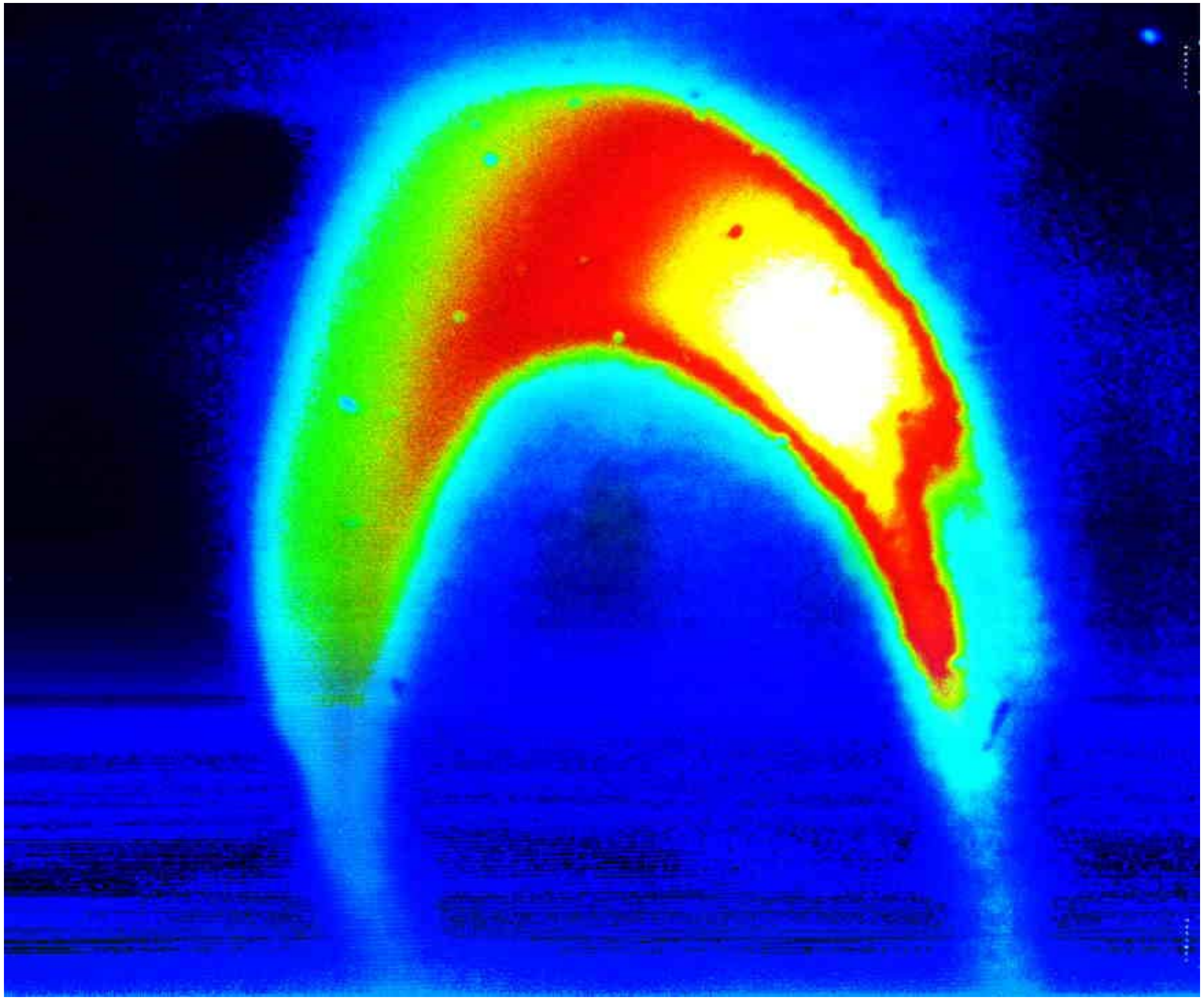
Halo generation & beam loss by ‘non-Hamiltonian’ processes

Frank Zimmermann

CLIC Lost Beam Day, 24.10.03

- compilation of processes
- some approximate expressions
  (mostly for relativistic beams)
- (very) few estimates for CTF-3
- summary & outlook

Is there halo in linear colliders?



Yes, measured beam distribution at the end of the SLAC linac (projection on the x-y plane)!

let us look at the SLC prediction…

S L C
DESIGN HANDBOOK

STANFORD LINEAR ACCELERATOR CENTER
STANFORD UNIVERSITY
Stanford, California 94305

December 1984

Prepared for DOE under Contract
No. DE AC03-76SF 00515

9.3 BACKGROUNDS This section is not yet ready for distribution.

we should avoid a similar fate!

Candidate Processes

Dispersion	linac
Space charge (?)	close to the source, in bends
Elastic scattering off residual gas	everywhere
Residual-gas bremsstrahlung	everywhere
Touschek scattering	everywhere
Intrabeam scattering	everywhere
Dark currents	cavities, linac
Nonlinear magnetic fields	ring, linac
Scattering off thermal photons	scattering
Scattering off laser field	photo gun
Incoherent & nonl. wake fields	e.g. collimators
Synchrotron radiation (coherent & incoherent)	in bends
Ion or electron-cloud effects	e- or e+ beams

Generation at time 0

beam halo may be generated by cathode surface roughness or by a spatially uneven or non-constant laser pulse at photo rf gun.

Deflection by photo-gun laser field

$$\frac{\Delta x'}{\sigma_{x'}} \approx \frac{r_e A_L \lambda_L}{2\pi m c^2 Z_R c \tau_L} \frac{1}{\gamma} \sqrt{\frac{\beta_x}{\varepsilon_n \gamma}}$$

laser energy A_L	5 μJ
wave length λ_L	250 nm
pulse length τ_L	1 ps?
Rayleigh length Z_R	10 m?
beta function β_x	1 m?
Lorentz factor γ	1
emittance ε_n	2 μm

(V. Telnov, 2002)

$$\frac{\Delta x'}{\sigma_{x'}} \approx 2\times 10^{-9}\,?$$

negligible effect?

Space Charge

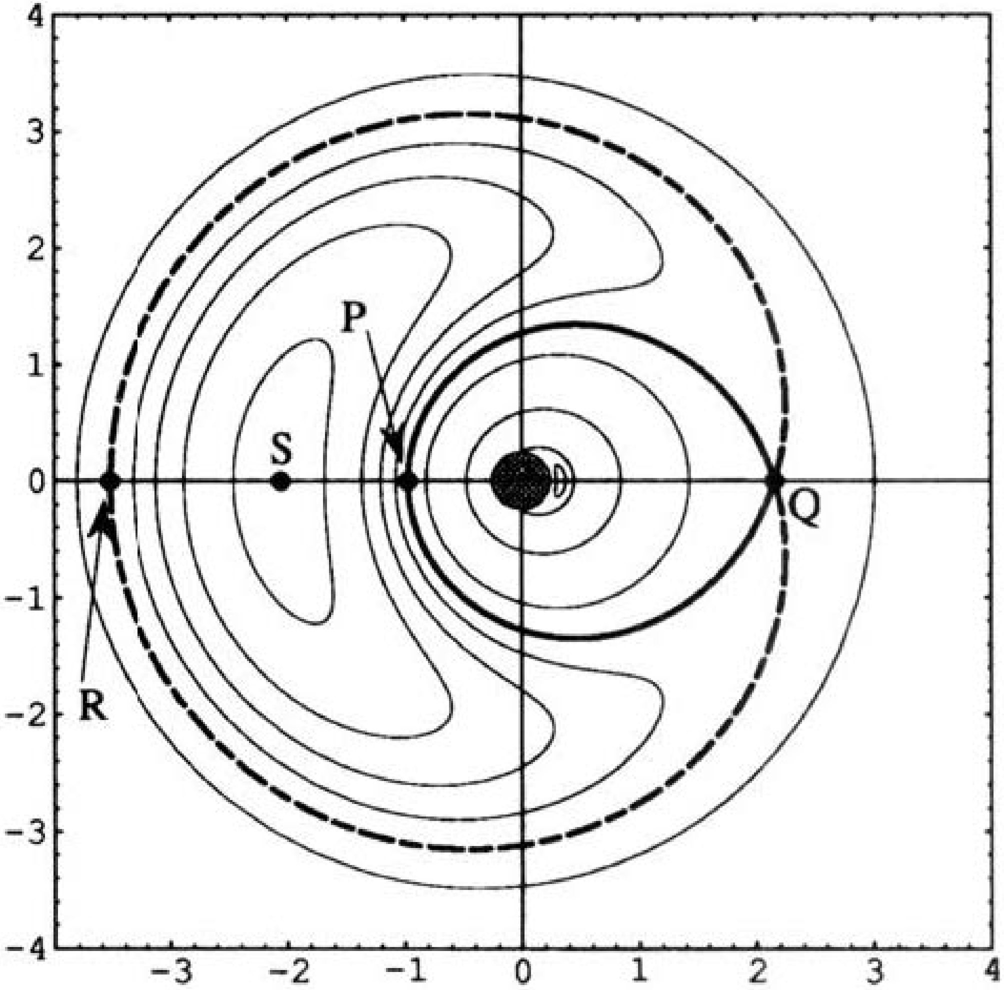
space charge can drive parametric resonances and thereby create transverse or longitudinal halo

extensive studies by R. Gluckstern et al. for protons & by B. Carlsten & T. Raubenheimer for electrons

beam loss results, if halo particles exceeds the (dynamic or physical) aperture of the linac, transfer lines or ring

in this context, what are the 6-dimensional acceptances of the CTF-3 (sub-)systems?

particle-core model



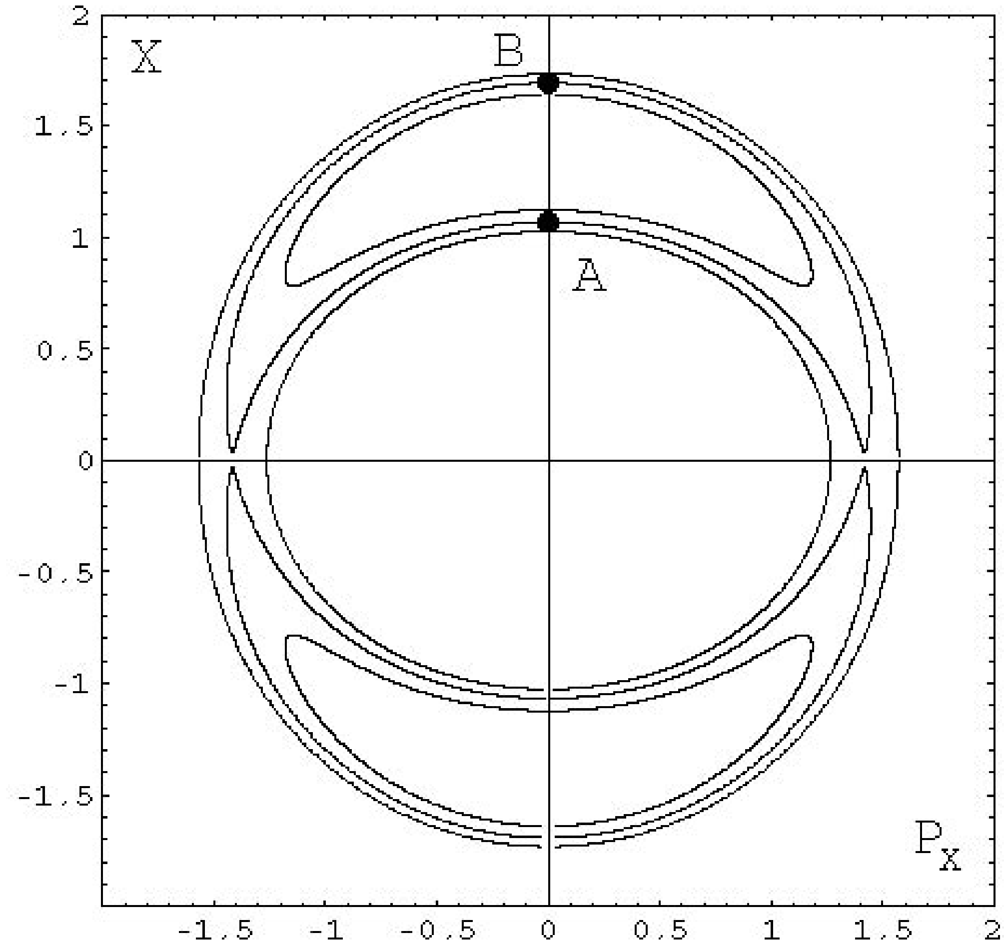
phase space of
test particle, illustrating
the parametric
resonance driven
by beam core
mismatch
in a linac or ring;
the resonance can
drive particles
to large amplitudes

also chaos near separatrix

R. Gluckstern, 1994

a signature of space-charge halo:
'peanut diagram'

particle-core model



phase space of
test particle, illustrating
the quadrupolar
resonance driven
by the beam core
in a linac or ring with
small quadrupole
gradient errors;
the resonance can
drive particles
to large amplitudes

R. Gluckstern & M. Venturini, 2000

Synchrotron radiation

number of photons per radian: $$\frac{dN_\gamma}{d\vartheta} = \frac{5}{2\sqrt{3}}\alpha\gamma \approx 20\frac{1}{\text{rad GeV}}$$

critical energy: $$E_{\gamma,c} = \frac{3}{2}\frac{\hbar c\gamma^3}{\rho} \text{ and } < E_\gamma >= \frac{8}{15\sqrt{3}}E_{\gamma,c} \approx 0.32 E_{\gamma,c}$$

energy spread: $$\Delta\delta_{rms}^2 = \frac{55}{24\sqrt{3}} r_e \bar{\lambda}_e \frac{\gamma^5}{\rho^2}\theta$$

emittance growth:
$$\Delta\varepsilon_x = C_Q E^5 \left\langle \frac{H_x}{\rho^3} \right\rangle l_b \text{ where } C_Q \approx 2\times10^{-11}\,\text{m}^2\text{GeV}^{-5}$$

tails: $$\frac{dN}{dE_\gamma} \approx \frac{P_\gamma}{E_{\gamma,c}^2}\frac{9\sqrt{3}}{8\sqrt{2\pi}}\frac{e^{-E_\gamma/E_{\gamma,c}}}{\sqrt{E_\gamma/E_{\gamma,c}}} \text{ where } P_\gamma = \frac{cC_\gamma}{2\pi}\frac{E^4}{\rho^2}$$

Bunch Compression

Space charge in bends

maybe these are Hamiltonian

$$\Delta(\gamma\varepsilon_x) \approx 0.14 \frac{(2\sigma_x)^{3/2}}{\sqrt{R}\,4\sigma_z} \ln\left(\frac{b}{2\sigma_x}\right) \frac{N_b c}{\sqrt{2\pi}\,\sigma_z I_A} b\theta$$

$$\Delta(\gamma\varepsilon_x) \approx 0.38 \frac{(2\sigma_x)^{2}}{4\sigma_z} \ln\left(\frac{b}{2\sigma_x}\right) \frac{N_b c}{\sqrt{2\pi}\,\sigma_z I_A} \theta^2$$

Carlsten
& Rauben-
heimer, 1995

Coherent synchrotron radiation

this is emittance growth but how about the halo?

$$\Delta\delta_{rms} \approx 0.2 \frac{N_b r_e L_d}{\gamma R^{2/3} \sigma_z^{4/3}}$$

$$\Delta(\gamma\varepsilon_x) \approx \gamma(\sigma_x D'_x + \sigma_{x'} D_x)(\Delta\delta_{rms})$$

Derbenev et
al., 1995

shielding for full aperture $h < h_{crit} \approx \left(\pi\sigma_z\sqrt{R}\right)^{2/3}$

Dark current

'modified' Fowler-Nordheim equation

$$I_{FN} \propto A\frac{c_1}{\phi}(\beta E)^2 \exp\left(-\frac{c_2\phi^{3/2}}{\beta E}\right)$$

A : active emitter area

β : field enhancement factor ($40 < \beta < 600$)

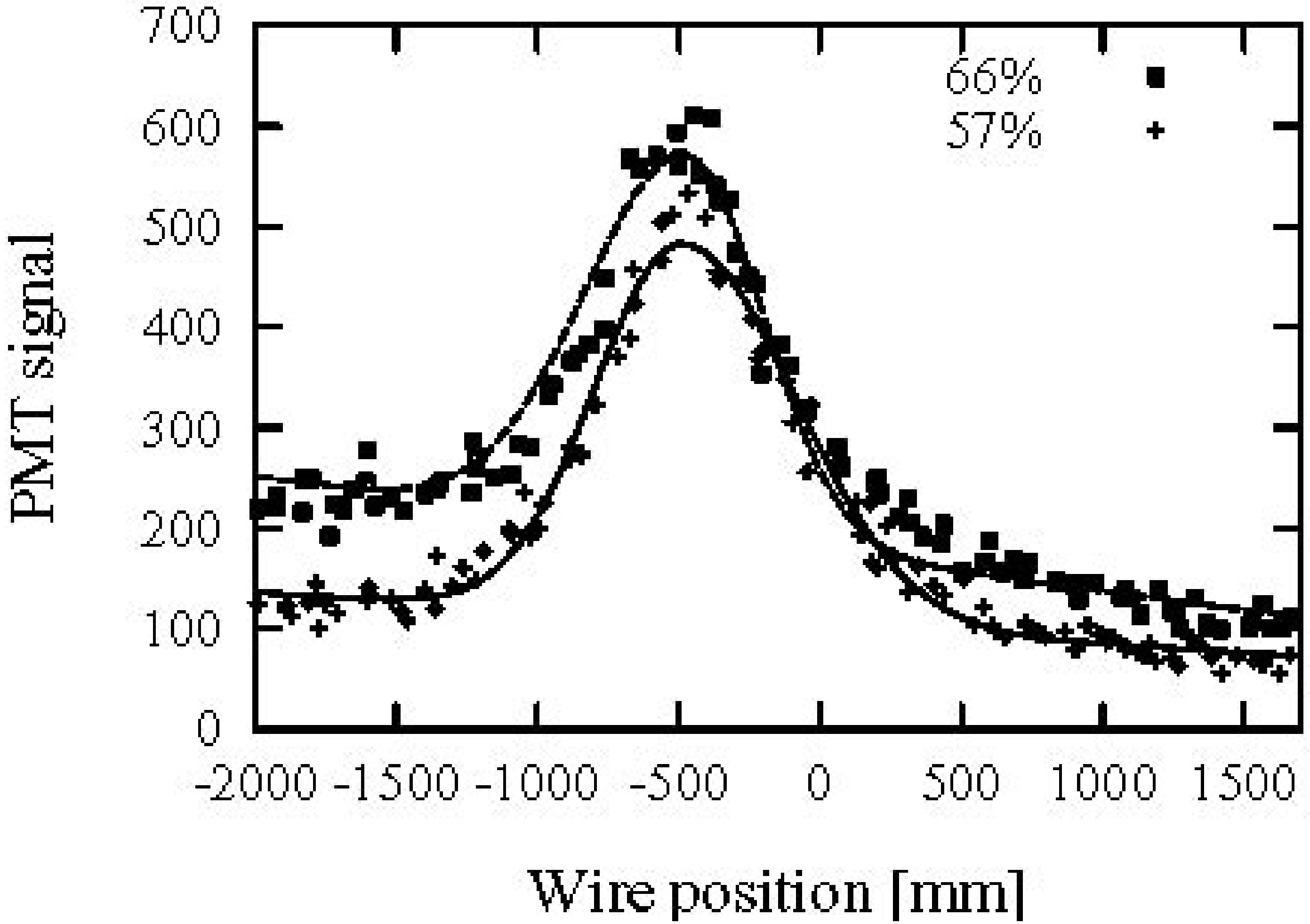
c_1, c_2 : constants

typical dark current in accelerating structure: 10 µA – 1 mA

- random character
- excites random wake-field forces
- dark-current e- are lost after ~one FODO cell

C. Stolzenburg, 1996; R. Assmann et al., 1997; D. Sertore et al., 2000

dark current at the SLC

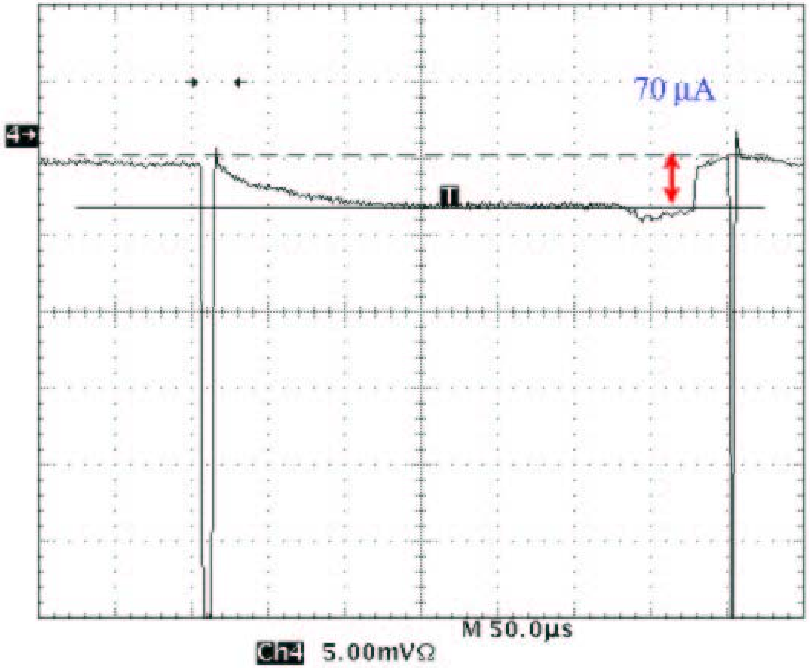


Transverse beam profile measured with two different drive settings for upstream klystron. The background was almost halved when klystron drive was reduced from 66% to 57% (R. Assmann, et al.)

dark current at the TTF

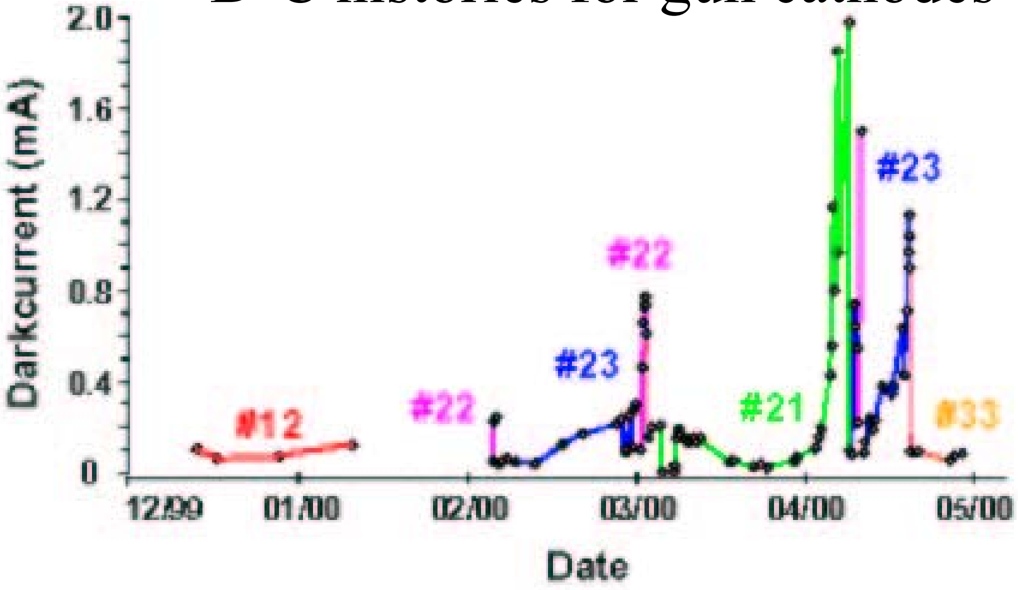
“The main effect related to dark current during linac operation is radiation losses in the linac components”

also dark-current induced charging of dielectric mirrors, causing beam jumps



Oscilloscope trace used for D-C measurements; the pedestal is due to dark current

D-C histories for gun cathodes



Nonlinear magnetic fields

fringe fields

magnet geometry, remanence or saturation

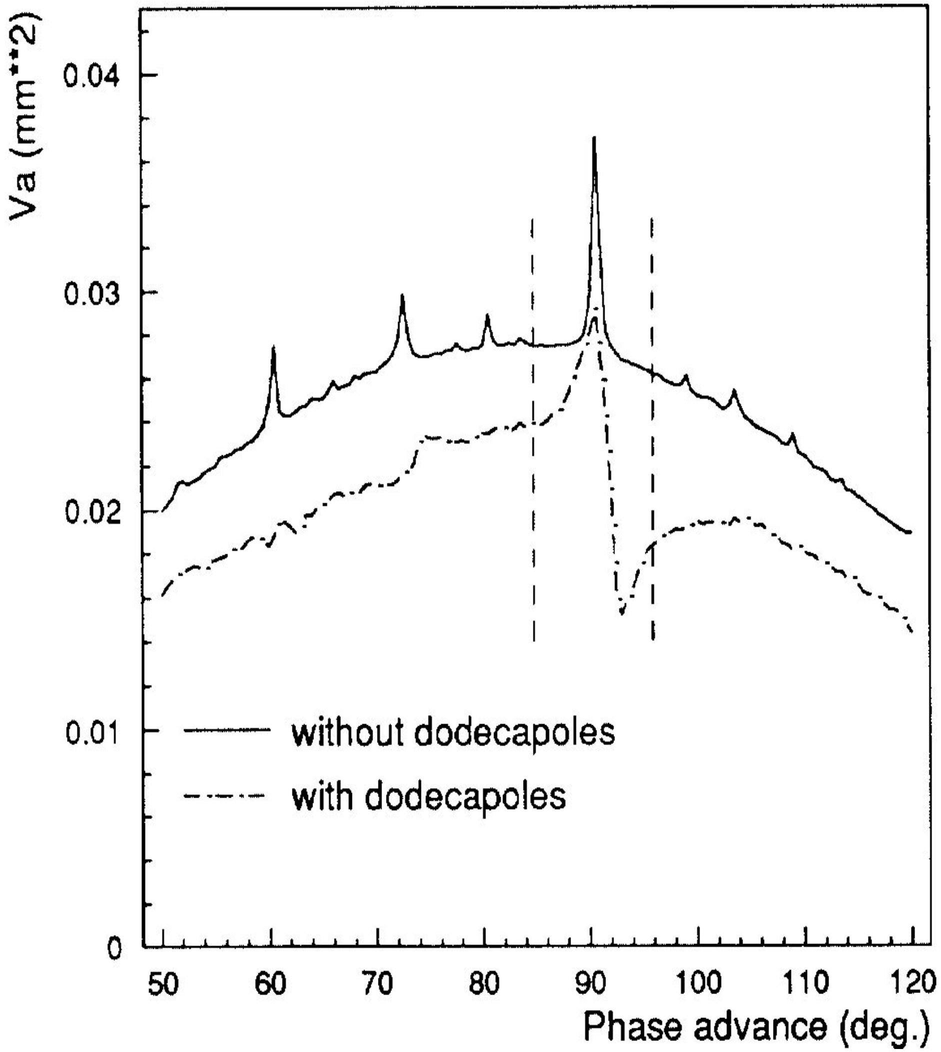
intentional nonlinear elements, e.g., *n*-pole

$$\frac{\Delta x'}{\sigma_{x'}} = -\frac{\beta}{\sigma_{x'}} \frac{k_n}{(n-1)!} x^{n-1}$$, where

$$k_n = \frac{\partial^n B_y / \partial x^n}{(B\rho)} l_n$$

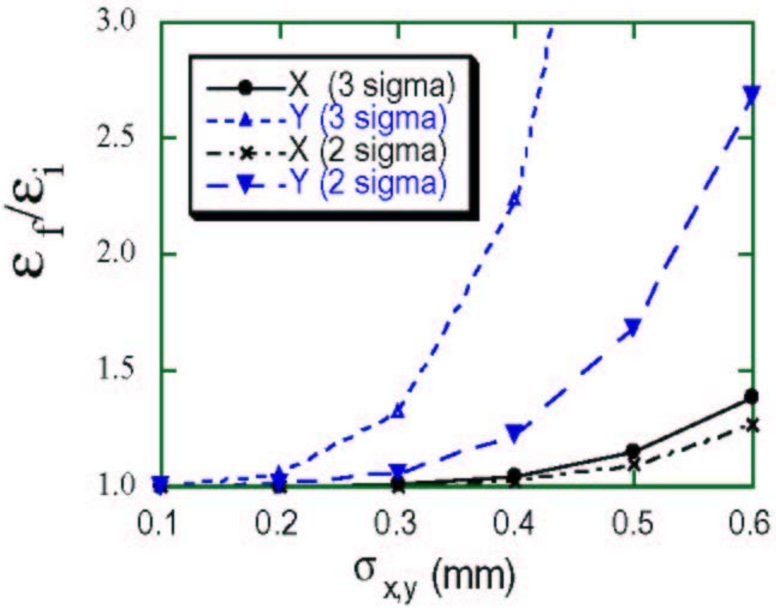
(neglecting y-motion here)

nonlinear resonances in a periodic linac lattice



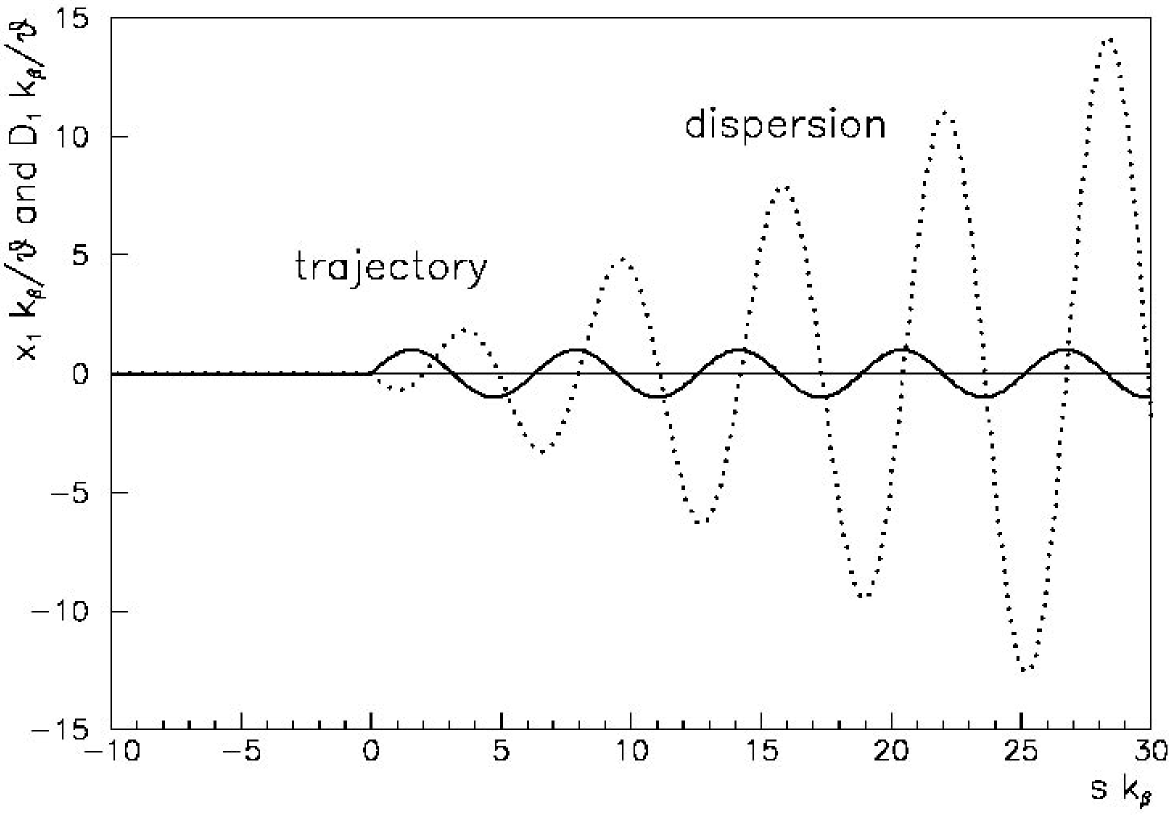
effect of 12-poles on the acceptance in SLC e+ Return Line (Hans Braun, 1991)

effect of octupole misalignment in NLC version (P. Emma et al., 1997)

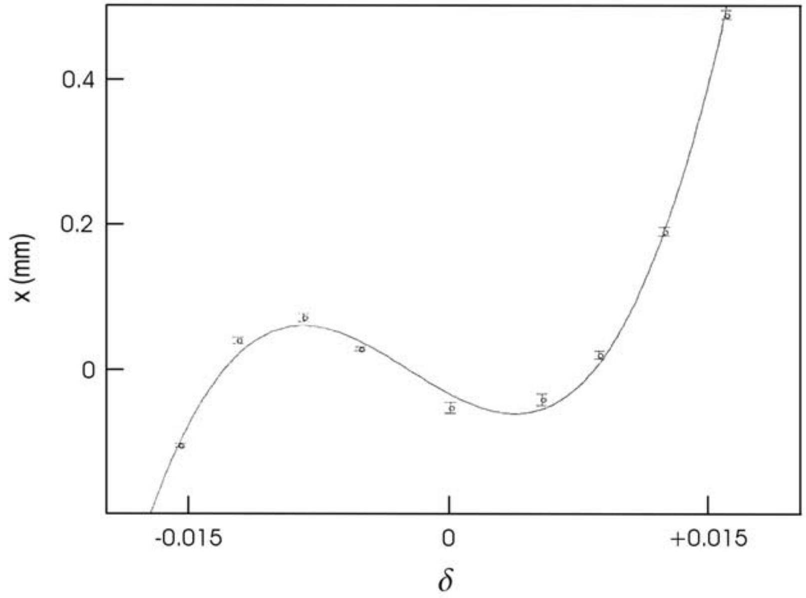


Linear & nonlinear dispersion

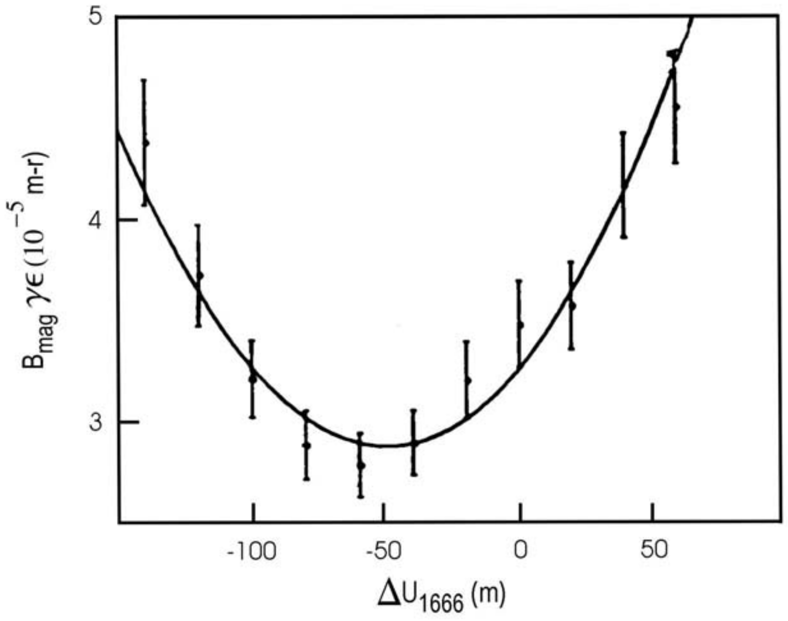
dispersion can grow resonantly along the linac,
this can drive off-energy particles to large amplitudes;
important effect at the SLC



Nonlinear dispersion at the SLC



evidence of 3rd order dispersion in the SLC TRL (P. Emma)



emittance minimization scanning an octupole corrector (P. Emma)

Incoherent wake fields

different particles acquire different phase advances

some can end up on a resonance and may be propelled
to large amplitudes

example: quadrupolar wakes for flat beam pipe or collimators

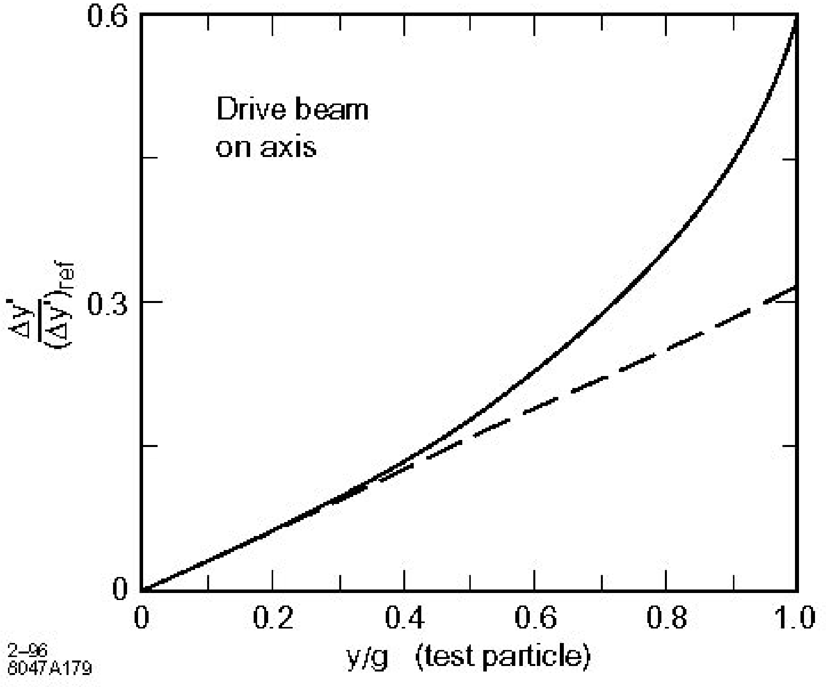
example: resistive wall wake fields

both single bunch & coupled bunch wakes can exhibit this

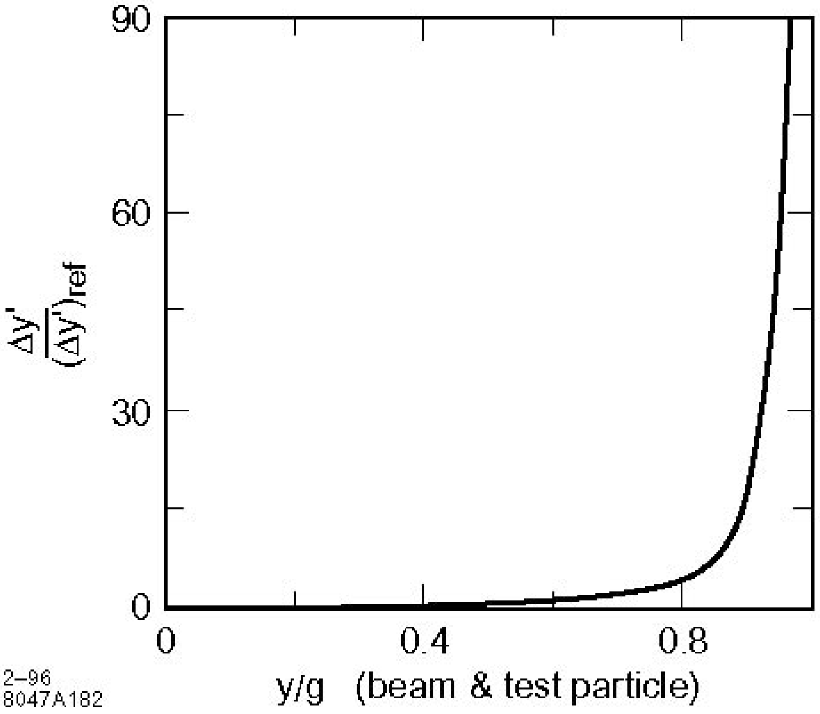
effect of B-field penetration through the chamber wall?

Nonlinear wake fields

wake can be highly nonlinear near the wall (NLC ZDR)

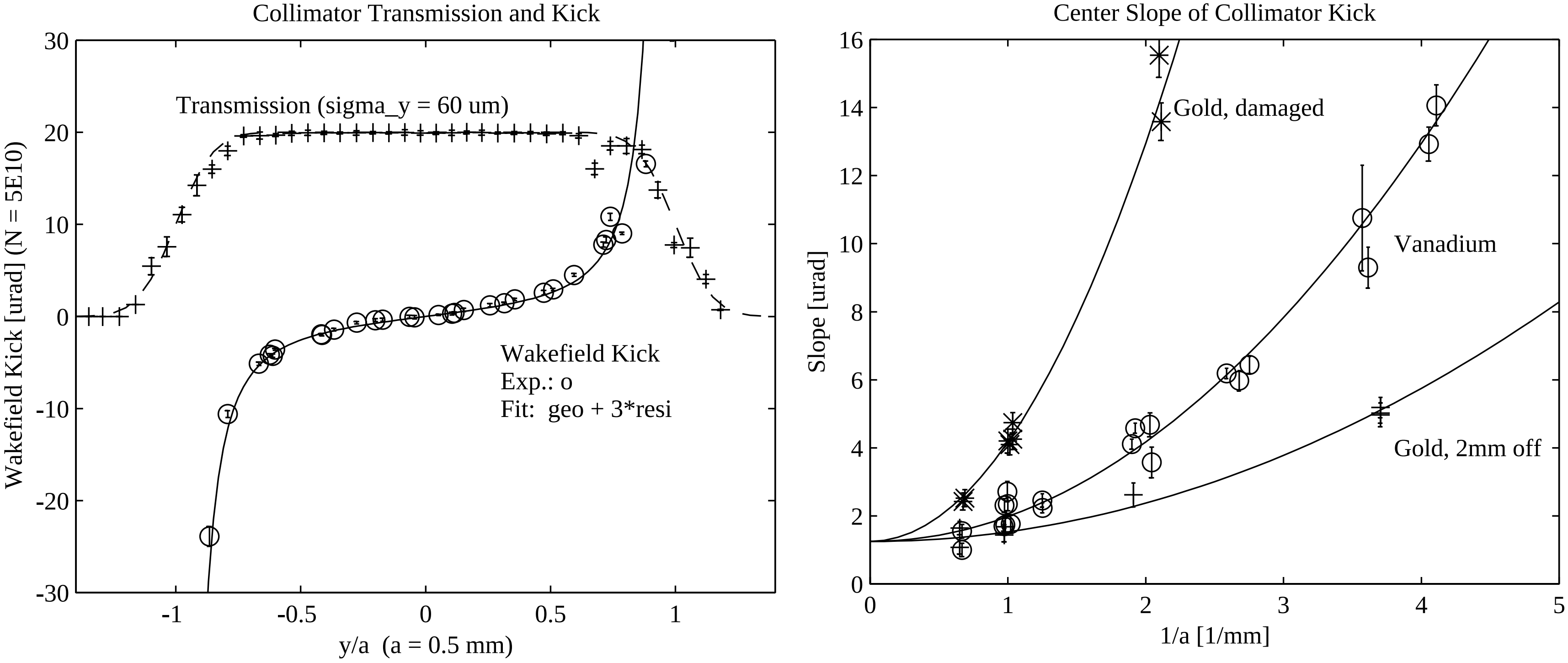


deflection vs. position, beam centered



deflection vs. position of beam and test particle

Measured SLC collimator wake field



Measured transmission and beam deflection for different beam offsets y/a and fixed collimator opening a (left side). The right part shows the slope of the wake field kick as a function of different collimator surfaces and openings.

Bremsstrahlung

electrons lose energy in inelastic scattering events with the residual gas (e.g., SLAC-PUB-8012 and references therein)

$$\frac{d\sigma_{brems}}{dk} = \frac{A}{N_A X_0}\frac{1}{k}\left(\frac{4}{3}-\frac{4}{3}k+k^2\right)$$

where

$$\frac{1}{X_0} \approx 4\alpha r_e^2 N_A \frac{Z^2}{A}\ln\left(\frac{183}{Z^{1/3}}\right)$$

total cross section for energy loss > 1% is 6.5 barn for CO

$$\sigma_{brems} \approx -\frac{16}{3} r_e^2 \alpha Z^2 \ln\delta_{\min} \ln\left(\frac{183}{Z^{1/3}}\right)$$

$$\Delta N_b = \sigma_{brems}\frac{p}{k_B T} L N_b$$

remains important at high energies

Elastic Coulomb scattering

total cross section

$$\sigma_{el} \approx 0.2\pi Z^{8/3} \bar{\lambda}_C^2$$

for scattering above minimum angle

$$\theta_{\min} \approx \frac{\hbar}{pa}, \quad \text{where} \quad a \approx 0.22 \frac{\bar{\lambda}_e}{\alpha} Z^{1/3}$$

scattered electrons:

$$\Delta N_b = \sigma_{el} \frac{p}{k_B T} L N_b$$

scattering angle decreases at higher energies

Mathematical apparatus for scattering

‘filtered Poisson process’: $$y(t)=\sum_{t_n=-\infty}^{\infty}\theta_n w(t-t_n)$$ (K. Hirata, T. Raubenheimer)

cumulants $$\kappa_n=\nu\left\langle\theta^n\right\rangle\int_{-\infty}^{\infty}w^n(t)dt$$

characteristic function $$\ln\psi(z)=\sum_{n=1}^{\infty}(iz)^n\frac{\kappa_n}{n!}$$

beam distribution $$f(x)=\frac{1}{2\pi}\int e^{-ixz}\psi(z)dz$$

filter function in storage ring $$w(s)=\beta e^{-s\alpha/c}\sin\left(s/\beta\right)$$

filter function in linac $$w(s)\approx\beta\sqrt{\frac{\gamma_0}{\gamma_0+(d\gamma/ds)s}}\sin\left(s/\beta\right)?$$

Touschek Scattering

single scattering of particles inside the same bunch off each other, so that they end up outside the momentum acceptance (of downstream systems)

for a round beam (see also LHC PN 244)

$$\frac{dN_b}{ds} = \frac{r_e^2}{8\sqrt{\pi}\gamma^2} \frac{1}{(\gamma\varepsilon_x)(\gamma\varepsilon_y)\sigma_z\eta} D\left(\frac{\gamma\sigma_x}{\beta_x\eta}\right) N_b^2$$

$$D(\xi) \equiv \sqrt{\xi}\int_{\xi}^{\infty} \frac{e^{-u}}{u^{3/2}}\left(\frac{u}{\xi} - 1 - \frac{1}{2}\ln\frac{u}{\xi}\right) du$$

$$\Delta N_b \approx \frac{r_e^2}{8\sqrt{\pi}\gamma_0 (d\gamma/ds)} \frac{N_b^2}{(\gamma\varepsilon_x)(\gamma\varepsilon_y)\sigma_z\eta} D\left(\frac{\gamma\sigma_x}{\beta_x\eta}\right)$$

total loss

causes off-energy halo

example parameters

parameter	value
η	1%?
N	10^{11} (~7 times CTF3)
$\gamma\varepsilon$	70 mm mrad
γ	5
$d\gamma/ds$	100 m^{-1}
β_x	10 m
σ_z	1.5 mm

$\Delta N_b \approx 30$ *small number!*

Intrabeam Scattering

emittance growth from multiple scattering inside the bunch;
K. Bane's approximation to Bjorken-Mtingwa formalism

$$\frac{1}{\tau_{\mathrm{IBS},\delta}} \equiv \frac{1}{\sigma_\delta}\frac{d\sigma_\delta}{dt}$$

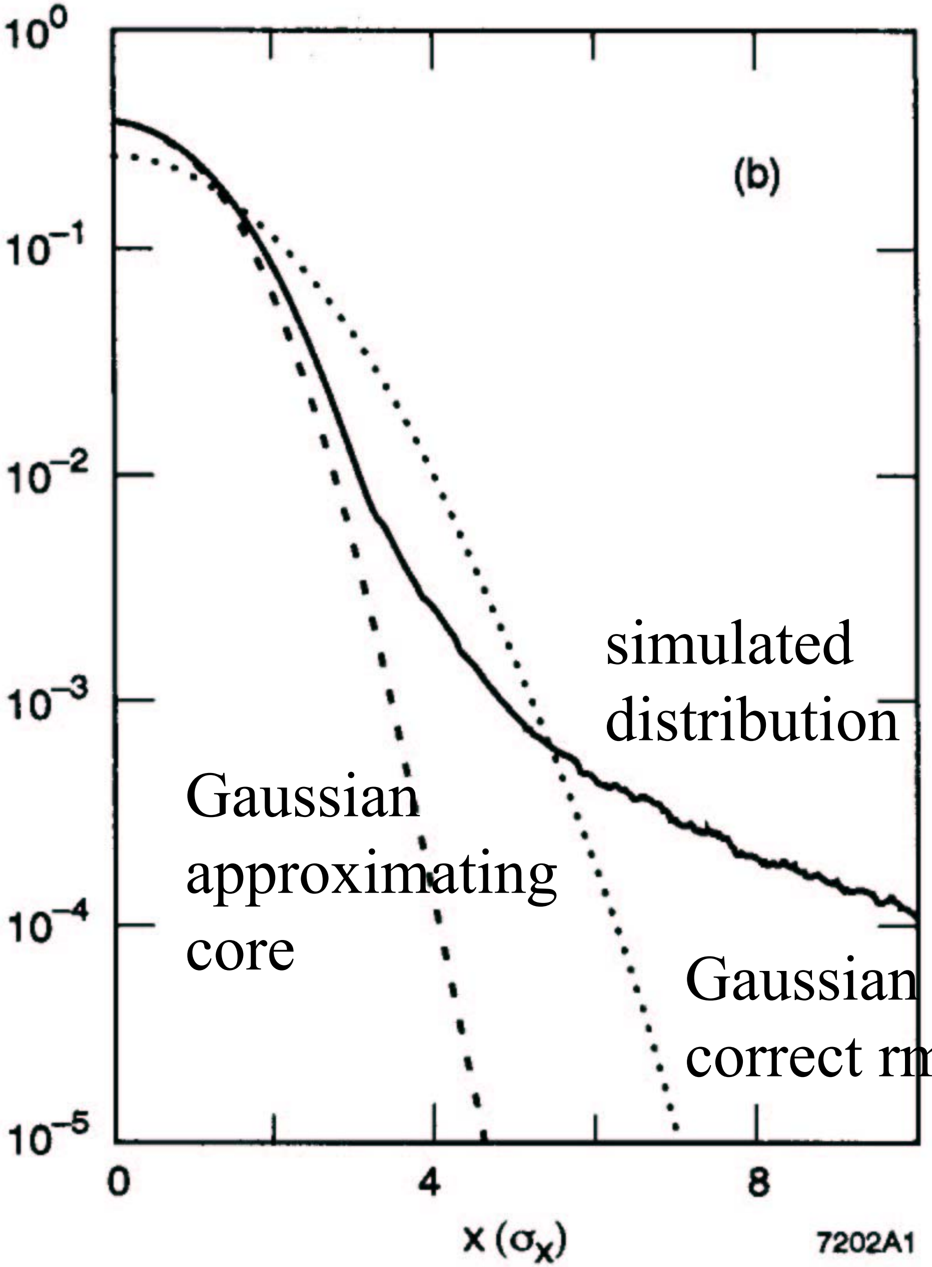
$$\approx \frac{r_e^2 c N (\log)}{16\gamma^3 \varepsilon_\perp^{3/2}\sigma_z\sigma_\delta^3}\frac{1}{\sqrt{\beta_{x,y}}\sqrt{\frac{1}{\sigma_\delta^2}+\frac{\langle H_x\rangle}{\varepsilon_x}}}$$

$$\frac{1}{\tau_{\mathrm{IBS},x}} = \frac{\sigma_\delta^2\langle H_x\rangle}{\varepsilon_x}\frac{1}{\tau_{\mathrm{IBS},\delta}}$$

likely causes
non-Gaussian
distribution

Coulomb logarithm (log)~24

important at low energies & in damping ring

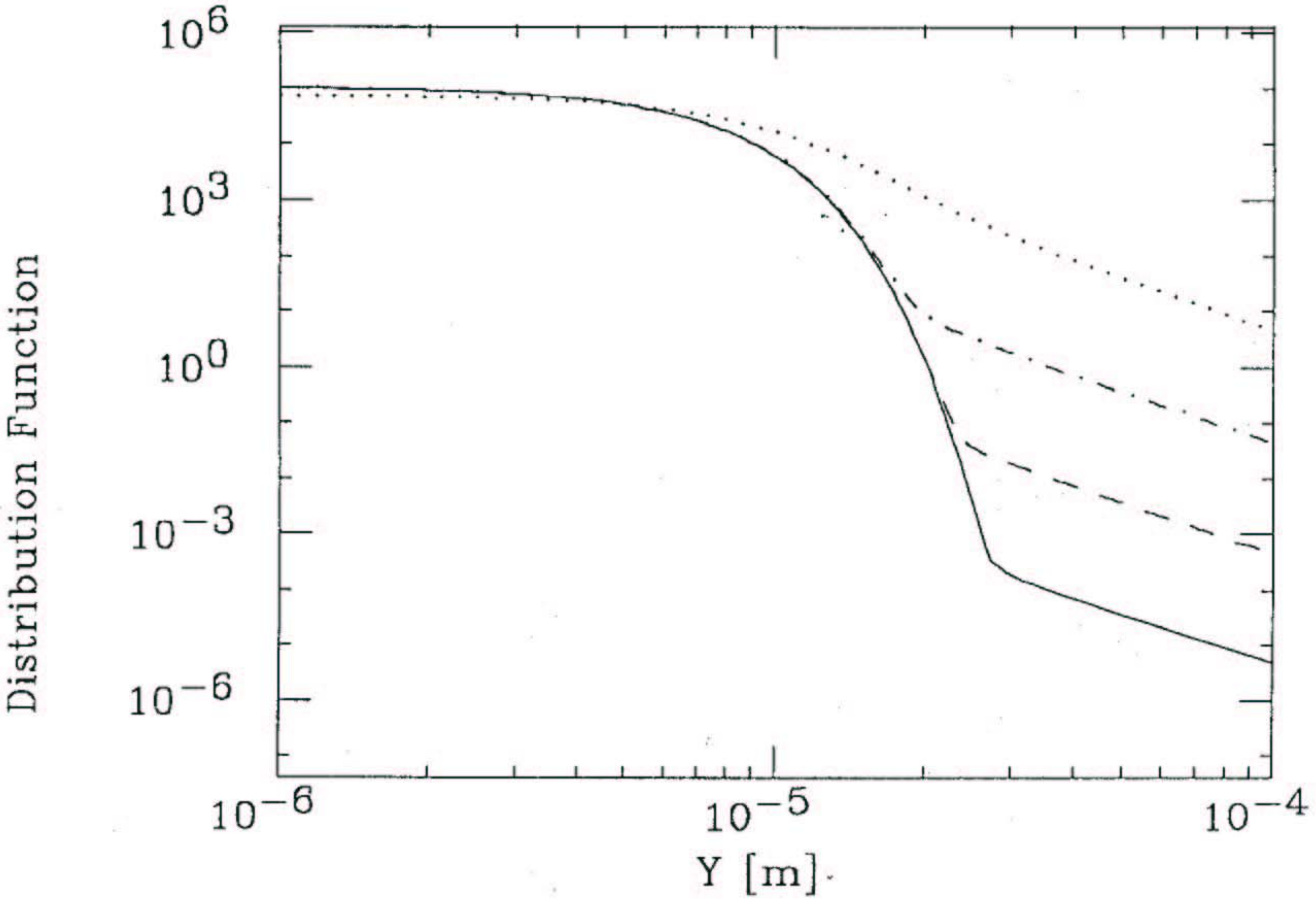


simulated distribution

Gaussian approximating core

Gaussian with correct rms

theory and simulation of 10^9 scattering events by T. Raubenheimer suggest non-Gaussian distribution with long tails at large amplitudes tail from elastic gas scattering like ~$1/y^3$



Tor Rauben-heimer, 1992

Fig. 1 Beam distribution in the NLC damping ring with *CO* gas pressures of 10^{-12} Torr (solid), 10^{-10} Torr (dashed), 10^{-8} Torr (dot-dash), and 10^{-6} Torr (dotted).

Scattering off thermal photons

total cross section is close to the Thomson cross section $\sigma_\gamma=8\pi/(3r_0^2)=0.665$ barn

density of photons is $\rho_\gamma=2\mathrm{x}10^7\ T^3/m^3$; at room temperature $\rho_\gamma=5.3\mathrm{x}10^{14}/m^3$

number of scattered particles: $\Delta N_b=\sigma_\gamma\ \rho_\gamma\ L\ N_b$

maximum energy loss $y_{max}=x/(1+x)$, where $x=15.3\ [E/\mathrm{TeV}]\ [E_\gamma/\mathrm{eV}]\ \cos^2(\alpha/2)$

average photon energy $E_\gamma=2.7\ k_BT$ (10 meV at 300 K)

this process becomes relevant for beam energies above 50 GeV, when the mean relative energy loss in a scattering event exceeds 1%

Electron cloud

generated by beam-induced multipacting and/or SR

causes SB&CB instabilities, and tune shift along train

nonlinear force could drive tails (in some SPS MDs off-energy particles were lost first)

mainly relevant for positron beams

$$\rho_e^{\mathrm{sat}} = \frac{< E_0 >}{m_e c^2}\frac{1}{b^2 r_e}$$

e- density due to space charge and thermal energy [modified after S. Heifets, ECLOUD'02]

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

e- density due to charge neutralization [F.Z., LHC Project Report 95, 1997]

$$W \sim (4...8)\pi \rho_e C / N_b$$

SB and CB wake of e- cloud
[K. Ohmi + F.Z., PRL 85, 3821, 2000,
G. Rumolo + F.Z., APAC 2001, Beijing]

$$\tau_{e,\mathrm{CB}} \approx \frac{\gamma \omega_\beta}{2\pi r_p c^2 \rho_e}$$

estimate of CB growth rate
[G. Rumolo + F.Z., APAC 2001, Beijing]

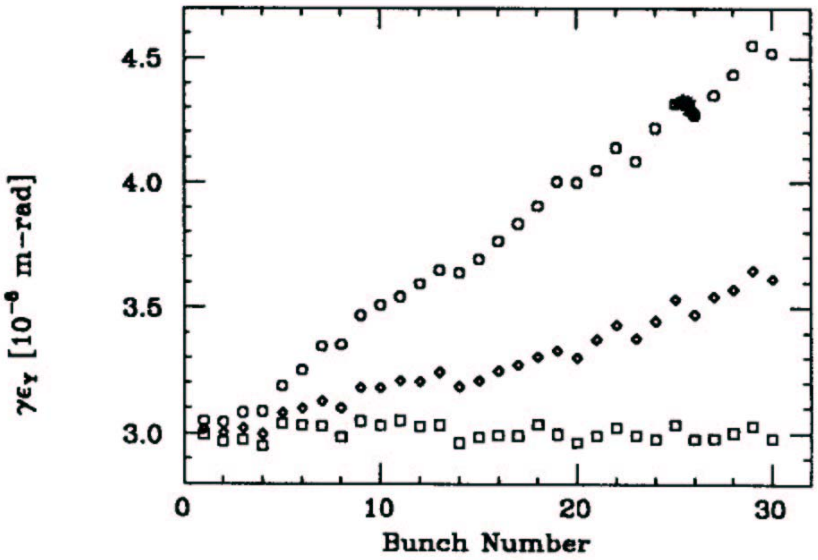
$$\rho_{\mathrm{thresh}} \approx \frac{2\gamma Q_s}{\pi \beta_y r_p C}$$

estimate of TMCI (SB) threshold (for DR)
[K. Ohmi + F.Z., PRL 85, 3821, 2000]

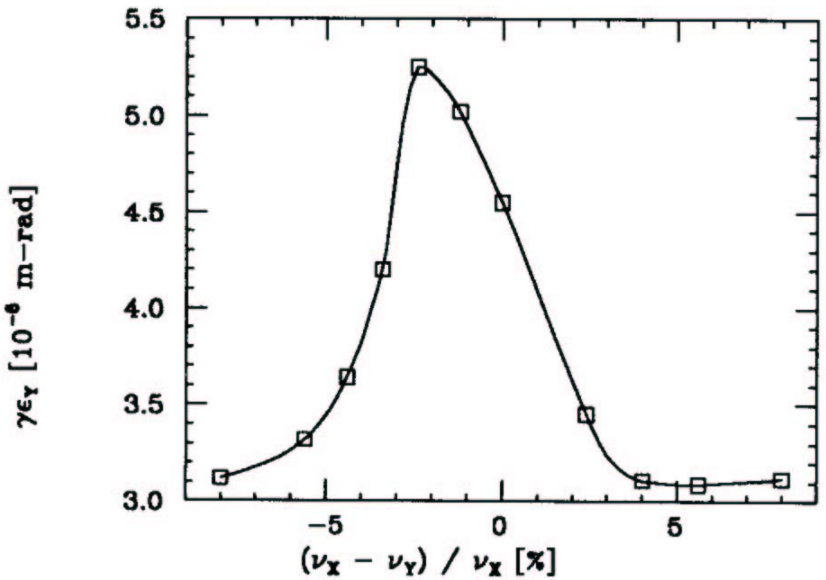
$$\Delta Q \approx \frac{r_e}{2\gamma} < \beta > \rho_e C$$

tune shift & spread due to e- cloud
[K.O. +S.H. + F.Z., APAC2001, Beijing]

Nonlinear transverse coupling by ions



4 Vertical emittance vs. bunch number in the NLC pre-linac at the beginning (squares), middle (diamonds), and end (circles); the linac has equal horizontal and vertical focusing of 90° per cell and a *CO* partial pressure of 10^{-7} Torr.



5 Vertical emittance vs. difference between horizontal and vertical quadrupole focusing in the NLC pre-linac; the emittance is that of the 30th bunch and the partial pressure of *CO* is 10^{-7} Torr. Note the peak occurs when the horizontal focusing is weaker than the vertical.

nonlinear ion potential drives parametric resonances
(T. Raubenheimer and P. Chen, 1992)

Fast beam-ion instability

CB instability of electron beams

transient effect

same mechanism in ring or linac

last bunches are driven to large amplitudes

$$\frac{1}{\tau_{\mathrm{FBII}}} = \frac{4 d_{\mathrm{gas}} \sigma_{\mathrm{ion}} \beta_y N_b^2 r_e^{3/2} n_b^2 L_{\mathrm{sep}}^{1/2} c}{\sqrt{27}\, \gamma \sigma_y^{3/2} (\sigma_x + \sigma_y)^{3/2} A^{1/2}}$$

Conclusions

This overview was rather general and incomplete. Lots of processes can cause beam halo. For several of them there exists no theory of halo generation yet. (SLC halo was never successfully modelled!) For the different sections of CTF-3, the CLIC drive beam and CLIC main beam, dominant halo sources should be identified, and then studied in detail, e.g., by computer simulation. 6-dim. CTF-3 acceptances & parameters needed as input. It is likely that various effects enhance each other, e.g., initial perturbations from the source are amplified by linac wake fields.