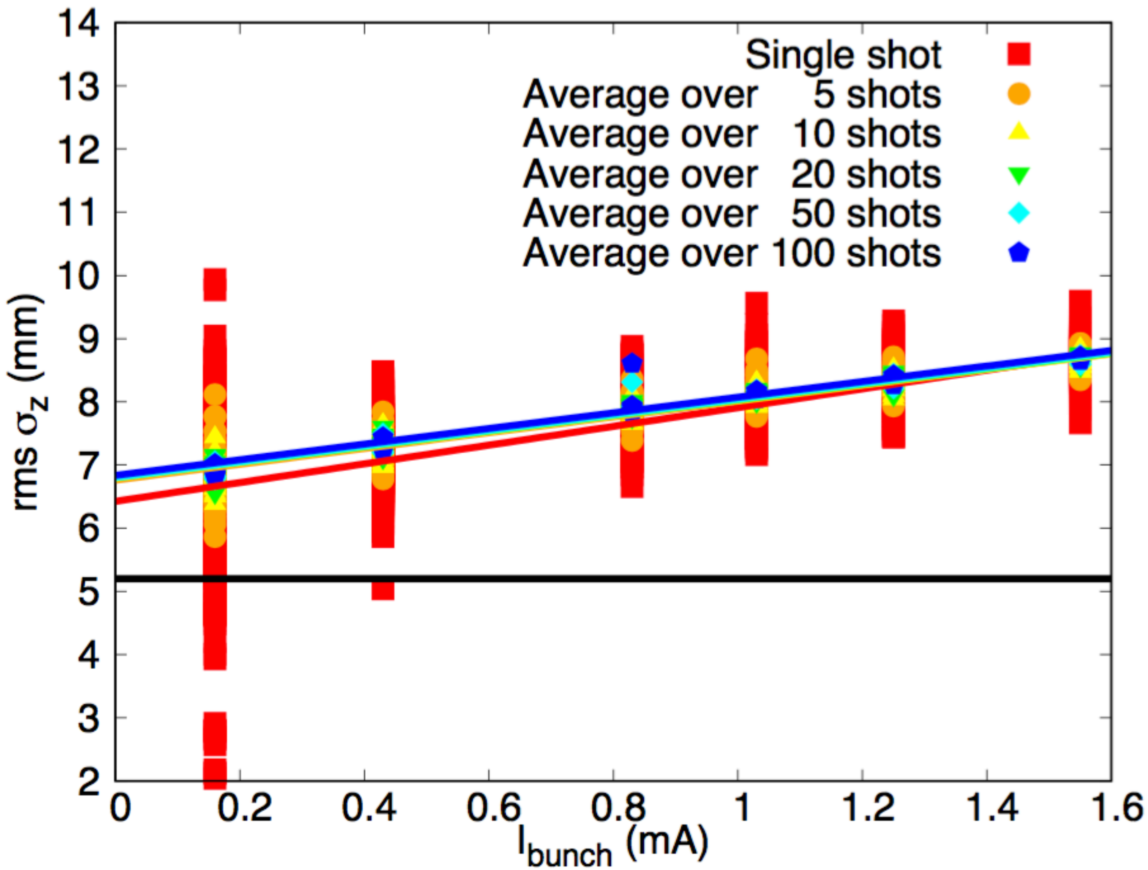
2. Impedance in KEKB Streak Camera Measurements

(D. Zhou slide)

- **HER (2009.10.26): nominal bunch length 5.2mm**
  - **Single-shot measurement (100 shots per current) by J. Flanagan**
  - **Average over different number of shots: Converge to same results**
  - **Shot noise and timing jitter are small**
  - **D.Z.: There were systematic errors in the SC system?**



$f_1(I_b)=6.42+1.48I_b$

$f_2(I_b)=6.76+1.25I_b$

$f_3(I_b)=6.79+1.23I_b$

$f_4(I_b)=6.80+1.24I_b$

$f_5(I_b)=6.81+1.24I_b$

$f_6(I_b)=6.84+1.24I_b$

http://research.kek.jp/people/dmzhou/BeamPhysics/mwi/20160908_Bunch_Length_dmzhou.pdf

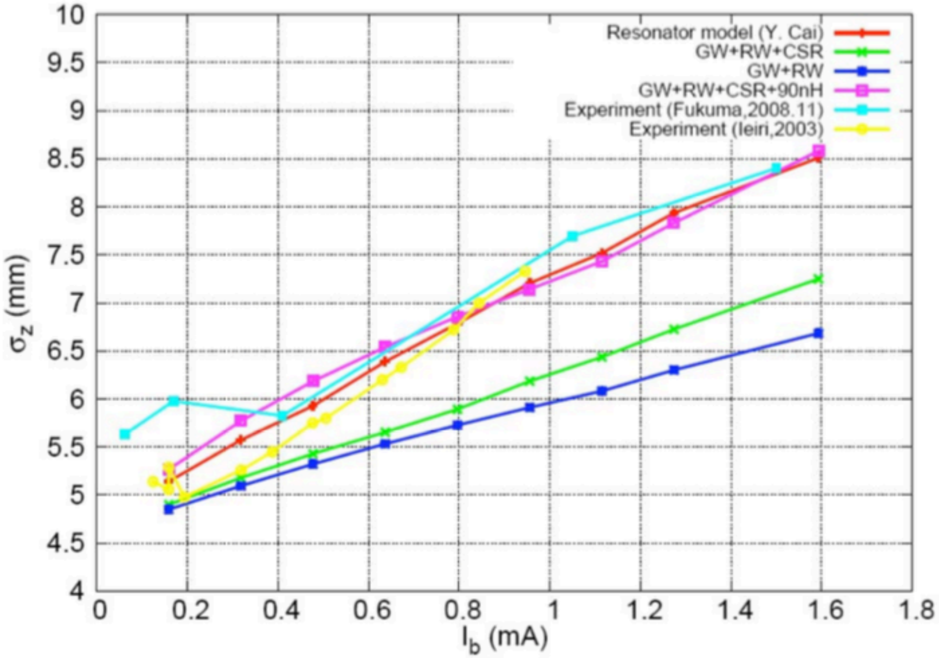
Comparison with Theory

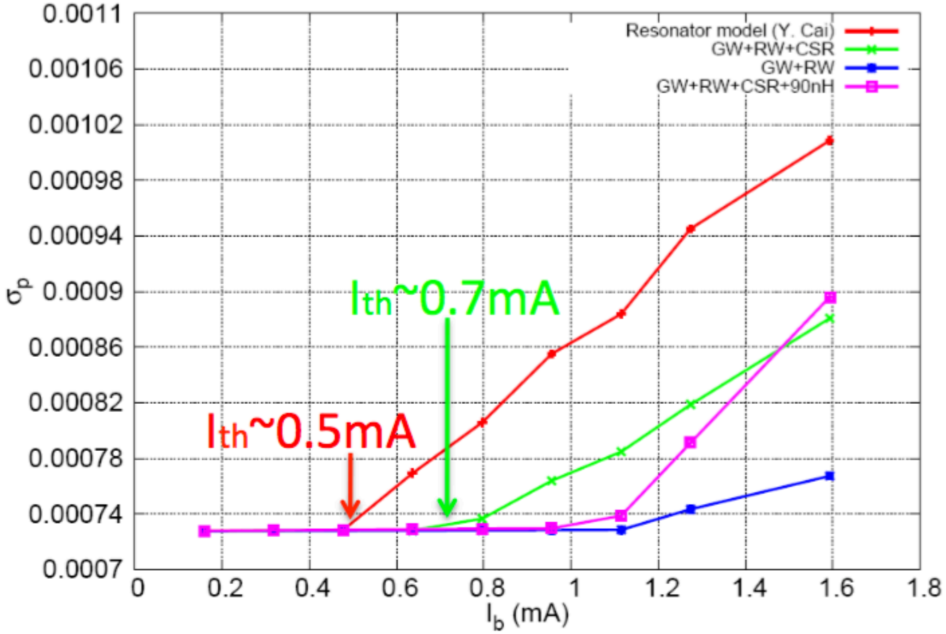
(D. Zhou slide)

2. Impedance in KEKB

Need to add 90 nH to calculated wake for agreement with measurement

- ➤ **Simulations using Pseudo-Green function wake**
  - **Use VFP solver to simulate bunch lengthening and MWI**
  - **CSR plays a role but seems not serious**
  - **D.Z.: Missing impedance sources? CSR/CWR/RW not well modeled [pseudo-wake function with 0.5mm bunch] in MWI simulations? Or systematic errors in bunch length measurements?**

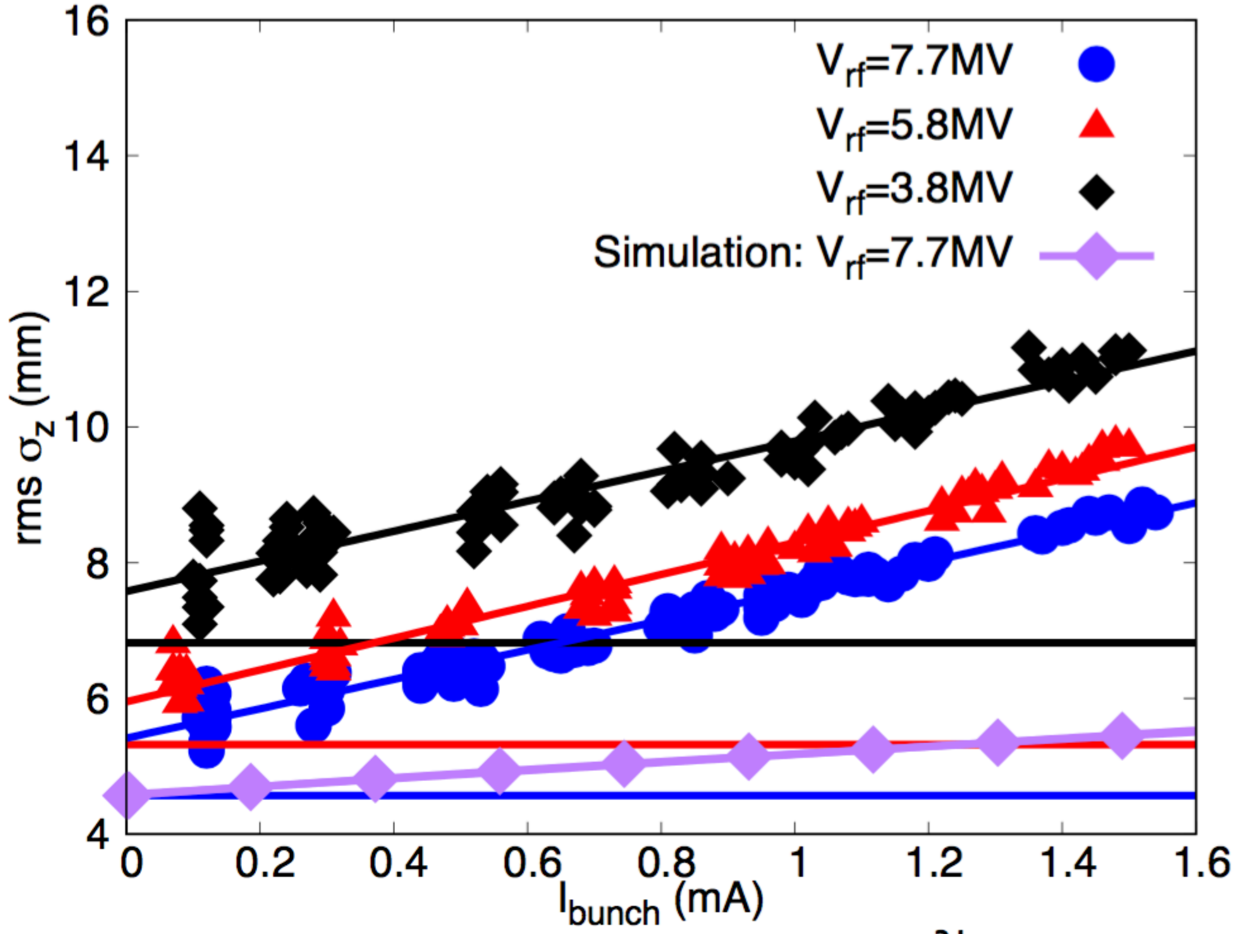




4. Streak camera measurement: SLER

(D. Zhou slide)

- **Fitting model: $f(I_b)=a*I_b+b$** $\psi(z) = I_0 * e^{-\frac{(z-\bar{z})^2}{2[1+\mathrm{sign}(z-\bar{z})A]^2\sigma^2}} + I_1$
- **σ_z from SAD simulation: 4.6, 5.3, 6.8mm at zero current**
- **Large discrepancy in zero-current bunch length between SAD simulation and measurements**



Because of dimness of light, each plotting symbol represents the average of 100 shots

$f_1(I_b)=5.41+2.17I_b$

$f_2(I_b)=5.95+2.35I_b$

$f_3(I_b)=7.58+2.21I_b$

$f_4(I_b)=4.58+0.59I_b$

Impedance Calculation and Verification in Storage Rings

Karl Bane

SLAC Linear Accelerator Center

April 14, 2017

(Adapted from CARE-HHH talk at CERN, Nov 2004)

Introduction

The longitudinal broad-band impedance of a ring can cause current dependent bunch lengthening, energy spread increase, and time dependent (e.g. bursting) behavior

Outline of talk

- Longitudinal impedance calculations/measurements for
  - SLC damping rings (1988-95)—many SLAC contributors
  - Dafne (1994-2000) –M. Zobov
  - KEK's ATF damping ring (2000-01)—ATF group

Programs for longitudinal impedance (broad-band)

- Short bunch wake: time domain 2D and 3D programs like those found in MAFIA, ECHO, GdfidL, CST Studio, …

- Macro-particle Tracking, Vlasov-Fokker-Planck Solver (Warnock)

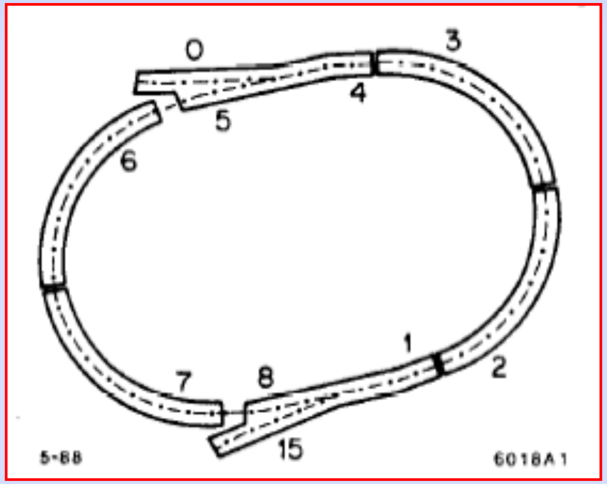
- Linearized Vlasov equation solver for finding threshold (Oide)

SLC Damping Rings

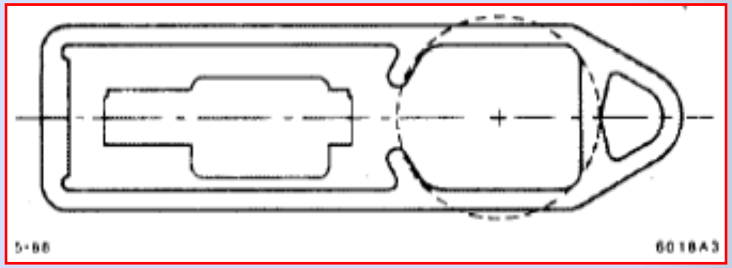
- 3 versions: (i) original, (ii) old (shielded bellows), (iii) new (current; new, smoother vacuum chamber)

- Nominal σ_z~ 5 mm, half aperture *a* ~1 cm

- Old ring inductive (small objects dominated impedance); new ring resistive



Layout of north damping ring. Circumference is 35 m.



Cross-section of a bend chamber. Dashed circle shows the size of a quad chamber.

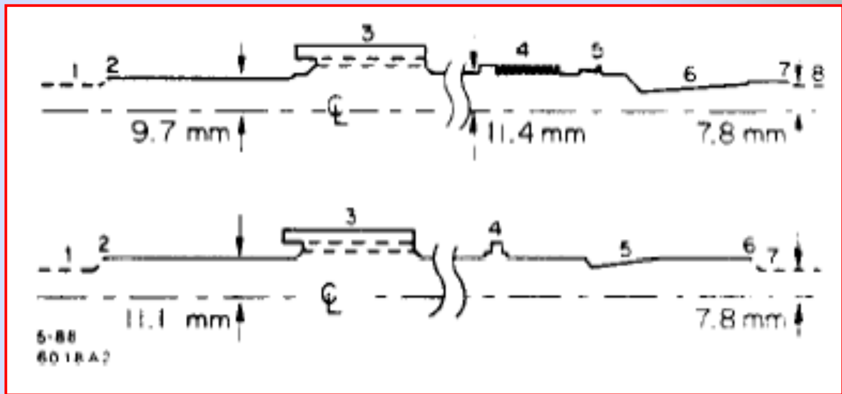
Calculations: old ring

- Old ring was inductive; generated a table of strength of inductive elements

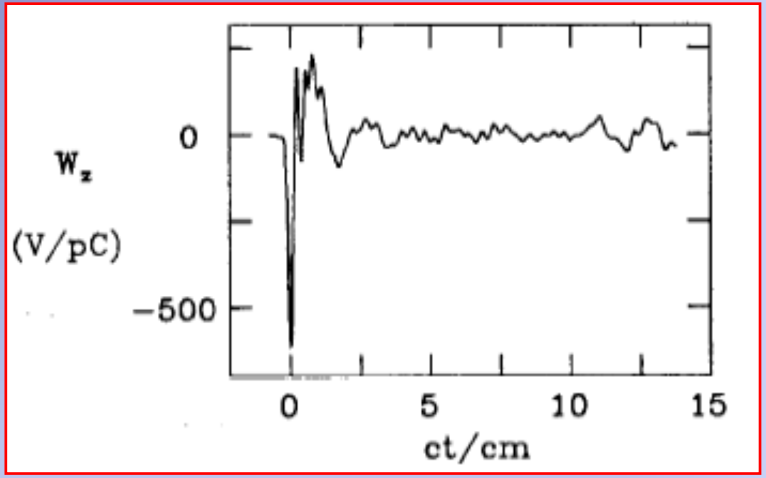
- Pseudo-Green function: for a short Gaussian bunch (σ_z= 1 mm) find an accurate wake; to be used in potential well/instability calculations; used T2 of MAFIA

Single Element Inductance		Contribution in Ring		
Type	L/(nH)	Factor	Number	L/(nH)
QD bellows	.62	1.0	20	12.5
QD & QF masks	.47	1.0	20	9.5
QD & QF trans.	.52	.9	20	9.3
ion pump slots	1.32	.1	40	5.3
kicker bellows	2.03	1.0	2	4.1
flex joint	.18	1.0	20	3.6
1" BPM trans.	.10	.8	40	3.3
other				2.4
			Total	50.0

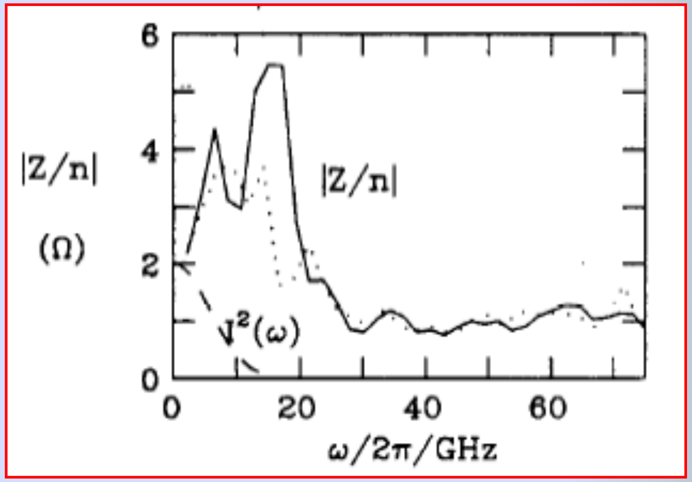
The inductive vacuum chamber objects. The total yields |Z/n|= 2.6 Ω.



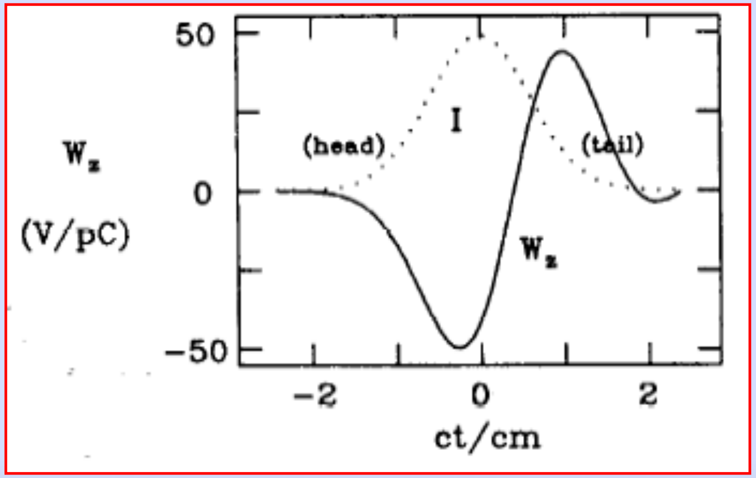
Vertical profile of QF segment (top) and QD segment (bottom). There are 20 of each in the ring. Dashes represent non-cylindrically symmetric objects.



Pseudo-Green function

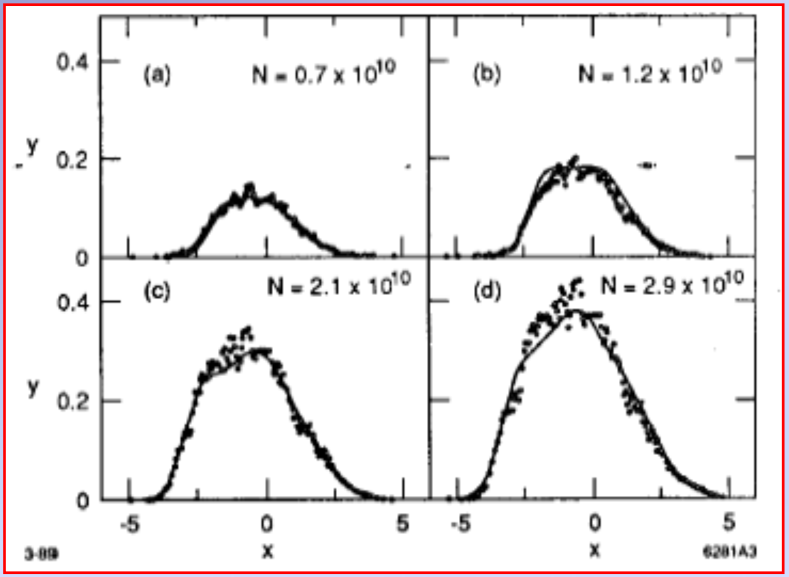


Fourier transform of Green function. Dots give result when bellows are shielded.

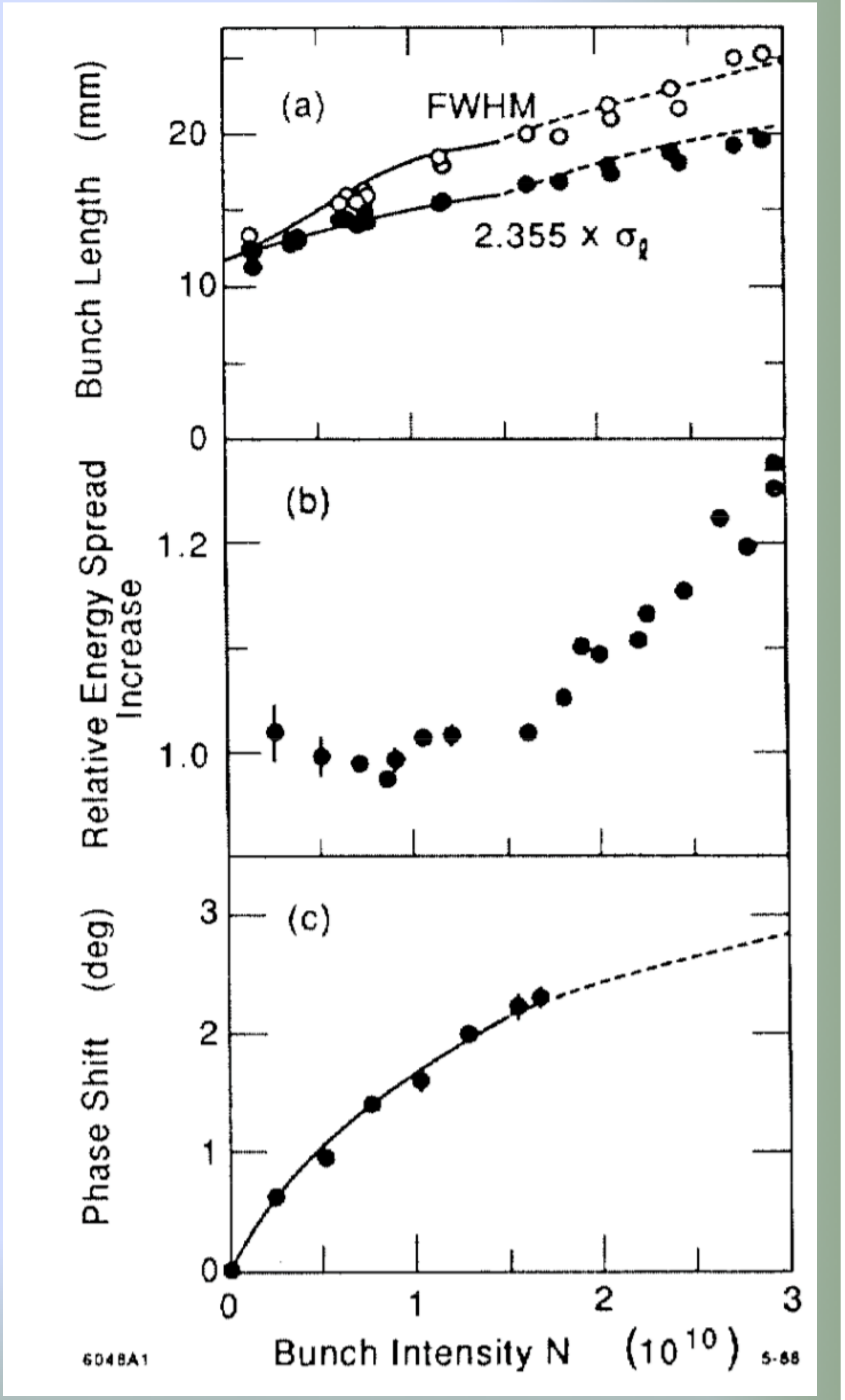


Green function convolved with σ_z= 6 mm Gaussian bunch. Wake is inductive.

Comparison with measurement

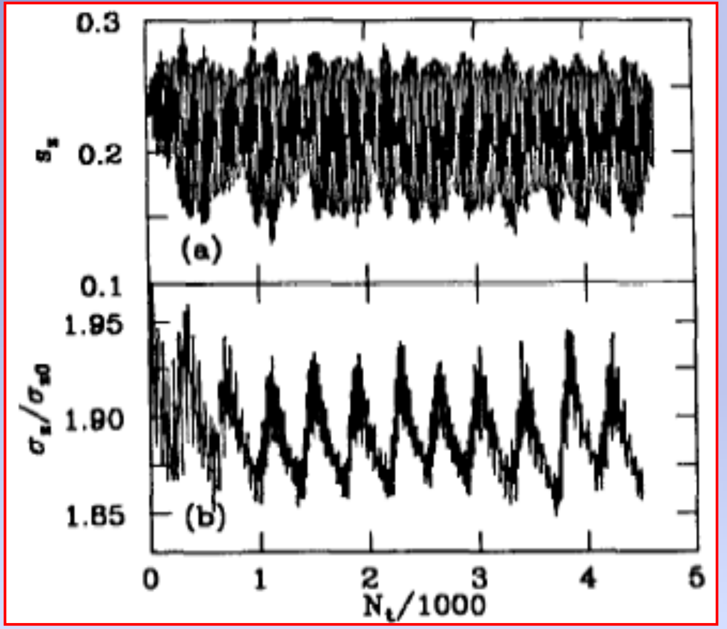


Haissinski solution for bunch shapes (head is to the left). Plotting symbols are measurement data.

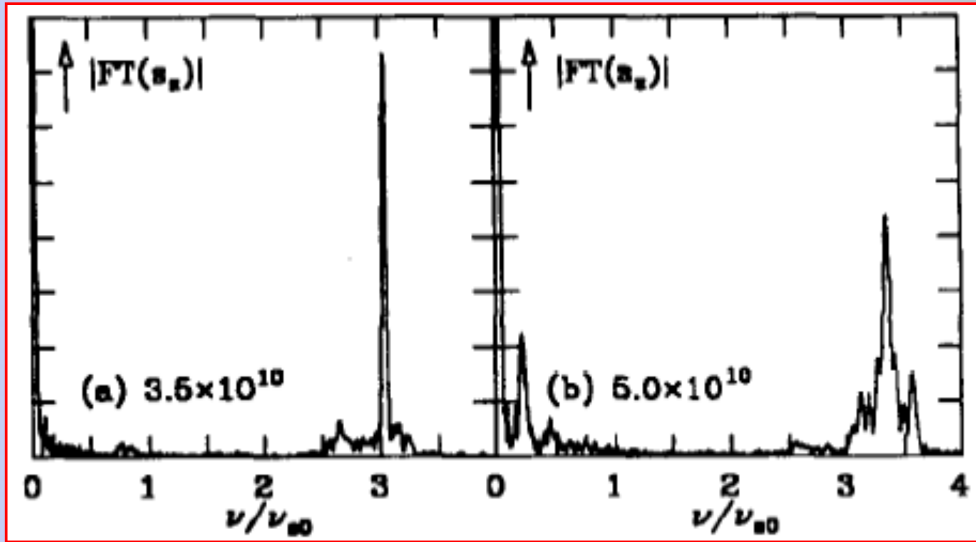


(a) Bunch length, (b) relative energy spread, and (c) centroid shift. Plotting symbols are measurement data.

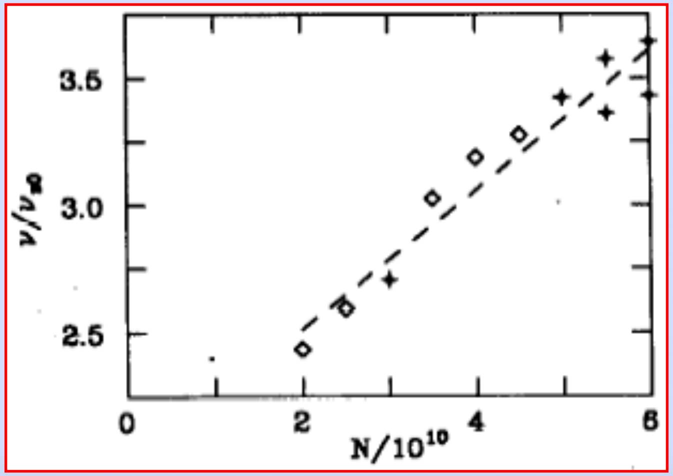
Tracking



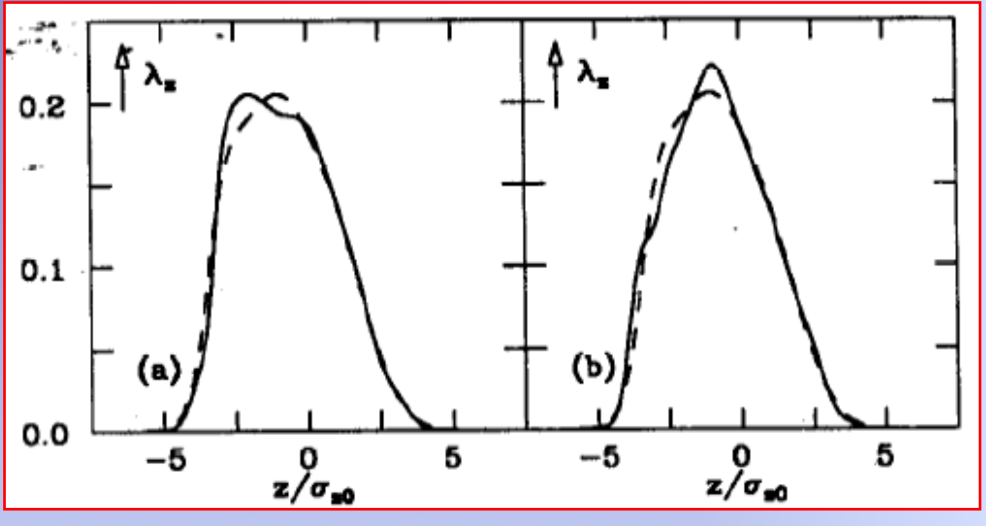
(a) Turn-by-turn skew when N= 3.5e10. (b) Rms when N= 5e10.



Fourier transforms of plots at left.

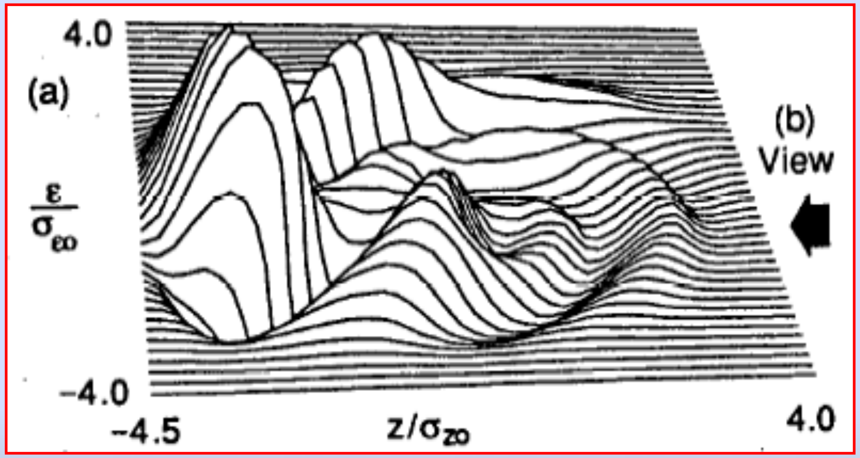


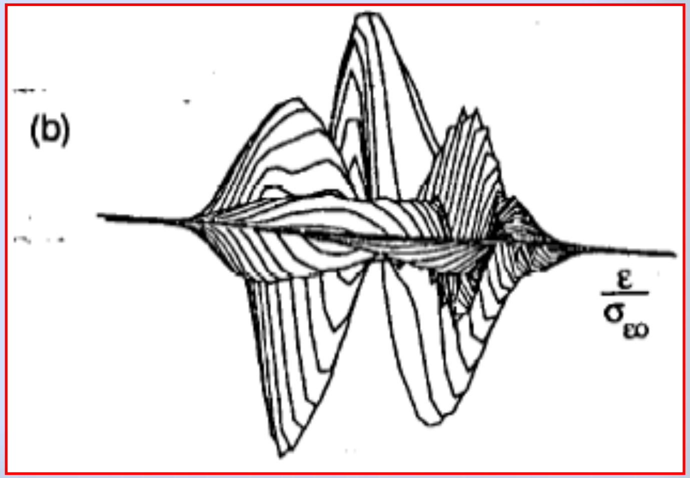
Position of peaks in skew signal FT vs. N. “Sextupole” mode seen in measurements with same $d\nu/dN$.



N= 3.5e10

Bunch shape at two phases 180 deg. apart.

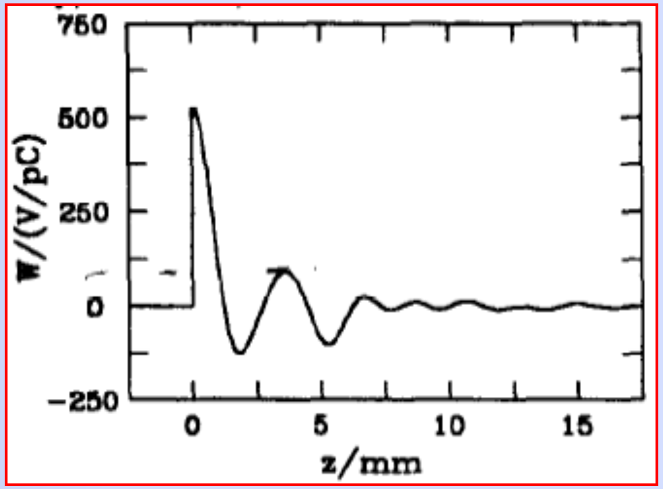




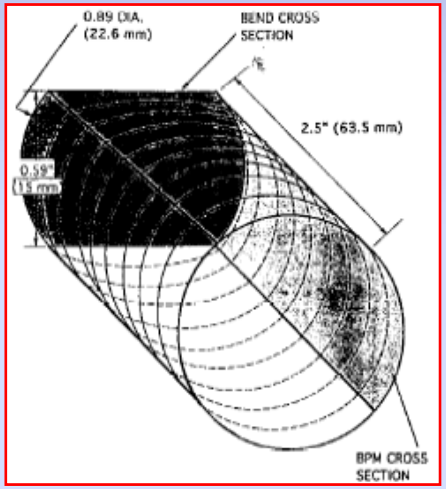
Shape of the mode: density of phase space when subtracted from the average.

New ring

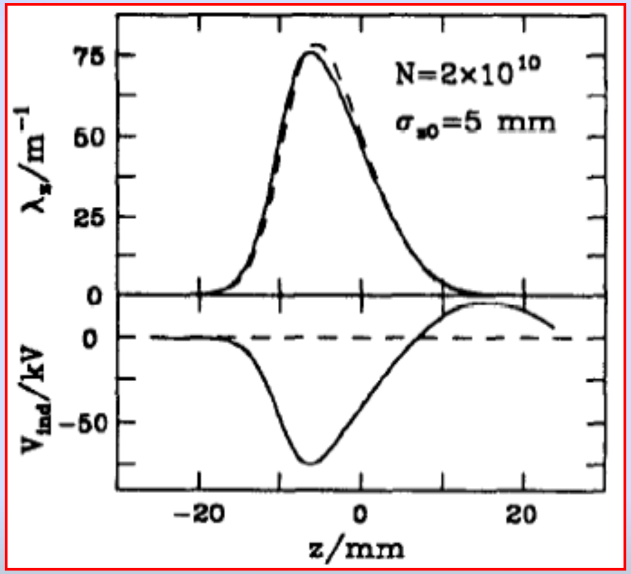
- New, smoother vacuum chamber was installed



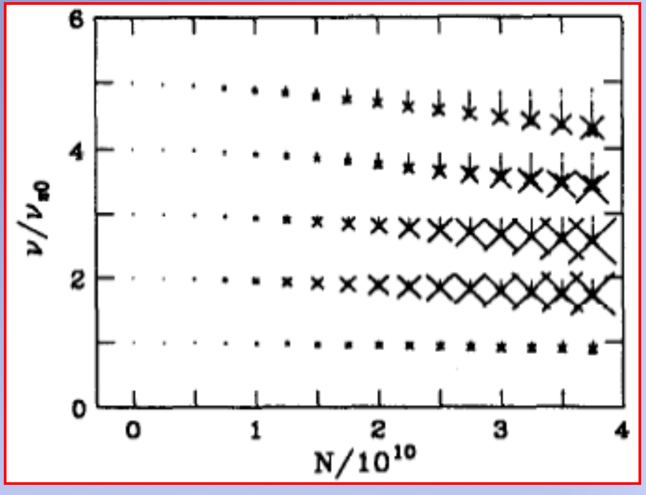
New Green function

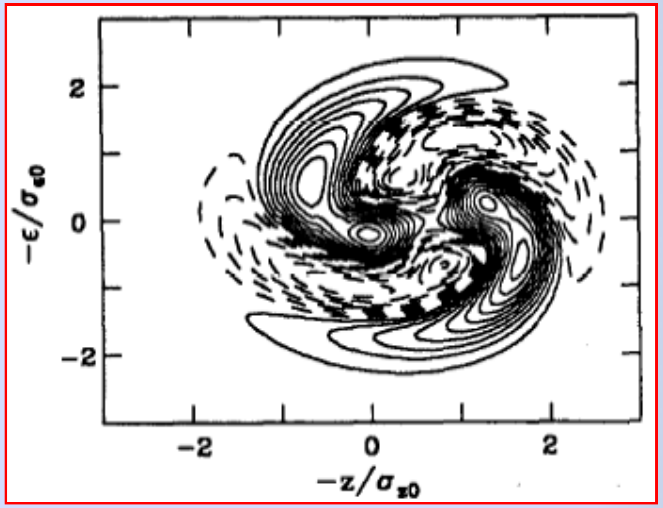


New bend-to-quad transition



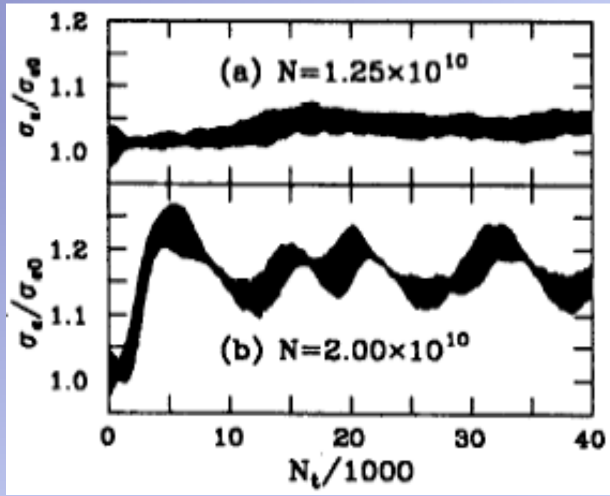
Potential well calculation





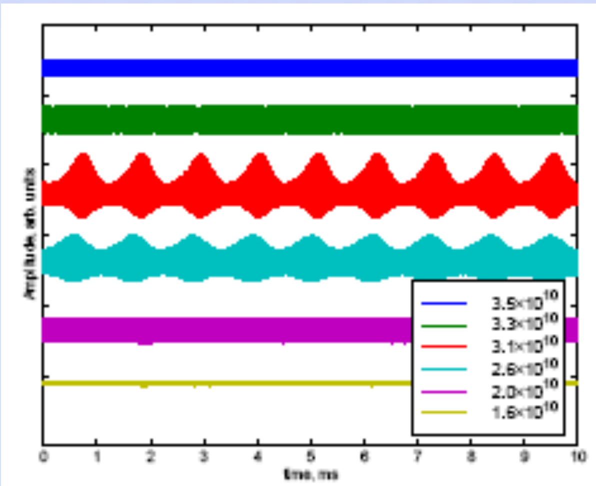
Vlasov equation mode calculation. Unstable mode begins at N= 1e10 with ν*= 1.95*ν_{s0}*. New type of mode.*

Shape of unstable mode

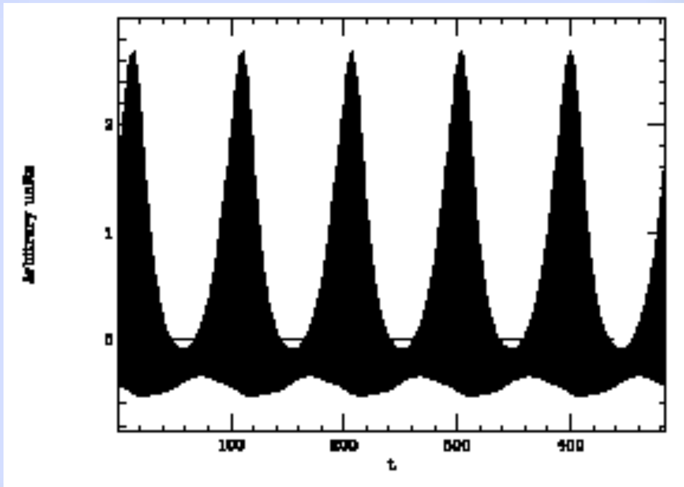


New SLC damping ring

Rms energy spread just above threshold (a) and at 2e10 (b) as obtained by tracking with 30,000 macroparticles.



Experimental oscilloscope traces (B. Podobedov).



Simulated oscilloscope trace using the new SLC DR wake and the VFP program. N= 3e10. (Warnock and Ellison)

SLC damping ring summary

At SLC new type of instability discovered (recognized by Oide):

•"Weak mode": sensitive to tune spread, radiation damping time

•Contrast to "strong mode": Boussard criterion; insensitive to tune spread, radiation damping

version	threshold calculated	threshold measured
original	1.1e10	1.5e10
old	2.0e10	3.0e10
new	2.0e10*	1.5e10

"sextupole" mode

quadrupole mode

*if add 2nH (0.1Ω) inductance

- How to understand: from old to new ring reduced the impedance and threshold dropped?
  old, inductive ring—strong mode—tune spread—weak modes Landau damped
  new, resistive ring—weak mode—little tune spread—no Landau damping

- Note: old ring, SLC operation limited to 3e10, new ring—5e10

DAΦNE Vacuum Chamber RF Design

M. Zobov

The DAΦNE vacuum chamber is complicated. Despite a short collider circumference of 97 m the vacuum chamber of each ring contains:

- Two 10 m long interaction regions
- Four 5 m long narrow gap wiggler vacuum chambers
- Straight sections fo allocation of RF cavities, injection kickers, longitudinal feedback kickers, transverse feedback kickers
- Tapers connecting straight sections, bending arcs, wiggler sections, interaction regions.
- Many others components

Being a high current collider all the vacuum chamber components were designed to avoid beam instabilities and excessive power losses. New designs and ideas were incorporated in:

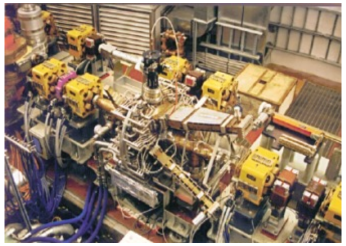
- Main RF cavity
- Third harmonic cavity
- Longitudinal feedback kicker
- Injection kicker
- Transverse feedback kicker
- Beam position monitor
- Direct current monitor
- Interaction point shield
- Bellows
- Pumping ports
- Clearing electrodes
- Tapers
- Flanges
- Valves
- Scrapers
- Etc…

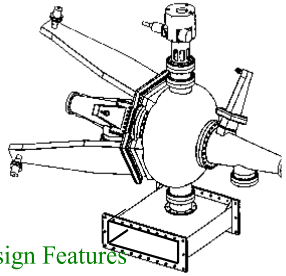
Numerical Codes Used:

ABCI, URMEL, MAFIA (2.04), HFSS

DAΦNE Main RF Cavity

(Particle Accelerators, Vol. 48, p.213 (1995)





Principal Design Features

-Rounded body: simple mechanical design, no multipacting

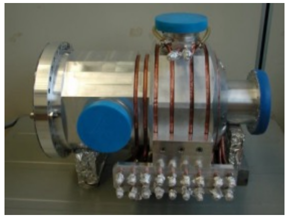
-Long tapers: low broad-band impedance, lower RF losses

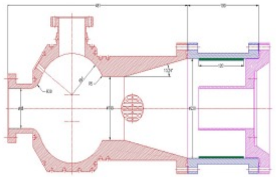
-HOM positions far from principal beam harmonics

-Damping waveguides with broad-band transitions to external loadings

-No dissipative materials under high vacuum

DA NE 3^{rd} Harmonic RF Cavity

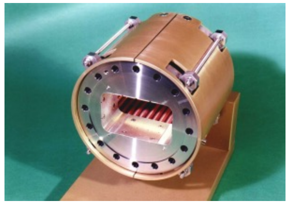


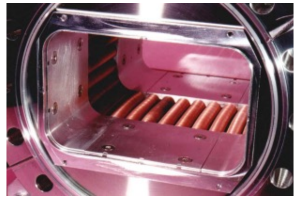


- Main Purpose:
  - Bunch length control for lifetime improvem
  - Additional Landau damping
- Design Features:
  - Single mode cavity. All HOM propagate an damped by ferrite absorber
  - KEKB ferrite absorber is used which create coaxial together with the beam pipe
  - Taper is used for gradual matching between cavity pipe and the coaxial absorber.

Publications
  - Nucl. Instrum. Meth. A354: 215-223, 1995
  - Phys.Rev. ST Accel. Beams 6: 074401, 200

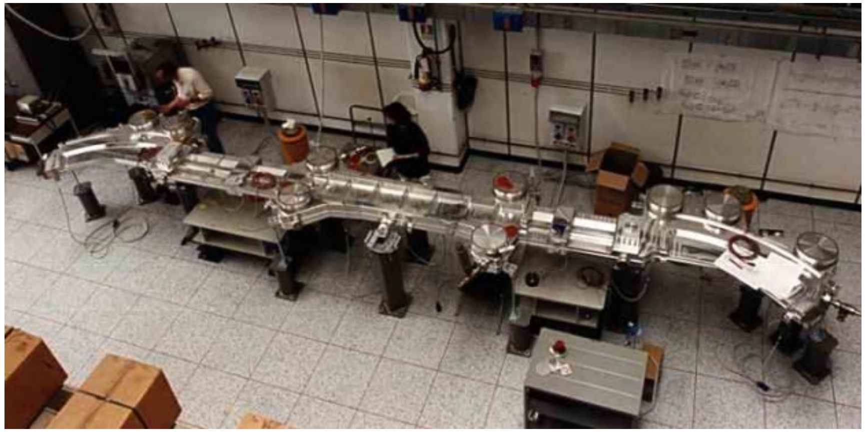
Short Shielded Bellows





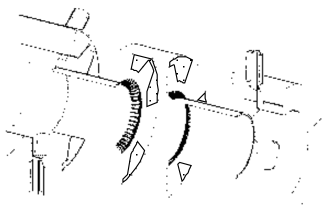
- There are 20 bellows placed in straight sections. They are 45 mm long and must provide 10 mm longitudinal expansion (Short Bellows)
- The bellows screen is made of Mini Bellows with a diameter of 7.9 mm and paced by 1 mm fitting the vacuum chamber cross section.
- The 1-3 cm long bunch does not "see" the Mini Bellows corrugations. Indeed, no any notable coupling impedance has been measured till 3.5 GHz

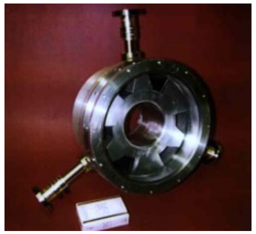
Arc Vacuum Chamber



A system of long gradual transitions between different arc vacuum chamber cross-sections is used to minimize the coupling impedance

Longitudinal Feedback Kicker





Purpose:
- used to provide correcting longitudinal kick

Design Features:
- heavily loaded pill-box cavity
- 6 ridged wave guides rounded to fit cavity shape
- special transitions to coaxial feed through

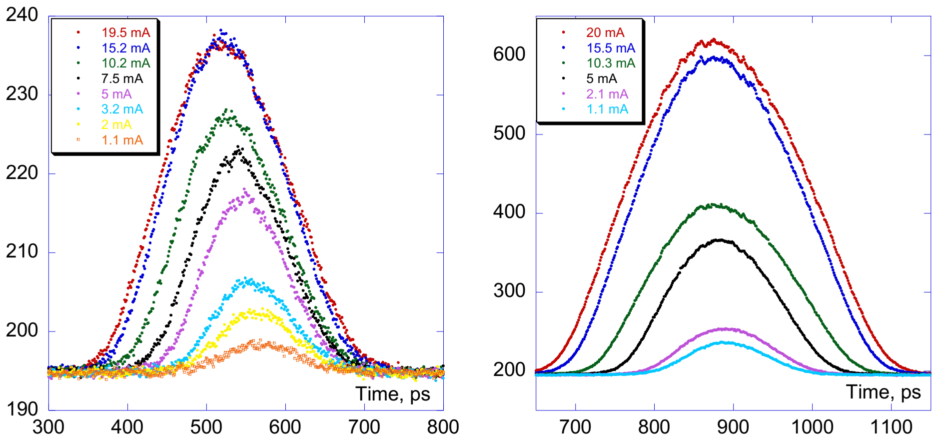
Advantages
- High broad-band shunt impedance
- All HOM are damped

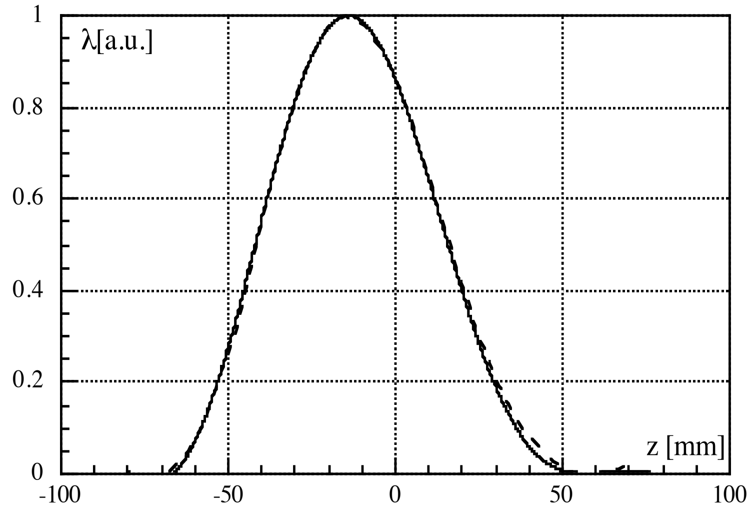
- Publications
  - Part. Accel. 52: 95-113, 1996 (>30 citations in HEP)
- Successful Experience in:
  - DAΦNE, KEKB, BESSYII, PLS, SLS, HLS,ELETTRA
  - PEP-II (upgrade, December 2003)
  - SPEAR-3, CESR (considered)

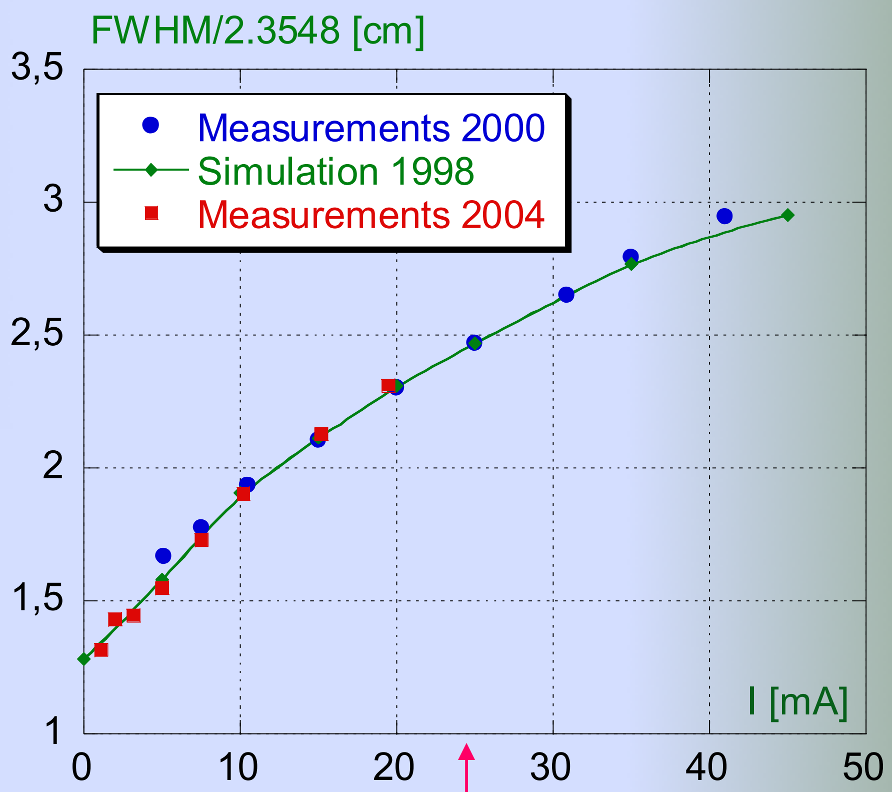
Bunch Lengthening in DAΦNE

Typical Measured Bunch Distributions

e+ Ring *e- Ring*

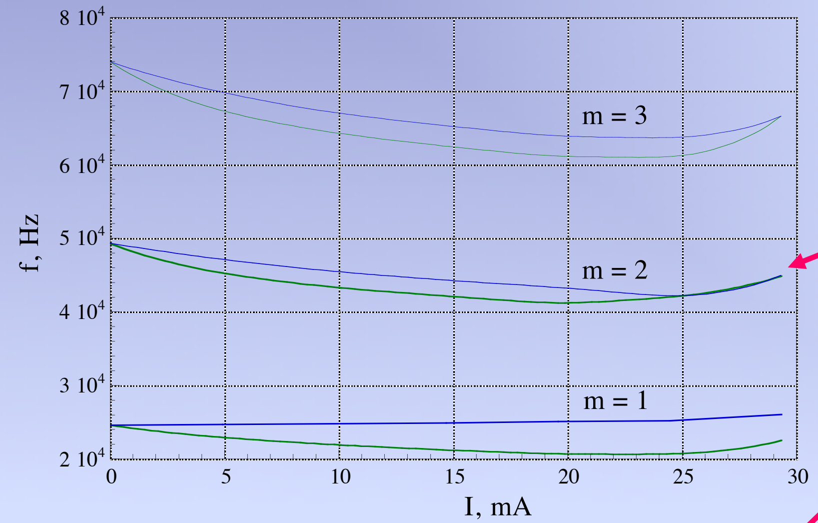


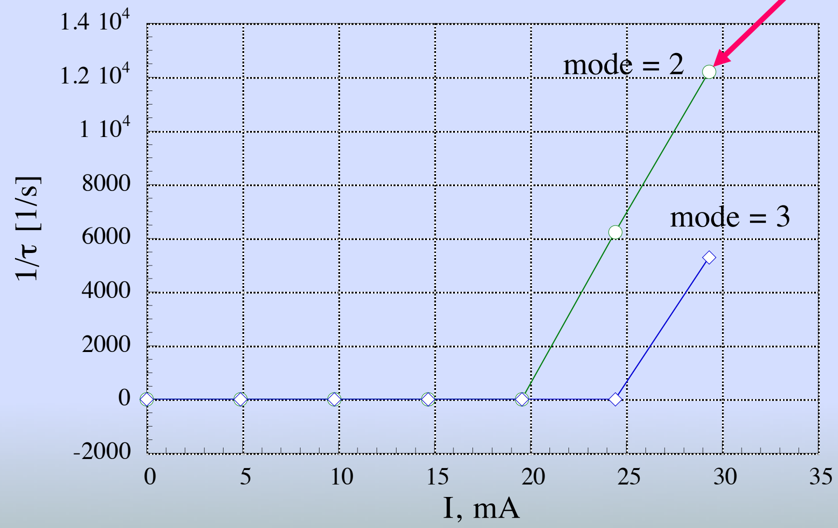


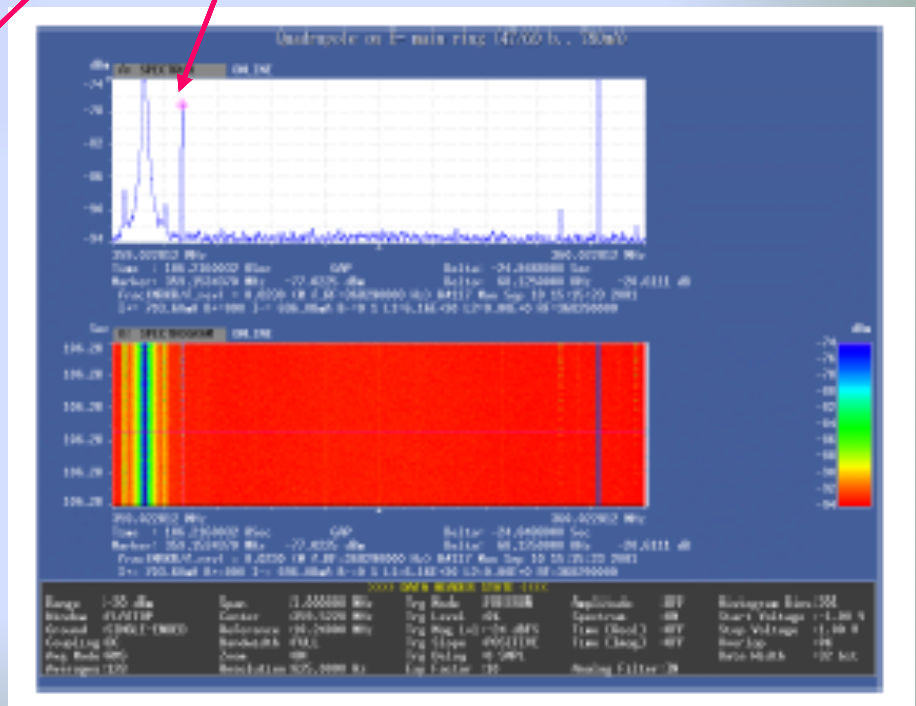


Comparison with Simulations

DAΦNE Quadrupole Instability

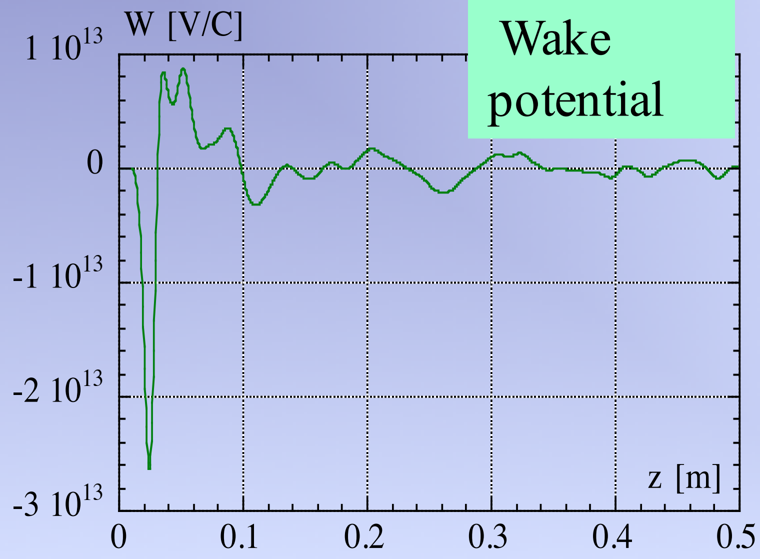


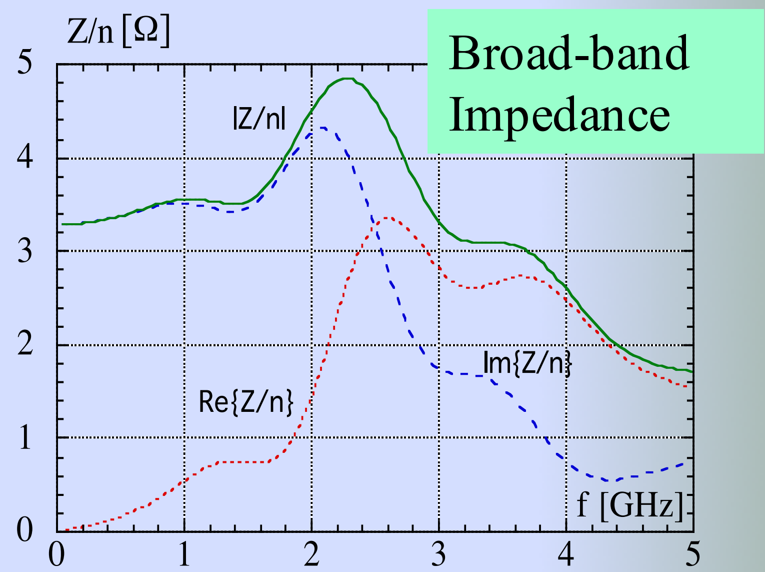


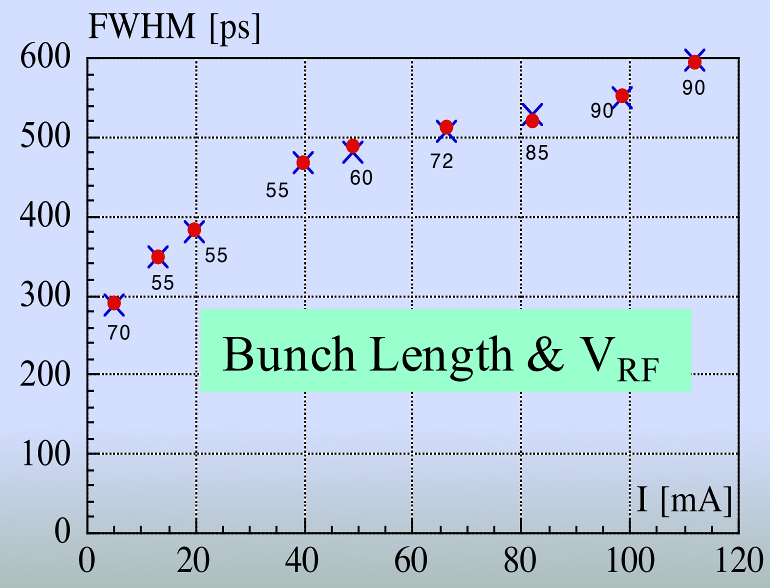


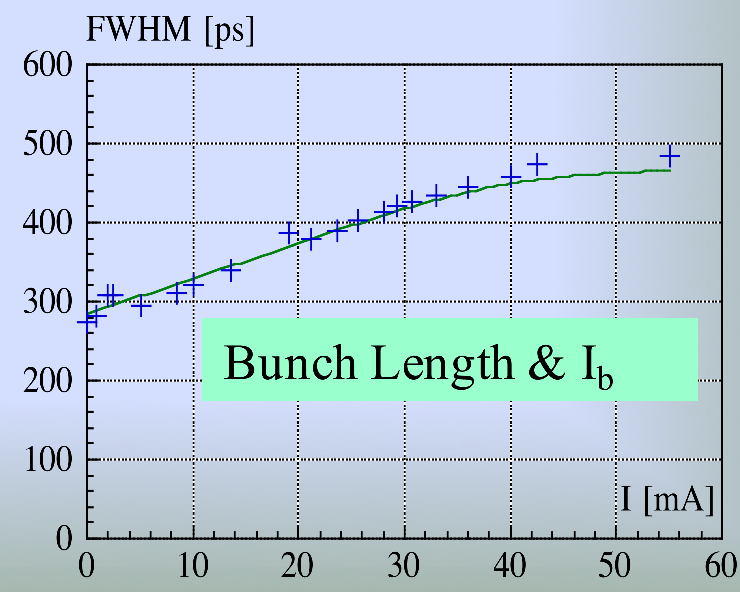
Bunch Lengthening in DAΦNE Accumulator Ring

(Nucl. Instrum. Meth. A418: 241-248, 1998)





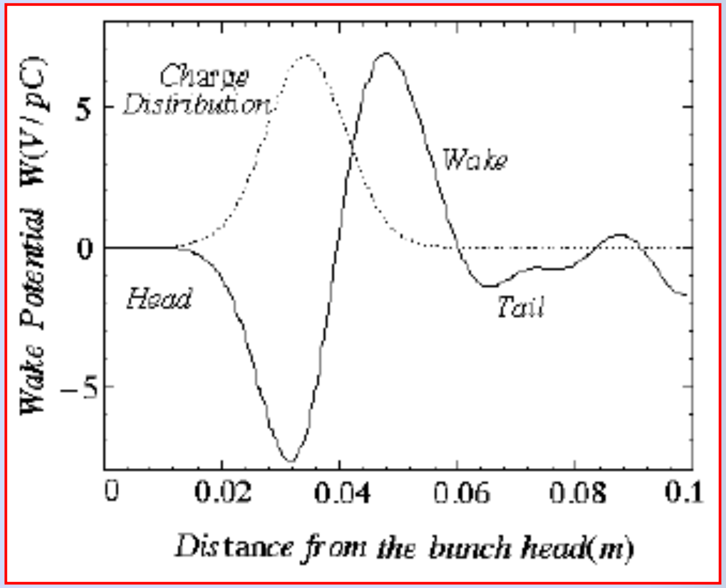




ATF damping ring

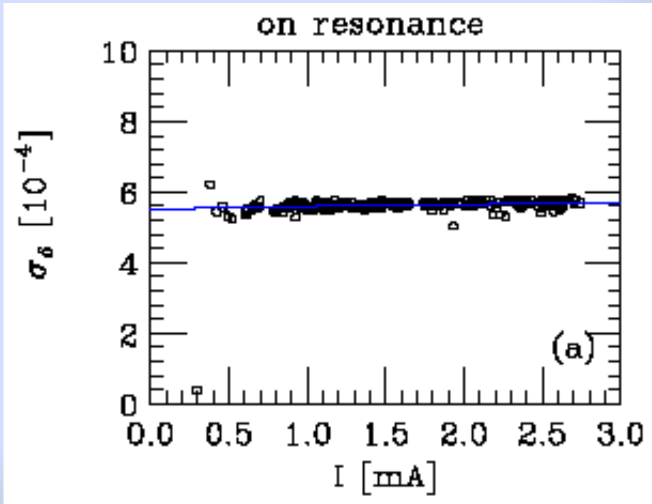
Components	Number	$\|Z_{\|\|}/n\|$ (Ω)	L(nH)
BPM	96	0.064	4.8
Normal Bellows	56	0.02	1.568
Elliptic Bellows	8	0.0058	0.46
Ext. kicker Bellow	1	0.01411	
Ext. kicker Bellow	1	0.01017	
Wiggler Mask	8	0.00096	0.0713
Mask in straight sec.	8	0.047	3.544
120 mm Tapers	2	0.0093	0.70
170 mm Tapers	2	0.008	0.602
Septum	1	0.0082	0.6224
Injec. kicker taper	1	0.0015	0.1203
Injec. kicker step	1	0.00008	
RF cavitity	2	0.03144	0.687
RF absorber	4	0.0089	0.671
Total		0.23	13.9

Important components to ring impedance (E-U Kim)

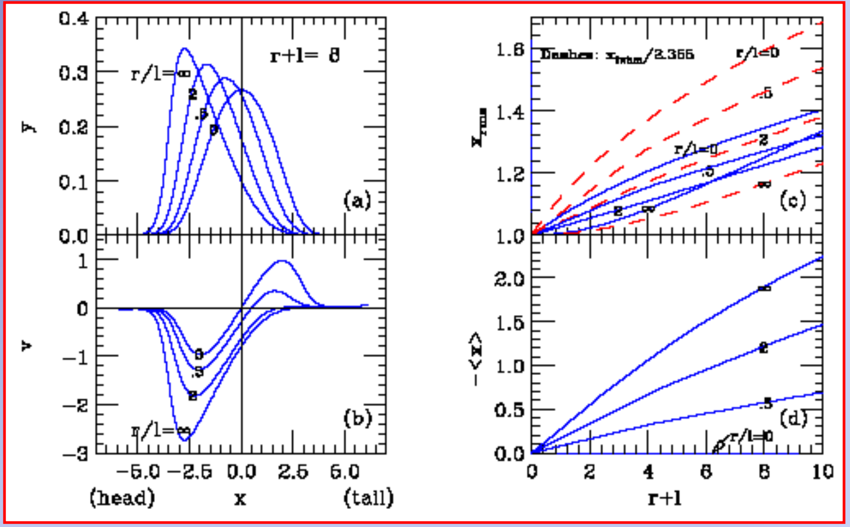


Wake of 6.8 mm Gaussian bunch (E-U Kim)

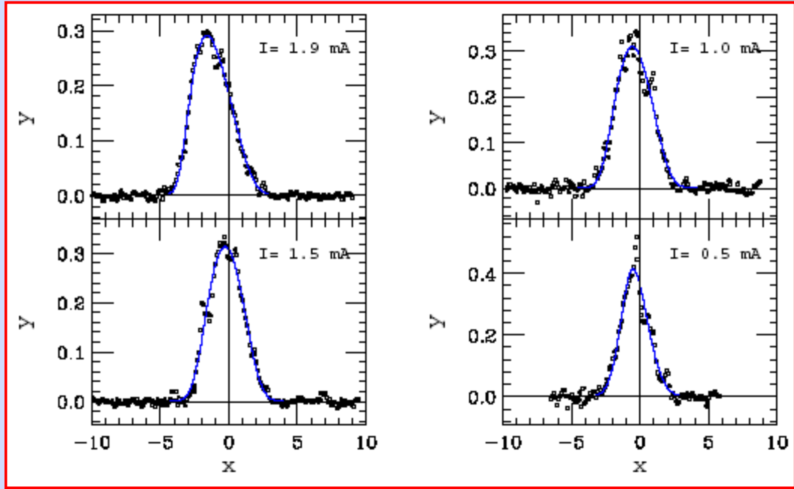
- When beam is on coupling resonance σ_E does not increase with current
- Fit bunch length measurements to Haissinski solution of R+L in series (done successfully at CESR)



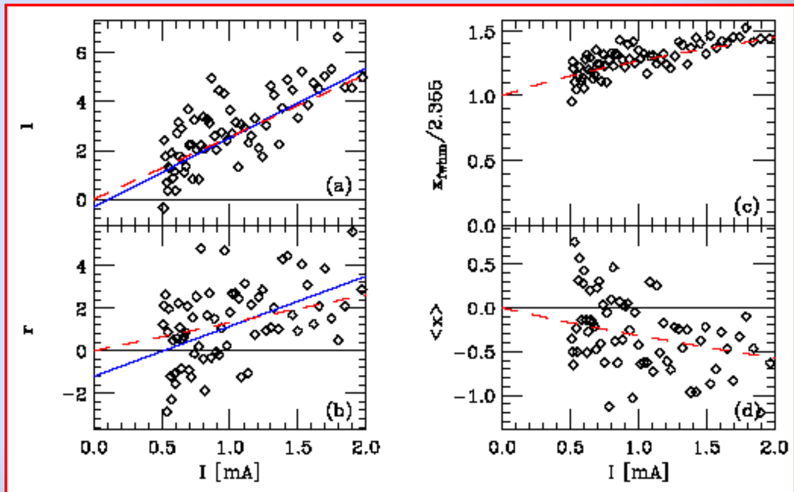
Energy spread for V= 300 kV



Haissinski solution of series R+L impedance. Shown are bunch shape and induced voltage (left) and rms and centroid of shape (right); r (l) is normalized R (L) times current.



Sample measurements with fits



Summary of fits

V_c (kV)	R (kΩ)	L (nH)
150	$1.3\pm.05$	$54\pm.7$
200	$1.7\pm.05$	$50\pm.6$
250	$1.1\pm.04$	$39\pm.4$
300	$0.8\pm.04$	$35\pm.4$

Fitting summary

Overall: R= 1.25±.35 kΩ
L= 44.5±7.5 nH

(Impedance calculations:
R= 100 Ω
L= 15 nH)

- Measurement repeated 6 months later with slightly different analysis, getting: R= 1.65±.20 kΩ, L= 32.5±1.0 nH
- Error in pseudo-Green function calculation?
- Systematic errors in streak camera?
- synchroscan streak camera to measure centroid shift

Programs assessment

Wake calculation:

-as rings become cleaner 3d objects become more important; for short bunch, wakes of long 3d objects become difficult to calculate

-To how high frequencies do impedances reach? For normal vacuum chambers to ~10’s of GHz. Normally one doesn’t generate THz in structures—except for coherent synchrotron radiation (CSR) due to bends

-shielded CSR (parallel plates) can well describe interaction in machines with very short bunches (e.g. ANKA in Germany); for SKEKB, CSR appears to be significant, though not dominant (D. Zhou)

-for short bunch interaction can occur over long distances (catch-up problem); wake of objects can interfere with neighbors

-short bunch, long structure, small features: difficult to calculate; numerical noise; numerical dispersion

=> improved algorithms: ECHO, GdfidL, CST Studio can reliably find wakes for short bunches in large structures

Summary

- The bottom-up approach to finding a ring impedance, performing wake calculations starting from drawings of the vacuum chamber objects, has been shown to work well in many storage rings
- To verify a ring impedance, one performs streak camera measurements, where the first and second moments of the distributions are sensitive to ReZ and ImZ, respectively. Other supportive measurements are of: beam phase (independent of streak camera), energy spread, and beam spectrum
- In the SLC experience a new, so-called weak instability was discovered, one that, rather than being described by the Boussard criterion, can be approximated by the simple theory by Oide
- The correspondence at Dafne between calculation and measurement is extremely good. The large missing impedance at the ATF at KEK is still not understood. Possibly there is error in the wake calculations