Impedance and instabilities in lepton colliders

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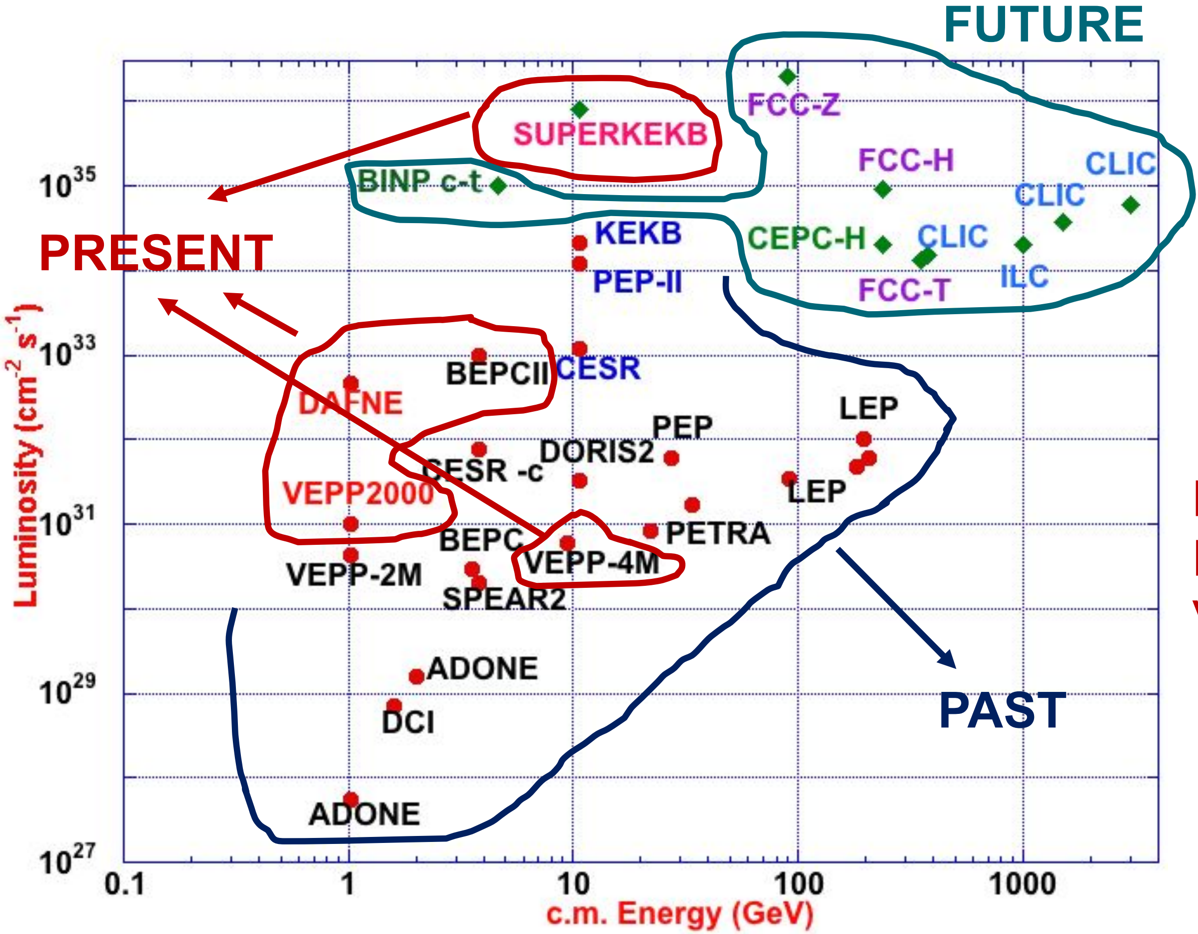
INFN LNF Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Frascati

Outline

- Lepton colliders around the world
- Low impedance vacuum chambers of lepton factories
- Hardware failures due to high circulating currents in factories
- Measures to overcome heating and reduce impedance
- Typical instabilities in lepton factories
- Instability cures

Lepton colliders around the world



M. Biagini
EPS-HEP
Venice 2017

Past, present, and future lepton colliders around the world

Lepton factories around the world

2.00 A and 1.40 A without crab cavities

will enter phase II in 2018

No more B-factory

Accelerator	PEP-II (turned off)	KEKB (turned off)	SuperKEKB	CESR	DAΦNE	BEPC-II
Location	SLAC	KEK	KEK	Cornell	INFN-LNF	IHEP
Ring	double	double	double	single	double	double
Circumference, m	2200	3016	3016	768	97.7	237.5
Beam energy, GeV	3.1 / 9	3.5 / 8	4 / 7	4.7 - 5.6	0.51	1 - 2.1
Bunch length, mm	15	6	6 / 5	20	10 - 16	11 - 15
Beam current, e+e-, A	3.21 / 2.07	1.70/1.25	3.6/2.6	0.365	1.40/2.45	.848/.862
Crossing angle, mrad	<0.1	±11	±41.5	±2.5~3.3	±10~15	±11
Luminosity, $10^{32}/cm^2/s$	120	210	8000	12.5	4.53	10

Maximum positron beam current

Maximum currents with SC cavities

Maximum electron beam current

Future lepton factories

Accelerator	FCC-ee				CEPC			SuperC-Tau
Location	CERN				China			Novosibirsk
Ring	double				double			double
Circumference, m	97750				100000			800
Crossing angle, mrad	±15				±16.5			±30
Beam energy, GeV	45.6	80	120	175	45.5	80	120	2
Bunch length, mm	3.5	3.3	3.15	2.45	4	3.4	2.7	10
Beam current, mA	1390	147	29	64	465.8	97.1	19.2	1700
Luminosity, $10^{32}/cm^2/s$	13700*	1640*	460*	135*	1190*	515*	200*	1000

*for IP

Low impedance vacuum chambers of lepton factories

- Coupling impedance evaluation is nowadays mainly performed by 2D or 3D electromagnetic codes, which solve the e.m. problem in the frequency or in the time domain.
- There are several useful codes for the em design of accelerator devices, and new ones are developed:
- ABCI: Azimuthal Beam Cavity Interaction
- MAFIA: solution of Maxwell's equations by the Finite Integration Algorithm
- CST Microwave Studio: Computer Simulation Technology
- GdfidL: Gitter drüber, fertig ist die Laube, literally: a simple way to build an arbour, is by putting up a mesh
- ACE3P: Advanced Computational Electromagnetic 3D Parallel software
- Echo2D (3D): Electromagnetic Code for Handling Of Harmful Collective Effects
- PBCI: Parallel Beam Cavity Interaction

Low impedance vacuum chambers of lepton factories

- Resistive wall due to beam pipe shape and dimensions, coating, BPMs, vacuum ports, RF fingers, RF cavities, tapers and transitions, bellows, scrapers and collimators are main sources of impedance

KEKB - D. Zhou et al., ICAP09, TH2IOpk02

Component	Number	Software
ARES cavity	20	GdfidL
Movable mask	16	GdfidL
SR mask (arc/wiggler)	1000 (905/95)	GdfidL
Bellows	1000	GdfidL
Flange gap	2000	GdfidL
BPM	440	MAFIA
Pumping port	3000	GdfidL
Crab cavity	1	ABCI
FB kicker/BPM	1/40	GdfidL
Tapers ARES/Crab/Abort/Injection IR(IP/QCSL/QCSR)	 4/2/2/2 6(2/2/2)	GdfidL
Gate valves f94/f150/94x150	26/13/2	GdfidL

KEKB - Y. Cai et al., PRST-AB 12, 061002 (2009)

Parameter	Description	LER	HER
L (nH)	Inductance	116.7	109.1
R (KΩ)	Resistance	22.9	12.5
C (fF)	Capacitor	0.22	0.69

DAΦNE – M. Zobov et al., LNF-95/041 (P), 1995

Element	Im Z_L/n [Ω]
Tapers	0.156
Transverse feedback kickers (low frequency)	0.128
Scrapers	0.062
Bellows	0.024
Resistive wall (at roll - off frequency)	0.013
BPMs	0.01
Vacuum pump screens	0.02
Injection port	0.0031
Antechamber slots	0.0005
Synchrotron radiation	< 0.015
Space charge	-0.0021
Other inductive elements	0.1
Total	**0.53 Ω**

Low impedance vacuum chambers of lepton factories

Main contributions to the inductive impedance of PEP-II

S. Heifets et al., SLAC PUB 6989, 1996

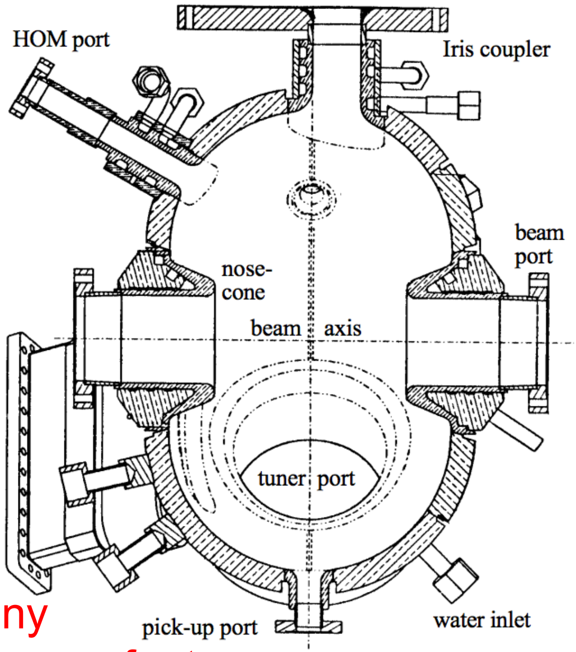
	L (nH)	k_l (V/pC)
Dipole screens	0.10	
BPM	11.	0.8
Arc bellow module	13.5	1.41
Collimators	18.9	0.24
Pump slots	0.8	
Flange/gap rings	0.47	0.03
Tapers oct/round	3.6	0.06
IR chamber	5.0	0.12
Feedback kickers	29.8	0.66
Injection port	0.17	0.004
Abort dump port	0.23	0.005
Total	83.3	3.4

SuperKEKB - D. Zhou et al., IPAC14, TUPRI021

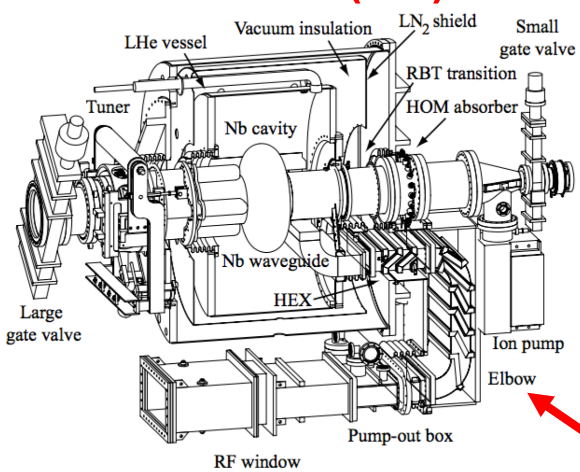
Component	LER			HER		
	$k_{\|\|}$	R	L	$k_{\|\|}$	R	L
ARES cavity	8.9	524	-	3.3	190	-
SC cavity	-	-	-	7.8	454	-
Collimator	1.1	62.4	13.0	5.3	309	10.8
Res. wall	3.9	231	5.7	5.9	340	8.2
Bellows	2.7	159	5.1	4.6	265	16.0
Flange	0.2	13.7	4.1	0.6	34.1	19.3
Pump. port	0.0	0.0	0.0	0.6	34.1	6.6
SR mask	0.0	0.0	0.0	0.4	21.4	0.7
IR duct	0.0	2.2	0.5	0.0	2.2	0.5
BPM	0.1	8.2	0.6	0.0	0.0	0.0
FB kicker	0.4	26.3	0.0	0.5	26.2	0.0
FB BPM	0.0	1.1	0.0	0.0	1.1	0.0
Long. kicker	1.8	105	1.2	-	-	-
Groove pipe	0.1	3.8	0.5	-	-	-
Electrode	0.0	0.7	5.7	-	-	-
Total	19.2	1137	36.4	29.0	1677	62.1

Low impedance vacuum chambers of lepton factories

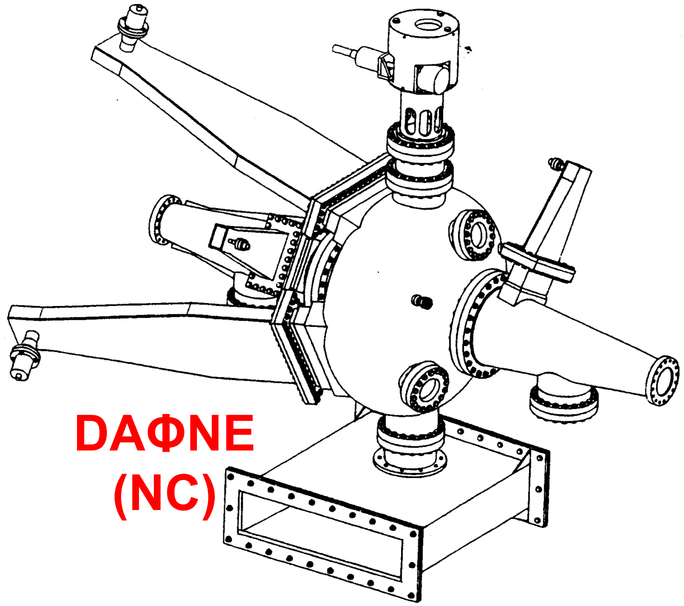
PEP-II (NC)



CESR (SC)

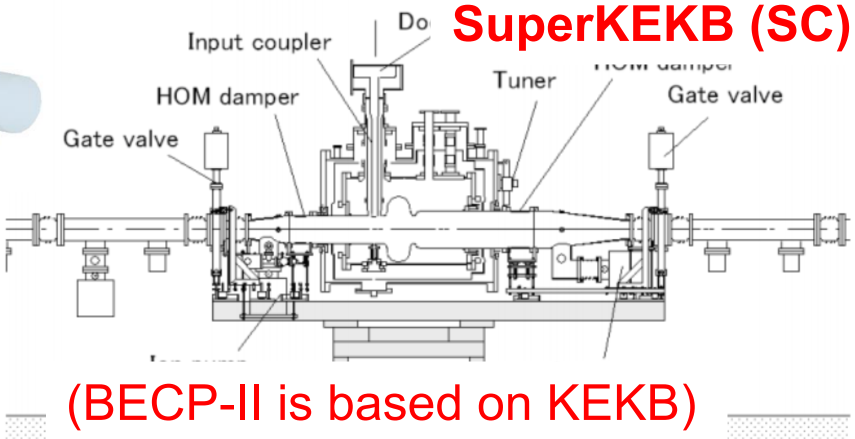


DAΦNE (NC)

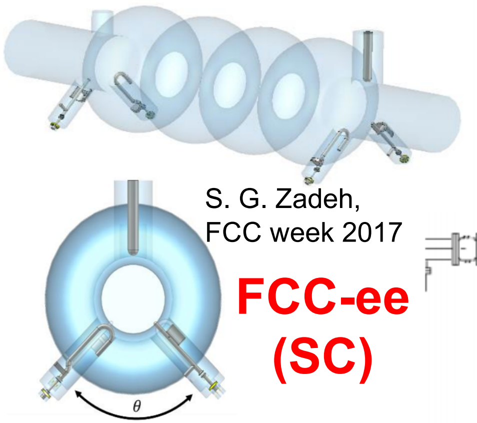


many common features

KEKB/ SuperKEKB (SC)

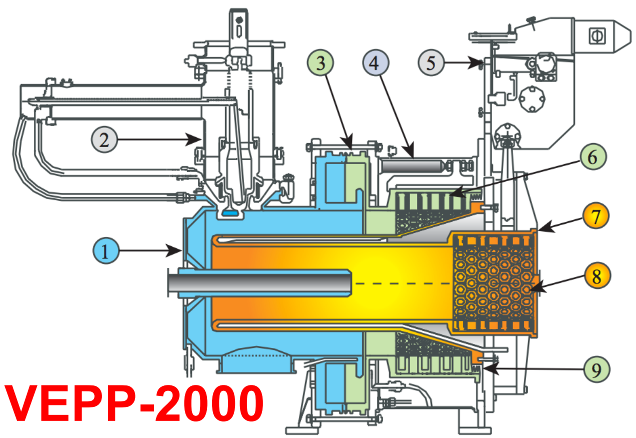


(BECP-II is based on KEKB)



S. G. Zadeh, FCC week 2017

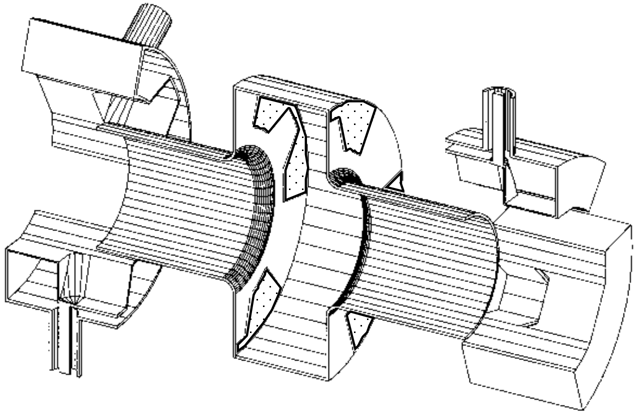
FCC-ee (SC)



VEPP-2000 (NC)

Low impedance vacuum chambers of lepton factories

- Feedback systems to cure coupled bunch instabilities are based on similar bunch-by-bunch scheme.
- A common used kicker is of DAΦNE type



- 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 HOMs are damped
- This design is adopted for kickers in:
- DAΦNE, KEKB, BESSY-II, PLS, HLS, TLS, ELETTRA/SLS, BEPC-II, KEK Photon Factory, Duke storage ring, PEP-II, SuperKEKB, DELTA, ELSA, ALS, Diamond, ESRF, LNLS-UVX, PETRA-III, MAX-IV…

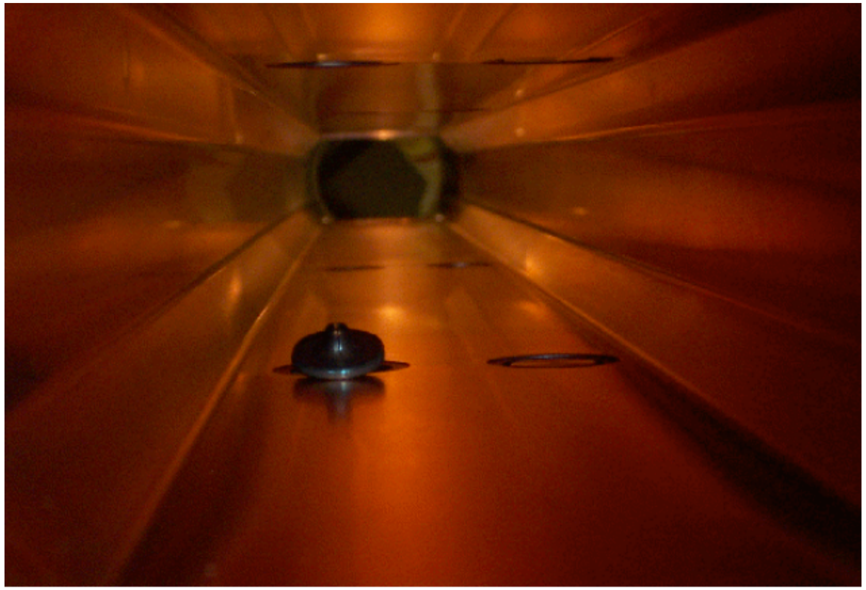
Hardware failures due to high circulating currents in factories

heating and damage observations in PEP II

- RF seals: breakdowns, sparks
- vacuum valves: melted fingers
- shielded bellows: melted fingers
- BPM buttons: falling down
- ceramic tiles: sparks

Melted feed-through of a lower button and the fallen upper button (S. Weathersby, ICAP09)

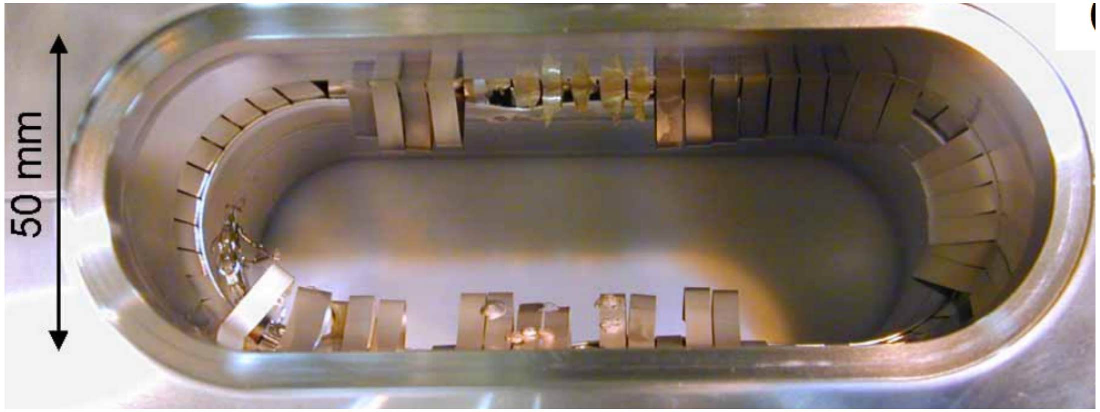
A button of an upper BPM fell off onto a lower button (S. Weathersby, ICAP09)

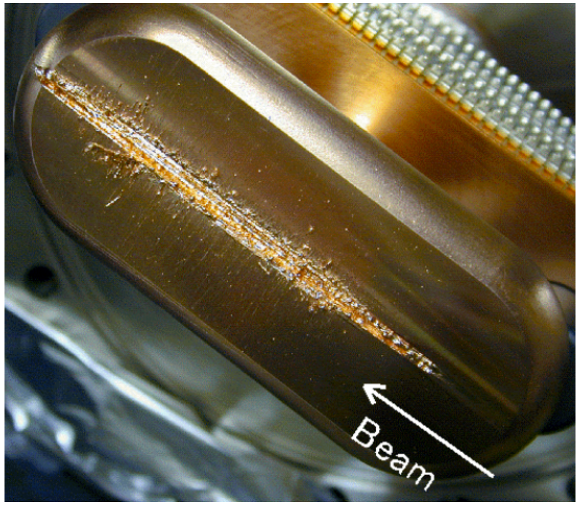


Hardware failures due to high circulating currents in factories

- Heating and damage observations in KEKB (Y. Funakoshi, Super B-Factory Meeting at LNF - Frascati - 2005)

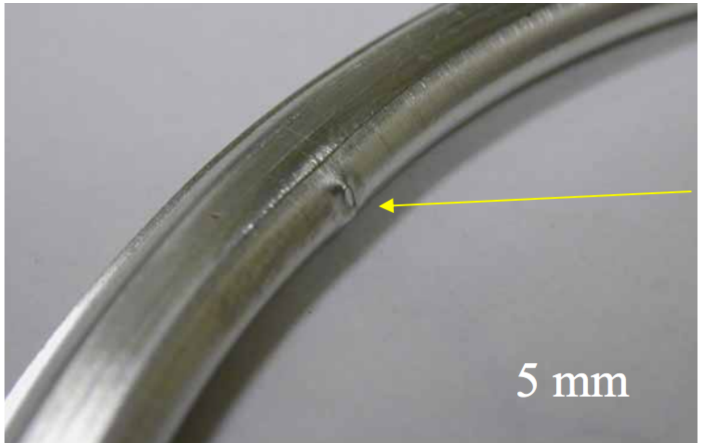
RF fingers damage due to HOMs





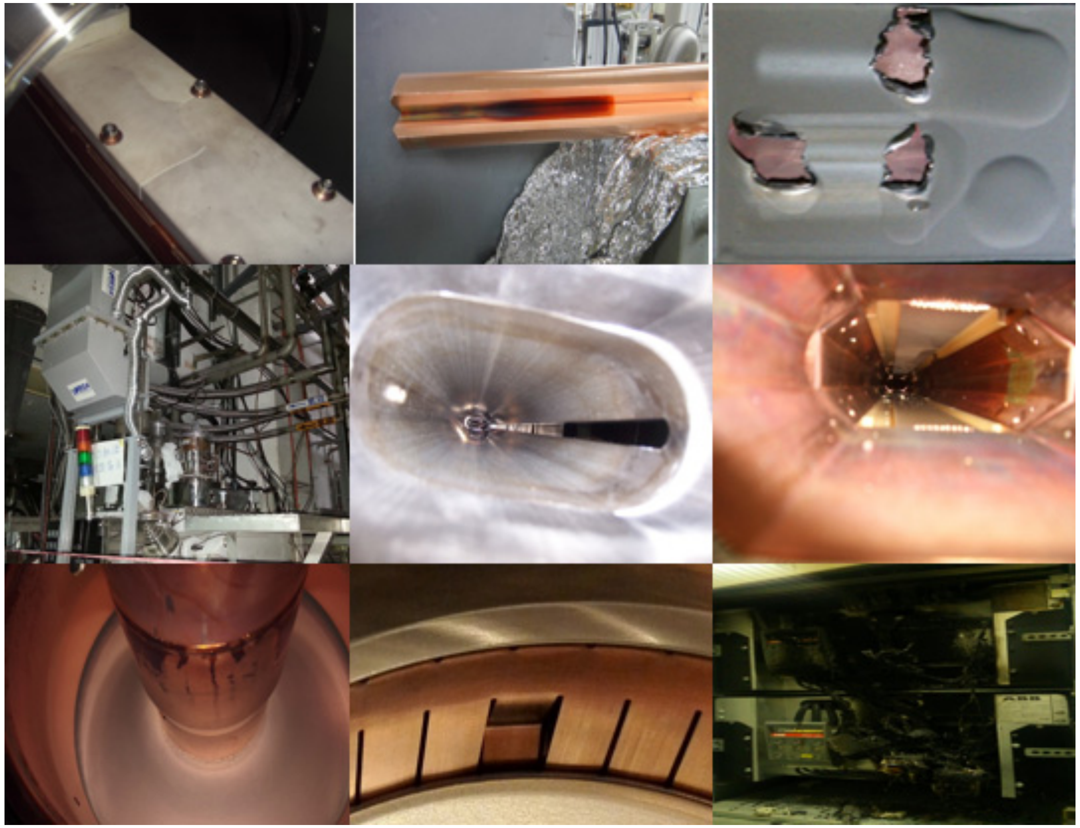
Groove on a movable mask head dug directly by the beam

Gasket vacuum leak due to SR



Hardware failures due to high circulating currents in factories

- Hardware failures which limited the increase of beam current BEPC-II (C. H. Yu et al., IPAC2016)



From the paper:

It's very hard to increase the beam current, especially above 700 mA due to heating problems, which were mainly caused by synchrotron radiation power and high order modes.

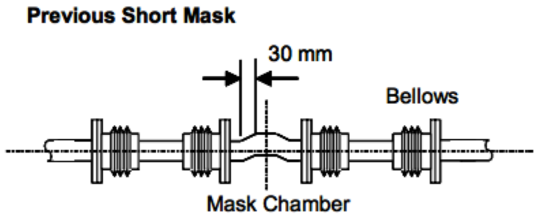
Several serious hardware failures happened during the operation, such as kicker magnet, RF coupler, SR monitor, bellows, feedback system, etc.

Measures to overcome heating and reduce impedance

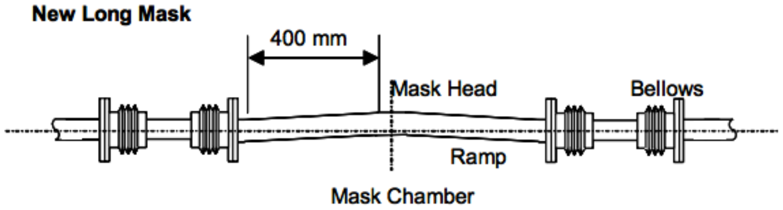
- In addition to overcome excessive heating, the coupling impedance needs to be reduced also in order to increase longitudinal and transverse instability thresholds.
- General indications:
  - Design a vacuum chamber as smooth as possible
  - Use long tapers
  - Design damped HOMs elements
  - Use HOMs absorbers in every region having discontinuity
  - Novel design of devices (e.g. comb-type RF shielding instead of finger-type for bellows)
  - …

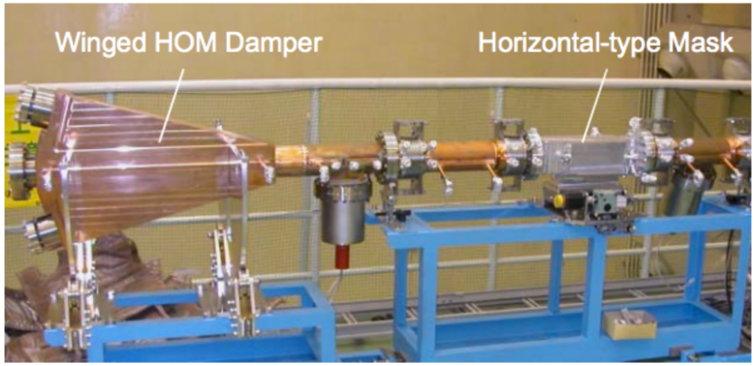
Measures to overcome heating and reduce impedance

- Solutions in KEKB - SuperKEKB



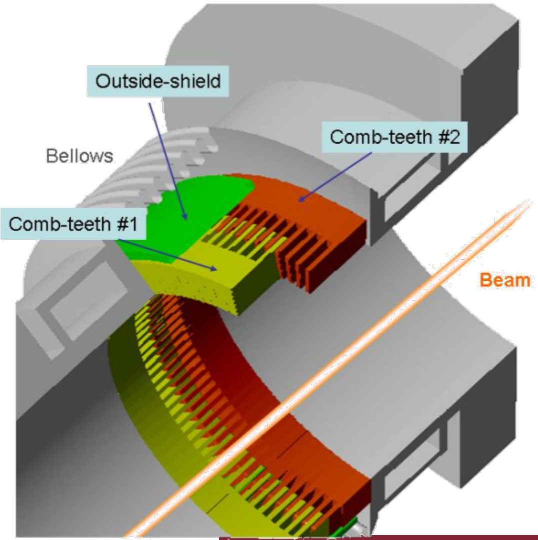
K. Shibata et al.,PAC03



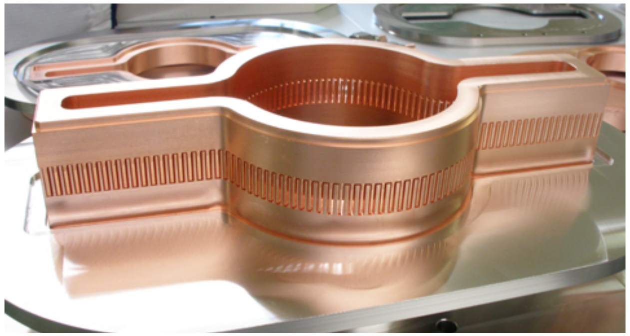


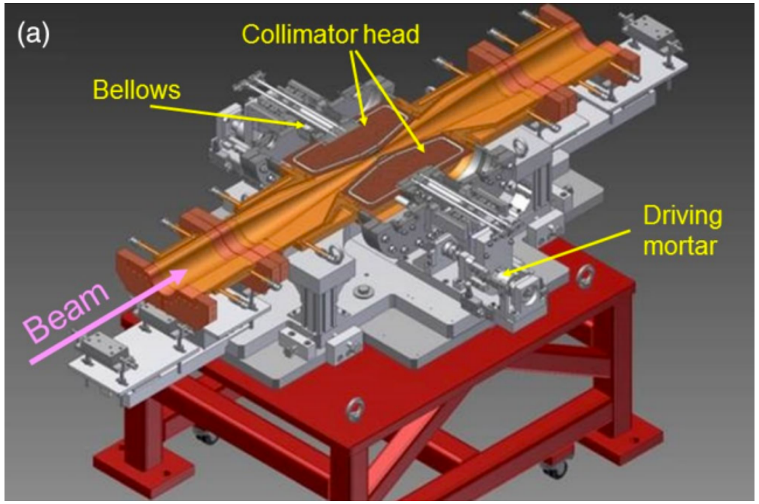
Y. Suetsugu et al., PAC03

Y. Suetsugu et al., PRST-AB, 19, 121001 (2016)



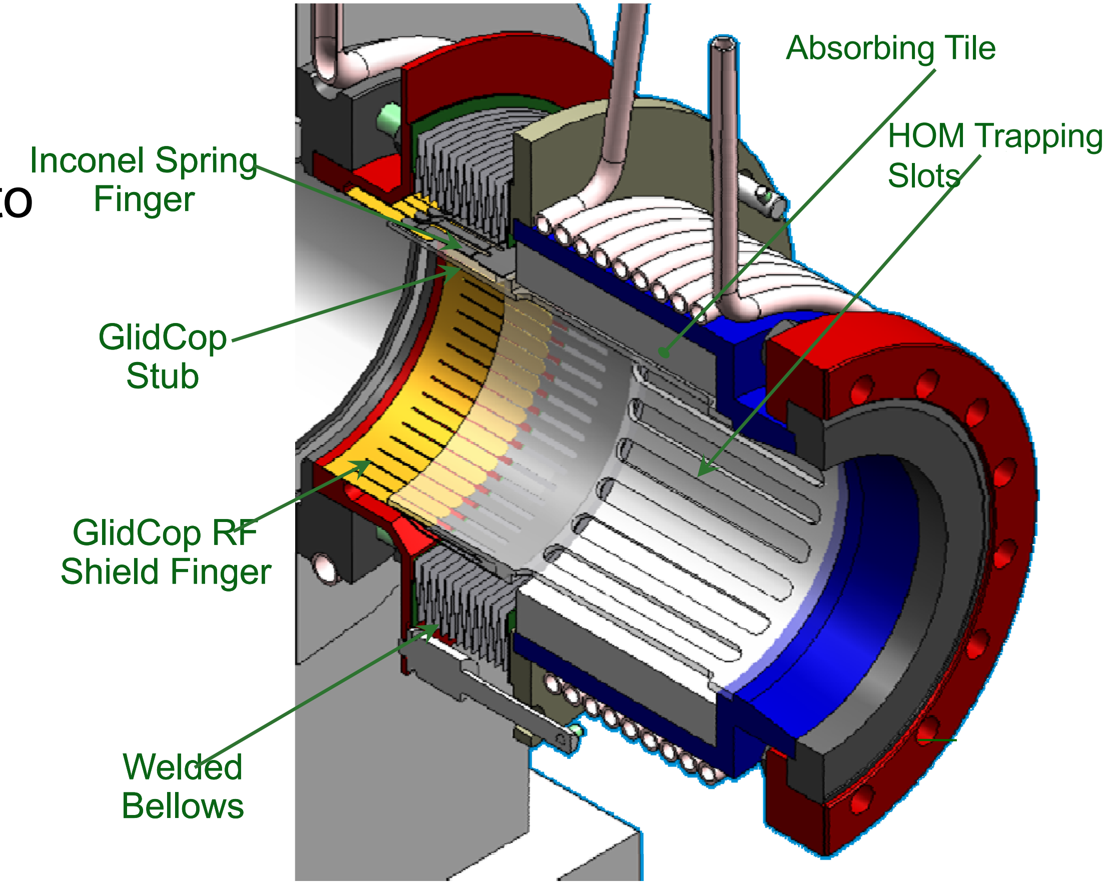
Y. Suetsugu, Japan-Italy Collaboration Meeting "Crab Factories" 2008 (INFN-LNF)





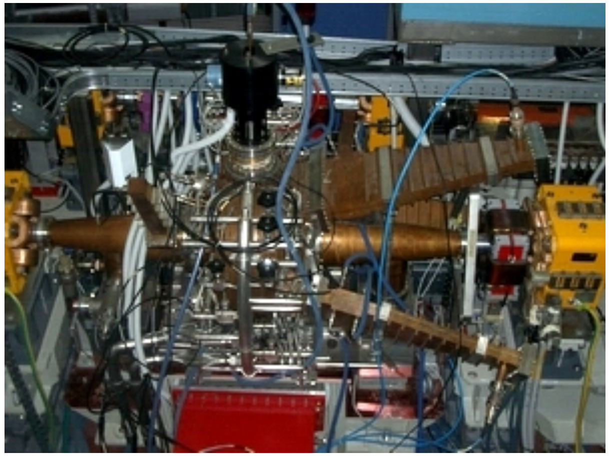
Measures to overcome heating and reduce impedance

- Solutions in PEP-II:
  - Install more cooling (temperature raise due to HOM in vertex bellows)
  - new design (e.g. gasket of vacuum valves)
  - design a new HOM absorber to damp em fields that propagate through the slots in bellows, vacuum valves and pump screens.

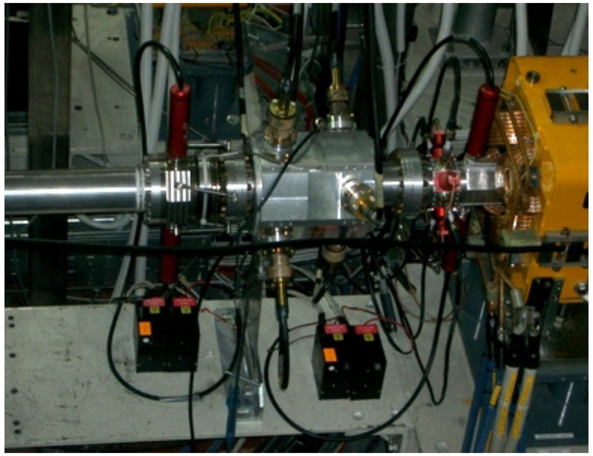


A. Novokhatski et al., PRST - AB 10, 042003 (2007) and Mini-workshop “Simulation of Power Dissipation and Heating from Wake Losses in Accelerator Structures” DIAMOND, 2013

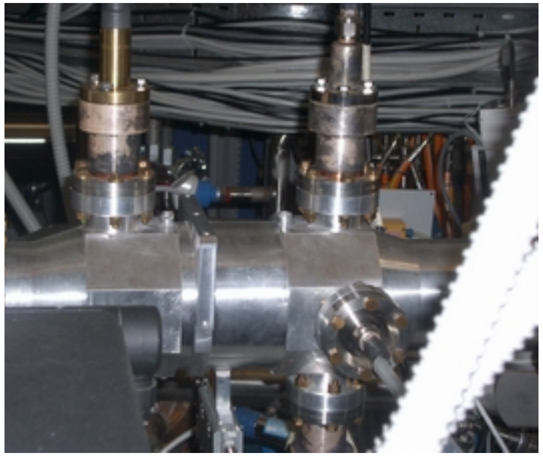
Measures to overcome heating and reduce impedance
DAΦNE Damped HOMs Vacuum Chamber Elements



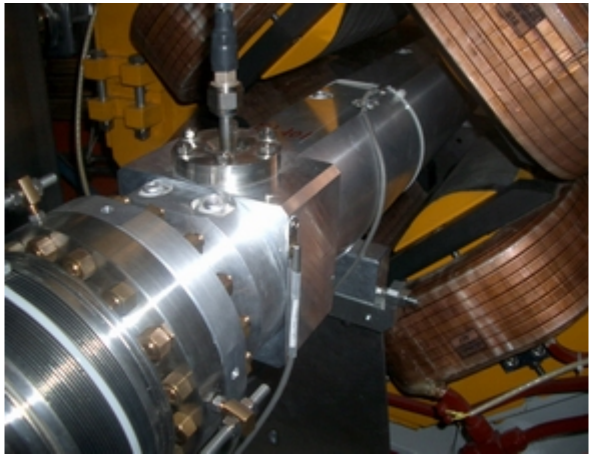
RF CAVITY



LONGITUDINAL
KICKER

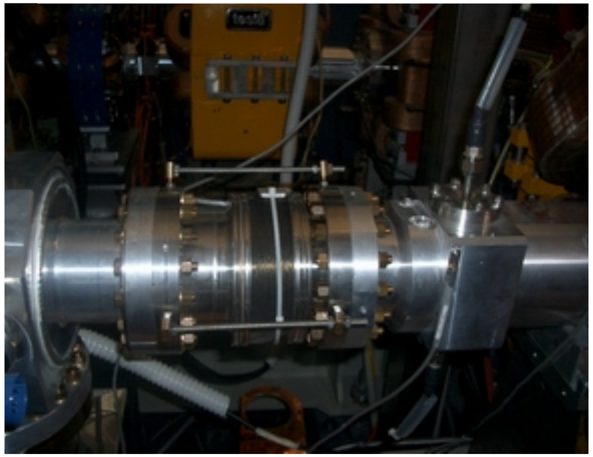


TRANSVERSE
KICKER



INJECTION
KICKER

WALL CURRENT &
DCCT MONITOR

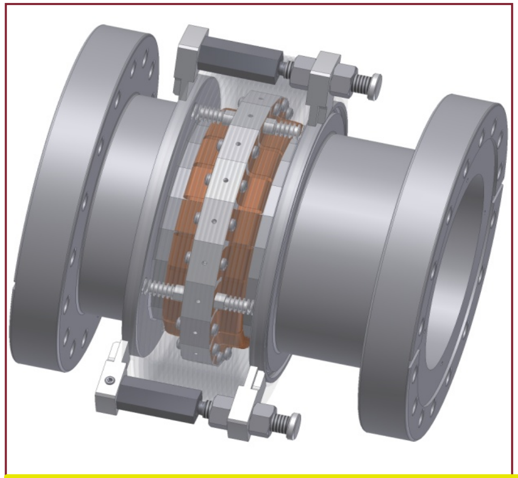


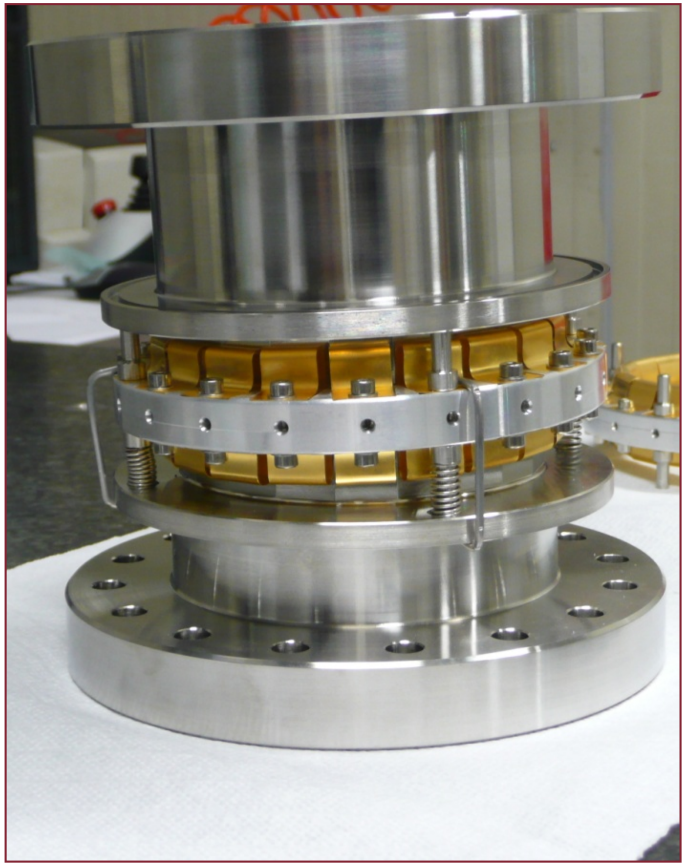
SHIELDED
BELLOWS

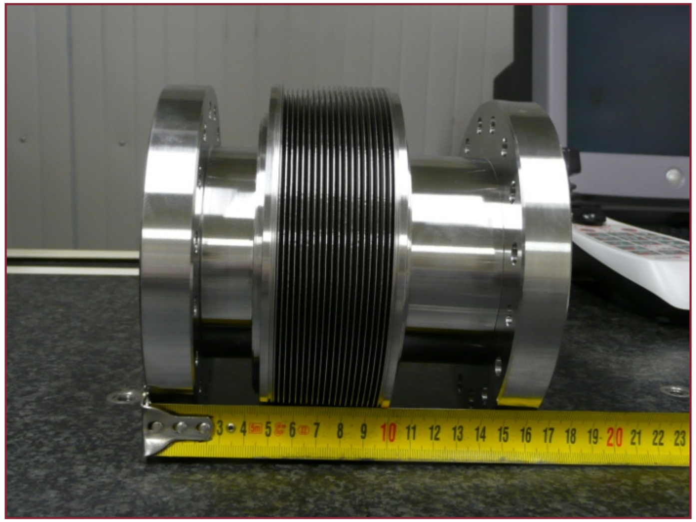
Measures to overcome heating and reduce impedance

M. Zobov, CERN-LNF Meeting at LNF INFN, (2016)

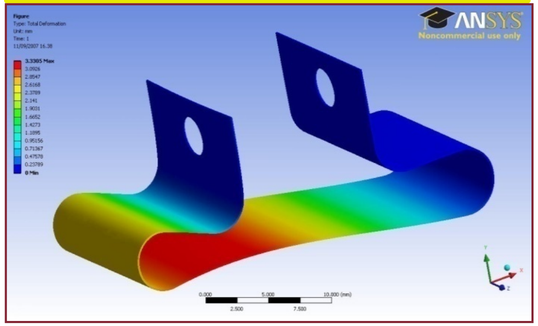
- DAΦNE new bellows

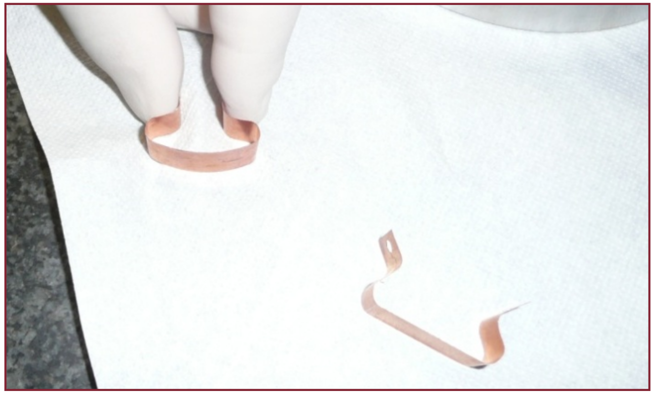






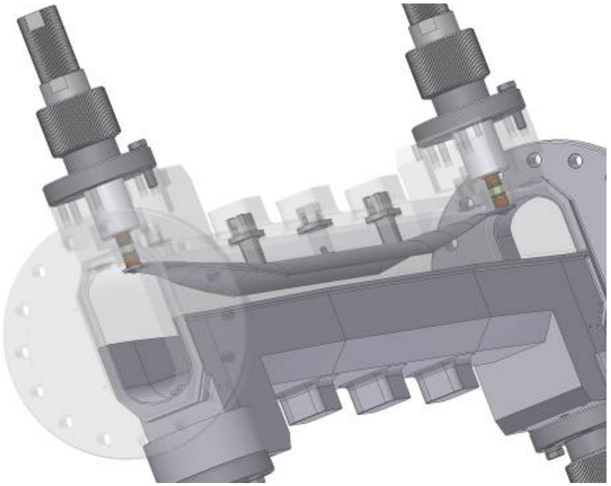
- Shielding based on Be-Cu Ω strips 0.2 mm thickness





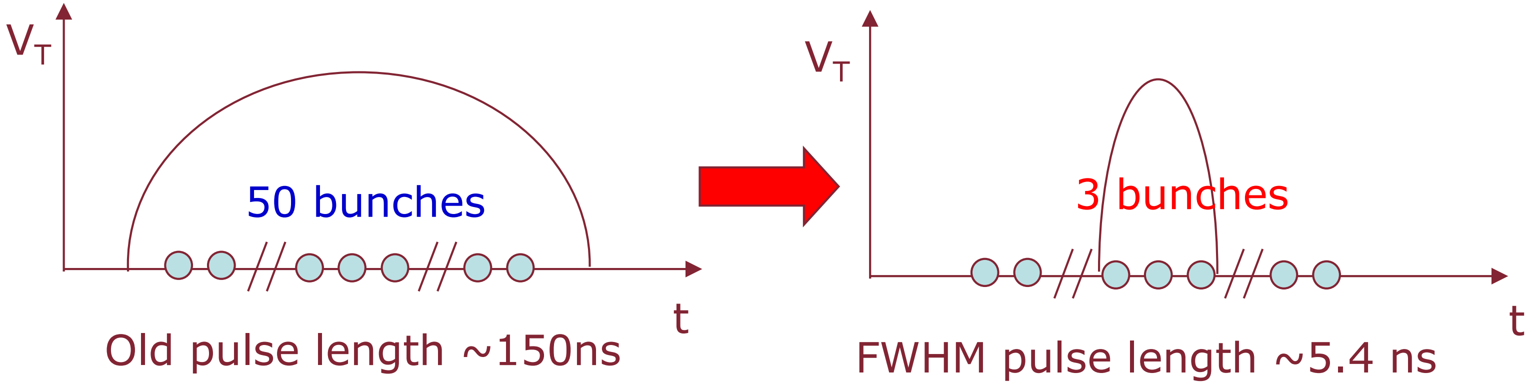
Measures to overcome heating and reduce impedance

- DAΦNE new injection kickers



M. Zobov, CERN-LNF Meeting at LNF INFN, (2016)

New injection kickers with 5.4 ns pulse length to reduce perturbation on stored beam



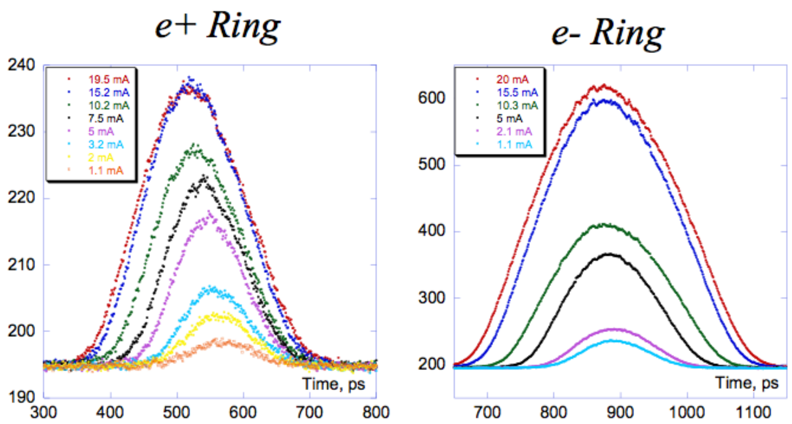
Typical instabilities in lepton factories

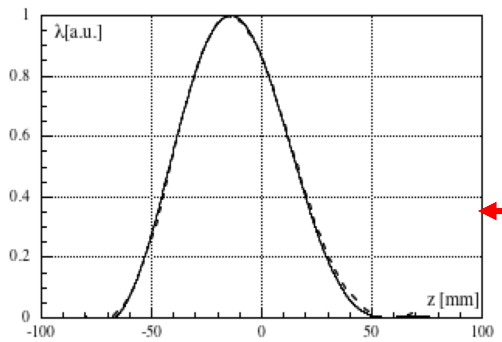
- The wake potentials given by numerical codes depend on the charge distribution of the bunch
- For beam dynamics simulations it is necessary to know the Green function
- For a lepton machine this task could be hard to achieve due to the small bunch length
- Different approaches are used:
  - Approximate the total coupling impedance by a broadband resonator (or RL) model (see e.g. KEKB, Y. Cai et al., PRST-AB 12, 061002, 2009)
  - Use a bunch as short as possible and consider it as wake field (see, e.g. DAΦNE, M. Zobov et al., LNF-95/041 (P), 1995)
  - Approximate the total impedance by an expansion over $\sqrt{\omega}$ (see, e.g. PEP-II, K. Heifets et al., SLAC PUB 6989, 1996)
  - Other approaches: see, e.g. M. Migliorati et al., PRST-AB 18, 031001, 2015 or B. Podobedov, G. Stupakov, PRST-AB 16, 024401, 2013

Typical instabilities in lepton factories

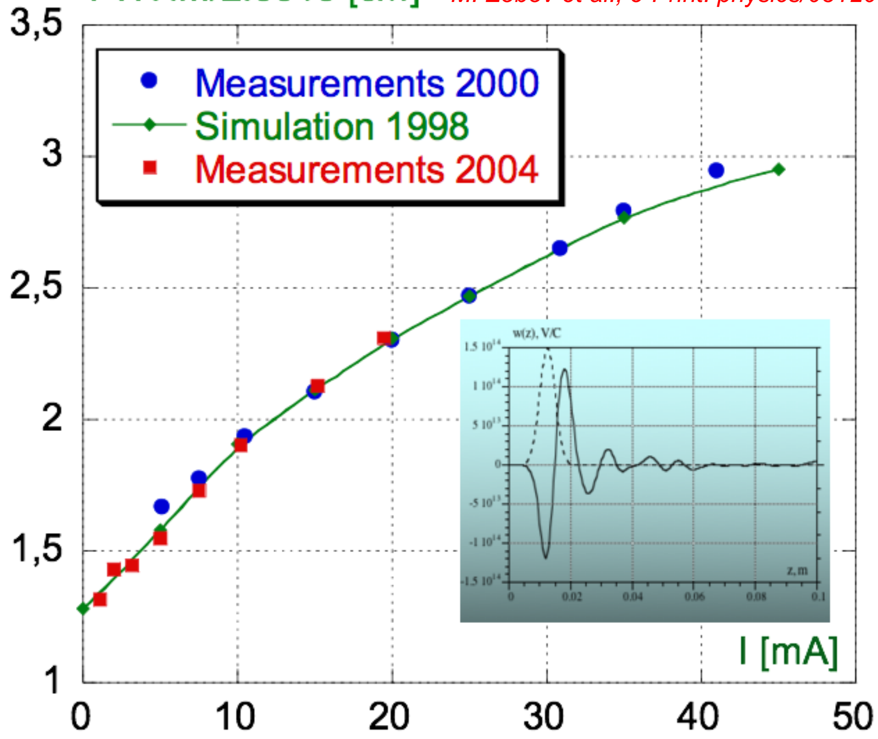
- Bunch lengthening and potential well distortion in DAΦNE

Typical Measured Bunch Distributions



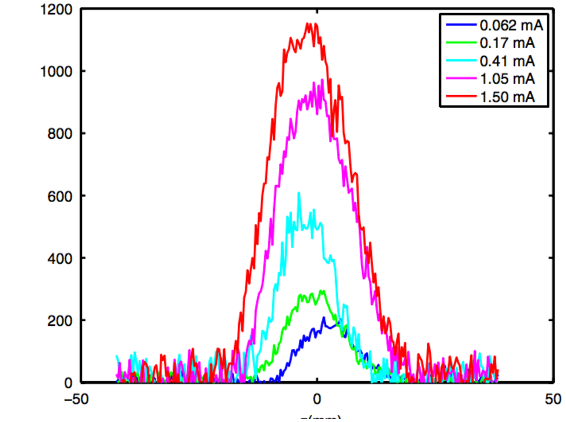


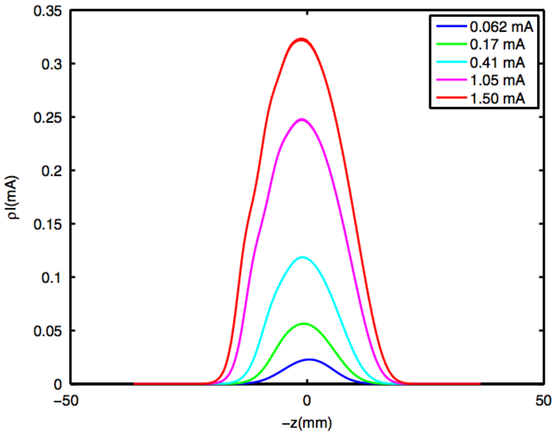
Comparisons with simulations



Typical instabilities in lepton factories

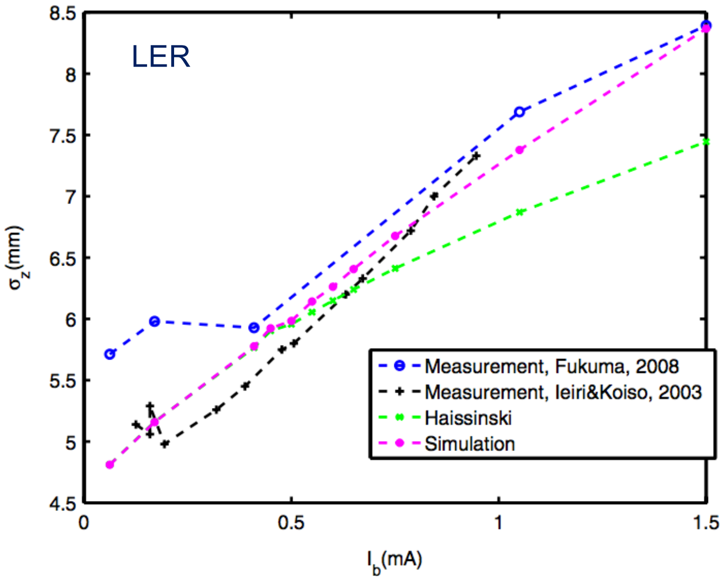
- Bunch lengthening and potential well distortion in KEKB

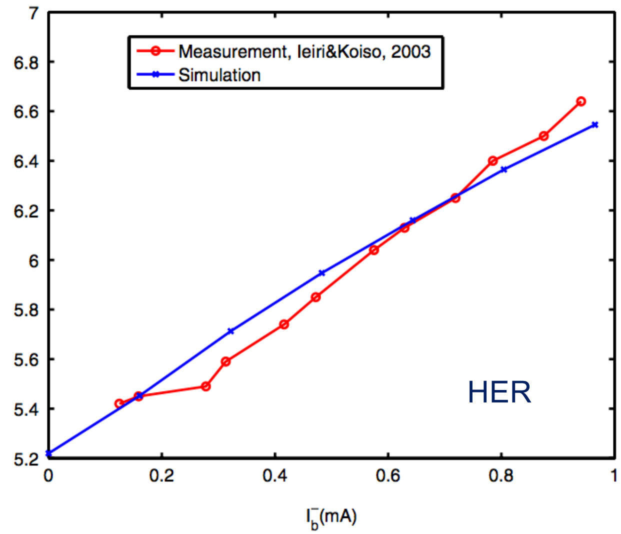




Measured and Haissinski distributions at various positron bunch currents in the LER of KEKB

Y. Cai et al., PRST-AB 12, 061002 (2009)





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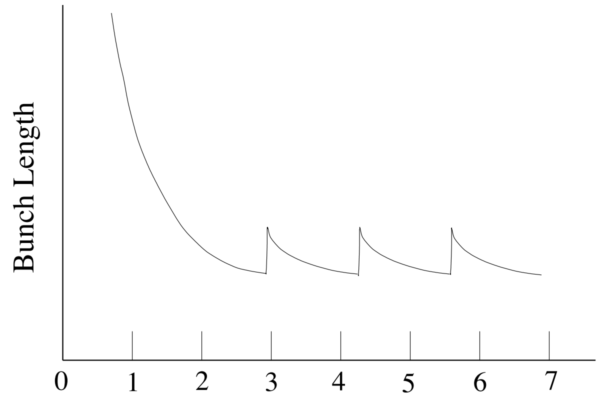
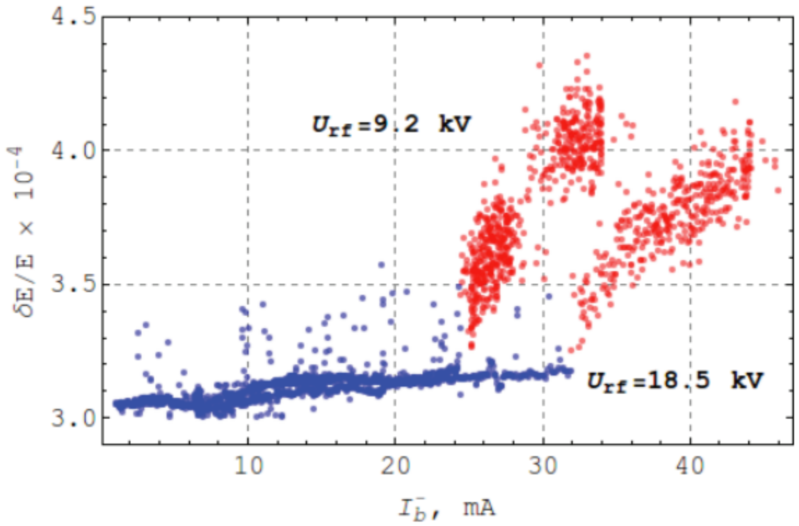
Typical instabilities in lepton factories

- Microwave instability: sawtooth instability of the SLAC Damping ring

K. Y. Ng, Physics of intensity dependent beam instabilities

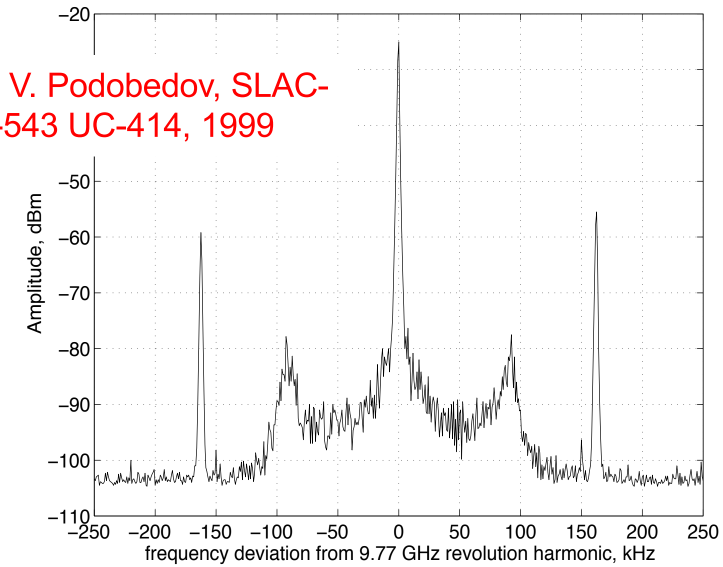


- Microwave instability observed in VEPP-2000.



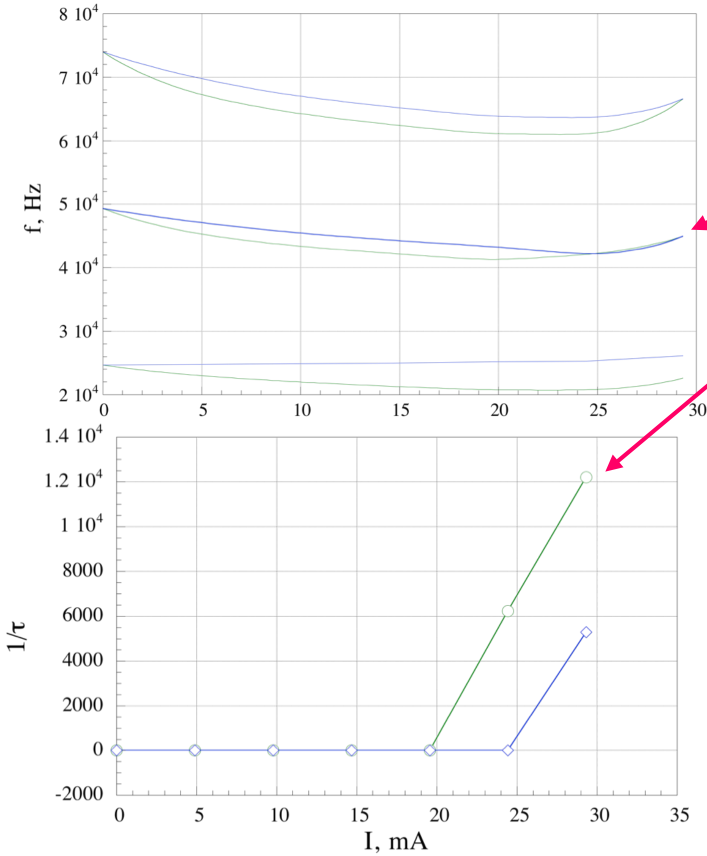
Y. Rogovsky, RuPAC2016, THPSC060

B. V. Podobedov, SLAC-R-543 UC-414, 1999



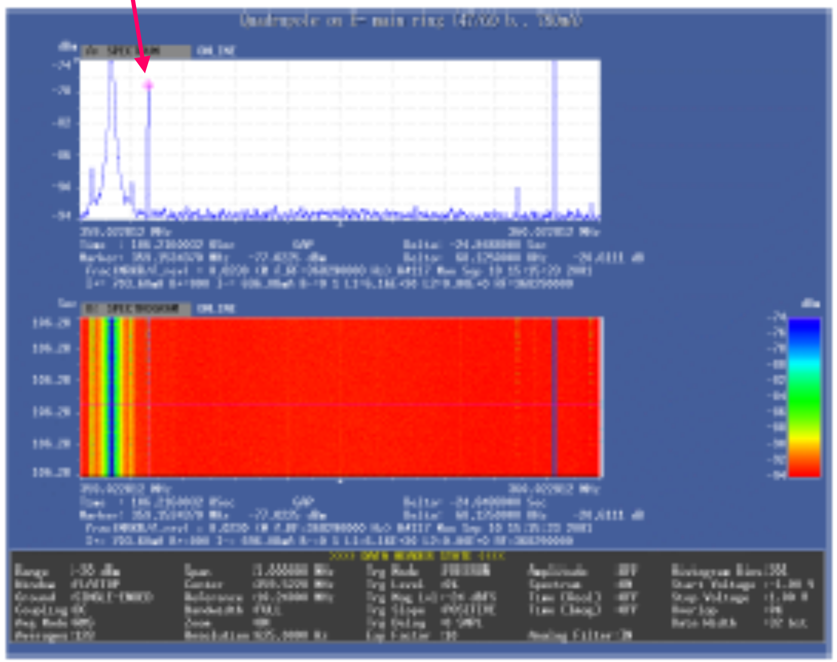
Typical instabilities in lepton factories

- Microwave instability: DAΦNE quadrupole instability in the positron ring



$2f_s$

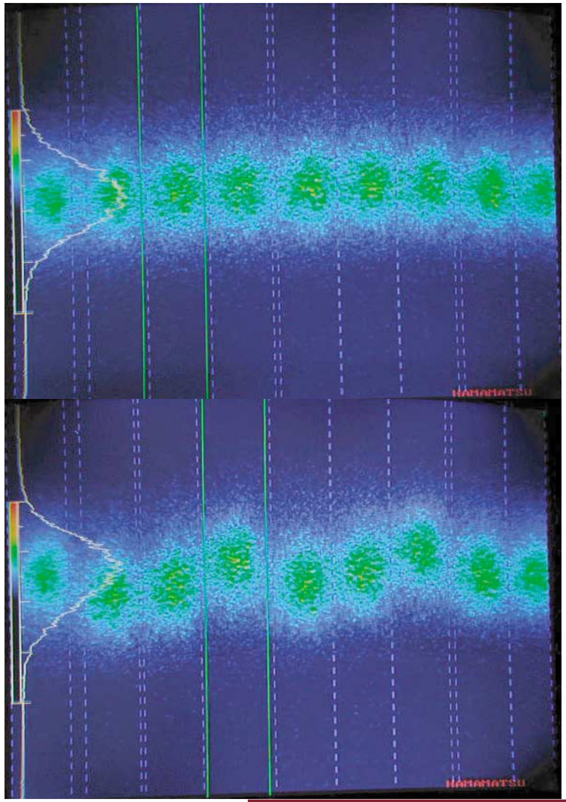
M. Zobov et al., e-Print: physics/0312072



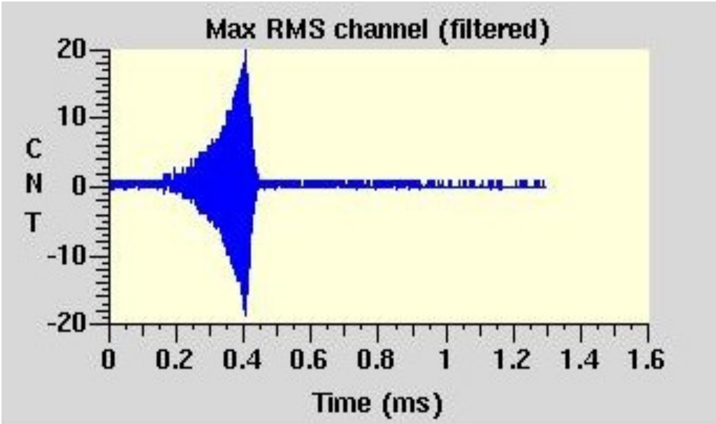
Typical instabilities in lepton factories

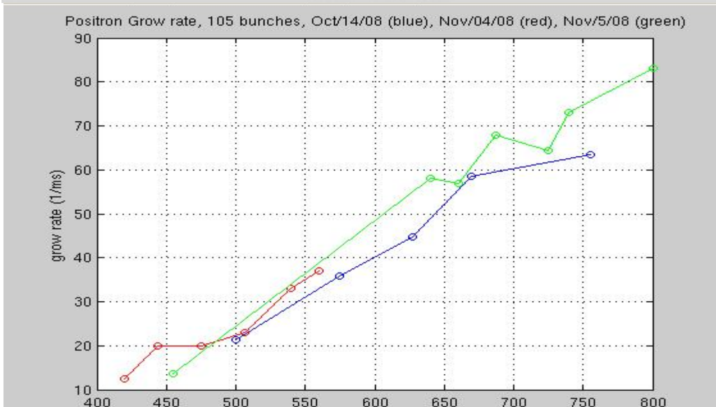
- Coupled bunch instabilities

Time domain: images of stable and unstable positron bunches in CESR:
R. Holtzapple et al., PRST-AB 5, 054401 (2002)



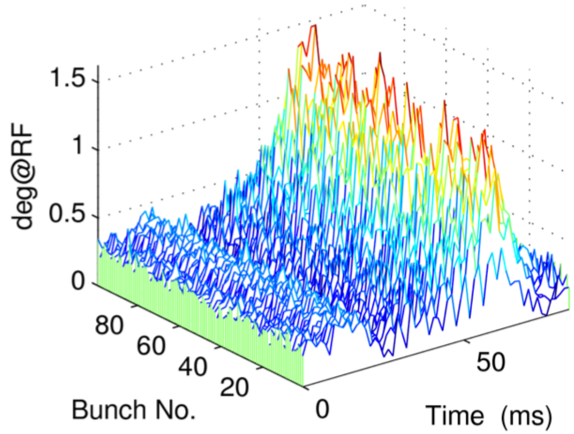
DAΦNE: horizontal oscillations of positron beam with 500mA



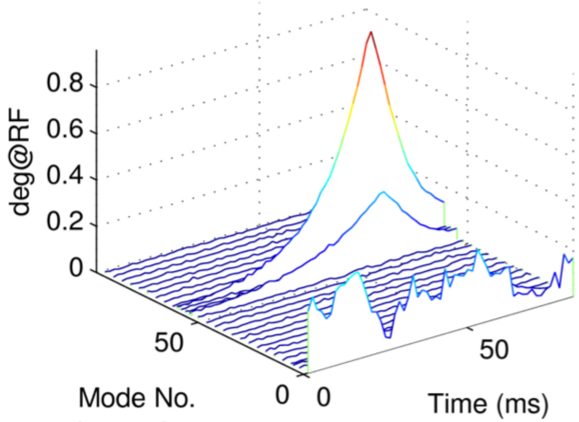


Courtesy of A. Drago

a) Osc. Envelopes in Time Domain



b) Evolution of Modes



Freq. domain: Y. Junhui et al., Longitudinal Instabilities in BEPC-II, 2008

Typical instabilities in lepton factories

- The electron cloud instabilities are the most severe ones and among the principal factors limiting the performance of the lepton factories.
- For example, the maximum positron beam current stored in DAFNE is substantially lower than the circulating electron beam current. In order to cope with the e-cloud effects, PEP-II and KEKB, for example, had to increase the number of empty buckets between successive bunches.
- During their operation all the lepton colliders implemented different techniques to mitigate the electron cloud effects. In addition to the use of feedbacks, solenoids, particular bunch filling schemes with empty buckets, PEP-II employed the TiN vacuum chamber coating. This, certainly, helped to accumulate the world record current of 3.21 A in the PEP-II positron ring.
- Considering the importance of the electron cloud suppression, SuperKEKB collider, that is under commissioning in Japan, will use almost all the know mitigation techniques.

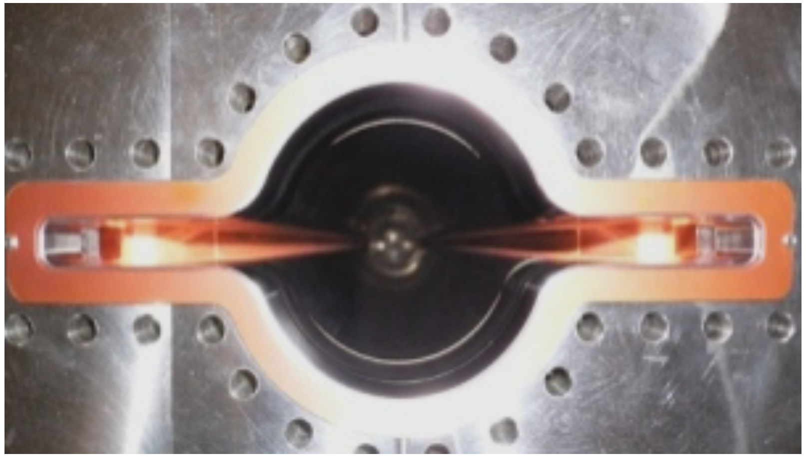
Instability cures

Many similar and several different mitigation techniques are used to suppress the e-cloud instability

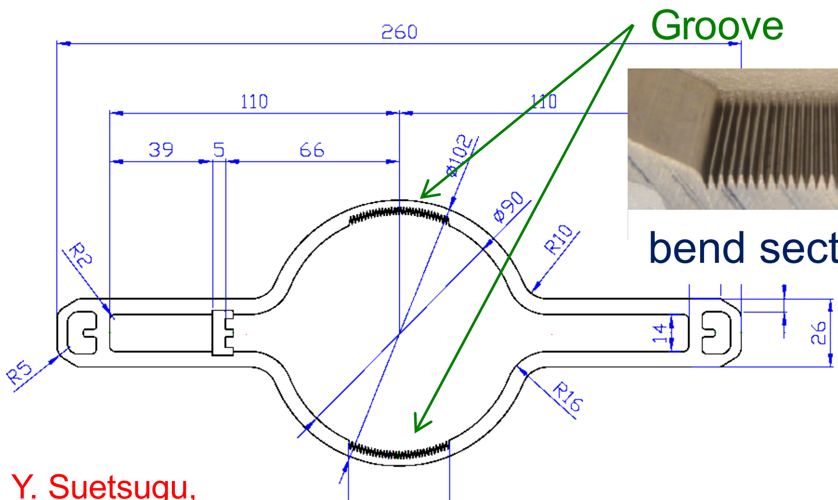
Technique	DAΦNE	PEP-II	KEKB	SuperKEKB
Empty gaps	No	Yes	Yes	Yes
Feedback Systems	Yes	Yes	Yes	Yes
Solenoids	Yes	Yes	Yes	Yes
Coatings	No	Yes	No	Yes
Antechamber	Yes	Yes	No	Yes
Grooved Surface	No	No	No	Yes
Clearing Electrodes	Yes	No	No	Yes
Permanent magnets	No	No	No	Yes

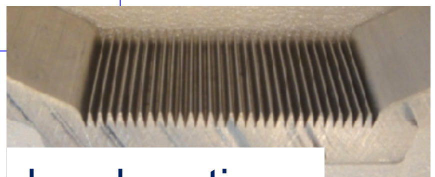
Instability cures

Examples from SuperKEKB



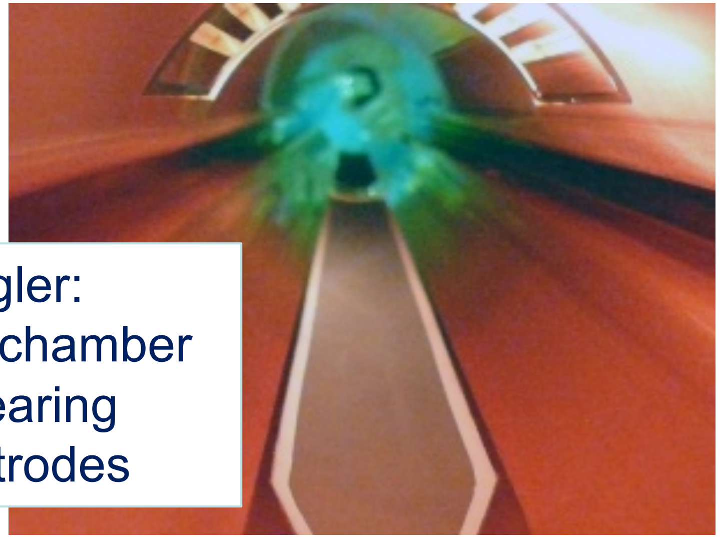
Drift and bend sections: antechamber + TiN coating





bend sections

Drift section: solenoid



Wiggler: antechamber + clearing electrodes

Y. Suetsugu, ECLOUD'10

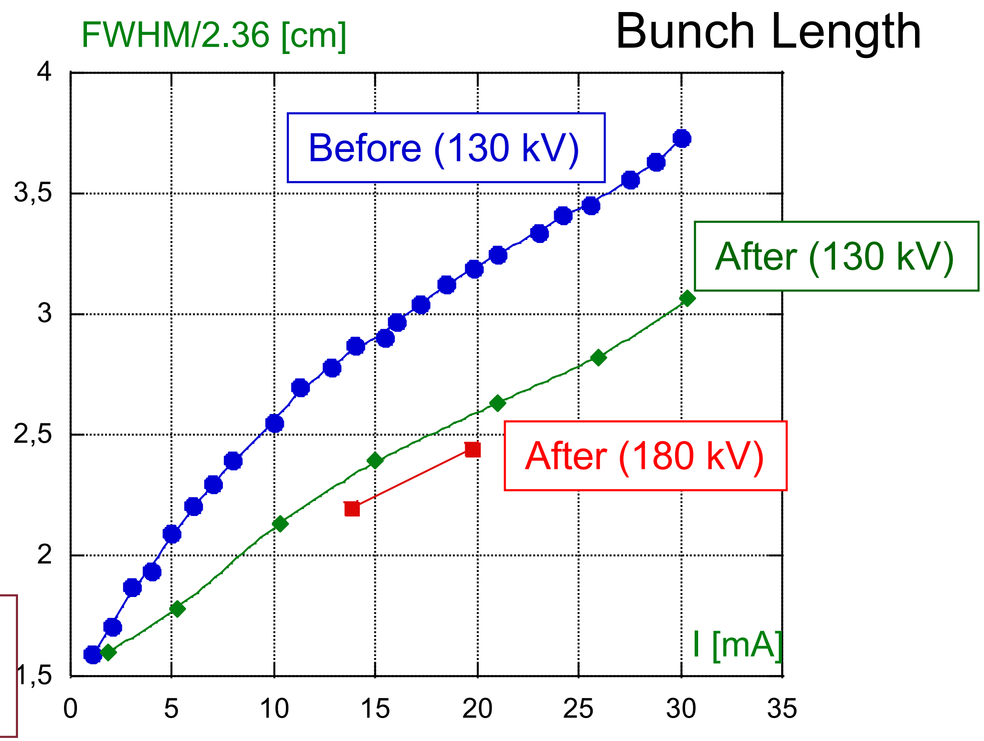
Instability cures

- Impedance reduction

The microwave instability in DAΦNE electron ring was first cured with longitudinal feedback system in a special manner by kicking the tail and the head of bunches in a different way

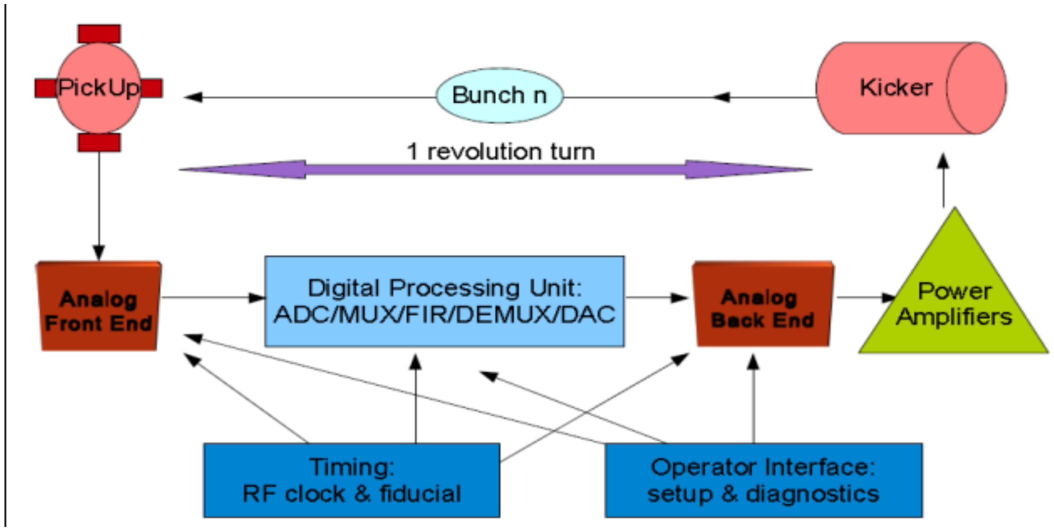
The problem was solved completely by removing the ion clearing electrodes that gave a substantial contribution into the beam coupling impedance. In addition, the bunch became shorter.

M. Zobov et al., Journal of Instrumentations 2, P.08002, 2007



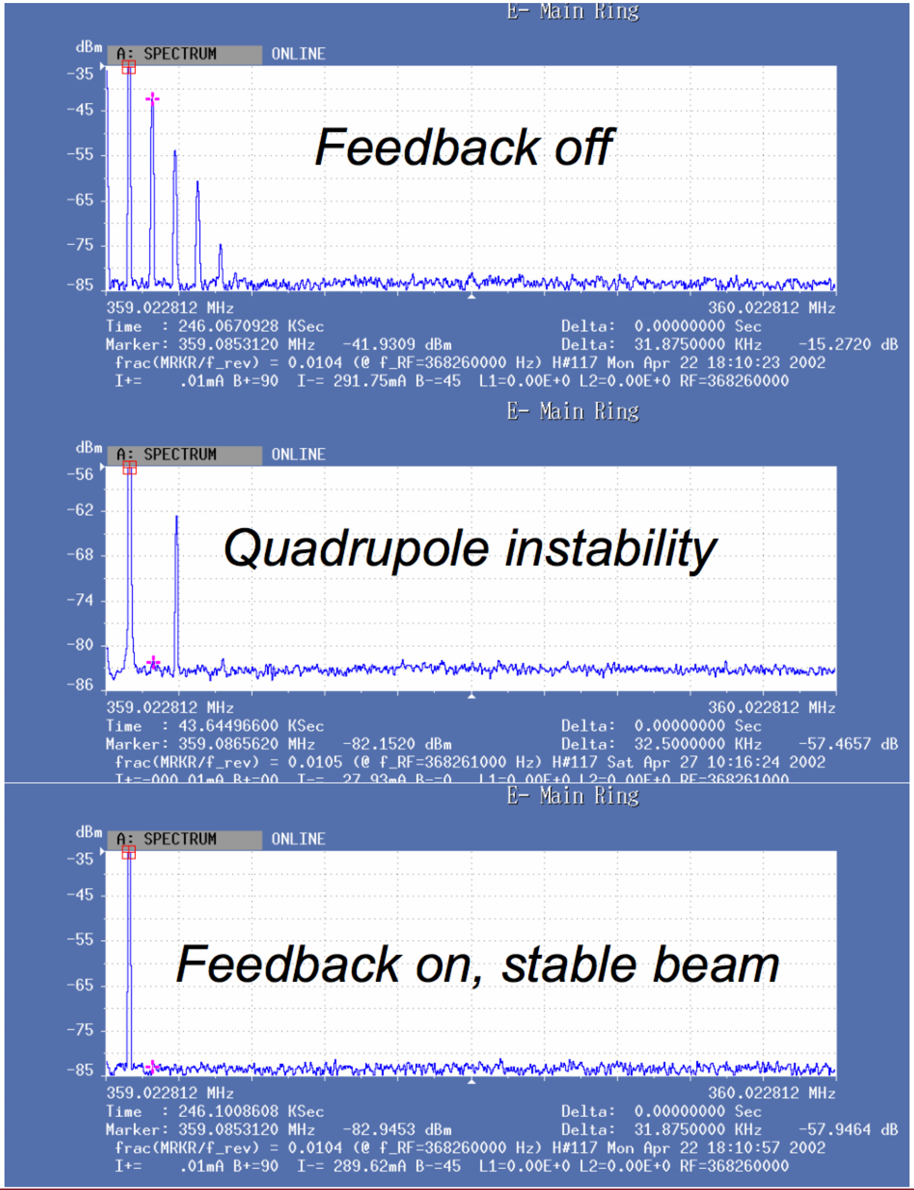
Instability cures

- Bunch-by-bunch feedback systems for coupled bunch instability to damp:
  - Dipole mode instability
  - Quadrupole mode instability



Courtesy of A. Drago

A. Drago et al., PRST-AB 6, 052801 (2003)



Conclusions

- The present generation of lepton factories has been very successful, achieving or even exceeding their design luminosities.
- One of the main ingredients to reach this exciting result was the stable collision of very intense multibunch beams.
- This has become possible due to the careful design of the low impedance vacuum chambers and to the adopted cures of beam instabilities.
- This experience is believed to be very useful for designing and commissioning of the future particle colliders.