# The Bonn
# Electron-Stretcher Accelerator

ELSA

## Project D2 / 2013

***Beam and spin dynamics***
***in a fast ramping stretcher ring***

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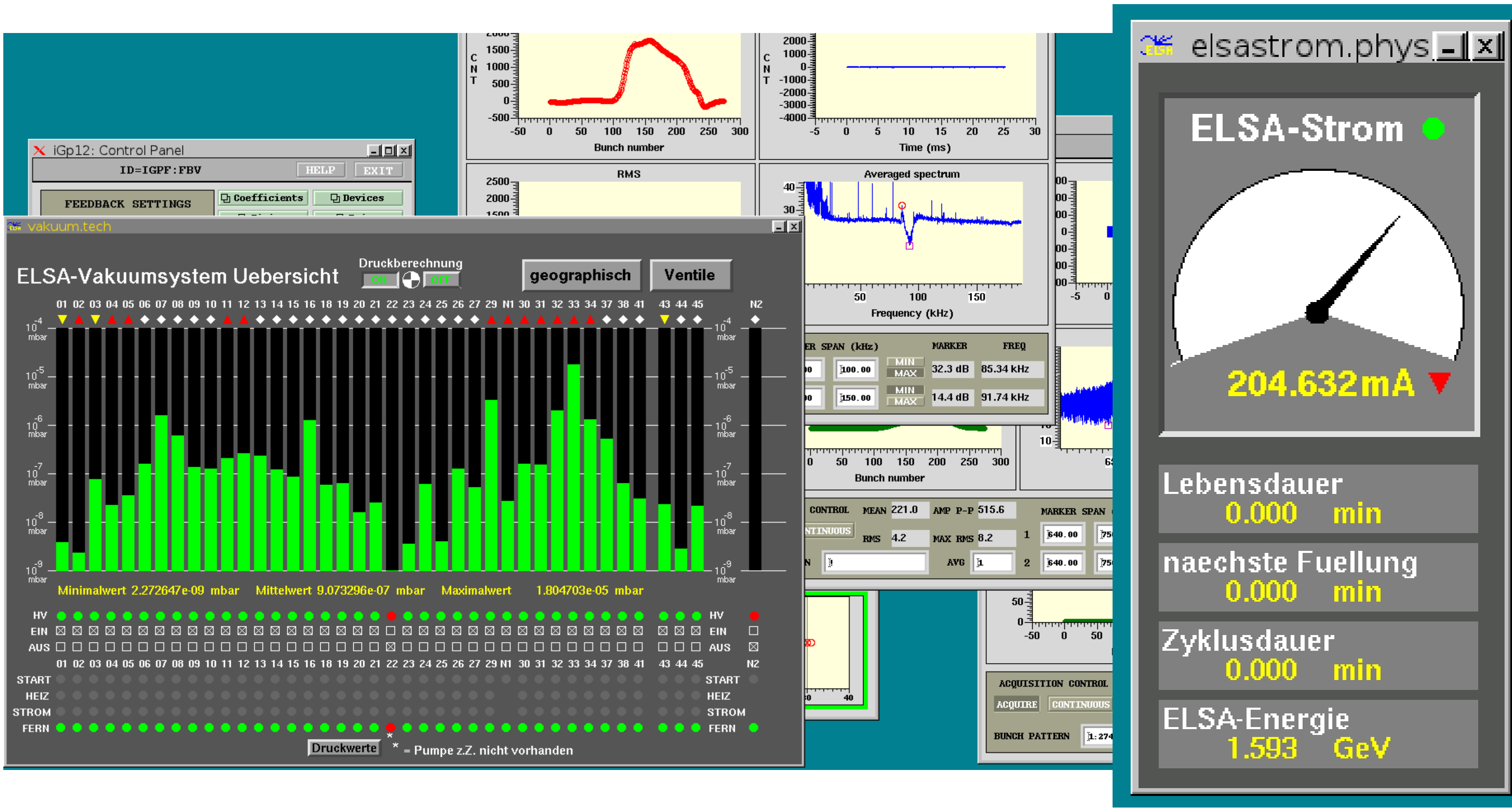
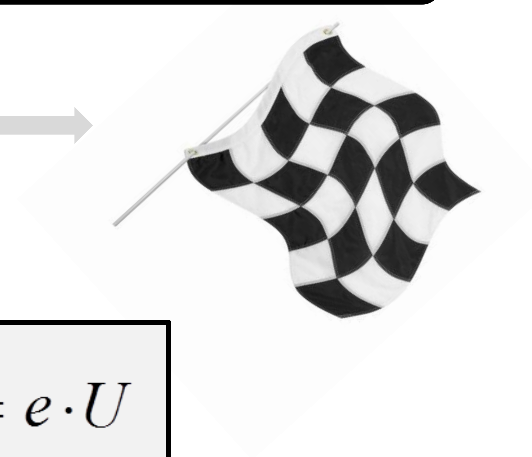
1. **The Challenge of High Intensities**

( 2. The Mystery of Resonance Extraction
3. The Hunt for Highest Polarization ) → next meetings…

# The Challenge of High Intensities



# Why not $I$ = 10A in ELSA???



**Stored energy in the beam:**

$$W = \int \vec{F} \cdot d\vec{s} = e \cdot \int \left( \vec{E} + \vec{\mathrm{v}} \times \vec{B} \right) \cdot d\vec{s} = e \cdot U$$

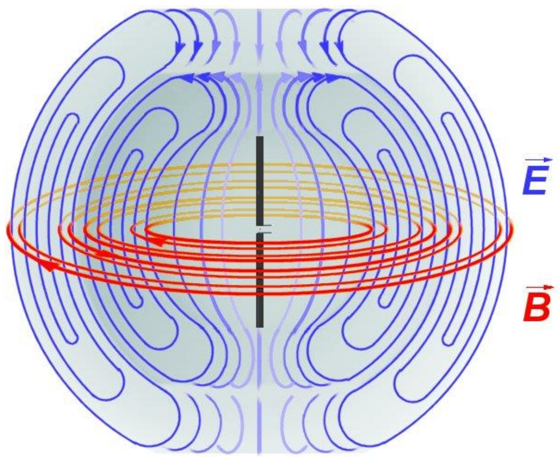
**Required power:**

$$P = \dot{U} \cdot I \cdot T_{\mathrm{rev}} = 7.5[\mathrm{GeV/s}] \cdot 10[\mathrm{A}] \cdot 548[\mathrm{ns}] = 41.1[\mathrm{kW}]$$

**We have more than 200 kW of RF power!!!**

# Synchrotron Radiation

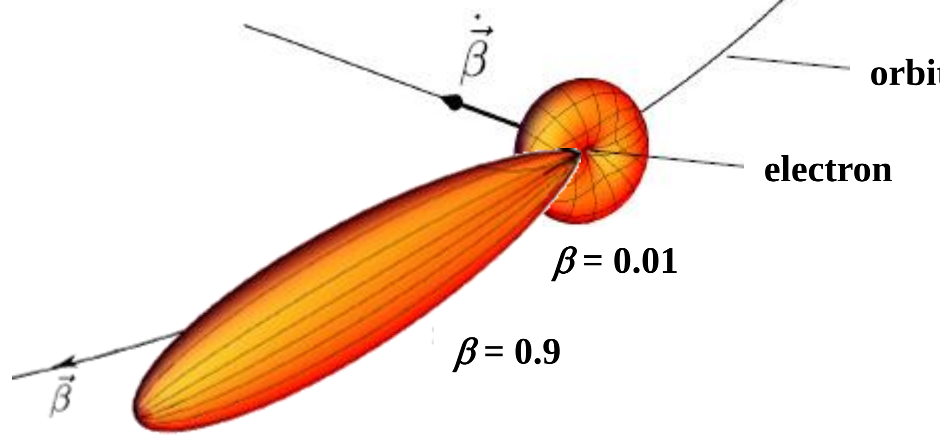
## Hertz Dipole:




$$P = \frac{e^2}{12\pi\varepsilon_0 c^3} \cdot \omega^4 d^2$$

$\longrightarrow$

## Curved Orbit:



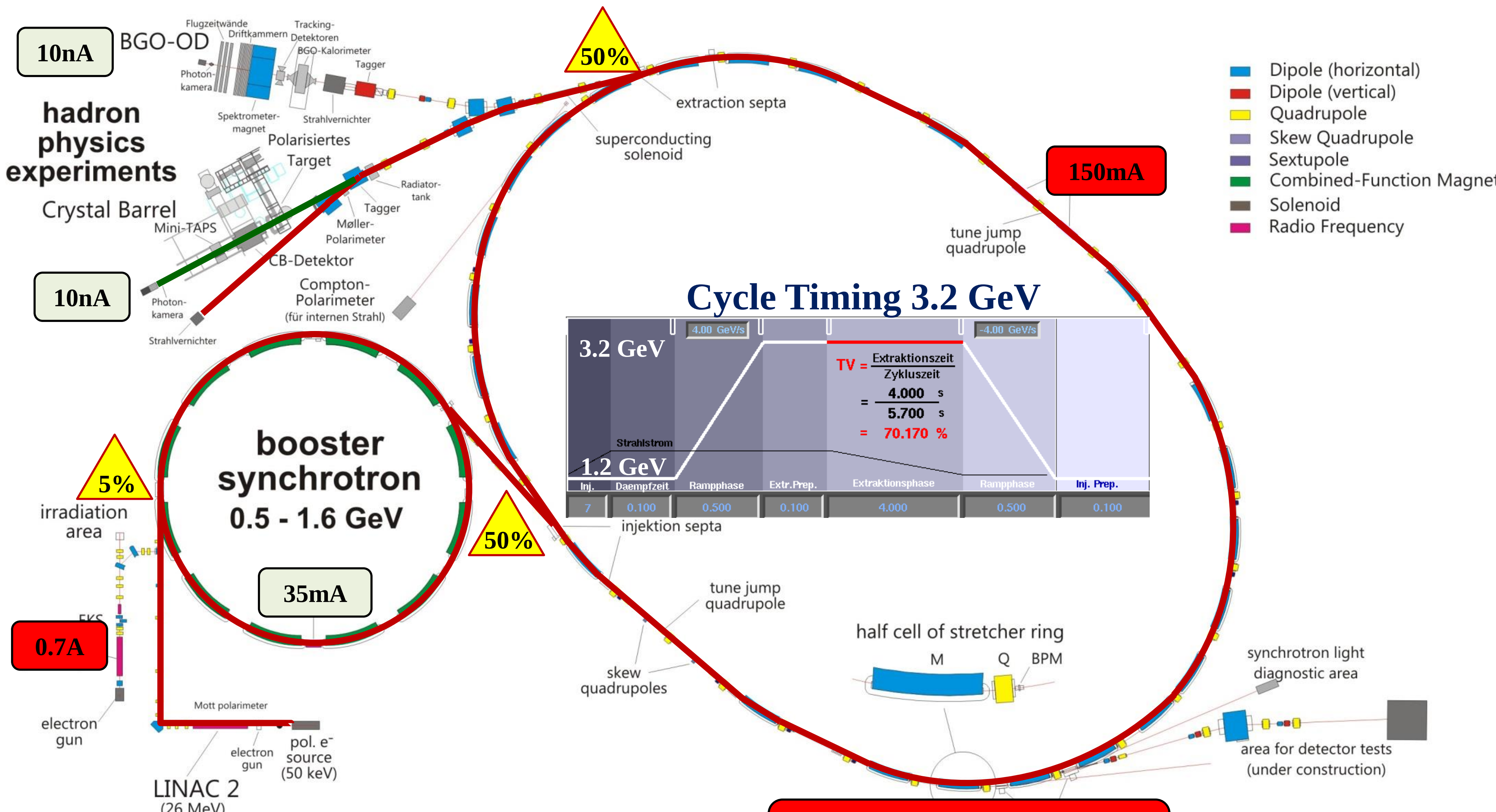

$$P = \frac{e^2 c}{6\pi\varepsilon_0} \cdot \frac{\gamma^4}{R^2}$$

$$U\,[\mathrm{kV}] = 88.5 \cdot \frac{E^4\,[\mathrm{GeV}^4]}{R\,[\mathrm{m}]} \quad \Rightarrow \quad U\Big|_{E=3.2\mathrm{GeV}} = 844\,\mathrm{kV}$$

$$P_{rad}\,(10\mathrm{A}\ @\ 3.2\,\mathrm{GeV}) = 8.4\mathrm{MW}$$

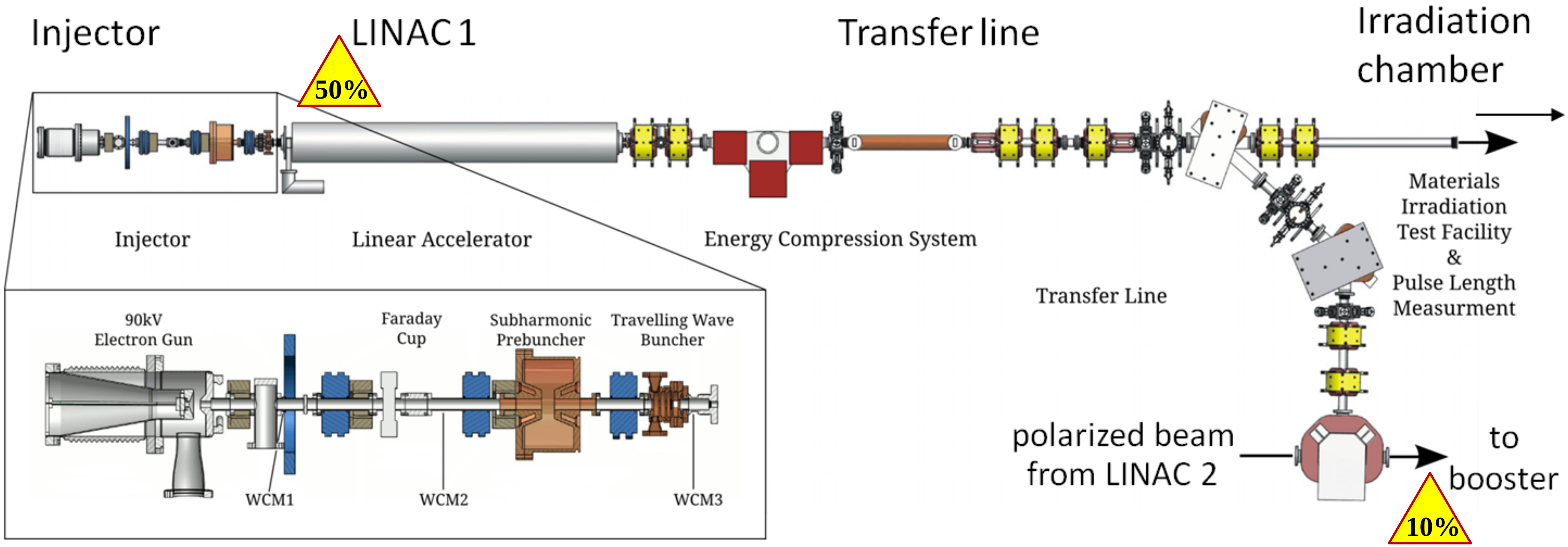
(But 200mA ↔ $P_{\mathrm{rad}}$ = 160kW should still be possible with $P_{\mathrm{RF}}$ = 200kW?!)

# Intensity Requirements




$P_{heat} = 1$ W/mm

# LINAC I




<u>**Thermionic Gun:**</u>

- $U$ = 90 kV
- ***I* = 800 mA (1-2µs) / 2 A (1ns)**

<u>**Bunching:**</u>

- 500 MHz Prebuncher
- 3 GHz TW Buncher (4 cells)

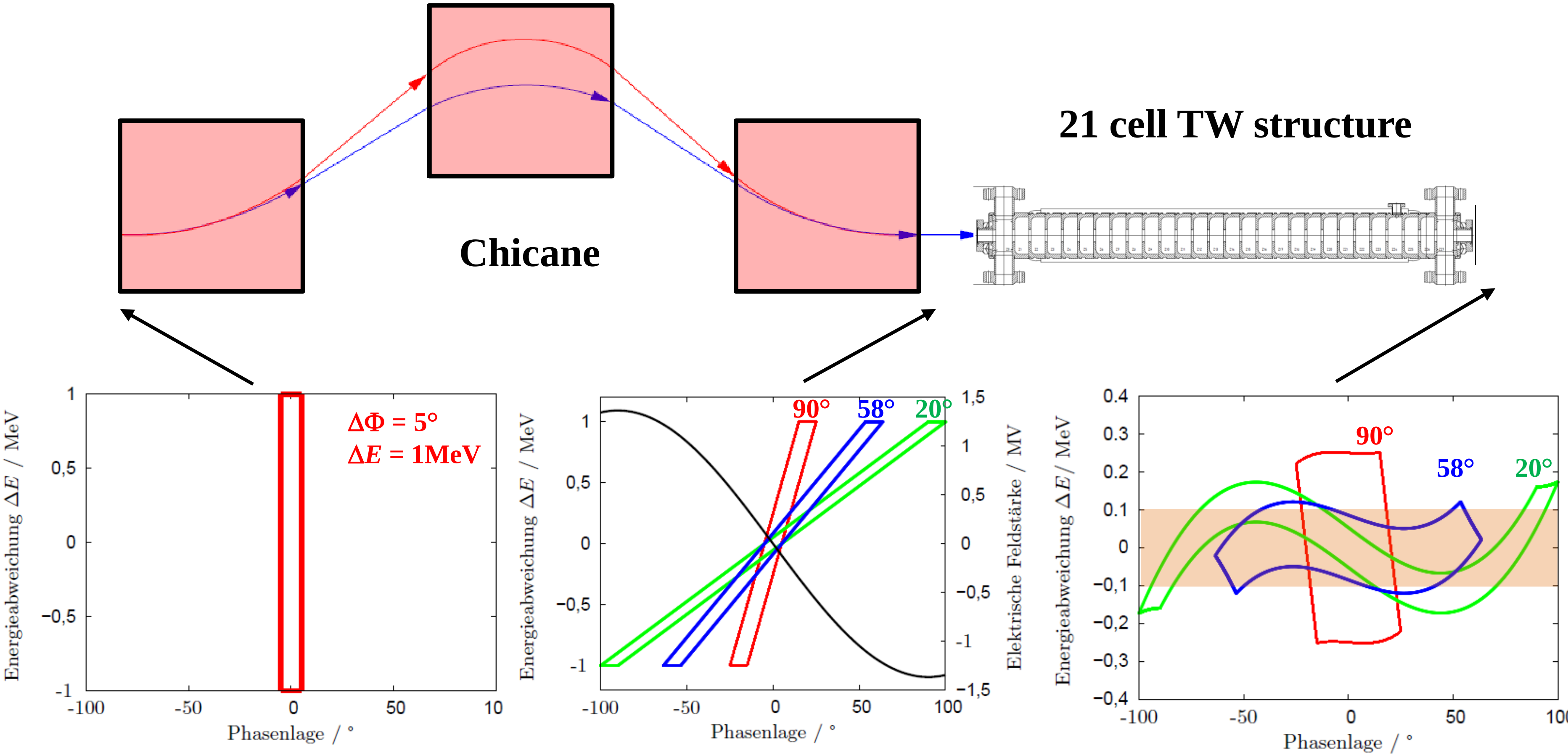
<u>**LINAC:**</u>

- **20 MV 3GHz TW structure ($P_{RF}$ = 25MW)**
- Modulator with new charging unit

<u>**Energy Compression System:**</u>

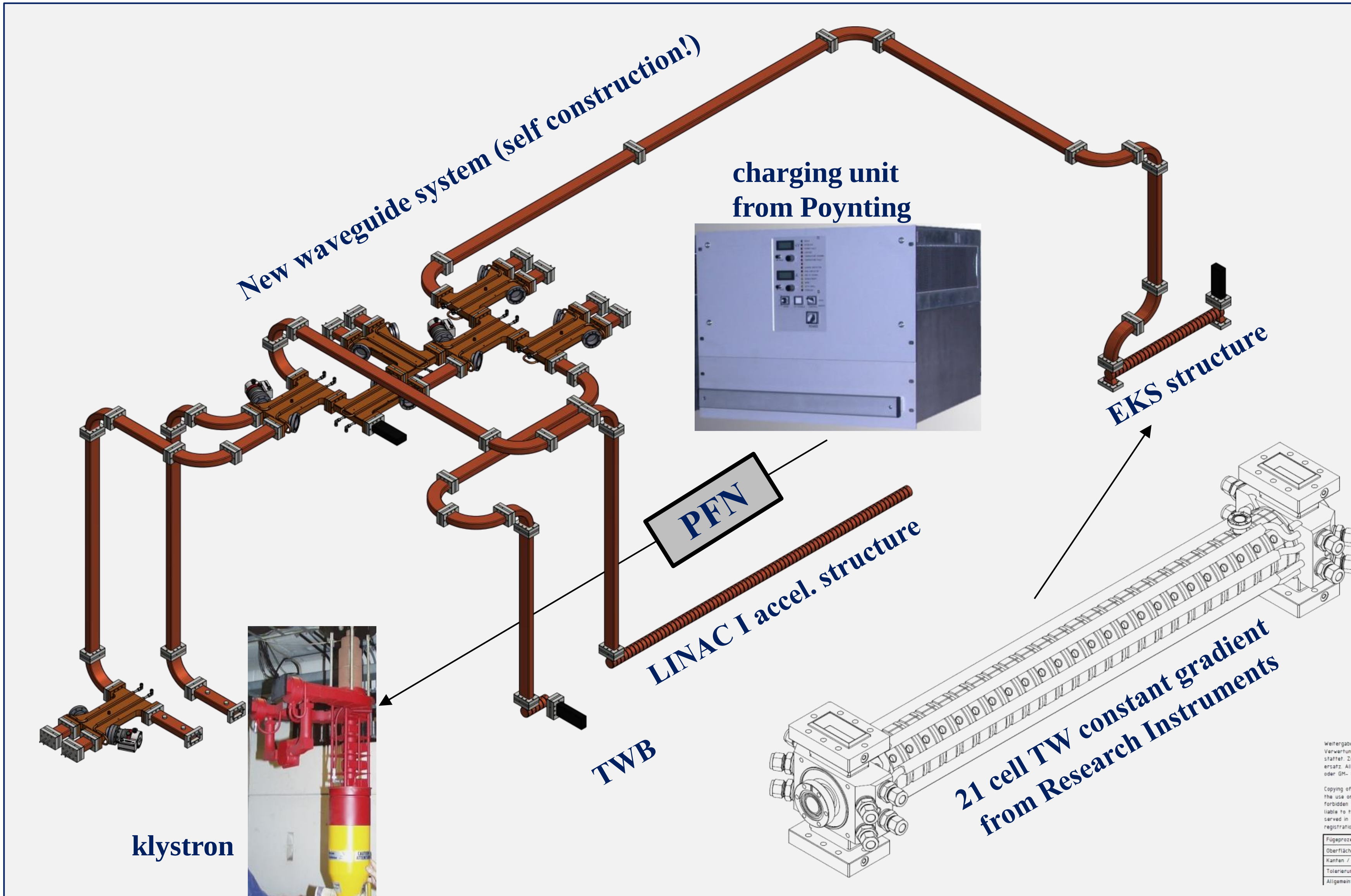
- **3-bend magnetic chicane**
- **3GHz TW Structure**

# Energy Compressing System

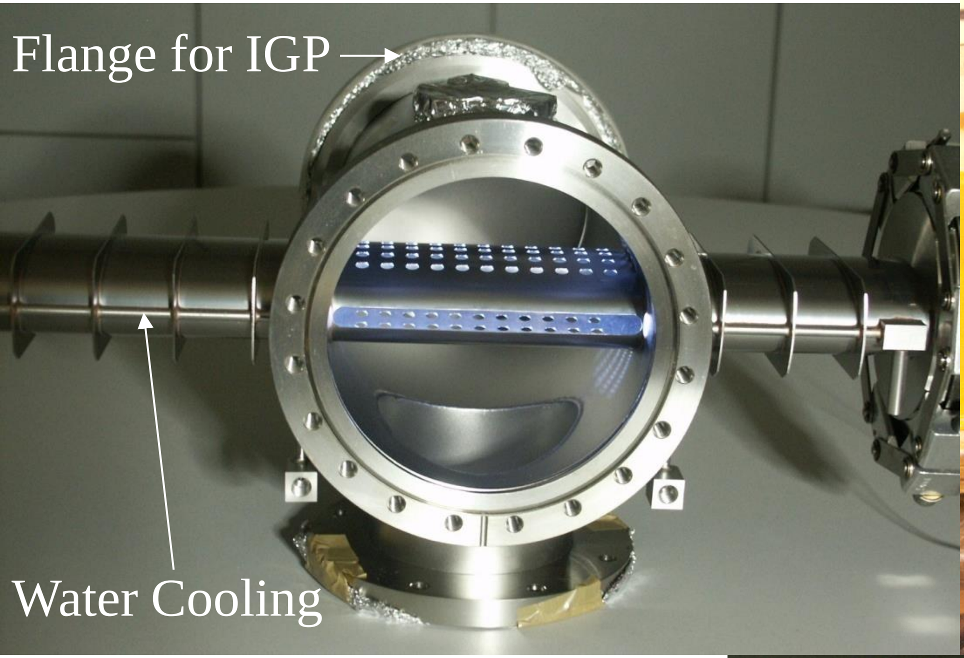


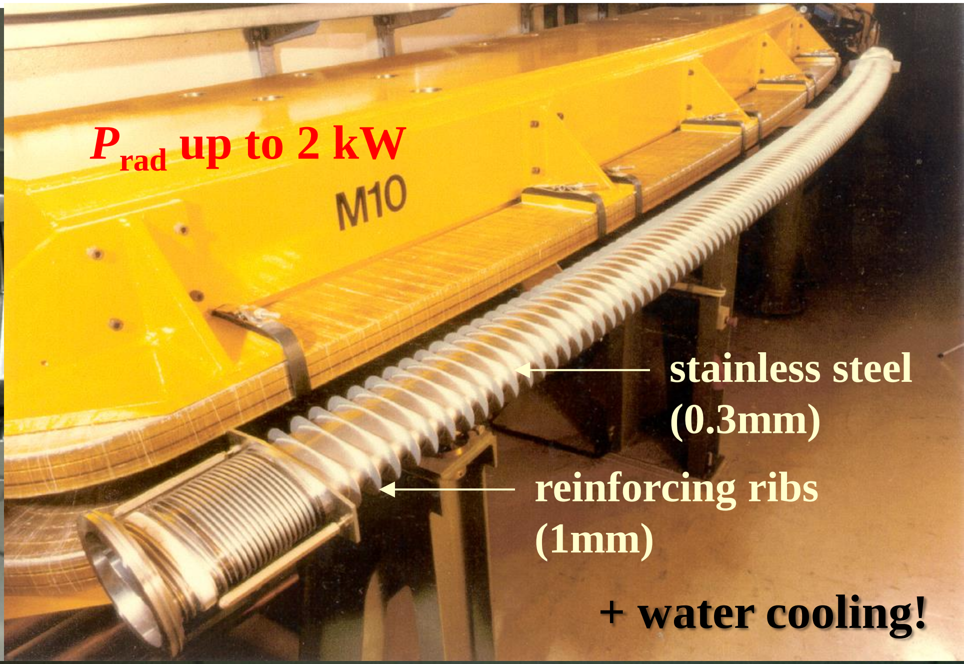

**Reduction of $\Delta E$ by factor of 10 possible!**

# Ongoing work @ LINAC I



# ELSA Vacuum Chambers

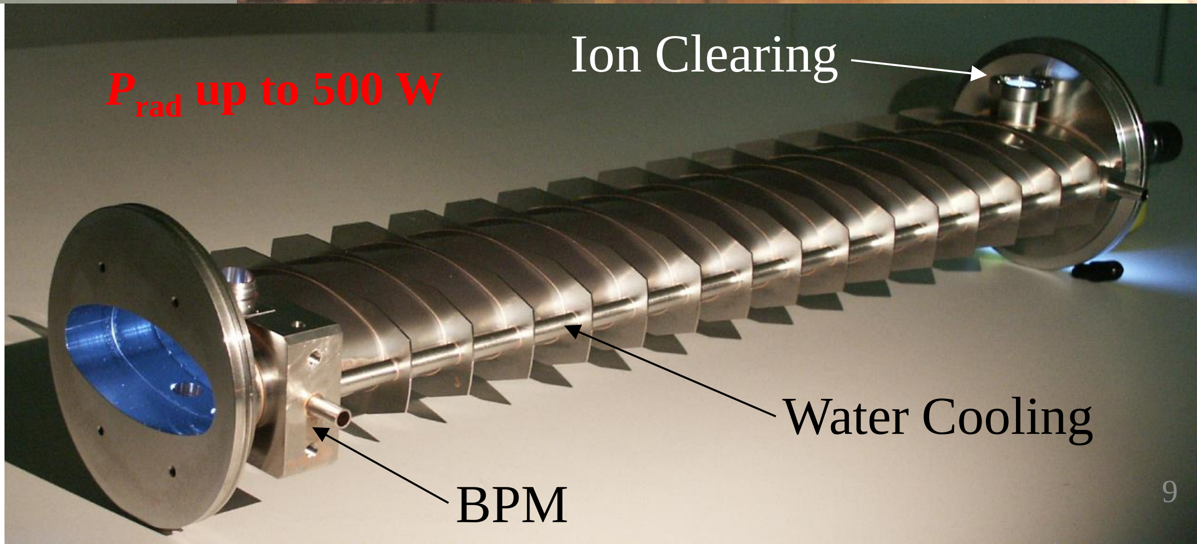



**"Fast" Ramping Operation:**

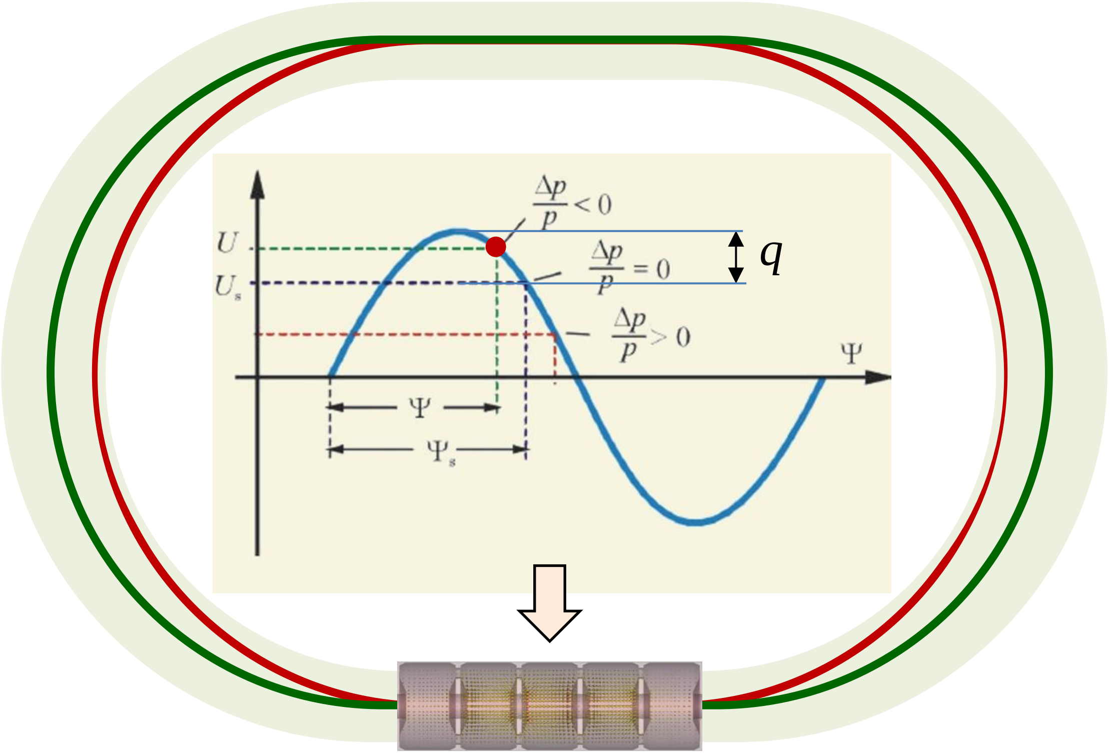
- $\dot{E} \leq 7.5$ GeV/s
- $\dot{B} \leq 2.1$ Tesla/s

→ reduction of **eddy currents**

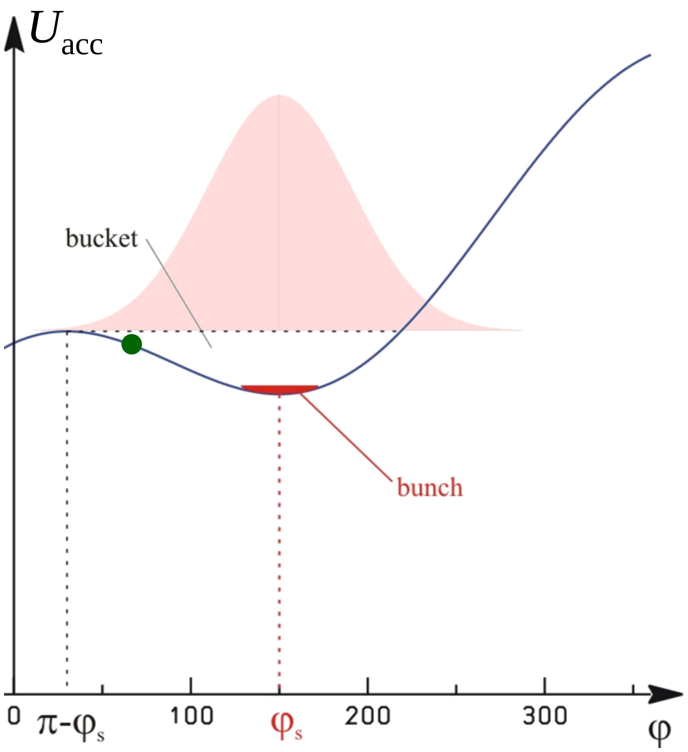


# Overvoltage Factor

**Phase Focusing:**




**Potential Energy:**

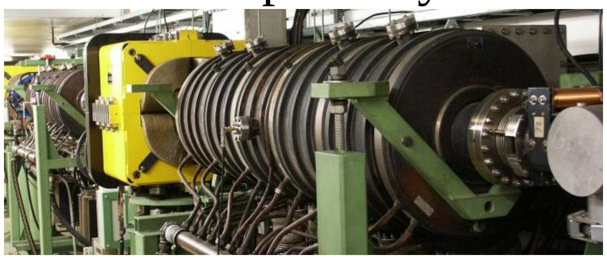


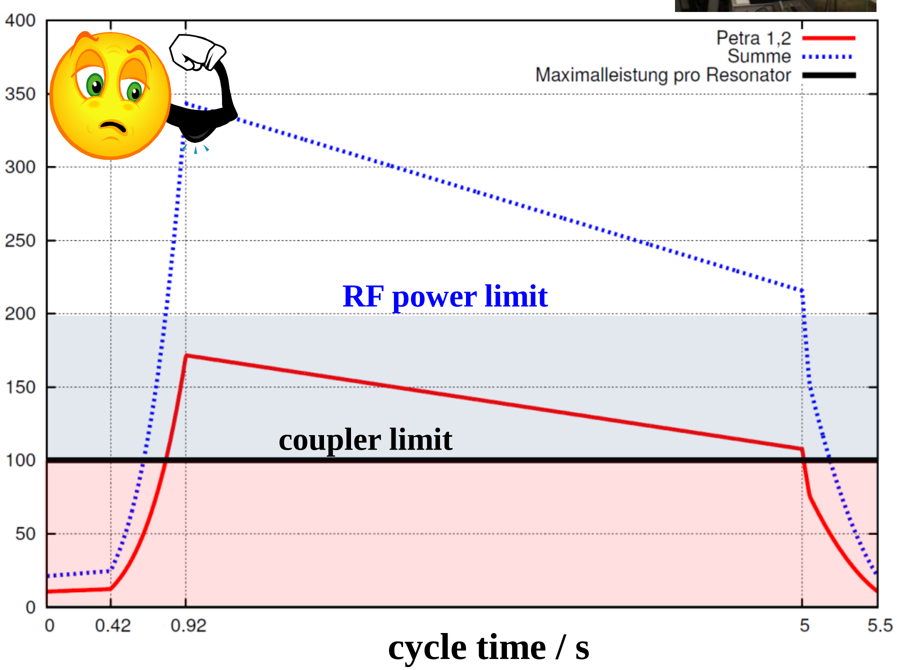

Overvoltage Factor $q = U_0/U_s$

# RF Upgrade: towards 200mA@3.2GeV

## Actual Situation:

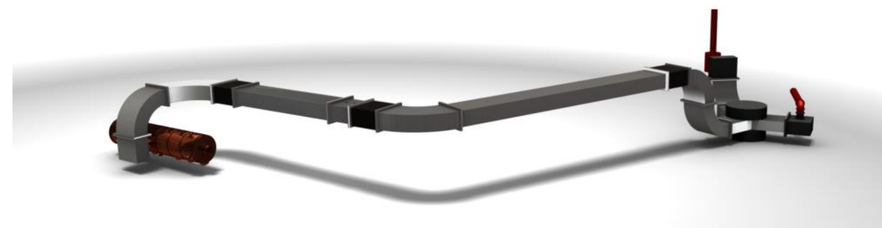
- 2 PETRA resonators (5 cells)
- 1 Thompson klystron 200kW

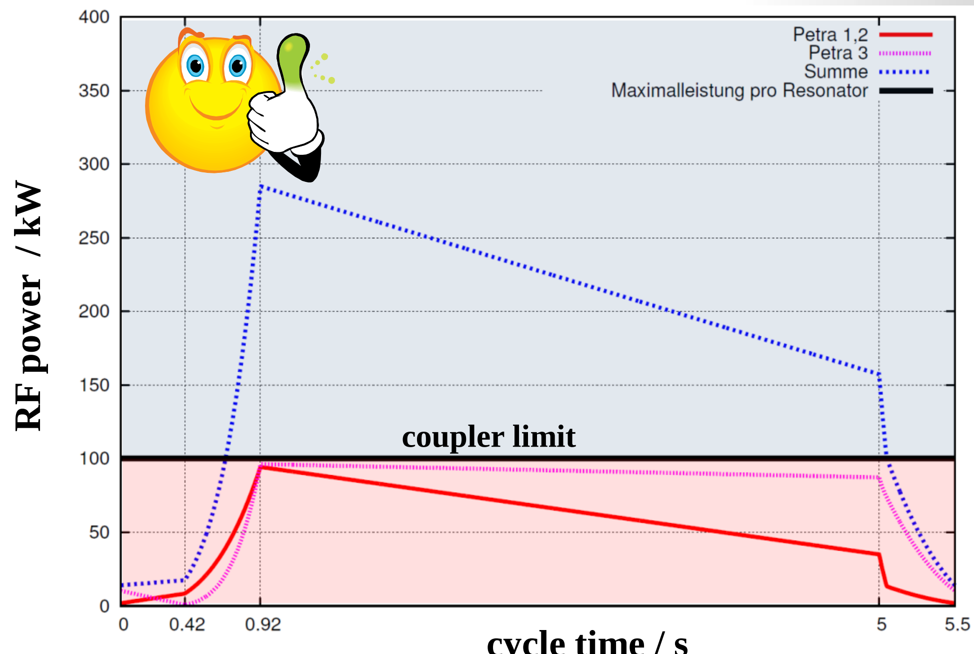




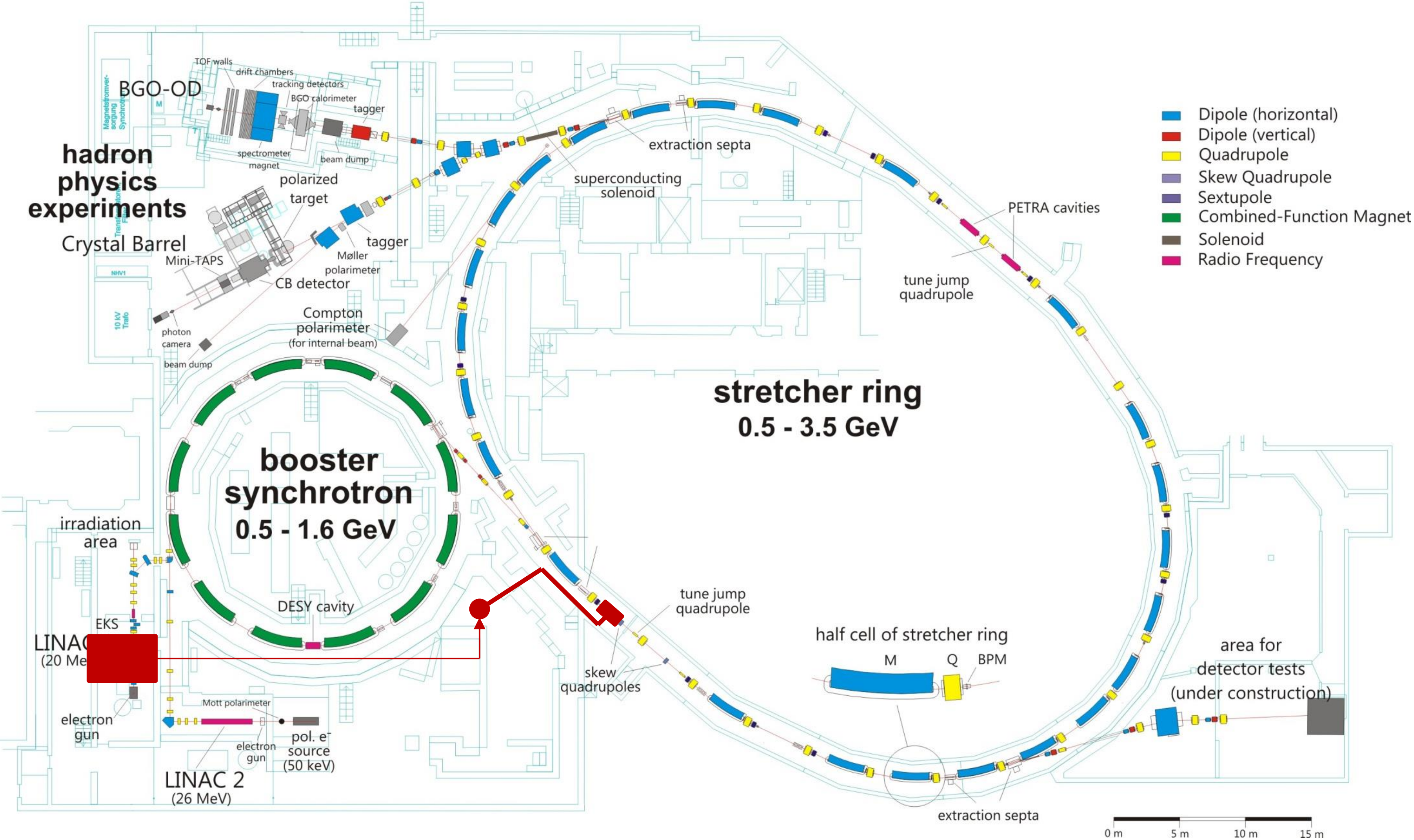

## New RF plant:

- 1 add. PETRA resonator (7 cells!)
- 1 add. Thompson klystron 200kW



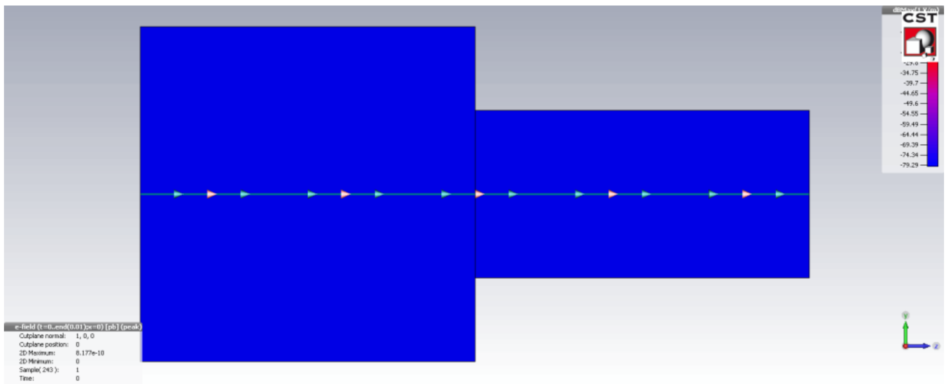


# Electron Stretcher Accelerator (ELSA)



# Chamber Impedances

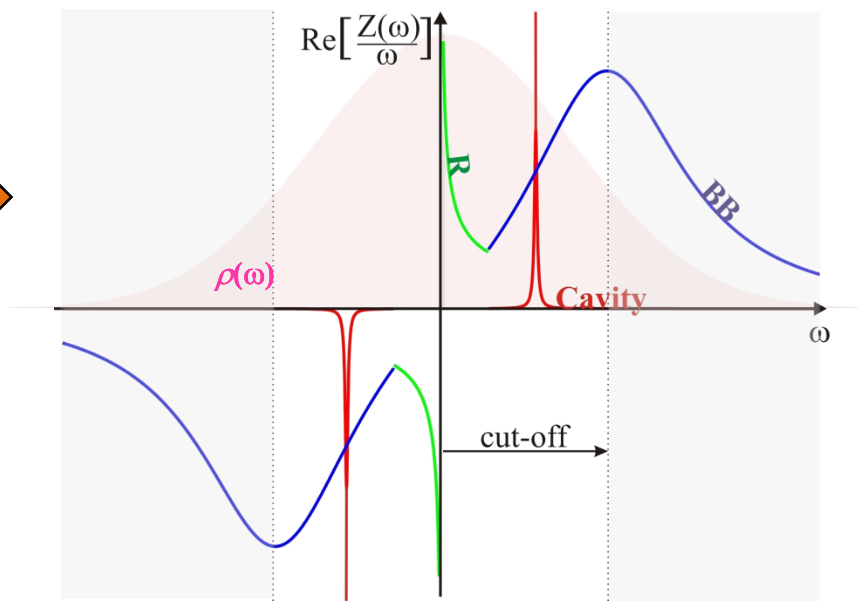
## Generation of wake fields:



## Energy loss per turn:

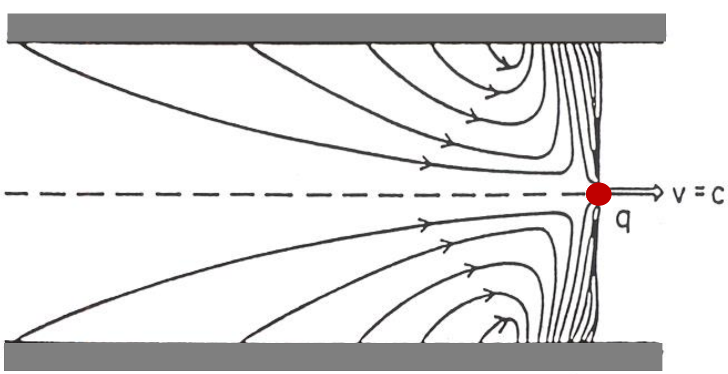
$$\mathbf{W}_{\mathrm{wf}}(r) = \frac{1}{2\pi} \int_{-\infty}^{\infty} |\rho(\omega)|^2 \,\mathrm{Re}\left[ Z_{\|}(\vec{r},\omega) \right] d\omega$$

Coupling impedance $Z_{\|}$:



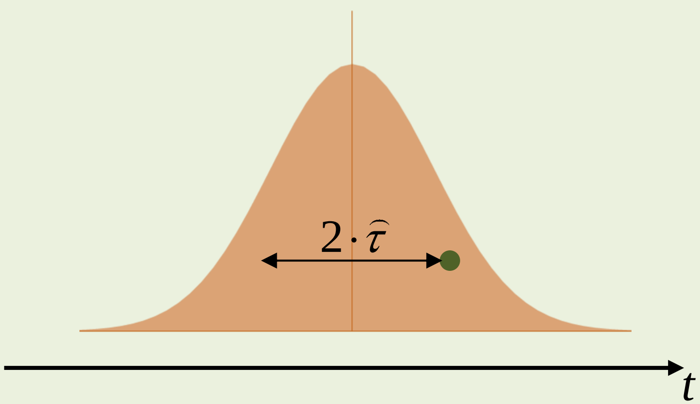

(simple model based on LCR-circuit)

## Resistive wall effect:



# Effects on the "stationary" bunch

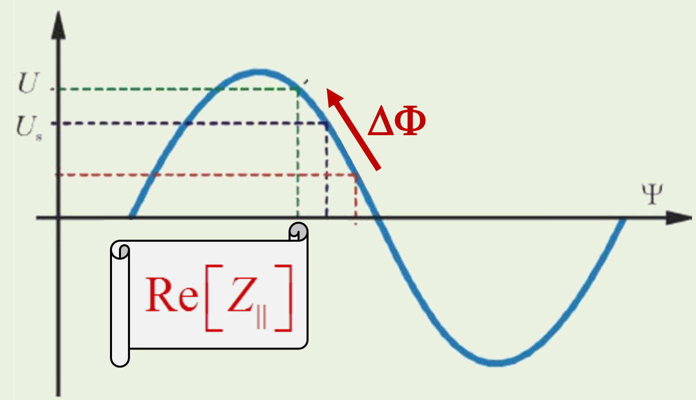
**Synchrotron oscillation with external excitation:**



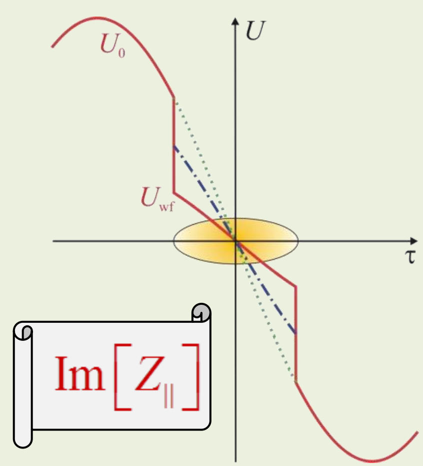

$$\ddot{\tau} + 2\alpha_S \cdot \dot{\tau} + \Omega_0^2 \cdot \tau = \frac{\eta\,\omega_0}{2\pi E_0} \mathbf{W}_{wf}(\tau)$$

energy loss of an e⁻ per turn

$$\ddot{\tau} + 2\alpha_S \cdot \dot{\tau} + \Omega_S^2 \cdot \tau = 0$$



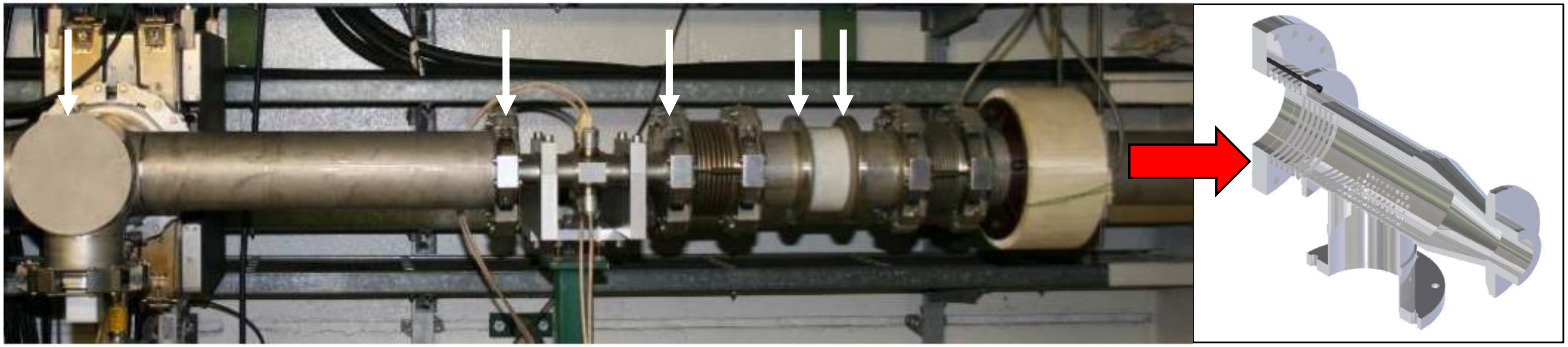

**Increasing losses → shift of ΔΦ**



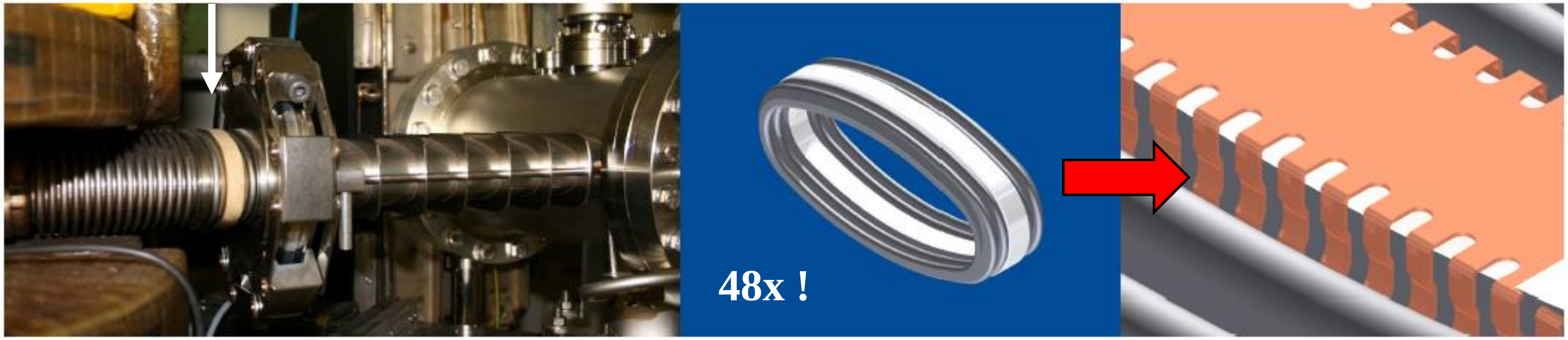

**Deformation of the RF potential**
**↓**
**decrease of $\Omega_0$**

# “Bad” ideas in the past …

**Chamber discontinuities:**



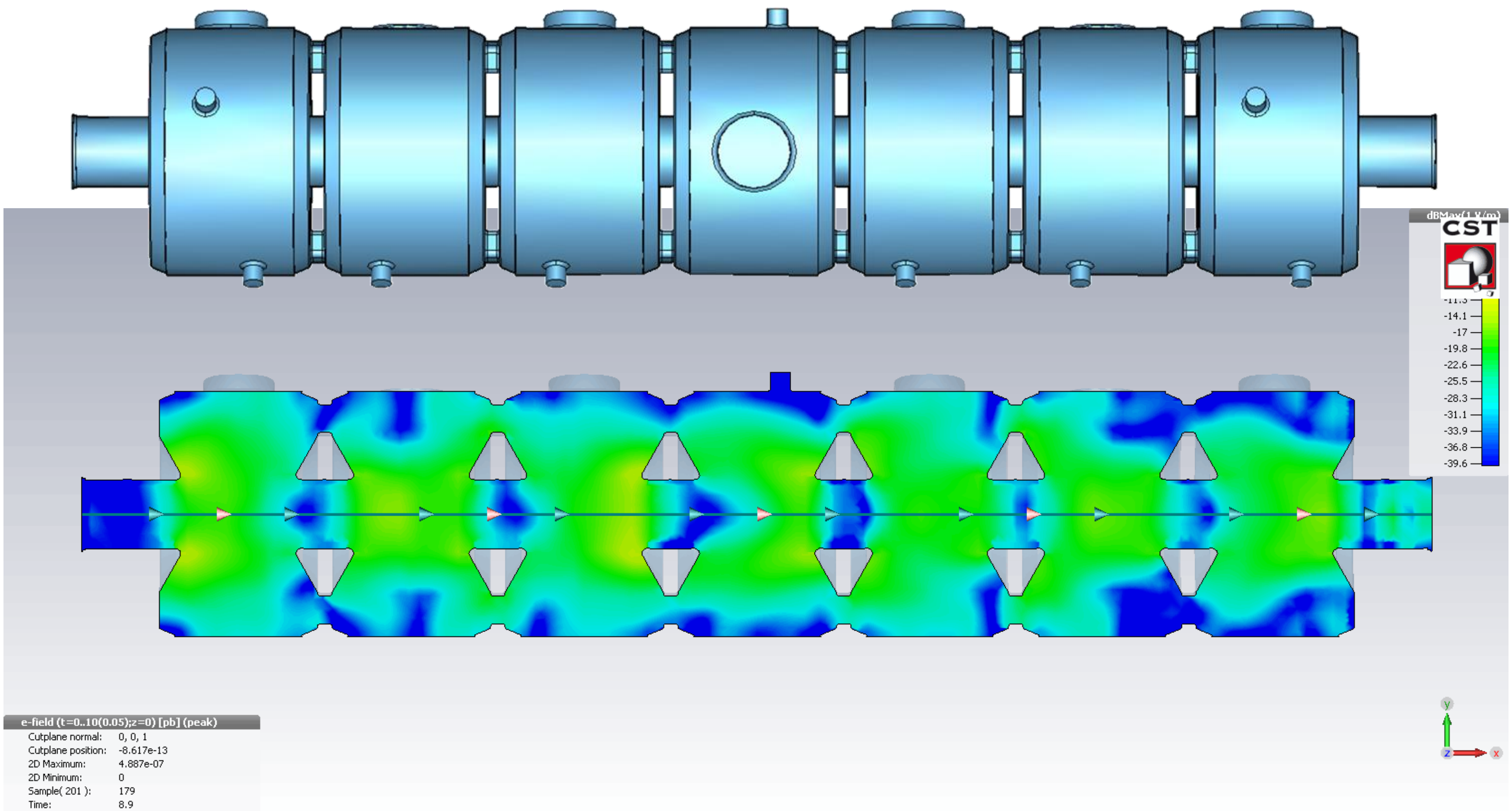
**Ceramic breaks:**




**Bridging with springs: significant reduction!**

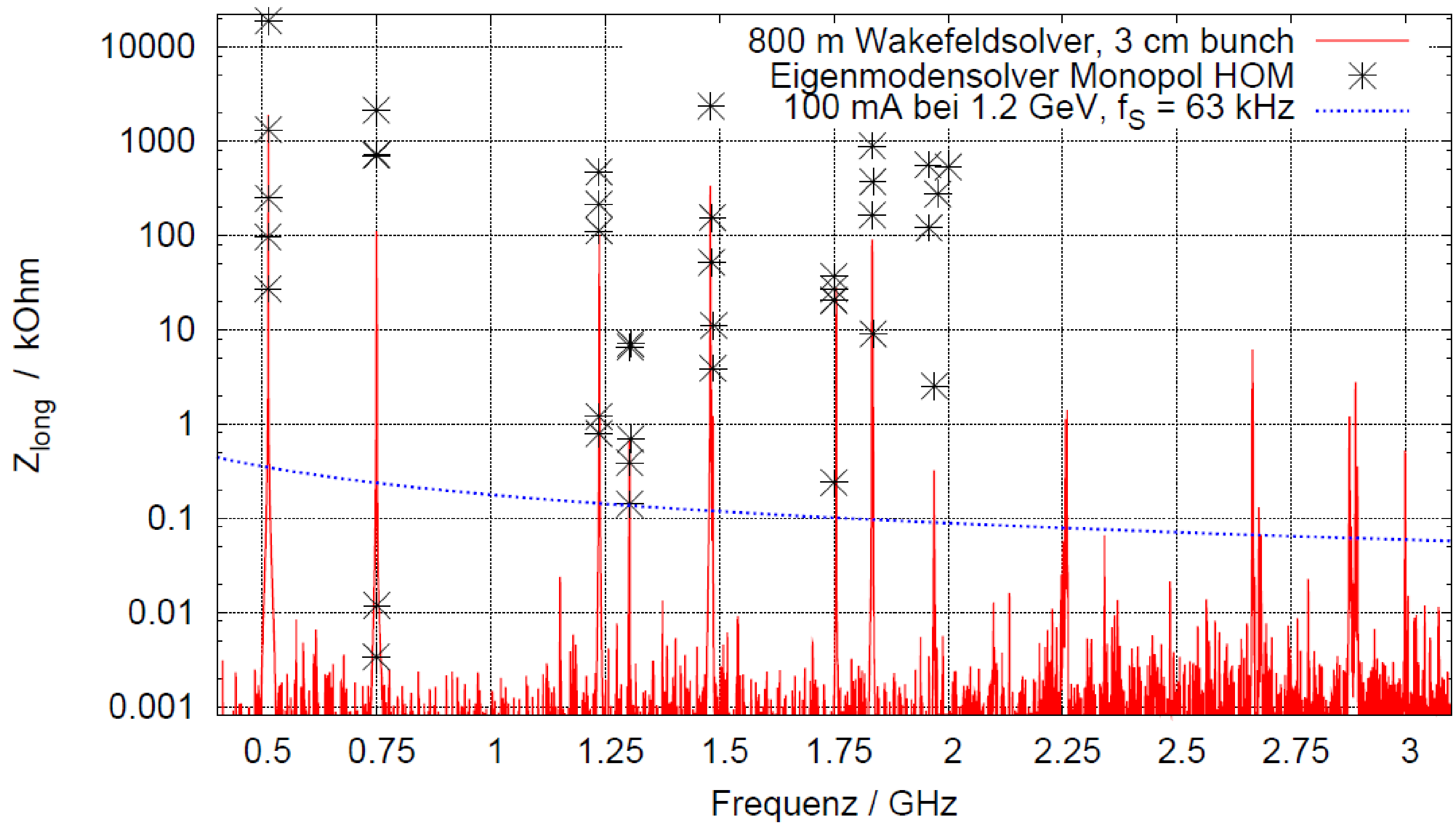
# Parasitic Resonators

## … e.g. accelerating cavities:



# Higher Order Modes (HOM)

Numerical simulation:




**Could this be a possible source of beam instabilities???**

# Mathematical Treatment

Energy loss per turn, bunch oscillates with $\Omega_c = m\Omega_s + \Delta\Omega_{cm}$:

$$\mathbf{W}_{wf}(\tau,t) = \frac{eI}{\omega_0} \cdot e^{j\Omega_c t} \cdot \int_{-\infty}^{\infty} d\omega \Delta\tilde{\mathcal{P}}(\omega) Z_{\|}(\vec{r},\omega) e^{j\omega\tau}$$

Spectral function of the bunch with $\Delta\rho(\hat{\tau},\phi_0;t) = g_m(\hat{\tau}) \cdot e^{-jm\phi_0} \cdot e^{j\Delta\Omega_{cm} t}$:

$$\Delta\tilde{\mathcal{P}}(\omega) = 2\pi\omega_0 \sum_{p=-\infty}^{\infty} \delta(\omega - p\omega_0) \cdot \underbrace{j^{-m} \int_0^{\infty} \hat{\tau} \cdot J_m(p\omega_0\hat{\tau}) \cdot g_m(\hat{\tau}) d\hat{\tau}}_{\equiv \mathbb{S}_m(p)}$$

Equation of motion, coherent "force" $F_c$:

$$\ddot{\tau} + \Omega_S^2 \cdot \tau = F_c = \frac{2\pi I \Omega_S^2 e^{j\Omega_c t}}{h\omega_0 U_{wf} \cos\varphi_S} \cdot \sum_{p,m=-\infty}^{\infty} Z_{\|}(p) \cdot \mathbb{S}_m(p) \cdot e^{-jp\omega_0\tau}$$

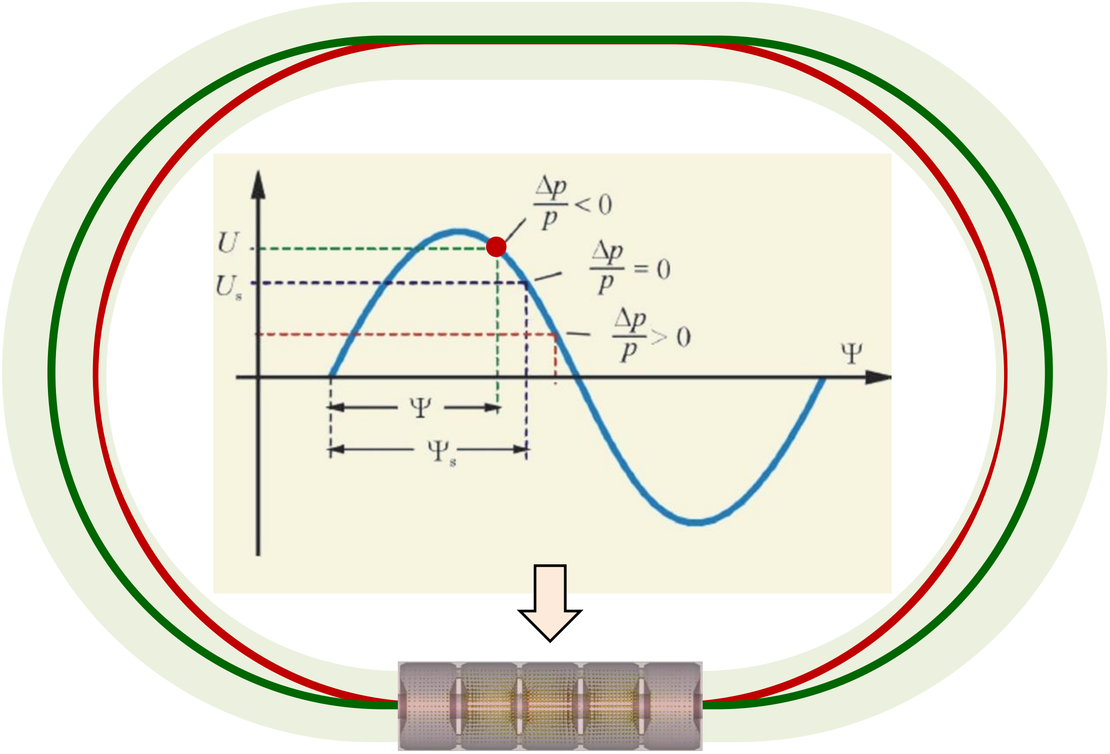
Vlasov Equation links $t$ (osc. of the bunch) and $\tau$ (osc. inside the bunch):

$$\frac{d\rho}{dt} = 0 \quad \Rightarrow \quad j e^{j\Omega_c t} \sum_{m=-\infty}^{\infty} (\Omega_c - m\Omega_S) \cdot g_m(\hat{\tau}) \cdot e^{-jm\phi} = -\frac{\partial g_0(\hat{\tau})}{\partial\hat{\tau}} \cdot \frac{d\hat{\tau}}{dt} \quad \text{with} \quad \frac{dt}{d\tau} = -\frac{F_c}{\Omega_S}\sin\phi$$

$$\sum_{l=-\infty}^{\infty} (\Omega_c - l\Omega_S) \hat{\tau} g_l(\hat{\tau}) e^{-jl\phi} = \frac{2\pi I \Omega_S}{h\omega_0^2 U_{wf} \cos\varphi_S} \frac{\partial g_0(\hat{\tau})}{\partial\hat{\tau}} \sum_{p,k=-\infty}^{\infty} \frac{Z_{\|}(p\omega_0)}{p} j^{k-1} e^{-jk\phi} k J_k(p\omega_0\hat{\tau}) \sum_{m=-\infty}^{\infty} \mathbb{S}_m(p\omega_0)$$

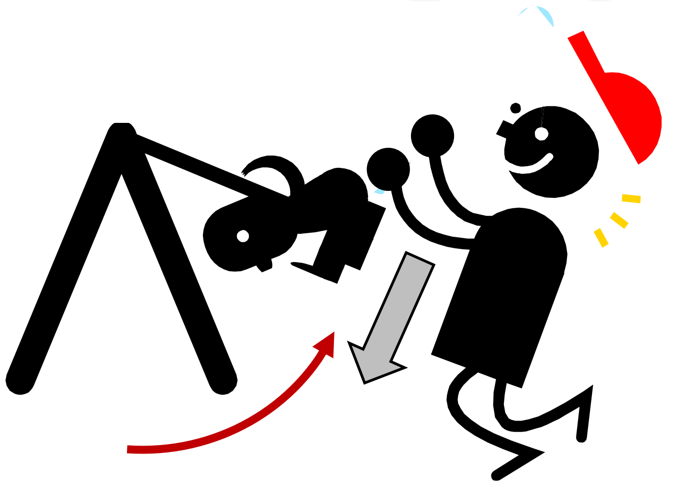
# Clear / Intuitive Explanation?!

**Coherent Synchrotron Oscillations:**



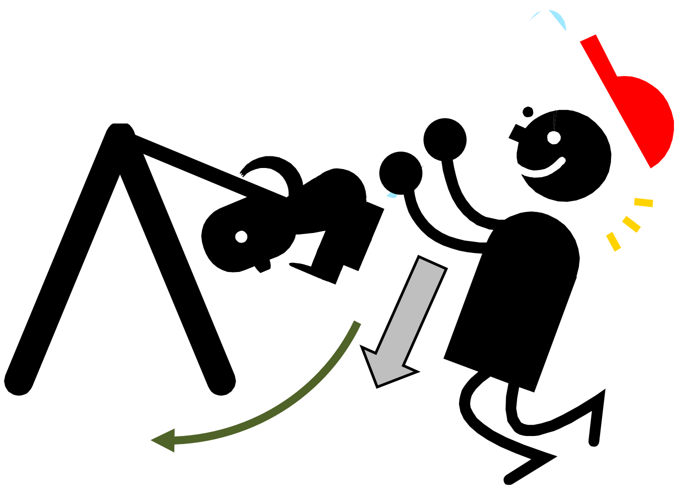

**Let‘s try using a simple picture:**

# Damping and Excitation



**Damping!**

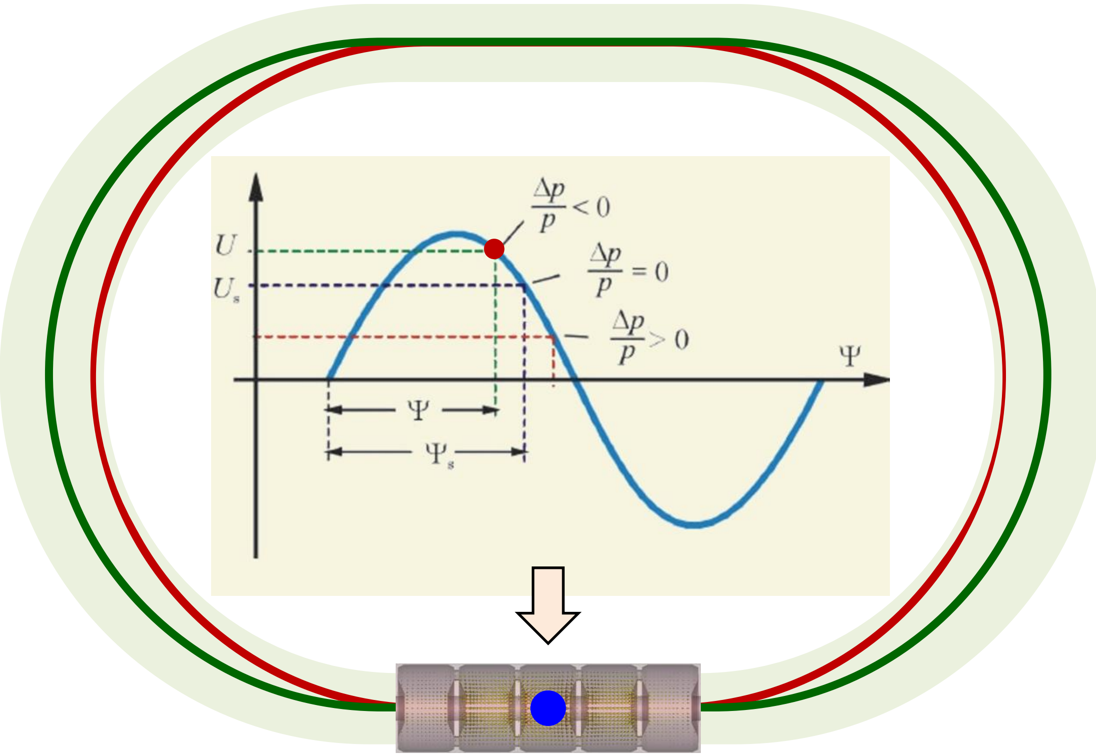
***The phase determines what will happen …***



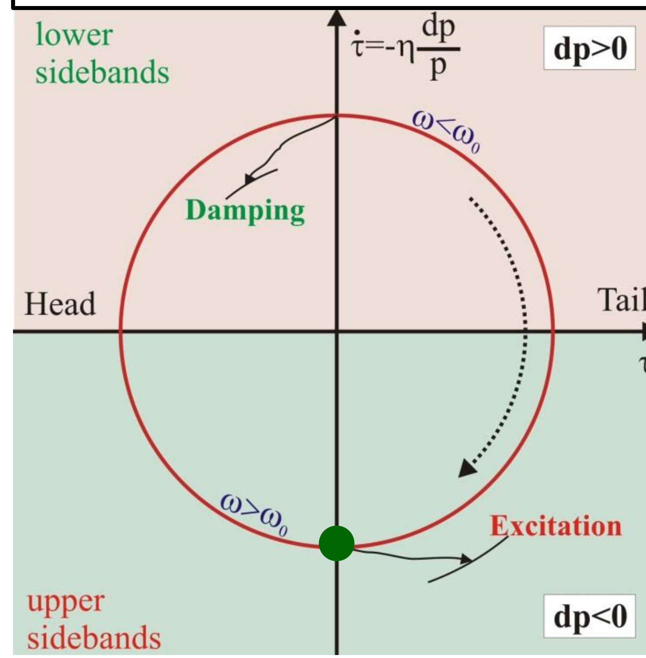
**Excitation!**

# Damping and Excitation II

Synchrotron Oscillation ↔ Energy Oscillation



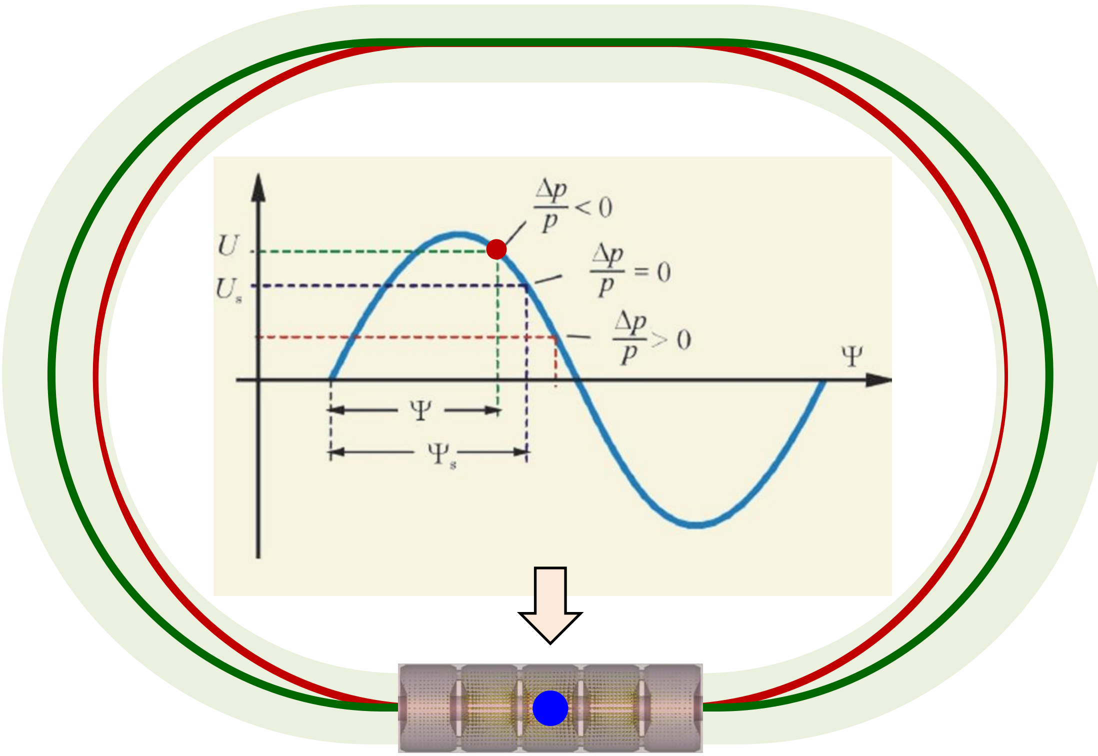

**normalized phase space**



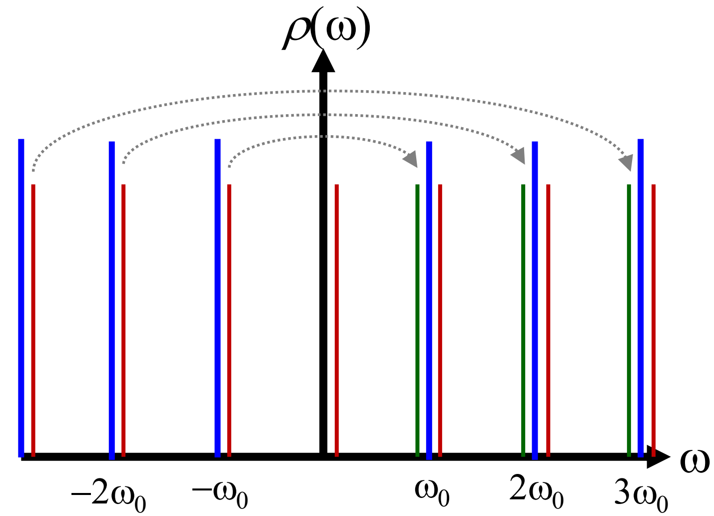

Revolution time and frequency change periodically!

**Excitation of coherent oscillations if $\omega_{ext} > \omega_0$**

# Synchrotron Satellites



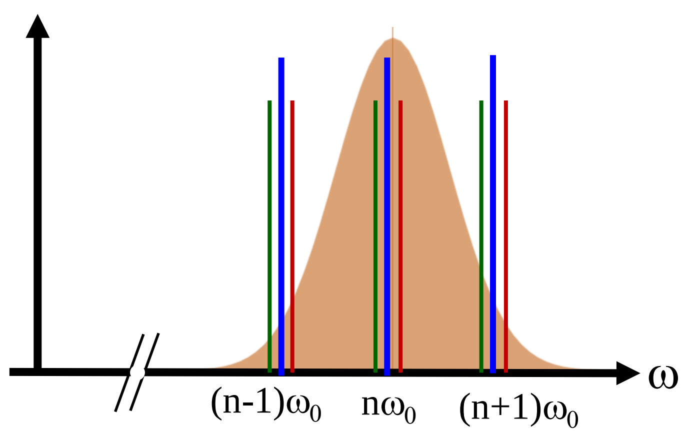

Spectral function of the bunch




**Instability of the upper sidebands!**

effect of a narrow band resonator:

$$W_{wf} = \frac{e}{2\pi}\int_{-\infty}^{\infty} \rho(\omega)\cdot Z_{\|}(\omega)\cdot e^{j\omega\tau}\,d\tau$$




**Single Bunch Case:**

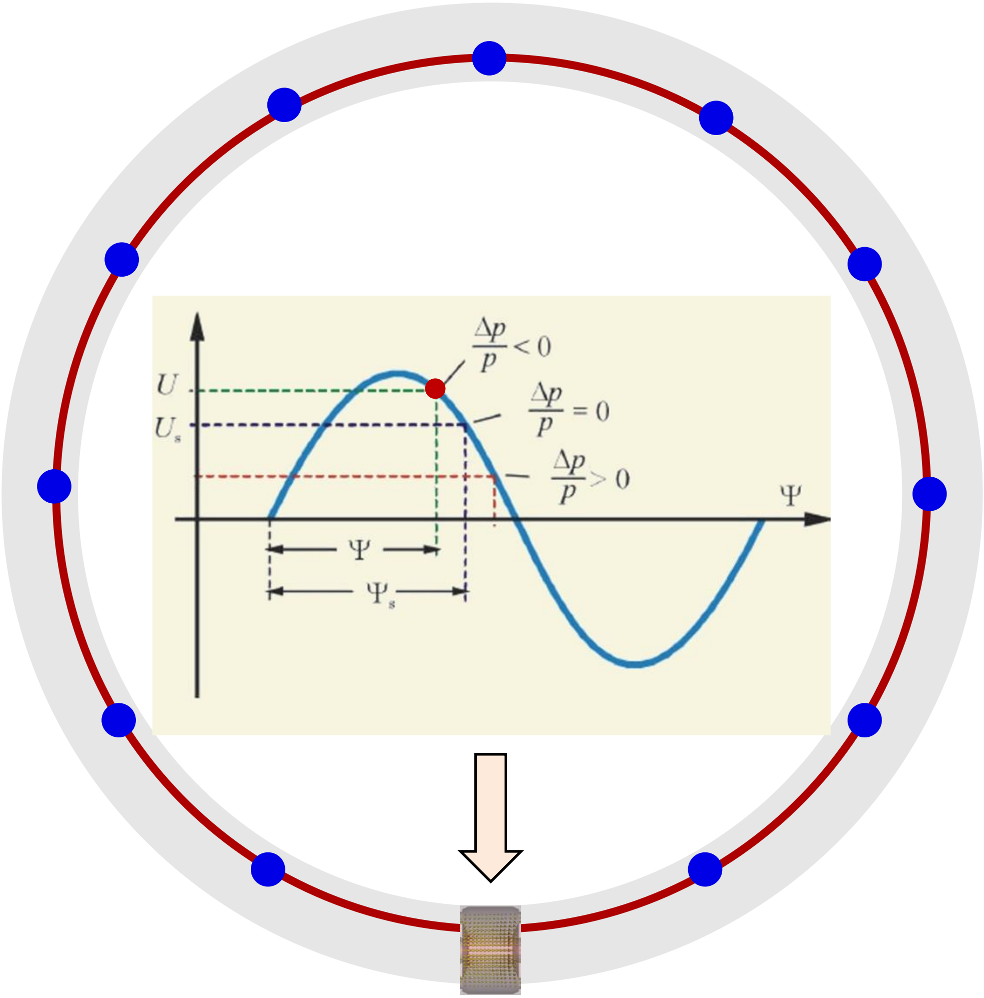
**$2\Omega_S \approx 0.1$ MHz**

**$n\omega_0 \approx 1$ GHz**

$\downarrow$

**$Q_{res} > 10^4$ !!!**

# Multibunch Case




**Each bunch oscillates with $\Omega_S$!**

(individually)

They can oscillate all in phase …

**or**

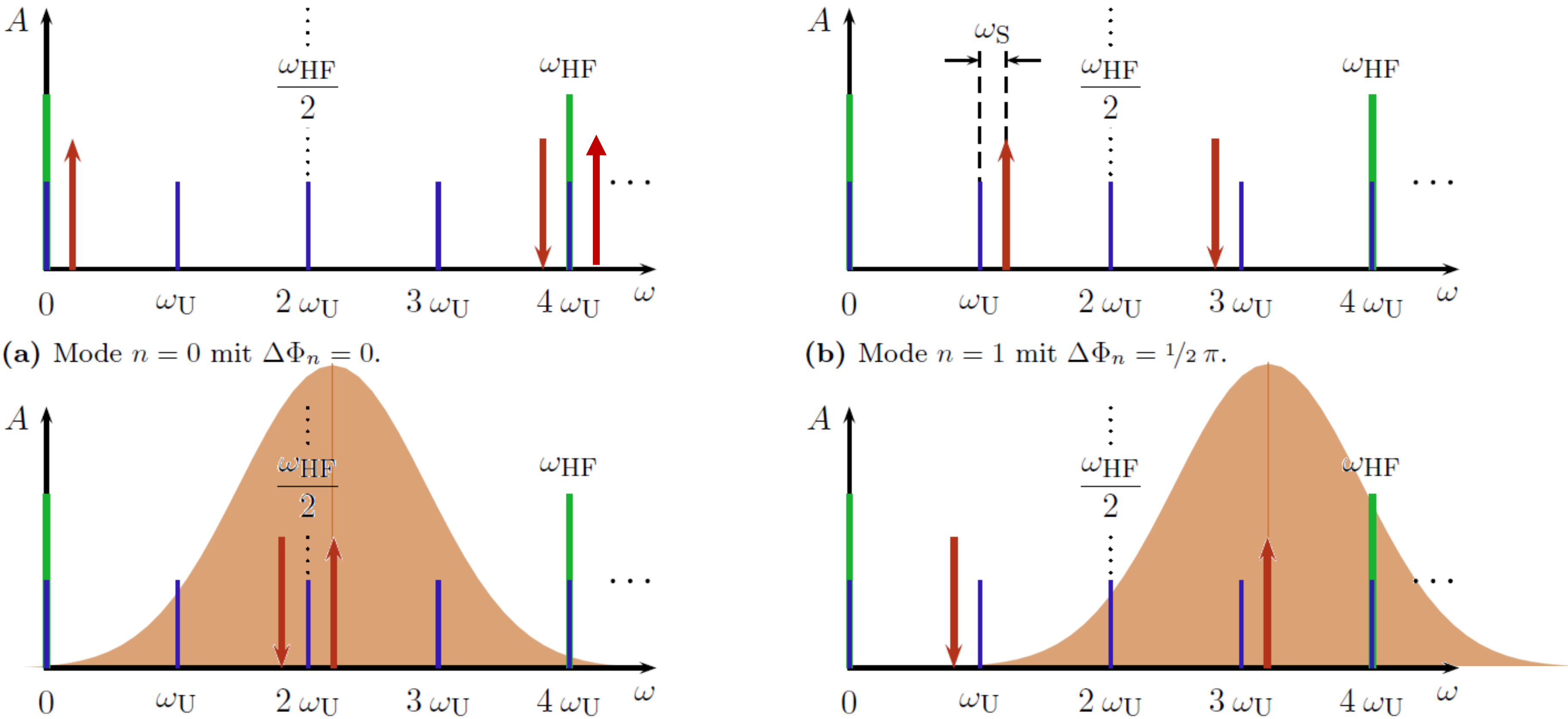
… there can be a phase shift between the *M* individual oscillations:

$$\Delta\varphi_{BB} = n\frac{2\pi}{M}, \qquad 0<n<M$$

So, we can have *M* different modes of **multibunch oscillations!**

# Multibunch Oscillations

## For simplicity case *M*=4:




**(a)** Mode $n = 0$ mit $\Delta\Phi_n = 0$.

**(b)** Mode $n = 1$ mit $\Delta\Phi_n = {}^1\!/_2\,\pi$.

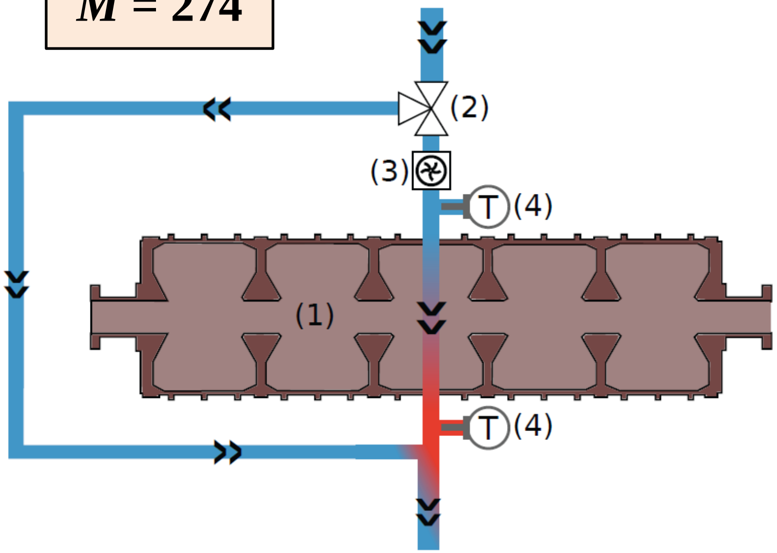
**(c)** Mode $n = 2$ mit $\Delta\Phi_n = \pi$.

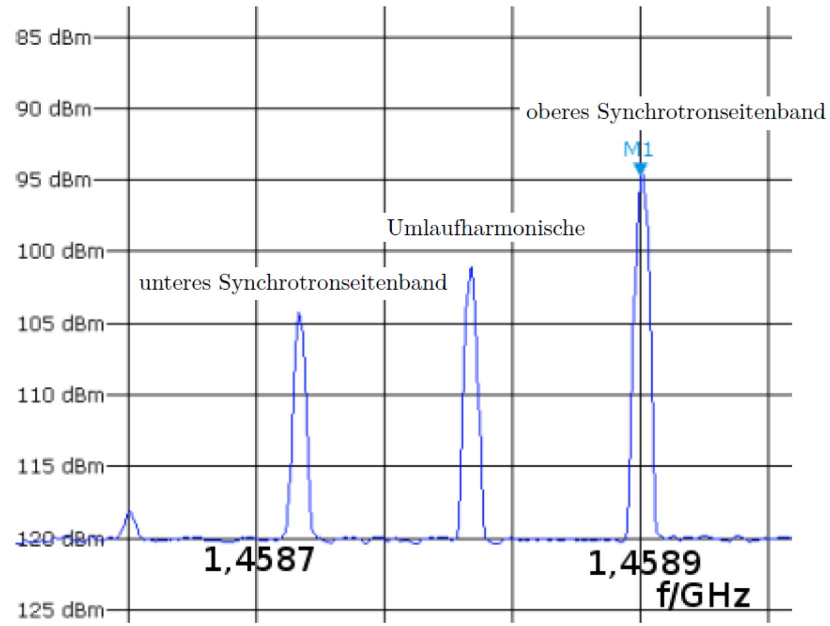
**(d)** Mode $n = 3$ mit $\Delta\Phi_n = {}^3\!/_2\,\pi$.

**Large distances between upper and lower sidebands can occur!**

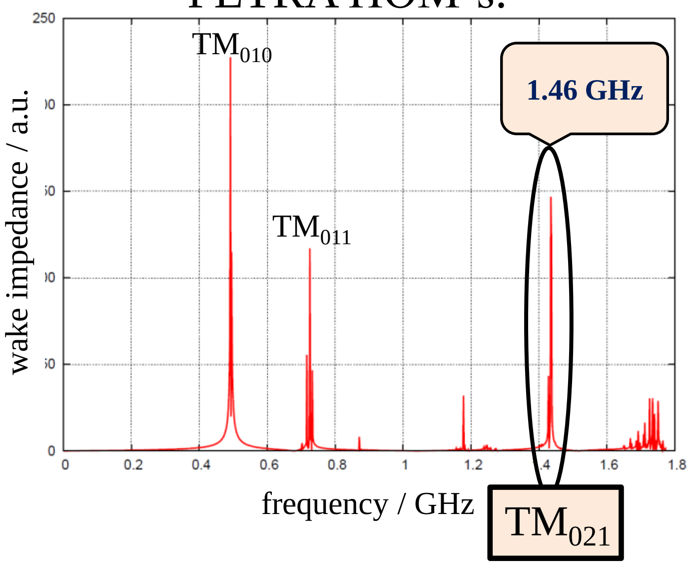
# ELSA's favorite mode:

***M* = 274**




PETRA HOM's:



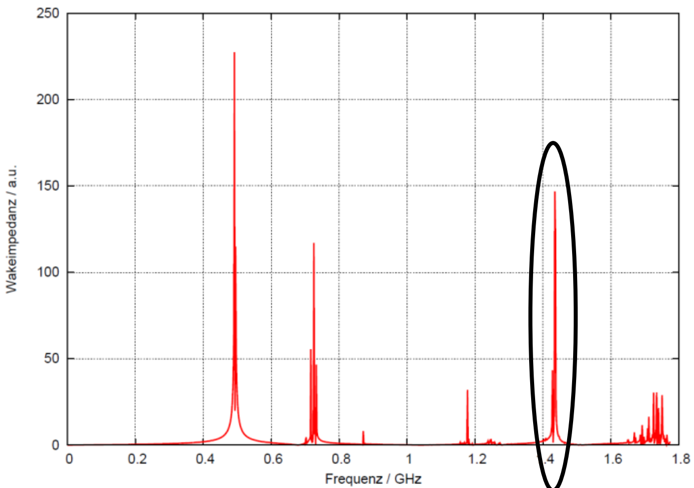

**HOM @ 1.460GHz ↔ Mode 252**

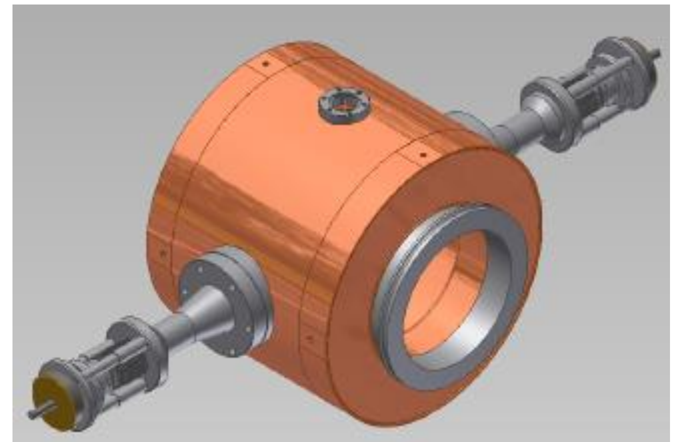
$$\omega_n = (n + pM) \cdot \omega_0 + m\Omega_S$$

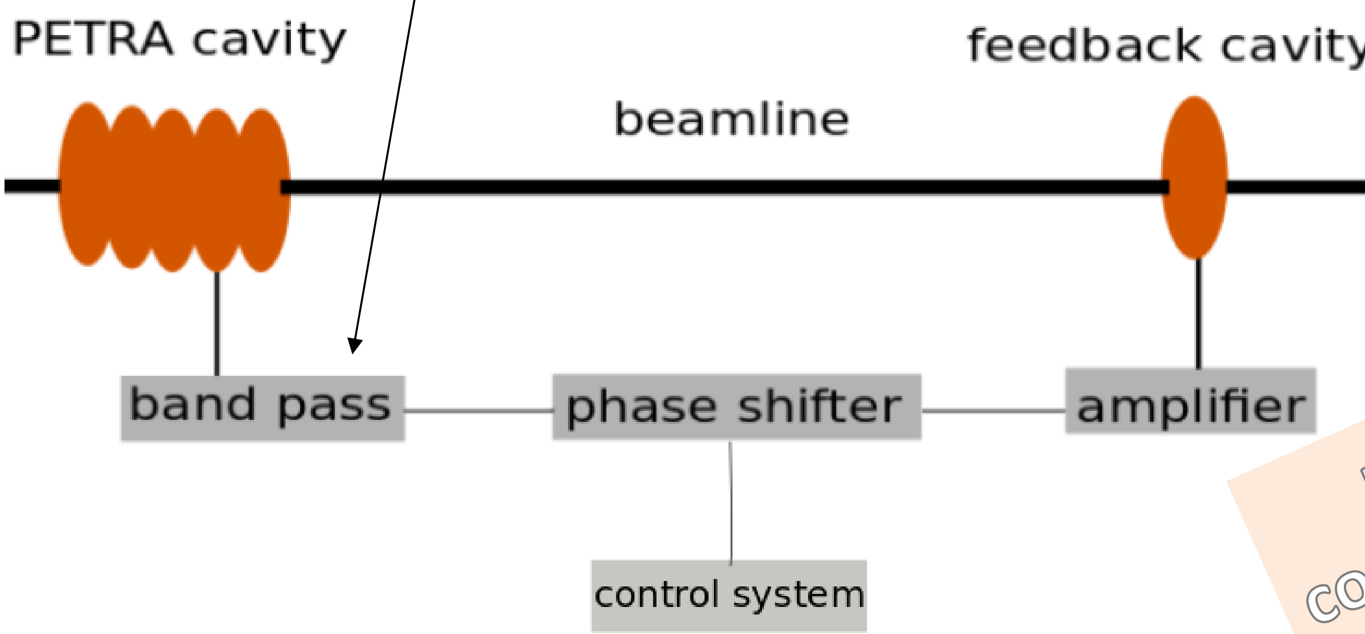
$$= (252 + 2 \cdot 274) \cdot 1.824\,\mathrm{MHz} + \Omega_S$$

$$\approx 1.460\,\mathrm{GHz}$$

# Narrow Band Feedback

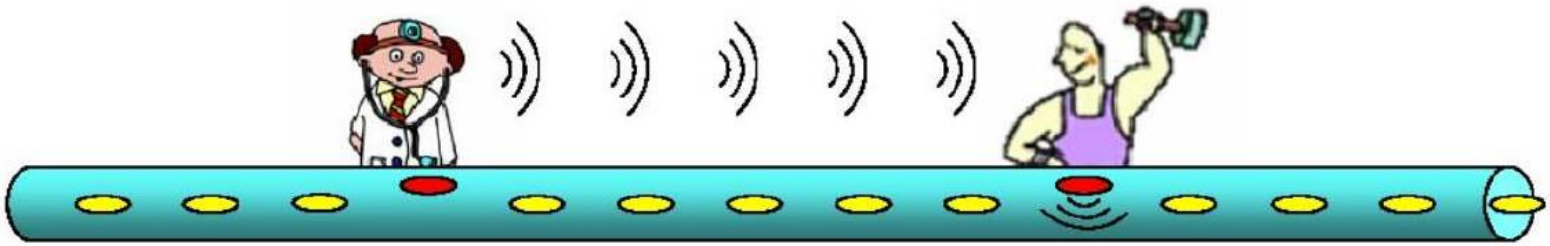


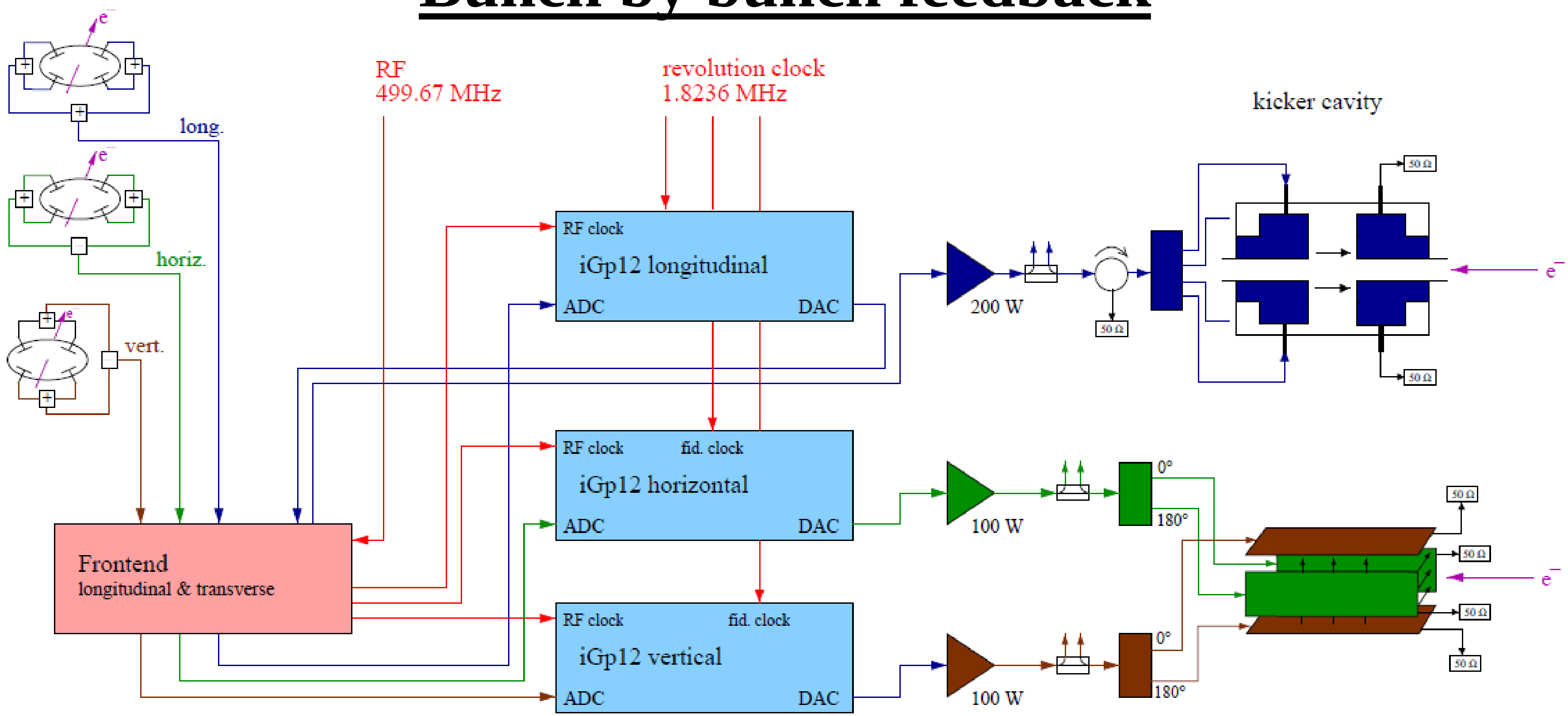



under construction

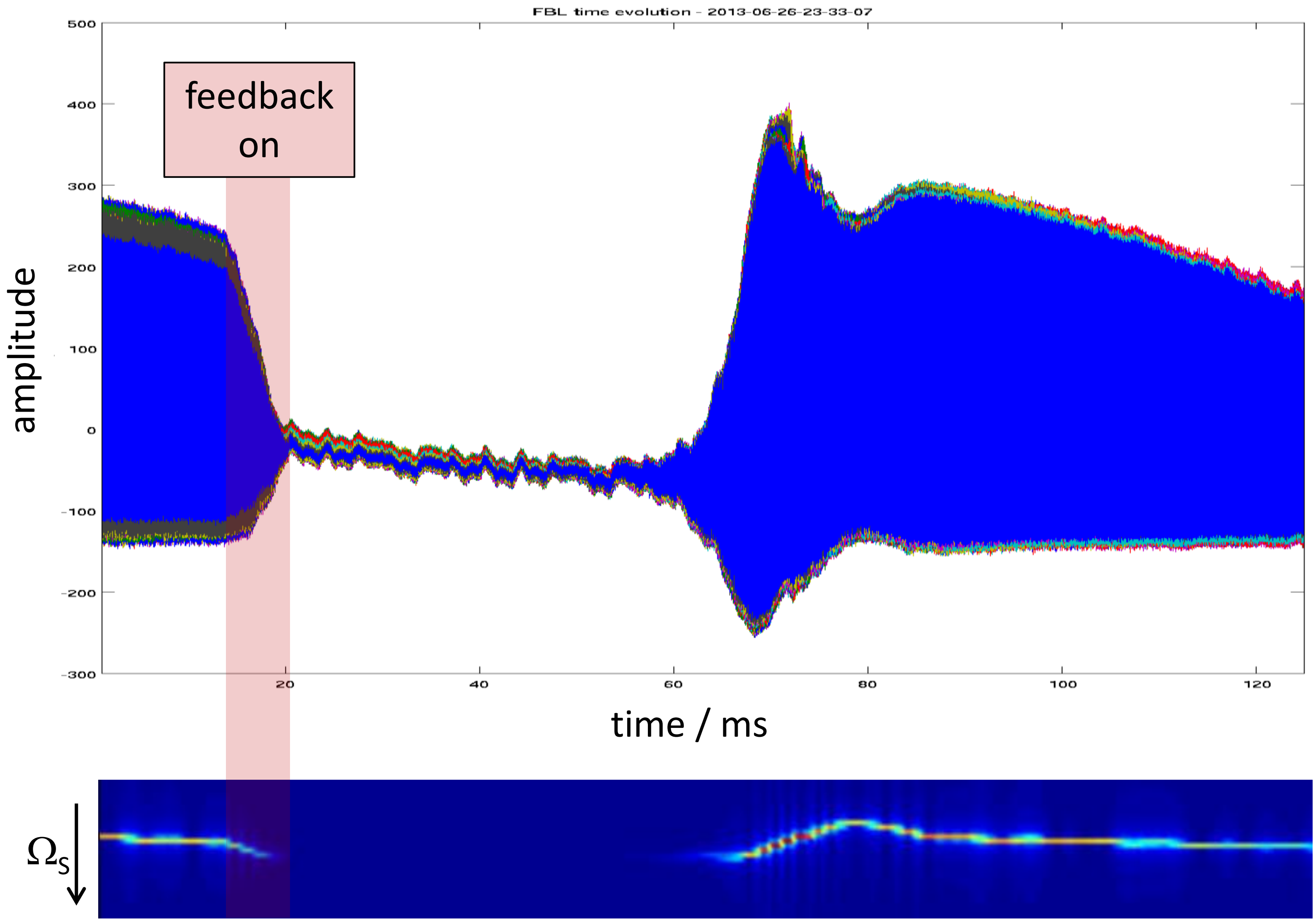
# Countermeasures



## Bunch by bunch feedback



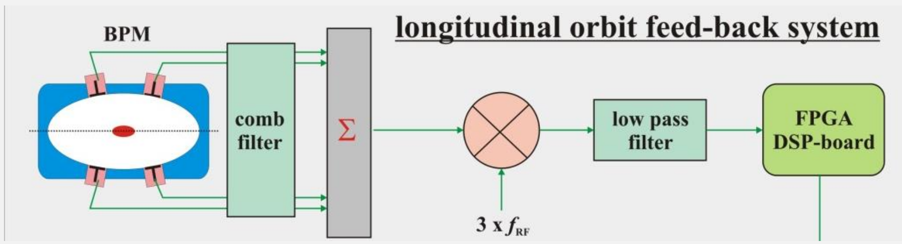
# Feedback Performance



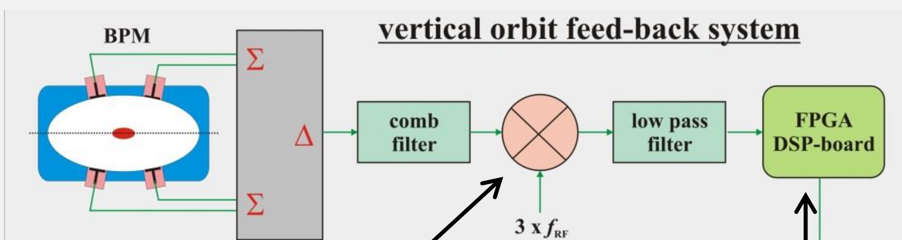
# The problem of the RF phase

**Feedback signal down-conversion:**

a) phase demodulation:




b) amplitude demodulation:

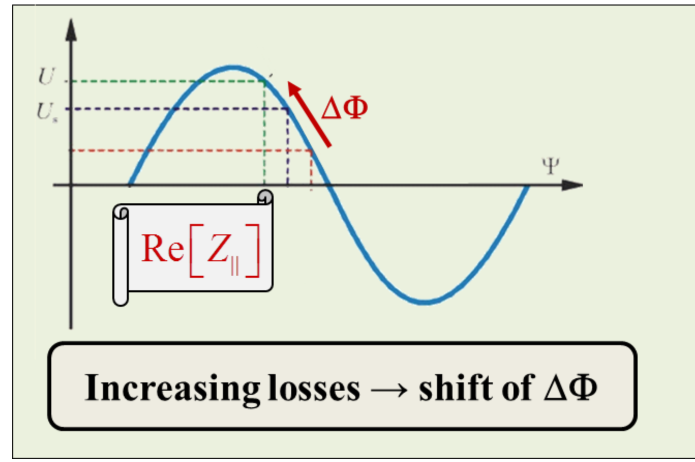



Sensitive to phase shifts

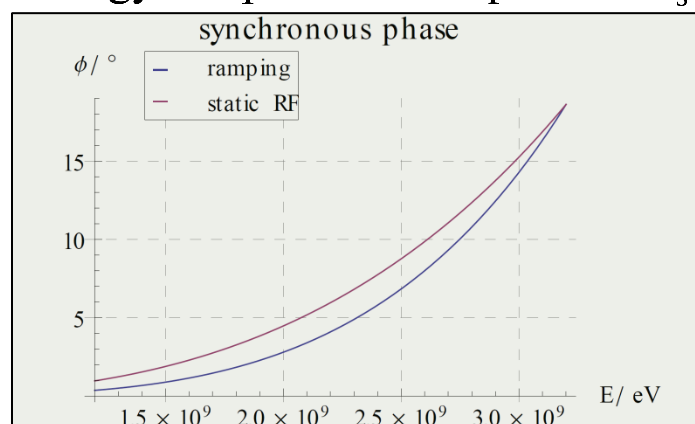
Sensitive to frequency shifts

**full ampl. & phase control of RF required!**

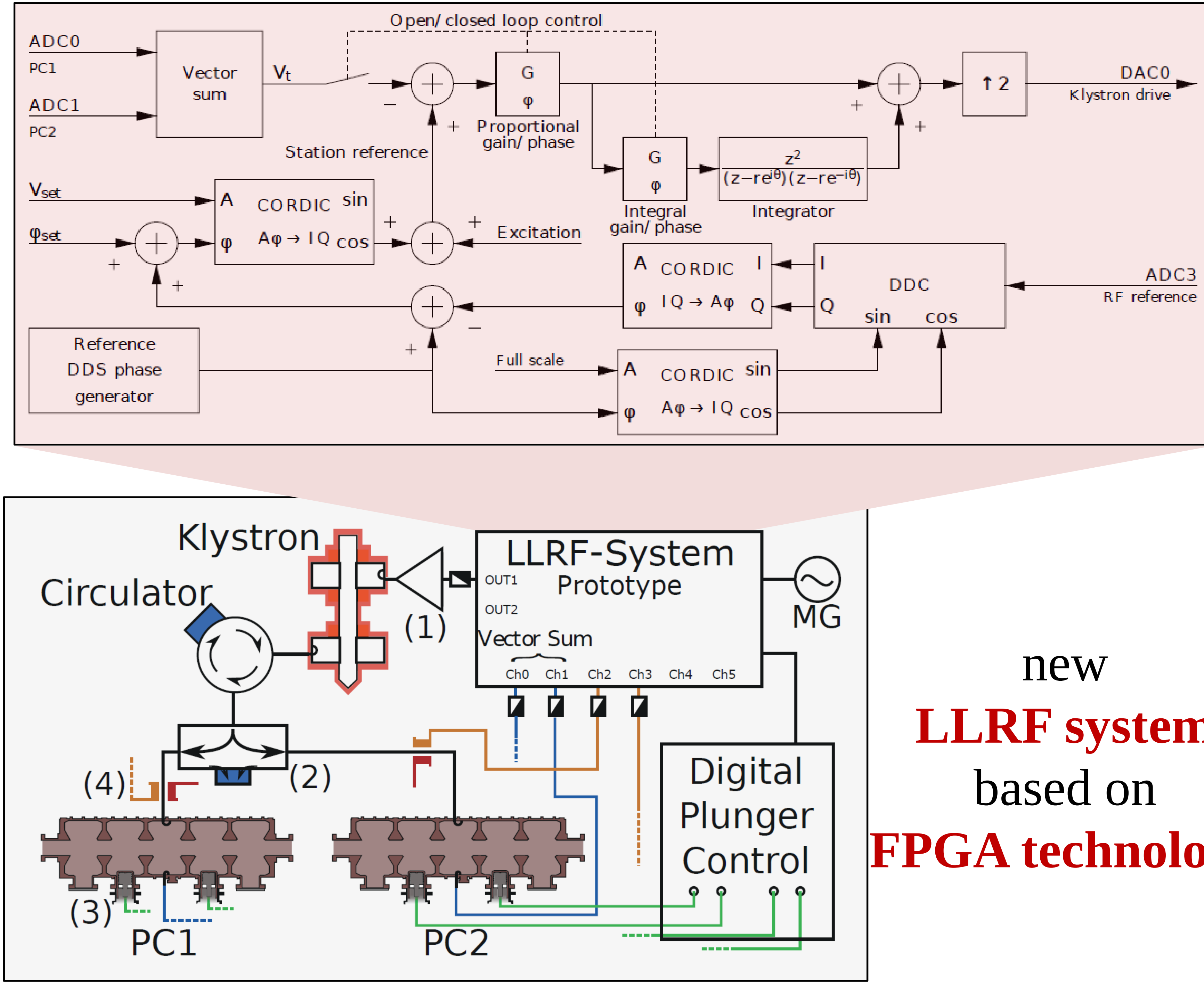
Beam injection: increasing current!




Energy ramp ↔ RF-ramp to fix $\Omega_s$




but the phase is still moving!!!



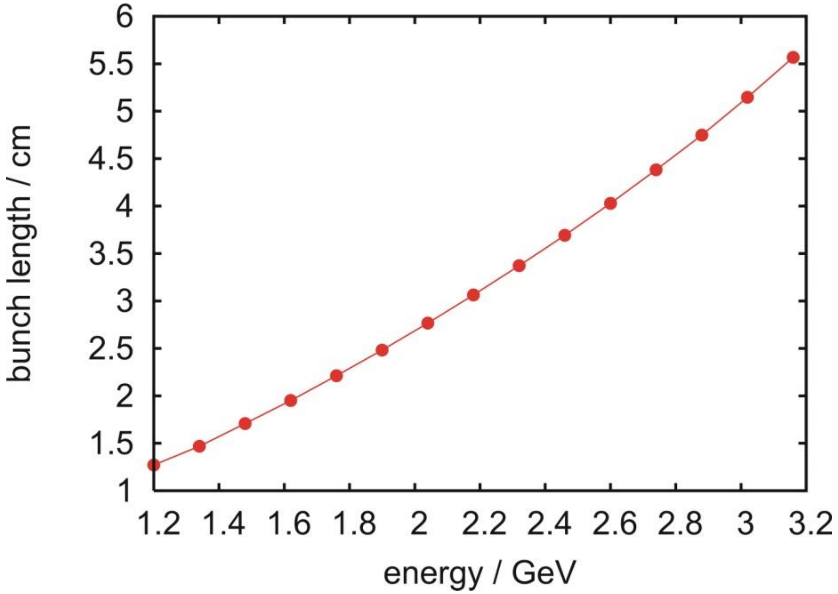

new
**LLRF system**
based on
**FPGA technology**

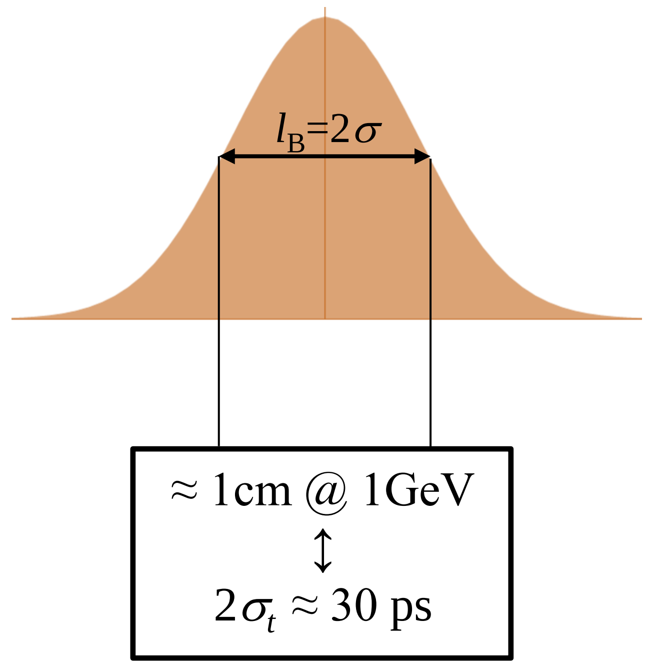
# Measurement of $\rho(\tau, t)$?!

**(nondestructive!)**

## Requirements:

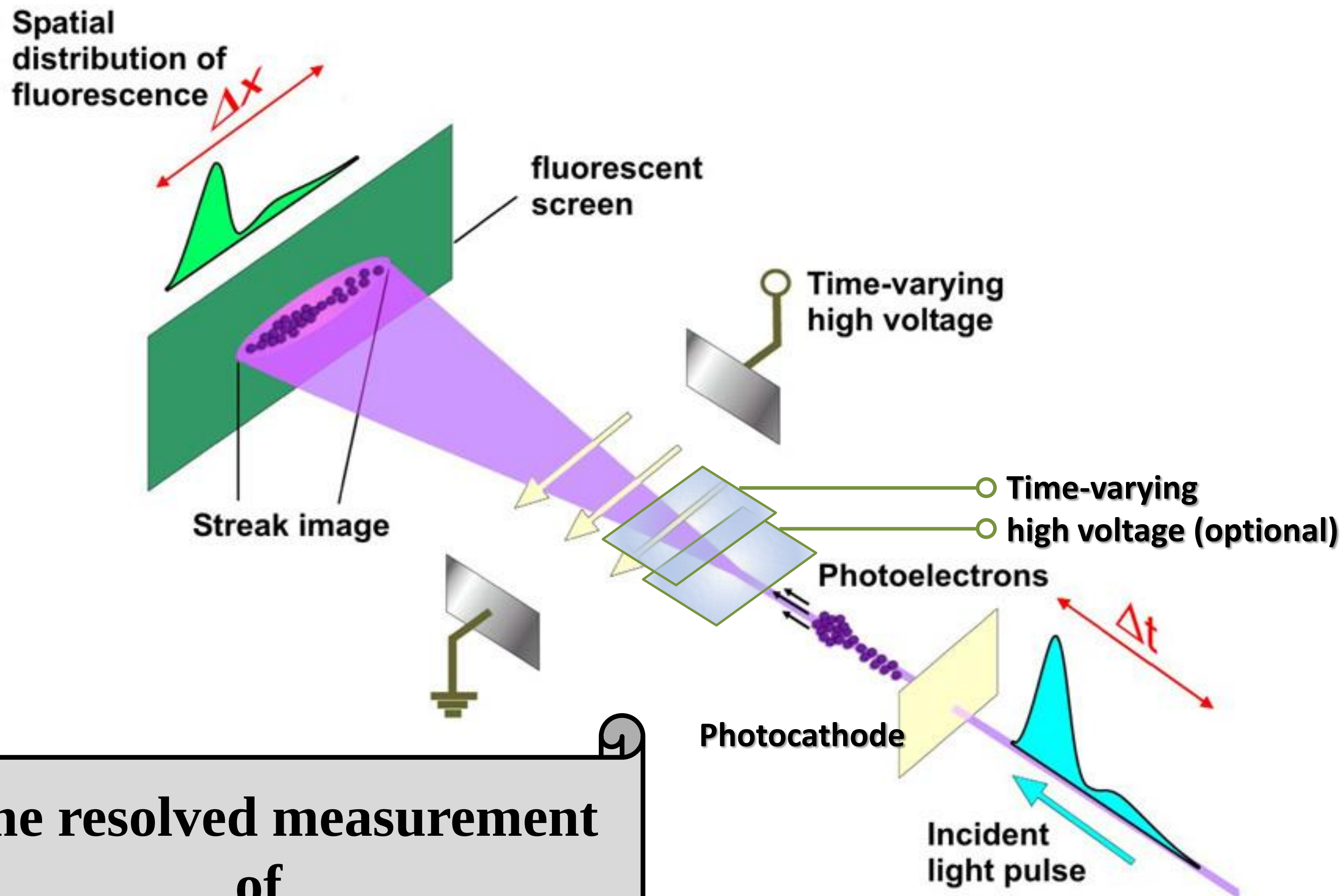
**Bunch length from measurement of coherent synchrotron oscillations:**



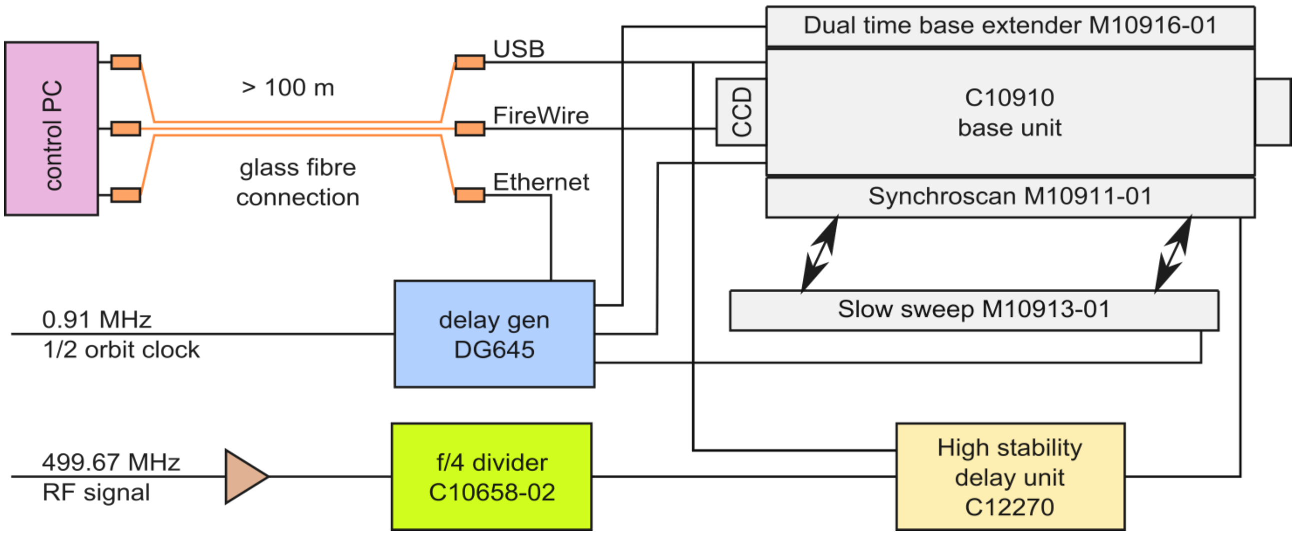

**Required time resolution: $\approx$ 1 picosecond !!!**

# Streak Camera

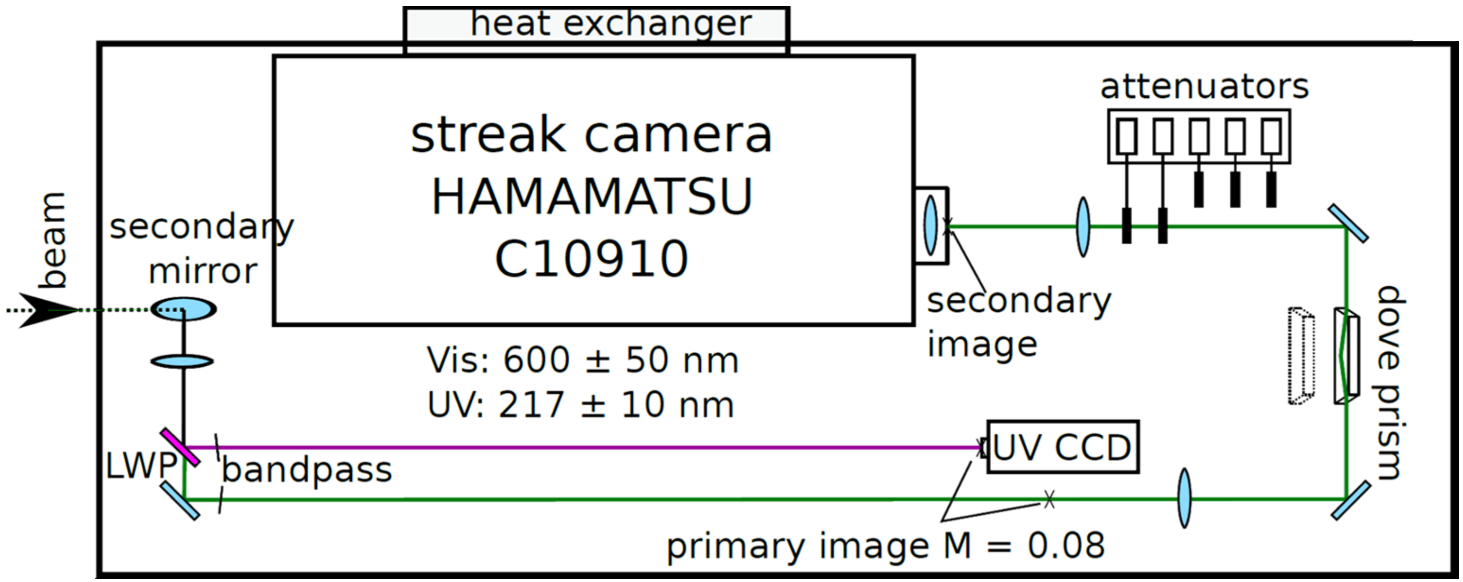



Time resolved measurement
of
intensity (distributions)


Digital delay generator
Synchroscan unit M10
Slow single sweep unit
Digital CCD camera OR

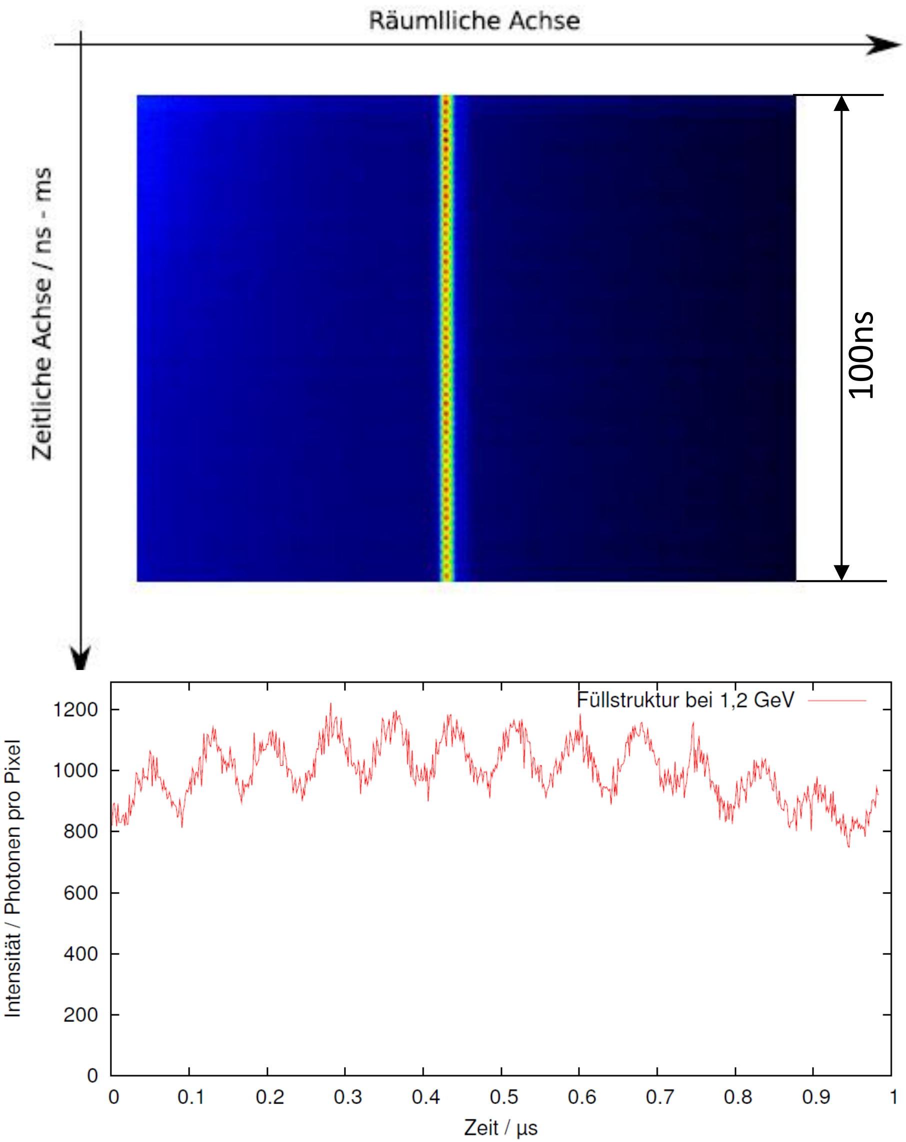



# System set-up:

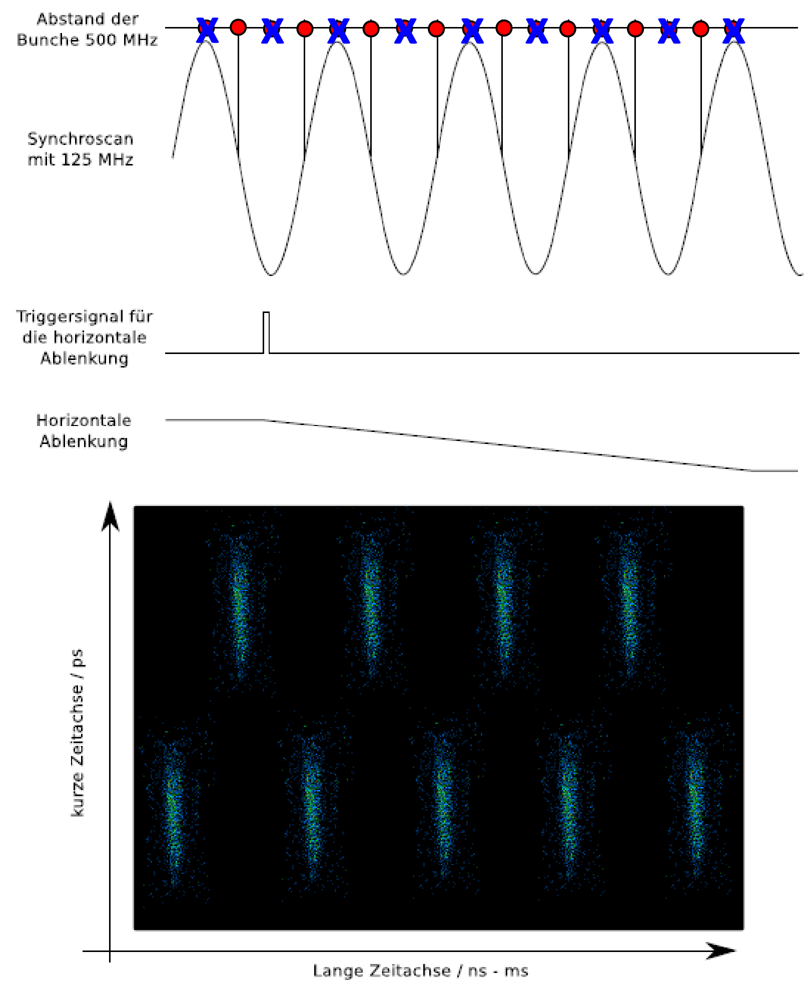


# First Measurements

## Slow Sweep:

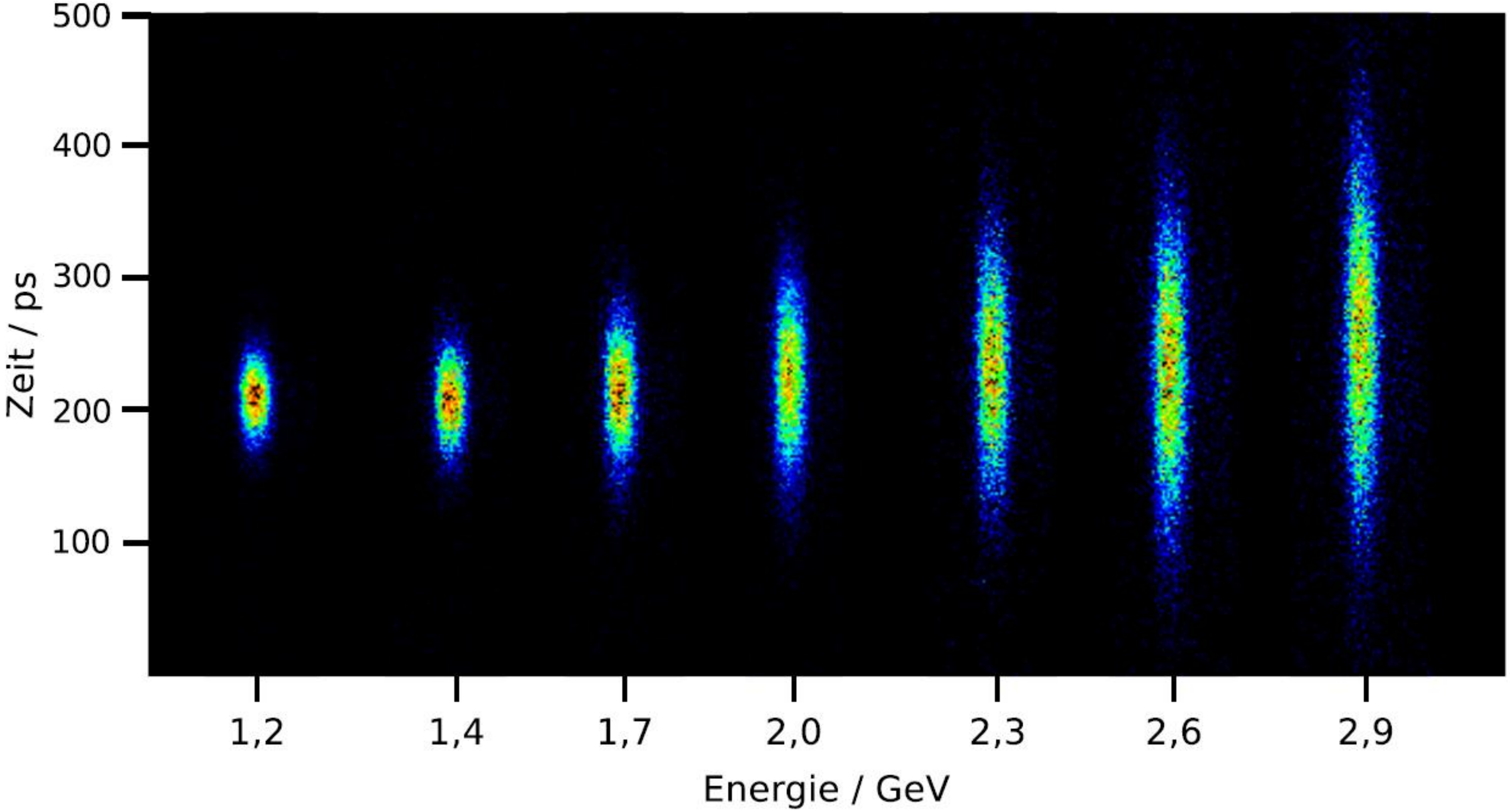



## Dual Scan:



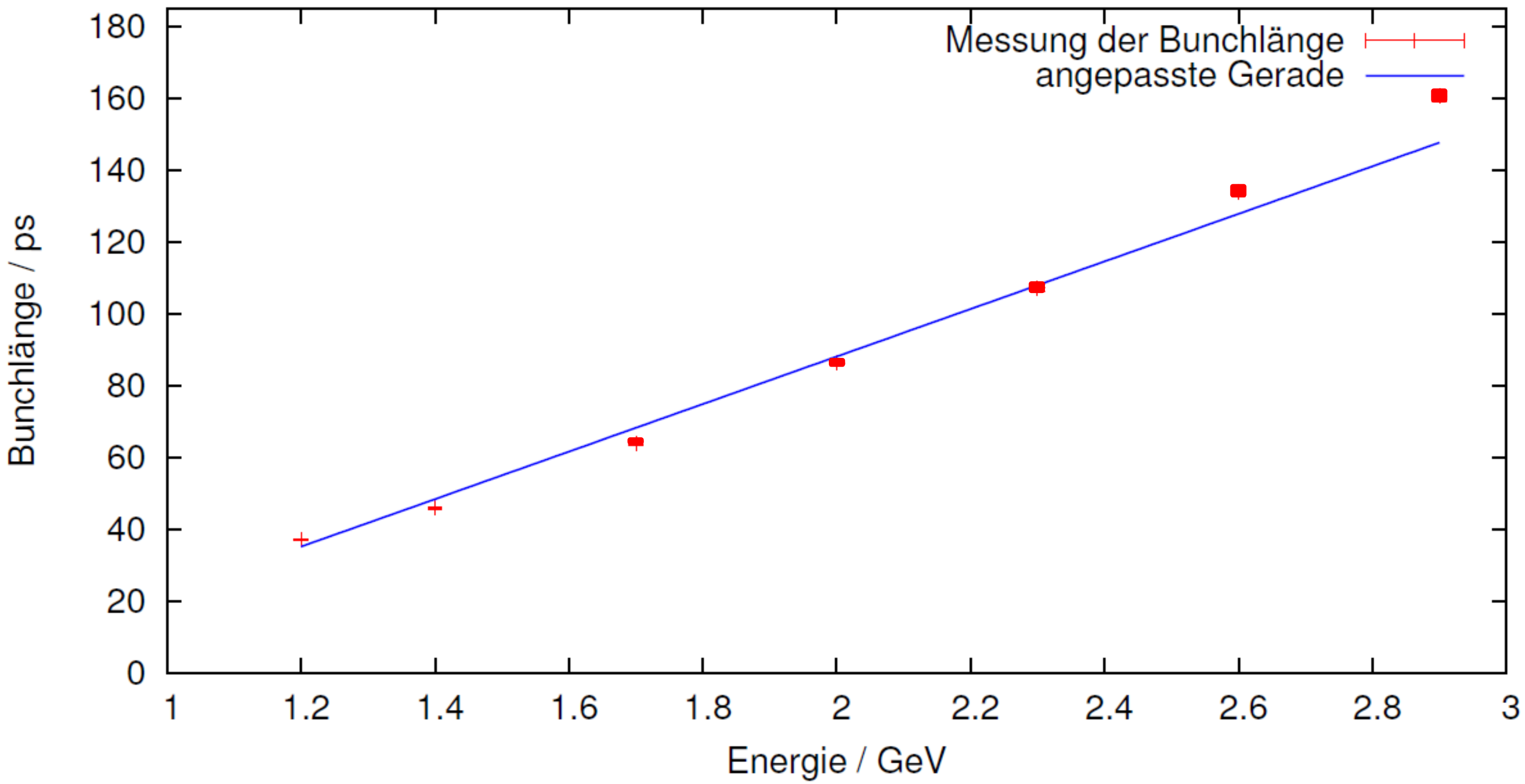
# Bunch Length: $\rho(\tau, \not{t})$

## Integrating Measurement using Synchroscan:



# Bunch Length: $\rho(\tau,\not{t})$

## Integrating Measurement using Synchroscan:




**Coming: Optimization of optical adjustments for single shot measurements**

# Conclusions

**ELSA is on its way towards high intensities!**

## Damping of instabilities:

- 3D bunch by bunch feedback fully operational
- narrow band feedback in fabrication

## Beam current and RF power:

- LINAC I will supply required beam current (and single bunches) in 2014
- new RF system under construction, will be installed soon
- new LLRF system will provide excellent amplitude and phase stability and control, required for efficient feedback operation

## Beam diagnostics:

- streak camera is operational and appears to be very useful

**ELSA is successfully running for CB after a 2 years break!**
**Beam line to BGO-OD is fully installed and operational!**