R&D @ the Bonn Electron Stretcher Accelerator

Project D.2 / 2004 - 2016

*04-08 Acceleration of **polarized electrons** in a medium sized stretcher ring up to 5 GeV*

*08-12 Acceleration of **high currents** in a fast ramping stretcher ring*

*12-16 **Beam and spin dynamics** in a fast ramping stretcher ring*

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Experimenters Wish List

Photoproduction Experiments:

- quasi continuous γ beam (10^7 γ/sec, GeV)
- high and stable linear and circular polarization

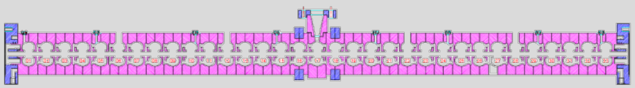
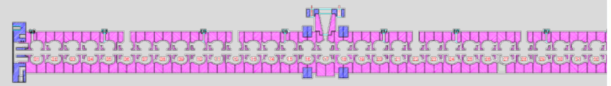
→ quasi continuous electron beam (1-10 nA, GeV)

→ high polarization, beam pointing & reliability

Different Ways to ≈3 GeV Electrons

Linear Accelerator (LINAC):

20 GeV

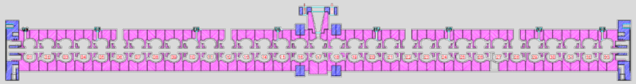
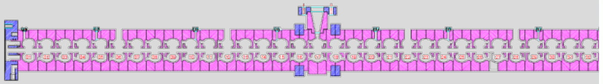
. . .  . . . 

nc: 1 MeV/m → $L \approx 3$ km, sc: > 20 MeV/m → $L \approx 200$ m

Different Ways to ≈3 GeV Electrons

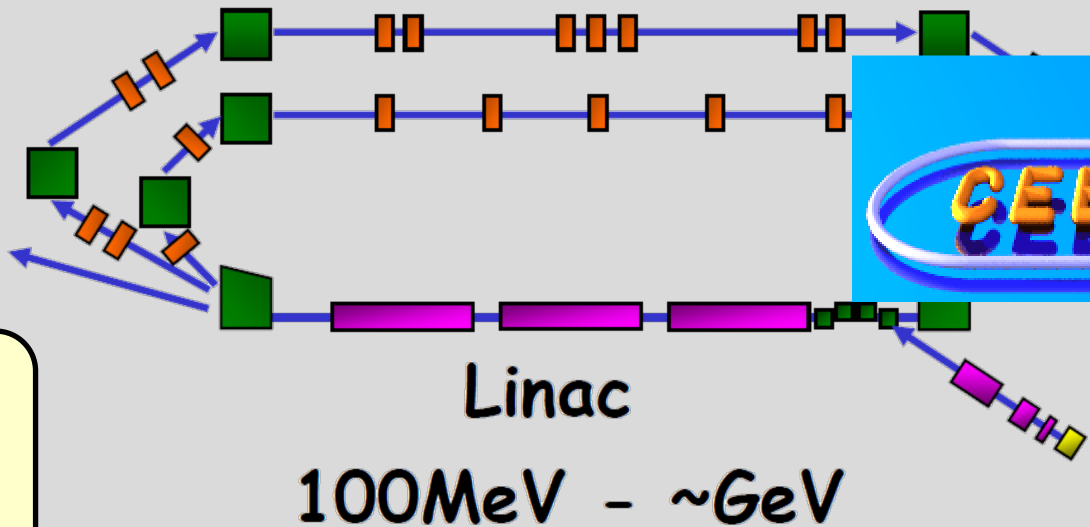
Linear Accelerator (LINAC):

20 GeV
European XFEL

…  … 

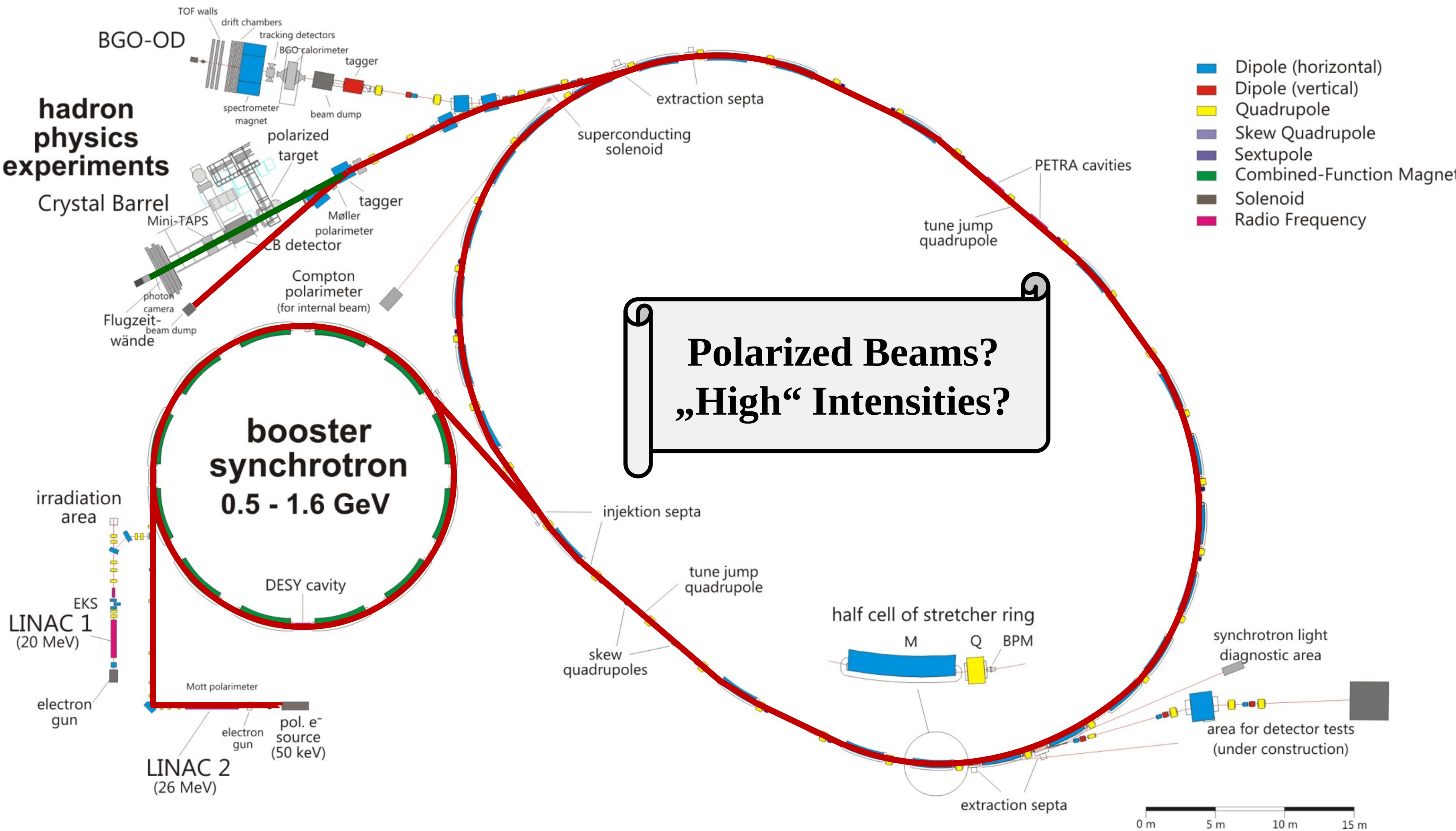
nc: 1 MeV/m → $L \approx 3$ km, sc: > 20 MeV/m → $L \approx 200$ m

Recirculating LINAC:

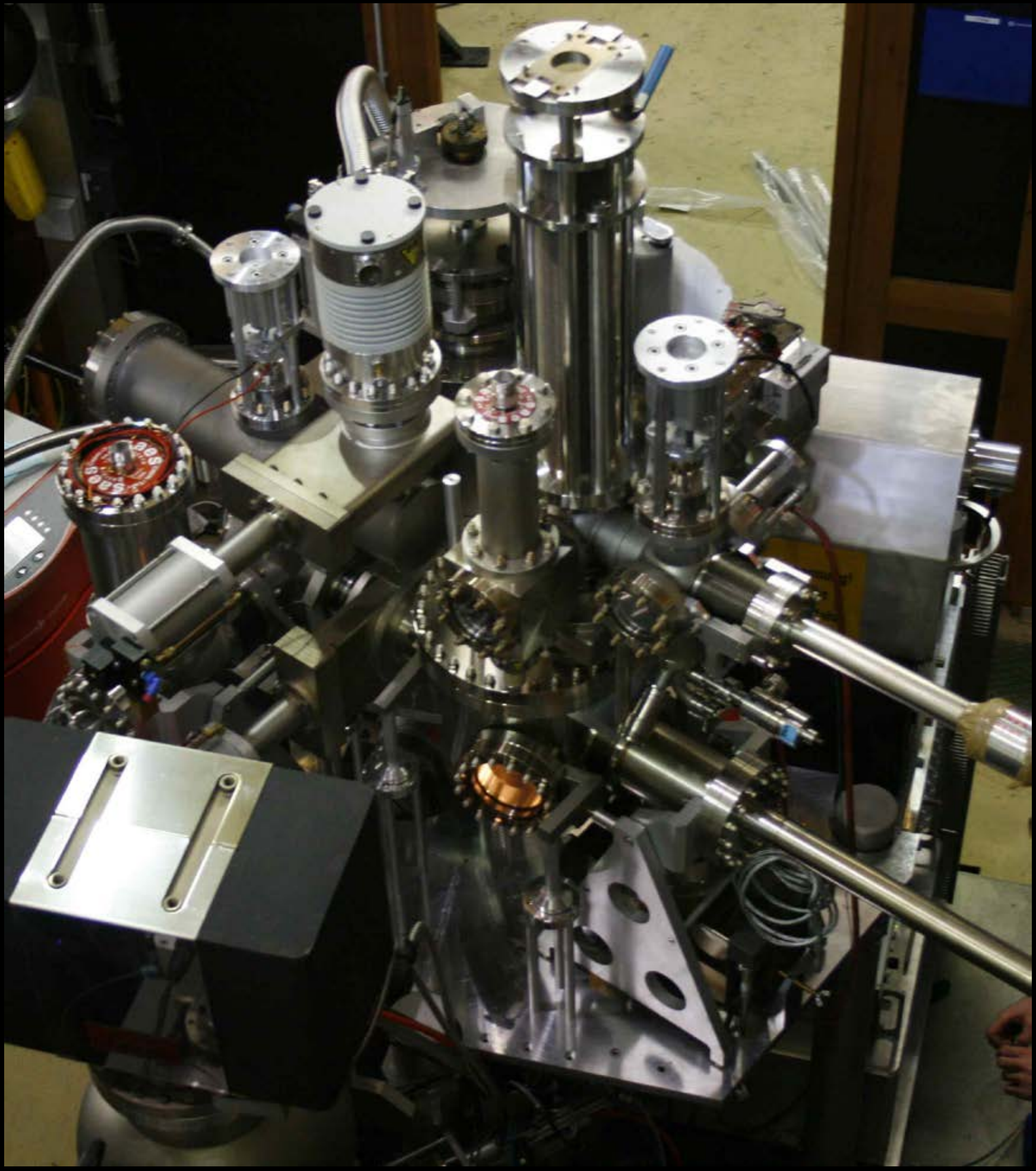


Bonn:
1 nA / 3 GeV
= 3 Watts!!!

Electron Stretcher Accelerator (ELSA)



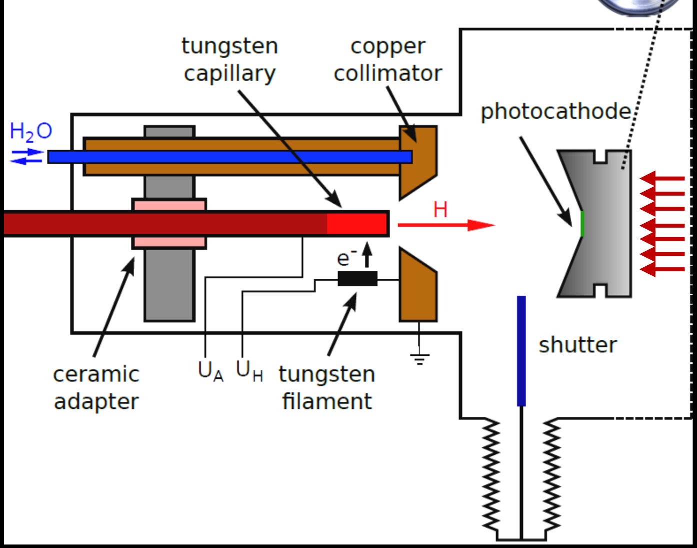
Source of Polarized Electrons



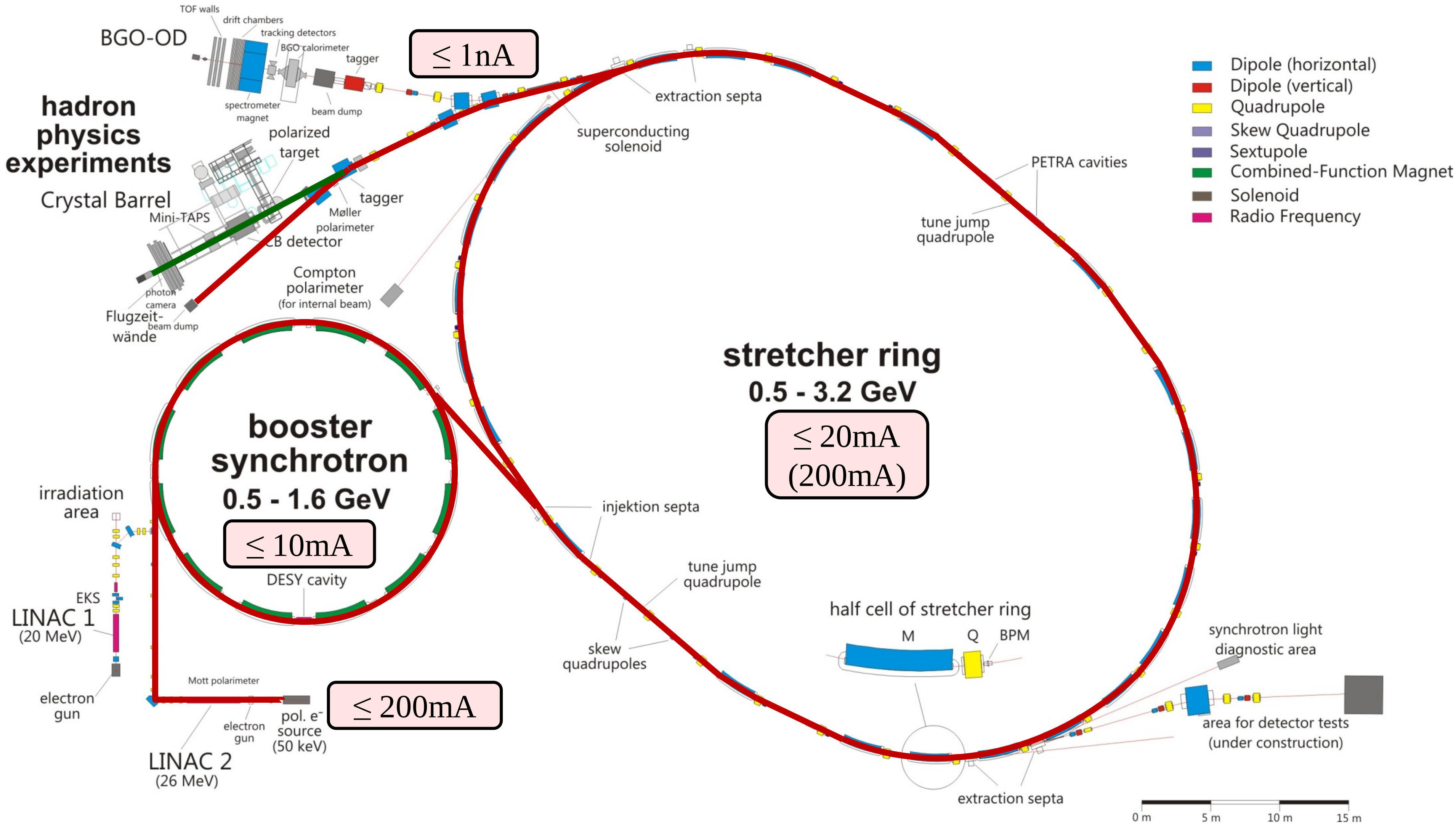
Specific features:

- 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

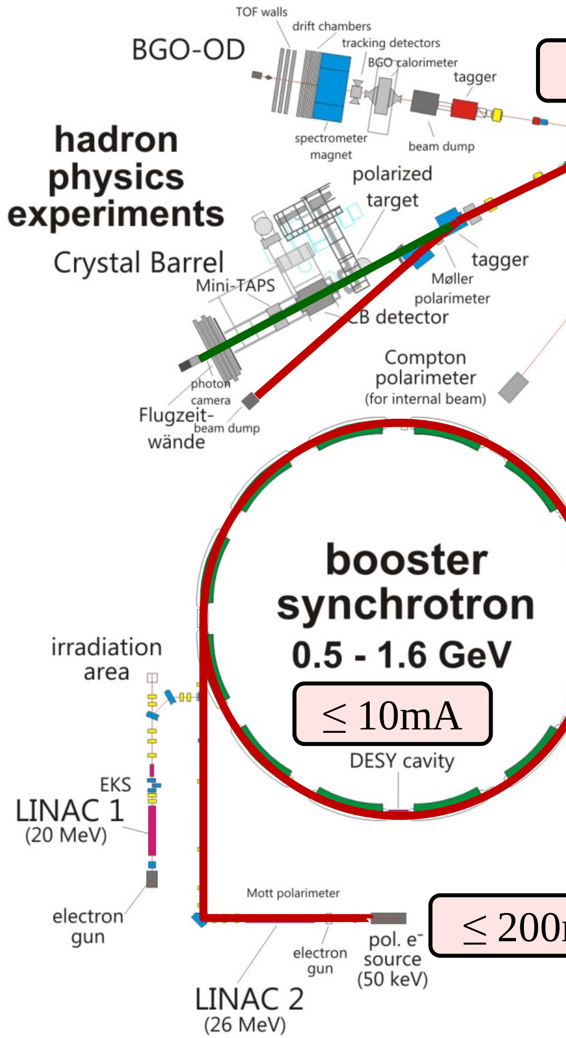
Cleaning of PC @ 450°C:



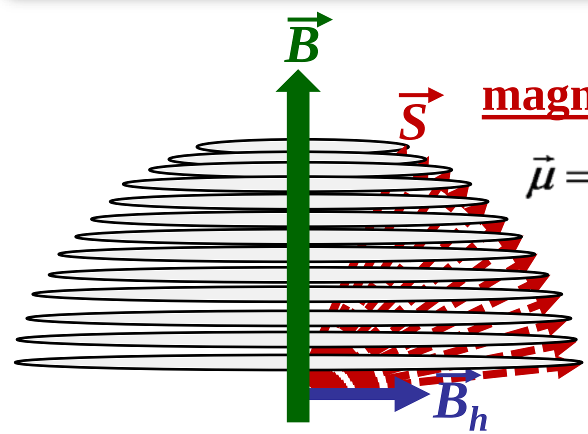
Acceleration of polarized electrons



Acceleration of polarized electrons



→ Spin-Tune: $Q = \gamma a$



magn. moment:

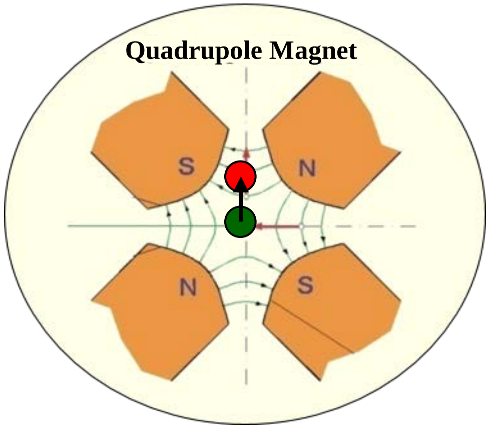
$$\vec{\mu} = g\frac{e}{2m}\cdot\vec{S}$$

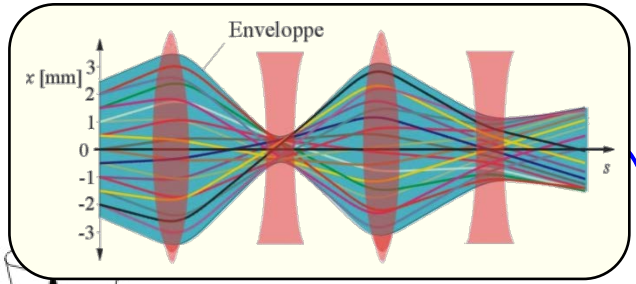
$$\vec{\Omega}^* = -\frac{e}{m_0}(1+a)\cdot\vec{B}$$

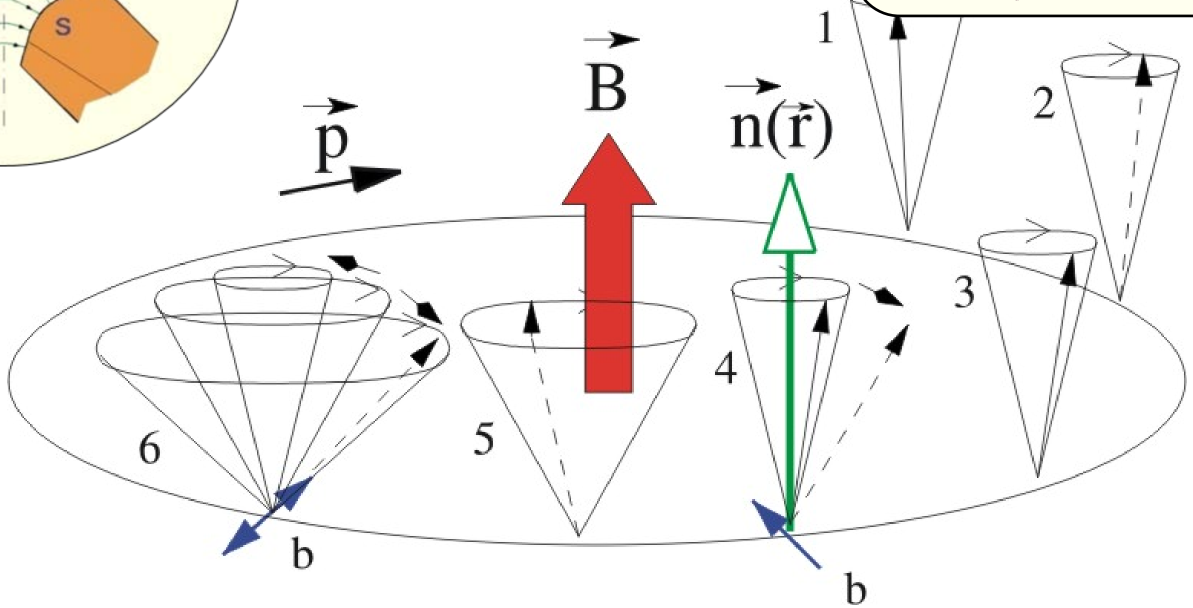
$$\boxed{\frac{g-2}{2} \approx 10^{-3}}$$

Lab frame: factor γ!

Depolarizing Resonances





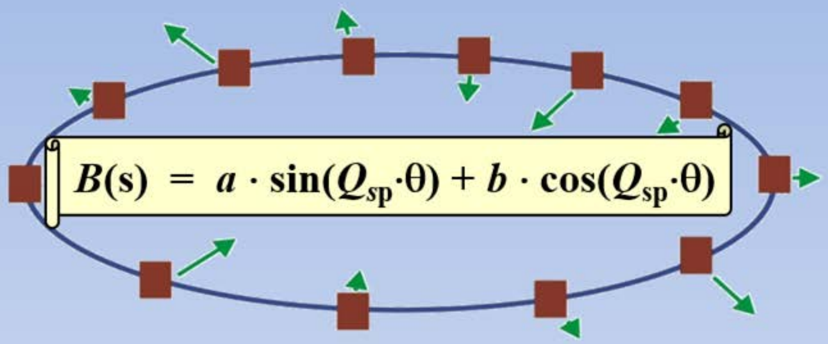


Imperfection Resonance:	$\gamma \cdot a = n, \qquad n \in Z$
Intrinsic Resonance:	$\gamma \cdot a = n \cdot P \pm Q_z, \quad n \in Z$

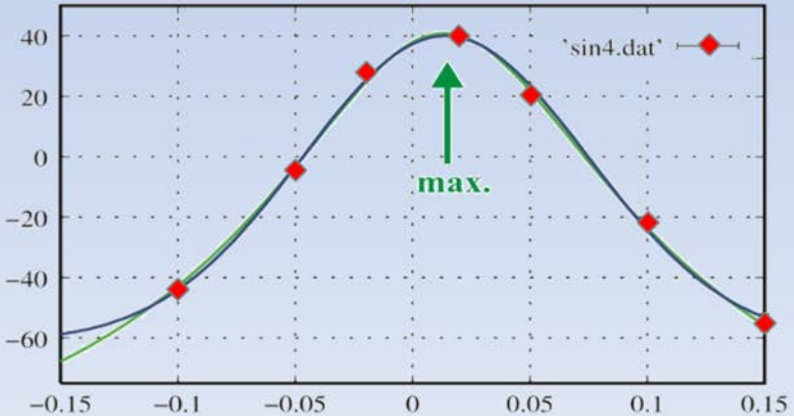
Acc. of Polarized Electrons

Integer Resonances: $\gamma a = n$

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

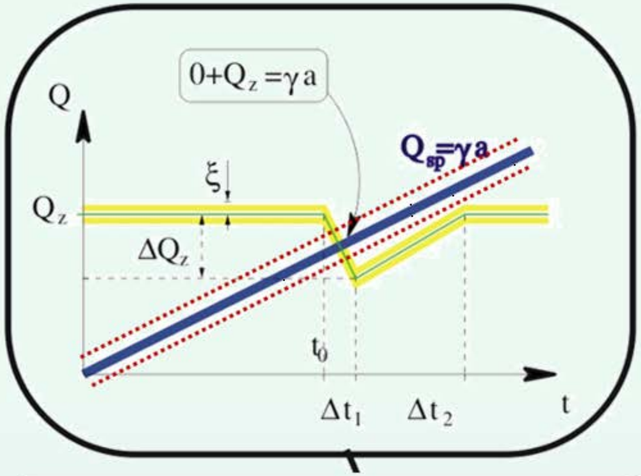


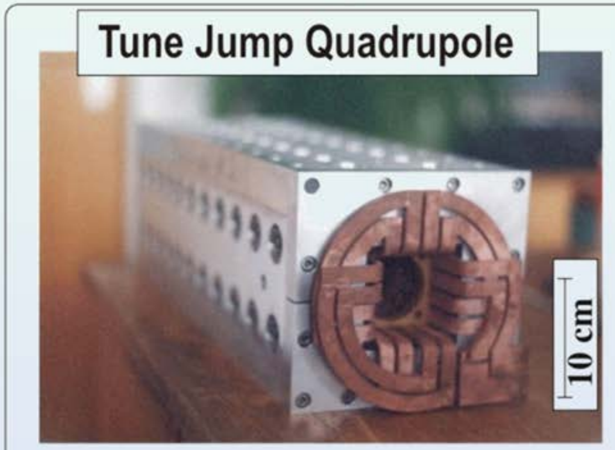
→ scan of sin amplitude:



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

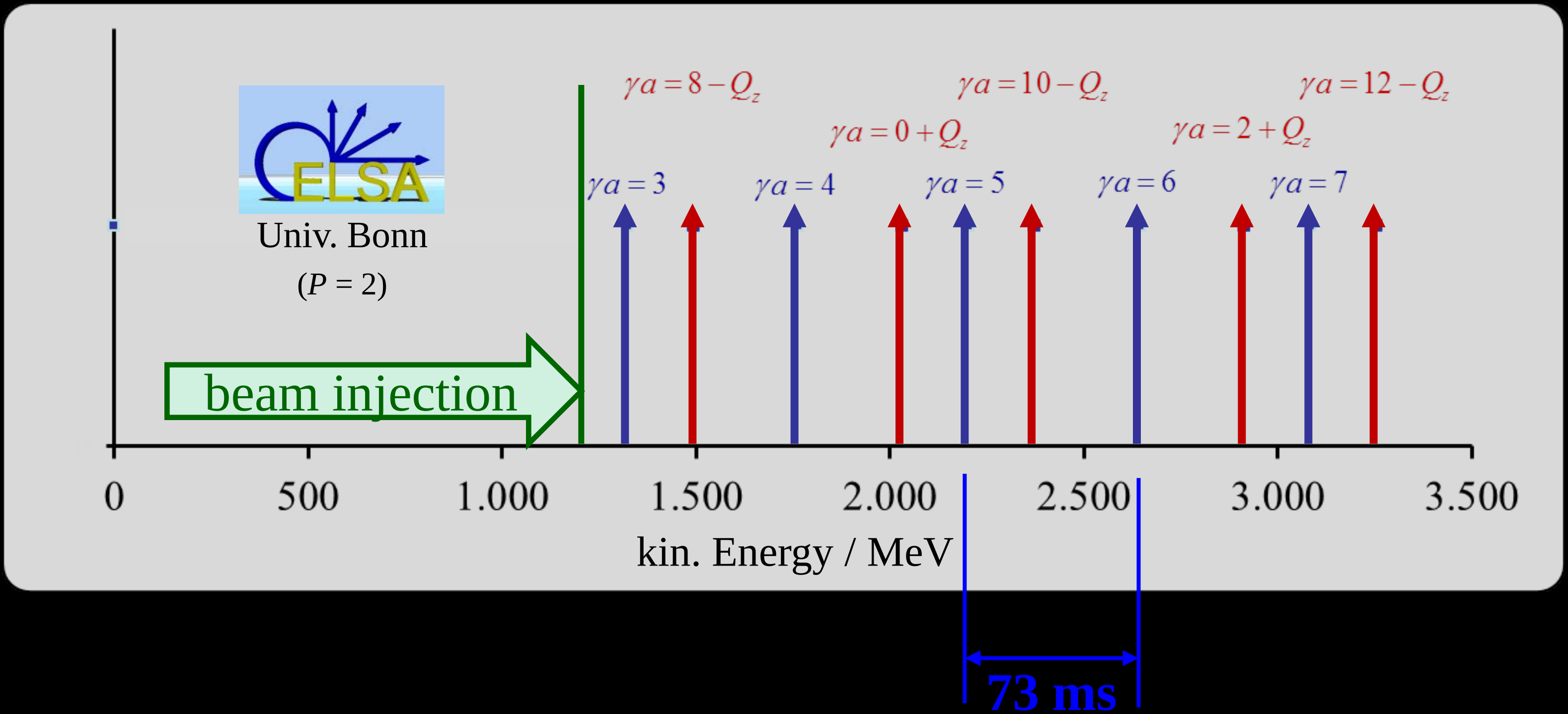
- small vertical beam size
- tune jumping with pulsed quads





Depolarizing Resonances

Situation at ELSA:

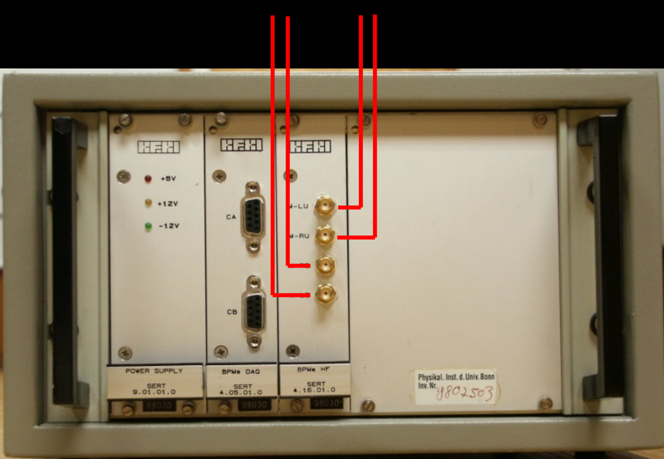


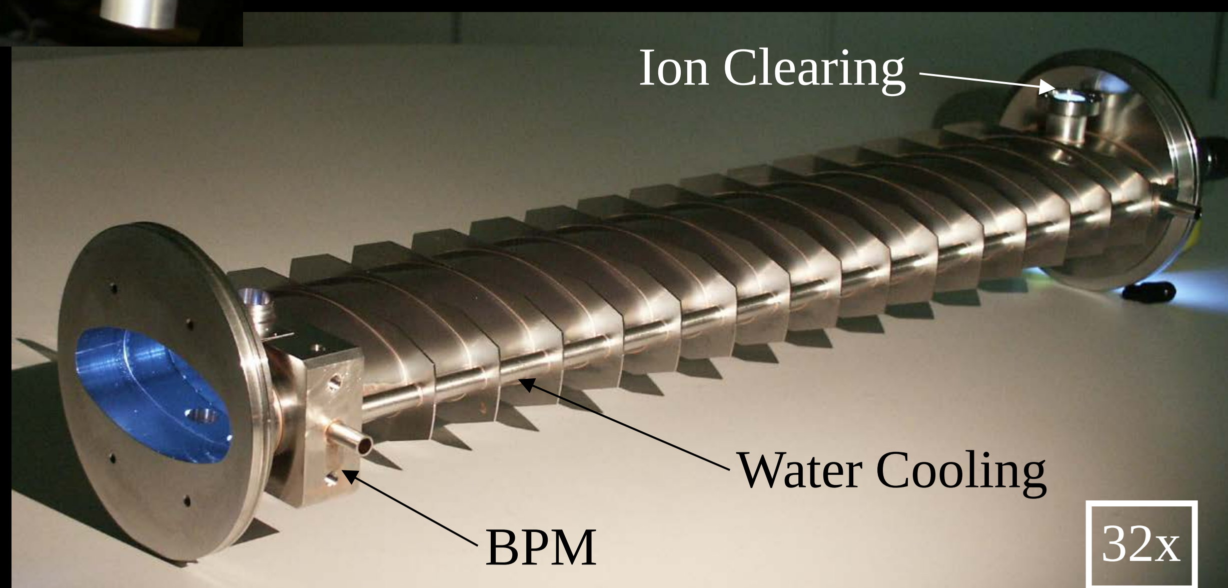
Imperfection Resonance: $\gamma \cdot a = n, \quad n \in Z$

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

32 New Pick-Up BPMs

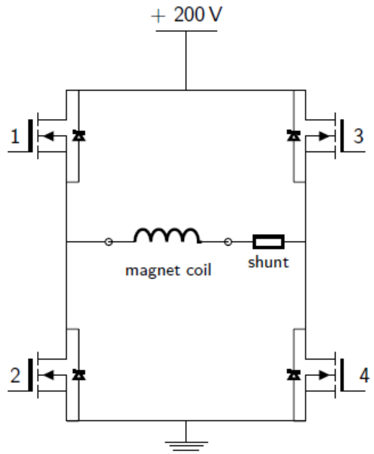
- BPMs at the Quadrupoles
- BPMs fixed to the Quadrupoles
- Smooth Geometry → low Impedances
- Clearing Electrodes close to the Quadrupoles
- Water Cooling

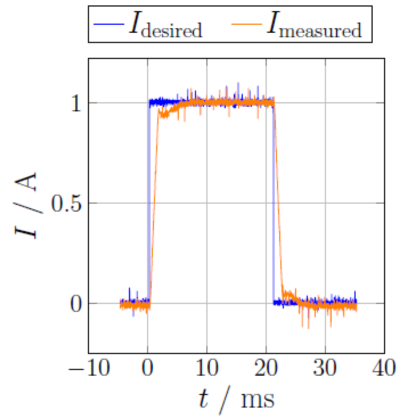




Fast Correction System

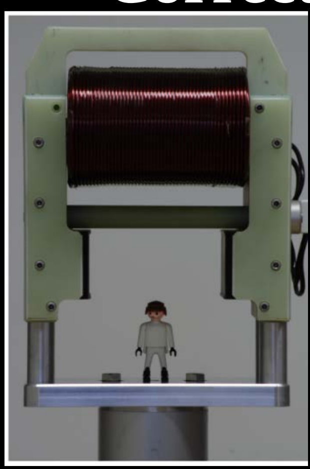
Programmable 4-Quadrant PS:





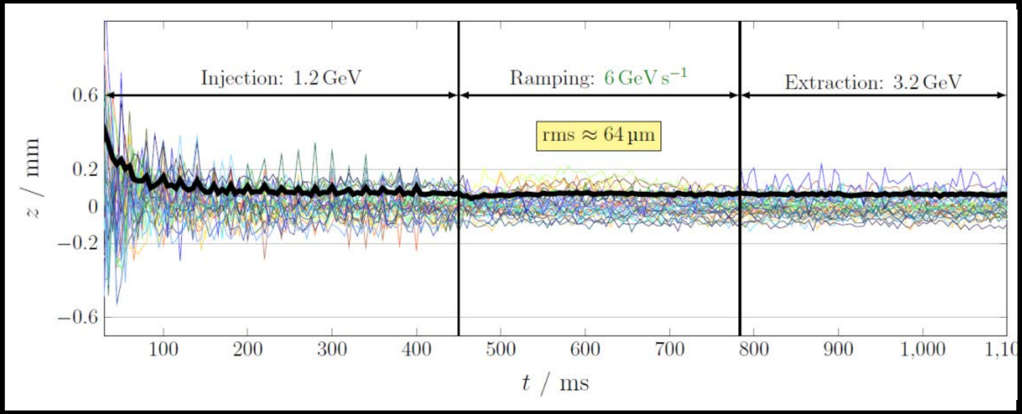
- 20 kHz pulsed H-bridge
- PI-controller
- current precision ≈ 1 ‰
- CAN-Bus module
- stored current ramps
- external trigger
- in total 54 power supplies distributed in 14 cabinets along the ELSA tunnel

Correction Coils:



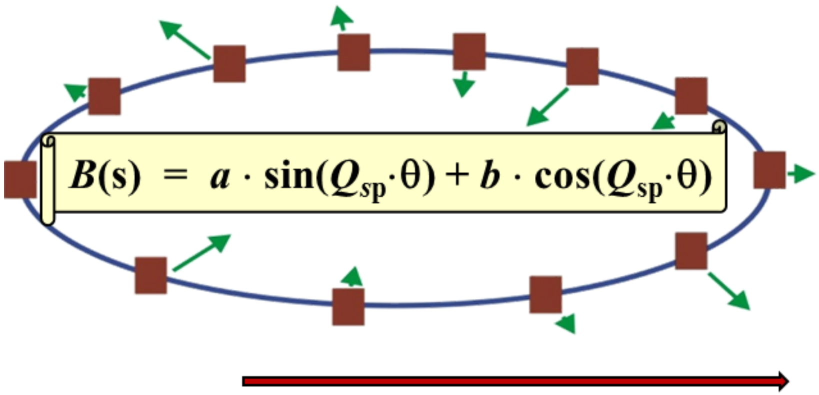
	new
voltage	200 V
max. current	8.0 A
inductance	260 mH
max. field	40 mT
weight	30 kg
field integral	9.8 mT m

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

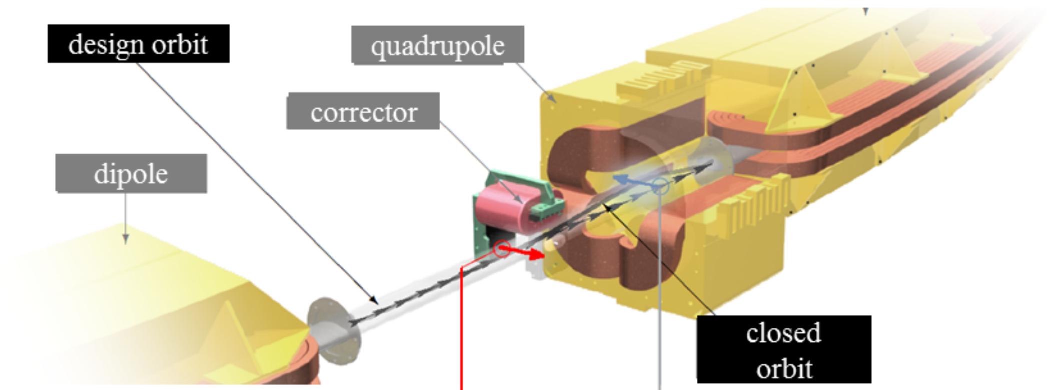


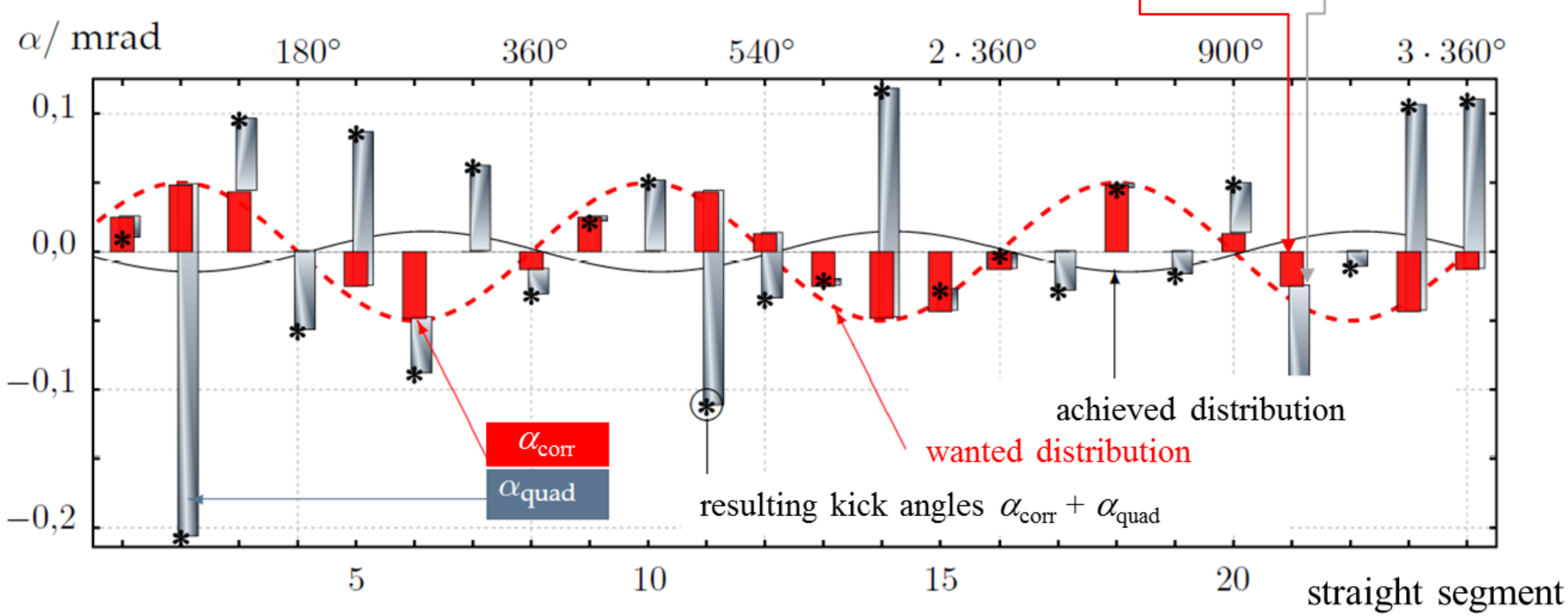
Harmonic Correction

(simple approach)

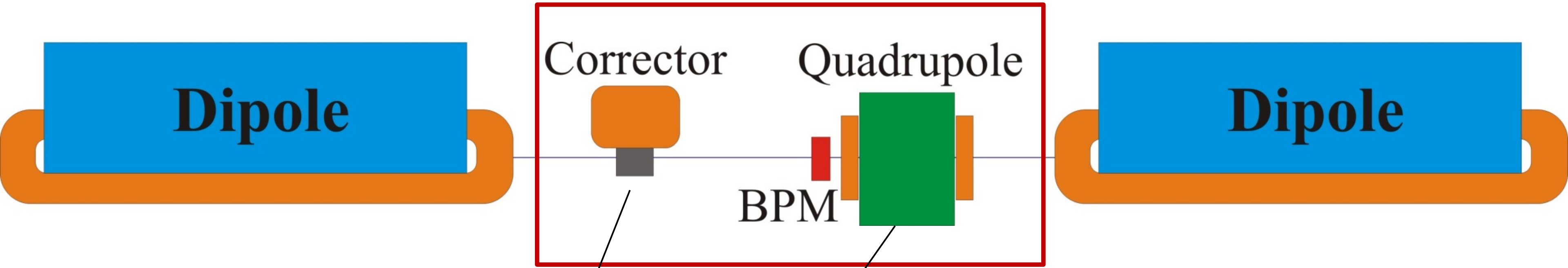


$$B(s) = a \cdot \sin(Q_{sp} \cdot \theta) + b \cdot \cos(Q_{sp} \cdot \theta)$$





Spin-Orbit Response Technique



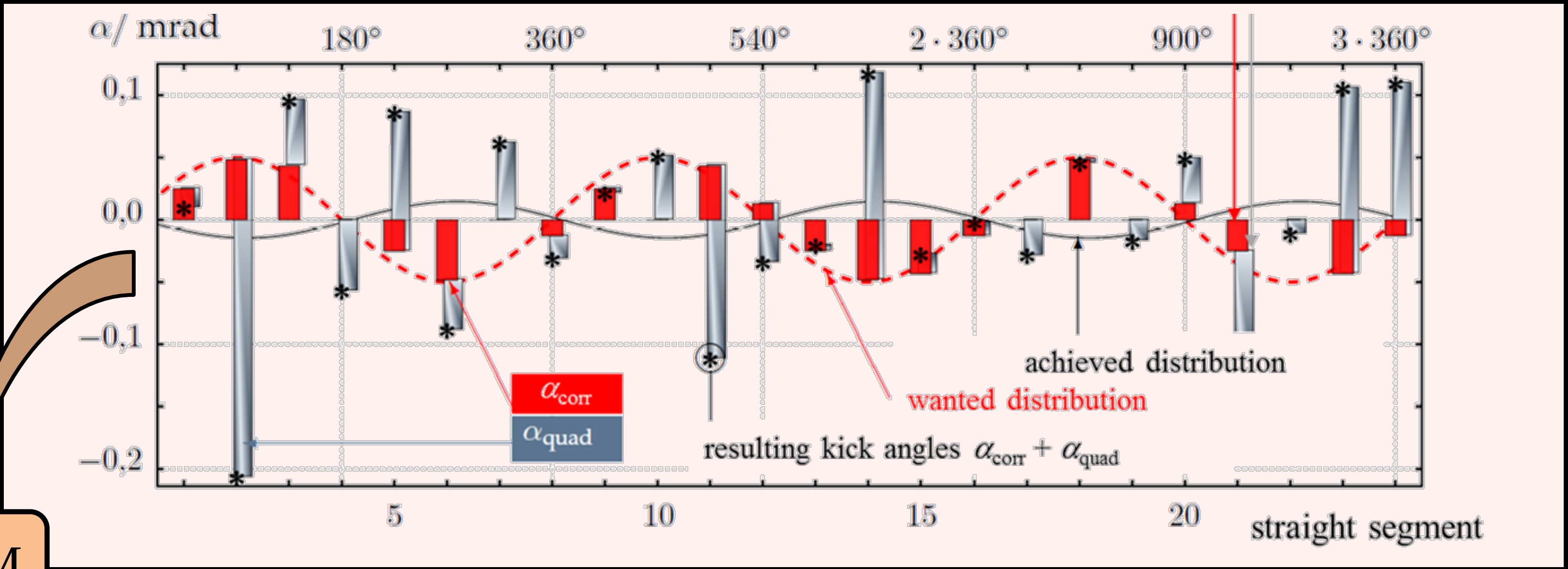
2 Contributions: $\alpha_n = \boxed{\sum_{j\in Dip_n} \alpha_{corr,j}} + \boxed{l \cdot \sum_{j\in Dip_n} k_j \cdot \Delta z_j} = \sum_{j\in Dip_n} \alpha_{corr,j} + l \cdot \sum_{j\in Dip_n} k_j \cdot \left(\mathbf{ORM} \cdot \vec{\alpha}_{corr}\right)_j$

$\Downarrow$

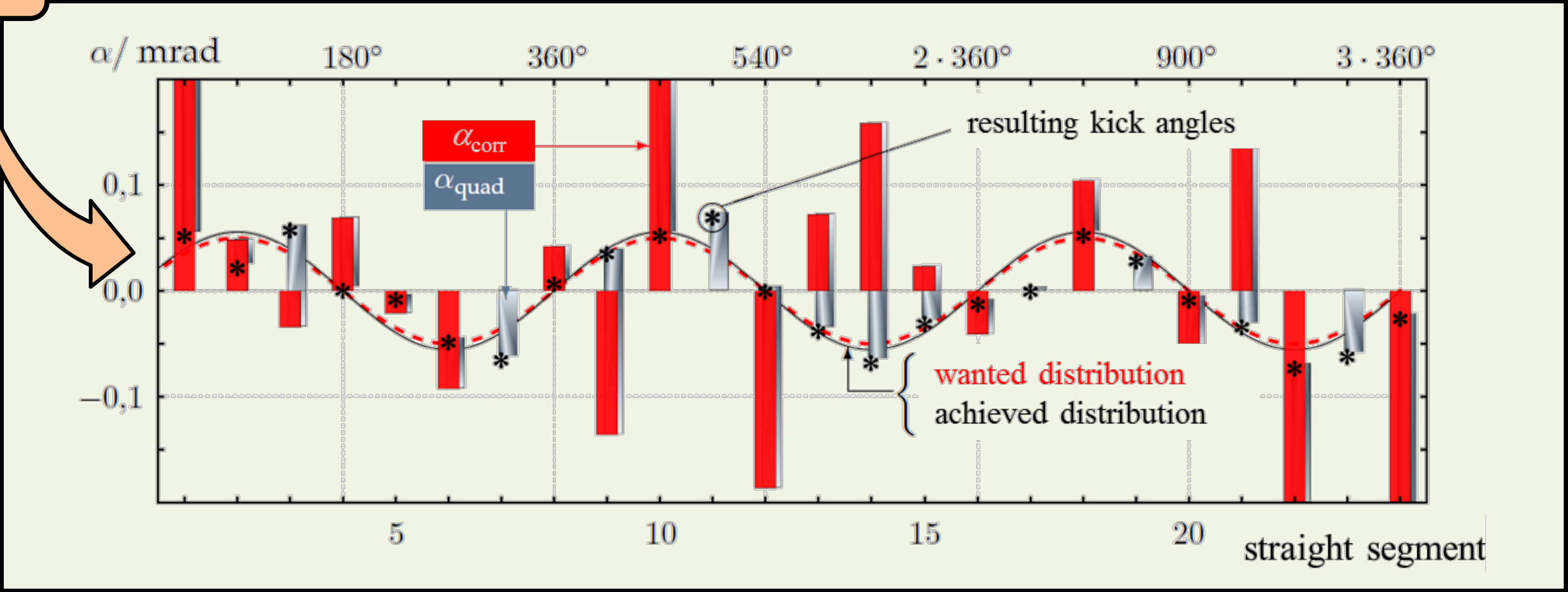
Harmonic Correction Matrix: $\vec{\alpha}_{harm} = \mathbf{HCM} \cdot \vec{\alpha}_{corr}$

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

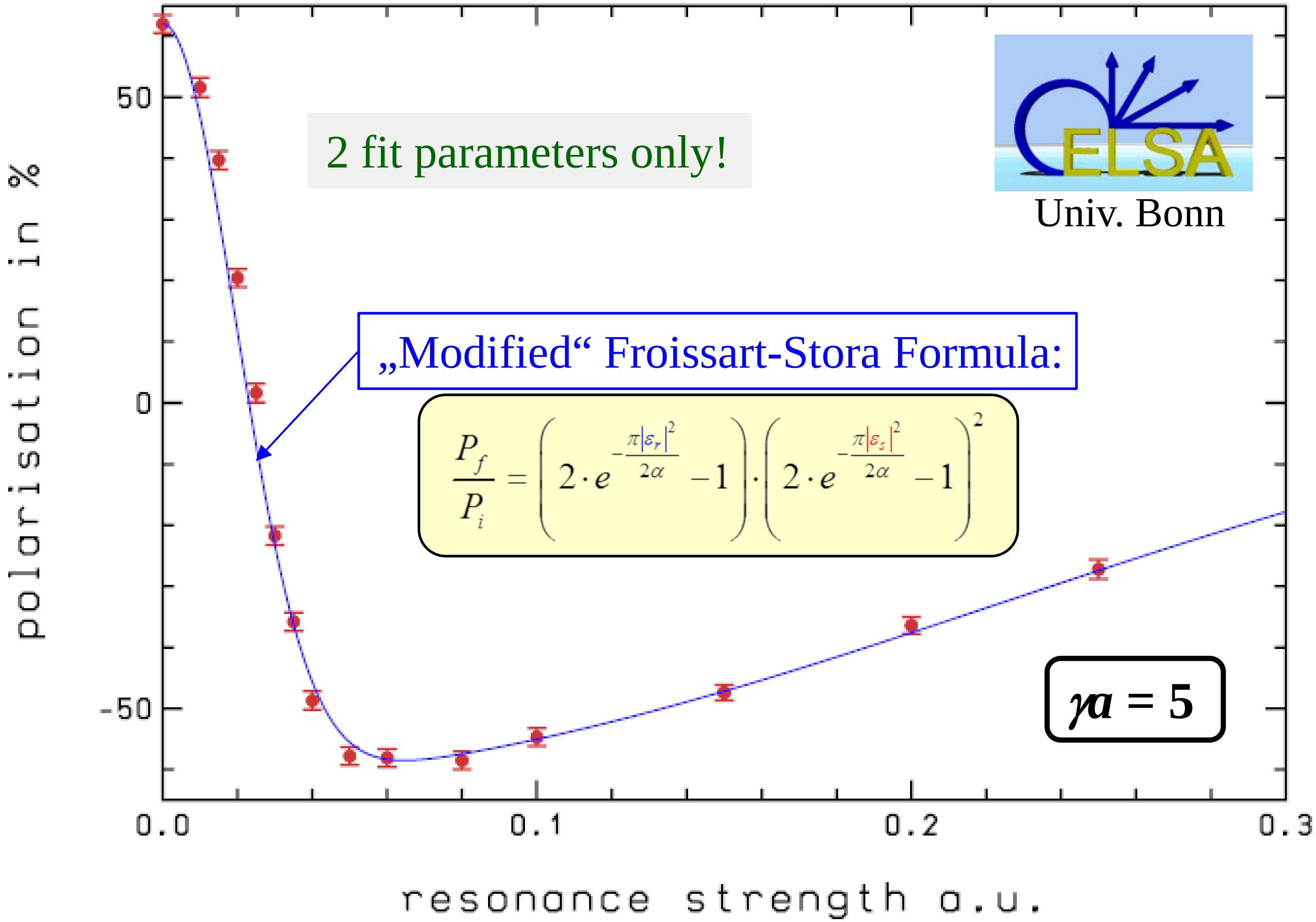
Spin-Orbit Response Technique



HCM



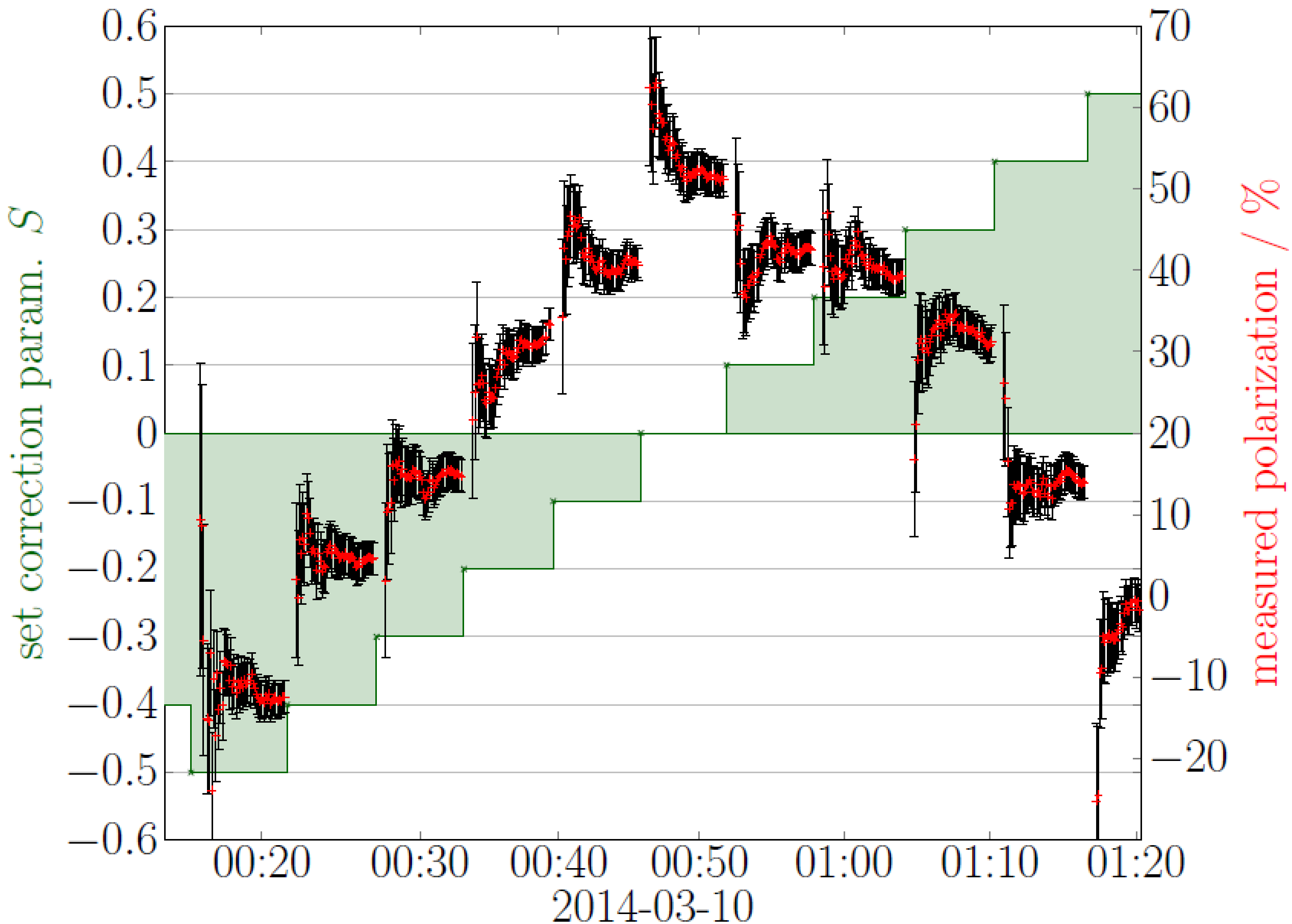
Resonance Crossing



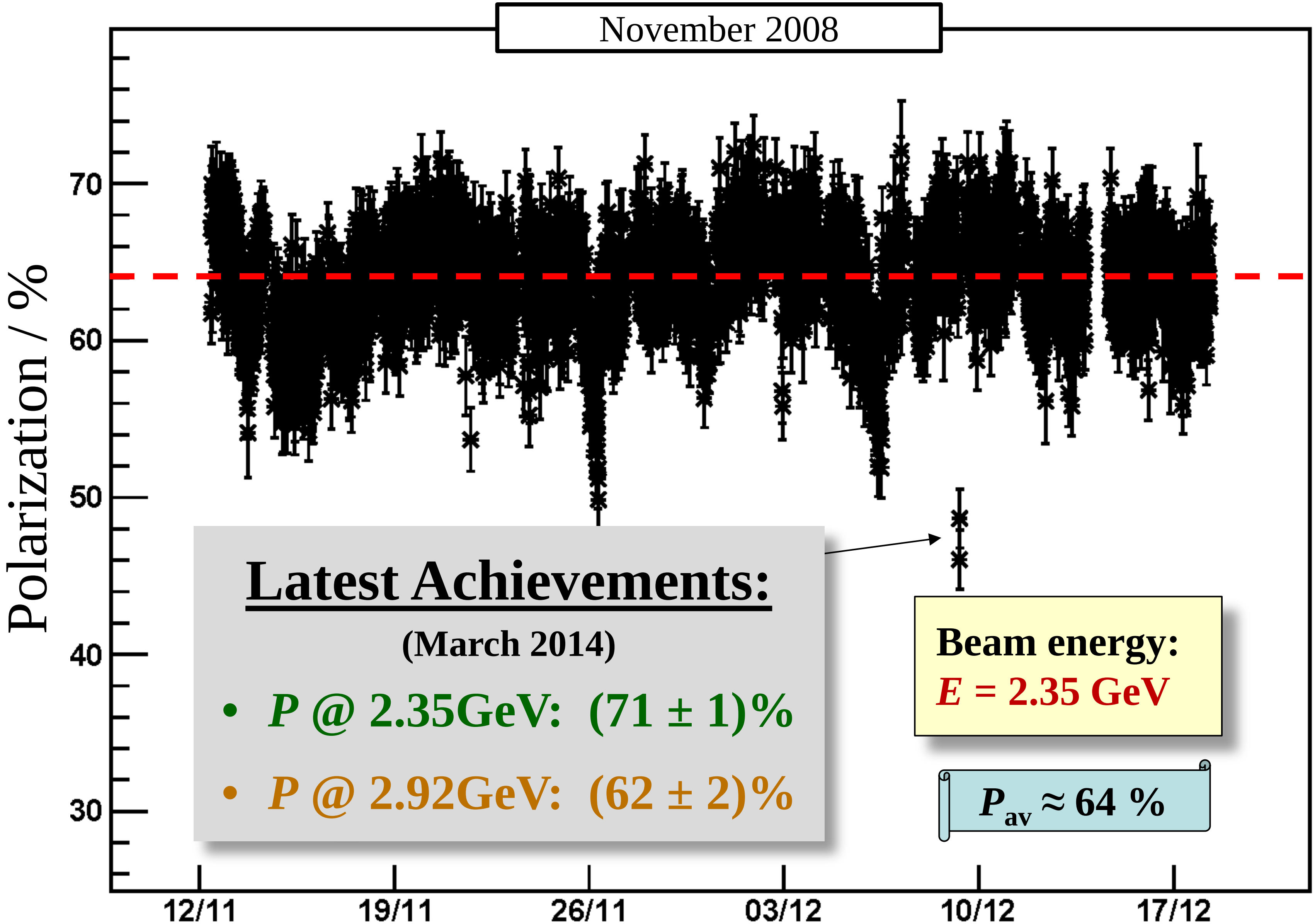
Beam excitation will only cause partial spin flip → depolarization!

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

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



Polarization at CBELSA/TAPS



Latest Achievements:

(March 2014)

- ***P* @ 2.35GeV: (71 ± 1)%**
- ***P* @ 2.92GeV: (62 ± 2)%**

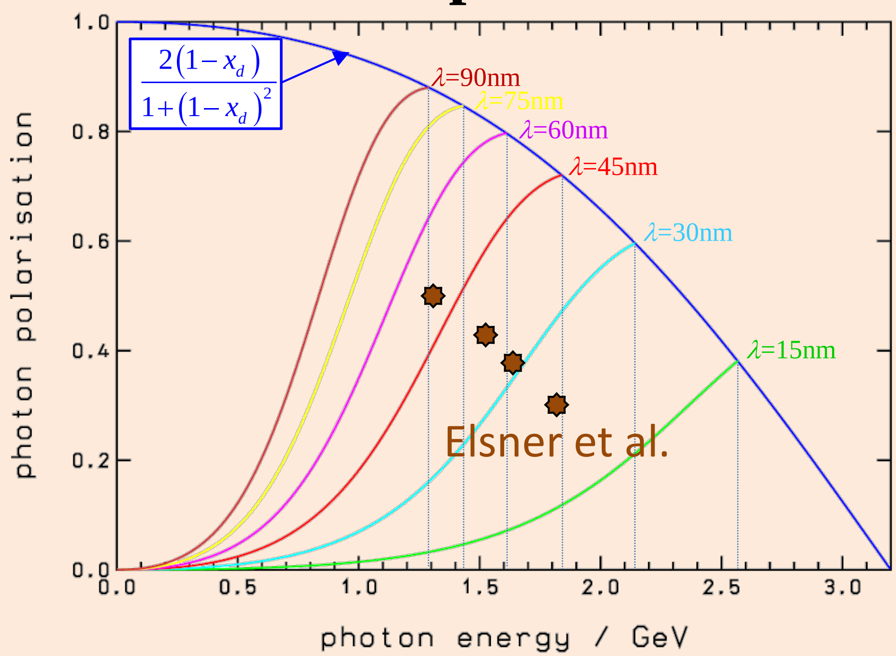
Beam energy:
***E* = 2.35 GeV**

$P_{av} \approx 64$ %

Coherent Bremsstrahlung

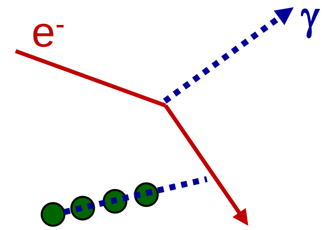
Beam energy: 3.2 GeV

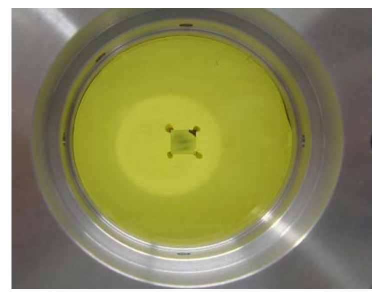
Linear polarization

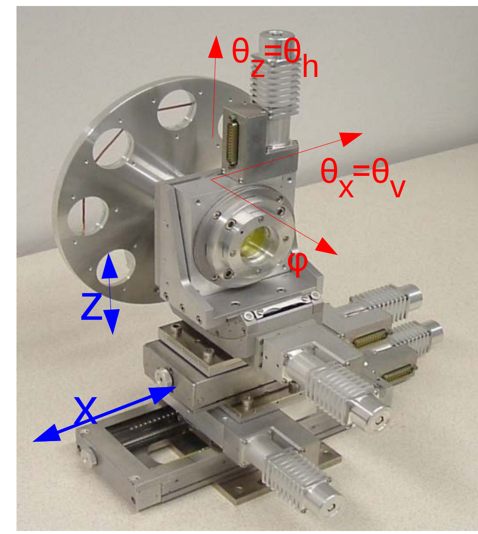


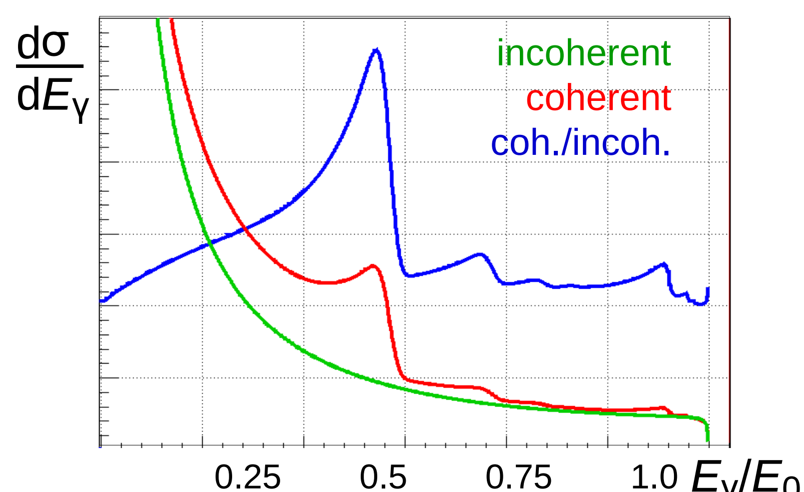
$$P=\frac{2x^2Q^2}{1-x}\left\{1+(1-x)^2-\frac{4x^2Q^2}{1-x}\left(\frac{1-x}{xQ}-1\right)\right\}^{-1}$$

High beam pointing stability required

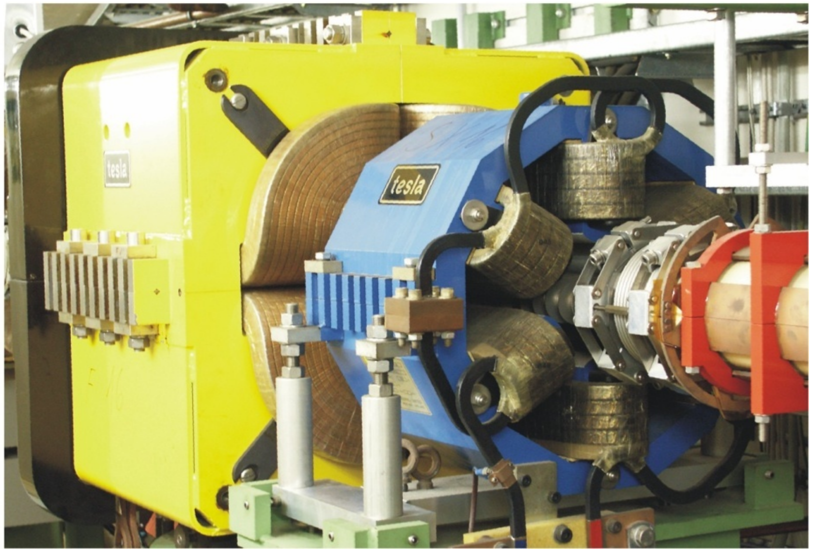


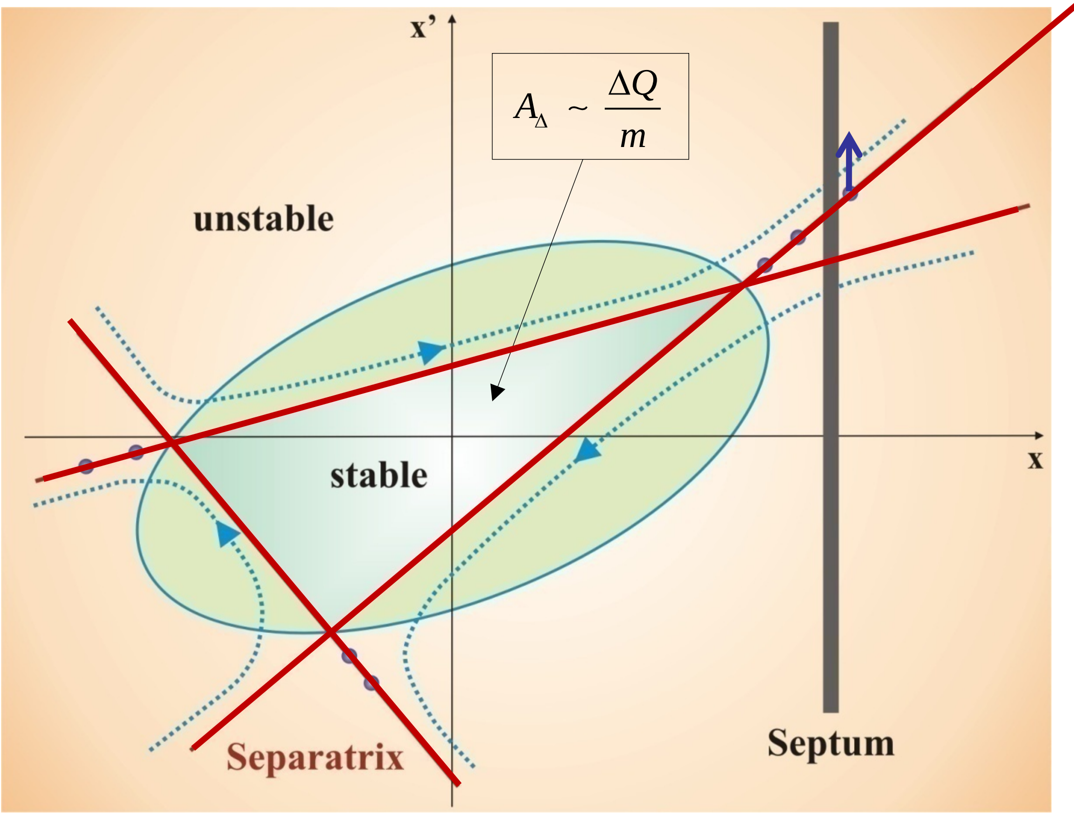






Slow Beam Extraction

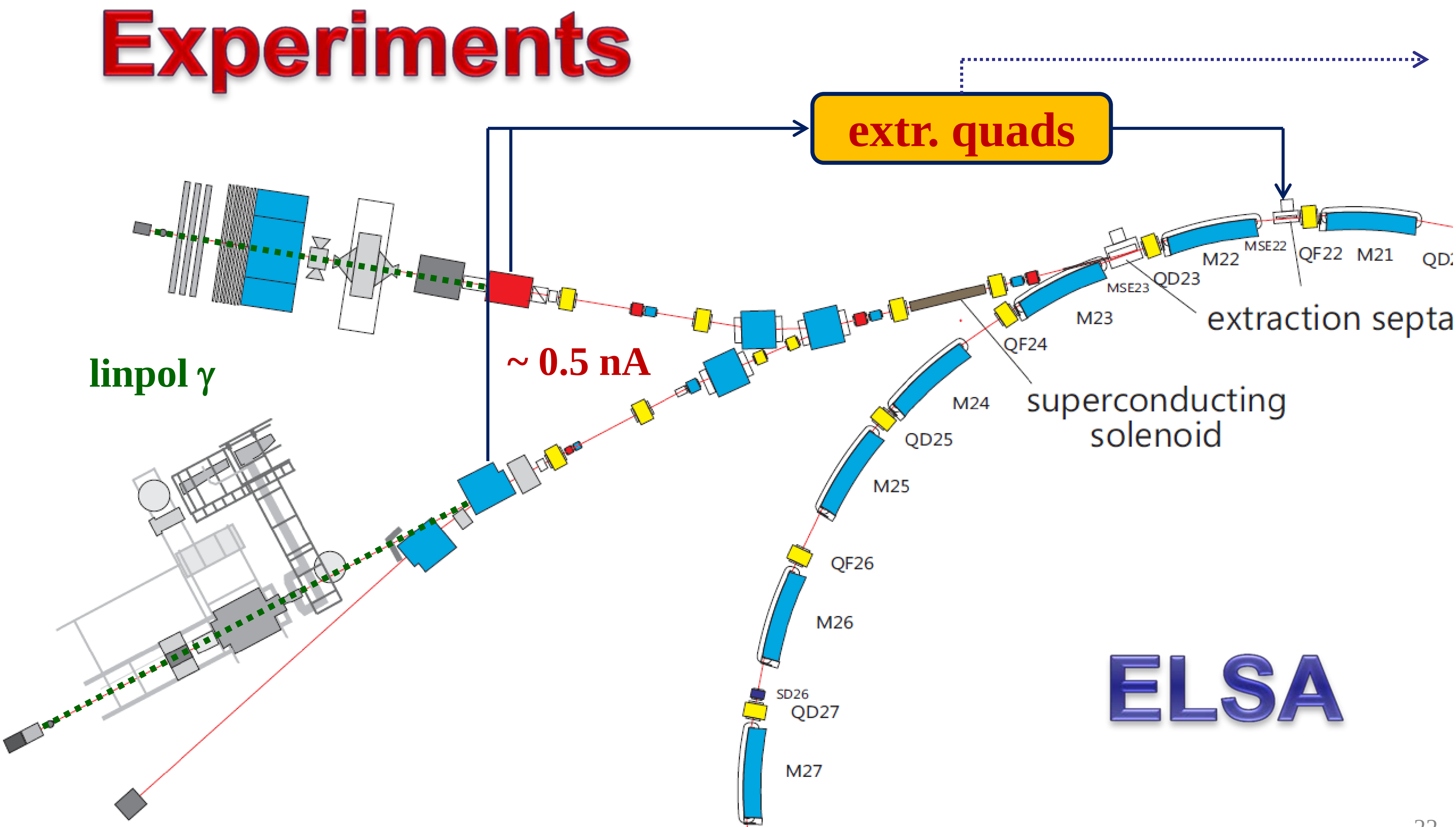




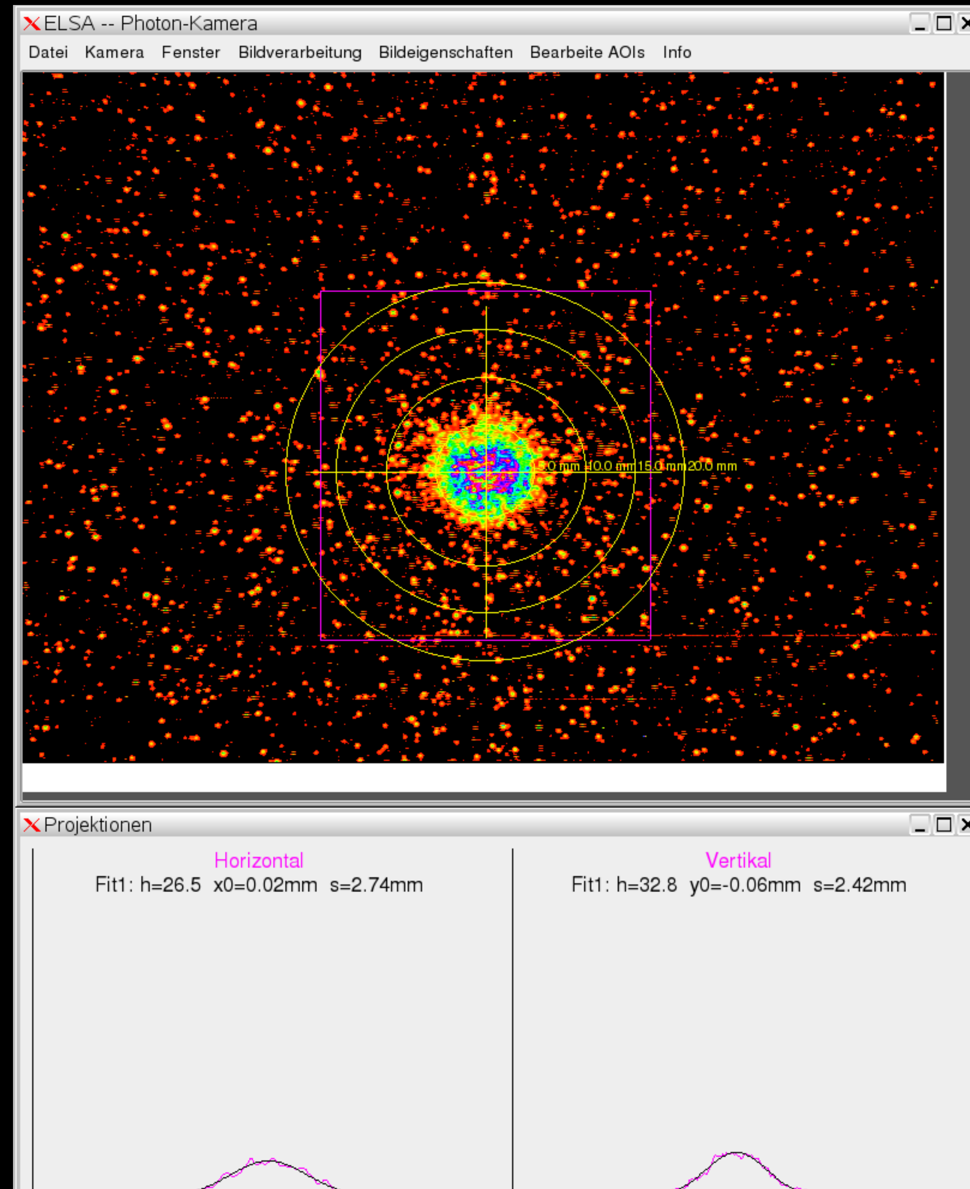
Sextupole Magnets (Extraction):
Excitation of a third integer resonance

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

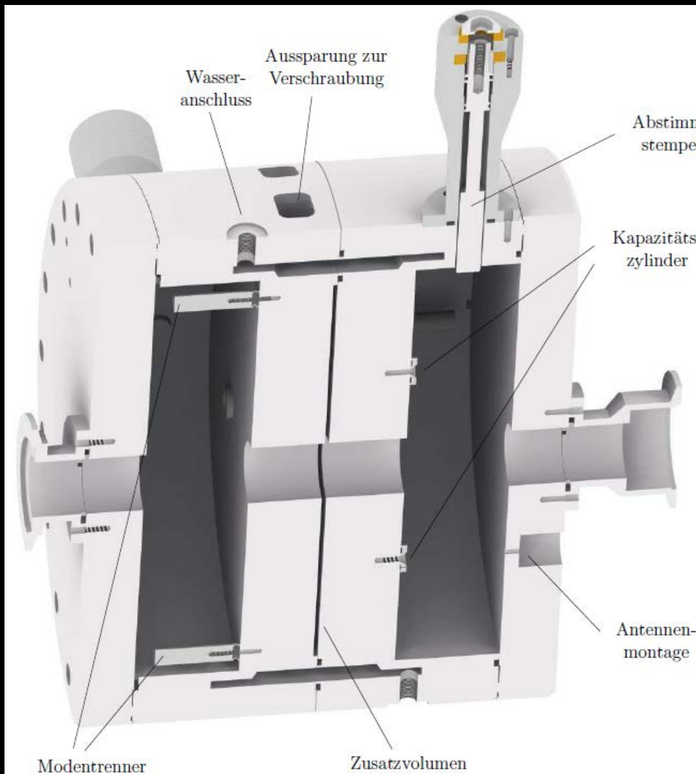
Intensity & Position Stabilisation

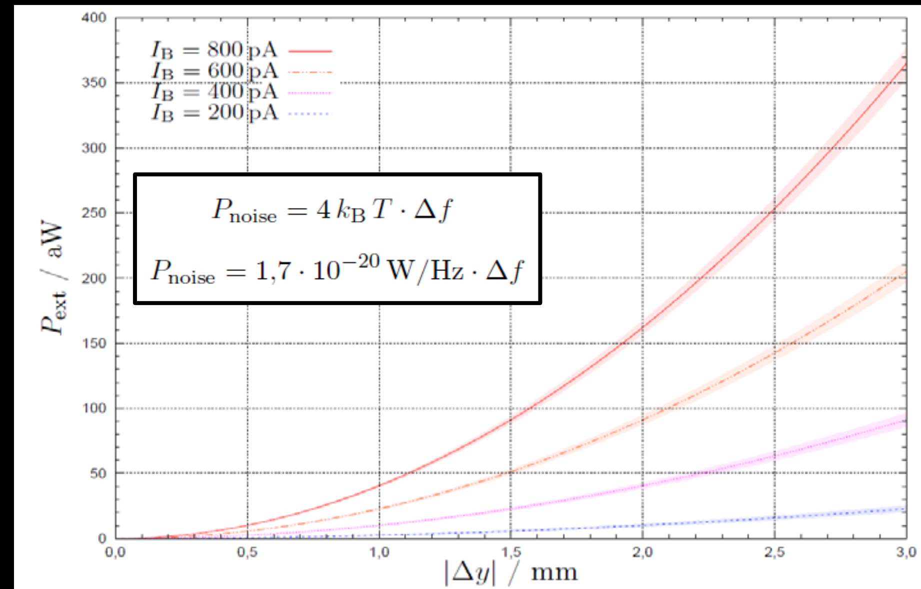


Photon Camera



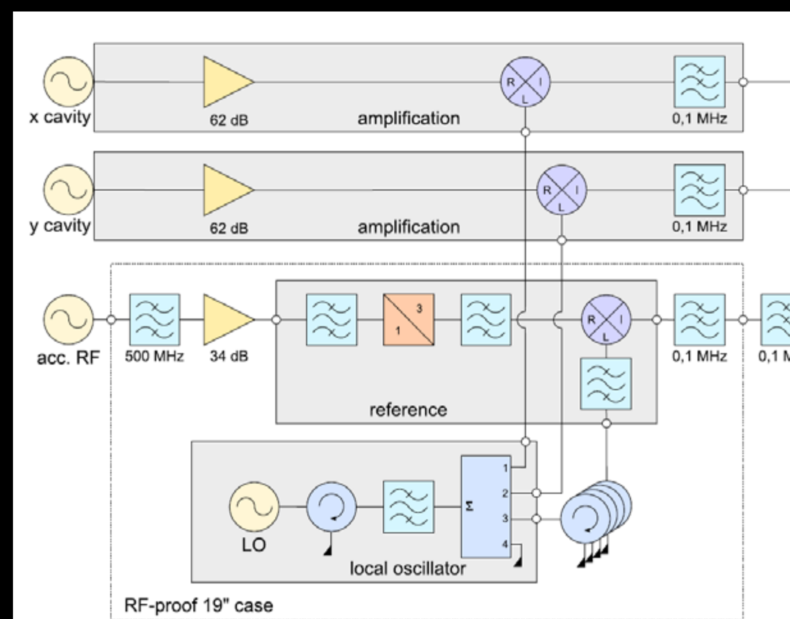
Position Measurement in the pA-Regime



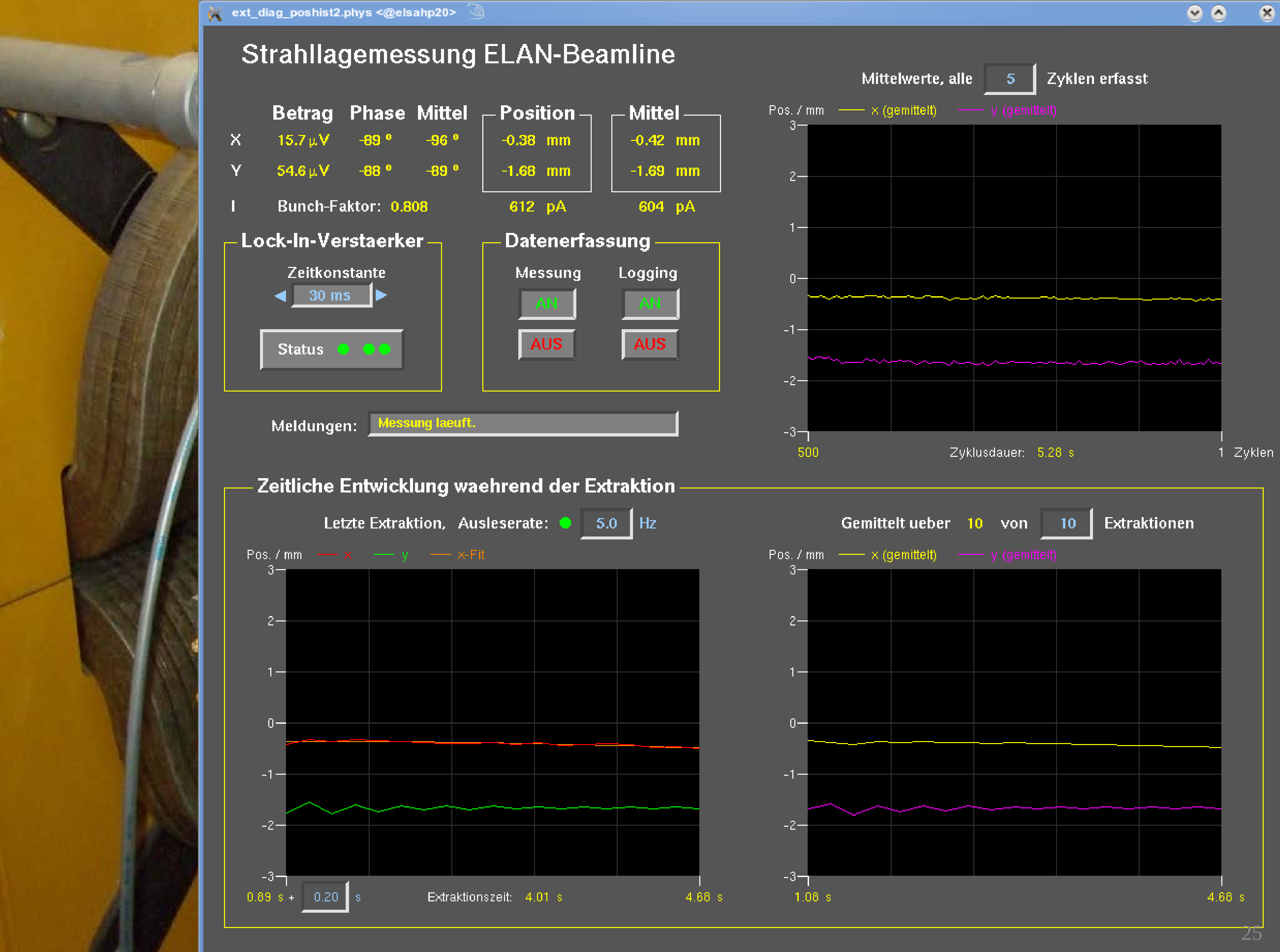


$\Delta x < 50\mu m$ @ $I = 100$ pA, $dx = 1$mm

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

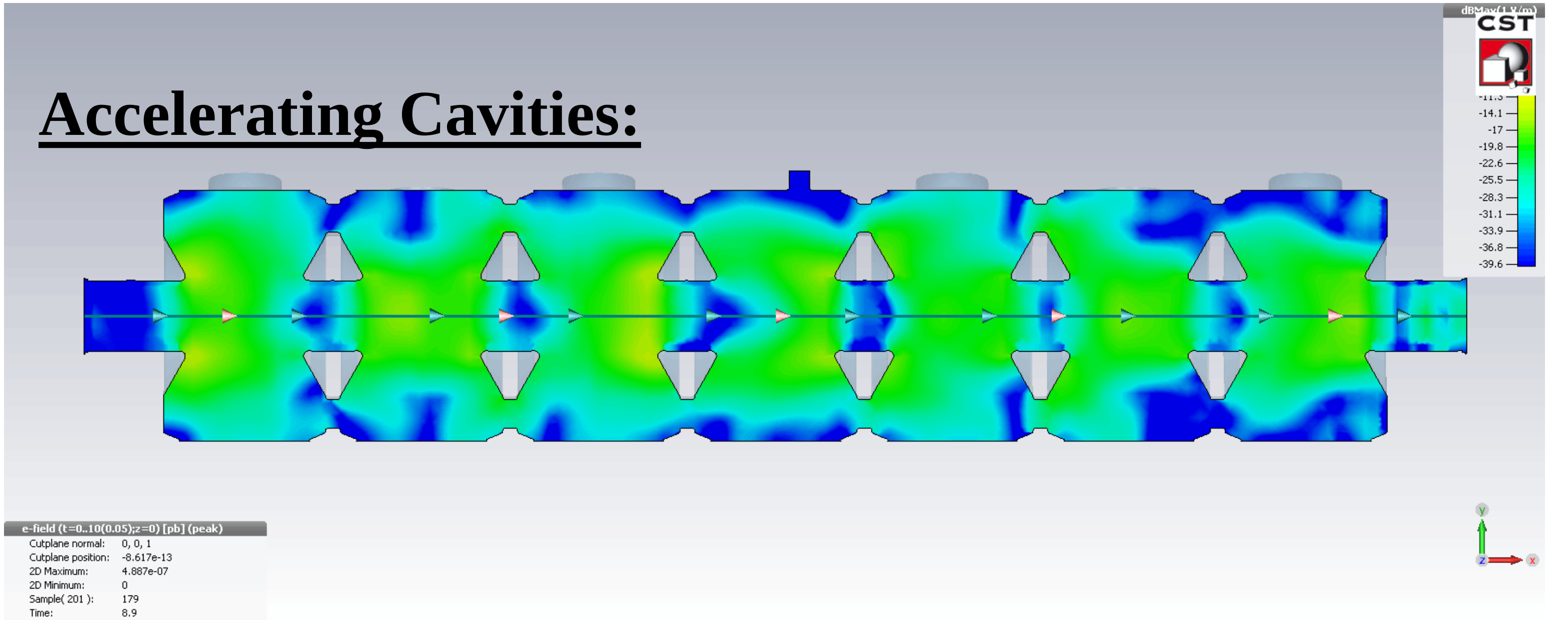


lock-in technique!

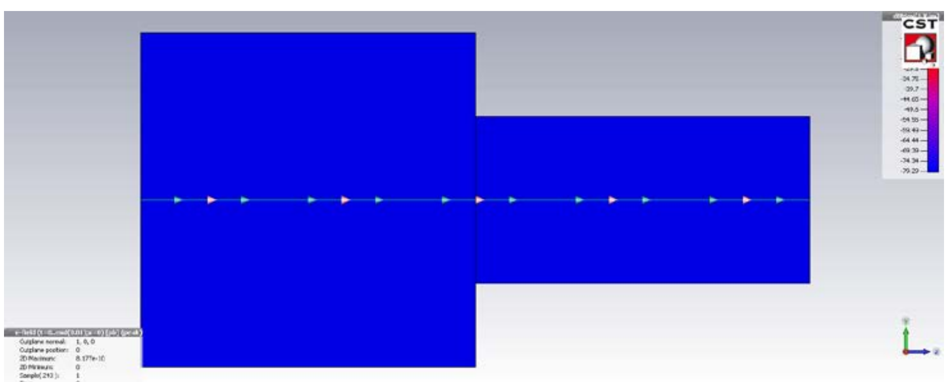

ext_diag_poshist2.phys <@elsahp20>
Strahllagemessung ELAN-Beamline
Mittelwerte, alle 5 Zyklen erfasst
Betrag Phase Mittel
X 15.7 µV -89 ° -96 °
Y 54.6 µV -88 ° -89 °
I Bunch-Faktor: 0.808
Position
-0.38 mm
-1.68 mm
612 pA
Mittel
-0.42 mm
-1.69 mm
604 pA
Lock-In-Verstaerker
Zeitkonstante
30 ms
Status
Datenerfassung
Messung
Logging
AN
AUS
Meldungen: Messung laeuft.
Pos. / mm
x (gemittelt)
y (gemittelt)
500
Zyklusdauer: 5.28 s
1 Zyklen
Zeitliche Entwicklung waehrend der Extraktion
Letzte Extraktion, Ausleserate: 5.0 Hz
Gemittelt ueber 10 von 10 Extraktionen
Pos. / mm
x
y
x-Fit
0.89 s + 0.20 s
Extraktionszeit: 4.01 s
4.68 s
1.08 s
4.68 s

High Intensities

Accelerating Cavities:



Beam-Pipe Discontinuities:



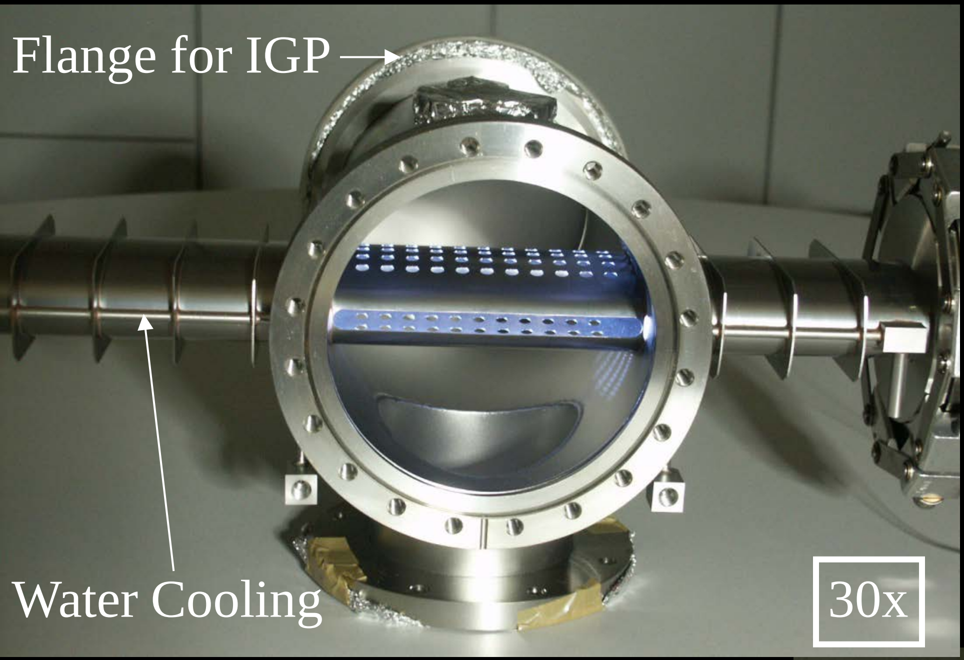
Generation of wake-fields

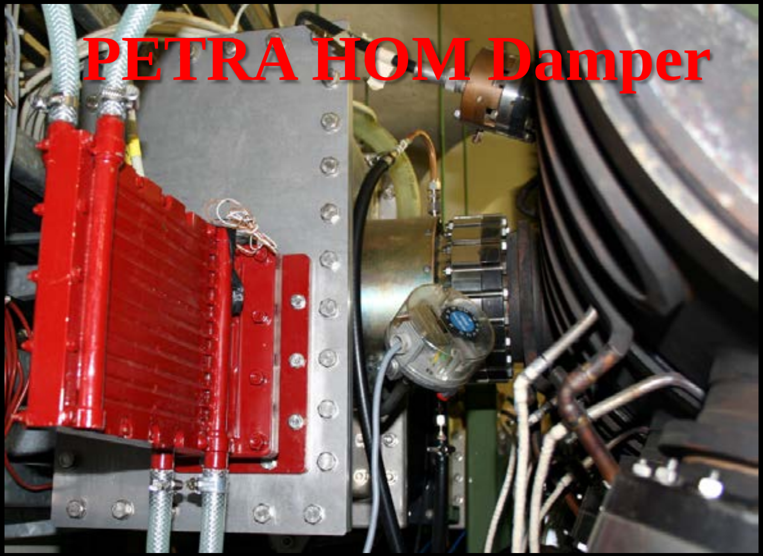
→ excitation of beam instabilities

Countermeasures:

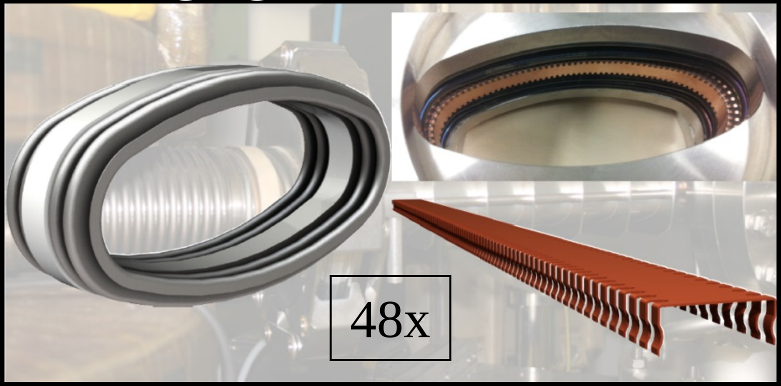
- Suppression of acc. cavities' HOM
- Reduction of coupling impedance
- **Active damping of instabilities**

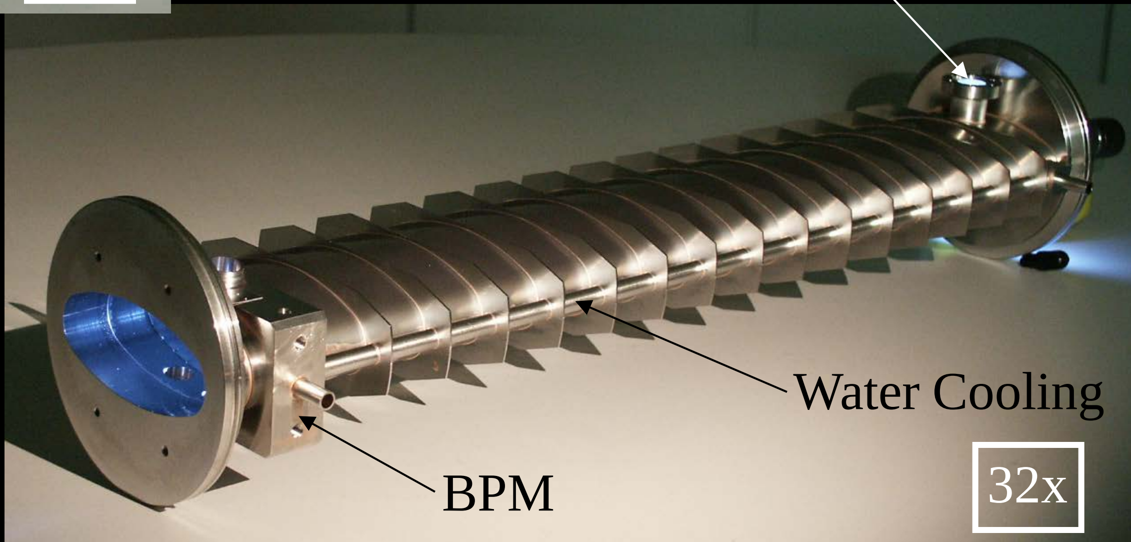
Impedance Reduction





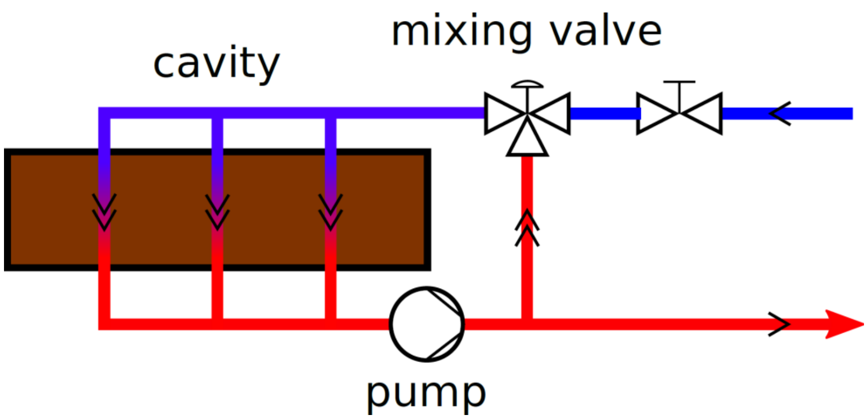
Bridging of Ceramic Brakes

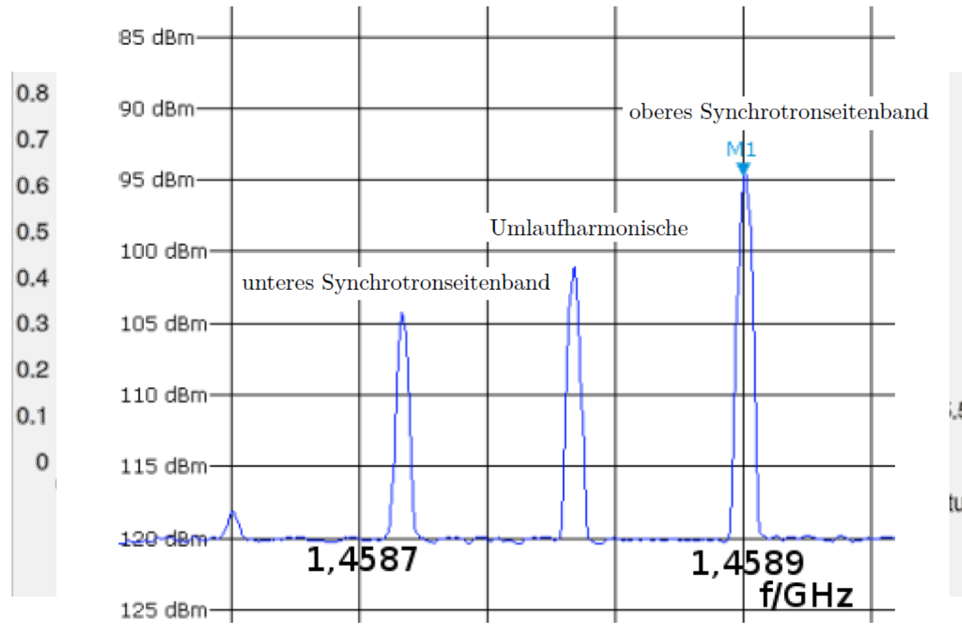




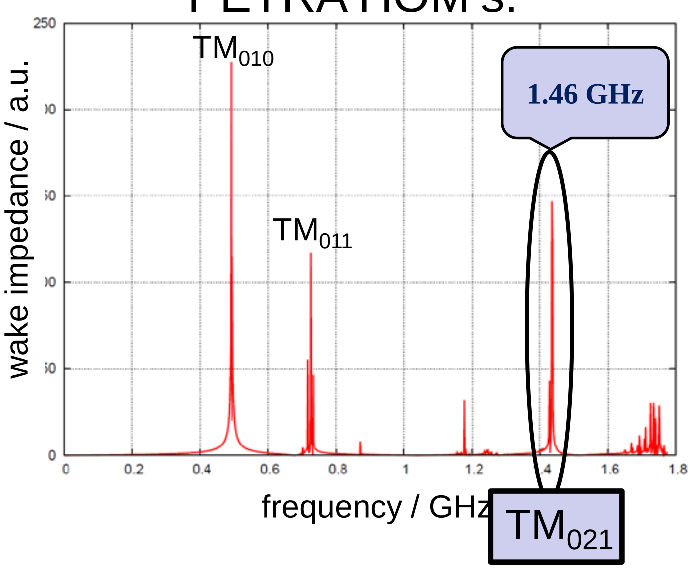
HOM Suppression Acc. Cavities

$M = 274$





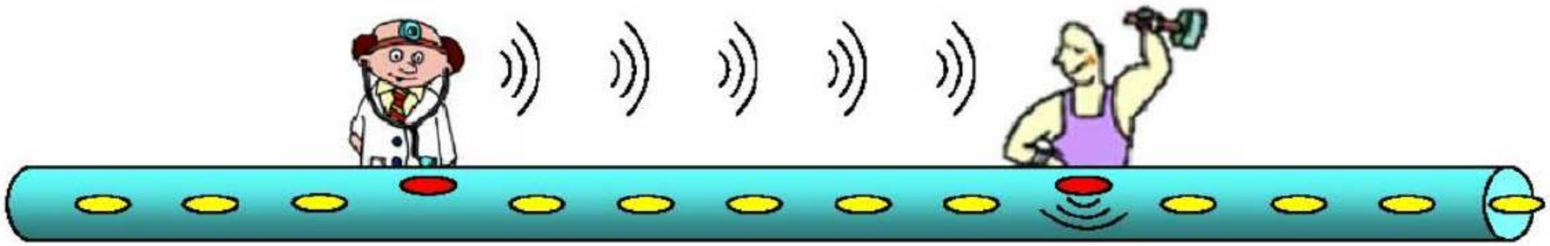
PETRA HOM's:



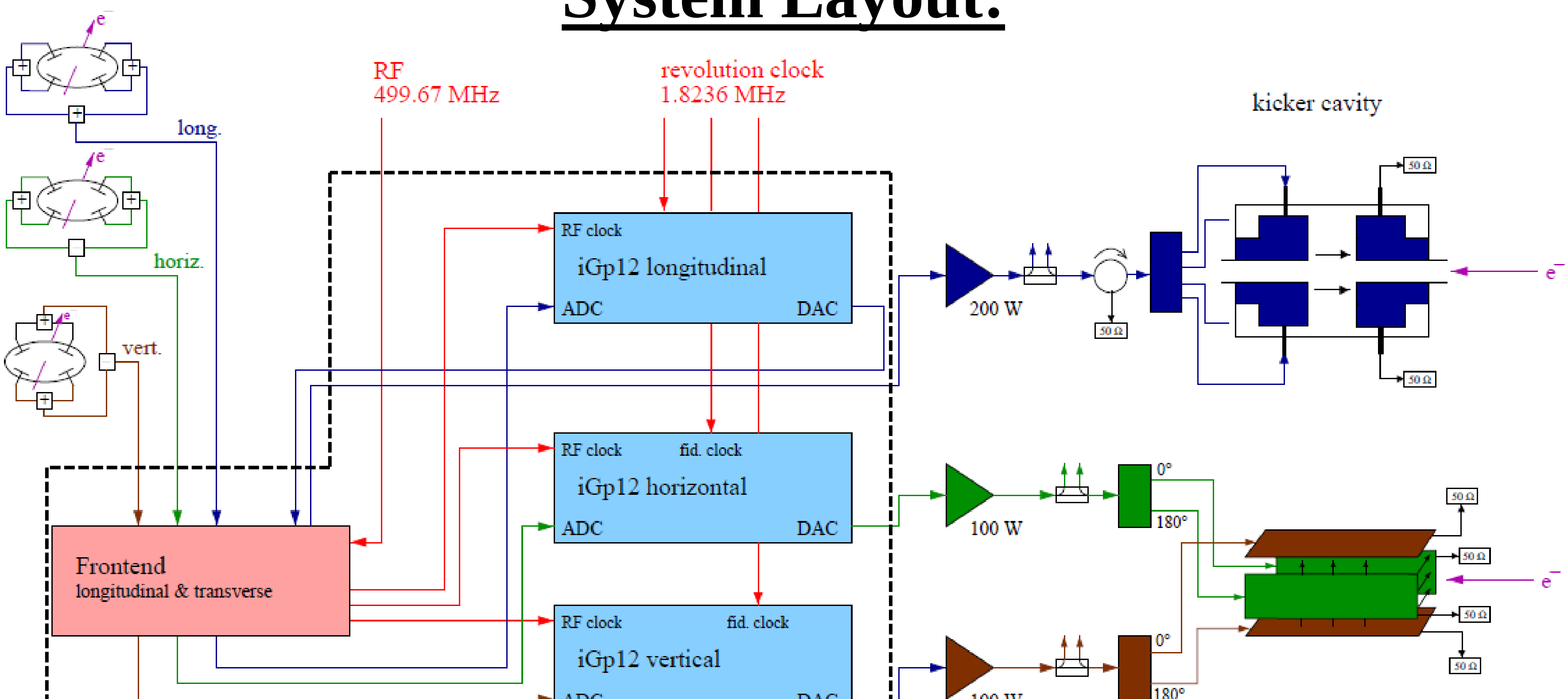
HOM @ 1.460GHz ↔ Mode 252

$$\omega_n = (n + pM)\cdot\omega_0 + m\Omega_S$$
$$= (252 + 2\cdot 274)\cdot 1.824\,\text{MHz} + \Omega_S$$
$$\approx 1.460\,\text{GHz}$$

Bunch-by-Bunch Feedback



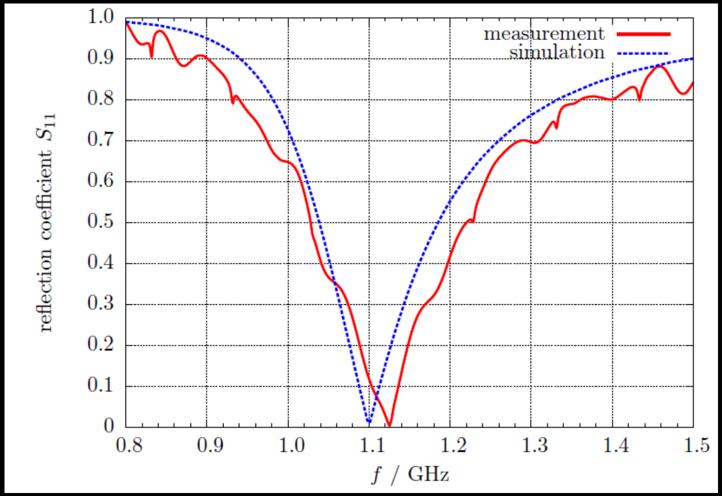
System Layout:



Broad-Band Kickers

(developed and constructed in-house)

Longitudinal: Kicker Cavity

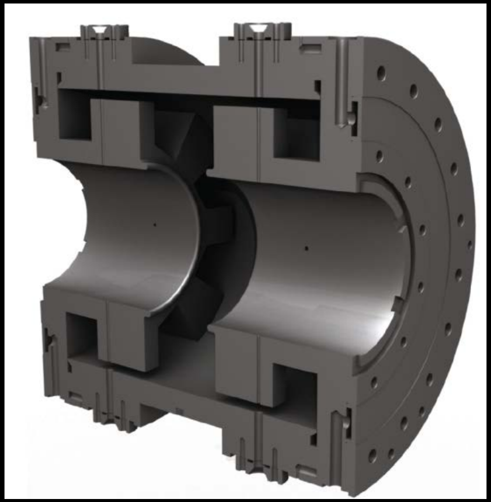


ν = 1.13 GHz

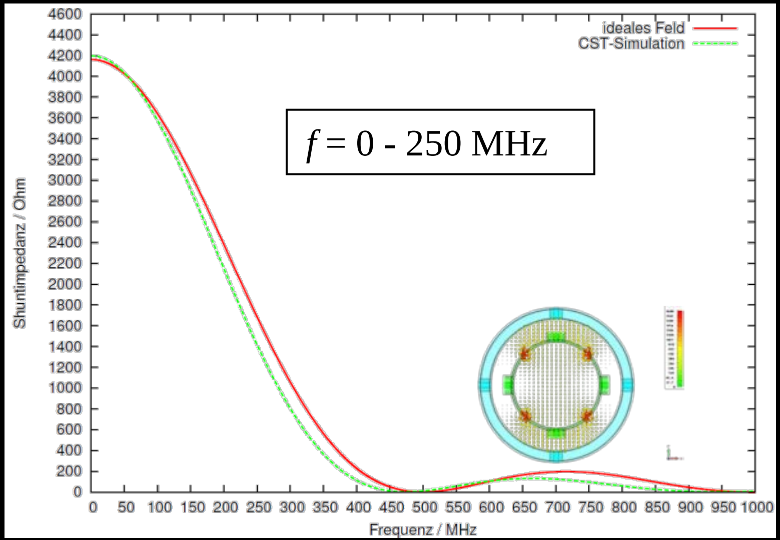
Q_L = 3.78

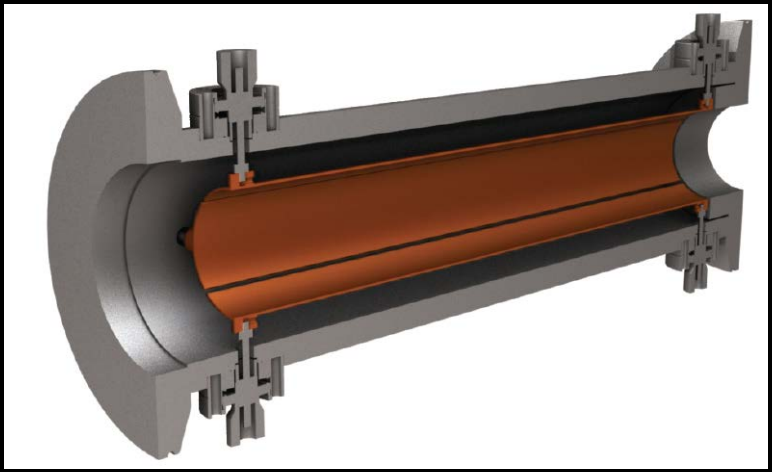
R_S = 387 Ω

BW = 255 MHz



Transverse: Stripline Kicker

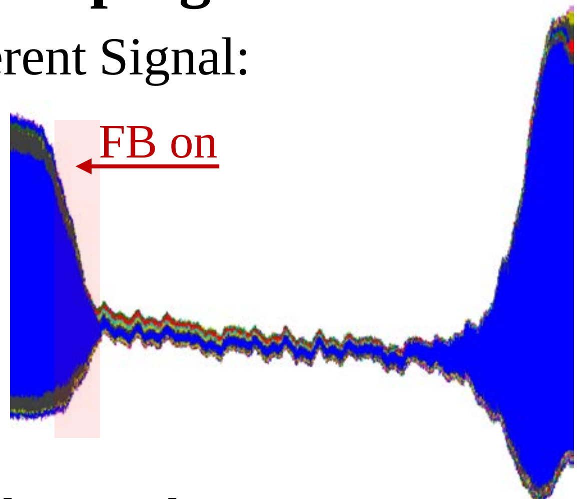




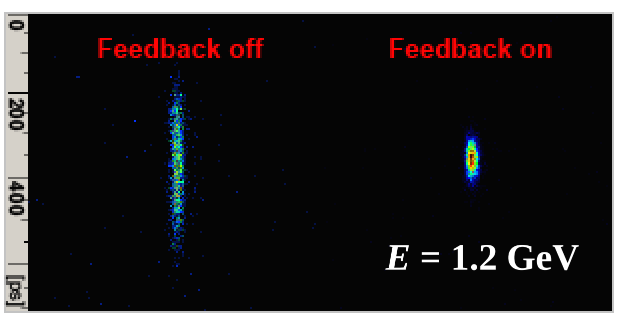
Feedback Performance

Damping of instabilities:

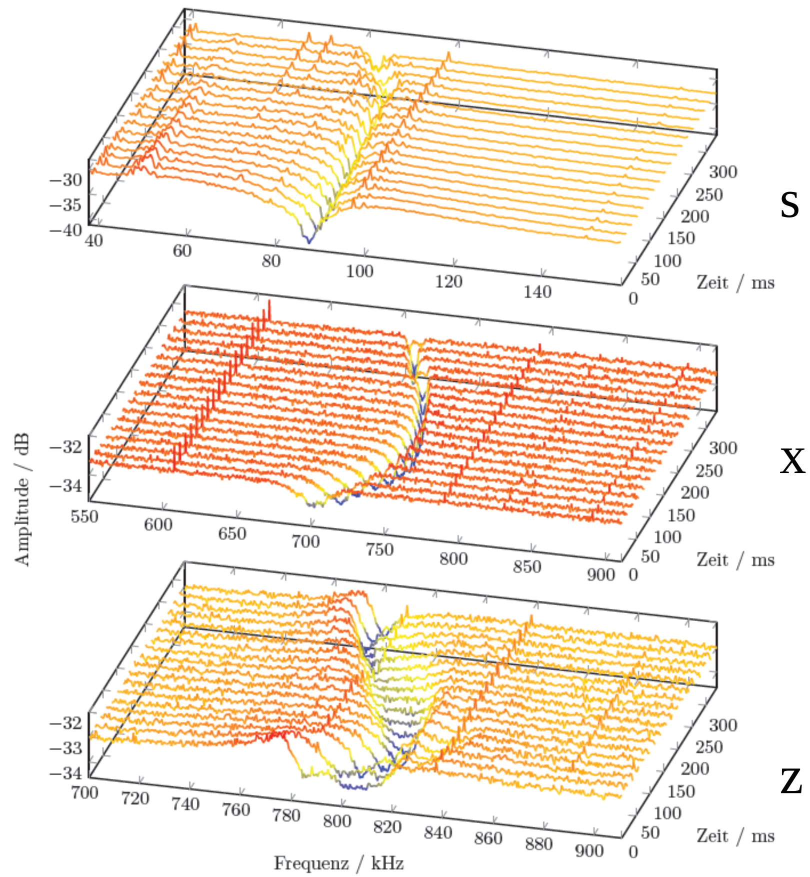
Coherent Signal:



Bunch Length:

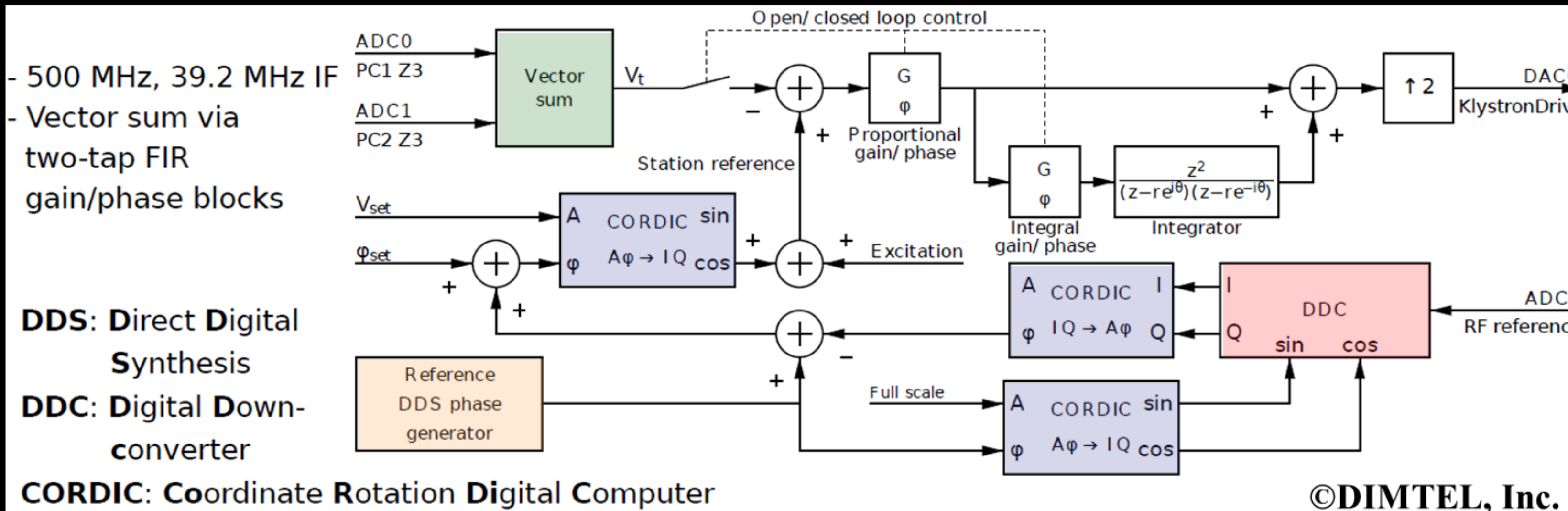


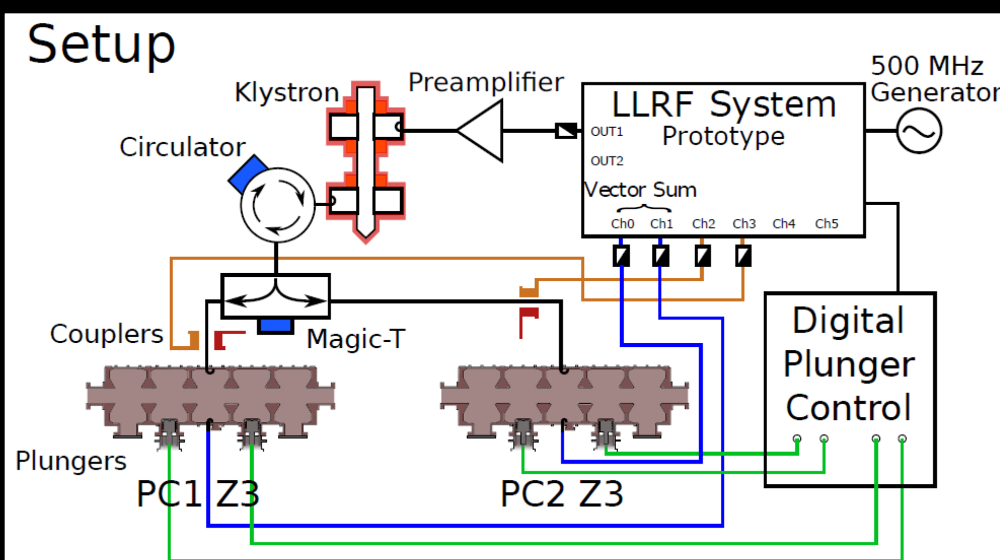
Measurement of the Tunes:

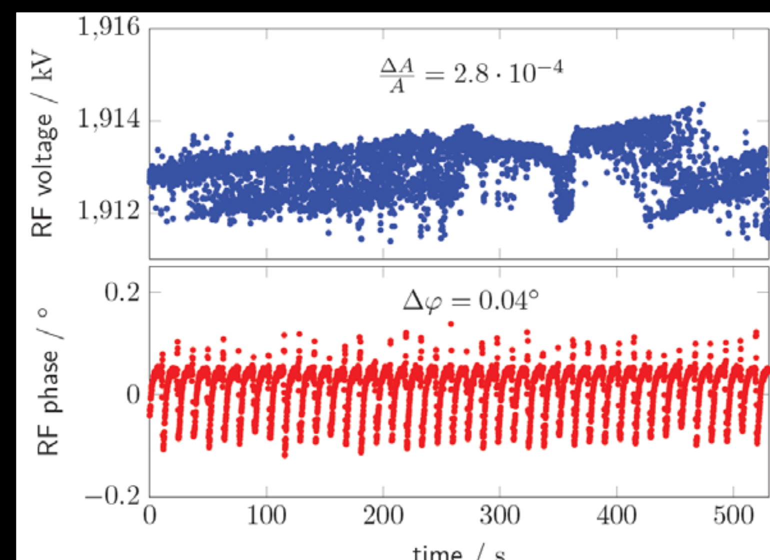


Allows stable operation of ELSA with currents up to 200mA!

RF Control & Stabilization



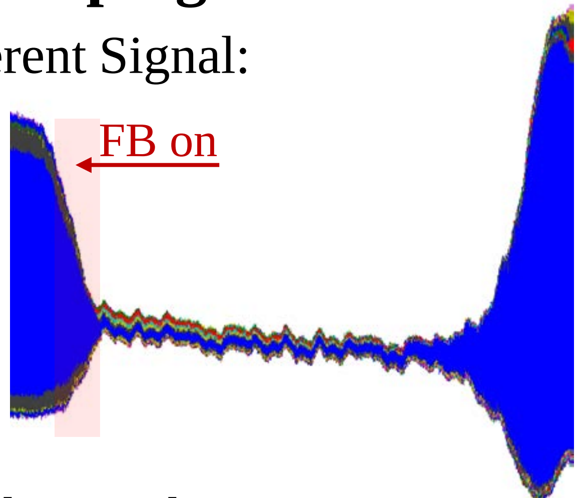




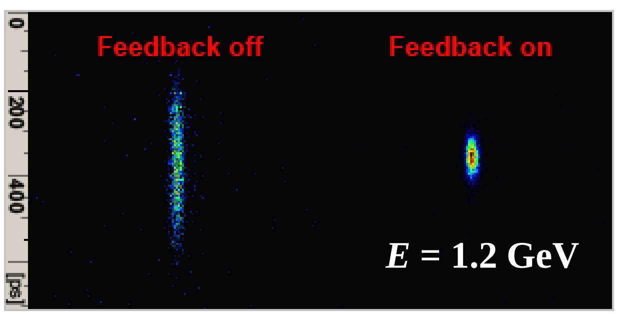
Feedback Performance

Damping of Instabilities:

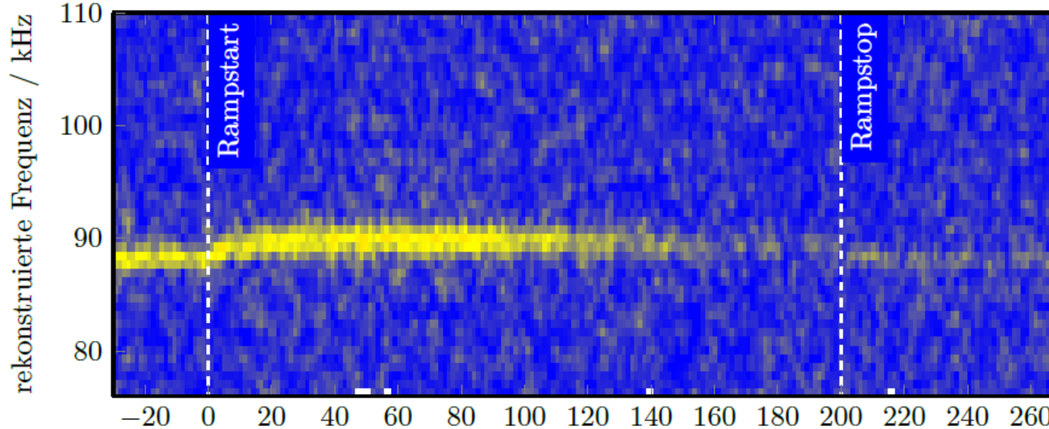
Coherent Signal:

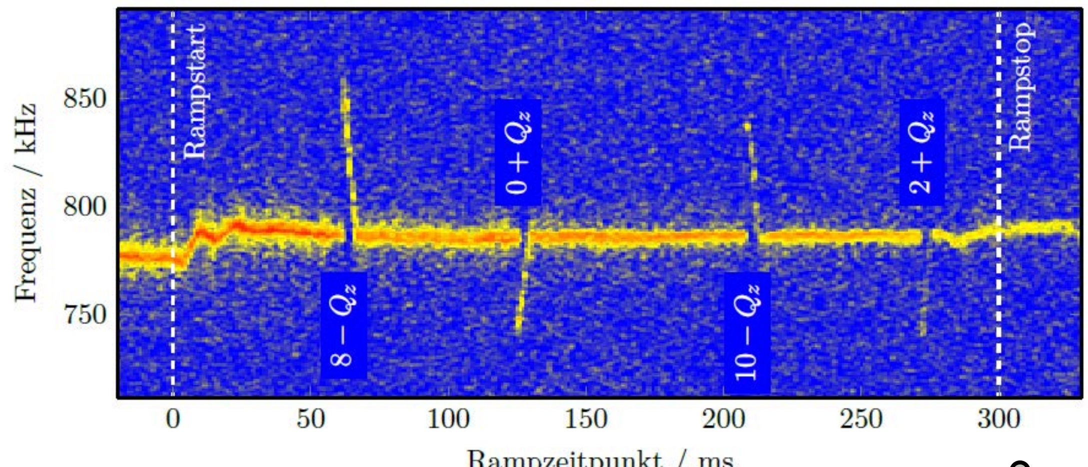


Bunch Length:



Stabilization of the Tunes:





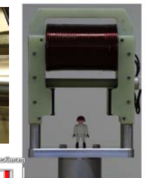
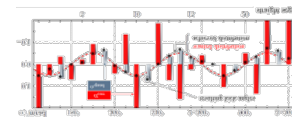
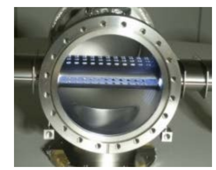
Allows stable operation of ELSA with currents up to 200mA!

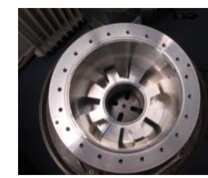
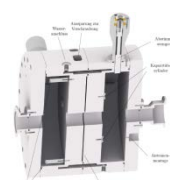
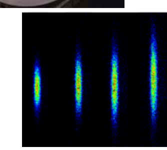
List of Research Efforts

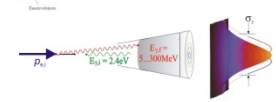
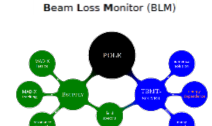
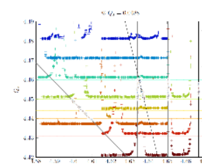
($P \rightarrow 80\%$, $I \rightarrow 200\text{mA}$, reliable operation)

- Source of polarized electrons with full load-lock
- Precise and fast BPM system: $\Delta_{x,z} \approx \mu\text{m}$, 1 kHz
- 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: $\Delta_{x,z} \approx 0.1\,\text{mm}$, 100 pA
- Mott, Møller and Compton polarimetry
- Beam loss monitoring system
- Optimization of tune settings and slow extraction
- Numerical simulation of spin dynamics



Bye, bye, SFB/TR 16!

> 50 acc. related B.Sc. M.Sc., diploma and PhD theses

We had a great time filled with impressive R&D @ ELSA!

> 100 proc./papers with ELSA contr.!