Accelerator R&D @ ELSA:

Towards intense GeV-beams of highly polarized electrons

Wolfgang Hillert

ELectron Stretcher Accelerator

SFB/TR 16

Physics Institute of Bonn University

3 simple questions:

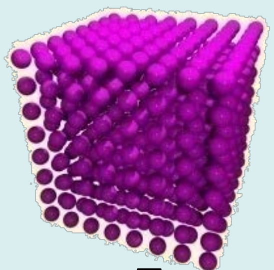
- ***Why?*** …do we need polarized electrons?
- ***How?*** …do we generate and accelerate polarized electrons?

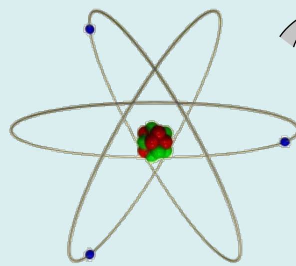
- ***What?*** …R&D activities would be pursued @ HZDR ?

Matter and Forces

Electromagnetic Interaction

Crystal Lattice — Atom





10^{-9}m — 10^{-10}m

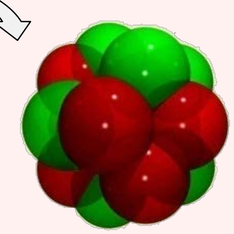
„Nanometer“

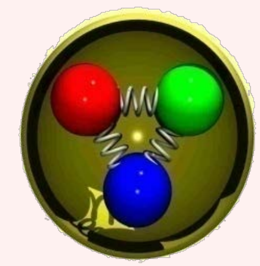
Crystalline and amorphous structure?
Ultrafast dynamic phenomena?

→ Coherent ultrashort X-rays pulses!

Strong Interaction

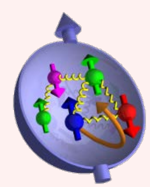
Nucleus — Hadron





10^{-14}m — 10^{-15}m

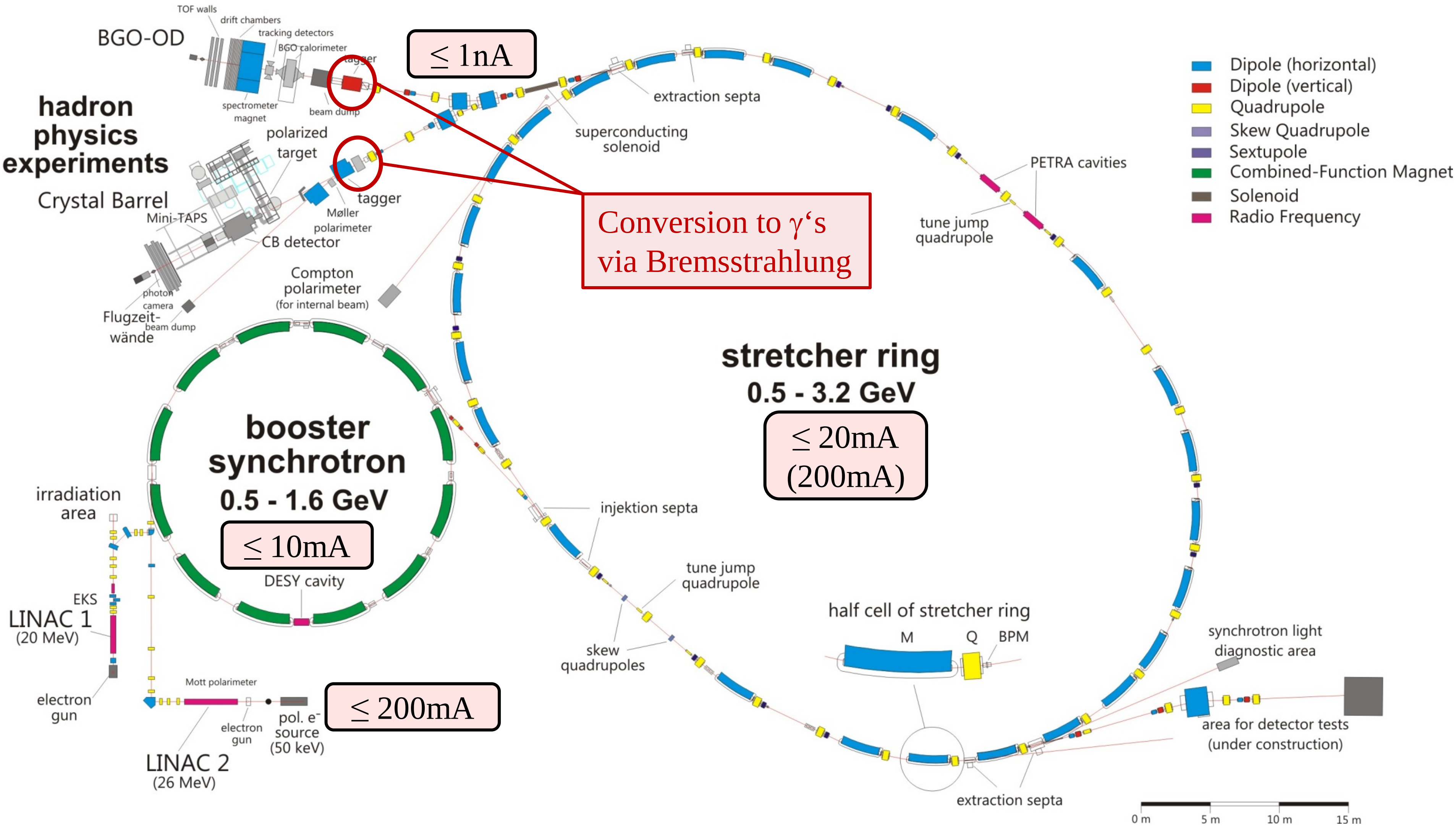
„Femtometer“



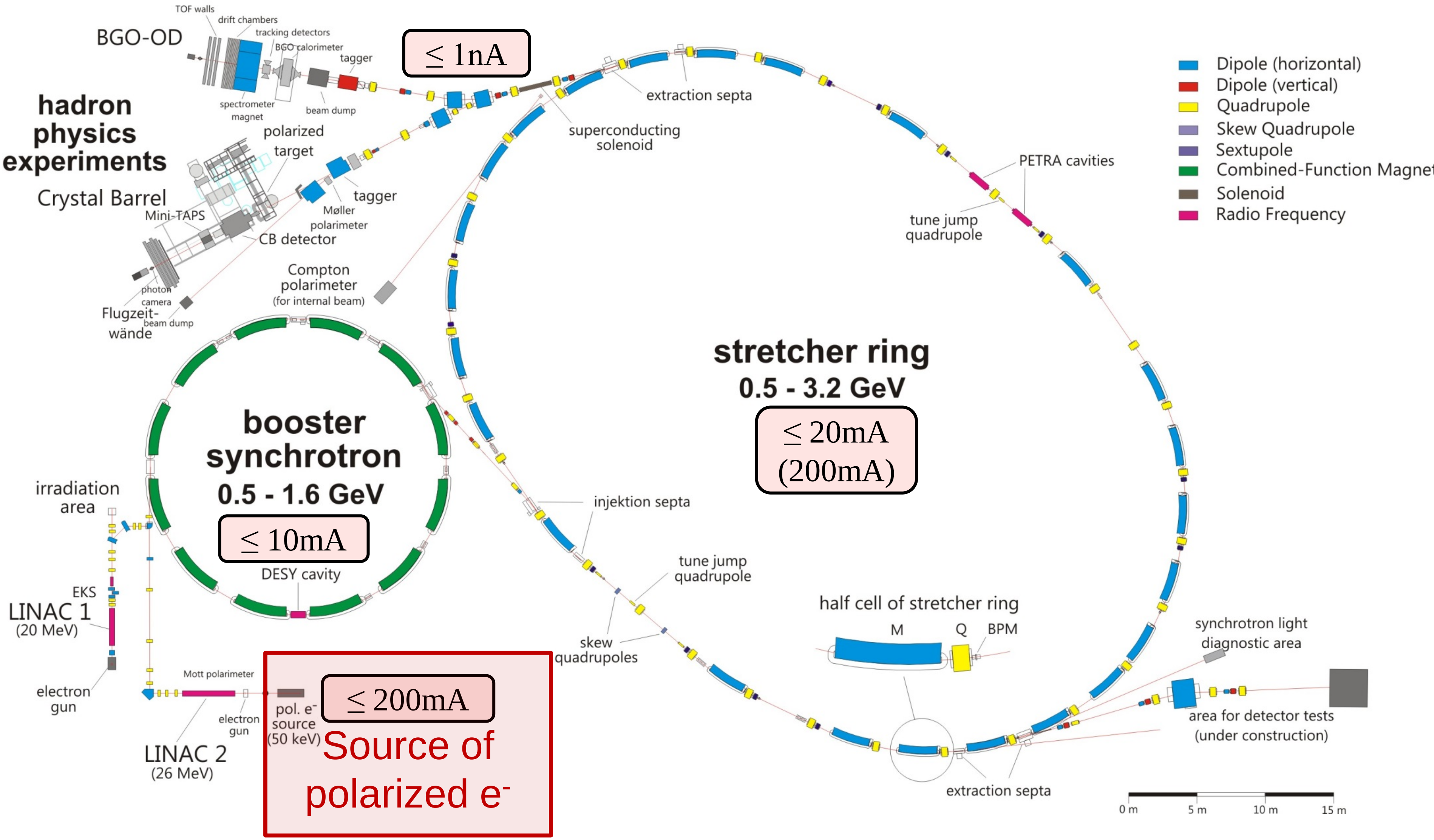
Mass of the nucleon?
Spin structure of the nucleon?

→ Intense polarized GeV γ-beams!

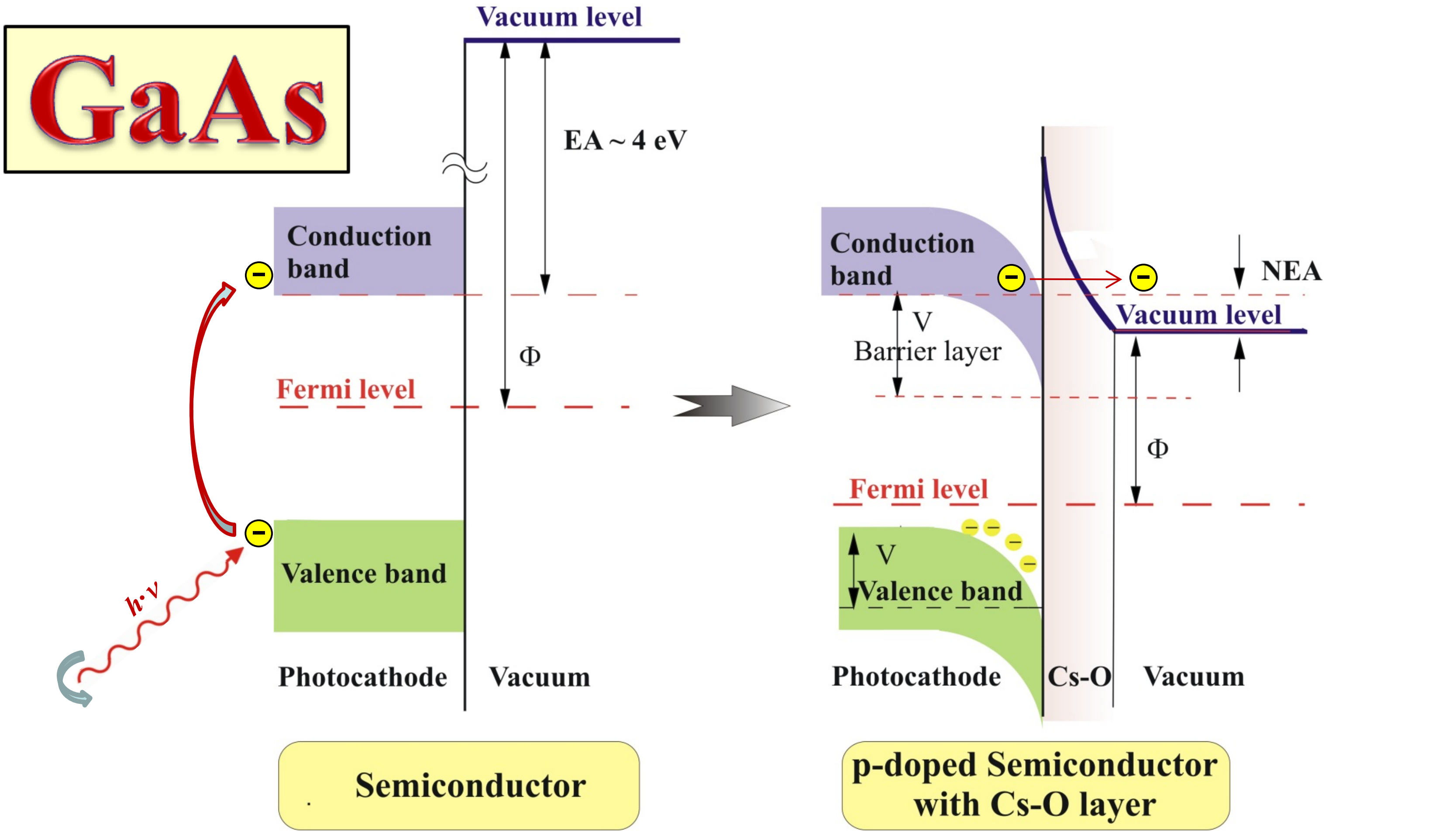
Electron Stretcher Accelerator (ELSA)



Electron Stretcher Accelerator (ELSA)



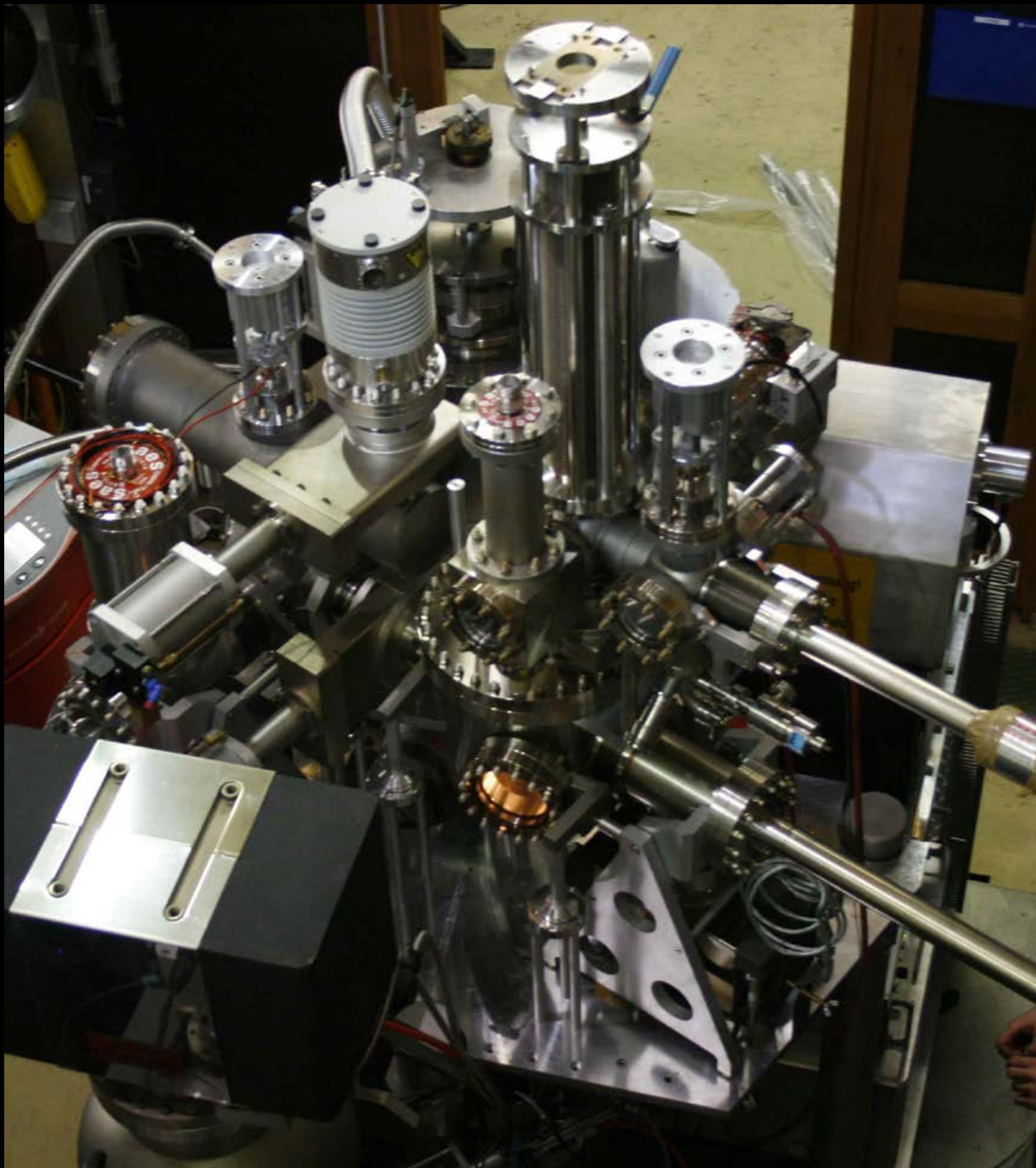
Generation of Polarized Electrons



Operation, heat cleaning and activation in extreme UHV

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

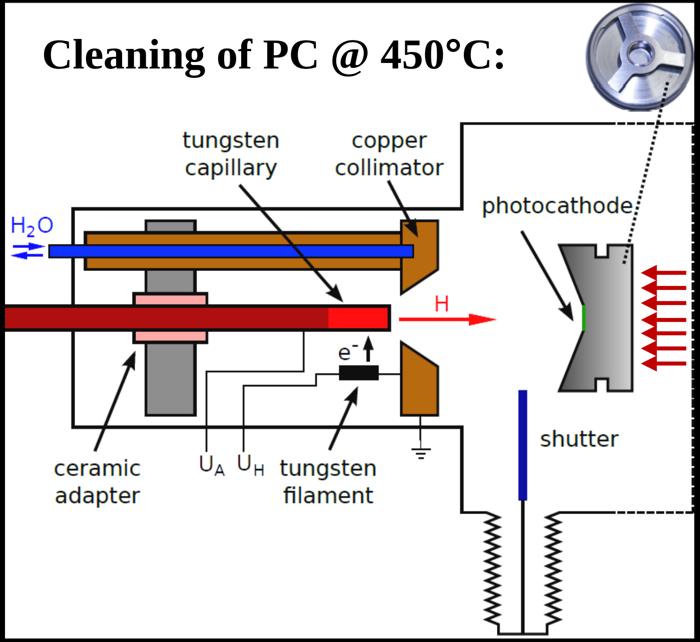
Source of Polarized Electrons



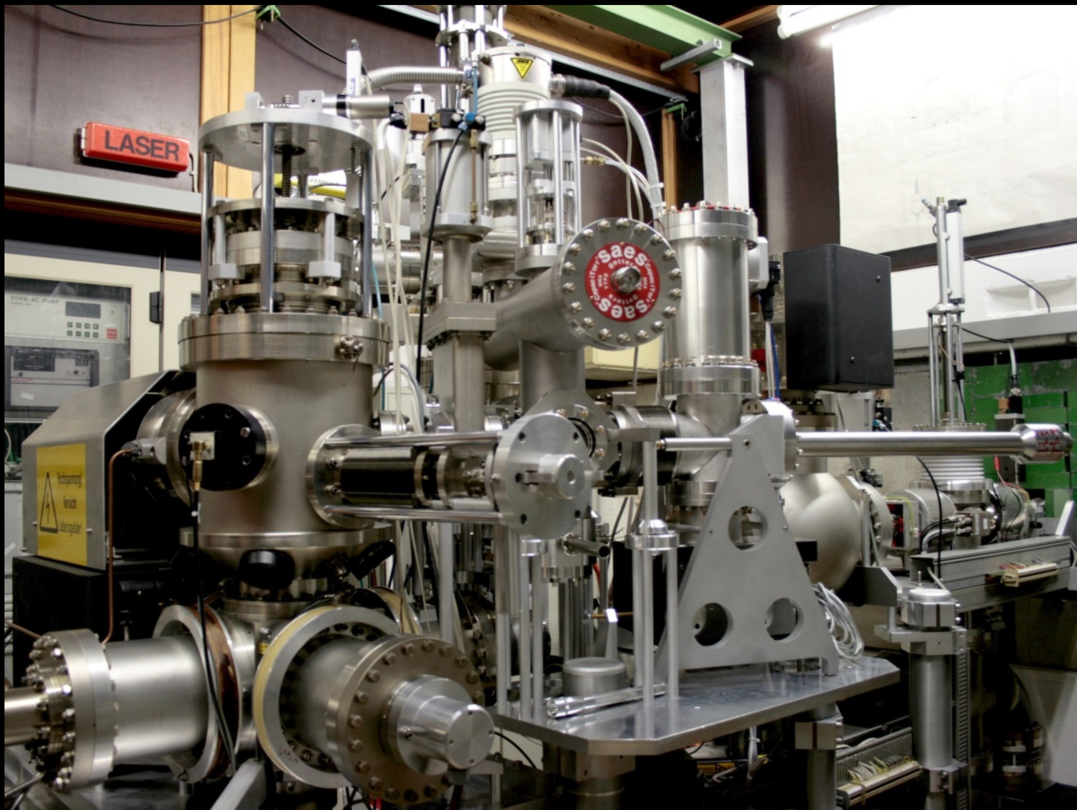
Specific features:

- inverted HV geometry
- adjustable perveance
- full load lock system
- H-cleaning
- $P > 80\%$ @ $E = 48$ keV
- $I = 200$ mA @ $\tau = 1\mu s$
- QE-lifetime > 1000 h

Cleaning of PC @ 450°C:



Source of Polarized Electrons



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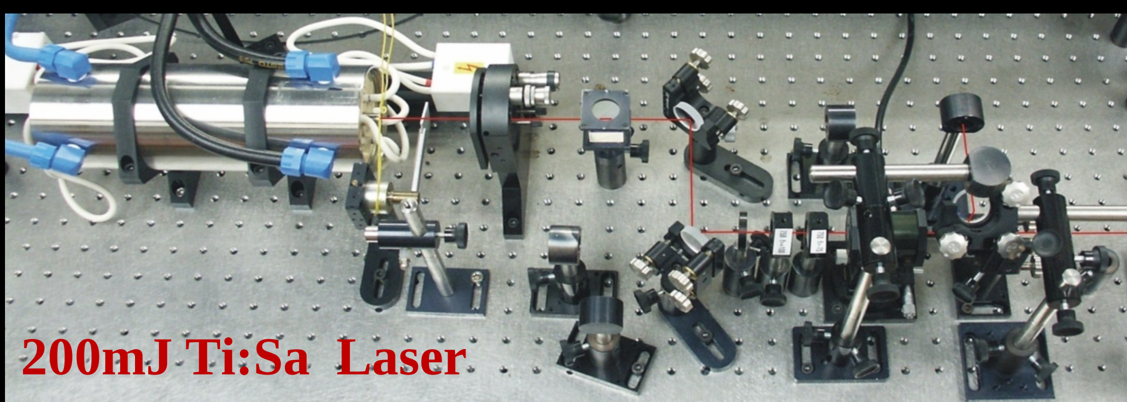
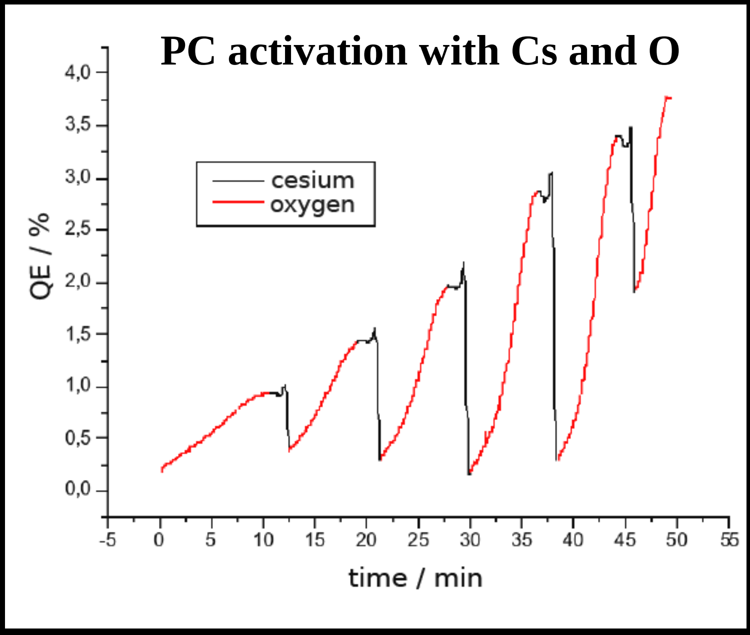
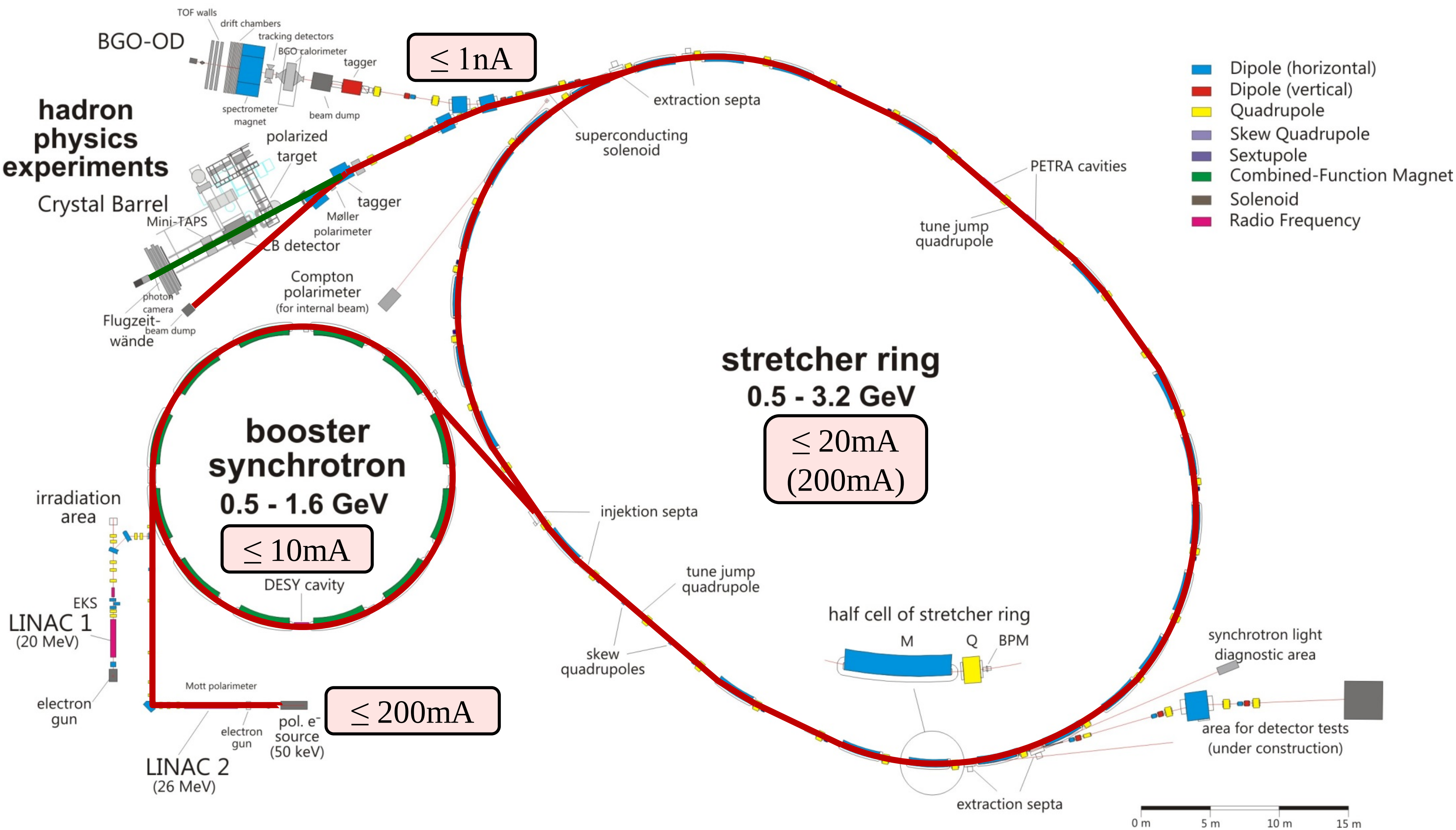
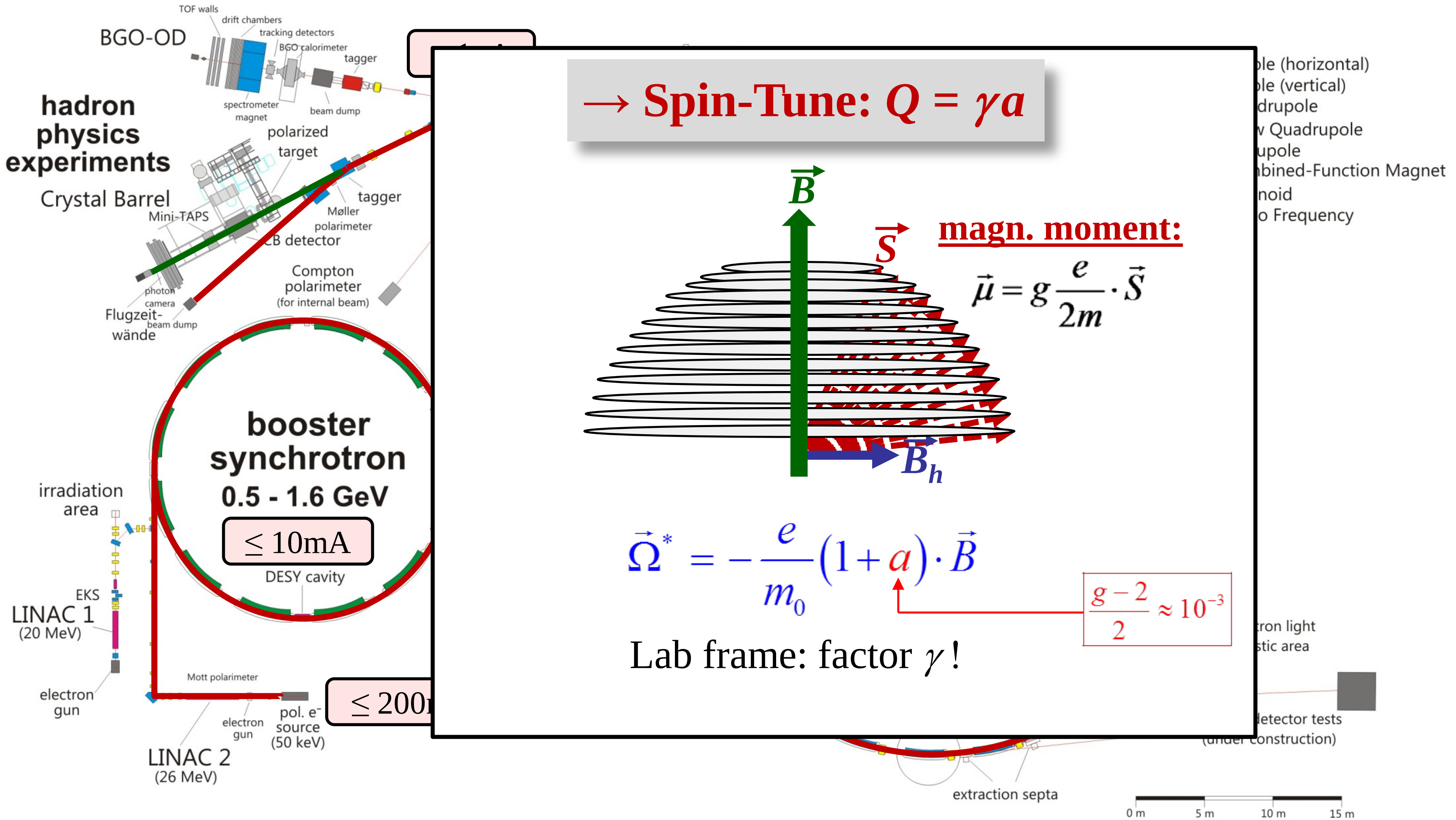




Acceleration of polarized electrons



Acceleration of polarized electrons



→ Spin-Tune: $Q = \gamma a$

magn. moment:

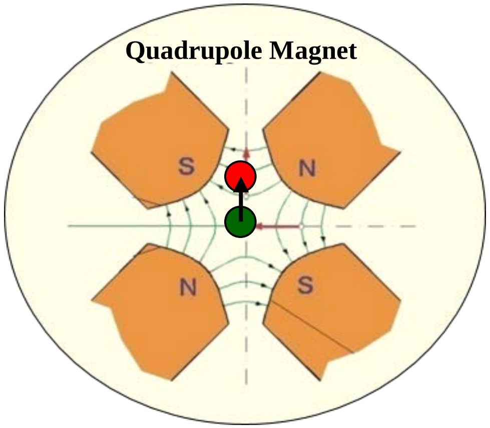
$$\vec{\mu} = g \frac{e}{2m} \cdot \vec{S}$$

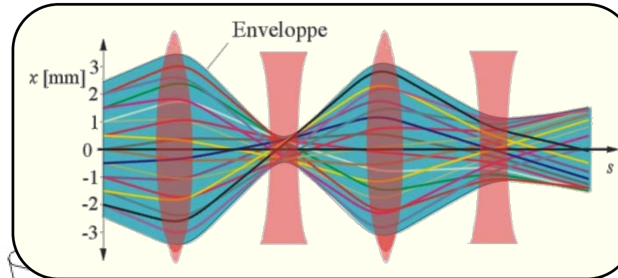
$$\vec{\Omega}^* = -\frac{e}{m_0}(1+a) \cdot \vec{B}$$

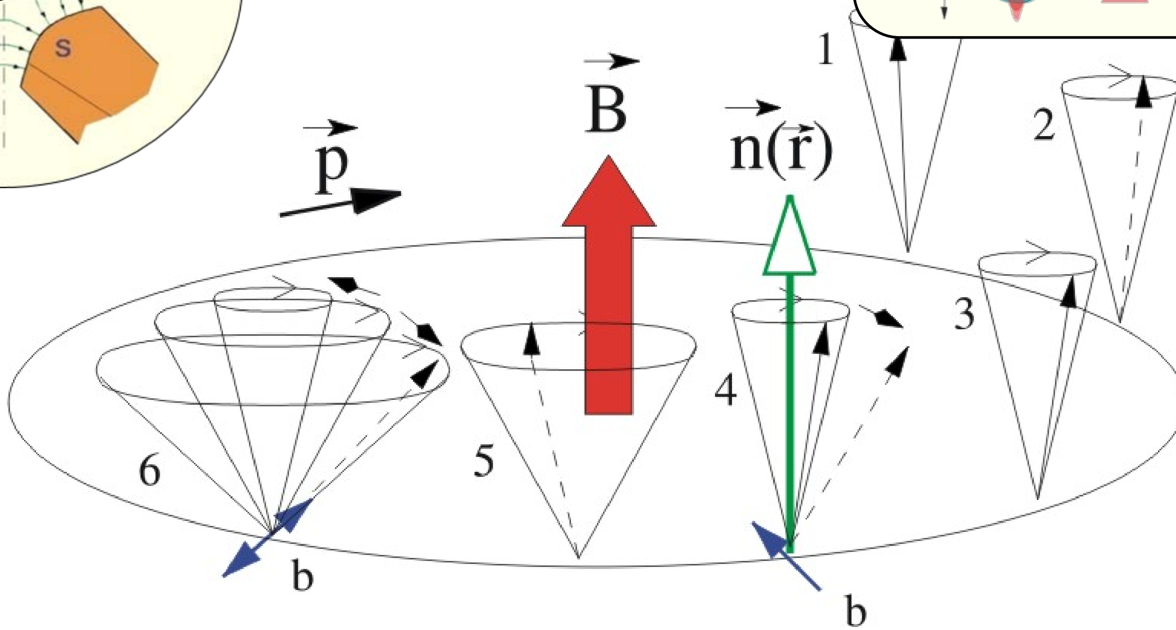
$$\boxed{\frac{g-2}{2} \approx 10^{-3}}$$

Lab frame: factor γ !

Depolarizing Resonances





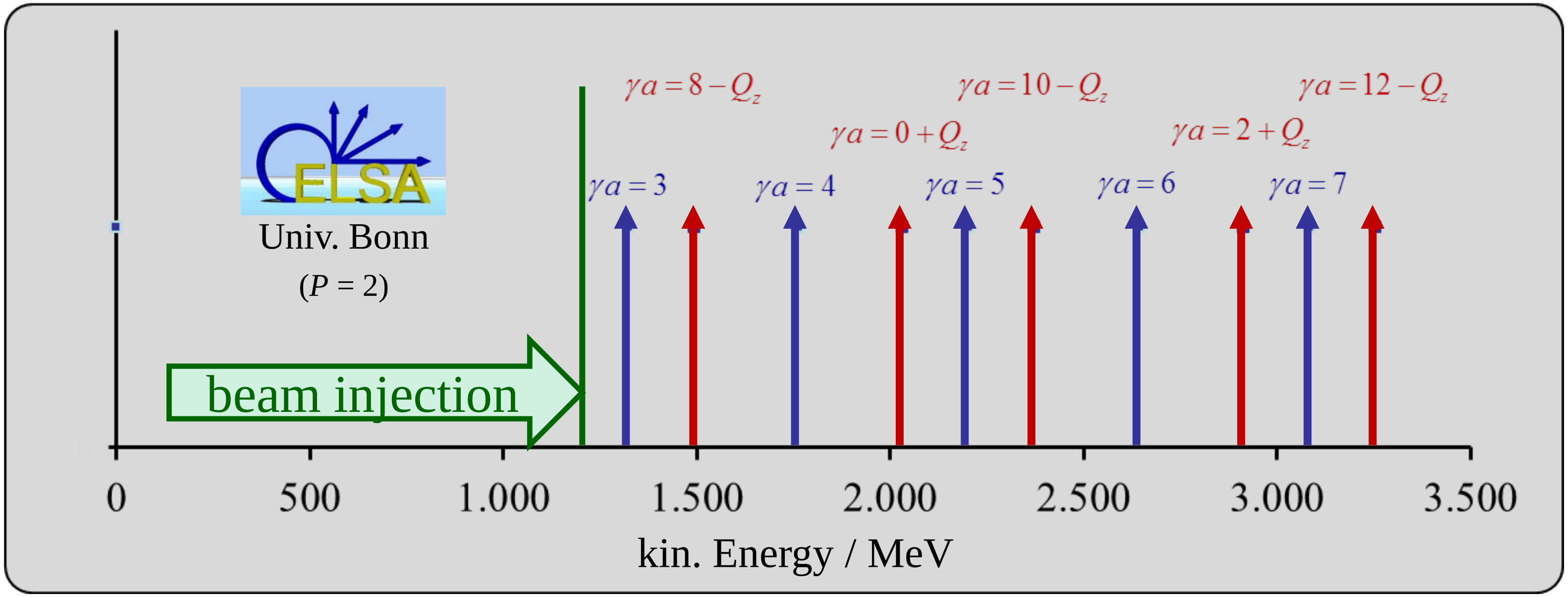


Imperfection Resonance: $\gamma \cdot a = n, \qquad n \in Z$

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

Depolarizing Resonances

Situation at ELSA:

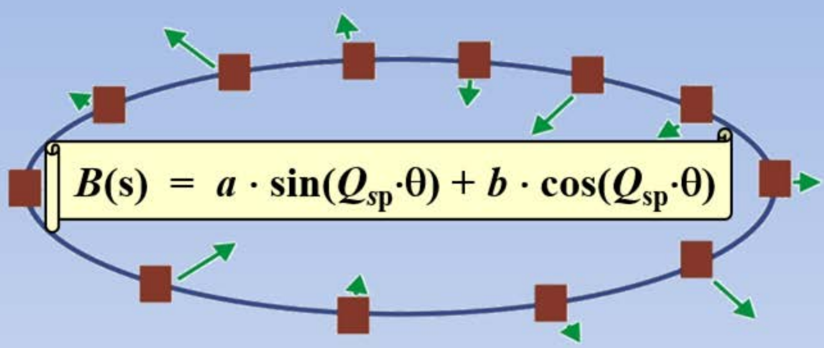


Imperfection Resonance:	$\gamma \cdot a = n,$	$n \in Z$
Intrinsic Resonance:	$\gamma \cdot a = n \cdot P \pm Q_z,$	$n \in Z$

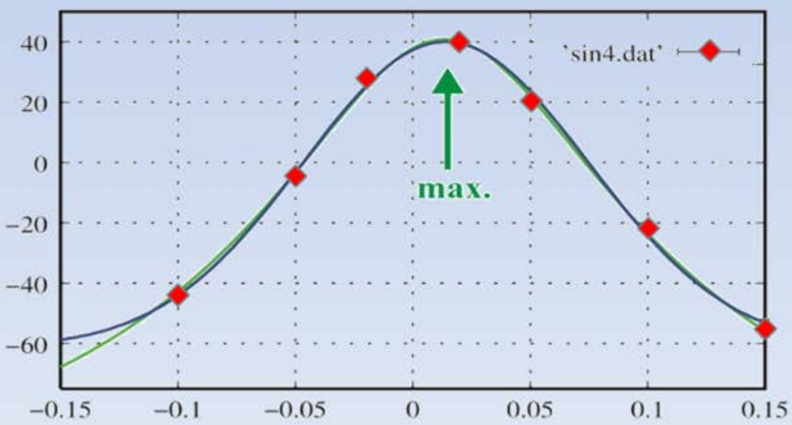
Acc. of Polarized Electrons

Integer Resonances: $\gamma a = n$

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

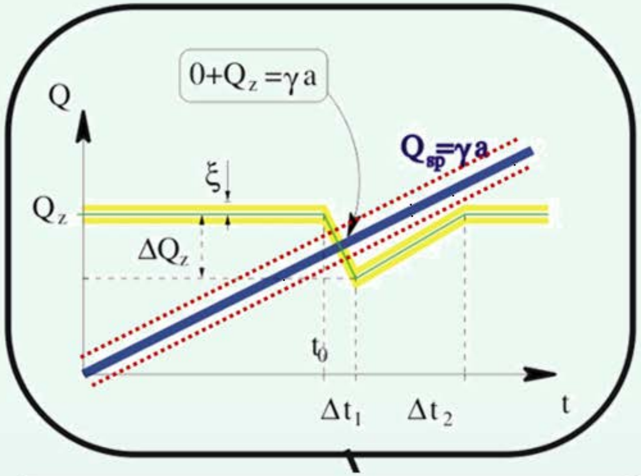


→ scan of sin amplitude:

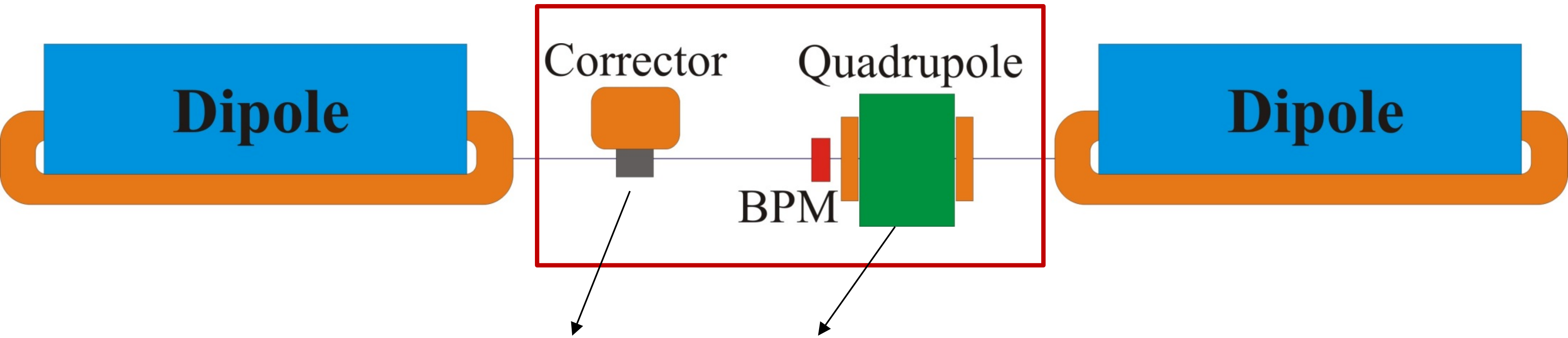


Intr. Resonances: $\gamma a = nP \pm Q_z$

- small vertical beam size
- tune jumping with pulsed quads



Spin-Orbit Response Technique

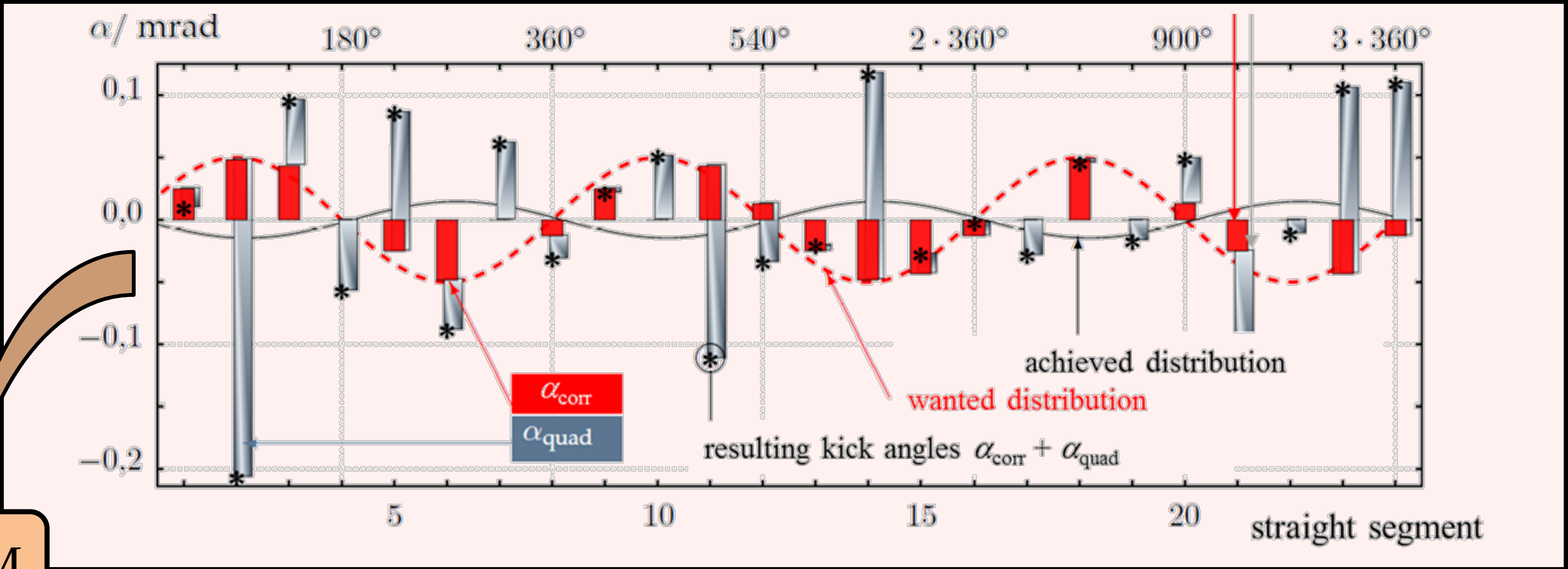


2 Contributions: $\alpha_n = \boxed{\sum_{j\in Dip_n} \alpha_{corr,j}} + \boxed{l\cdot \sum_{j\in Dip_n} k_j \cdot \Delta z_j} = \sum_{j\in Dip_n}\alpha_{corr,j} + l\cdot\sum_{j\in Dip_n} k_j\cdot\left(\mathbf{ORM}\cdot\vec{\alpha}_{corr}\right)_j$

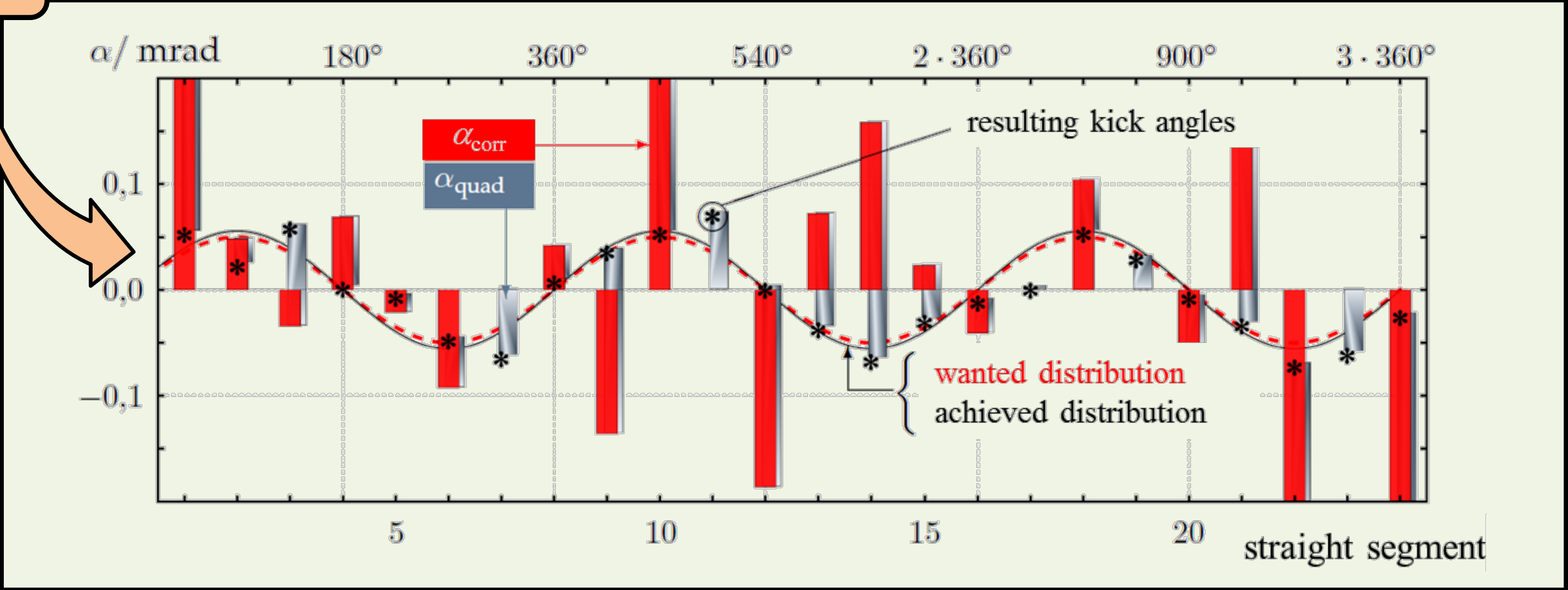
Harmonic Correction Matrix: $\vec{\alpha}_{harm} = \mathbf{HCM}\cdot\vec{\alpha}_{corr}$

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

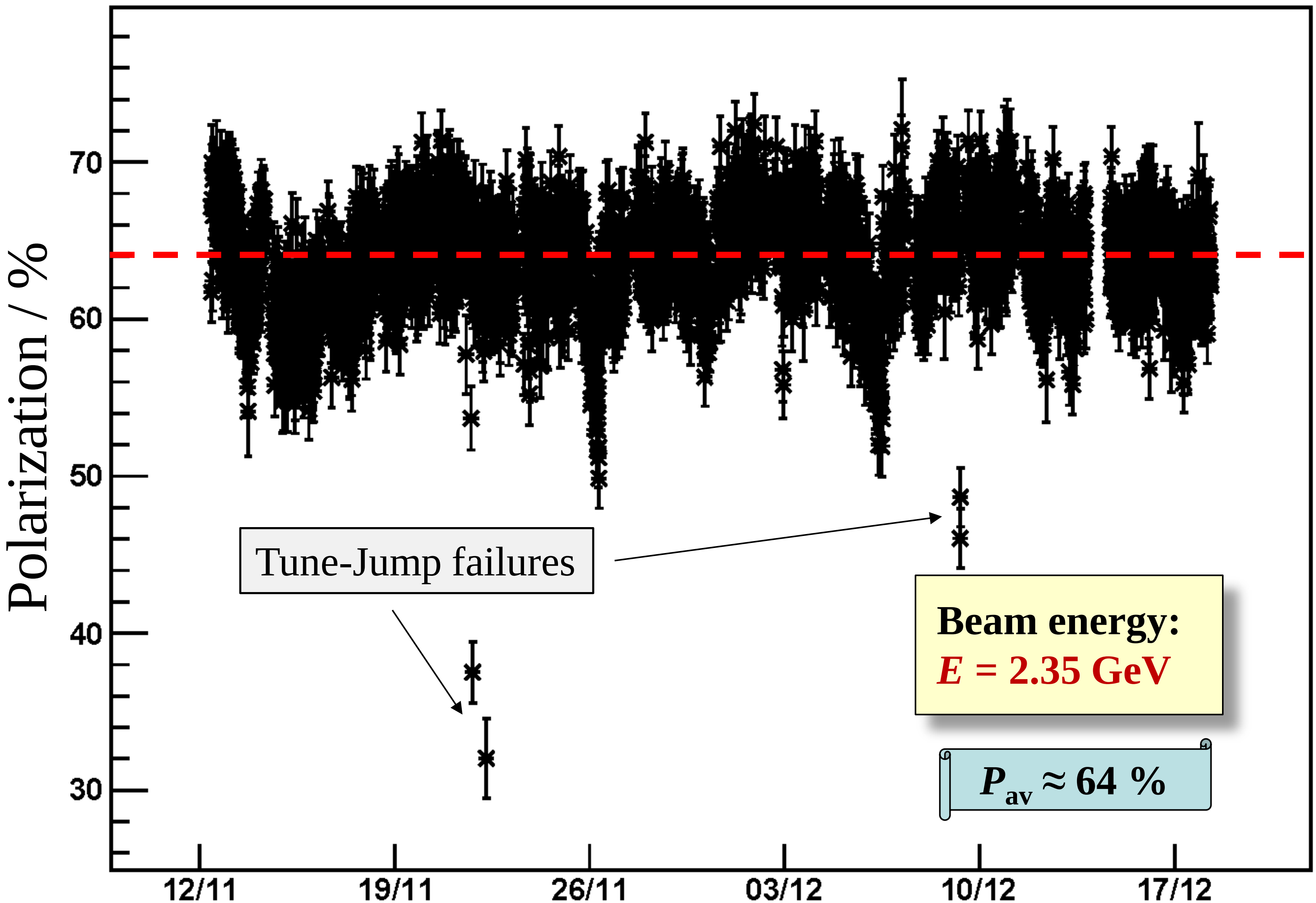
Spin-Orbit Response Technique



HCM



Polarization at the Experiment

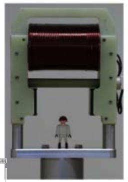
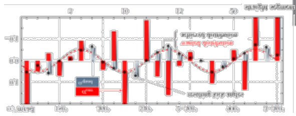
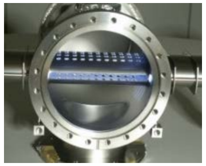


List of Research Efforts

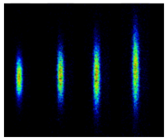
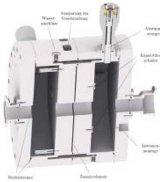
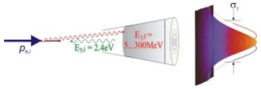
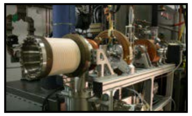
($P \rightarrow 80\%$, $I \rightarrow 200\text{mA}$)

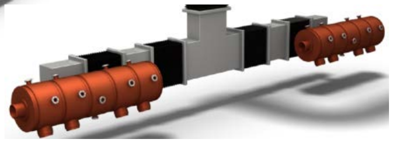
- **Source of polarized electrons**
- Precise and fast BPM system: $\Delta_{x,z} \approx \mu\text{m}$, 1kHz
- Fast bipolar steerer system: $\dot{B} = 2\text{T/sec}$, $B{\cdot}l \approx 0.01\,\text{T}{\cdot}\text{m}$
- **Harmcorr based on spin-orbit response technique**
- Low-impedance vacuum chambers
- 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: $\Delta A/A < 3{\cdot}10^{-4}$, $\Delta\phi < 0.04°$
- 3D ps-diagnosis based on a streak camera system
- Cavity-based BPM for low intensities: $\Delta_{x,z} \approx 0.1\text{mm}$, 100pA
- Mott, Møller and Compton polarimetry
- High current single-bunch injector
- New RF station and cavities
- Numerical simulation of spin dynamics





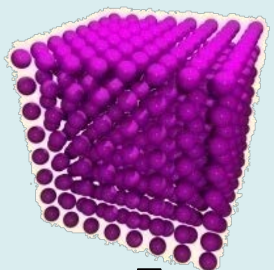





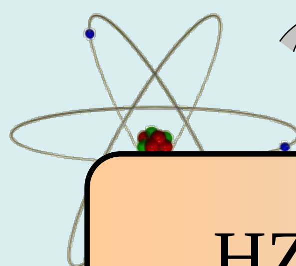


Matter and Forces

Electromagnetic Interaction

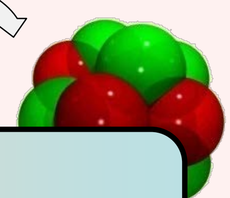
Crystal Lattice | Atom





Strong Interaction

Nucleus | Hadron



HZDR ← Bonn

10^{-9}m | 10^{-10}m | 10^{-14}m | 10^{-15}m

„N… ometer“ | *„Fem… eter“*

Crystal… amorphous structure?
Ultrafast d… amic phenomena?

→ Compact sources of intense (and coherent) secondary beams!

Mass of the … n?
Spin structur… e nucleon?

→ Intense polarized GeV γ-beams!

Challenges for Light Sources

(with respect to X-ray production)

Future R&D will concentrate on:

- highest intensities
- ultrashort pulses

$\Big\}$ → SASE FELs

- 3D coherent x-ray beams → adv. seeding methods

or shortly: **higher-faster-further**

But another focus should be laid on

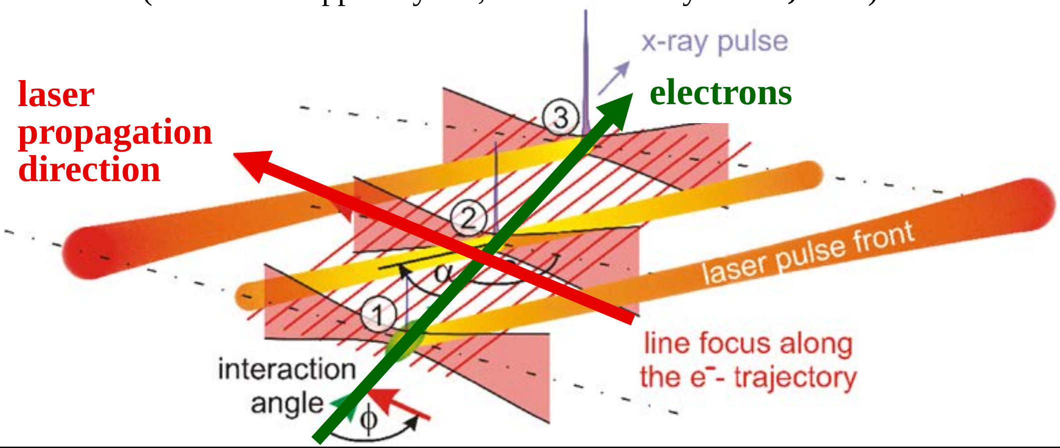
making facilities more compact and efficient

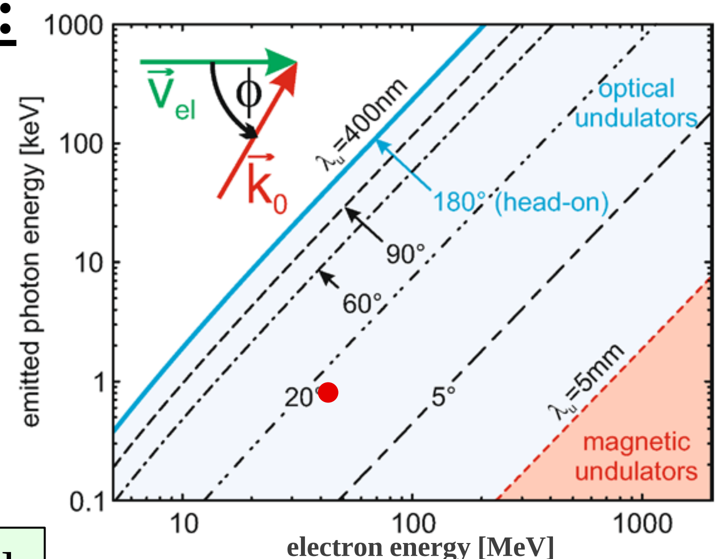
(which has been explicitly mentioned on the last strategy meeting by BMBF!)

Compact EUV FELs

TW Thomson Scattering (TWTS-OFEL):

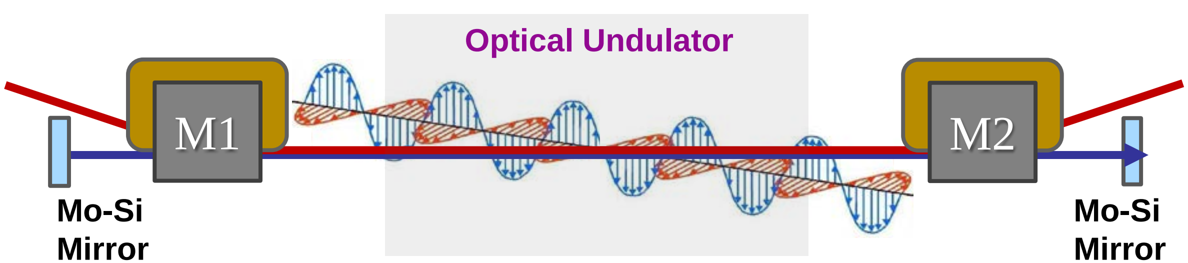
(taken from Appl. Phys. B, 2010 and J. Phys. B **47,** 2014)



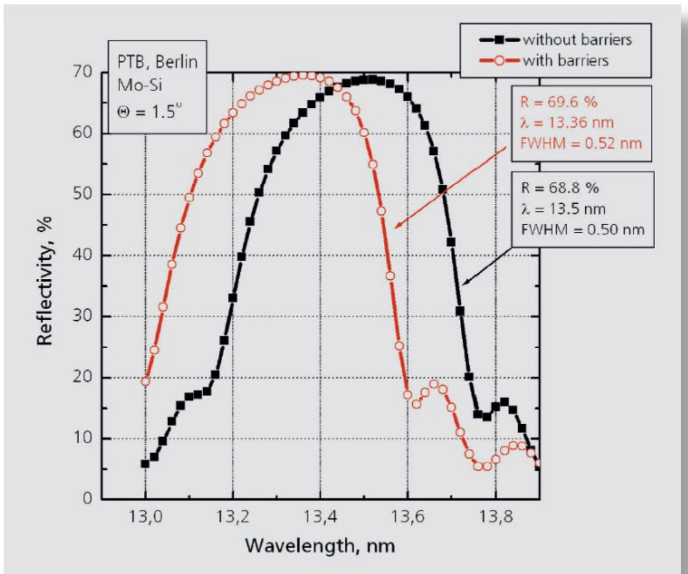


λ = 13.5nm requires τ =150fs, q =1nC, ε_n=0.92μm·rad

Cavity-based seeding (TWTS-OFELO):

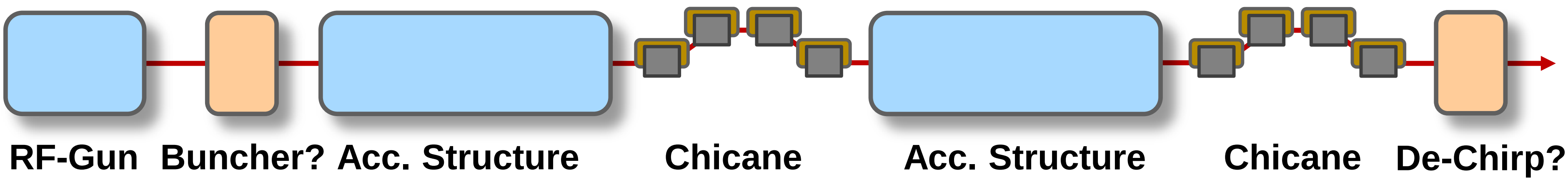


full 3D coherent EUV radiation @ λ = 13.5nm!



Intense and Short Bunches with low Emittances

Set-up @ ELBE:



- Optimization of ballistic and magnetic bunching
- Precise synchronization and stabilization of accelerator RF
- Upgrade of SRF-gun, use of high QE photocathodes (Cs_2KSb, GaAs, GaN)
- …

Program will benefit from extensive experience with SRF-guns!

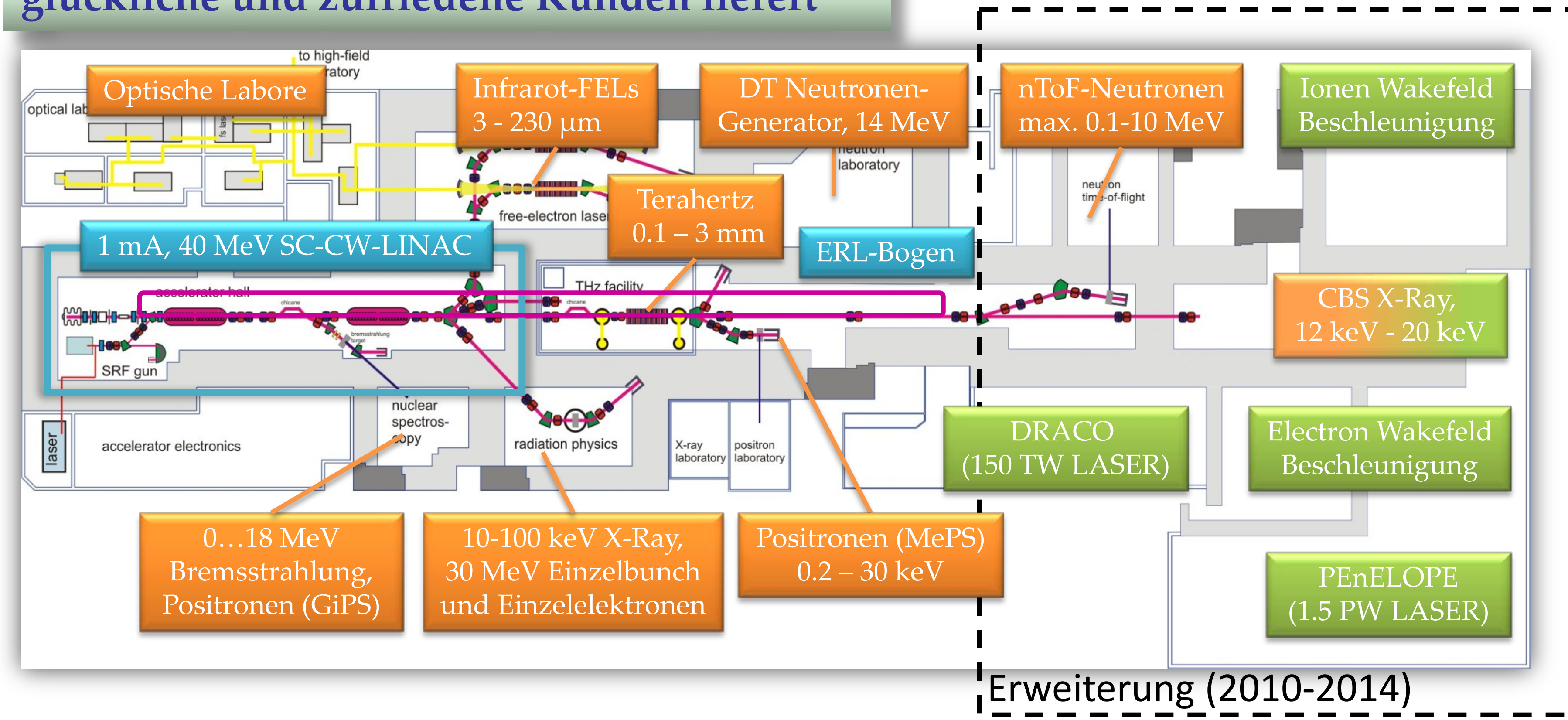
→ super-radiant THz generation in quasi-cw mode (beyond 10 THz)
→ injection into Laser-Plasma-Wakefield-Accelerator (inj-LWPA)
→ intense coherent EUV photon beams with TWTS-OFEL
→ fully 3D coherent quasi-cw EUV photon beams with TWTS-OFELO

Strahlungsquelle ELBER

Elektronen-Linearbeschleuniger mit hoher Brillanz und Energie-Rückgewinnung

Wikipedia: "Die eierlegende Wollmilchsau … die nur Vorteile hat, alle Bedürfnisse befriedigt und allen Ansprüchen genügt"

… und noch mehr Milch und Wolle für glückliche und zufriedene Kunden liefert"



Dr.-Ing. André Arnold | Institut für Strahlenphysik | www.hzdr.de

Conclusions

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

- **Challenging Perspectives @ HZDR:**
  - **demonstration of injection into LWPA**
  - **coherent EUV photons** from TWTS-OFEL (compact, efficient)
  - **3D coherent EUV photons (quasi cw)** from TWTS-OFELO
  - **higher intensities** - with energy recovery mode?
  - …

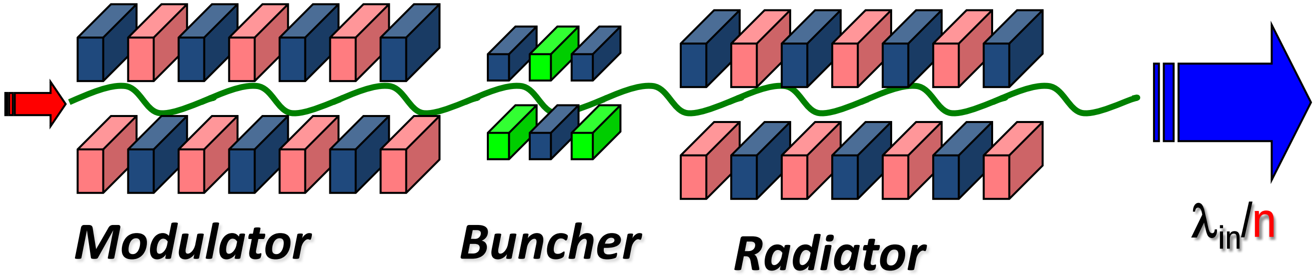
Thank you for your attention!

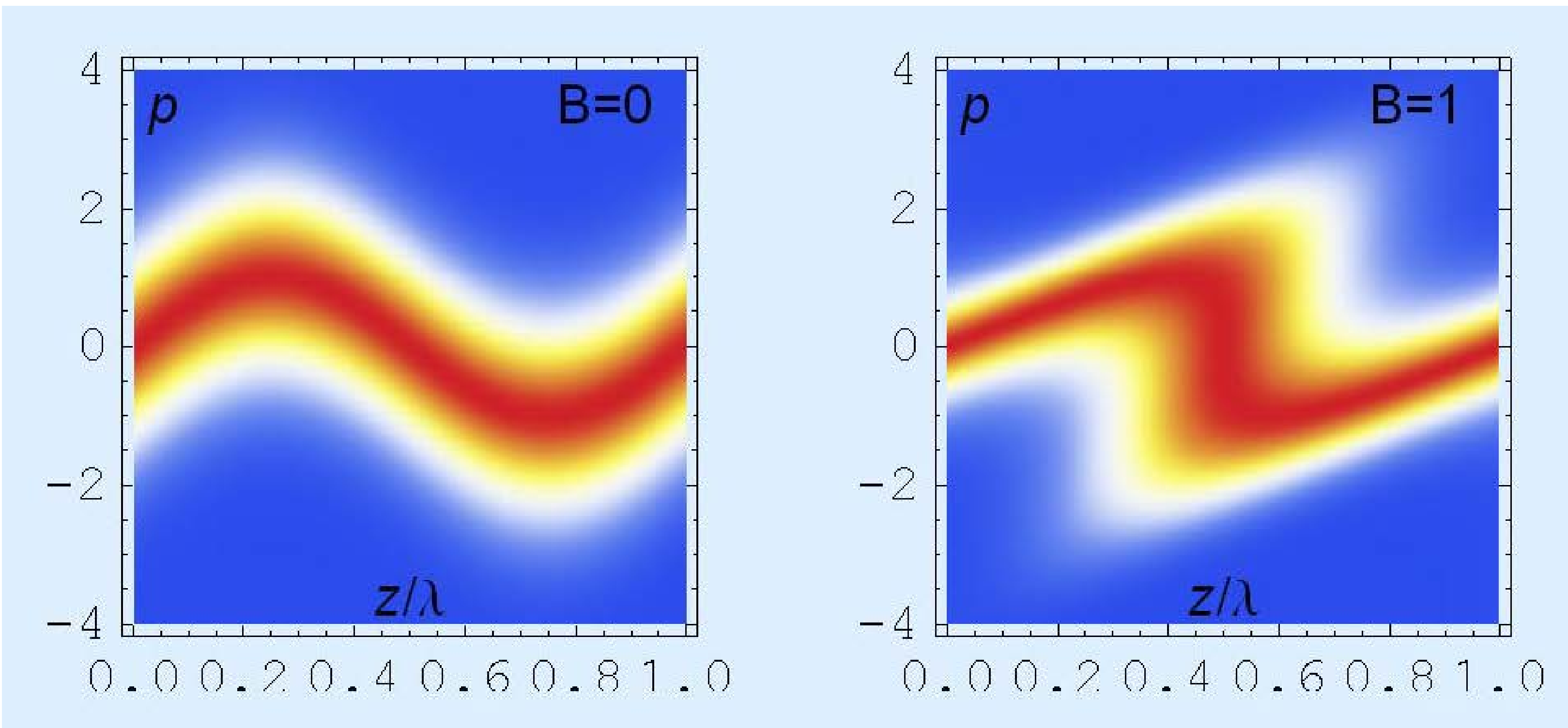
Machine Development: PhD students in the ELSA control room

Seeding of FELs

HGHG

(high gain harmonic generation)

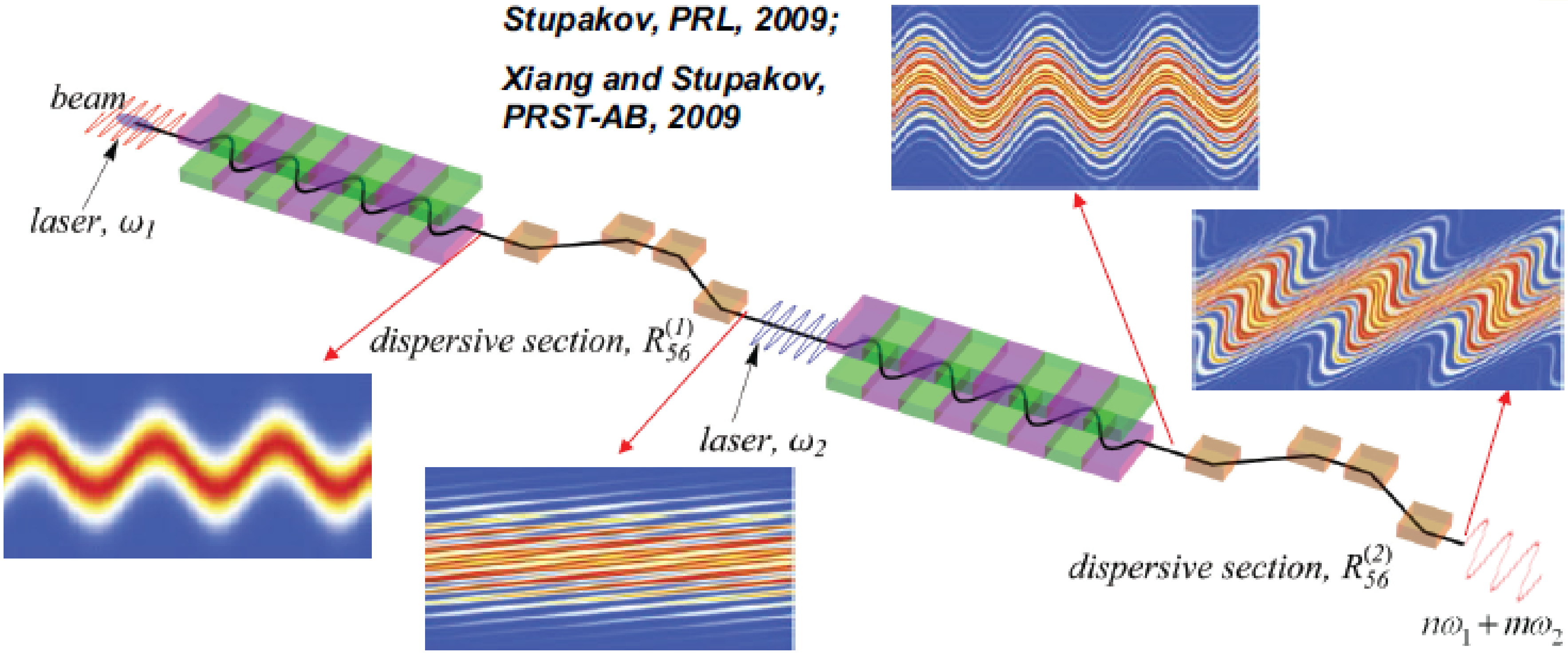




EEHG (Echo-enabled harmonic generation)

Stupakov, PRL, 2009;

Xiang and Stupakov, PRST-AB, 2009



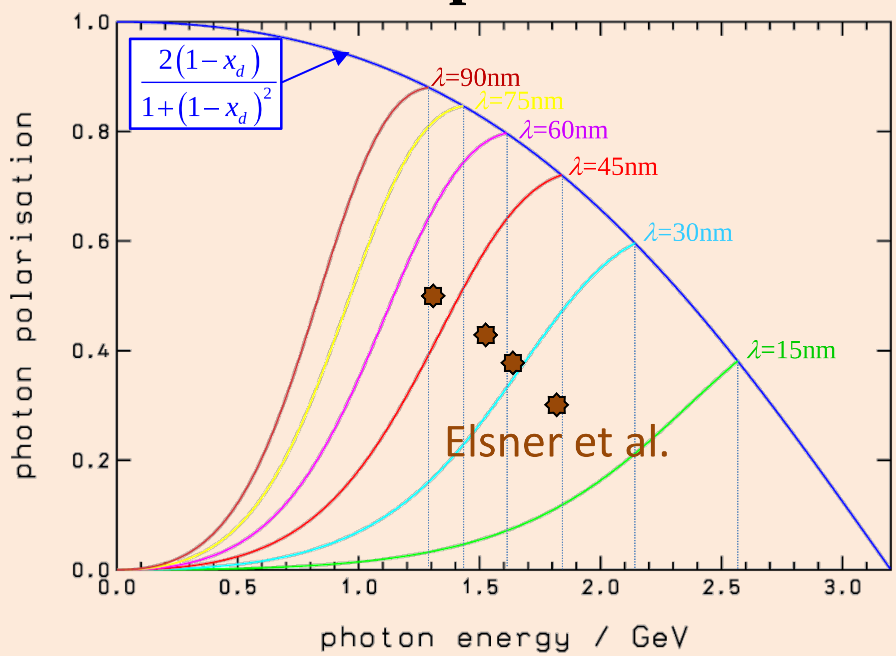
- First laser to generate energy modulation in electron beam
- First strong chicane to split the phase space
- Second laser to imprint energy modulation
- Second chicane to convert energy modulation into density modulation

$$n \gg \Delta E/\sigma_E$$

Coherent Bremsstrahlung

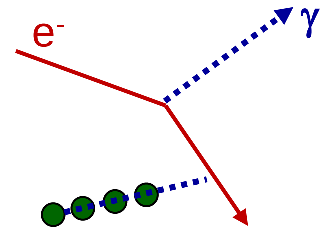
Beam energy: 3.2 GeV

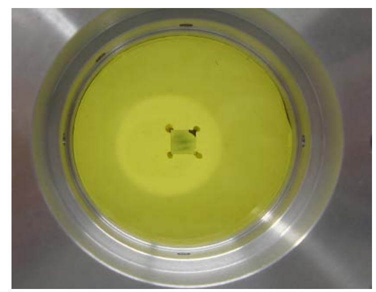
Linear polarization

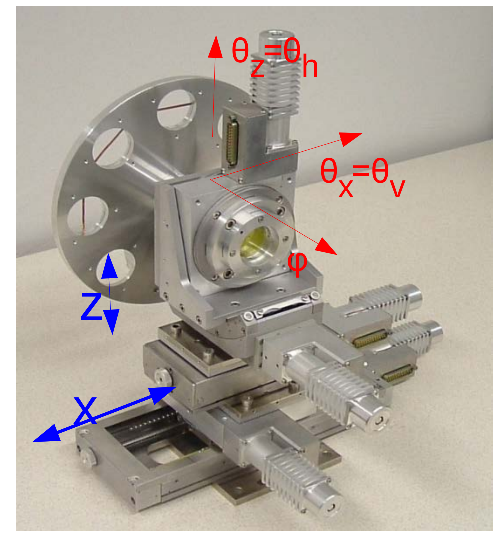


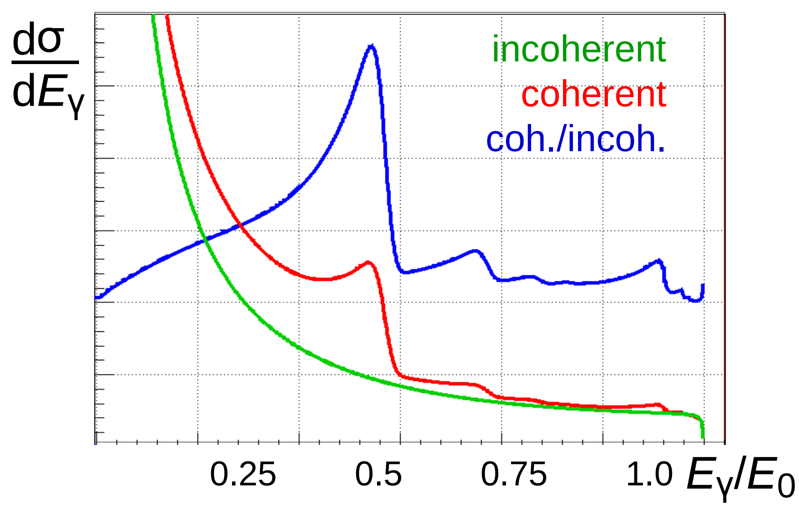
$$P = \frac{2x^2Q^2}{1-x}\left\{1+(1-x)^2 - \frac{4x^2Q^2}{1-x}\left(\frac{1-x}{xQ}-1\right)\right\}^{-1}$$

Increase of beam energy desirable!









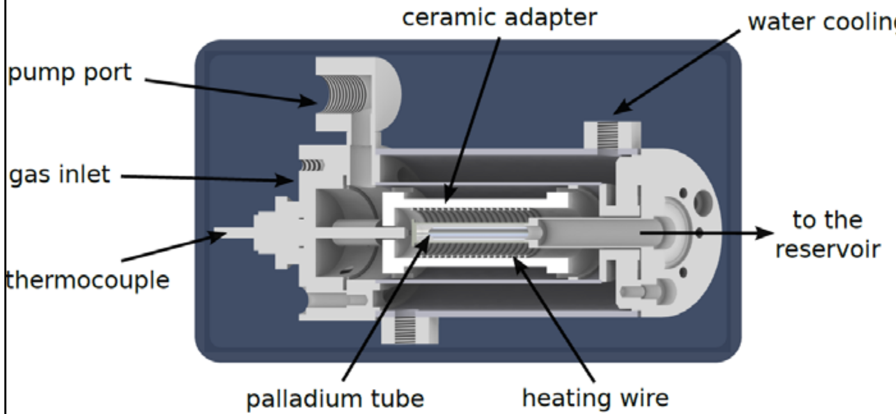
Hydrogen Cleaning

$$Ga_2O_3 + 4H \rightarrow Ga_2O + 2H_2O \uparrow$$

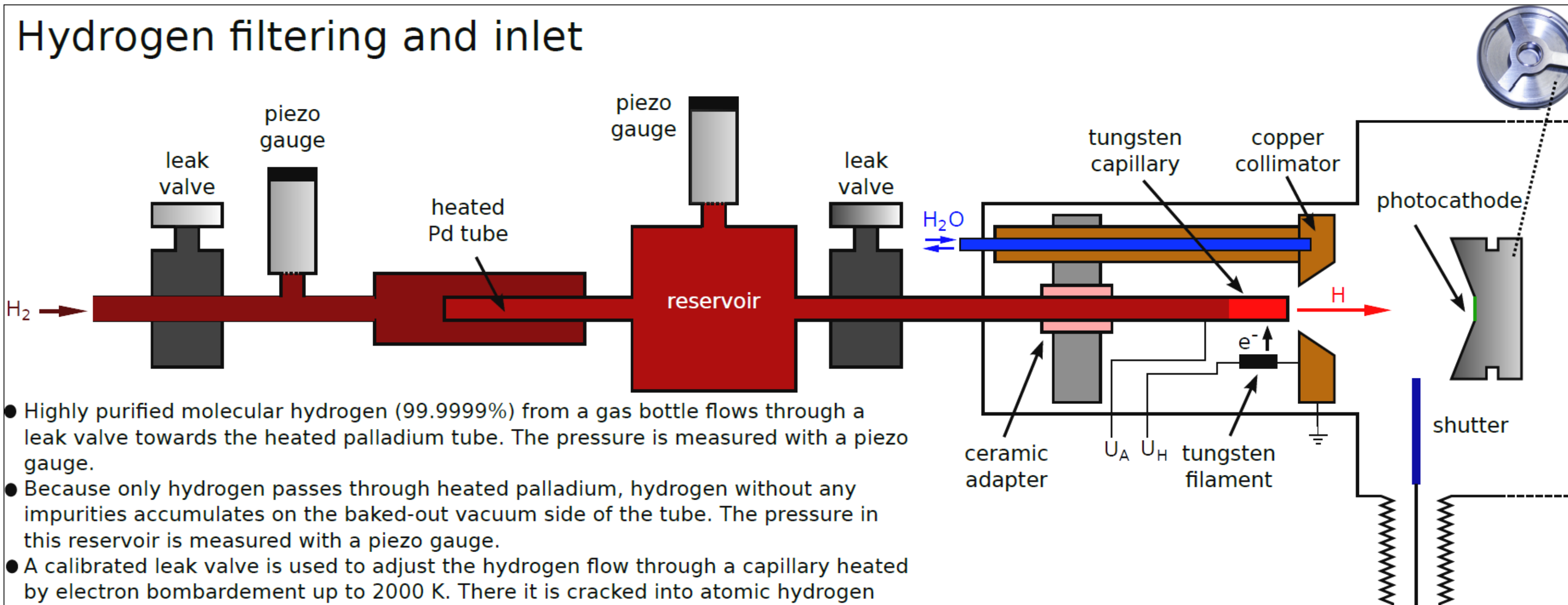
$$Ga_2O + 2H \rightarrow 2Ga + H_2O \uparrow$$

$$As_2O_x + 2xH \rightarrow As_2 + xH_2O \uparrow$$

Hydrogen Filter



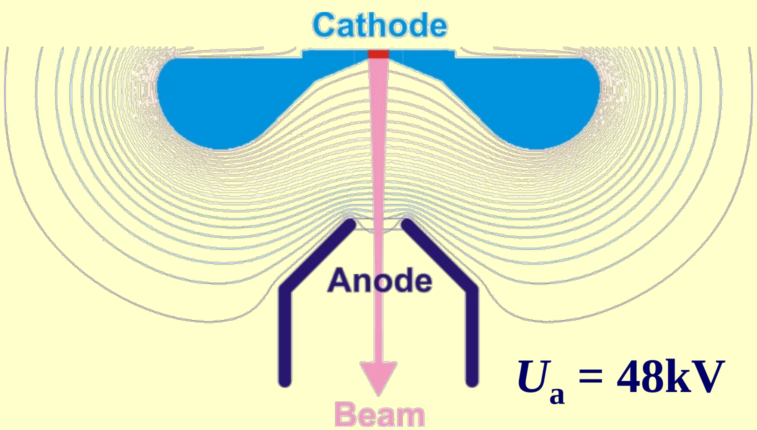
Hydrogen filtering and inlet



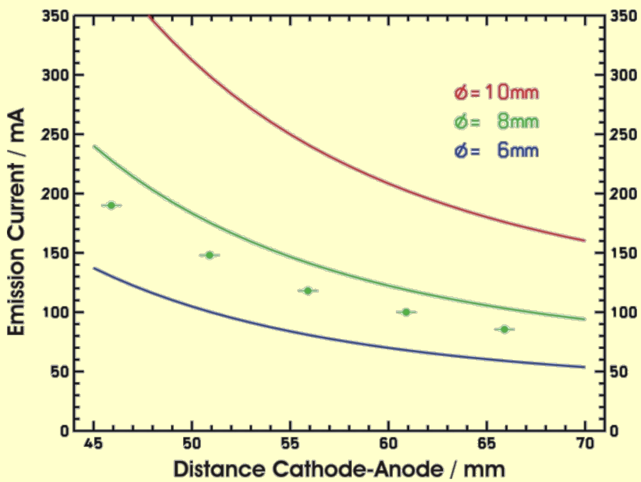
- Highly purified molecular hydrogen (99.9999%) from a gas bottle flows through a leak valve towards the heated palladium tube. The pressure is measured with a piezo gauge.
- Because only hydrogen passes through heated palladium, hydrogen without any impurities accumulates on the baked-out vacuum side of the tube. The pressure in this reservoir is measured with a piezo gauge.
- A calibrated leak valve is used to adjust the hydrogen flow through a capillary heated by electron bombardement up to 2000 K. There it is cracked into atomic hydrogen and is directed to the photocathode.

Space Charge limited Emission

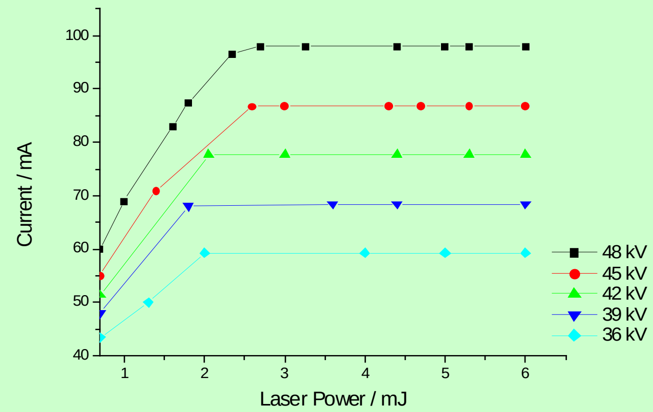
EGUN-Simulations:

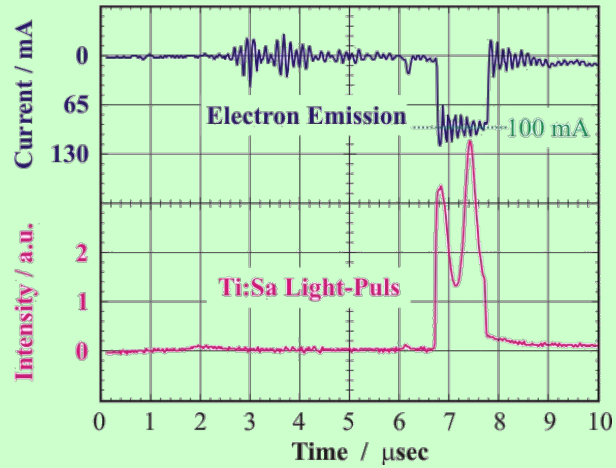


$U_a = 48\text{kV}$



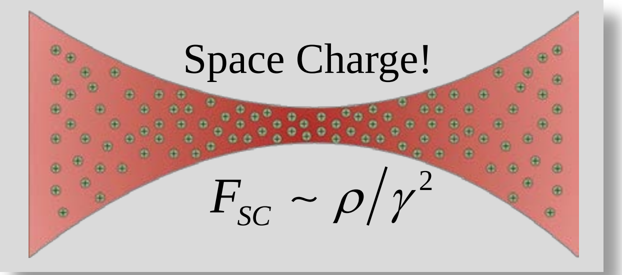
Measurements:

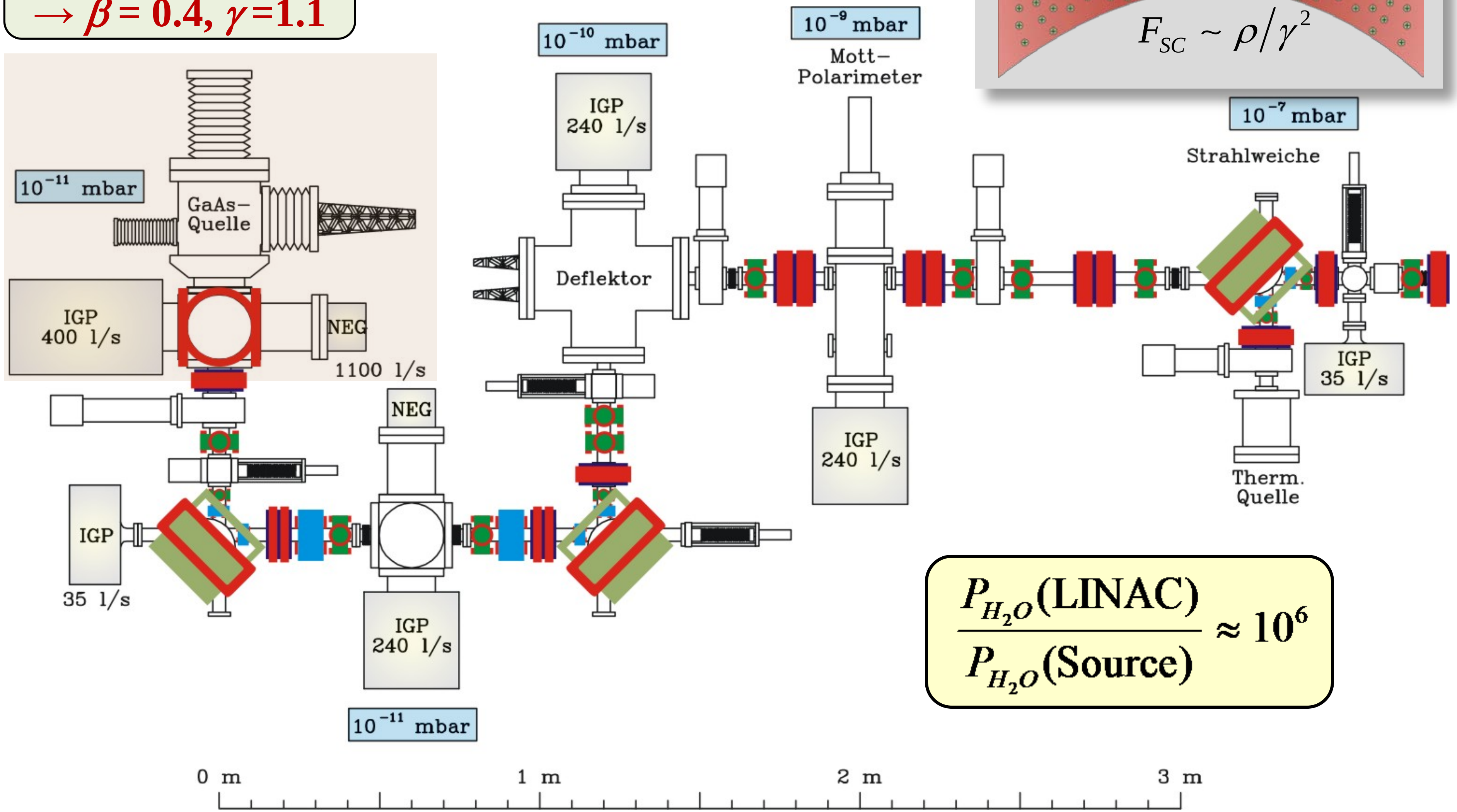




Source and Transfer Line

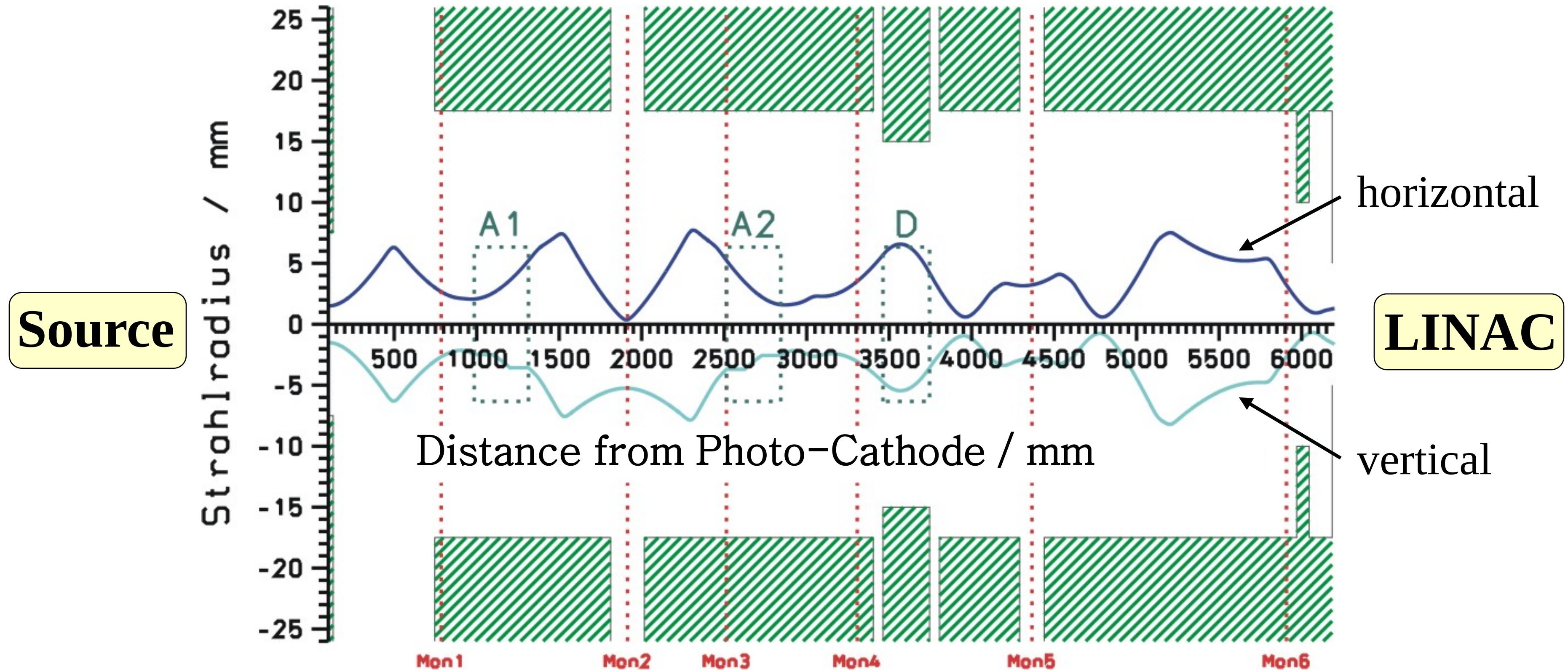
E = 48 keV
$\rightarrow \beta = 0.4,\ \gamma = 1.1$





$$\frac{P_{H_2O}(\text{LINAC})}{P_{H_2O}(\text{Source})} \approx 10^6$$

Space-Charge dominated Beam Transfer at 48 keV



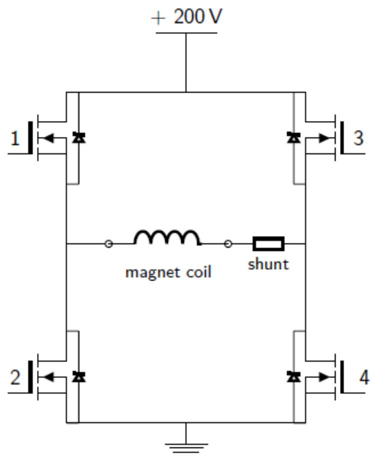
$$\frac{d^2x}{ds^2} + \left\{k_x(s) + S(s) + T(s)\right\} \cdot x - \frac{\varepsilon_x^2}{x^3} - \frac{2\zeta}{x+y} = 0$$

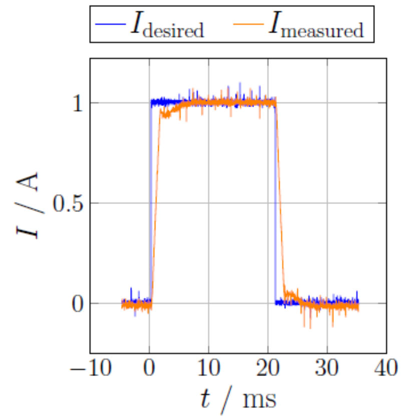
$$\frac{d^2y}{ds^2} + \left\{k_y(s) + S(s) + T(s)\right\} \cdot y - \frac{\varepsilon_y^2}{y^3} - \frac{2\zeta}{x+y} = 0$$

Transfer Efficiency > 99%

Fast Correction System

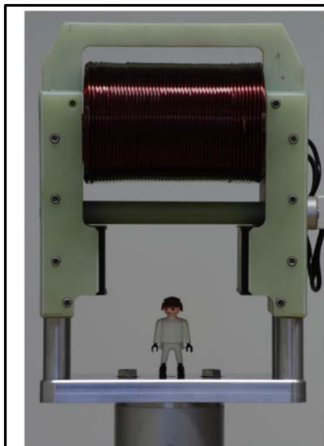
Programmable 4-Quadrant PS:





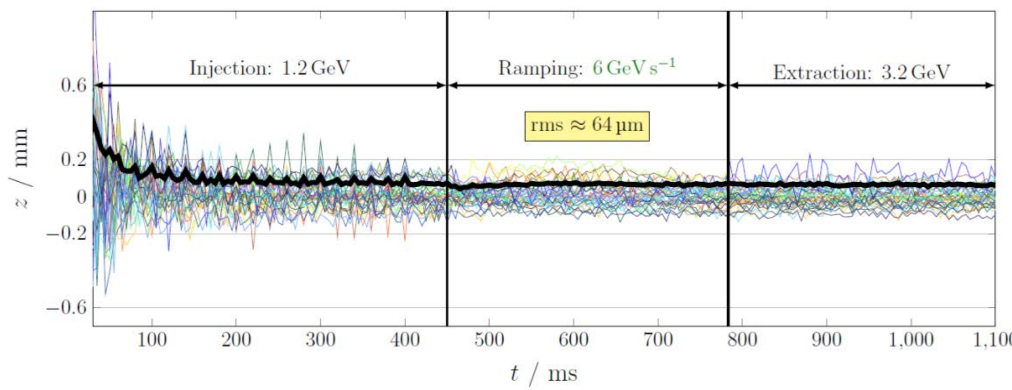
- 20 kHz pulsed H-bridge
- PI-controller
- current precision ≈ 1 ‰
- CAN-Bus module
- stored current ramps
- external trigger
- in total 54 power supplies distributed in 14 cabinets along the ELSA tunnel

Correction Coils:

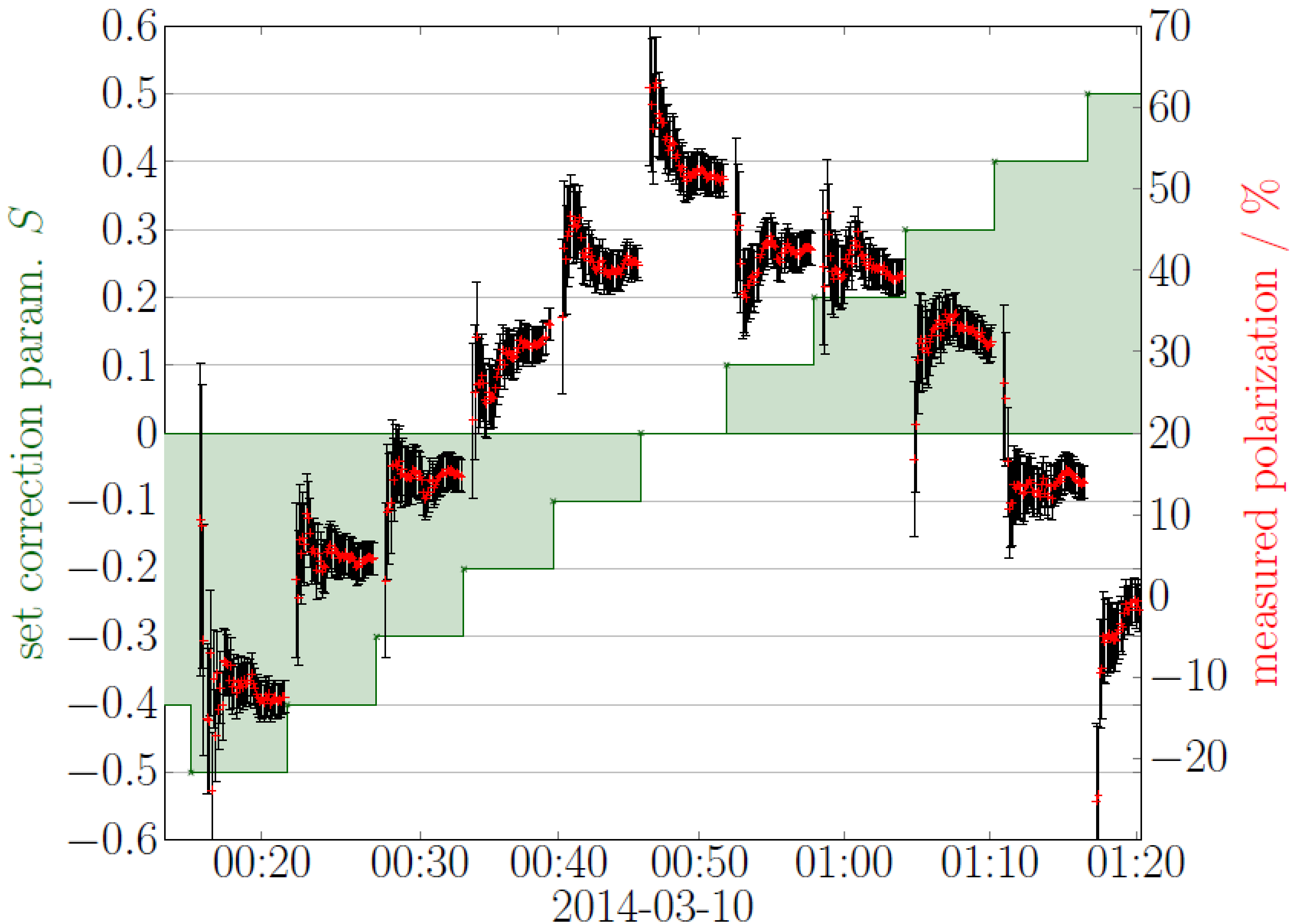


	new
voltage	200 V
max. current	8.0 A
inductance	260 mH
max. field	40 mT
weight	30 kg
field integral	9.8 mT m

$\dot{I} = 400$ A/sec ↔ $\dot{B} = 2$ Tesla/sec

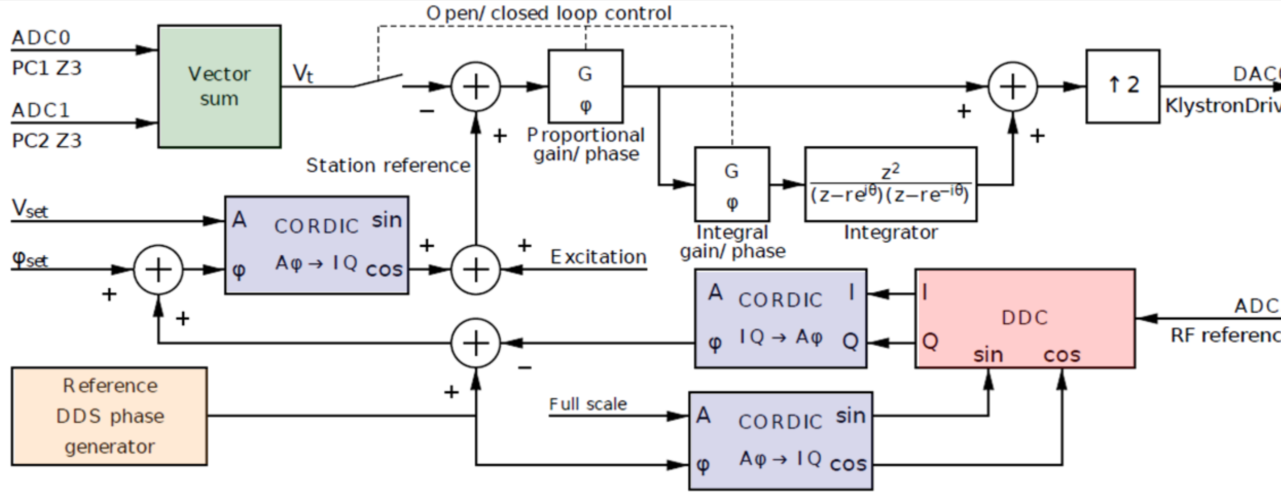


Harmcor (sine) of $\gamma a = 3$



RF Control & Stabilization

- 500 MHz, 39.2 MHz IF
- Vector sum via two-tap FIR gain/phase blocks

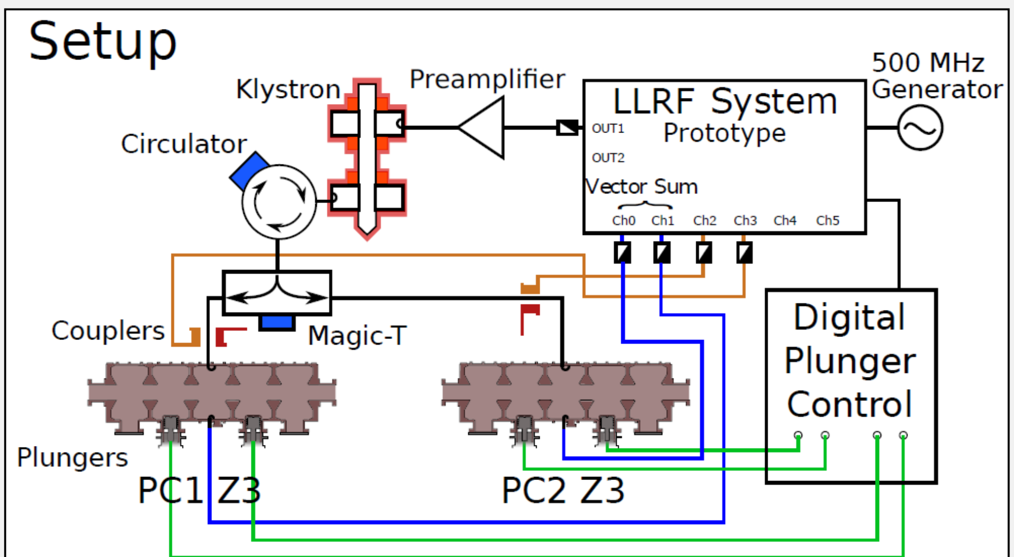


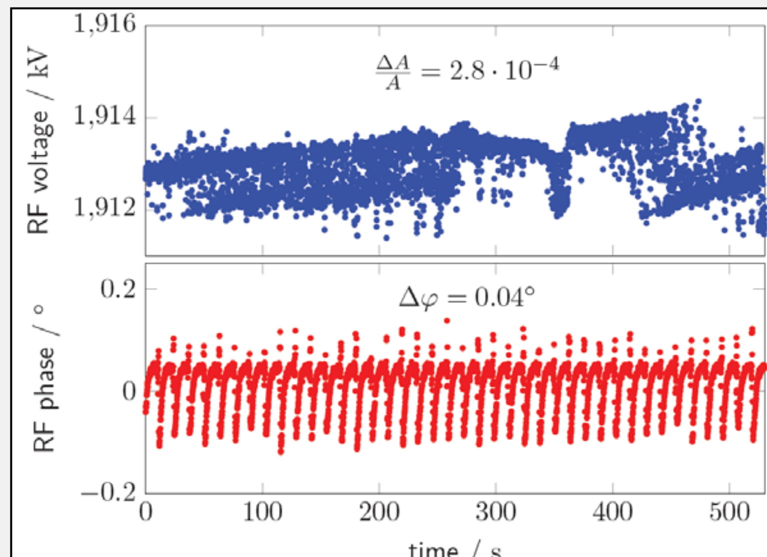
DDS: **D**irect **D**igital **S**ynthesis

DDC: **D**igital **D**own-converter

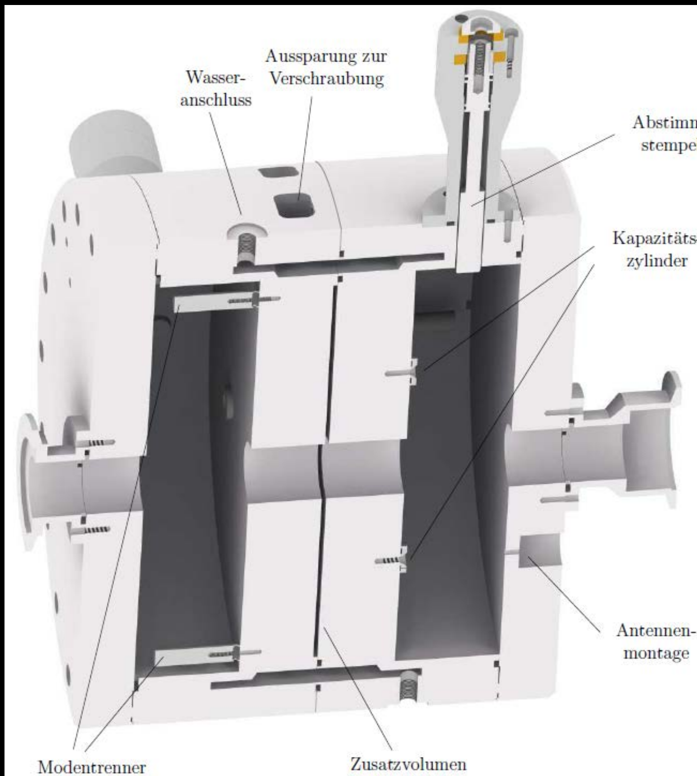
CORDIC: **Co**ordinate **R**otation **Di**gital **C**omputer

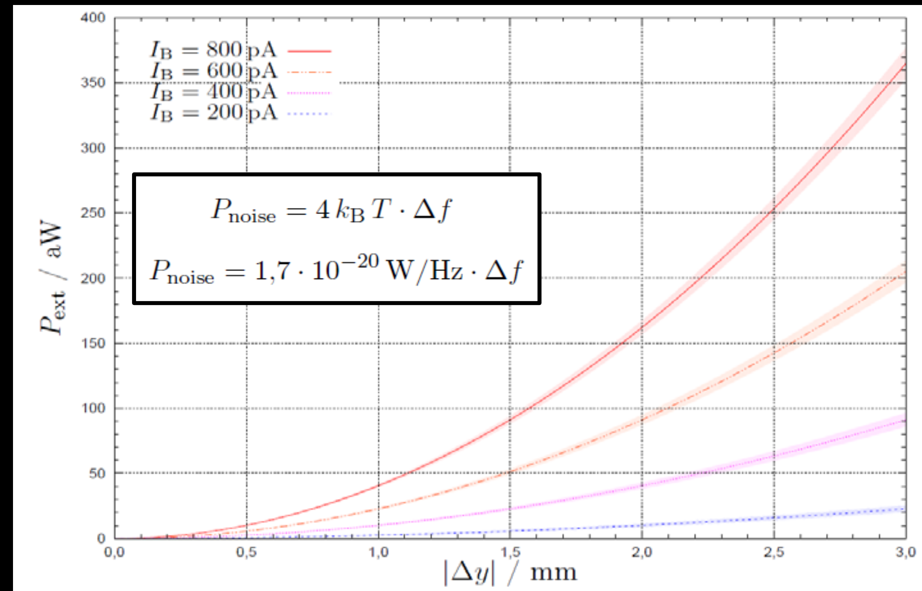
©DIMTEL, Inc.





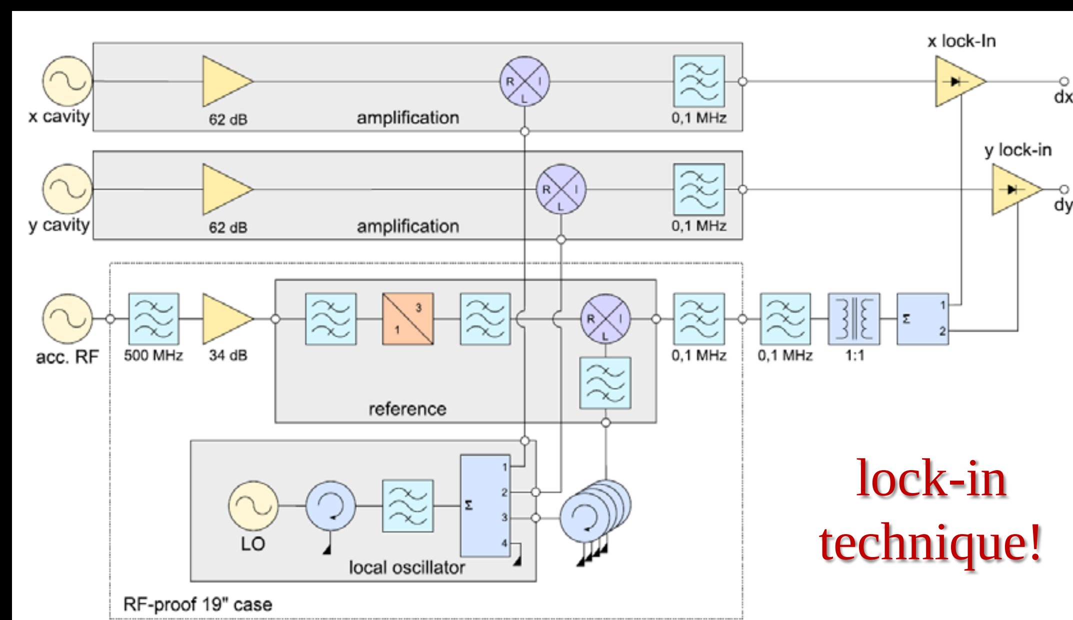
Position Measurement in the pA-Regime





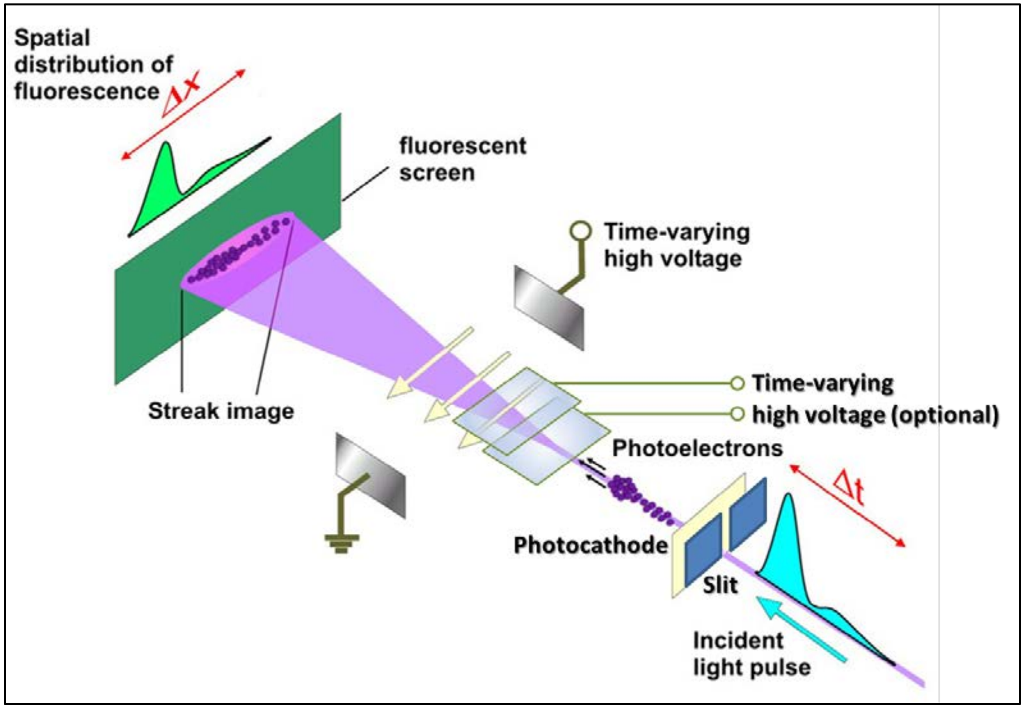
Δx < 50µm @ I = 100 pA, dx = 1mm

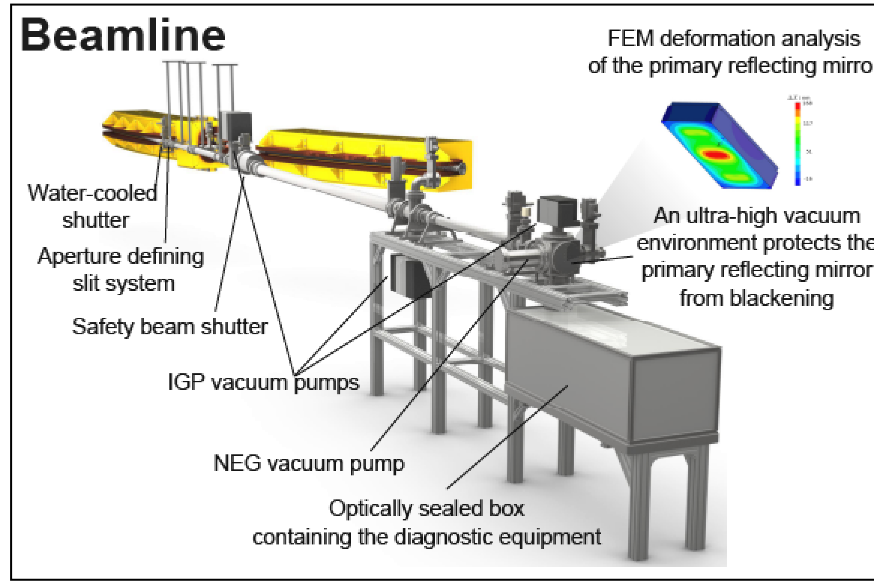
Parameter	Value
Mode	TM_{110}
Inner diameter	242 mm
Inner length	52 mm
Opening diameter	34 mm
Resonant frequency ν_0	1.499010 GHz
Shunt impedance $R_s/\Delta x^2$ (CST)	411 Ω/mm^2
Unloaded quality factor Q_0	11090
Coupling factor κ	0.89

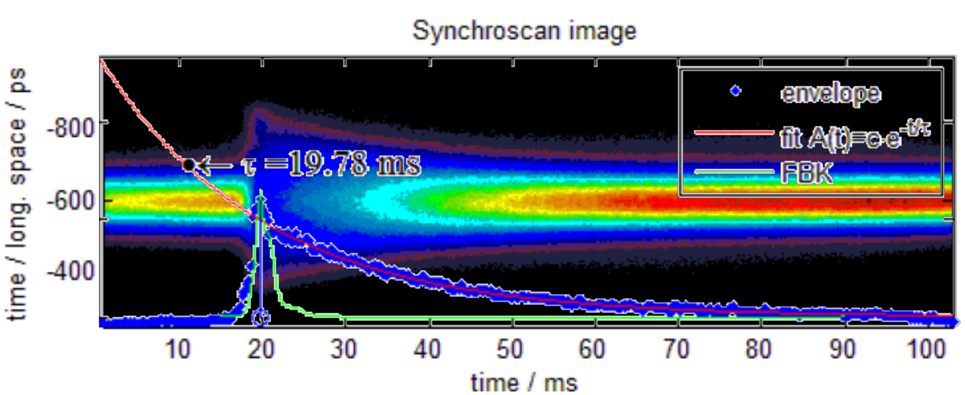


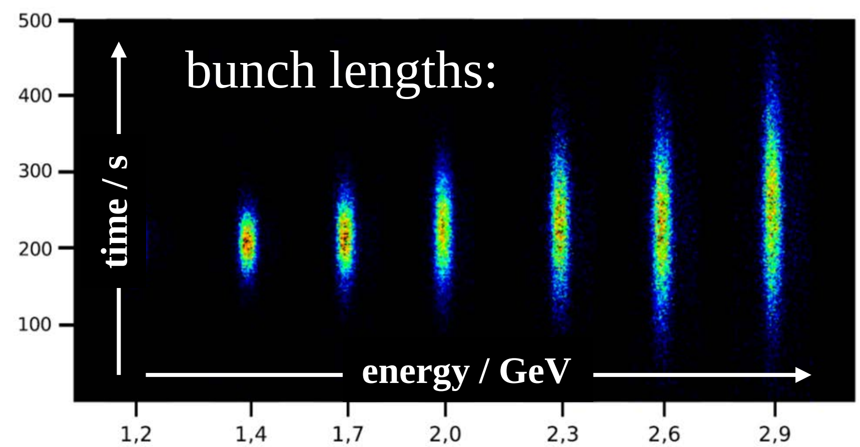
lock-in technique!

ps Diagnostics: Streak Camera

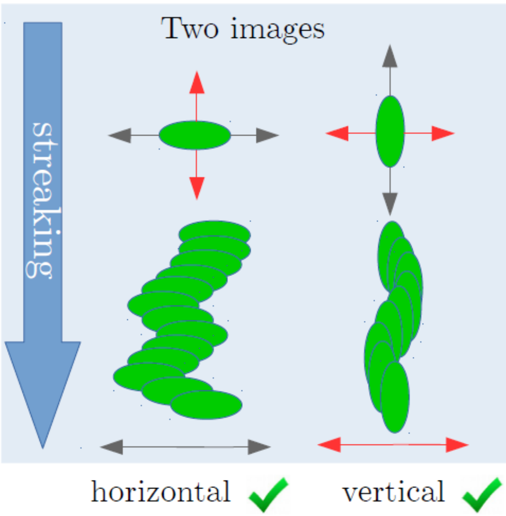


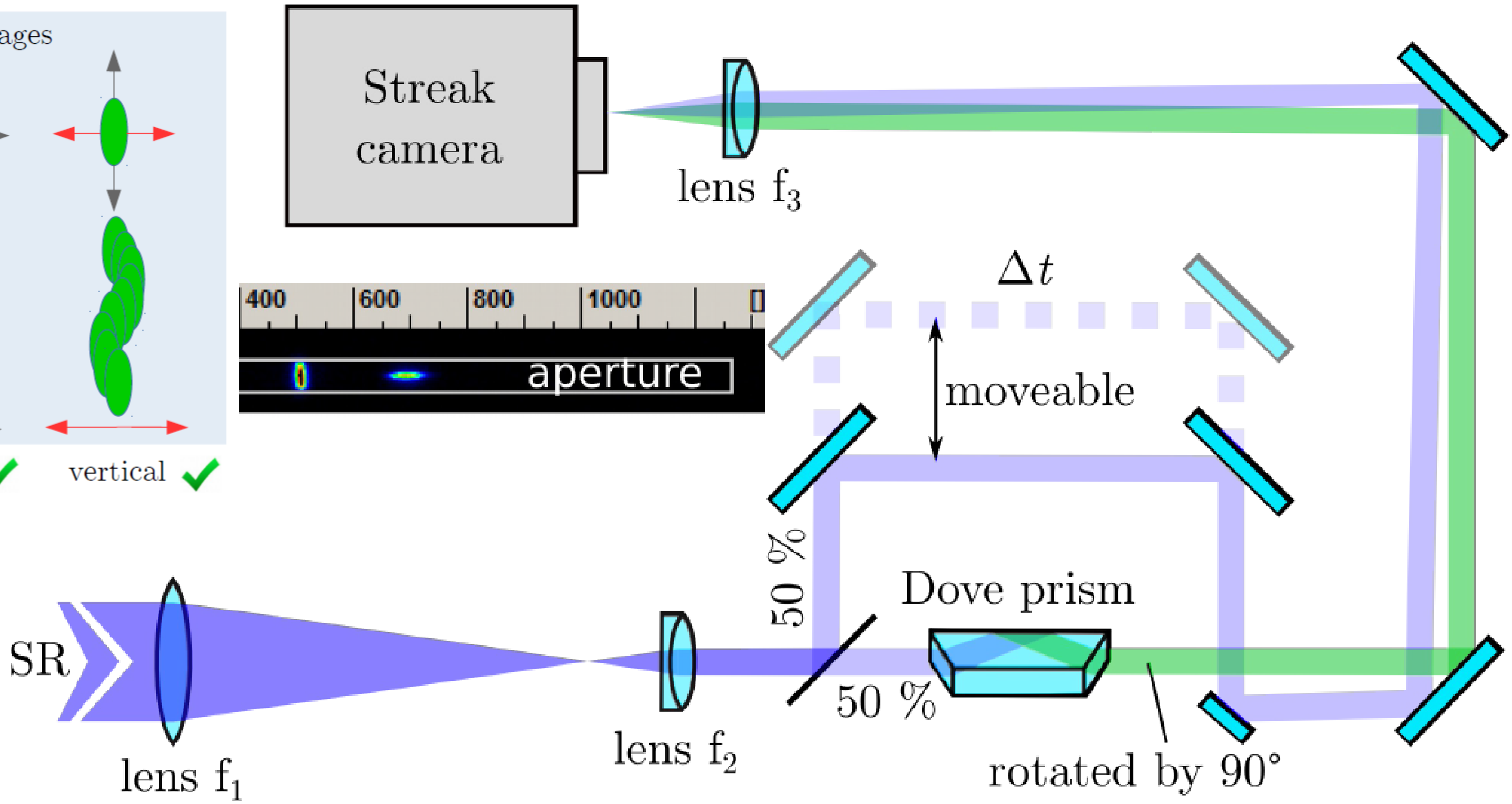


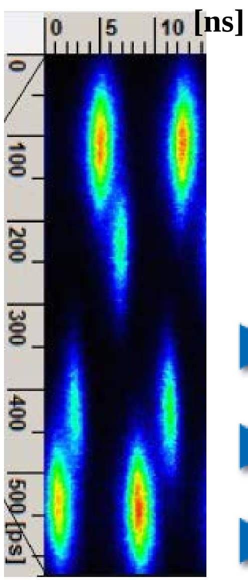




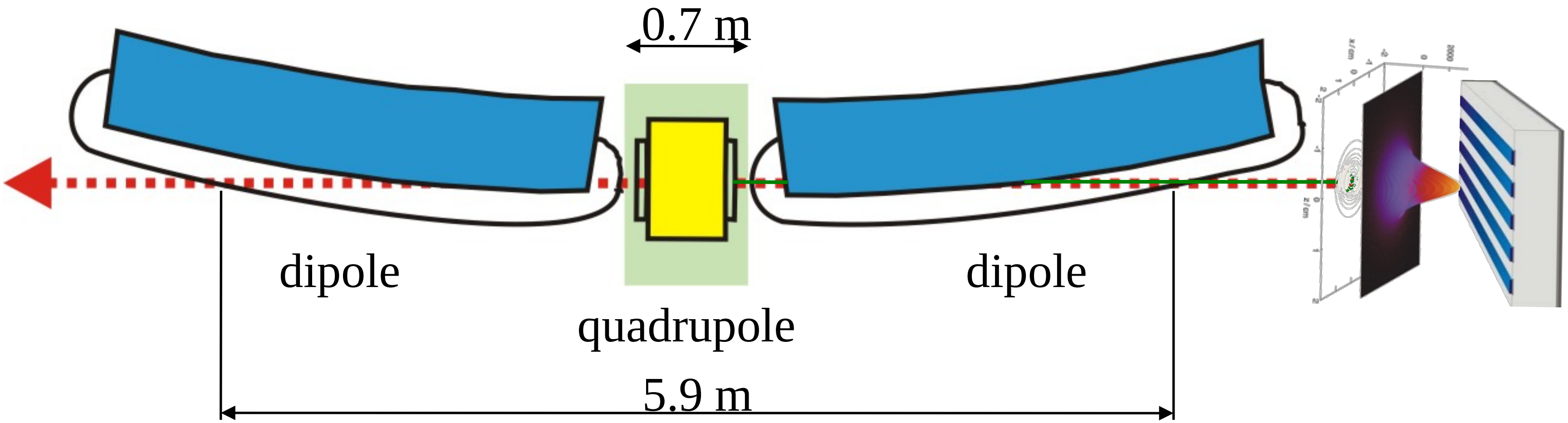
3D Imaging with ps Resolution

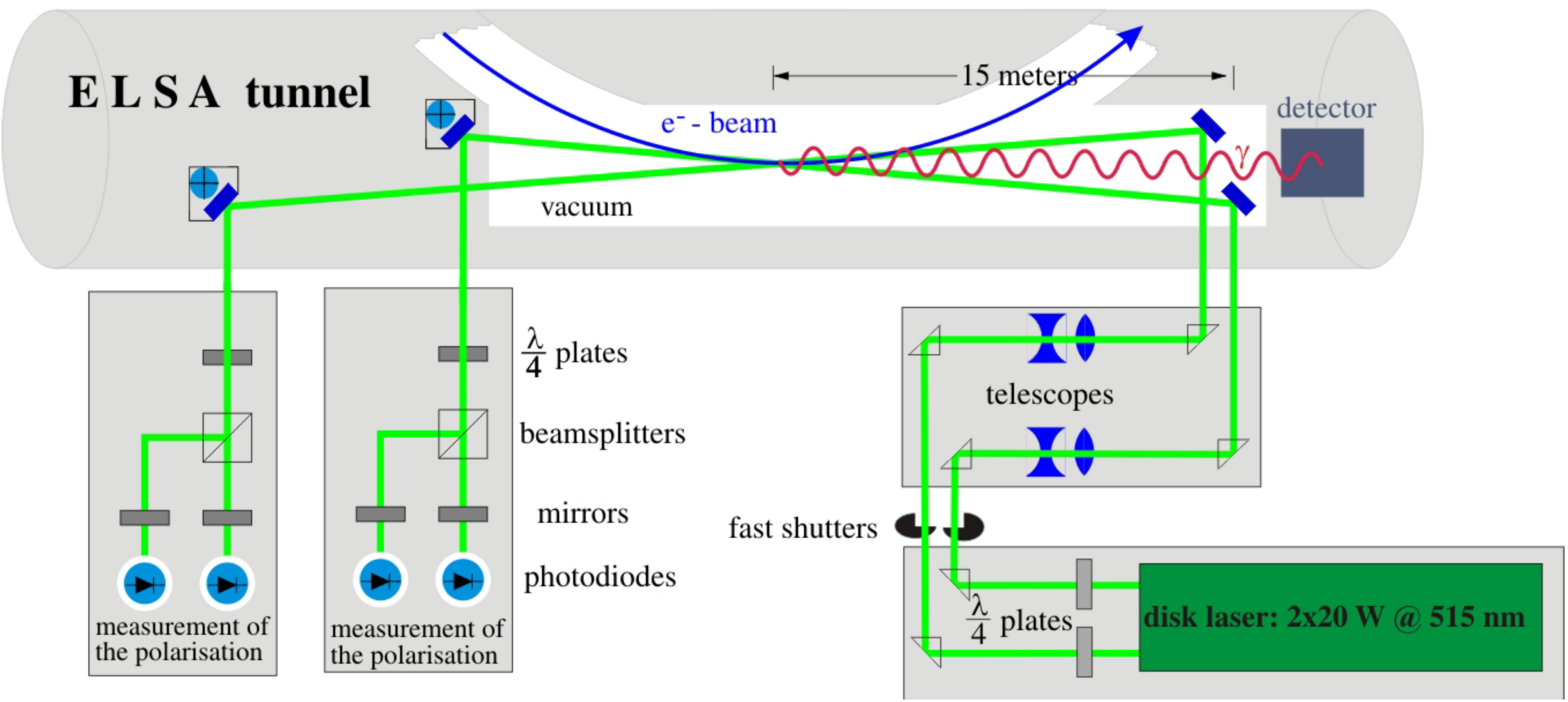




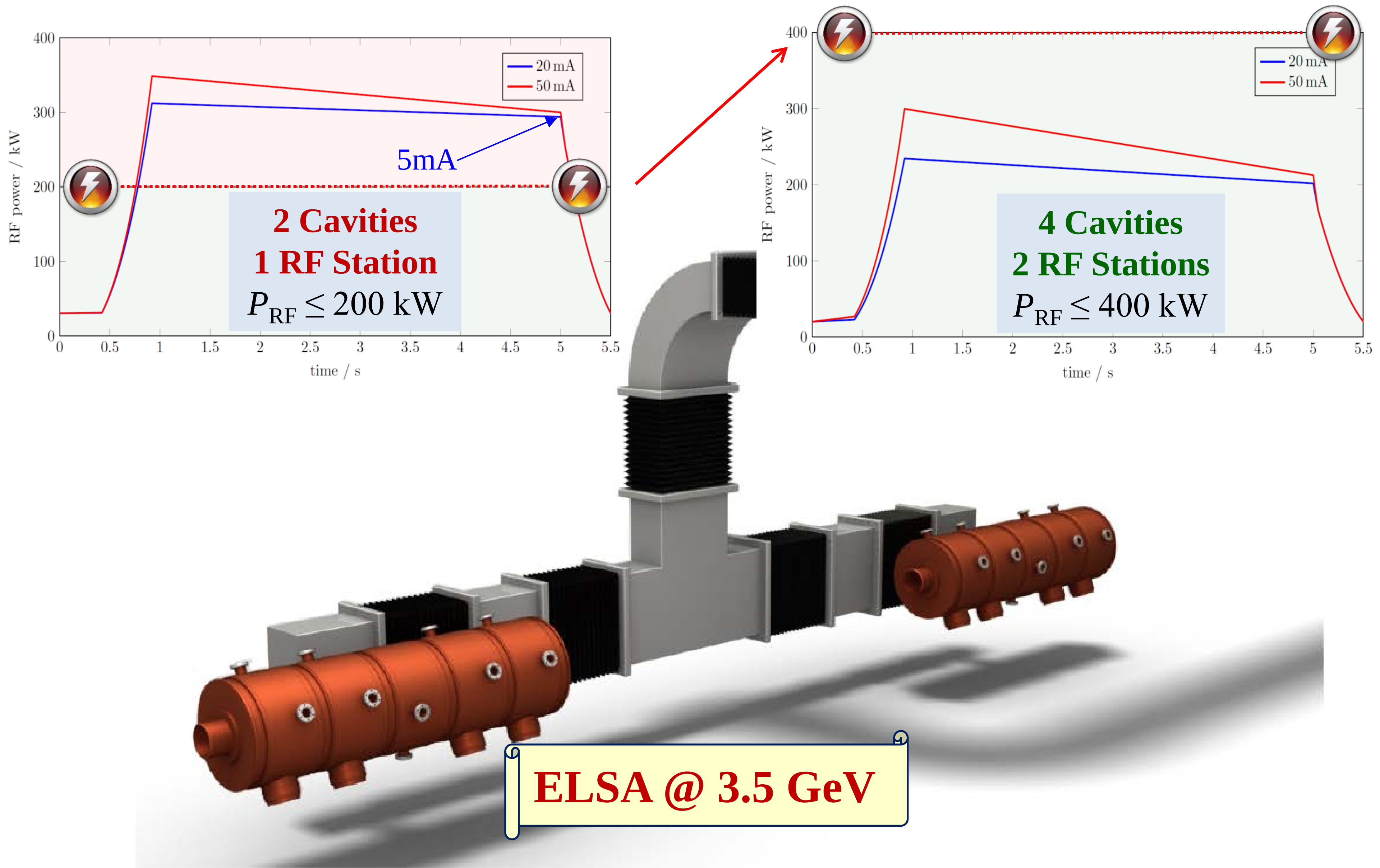


- Variable image magnification with lens pair f_3 & f_2
- Horizontal and vertical beam image projection simultaneously
- Variable path length allows photon TOF adjustment (0 – 300 ps)

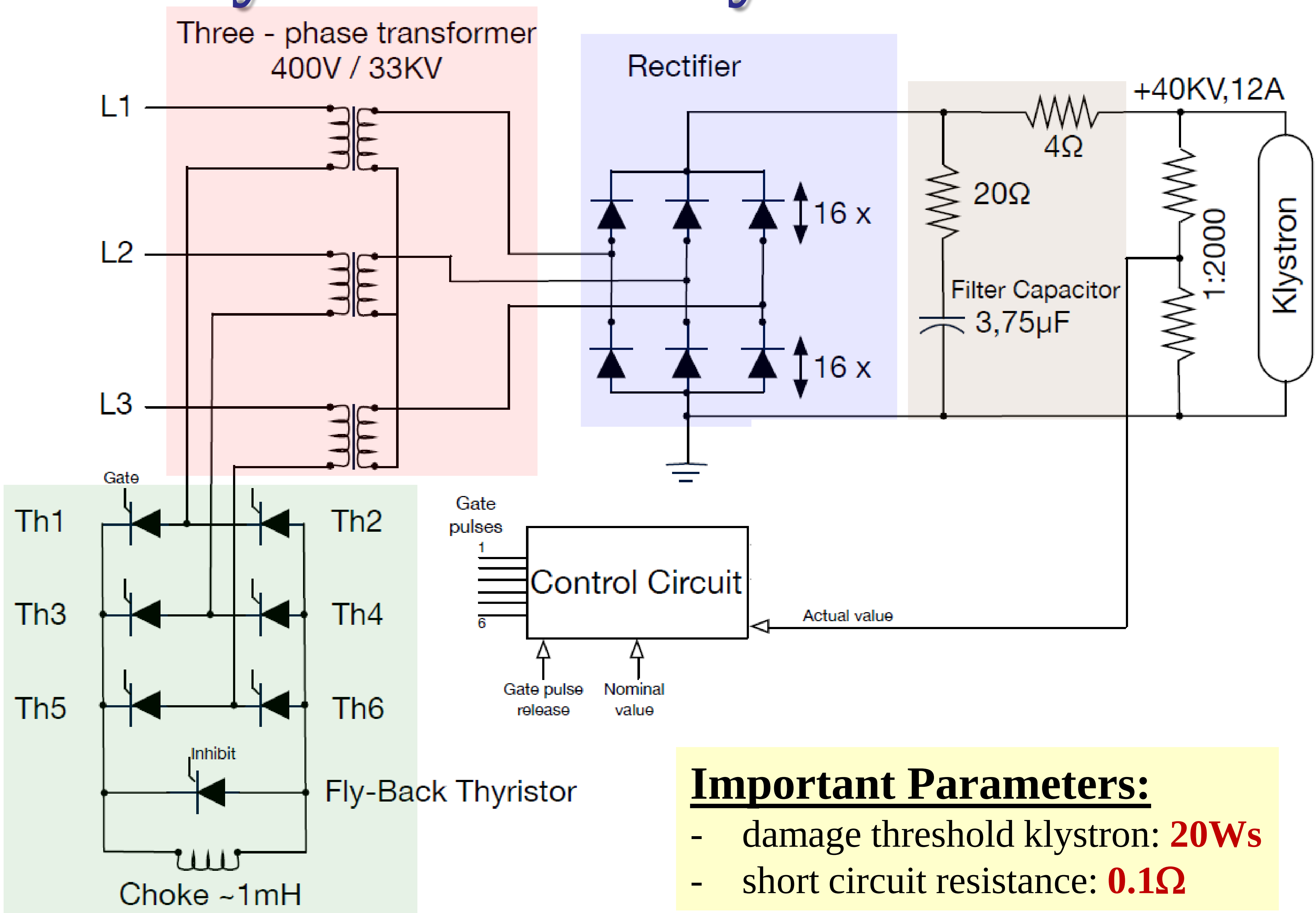

0.7 m
dipole
quadrupole
dipole
5.9 m


E L S A tunnel
15 meters
detector
e⁻ - beam
γ
vacuum
λ/4 plates
beamsplitters
mirrors
photodiodes
measurement of the polarisation
measurement of the polarisation
telescopes
fast shutters
λ/4 plates
disk laser: 2x20 W @ 515 nm

New RF System

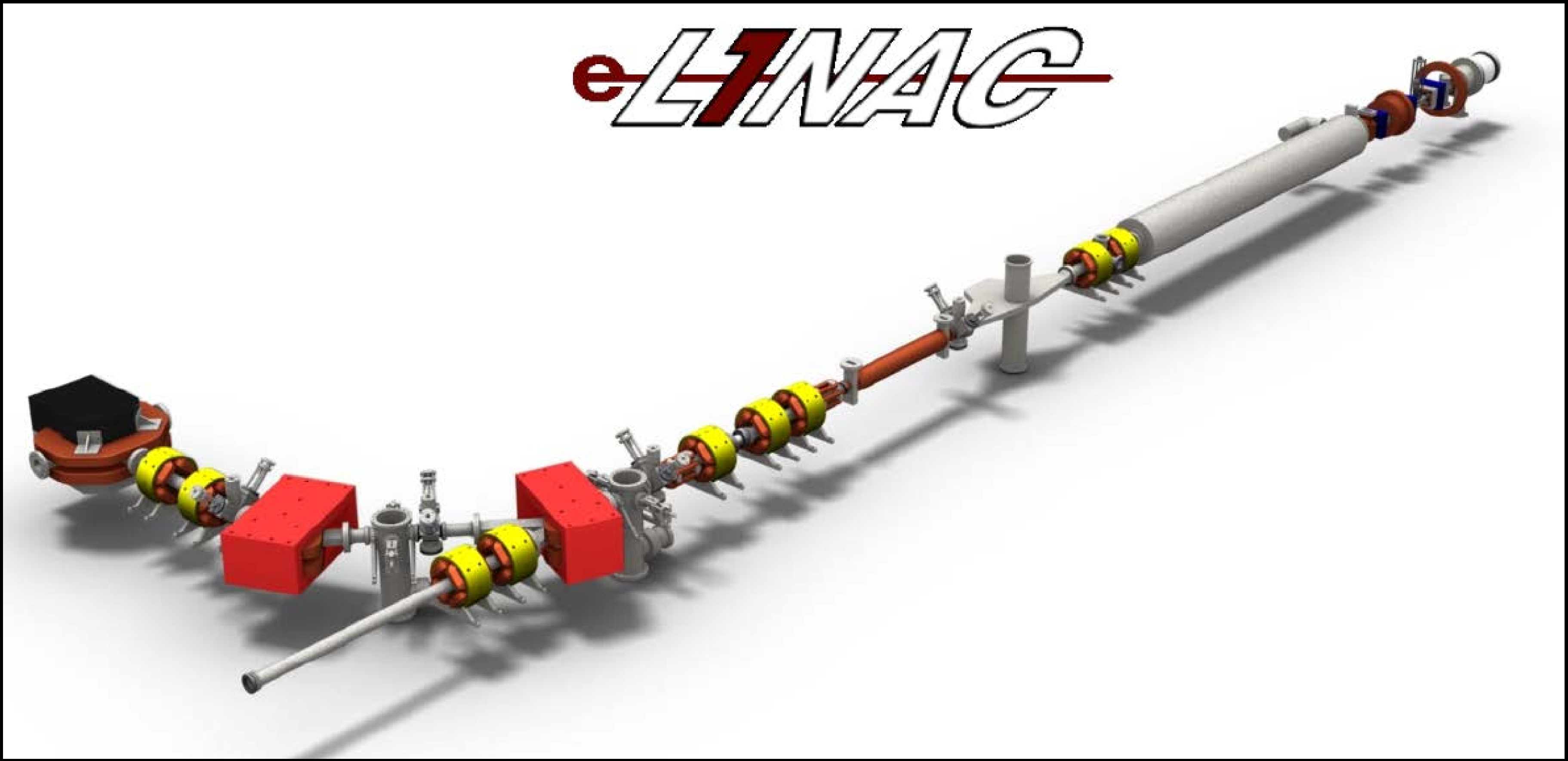


Layout of the Klystron HVPS



Important Parameters:

- damage threshold klystron: **20Ws**
- short circuit resistance: **0.1Ω**



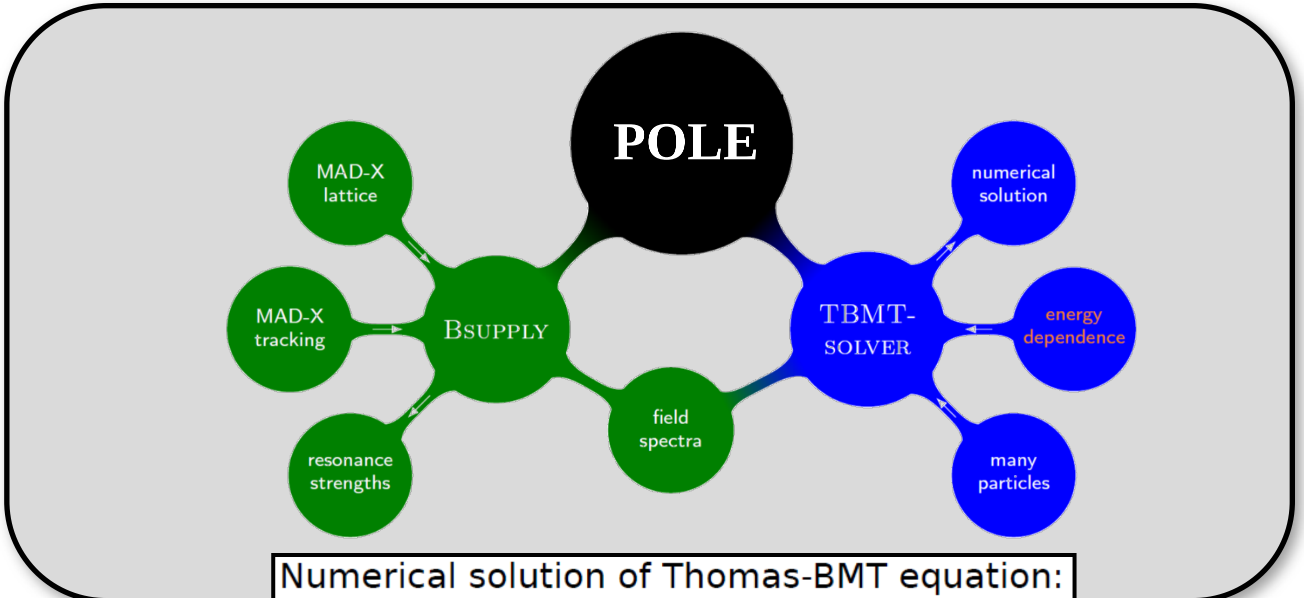
Thermionic Gun:
- U = 90 kV
- I = 800 mA (1-2μs) / 2 A (1ns)

Bunching:
- 500 MHz prebuncher
- 3 GHz TW buncher (4 cells)

LINAC:
- 20 MV 3GHz TW structure (constant gradient)
- ongoing overhaul of modulator and waveguides

Energy Compression System:
- 3-bend magnetic chicane
- 3GHz TW structure

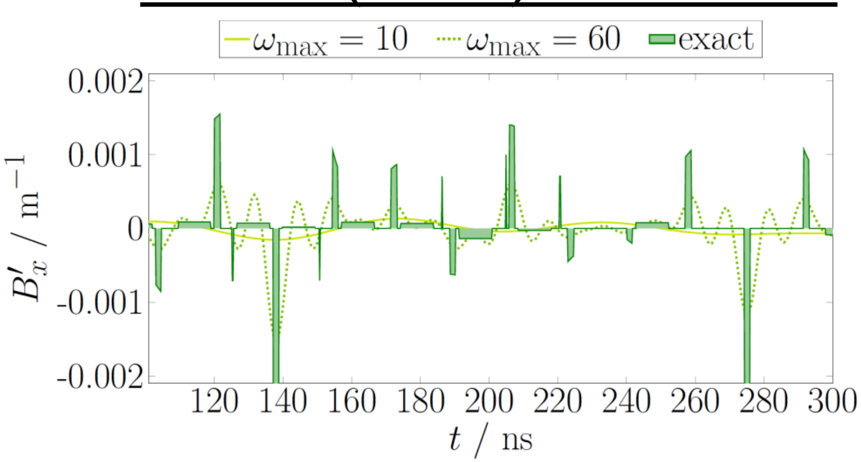
Simulation of Spin Dynamics



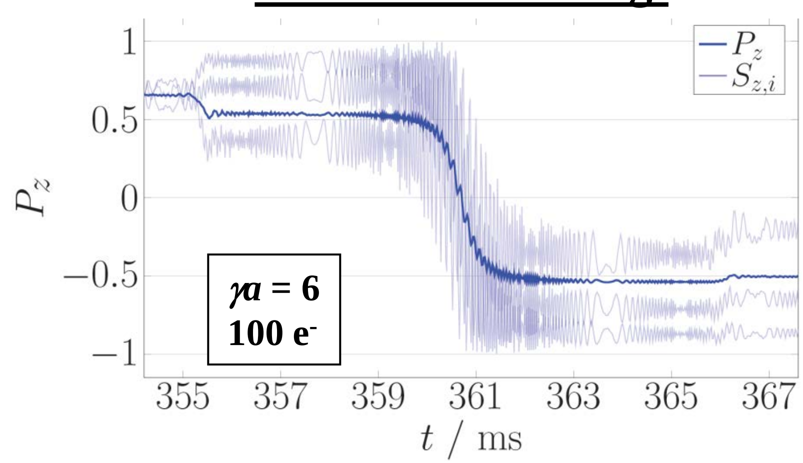
Numerical solution of Thomas-BMT equation:

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

_B_-field as (filtered) Fourier series:

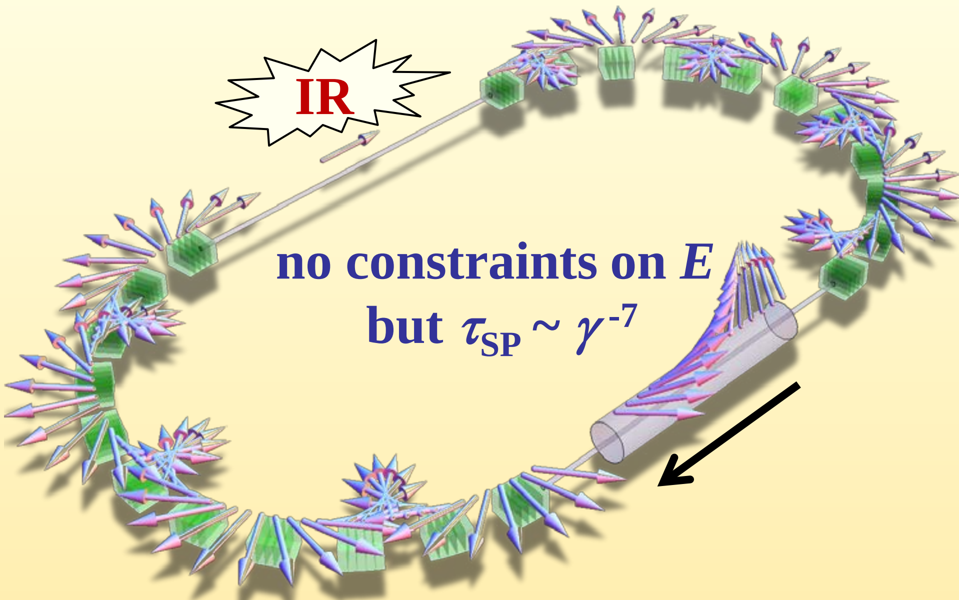


Resonance crossing:



Electron Ring: Spin Dynamics

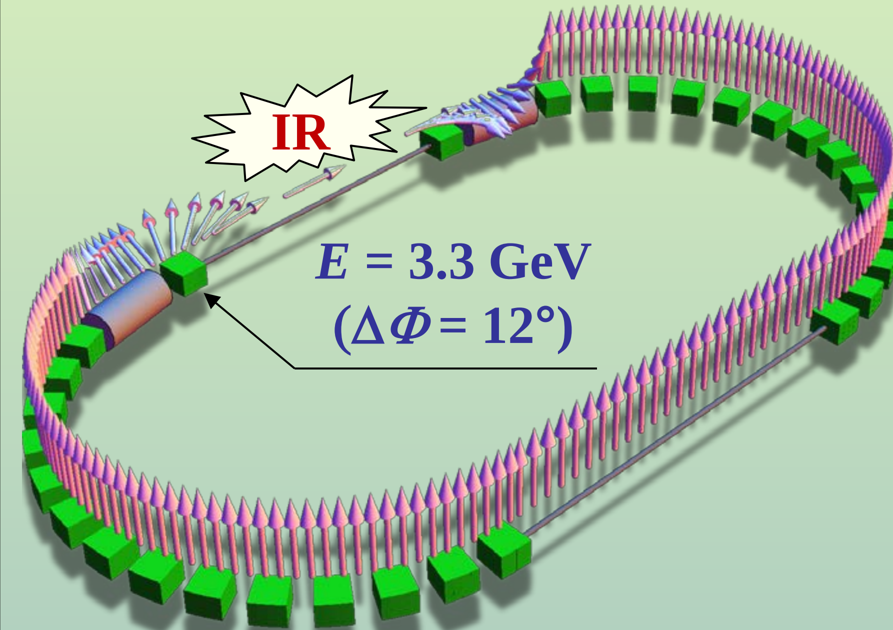
Concept 1: Sibirian (full) Snake



- **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)

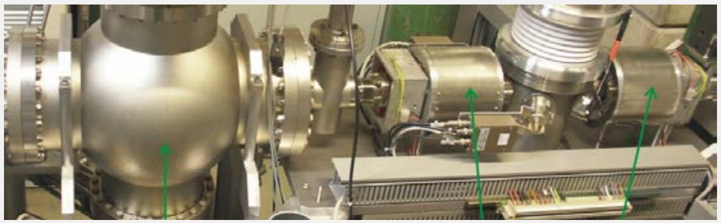
$\tau_{Sp} \approx$ 7 min @ 2.8 GeV

Concept 2: Spin Rotators

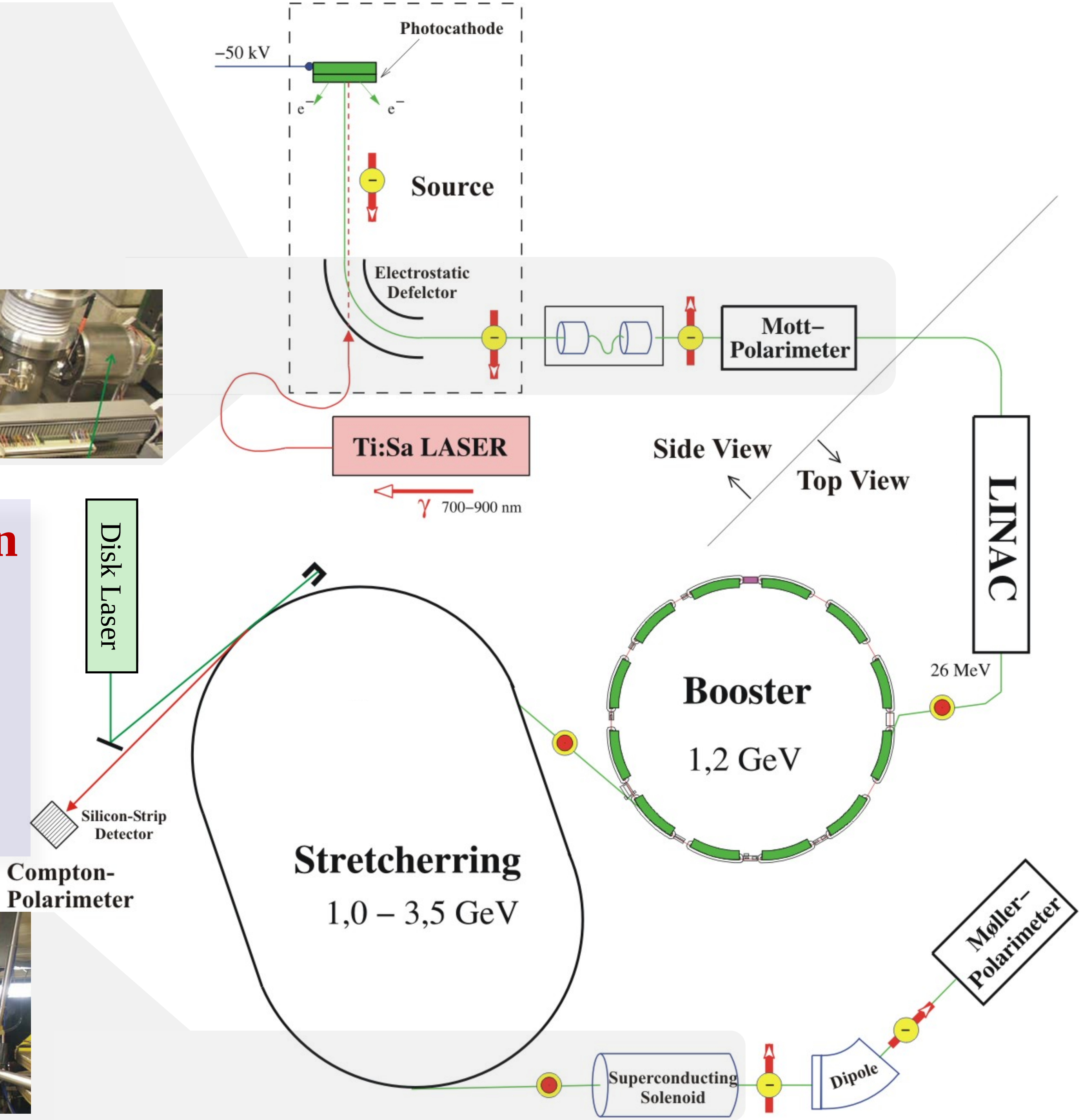


- **HBA**: 3 achromats à 6 dipoles
- $D = 0$ in straight with vert. spin
- 2 solenoid/dipole rotators, $\Delta S = 90°$
- $\beta_x = \beta_z$ at entrance/exit of achromats
- $\varepsilon_x = 3.8$, $\varepsilon_z = 3.1$ mm·rad (norm)

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



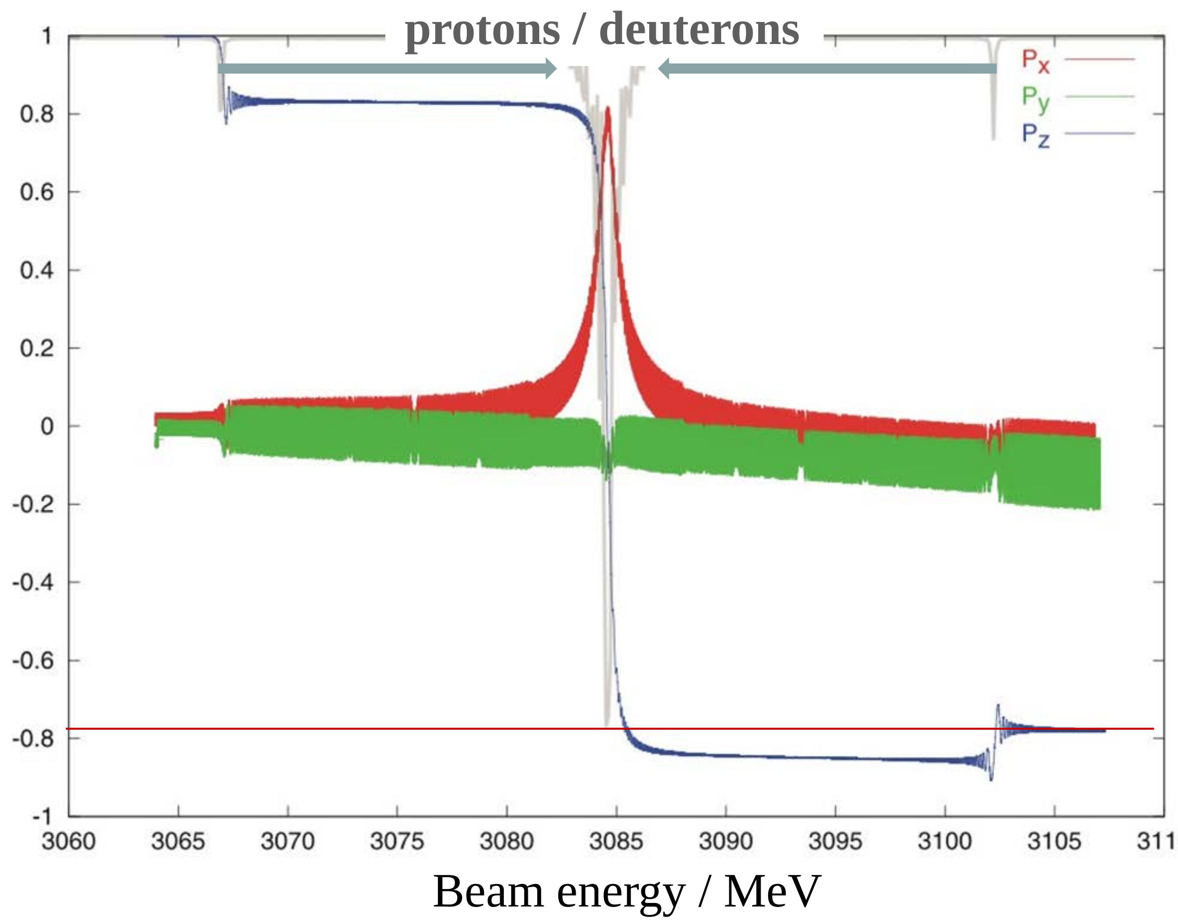
Spin Manipulation at



Synchrotron Oscillations

(= energy oscillations of beam's particles!)

Multiple crossing of depolarizing resonances due to energy oscillations

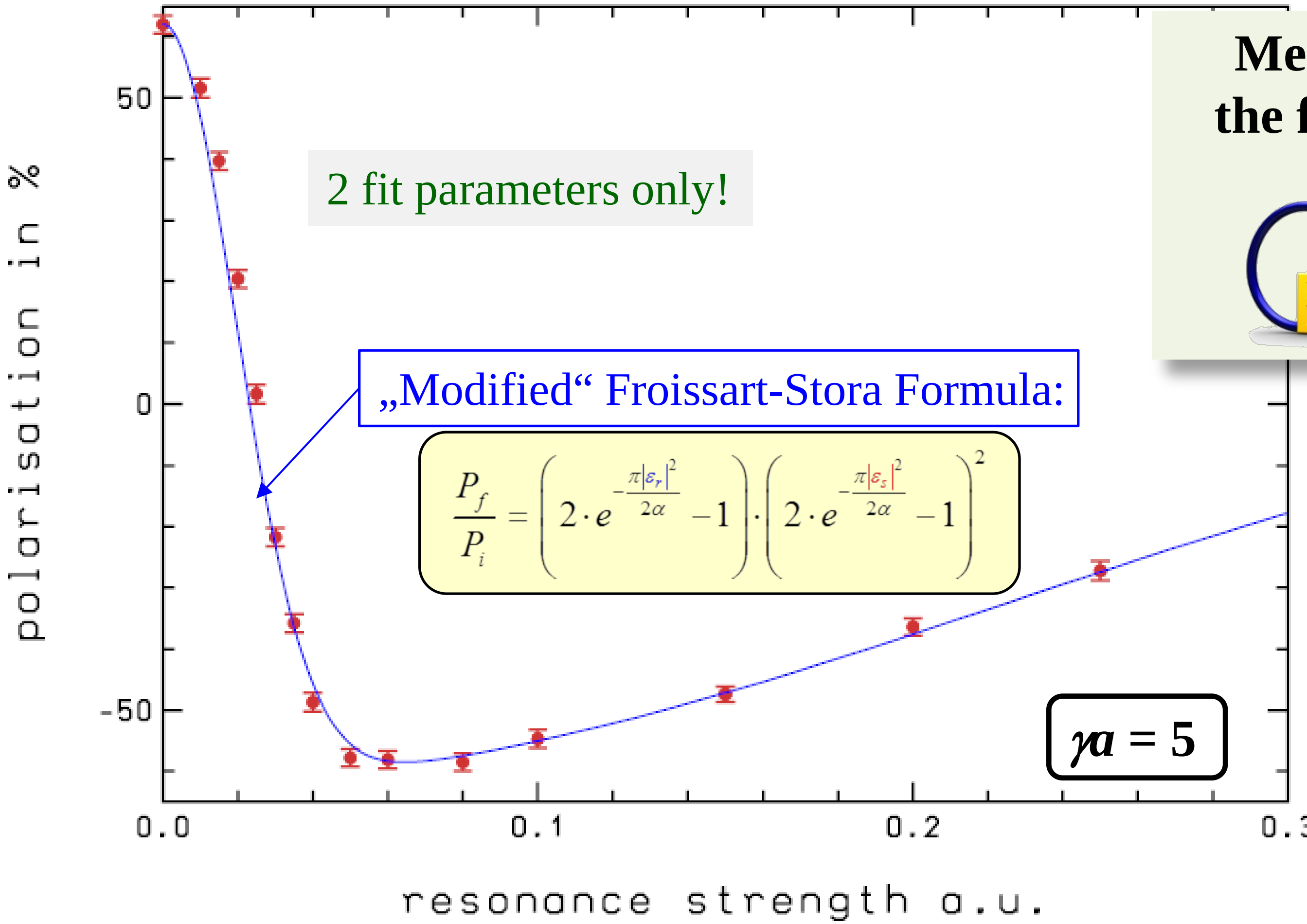


Oscillation frequency/tune:

- **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 Synchotron Sidebands



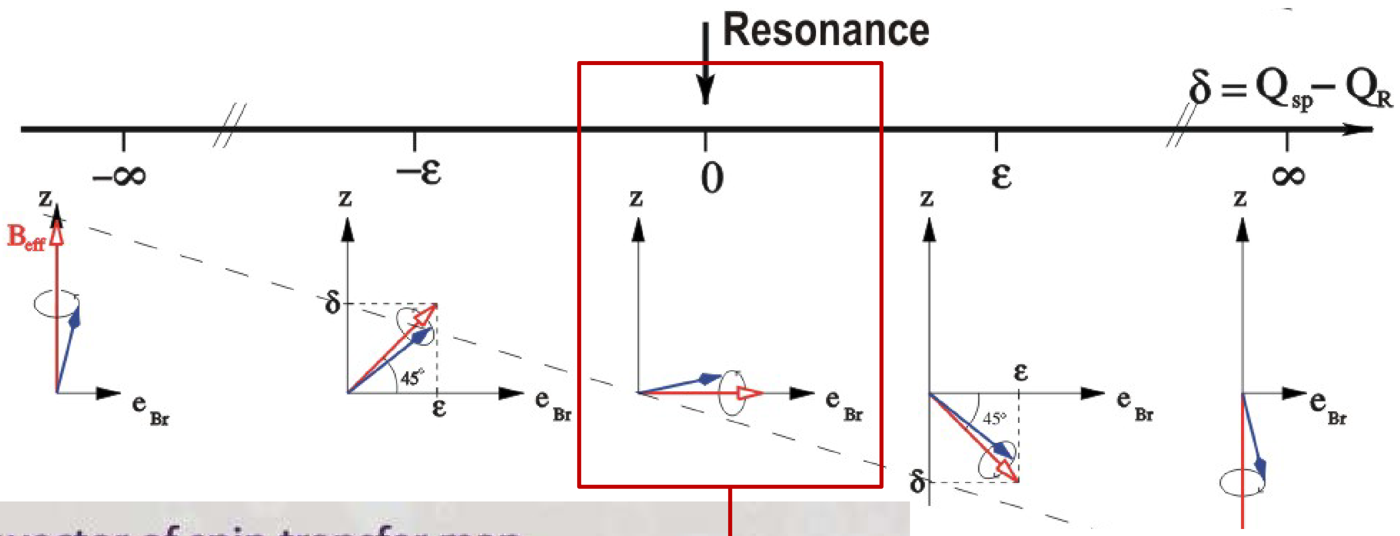
Measured for the first time at

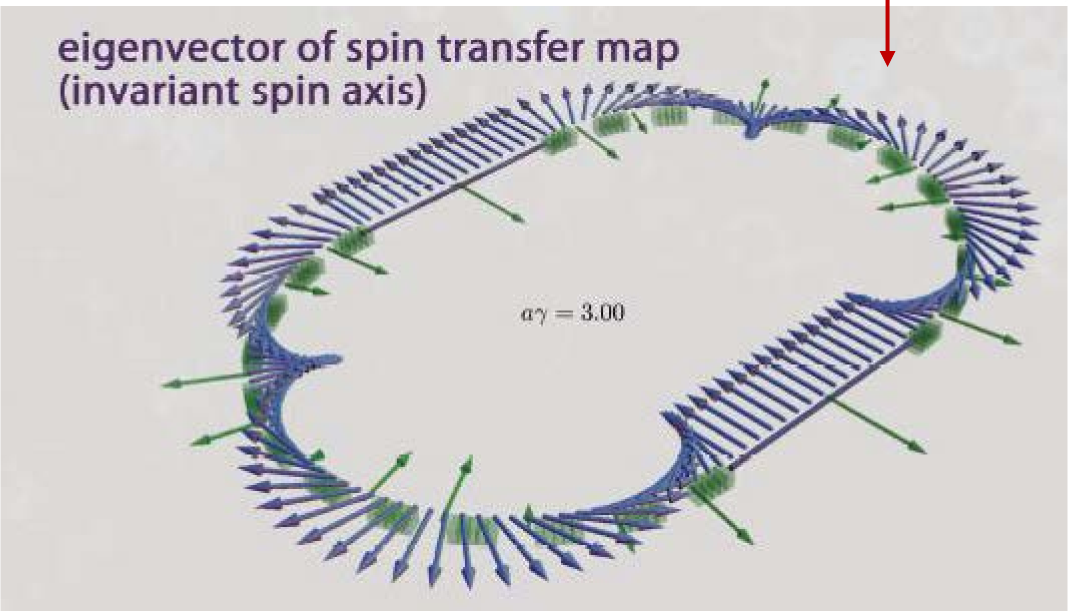
ELSA

Precise Measurement of Beam Depolarization:

→ Verification of the theoretical predictions (no full spin flip)

Horizontal Polarization





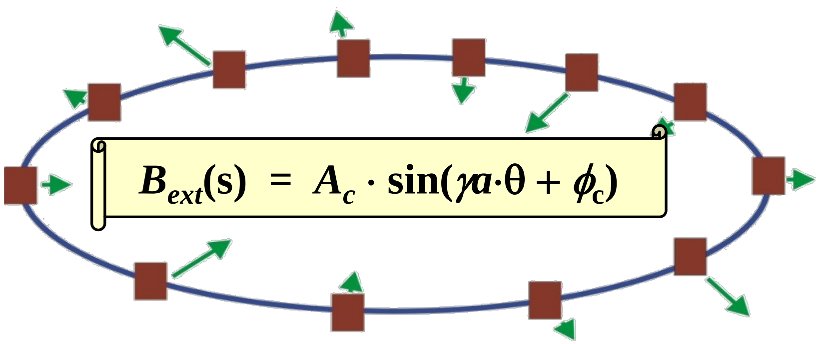
Integer Resonance $\gamma a = n$

- spin is aligned along the resonance driving B_x

$$B_x = B_{imp} + B_{ext}$$

- phase variation of the external corrector field allows change of spin orientation

Operation at $\gamma a = 3$

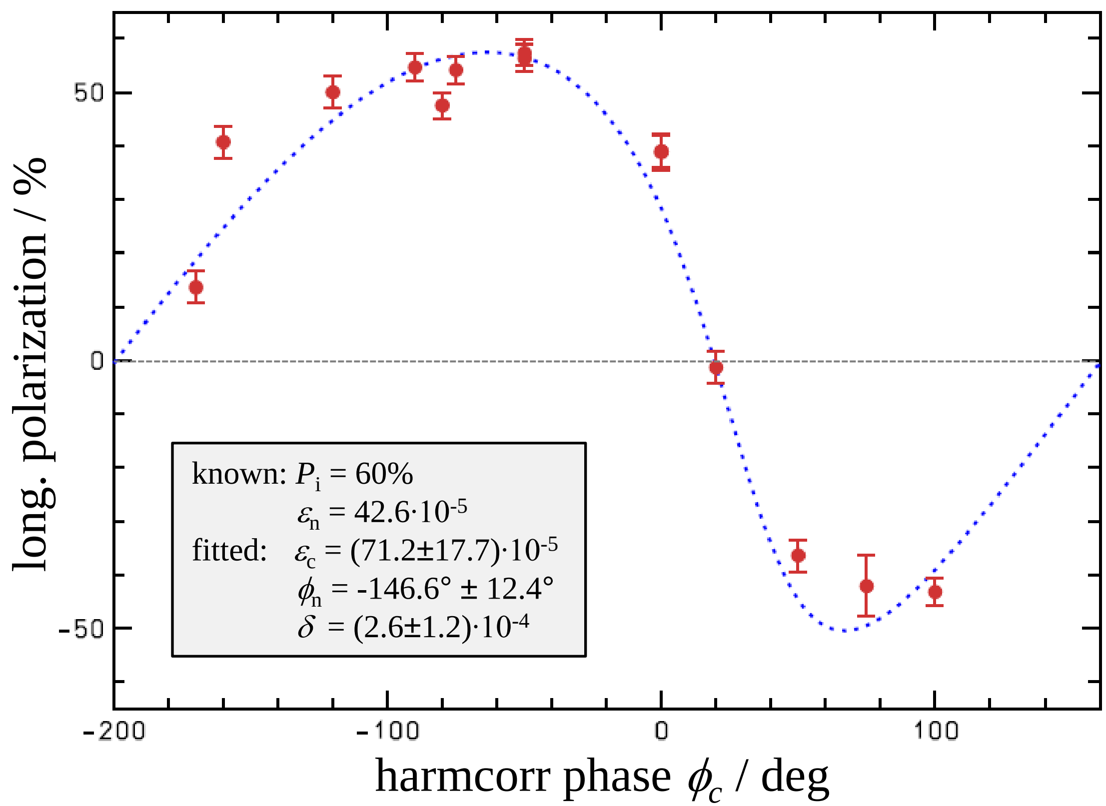


$$\vec{n}_0 = \frac{1}{\sqrt{|\varepsilon|^2 + \delta^2}} \begin{pmatrix} -\mathrm{Re}(\varepsilon) \\ \delta \\ \mathrm{Im}(\varepsilon) \end{pmatrix} \Rightarrow P_s = P_i \frac{|\varepsilon_n| \sin\phi_n + |\varepsilon_c| \sin\phi_c}{\sqrt{\left| |\varepsilon_n| e^{-i\phi_n} + |\varepsilon_c| e^{-i\phi_c} \right|^2 + \delta^2}}$$

$P_{\text{long}} \sim \sin\phi_c$ expected!

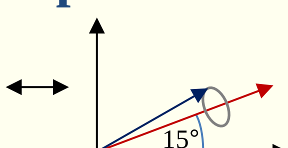
Observed distortion and offset caused by:

- superposition of $\varepsilon_n + \varepsilon_c$
- small energy shift ($\gamma a \neq 3$)

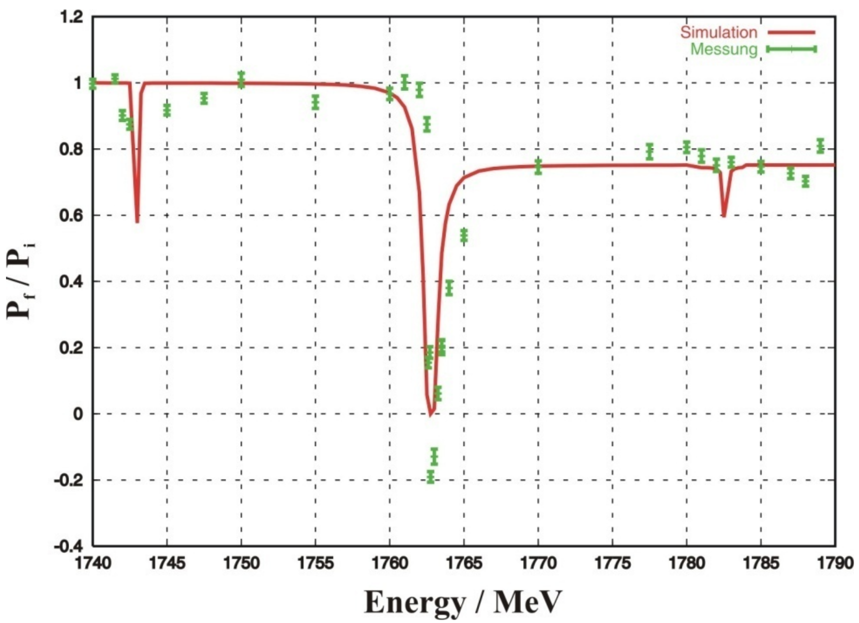


Fitted δ corresponds to:

$$\frac{\Delta E}{E_{res}} \approx 7.5 \cdot 10^{-5} \longleftrightarrow$$

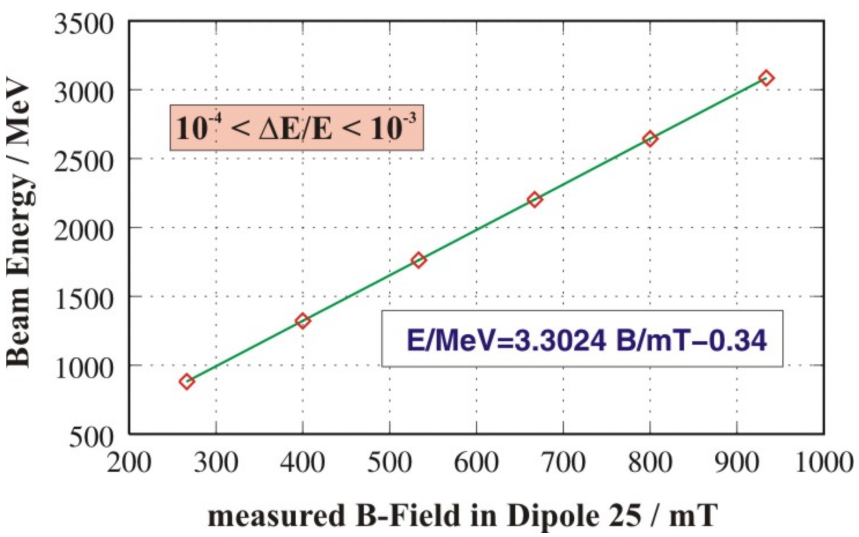


Energy Calibration

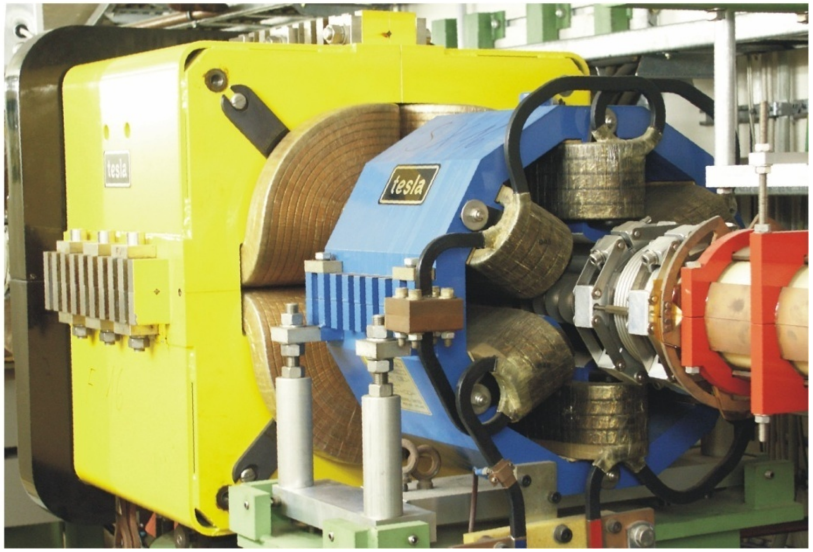


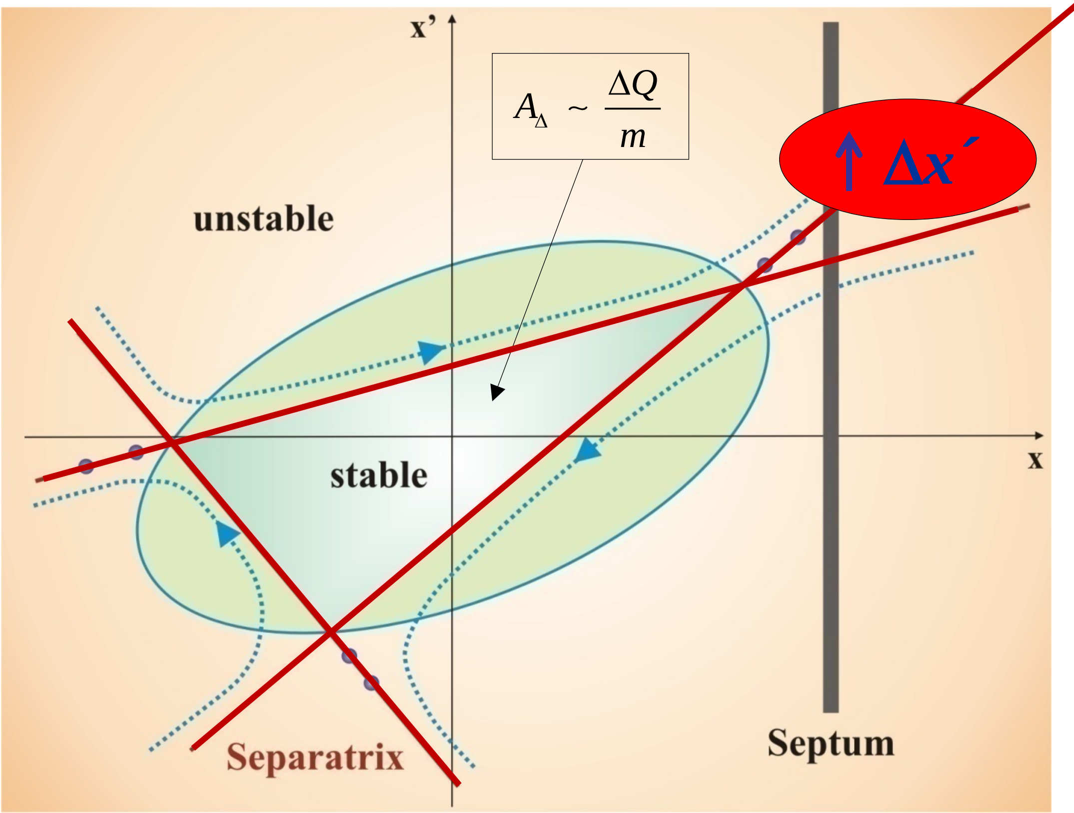
Beam Depolarization when crossing the Imperfection Resonance $\gamma a = 4$

Transformation of the measured B-Field to Beam Energy



Slow Beam Extraction





Sextupole Magnets (Extraction):
Excitation of a third integer resonance

Ironless Quadrupole Magnets (Extraction):
Shift of the horizontal betatron tune close to a third integer value, "current feedback-loop"

Beam-Line for Detector Testing

External Electron Beam:

- beam energy: **1.0 GeV < *E* < 3.5 GeV**
- beam current: **1 fA < *I* < 100 pA**
- beam radius: **0.5 mm < σ < 7 mm**

Single Pulse Operation!

Extraction of a single electron every 300 turns!