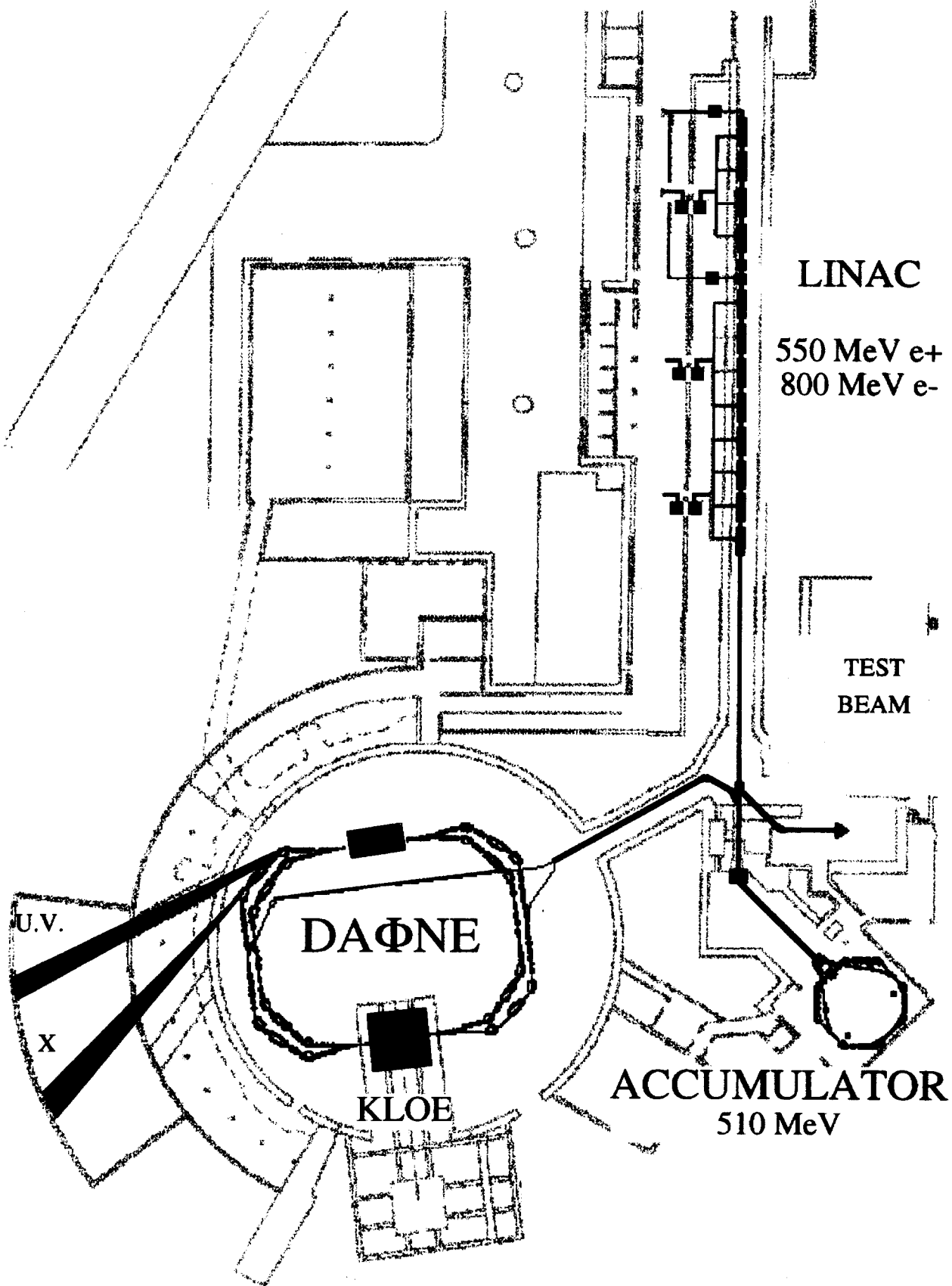


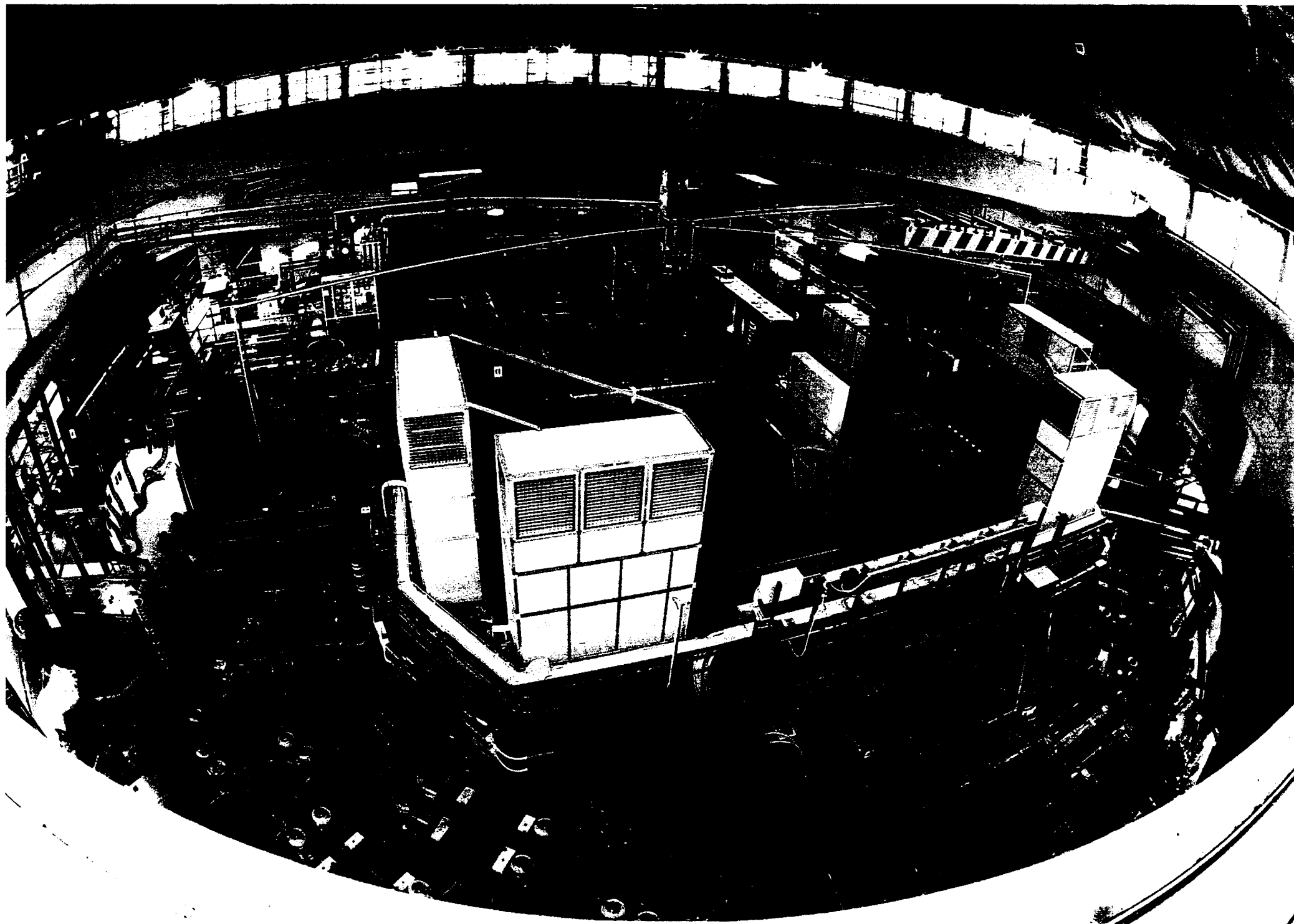
SINGLE BUNCH
DYNAMICS IN DAΦNE

ANDREA GHIO FOR

DAΦNE COMMISSIONING TEAM

The Frascati Φ -Factory



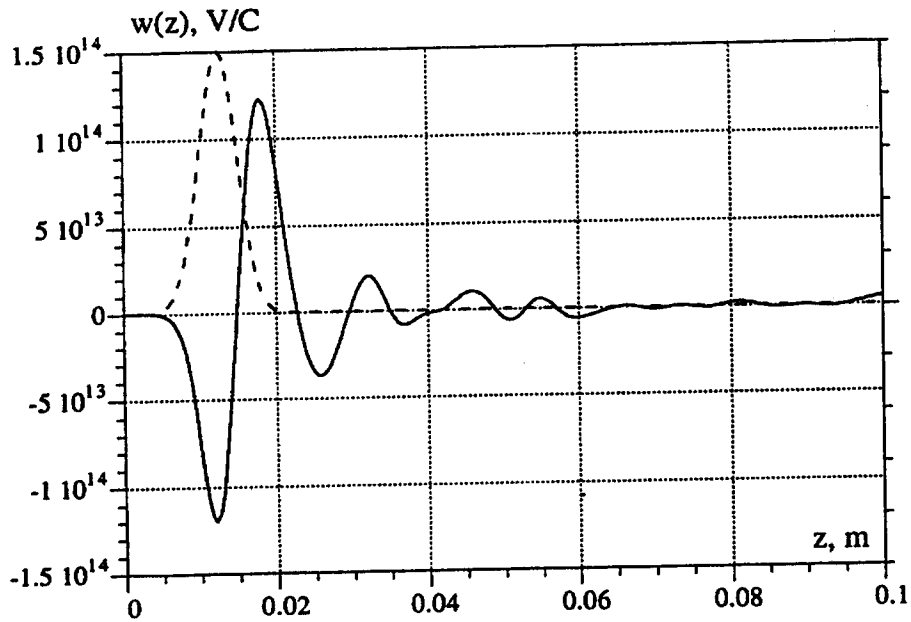


DAΦNE design parameters

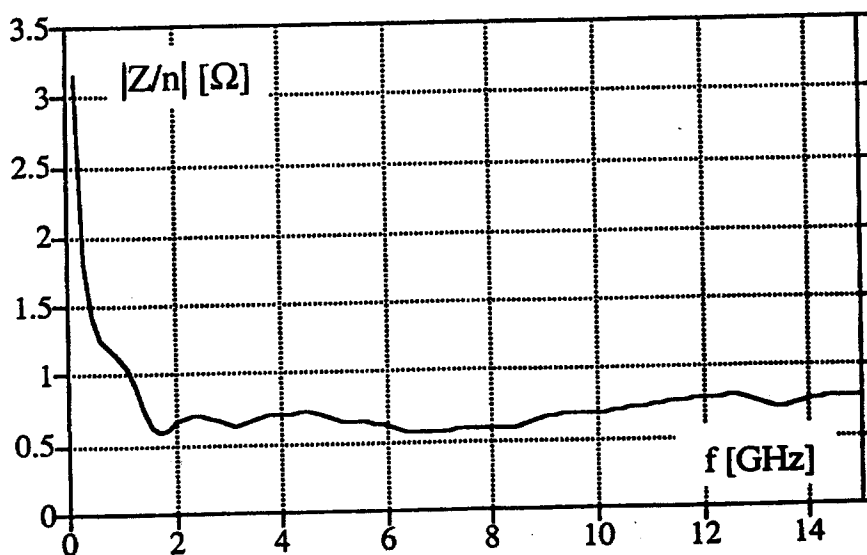
Energy	E	510.0	MeV
Emittance	ϵ_x / ϵ_y	1/0.01	mm·mrad
Beam-beam tune shift	ξ_x / ξ_y	0.04/0.04	
Betatron tune	ν_x / ν_y	5.09/5.07	
RF frequency	f_{rf}	368.263	MHz
RF voltage	V_{rf}	100 ÷ 250	kV
Harmonic number	h	120	
Revolution frequency	f_0	3.0688	MHz
Bunch average current	I_0	43.7	mA
Particles per bunch	N	$9.0 \cdot 10^{10}$	
Total beam current	I_b	1.3 (30 bunches) 5.2 (120 bunches)	A
Momentum compaction	α_c	0.017	
Natural energy spread	σ_{ϵ_0} / E	0.000396	
Bunch length	σ_z	2.0 ÷ 3.0	cm
Synchrotron radiation loss	U_0	9.3	keV/turn
Damping time	τ_e / τ_x	17.8/36.0	ms
Synchrotron tune	ν_s	0.011	
Beta functions at IP	β_x^* / β_y^*	450/4.5	cm
Single bunch luminosity	L_0	$4.4 \cdot 10^{30}$	$\text{cm}^{-2}\text{s}^{-1}$
Maximum luminosity	L	$5.3 \cdot 10^{32}$	$\text{cm}^{-2}\text{s}^{-1}$

Short range Wake and Broadband Impedance

The DAΦNE short-range wake function has been calculated by adding up the contributions of almost all the vacuum chamber discontinuities, that were estimated by analytical calculations or numerical 2D and 3D code (ABCI, MAFIA) simulations assuming a 2.5 mm gaussian distribution.



The normalized impedance $|Z/n|$ value is about 0.6Ω for frequencies higher than 1.5 GHz. The wake function and impedance have been assumed as the basic information to estimate the bunch lengthening process as well as to evaluate the microwave instability thresholds and analyze the bunch behaviour in the turbulent regime.



Bunch Lengthening Tracking Code

The DAΦNE bunch lengthening process has been simulated by a numerical tracking code using the computed wake potential.

The motion of N_s superparticles representing the beam is described in the longitudinal phase space by:

$$\varepsilon_i(n) = \varepsilon_i(n-1) - \frac{2T_0}{\tau_\varepsilon} \varepsilon_i(n-1) + 2\sigma_{\varepsilon 0} \sqrt{\frac{T_0}{\tau_\varepsilon}} R_i(n) - U_0 + \hat{V} \cos \left[\phi_s - \frac{2\pi h}{L_0} z_i(n) \right] + V_{ind}[z_i(n)]$$

$$z_i(n) = z_i(n-1) + \frac{\alpha c T_0}{E} \varepsilon_i(n)$$

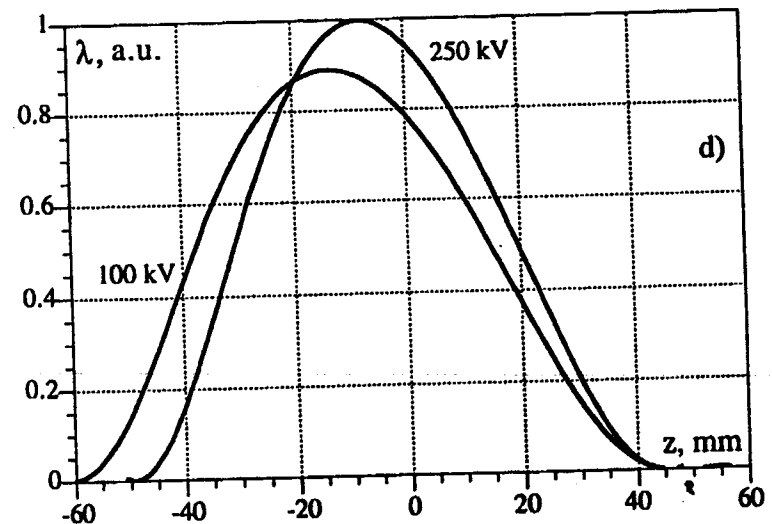
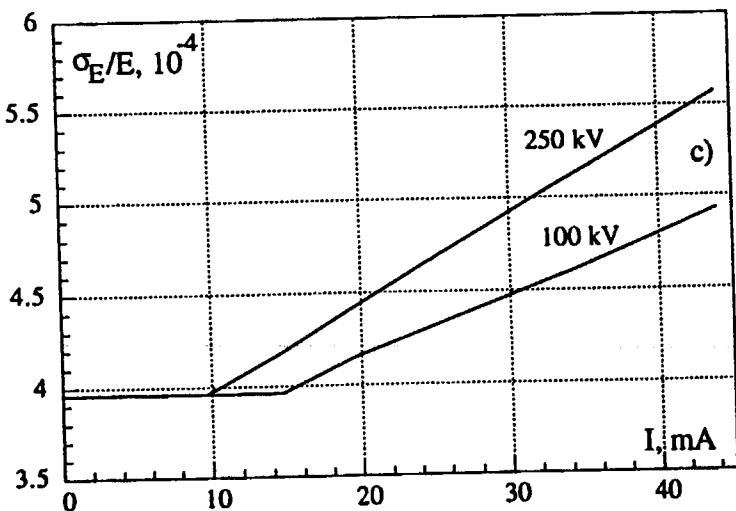
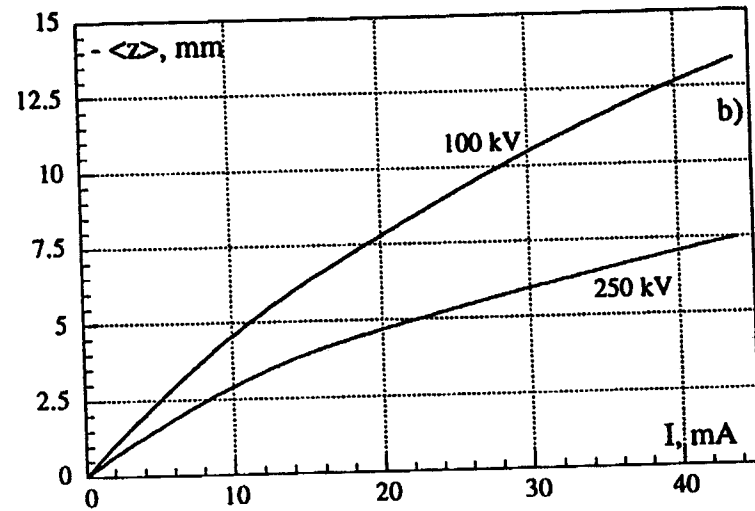
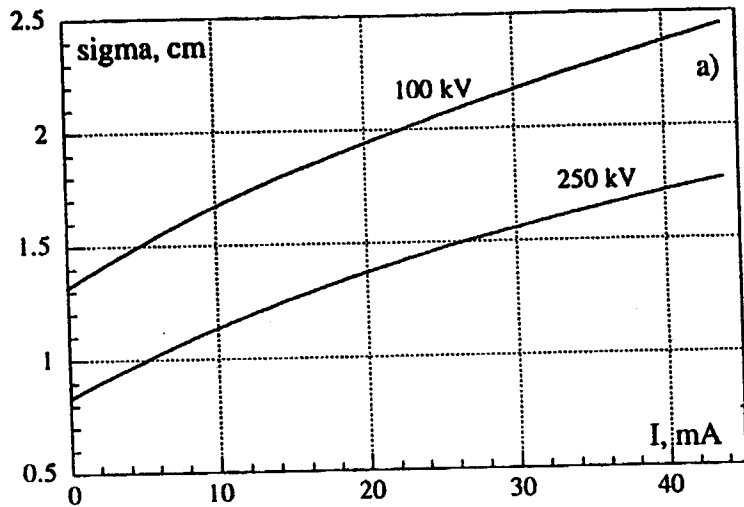
where $\varepsilon_i(n)$ and $z_i(n)$ are the energy and position coordinates of the i^{th} particle after n revolutions in the storage ring. T_0 is the revolution period; τ_ε the damping time; U_0 the energy lost per turn; ϕ_s the synchronous phase; h the harmonic number; L_0 the machine length; R_i a random number obtained from a normally distributed set with mean 0 and rms 1.

On each turn all the super particles are distributed in N_{bin} bins and the induced voltage V_{ind} is calculated by the wake of the superparticles ahead:

$$V_{ind}(z_j) = -\frac{Q}{N_s} \sum_{\substack{i=1, N_{bin} \\ z_i < z_j}} N_b(z_i) w(z_j - z_i)$$

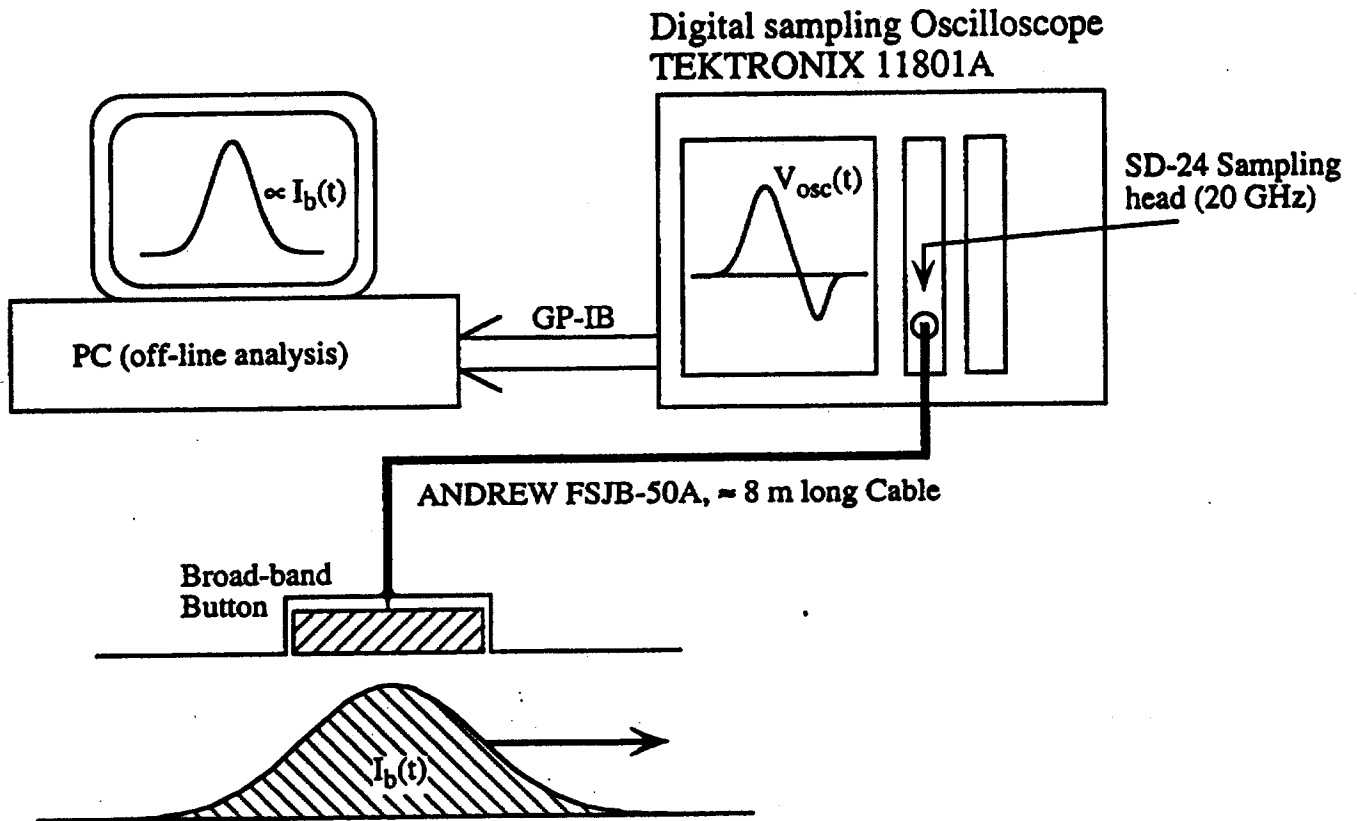
A good numerical convergence of this method requires N_s of the order of $\approx 10^5$,

DAΦNE bunch lengthening: tracking code simulation results



Results of DAΦNE bunch lengthening numerical simulations at RF voltage of 100 kV and 250 kV:
a) rms bunch length; b) bunch centroid; c) rms energy spread; d) bunch distribution at nominal current.

Bunch Length Measurement Schematics

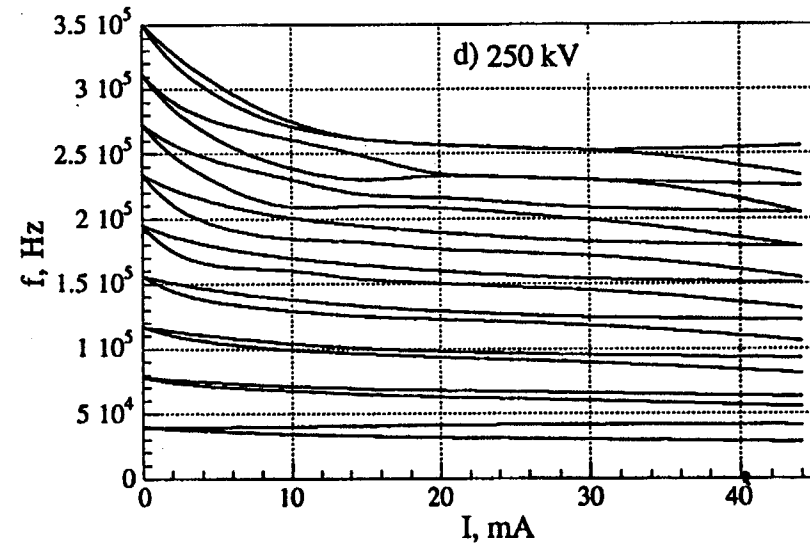
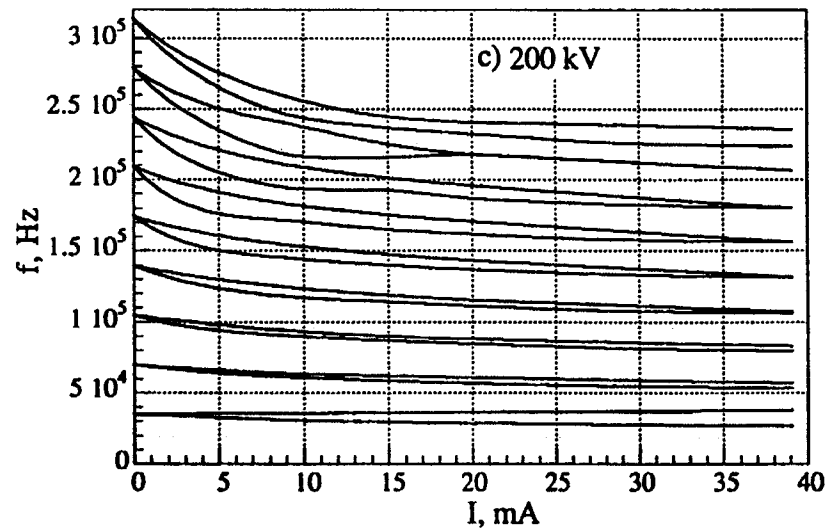
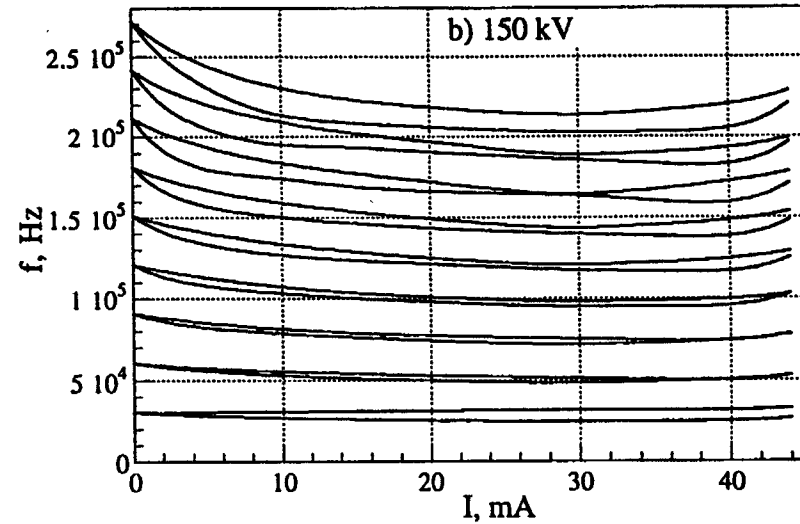
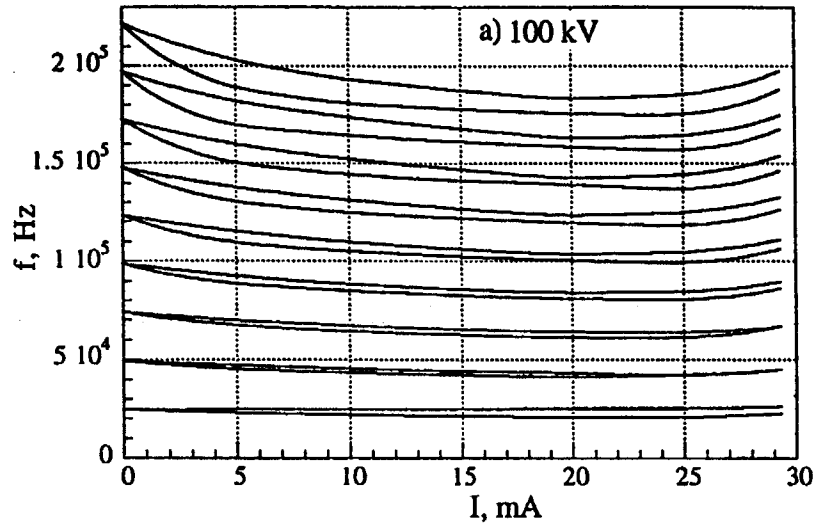


$$I_b(\omega) = \frac{V_{osc}(\omega)}{Z_{but}(\omega) \alpha_{cable}(\omega)}$$

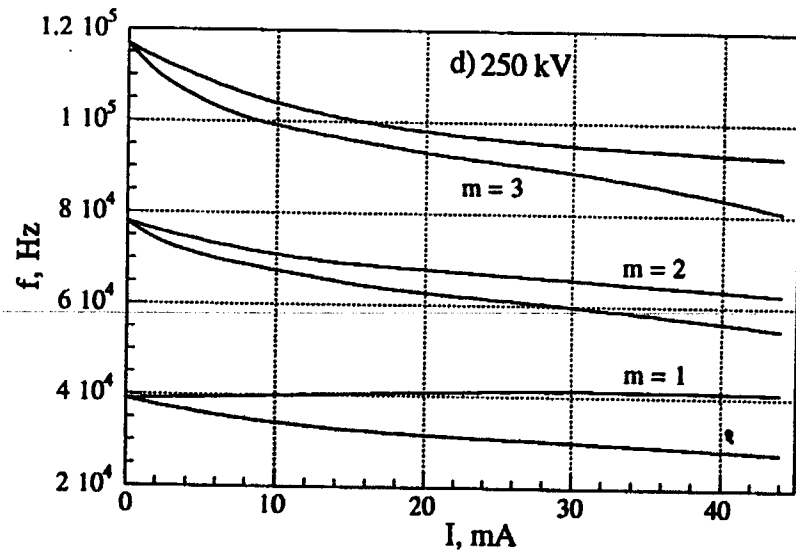
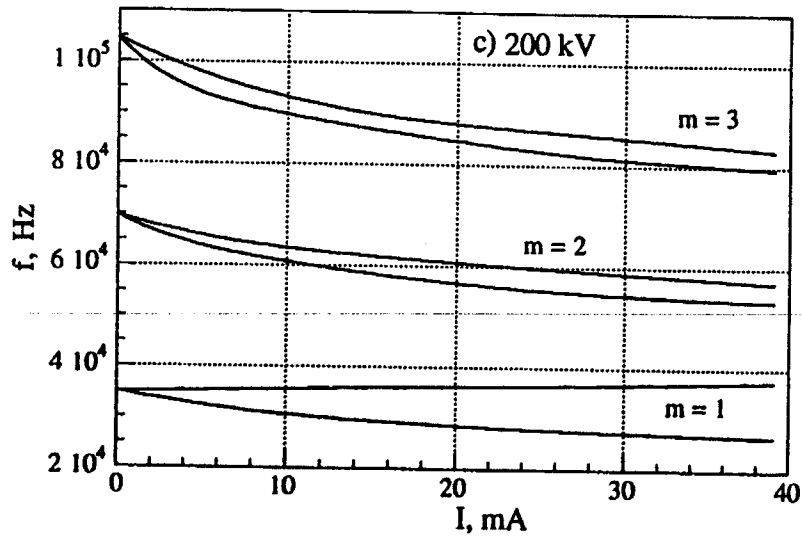
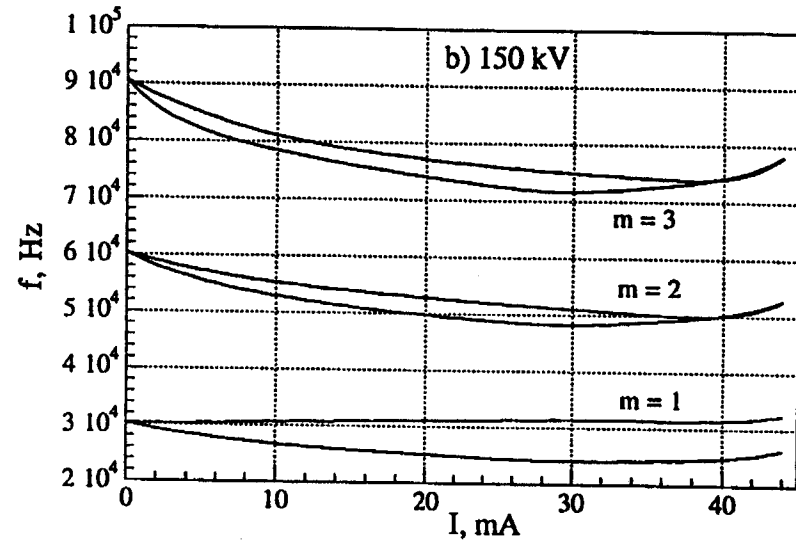
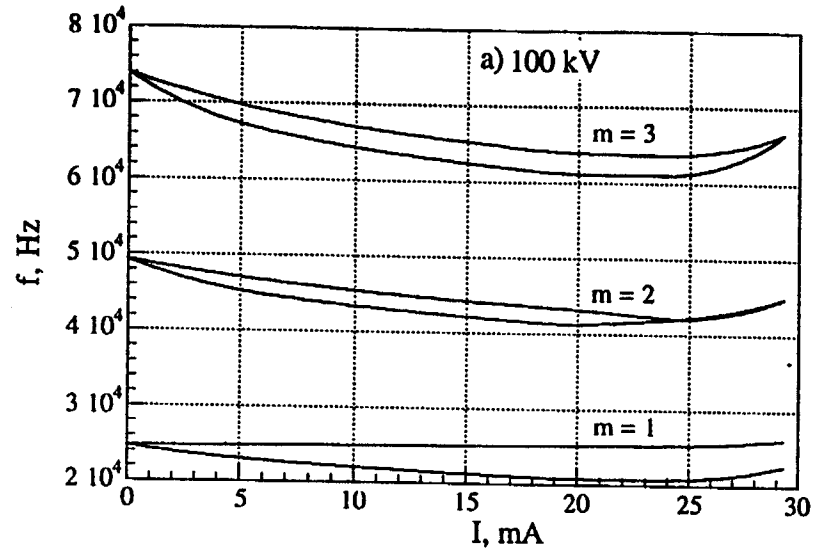
$$Z_{but}(\omega) = Z_b \frac{j\omega/\omega_0}{1 + j\omega/\omega_0} + \text{High Order Resonances}$$

$$\alpha_{cable}(\omega) = \exp[-(\omega/\omega_{cable})^{1/2}]$$

Longitudinal coherent mode coupling at different RF voltages:



Dipole ($m = 1$), quadrupole ($m = 2$) and sextupole ($m = 3$) mode coupling at different RF voltages:



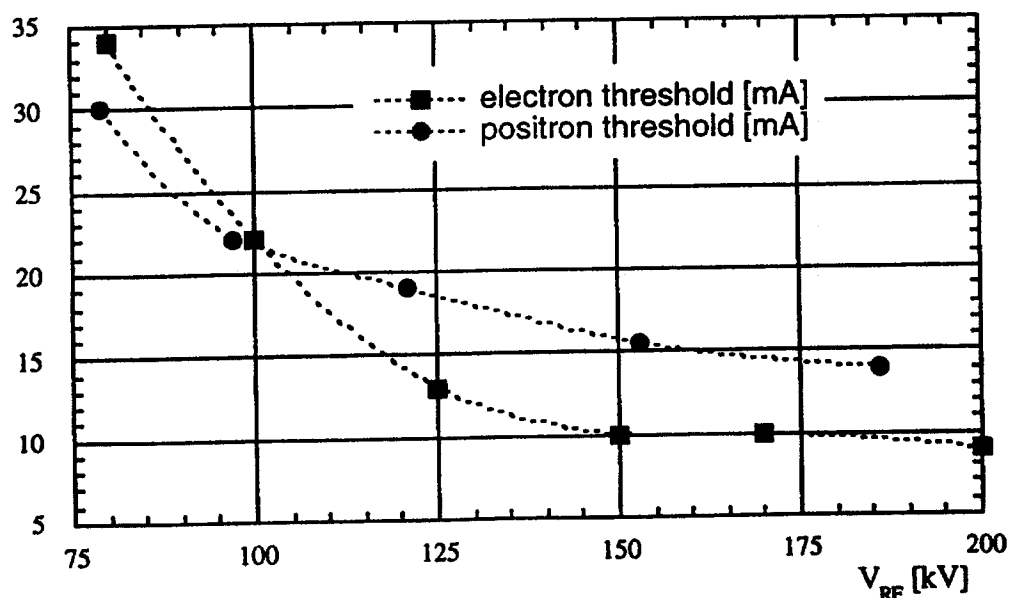
Microwave Instability: Experimental Observations

A) "DAY ONE" IRs

During the bunch length measurements at $V_{RF}=100$ kV we observed the presence of pure quadrupole and dipole thresholds at $I_b \approx 26$ mA and $I_b \approx 35$ mA respectively. By increasing the RF voltage to 150 kV, the quadrupole threshold was shifted to ≈ 38 mA and the dipole one was pushed beyond the nominal single bunch value. The observed thresholds are in good agreement with those predicted for the low azimuthal mode coupling by the double water bag method. At higher RF voltage we got no evidence of instability, even for single bunch currents much larger than nominal value.

B) New KLOE and DEAR IRs

Unfortunately, the well consistent scenario described above appeared to be modified after the insertion of the new interaction regions. Although we did not expect sizeable contributions to the machine wake function and impedance by the new IRs, an harmful quadrupole instability has appeared in both rings!



The current threshold increases as the RF voltage decreases. The behaviour is opposite to that observed in the early commissioning stage.

Microwave Instability

Analytical evaluations

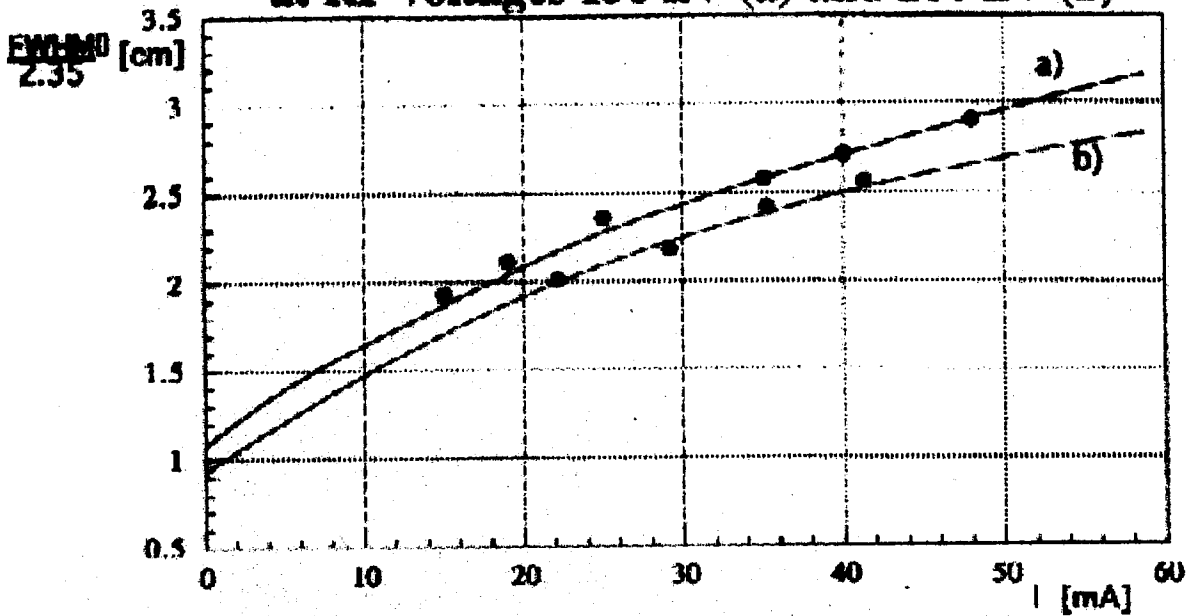
The coupling between bunch longitudinal coherent modes is the driving source of the microwave instability.

To study the microwave instability for the DAΦNE bunch we assumed again the machine wake function shown before and we used the double water-bag analytical method. This consists in approximating the real bunch distribution in the longitudinal phase space by a double water bag.

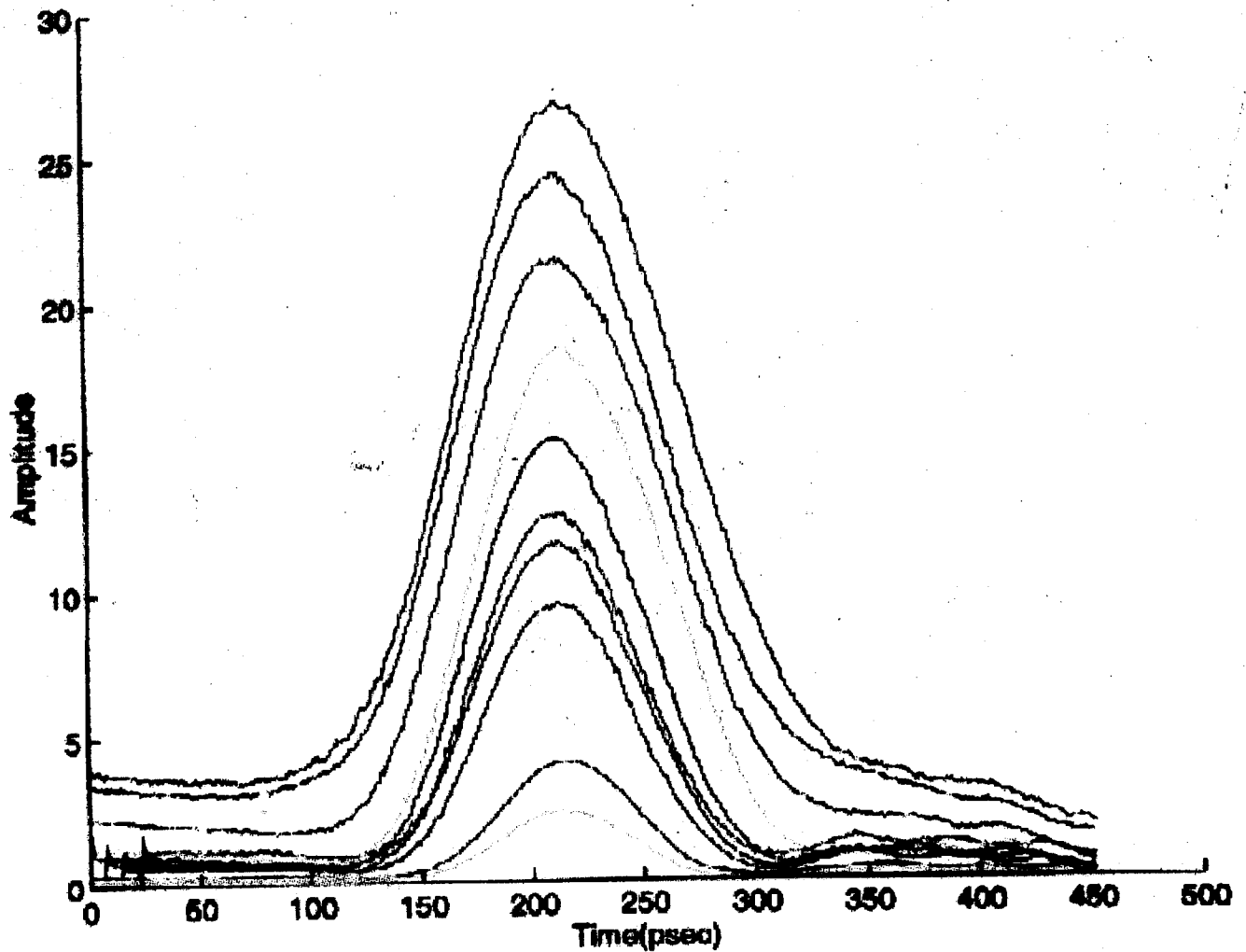
The approximated double water bag bunch distribution is put in the Vlasov equation to obtain, with a normal mode expansion of the distribution perturbation, an eigenvalue system with an infinite number of variables (the angular frequencies $\Omega_{m,k}$ of the coherent modes) and equations, labelled by the azimuthal and radial indexes m and k ($m=1\div\infty$; $k=0,1$). The system can be approximately solved by truncating it at some m_{\max} ; we limited our analysis to $m_{\max}=9$.

The plot of the calculated coherent mode frequencies $f_{m,k}$ ($m=1\div 9$; $k=0,1$) as a function of the bunch current for 4 different RF voltages (100, 150, 200 and 250 kV) are presented.

Bunch Lengthening in DAΦNE at RF voltages 150 kV (a) and 200 kV (b)



Comparison between the measurement results (dots) and the numerical simulation (line) of the bunch lengthening due to parasitic electromagnetic interaction of a bunch with different elements of the DAΦNE vacuum chamber



QUADRUPOLE MODE SINGLE BUNCH INSTABILITY

1. OBSERVATIONS

- a) Instability threshold rises as the RF voltage decreases;**
- b) Instability threshold is higher for higher momentum compaction;**
- c) the instability disappears at high single bunch current;**
- d) at high RF voltages (180-200 kV) the dipole mode gets unstable;**
- e) Instability threshold increases linearly with a number of bunches per beam until the number of bunches is less than 10-12. After that, the the threshold per bunch gets lower.**

2. CONCLUSIONS

- a) The threshold depends on the bunch length;**
- b) Possible source is the high frequency impedance (at 5-7 GHz);**
- c) The wake fields last longer than the bunch spacing and shorter than the ring circumference;**
- d) Possible candidate for the impedance source are the bellows in the IR.**

3. CURES

- a) Momentum compactions increase (bunch length increases; Touschek lifetime is higher; no microwave instability observed in simulations)**
- b) Higher harmonic cavity (bunch length increases; Touschek lifetime is higher; additional Landau damping of longitudinal multibunch instabilities. But a careful HOM-free design is necessary).**

Transverse single bunch dynamics

So far we did not carry out measurements especially dedicated to single bunch transverse dynamics, but some observations have shown that the DAΦNE broadband transverse impedance is small:

- First, an head-tail instability threshold as high as 13 mA with sextupoles off has been achieved after an accurate orbit correction;
- Second, the observed vertical tune shift is a small fraction of the synchrotron tune in the whole current range from 0 to the nominal value, indicating that the DAΦNE operation is quite far from the transverse mode coupling threshold.

SINGLE BUNCH DYNAMICS: CONCLUSIONS

- The single bunch dynamics measurements made during the DAΦNE commissioning are globally in good agreement with the expected beam behaviour. The very good agreement between the bunch length measurements and simulations indicates that the computed machine wake function and impedance are quite realistic, and the measured values of the single bunch thresholds (microwave, head-tail, ..) show that the design efforts aimed to reduce the longitudinal and transverse broadband impedances were successful.
- The appearance after the installation of the new IRs of a pure quadrupole longitudinal instability limiting the single bunch current to ≈ 15 mA is still an issue. This is probably a microwave threshold caused by an unexpected contribution to the high frequency part of the machine broadband impedance given by some element in the new interaction regions. Although the efforts to overcome this problem were ineffective so far, we are quite confident that the installation of an high harmonic RF system is the right solution to the problem since we have experimental evidence that the instability threshold raises with the bunch length; moreover we can also expect in this case a beneficial contribution from the Landau damping coming from the double RF system.