Deutsche Forschungsgemeinschaft DFG

Bundesministerium für Bildung und Forschung

Polarized Beams:

a powerful tool for hadron physics

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ELectron Stretcher Accelerator

ELSA

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universitätbonn

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

SFB/TR 16

PHYSICS AT THE TERA SCALE

Helmholtz Alliance

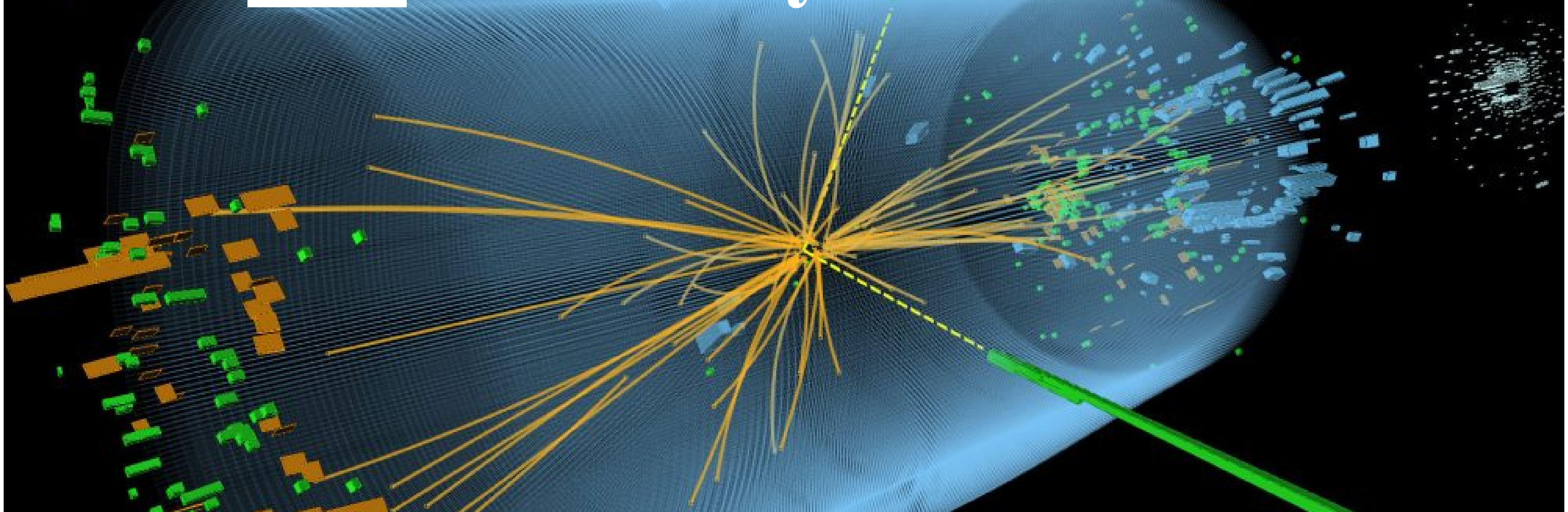
universitätbonn

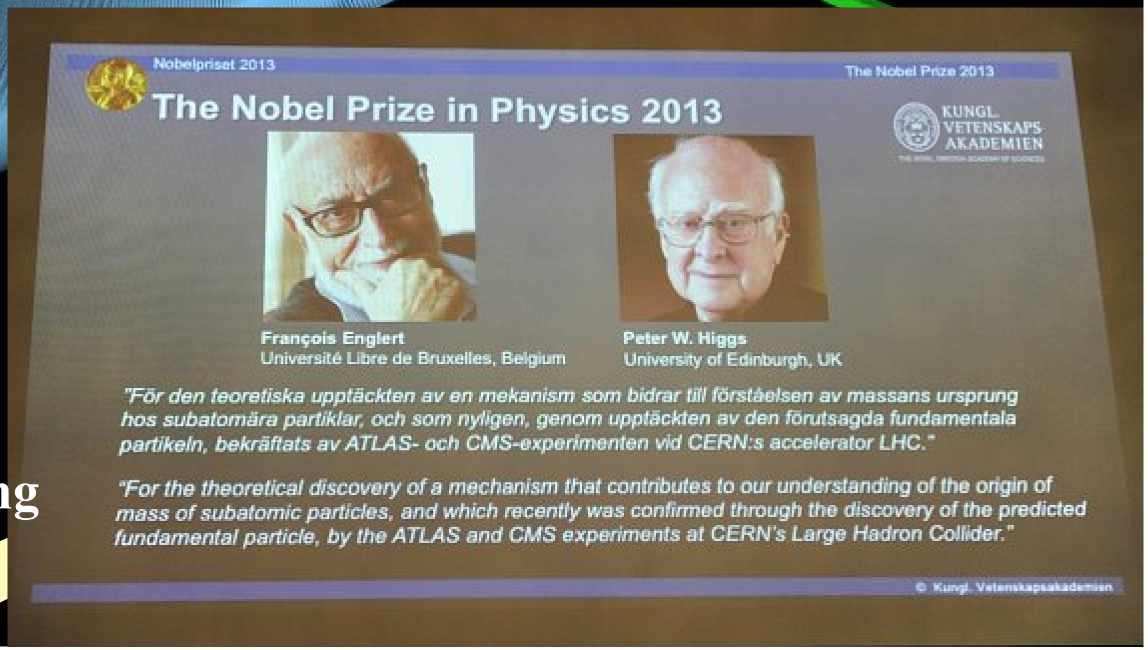
3 simple questions:

(mainly concentrating on electrons)

- ***Why?*** …do we need polarized electrons?
- ***How?*** …do we generate and accelerate polarized electrons?
- ***What else?*** …can be investigated using polarized beams?

The Discovery 2012/2013:





The long sought-for scalar field and Higgs Boson!
Everything is clear now concerning the generation of mass?

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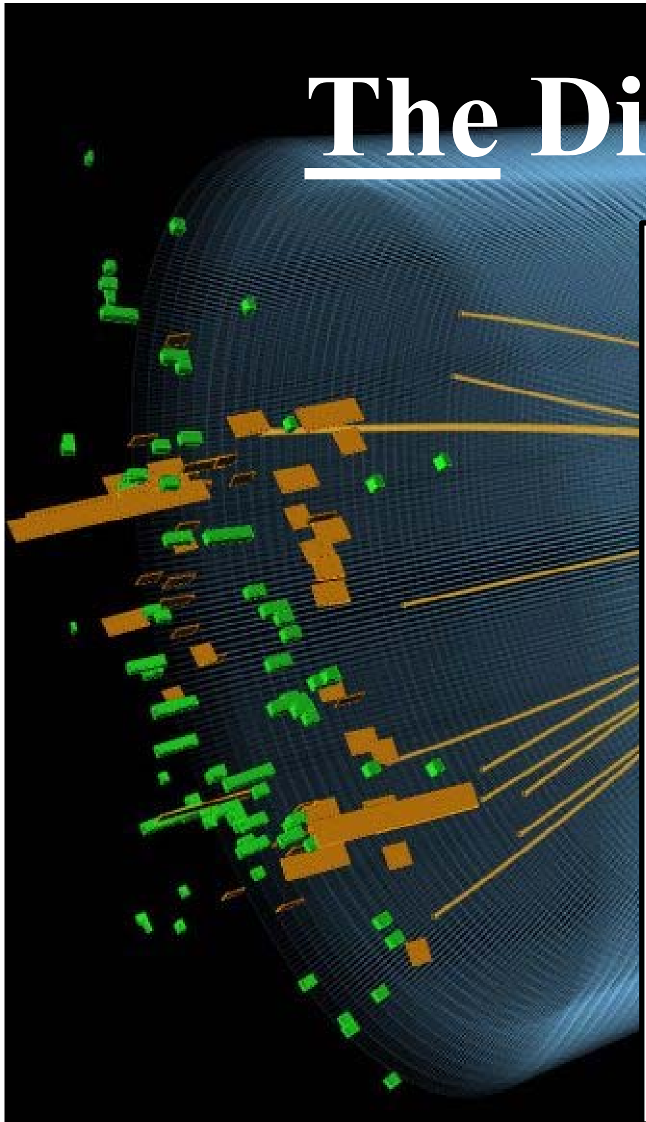


Masses of Elementary Particles:

Leptons:

electron e: 0.511 MeV
μ meson μ: 105.6 MeV
τ meson τ: 1.777 GeV

neutrino ν: „small“

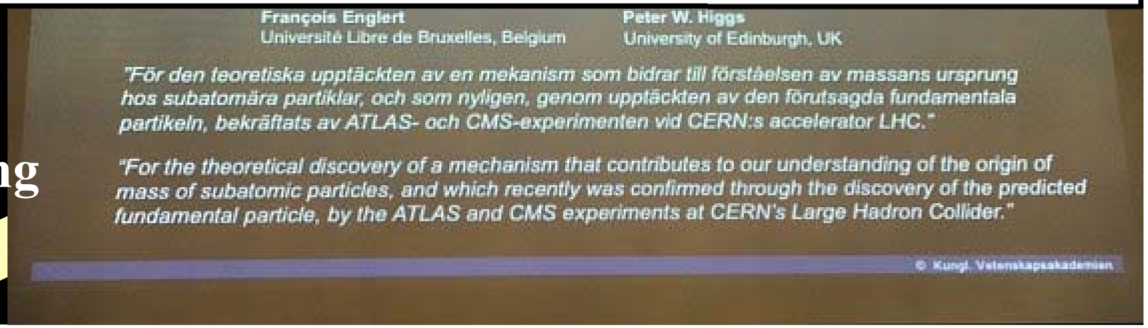
Quarks:

up quark u: 5 MeV
down quark d: 10 MeV
strange quark s: 150 MeV
charm quark c: 1200 MeV
bottom quark b: 4200 MeV
top quark t: 170 GeV

Nucleon: (“building block of matter”)

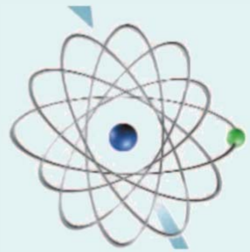
proton p: 938.3 MeV
neutron n: 939.6 MeV

The long sought-for scalar field and Higgs Boson!
Everything is clear now concerning the generation of mass?



Baryon Spectroscopy

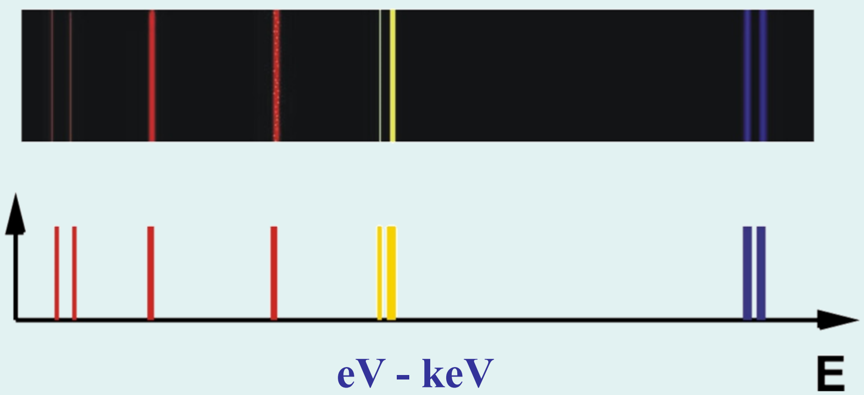
Atomic Physics



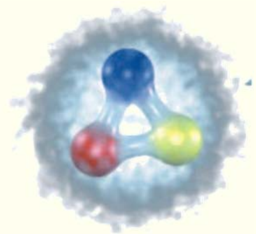
Atom: 10^{-10} m

Excitation with Photons:

Line Spectrum



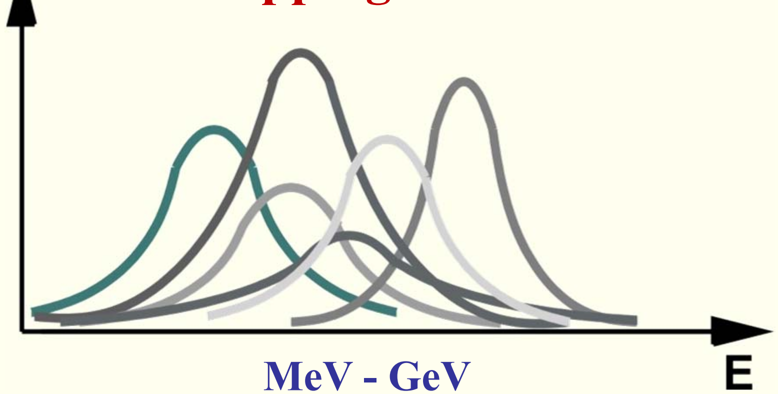
Hadron Physics



Hadron: 10^{-15} m

Excitation with Photons:

Overlapping Resonances



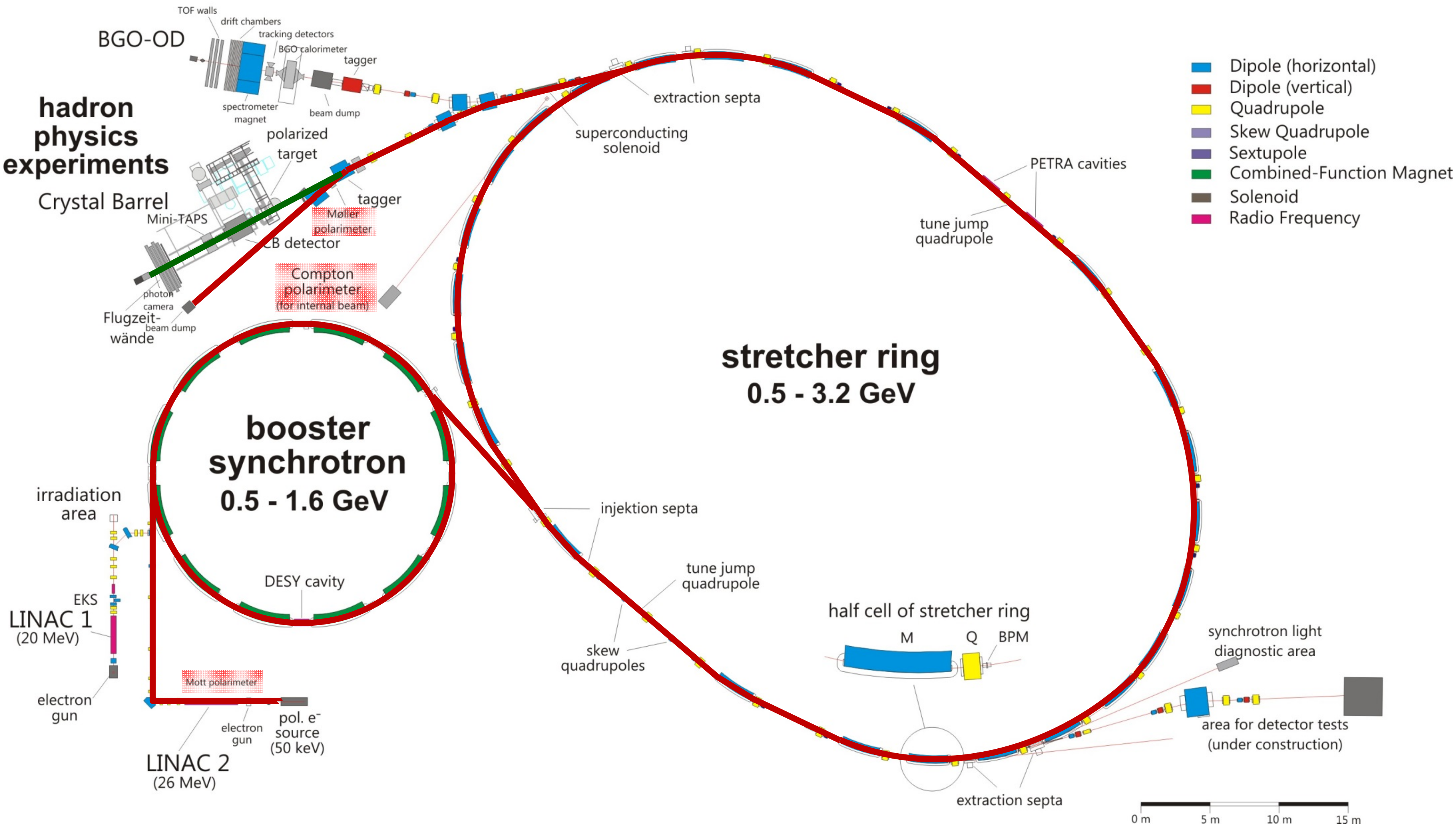
Spectral Linewidth from $\Delta E \cdot \Delta t \geq \hbar$

→ **Double Polarization Experiments**

How?

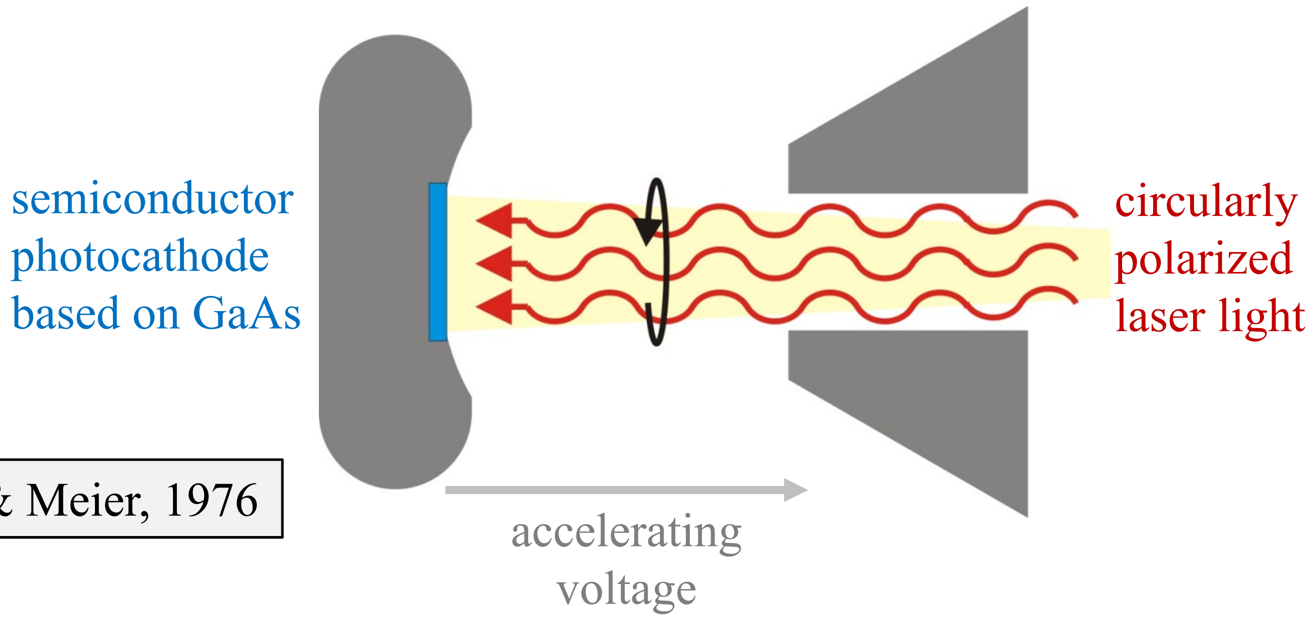
a) Source of polarized electrons

Electron Stretcher Accelerator (ELSA)



Generation of Polarized Electrons

Functional Principle:

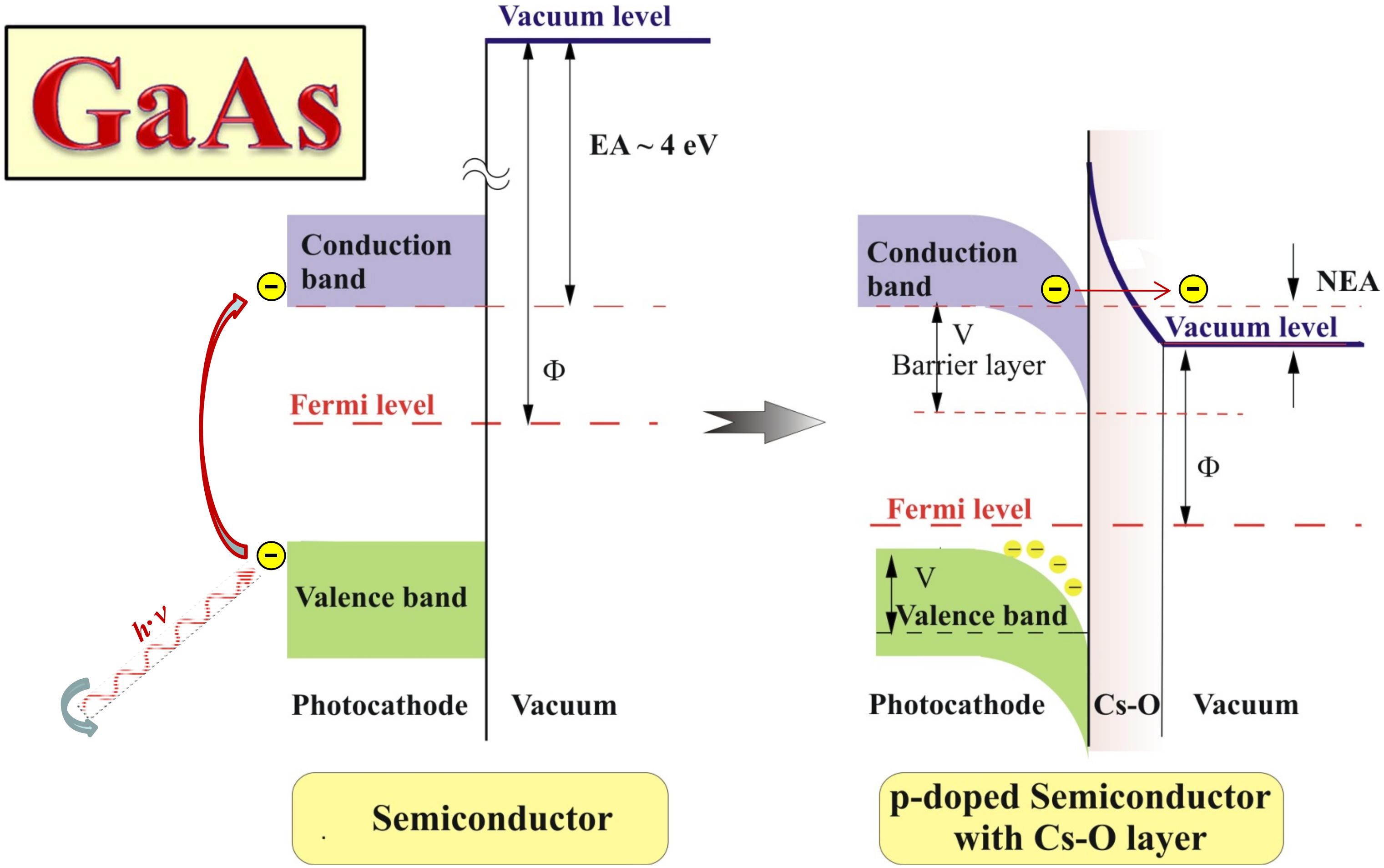


Pierce & Meier, 1976

Photoelectron emission from GaAs

polarization transfer from laser photons to emitted electrons

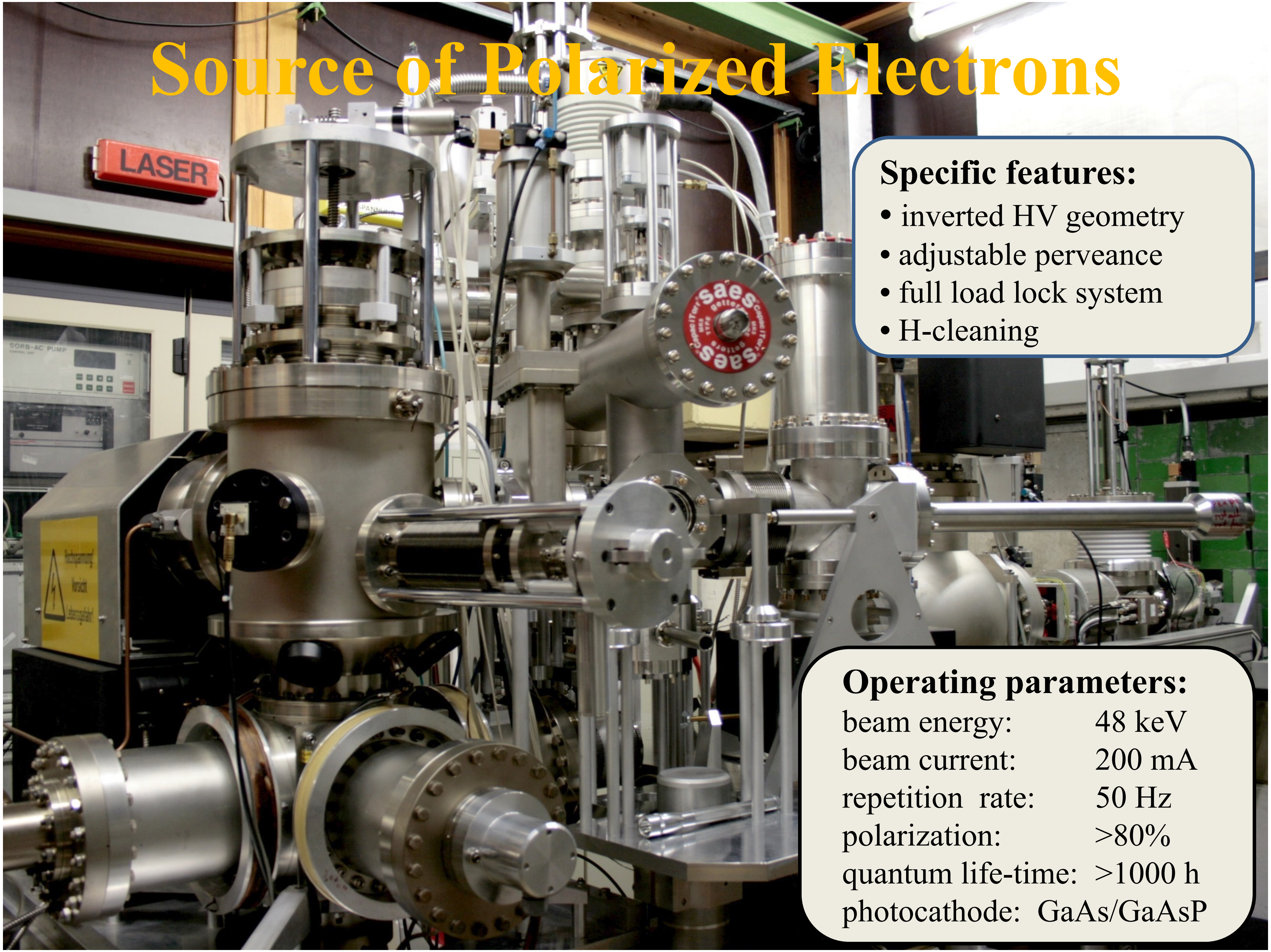
Generation of Polarized Electrons



Operation, heat cleaning and activation in extreme UHV

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

Source of Polarized Electrons



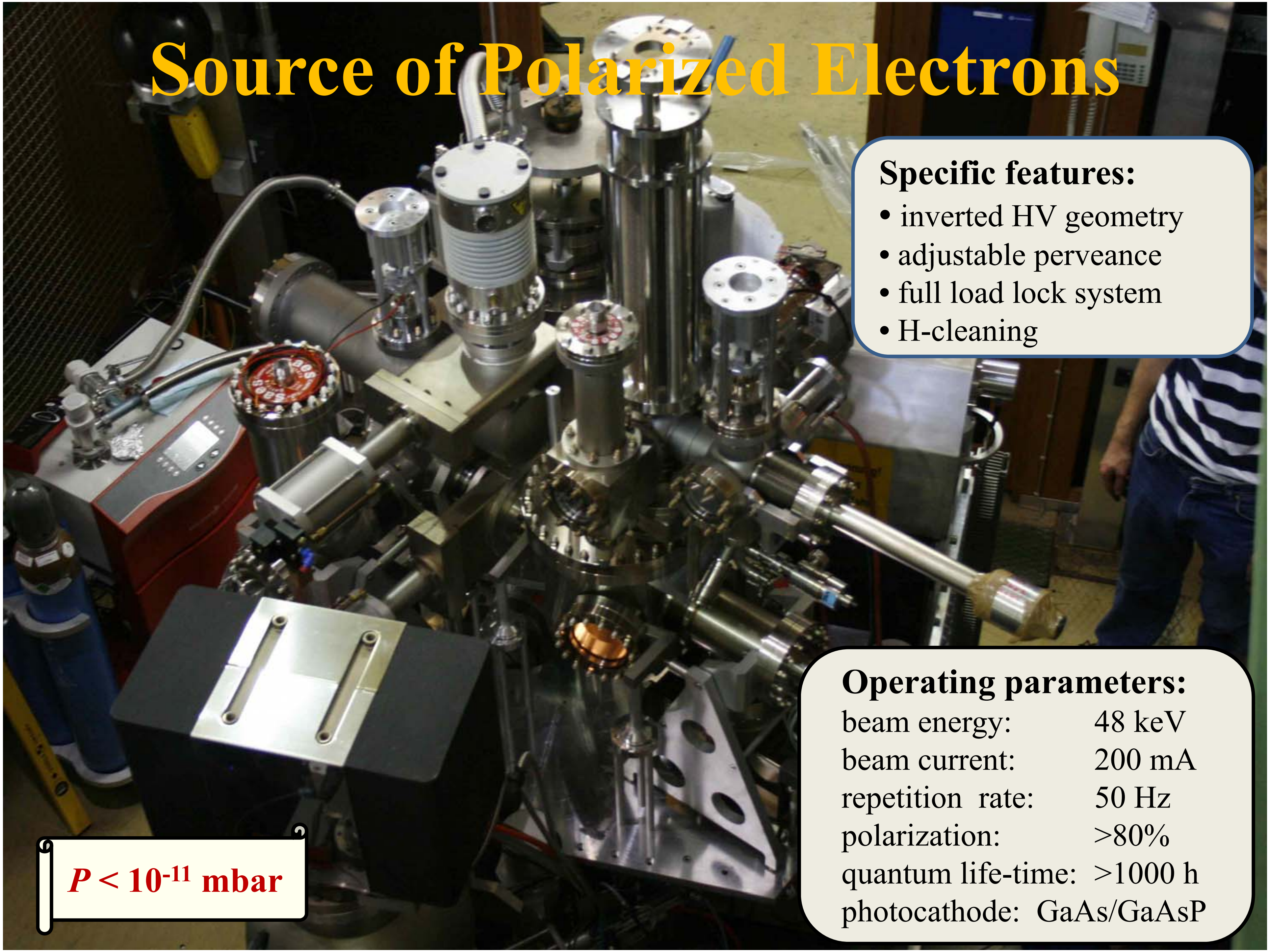
Specific features:

- inverted HV geometry
- adjustable perveance
- full load lock system
- H-cleaning

Operating parameters:

beam energy:	48 keV
beam current:	200 mA
repetition rate:	50 Hz
polarization:	>80%
quantum life-time:	>1000 h
photocathode:	GaAs/GaAsP

Source of Polarized Electrons



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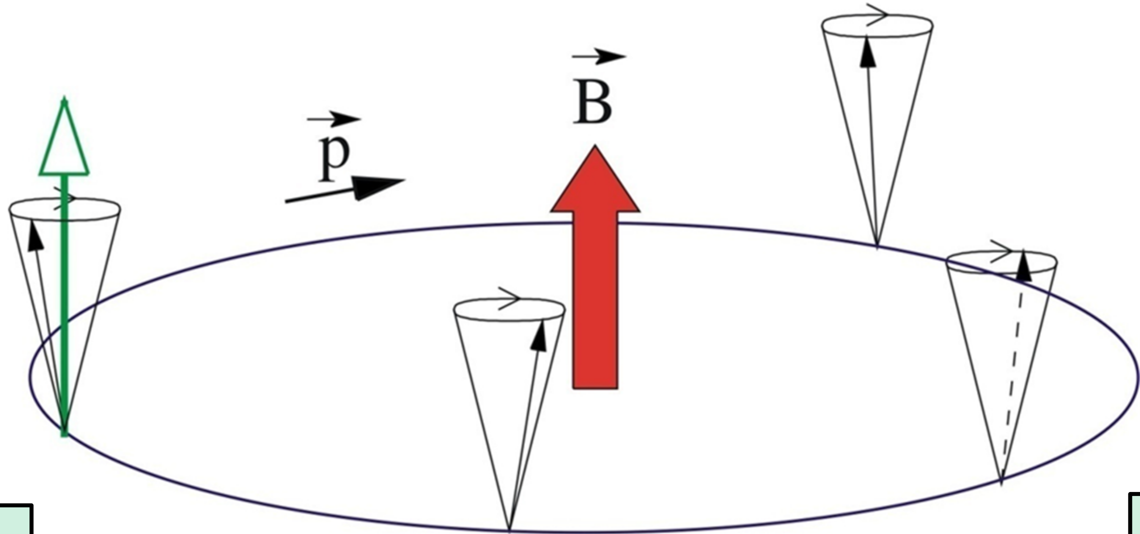
P **< 10^{-11} mbar**

How?

b) Acceleration of polarized electrons

Spins in Magnetic Fields

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



magn. moment:

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

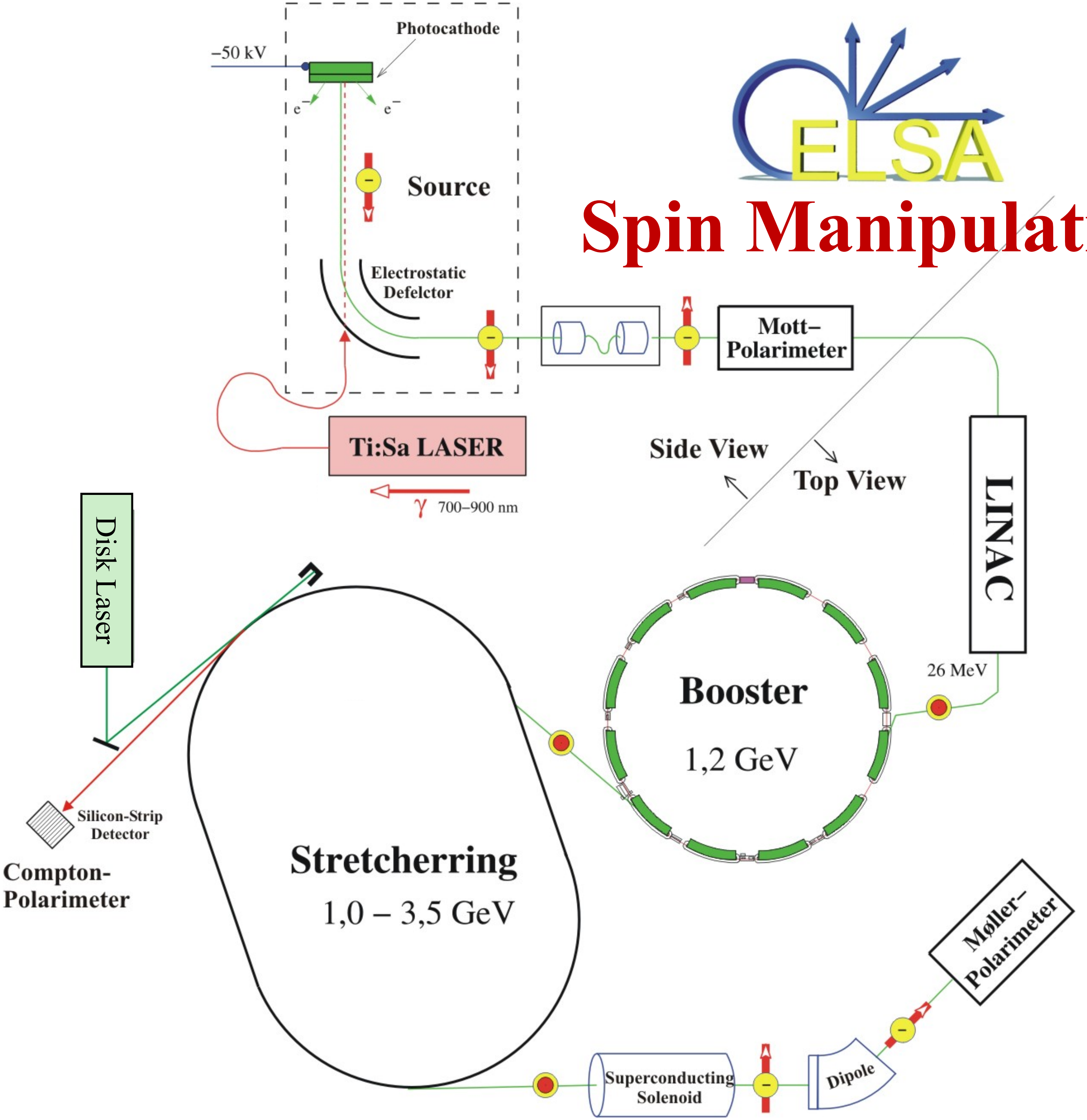
$$\frac{d\vec{S}}{dt} = \vec{\Omega}\times\vec{S}$$

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

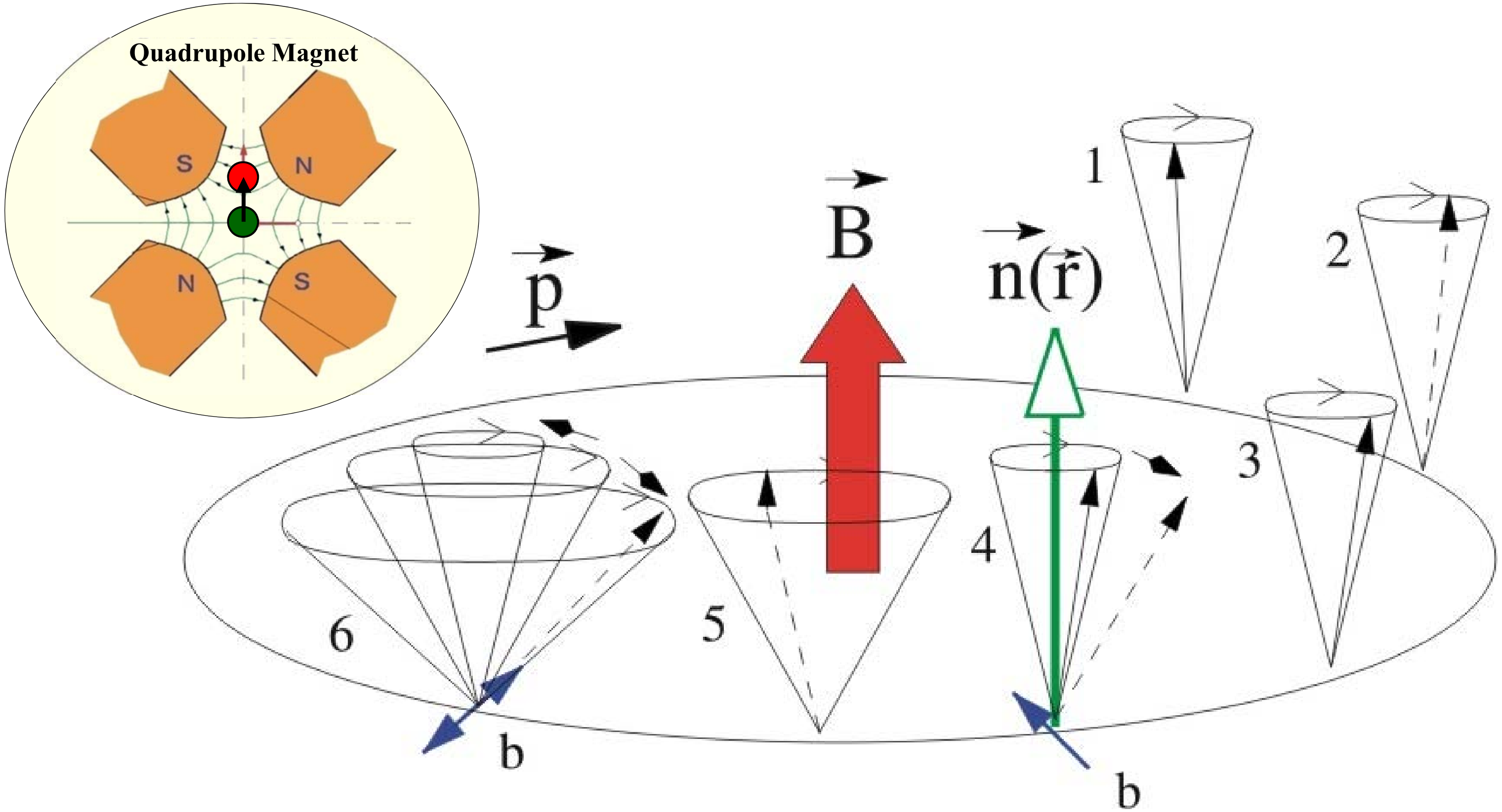
$a_{e^-} \approx 1.16\cdot10^{-3}$

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

Spin Manipulation

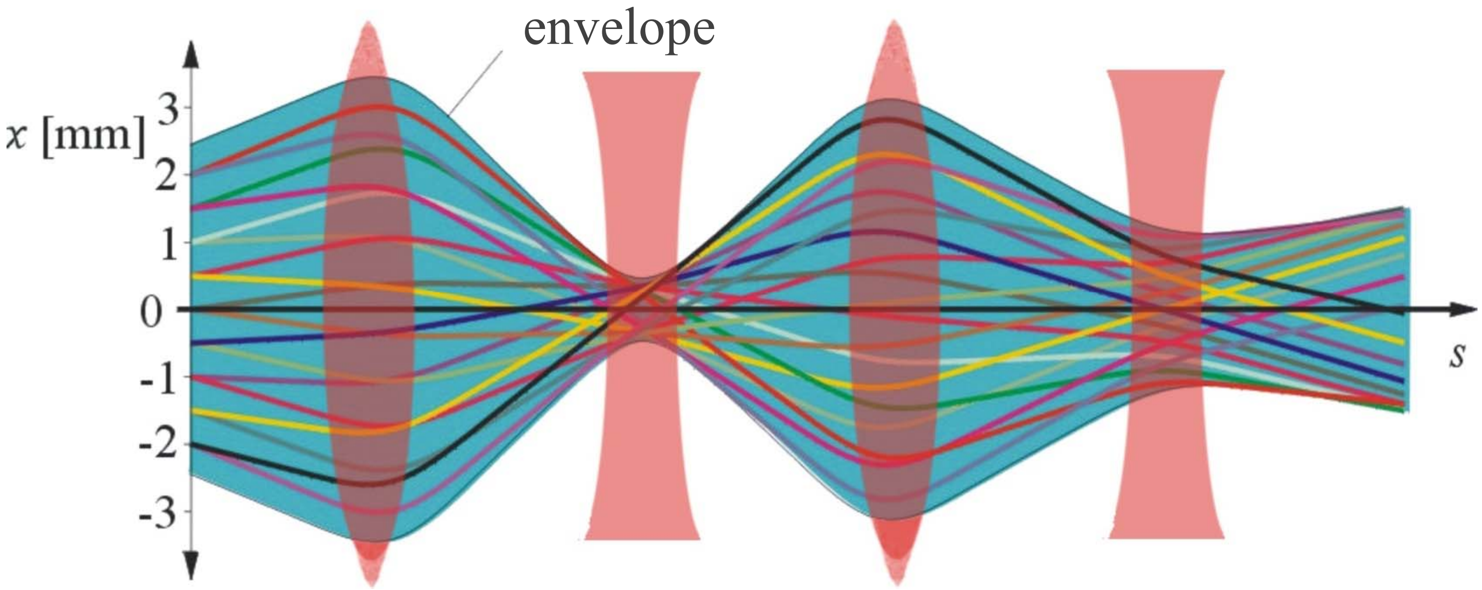


Depolarizing Resonances



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

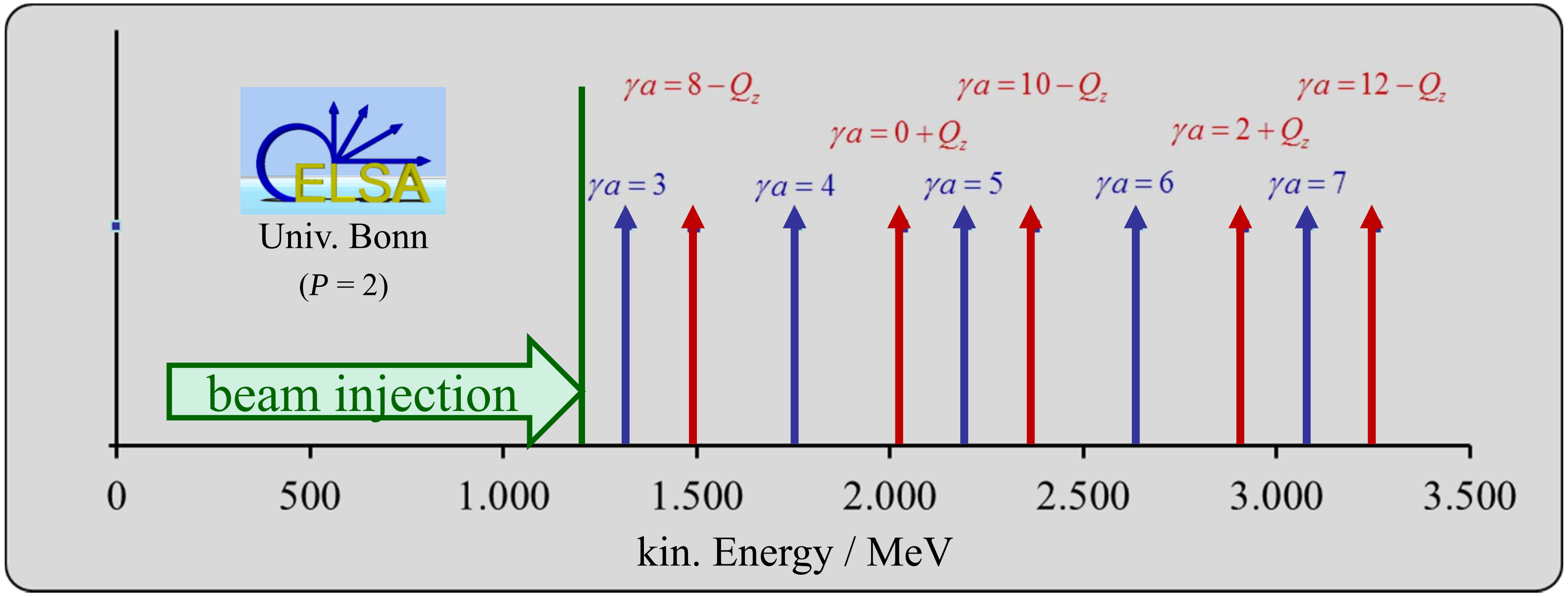
Depolarizing Resonances



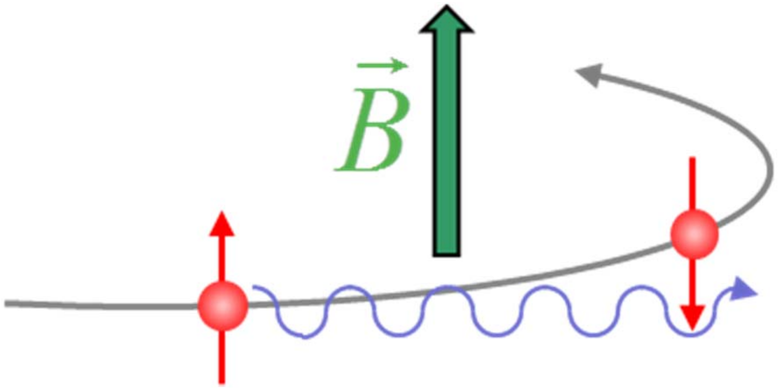
Strong Focusing: Betatron Oscillations!

Imperfection Resonance:	$\gamma \cdot a = n,$	$n \in Z$
Intrinsic Resonance:	$\gamma \cdot a = n \cdot P \pm Q_z,$	$n \in Z$

Resonances of 1st order



Synchrotron Radiation:

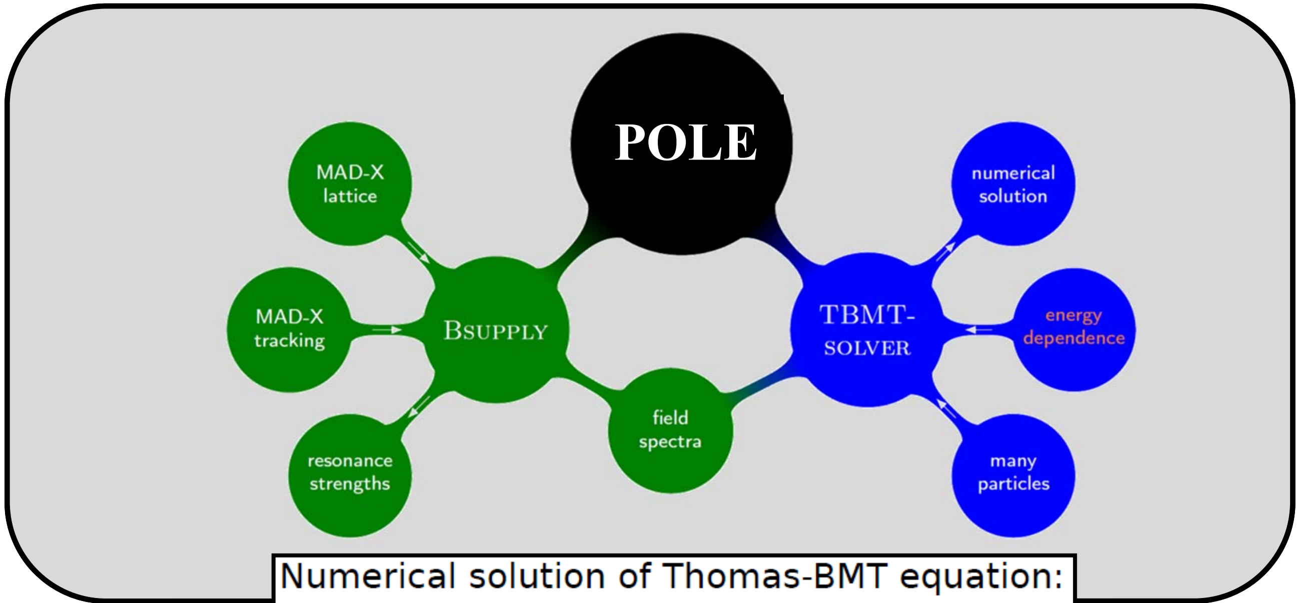


Emission of γ-Quants:

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

$\longrightarrow$ **Spin Diffusion!**

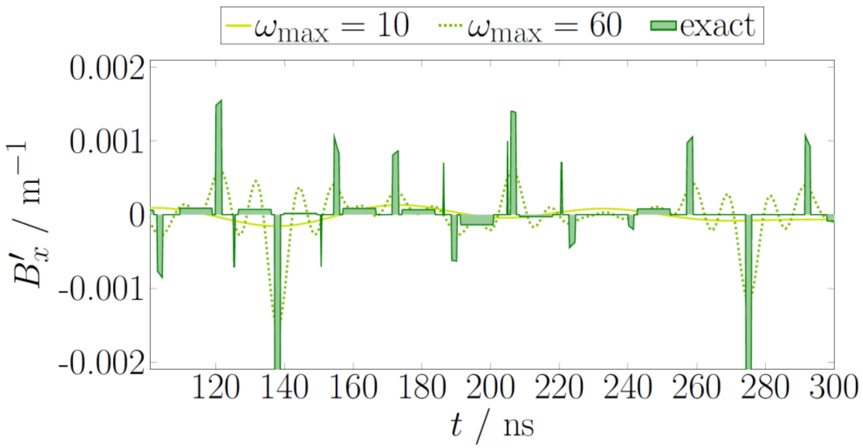
Simulation of Spin Dynamics



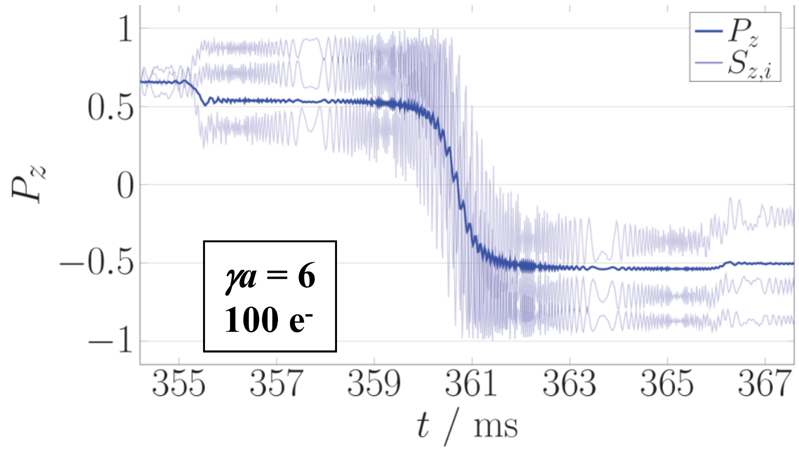
Numerical solution of Thomas-BMT equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\vec{S}(t) \approx c \cdot \vec{S}(t) \times \left[a\gamma(t)\vec{B}'_{\perp}(t) \; + \; a\vec{B}'_{\parallel}(t)\right]$$

<u>*B*-field as (filtered) Fourier series:</u>

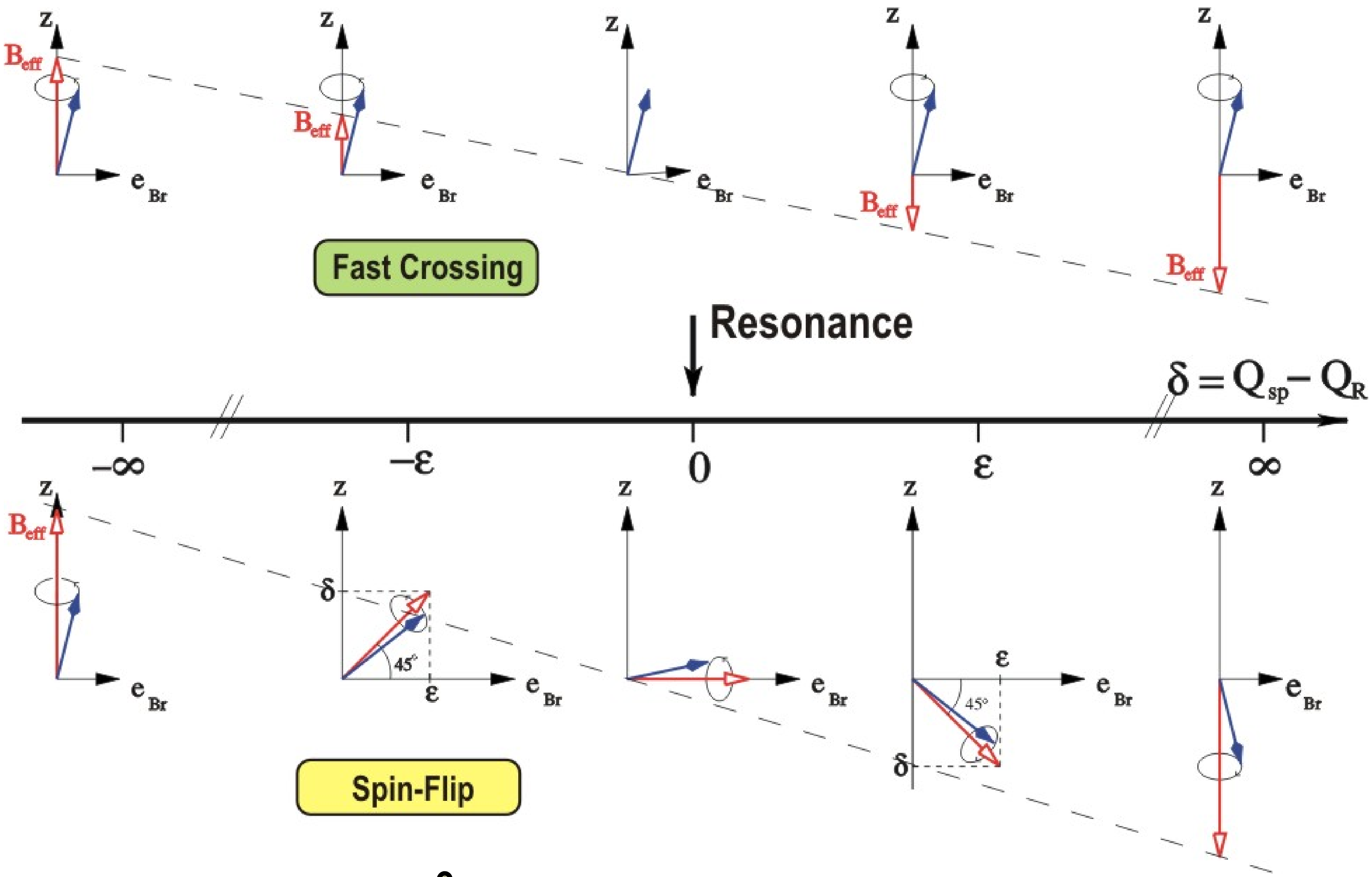


<u>Resonance crossing:</u>



Resonance Crossing

(isolated resonances only!)

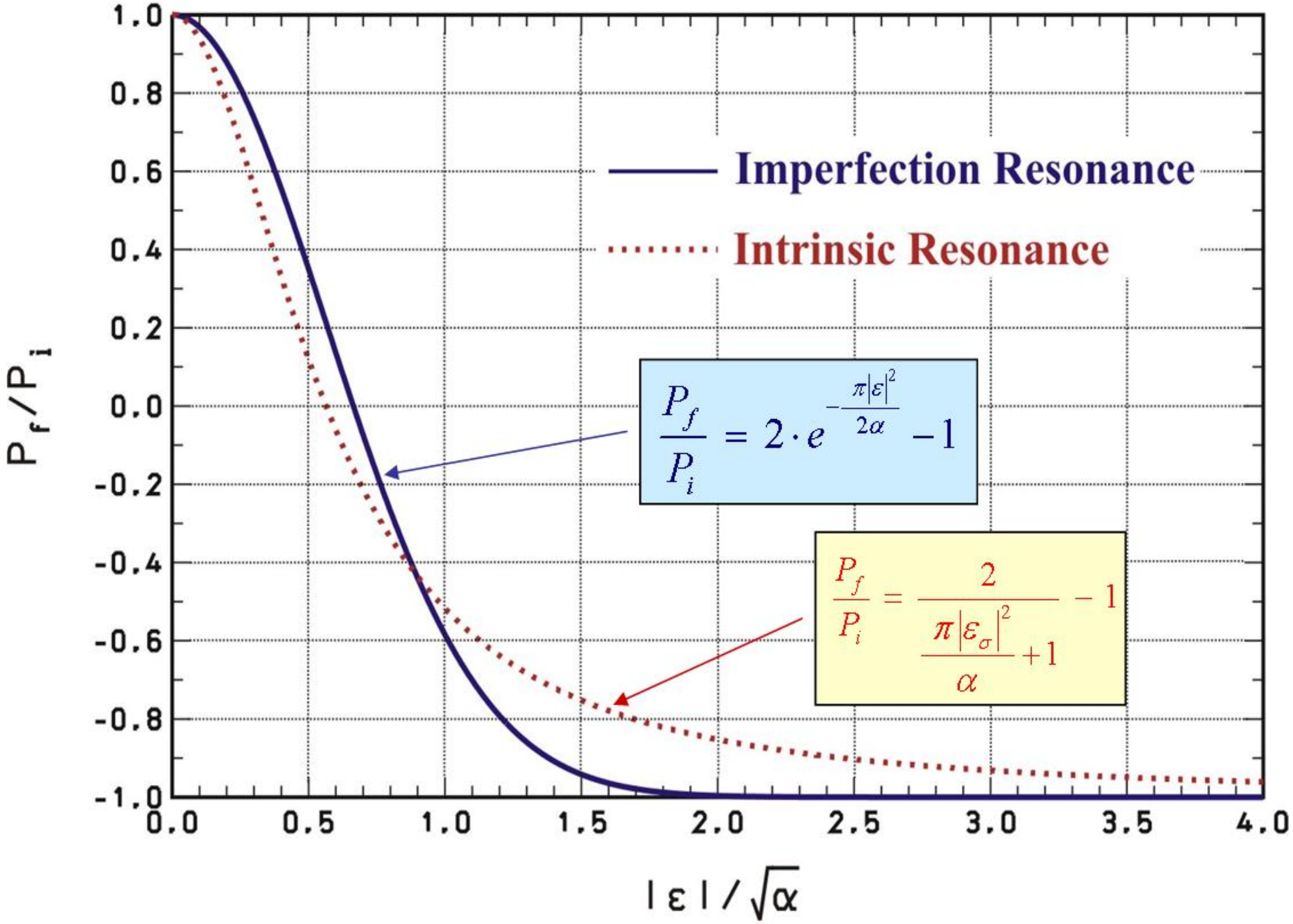


Crossing Speed: $\alpha = \dot{\gamma} a / \omega_{rev}$

→ Resonance Strength ε

Resonance Crossing

Froissart-Stora-Formula



Synchrotron Oscillations

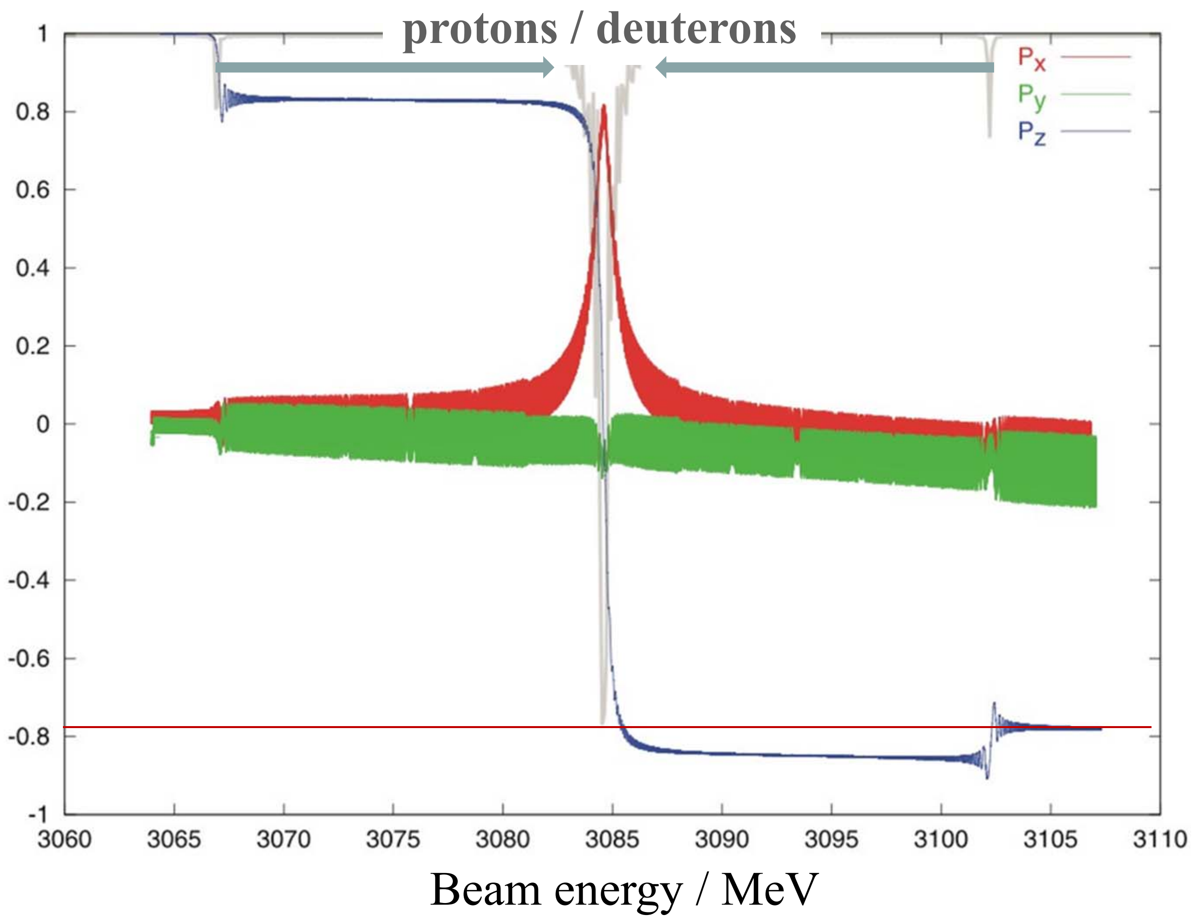
(= energy oscillations of beam's particles!)

Multiple crossing of depolarizing resonances due to energy oscillations

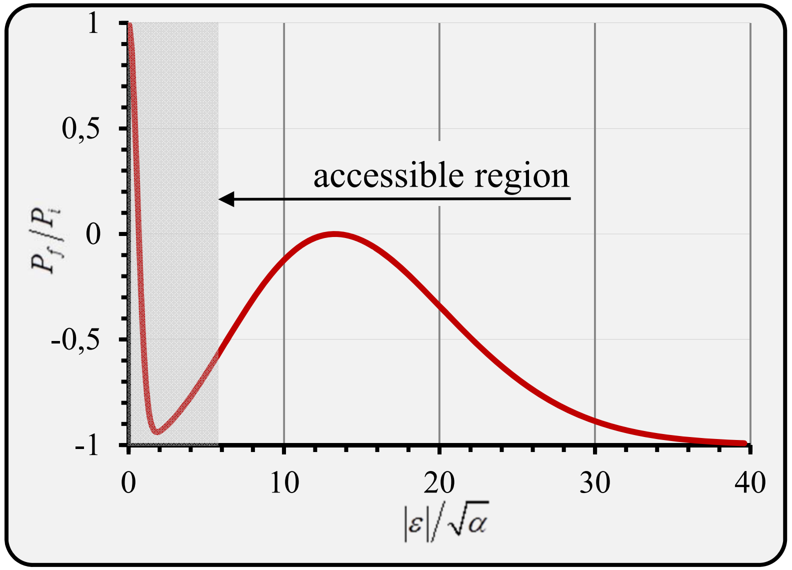
Oscillation frequency/tune:

- **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



Crossing of Synchrotron-Sidebands

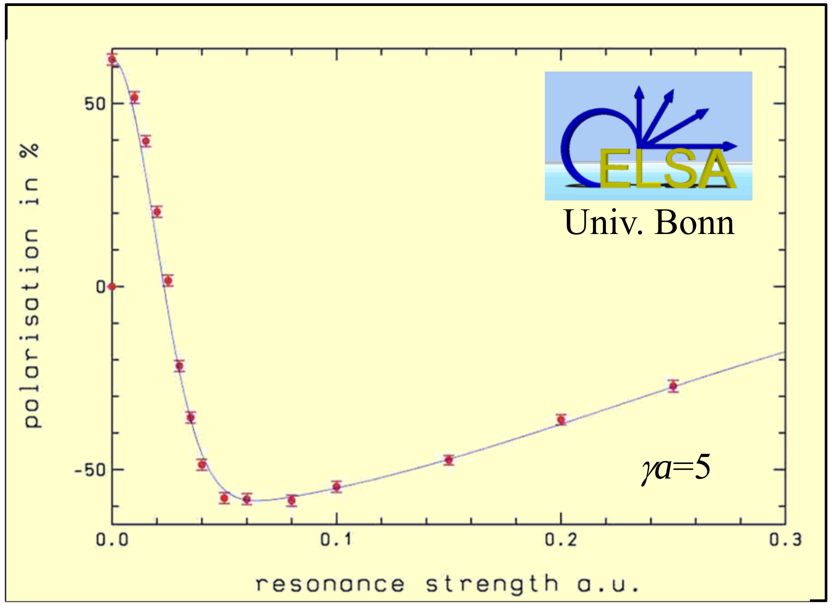


„Modified“ Froissart-Stora Formula:

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

Full Spin-Flip no longer possible!

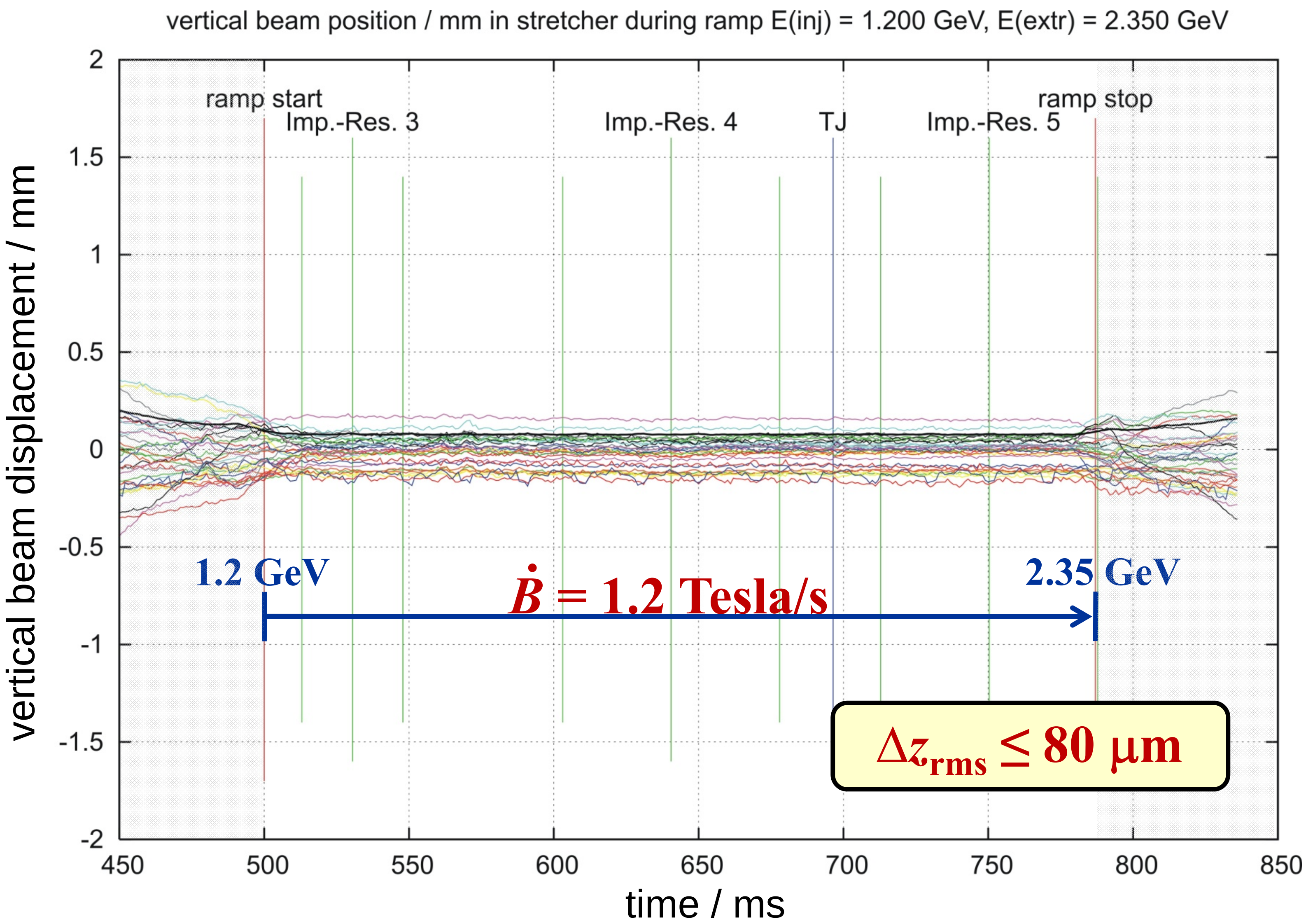
Experimental verification at ELSA:



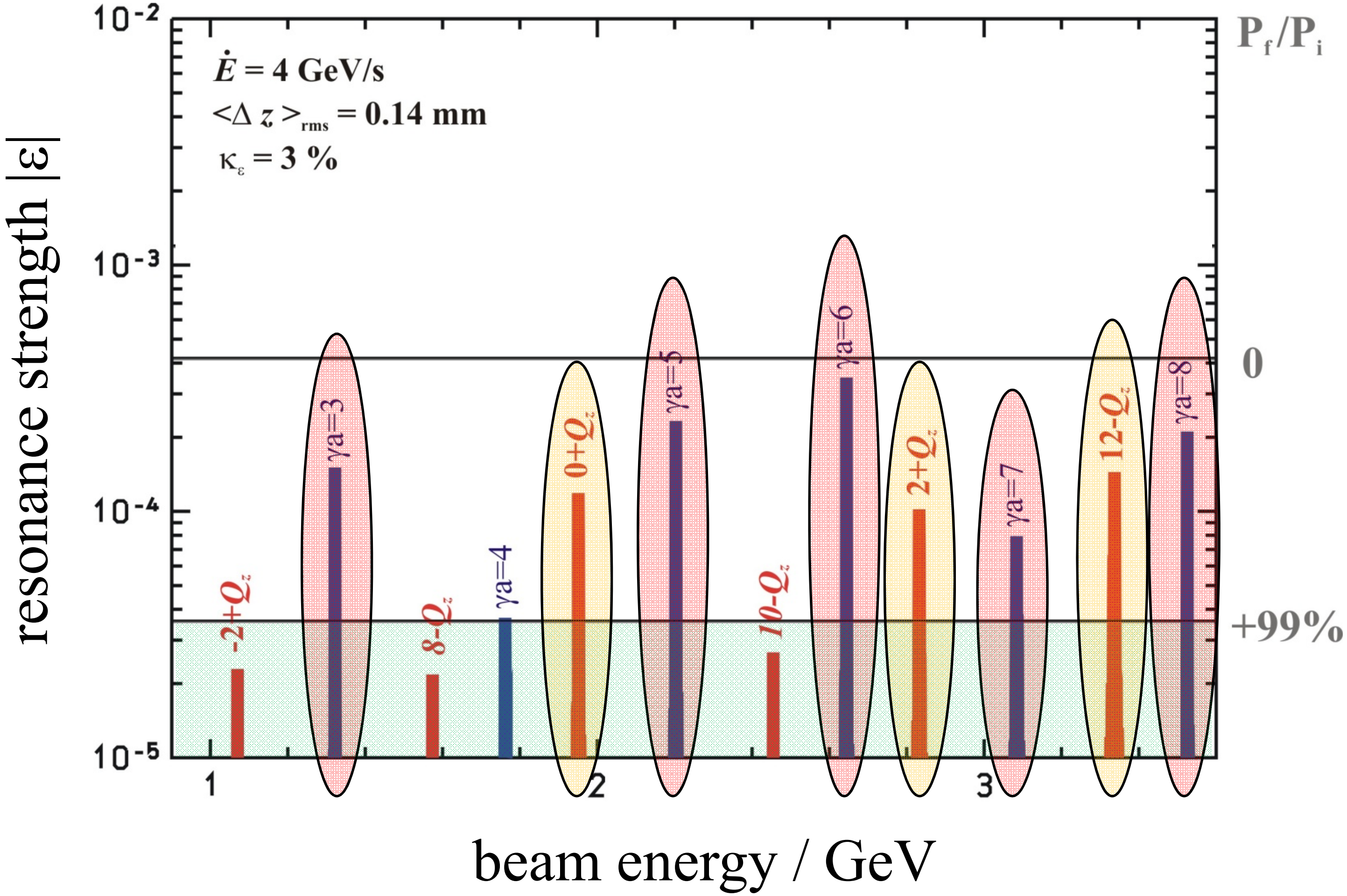
Beam excitation will only cause partial spin flip → depolarization!

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

Orbit Correction on the Ramp



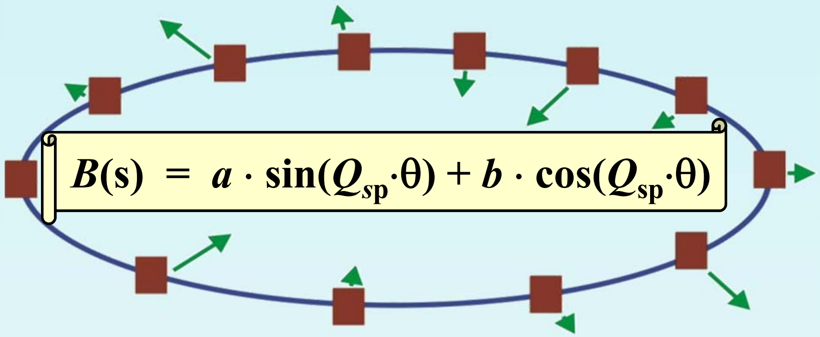
Resonance Strengths



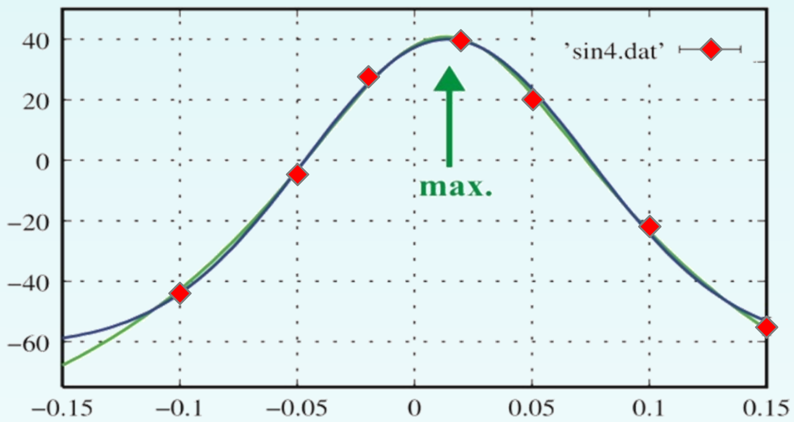
Acc. of Polarized Electrons

Integer Resonances: $\gamma a = n$

- precise CO correction ($z_{rms} < 80\mu m$)
- harmonic correction:

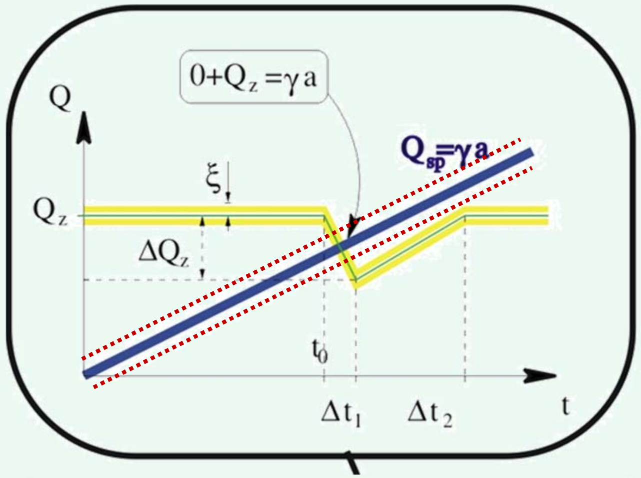


→ scan of sin amplitude:

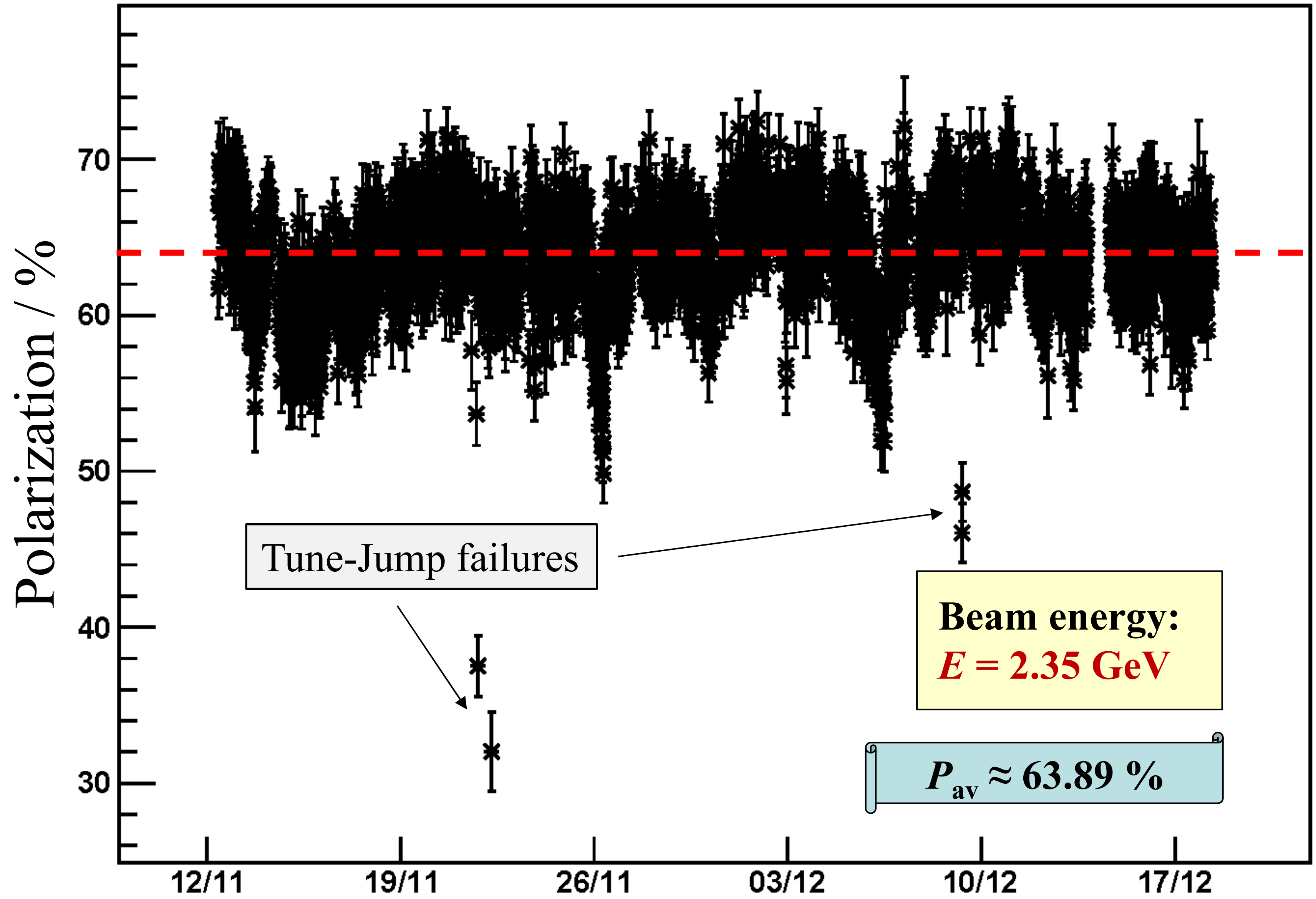


Intr. Resonances: $\gamma a = nP \pm Q_z$

- small vertical beam size
- tune jumping with pulsed quads

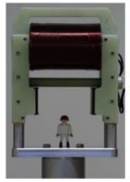


Polarization at the Experiment

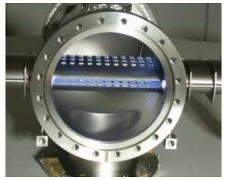


Improvements over the last years

($P \rightarrow 70\%$, $I \rightarrow 200\text{mA}$)

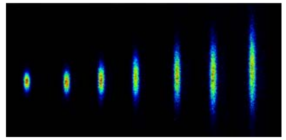



- Precise and fast **beam position monitoring**: $\Delta_{x,z} \approx \mu\text{m}$, 1kHz
- Fast **bipolar steerer system**: $\dot{B} = 2\,\text{T/sec}$, $B{\cdot}l \approx 0.01\,\text{T}{\cdot}\text{m}$



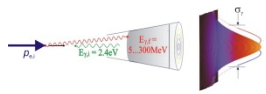
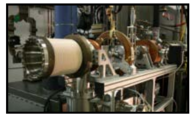

- **Low impedance** vacuum chambers
- Effective **ion clearing** (35 clearing electrodes)


- **HOM suppression** in accelerating cavities
- 3D **bunch by bunch feedback** system ($\Delta f = 250\,\text{MHz}$)
- **FPGA-based LLRF control**: $\Delta A/A < 3{\cdot}10^{-4}$, $\Delta\phi < 0.04°$

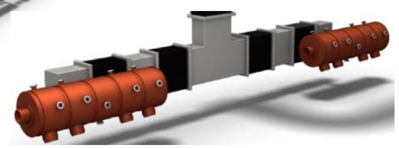


- ps diagnosis based on a **streak camera system**
- Cavity-based **BPM for low intensities**: $\Delta_{x,z} \approx 0.1\text{mm}$, 100pA

Future issues

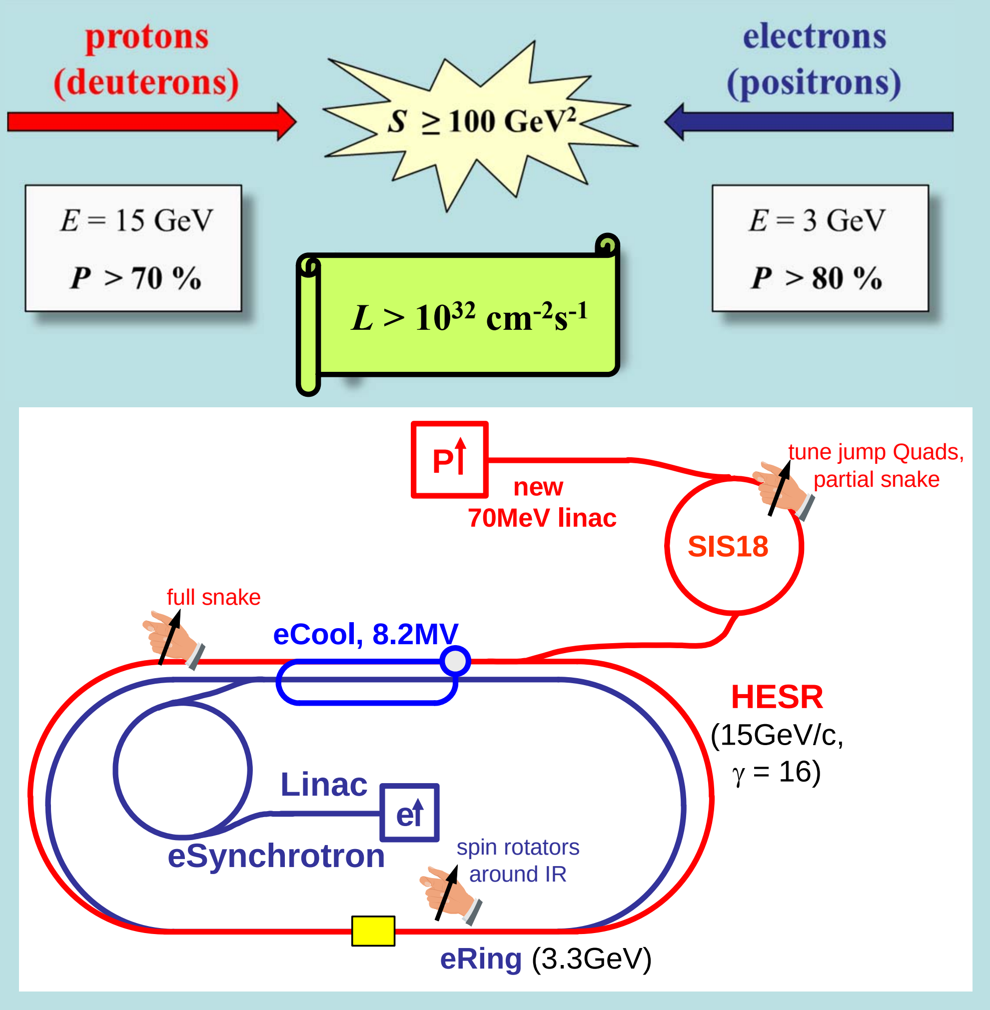
- **Compton polarimetry**
- Harmcorr based on **spin-orbit response technique**
- High current **single-bunch injector**
- **New RF station and cavities**



What else?

… perspectives for new measurements?

ENC@FAIR



High Energy Storage Ring HESR:

- $R = 30$ m, $L = 576$ m
- $E = 15$ GeV (Protons)
- $h = 100$, $n_p = 5{,}4 \cdot 10^{10}$
- $\varepsilon_n = 2$ mm mrad
- $P > 70$ %

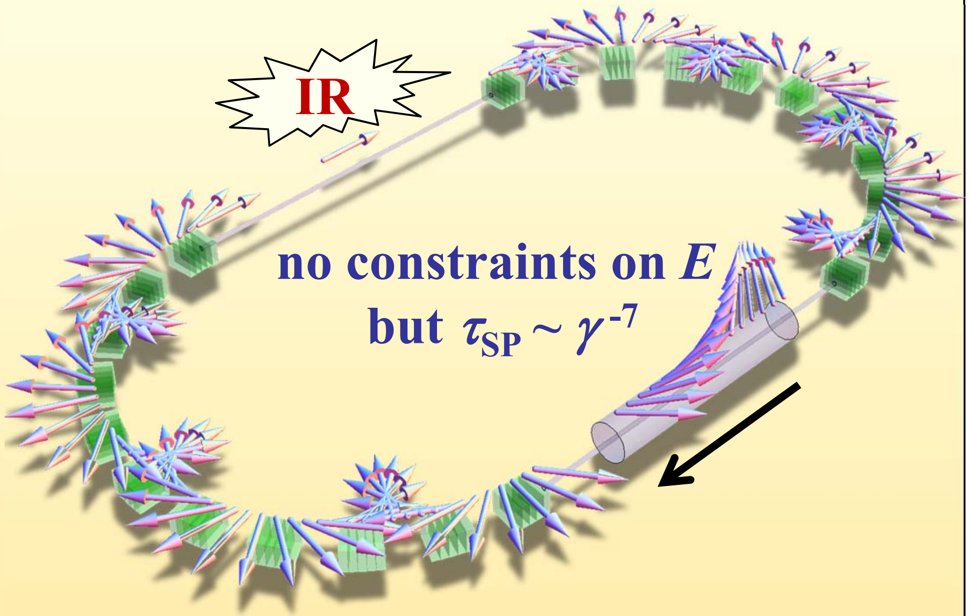
Electron Storage Ring:

- $R \approx 25$ m, $L = 577.1$ m
- $E = 3.3$ GeV ($Q_{sp} \approx 7.5$)
- $h = 100$, $I_e = 2$ A
- $\varepsilon_n = 2$ mm mrad
- $P > 80$ %

Acc. Working Group: GSI, JÜLICH Forschungszentrum, DESY, MAMI Mainzer Mikrotron, ELSA, DELTA, BROOKHAVEN NATIONAL LABORATORY

Electron Ring: Spin Dynamics

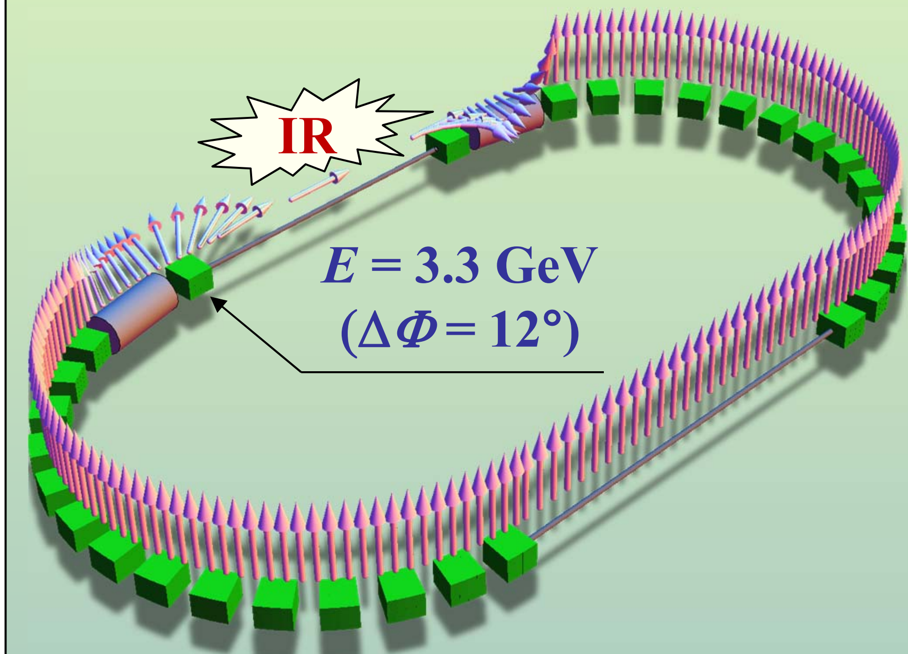
Concept 1: Sibirian (full) Snake



- **FODO** lattice in the arcs
- missing magnet → $D = 0$ in straights
- 1 solenoid, $\Delta S = 180°$
- $\beta_x = \beta_z$ in solenoid
- $\varepsilon_x = \varepsilon_z$ = 1.95 mm·rad (norm)

$\tau_{Sp} \approx$ **7 min @ 2.8 GeV**

Concept 2: Spin Rotators

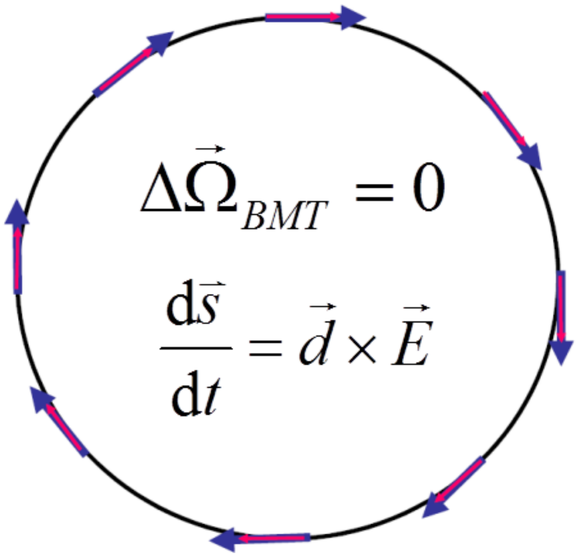


- **HBA**: 3 achromats à 6 dipoles
- $D = 0$ in straight with vert. spin
- 2 solenoid/dipole rotators, $\Delta S = 90°$
- $\beta_x = \beta_z$ at entrance/exit of achromats
- $\varepsilon_x = 3.8$, $\varepsilon_z = 3.1$ mm·rad (norm)

$\tau_{Sp} >$ **100 min @ 3.3 GeV**

Frozen Spin

Spins aligned along particles' momentum:



$$\Delta\Omega_{BMT} = -\frac{e}{m}\left\{ a \cdot \vec{B}_\perp + \left(\frac{1}{\gamma^2 - 1} - a \right) \frac{\vec{\beta} \times \vec{E}}{c} \right\}$$

<u>Magic Energies:</u>

- all electric ($B = 0$): $p = m/\sqrt{a}$
- combined ($E, B \neq 0$): $E_x = \frac{ac\beta\gamma^2}{1 - a\beta^2\gamma^2} B_z$

EDM would cause a development of vertical polarization!

$R \approx 30$m, all-in-one:

particle	*p* (GeV/c)	*E* (MV/m)	*B* (T)
proton	0.701	16.789	0.000
deuteron	1.000	−3.983	0.160
^{3}He	1.285	17.158	−0.051

EDM-Measurement in Storage Rings (srEDM)

Challenges:

- Suppression of **systematic effects** (cw and ccw beams)
- High **electric field gradients** required ($E \approx 17$ MV/m)
- Long **spin coherence time** ($T_{coh} \geq 1000$ sec)
- Continuous and **precise polarimetry** ($\Delta P \approx 10^{-6}$)
- Precise **beam positioning** (10 nm)
- Sophisticated **spin tracking**

Jülich Electric Dipole moment Investigation, goal: 10^{-29} e·cm

Conclusions

- **Polarized Electrons @ ELSA :**
  - pulsed **photo-injector** with I = 200 mA, P = 80%
  - acceleration to $E \leq$ **2.4 (3.2) GeV with** $P_{Exp} \geq$ **60%**
  - development of **sophisticated correction schemes**
  - **routine operation** for hadron physics experiments
  - upgrade to **200 mA internal current**

- **Challenging Perspective @ FZJ:**
  - **high precision EDM-measurement** of p, d, and ^{3}He in an *all-in-one* storage ring with combined E/B beam deflection

Thank you for your attention!

Machine Development: PhD students in the ELSA control room