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Longitudinal Beam Dynamics at cSTART

Markus Schwarz

ARD-ST3 Workshop, 21/09/30

Outline

- Basics of longitudinal beam dynamics
- cSTART

Acknowledgements

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STalks at ARD-ST3 meeting

E.O.M.: Arrival Time

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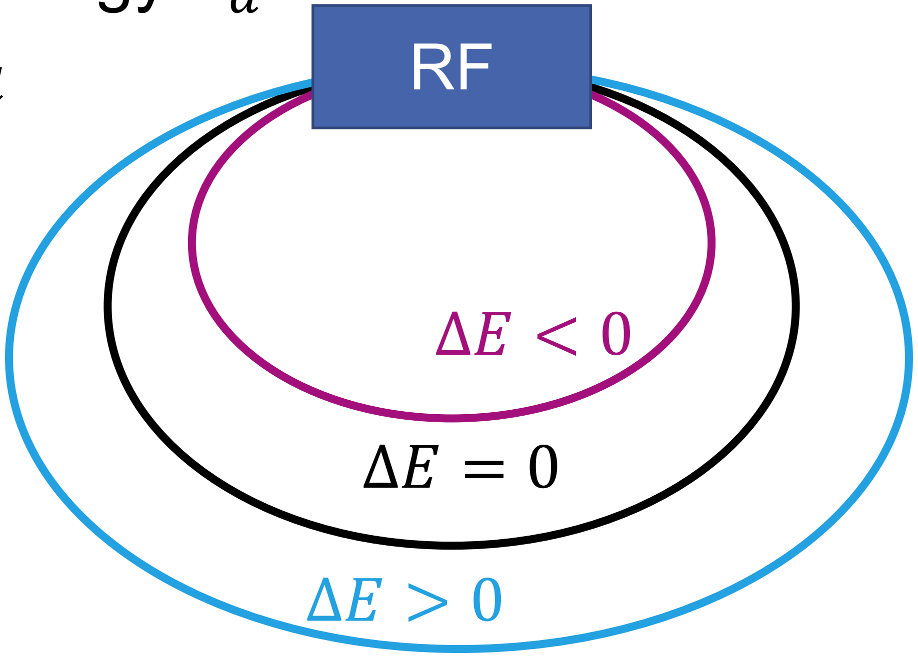
- Reference particle at design parameters, e.g. energy E_d
- **Arrival time** w.r.t. reference particle $\Delta t = t - T_d$
- **Energy** w.r.t. reference particle $\Delta E = E - E_d$
- Momentum compaction factor $\alpha = \frac{\Delta C}{C_d}\frac{p_d}{\Delta p}$
- Phase slip factor $\eta = \frac{p_d}{T_d}\frac{\Delta T}{\Delta p}$, $\eta_0 = \alpha_0 - {}^1/_{\gamma_d^2}$

α<0: STalk P. Schreiber

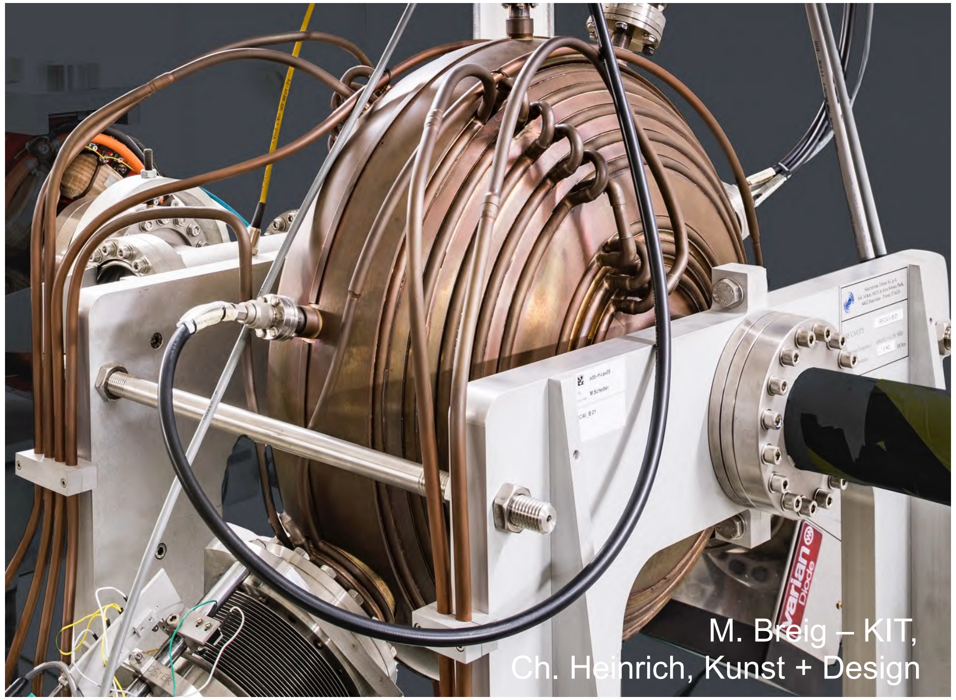


- $$\dot{\Delta t} = \frac{1}{1-\eta(\Delta E)} - 1 \simeq \frac{\eta_0}{\beta^2 E_d}\Delta E + \frac{\eta_0^2+\eta_1}{(\beta^2 E_d)^2}\Delta E^2 + \frac{\eta_0^3+2\eta_0\eta_1+\eta_2}{(\beta^2 E_d)^3}\Delta E^3$$

E.O.M.: Energy

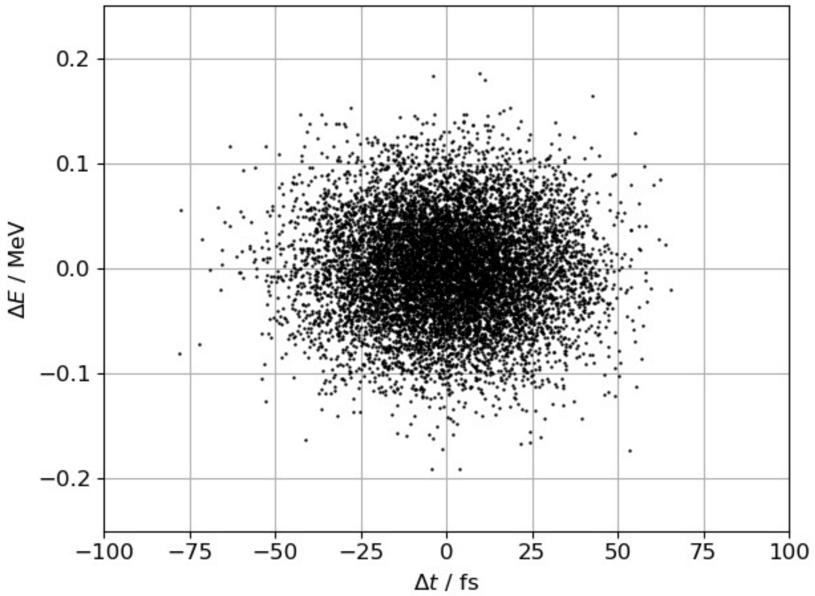
- Particle gains or looses energy due to
  - Electric fields in RF cavity $V_{RF}(\Delta t) = V \sin(\omega_{RF} \Delta t + \phi_{RF})$
  - Synchrotron radiation
  - Interaction with surroundings and other particles

$$\dot{\Delta E} = \frac{q}{T_d}\left[V_{RF}(\Delta t) + V_{ind}(\Delta t)\right] - \frac{U_0}{T_d}$$

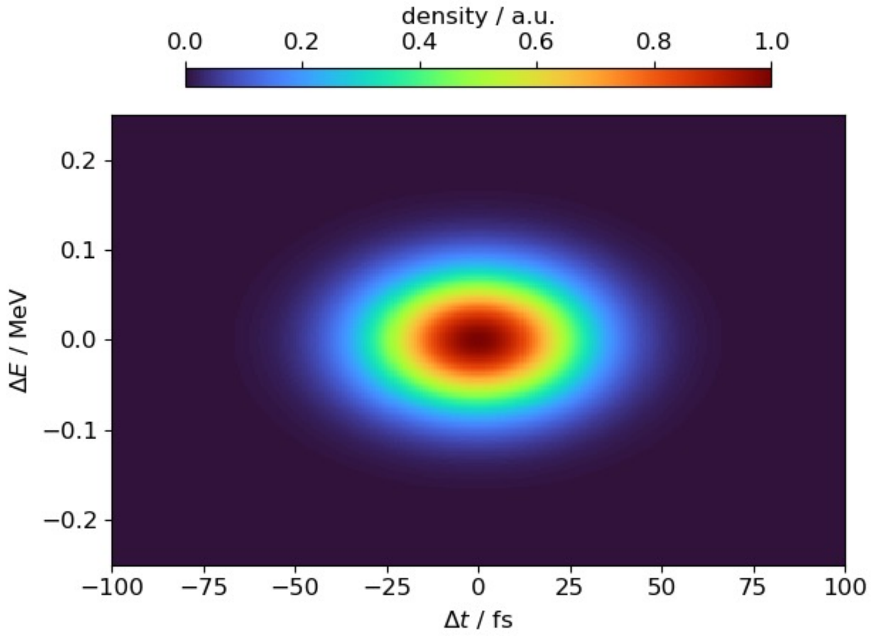

M. Breig – KIT,
Ch. Heinrich, Kunst + Design

Simulation Techniques

- Macro-particle tracking
  - ”easy to learn, difficult to master”
  - Can require many macro-particles
  - e.g. BLonD



- Vlasov-Fokker-Planck equation
  - Non-trivial to implement
  - Can be faster than MP tracking
  - e.g. Inovesa [P. Schönfeldt et al., PRAB **20**, 030704 (2017)]



RF-bucket

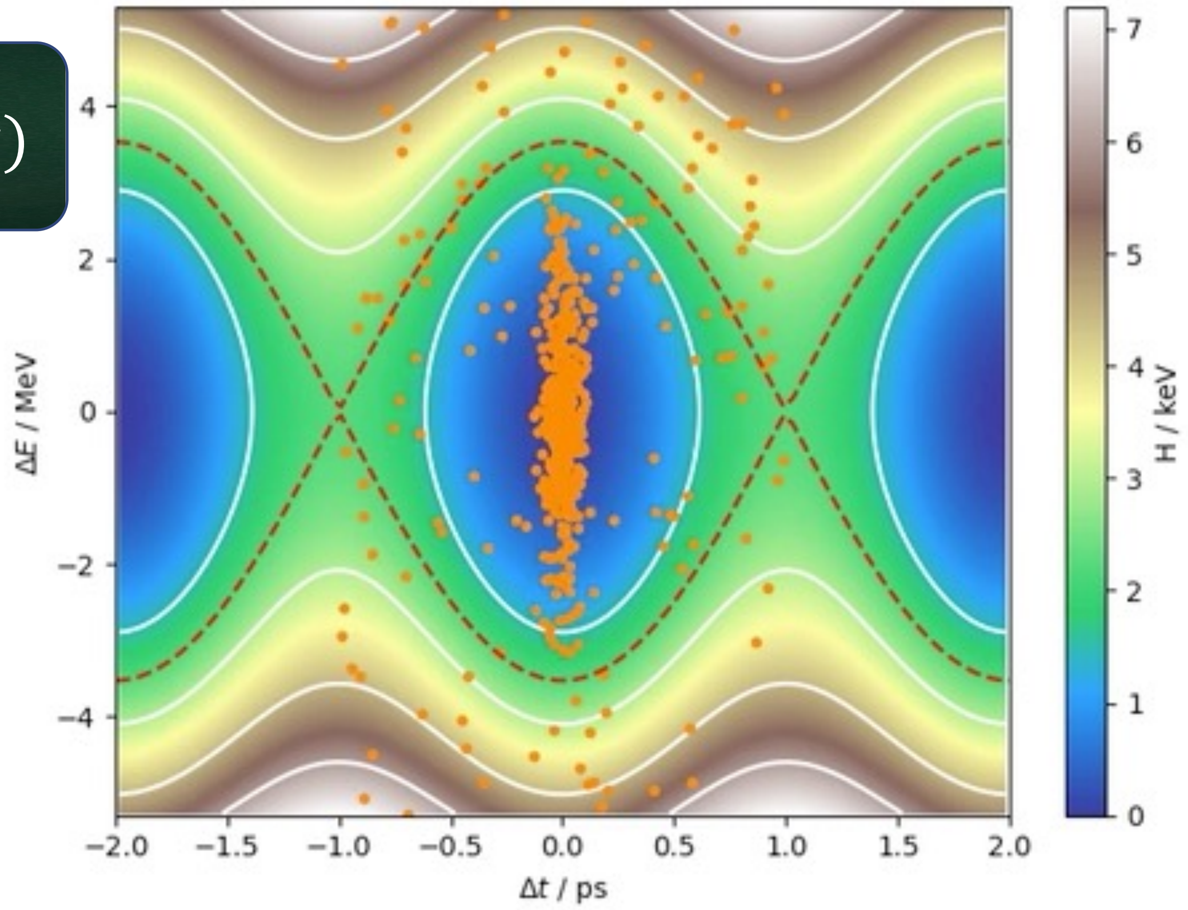
- Hamiltonian

$$H(\Delta t, \Delta E) \simeq \frac{\eta_0}{2\beta^2 E_d} \Delta E^2 + \frac{qV}{2\pi h} \cos(\omega_{rf} \Delta t)$$

- Bound motion around stable fix points
  ⇒ RF-bucket
- Synchrotron frequency

$$\omega_{s0} = \sqrt{\frac{-2\pi h \, qV \, \eta_d \cos\phi_s}{T_d^2 \, \beta^2 E_d}}$$

- Separatrix bounds stable region



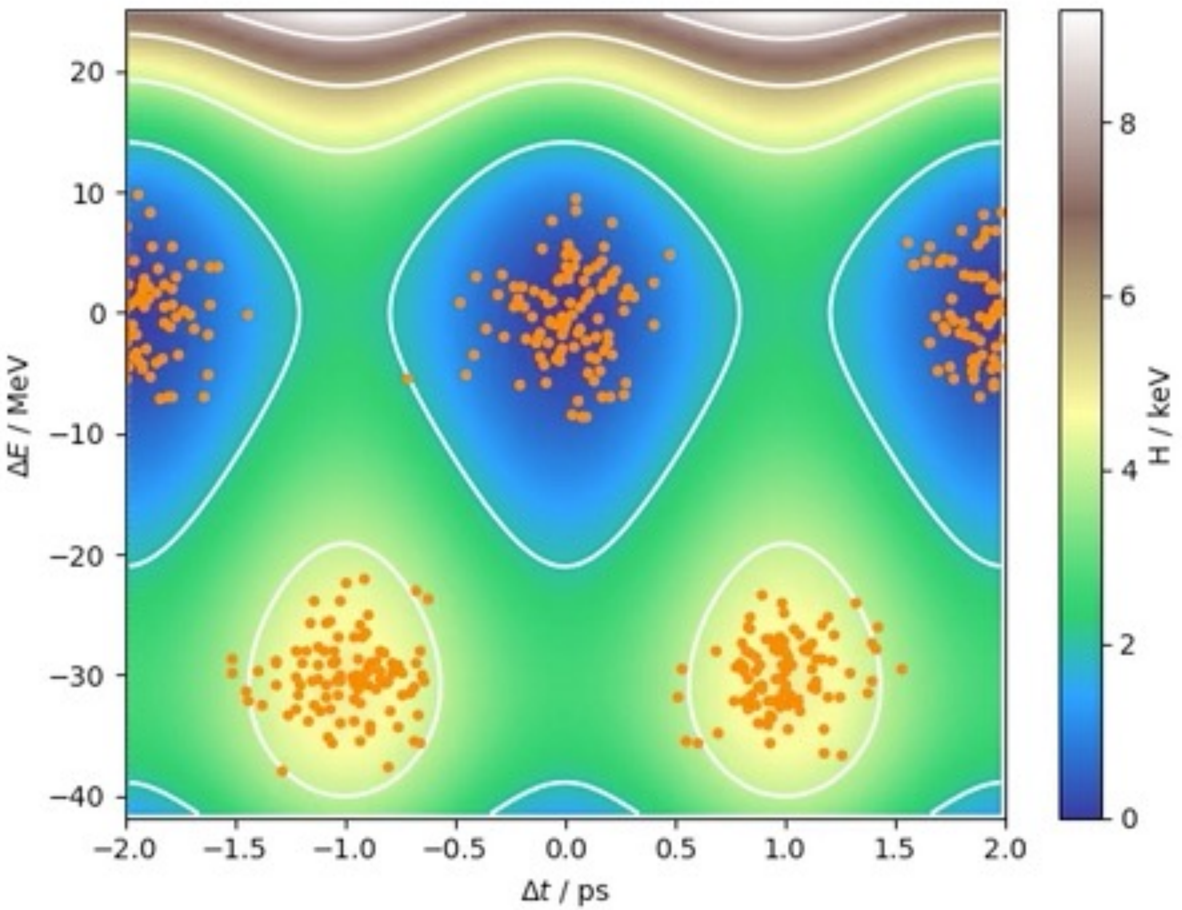
α-Bucket

- Higher-orders of α
- Stable regions also for $\Delta E \neq 0$
- Relevant when $\eta_0 \simeq 0$

[M. Ries et al., IPAC'11, TUOAB02]

[M. Attal et al., PRAB 16, 054001 (2013)]

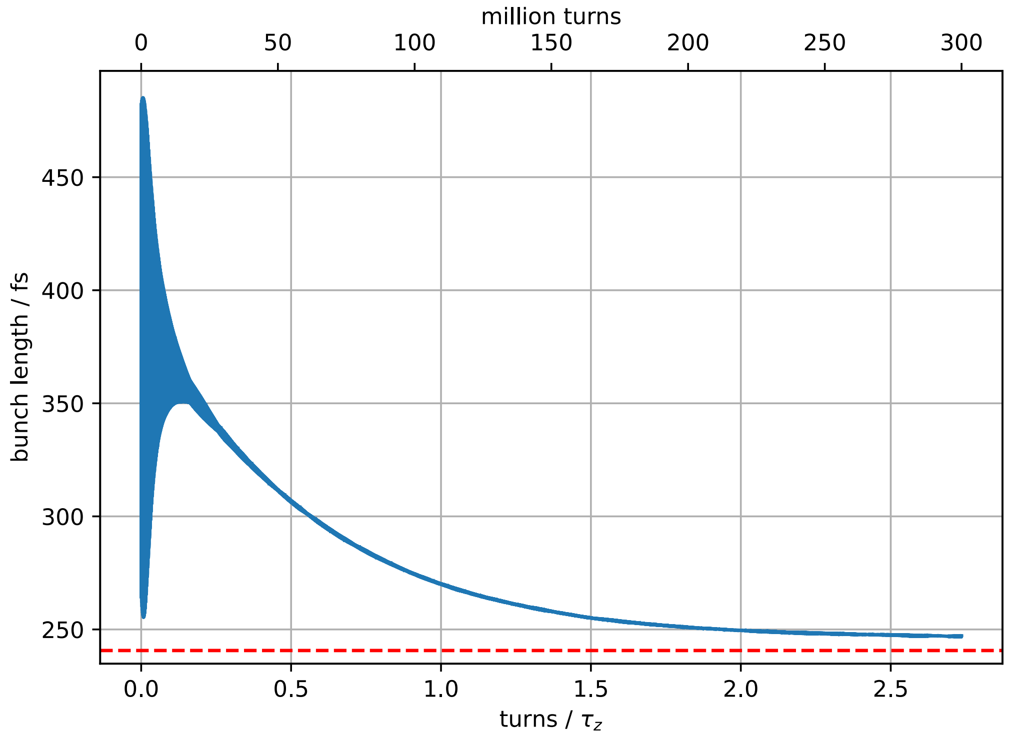
[A. Papash et al., Adv Theo Comp Phy 4, pp. 148 (2021)]



(incoherent) Synchrotron Radiation

- Energy loss $U_0 \propto q^2\gamma^4/r_{bend}$
- Radiation damping vs quantum excitation
  $\Rightarrow$ equilibrium reach in $\tau \propto T_d E_d / U_0$

Machine	Energy	Particle	Energy loss	Damping time
LHC	7 TeV	Proton	7 keV	7 h
KARA	2.5 GeV	Electron	621 keV	1.5 ms
KARA	0.5 GeV	Electron	1 keV	183 ms
cSTART	50 MeV	Electron	0.4 eV	16 s



Wake Fields

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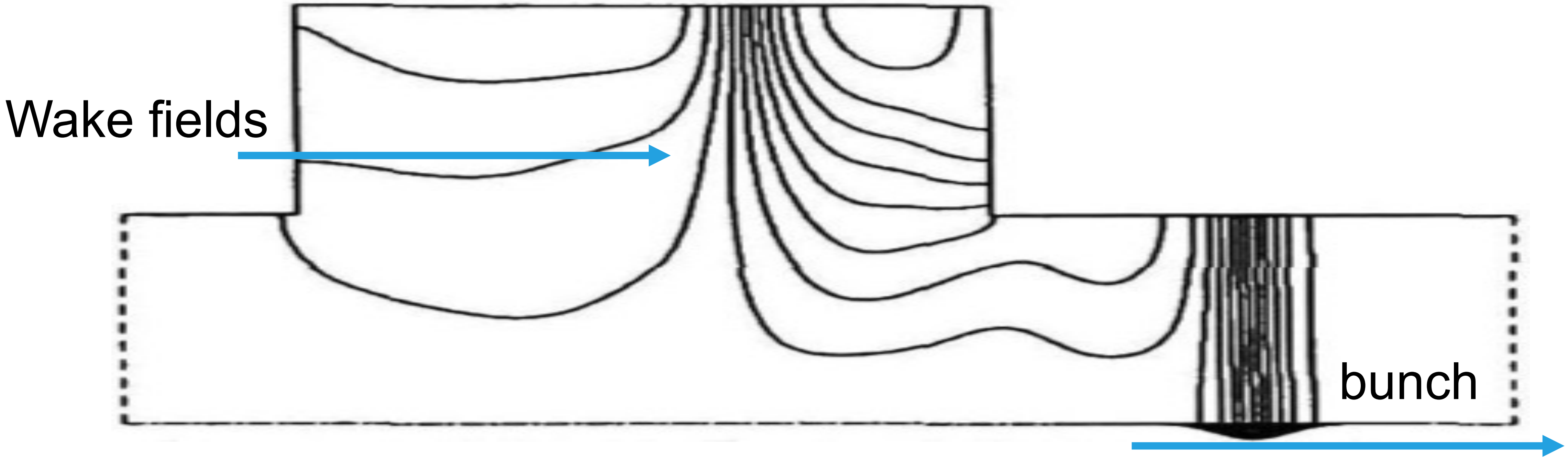
- EM fields created by changes in surroundings

Impedance chamber:
STalk S. Maier

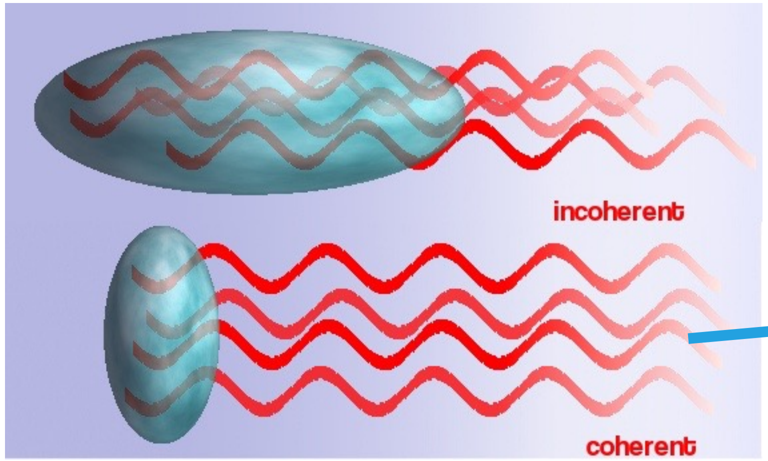


[Zotter, Khheifets, Impedances and Wakes, 1998]

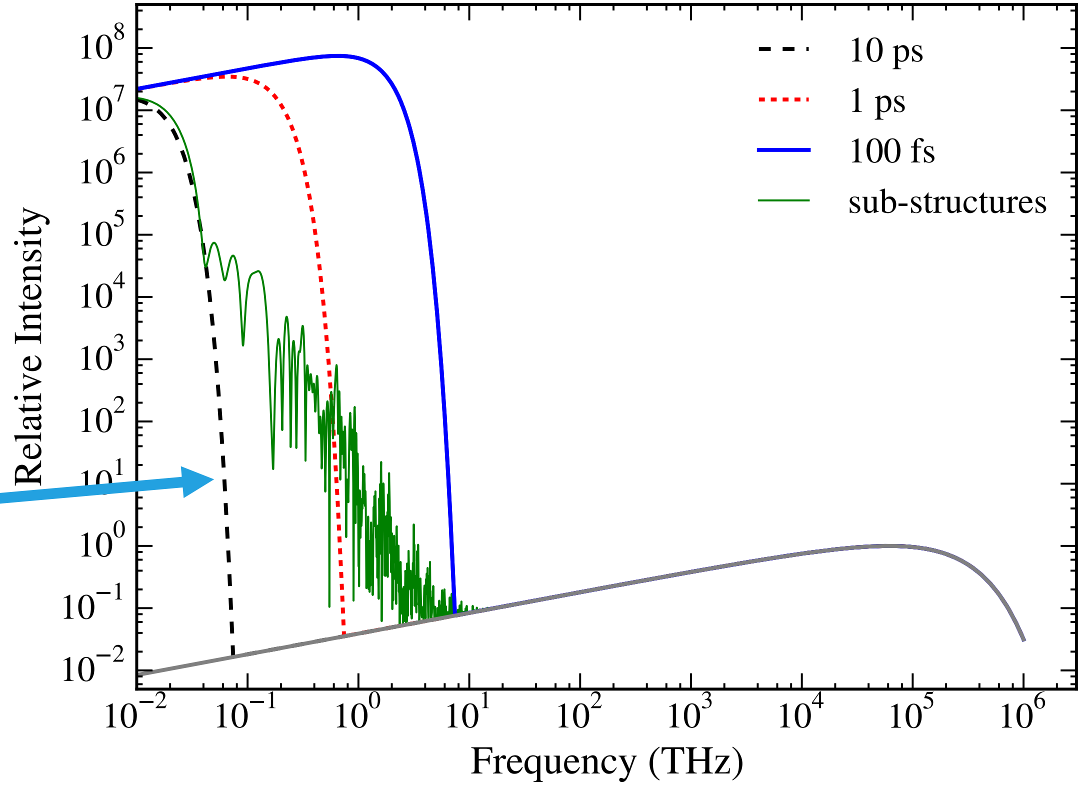
Coherent Synchrotron Radiation (CSR)

- Wavelength > emitting structure ⇒ intensity ∝ N^2

$$\frac{dI_N}{df} = \left[N + N^2|\Lambda(f)|^2\right]\frac{dI_1}{df}$$



[Courtesy A.-S. Müller]



[A.-S. Müller et al., Accl.-Based THz Radiation Sources in Springer 2021]

Instability: STalk M. Brosi

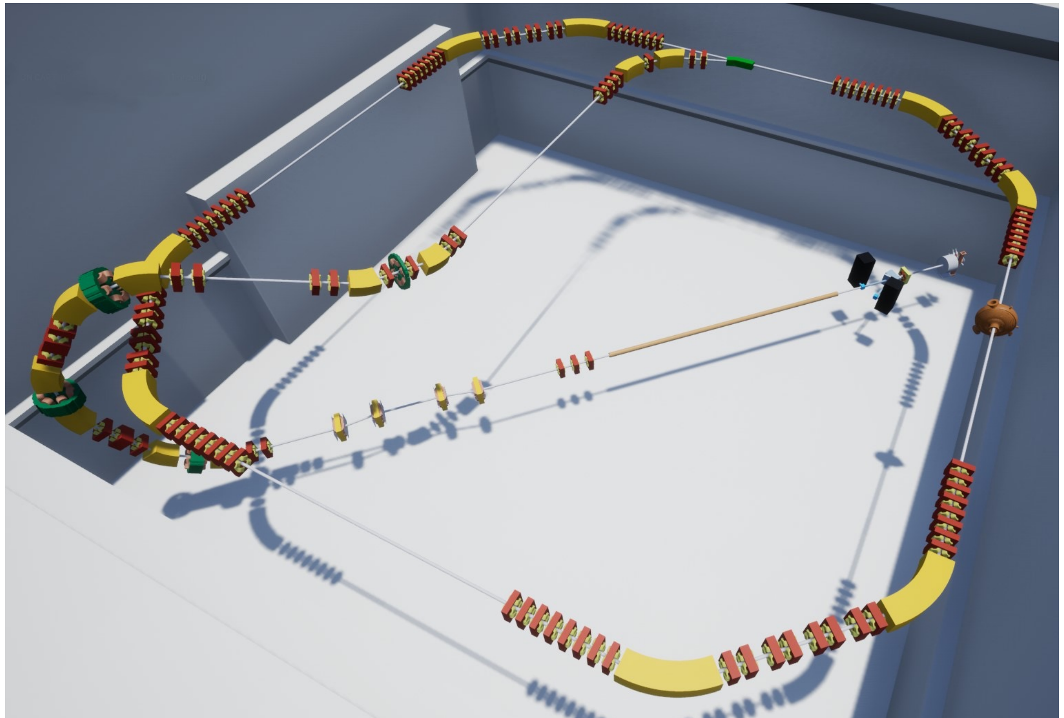
The cSTART Project

- Develop infrastructure and technology for a compact LWFA-based light source
- *V*ery-*L*arge *A*cceptance compact *S*torage *R*ing to inject and store sub-ps short electron bunches.

  [A. Papash et al., IPAC'21, MOPAB035]
- Two injectors
  - linac-based FLUTE
  - LWFA

    [S. Hillenbrand et al., NIM A **740**, 2014]

    [E. Panofski et al., IPAC'21, TUPAB163]


[Courtesy J. Schäfer]

Basic Parameters

Ring

Parameter	Value	Unit
Nominal energy	50	MeV
Injection rate	10	Hz
Revolution time	144	ns
Revolution frequency	6.9	MHz
α_0(nominal)	$1.8\text{x}10^{-2}$	1
SR damping time	16	s

Bunch

Parameter	Value	Unit
Bunch charge	1…1000	pC
Bunch length	3…300	µm
Bunch duration	10…1000	fs
Energy spread	$10^{-3}…10^{-2}$	1

Synchrotron Radiation

Parameter	Value	Unit
critical frequency	53	THz
Energy loss (incoherent)	0.4	eV
Energy loss (coherent, 1pC, 20 fs)	160	keV

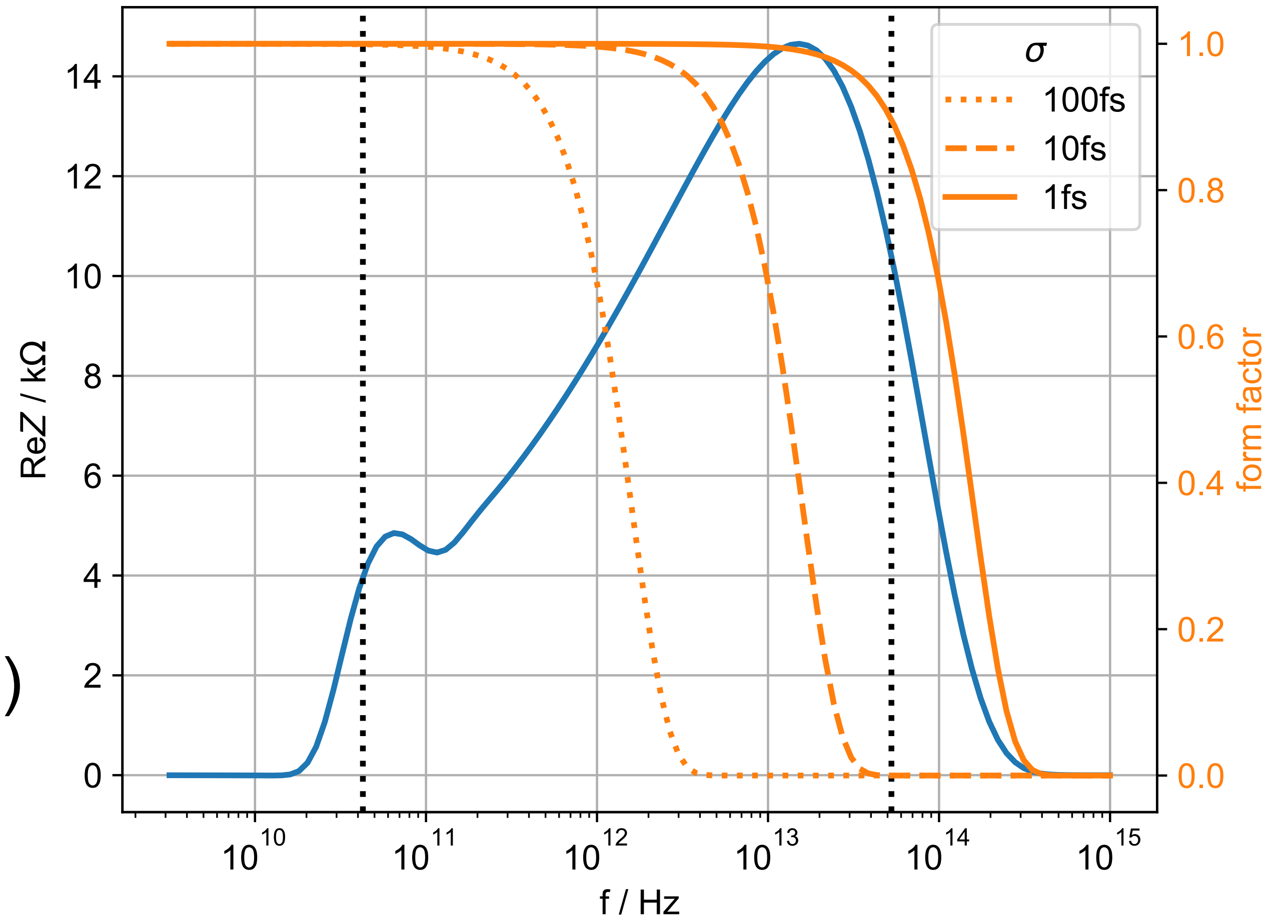
Diagnostics: STalk D. El Khechen

Synchrotron Radiation Properties

- Radiation spectrum ∝ $\Re Z$
- CSR intensity scales with overlap of $\Re Z$ and bunch form factor
- Average energy loss per electron

$$\bar{U} = 2e^2 N_e \int_0^\infty \Re Z(f) |\Lambda(f)|^2 df$$

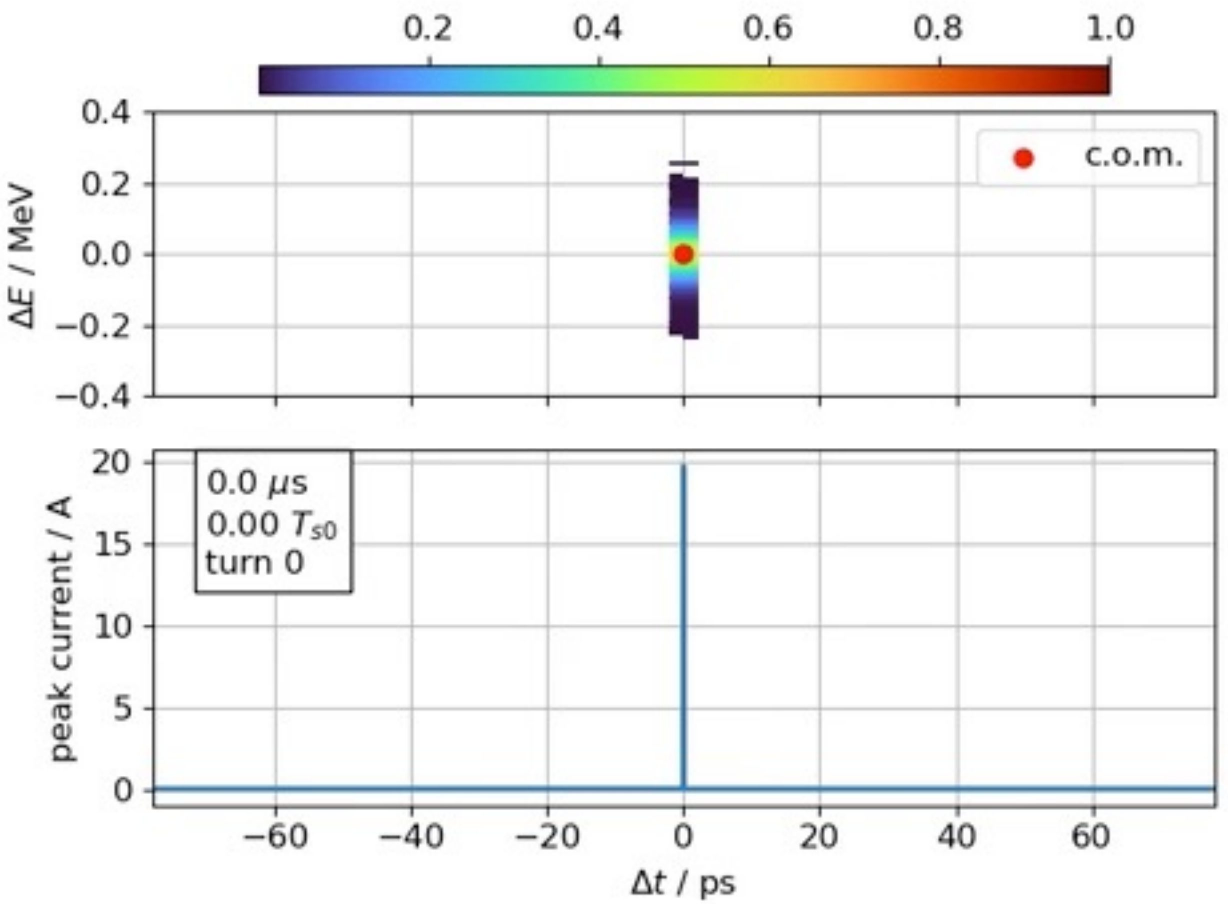
  - Coherent SR: 160 keV (1pC, 20 fs)
  - Incoherent SR: 0.4 eV



[M. Schwarz et al., IPAC'21, TUPAB255]

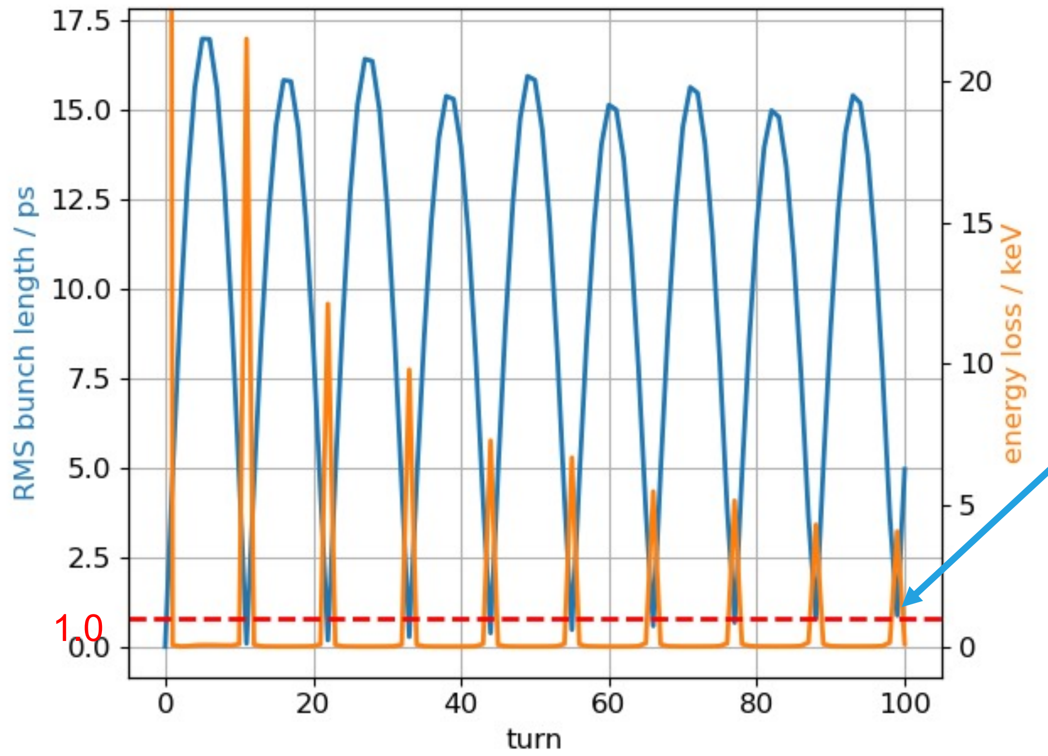
Simulated Beam Dynamics

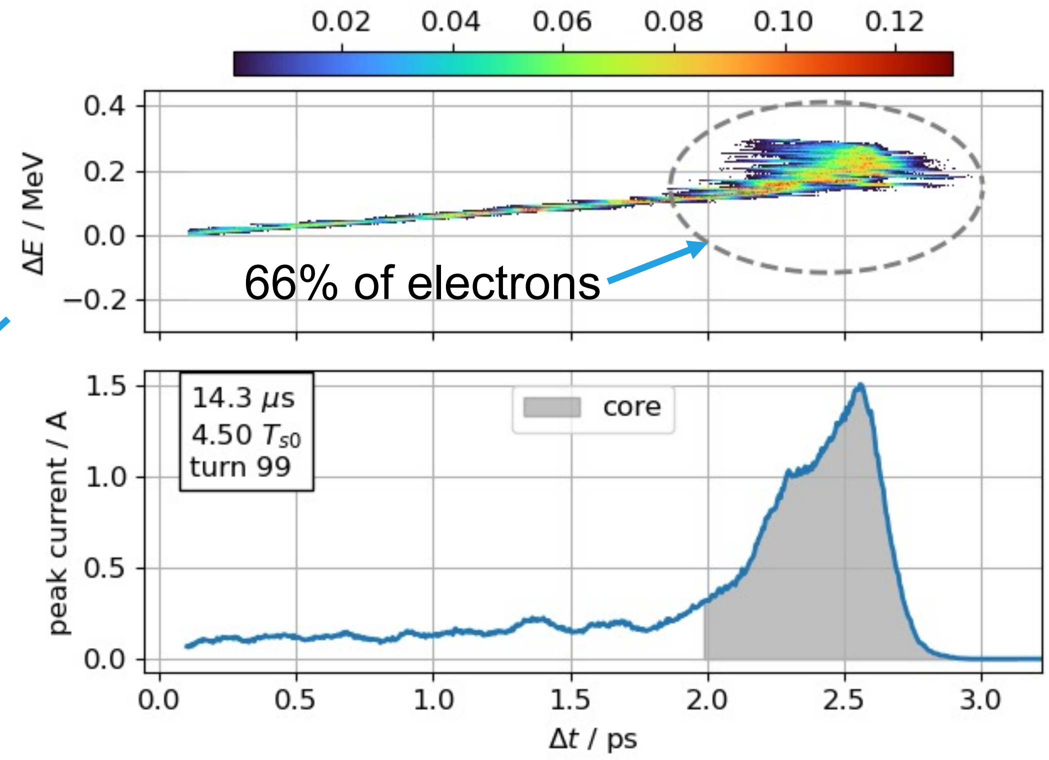
- Initial Gaussian bunch (1 pC)
  - $\sigma_{STD} = 20$ fs, $\sigma_{\Delta E} = 50$ keV
- Strong CSR
  ⇒ energy loss ~ 160 keV
  ⇒ dipole oscillation
- Energy spread
  ⇒ bunch lengthening



Periodic Recovery of sub-ps Bunch Duration

- Sub-ps bunch duration twice per synchrotron period





Summary

- cSTART:
  - Electron energy of 50 MeV ⇒ long **damping time ~16 s**
  - Synchrotron radiation spectrum up to 53 THz
    ⇒ ultra-short bunches radiate completely coherent
  - Emission of **intense CSR**
    ⇒ significant energy loss and non-linear effects
  - **Sub-ps short bunch duration recovered periodically**

Thank you for your attention!