Collective Instabilities in the LHC

- Technological and Beam Dynamics Challenges
  - Cold Beam Screen and Pumping Slots
  - Beam Parameters and Parasitic Losses
- Conventional Collective Effects
  - Impedance Database and Coherent Tune Shifts
  - Single- and Multi-Bunch Instabilities
  - Chromaticity, Landau Damping and Octupoles
- Electron Cloud Effects
  - Physical mechanism of the Electron Cloud build-up
  - E-Cloud Instability and Heat Load on the Beam Screen
  - Critical SEY versus Bunch Intensity and Spacing
  - Beam Scrubbing with Satellite Bunches

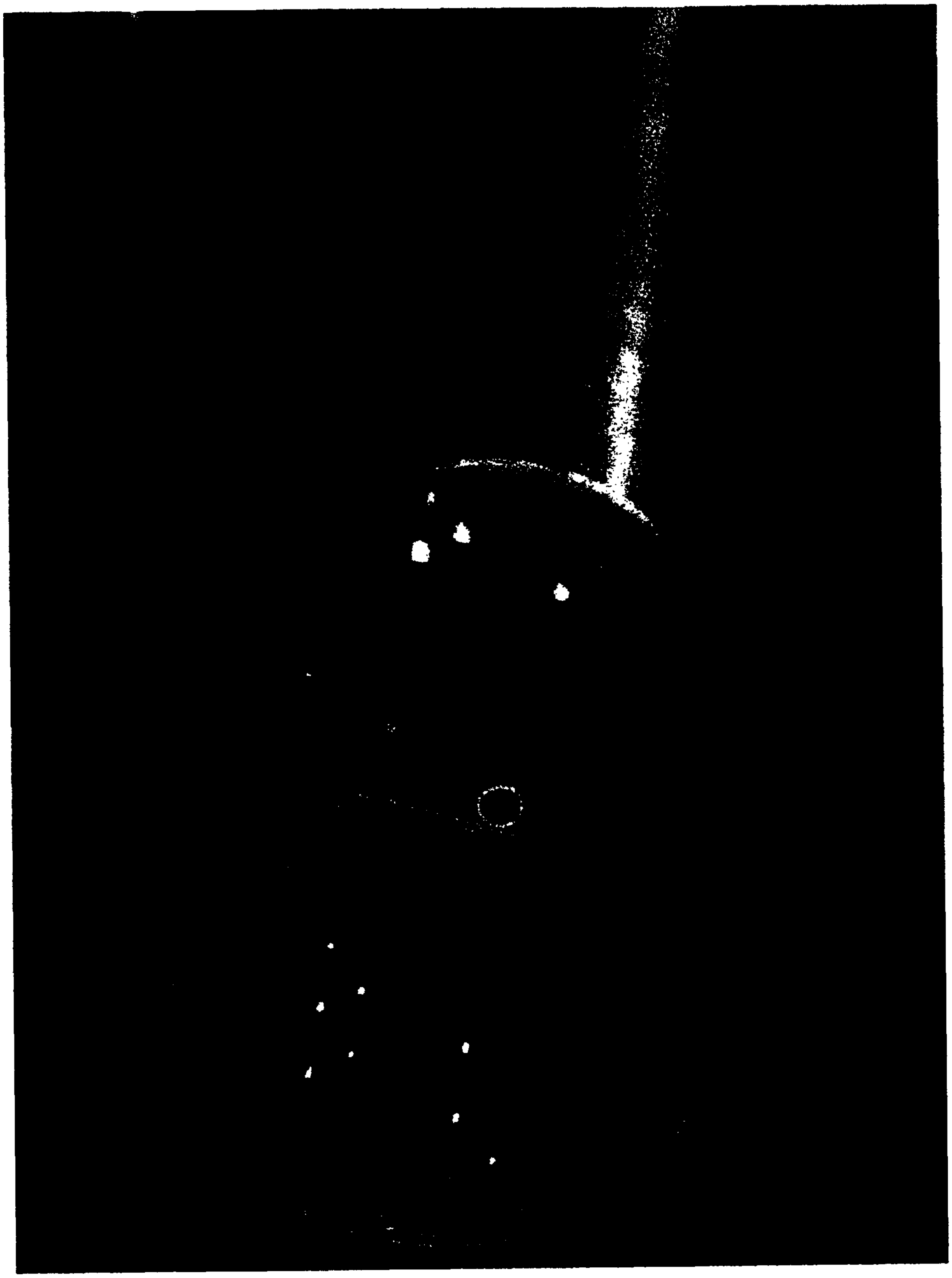
Technological and Beam Dynamics Challenges

The CERN Large Hadron Collider (LHC) has a *design energy of 7 TeV* per beam and an unprecedented *design luminosity of* $10^{34}\ cm^{-2}\ s^{-1}$. For cost optimization it makes use of the existing injector chain and has to be *accommodated in the LEP tunnel.*

Such design objectives are accompanied by several technological and beam dynamics challenges, ranging from the *8.3 T superconducting magnets* operating in superfluid helium at *1.9 K* to the *large number* of *low emittance*, *intense* proton bunches to be *injected at 450 GeV*, safely accelerated and collided at top energy.

The heat load of about 1 W/m, mainly due to *synchrotron radiation* and *beam image currents*, has to be taken by a *cold beam screen* operated around 20 K. At this temperature the cryopumping capacity is strongly reduced and about 4% of the screen surface will be covered by *pumping slots*, so that the cold bore at 1.9 K can pump away the gas, while being protected from synchrotron radiation.

LHC BEAM SCREEN



Estimate of beam scrubbing time

To get a rough estimate of the minimum time required for surface conditioning[a], let us assume a maximum heat load of 200 mW/m, compatible with cooling, and an average electron energy around 200 eV. This is consistent with simulation results for a nominal LHC proton beam with satellite bunches. The corresponding linear flux of electrons bombarding the screen surface is $6 \times 10^{15}\,\mathrm{s}^{-1}\mathrm{m}^{-1}$. Since a meter of LHC beam screen has a surface of 1.25×10^5 mm^2, the electron dose accumulated per hour is

$$\frac{200\,\mathrm{mW/m}}{200\,\mathrm{eV}}\;\frac{\mathrm{m}}{1.25 \times 10^5\,\mathrm{mm}^2}\;1.6 \times 10^{-19} C \simeq 8 \times 10^{-9}\;\frac{C}{\mathrm{mm}^2\,\mathrm{s}}$$

and the beam scrubbing time required to accumulate the required electron dose of 1 mC/mm^2 is about 35 hours.

[a]This estimate, independent of reflectivity and photoelectron yield, has been suggested by C. Benvenuti, P. Chiggiato and V. Rouzinov.

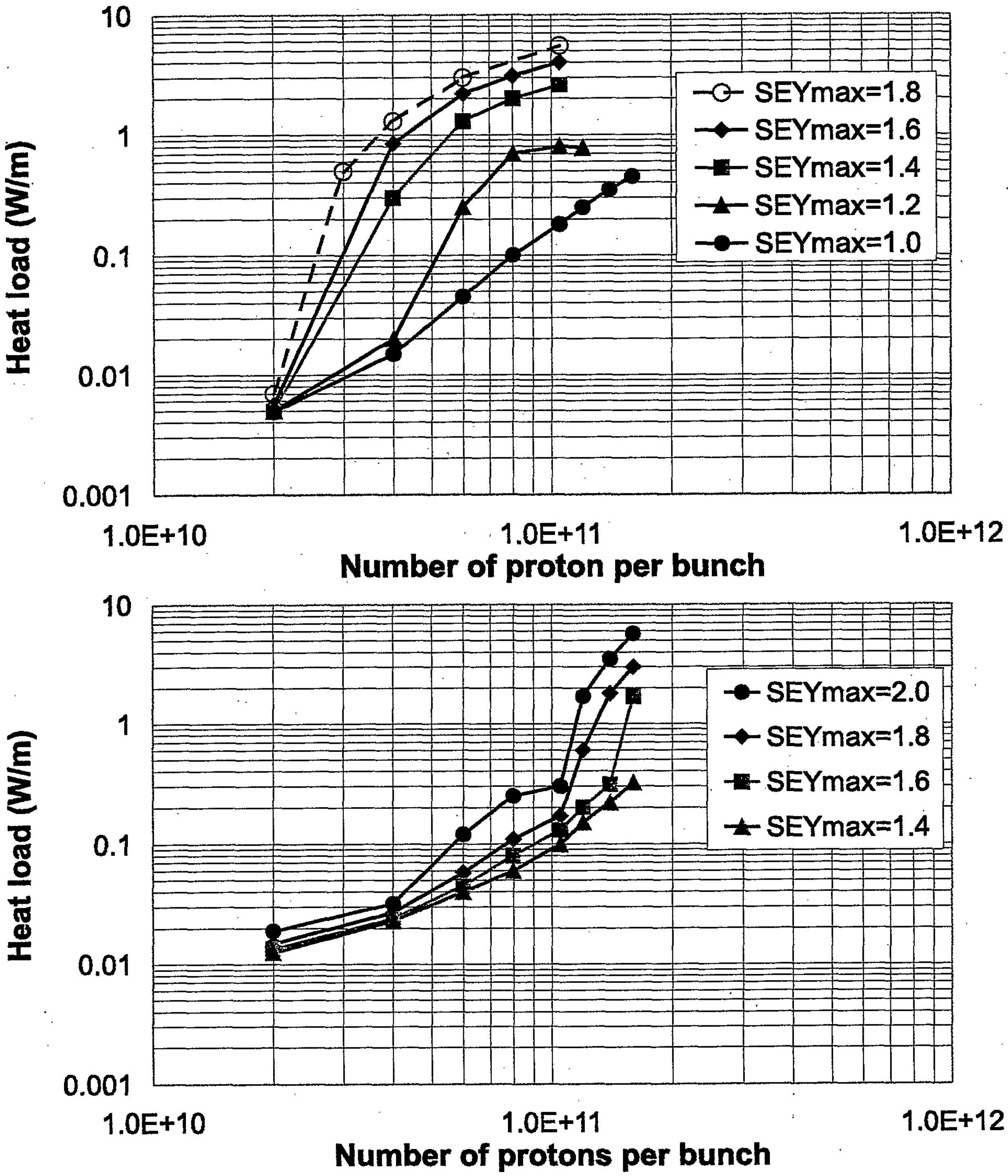
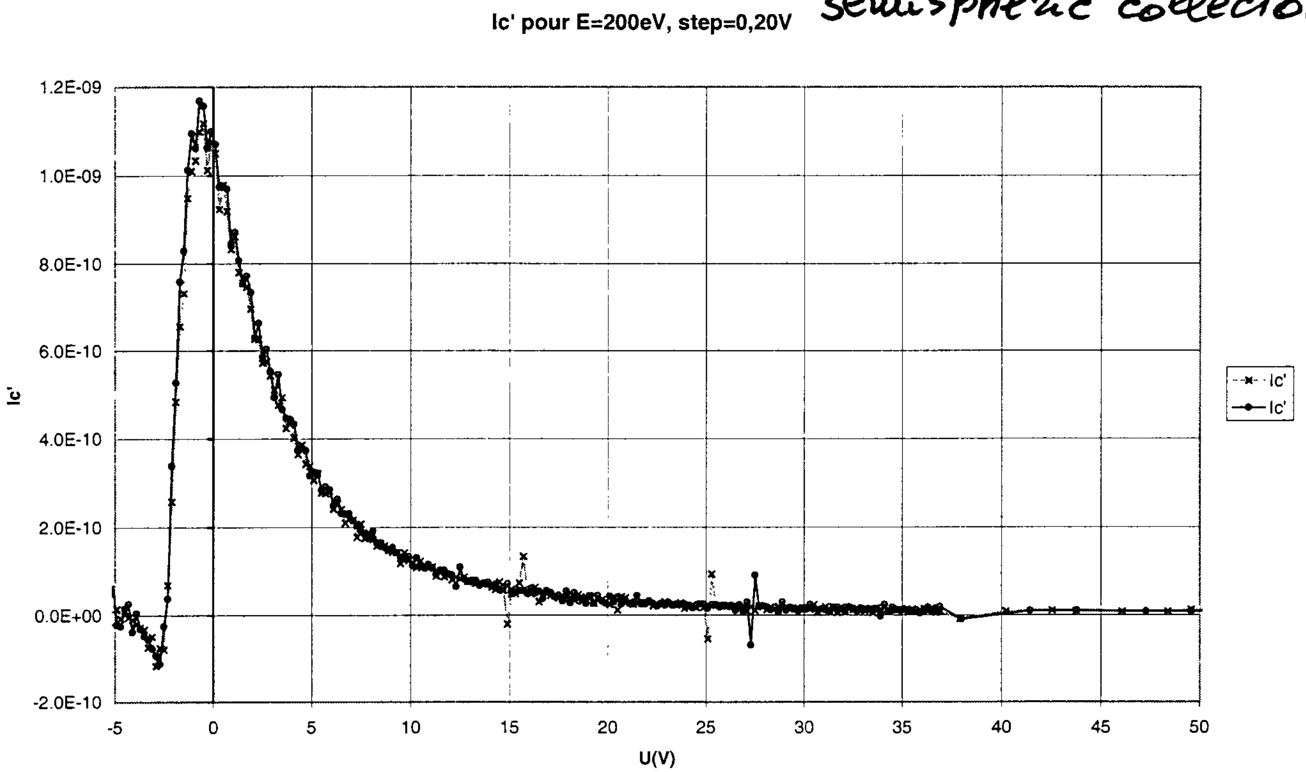
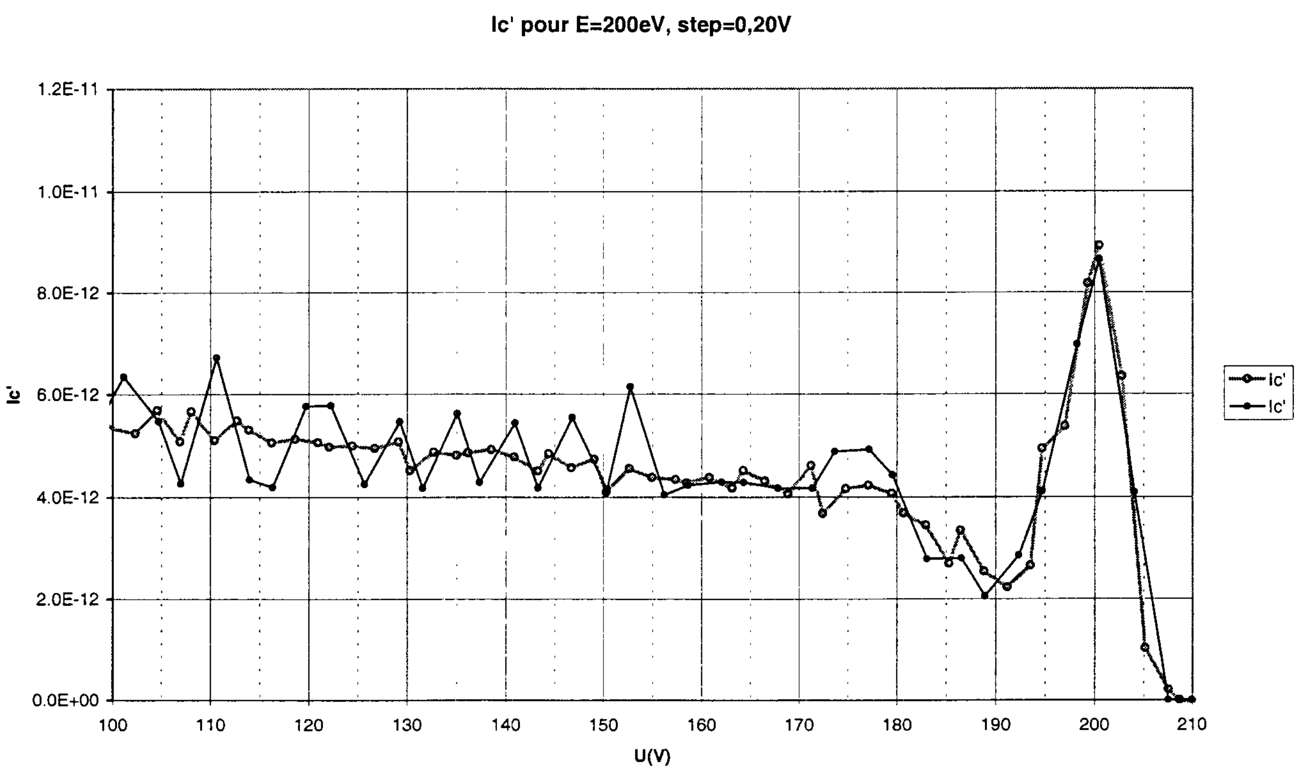


Figure 3: Heat load versus bunch population for different values of $\delta_{\max}$ and 10% reflectivity: without (top) and with (bottom) satellite bunches having 20% of the nominal bunch intensity and a spacing of 5 ns.

N. HILLERET : Energy distribution of secondary electrons measured with semispheric collector





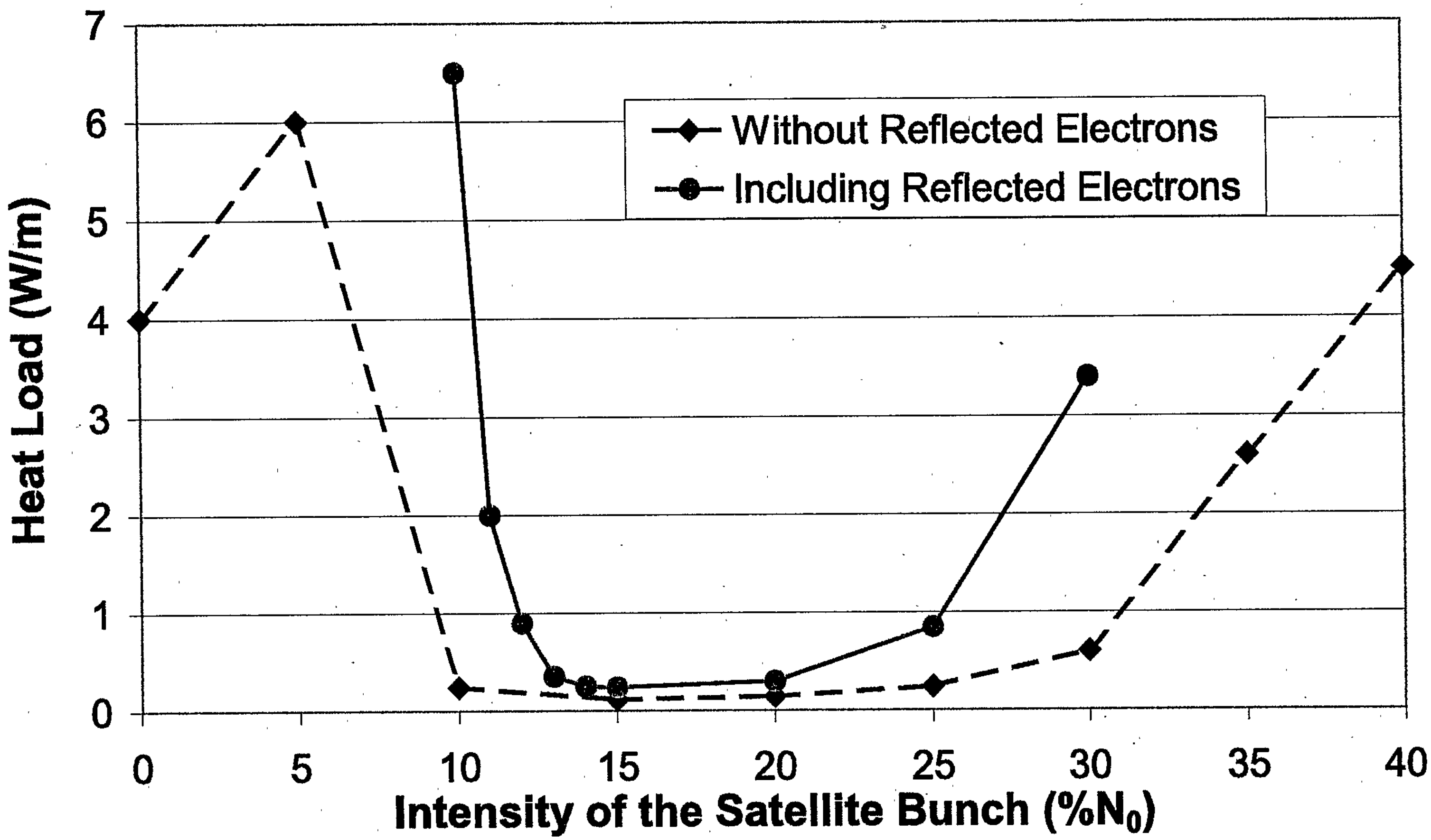


Figure 5: Heat load vs relative intensity of satellite bunches, following nominal LHC bunches at 2 RF wavelengths, with (solid line) or without (dashed line) elastic electron reflection as described in M. Furman and G.R. Lambertson, LBNL-41123 (1998) and Proc. MBI'97 (see in particular Eqs. (4.10) and (4.11)), with $\delta_{\max} = 1.6$ and 10% reflectivity.

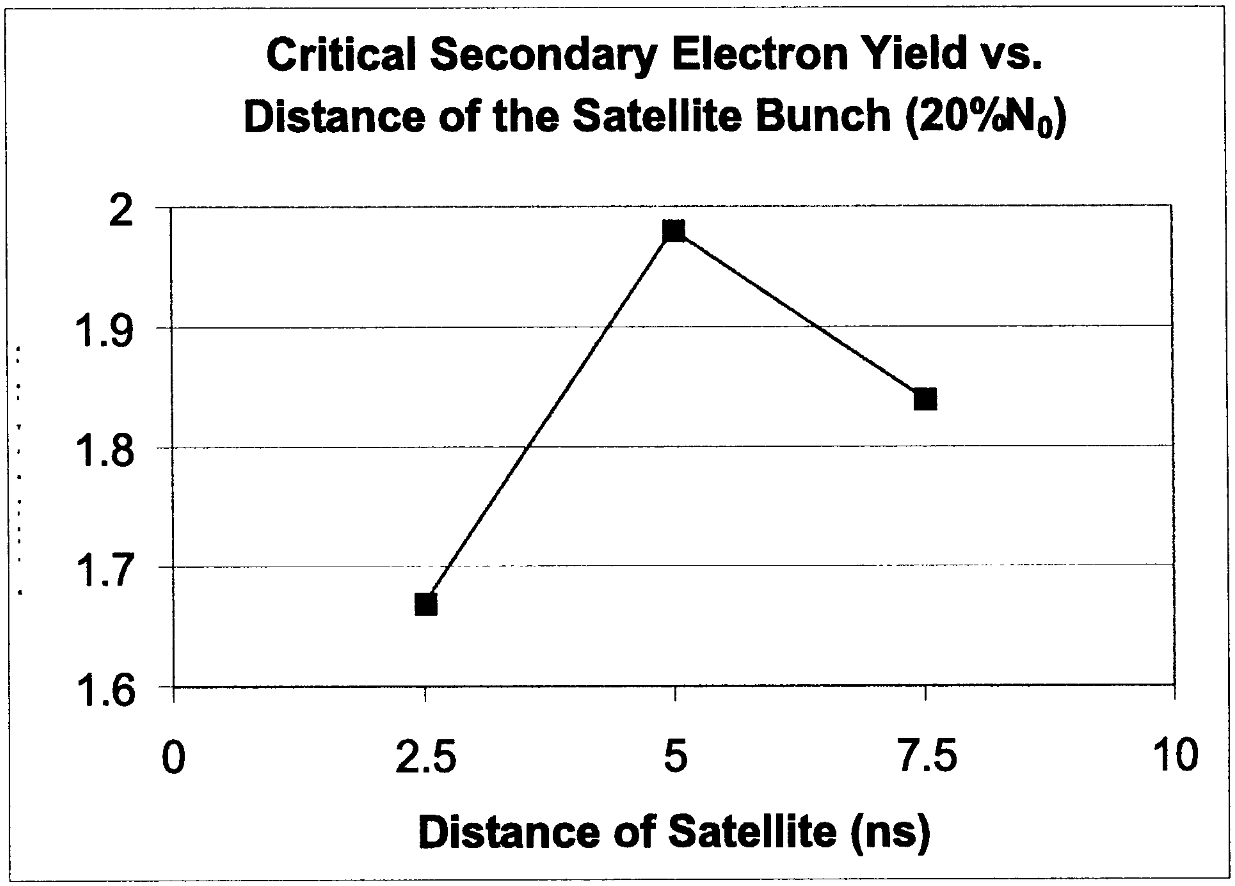
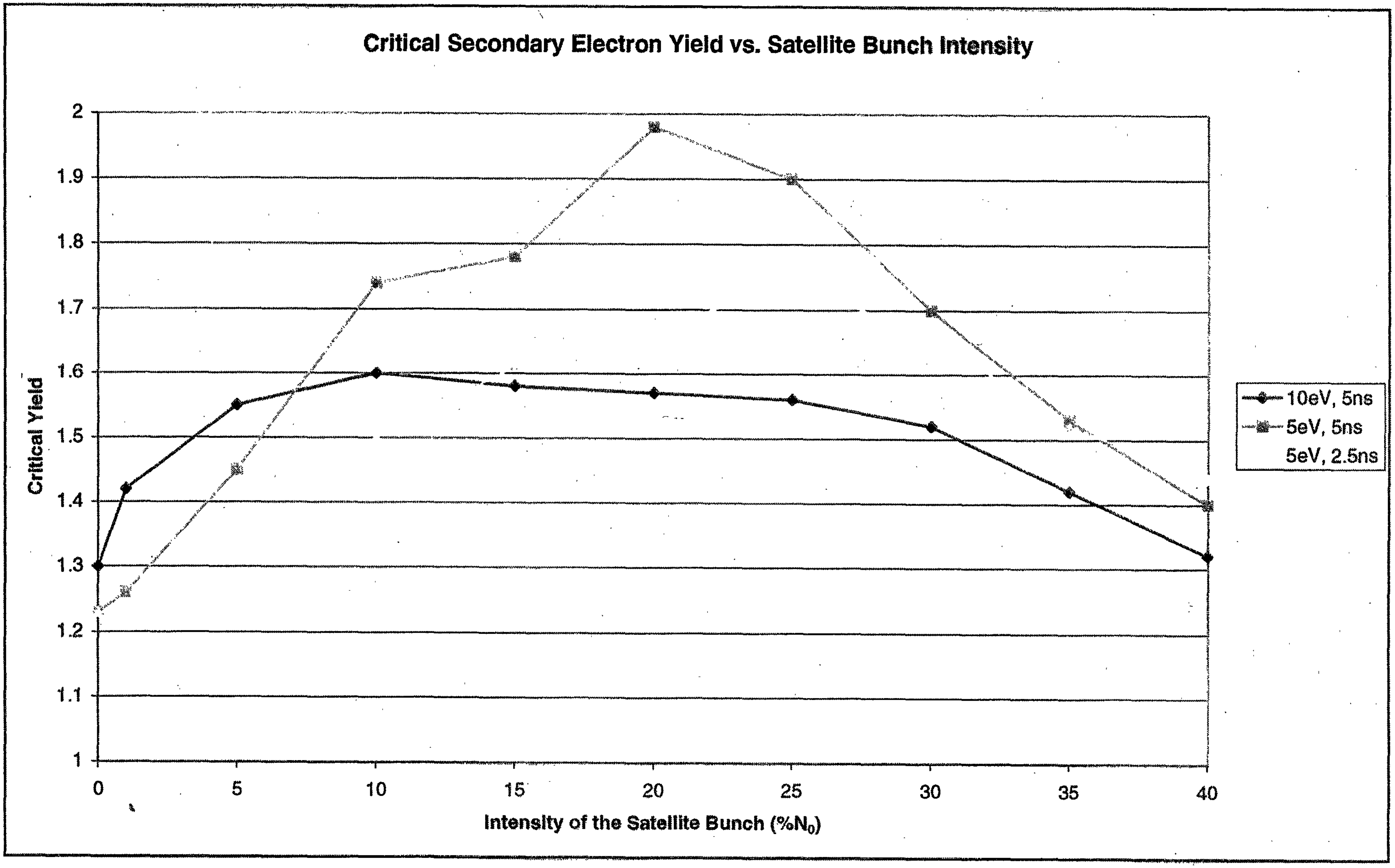
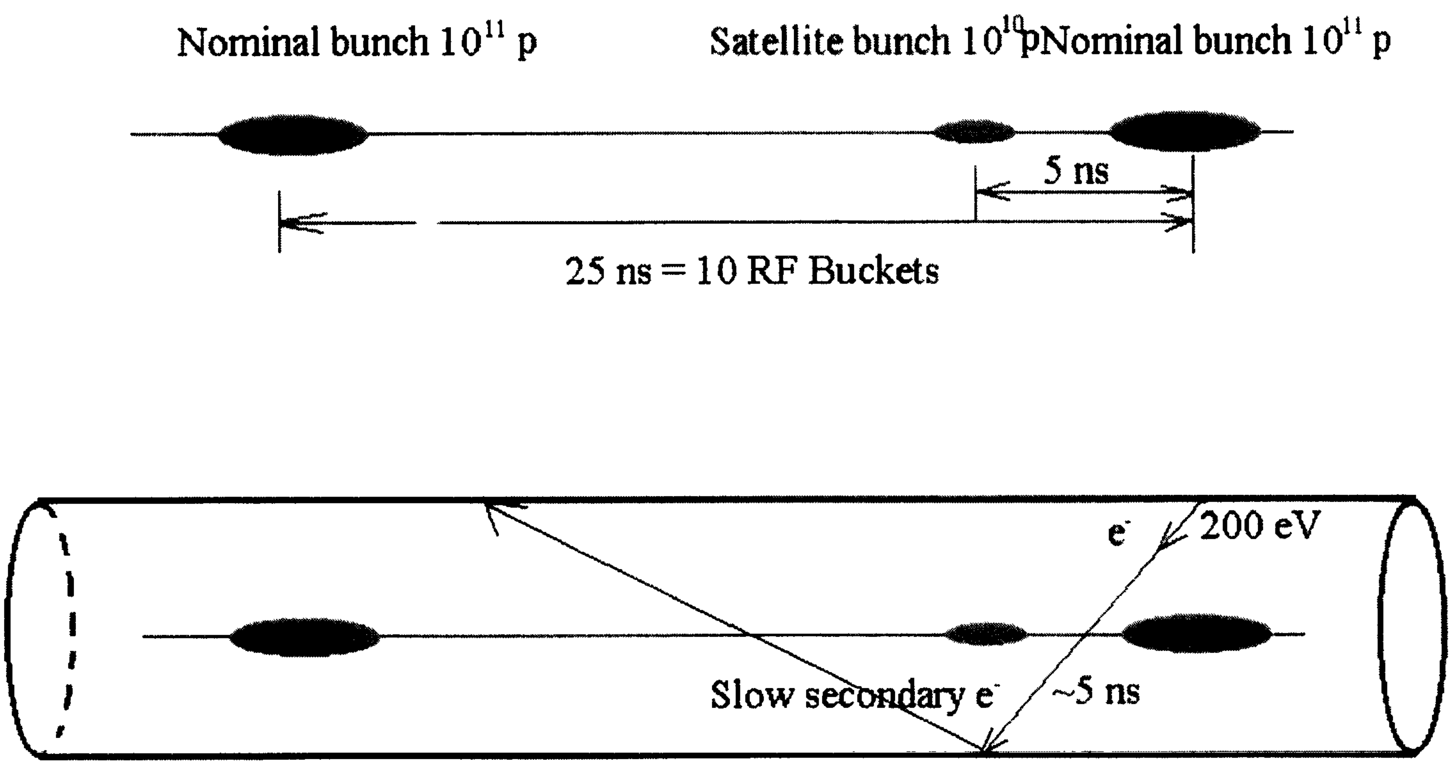


Figure 1: Critical value of the maximum Secondary Electron Yield $\delta_{\rm max}$ for satellite bunches having 20% of the nominal bunch intensity and following nominal LHC bunches at various distances. We assume a highly reflective beam screen surface, with $R \simeq 1$, and half-gaussian secondary electron energy distribution with 5 eV r.m.s. width.


Critical Secondary Electron Yield vs. Satellite Bunch Intensity
Critical Yield
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0
5
10
15
20
25
30
35
40
Intensity of the Satellite Bunch (%N$_0$)
10eV, 5ns
5eV, 5ns
5eV, 2.5ns



SIMULATIONS WITH SATELLITE BUNCHES

X. ZHANG

Electron Cloud Instability

Simulations performed by F. Zimmermann in 1997 assuming $\delta_{\mathrm{max}} = 1.5$, high reflectivity and large photoelectron yield ($R = 1$ and $Y = 1$) gave an instability rise time of *50 msec horizontally* and *130 msec vertically*. More recent simulations by X. Zhang with $R = 10\%$ and $Y = 0.2$ gave a slower instability with *340 msec horizontal* and *170 msec vertical* rise times.

According to the 1997 simulations, lowering δ_{max} from 1.5 to 1.1 reduces the horizontal wake by less than a factor of 2. If the beam current is a factor 2 smaller than the design value, the effective horizontal wakefield increases by about 25%! The wakefield does not decrease in proportion to the beam current, because, for lower current, the high-density region of the electron cloud is closer to the beam pipe center.

The vertical wake is instead very sensitive to the initial secondary-electron energy and may even change sign for maximum initial energies above 25 eV, when more than half of the secondaries cross the center of the beam pipe before the arrival of the next bunch.

F. ZIMMERMANN, LHC Project Report 95 (1997)

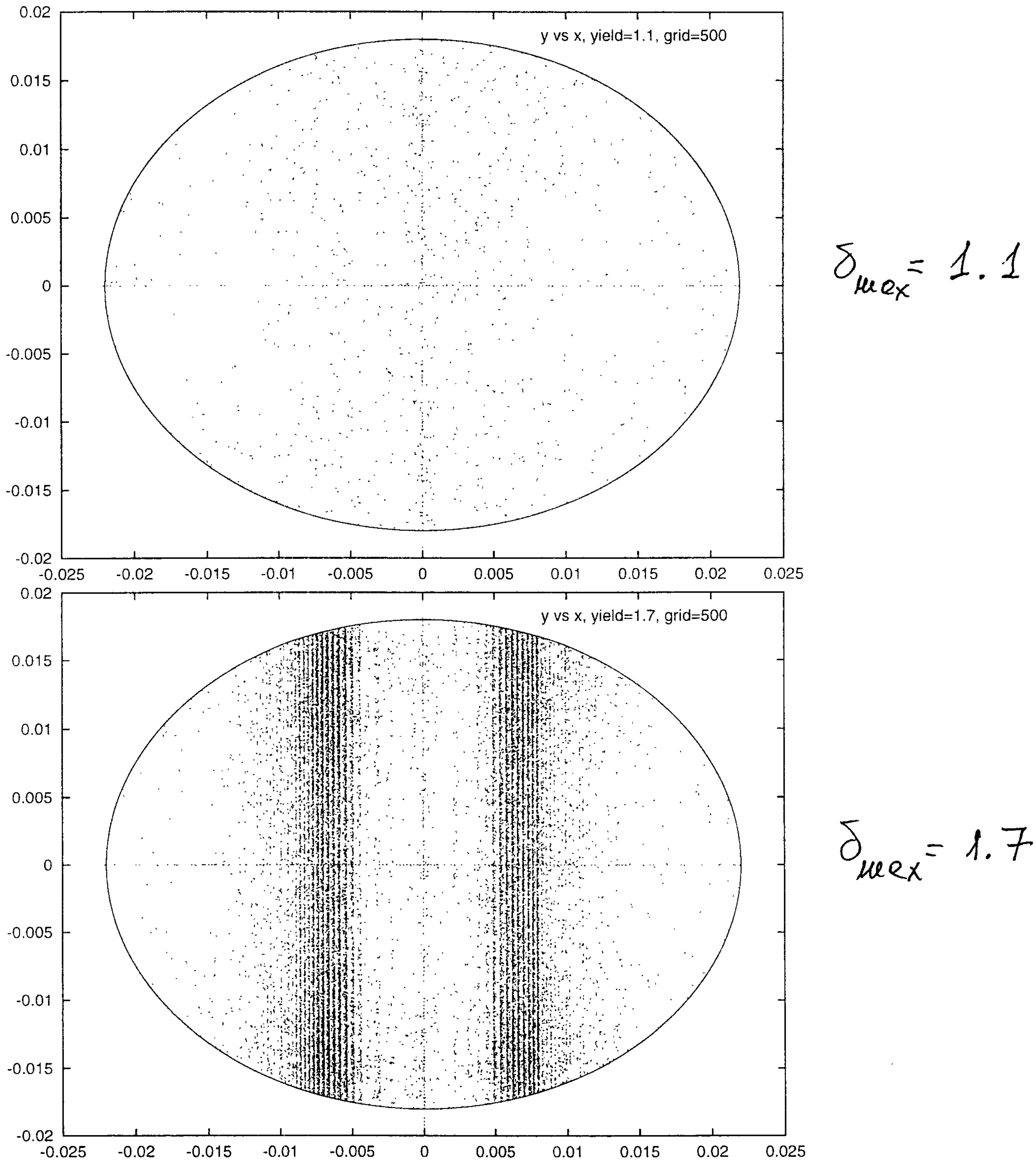
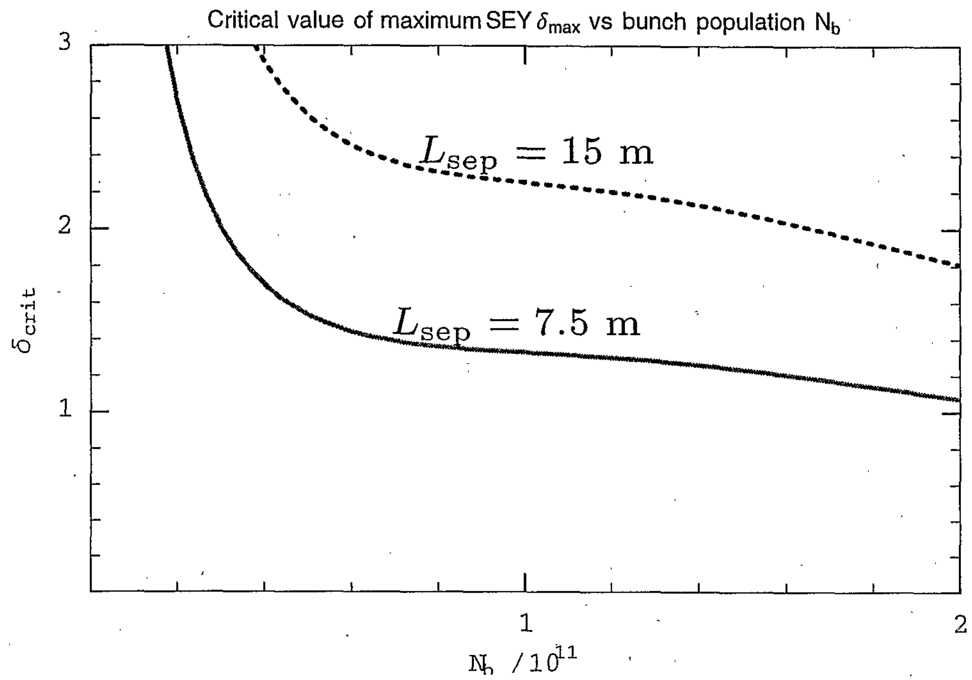
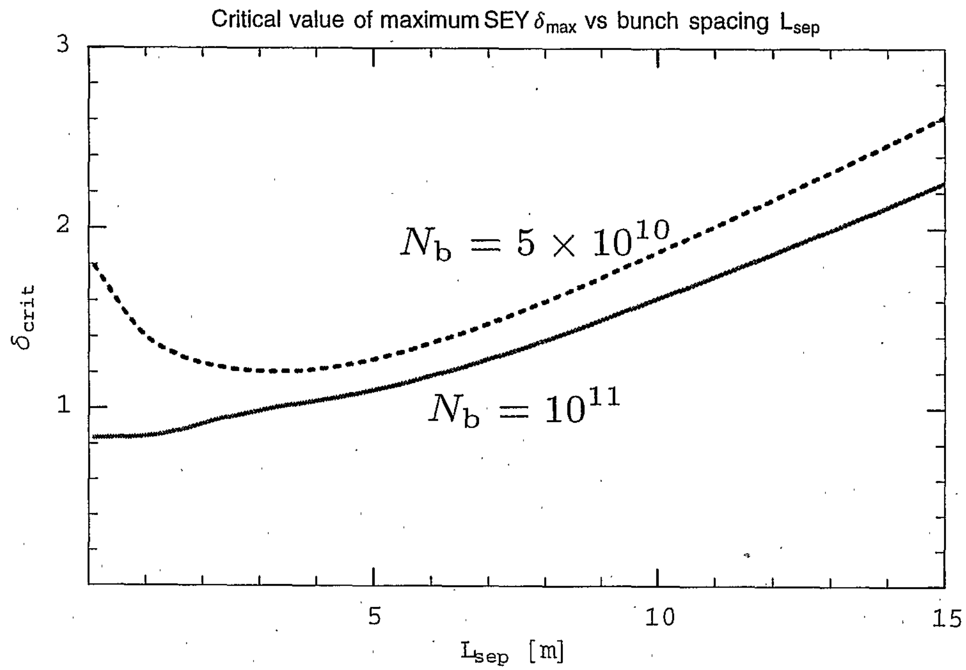


Figure 5: Transverse distribution of macroelectrons after 40 bunches for a maximum secondary emission yield δ_{max} of 1.1 (top) and 1.7 (bottom). Horizontal and vertical dimensions are given in units of m.





Minimum value of the critical secondary electron yield (G. Stupakov, 1997) for a circular screen of radius $a = 2$ cm and a secondary electron energy $W_s = 10$ eV, versus bunch population (left) and bunch spacing (right). The solid and dotted curves correspond to a bunch spacing of 7.5 m and 15 m (left) or to a bunch population of 10^{11} and 5×10^{10} (right), respectively.

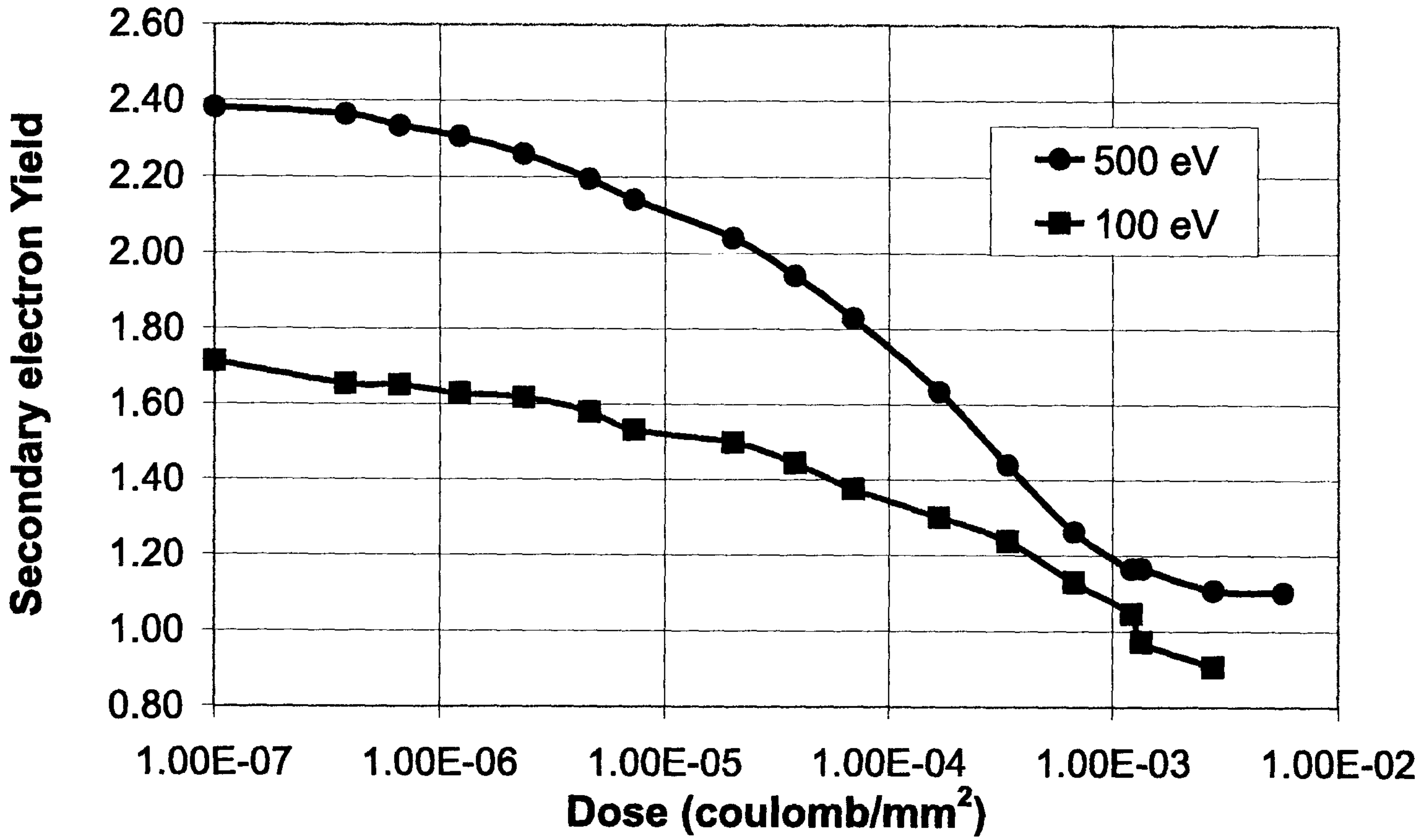


Figure 3: Secondary electron yield measured at the bombardment energy (respectively 500 eV and 100 eV) as a function of the dose received by the sample (N. Hilleret).

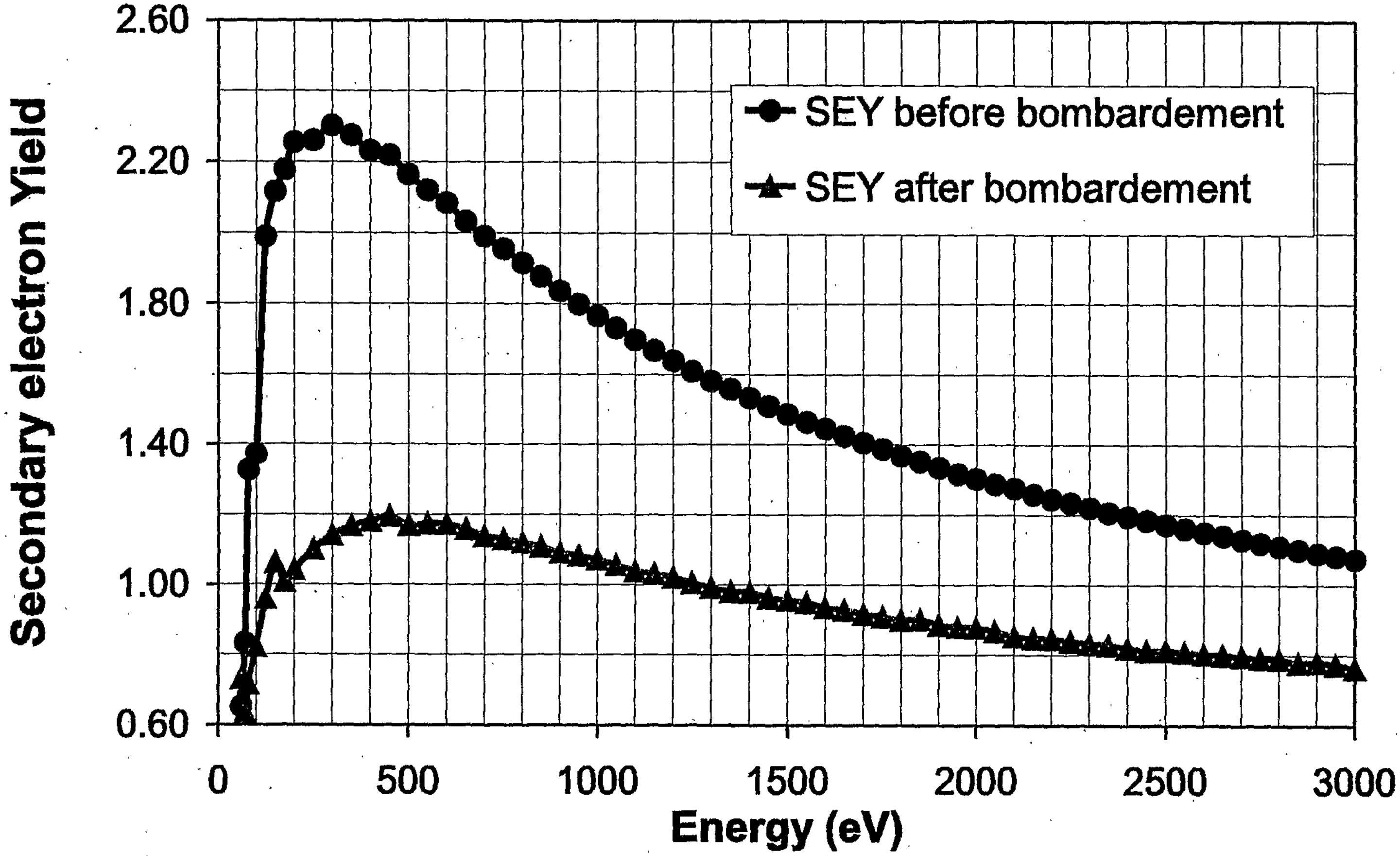


Figure 2: Variation of δ_{SEY} as a function of the primary electron energy, for a sample of copper colaminated on stainless steel, before and after bombardment with 500 eV electrons, corresponding to a dose of 5×10^{-3} C/mm^2 (N. Hilleret).

Secondary Electron Emission

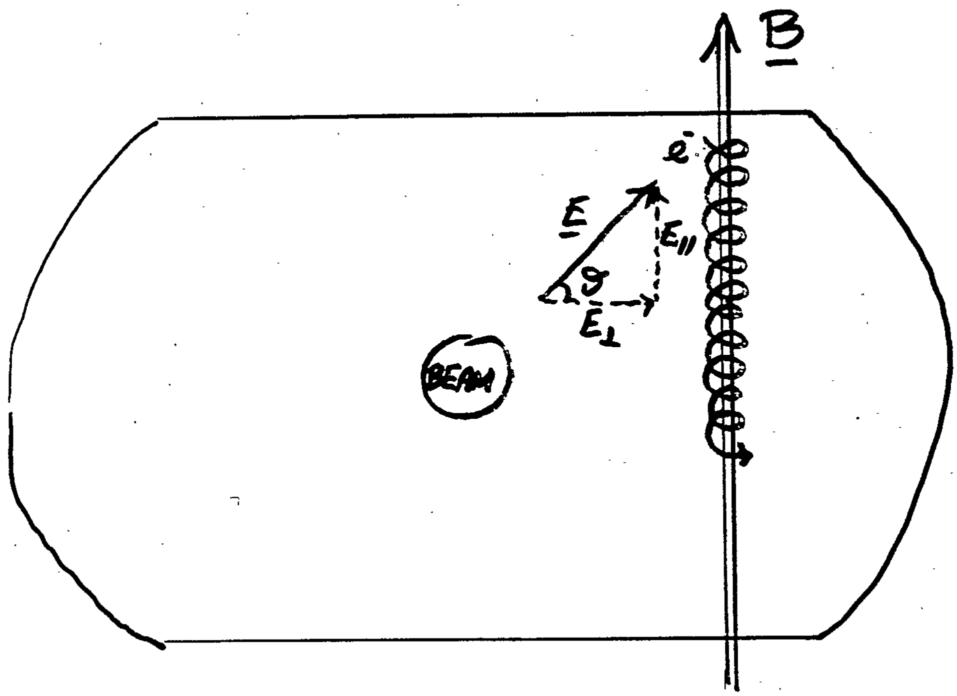
The average number of secondary electrons emitted when a primary electron of energy W hits a metal surface with incidence angle θ from the normal can be written

$$\delta_{\mathrm{SEY}}(W,\theta) = \frac{\delta_{\max}}{\cos\theta}\, h\left(\frac{W}{W_o}\right)$$

- the maximum yield $\delta_{\max}$, corresponding to a primary electron energy W_o typically around 400 eV, is a characteristic of the metal ($\delta_{\max} = 1.3 \div 2.5$ for copper, depending on surface preparation)

- h is a universal function having the phenomenological expression

$$h(\xi) = 1.11\,\xi^{-0.35}\left(1 - e^{-2.3\,\xi^{1.35}}\right)$$



IN A DIPOLE, ONLY THE BEAM ELECTRIC FIELD COMPONENT $E_{\parallel} = E \cdot \sin\vartheta$ PARALLEL TO THE MAGNETIC FIELD IS EFFECTIVE IN ACCELERATING PHOTOELECTRONS OR SECONDARY ELECTRONS

IF THE REFLECTIVITY IS LOW, PHOTOELECTRONS AND SECONDARY ELECTRONS ARE CONFINED TO SMALL VALUES OF ϑ AND $E_{\parallel}$ IS SMALL. THIS IS NOT TRUE IN FIELD-FREE REGIONS.

- For a uniform illumination of the beam screen, corresponding to *high surface reflectivity*, the average energy gain in a dipole magnet is smaller by a factor two, since only the vertical component of the beam force is effective in accelerating the electrons

- indeed they spiral along the vertical magnetic field lines with typical Larmor radii of a few μm and perform about *a hundred cyclotron rotations during a bunch passage.*

- the heat load in a dipole magnet can be *drastically reduced* if the screen reflectivity is much smaller than unity: in this case, photoelectrons and secondary electrons are produced only near the horizontal plane, where the vertical component of the beam force is very small.

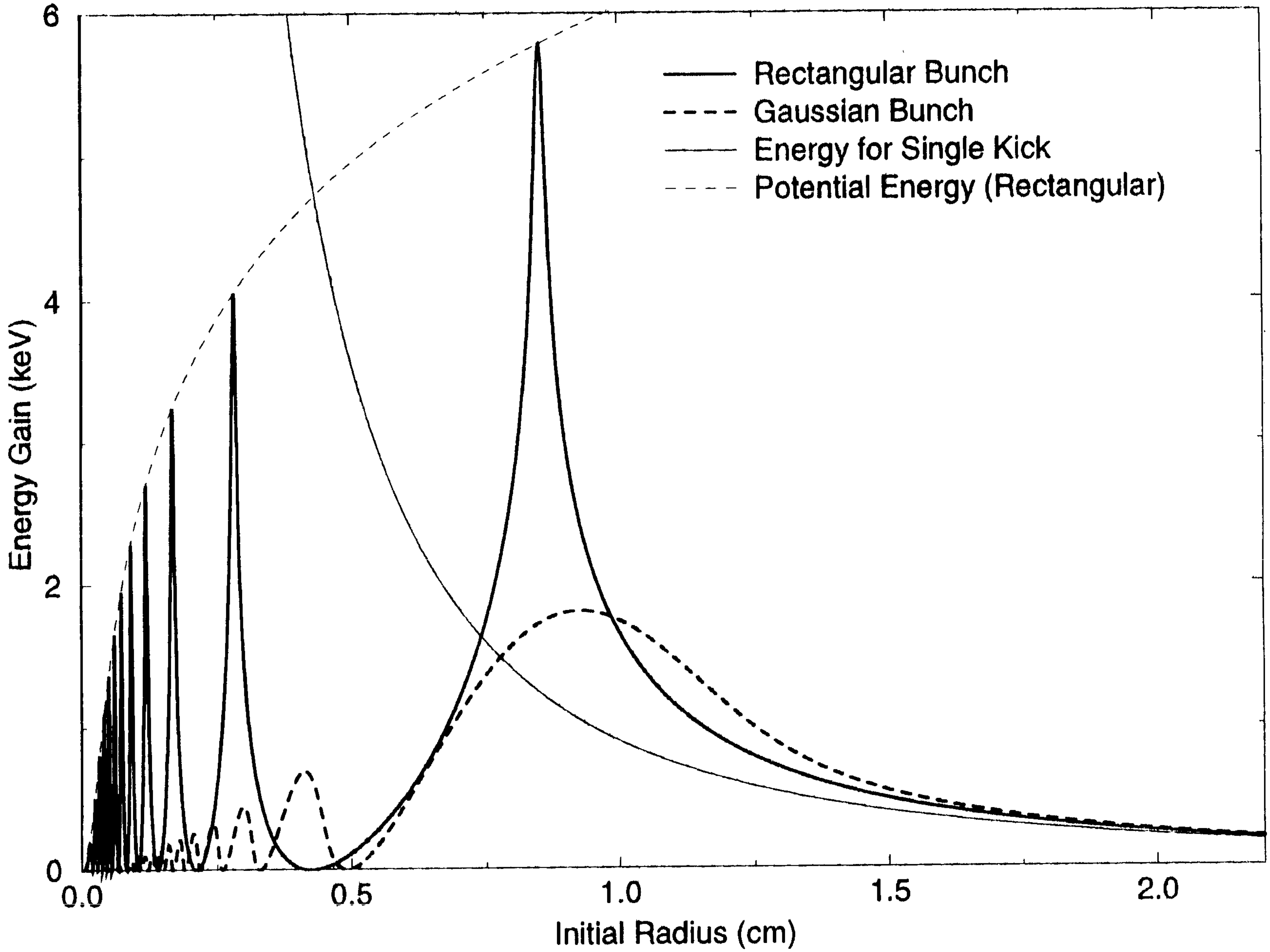
Some features of the current simulation codes (M. Furman and F. Zimmerman + O. Brüning):

- electrons are modeled by macro-particles (typically 1000 per bunch)
- slicing of each bunch and inter-bunch gap (typically 50 slices)
- generation of photoelectrons and secondary electrons
- image charges on elliptical boundary (beam screen)
- space charge computation using a two-dimensional mesh (typically 25×25)
- computation of heat load on the beam screen
- computation of electron cloud wake and beam instability growth rate

Scott Berg

Energy Gain of Stationary Electron (No Magnetic Field)

LHC: $\sigma_\perp$=0.2 mm, σ_l=7.7 cm, N=1.05×10^{11}



A first estimate [Gröbner, PAC97] of the heat load on the LHC beam screen, based on a photoelectron yield $\delta_{\gamma e} \simeq 0.02$ and an average energy gain from the proton bunch $\langle W \rangle \simeq 700$ eV (without magnetic field and for a uniform electron cloud distribution), gave

$$P = \Phi_\gamma \delta_{\gamma e} \langle W \rangle \simeq 0.2 \text{ W/m}$$

comparable to the heat load due to synchrotron radiation.

- this does not include a possible *electron cloud build-up* due to secondary emission, which according to earlier simulations [Zimmerman, 1997] can lead to a very fast horizontal instability
- an intensive research program has been set up at CERN to measure the relevant physical quantities, to validate analytic estimates and simulation results, and to propose effective remedies (for a fairly complete account of this 'crash program' see `http://wwwslap.cern.ch/collective/electron-cloud/`)

The linear photon flux due to synchrotron radiation in the LHC is

$$\Phi_\gamma = \frac{5}{2\sqrt{3}}\,\alpha\gamma\frac{N_\mathrm{b}}{\rho t_\mathrm{sep}} \simeq 10^{17}\,\frac{\mathrm{photons}}{\mathrm{m}\cdot\mathrm{s}}$$

α fine structure constant

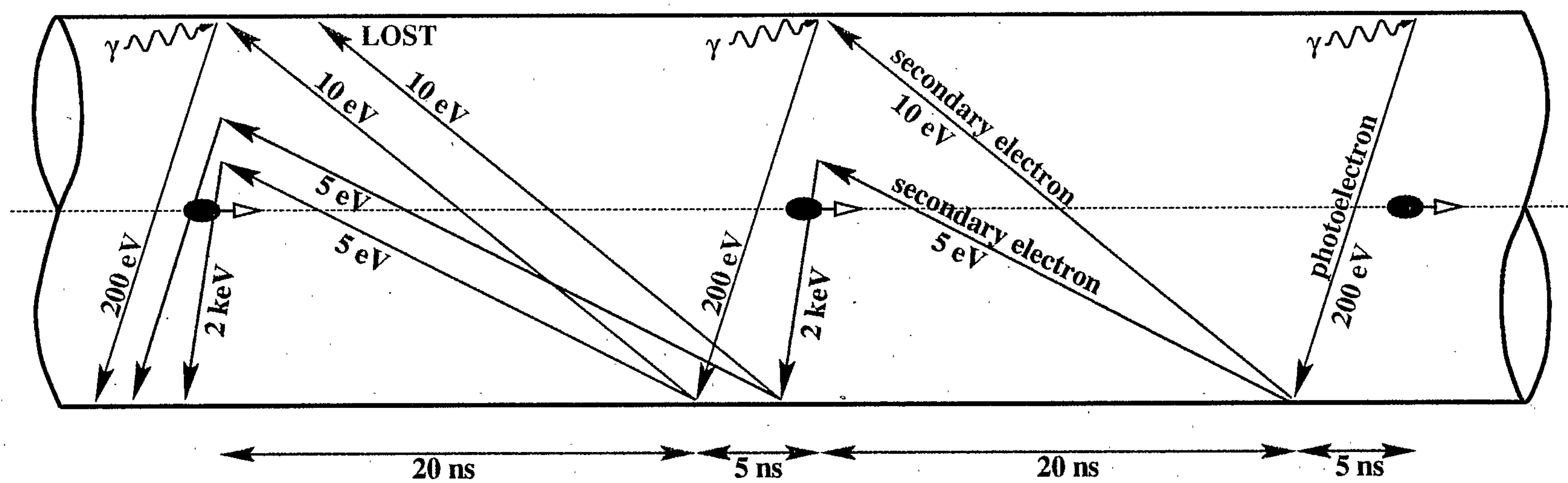
$\gamma \simeq 7000$ Lorentz factor for protons at 7 TeV

$\rho \simeq 2784$ m bending radius

$N_\mathrm{b} = 10^{11}$ nominal bunch population

$t_\mathrm{sep} = 25$ ns nominal bunch separation

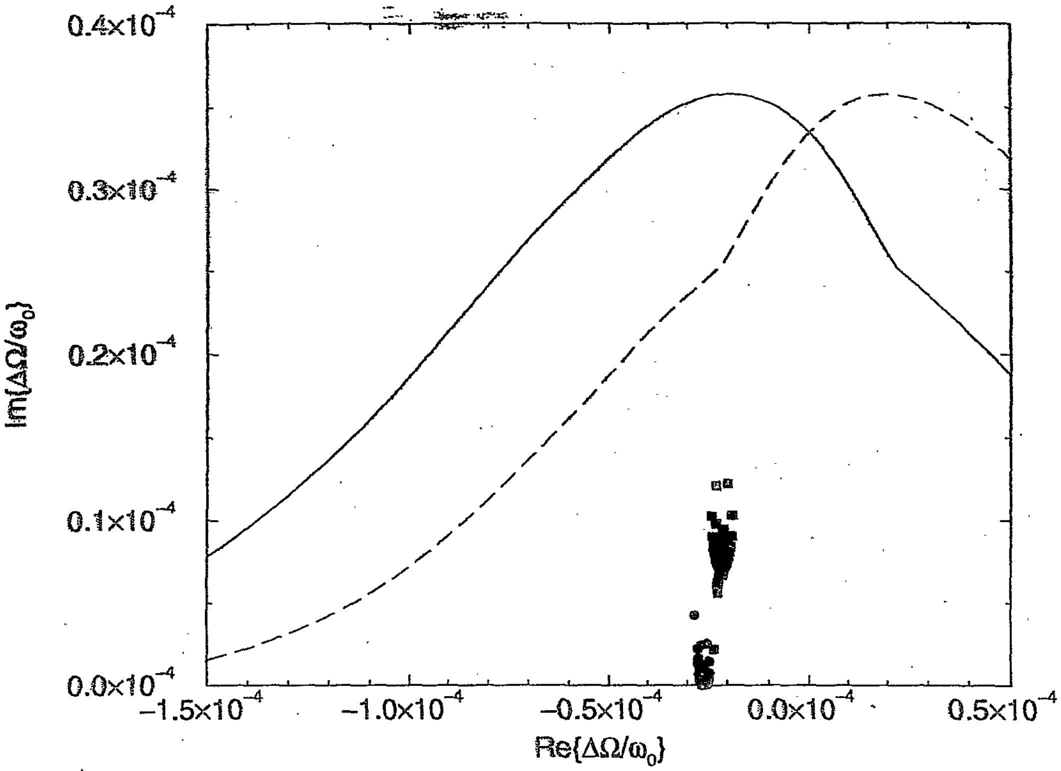
The critical energy of these photons is $\varepsilon_\mathrm{cr} = 3/2\,\gamma^3\hbar c/\rho \simeq 45$ eV, i.e., well above the work function for copper (a few eV)



- Photoelectrons created at the pipe wall are accelerated by proton bunches up to 200 eV and cross the pipe in about 5 ns.
- Slow secondary electrons with energies below 10 eV have a time-of-flight longer than 20 ns and survive until the next bunch. This may lead to an electron cloud build-up with potential implications for *beam stability* and *heat load on the LHC beam screen.*
- An effective solution is to condition the screen surface using electrons accelerated by a special proton beam, either with *increased bunch spacing* or with *weak satellite bunches* at 5 ns from the main bunches. These behave as 'clearing bunches' for slow secondary electrons.

Electron Cloud in the LHC

- synchrotron radiation from *proton* bunches creates *photoelectrons* at the pipe wall
- these photoelectrons are pulled towards the positively charged bunch
- when they hit the opposite wall, they generate secondary electrons which can in turn be accelerated by the next bunch if they are slow enough to survive
- depending on *surface reflectivity*, *photo-emission* and *secondary-emission* yields, this mechanism can lead to the fast build-up of an *electron cloud*, only limited by *space charge* effects, with potential implications for beam stability and heat load on the cold LHC beam screen



Stability of LHC pilot beam at 7 TeV[a]

[a]Scott Berg, LHC Project Report 100.

Complex coherent frequencies of $m = 0$ modes for multiple symmetric bunches at top energy with 16% of the nominal current, compared to Landau damping threshold curves. The ● are for a chromaticity of 0, and the ■ are for a chromaticity of -15. The Landau damping curves assume that the beam is always collimated at 6σ (and no less) and correspond to a negative (solid) or positive (dashed) horizontal detuning of 3.2×10^{-5} at 1σ, for a reduced normalised emittance of 1 μm-rad.

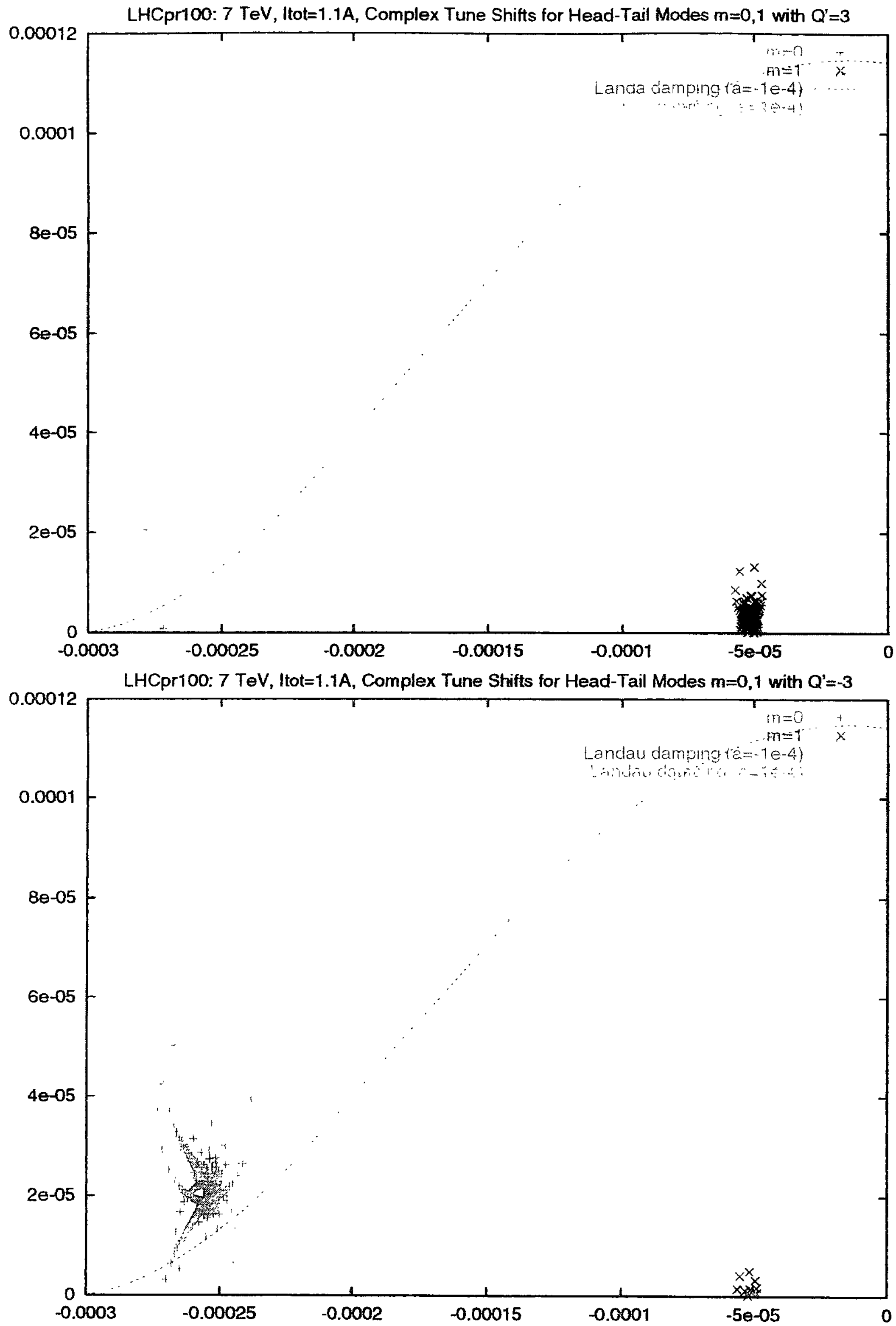
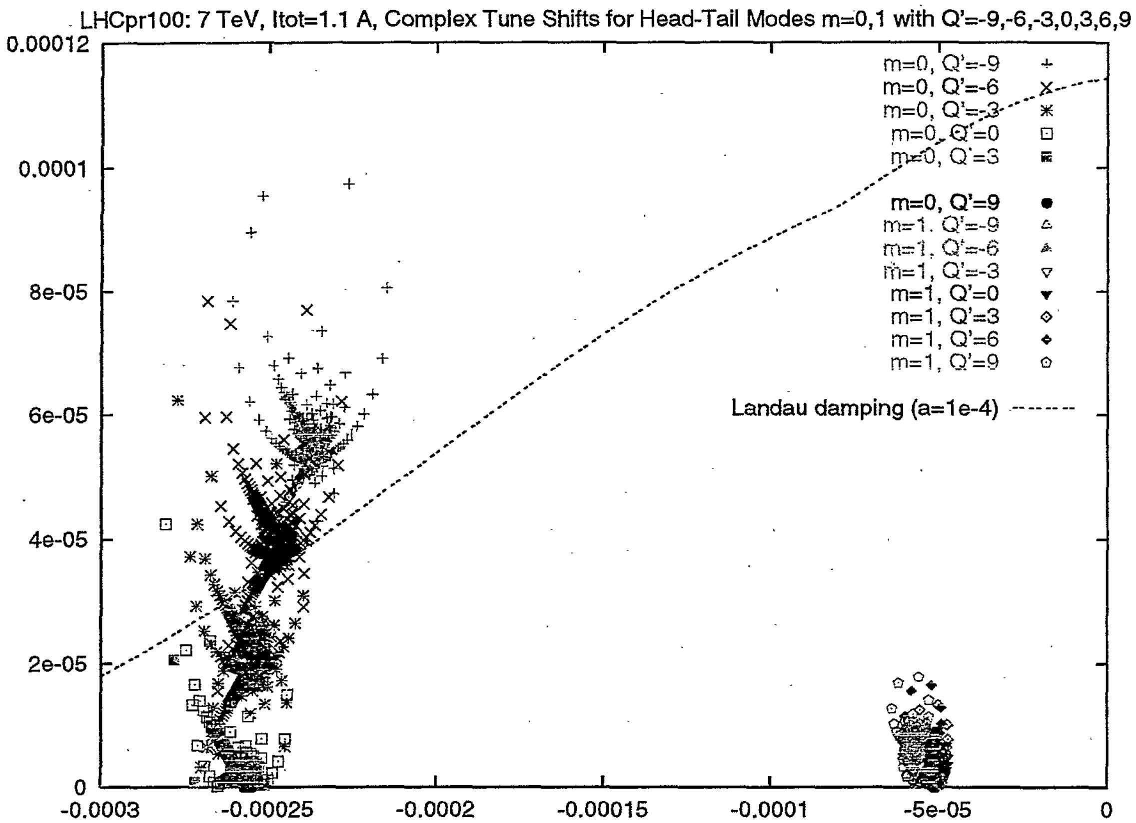


Figure 3: Complex tune shifts of the head-tail modes $m = 0$ and $m = 1$ for a chromaticity $Q' = +3$ (top) or $Q' = -3$ (bottom), at top energy and for multiple symmetric bunches with ultimate intensity $I_{\rm tot} = 1.1$ A, compared to Landau damping stability curves corresponding to a detuning of $\pm 10^{-4}$ at 1 r.m.s. beam size with opposite cross-anharmonicity $\mp 0.72 \times 10^{-4}$. The impedance model is the same as in LHC Project Report 100.



Stability of ultimate LHC beam: top energy[a]

[a]Francesco Ruggiero, LHC Project Note in preparation.

Complex tune shifts of the head-tail modes $m = 0$ and $m = 1$ for different chromaticities $Q' = -9 \ldots 9$, at top energy and for multiple symmetric bunches with ultimate intensity $I_{\rm tot} = 1.1$ A, compared to Landau damping stability curves for a quasi-parabolic beam distribution cut at 3.2σ, corresponding to a detuning of $\pm 10^{-4}$ at 1 r.m.s. beam size with opposite cross-anharmonicity $\mp 0.72 \times 10^{-4}$. An imaginary tune shift of 10^{-5} corresponds to an instability rise time of 16000 turns, i.e. about 1.5 sec. Same impedance model as in LHC Project Report 100.

$Q_x(J_x, J_y) = Q_0 + a J_x + b J_y \quad , \quad c = \frac{b}{a}$

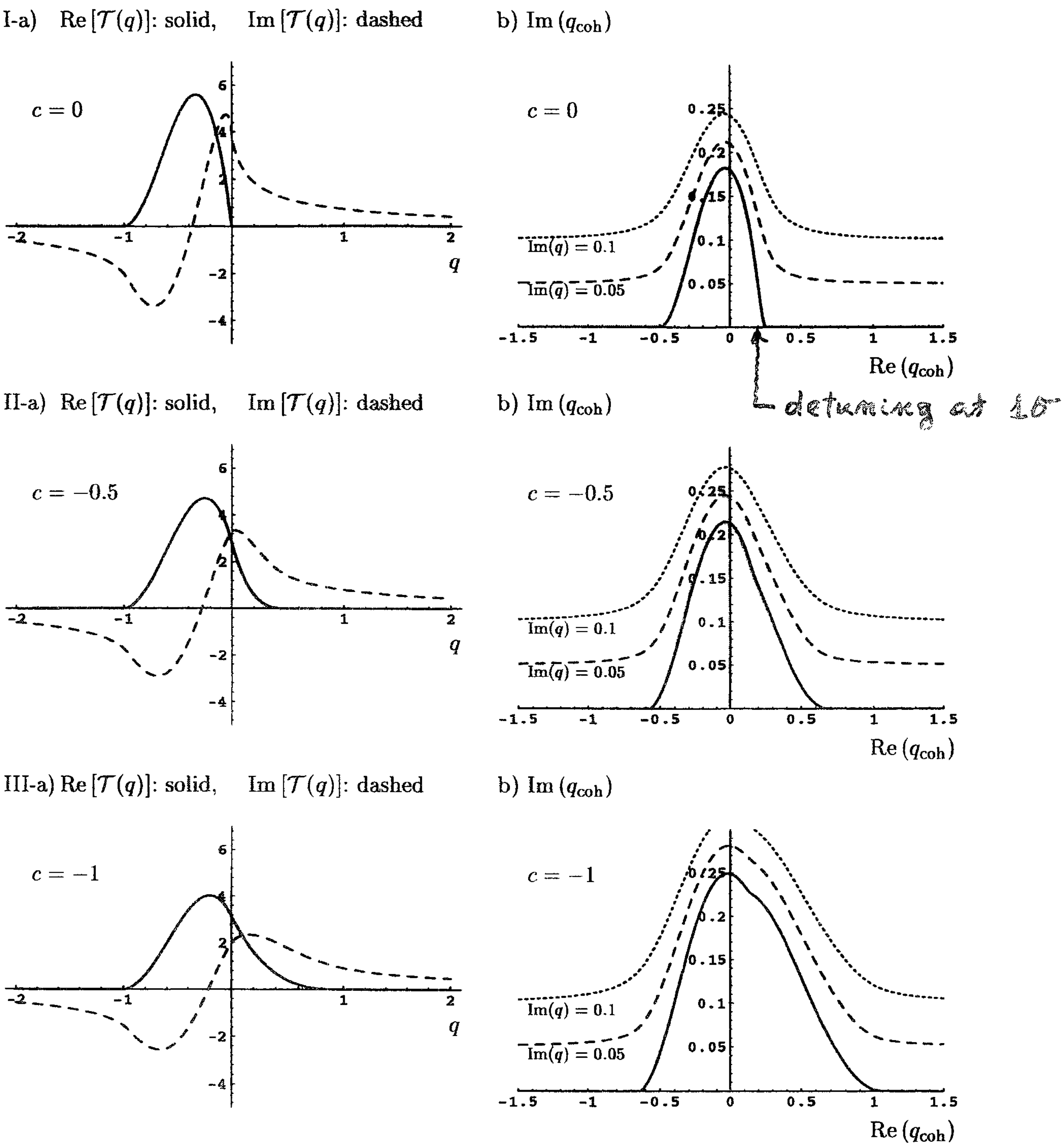


Figure 2: Beam transfer function (a) and stability limit (b) for relative cross-anharmonicities $c = 0$, $c = -0.5$, $c = -1$.

QUASI-PARABOLIC DISTRIBUTION

Octupole scheme for Landau Damping

The cross-anharmonicities for a system of octupoles located near the F and D arc quadrupoles are given by:

$$c \approx -\frac{4\beta_F \beta_D}{\beta_F^2 + \beta_D^2} = -0.72$$

where $\beta_F = 175.5$ m and $\beta_D = 32.5$ m are the betatron functions.

Assuming a positive value of the detuning coefficient a, the maximum normalised coherent tune shift for which the rigid dipole mode is stabilized by the tune spread is 0.8, while it would be only 0.25 in the 1D case:

$$q_{\text{coh}} = \frac{|\Delta Q_{\text{coh}}|}{5a\sigma^2} \leq 0.8 \qquad \text{or} \qquad a = \frac{\partial Q}{\partial J} \geq \frac{|\Delta Q_{\text{coh}}|}{4\epsilon}.$$

Assuming a safety margin of 2, i.e. a coherent tune shift $2 \times 2.3 \times 10^{-4}$ of the rigid head-tail mode, Landau damping requires a detuning at 1 σ of about 1.2×10^{-4}. The corresponding integrated strength can be obtained by 144 arc octupoles with $O_3 = 62000$ Tm^{-3} and $l = 0.328$ m.

Natural Tune Spreads at 7 TeV

Beams separated, Injection optics This situation is the most critical. The direct space charge decreases to about 1.4×10^{-5}. The octupolar field imperfections, mainly arising from geometry, are approximately independent of energy; the beam emittance decreases by a factor 16, yielding a maximum detuning of less than 10^{-5} at $1\ \sigma$, taking into account the crossing angle and the triplet imperfections. Head-tail modes up to at least order 4 are unstable.

Beams separated, Collision optics With the amplification of the triplet errors due to the high-β function, the detuning reaches about 3×10^{-5} at $1\ \sigma$. Head-tail modes of order 0 to 2 remain unstable.

Colliding beams Due to the beam-beam effect, the tune spread becomes as large as about 0.01 and is expected to Landau damp most instabilities except perhaps some coherent beam-beam modes.

Natural Tune Spreads at Injection

The amplitude detuning is due to second-order contributions in *systematic* b_3 and first-order contribution in the *uncertainty* of b_4. The systematic b_4 indeed changes sign from the inner to the outer channel and therefore does not contribute.

The maximum detuning observed over 60 possible LHC's is about 0.003 at 6σ, mostly due to b_4 (about 75%). Experience showed a good correlation between large detuning and small dynamic aperture.

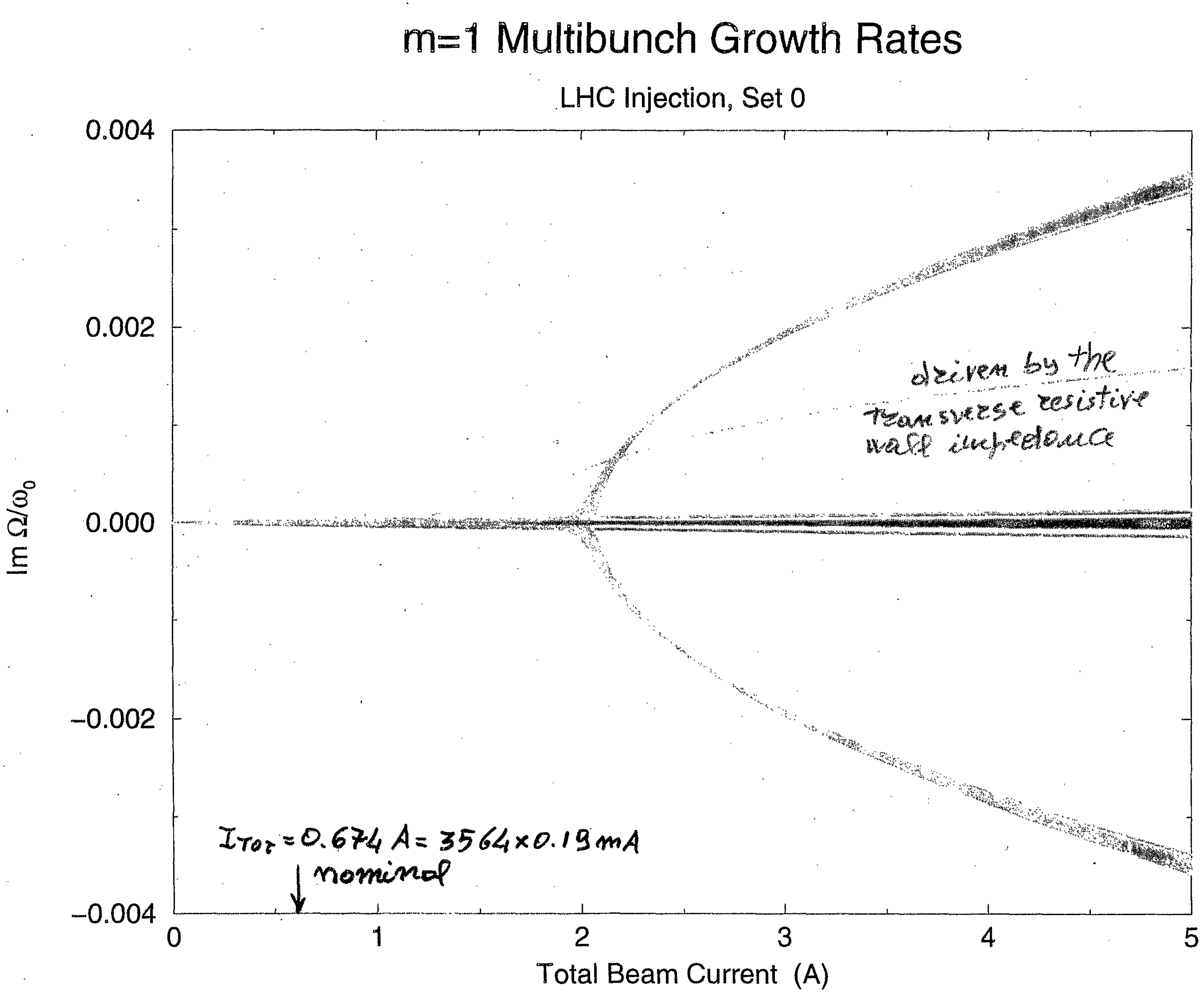
Our target is therefore to correct the detuning down to 0.0006 at 6 σ. The corresponding tune spread at 1 σ is as low as 2×10^{-5}; it is as uncertain as b_4 and far insufficient for Landau damping.

Another detuning arises from the direct space charge; its maximum occurs for particles at the centre of the bunch and for ultimate intensity it amounts to 1.9×10^{-3}. We rely on this spread to damp all higher-order head-tail modes. The dipole mode must be damped by a feedback.

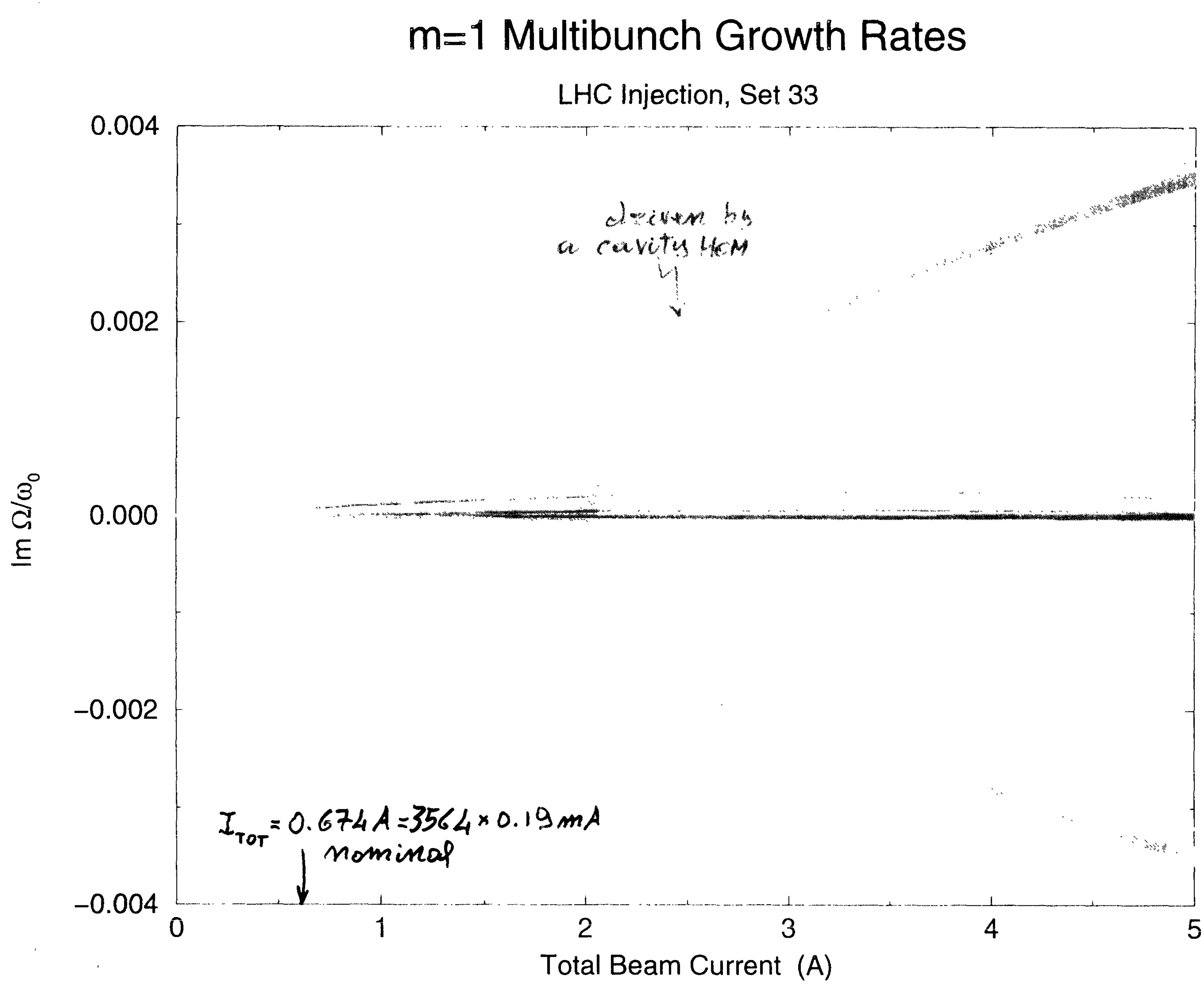
Single-Bunch Coherent Tune Shifts

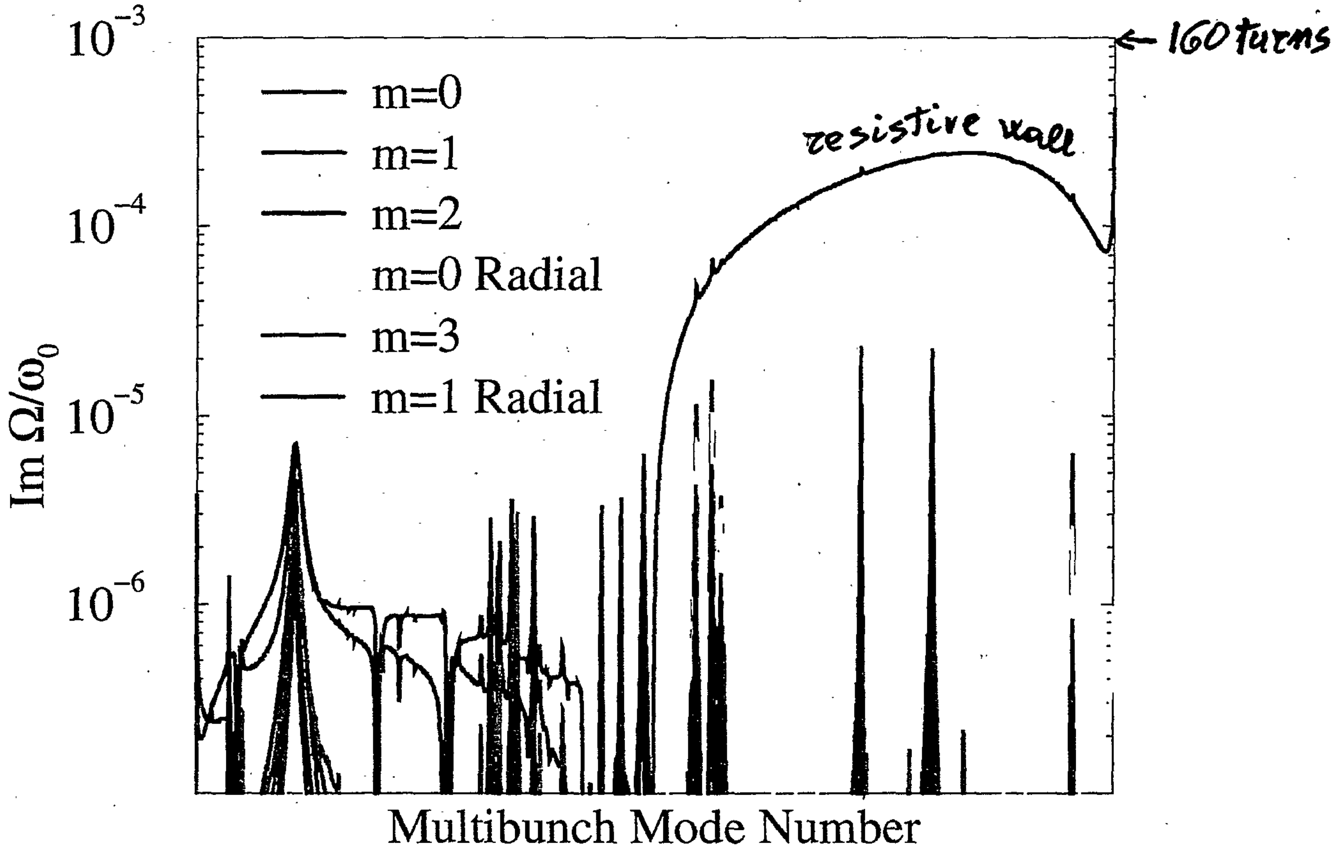
Mode	450 GeV	7000 GeV
$\Delta Q_T^{(0)}$	-2.787×10^{-3}	-0.232×10^{-3}
$\Delta Q_T^{(1)}$	-0.574×10^{-3}	-0.063×10^{-3}
$\Delta Q_T^{(2)}$	-0.358×10^{-3}	-0.042×10^{-3}
$\Delta Q_T^{(3)}$	-0.284×10^{-3}	-0.032×10^{-3}
$\Delta Q_T^{(4)}$	-0.228×10^{-3}	-0.026×10^{-3}

Transverse coherent tune shifts of the single bunch head-tail modes for the ultimate bunch population of 1.66×10^{11} protons and a Gaussian longitudinal distribution with an r.m.s. bunch length $\sigma_z = 13$ cm at injection and $\sigma_z = 7.5$ cm at top energy. The broad-band impedance is the same as in LHC Project Report 91, but to get a more conservative estimate we have not included coherent space charge detunings.



m=1 Multibunch Growth Rates
LHC Injection, Set 0
Im Ω/ω0
0.004
0.002
0.000
−0.002
−0.004
0
1
2
3
4
5
Total Beam Current (A)
driven by the transverse resistive wall impedance
ITOT = 0.674 A = 3564×0.19 mA
nominal


m=1 Multibunch Growth Rates
LHC Injection, Set 33
driven by
a cavity HOM
Im Ω/ω0
0.004
0.002
0.000
−0.002
−0.004
0
1
2
3
4
5
Total Beam Current (A)
I_TOT = 0.674 A = 3564 × 0.19 mA
nominal



Stability of LHC beam at injection[a]

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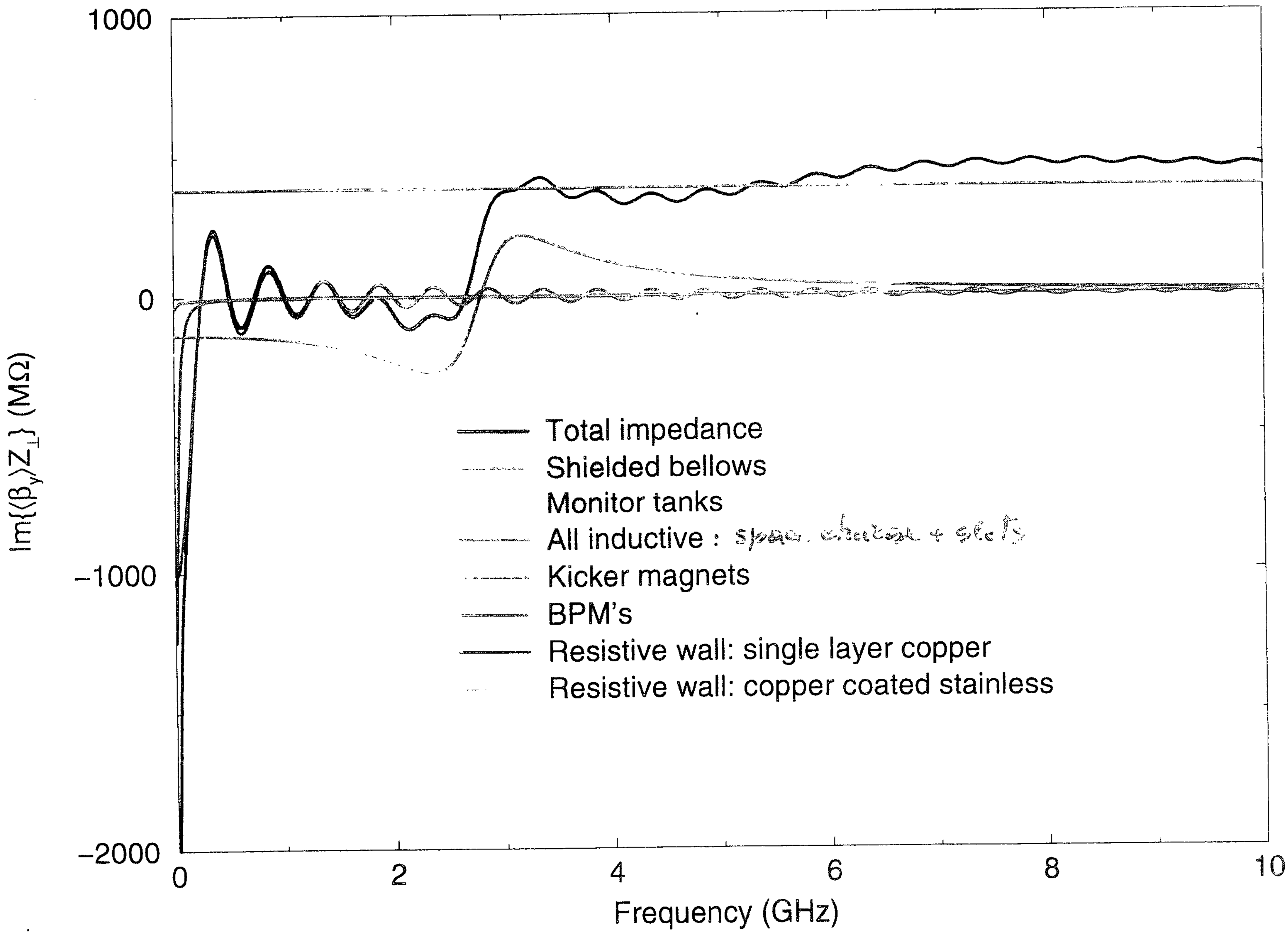
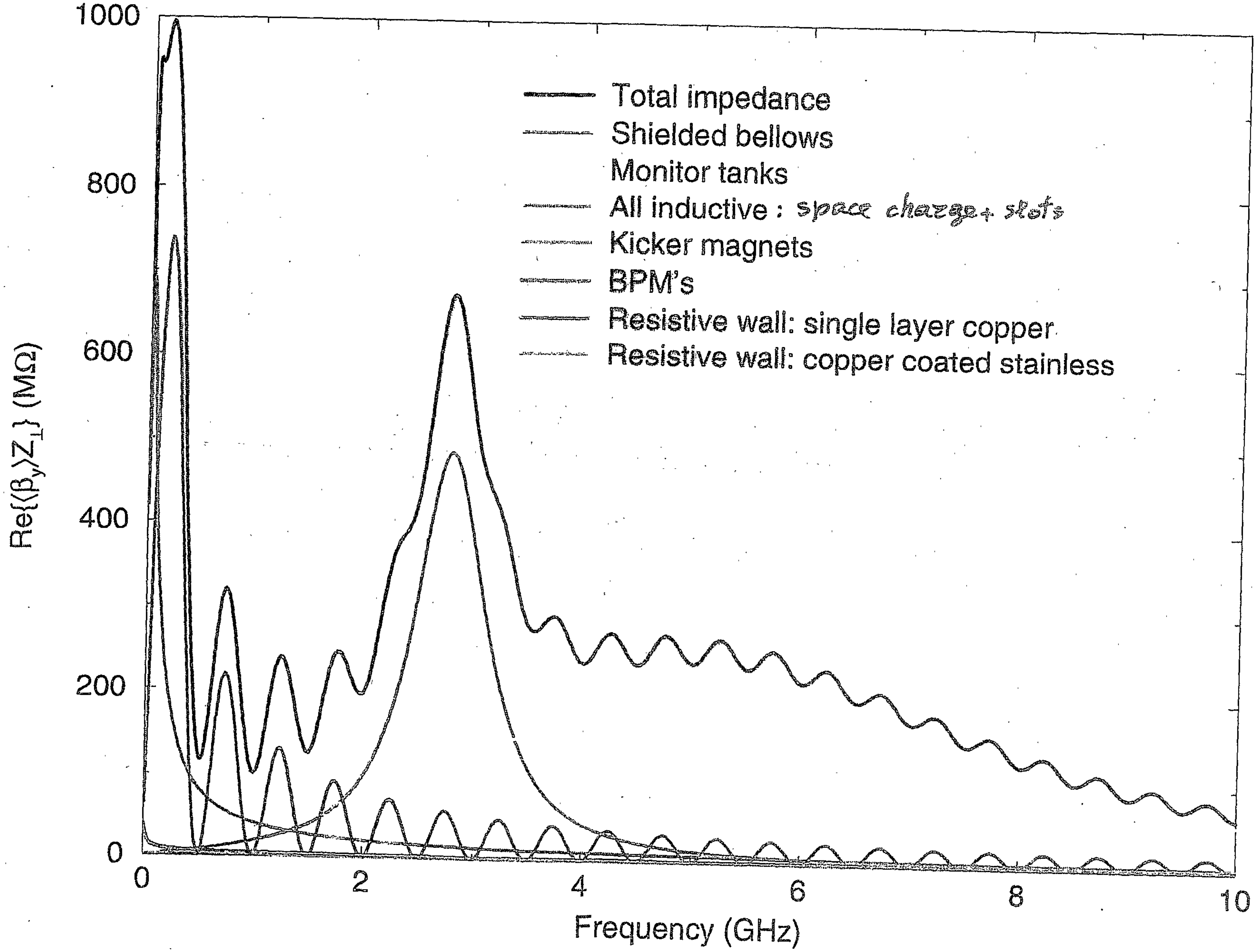
[a]F. Ruggiero et. al., LHC Project Report 120.

Vertical growth rates for nominal beam intensity at injection versus multi-bunch mode number, for rigid dipole modes ($m = 0$ red) and higher order head-tail modes. A growth rate of 10^{-3} corresponds to an instability rise time of 160 turns. The read peak on the right refers to rigid dipole modes driven by the resistive wall instability: the shortest rise time is about 400 turns.

LHC Broadband Impedance : $\mathrm{Im}(\langle\beta_\perp\rangle Z_\perp)$ at injection



LHC Broadband Impedance : $Re(\langle\beta_\perp\rangle Z_\perp)$ at injection



Parasitic losses: *nominal parameters*

Power loss [kW]	FOR A SINGLE BEAM	per unit length [mW/m]
3.60	Synchrotron radiation	206
3.73	Resistive wall (20° K)	140
0.53	Welds	20
< 0.27	Pumping slots	< 10
< 0.82	Shielded bellows	< 30
8.95	TOTAL	406

Machine parameters

$B = 8.386$	T	dipole magnetic field
$E = 7$	TeV	beam energy
$\rho_{\mathrm{Cu}} = 5.39 \times 10^{-10}$	Ωm	copper resistivity at 20 K
$I = 536$	mA	beam current
$N_{\mathrm{b}} = 1.049 \times 10^{11}$		particles per bunch
$R = 4242.893$	m	average machine radius
$\rho = 2784.32$	m	bending radius
$\sigma_{\mathrm{s}} = 7.5$	cm	r.m.s. bunch length
$k_{\mathrm{b}} = 2835$		number of bunches

Table 1: LHC effective impedance (in Ω) at 450 GeV.

INJECTION	$\text{Im}\,(Z_L/n)_{\text{eff}}$	$\beta_{\text{av}}\text{Im}\,(Z_T)_{\text{eff}} \times 10^{-6}$
Space charge	-0.0058	-442.3
Shielded bellows	0.0814	146.3
Monitor tanks	0.0400	214.6
Pumping slots	0.0156	38.9
Total broad band	0.1312	-42.5
Strip-line monitors	0.127	446.6
Abort kickers	0.007	182.4
SC cavities	0.010	0.4
Total low frequency	0.144	629.4

Table 2: LHC effective impedance (in Ω) at 7 TeV.

TOP ENERGY	$\text{Im}\,(Z_L/n)_{\text{eff}}$	$\beta_{\text{av}}\text{Im}\,(Z_T)_{\text{eff}} \times 10^{-6}$
Space charge	-3.3×10^{-5}	-28.6
Shielded bellows	0.0815	148.8
Monitor tanks	0.0400	214.6
Pumping slots	0.0156	38.9
Total broad band	0.1371	373.7
Strip-line monitors	0.073	257.9
Abort kickers	0.004	109.1
SC cavities	0.010	0.4
Total low frequency	0.087	367.4

LHC parameters

Energy	(TeV)	7.0
Dipole field	(T)	8.3
Coil aperture	(mm)	56
Distance between apertures	(mm)	194
Luminosity	(cm^{-2} s^{-1})	10^{34}
Beam-beam parameter		0.0032
Injection energy	(GeV)	450
Circulating current/beam	(A)	0.530
Bunch spacing	(ns)	25
Particles per bunch		10^{11}
Stored beam energy	(MJ)	332
Normalized transverse emittance	(mm)	3.75
r.m.s. bunch length	(m)	0.075
Beta values at I.P.	(m)	0.5
Full crossing angle	(mrad)	300
Beam lifetime	(h)	22
Luminosity lifetime	(h)	10
Energy loss per turn	(keV)	6.9
Critical photon energy	(eV)	45.6
Total radiated power per beam	(kW)	3.7

Catalog of Coherent Effects

	SINGLE-BUNCH (low-Q structures)	MULTI-BUNCH (high-Q structures)
LOSSES	broad-band impedance (resistive wall, random slots) photo-electrons	narrow-band impedance (HOM's of RF-cavities, . . .) secondary electrons
TUNE SHIFTS	broad-band impedance ↓ *loss of Landau damping* → INSTABILITIES	depend on multi-bunch mode → multi-bunch mode coupling
INSTABILITIES	head-tail modes mode coupling microwave	dipole modes (resistive wall, . . .) multi-bunch head-tail multi-bunch mode coupling electron-cloud instability