extensions of the impedance concept: ***electron cloud***

Frank Zimmermann, CERN

ICFA/HiLumi/LIU/INFN/EuCARD-XBEAM joint workshop
Impedance 2014, Erice, 25 April 2013

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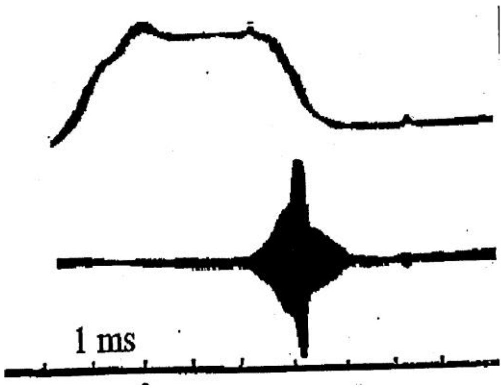
outline

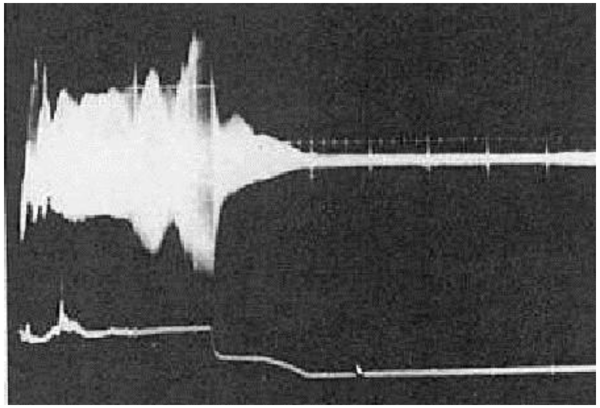
- brief history
- notion of “wake” or “impedance” for coupled bunch electron-cloud effects
- notion of “wake” or “impedance” for single bunch electron-cloud effects
- 2-D generalization of impedance for more accurate analysis of electron-cloud phenomena
- modification of conventional impedances by an electron cloud
- impedance for incoherent electron cloud effects?
- microwaves & electron cloud

historical observations of e-cloud effects

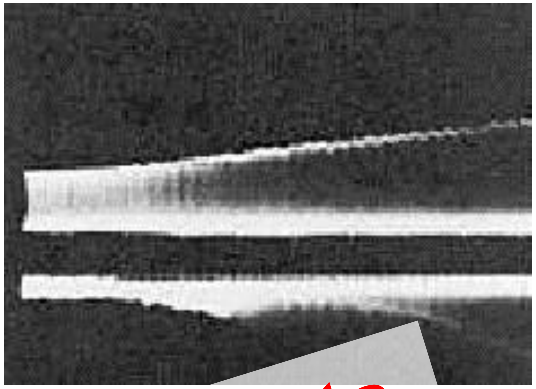
INP Novosibirsk, 1965



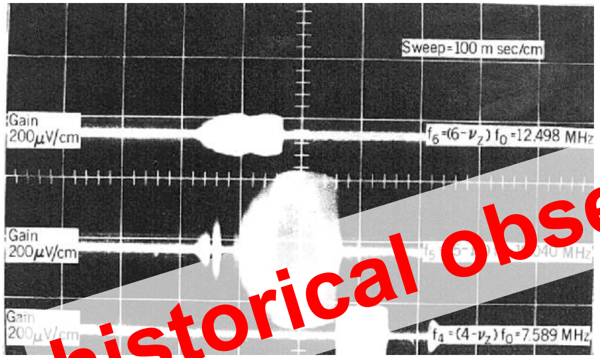
Argonne ZGS,1965



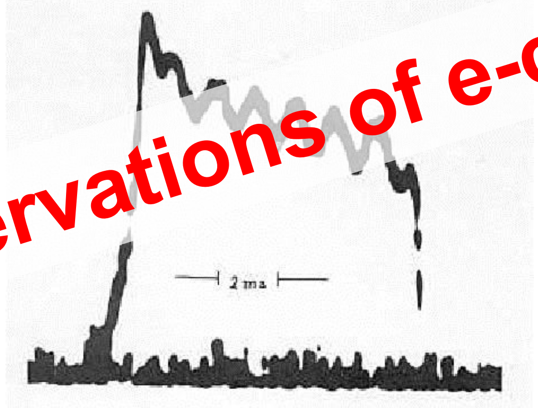
BNL AGS, 1965



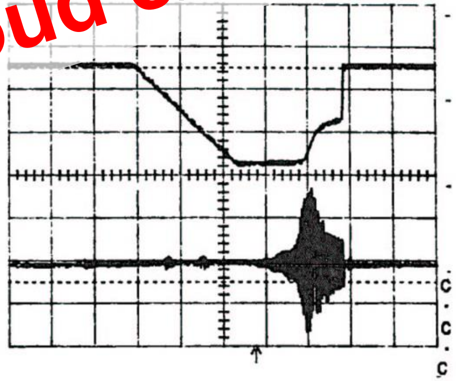
Bevatron, 1971



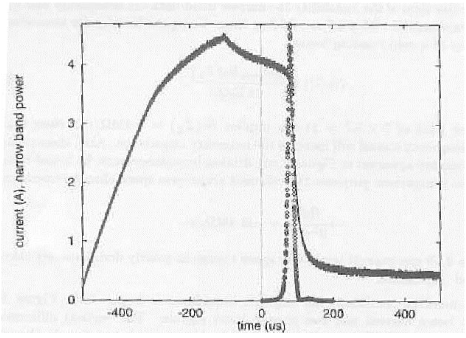
ISR, ~1972



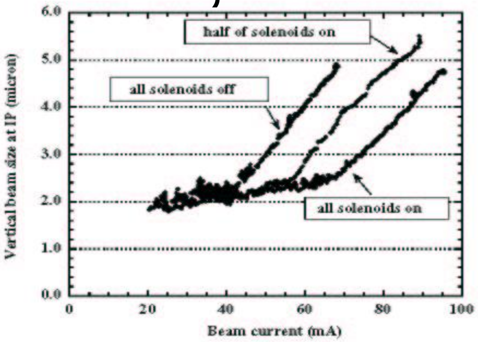
PSR, 1988



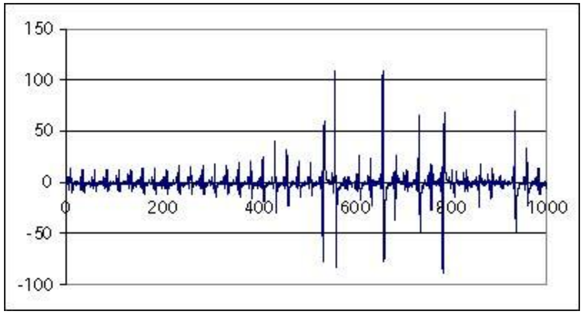
AGS Booster, 1998/99



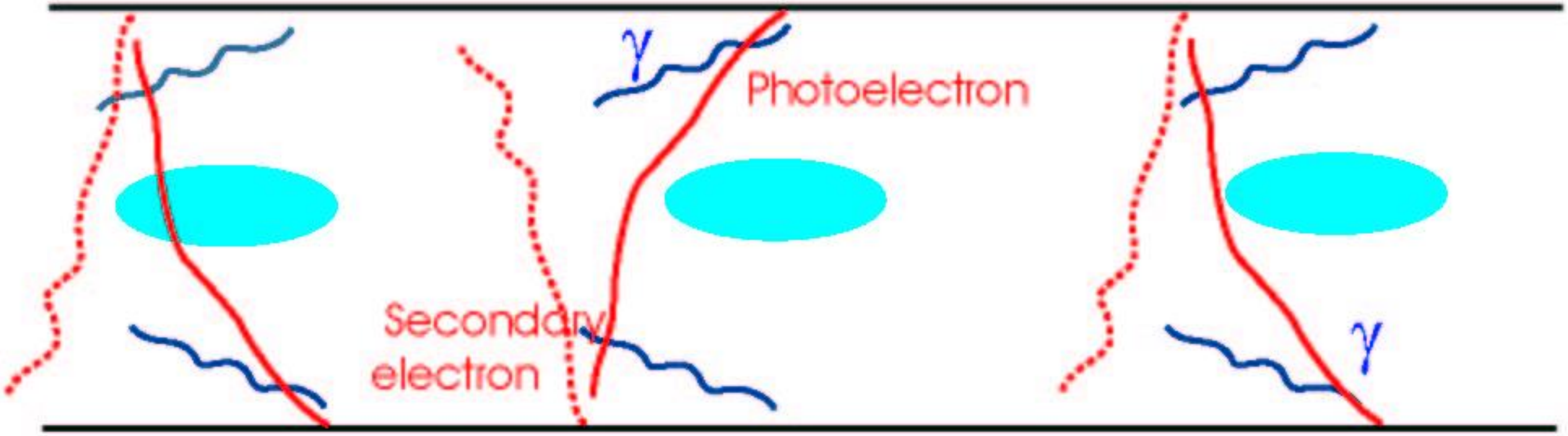
KEKB, 2000



CERN SPS, 2000

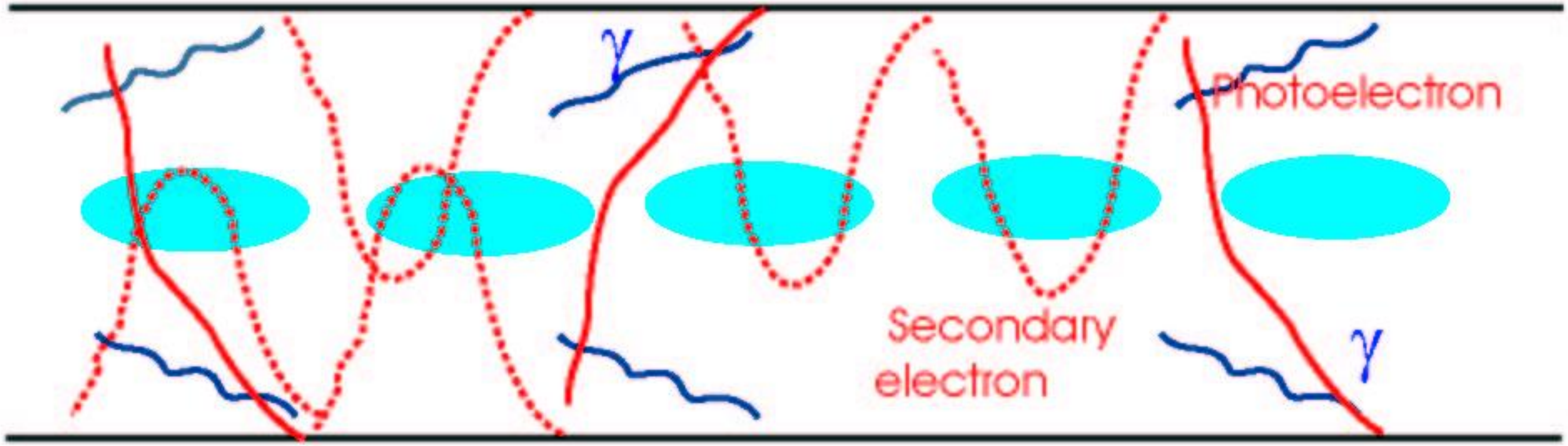


electron cloud: schematic of e- build up

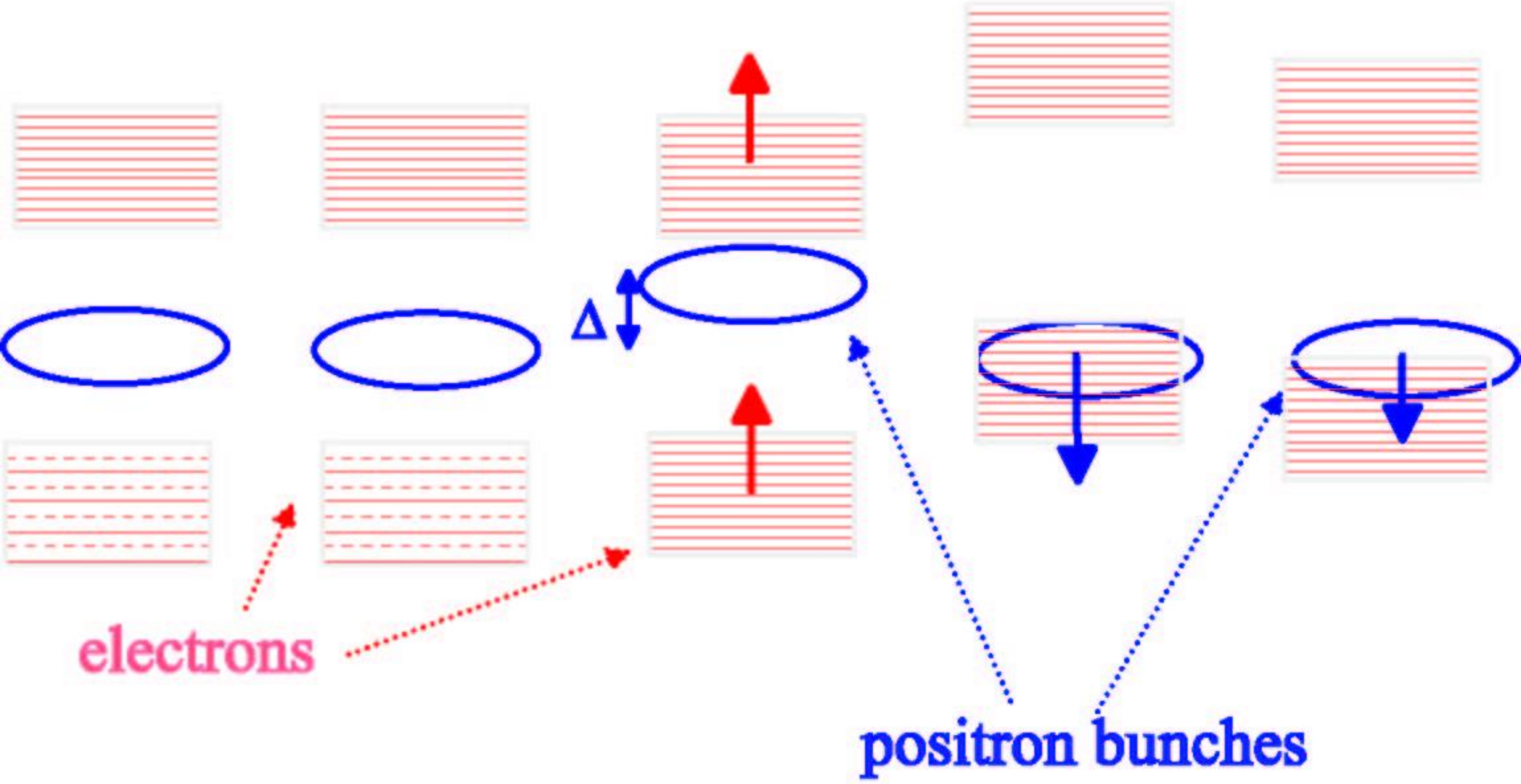


large spacing

short spacing



Coupled-Bunch Instability

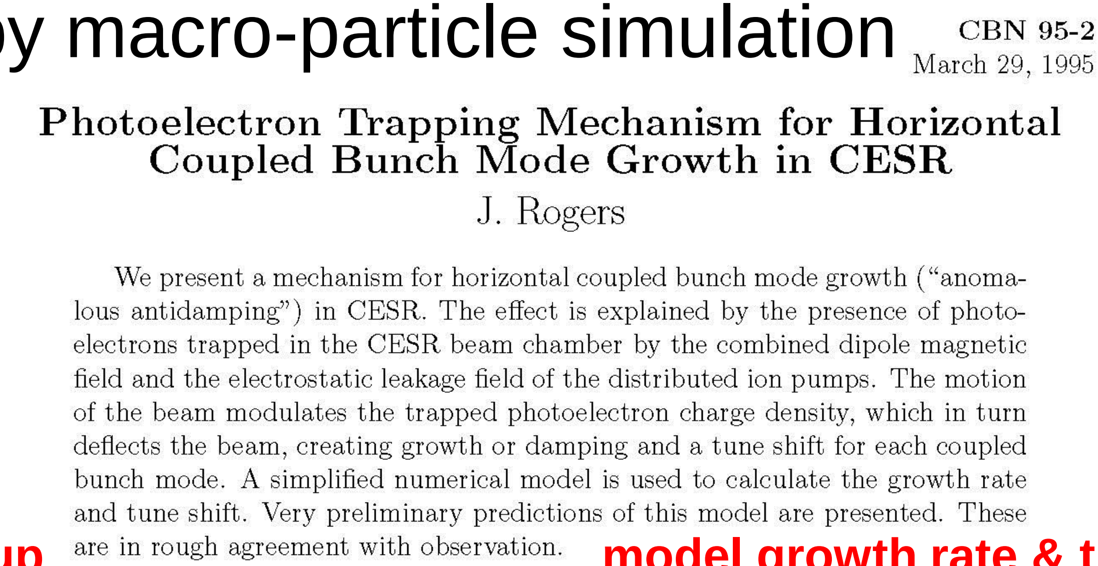


electrons

positron bunches

theory of coupled-bunch electron-cloud instability

- explanation for “anomalous antidamping” in CESR
- modelled by macro-particle simulation



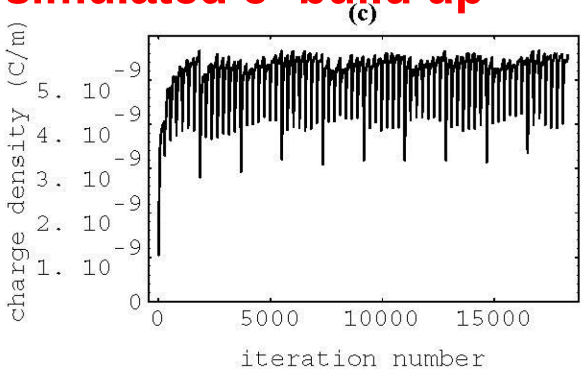
CBN 95-2
March 29, 1995

Photoelectron Trapping Mechanism for Horizontal Coupled Bunch Mode Growth in CESR

J. Rogers

We present a mechanism for horizontal coupled bunch mode growth (“anomalous antidamping”) in CESR. The effect is explained by the presence of photoelectrons trapped in the CESR beam chamber by the combined dipole magnetic field and the electrostatic leakage field of the distributed ion pumps. The motion of the beam modulates the trapped photoelectron charge density, which in turn deflects the beam, creating growth or damping and a tune shift for each coupled bunch mode. A simplified numerical model is used to calculate the growth rate and tune shift. Very preliminary predictions of this model are presented. These are in rough agreement with observation.

simulated e- build up



model growth rate & tune shifts

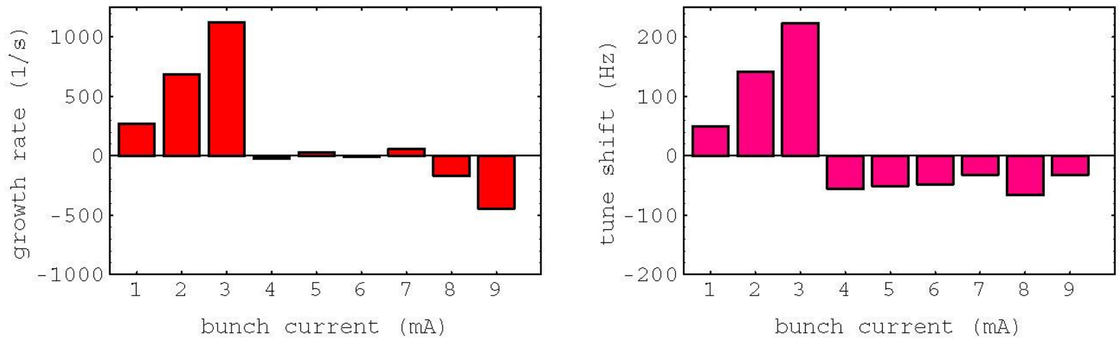
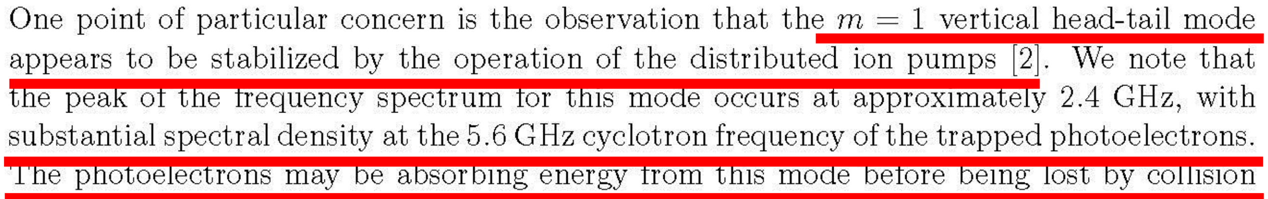


Figure 4: Calculated growth rate and tune shift vs. bunch current for 9 bunches in CESR.

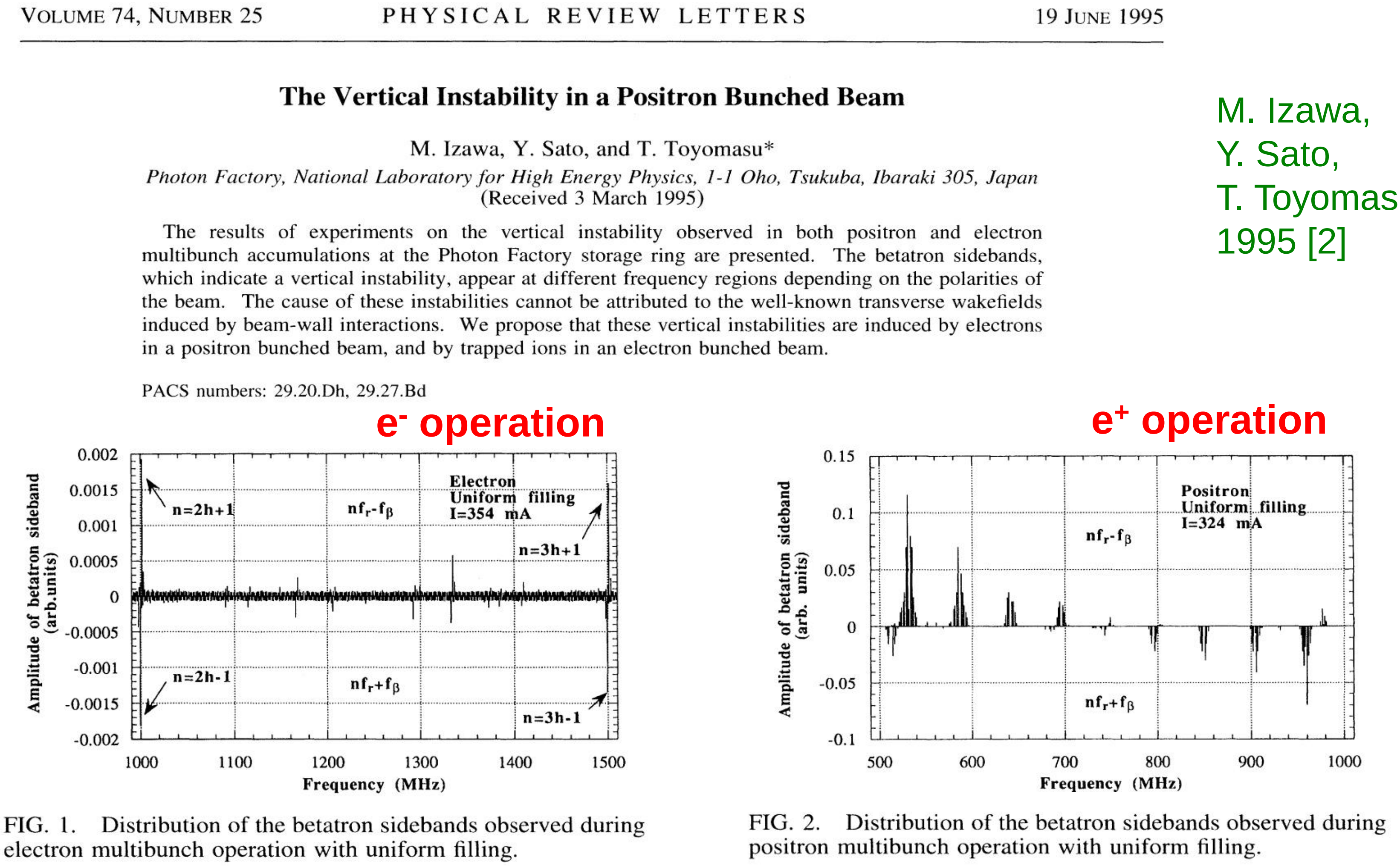


One point of particular concern is the observation that the $m = 1$ vertical head-tail mode appears to be stabilized by the operation of the distributed ion pumps [2]. We note that the peak of the frequency spectrum for this mode occurs at approximately 2.4 GHz, with substantial spectral density at the 5.6 GHz cyclotron frequency of the trapped photoelectrons. The photoelectrons may be absorbing energy from this mode before being lost by collision

J.T. Rogers, 1995 [1]

theory of coupled-bunch electron-cloud instability

- identified at KEK Photon Factory w e$^+$ operation
- described by wake model



VOLUME 74, NUMBER 25 PHYSICAL REVIEW LETTERS 19 JUNE 1995

The Vertical Instability in a Positron Bunched Beam

M. Izawa, Y. Sato, and T. Toyomasu*

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(Received 3 March 1995)

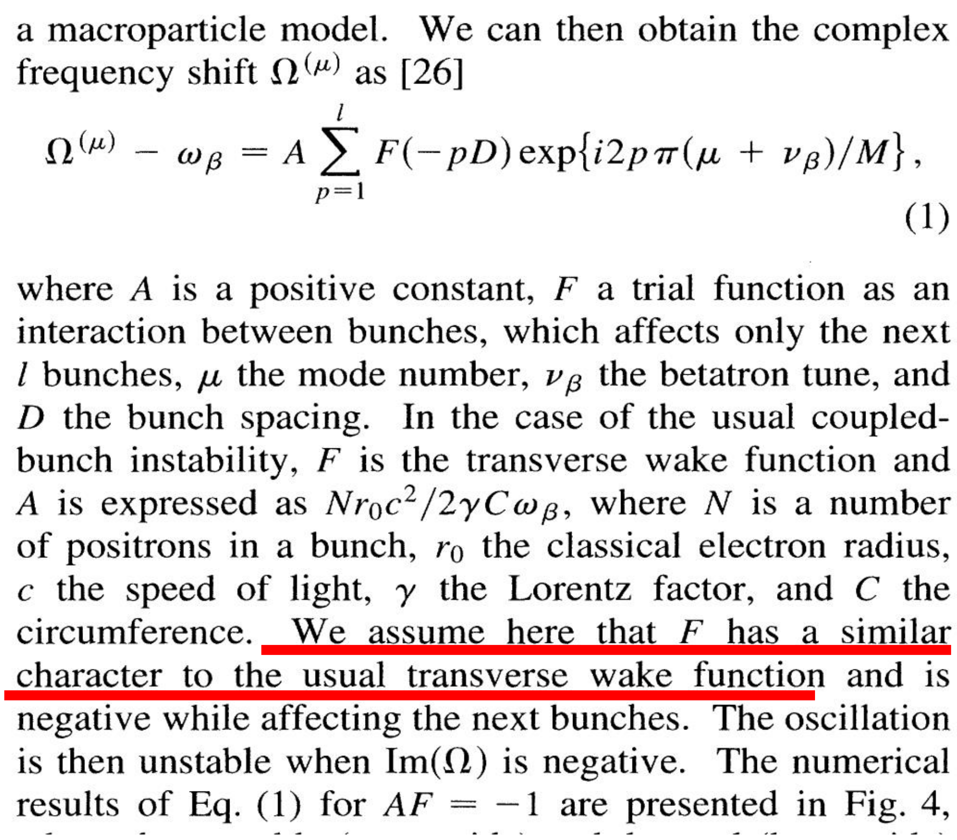
The results of experiments on the vertical instability observed in both positron and electron multibunch accumulations at the Photon Factory storage ring are presented. The betatron sidebands, which indicate a vertical instability, appear at different frequency regions depending on the polarities of the beam. The cause of these instabilities cannot be attributed to the well-known transverse wakefields induced by beam-wall interactions. We propose that these vertical instabilities are induced by electrons in a positron bunched beam, and by trapped ions in an electron bunched beam.

PACS numbers: 29.20.Dh, 29.27.Bd

FIG. 1. Distribution of the betatron sidebands observed during electron multibunch operation with uniform filling.

FIG. 2. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling.

M. Izawa,
Y. Sato,
T. Toyomasa,
1995 [2]



a macroparticle model. We can then obtain the complex frequency shift $\Omega^{(\mu)}$ as [26]

$$\Omega^{(\mu)} - \omega_\beta = A \sum_{p=1}^{l} F(-pD) \exp\{i2p\pi(\mu + \nu_\beta)/M\}, \tag{1}$$

where A is a positive constant, F a trial function as an interaction between bunches, which affects only the next l bunches, μ the mode number, ν_β the betatron tune, and D the bunch spacing. In the case of the usual coupled-bunch instability, F is the transverse wake function and A is expressed as $Nr_0c^2/2\gamma C\omega_\beta$, where N is a number of positrons in a bunch, r_0 the classical electron radius, c the speed of light, γ the Lorentz factor, and C the circumference. We assume here that F has a similar character to the usual transverse wake function and is negative while affecting the next bunches. The oscillation is then unstable when $\text{Im}(\Omega)$ is negative. The numerical results of Eq. (1) for $AF = -1$ are presented in Fig. 4,

M. Izawa, Y. Sato, T. Toyomasa, 1995 [2]

measurement

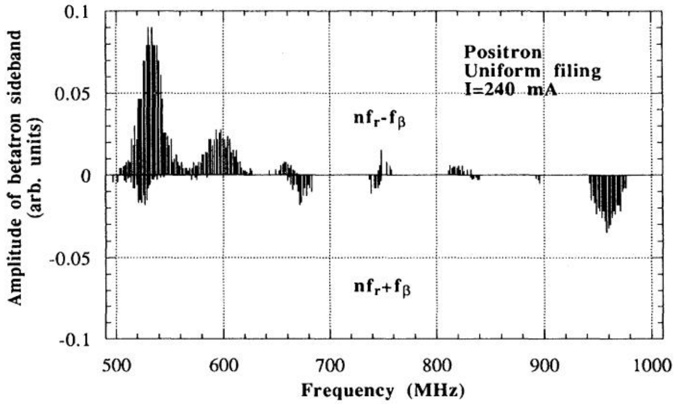


FIG. 3. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling. Only the stored current is different from Fig. 2.

wake model with range of 8 bunches (16 ns)

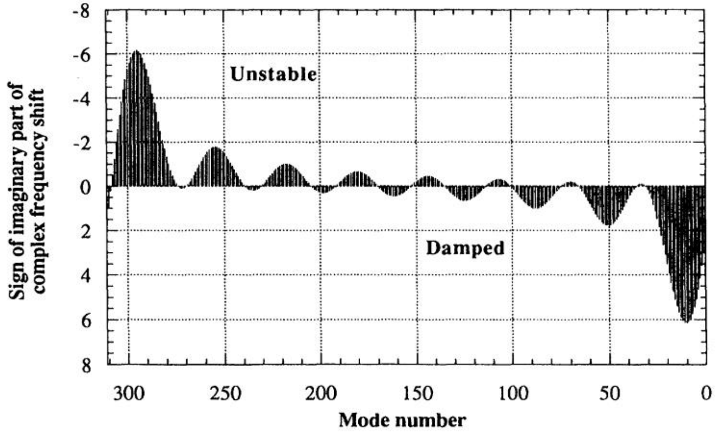
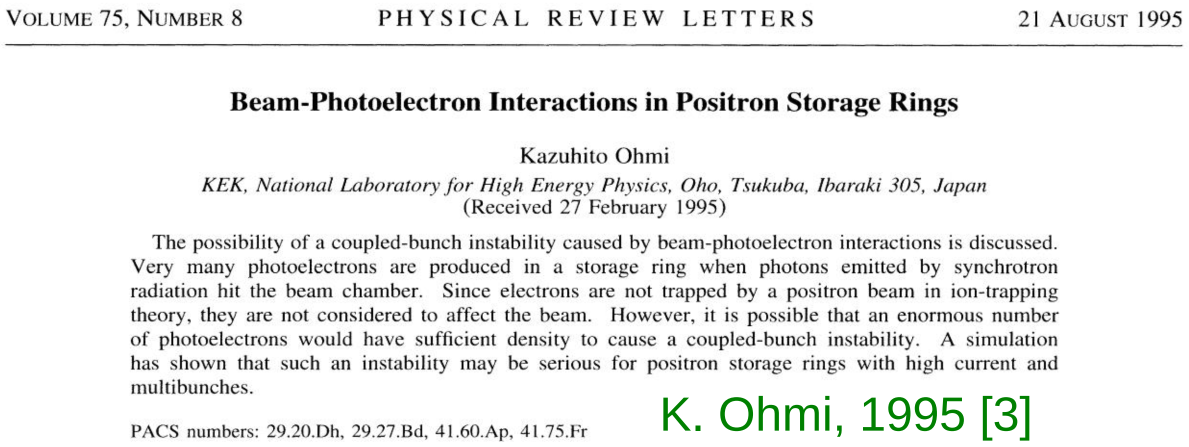


FIG. 4. Numerical results of Eq. (1) for $l = 8$.

theory of coupled-bunch electron-cloud instability

- identified at KEK Photon Factory w. e$^+$ operation
- wake field computed by macro-particle simulation



VOLUME 75, NUMBER 8 PHYSICAL REVIEW LETTERS 21 AUGUST 1995

Beam-Photoelectron Interactions in Positron Storage Rings

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KEK, National Laboratory for High Energy Physics, Oho, Tsukuba, Ibaraki 305, Japan
(Received 27 February 1995)

The possibility of a coupled-bunch instability caused by beam-photoelectron interactions is discussed. Very many photoelectrons are produced in a storage ring when photons emitted by synchrotron radiation hit the beam chamber. Since electrons are not trapped by a positron beam in ion-trapping theory, they are not considered to affect the beam. However, it is possible that an enormous number of photoelectrons would have sufficient density to cause a coupled-bunch instability. A simulation has shown that such an instability may be serious for positron storage rings with high current and multibunches.

PACS numbers: 29.20.Dh, 29.27.Bd, 41.60.Ap, 41.75.Fr

K. Ohmi, 1995 [3]

transient e$^-$ distribution

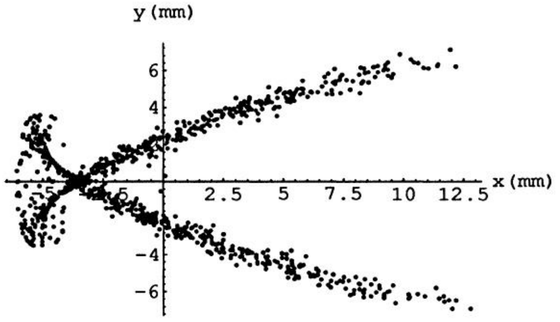


FIG. 1. Transient distributions of photoelectrons emitted by a bunch. The initial electron energy is 0.1 ± 0.01 eV. This is the distribution after the following 27 bunches pass.

simulated wake field

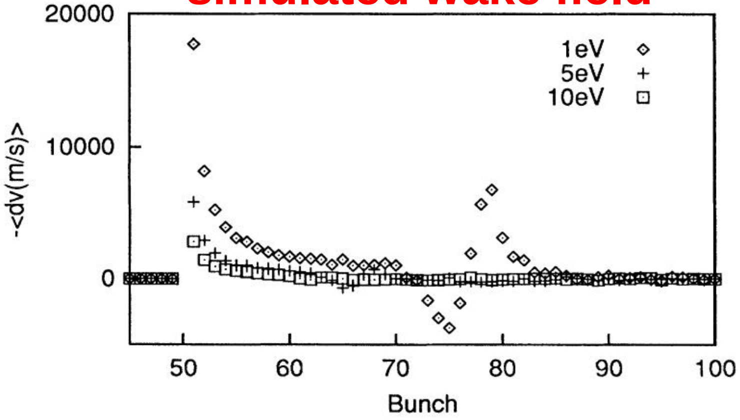


FIG. 3. Wake forces for each initial photoelectron energy. To obtain the wake, 10^6 virtual electrons in every bunch were used.

instability growth rate

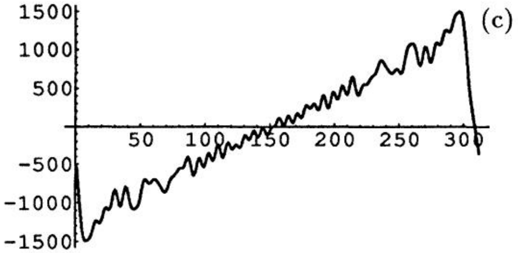
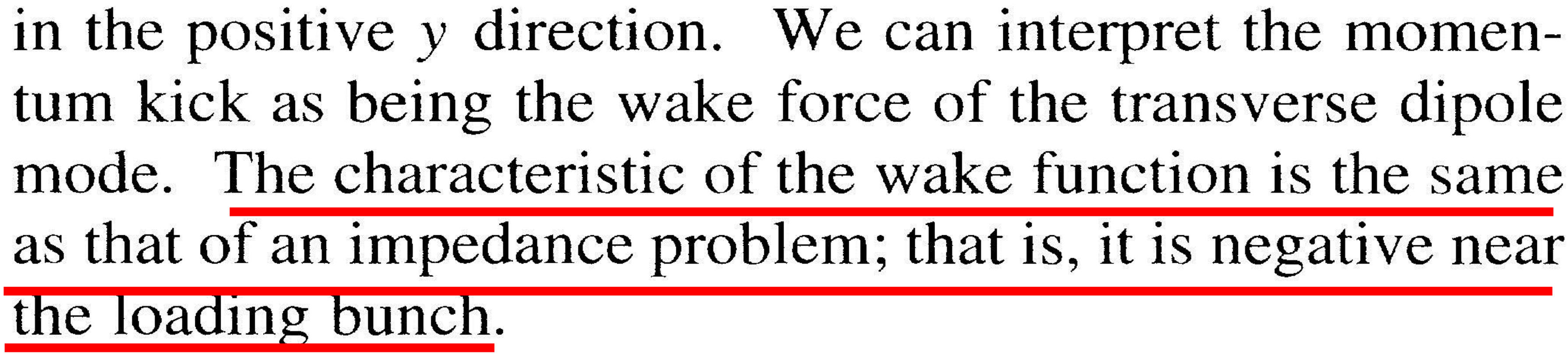


FIG. 4. Growth rates of the coupled-bunch instability. The positive values mean unstable modes. The wakes of 51 to 100 bunches in Fig. 3 were summed with Eq. (8). (a) $\epsilon_0 = 1$ eV. (b) $\epsilon_0 = 5$ eV. (c) $\epsilon_0 = 10$ eV.

$$\Omega_m - \omega_\beta = \frac{i}{4\pi\gamma\nu_y}\frac{N_{e\gamma}}{N_b}\sum_{n=1}^{n_0}\frac{d\bar{v}_y}{dy}\left(\frac{-ncT_{\rm rev}}{h}\right)e^{2\pi in(m+\nu_y)/h}$$

theory of coupled-bunch electron-cloud instability

- perhaps the first mentioning of *“impedance*” in connection with electron cloud

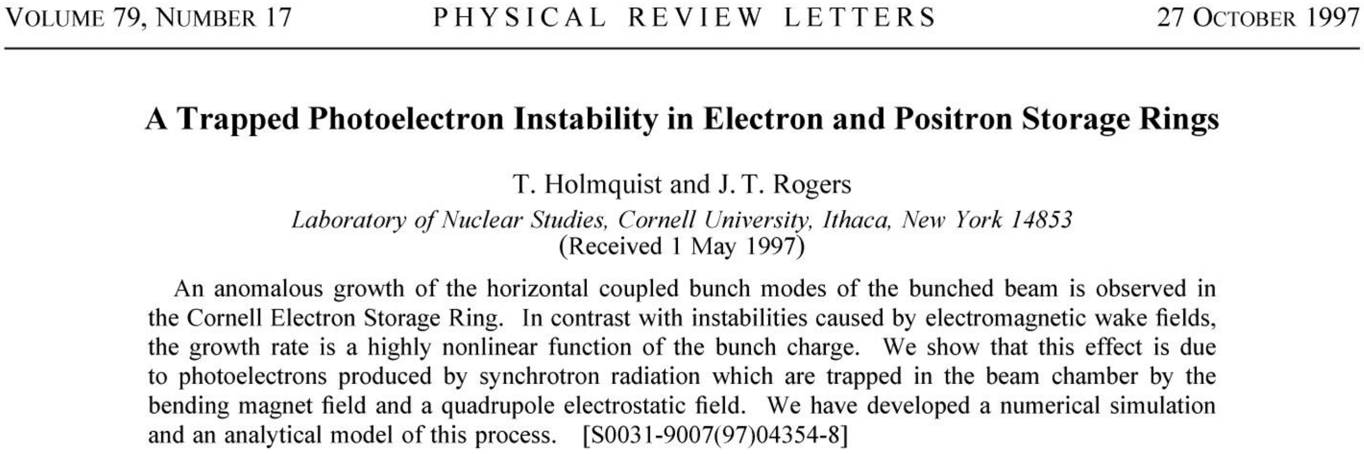


in the positive *y* direction. We can interpret the momentum kick as being the wake force of the transverse dipole mode. The characteristic of the wake function is the same as that of an impedance problem; that is, it is negative near the loading bunch.

K. Ohmi, 1995 [3]

theory of coupled-bunch electron-cloud instability

- explanation of “anomalous anti damping” in CESR
- macro-particle simulations J.T. Rogers & T. Holmquist, 1997 [5]



VOLUME 79, NUMBER 17 PHYSICAL REVIEW LETTERS 27 OCTOBER 1997

A Trapped Photoelectron Instability in Electron and Positron Storage Rings

T. Holmquist and J. T. Rogers
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853

(Received 1 May 1997)

An anomalous growth of the horizontal coupled bunch modes of the bunched beam is observed in the Cornell Electron Storage Ring. In contrast with instabilities caused by electromagnetic wake fields, the growth rate is a highly nonlinear function of the bunch charge. We show that this effect is due to photoelectrons produced by synchrotron radiation which are trapped in the beam chamber by the bending magnet field and a quadrupole electrostatic field. We have developed a numerical simulation and an analytical model of this process. [S0031-9007(97)04354-8]

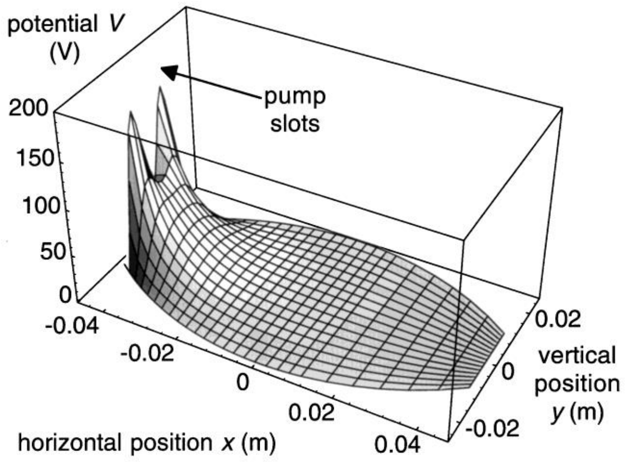


FIG. 1. Electrostatic potential in the CESR beam chamber due to the distributed ion pump.

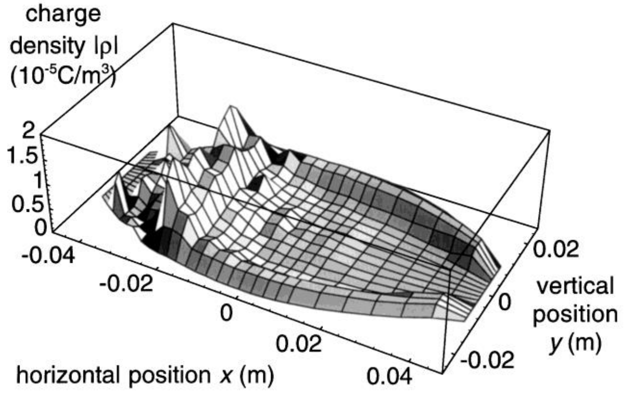


FIG. 2. Calculated charge density in the beam chamber 10 ns after the passage of a bunch.

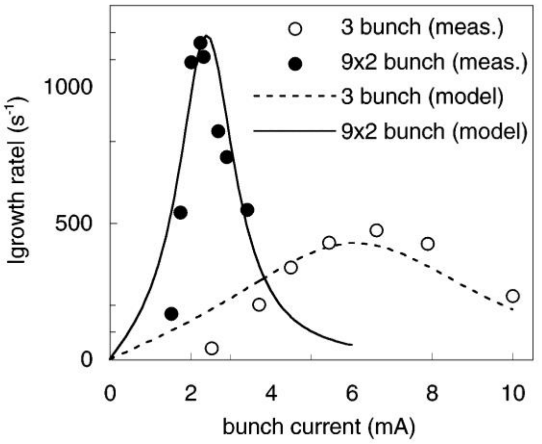
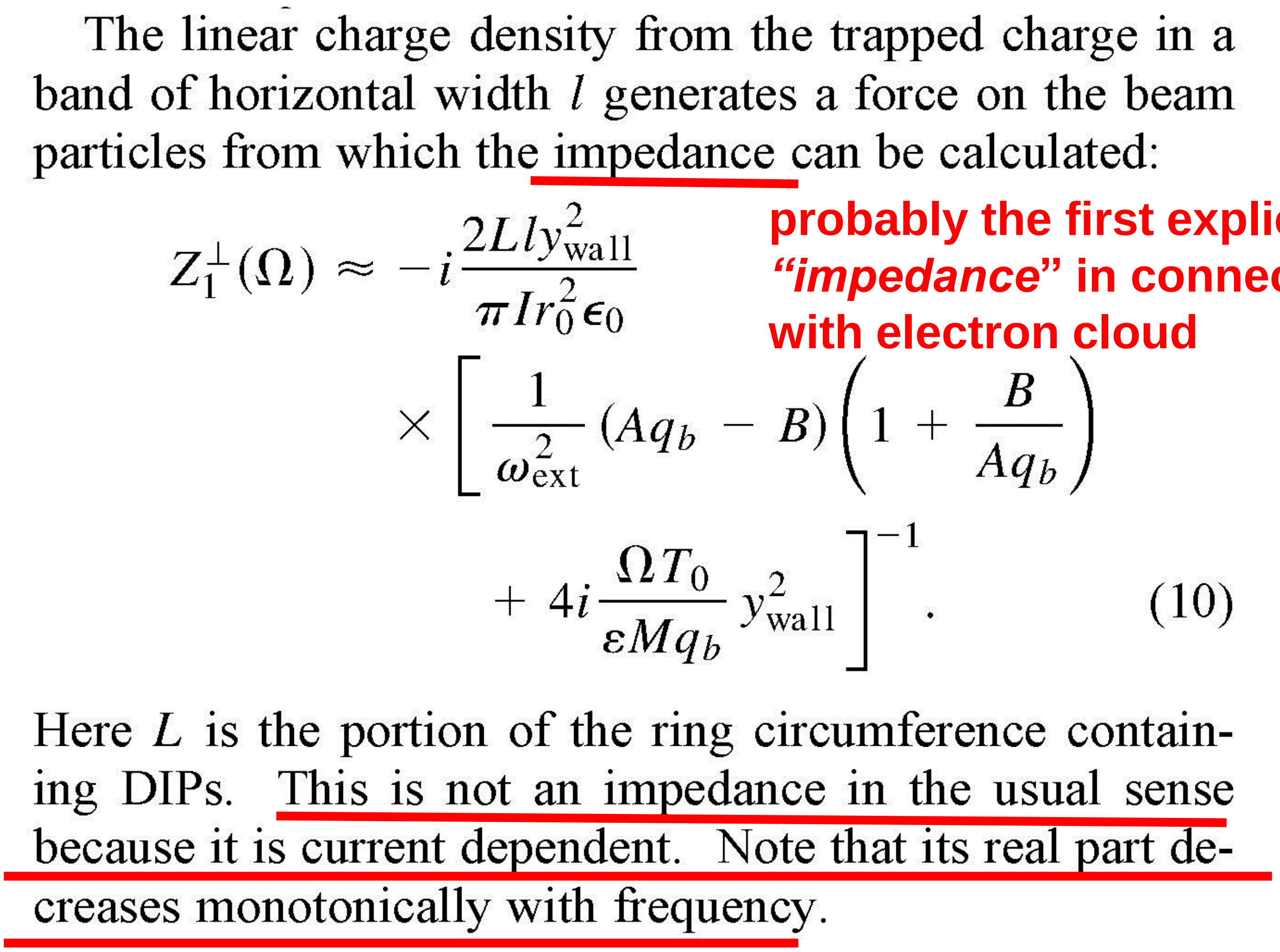


FIG. 4. Horizontal betatron growth rates for the lowest frequency mode, measured in CESR (points) and calculated by the photoelectron model (curves).



The linear charge density from the trapped charge in a band of horizontal width l generates a force on the beam particles from which the impedance can be calculated:

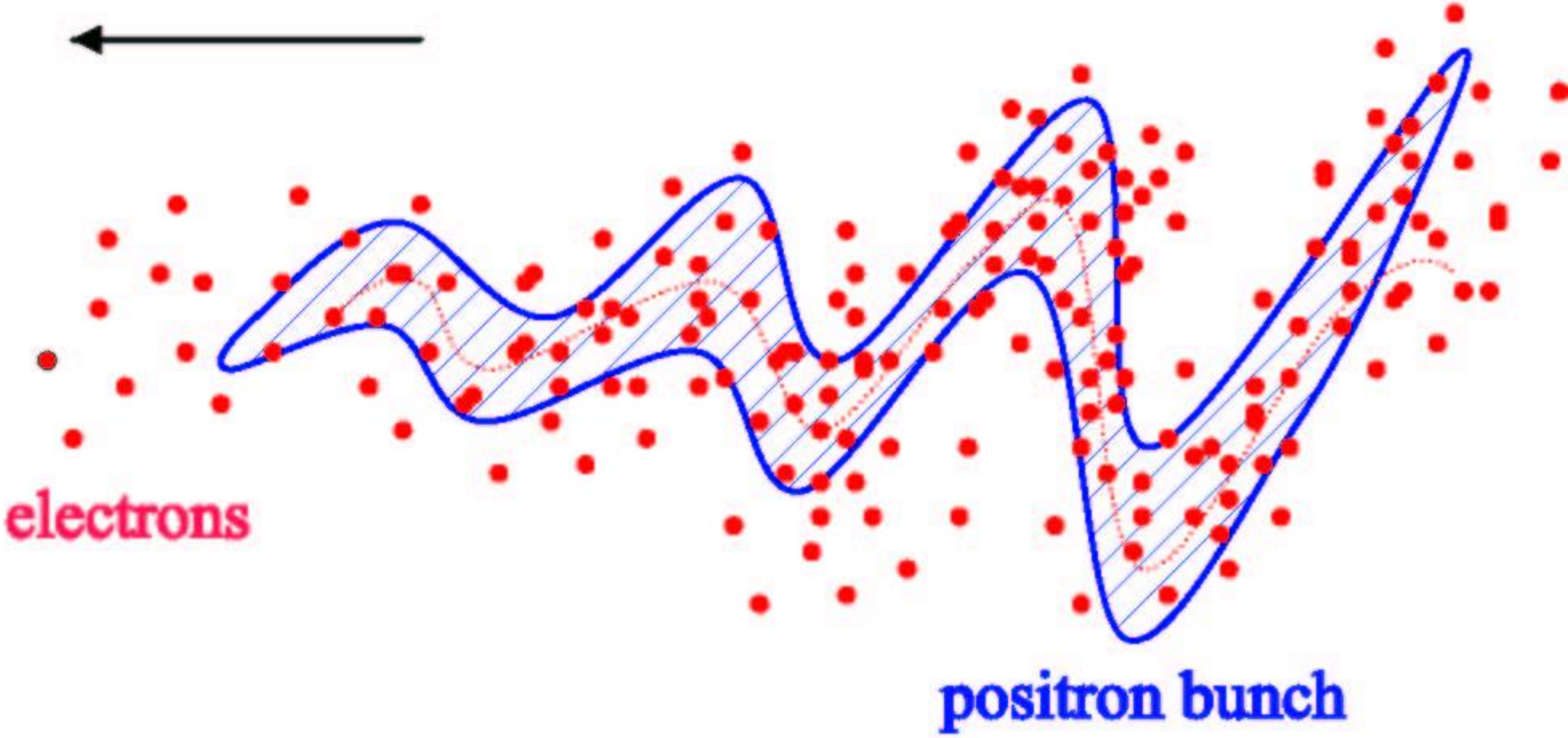
$$Z_1^{\perp}(\Omega) \approx -i\frac{2Lly_{\mathrm{wall}}^2}{\pi I r_0^2 \epsilon_0} \times \left[\frac{1}{\omega_{\mathrm{ext}}^2}(Aq_b - B)\left(1 + \frac{B}{Aq_b}\right) + 4i\frac{\Omega T_0}{\varepsilon M q_b}y_{\mathrm{wall}}^2\right]^{-1}. \qquad (10)$$

Here L is the portion of the ring circumference containing DIPs. This is not an impedance in the usual sense because it is current dependent. Note that its real part decreases monotonically with frequency.

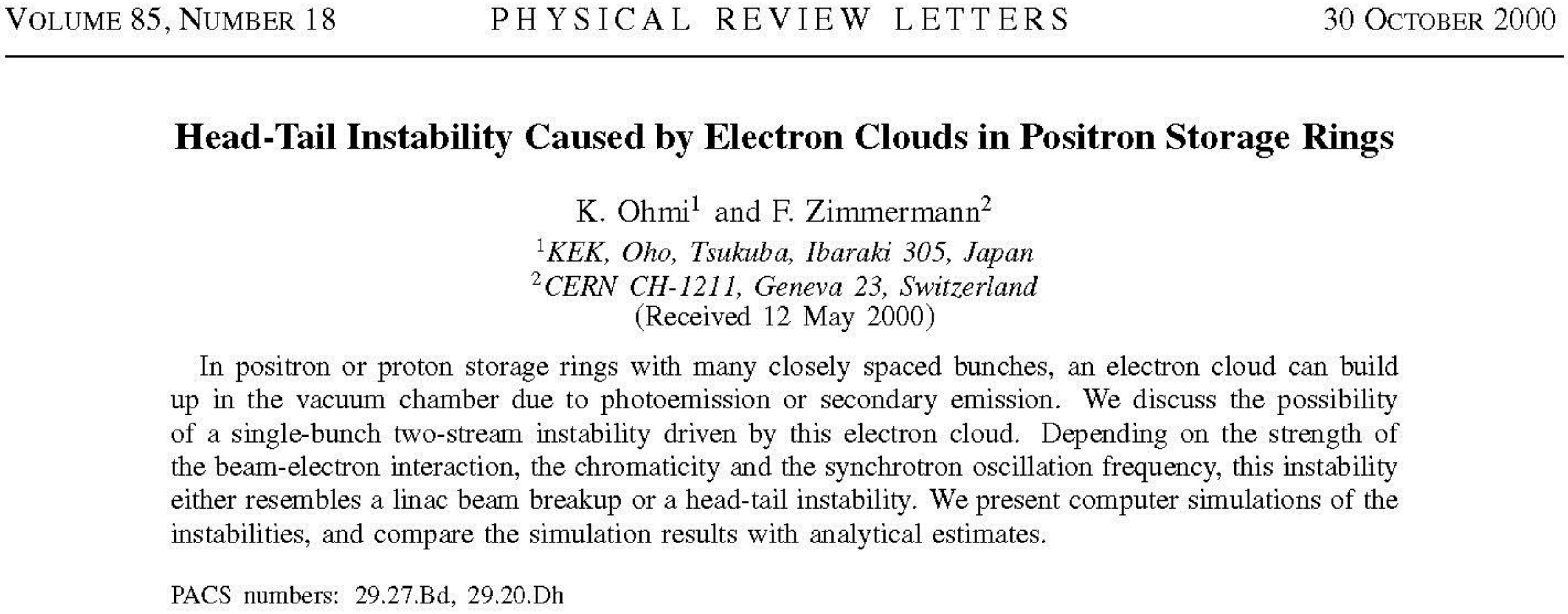
probably the first explicit *“impedance”* in connection with electron cloud

J.T. Rogers & T. Holmquist, 1997 [5]

Single-Bunch e - Cloud Instability



simple wake field model for short bunches



VOLUME 85, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 2000

Head-Tail Instability Caused by Electron Clouds in Positron Storage Rings

K. Ohmi[1] and F. Zimmermann[2]
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[2]*CERN CH-1211, Geneva 23, Switzerland*

(Received 12 May 2000)

In positron or proton storage rings with many closely spaced bunches, an electron cloud can build up in the vacuum chamber due to photoemission or secondary emission. We discuss the possibility of a single-bunch two-stream instability driven by this electron cloud. Depending on the strength of the beam-electron interaction, the chromaticity and the synchrotron oscillation frequency, this instability either resembles a linac beam breakup or a head-tail instability. We present computer simulations of the instabilities, and compare the simulation results with analytical estimates.

PACS numbers: 29.27.Bd, 29.20.Dh

analytical estimates of equilibrium electron density, wake field and coherent tune shift

$$\rho_e^{sat} = \frac{\langle E_0 \rangle}{m_e c^2} \frac{1}{b^2 r_e}$$

e$^-$ density due to space charge and thermal energy

S. Heifets, 2002 [11]

$$\rho_e^{sat} = \frac{N_b}{\pi b^2 L_{sep}}$$

e$^-$ density due to charge neutralization

F.Zimmermann, 1997 [4]

$$W_0 \approx (4...8) \frac{\pi \rho_e C}{N_b}$$

SB and CB wake of e$^-$ cloud

K. Ohmi, F.Zimmermann, 2000 [6]

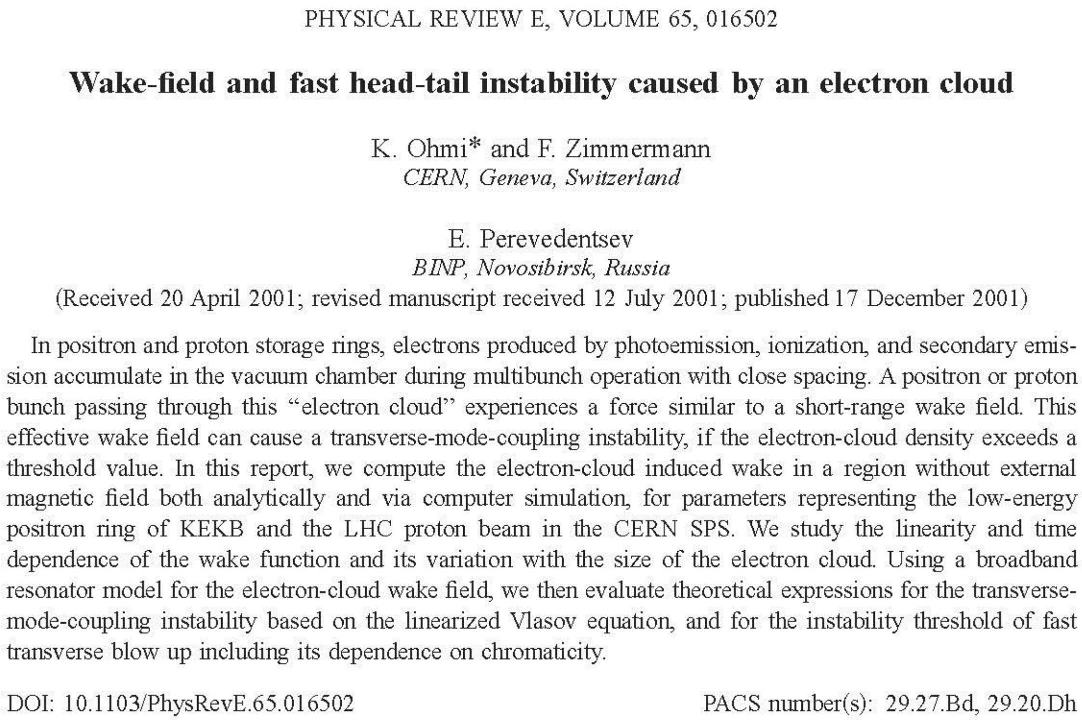
G. Rumolo, F.Zimmermann, 2001[9]

$$\Delta Q \approx \frac{r_e}{2\gamma} \langle \beta \rangle \rho_e C$$

coherent tune shift due to e$^-$ cloud

K.Ohmi, S.Heifets, F.Zimmermann, 2001 [8]

resonator model of e-cloud wake



PHYSICAL REVIEW E, VOLUME 65, 016502

Wake-field and fast head-tail instability caused by an electron cloud

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E. Perevedentsev
BINP, Novosibirsk, Russia

(Received 20 April 2001; revised manuscript received 12 July 2001; published 17 December 2001)

In positron and proton storage rings, electrons produced by photoemission, ionization, and secondary emission accumulate in the vacuum chamber during multibunch operation with close spacing. A positron or proton bunch passing through this "electron cloud" experiences a force similar to a short-range wake field. This effective wake field can cause a transverse-mode-coupling instability, if the electron-cloud density exceeds a threshold value. In this report, we compute the electron-cloud induced wake in a region without external magnetic field both analytically and via computer simulation, for parameters representing the low-energy positron ring of KEKB and the LHC proton beam in the CERN SPS. We study the linearity and time dependence of the wake function and its variation with the size of the electron cloud. Using a broadband resonator model for the electron-cloud wake field, we then evaluate theoretical expressions for the transverse-mode-coupling instability based on the linearized Vlasov equation, and for the instability threshold of fast transverse blow up including its dependence on chromaticity.

DOI: 10.1103/PhysRevE.65.016502 PACS number(s): 29.27.Bd, 29.20.Dh

K. Ohmi, F. Zimmermann,
E. Perevedentsev, 2001 [7]

analytical solution for coasting beam, rigid Gaussian cloud of size equal to beam size and linear force

$$W_1(z)[\mathrm{m}^{-2}] = cR_S/Q \sin\left(\frac{\omega_c}{c} z\right) \quad \text{for} \quad z<0,$$

$$cR_S/Q = \frac{\gamma \omega_b^2 \omega_c}{\lambda_b r_c c^3} L \qquad \text{with} \qquad \omega_{b,y}^2 = \frac{2\lambda_c r_e c^2}{\gamma k_y(\sigma_x+\sigma_y)\sigma_y}, \qquad \omega_{c,y}^2 = \frac{2\lambda_b r_e c^2}{k_y(\sigma_x+\sigma_y)\sigma_y},$$

simulated e-cloud wake for varying cloud size

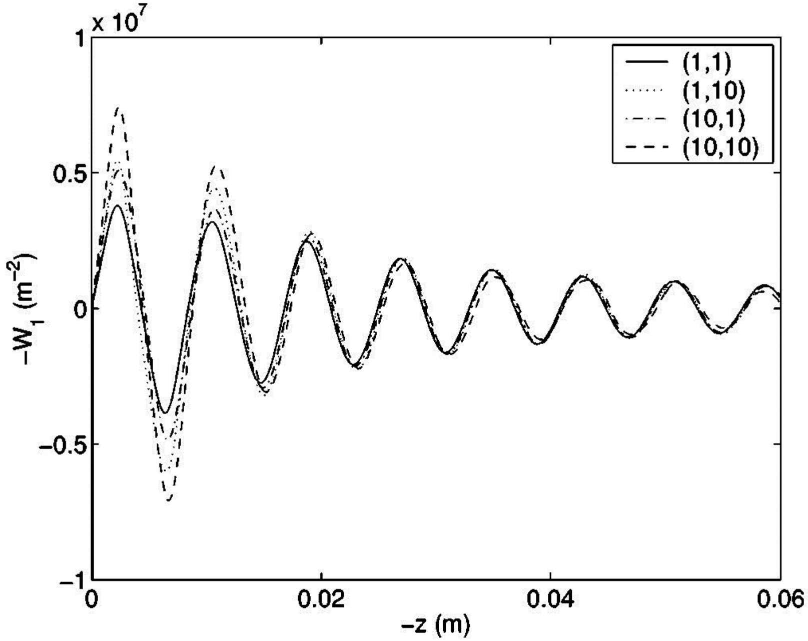


FIG. 1. Vertical wake force (W_1) induced by an electron cloud. Each line corresponds to a different size of the electron cloud: (1,1), (1,10), (10,1), and (10,10), in units of (σ_x, σ_y).

K. Ohmi, F. Zimmermann,
E. Perevedentsev, 2001 [7]

fitted to

$$W(z) = c\,\frac{R_S}{Q}\,\frac{\omega_R}{\bar{\omega}}\exp\left(\frac{\alpha}{c}z\right)\sin\left(\frac{\bar{\omega}}{c}z\right)$$

where $\alpha = \omega_R/2Q$ and $\bar{\omega} = \sqrt{\omega_R^2 - \alpha^2}$. Note that z is negative for the tail of the beam.

wake strength vs cloud size

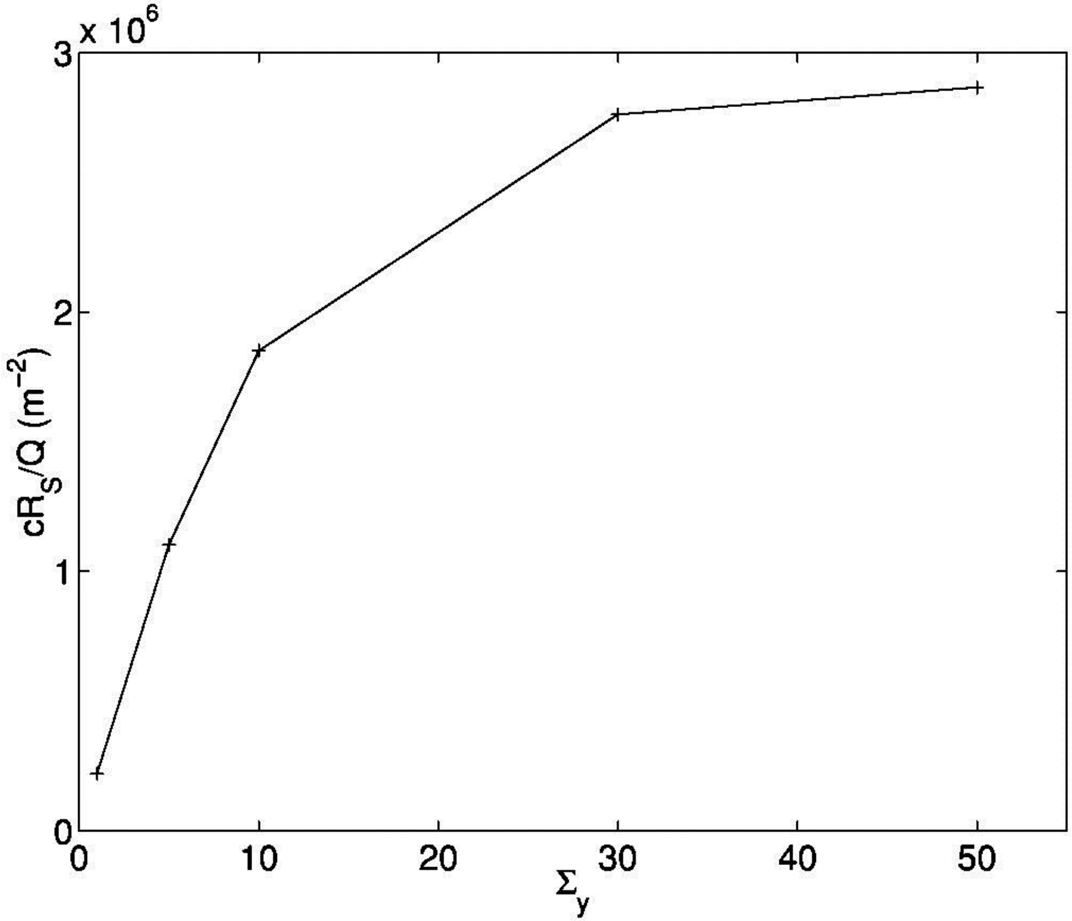


FIG. 3. Variation of cR_S/Q fitted from the simulation as a function of the vertical cloud size. The horizontal cloud size is held constant, equal to $10\times\sigma_x$.

K. Ohmi, F. Zimmermann,
E. Perevedentsev, 2001 [7]

fitted vs analytical wake

analytical
calculation
$\sigma_e = \sigma_{beam}$

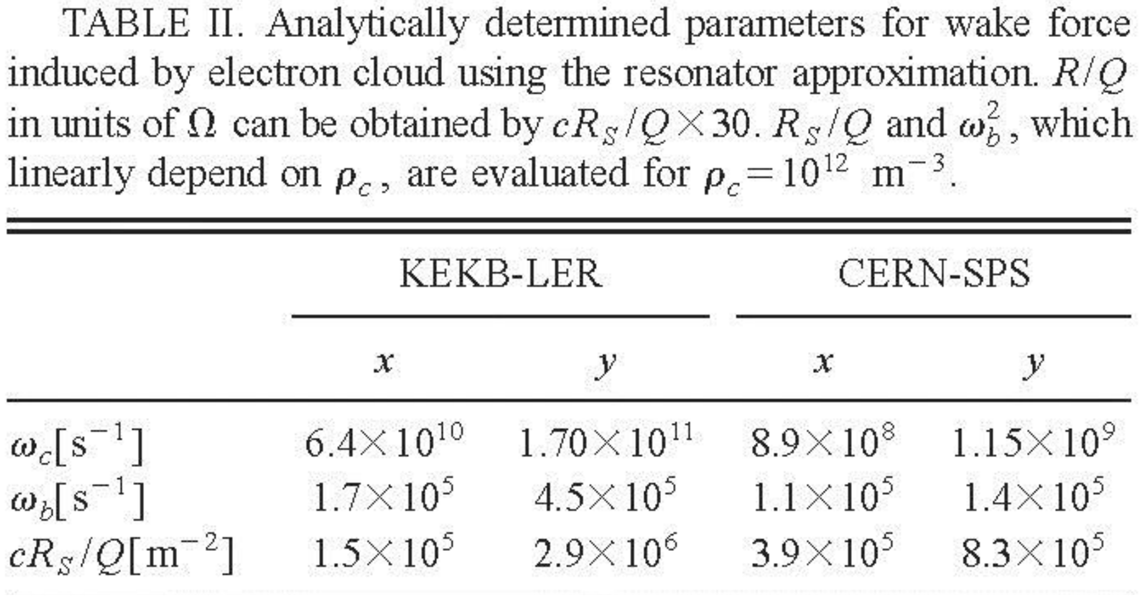


TABLE II. Analytically determined parameters for wake force induced by electron cloud using the resonator approximation. R/Q in units of Ω can be obtained by $cR_S/Q \times 30$. R_S/Q and ω_b^2, which linearly depend on ρ_c, are evaluated for $\rho_c = 10^{12}\ \mathrm{m}^{-3}$.

	KEKB-LER		CERN-SPS	
	x	y	x	y
$\omega_c[\mathrm{s}^{-1}]$	6.4×10^{10}	1.70×10^{11}	8.9×10^{8}	1.15×10^{9}
$\omega_b[\mathrm{s}^{-1}]$	1.7×10^{5}	4.5×10^{5}	1.1×10^{5}	1.4×10^{5}
$cR_S/Q[\mathrm{m}^{-2}]$	1.5×10^{5}	2.9×10^{6}	3.9×10^{5}	8.3×10^{5}

simulation
$\sigma_e =$
$10\text{-}50\ \sigma_{beam}$

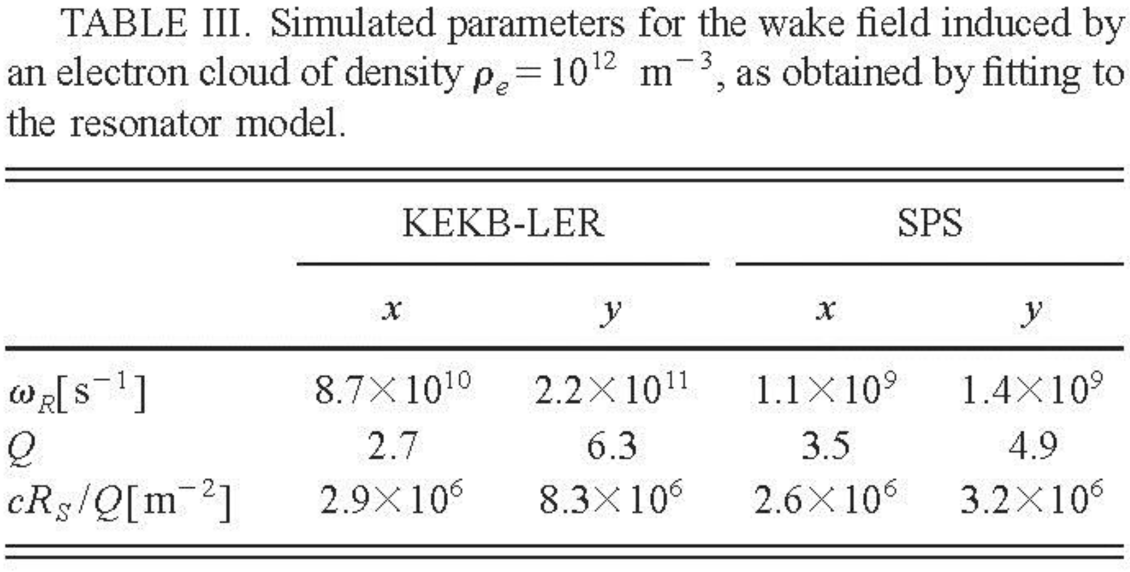


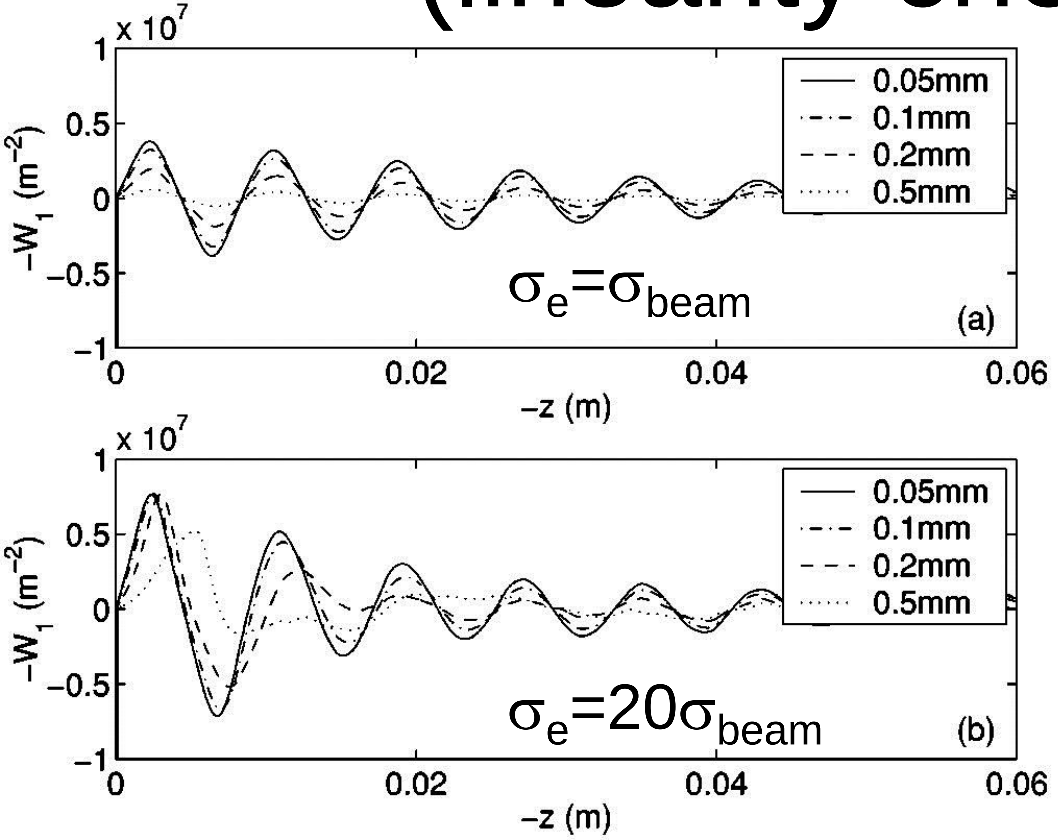
TABLE III. Simulated parameters for the wake field induced by an electron cloud of density $\rho_e = 10^{12}\ \mathrm{m}^{-3}$, as obtained by fitting to the resonator model.

	KEKB-LER		SPS	
	x	y	x	y
$\omega_R[\mathrm{s}^{-1}]$	8.7×10^{10}	2.2×10^{11}	1.1×10^{9}	1.4×10^{9}
Q	2.7	6.3	3.5	4.9
$cR_S/Q[\mathrm{m}^{-2}]$	2.9×10^{6}	8.3×10^{6}	2.6×10^{6}	3.2×10^{6}

K. Ohmi, F. Zimmermann,
E. Perevedentsev, 2001

wake strength vs transverse offset (linearity check)

K. Ohmi, F. Zimmermann, E. Perevedentsev, 2001 [7]



$\sigma_e = \sigma_{beam}$

$\sigma_e = 20\sigma_{beam}$

FIG. 4. Linearity of the vertical wake force induced by an electron cloud for a flat beam. Each line corresponds to a different displacement, of 0.05, 0.1, 0.2, and 0.5 mm. The vertical beam size is 0.06 mm. The two pictures refer to cloud sizes of (1,1) and (20,20), respectively.

wake strength vs longitudinal position of displaced "slice"

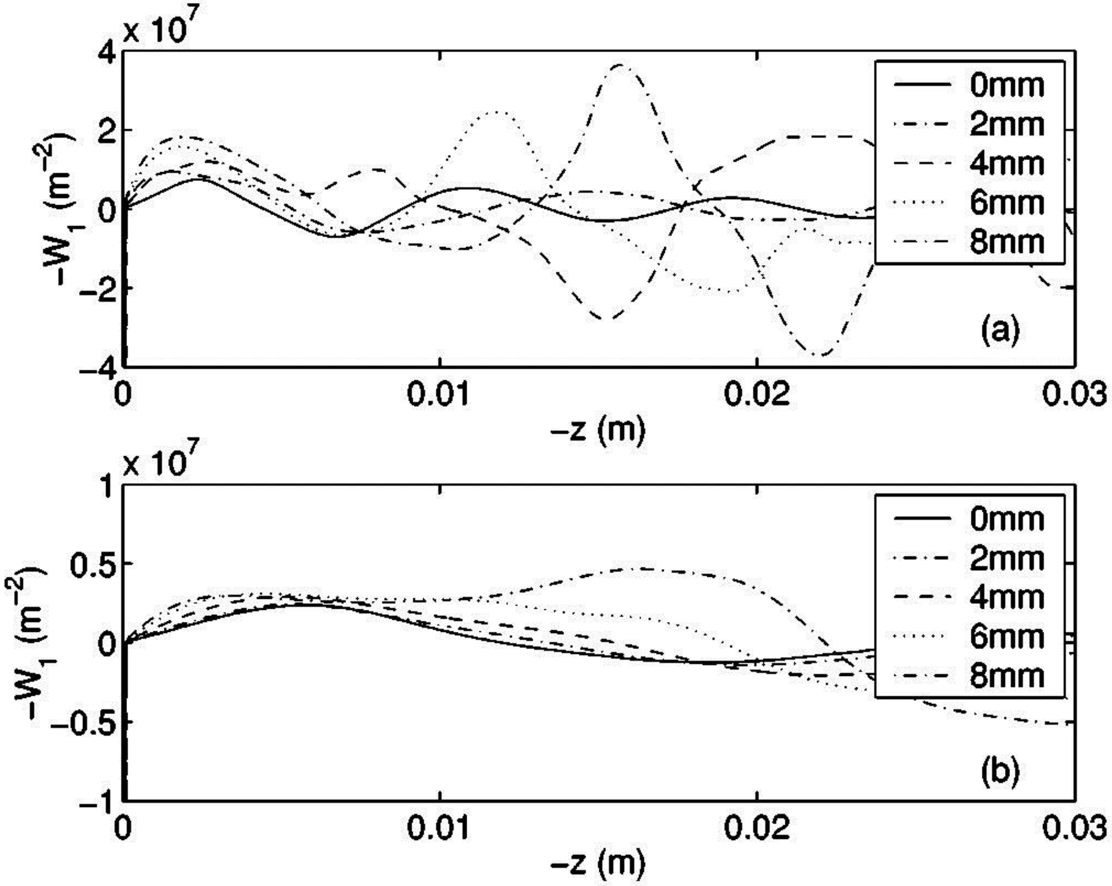


FIG. 6. Vertical and horizontal wake field computed by displacing microbunches at various longitudinal positions along the bunch, for electron-cloud sizes of (10,10) and (10,50), respectively.

KEKB-LER

K. Ohmi,
F. Zimmermann,
E. Perevedentsev,
2001 [7]

wake strength vs longitudinal position of displaced “slice”

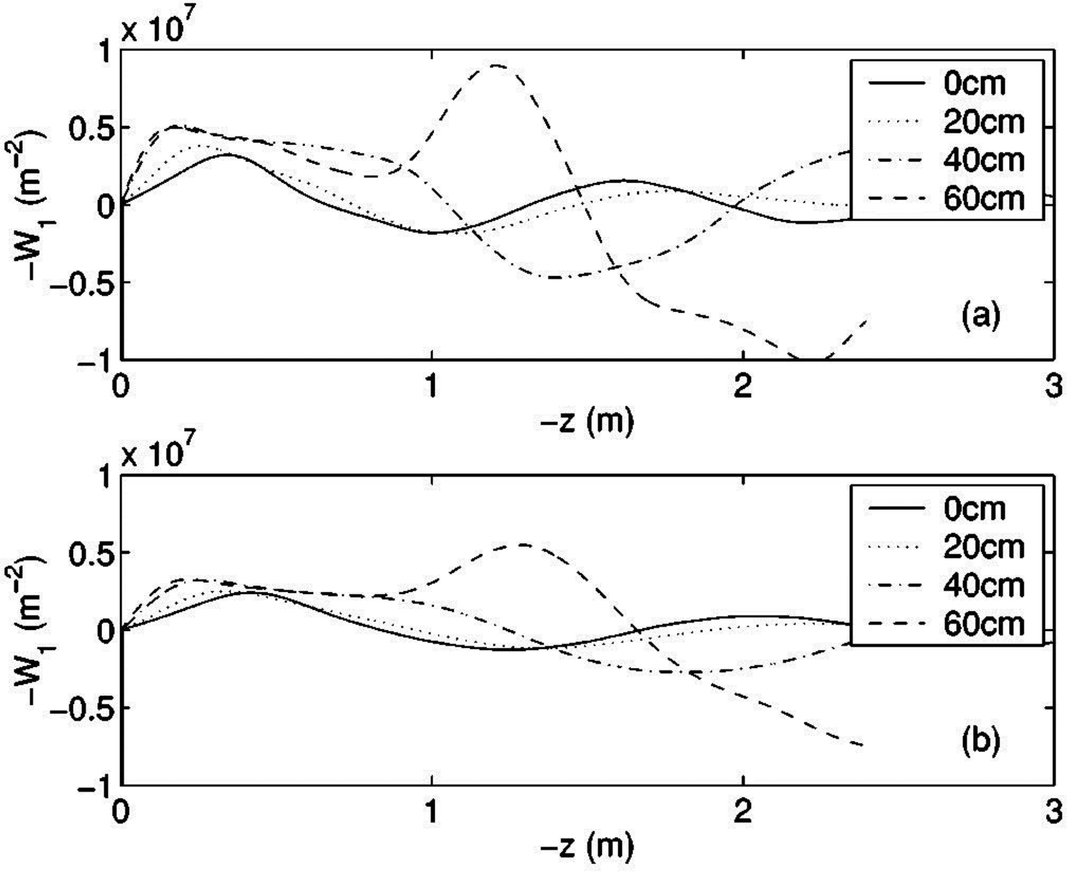


FIG. 9. Vertical and horizontal wake field computed for displacements of microbunches at various longitudinal positions, and an electron-cloud size of (20,20) in units of the two rms beam sizes.

SPS

K. Ohmi,
F. Zimmermann,
E. Perevedentsev,
2001 [7]

e-cloud resonator impedance

$$Z_1(\omega)=i\int_{-\infty}^{\infty}\frac{dz}{c}e^{-i\omega z/c}W(z)$$

$$Z_1(\omega)=\frac{c}{\omega}\frac{R_S}{1+iQ\left(\frac{\omega_R}{\omega}-\frac{\omega}{\omega_R}\right)}.$$

K. Ohmi,
F. Zimmermann,
E. Perevedentsev,
2001 [7]

wake fields from 3-D e-cloud computations (e.g. for wiggler)

average e- cloud density in 2D and 3D calculation

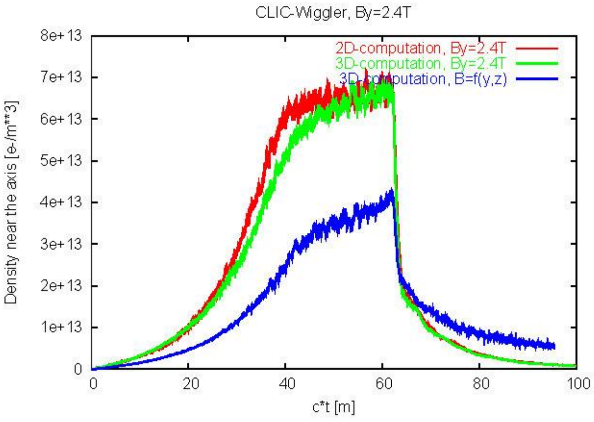


Figure 3: Time dependence of the electron density near the axis in a wiggler section with a period length of 5 cm. The transverse dimensions of the beam pipe are 32 mm times 18 mm. The amplitude of the wiggler field is 2.4 Tesla. Red curve: Result of a 2D computation, ie no Ez-fields are possible. Green: Result of a 3D-computation, but the wiggler field is assumed to be By=2.4 Tesla everywhere. Blue: Result of a 3D-computation, where the Wigglerfield is a realistic 3D field with amplitude 2.4 Tesla.

***s*-dependent e- cloud density in 3D calculation**

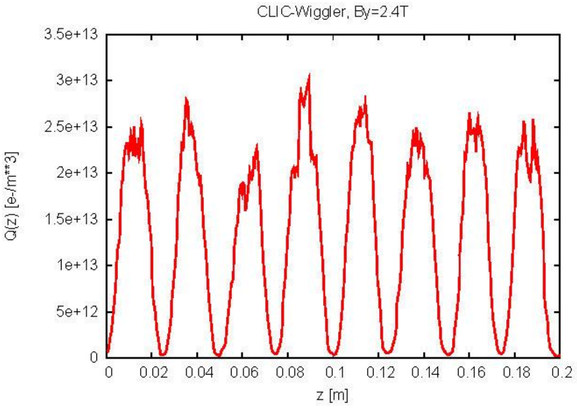


Figure 5: Time average of the electron density near the axis in the wiggler. The minima of the density occur at the zeros of the By-component. Four wiggler periods were modeled to also be able to model the periodic occurence of the exciting charge, which has a periodicity of c*T = 0.2 metres.

***z=ct*-dependent e- cloud wake potential**

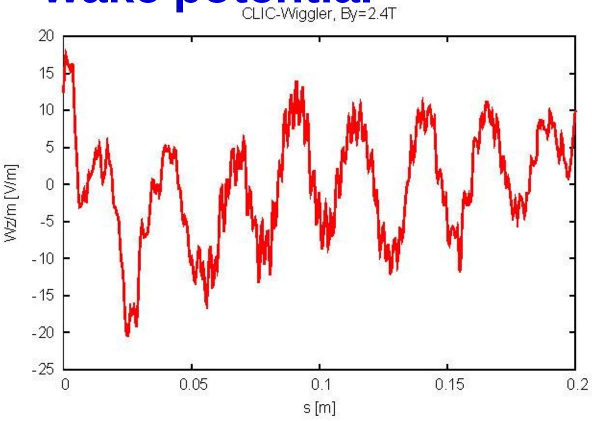
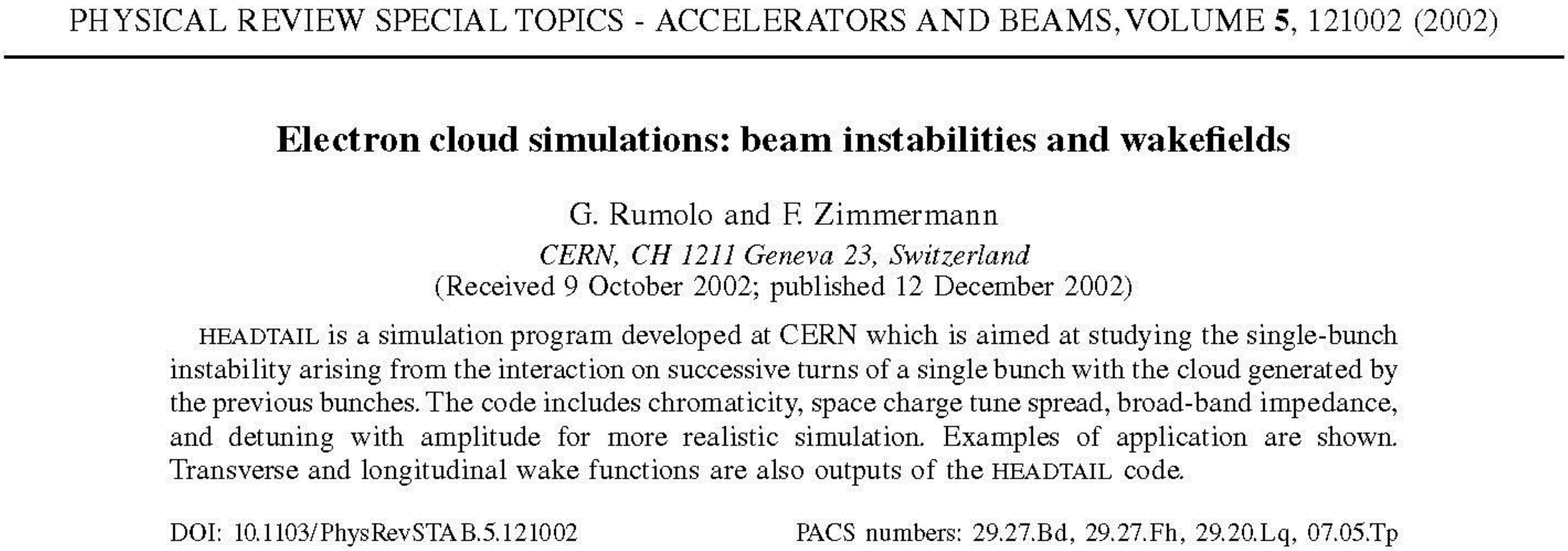


Figure 7: Wakepotential due to the electron cloud in the wiggler. The exciting bunches have a periodicity of 0.2 m, therefore the shown data repeats after 0.2 metres. The seen period length corresponds to the period of the magnetic field.

W. Bruns et al,
PAC07,
2007

unusual wake behavior



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **5**, 121002 (2002)

Electron cloud simulations: beam instabilities and wakefields

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CERN, CH 1211 Geneva 23, Switzerland
(Received 9 October 2002; published 12 December 2002)

HEADTAIL is a simulation program developed at CERN which is aimed at studying the single-bunch instability arising from the interaction on successive turns of a single bunch with the cloud generated by the previous bunches. The code includes chromaticity, space charge tune spread, broad-band impedance, and detuning with amplitude for more realistic simulation. Examples of application are shown. Transverse and longitudinal wake functions are also outputs of the HEADTAIL code.

DOI: 10.1103/PhysRevSTAB.5.121002 PACS numbers: 29.27.Bd, 29.27.Fh, 29.20.Lq, 07.05.Tp

simulated by HEADTAIL code

G. Rumolo, F. Zimmermann, 2002 [12]

unusual wake behavior

wake averaged over a beam slice ≠ wake on axis

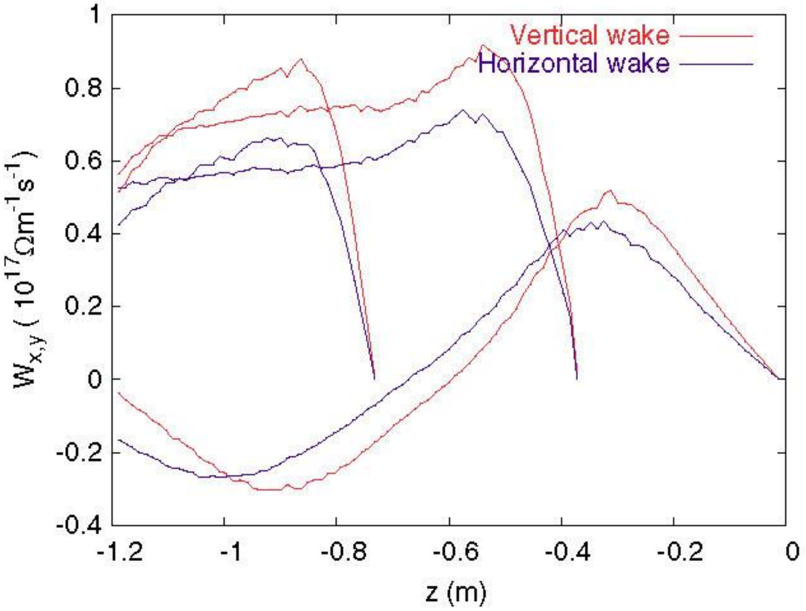


FIG. 7. (Color) Horizontal and vertical averaged dipole wake functions for a uniform SPS bunch, evaluated displacing three different bunch slices at $t = 0$, $3/10\Delta t_b$, and $3/5\Delta t_b$. The simulation has been carried out in a field-free region.

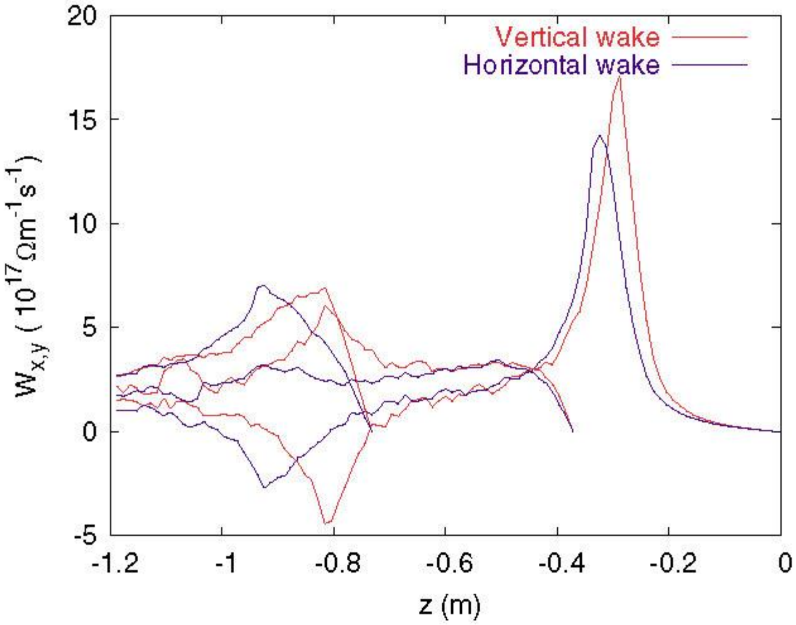


FIG. 8. (Color) Horizontal and vertical wake functions on axis for a uniform SPS bunch, evaluated displacing three different bunch slices at $t = 0$, $3/10\Delta t_b$, and $3/5\Delta t_b$. The simulation has been carried out in a field-free region.

wake depends on longitudinal position of displaced slice

G. Rumolo, F. Zimmermann, 2002 [12]

generalization of transverse impedance

- must consider wake $W_1(z,z')$, not $W_1(z-z')$

$$W_1(z,z') = \int\int \frac{d\omega}{2\pi}\frac{d\omega'}{2\pi}\frac{1}{i}\hat{Z}_1(\omega,\omega')e^{i(\omega z-\omega' z')/c}$$

2-dimensional Fourier transform

E. Perevedentsev, 2002 [10]

- the wake $W_1(z,z')$ can be obtained from simulations

Standard case: Wake Function in the form $W(z-z')$

In the TMC theory obtained from Vlasov equation, the complex frequency shift due to an external impedance is solution of the eigenvalue problem:

$$\frac{\Omega-\omega_\beta}{\omega_s}a_{lk} = F(M_{l,k,l',k'})\ ,$$

standard TMCI

where

$$M_{l,k,l',k'} = -\mathrm{i}\frac{N_b \mathrm{r}_e \mathrm{c}}{2\gamma T_0 \omega_\beta \omega_s}\mathrm{i}^{(l-l')}\int_{-\infty}^{\infty} Z_1(\omega) g_{lk}(\omega-\omega_\xi) g_{l'k'}(\omega-\omega_\xi)\mathrm{d}\omega\ .$$

The wake force enters via its impedance representation:

$$Z_1(\omega) = \mathrm{i}\int_{-\infty}^{\infty}\frac{\mathrm{d}z}{\mathrm{c}}\mathrm{e}^{\mathrm{i}\omega z/\mathrm{c}}W_1(z)$$

This is true if the wake field is a function only of the difference $z-z'$ (distance between the displaced slice and the slice on which the wake acts)

E. Perevedentsev, 2002 [12]

General case: Wake Function in the form $W(z,z')$

For more general situations, such as the e-cloud response to dipole perturbations, translation invariance does not hold. We need to introduce a *generalized impedance*:

generalized TMCI

$$\hat{Z}_1(\omega,\omega') = \mathrm{i}\int\!\!\int \frac{\mathrm{d}z}{c}\frac{\mathrm{d}z'}{c} W(z,z')\mathrm{e}^{\mathrm{i}\frac{\omega z - \omega' z'}{c}}$$

The eigenvalue problem becomes

$$\left(\frac{\Omega-\omega_\beta}{\omega_s} - l\right) a_{lk} = -\frac{N_b r_e c}{2\gamma\omega_\beta\omega_s T_0}\sum_{l'k'}\hat{M}_{lk,l'k'}a_{l'k'} \ ,$$

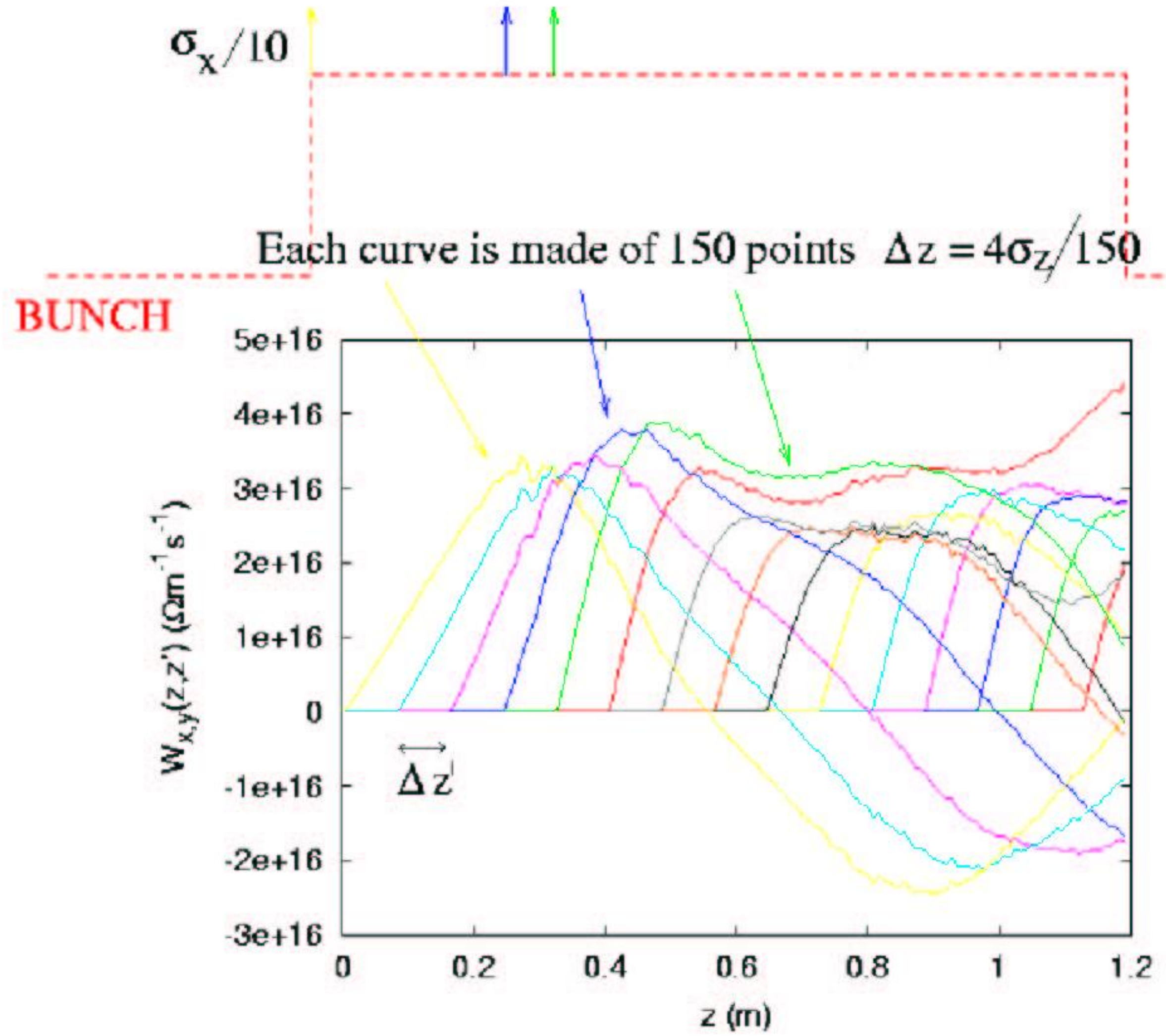
where the $\hat{M}_{lk,l'k'}$ are a function of the double frequency impedance. For a Gaussian bunch, for instance:

$$\hat{M}_{lk,l'k'} = -\mathrm{i}\frac{N_b r_e c}{8\pi^2\gamma\omega_\beta\omega_s T_0}\frac{\mathrm{i}^{(l-l')}\epsilon(l)\epsilon(l')}{\sqrt{k!(|l|+k)!k'!(|l'|+k')!}}$$

$$\times\int\!\!\int \mathrm{d}\omega \mathrm{d}\omega' \hat{Z}_1(\omega+\omega_\xi,\omega'+\omega_\xi)\left(\frac{\omega\sigma}{\sqrt{2}c}\right)^{|l|+2k}\left(\frac{\omega'\sigma}{\sqrt{2}c}\right)^{|l'|+2k'}\mathrm{e}^{-(\omega^2+\omega'^2)\sigma^2/2c^2}$$

E. Perevedentsev, 2002 [12]

extracting the 2-dimensional wake

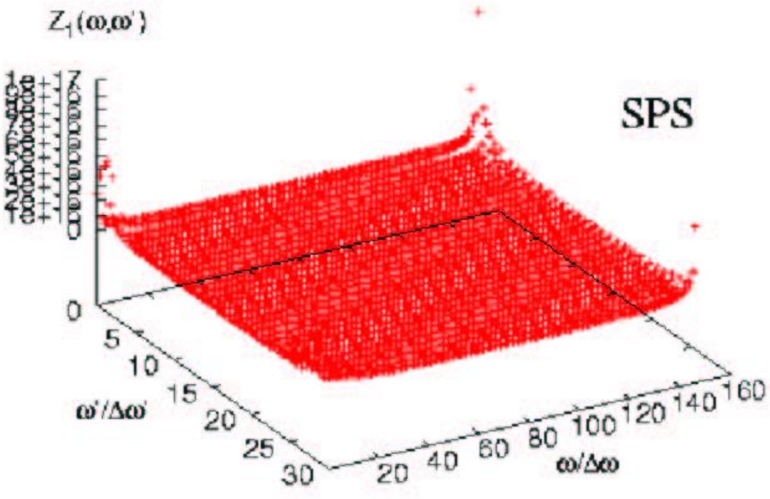


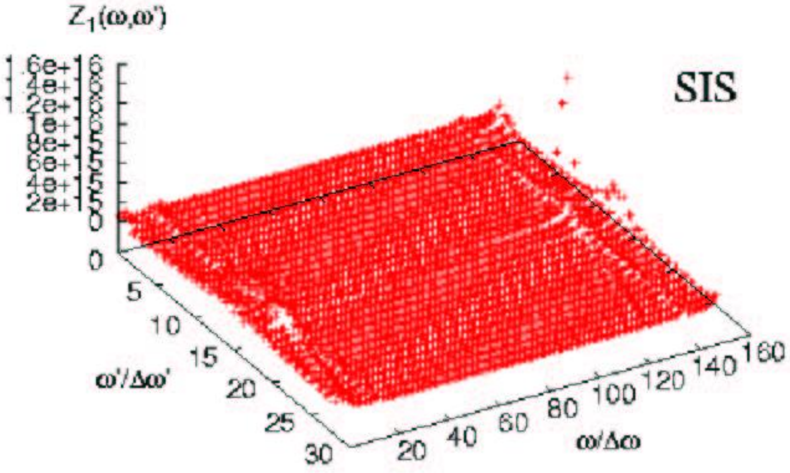
All the points have been ordered in a matrix, on which we have subsequently performed a double Fourier transform.

We have used a uniform bunch profile in order to get the Green function, and tranform it to get the impedance.

G. Rumolo, 2002 [13]

2-dimensional impedance for SPS & SIS





G. Rumolo, 2002 [13]

2-dimensional wake matrix for KEKB-LER

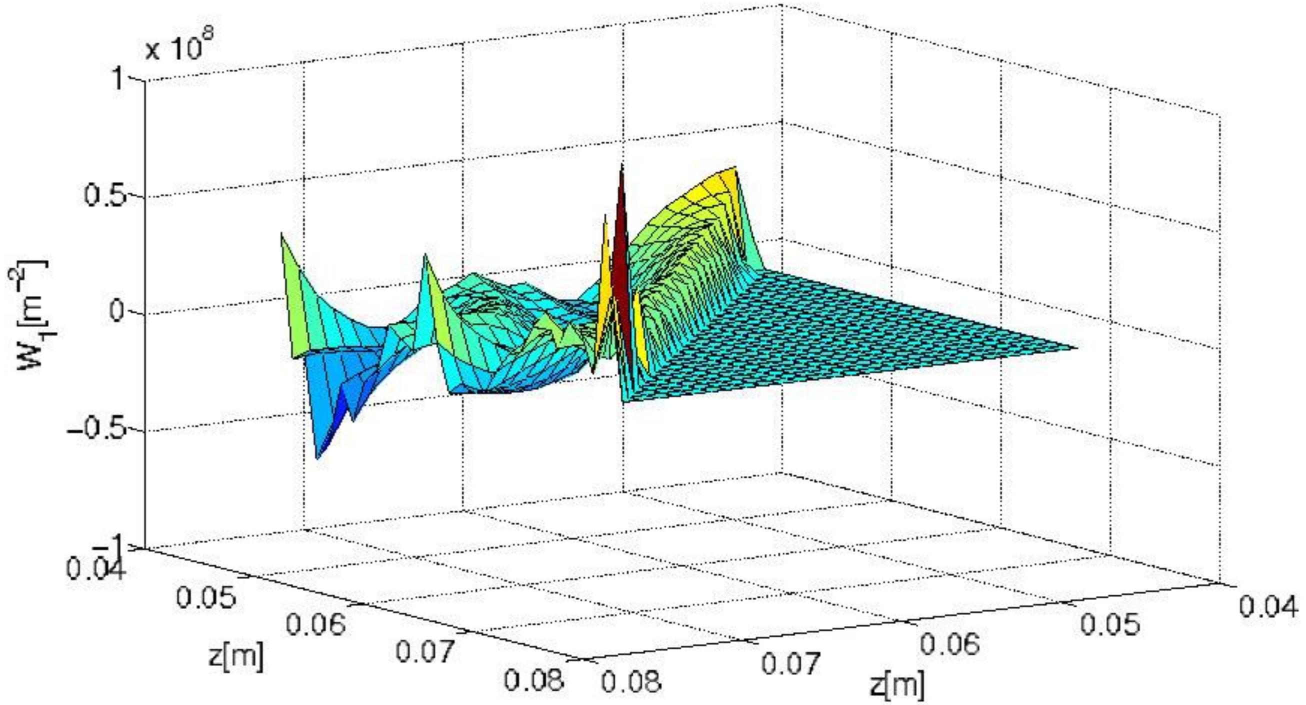


Figure 5.12: Two-variable wake field $W_1(z_j, z_i)$ for the KEKB-LER, $M = 30$ slabs. Both z axes represent the length of the bunch, the higher value corresponds with the beginning of the bunch and the lower the end of the bunch in longitudinal direction.

A. Markovik, 2011 & 2013 [16]

tracking with wake matrix for KEKB-LER

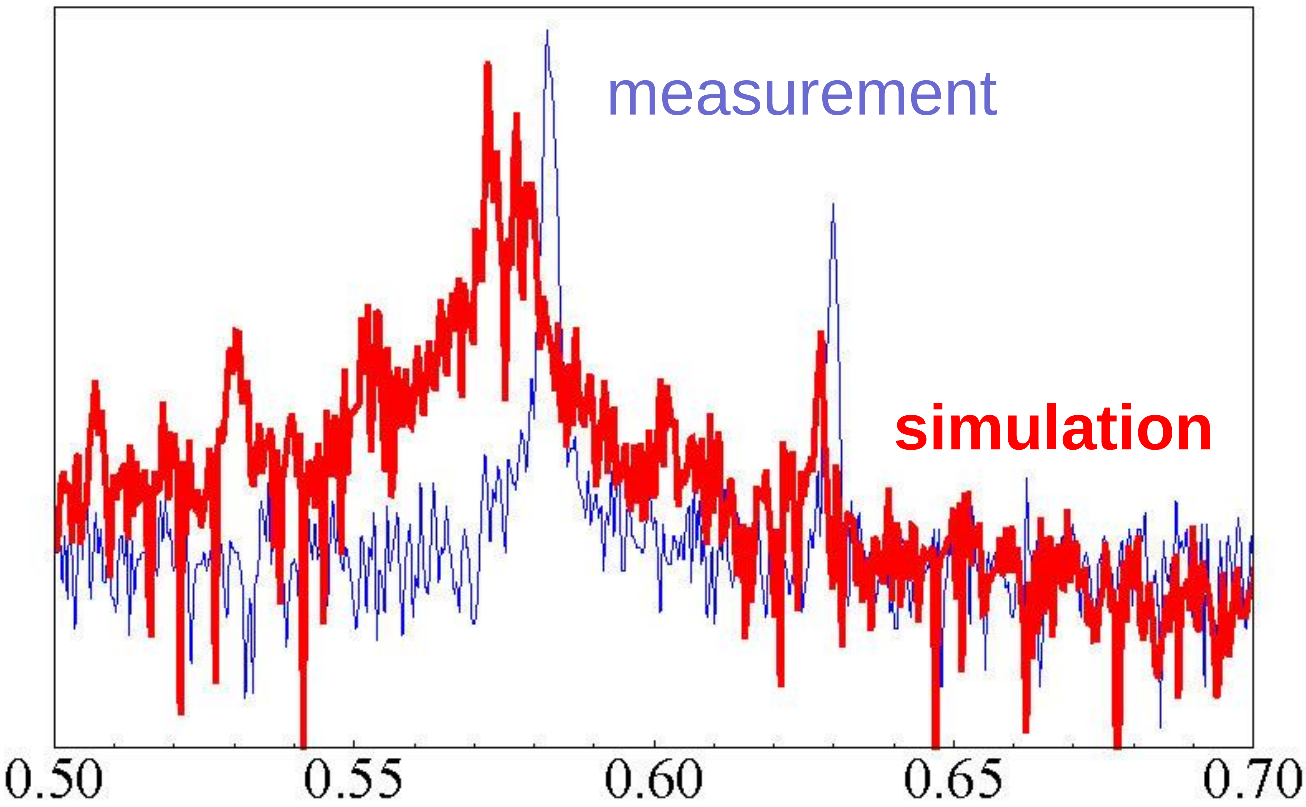
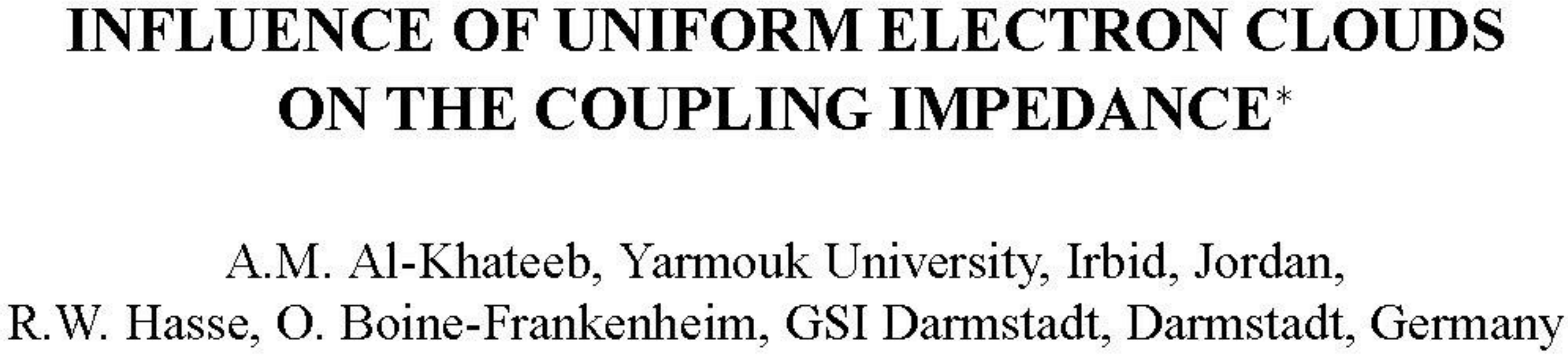


Figure 5.19: Fractional tune of the vertical betatron motion of a single bunch in a train of 100 bunches, measurement (blue) vs. simulation (red) with $M = 30$ slices.

A. Markovik et al, 2011 & 2013 [16]

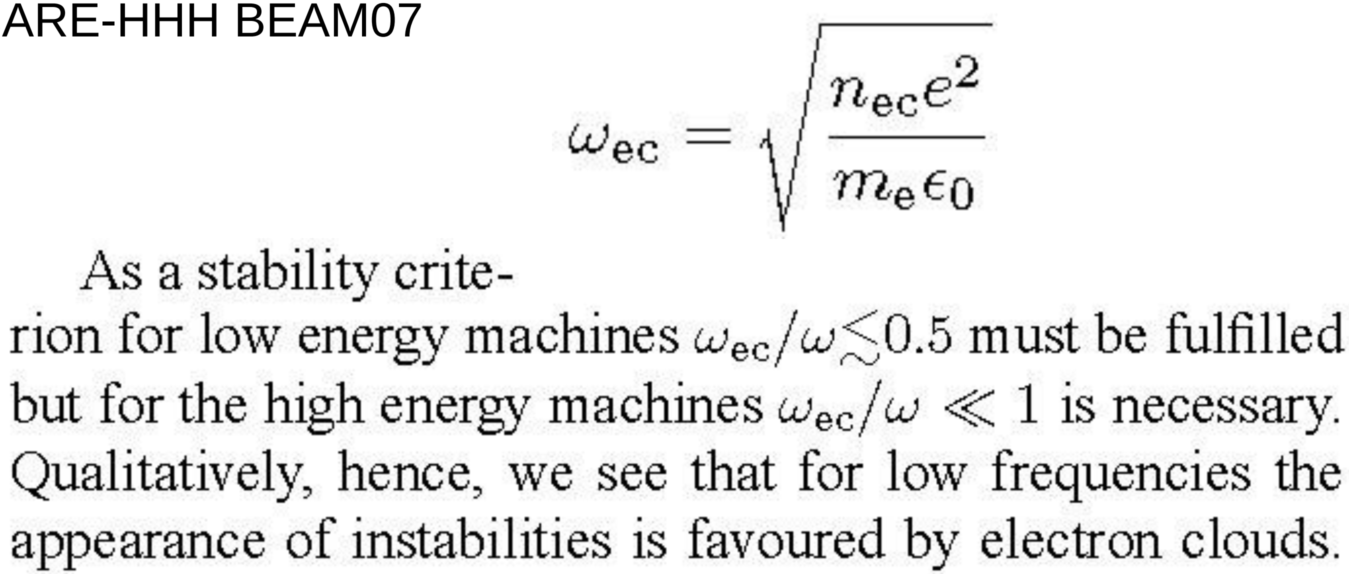
resistive-wall impedance with space charge & electron cloud



INFLUENCE OF UNIFORM ELECTRON CLOUDS ON THE COUPLING IMPEDANCE*

A.M. Al-Khateeb, Yarmouk University, Irbid, Jordan,
R.W. Hasse, O. Boine-Frankenheim, GSI Darmstadt, Darmstadt, Germany

Proc. CARE-HHH BEAM07



$$\omega_{\mathrm{ec}} = \sqrt{\frac{n_{\mathrm{ec}} e^2}{m_{\mathrm{e}} \epsilon_0}}$$

As a stability criterion for low energy machines $\omega_{\mathrm{ec}}/\omega \lesssim 0.5$ must be fulfilled but for the high energy machines $\omega_{\mathrm{ec}}/\omega \ll 1$ is necessary. Qualitatively, hence, we see that for low frequencies the appearance of instabilities is favoured by electron clouds.

A.M. Al-Khateeb, R. Hasse, O. Boine-Frankenheim, 2007 [15]

resistive-wall impedance with electron cloud

dielectric function

$$\varepsilon_{\mathrm{ec}} = 1 - \frac{\omega_{\mathrm{ec}}^2}{\omega^2}$$

combined resistive wall, space-charge & e-cloud impedance:

$$Z_{\parallel}(\omega) = -\frac{2L}{Qa^2}\left[A_1\left(\frac{I_{\nu-1}(\sigma_{\mathrm{ec}}a)}{\sigma_{\mathrm{ec}}a^{\nu-1}} - \frac{\sigma_{\mathrm{ec}}^{\nu-2}}{2^{\nu-1}\Gamma(\nu)}\right) - i\frac{Q}{\pi a^2\epsilon_0\varepsilon_{\mathrm{ec}}k_z\beta c}\frac{a^2}{2}\right]$$

A.M. Al-Khateeb, R. Hasse, O. Boine-Frankenheim, 2007 [15]

shielding of resistive wall

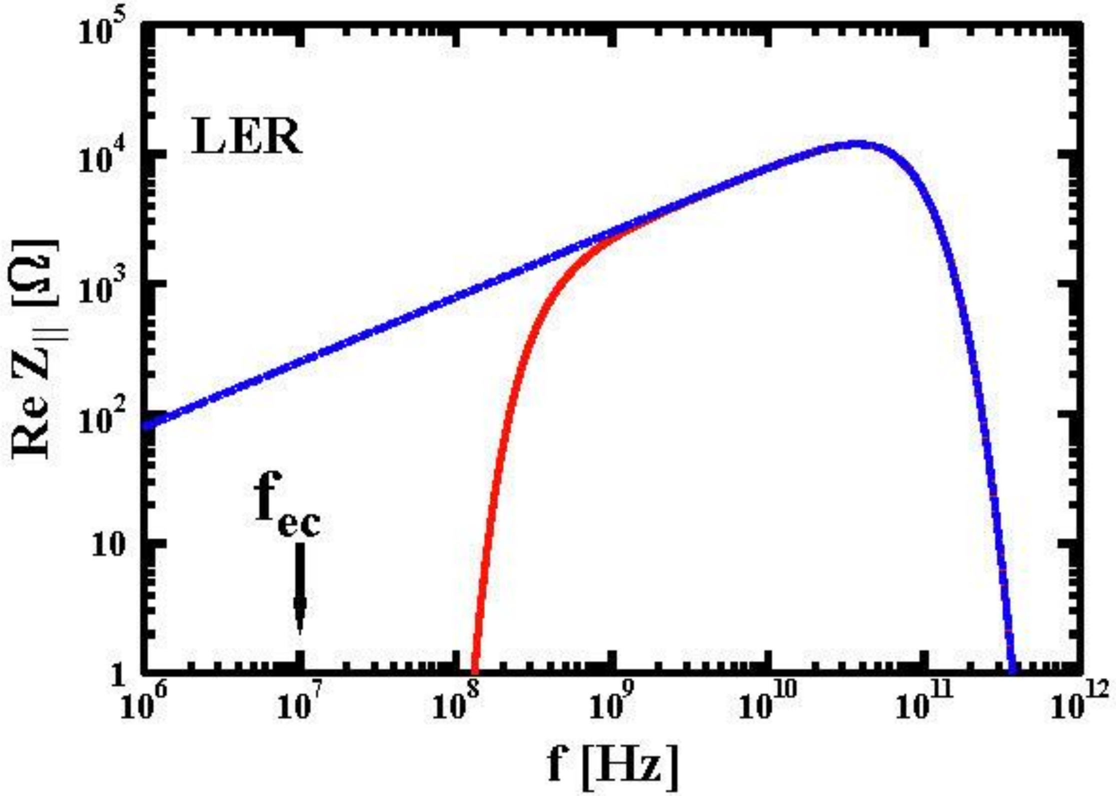


Figure 1: Dependence of the real part of the longitudinal resistive wall impedance on the excitation frequency for f_{ec} = 10 MHz. (KEKB LER). The blue dotted line shows the impedance without electron cloud and the full red line with EC.

coupling impedance depleted up to 500 MHz (50x f_{ec})

A.M. Al-Khateeb, R. Hasse, O. Boine-Frankenheim, 2007 [15]

impedance for $\omega<\omega_{ec}$: shielding of resistive wall

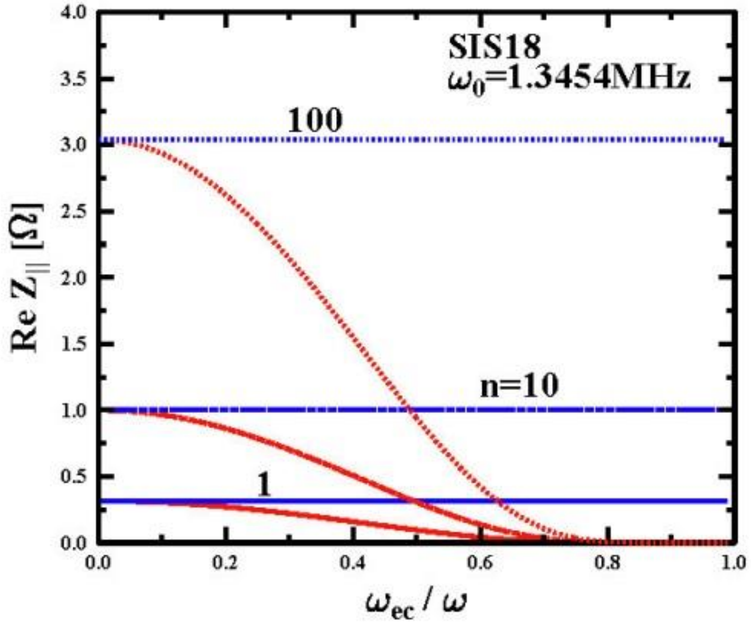


Figure 2: Dependence of the real part of the longitudinal resistive wall impedance on the ratio of electron cloud plasma frequency to excitation frequency $\omega = n\omega_0$ (GSI–SIS18). The blue lines show the impedance for $\omega_{ec} = 0$ and n indicates the harmonic number.

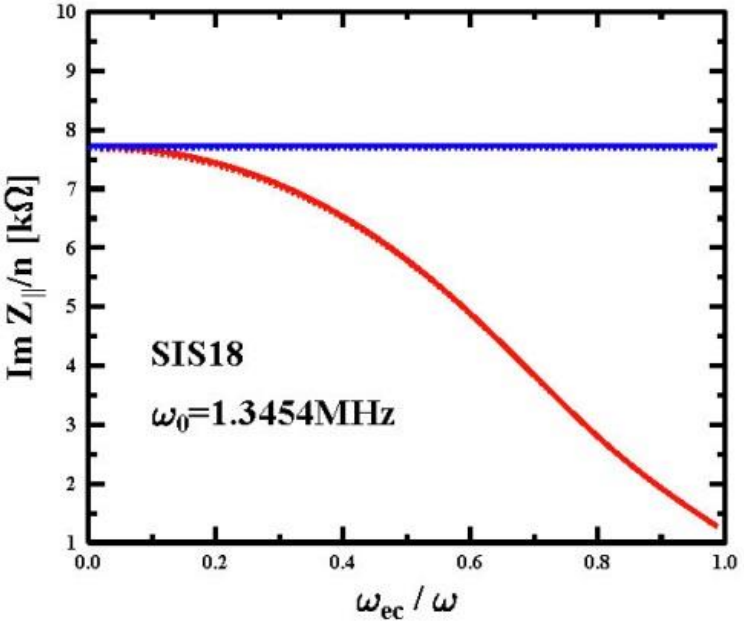


Figure 4: Comparison between the imaginary parts of the longitudinal resistive wall impedance per harmonic (GSI–SIS18) with and without electron cloud. Same notation as in Fig. 2.

A.M. Al-Khateeb, R. Hasse, O. Boine-Frankenheim, 2007 [15]

difference between high- and low-energy machines

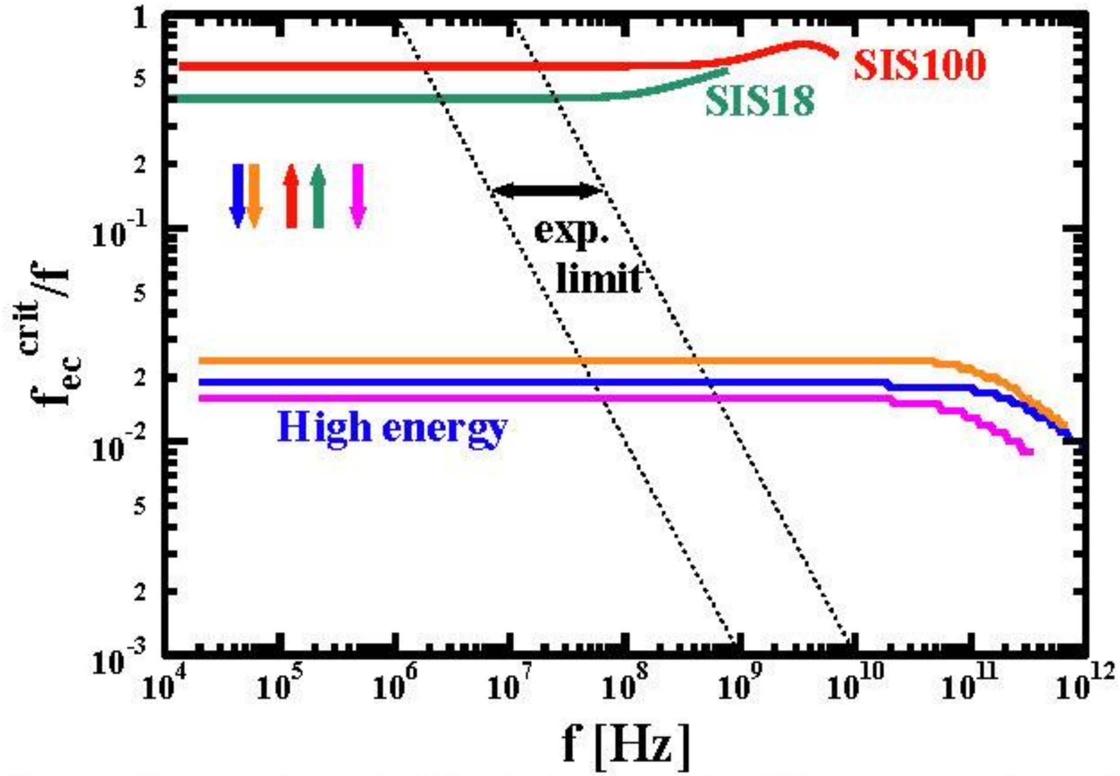


Figure 6: Fraction of critical electron cloud frequency where the longitudinal resistive wall impedance is half depleted as compared to the excitation frequency. The dahed lines idicates the measured value of electron cloud density of 10^{12} m^{-3} and 10^{11} m^{-3} in the SPS and LER. The arrows point to the respective revolution frequencies.

instabilities at

≤ 2-20 MHz
(low energy)

≤ 50-500 < MHz
(high energy)

A. Al-Khateeb,
W. Hasse,
O. Boine-Frankenheim,
BEAM’07 [15]

impedance for $\omega>\omega_{ec}$: evanescent & overdamped surface waves

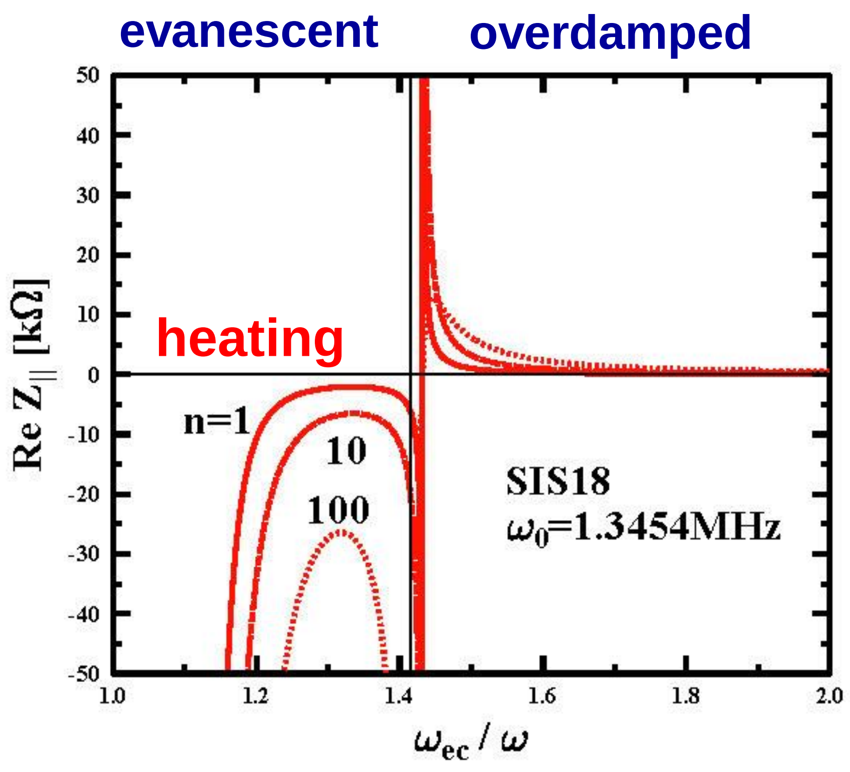


Figure 8: Same as Fig. 2 but for $\omega_{ec} > \omega$. The thin vertical line points to the ower limit of surface waves $\omega_{ec}/\omega = \sqrt{2}$ (SIS18).

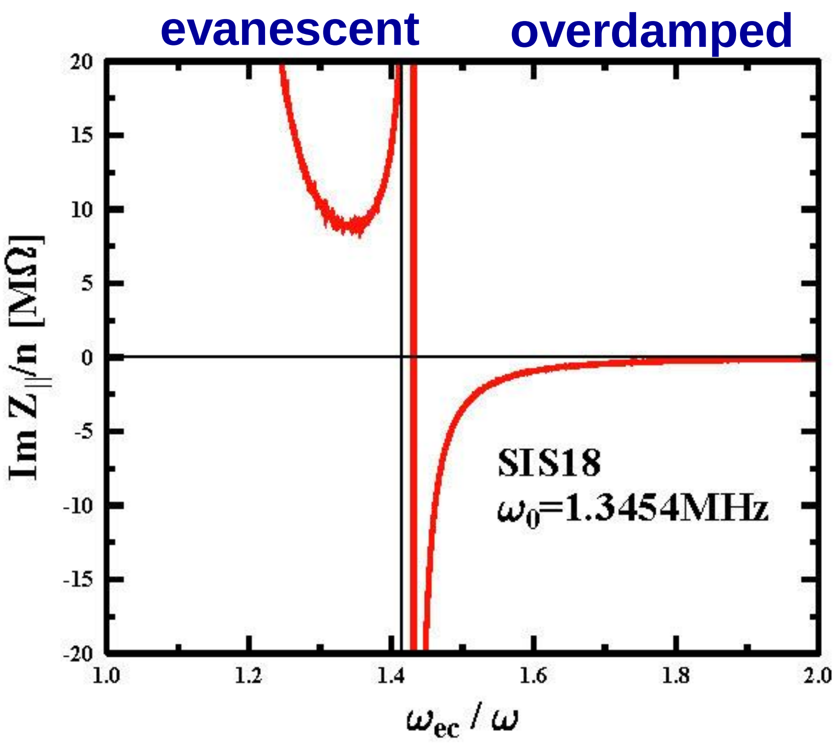
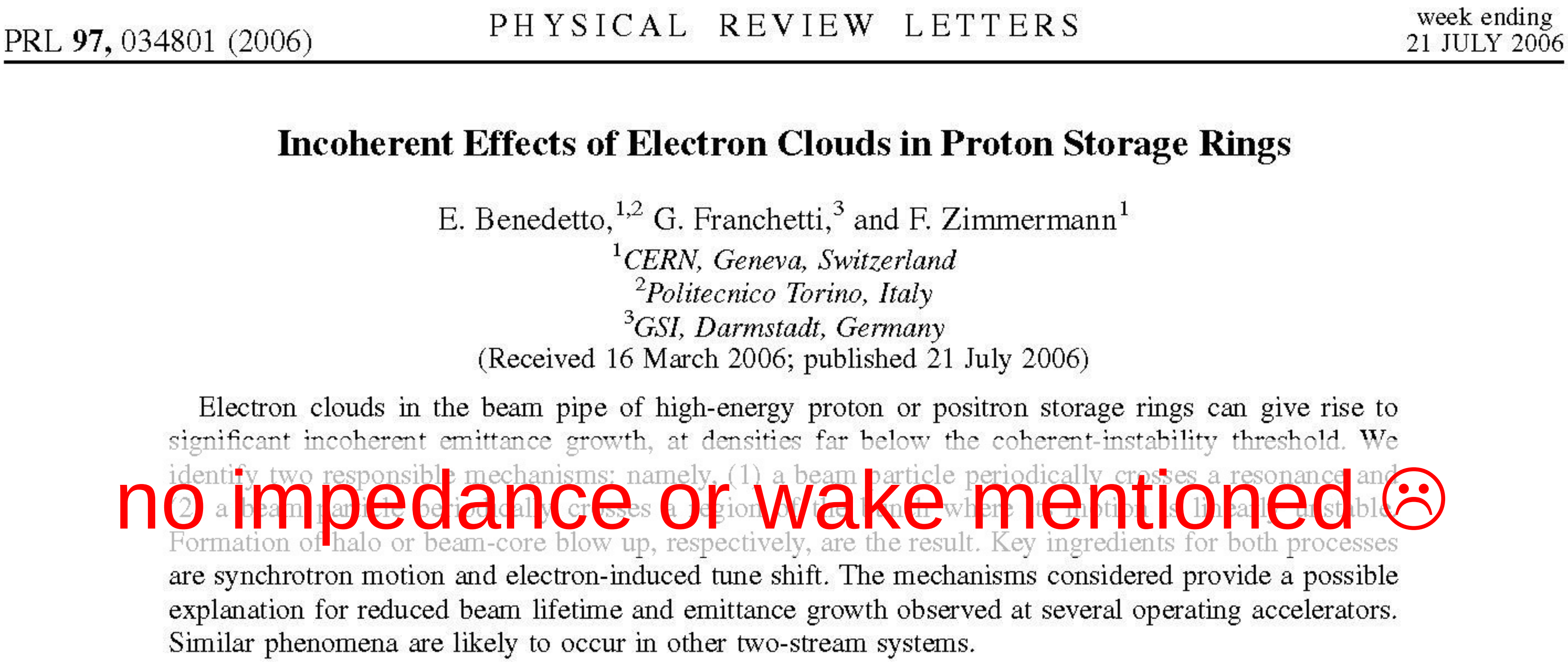


Figure 9: Same as Fig. 4 but for $\omega_{ec} > \omega$ (SIS18).

A. Al-Khateeb, W. Hasse, O. Boine-Frankenheim, BEAM’07 [15]



PRL **97,** 034801 (2006) PHYSICAL REVIEW LETTERS week ending 21 JULY 2006

Incoherent Effects of Electron Clouds in Proton Storage Rings

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(Received 16 March 2006; published 21 July 2006)

Electron clouds in the beam pipe of high-energy proton or positron storage rings can give rise to significant incoherent emittance growth, at densities far below the coherent-instability threshold. We identify two responsible mechanisms: namely, (1) a beam particle periodically crosses a resonance and (2) a beam particle periodically crosses a region of the bunch where its motion is linearly unstable. Formation of halo or beam-core blow up, respectively, are the result. Key ingredients for both processes are synchrotron motion and electron-induced tune shift. The mechanisms considered provide a possible explanation for reduced beam lifetime and emittance growth observed at several operating accelerators. Similar phenomena are likely to occur in other two-stream systems.

no impedance or wake mentioned ☹

E. Benedetto, G. Franchetti, F. Zimmermann, 2006

incoherent electron-cloud impedance?
(in analogy to “space charge impedance”)

microwaves & electron cloud

1) vertical *m*=1 **head-tail mode stabilized by trapped electron cloud in CESR-c** (R. Littauer, CNLS 88/847, 1988) due to coupling w. e^- cyclotron resonance
2) proposals **to inject of microwaves to suppress or enhance (for conditioning purposes) the electron-cloud build up** in a storage ring (A. Chao 1997, F. Caspers 2002, M. Mattes, E. Sorolla & F.Z. , ECLOUD’12 & IEEE APWC - EEIS '12)
3) evidence for an **interplay of beam-induced ``wake fields'' and electron-cloud build up seen at the PEP-II collider** (F. Decker et al, Proc. ECLOUD’02)
4) suggested **“magnetron effect”: under the influence of a beam-induced electromagnetic wake field and for certain values of the external dipole magnetic field, the cloud electrons oscillate and radiate coherently**, at frequencies so high that the inner ``beam screen'' of the LHC is no longer shielding, which could lead to the quench of all superconducting magnets (F. Caspers, May 2005).

thank you!

"To have seen Italy without having seen Sicily is not to have seen Italy at all, for Sicily is the clue to everything."

Johann Wolfgang von Goethe

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