Karlsruhe Institute of Technology

Institute for Beam Physics and Technology

Particle Accelerator Physics

Anke-Susanne Müller, Axel Bernhard, Bastian Härer, Bennet Krasch, Nathan Ray

VII - Performance limits of accelerators

- Circular accelerators
  - Impedance
  - Tune and beam current
  - Synchrotron tune in extreme cases
  - Head-tail effects

- Protons
  - High-intensity beams
  - Beam-beam effects (in case of colliders)

- Electrons
  - Ultra-short pulses & CSR

Impedances and wakefields

- A high intensity bunch is a source of electromagnetic fields.
- The beam environment (cavities, vacuum chamber, etc.) interacts with these fields, creating a feedback loop that changes the betatron and synchrotron frequencies of the beam.

  $\rightarrow$ Resonances!

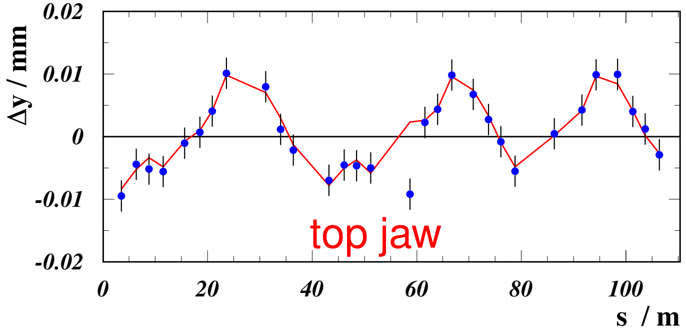
- The **impedance** is defined by the current and induced voltage for a given frequency, $Z(\omega) = V(\omega)/I(\omega)$, and is generally complex.
  - $\mathrm{Re}\ Z(\omega)$ leads to energy losses
  - $\mathrm{Im}\ Z(\omega)$ leads to frequency changes

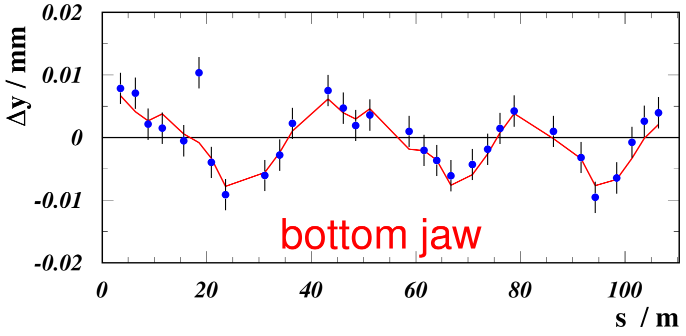
- The **"wakefield"** W is the representation of the impedance in the time domain
  - Longitudinal: The induced voltage causes a loss of energy
  - Transverse: A non-centered beam experiences a deflection. Both dipole kick and quadrupole kick ("wakefield as lens") occur.

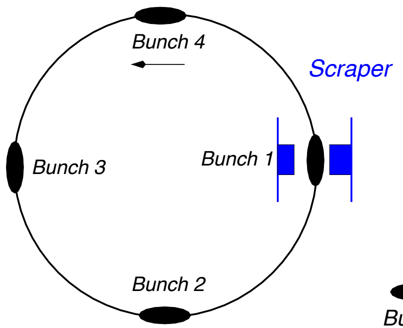
- Checking the total impedance is of great importance!

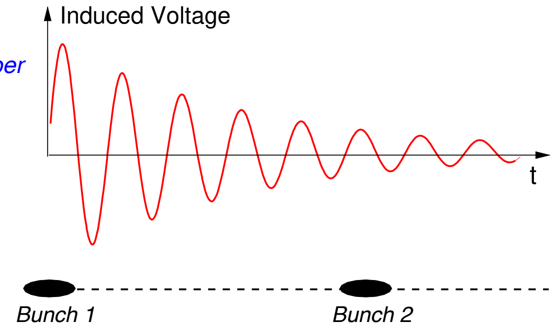
Scraper wakefields

- A scraper/collimator is a local aperture change
  - leads to lifetime reduction
  - wakefields stimulate oscillations
- The strength of the wakefield can be measured by the effect (kick) on the (closed) orbit.
- The effective wake field kick is determined by means of a fit of the MAD model to the measured differential orbit.







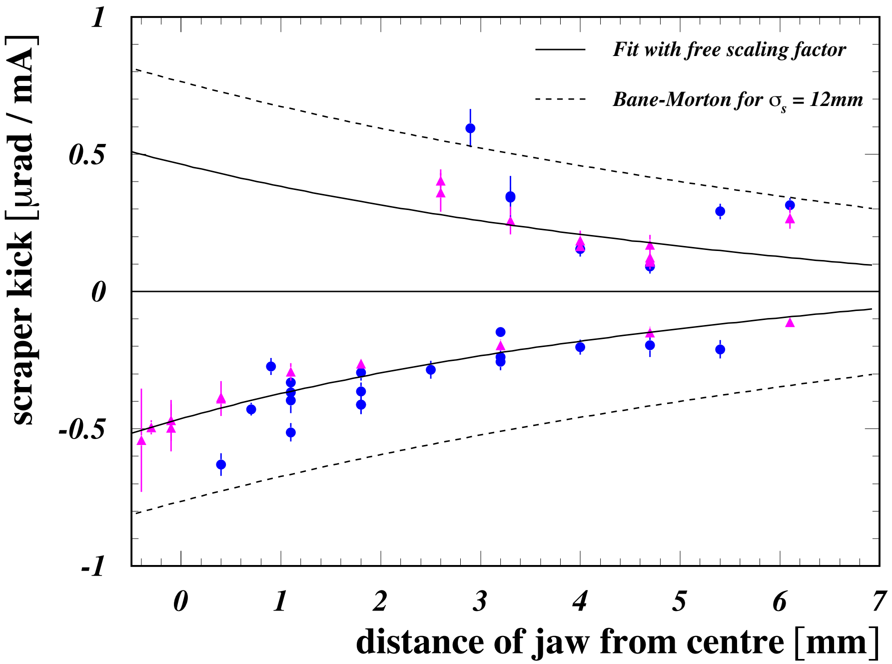


Scraper kicks

- Geometric impedance dominates
- Half height of the KARA vacuum chamber: $b = 16\,\mathrm{mm}$; distance of the scape knife to the center of the vacuum chamber a
- Bane-Morton-formula for asymmetric gap:

$$\langle y' \rangle = 0.71 \left(\frac{\pi}{2}\right)^{\frac{3}{2}} \frac{r_\mathrm{e} N_\mathrm{b}}{\sigma_z \gamma} \left(\frac{b-a}{b+a}\right)$$

  - Describes observation
  - Allows to determine the effective bunch length (would be difficult to measure at KARA for low energies E_0 because of an instability).

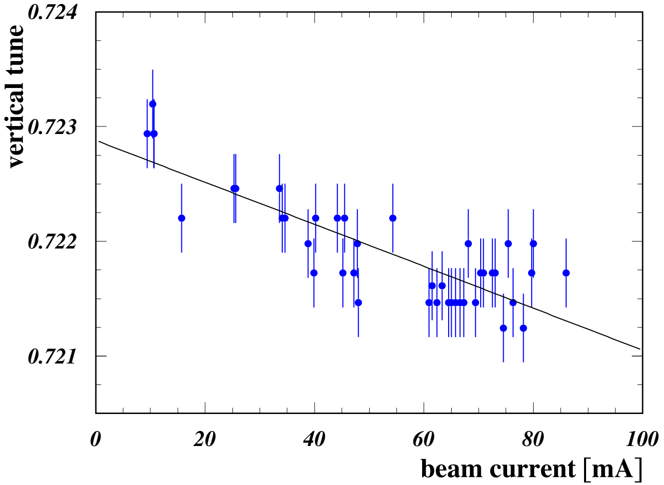


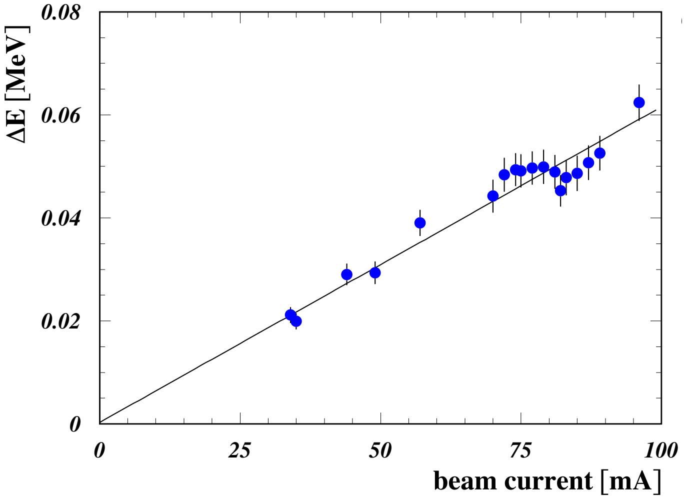
Measurement of the global impedance

- Tune shift due to an (effective) impedance:

$$\Delta Q \propto \frac{N_\mathrm{b}}{E_0\ \sigma_s}\ (Z^\perp)_\mathrm{eff}$$

- The impedance can thus be determined from the tune as a function of the current.





- Energy change leads to a shift in transverse position:

$$\frac{\Delta x_\mathrm{co}}{D_x} \approx \frac{\Delta E}{E_0} = \frac{1}{E_0}\kappa_{||} e T_0 \Delta I_\mathrm{bunch}$$

- The longitudinal "loss factor" is

$$\kappa_{||} \propto \int_0^\infty d\omega\ \mathrm{Re}\, Z_{||}(\omega)\ h(\omega, \sigma)$$

Head-tail effects

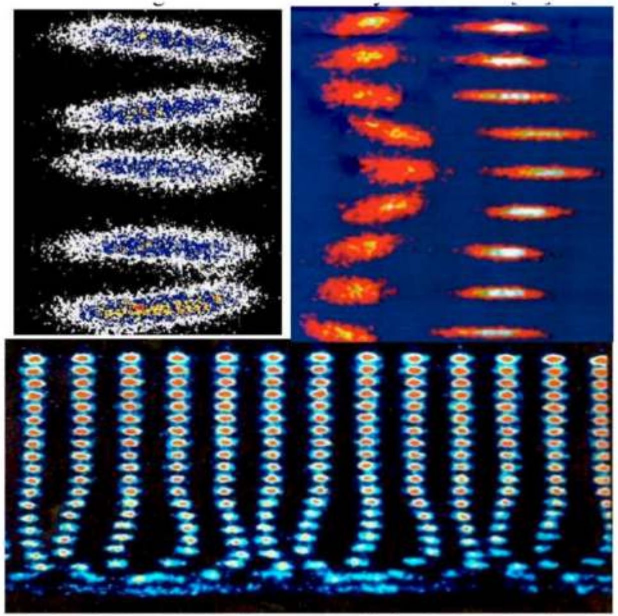
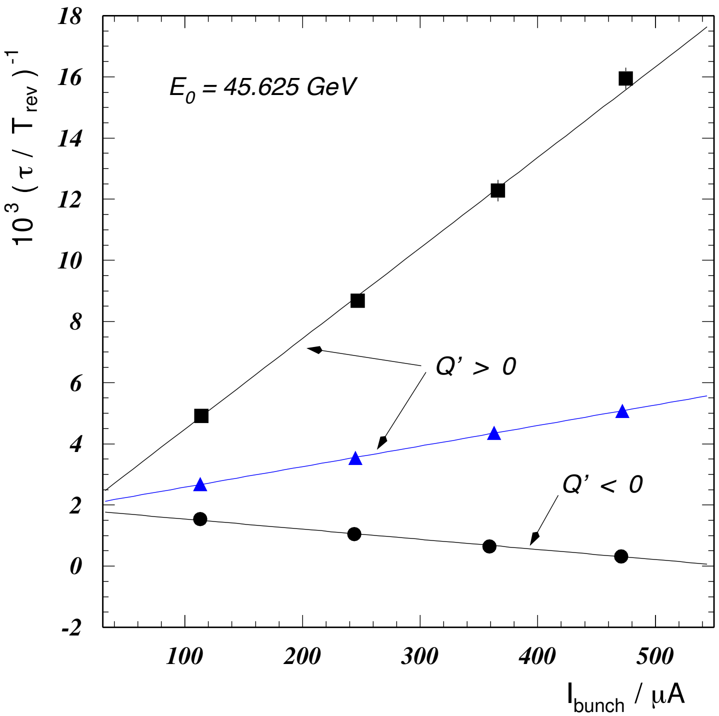


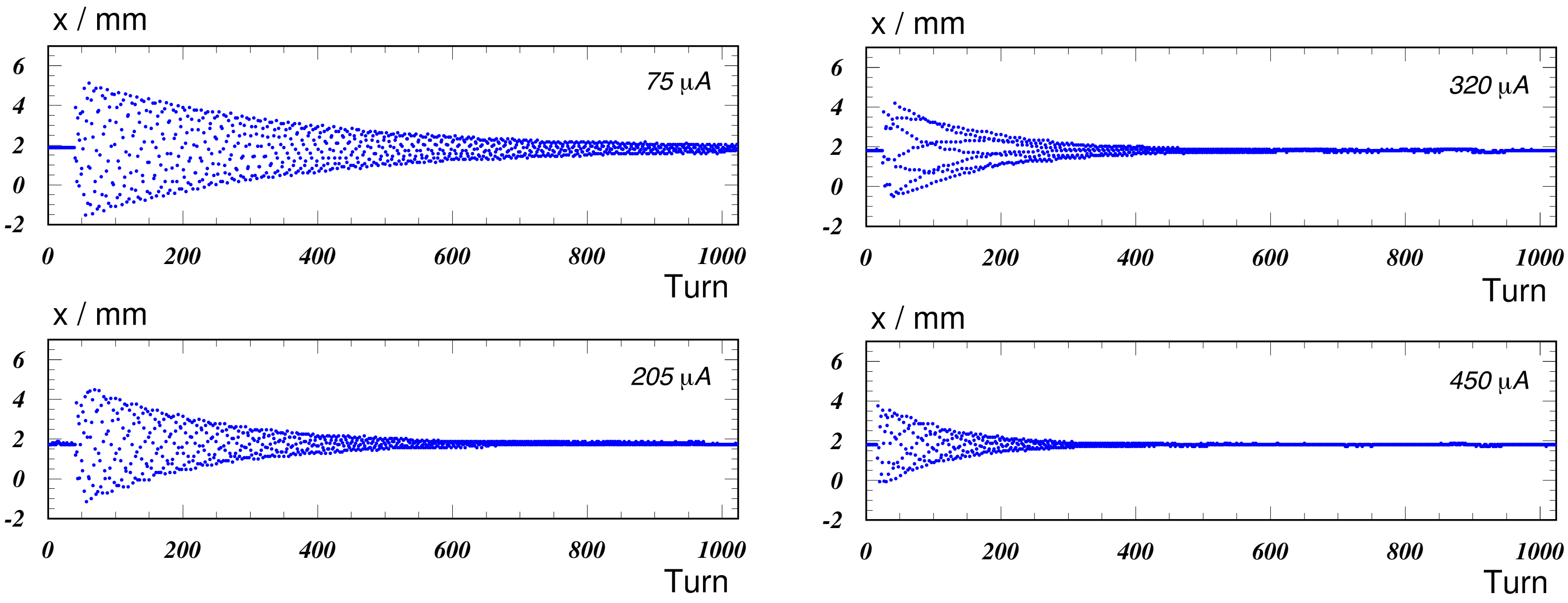
Fig.6a (left) : ESRF five turns of single bunch showing vertical Head-Tail instability,
Fig.6b (right) : LEP top & side views of bunch over 9 turns showing vertical Head-Tail effects, transverse motions and bunch length fluctuations,
Fig.6c (bottom) : APS horizontal coherent motions at trail of the 60ns filling pattern over 13 turns



- Coherent damping:

$1/\tau_{coh} = 1/\tau_0 + 1/\tau_{head-tail}$ with $1/\tau_{head-tail} \propto \frac{U_0 \sigma_s Q'}{E_0\ \alpha_c} I_b$

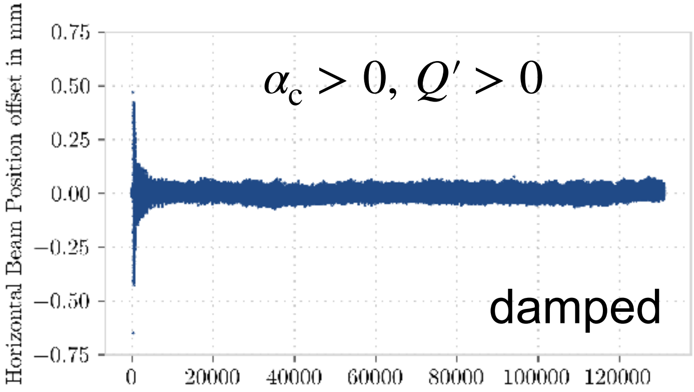
Head-tail effect and current

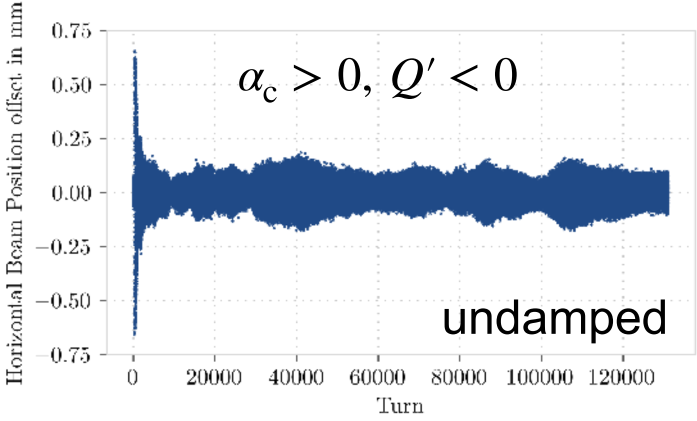


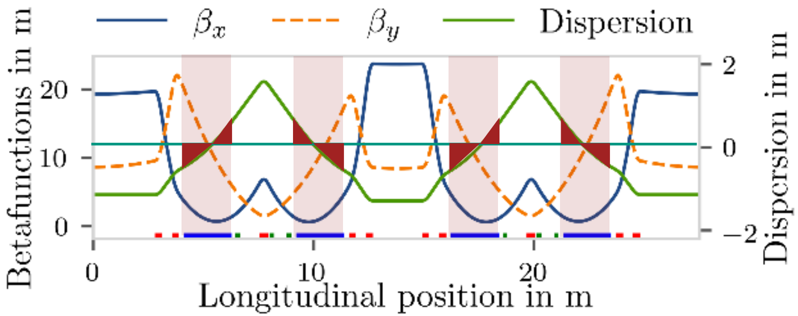
- Coherent damping: $1/\tau_{\rm coh} = 1/\tau_0 + 1/\tau_{\rm head-tail}$ with $1/\tau_{\rm head-tail} \propto \dfrac{U_0 \sigma_s Q'}{E_0\ \alpha_c} I_b$

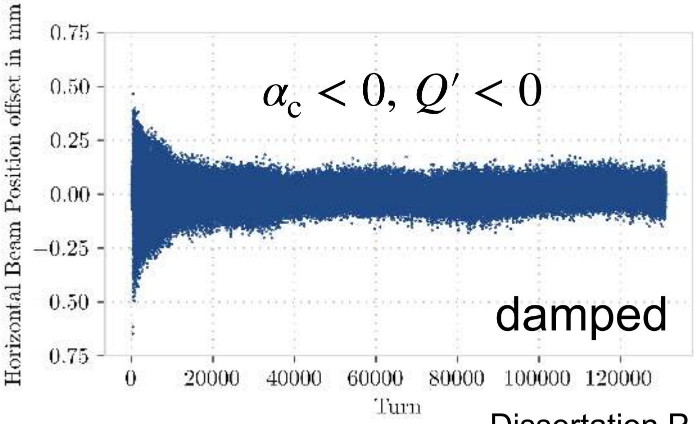
Negative alpha

$$1/\tau_{\text{head-tail}} \propto \frac{U_0 \sigma_s Q'}{E_0\ \alpha_c} I_b \qquad \alpha_c = \frac{1}{L}\oint \mathrm{d}s\, \frac{D(s)}{\rho(s)}$$









Dissertation P. Schreiber

Synchrotron tune in extreme cases

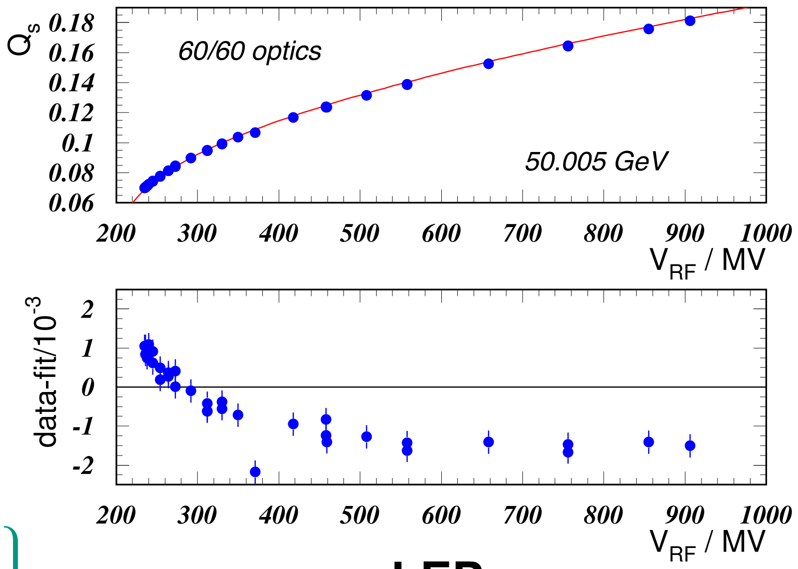
- For high beam energies and large synchrotron radiation losses the simple equation

$$Q_s^2 = \left(\frac{\alpha_c h}{2\pi E}\right)\sqrt{e^2\, V_{\mathrm{RF}}^2 - U_0^2}$$

  no longer applies.
- Energy loss in quadrupoles and corrector magnets have to be taken into account.
- In addition, there are current-dependent losses.

- The full expression is:

$$Q_s^4 = \left(\frac{\alpha_c h}{2\pi}\right)^2 \left\{ \underbrace{\frac{g^2 e^2 V_{\mathrm{RF}}^2}{E_c^2} + M g^4 V_{\mathrm{RF}}^4}_{\text{RF contributions}} - \frac{1}{E_c^2} \underbrace{\left(\frac{C_\gamma}{\rho} E^4 + K\right)}_{\text{total energy loss}}^2 \right\}$$



LEP

Q_s and current

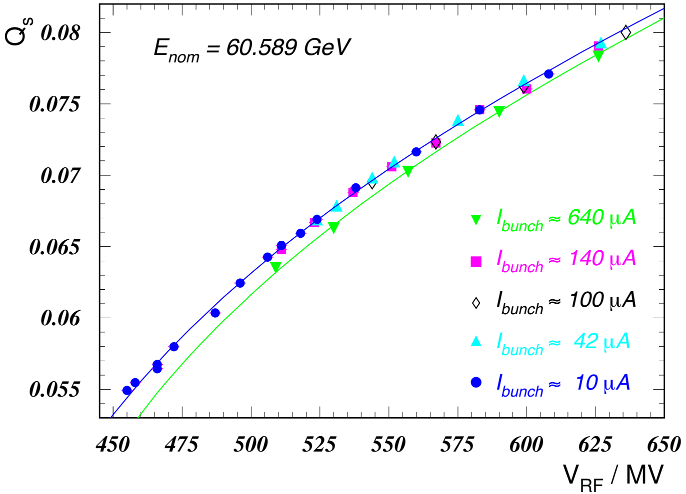
- The energy loss term in the expression for Q_s^4 contains a current dependent component:

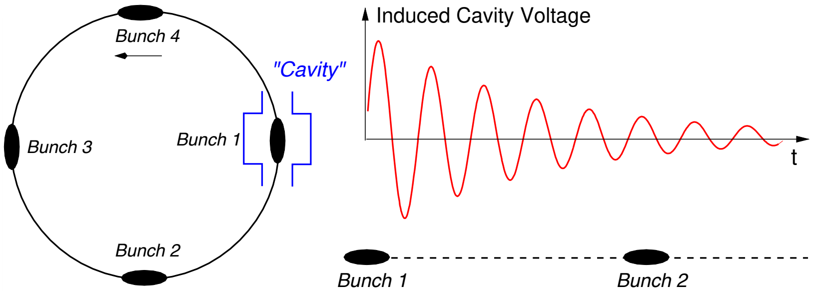
$$U_{pm} = e\ T_{rev}\ I_b\ \kappa_{||}$$

- The so-called “loss factor” is given by

$$\kappa_{||} \ \propto \int_0^\infty d\omega\ \mathrm{Re}Z_{||}(\omega)\ h(\omega,\sigma)$$

- $Z_{||}$ is the longitudinal impedance the ring, which is caused by the structure of the aperture along s.





Sawtooth orbit

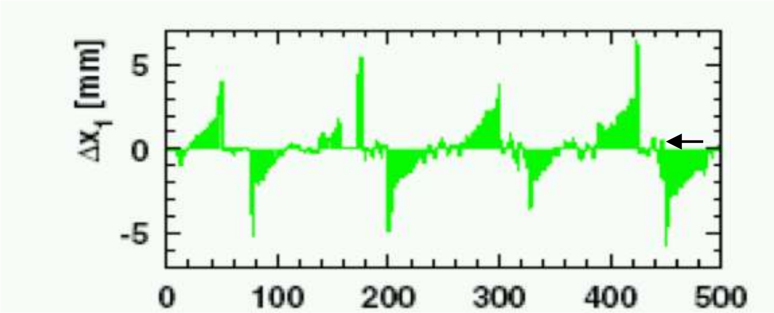
- Particles continuously lose energy
- Horizontal drift in dispersive sections proportional to energy

$$x(s) = \sqrt{\epsilon_x \beta_x(s)} + D_x(s)\delta$$

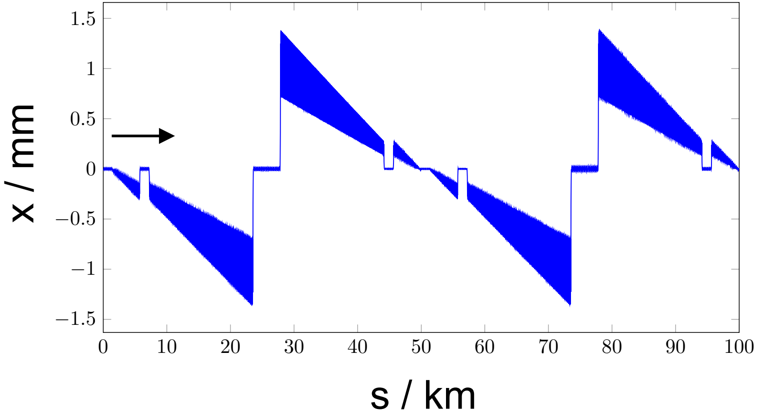
- Energy is restored at the RF cavities
- Periodic boundary conditions actually lead to overcompensation

- FCC-ee: Adjustment of magnetic field to the local beam energy

LEP



FCC-ee (old version)



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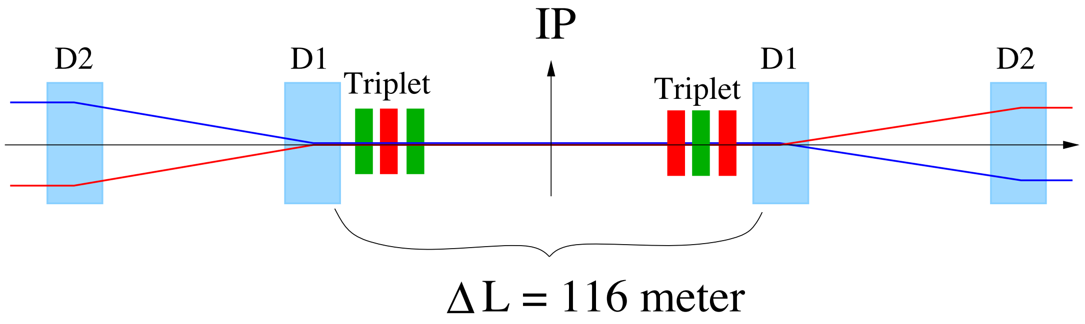
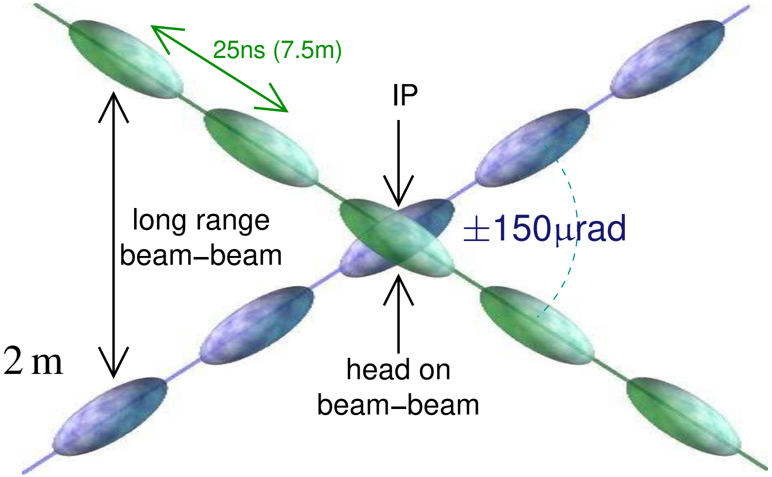
Interaction region and collision angle





- **Head-on:** Additional collisions for bunch separation below $232\,\mathrm{m}$

  $\Rightarrow$ For $C = 26.7\,\mathrm{km}$ only 115 bunches can be filled
  ($\mathscr{L} < 4.9 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

- **Solution:** Separation of the two beams and collision angle at the IP
- Challenges:
  - Additional tune shift
  - Larger aperture required
  - Coupling, resonances, smaller overlap

Beam-beam interaction

- The beam-beam effect limits the performance (luminosity) of a collider.
- The collisions represent periodic disturbances that influence the beam dynamics and increase with the current.

- **Simplest case:** Head-on collision of two Gaussian bunches with RMS length σ_s an n particles per unit length and the transverse charge density distribution

$$\rho(r) = \frac{ne}{2\pi\sigma_r^2} e^{-r^2/2\sigma_r^2}$$

- A test particle of the oncoming colliding bunch in transverse distance r from the center experiences the Lorentz force

$$\vec{F} = e(\vec{E} + \vec{v} \times \vec{B}) = e(E_r + \beta c B_\phi)\hat{r}$$

- The electric and magnetic fields are obtained from Gauss's and Ampere's laws:

$$2\pi r E_r = \frac{1}{\varepsilon_0}\int_0^r dr'(2\pi r' \rho(r')) \quad \Rightarrow \quad E_r = \frac{ne}{2\pi r \varepsilon_0}\left(1 - e^{-r^2/2\sigma_r^2}\right)$$

$$2\pi r B_\phi = \mu_0 \int_0^r dr'(2\pi r'(\beta c)\rho(r')) \quad \Rightarrow \quad B_\phi = \frac{ne\mu_0(\beta c)}{2\pi r}\left(1 - e^{-r^2/2\sigma_r^2}\right)$$

Beam-beam kick

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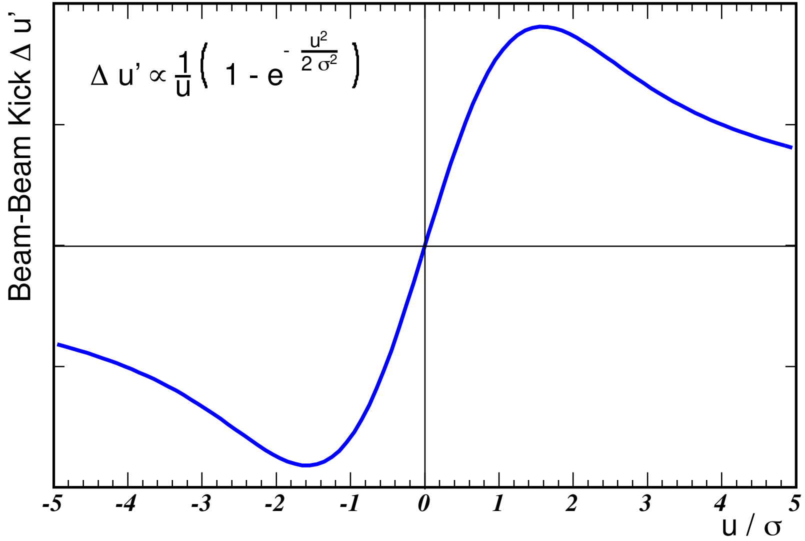
- With the fields determined in this way, we obtain for the Lorentz force

$$\left(E_r = \frac{ne}{2\pi r \varepsilon_0}\left(1 - e^{-r^2/2\sigma_r^2}\right), \quad B_\phi = \frac{ne\mu_0(\beta c)}{2\pi r}\left(1 - e^{-r^2/2\sigma_r^2}\right), \quad c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \right)$$

$$\begin{aligned} F_r &= e(E_r + \beta c B_\phi) \\ &= e\frac{ne}{2\pi r}\left[\frac{1}{\varepsilon_0} + \beta^2 c^2 \mu_0\right]\left(1 - e^{-r^2/2\sigma_r^2}\right) \\ \Rightarrow F_r &= \frac{ne^2}{2\pi r \varepsilon_0}(1+\beta^2)\left(1 - e^{-r^2/2\sigma_r^2}\right) \end{aligned}$$

- The transverse “kick” is $\Delta u' = p_u/p$ with $p = eB\rho$, $p_u = F_r \Delta t = F_r(\sigma_s)/(2\beta c)$, and the number of particles per bunch $N_\mathrm{b} = n\sigma_s$:

$$\Delta u' = \frac{N_\mathrm{b} e}{2\pi\varepsilon_0(\beta c)(B\rho)}\frac{1}{u}\left(1 - e^{-\frac{u^2}{2\sigma_u^2}}\right)$$



Beam-beam tune shift

- For small amplitudes ($u \approx \sigma_u$) the beam-beam kick can be considered as a thin lens:

$$\frac{1}{f} = \frac{\Delta u'}{u} = \frac{1}{\sigma_u} \frac{N_\mathrm{b} e}{2\pi\varepsilon_0 (\beta c)(B\rho)\sigma_u} \left(1 - e^{-1/2}\right)$$

- Using $B\rho = \beta E/ec = \beta\gamma m_0 c^2/ec$, $\beta \approx 1$ and the classical particle radius $r_o = e^2/(4\pi\varepsilon_0 m_0 c^2)$:

$$\frac{1}{f} = \frac{N_\mathrm{b} e^2}{4\pi\varepsilon_0 \beta^2 \gamma m_0 c^2} \frac{1}{\sigma_u^2} = \frac{N_\mathrm{b} r_0}{\gamma \sigma_u^2}$$

- The change in the optical functions is derived from the perturbed transfer matrix for one turn ($\alpha = 0$ at the interaction point)

$$\begin{pmatrix} \cos(\mu + \Delta\mu) & \beta^* \sin(\mu + \Delta\mu) \\ -\frac{1}{\beta^*} \sin(\mu + \Delta\mu) & \cos(\mu + \Delta\mu) \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{2f} & 1 \end{pmatrix} \begin{pmatrix} \cos\mu & \beta_0^* \sin\mu \\ -\frac{1}{\beta_0^*} \sin\mu & \cos\mu \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2f} & 1 \end{pmatrix}$$

$$\Rightarrow \quad \cos(\mu + \Delta\mu) = \cos\mu - \frac{\beta_0^*}{2f} \sin\mu = \cos\mu - 2\pi \boxed{\xi} \sin\mu$$

- The linear tune shift is described by the beam-beam parameter $\xi = \Delta\mu/2\pi = N_b r_0 \beta^*/(4\pi\gamma\sigma_u^2)$

  The betafunction changes by $\Delta\beta^*/\beta_0^* = -2\pi\ \xi\ \cot\mu$.

Tune shift, stability and luminosity

- Reminder: The incoherent (single particle) motion is stable, if $\left|\frac{1}{2}\mathrm{tr}\,\mathbf{M}\right| \leq 1$. That means in this case

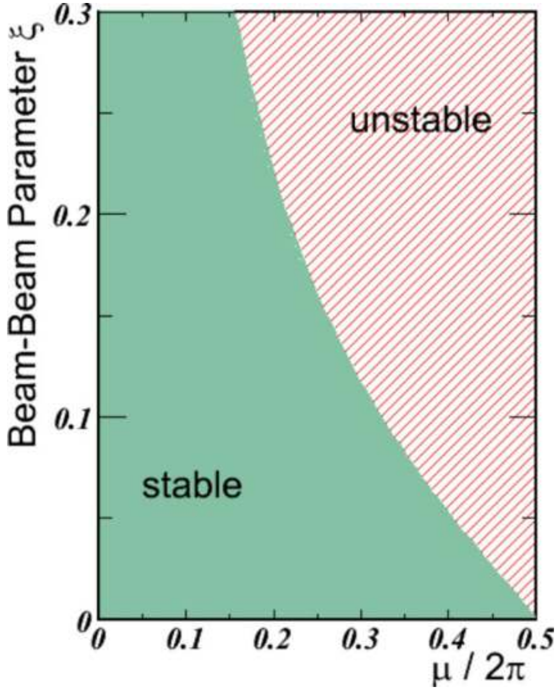
$$\cos\mu - 2\pi\,\xi\,\sin(\mu) \leq 1 \quad \text{or} \quad \xi \leq \frac{1}{2\pi}\cot(\mu/2)$$

- For elliptical beams the beam-beam parameter is

$$\xi_{x,y} = \frac{N_b r_0}{2\pi\gamma(\sigma_x + \sigma_y)}\,\frac{\beta^*_{x,y}}{\sigma_{x,y}} \propto \frac{N_b}{\varepsilon}$$

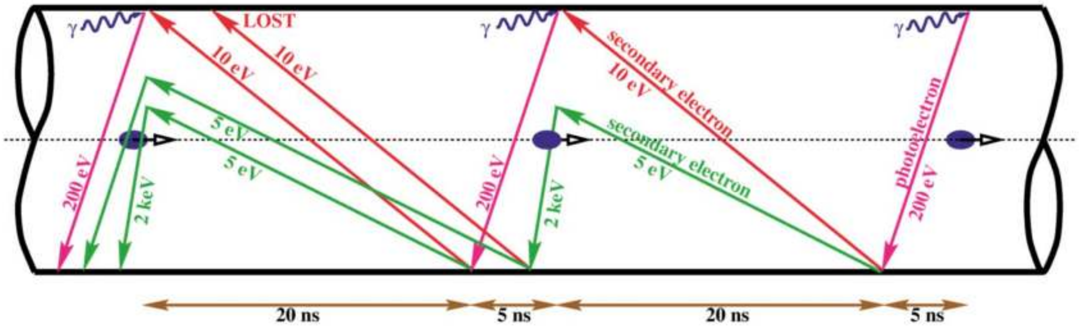
- The emittance is determined by the quality of the magnetic fields and the aperture. The limitation of the beam-beam tune shift to $< 5\times 10^{-3}$ also puts the limit on the number of protons per bunch to $N_b = 10^{11}$.
- The luminosity can be written as a function of ξ:

$$\mathscr{L} = \frac{N_b^2 n_b f_{rev}}{4\pi\sigma_x\sigma_y} = \frac{N_b n_b f_{rev}\gamma}{2 r_0 \beta^*_y}\,\xi\left(\frac{\sigma_x + \sigma_y}{\sigma_x}\right)$$



Two stream instabilities

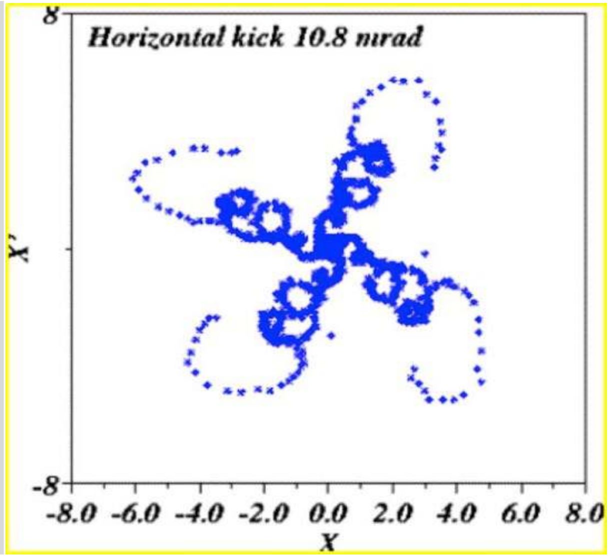
F. Zimmermann, G. Rumolo, et al. CERN

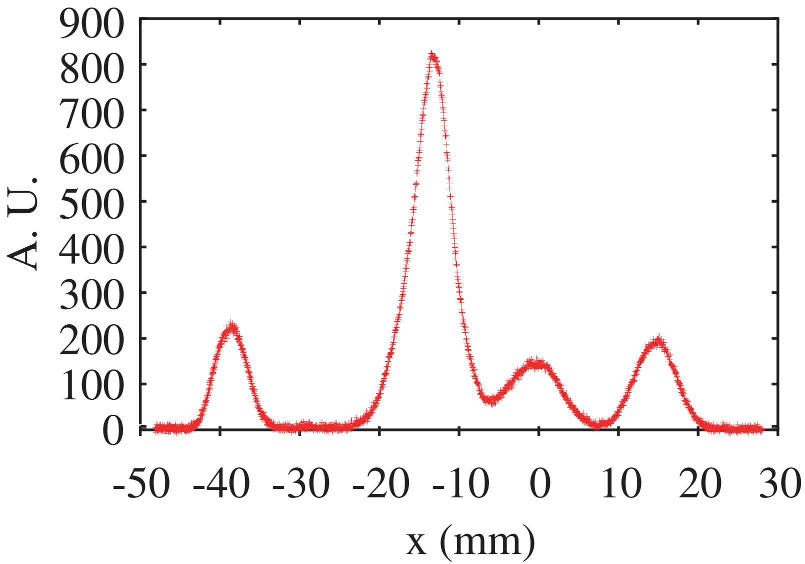


- **Proton beams**
  - Synchrotron radiation photons interact with the vacuum chamber and create photoelectrons that can be amplified under unfavorable conditions.
  - A charge cloud (“electron cloud”) forms, which influences the beam.
- **Electron beams**
  - In this case, ion clouds impair the beam stability.

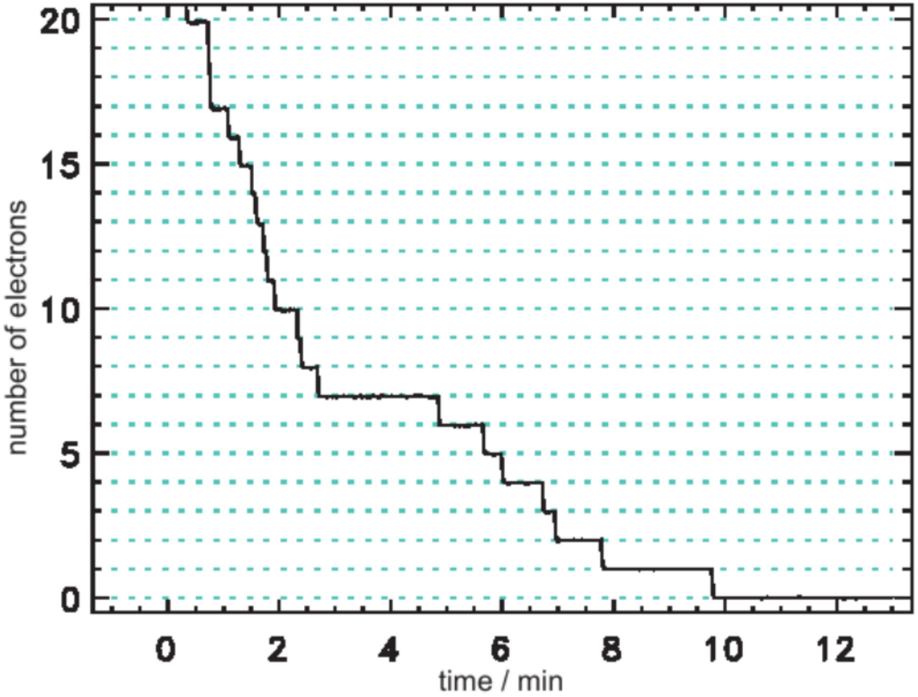
High intensity beams

- Extraction of high intensity beams using “resonant islands” in transverse phase space (Example: CERN PS)





Smallest intensities



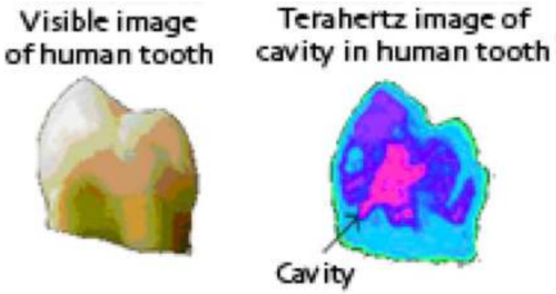
- Counting individual electrons by measuring the decay of the synchrotron radiation intensity with cooled photodiodes

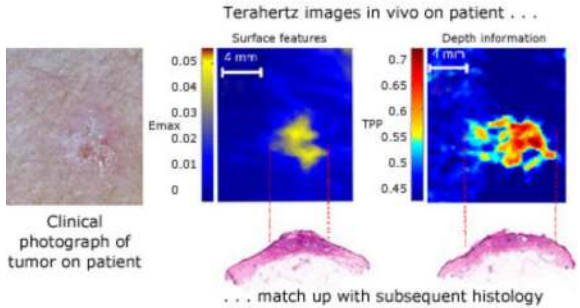
  (Example: MLS, R. Klein et al., EPAC08)

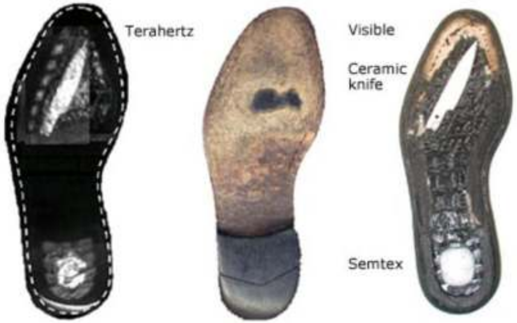
THz radiation

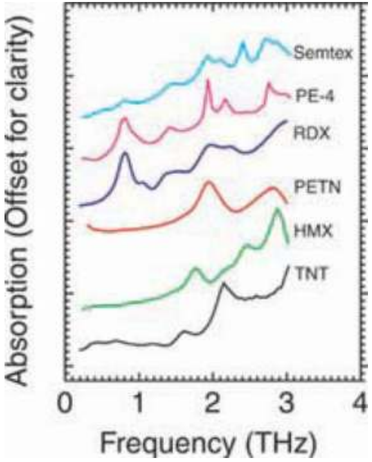
- Radiation in the THz gap is difficult to generate.
- Spectroscopic methods using THz radiation are extremely powerful.
- There is a great worldwide demand for THz radiation in physics, chemistry, biology, materials science and medicine.
- Allows to study and control systems with time constants of 1 ps.
- Has the same temperature as the background radiation.
- KARA can generate stable coherent THz radiation.

Examples from medicine and security technology









Britische Überwachungspläne

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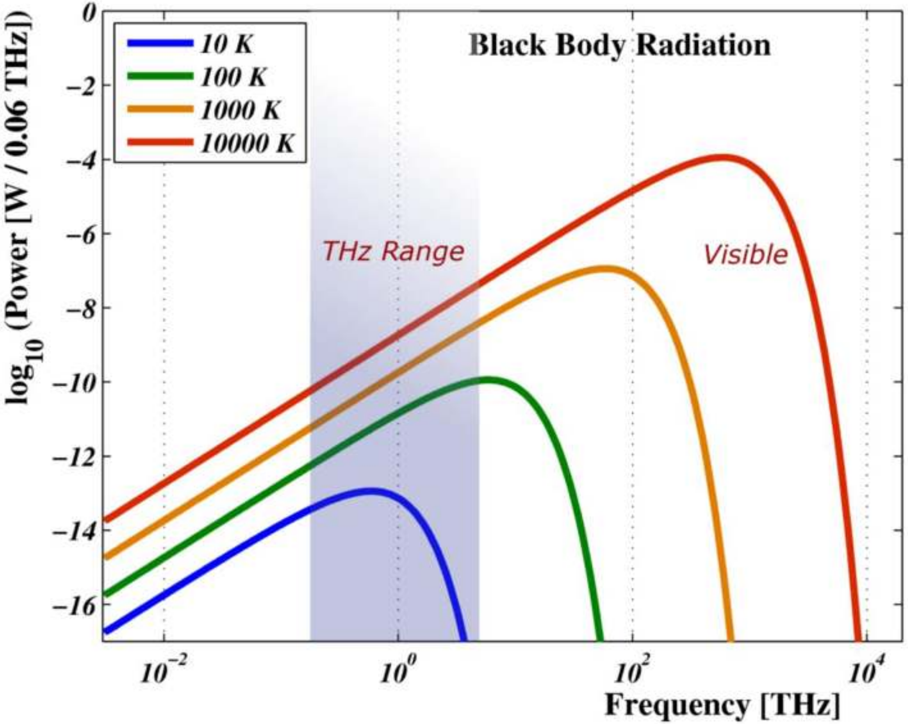
Großbritannien ist führend im Überwachen unbescholtener Bürger. Nach einem Bericht der "Sun" plant das Innenministerium nun einen weiteren Einschnitt: In Straßenlaternen sollen Durchleuchtungs-Kameras eingebaut werden, die Dank Spezialtechnik durch Kleidung sehen können.

29.01.2007, 13.47 Uhr

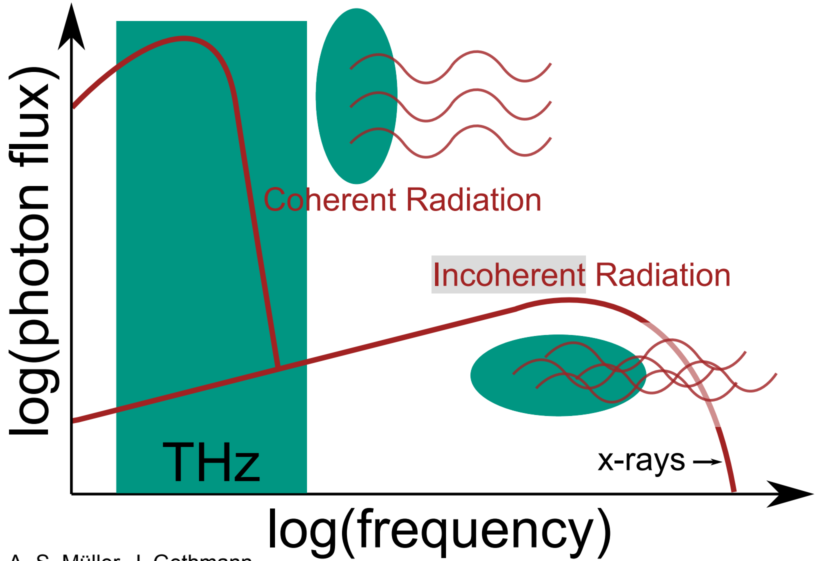
[…] “Die Entdeckung von Waffen und Sprengstoff wird einfacher", heißt es angeblich in einem internen Schreiben des britischen Innenministeriums vom 17. Januar. Und zwar mit Hilfe von Röntgenkameras. Die könnten, so die Autoren des Papiers laut "Sun", in "Straßenmobliar" eingebaut werden, also etwa in Straßenlaternen, Mülleimern oder Parkbänke. Möglich ist das zum Beispiel mit sogenannter Terahertz-Strahlung, die wie Mikrowellen Material wie Textilien oder bestimmte Kunststoffe durchdringen kann. Entsprechende Scanner stellt zum Beispiel das britische Sicherheitsunternehmen Qinetiq her. […]

Durchleuchtung mit Terahertz-Strahlung, Mann mit verstecktem Messer: "Entdeckung von Waffen und Sprengstoff wird einfacher" Foto: Qinetiq

Thermal radiation of an ideal black body



THz radiation in a storage ring

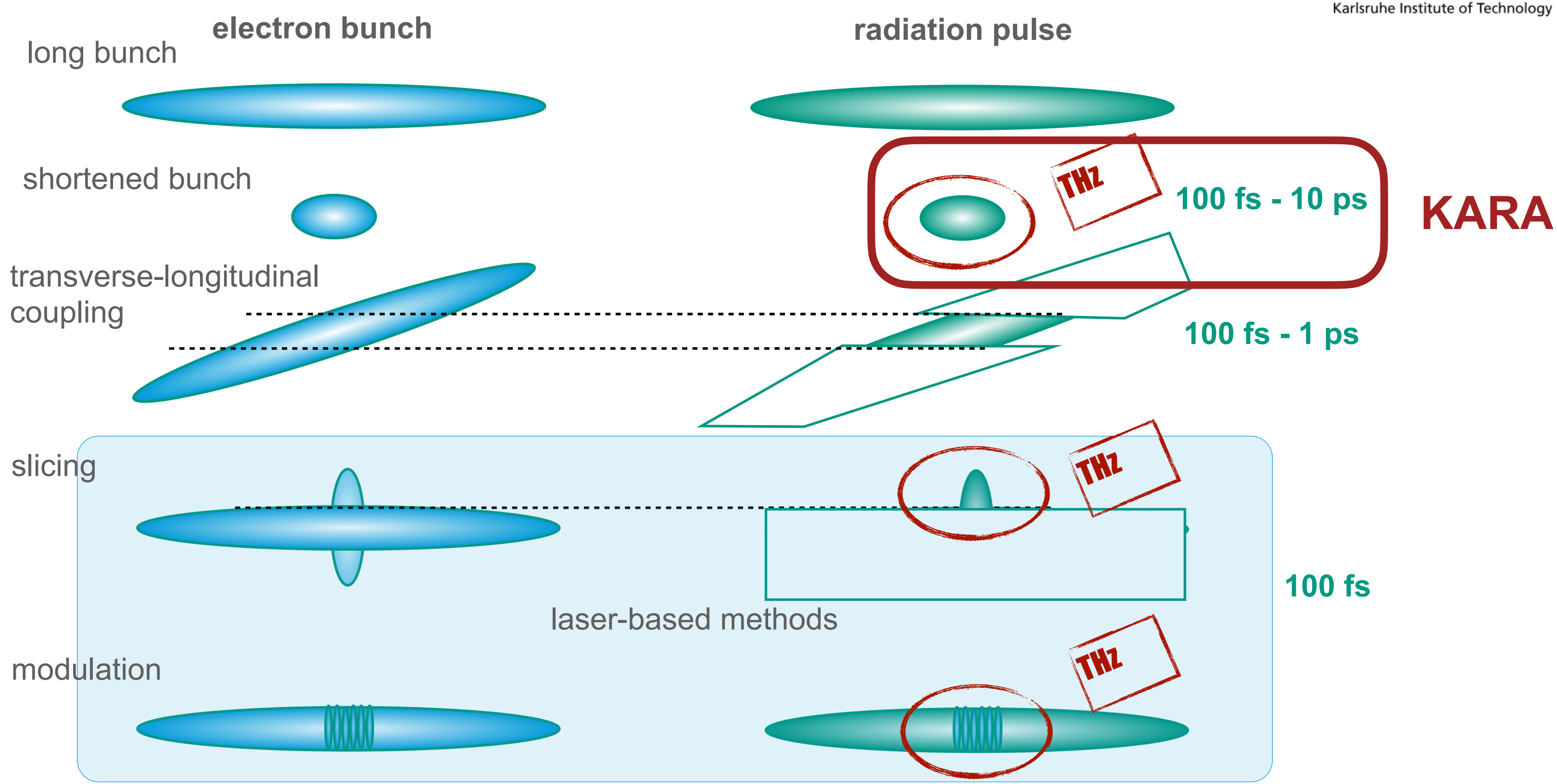


A.-S. Müller, J. Gethmann

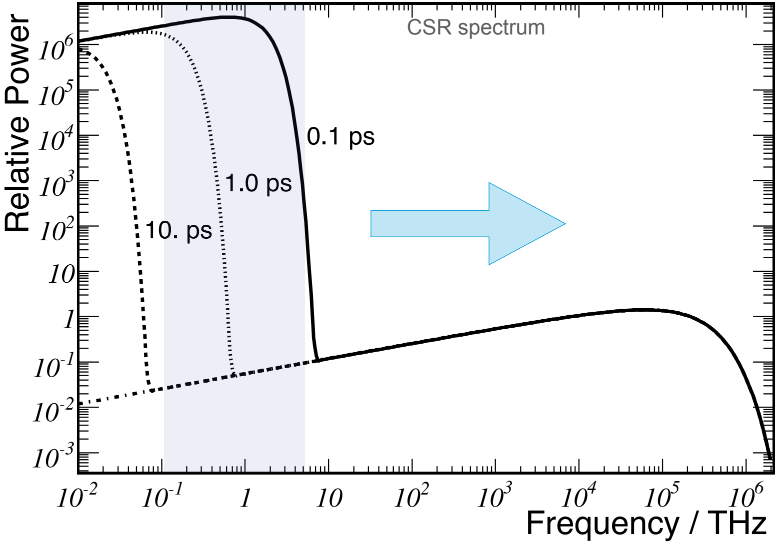
Short electron bunches emit coherent radiation

- Broadband emission
- Enormous increase of radiation in the THz range
- High brilliance

Short-pulse generation



Short bunch mode at KARA



- Bunch length: $50\,\mathrm{ps} \rightarrow 1 - 10\,\mathrm{ps}$

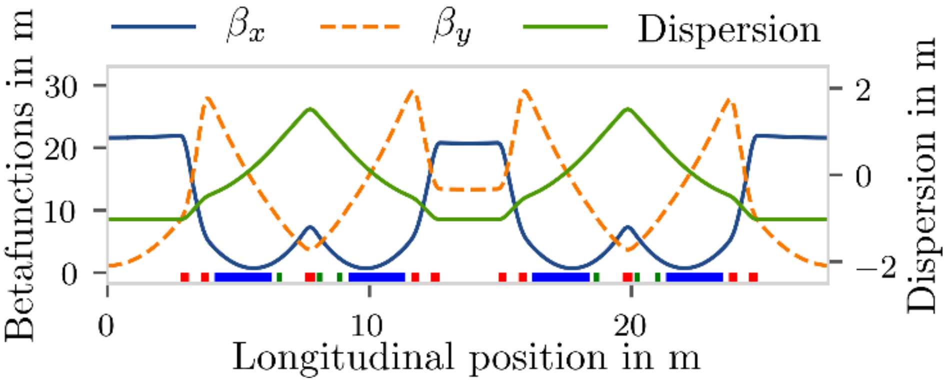
$$\sigma_s = \frac{\sqrt{2\pi}}{\omega_0}\sqrt{\frac{\alpha_c E}{heV_{RF}\cos\phi_s}}\left(\frac{\sigma_E}{E}\right)$$

- Reduce beam energy:

  $E = 2.5\,\mathrm{GeV} \rightarrow 1.3\,\mathrm{GeV}$

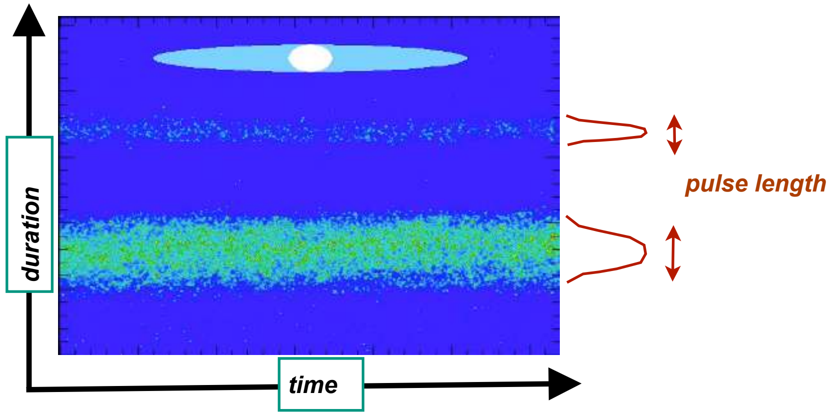
- Reduce momentum compaction factor:

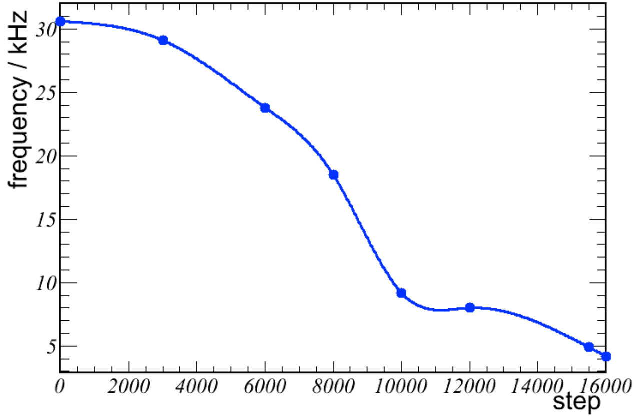
  $\alpha_c = 9 \times 10^{-3} \rightarrow 1 \times 10^{-4}$



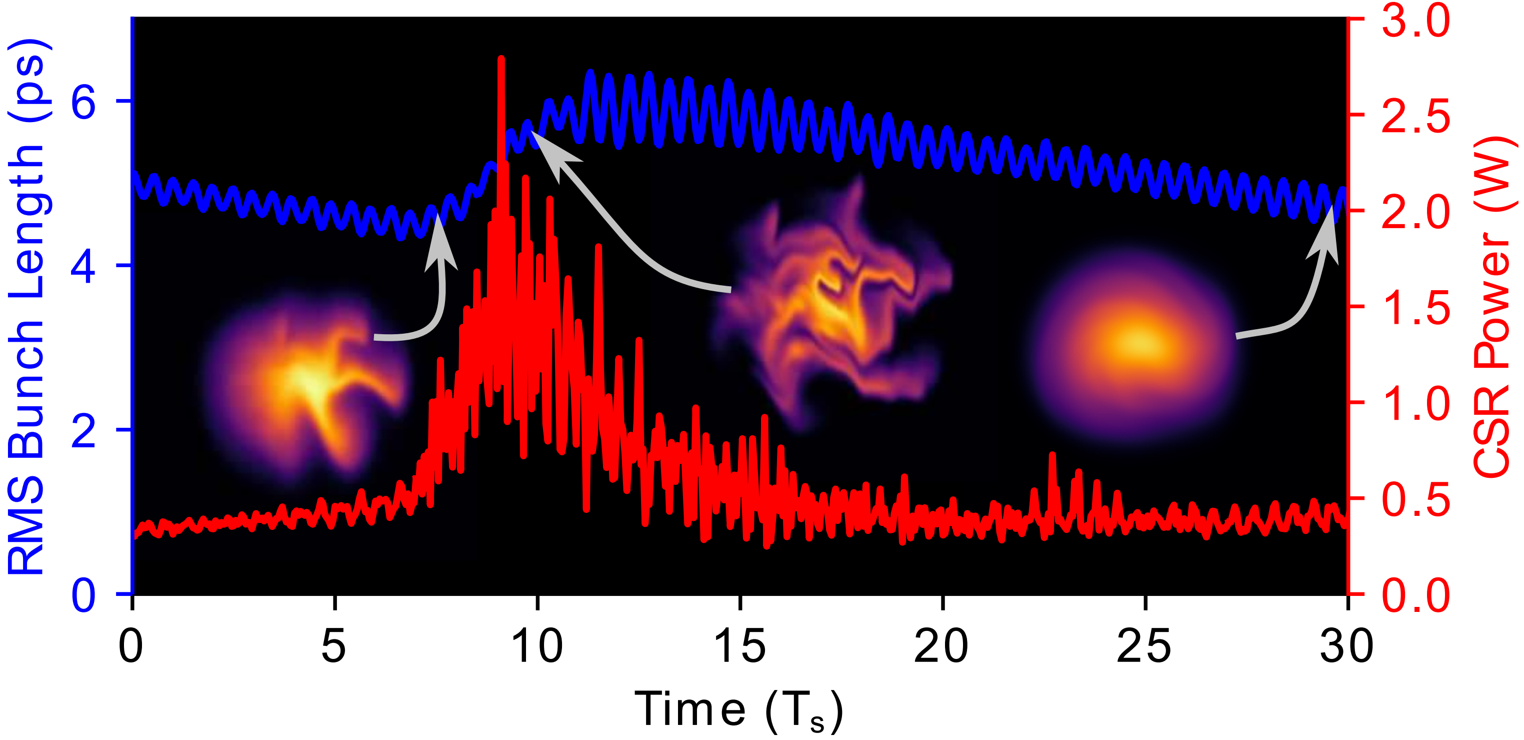
Short pulses in practice: at KARA

- (Incoherent) length of the visible light pulse measured with a streak camera (~1 ps)

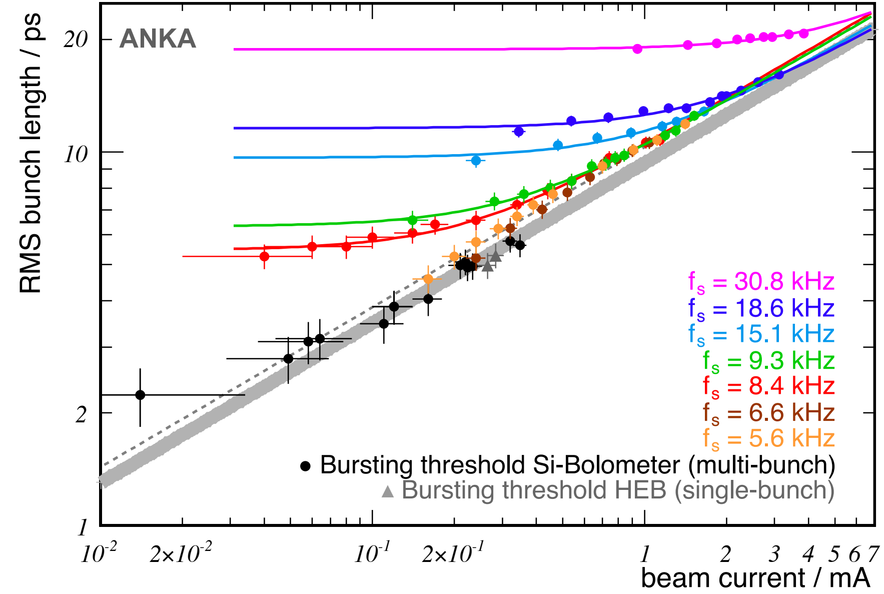




Strahlungsausbruch und long. Phasenraum

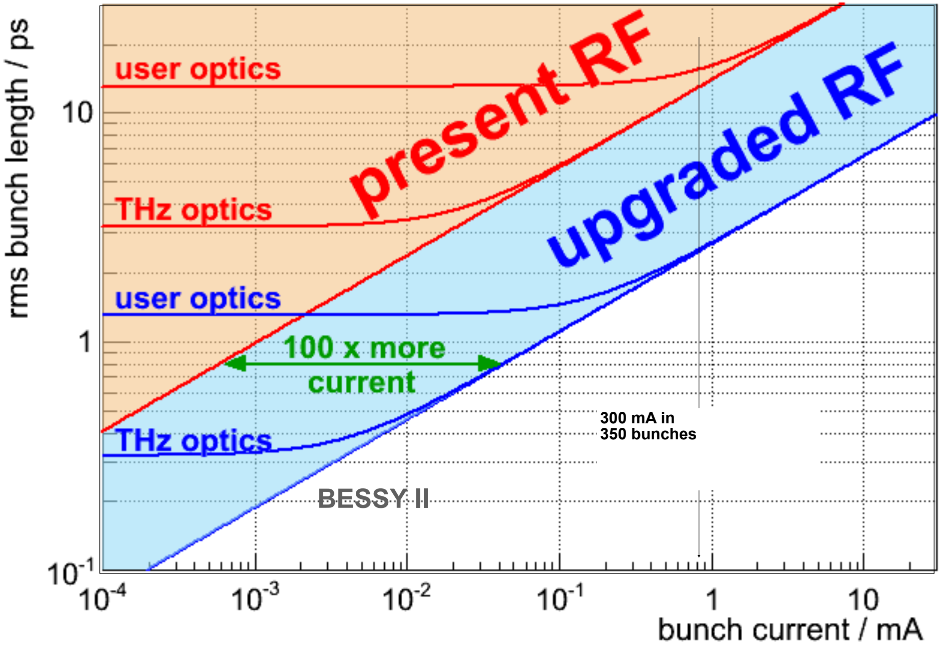


Bunch length, current and instabilities

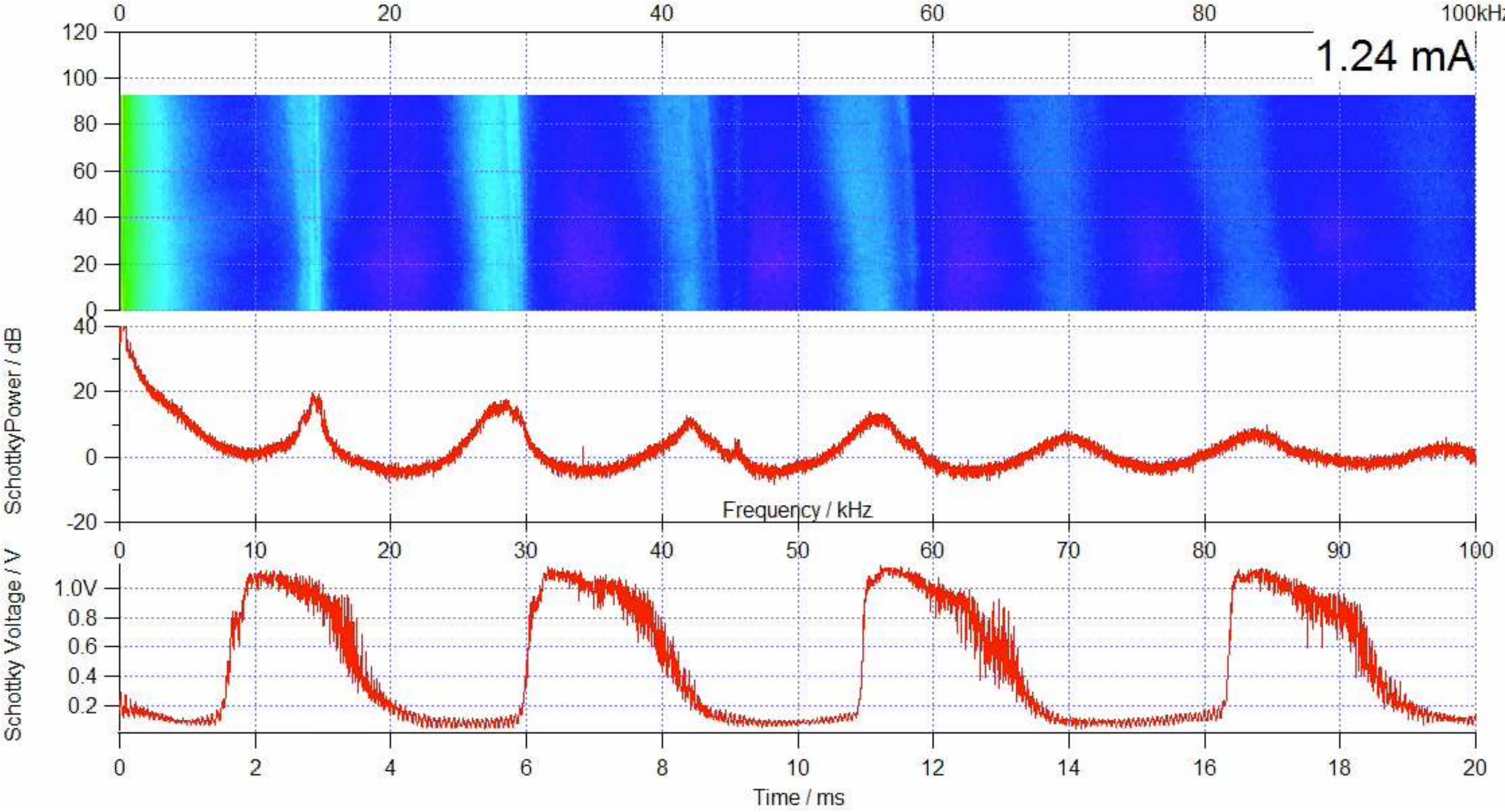


Beam Dynamics Newsletter 57 (2012) 154

G. Wüstefeld et al., IPAC2011, THPC014

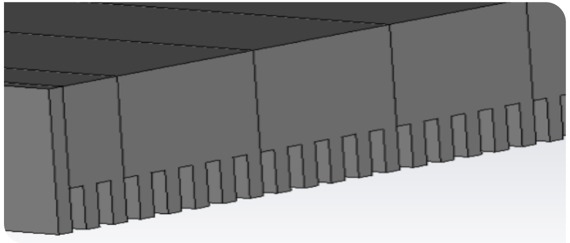


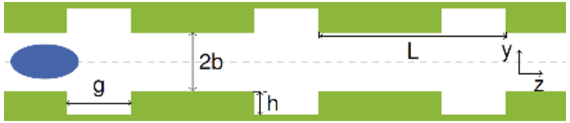
Current dependent radiations bursts

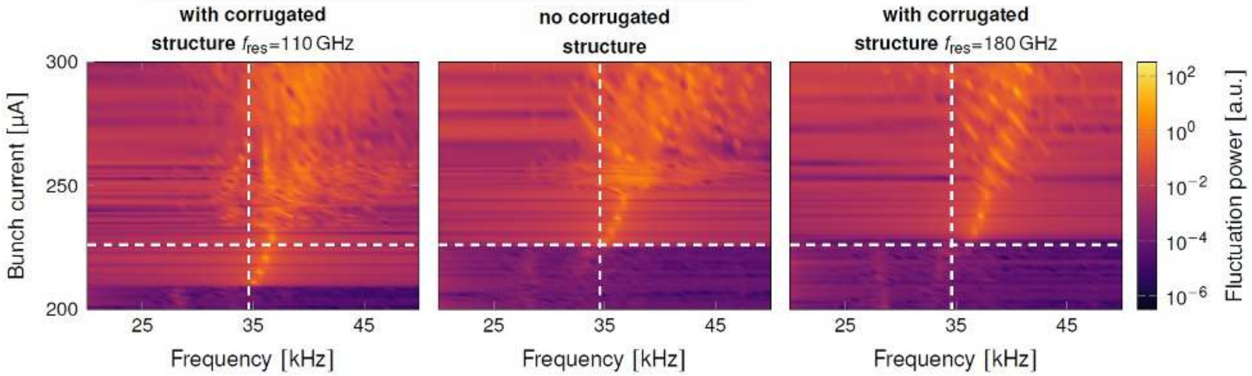


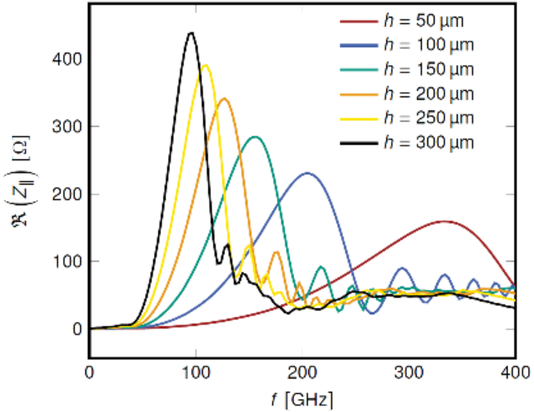
Impedance manipulation at KARA

- **Goal:** Observe, understand, and control the microbunching instability
- **Corrugated plates** will be installed at KARA
- Affecting threshold current and/or bursting frequency with additional impedance



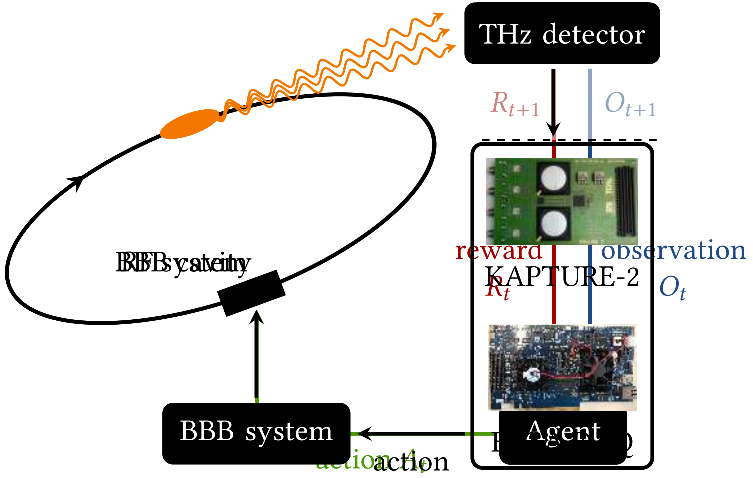






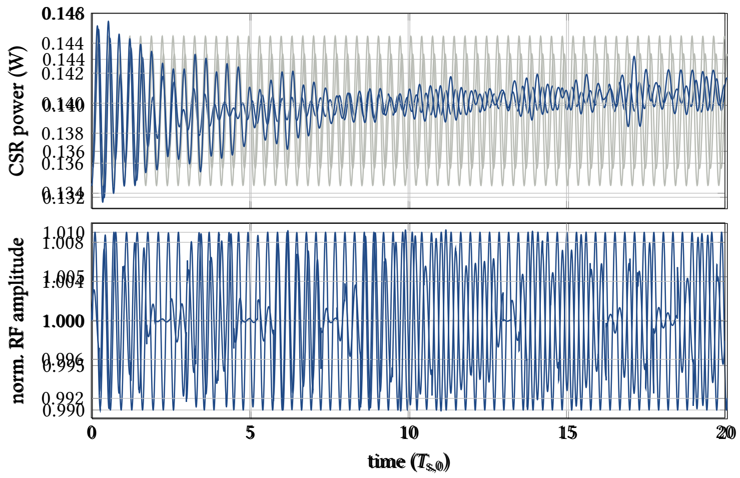
Microbunching instability: Feedback system

Dissertation T. Boltz



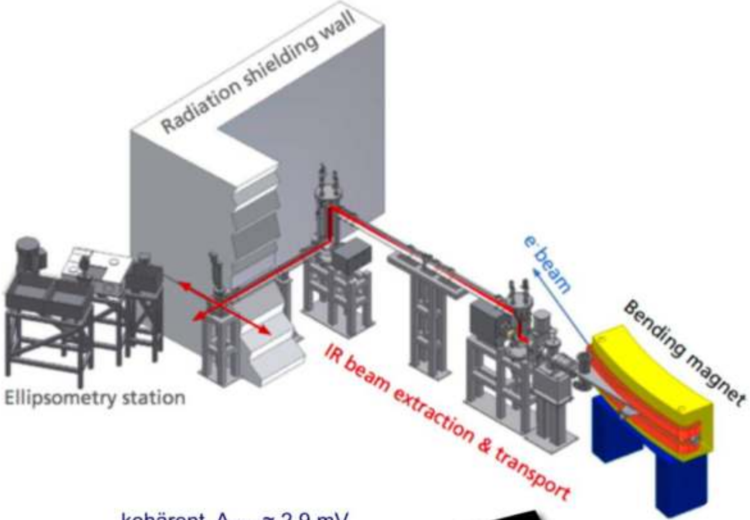
- Use RF modulation to mitigate CSR power fluctuations

- Feedback design based on reinforcement learning
- Simulation results are promising, hardware in commissioning

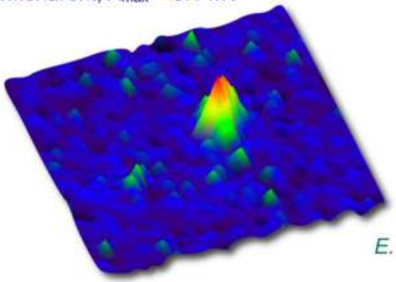


THz-radiation at KARA

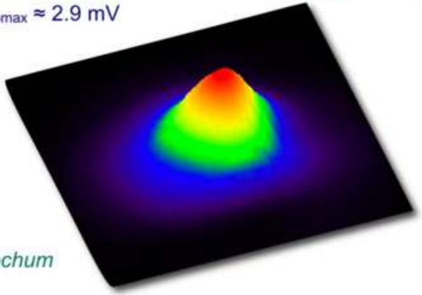
Karlsruhe Institute of Technology



inkohärent, $A_{max} \approx 0.1$ mV



kohärent, $A_{max} \approx 2.9$ mV



E. Bründermann, U Bochum

THz detectors: Some examples

Quasi-optical broadband detector

room temperature

response time <200ps

50 GHz up to 1 THz

based on schottky diode

ACST (acst.de)

Hot Electron Bolometer (NbN)

cryogenic (LHe)

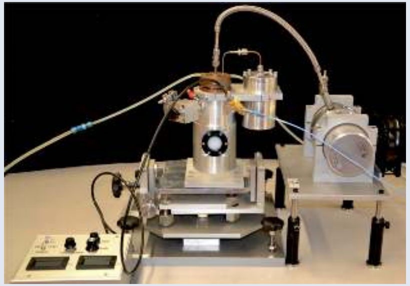
response time <165ps

200 GHz up to 4 THz

high sensitivity

M. Brosi

YBCO detector



cryogenic (LN2)

response time <15ps

30 GHz up to 2.5 THz

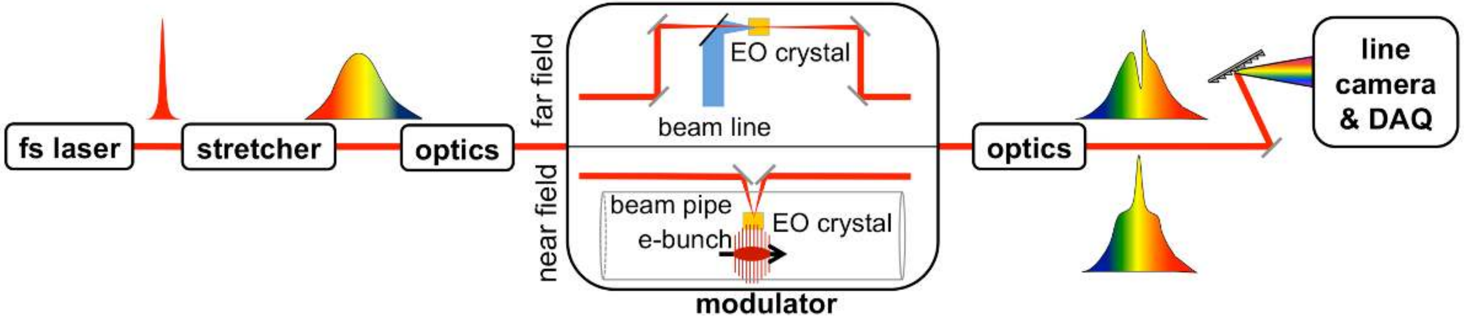
(KIT - IMS)

J. Raasch [1]

- Resolve intensity of each bunch (minimal bunch spacing 2 ns)

[1] Thoma, P.; Raasch, J.; et al.; IEEE Trans. Appl. Supercond., vol.23, no.3, pp.2400206,2400206, June 2013

Electro-optical diagnostics



Near-field

- EO crystal in the beam pipe picks up the electric field of the bunch and modulates a laser pulse
- Resolving electron bunch profile in every turn @ 2.7 MHz
- Capable of uninterrupted data acquisition for up to several millions of turns

Far-field

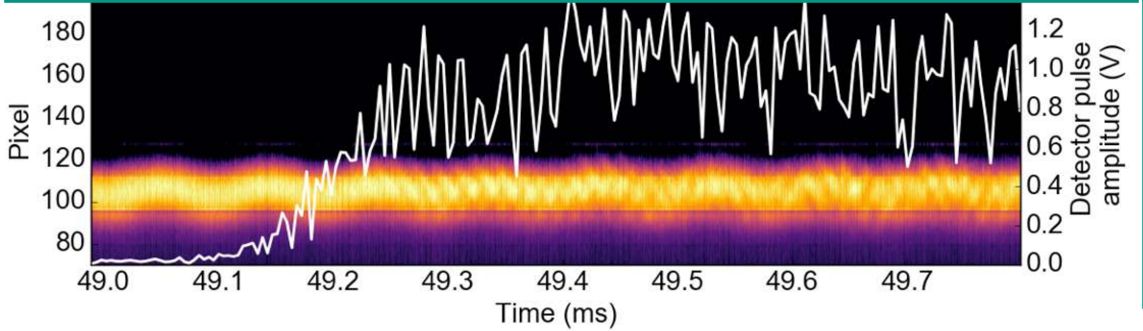
- EO crystal is placed in a beamline
- The electric field of a synchrotron radiation pulse is used to modulate the laser pulse
- No impedance effects
- Experiment under commission
- Aiming to measure the complete THz pulse in single-shot

Beam diagnostics at KIT

- Complete chain established at KIT:
  physics ➜ detectors ➜ DAQ ➜ data analysis/modelling ➜ physics
- First & only near-field electro-optical setup in a storage ring
- Our systems are in use at many other facilities and laboratories (European XFEL, FLASH, TELBE, DELTA, SOLEIL, ...)

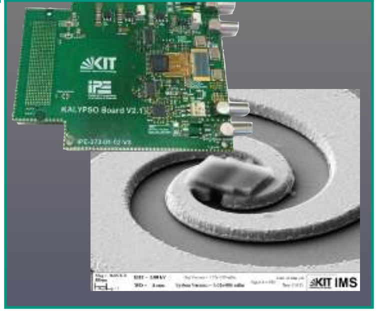
Electro-optical crystal

Microstructures: continuous bunch profiles and THz signal KAPTURE & KALYPSO



N. Hiller, et al., IBIC'2014, MOPD17 (2014)
P. Thoma et al., Applied Physics Letters 101 (2012)

DAQ & THz sensor

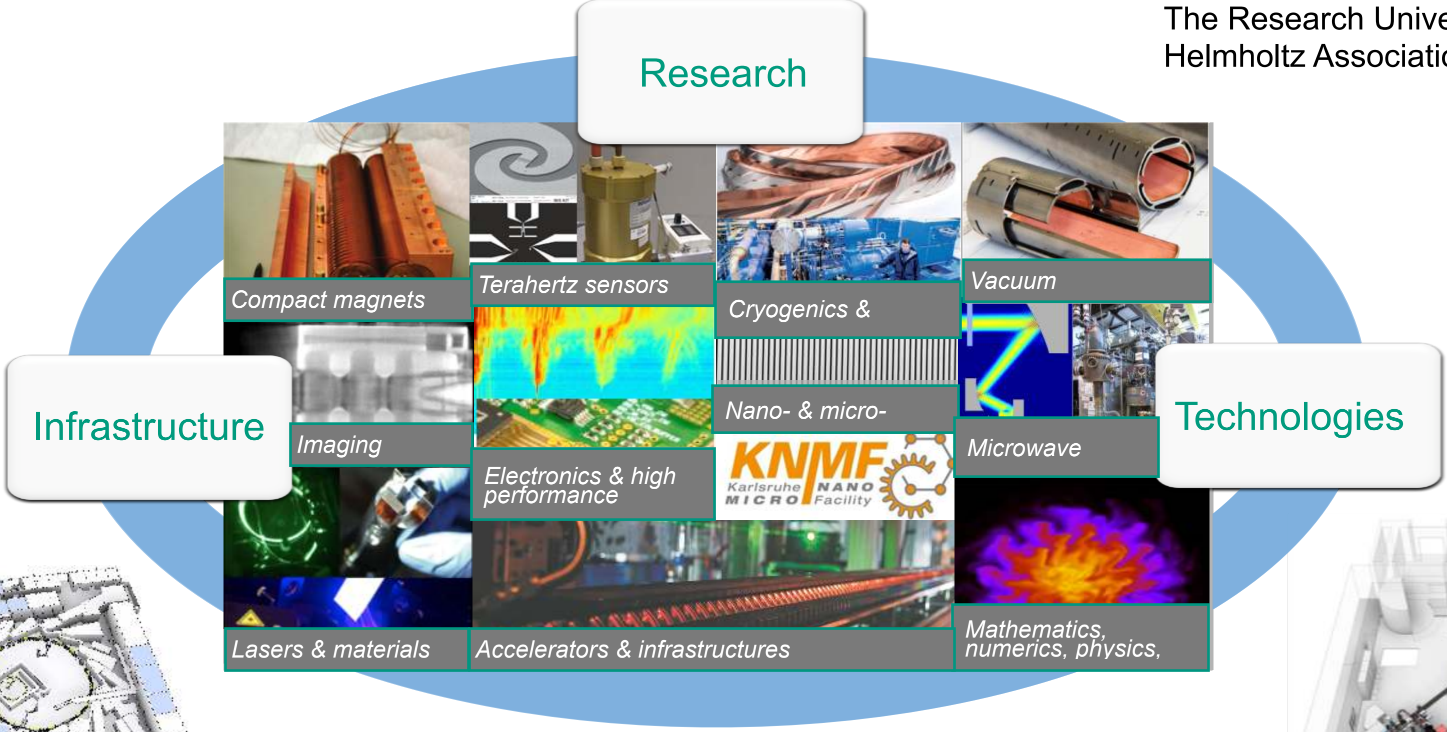


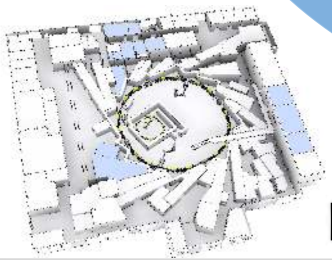
M. Caselle et al., JINST 12, C01040 (2017)
L. Rota et al., TWEPP-2017 (2017)

MT **Matter and Technologies**

KIT Accelerator Technology Platform

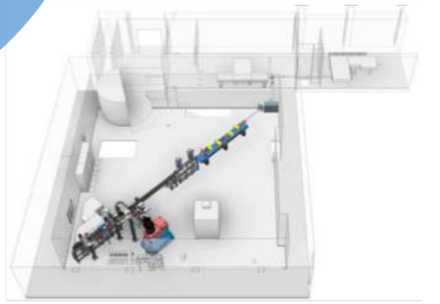
The Research University in the Helmholtz Association





KARA

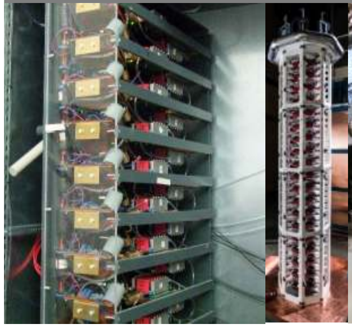
FLUTE



Karlsruhe Institute of Technology

Test facilities & technologies - examples

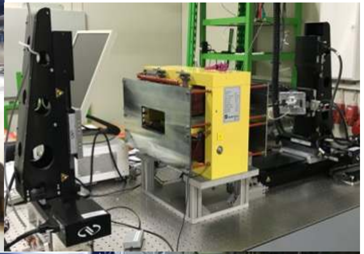
Pulse power technology   *Gyrotrons*

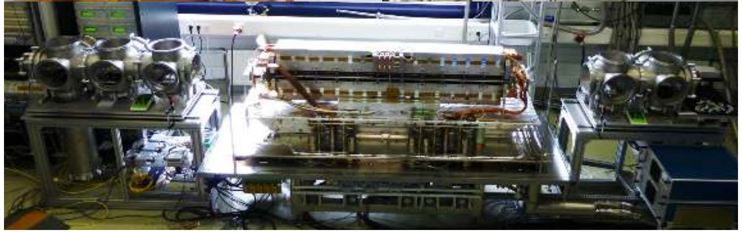


Winding technologies

Magnet test facilities

Accelerator Technology Platform @ KIT

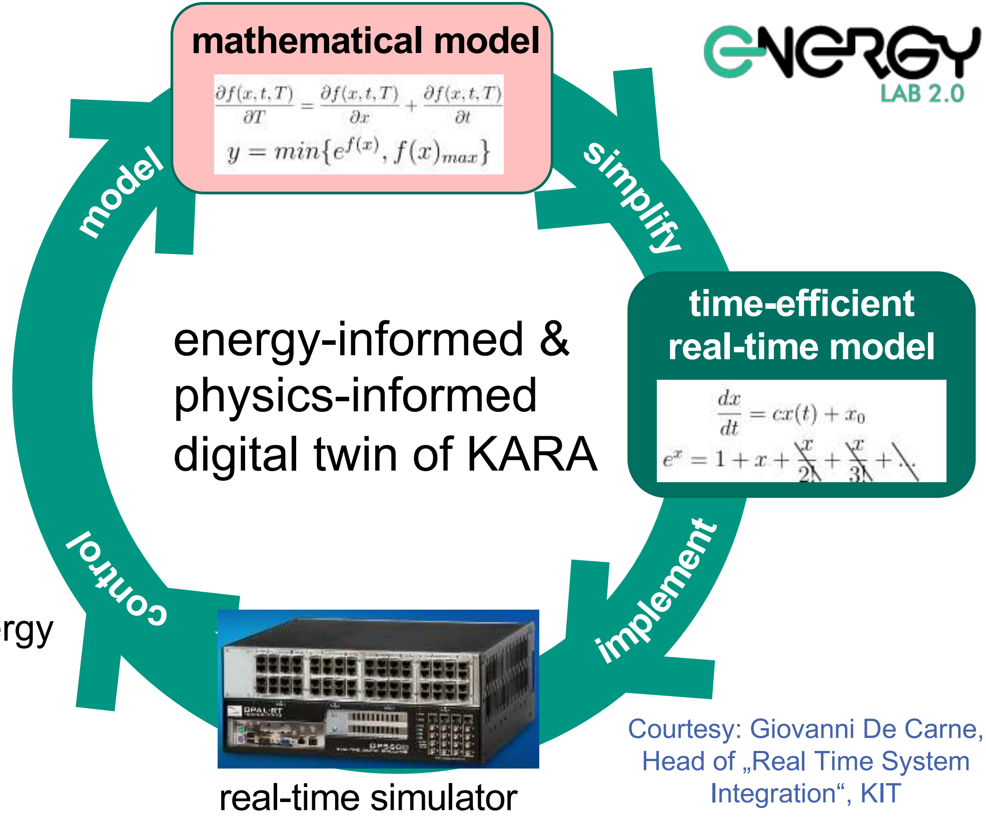




Cable technologies   *High temperature superconductors*

Accelerator & energy systems
Test field KITTEN

- Digital twin of KARA
  - Analyzing, developing and testing future energy solutions for research infrastructures
- InnovEEA
  - Load management (grid stability)



Courtesy: Giovanni De Carne, Head of „Real Time System Integration“, KIT