Coherent Synchrotron Radiation & Touschek Scattering in the CLIC Damping Ring

- o Motivation
- o Touschek effect
- o New Touschek Module in MADX
- o Touschek Lifetime for CLIC DR
- o CSR treatments & predictions
- o Novel CSR Program by T. Agoh and K. Yokoya
- o results for Super KEKB
- o CSR μ-wave threshold in CLIC DR
- o Conclusion

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CLIC Seminar 14.01.2005

motivation

high charge density
(small emittance)
& short bunch length
in CLIC damping ring

could aggravate
the effects of coherent
synchrotron radiation
and Touschek scattering

+ availability of new tools to quantify these effects

Touschek effect:

single particle-particle scattering inside bunch; momentum transfer from transverse into longitudinal plane; particle kicked outside of rf bucket; intrabeam ~ multiple, Touschek ~single scattering

lifetime limit was first seen in the small AdA storage ring [C. Bernadini et al., PRL, v. 10, 1963, p. 407] and first explained by Bruno Touschek

main limitation of beam lifetime for all low-energy lepton rings, e.g., LERs of PEP-II and KEKB, and most light sources; causes proton beam loss & halo at LHC

ATF uses Touschek lifetime ~(bunch volume) for emittance tuning & acceptance measurements [F.Zimmermann et al, ATF-98-10; T.Okugi et al., NIMA 455, 207, 2000], $\tau_{Touschek}$~5 min. at ATF

in CLIC 100-Hz operation beam stored for 90 ms; but ***strong IBS!***

Touschek lifetime

A. Wolski, ILC America Workshop

- Large-angle scattering within bunch leads to particle loss because of limited momentum acceptance.
- Main lifetime limitation in 3rd generation synchrotron light sources.
  - Generally operate with emittance ratio 1% or more to achieve lifetime of several hours
  - Lifetime falls to a few minutes with very low coupling in low energy machines
  - Strongly dependent on momentum acceptance (limited by dynamics or RF voltage)
- An issue for damping rings during commissioning and tuning

$$\frac{1}{\tau} = \frac{r_e^2 c N_0}{8\pi\gamma^2\delta_{\max}^3\sigma_z}\int_0^C \frac{D(\varepsilon)}{\sigma_x\sigma_y}\,ds \qquad \varepsilon = \left(\frac{\delta_{\max}\beta_x}{\gamma\sigma_\delta}\right)^2$$

$$D(\varepsilon) = \sqrt{\varepsilon}\left[-\tfrac{3}{2}e^{\varepsilon-} + \frac{\varepsilon}{2}\int_\varepsilon^\infty \frac{e^{-u}\ln u}{u}\,du + \tfrac{1}{2}(3\varepsilon - \varepsilon\ln\varepsilon + 2)\int_\varepsilon^\infty \frac{e^{-u}}{u}\,du\right]$$

(leDuff formula)

Lattice	Touschek lifetime (δ_{max} = 1.5%)
17 km	319 minutes
6 km	82 minutes
3 km	63 minutes

ILC estimates

general behavior and scaling

$$\frac{dN_b}{dt} = -\alpha N_b^2 \quad \rightarrow \quad N(t) = \frac{1}{1+\alpha N_0 t} N_0$$

non-exponential decay

approximate formalism [H. Bruck, J. le Duff, 5th HEACC 1965; R.P. Walker, PAC87; U. Voelkel, DESY 67/5, 1967; H. Wiedemann, PEP-Note 27, 1973]]

$$\alpha = \frac{4\pi r_p^2 c}{\gamma^2 \eta^2 V} J(\eta, \delta q)$$

with

$$J(\eta,\delta q) \approx \frac{1}{4\sqrt{\pi}\,\delta q}\left(-\ln\left(\frac{\eta}{\delta q}\right)^2 - 2.077\right)$$

V: bunch volume $V = 8\pi^{3/2}\sigma_x\sigma_y\sigma_z$

and

$$\eta \equiv \left(\frac{2e}{\pi\alpha_C E_0}\left[\frac{\hat{V}_{rf,1}}{h_1} + \frac{\hat{V}_{rf,2}}{h_2} + \ldots\right]\right)^{1/2}$$

energy acceptance

$$\delta q = \gamma\sigma_x / \beta_x$$

'uncorrelated' transverse momentum spread

exact formalism including horizontal and vertical dispersion implemented in MADX – in collaboration with C. Milardi/INFN and with help by F. Schmidt

reference:

THE TOUSCHEK **EFFECT IN STRONG FOCUSING STORAGE RINGS.**
By A. Piwinski (DESY), DESY-98-179

$$\frac{1}{T_\ell} = \left\langle \frac{r_p^2 c N_p}{8\pi\gamma^2\sigma_s\sqrt{\sigma_x^2\sigma_z^2 - \sigma_p^4 D_x^2 D_z^2}\,\tau_m} F(\tau_m, B_1, B_2) \right\rangle \qquad (41)$$

with

<>: average around the ring

$$F(\tau_m, B_1, B_2) = \sqrt{\pi(B_1^2 - B_2^2)}\,\tau_m \int_{\tau_m}^{\infty} \left(\left(2 + \frac{1}{\tau}\right)^2 \left(\frac{\tau/\tau_m}{1+\tau} - 1 \right) + 1 - \frac{\sqrt{1+\tau}}{\sqrt{\tau/\tau_m}} - \frac{1}{2\tau}\left(4 + \frac{1}{\tau}\right) \ln \frac{\tau/\tau_m}{1+\tau} \right) e^{-B_1\tau} I_o(B_2\tau) \frac{\sqrt{\tau}\, d\tau}{\sqrt{1+\tau}} \qquad (42)$$

where $B_1^2 - B_2^2$ is given by Eq.(34). A faster numerical integration is achieved by substituting $\tau = \tan^2\kappa$, $\tau_m = \tan^2\kappa_m$:

$$F(\tau_m, B_1, B_2) = 2\sqrt{\pi(B_1^2 - B_2^2)}\,\tau_m \int_{\kappa_m}^{\pi/2} \left((2\tau+1)^2 \left(\frac{\tau/\tau_m}{1+\tau} - 1 \right)/\tau + \tau - \sqrt{\tau\tau_m(1+\tau)} - \left(2 + \frac{1}{2\tau}\right) \ln \frac{\tau/\tau_m}{1+\tau} \right) e^{-B_1\tau} I_o(B_2\tau)\sqrt{1+\tau}\, d\kappa$$

Eqs.(41) and (42) describe the most general case with respect to the horizontal and vertical betatron oscillation, the horizontal and vertical dispersion, and the derivatives of the amplitude functions and dispersions. Special cases with some simplifications

I_o is the modified Bessel function and the other quantities are given by

$$\frac{1}{\sigma_h^2} = \frac{1}{\sigma_p^2} + \frac{D_x^2 + \tilde{D}_x^2}{\sigma_{x\beta}^2} + \frac{D_z^2 + \tilde{D}_z^2}{\sigma_{z\beta}^2} = \frac{1}{\sigma_p^2\sigma_{x\beta}^2\sigma_{z\beta}^2}\left(\tilde{\sigma}_x^2\sigma_{z\beta}^2 + \tilde{\sigma}_z^2\sigma_{x\beta}^2 - \sigma_{x\beta}^2\sigma_{z\beta}^2\right) \qquad (32)$$

$$B_1 = \frac{\beta_x^2}{2\beta^2\gamma^2\sigma_{x\beta}^2}\left(1 - \frac{\sigma_h^2\tilde{D}_x^2}{\sigma_{x\beta}^2}\right) + \frac{\beta_z^2}{2\beta^2\gamma^2\sigma_{z\beta}^2}\left(1 - \frac{\sigma_h^2\tilde{D}_z^2}{\sigma_{z\beta}^2}\right) \qquad (33)$$

$$B_2^2 = \frac{1}{4\beta^4\gamma^4}\left(\frac{\beta_x^2}{\sigma_{x\beta}^2}\left(1 - \frac{\sigma_h^2\tilde{D}_x^2}{\sigma_{x\beta}^2}\right) - \frac{\beta_z^2}{\sigma_{z\beta}^2}\left(1 - \frac{\sigma_h^2\tilde{D}_z^2}{\sigma_{z\beta}^2}\right)\right)^2 + \frac{\sigma_h^4\beta_x^2\beta_z^2\tilde{D}_x^2\tilde{D}_z^2}{\beta^4\gamma^4\sigma_{x\beta}^4\sigma_{z\beta}^4} = B_1^2 - \frac{\beta_x^2\beta_z^2\sigma_h^2}{\beta^4\gamma^4\sigma_{x\beta}^4\sigma_{z\beta}^4\sigma_p^2}\left(\sigma_x^2\sigma_z^2 - \sigma_p^4 D_x^2 D_z^2\right) \qquad (34)$$

$$\tau_m = \beta^2\delta_m^2 \qquad (35)$$

In order to simplify the representation we have introduced

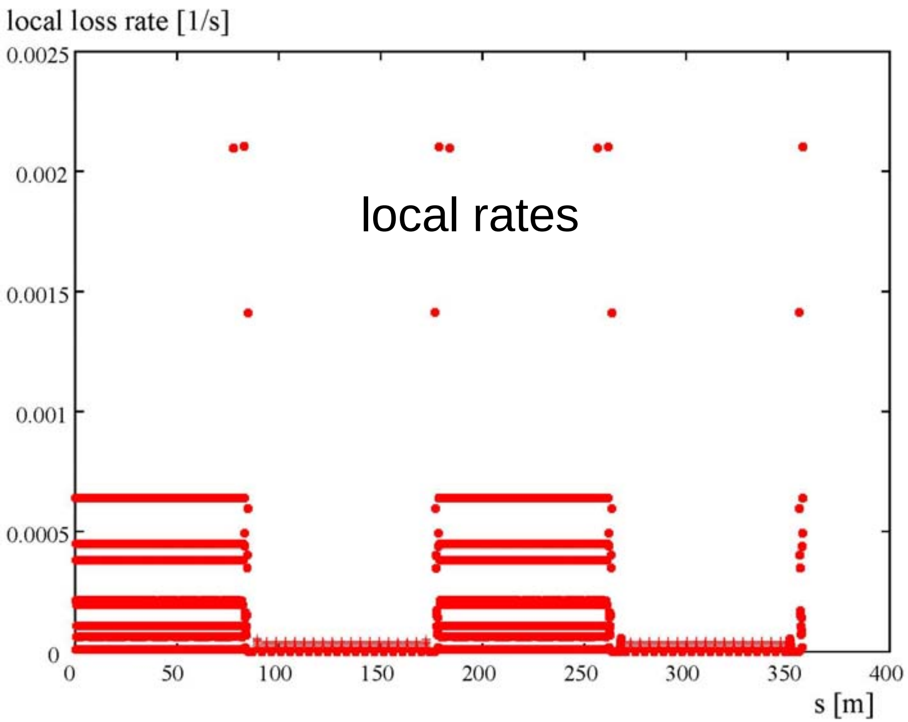
$$\tilde{D}_{x,z} = \alpha_{x,z}D_{x,z} + \beta_{x,z}D'_{x,z} \qquad (36)$$

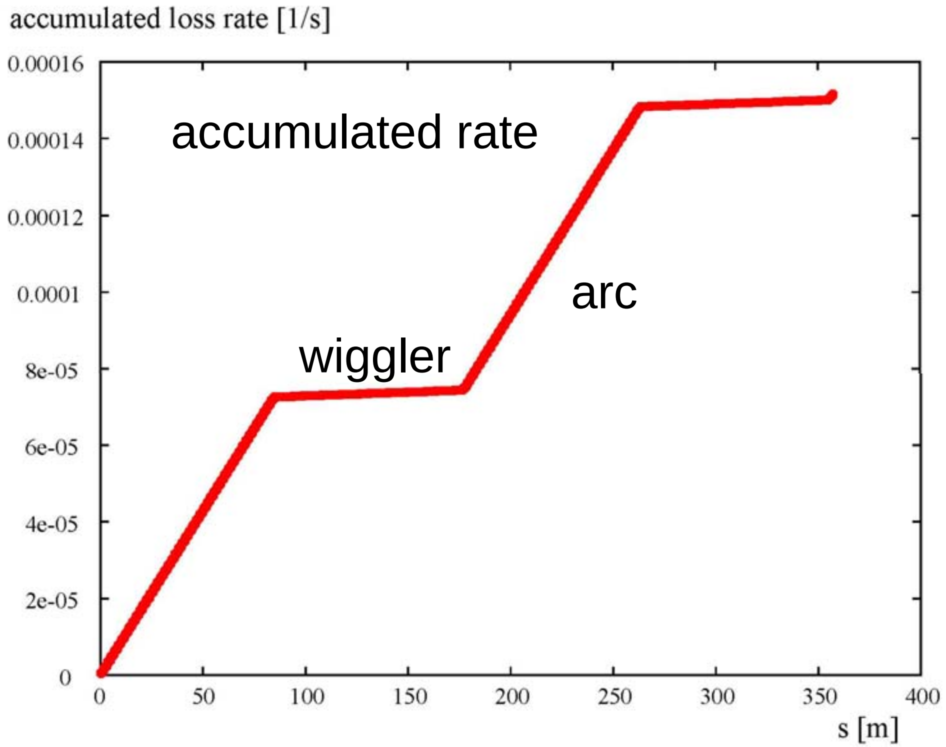
and

$$\tilde{\sigma}_{x,z}^2 = \sigma_{x,z}^2 + \sigma_p^2\tilde{D}_{x,z}^2 = \sigma_{x\beta,z\beta}^2 + \sigma_p^2(D_{x,z}^2 + \tilde{D}_{x,z}^2) \qquad (37)$$

these equations implemented in MADX

Touschek scattering rates in CLIC Damping Ring





Touschek lifetime ~4.19 hr (> ILC lifetime)
more than sufficient for beam tuning
note: rates much larger in the arcs than in wiggler

<u>parameters:</u>

V_{rf}=2.43 MV, f_{rf}=1.5 GHz, N_b=3.1x10^9, σ_z=1.62 mm, σ_δ=0.128%, ε_x=0.12 nm, ε_y=675 fm, E=2.424 GeV, $\gamma\varepsilon_x$=0.57 μm, $\gamma\varepsilon_y$=3.2 nm, "$\gamma\varepsilon_{||}$"=5030 eVm, h=1800

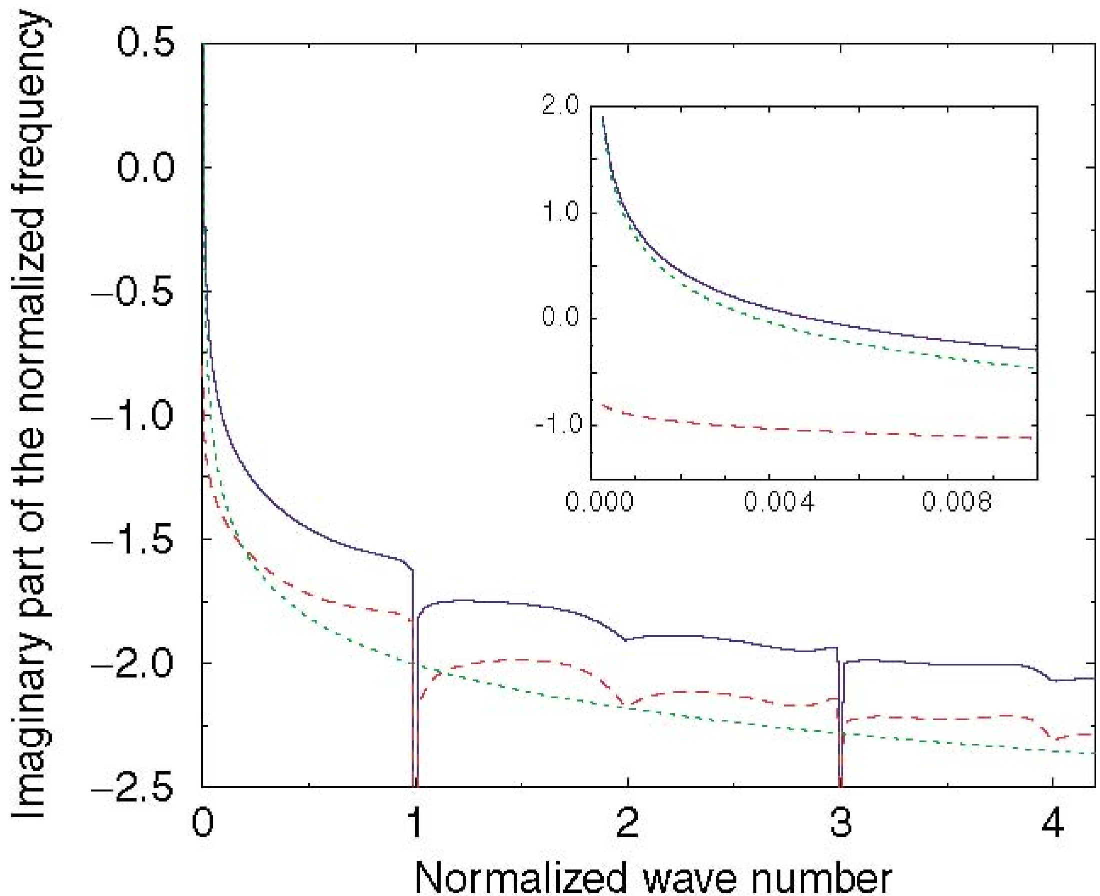
Coherent synchrotron radiation:

bunch interacts with long-wavelength coherent synchrotron radiation from dipoles and wigglers; similar to impedance effect, but ‘CSR wake’ in front of the source

can cause energy spread, emittance growth, μwave instability

various formulae for bunch compressors exist from Russia, DESY (Saldin et al., Derbenev), BNL, SLAC (Warnock, Stupakov), LBNL (Venturini),…

SLAC estimate for damping rings first presented at Nanobeam’02 by T. Raubenheimer; later extended results published in “Impact of the wiggler coherent synchrotron radiation impedance on the beam instability and damping ring optimization,” J. Wu, G. V. Stupakov, T. O. Raubenheimer, and Z. Huang Phys. Rev. ST Accel. Beams 6, 104404 (2003)



J. Wu et al., Phys. Rev. ST Accel. Beams 6, 104404 (2003)

FIG. 1. (Color) The imaginary part of the normalized frequency Ω as a function of the normalized wave number k/k_0 for the NLC main damping ring [16], where k_0 is the on-axis wiggler fundamental radiation wave number defined in Eq. (14). The solid curve includes the entire CSR impedance while the dotted and dashed curves include either the steady state dipole CSR impedance or the wiggler CSR impedance, respectively. The inset shows a blowup of the low frequency region where the beam is unstable.

beam unstable only at low frequencies; lower than shielding cutoff

instability driven by dipole CSR effect

wiggler acts slightly stabilizing!

ILC always stable

estimates & scaling

CSR can increase energy spread & emittance & cause μwave-like instability

CSR causes instability if $\lambda_{th} < \lambda_{sh}$ (G. Stupakov, et al.)

Landau damping at wavelengths shorter than λ_{th} ↔ *dispersion relation*

beam pipe shields at wavelengths above

$$\lambda_{sh} \approx 4\sqrt{2}a^{3/2}R^{-1/2}$$

for two infinitely wide plates

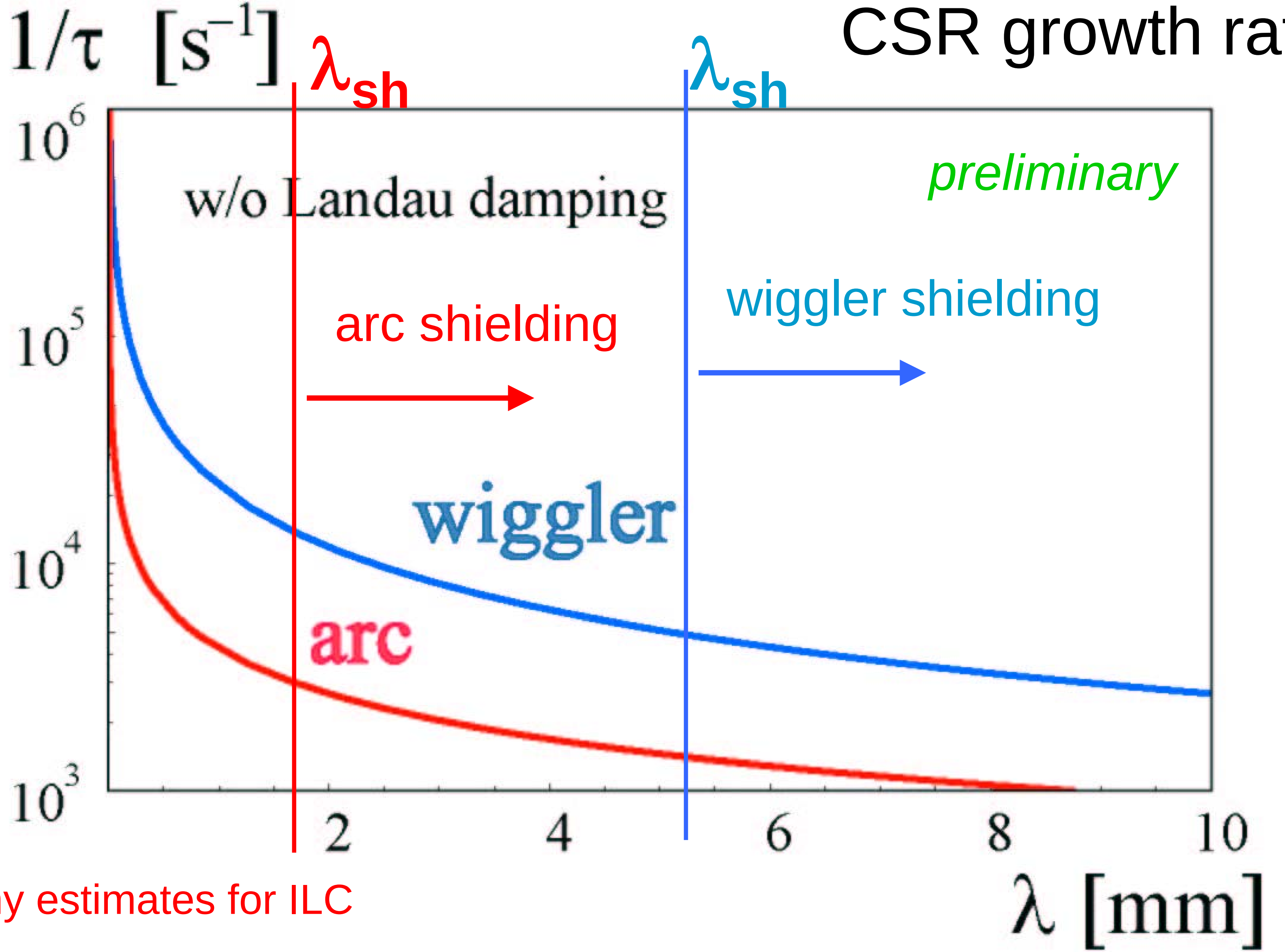
$$1 = -\frac{iZ(k)\Lambda}{\sqrt{2\pi}k}\int_{-\infty}^{\infty} dp\,\frac{pe^{-p^2/2}}{\Omega + p} \approx i\frac{Z(k)\Lambda}{k\Omega^2}$$

with Landau damping

approximation w/o Landau damping

$$\Lambda = \frac{N_b r_0}{\sqrt{2\pi}|\eta|\gamma\sigma_z\sigma_\delta^2},\quad \Omega = \frac{\omega}{ck|\eta|\sigma_\delta}$$

CSR growth rates



my estimates for ILC

numbers refer to the parameters Λ~11 (34), *R*~86 (10) m, *L*~100 (317) m, η~1.2x10^{-4}, *C*~17 km, σ_δ~1.3x10^{-3}, *I*~64 A, *a*~2 cm for arc (wiggler)

CLIC: R~10 m (5) m in arc (wiggler); shielding cutoffs somewhat higher

CSR impedance [Saldin et al., Stupakov et al., Wu,…]

arc

$$Z_{arc}^{CSR}(k) = -iA\frac{k^{1/3}}{R^{2/3}}$$

with $A = 3^{-1/3}\Gamma\left(\frac{2}{3}\right)\left(\sqrt{3}i - 1\right)$

wiggler

$$Z_{wiggler}^{CSR}(k) \approx \pi k_w \frac{k}{k_*}\left[1 - \frac{2i}{\pi}\log\frac{k}{k_*}\right]$$

for $k << k_*$

steady-state free space

where $k_* = 4\gamma^2 k_\omega / K^2 \approx 7\times10^5\,\mathrm{m}^{-1}$

$$K \approx 93.4\, B_\omega[\mathrm{T}]\lambda_\omega[\mathrm{m}] \approx 80$$

values refer to 1.7-T peak field, 500 mm period, 40 m length

$$\left|\frac{\mathrm{Im}\, Z_{wiggler}^{CSR}(\omega)}{n}\right| \approx \frac{K^2}{4\gamma^2}\frac{Z_0 L_{wiggler}}{C}\left|\log\frac{k}{k_*}\right| << \left(\frac{Z}{n}\right)_{KSBthreshold}$$

for $k > k_{\mathrm{sh}}$

100-200 mΩ for ILC
50 mΩ for CLIC

$$\left(\frac{Z_\parallel}{n}\right)_{KSB} = Z_0\sqrt{\frac{\pi}{2}}\frac{\gamma\alpha_c\sigma_\delta^2\sigma_z}{N_b r_e}$$

suggesting wiggler CSR not a danger

recent progress:
novel code was developed to calculate CSR effects in a storage ring over many turns; shielding computed from actual vacuum chamber boundaries, no parallel-plate approximation

<u>reference:</u>
Calculation of coherent synchrotron radiation using mesh
T. Agoh and K. Yokoya, Phys. Rev. ST Accel. Beams **7**, 054403 (2004)

<u>caveats:</u>
at the moment code only treats longitudinal CSR effects;
considers only arc dipole magnets, wigglers not yet included (should have a negligible contribution if SLAC paper correct)

extension to wigglers, transverse plane and bunch compressors is foreseen in near future;
this code can also compute wake of tapered collimator

main approximations in Agoh-Yokoya code:

(c) The radiation components propagating at large angles with respect to the beam are ignored (paraxial approximation). In particular, this assumption excludes a vacuum chamber having a projection from the wall, which would cause a wave propagating along the opposite direction.

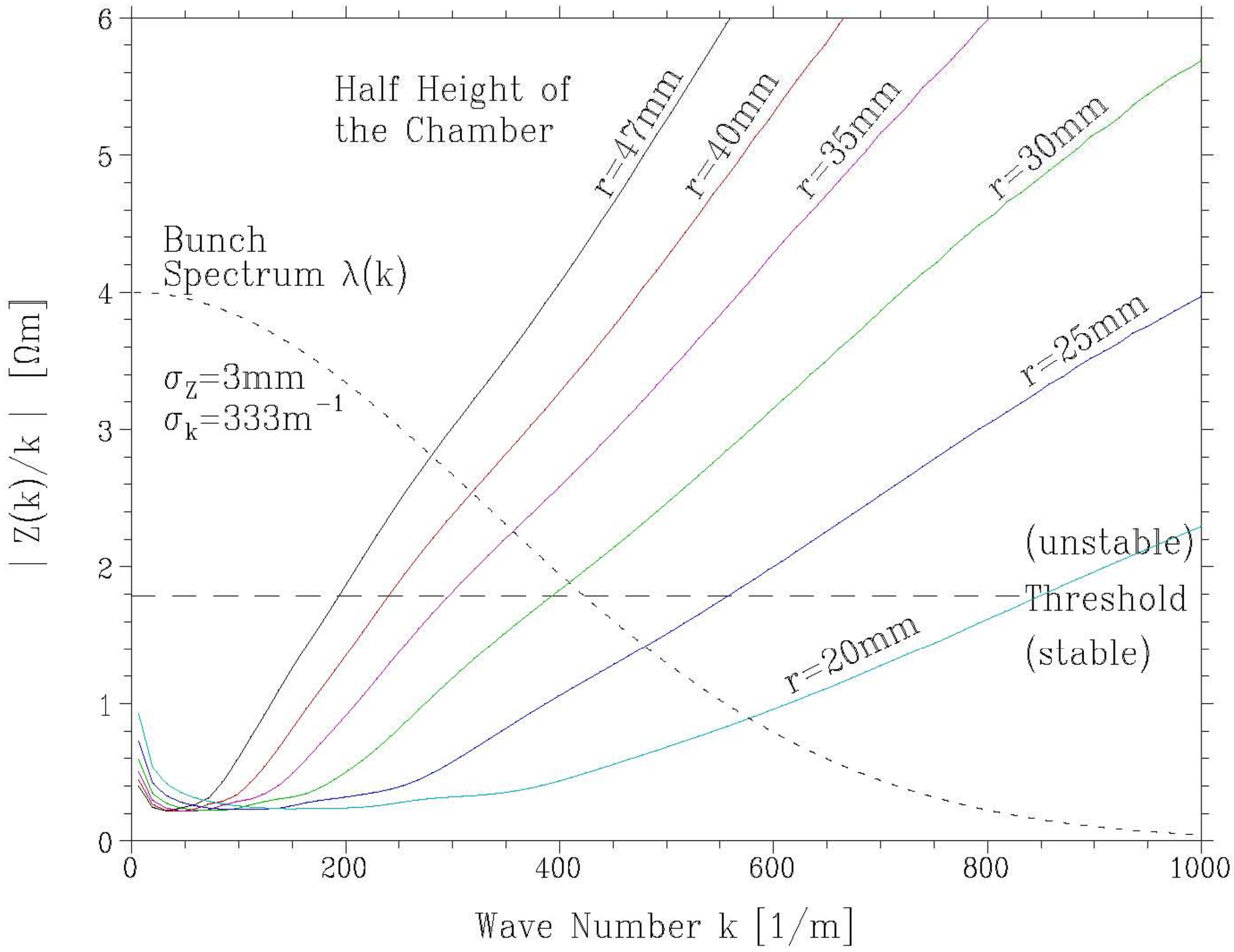
(d) The bunch shape does not change. This assumption can be relaxed so as to include "predictable" changes (those estimated by a simple optics calculation). The dynamic change of the bunch shape due to the CSR itself cannot be included.

T. Agoh, presentation at 6th higher-luminosity B factory workshop in KEK

SuperKEKB

impedance from code & KSB criterion

- $|Z(k)/k|$ vs k for different chamber sizes. ($r =$ Half Height)



Threshold

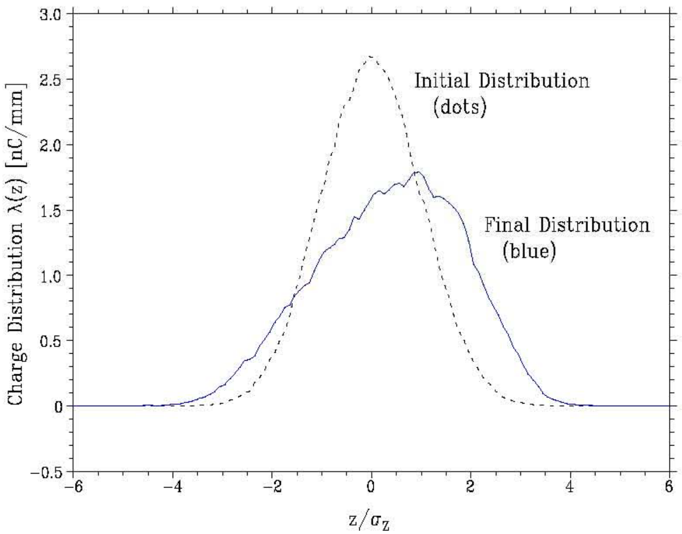
$\begin{cases} \sigma_z = 3\text{mm} \\ I_0 = 2\text{mA} \end{cases}$

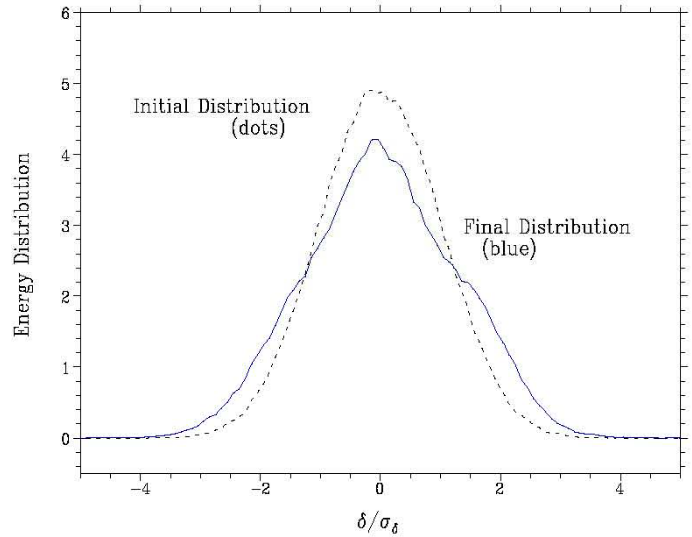
(3mm, 2mA) bunches are stable in the chamber: $r < 20 \sim 25$mm.

T. Agoh, presentation at 6th higher-luminosity B factory workshop in KEK

threshold by particle tracking with CSR (SR, QE & RW also included)

- Charge Distribution and Energy Spread in SuperKEKB ($r = 47$mm)





Initial

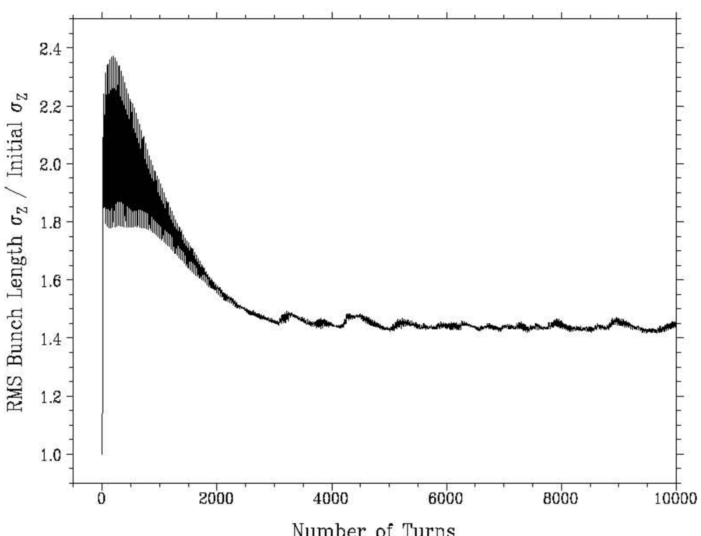
Bunch Length

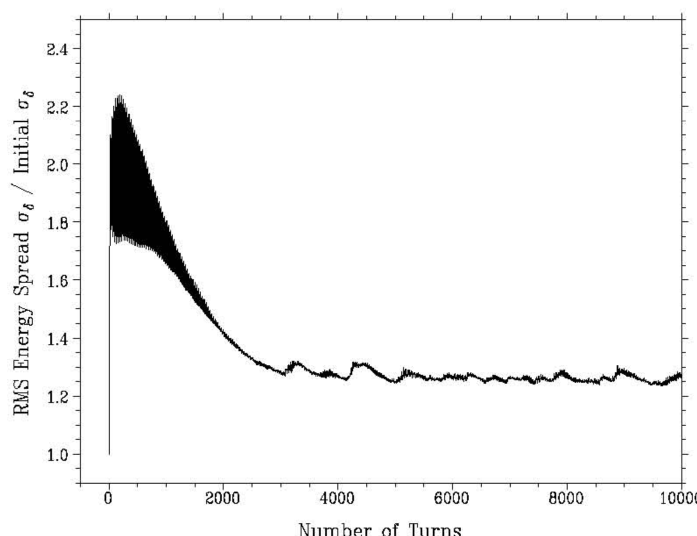
$\sigma_z = 3.0$mm

Initial

Energy Spread

$\sigma_\delta = 7.1 \times 10^{-4}$





Equilibrium

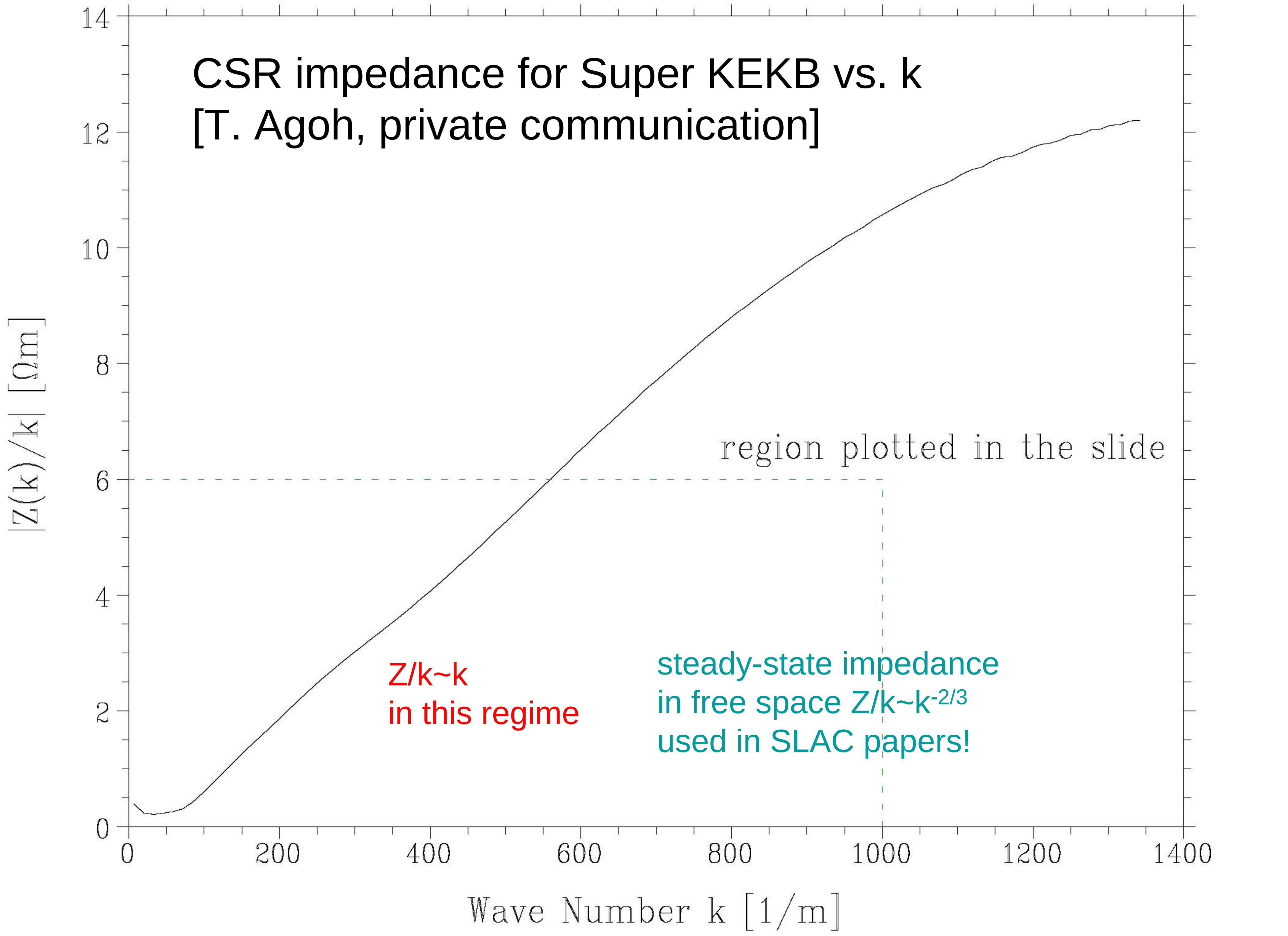
Bunch Length

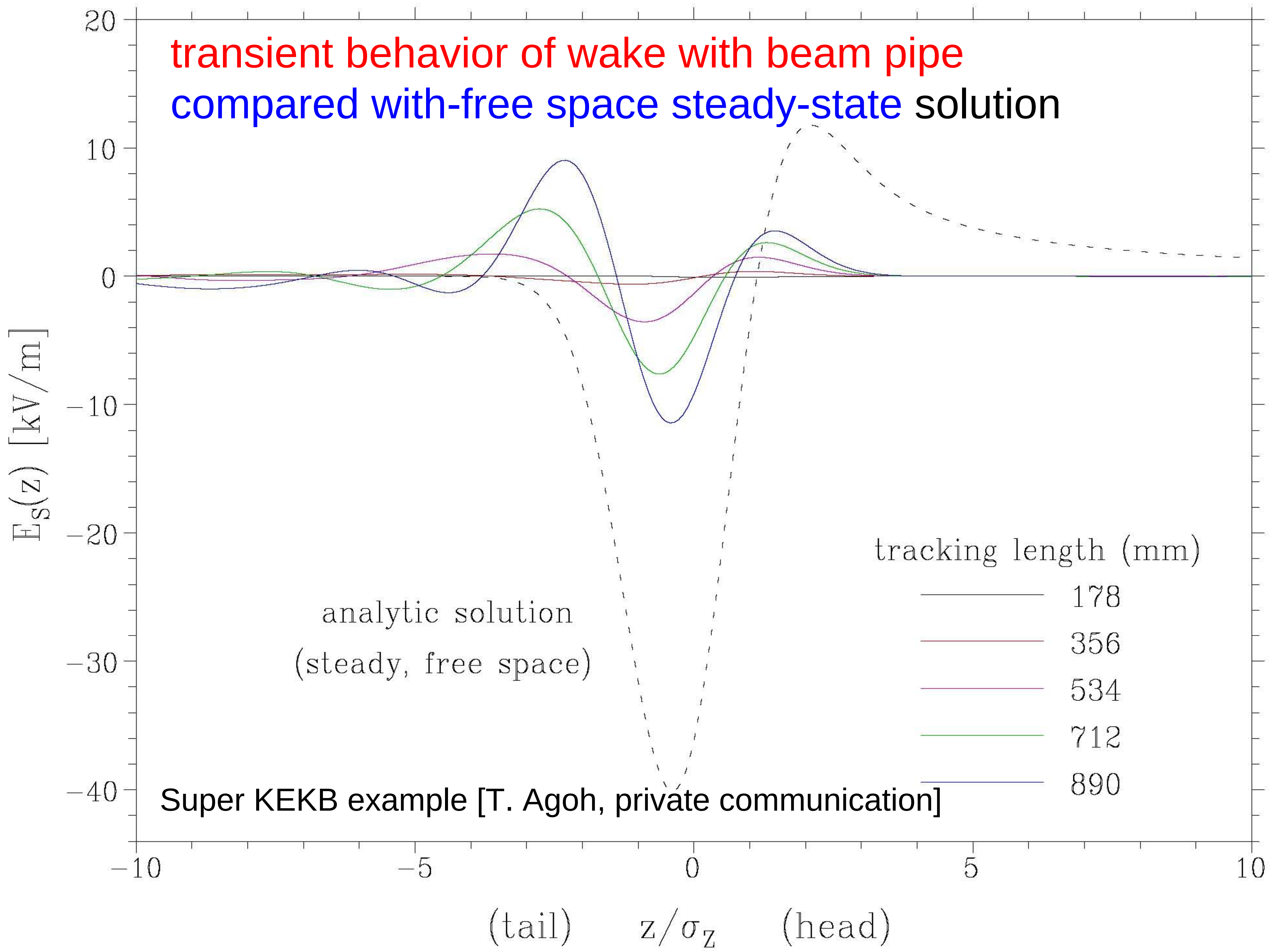
$\sigma_z \sim 4.3$mm

Equilibrium

Energy Spread

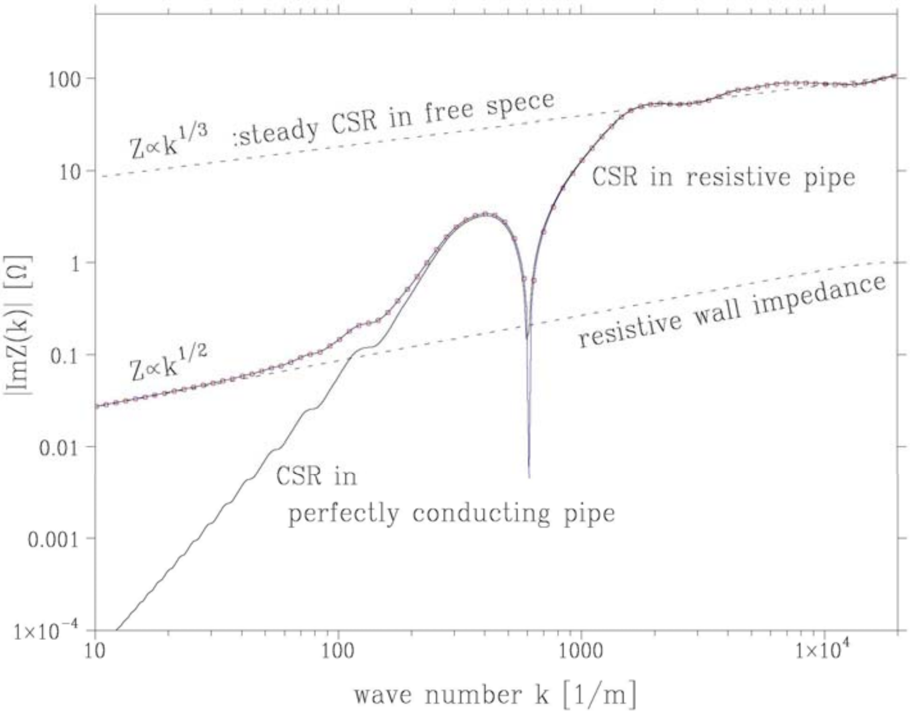
$\sigma_\delta \sim 9.0 \times 10^{-4}$

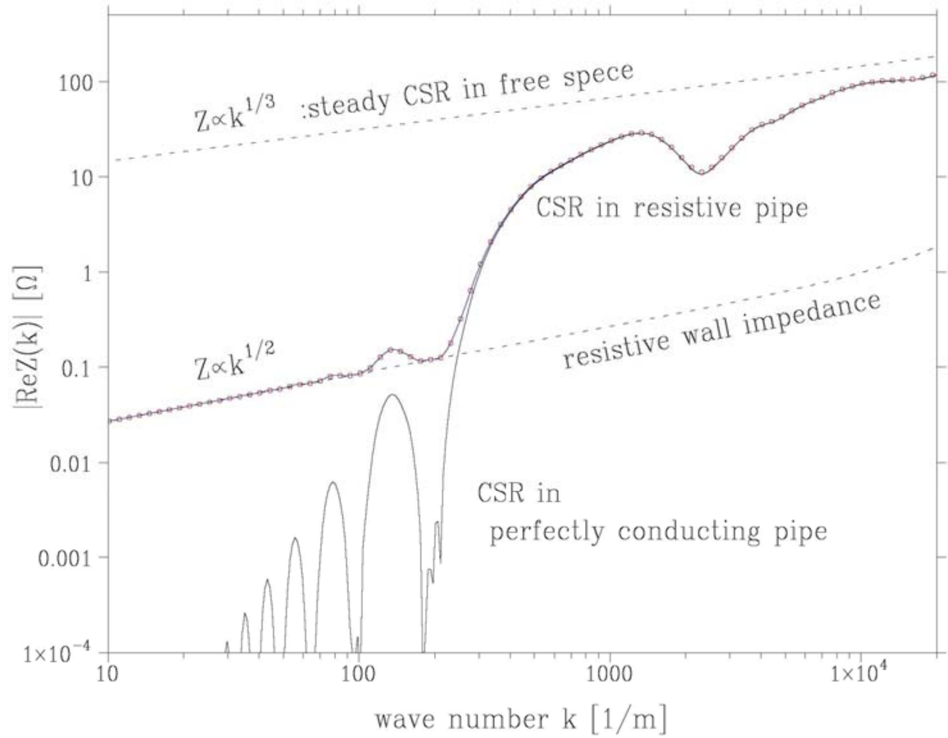

CSR impedance for Super KEKB vs. k
[T. Agoh, private communication]
region plotted in the slide
Z/k~k
in this regime
steady-state impedance
in free space Z/k~k-2/3
used in SLAC papers!
|Z(k)/k| [Ωm]
Wave Number k [1/m]
0
2
4
6
8
10
12
14
0
200
400
600
800
1000
1200
1400



transient behavior of wake with beam pipe
compared with-free space steady-state solution
20
10
0
−10
−20
−30
−40
$E_S(z)$ [kV/m]
tracking length (mm)
178
356
534
712
890
analytic solution
(steady, free space)
Super KEKB example [T. Agoh, private communication]
−10
−5
0
5
10
(tail) z/σ_Z (head)

imaginary and real part of CSR and RW impedance vs k for SuperKEKB example [T.Agoh, private communication]





- at small k, CSR impedance is strongly suppressed
- so at small k, CSR in resistive pipe approaches the RW impedance
- for large k, CSR in resistive pipe ~approaches unshielded CSR formula.
- at large k, remaining difference between CSR in resistive pipe and CSR formula due to transient effect and shielding
- sum of CSR and RW impedances nearly equals CSR in resistive pipe. [blue line(2) and the red dots(5) is almost same; (2)=(1)+(4)holds !]

Effect of CSR in the CLIC Damping Ring

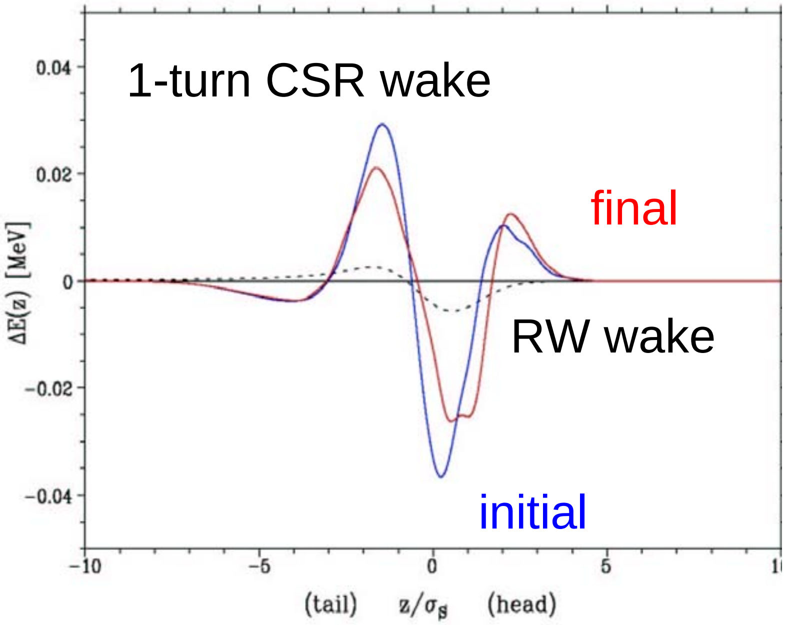
T. Agoh, K. Yokoya, M. Korostelev, F. Zimmermann

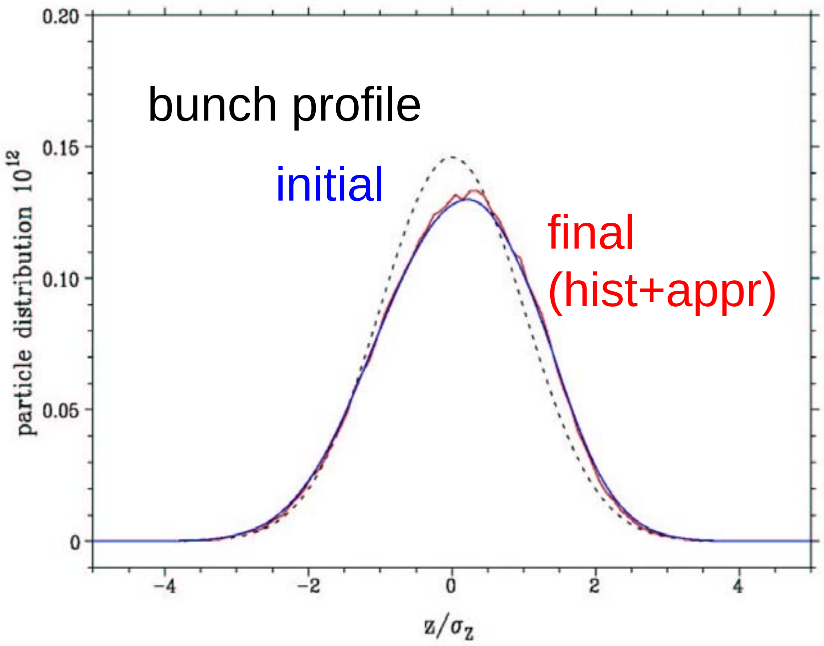
Parameter	symbol	value
bunch population	N_b	3x10^{9}
rms bunch length	σ_z	1.3 mm
ring circumference	C	357 m
beam-pipe radius	a	2 or 4 cm
number of arc bends	n_{bend}	96
Inverse bending radius	$1/\rho$	0.115 m^{-1}
length of arc bend	l_b	0.545 m
revolution frequency	f_{rev}	840 kHz
bunch current	I_{bunch}	0.4 mA
momentum compaction	α_C	0.731x10^{-4}
rf frequency	V_{rf}	1.5 GHz
harmonic number	h	1786
energy loss / turn	U_0	2.192 MeV
rf voltage	V_{rf}	3 MV
beam energy	E_b	2.424 GeV
damping time	$\tau_{\|\|}$	1.32 ms
no. of macroparticles	N_{macro}	10^{5}
no. turns	N_{turn}	8192

Parameters
for CSR simulation

Longitudinal CSR Green-function wake field is first computed by field matching of the forward waves and it is then used in a multi-particle tracking simulation including radiation damping and resistive-wall wake field. The calculation includes all transient effects.

beam pipe radius 2 cm

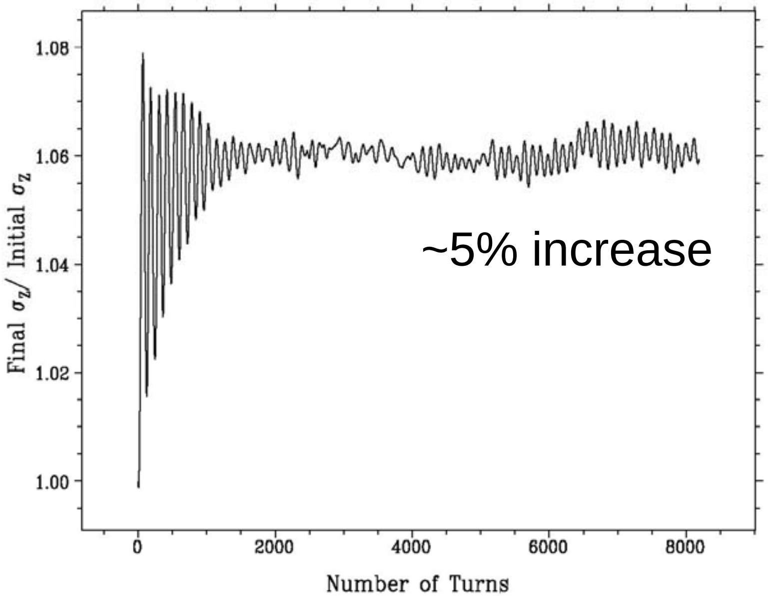




CLIC Damping Ring

beam pipe radius 2 cm

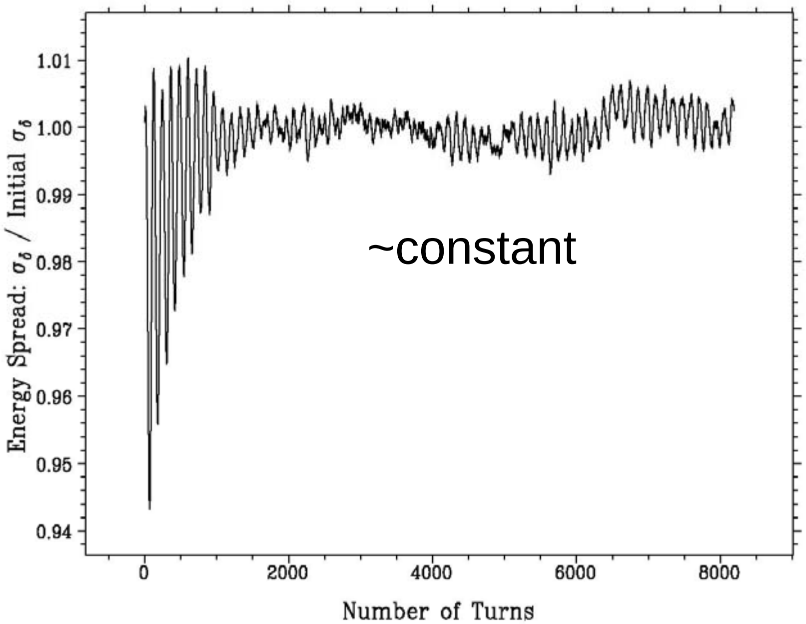
bunch length evolution



~5% increase

9000 turns

momentum spread evolution



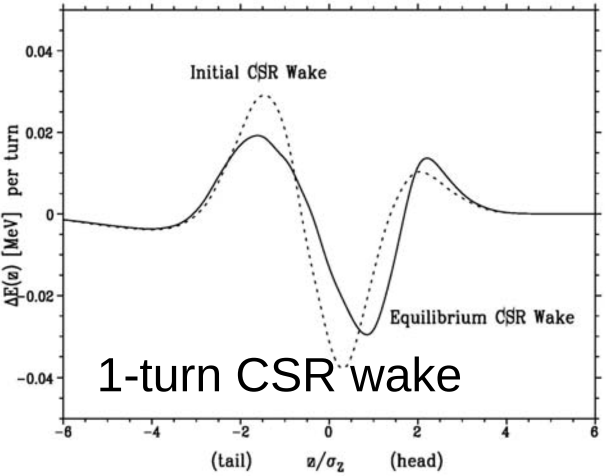
~constant

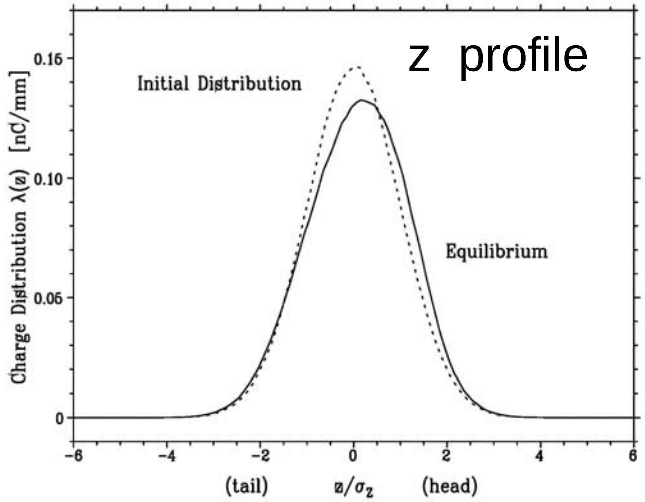
9000 turns

note: longitudinal damping time ~1100 turns

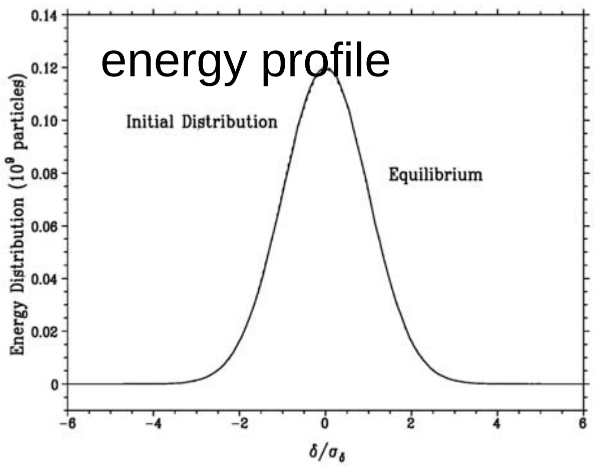
CLIC Damping Ring

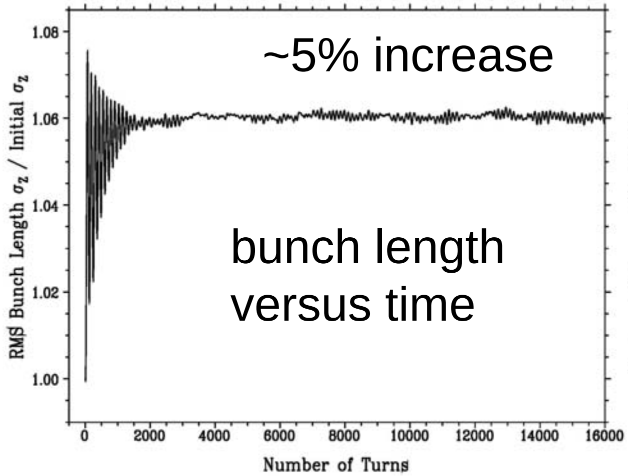
beam pipe radius 2 cm

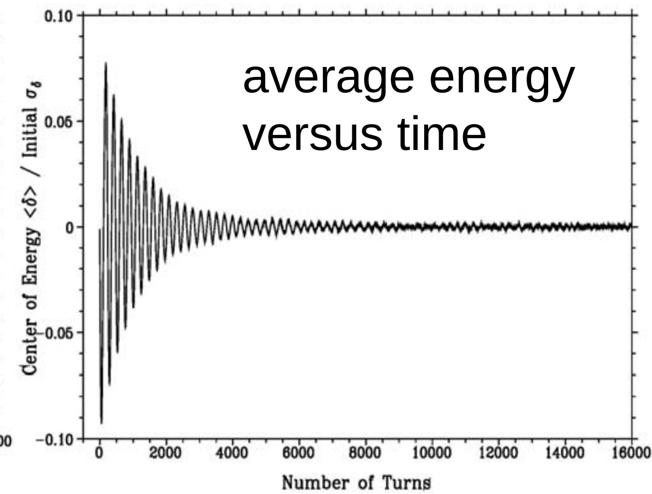




repetition of calculation with improved resolution

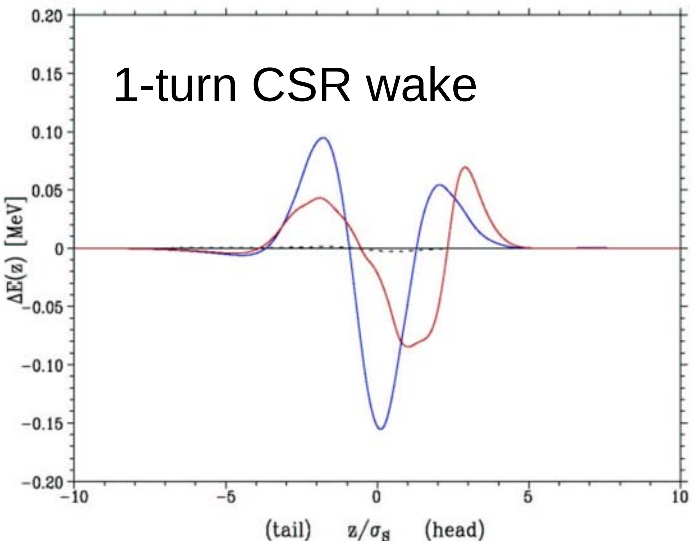


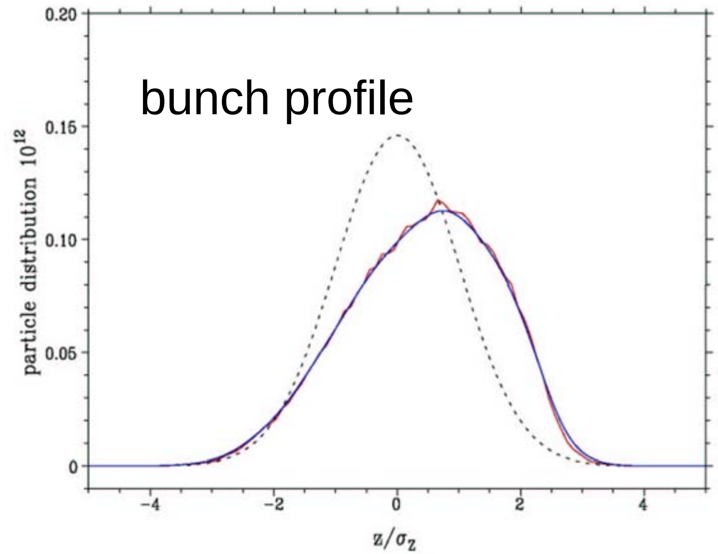


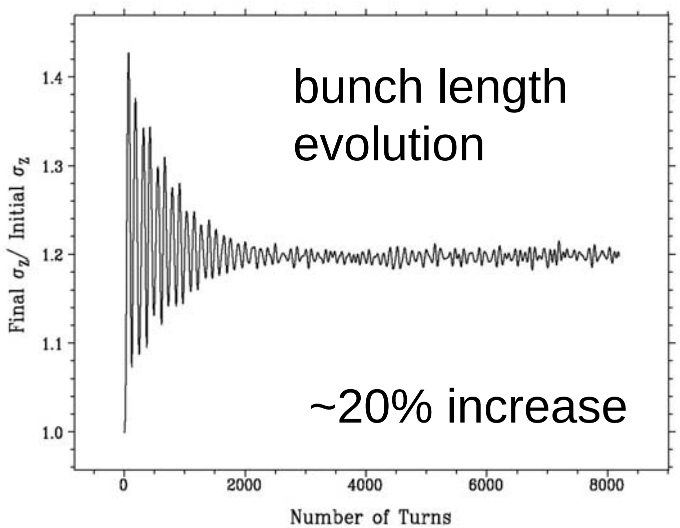


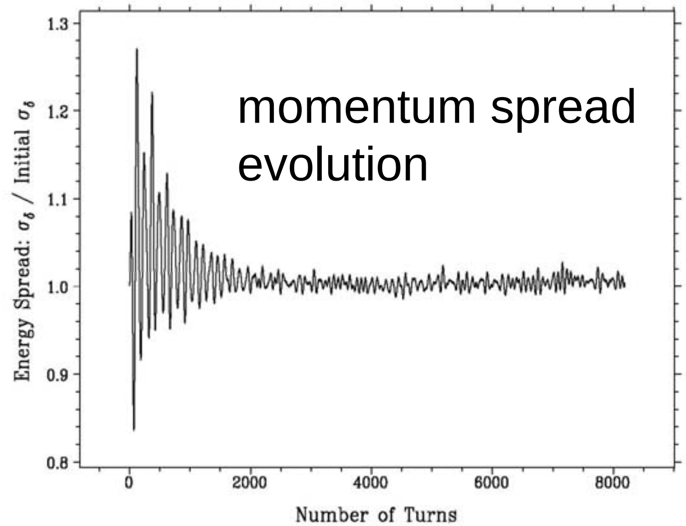
CLIC Damping Ring

beam pipe radius 4 cm

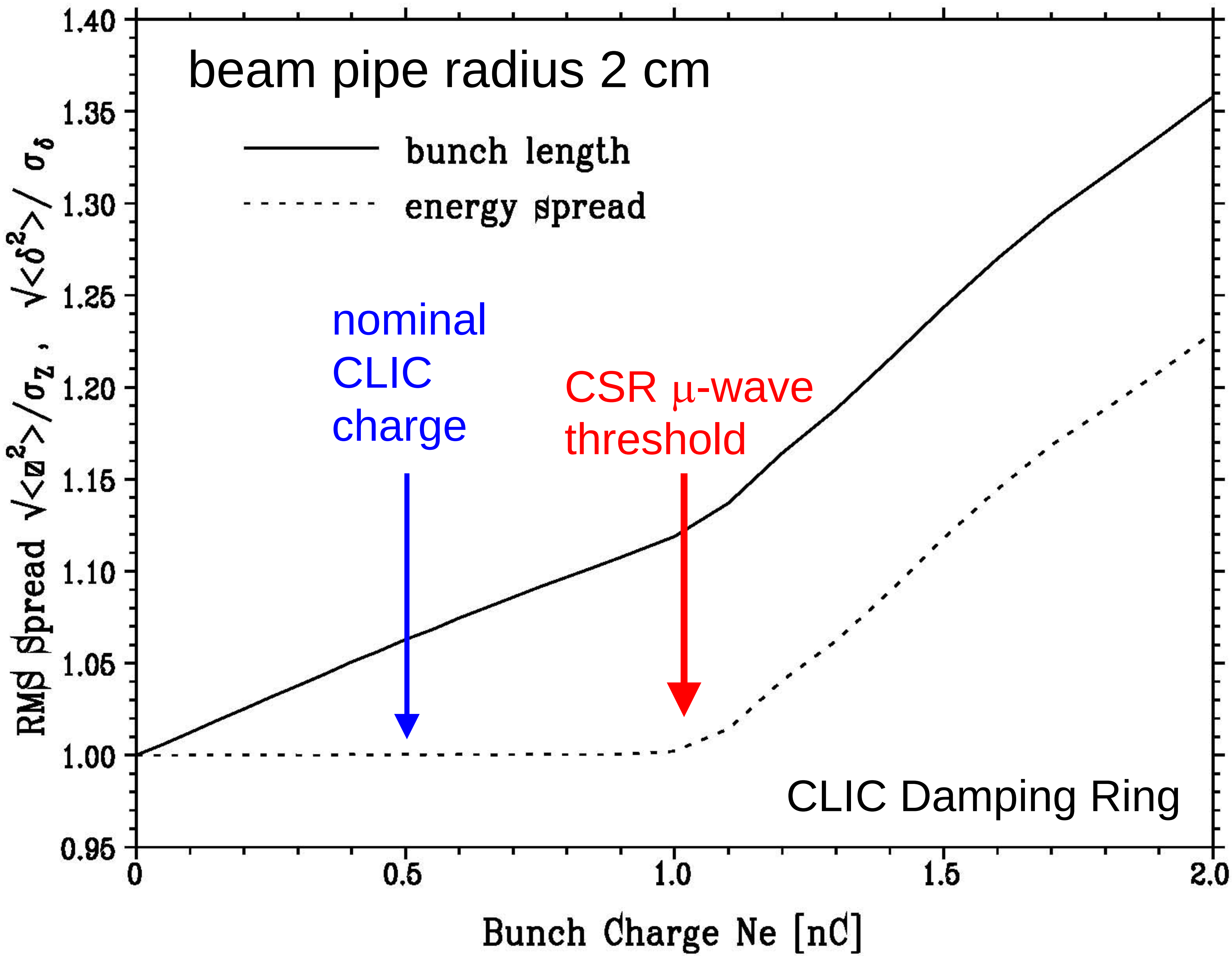








CLIC Damping Ring



beam pipe radius 2 cm
bunch length
energy spread
nominal CLIC charge
CSR μ-wave threshold
CLIC Damping Ring
RMS Spread $\sqrt{<z^2>}/\sigma_z$, $\sqrt{<\delta^2>}/\sigma_\delta$
Bunch Charge Ne [nC]
1.40
1.35
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0
0.5
1.0
1.5
2.0

conclusions

"CLIC works!" [T. Agoh*]

→ CSR & Touschek surprisingly benign for CLIC parameters and present CLIC damping-ring lattice

→ further CLIC CSR calculations are planned with T. Agoh

*CLIC result became a chapter in his Tokyo University Ph.D. thesis