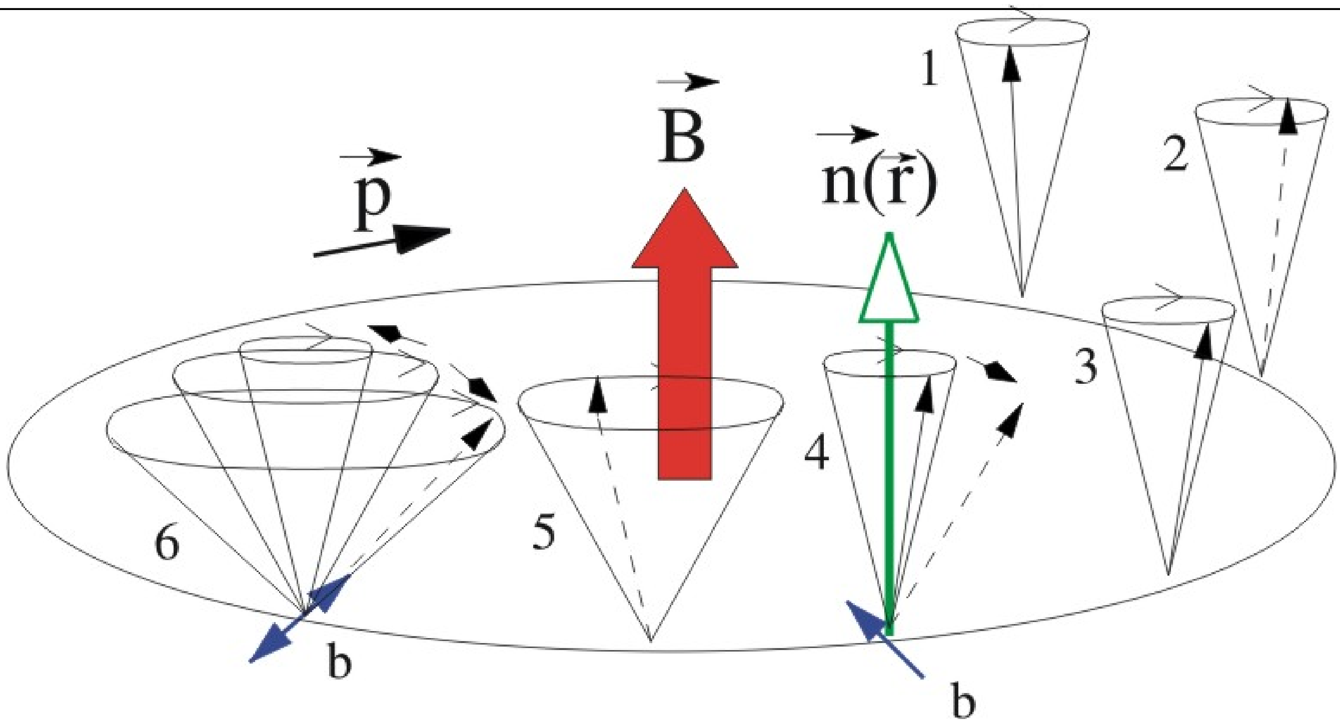
Spin-Tune: $Q_{Sp} = \gamma a, \quad a = \frac{g-2}{2}$



<u>**Magic Energies ($\gamma \cdot a = n$)**</u>

- **electrons:** $\gamma = 862.31 \cdot n \quad \leftrightarrow \quad \Delta E_{kin} = 440.6$ MeV
- **protons:** $\gamma = 0.5578 \cdot n \quad \leftrightarrow \quad \Delta E_{kin} = 523.3$ MeV
- **deuterons:** $\gamma = 6.9936 \cdot n \quad \leftrightarrow \quad \Delta E_{kin} = 13.12$ GeV !!!

Depolarizing Resonances



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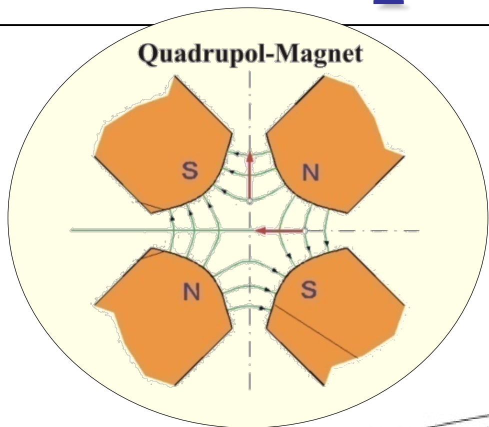
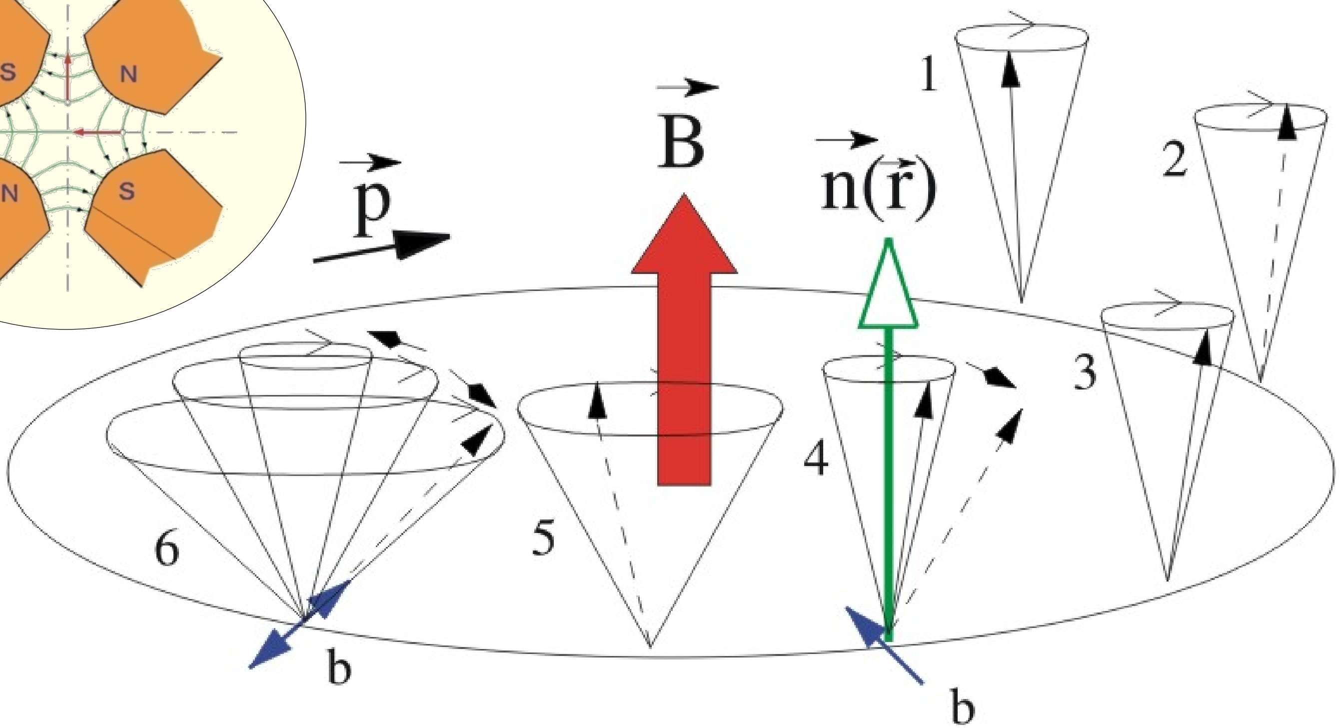
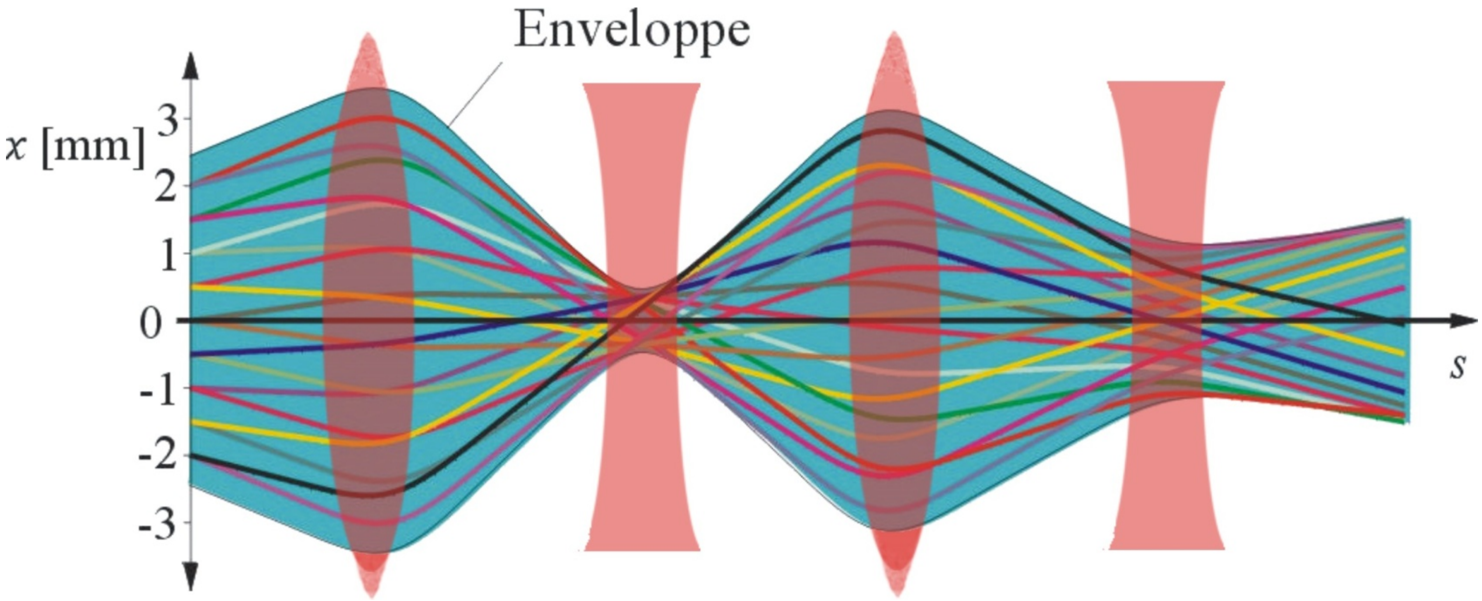
Depolarizing Resonances





Imperfection Resonance: $\gamma \cdot a = n, \qquad n \in Z$

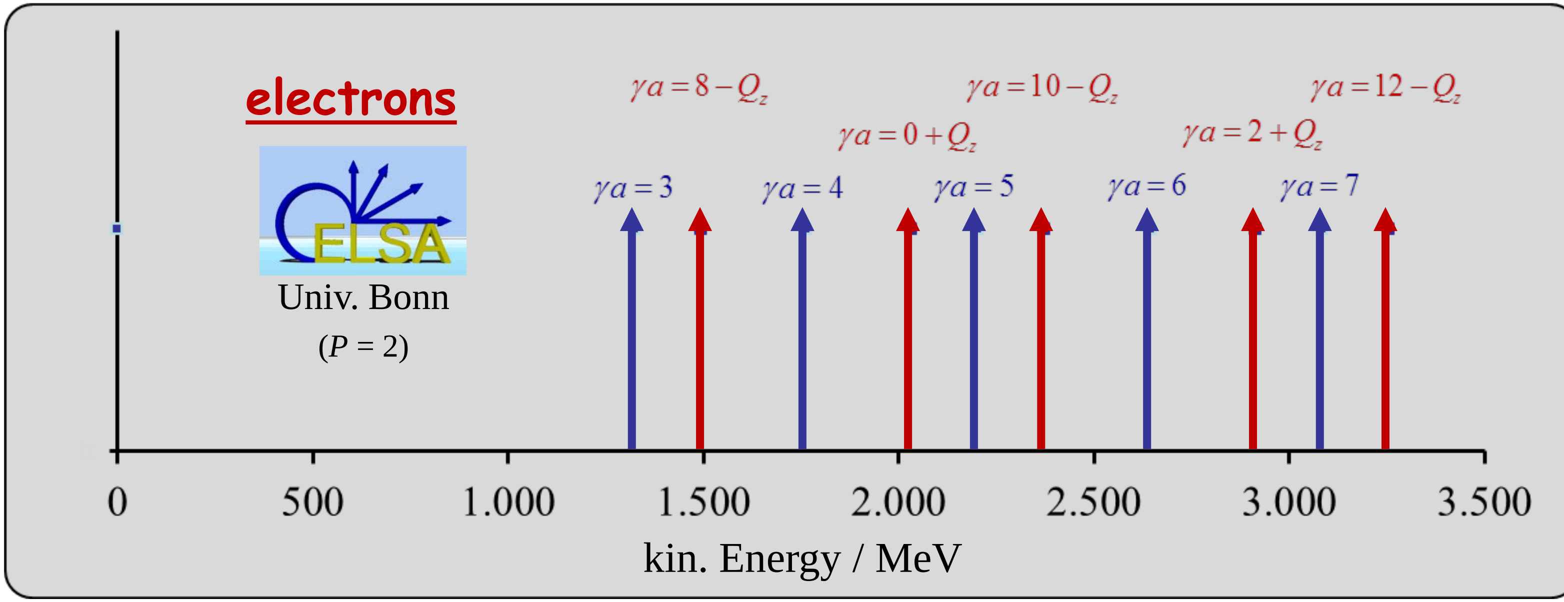
Depolarizing Resonances

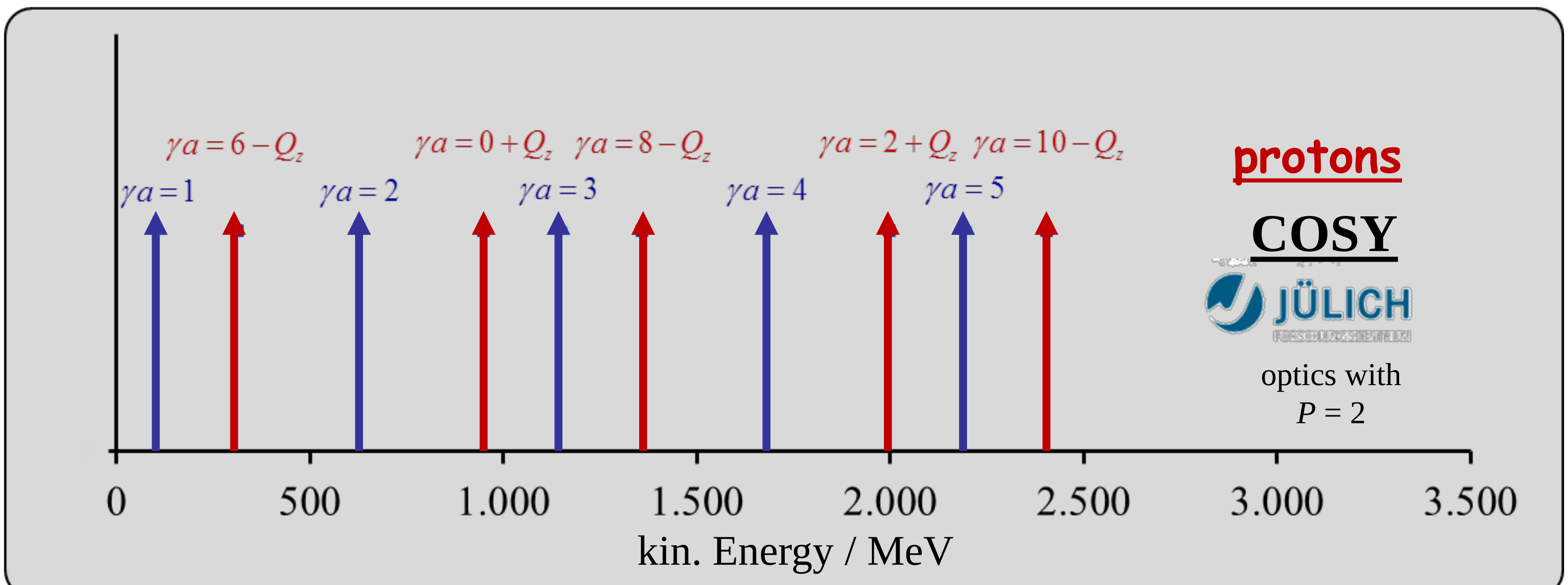


Strong Focusing: Betatron Oscillations!

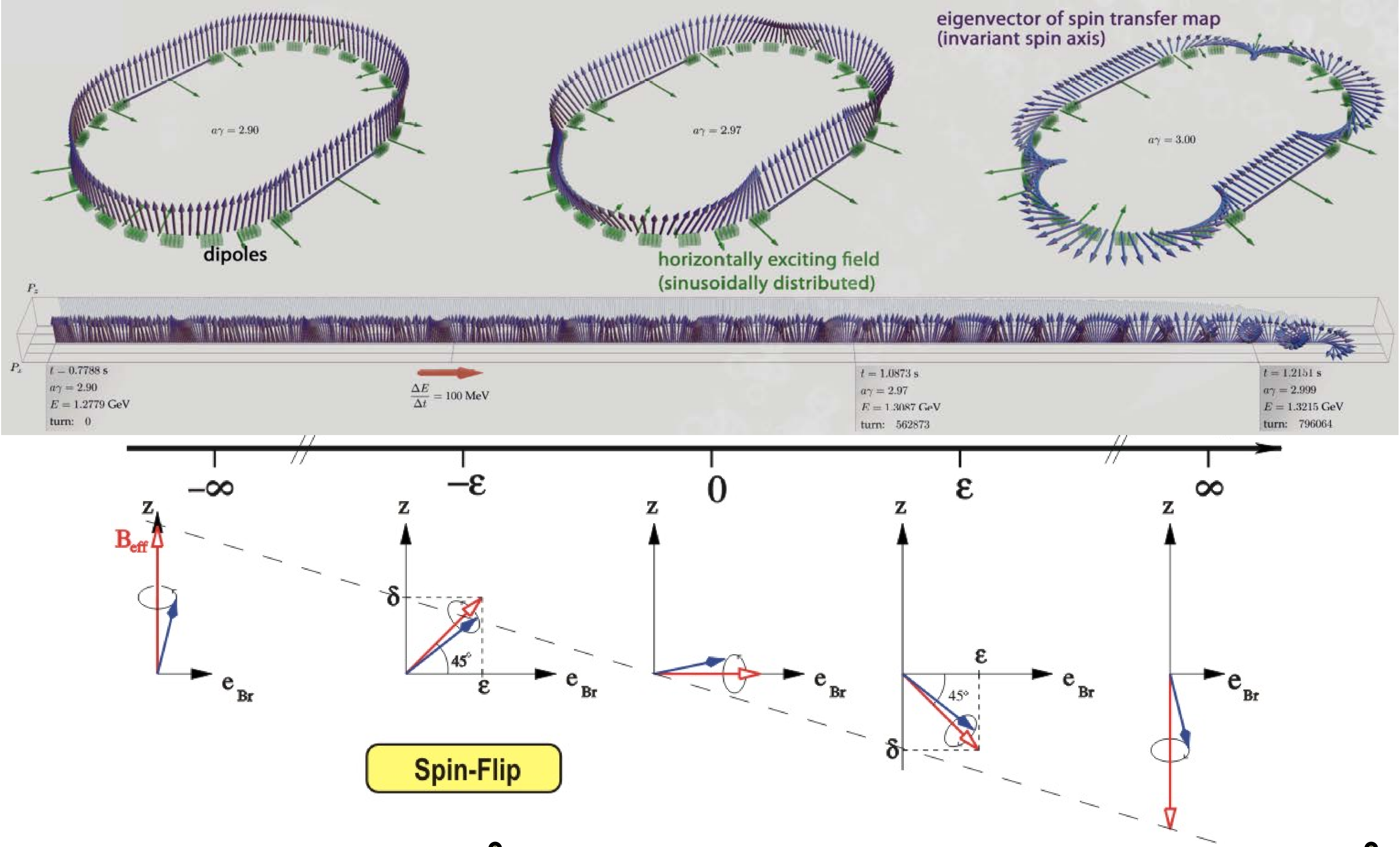
Imperfection Resonance: $\gamma \cdot a = n, \qquad n \in Z$

Resonances of 1st order





Resonance Crossing

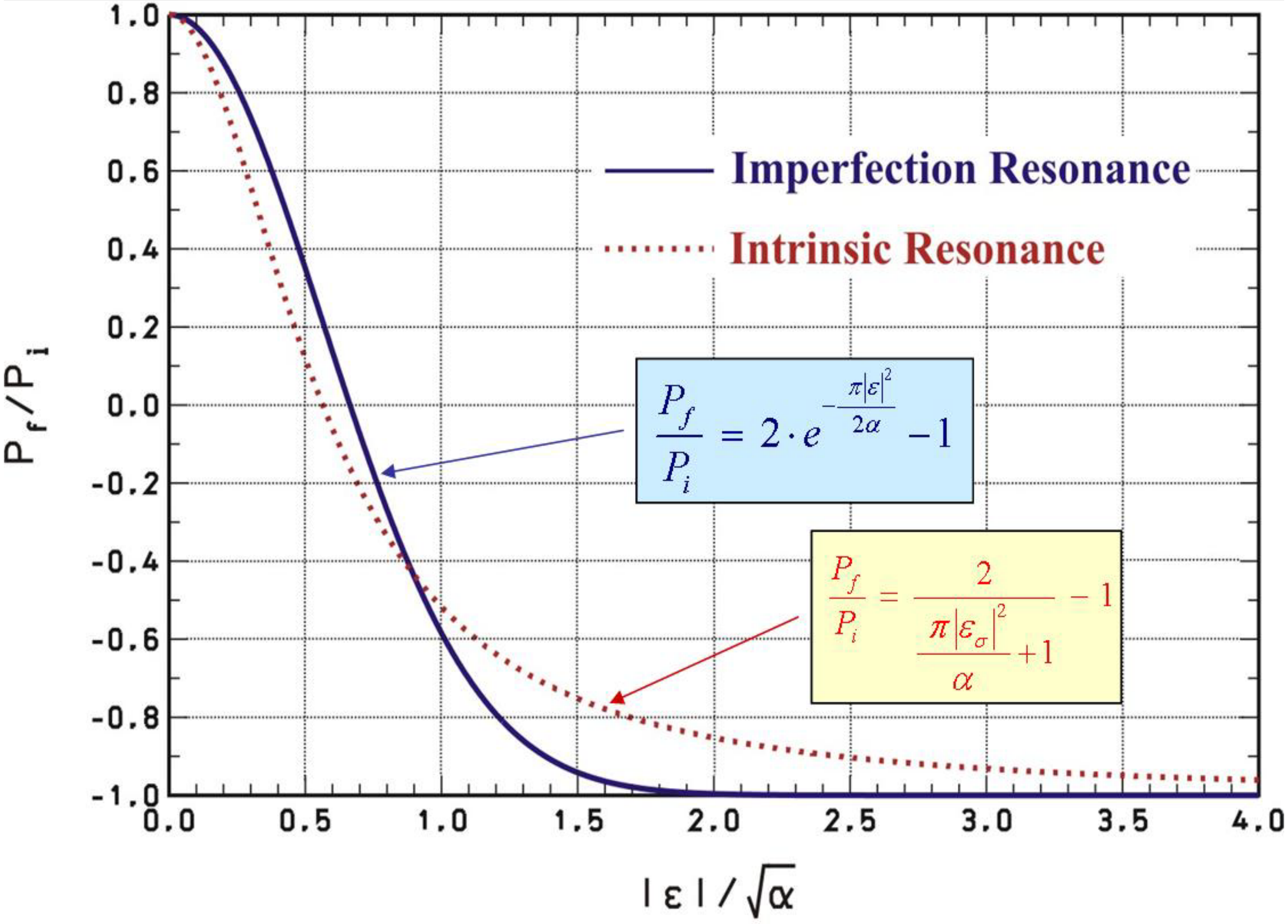


Crossing Speed: $\alpha = \dot{\gamma} a / \omega_{rev}$

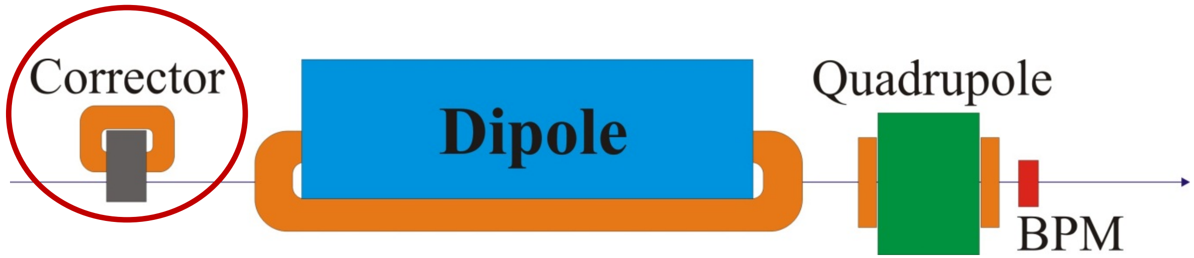
→ Resonance Strength ε

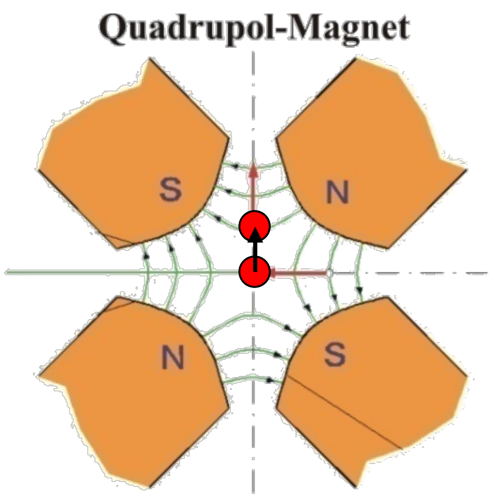
Resonance Crossing

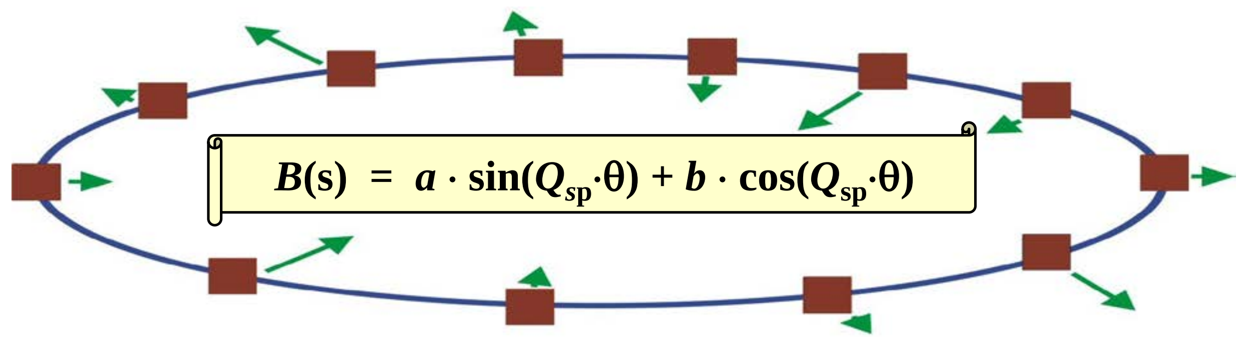
Froissart-Stora-Formula

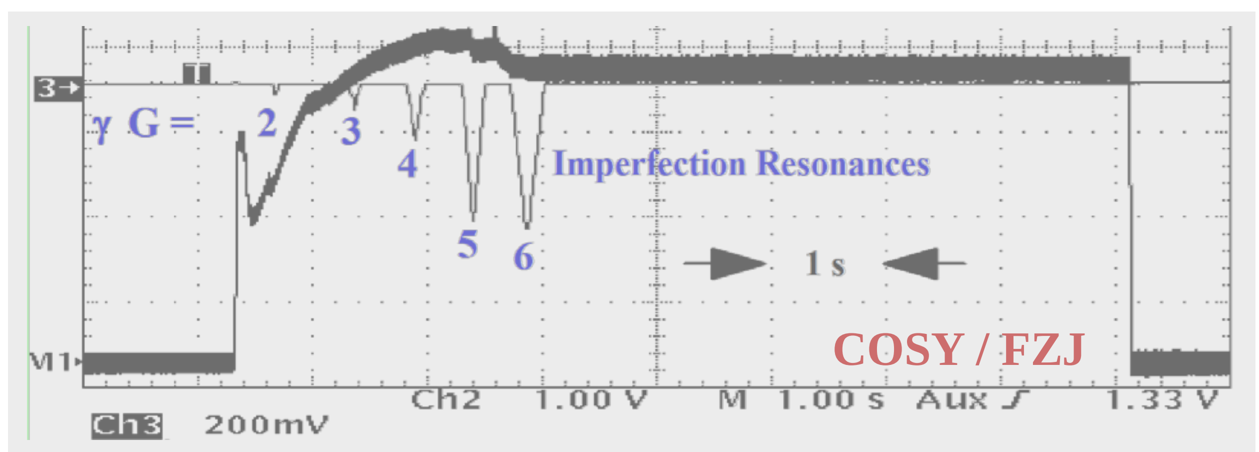


Vertical Orbit Excitations



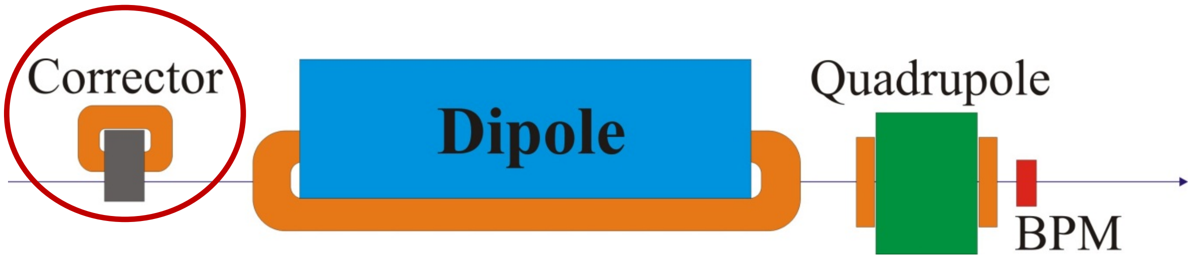


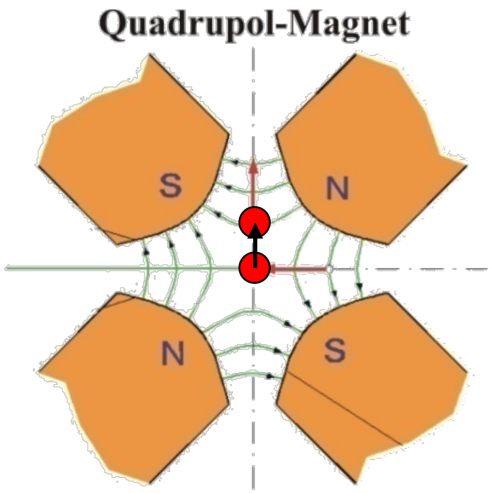


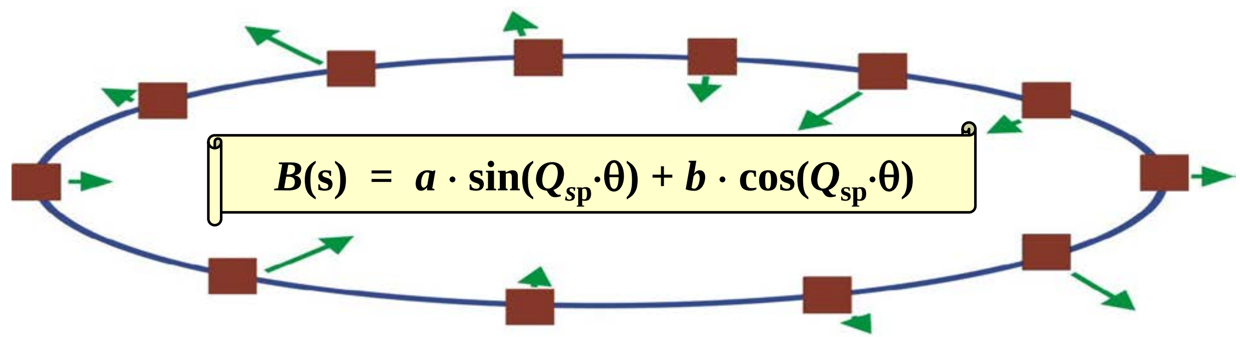


Take care of the resonance-driving harmonics $\gamma \cdot a = n$!

Vertical Orbit Excitations







$$B(s) = a \cdot \sin(Q_{sp} \cdot \theta) + b \cdot \cos(Q_{sp} \cdot \theta)$$

Take care of the resonance-driving harmonic $\gamma \cdot a = n$!

Advantages:

- Distortions have only to be sufficiently strong
- No detailed optimization required

Disadvantages:

- CO excursions may be to large for available aperture

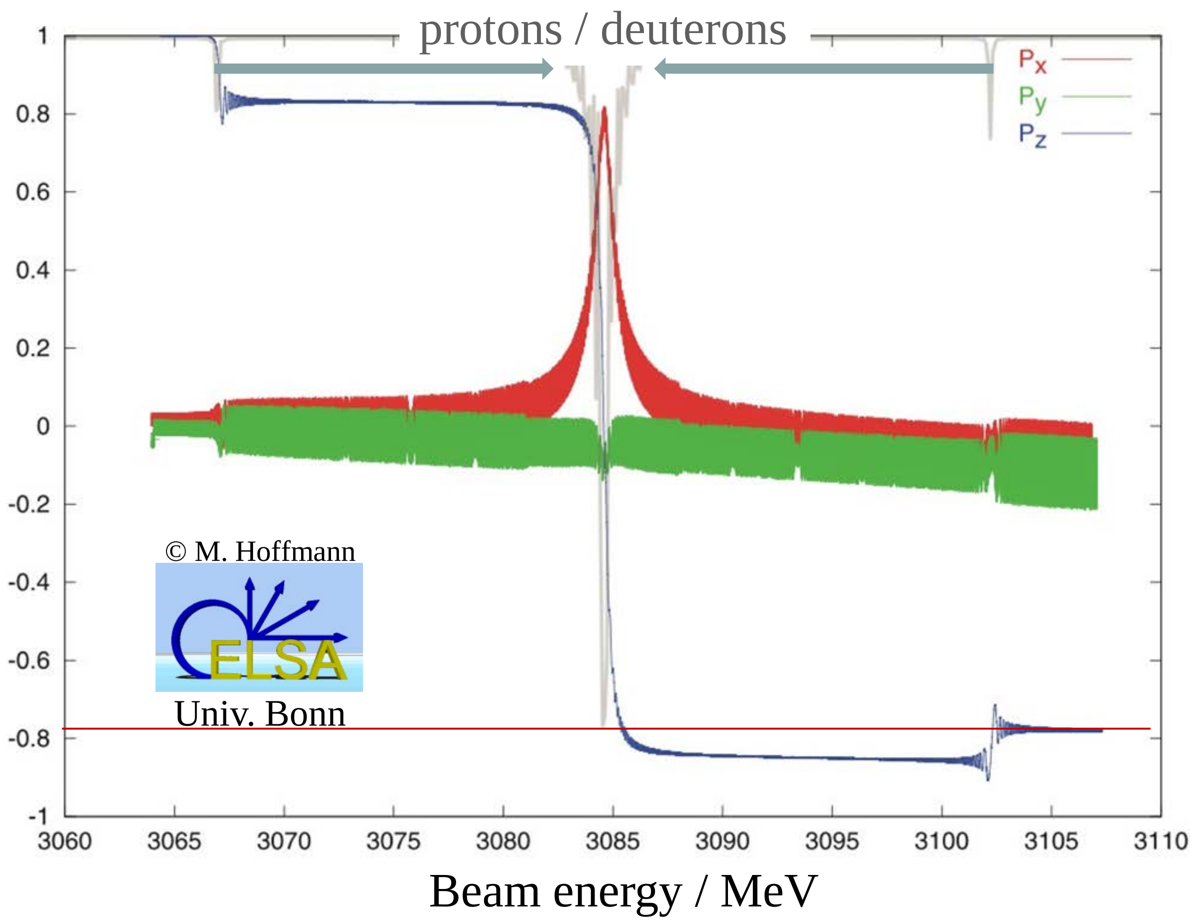
Synchrotron Oscillations

Multiple crossing of depolarizing resonances due to energy oscillations

Oscillation frequency/tune:

- **electrons** (ELSA)**:**
  $\Omega \approx 80$ kHz $\leftrightarrow Q_s \approx 0.04$
- **protons** (COSY)**:**
  $\Omega \approx 0.5$ kHz $\leftrightarrow Q_s \approx 0.0006$

Crossing of (weaker) sidebands around imperfection resonance



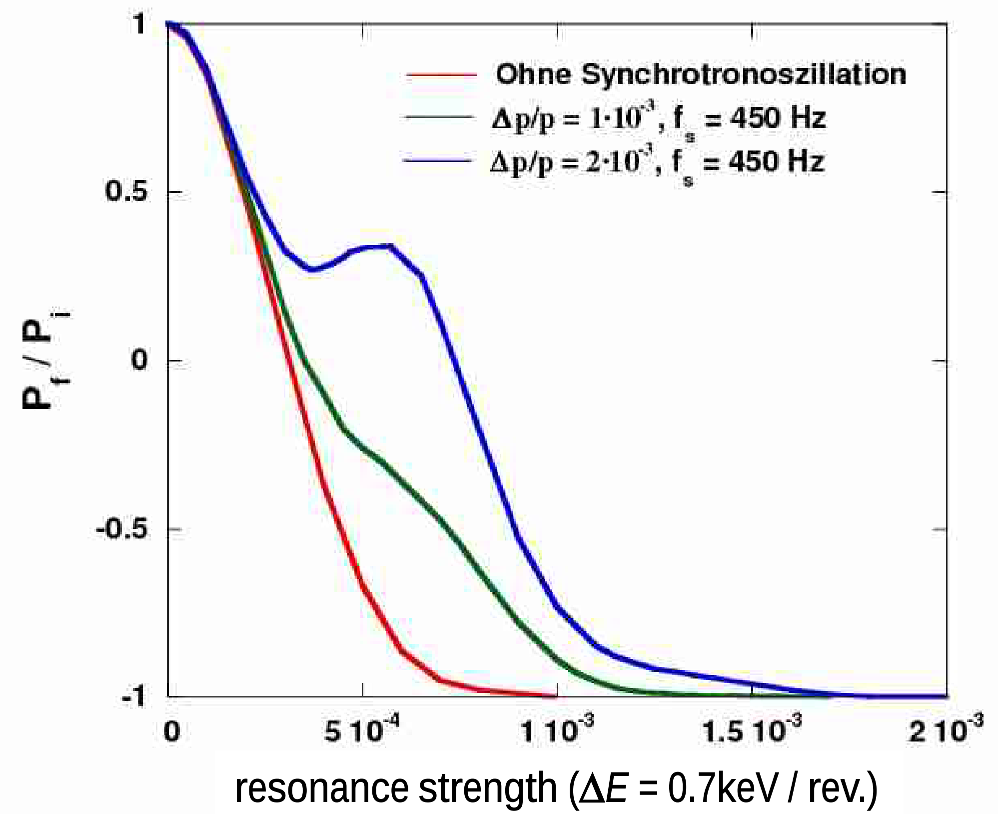
Synchrotron Oscillations

Multiple crossing of depolarizing resonances due to energy oscillations

Protons: synchrotron sattelites close by
→ „broader“ resonance
→ larger values required for full spin flip

Oscillation frequency/tune:

- **electrons** (ELSA)**:**
  $\Omega \approx 80$ kHz $\leftrightarrow Q_s \approx 0.04$
- **protons** (COSY)**:**
  $\Omega \approx 0.5$ kHz $\leftrightarrow Q_s \approx 0.0006$



Crossing of (weaker) sidebands around imperfection resonance

(figure taken from habil. A. Lehrach)

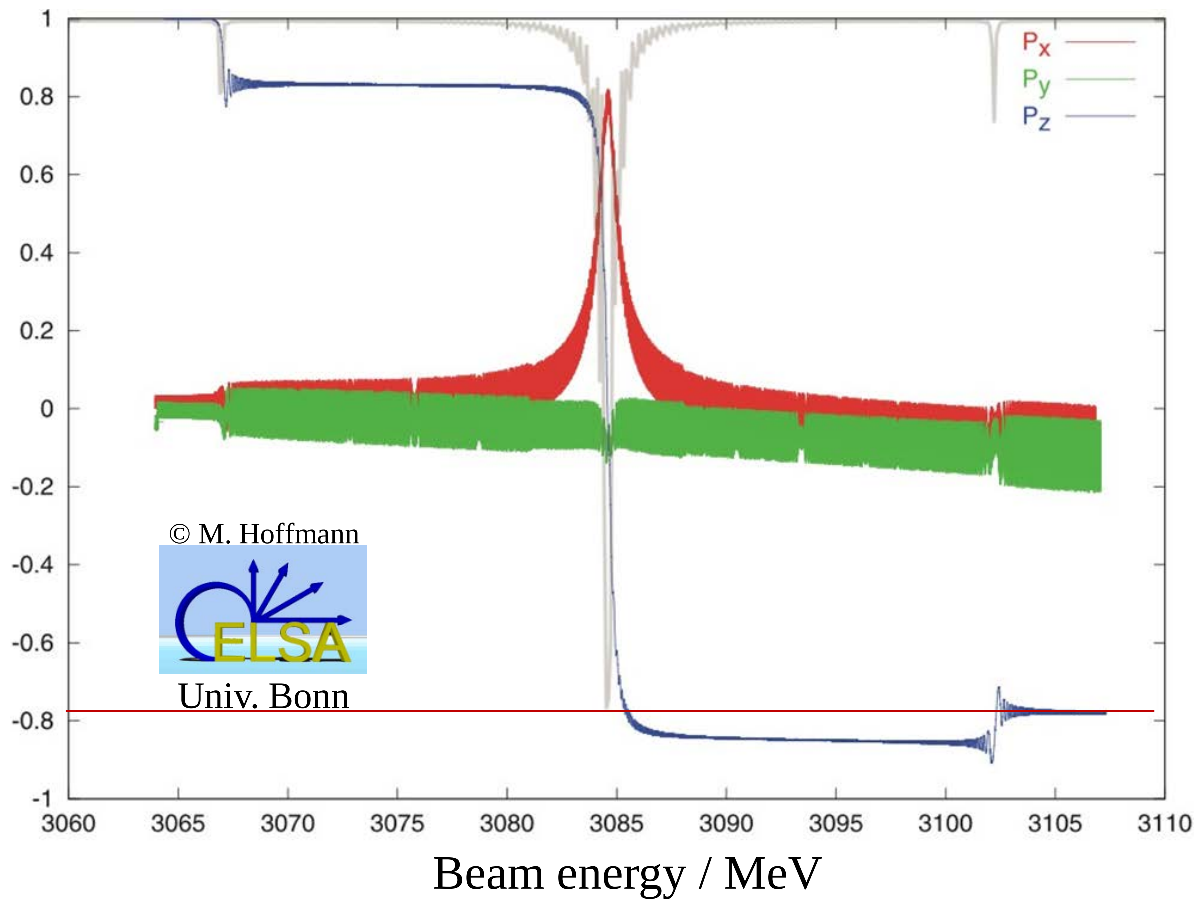
Synchrotron Oscillations

Multiple crossing of depolarizing resonances due to energy oscillations

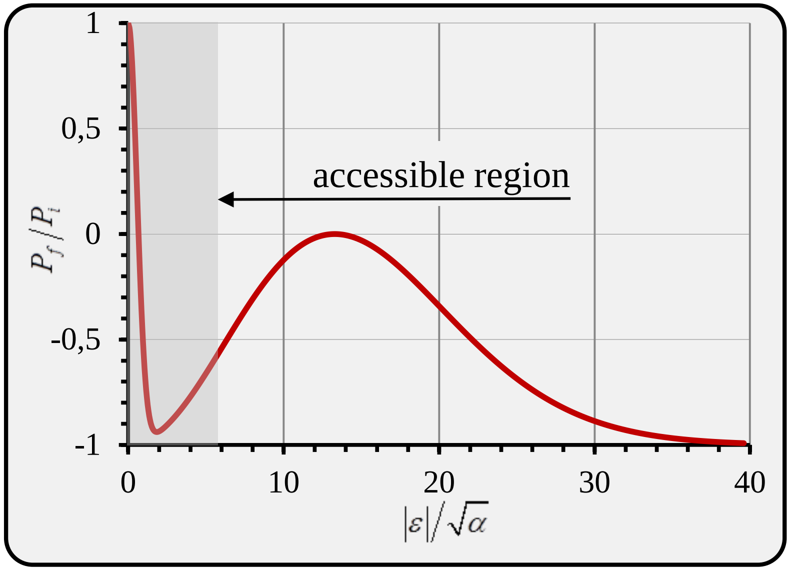
Oscillation frequency/tune:

- **electrons** (ELSA)**:**
  $\Omega \approx 80\text{ kHz} \leftrightarrow Q_s \approx 0.04$
- **protons** (COSY)**:**
  $\Omega \approx 0.5\text{ kHz} \leftrightarrow Q_s \approx 0.0006$

Crossing of (weaker) sidebands around imperfection resonance



Crossing of Synchrotron-Sidebands

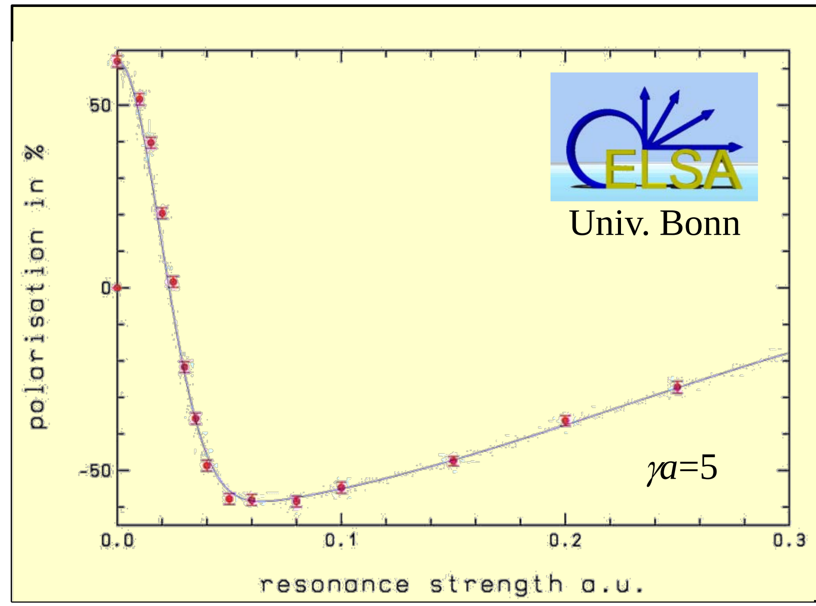


„Modified“ Froissart-Stora Formula:

$$\frac{P_f}{P_i} = \left(2 \cdot e^{-\frac{\pi |\varepsilon_r|^2}{2\alpha}} - 1 \right) \cdot \left(2 \cdot e^{-\frac{\pi |\varepsilon_s|^2}{2\alpha}} - 1 \right)^2$$

Full Spin-Flip no longer possible!

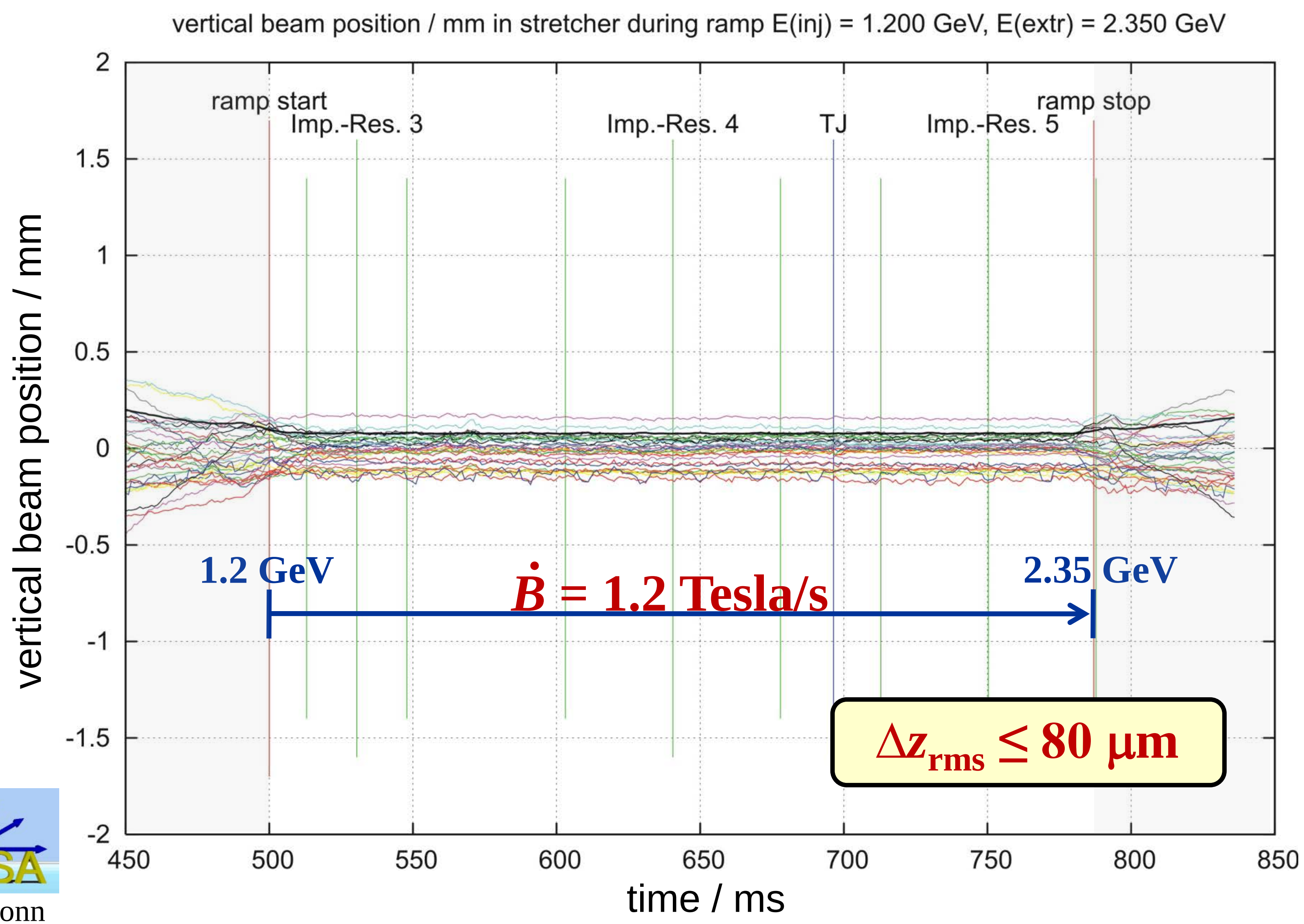
Experimental verification at ELSA:



Beam excitation will only cause partial spin flip → depolarization!

- Reduce resonance strength by **proper centering in the quads**
- Compensate **resonance driving horizontal magnetic fields**

CO Correction on the Ramp



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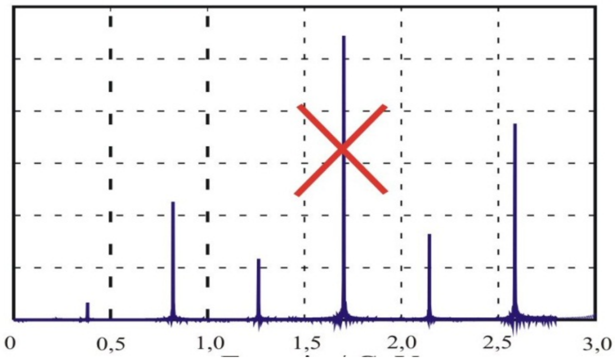
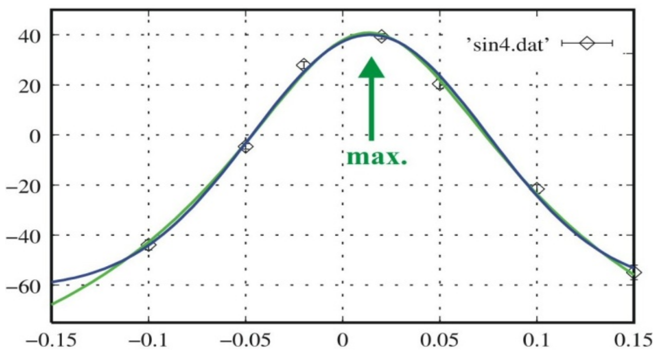
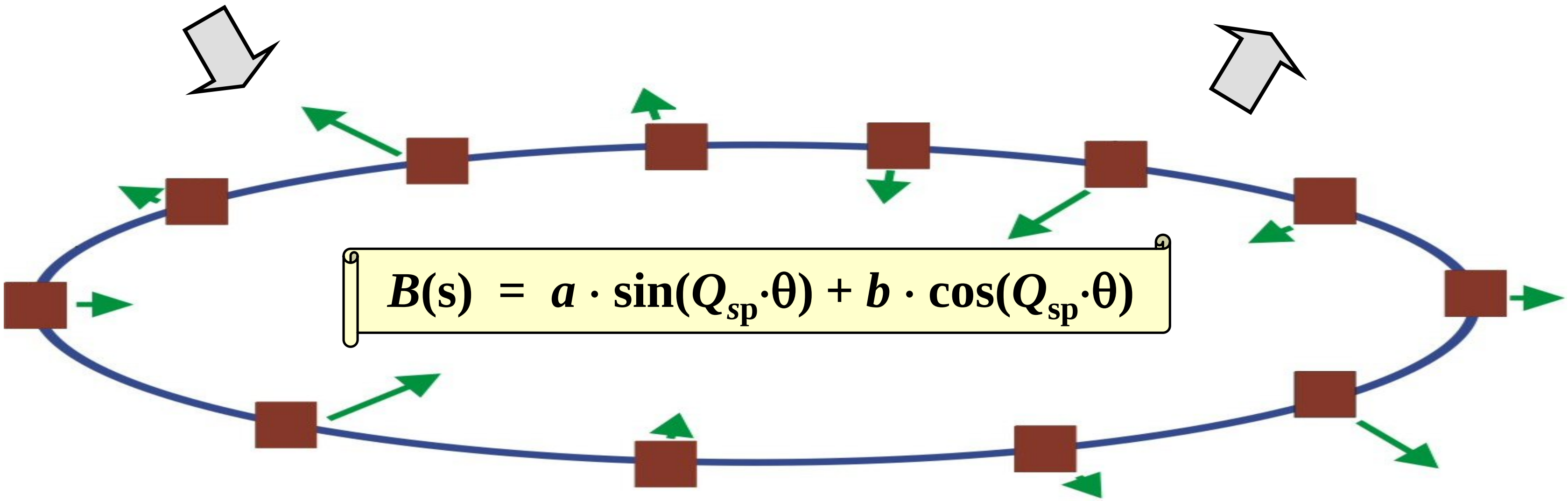
Harmonic Correction

(Imperfection-Resonances)

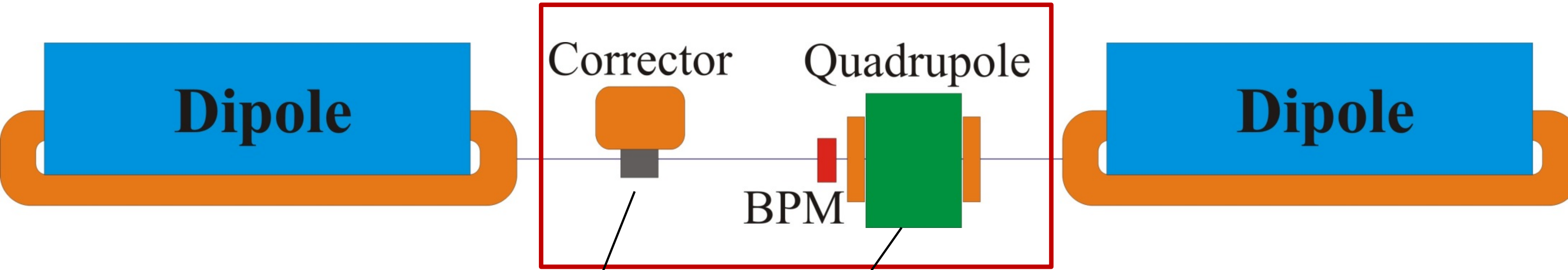






$$B(s) = a \cdot \sin(Q_{sp} \cdot \theta) + b \cdot \cos(Q_{sp} \cdot \theta)$$

Spin-Orbit Response Technique

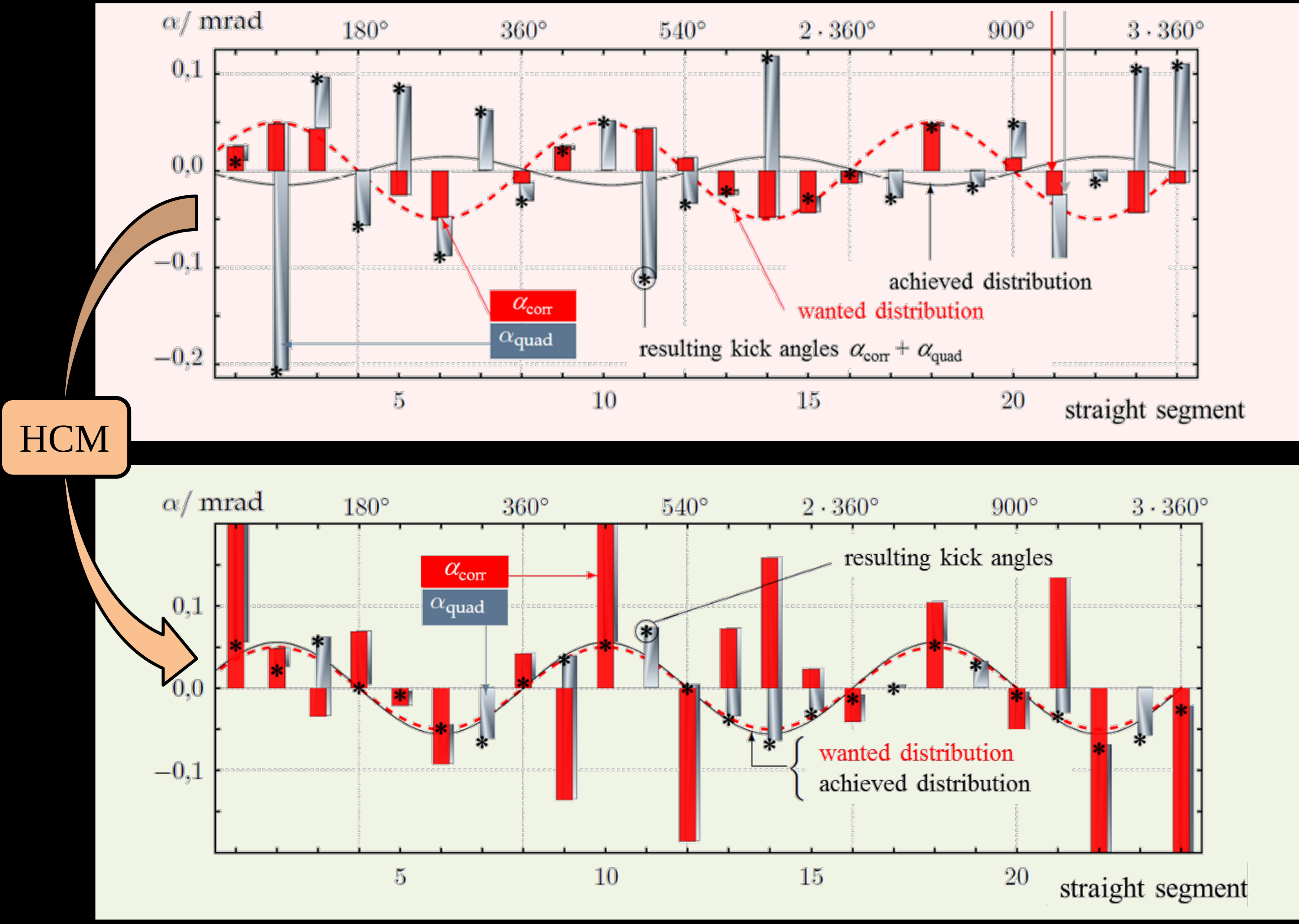


2 Contributions: $\alpha_n = \boxed{\sum_{j\in Dip_n} \alpha_{corr,j}} + \boxed{l \cdot \sum_{j\in Dip_n} k_j \cdot \Delta z_j} = \sum_{j\in Dip_n} \alpha_{corr,j} + l \cdot \sum_{j\in Dip_n} k_j \cdot \left(\mathbf{ORM} \cdot \vec{\alpha}_{corr}\right)_j$

Spin-Orbit Response Matrix: $\vec{\alpha}_{harm} = \mathbf{HCM} \cdot \vec{\alpha}_{corr}$

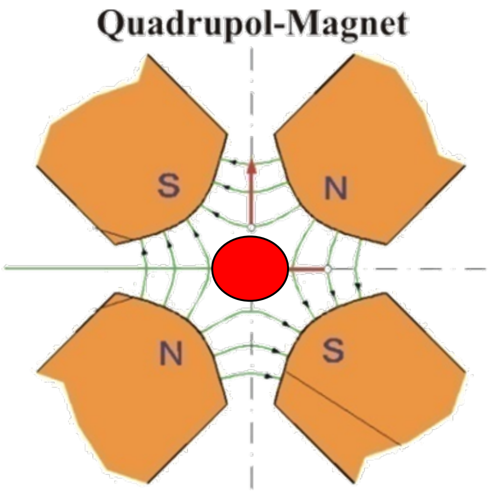
$$\mathbf{HCM}_{i,k} = \delta_{i,k}^{\mathrm{VC}} + \sum_{m=1}^{32} \delta_{m,k}^{\mathrm{Q}} \cdot l_m \cdot k_m \cdot \mathbf{ORM}_{m,i}$$

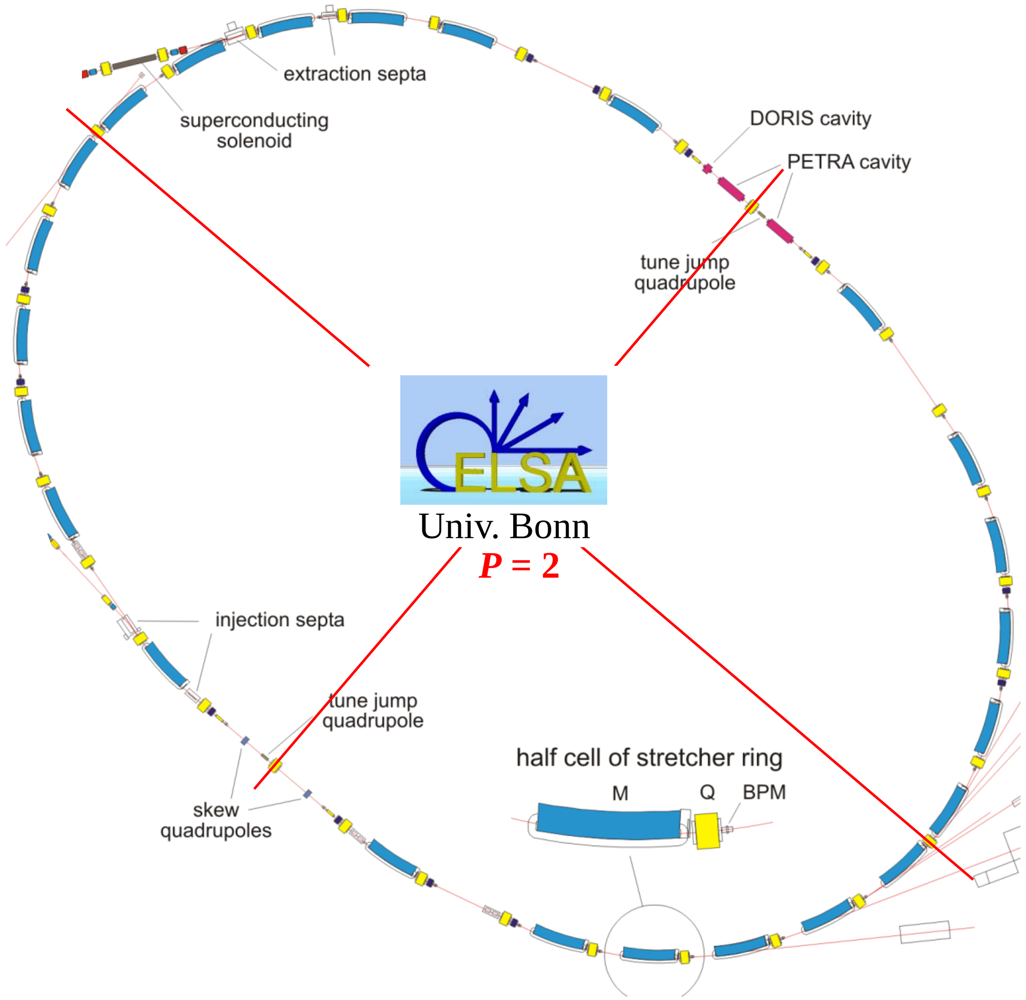
Spin-Orbit Response Technique



Intrinsic Resonances

$$\gamma \cdot a = n \cdot P \pm Q_z$$





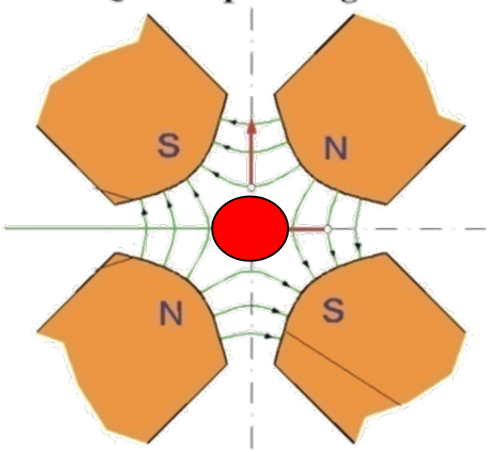
Countermeasures:

- high superperiodicity *P* (lattice, machine optics)
- reduce vertical beam size (cooling, skew quads, optics)
- increase crossing speed (tune jumping)

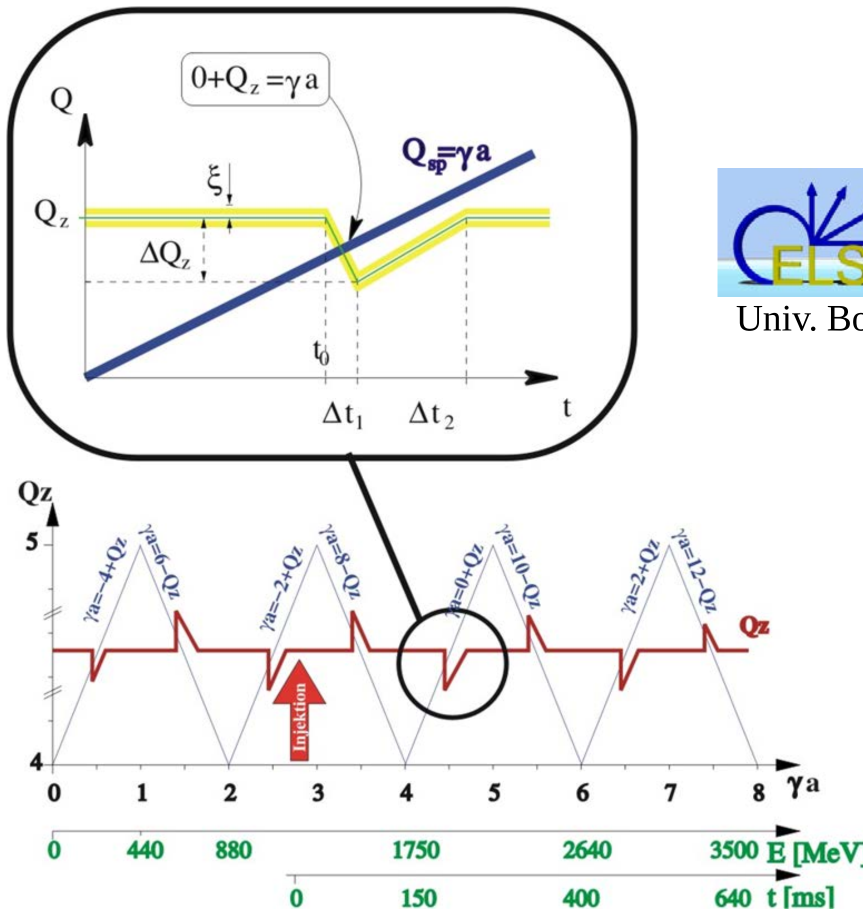
Intrinsic Resonances

$$\gamma \cdot a = n \cdot P \pm Q_z$$

Quadrupol-Magnet



Tune Jumping:



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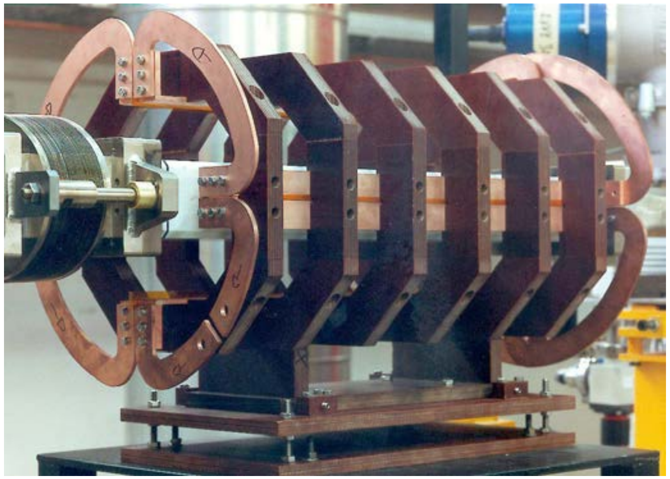
Countermeasures:

- high superperiodicity *P*
  (lattice, machine optics)
- reduce vertical beam size
  (cooling, skew quads, optics)
- increase crossing speed
  (tune jumping)

Tune Jump Quadrupoles



Tune-Jump Quadrupole

- Copper coil air core
- Length 0.6 m
- Max. current ±3100 A
- Max gradient 0.45 T/m
- Rise time 10 µs,
- Fall time 10 to 40 ms

COSY

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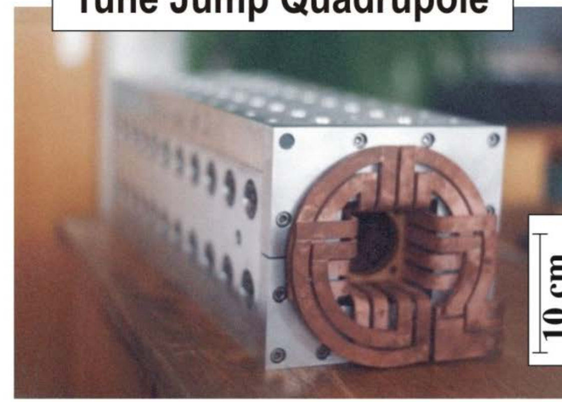
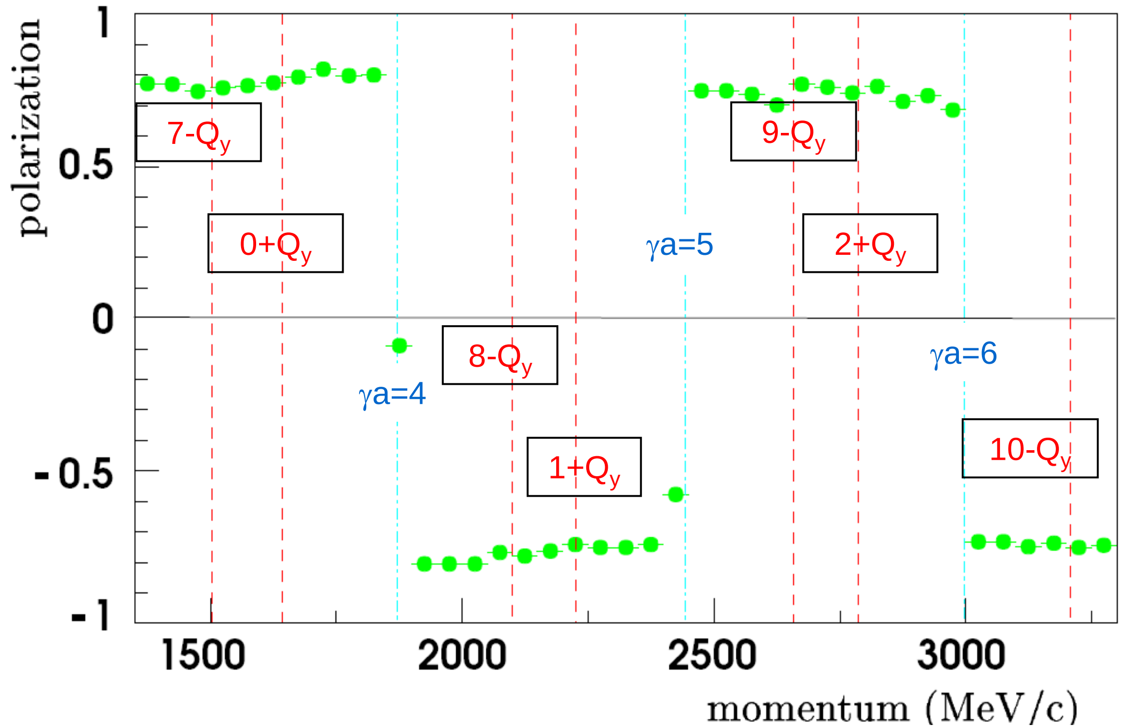
Tune Jump Quadrupole



Panofsky type quadrupole with ferrite yoke

vakuum chamber:	AL_2O_3 ceramics with 10 µm titanium coating
resistance:	(4,298±0.001) mΩ (DC)
inductance:	(9,0±0,1) µH (DC)
max. pulse current:	500 A
max. field gradient:	(1,1241±0,005) T/m
rising edge:	4 - 14 µs
falling edge:	4 - 20 ms

Polarization during Acceleration



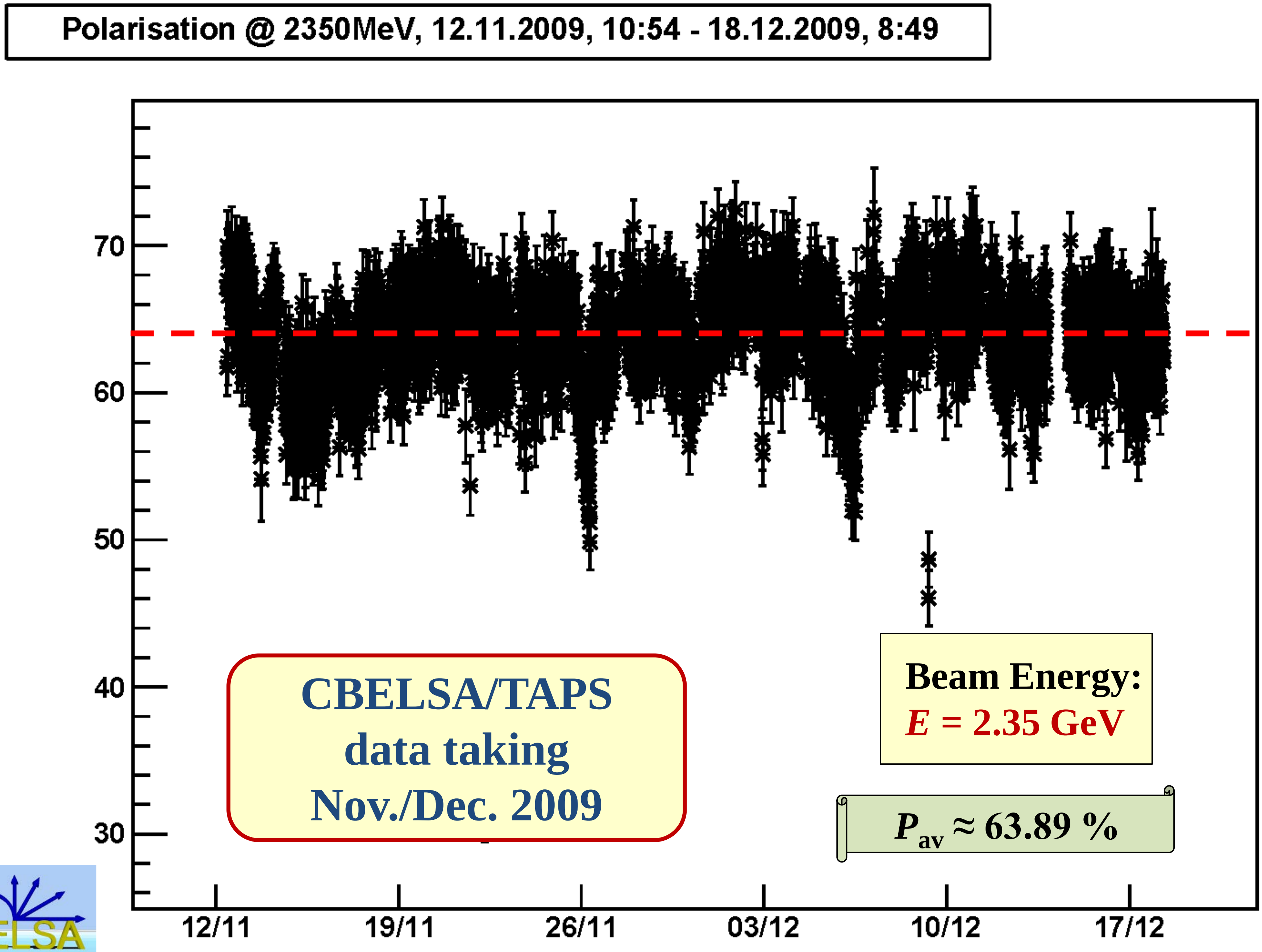
COSY

JÜLICH

Intrinsic resonances → tune jumps

Imperfection resonances → vertical orbit excitation

***P* > 75% at 3.3 GeV/c**


Polarisation @ 2350MeV, 12.11.2009, 10:54 - 18.12.2009, 8:49
70
60
50
40
30
12/11
19/11
26/11
03/12
10/12
17/12
CBELSA/TAPS
data taking
Nov./Dec. 2009
Beam Energy:
E = 2.35 GeV
P_av ≈ 63.89 %

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Polarization at „highest“ energies

Why not having a polarized beam in:

- **LEP** (@ 100 GeV)?
- **HERA-p** (920 GeV)?
- **Tevraton** (1 TeV)?
- **LHC** (7 TeV)?

None of
- adiabatic spin flip
- harmonic correction
- tune jumping

will work any longer!

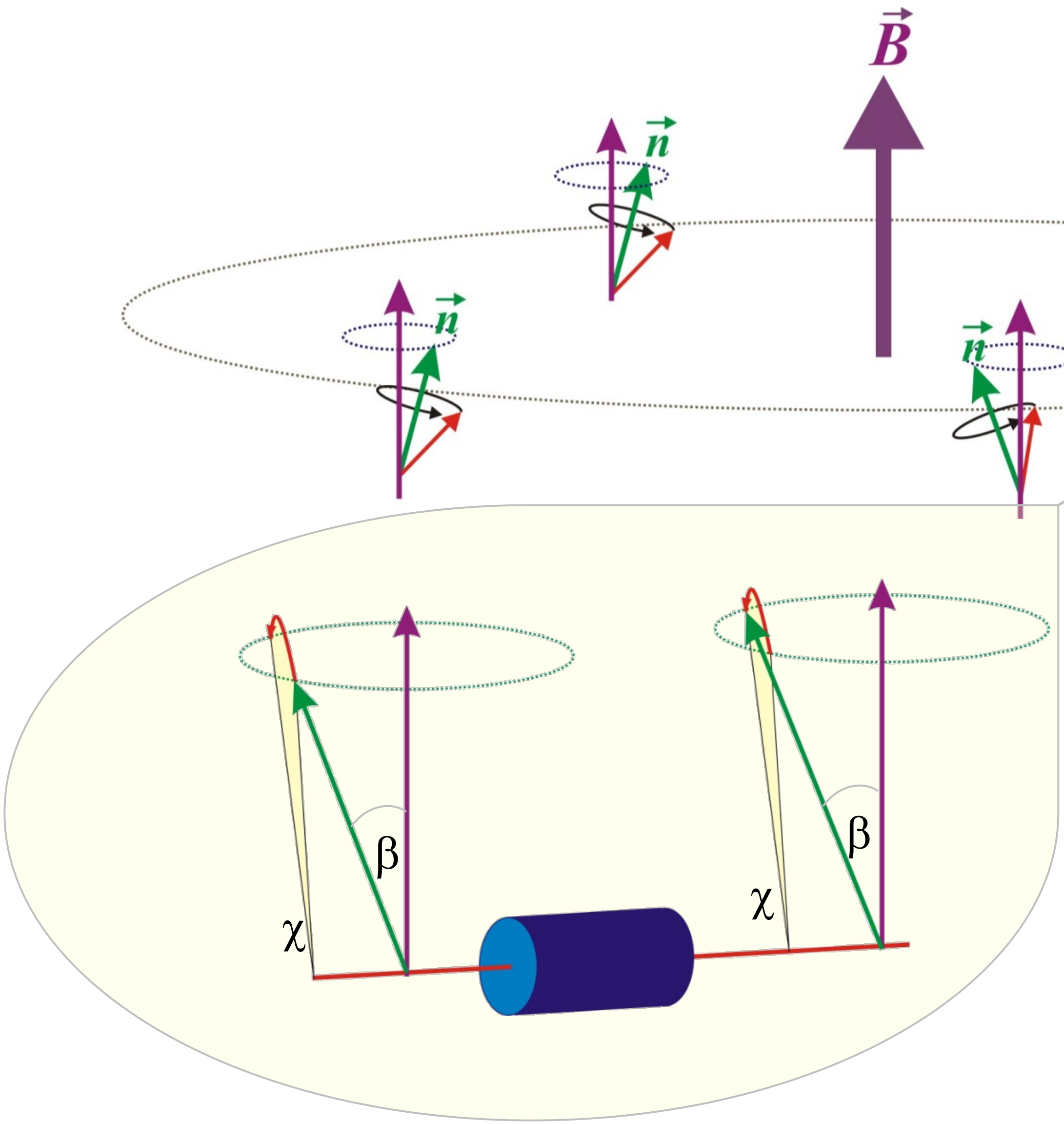
Remember:

Typically, at least every 500 MeV
a depolarizing resonance is waiting for you!

Energy spread of the beam > 10^{-4} (↔ >100MeV typ for machines above!)

- large number of resonances, no longer isolated from each other
- strong synchrotron sidebands

Siberian Snakes



partial snake:

$0 < \chi < 180°$

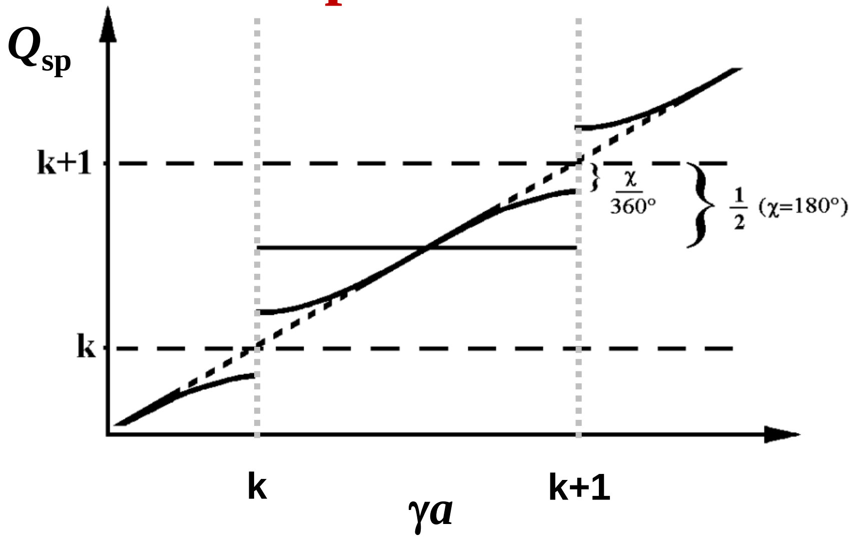
full snake:

$\chi = 180°$

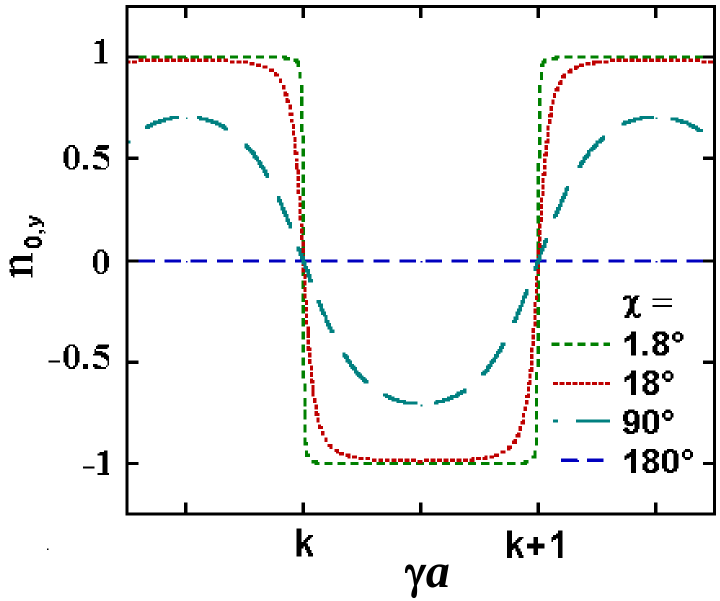
Invariant Spin Axis $\vec{n}$

Siberian Snakes

Spin Tune



Invariant Spin Axis



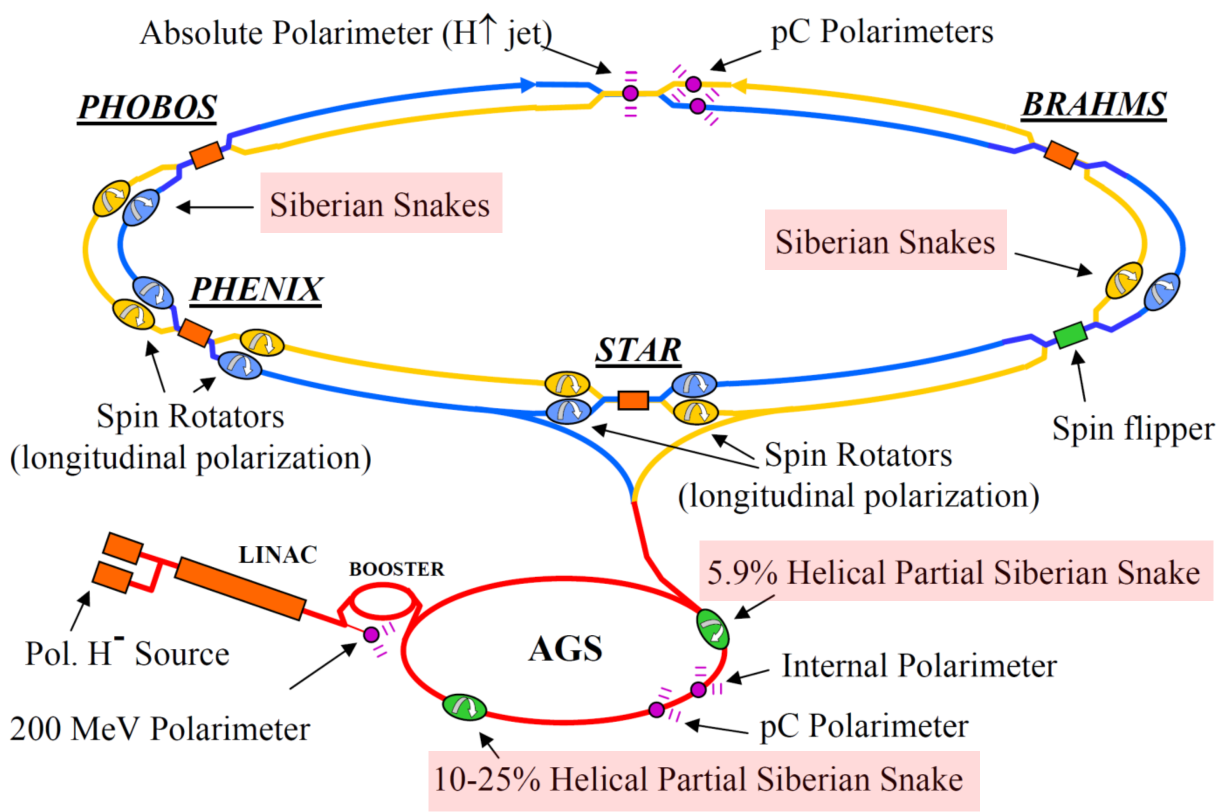
Partial Snake:

- **Increase of the Resonance Strength by** $|\varepsilon_\chi| = \chi/2\pi$
- Adiabatic Crossing of Imperfection Resonances if $\chi \gg 2\pi|\varepsilon_r| + \sqrt{8\pi\alpha}$

Full Snake:

- **Invariant Spin Axis lies in the Accelerator Plane**
- **Snake Resonances:** $k + ½ = Q_{sp} = \pm l \cdot Q_x \pm m \cdot Q_z$

Relativistic Heavy-Ion Collider RHIC



RHIC beam energy:

100 GeV/u gold
250 GeV polarized protons

Spin resonances:

AGS: two partial snakes (11° and 45° spin rotators)

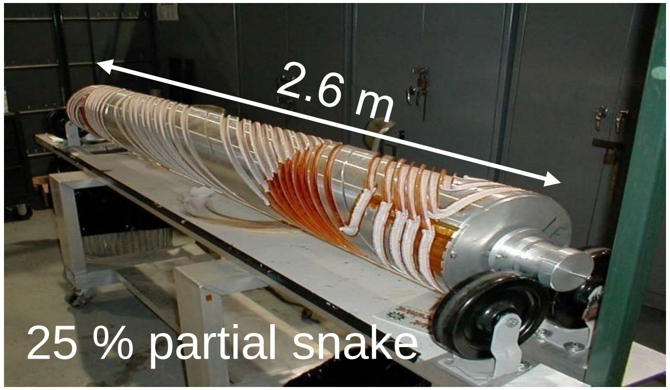
RHIC: ~1000 spin resonances
→ two full Siberian snakes per ring

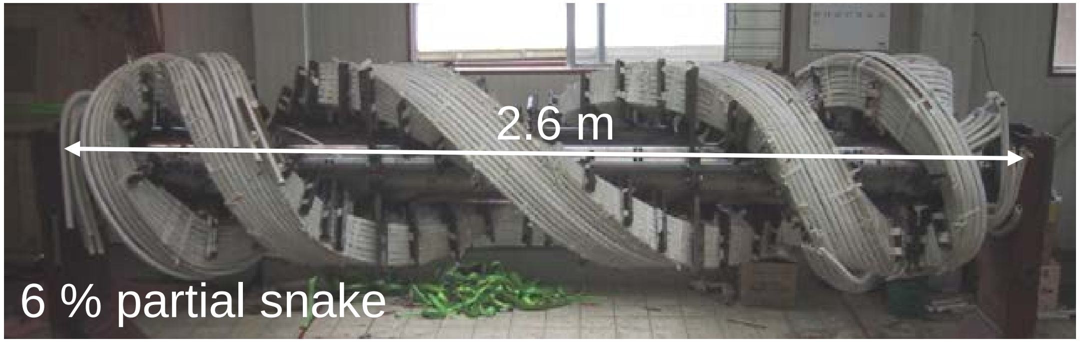
Remember: $\vec{\Omega}_{BMT} = -\frac{e}{m_0\gamma}\left\{(1+a\gamma)\cdot\vec{B}_{\perp}+(1+a)\cdot\vec{B}_{\parallel}\right\}$

Siberian Snakes

AGS snake magnets:

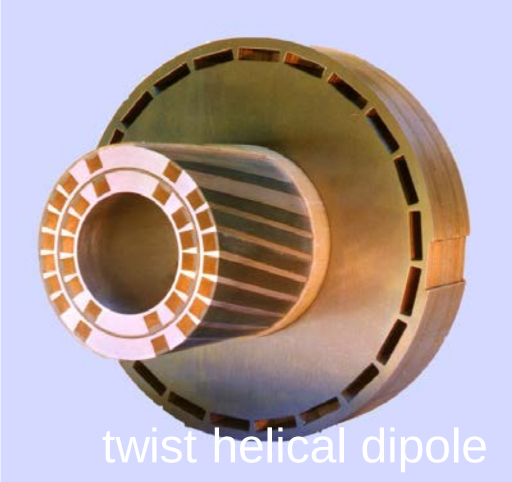
twist helical dipoles 3 T superconducting (left), 1.5 T room temperature (right)



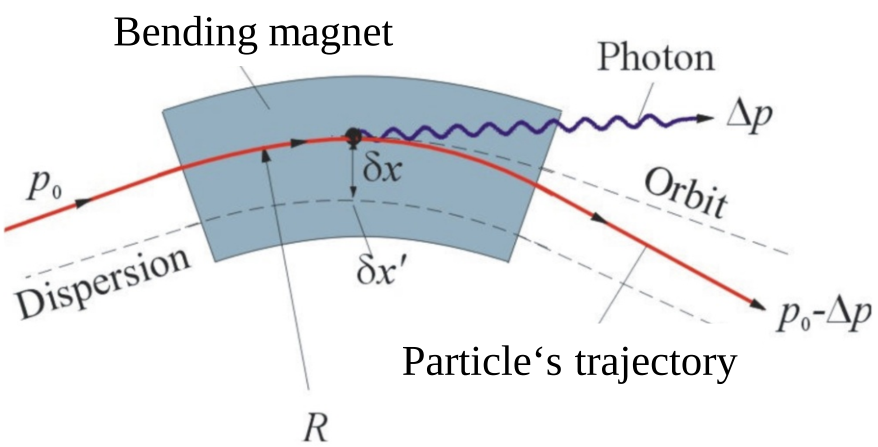


RHIC snake magnet:

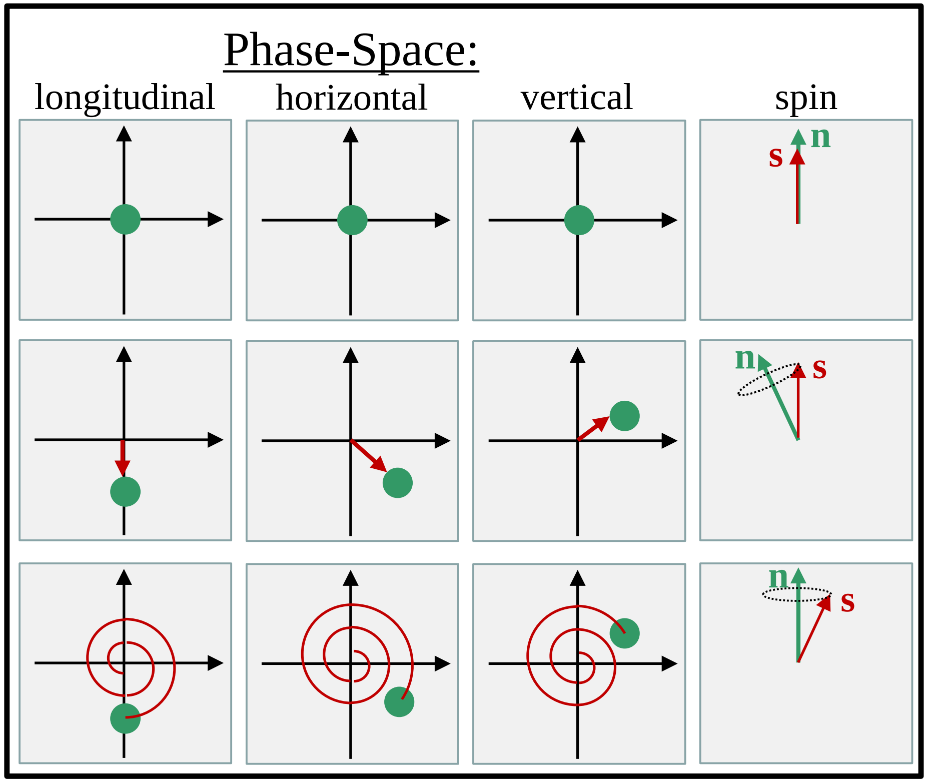
4 superconducting 4 T helical dipoles, 2.4 m long with 360° twist



Synchrotron Radiation



Simple model:



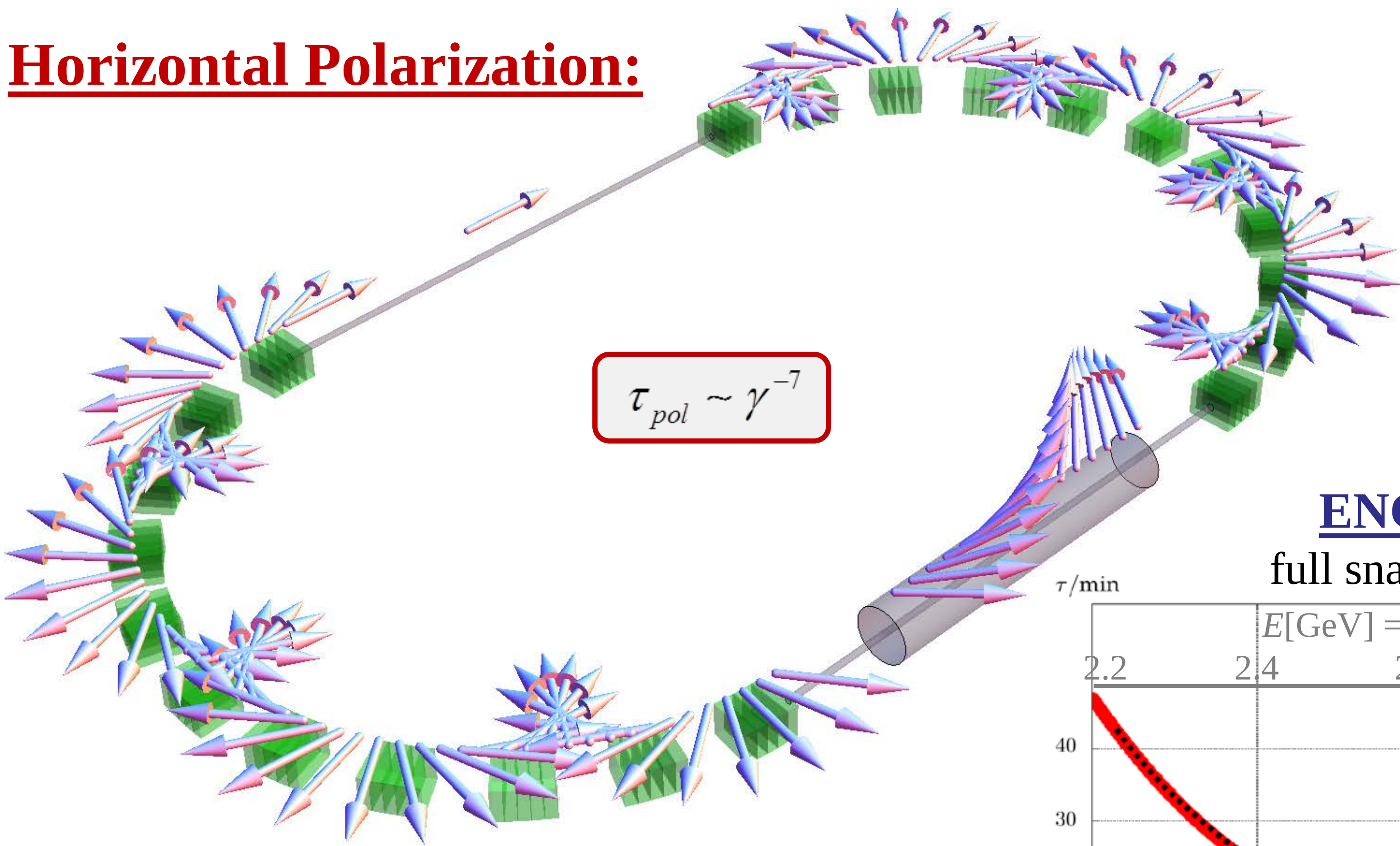
Emission of γ-Quants:

- **Perturbation of the Orbit** (recoil, dispersion)
- Slightly tilted **invariant spin axis**

→ **Spin Diffusion!**

Polarization Lifetime

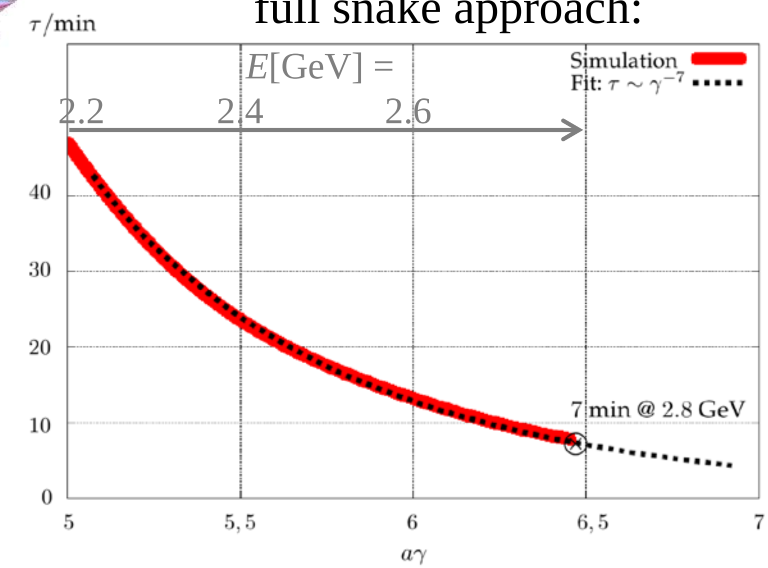
Horizontal Polarization:



$$\tau_{pol} \sim \gamma^{-7}$$

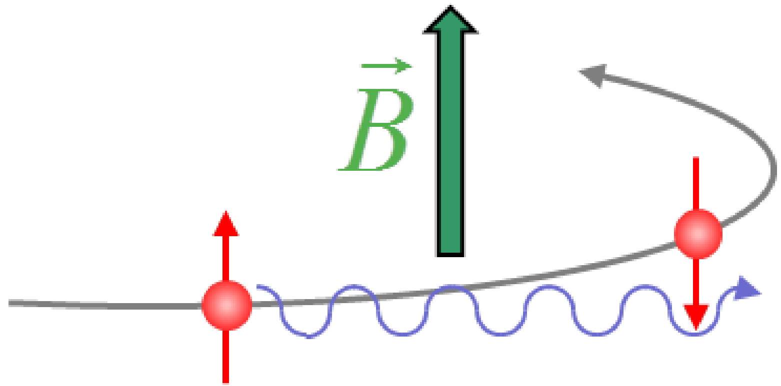
ENC@FAIR

full snake approach:



Siberian snakes will not work for high energy electron storage rings!

Synchrotron Radiation



Transition Rates :

- no spin flip: $w_{\uparrow\uparrow}$, $w_{\downarrow\downarrow}$
- with spin flip: $w_{\uparrow\downarrow}$, $w_{\downarrow\uparrow}$

Probability of a spin-flip transition:

$$\frac{w_{\uparrow\downarrow}+w_{\downarrow\uparrow}}{\left(w_{\uparrow\uparrow}+w_{\downarrow\downarrow}\right)+\left(w_{\uparrow\downarrow}+w_{\downarrow\uparrow}\right)}=\frac{1}{3}\cdot\left(\frac{\hbar\omega_c}{E}\right)^2<10^{-10}$$

= very small, but:

The beam will get polarized in a while due to $w_{\uparrow\downarrow} > w_{\downarrow\uparrow}$!

Sokolov-Ternov-Effect: $P(t)=P_{ST}\left(1-e^{-t/\tau_P}\right)$ **with** $P_{ST}=\frac{w_{\uparrow\downarrow}-w_{\downarrow\uparrow}}{w_{\uparrow\downarrow}+w_{\downarrow\uparrow}}=\frac{8}{5\sqrt{3}}=92.4\%$

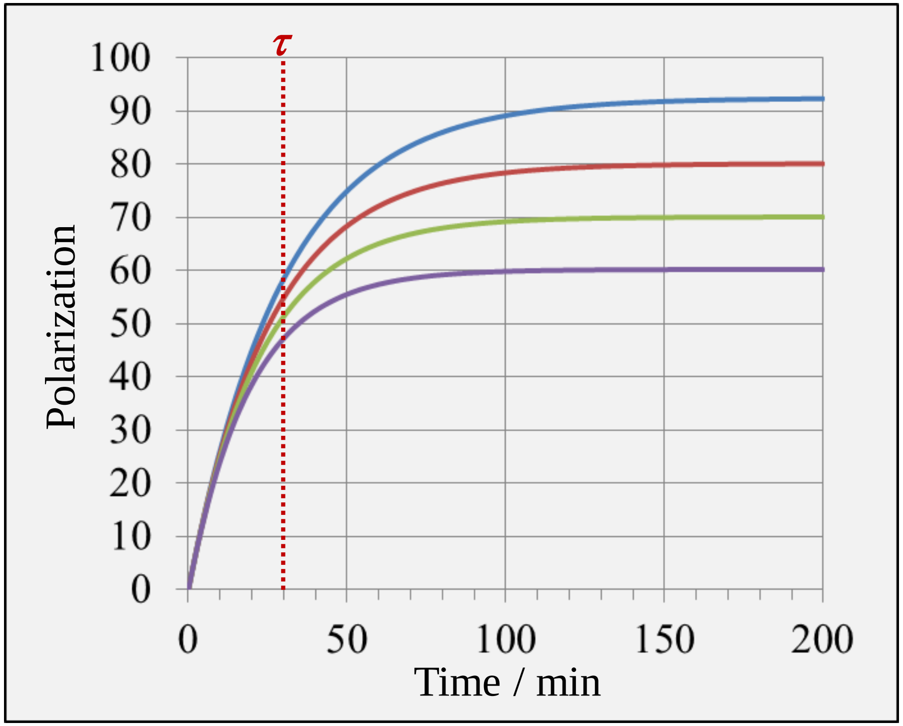
Rise time: $\tau_P=\left(\frac{8}{5\sqrt{3}}\frac{c\lambda_c r_e}{2\pi}\frac{\gamma^5}{R^3}\right)^{-1}$

Depolarizing effects: $P_\infty=P_{ST}\frac{\tau_{depol}}{\tau_P+\tau_{depol}}$ and $\frac{1}{\tau}=\frac{1}{\tau_P}+\frac{1}{\tau_{depol}}$

Polarization Rise Times

Some Accelerator Facilities:

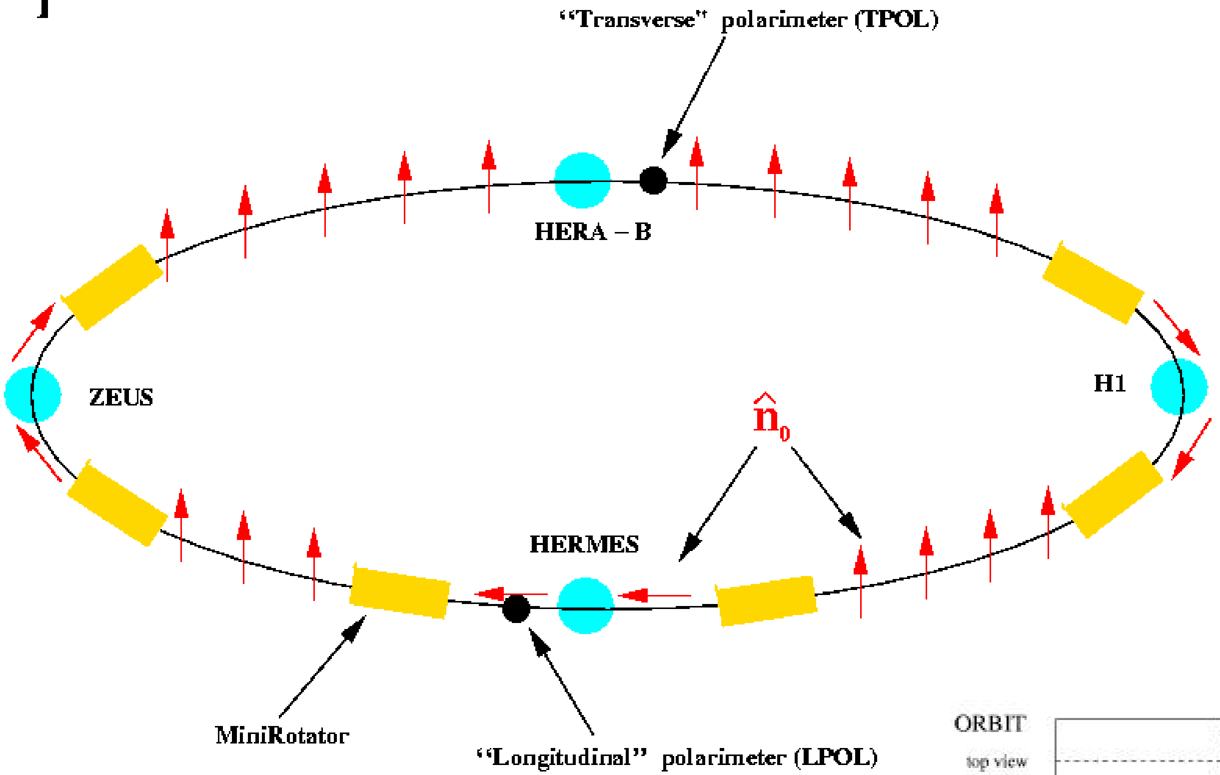
- **BESSY I** / Berlin (0.8 GeV)
  τ = 150 min, P > 75%
- **SPEAR** / SLAC (3.7 GeV)
  τ = 15 min, P > 70%
- **CESR** / Cornell (4.7 GeV)
  τ = 300 min, P > 75%
- **DORIS** / DESY (5.0 GeV)
  τ = 4 min, P = 80%
- **PETRA** / DESY (16.5 GeV)
  τ = 18 min, P > 80%
- **HERA** / DESY (27.5 GeV)
  τ = 35 min, P = 70%
- **LEP** / CERN (46.5 GeV)
  τ = 300 min, P = 57%

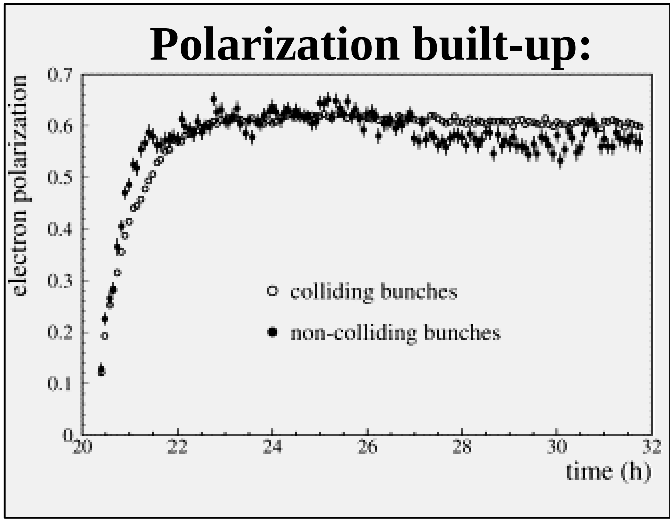


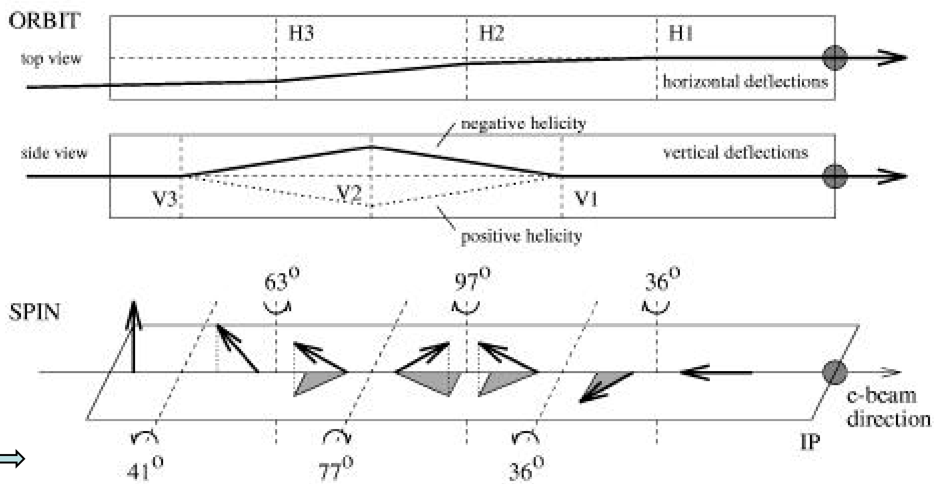
Useful for energy calibration…

Polarization comes „for free“, but that may take some time …

HERA with long. polarization







HERA MiniRotator:

56 meters „short“, no quadrupoles

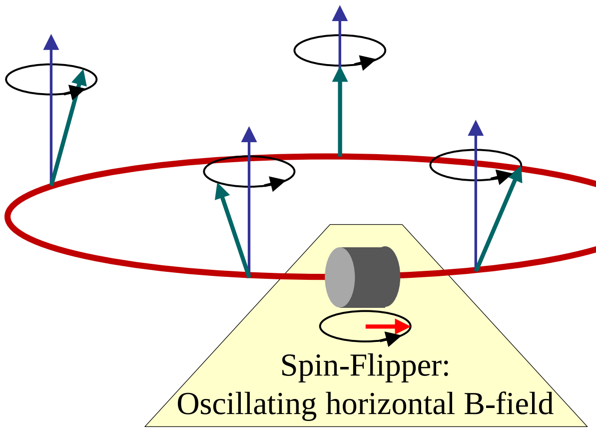
27 – 39 GeV, both helicities

HERA MiniRotators

How?

c) Spin management, energy calibration

Spin Flip with RF Fields



Spin oscillation frequency:

$$\omega_{sp} = \omega_{rev} \cdot \gamma \cdot a$$

Resonance condition:

$$\omega_{-} = \omega_{rev} \cdot (k + \gamma \cdot a)$$

$$\omega_{+} = \omega_{rev} \cdot (k + 1 - \gamma \cdot a)$$

Generation of rotating B-field by linear oscillating horizontal B-field (superposition!)

Causes **depolarizing resonance**:

longitudinal: $$\varepsilon_{B_{||}dl} = \frac{e}{p} \cdot \frac{1+a}{2\sqrt{2}\pi} \cdot \int B_{||}^{rms} dl$$

transverse: $$\varepsilon_{B_{\perp}dl} = \frac{e}{p} \cdot \frac{1+\gamma a}{2\sqrt{2}\pi} \cdot \int B_{\perp}^{rms} dl$$

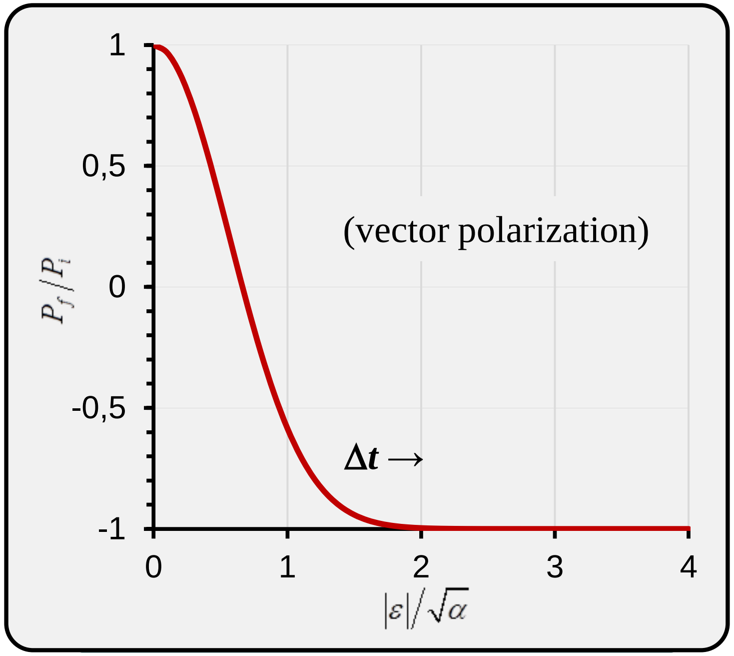
Slow resonance crossing by slowly varying the oscillation frequency of the spin-flipper

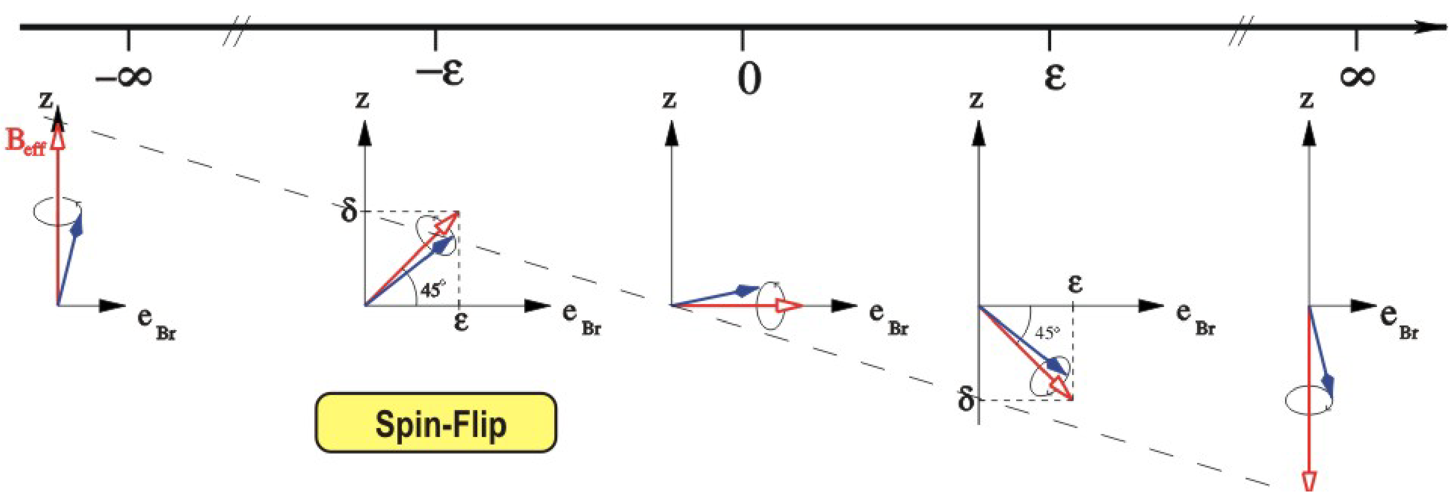
Spin Flip with RF Fields

Slow „Froissart-Stora" Transition ($\Delta\nu$ over Δt) causes spin flip:

Vector Polarization:
$$\frac{P_f}{P_i} = 2\cdot e^{-\frac{(\pi\varepsilon\nu_0)^2}{\Delta\nu/\Delta t}} - 1$$

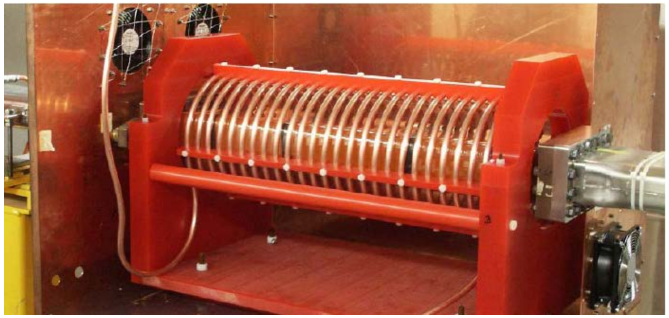
Tensor Polarization:
$$\frac{P_f}{P_i} = \frac{3}{2}\left(2\cdot e^{-\frac{(\pi\varepsilon\nu_0)^2}{\Delta\nu/\Delta t}} - 1\right)^2 - \frac{1}{2}$$





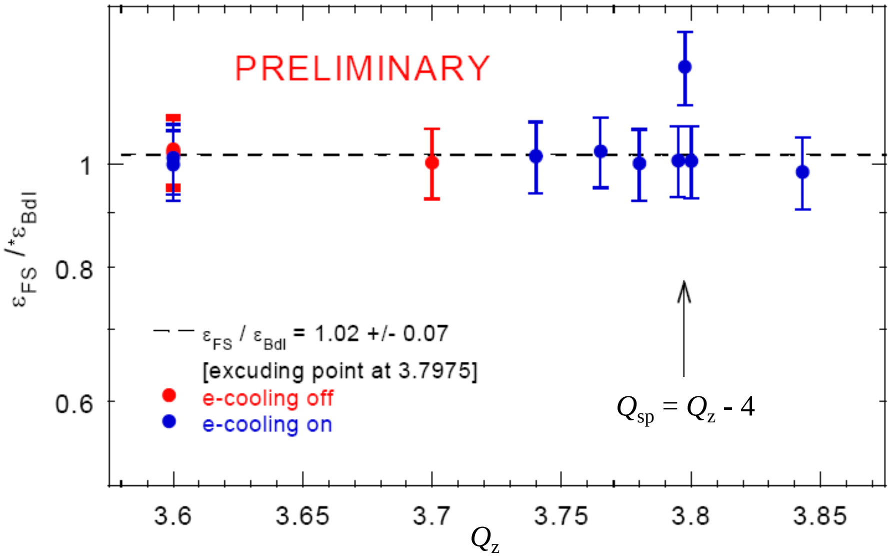
Results from COSY / FZJ

RF Solenoid



$$\int B_{rms} dl = 0.69\ \mathrm{T\,mm}$$

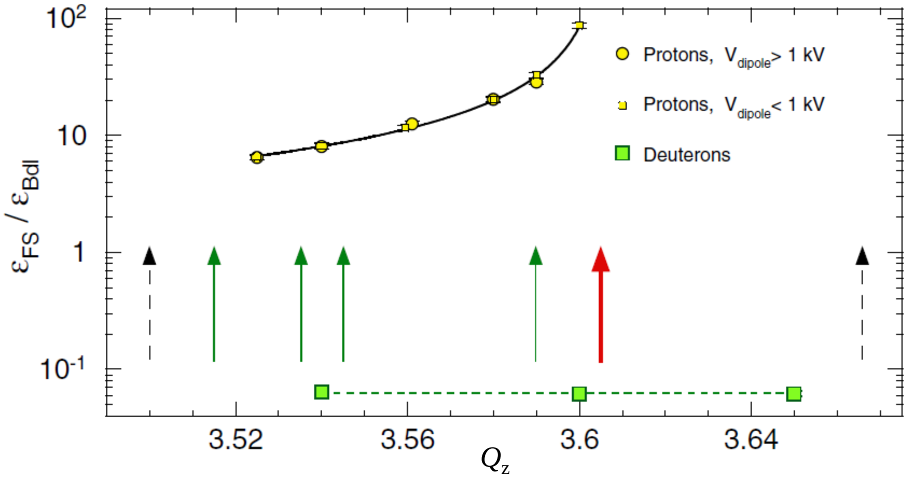
No influence on CO, but only useful at low Lorentz-γ



RF Dipole

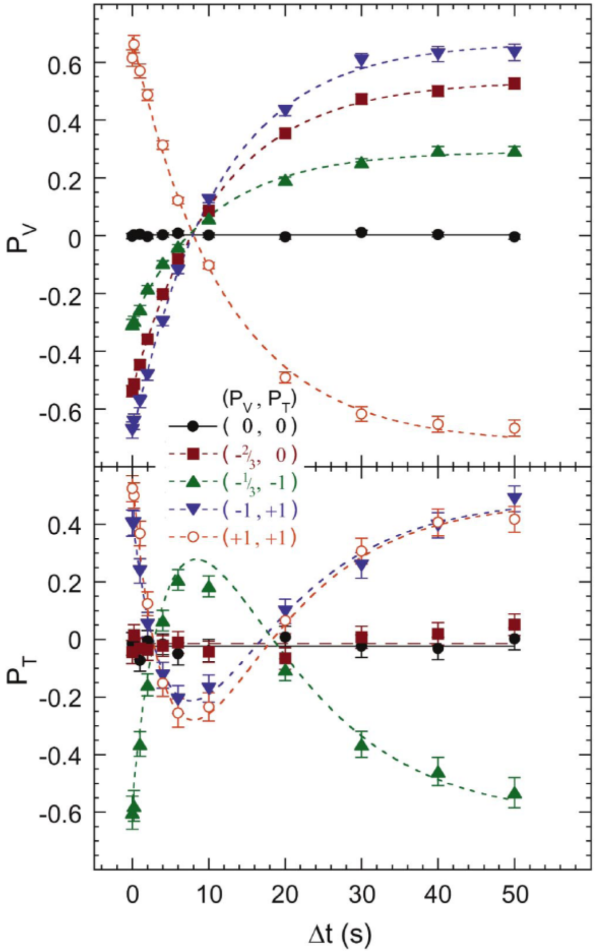
$$\int B_{rms} dl = 0.54\ \mathrm{T\,mm}$$

Enhancement by Lorentz-γ, causes CO distortions

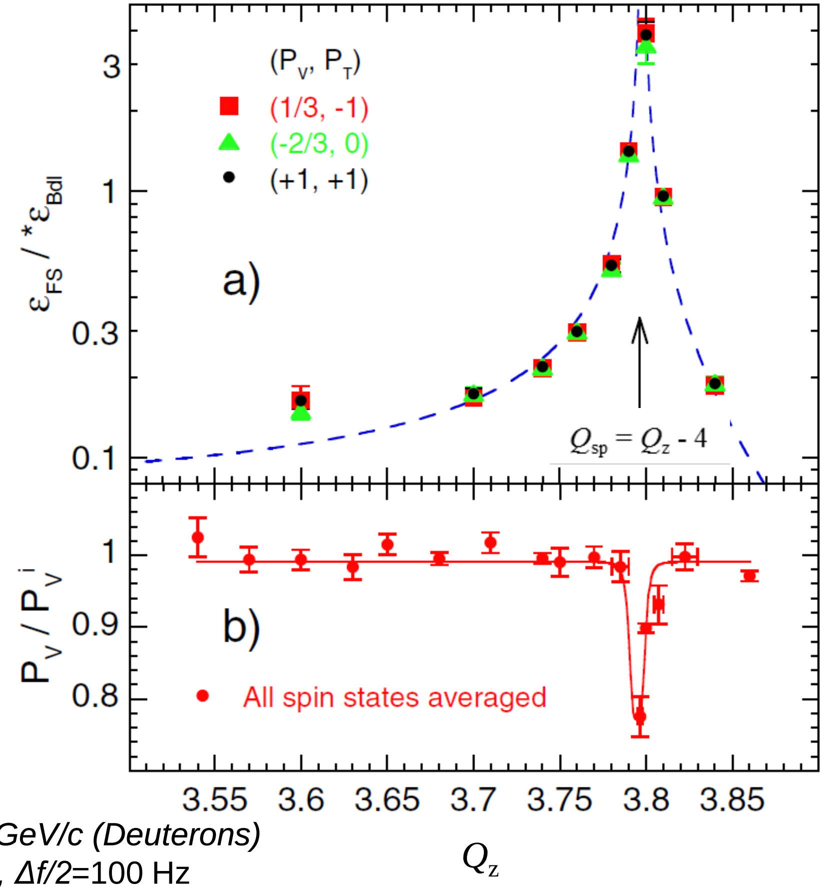


Results from COSY / FZJ

Spin flipping



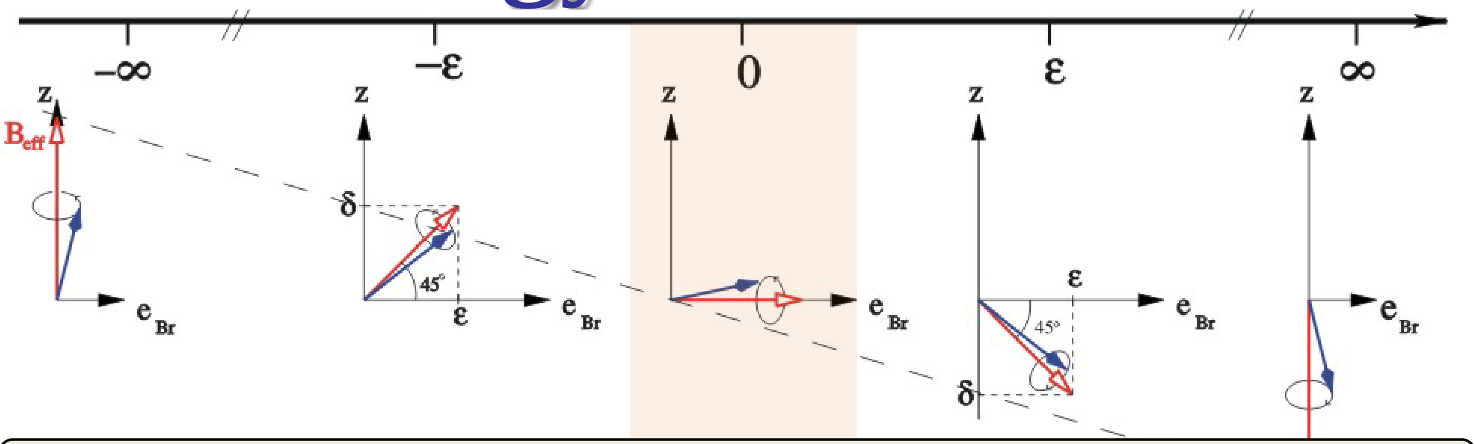
Resonance strength



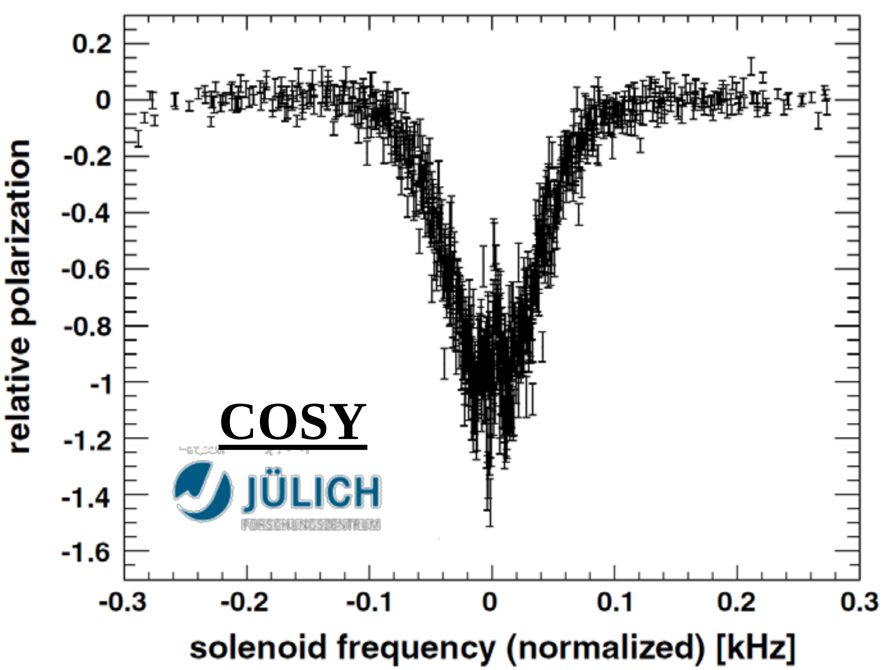
p=1.85 GeV/c (Deuterons)
Δt=0.2s, Δf/2=100 Hz
$\int B_{rms} dl$=0.6 T·mm

Proton spin-flip efficiency: 99.92±0.04%
Deuteron spin-flip efficiency: 97 ± 1%

Energy Calibration



Operation on top of an integer resonance → vertical polarization vanishes!



Beam energy from flipper oscillation frequency:

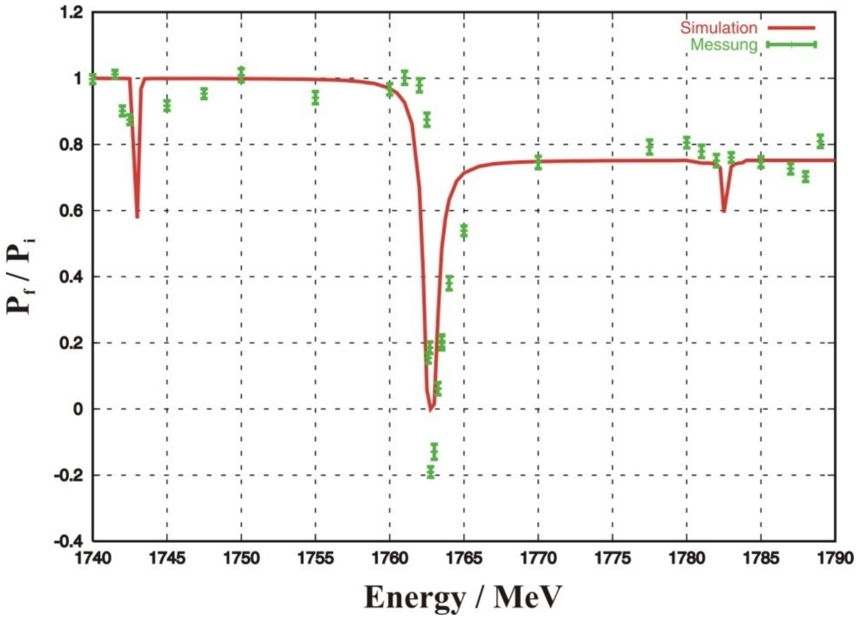
$$\omega_{sf} = \omega_{rev} \cdot (k \pm \gamma a)$$

measured: ω_{sf}, ω_{rev} — known: k, a

Nominal beam momentum	3150.5 [MeV/c]
Revolution frequency	1 403 832 ± 6 [Hz]
Spin-resonance frequency	1 011 810 ± 15 [Hz]
Orbit length	183.4341 ± 0.0002 [m]
Relativistic γ factor	1.9530 ± 0.0001
Reconstructed beam momentum	3146.41 ± 0.17 [MeV/c]

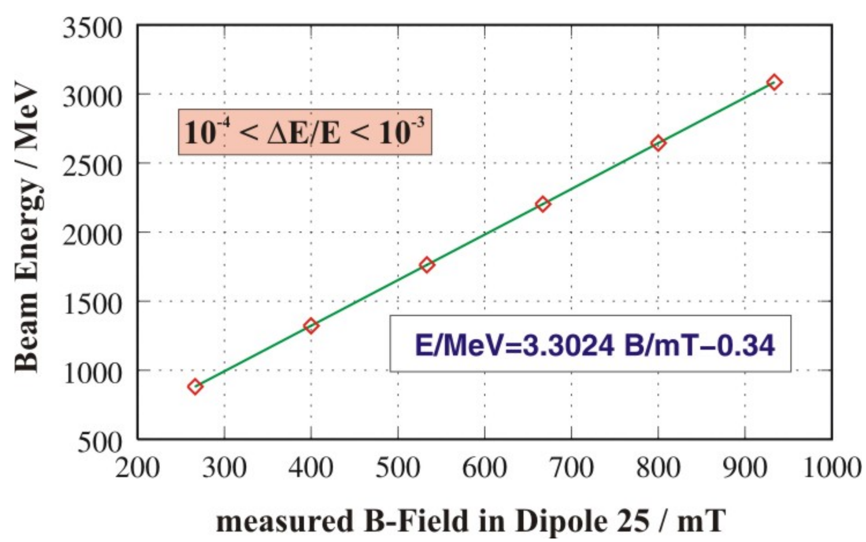
$\Delta p < 10^{-4}$!

Energy Calibration



Beam Depolarization when crossing the Imperfection Resonance γa = 4

Transformation of the measured B-Field to Beam Energy



Coming?

Polarized anti-particles, new projects

New Projects

e^+/e^- - Collider:

- International Linear Collider (500 GeV)
- CERN Compact Linear Collider (3 TeV)

→ **polarized positrons**

$p/\bar{p}$-Collider:

→ **polarized antiprotons** @ HESR/GSI ??????????

Polarized Antiproton EXperiments

Electron-Ion-Collider:

- ELIC @ CEBAF / Jefferson Lab !
- eRHIC @ RHIC / BNL ?
- ENC @ HESR / GSI ???

Conclusions: what should be remembered?

(Spin dynamics is complicated ?! ☺)

Generation of polarized beams:

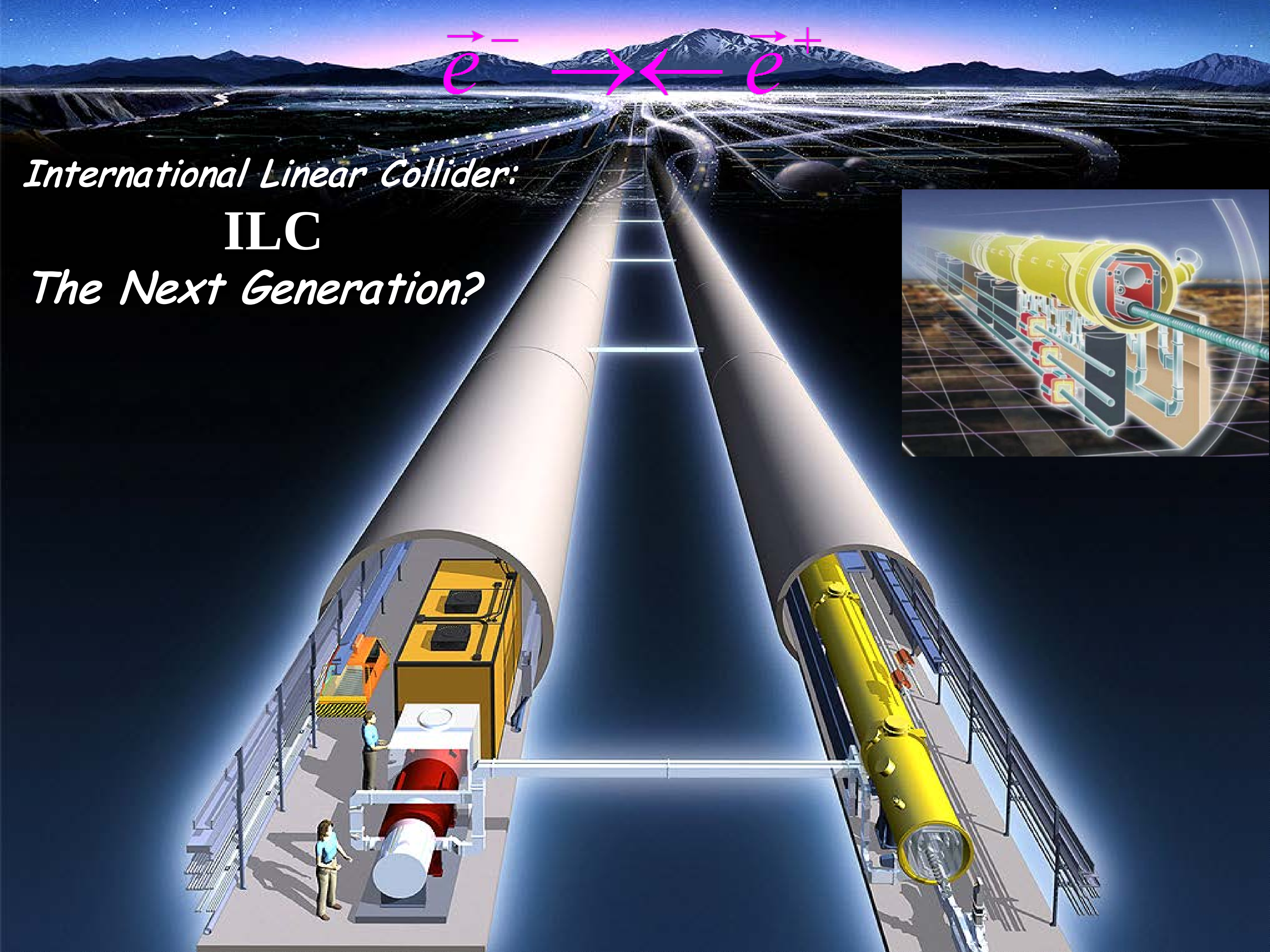
- Sources for polarized protons/deuterons and electrons
- Self polarization of electrons in storage rings

Acceleration of polarized beams:

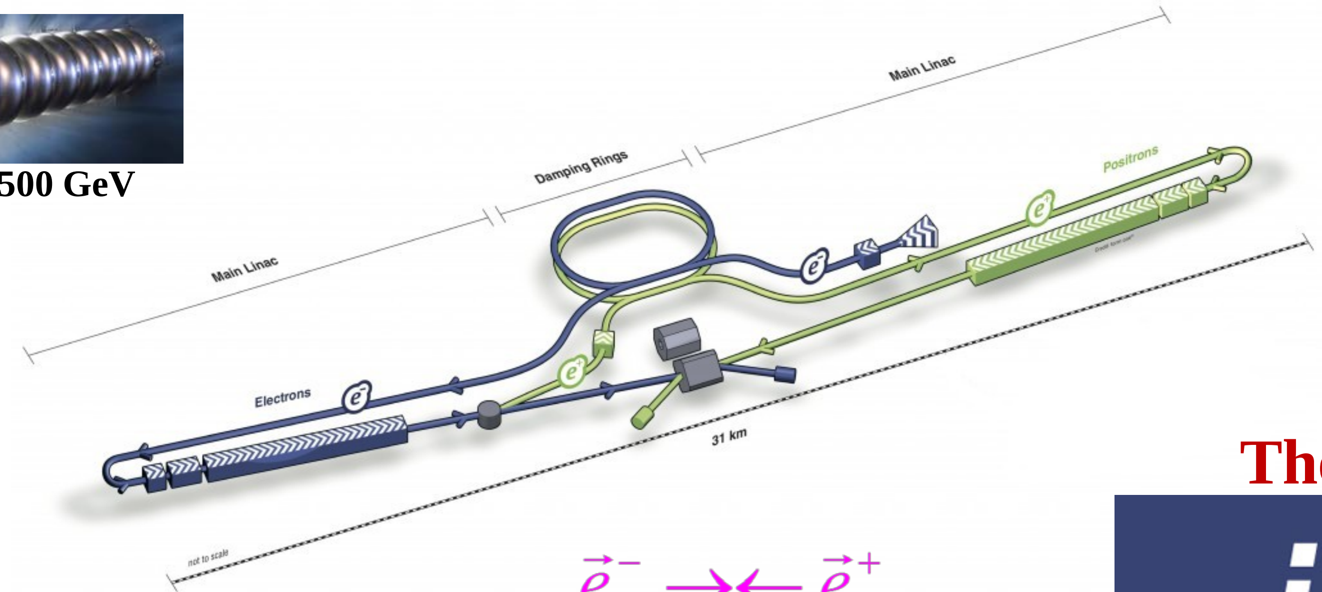
- Depolarizing resonances ↔ compensation measures
- Spin management → precise energy calibration

There are new projects on the horizon …

Thank you for your attention!

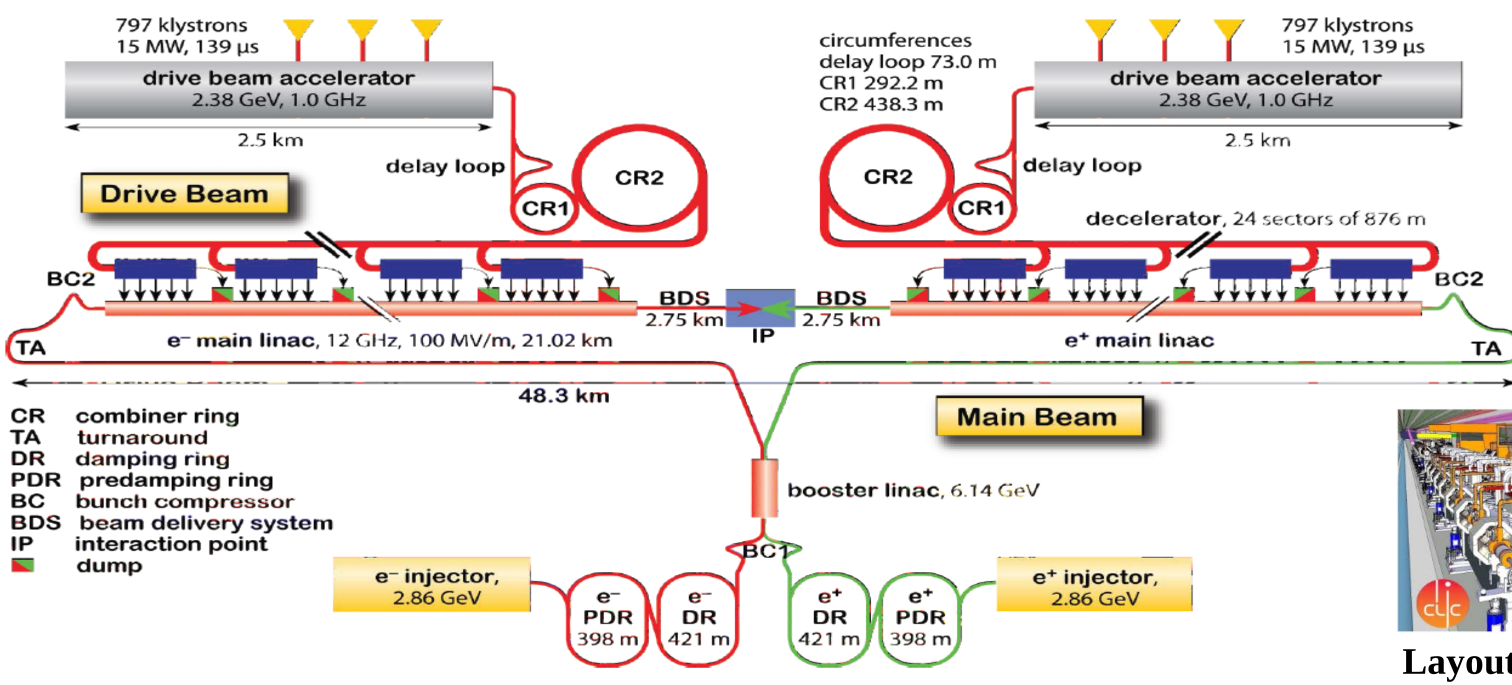

$\vec{e}^{\,-} \rightarrow \leftarrow \vec{e}^{\,+}$
International Linear Collider:
ILC
The Next Generation?

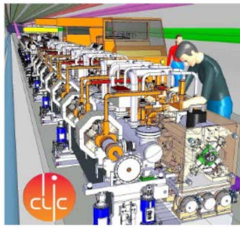
Layout at 500 GeV



$\vec{e}^{\,-} \rightarrow\!\!\leftarrow \vec{e}^{\,+}$

The "*Rivals*":

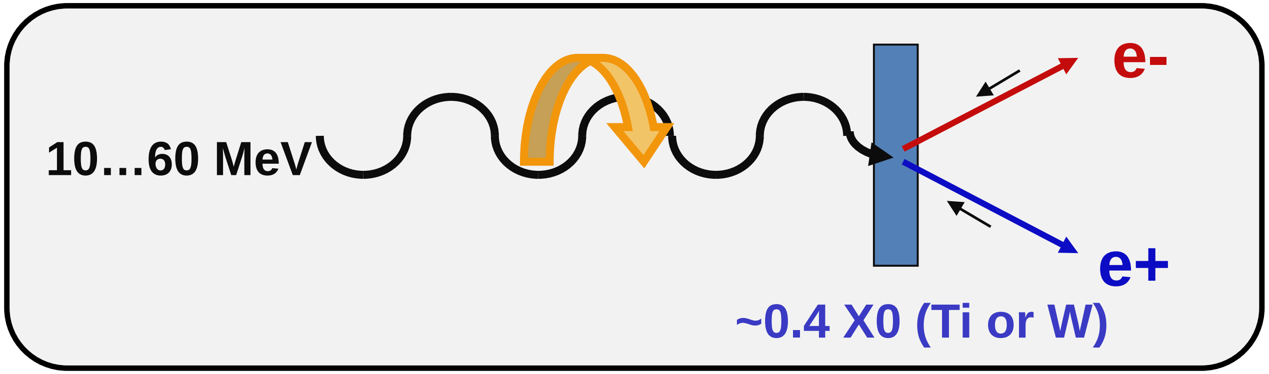




Layout at 3 TeV

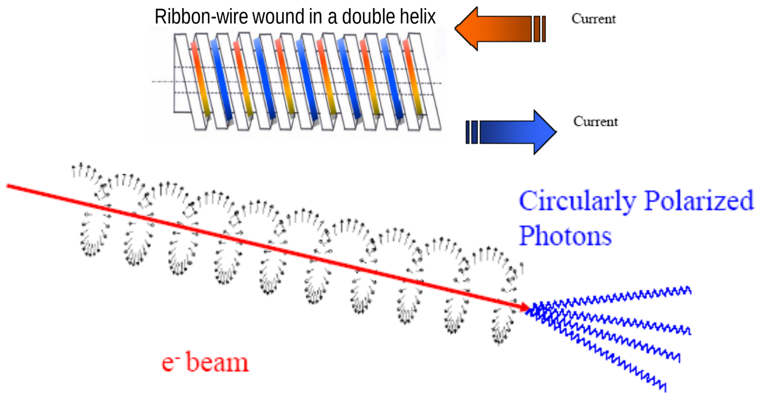
Generation of Polarized Positrons

Idea: Circularly polarized $\gamma \rightarrow$ longitudinally polarized e^- and e^+

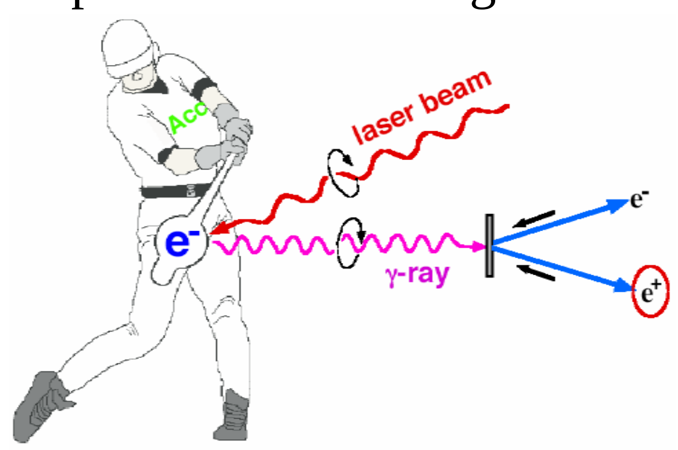


Methods to produce circularly polarized photons:

Helical Undulator

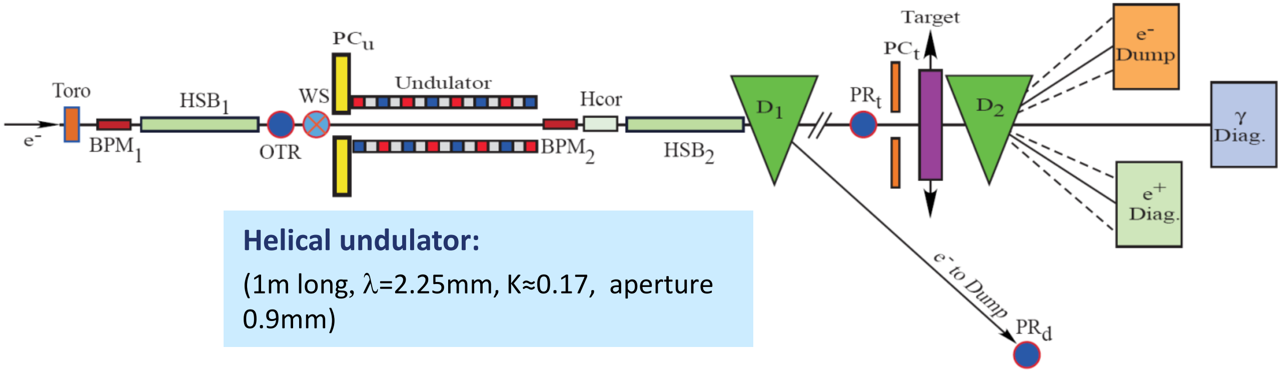


Compton Backscattering

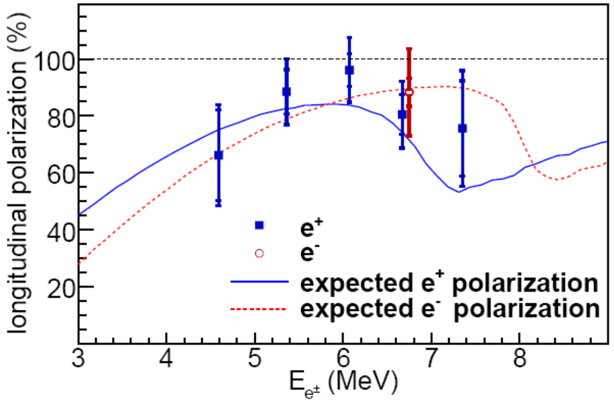


Demonstration Experiments

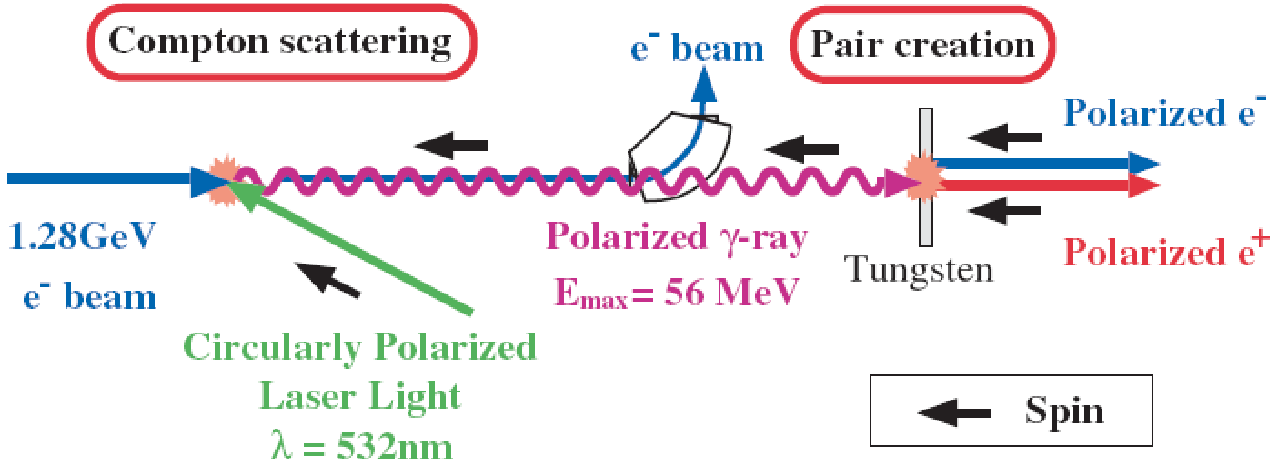
E166 @ SLAC: 46.6 GeV e- beam



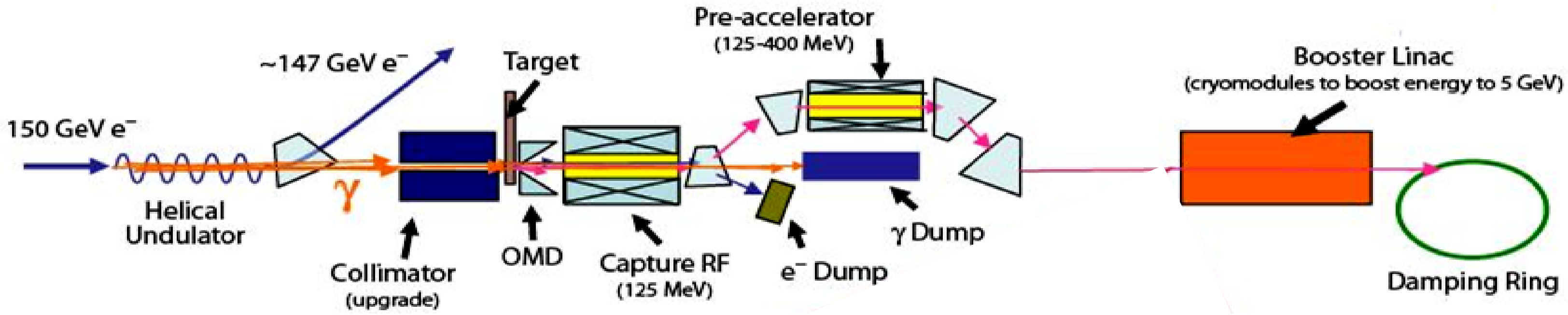
Helical undulator:
(1m long, λ=2.25mm, K≈0.17, aperture 0.9mm)



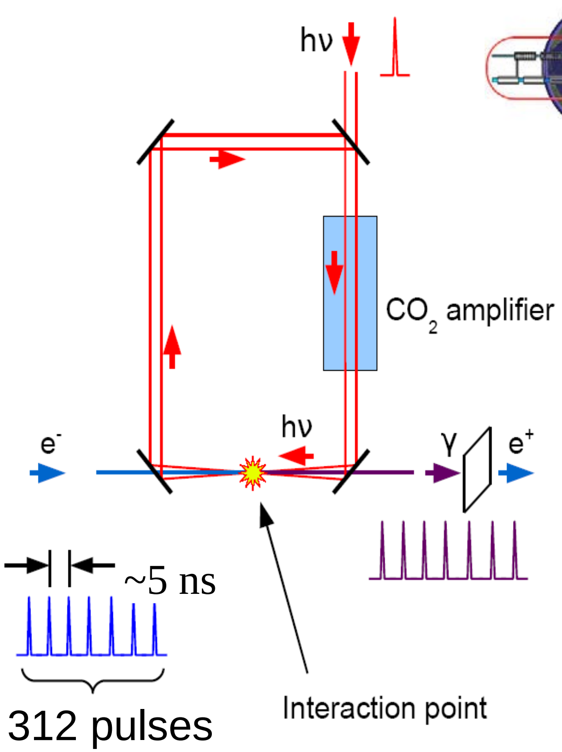
KEK-ATF: 1.28 GeV e^- from ATF
2nd harmonic of TAG laser
→ γ with maximum energy of 56 MeV



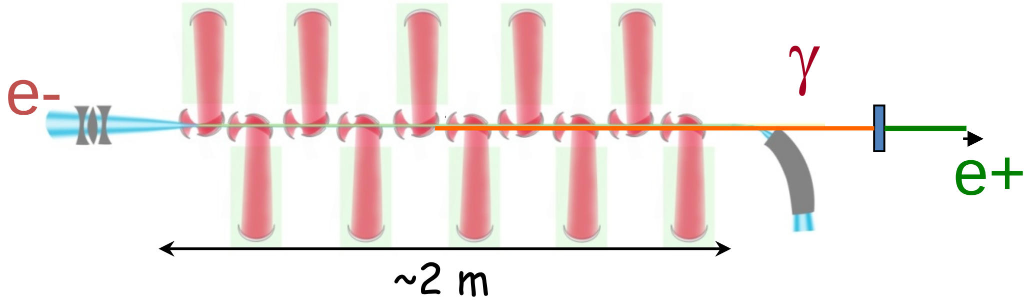
ILC Positron Source Layout



CLIC Compton Linac



- Compton backscattering inside a CO_2 laser amplifier cavity
- Production of 1 photon per electron (demonstrated at BNL)

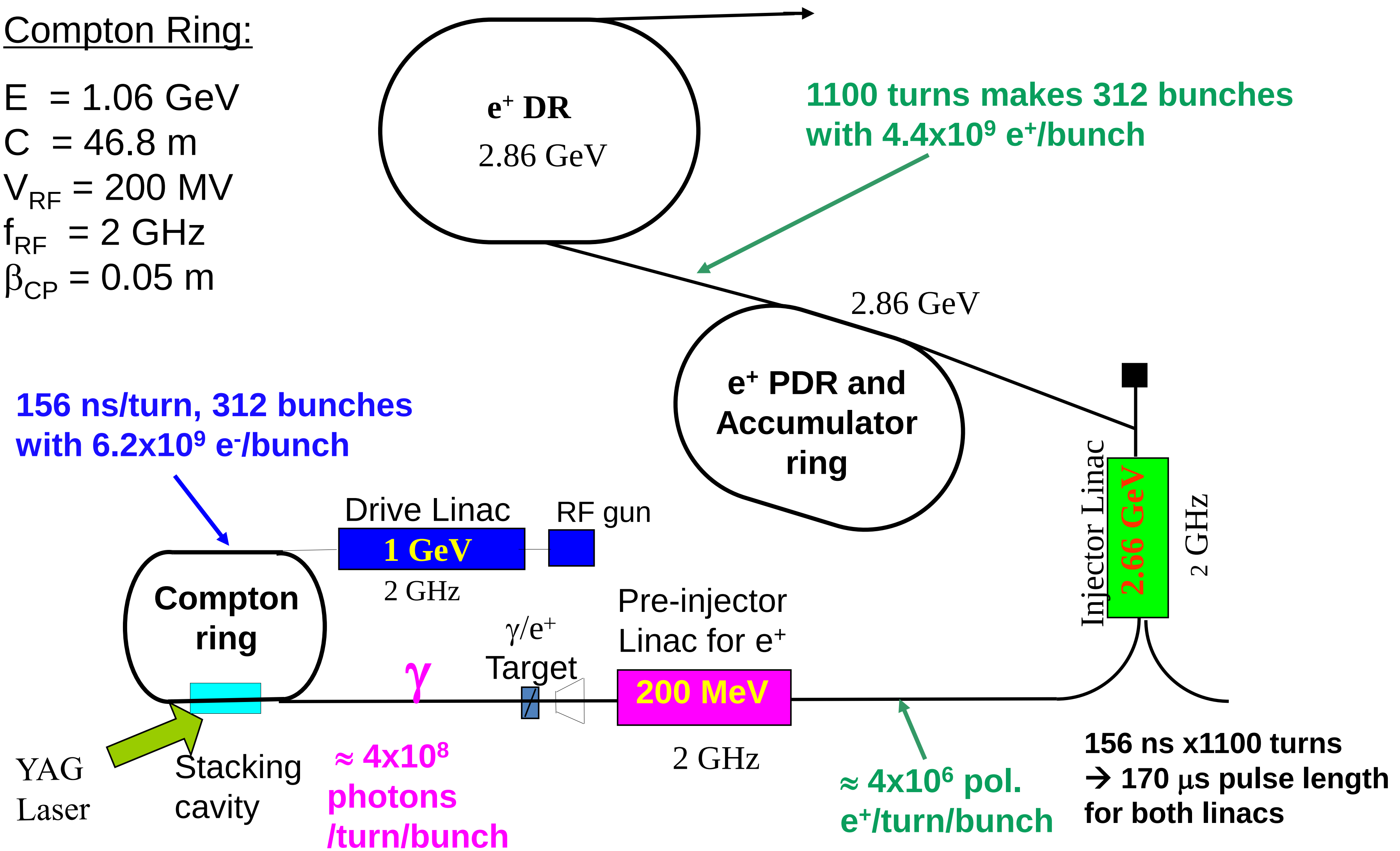


- 10 consecutive Compton IPs to accumulate γ flux

CLIC e^+ Injector with Compton Ring

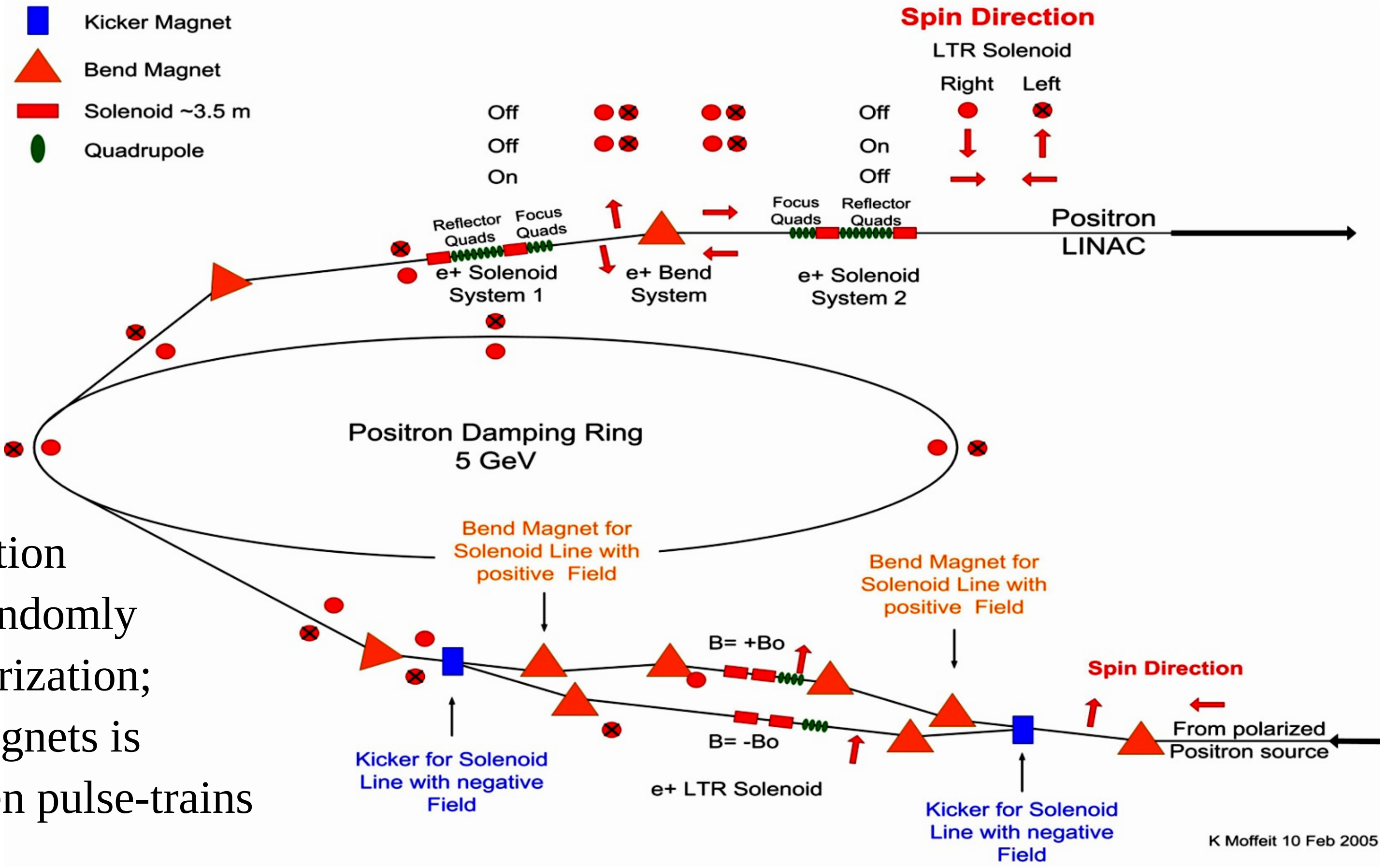
Compton Ring:

E = 1.06 GeV
C = 46.8 m
V_{RF} = 200 MV
f_{RF} = 2 GHz
β_{CP} = 0.05 m



Spin rotation and helicity reversal @ 5GeV

K. Moffeit et al., SLAC-TN-05-045 → fast reversal before DR (5 GeV)

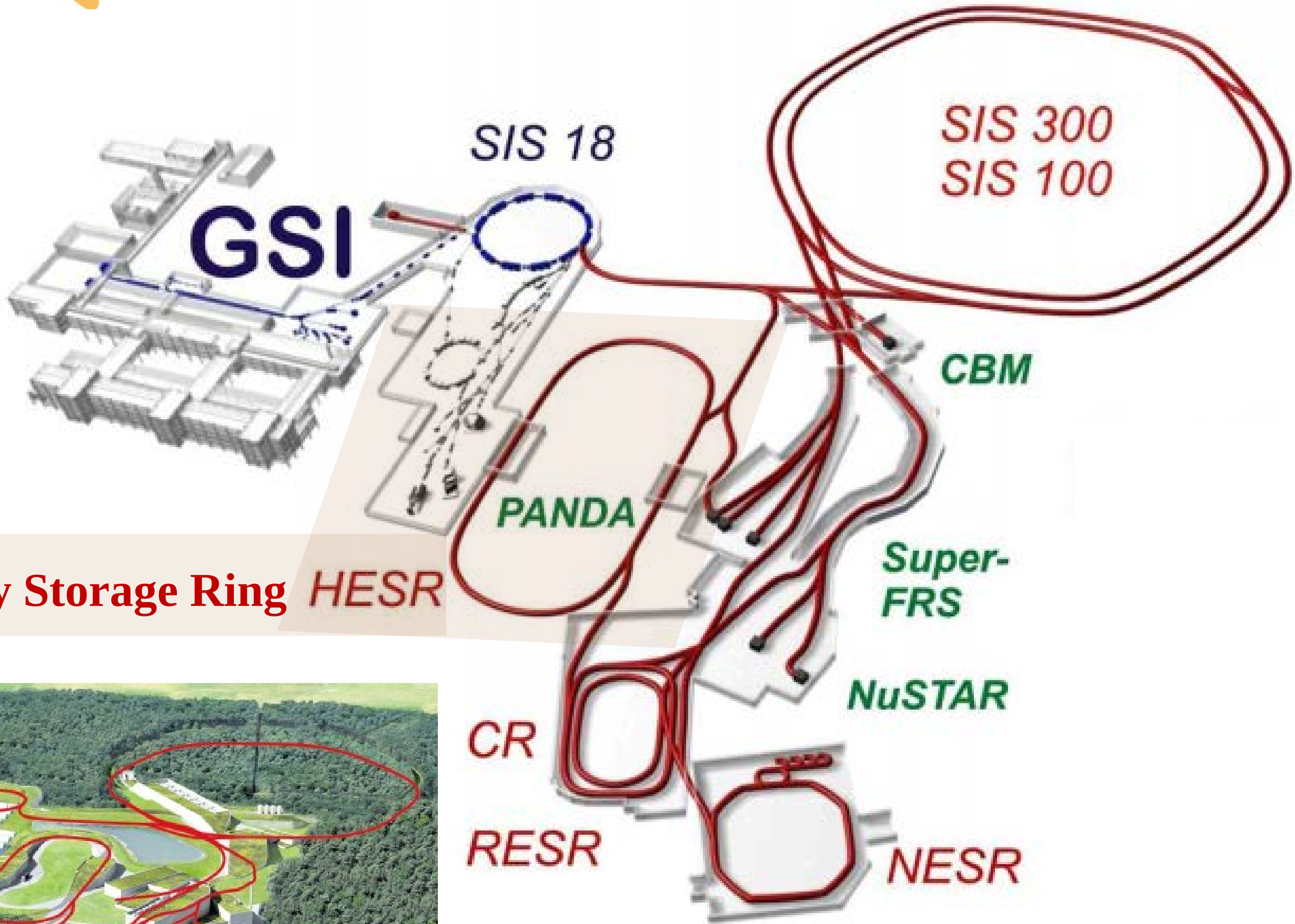


parallel spin rotation beam lines for randomly selecting e+ polarization; pair of kicker magnets is turned on between pulse-trains

"Compton source":

fast helicity reversal for e+ by reversing polarization of laser

FAIR @ GSI / Darmstadt

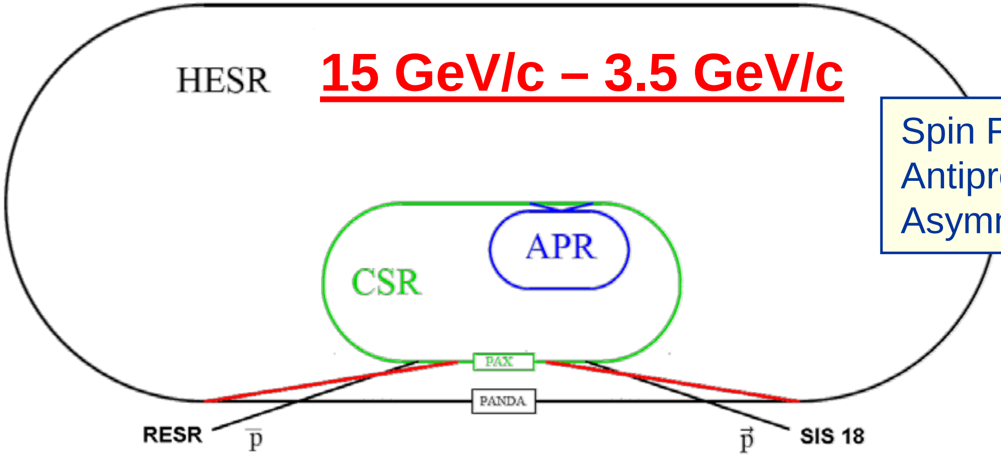


High Energy Storage Ring

Future HESR Upgrade Options

Polarized Proton-Antiproton Collider

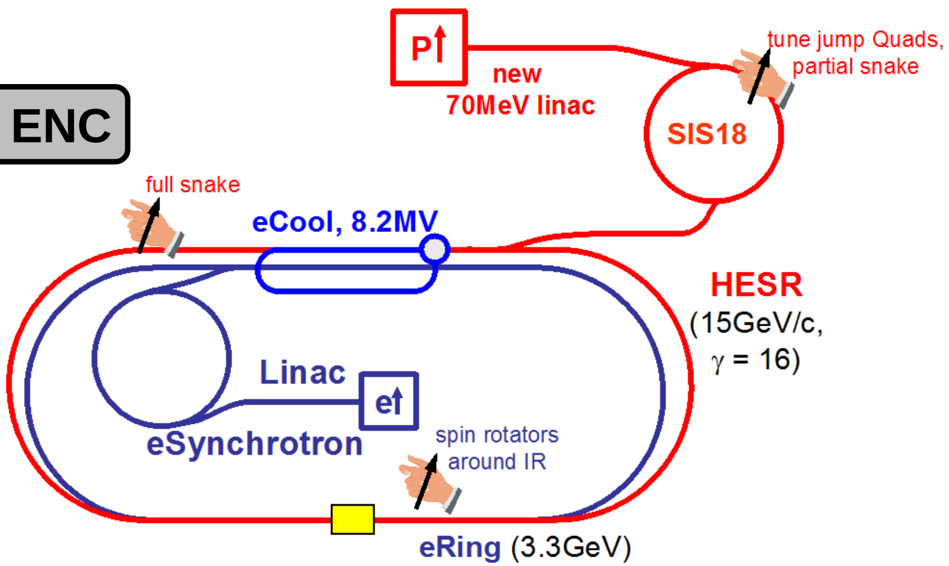
Polarized Antiproton EXperiments



Spin Filtering
Antiproton Polarizer (APR)
Asymmetric Collider

Polarized Electron-Nucleon Collider ENC

Accelerator Working Group:



Polarized Antiprotons

$$\sigma_{tot} = \sigma_0 + \sigma_\perp \cdot \vec{P} \cdot \vec{Q} + \sigma_{||} \cdot (\vec{P} \cdot \vec{k})(\vec{Q} \cdot \vec{k})$$

P beam polarization
Q target polarization
k || beam direction

For initially equally populated spin states: ↑ (m=+½) and ↓ (m=-½)

transverse case:

$$\sigma_{tot\pm} = \sigma_0 \pm \sigma_\perp \cdot Q$$

longitudinal case:

$$\sigma_{tot\pm} = \sigma_0 \pm (\sigma_\perp + \sigma_{||}) \cdot Q$$

Unpolarized antiproton beam

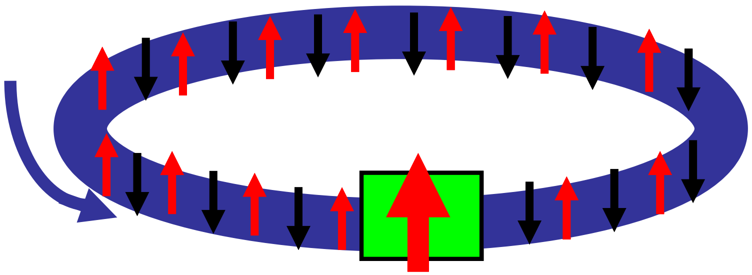
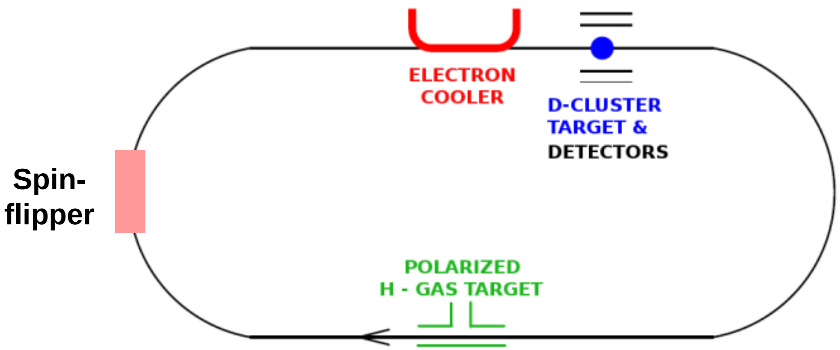


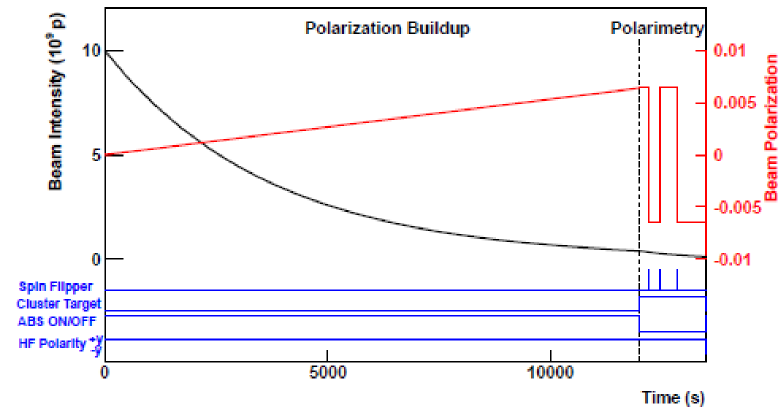
Figure of merit: *$P^2 \cdot I$*
→ Two beam life times

Polarization of a Stored Beam by Spin-Filtering

Experiment with COSY / schematic



COSY Cycle / schematic

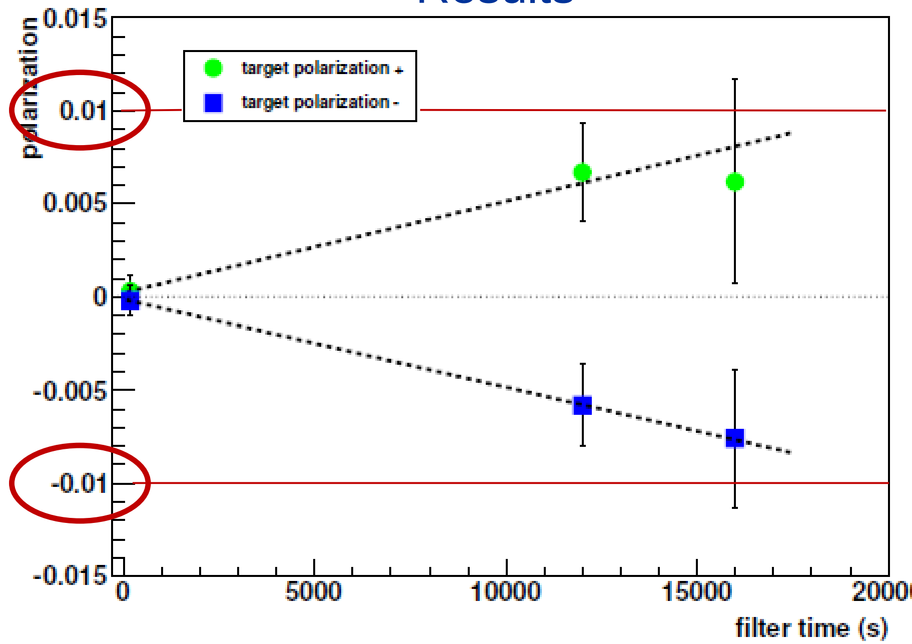


COSY Cycle

- Stacking injection at 45 MeV
- Electron cooling on
- Acceleration to 49.3 MeV
- Start of spin-filter cycle at PAX: 16 000 s
- PAX ABS off
- ANKE cluster target on
- Polarization measurement (2 500 s) at ANKE
- Spin flips with RF Solenoid

- New cycle
  with different direction of target polarization

Results



PAX Collaboration

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