Workshop of Beam Instabilities
BNL June 28 - July 1, 199

Beam Instabilities in the JHF Synchrotrons

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Beam Instabilities in the JHF Synchrotrons

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JHF (Japan Hadron Facility) ,KEK

===> "Joint Project"

Neutron Science Project, JAERI

Accelerator Complex of the Joint Project

(1) 400-MeV linac

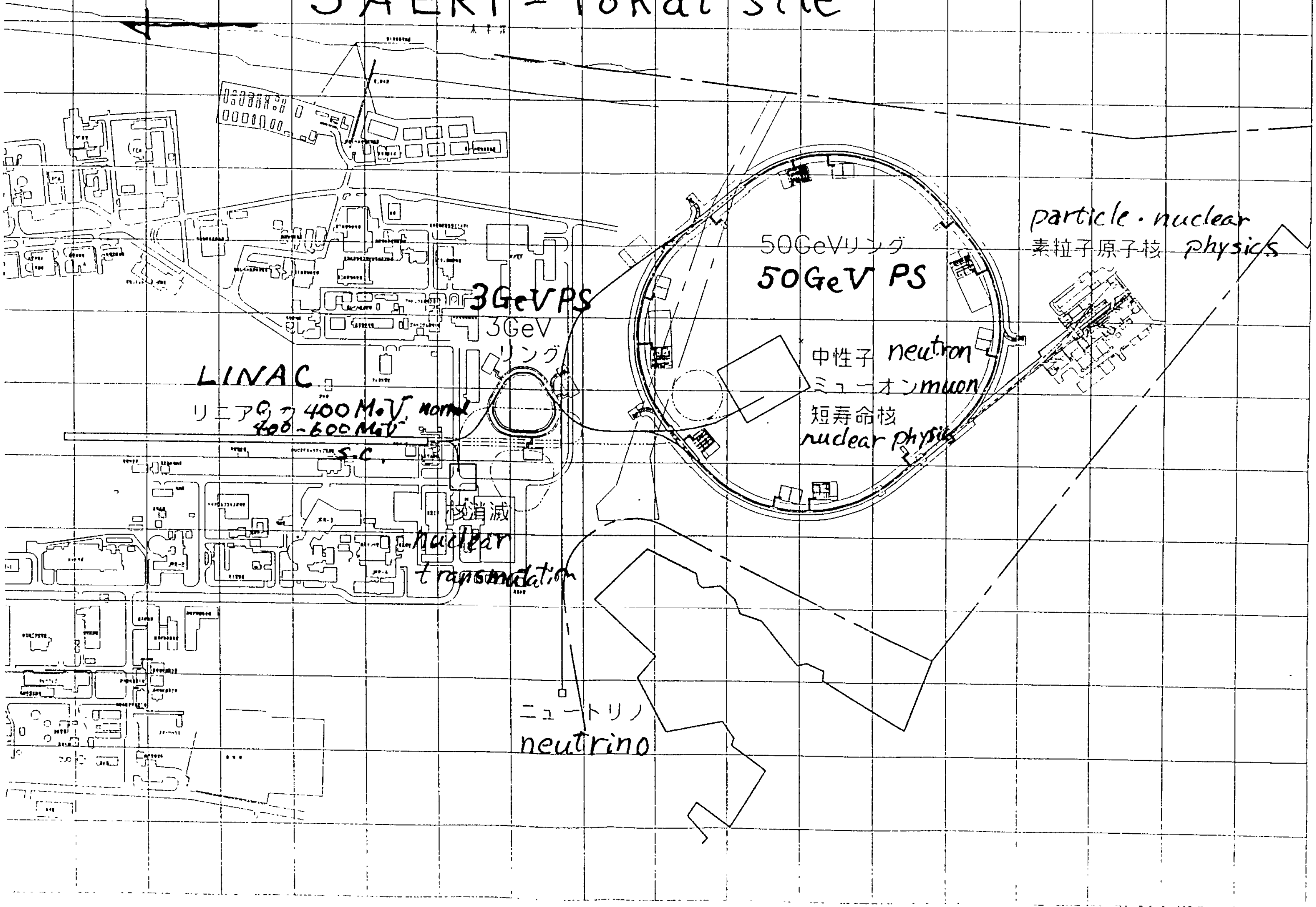
(2) 3-GeV Booster Synchrotron

$N=8\times10^{13}$ppp, 25Hz, $I=333\mu A$

(3) 50-GeV Main Synchrotron

$N=3.2\times10^{14}$ppp, 0.3Hz, $I=15.6\mu A$

JAERI - Tokai site



50-GeV Main Ring — General

Yoshiharu Mori (KEK-Tanashi)

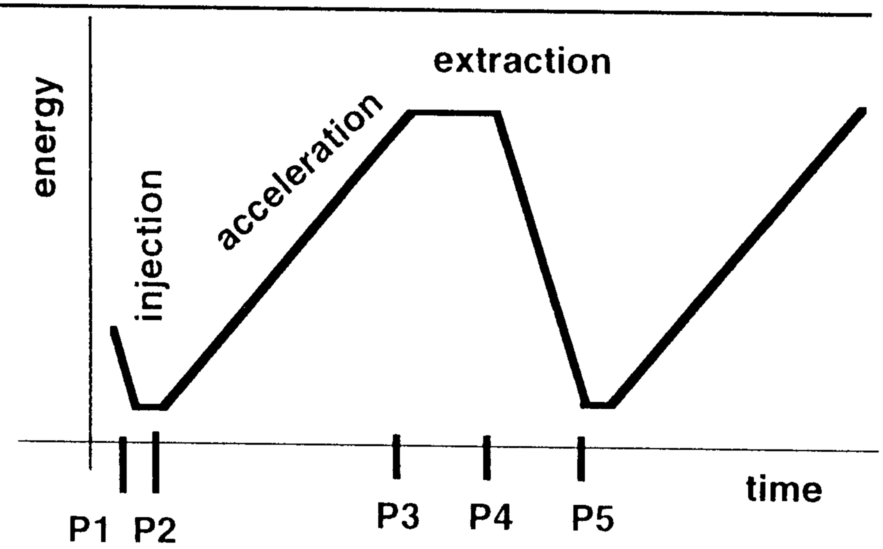
$$\alpha = \frac{1}{C}\oint \frac{D(s)}{\rho(s)} ds$$

Features

- a) Imaginary g_t lattice
  - ρ- modulation
    - module : 3-cell DOFO
- b) Small beam loss at slow beam extraction
  - beam loss < 1%
- c) RF system with MA cavity
  - high gradient : >50kV/m
  - low R/Q : ~100Ω/gap
- d) Magnet power supply
  - No-generation of reactive power
  - Converter with IGBT : model , P=1MW

Parameters

Circumference	1445 m
Average Radius	229.979 m
Injection Energy	3 GeV
Extraction Energy	50 GeV
Particle Per Pulse	2 x 10^{14}
Revolution Period	
at Injection	4.9629 ms
at Extraction	4.8209 ms
Repetition Rate	0.3 Hz
Injection	0.12 s
Acceleration	1.9 s
parabola	0.1 s
linear	1.7 s
parabola	0.1 s
Slow Extraction	0.7 s
Decreasing Field	0.7 s
Average Current	9.4 mA
Circulating Current	
at Injection	6.86 A
at Extraction	7.06 A
Bunching Factor	
at Injection	0.273
at Extraction	0.038



P1 - P2(injection)	0.12 s
P2 - P3(acceleration)	1.9 s
P3 - P4(extraction)	0.7 s
P4 - P5	0.7 s
total	3.42 s
slow extraction of 50GeV	
duty factor	0.20
average current	9.4μA

Answers to the Comments and Questions by the Committee

1. upgrade and commissioning issues

	average beam current		repetition rate		duty	intensity
	slow	fast	slow	fast		
design	9.4μA	11.8μA	0.29Hz	0.37Hz	20%	2×10^{14} ppp ($\nu_{inc}=0.08$)
bar. buck.	26μA	31.6μA	0.27Hz	0.33Hz	18%	6×10^{14} ppp ($\nu_{inc}<0.24$)
high ramp.	52μA	82.1μA	0.53Hz	0.85Hz	37.4%	6×10^{14}ppp

Beam Instabilities and Impedance in the JHF 3-GeV and 50-GeV rings

KEK

Yong Ho Chin

December 9,1998
JHF Accelerator Advisory Committee Review

Outline

- Introduction
- Longitudinal
  - Single-bunch instability
    - Space charge
    - Inductance
    - Cavity fundamental
  - Multibunch Instability
    - Fundamental mode
    - Parasitic resonances
  - Stability in double RF system (3-GeV ring)
- Transverse
  - Single-bunch instability
    - Transverse mode-coupling instability
  - Multibunch instability
    - Resistive-wall
    - Kicker magnets
    - RF shieldings for ceramic chamber (3-GeV ring)
    - Choice of chamber material (50-GeV ring)
- Summary of the findings

Introduction

- Challenges of the 3-GeV and 50-GeV rings are

Store the very high beam currents stably.

- The circulating current

  = 4-7A at 3-GeV ring
  = 7A at 50-GeV ring

Main concerns are:

- Space charge impedance at injection (E_k=0.2GeV) in the 3-GeV ring
- Inductance at 50 GeV in the 50-GeV ring
- What is optimum Q-value?
  - Beam-loading effect
  - Coupled-bunch instability due to the cavity fundamental
  - Higher-order synchrotron modes (quadrupole, sextupole, etc.)
  - Coupled-bunch instability due to cavity parasitics
- Choice of chamber material (50-GeV ring)
- Ceramic chamber and its RF shieldings (3-GeV ring)

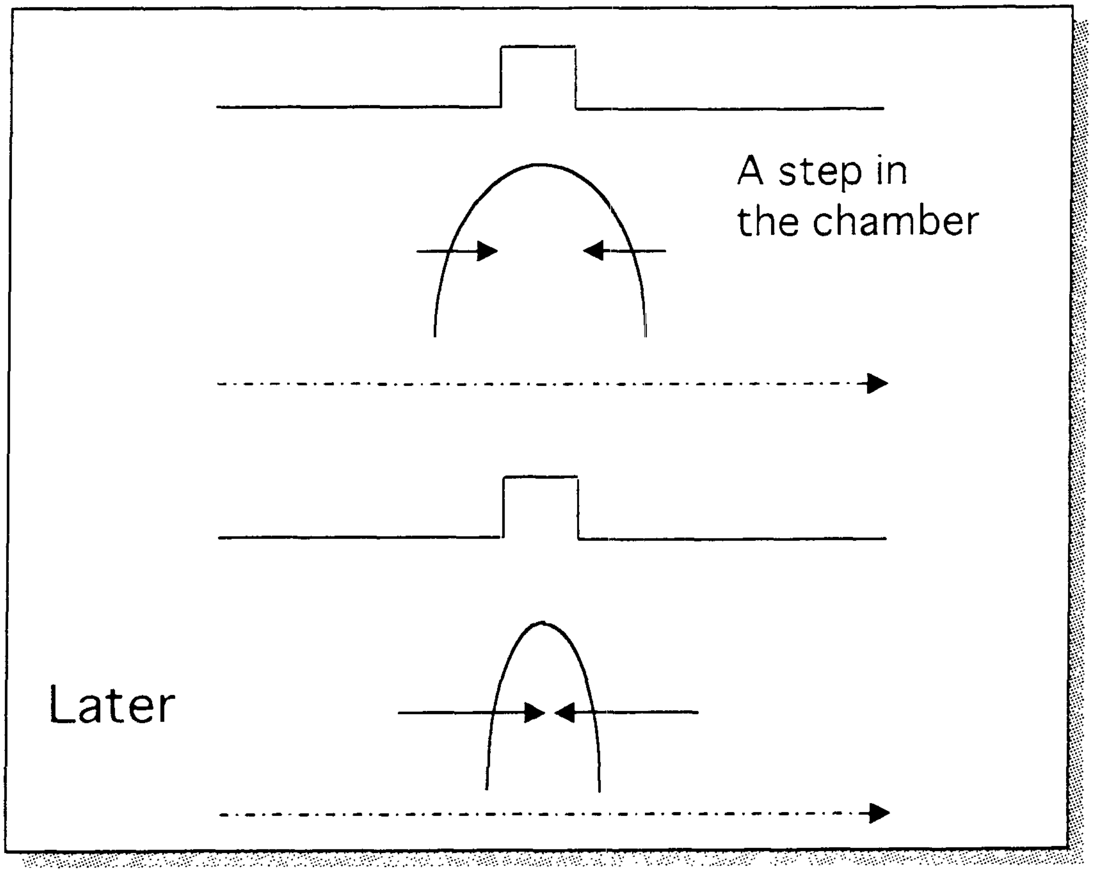
Main parameters of the 50-GeV ring

Injection energy,	3 GeV			
Circumference,	1445 m			
Harmonic number,	17			
Momentum compaction factor,	0.001			
Natural chromaticity,	20			
Horizontal tune,	21.80			
Circulating current,	6.86 A	(at 3 GeV)	7.06A	(at 50 GeV)
Slippage factor,	-0.057	(at 3 GeV)	-0.00134	(at 50 GeV)
Momentum spread, *	0.42 %	(at 3 GeV)	0.23 %	(at 50 GeV)
Rms bunch length in time, *	30 ns	(at 3 GeV)	4.2 ns	(at 50 GeV)
Bunching factor,*	0.27	(at 3 GeV)	0.038	(at 50 GeV)
Synchrotron tune,	0.003 4	(at 3 GeV)	0.0003	(at 50 GeV)
Loaded shunt impedance of the cavity fundamental,	14 kΩ			
Q-value of the cavity fundamental,	Variable (typically about 2)			
Resonant frequency of the cavity fundamental,	3.43 MHz			

* Values for the longitudinal emittance of 3eVs at injection

Longitudinal Single-Bunch Instability

- Main concerns are two types of instabilities:
  - Microwave instability
    - Increases the bunch length and momentum spread
  - Negative-mass instability
    - Driven by the ring inductance
    - Contracts the bunch until it collapses



- Keil-Schnell-Boussard criterion for the threshold impedance:

$$\left|\frac{Z_L}{n}\right| \le \frac{E\beta^2|\eta|}{eI_p}\left(\frac{\Delta p}{p}\right)^2_{FWHH}$$

  - E = the beam energy
  - β = the beam velocity divided by the speed of light
  - η = the slippage factor
  - I_p = the peak beam current
  - $(\Delta p/p)_{FWHH}$ = the full width momentum spread at half height

Numerically,

3-GeV ring		50-GeV ring $\varepsilon_L = 1eV\cdot s$	
$\left\|\frac{Z_L}{n}\right\| \le 420\Omega$	at 0.2 GeV	$\left\|\frac{Z_L}{n}\right\| \le 30\Omega$	at 3 GeV
$\left\|\frac{Z_L}{n}\right\| \le 6.6\Omega$	at 3 GeV	$\left\|\frac{Z_L}{n}\right\| \le 0.4\Omega$	at 50 GeV

Space Charge

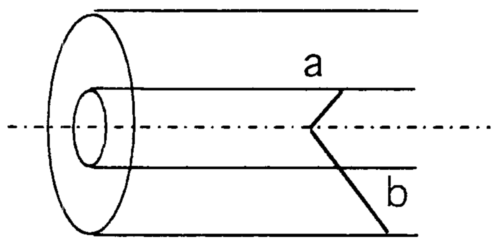
- At low energy, the space charge is the dominant source of the longitudinal broad-band impedance.

$$\left(\frac{Z}{n}\right)_{SC} = i\frac{g_0 Z_0}{2\beta\gamma^2}$$

where

$$g_0 = 1 + 2\ln\frac{b}{a}$$

~ 2.3



b~100mm (3-GeV)
~ 53mm (50-GeV)

Numerically,

3-GeV ring

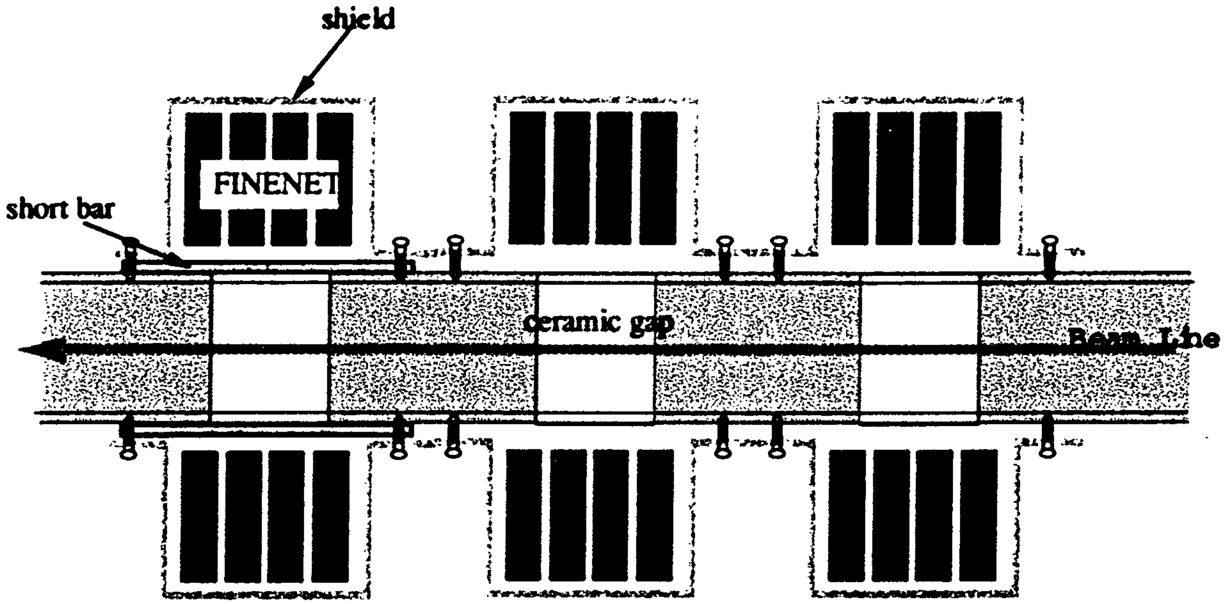
$$\left(\frac{Z}{n}\right)_{SC} \begin{cases} = 520\Omega & \text{at 0.2 GeV} \\ = 25\Omega & \text{at 3 GeV} \end{cases}$$

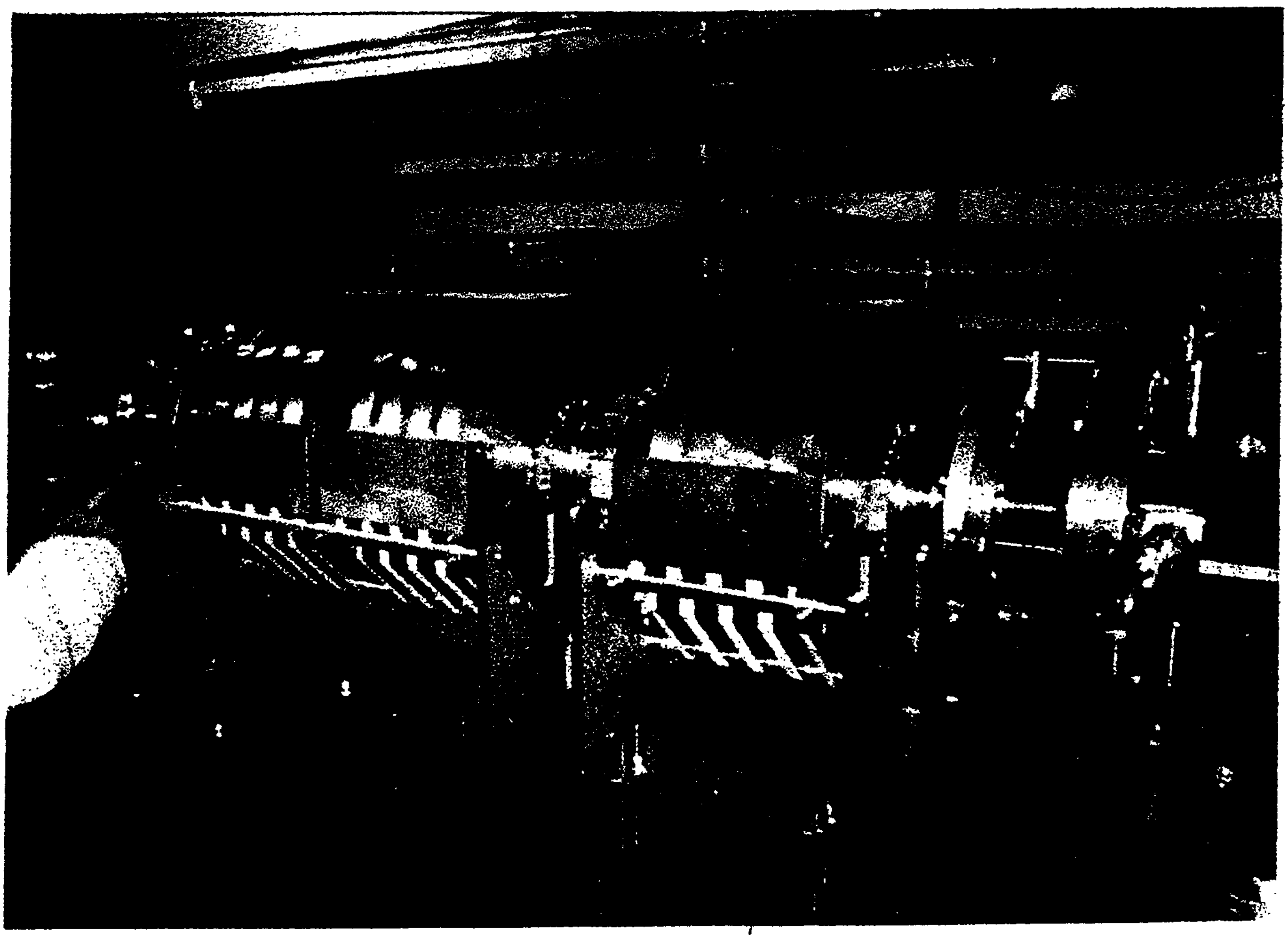
50-GeV ring

$$\left(\frac{Z}{n}\right)_{SC} \begin{cases} = 25\Omega & \text{at 3 GeV} \\ = 0.15\Omega & \text{at 50 GeV} \end{cases}$$

<u>Conclusion 1</u>
The space charge impedance exceeds the tolerance in the 3-GeV ring. It is better to reduce it by e.g., impedance tuner.

Impedance Tuner (KEK-PS)





Inductance

- In modern machines, the total inductance of the ring can be reduced to a few Ω or less by carefully designing the beamline components, such as the kicker magnets and steps in the beam chamber.

Conclusion 2.1
The inductive impedance is no problem in the 3-GeV ring.

- However, even by doing so, it will be very difficult to achieve the stability condition at 50 GeV in the 50-GeV ring:

$$\left|\frac{Z_L}{n}\right| \leq 0.4\Omega \quad \text{at} \quad \boxed{\varepsilon_L = 1eV \cdot s}$$

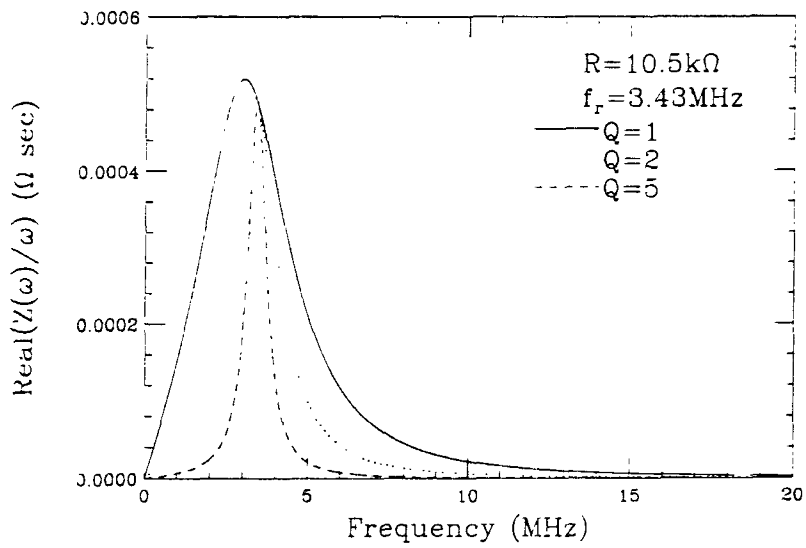
Conclusion 2.2
Blow up the longitudinal emittance to 3eVs before acceleration to 50 GeV in the 50-GeV ring

- Then, the stability condition at 50 GeV can be relaxed to

$$\left|\frac{Z_L}{n}\right| \leq 2\Omega \quad \text{at 50 GeV and} \quad \boxed{\varepsilon_L = 3eV \cdot s}$$

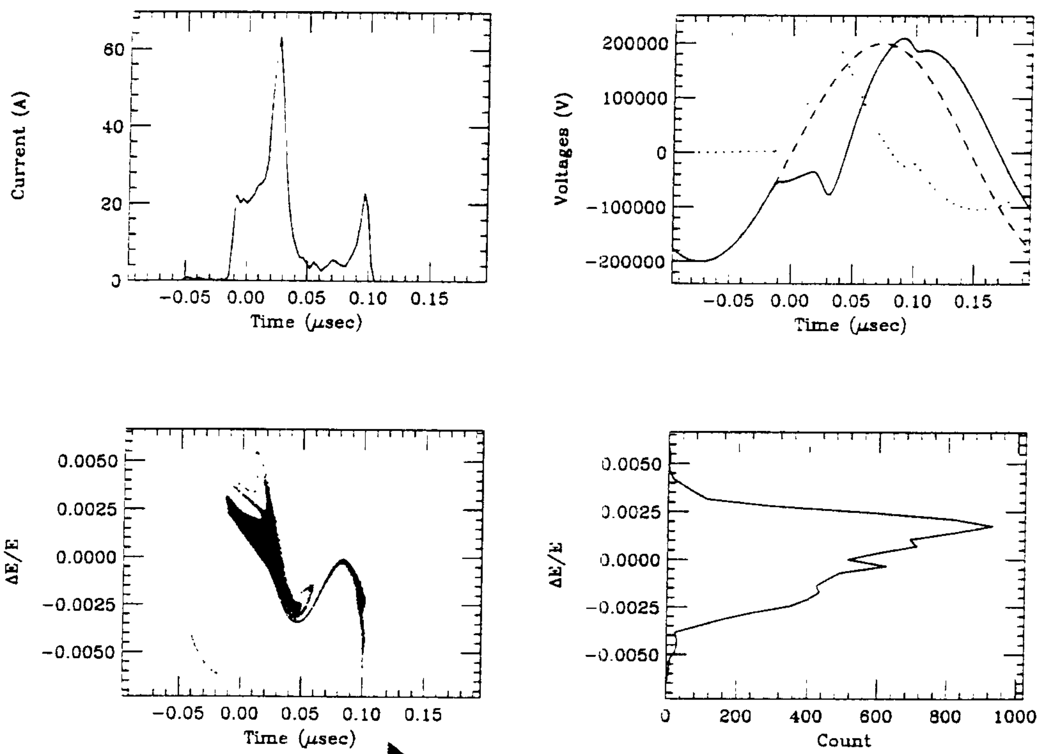
Cavity Fundamental

- Main concern is the beam-loading effect:
  - Distortion of the RF bucket
  - Spill-out of particles from the bucket
- When a low-Q cavity (Q ~1) is used, higher-harmonic components of the beam-induced voltage can produce a strong nonlinear fields inside the RF bucket.



- The beam-loading effect can be compensated by a cavity feedback
  - But, it needs a wideband RF amplifier

2.5ms later



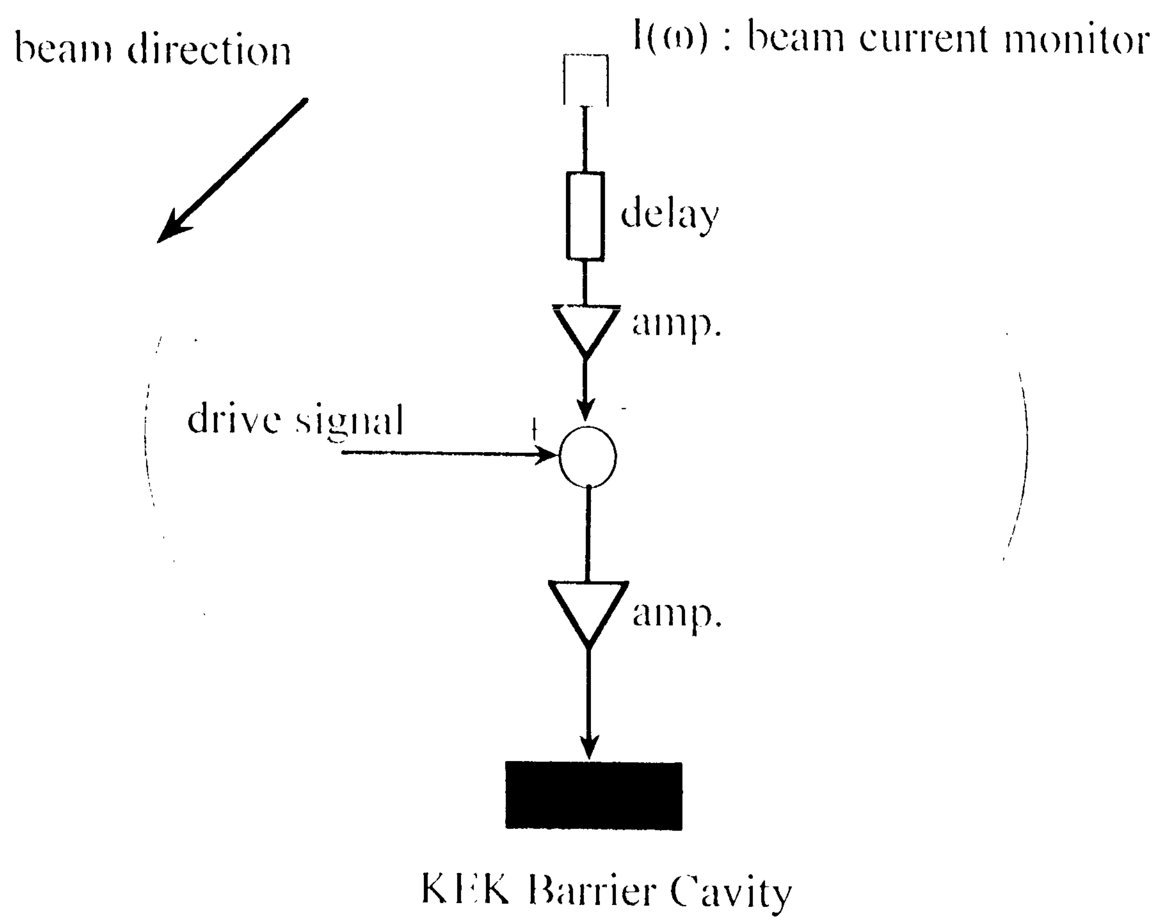
Large spill-out of particles

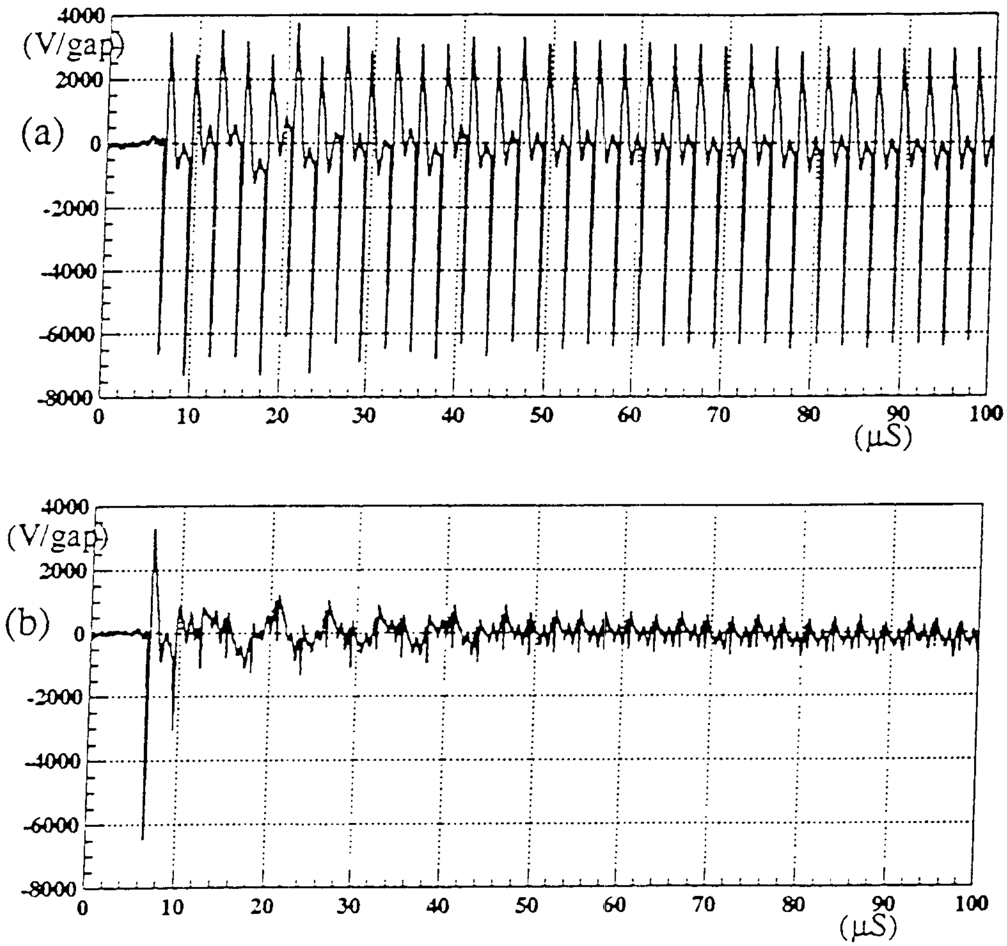
R=10.5 kΩ, Q=1, no beam-loading compensation on (MA cavity)

Conclusion 3.1

Beam-loading compensation is needed for stable operation at present impedance of R=10.5kΩ, regardless of Q-value (1 ~ 2) in the 3-GeV ring, unless the shunt impedance is reduced to below 5kΩ, and Q-value is increased to larger than 2.

Feedforward Compensation



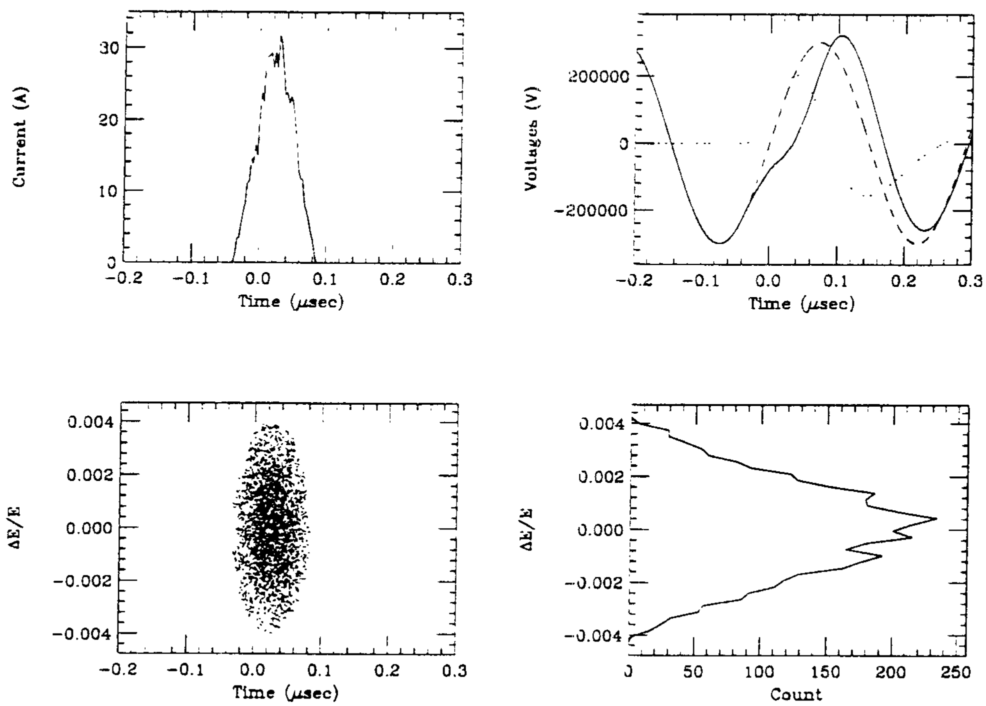

4000
(V/gap)
2000
(a)
0
-2000
-4000
-6000
-8000
0
10
20
30
40
50
60
70
80
90
100
(μS)
4000
(V/gap)
2000
(b)
0
-2000
-4000
-6000
-8000
0
10
20
30
40
50
60
70
80
90
100
(μS)

Conclusion 3.1

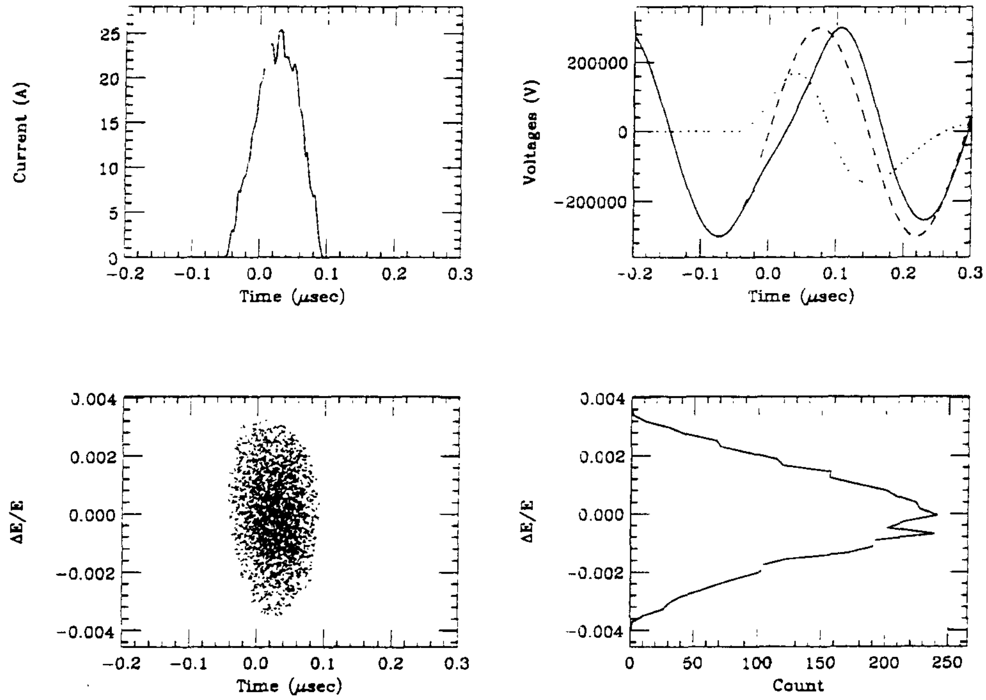
Beam-loading compensation is needed for stable operation at present impedance of R=10.5kΩ, regardless of Q-value (1 ~ 2) in the 3-GeV ring, unless the shunt impedance is reduced to below 5kΩ, and Q-value is increased to larger than 2.

50-GeV Ring at Injection

- Simulation results done by ECLIPS code
  - Loaded shunt impedance = 14 kΩ (gap voltage=10 kV)
  - No beam-loading compensation as the worst-case scenario



Phase space distribution before wake fields are turned on



Phase space distribution at 100 ms after wake fields are turned on.

- Only a small widening of bunch distribution
- No particle loss found
- The phase shift of 40 degrees should be compensated by tuning of the RF phase

Conclusion 3.2
No beam-loading compensation is needed at injection in the 50-GeV ring. But, (continued to the next page)

50-GeV Ring at 50 GeV

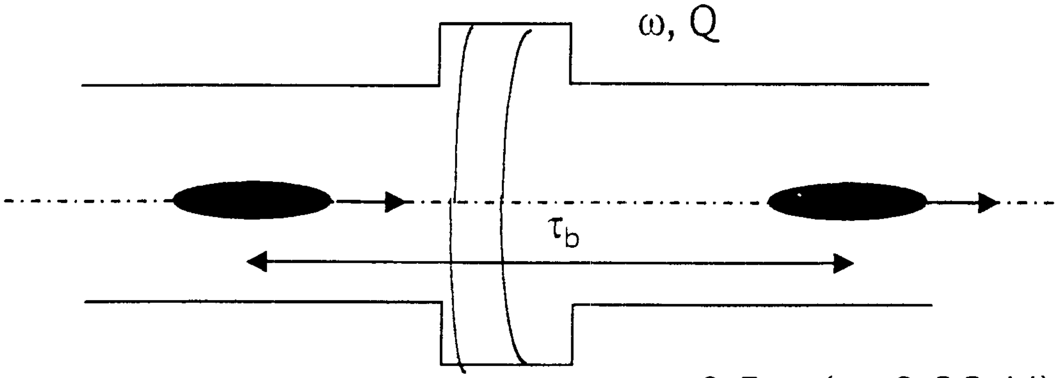
- The stability condition at 50 GeV (or even at lower energy) is very tight:

$$\left|\frac{Z_L}{n}\right| \leq 2\Omega \quad \text{at 50 GeV and} \quad \boxed{\varepsilon_L = 3eV \cdot s}$$

- Beam-loading due to cavities should and will be compensated during acceleration to avoid a blow-up of energy spread.
- RF is then shorted and turned off at 50 GeV within several ms for debunching to avoid a blow-up of energy spread at the flat top.

Longitudinal Multibunch Instability

- Different bunches can interact to each other through wake fields deposited in high-Q resonant structures.



τ_b=0.5μs (at 0.2GeV)
=0.3μs (at 3 GeV)

- Wake fields decay before the next bunch arrives by a factor of

$$\exp(\tau_b \frac{\omega}{2Q})$$

  - For an ample decay,

$$\tau_b \frac{\omega}{2Q} \geq 1 \longrightarrow \quad Q \leq 8 \text{ at 0.2 GeV}, \quad Q \leq 5 \text{ at 3 GeV}$$

($\omega = 2\pi$x6MHz)

Low-Q wake fields decay quickly

- Growth rate formula

$$\tau_m^{-1} = \frac{\eta e I_c}{\beta^2 \omega_s \sigma_\tau^2 E T_0} \sum_{p=-\infty}^{\infty} \frac{Z(\omega')}{\omega'} h_m(\omega')$$

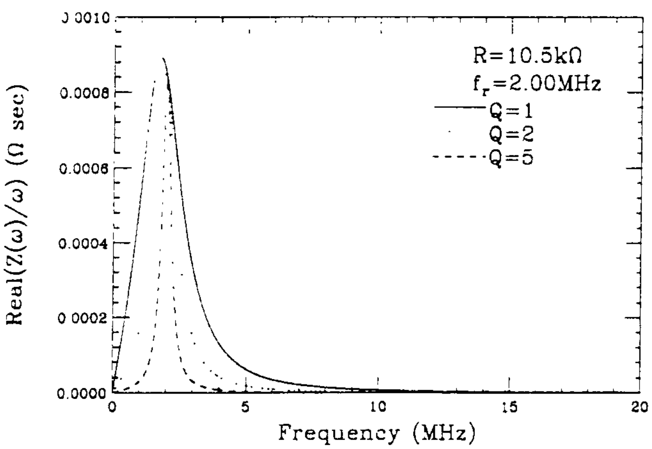
where

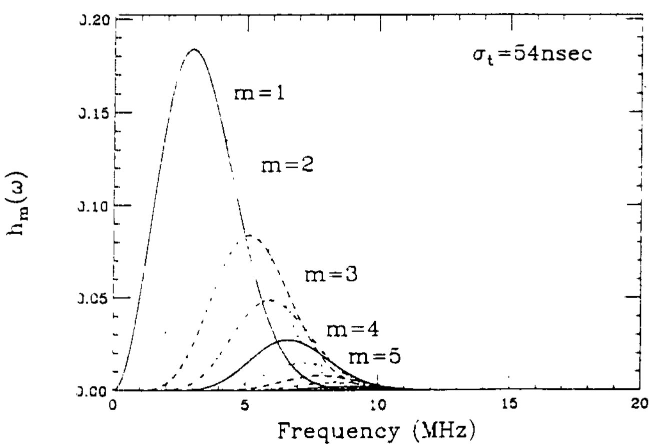
Synchrotron mode number

$$h_m(\omega') = \frac{1}{(m-1)!}\left(\frac{\sigma_\tau^2 \omega'^2}{2}\right)^m \exp(-\sigma_\tau^2 \omega'^2)$$

$$\omega' = (ph + \mu)\omega_0 + \omega_s$$

Coupled-bunch mode number





Low-Q wake fields excite higher-order synchrotron modes more

- Hofmann's stability condition (Landau damping included):

$$\tau^{-1} \le \frac{\Delta\omega_s}{4}$$

$\Delta\omega_s$=synchrotron frequency spread

Numerically,

3-GeV ring $\tau^{-1}\begin{cases}\le 900\,Hz \\ \le 12\,Hz\end{cases}$ at 0.2 GeV / at 3 GeV

50-GeV ring $\tau^{-1} \le 100\,Hz$ at 3 GeV (where the instability is strongest)

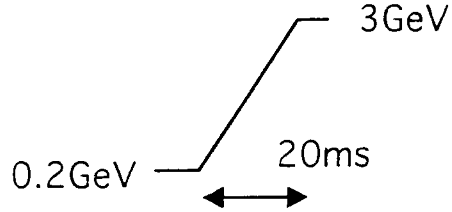
- In this method, the tolerance at 3 GeV in the 3-GeV ring becomes even slower than the repetition rate of 25 Hz (continued to the next page)

- A larger growth rate can be tolerated in the 3-GeV ring if a beam is extracted before the instability grows too much.

4 e-folding time is OK in 20ms

↓

$\tau^{-1} \le 200Hz$ at any energy



- Hereafter, we consider only the fastest-growing coupled-bunch mode.

- When the Q-value is more than 2, the most stable fundamental frequency becomes almost a unique function of the beam energy.

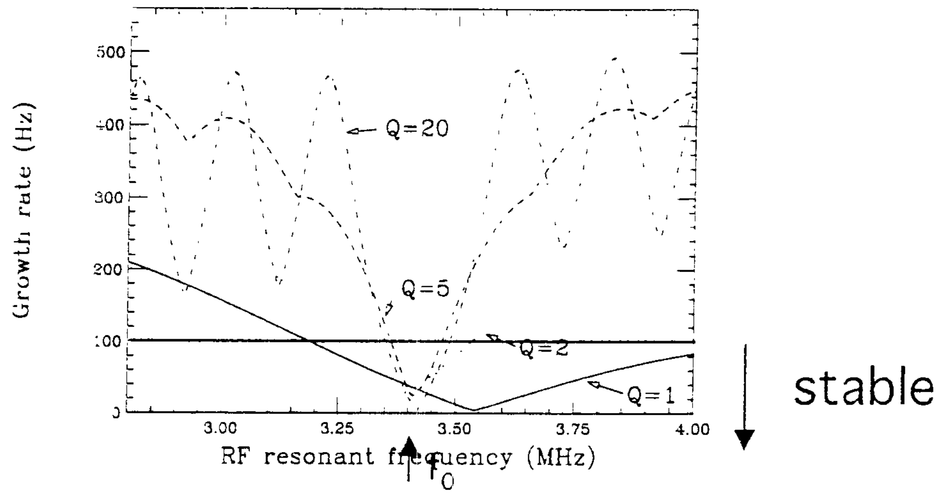
↓

Easier programming of the cavity detuning beforehand

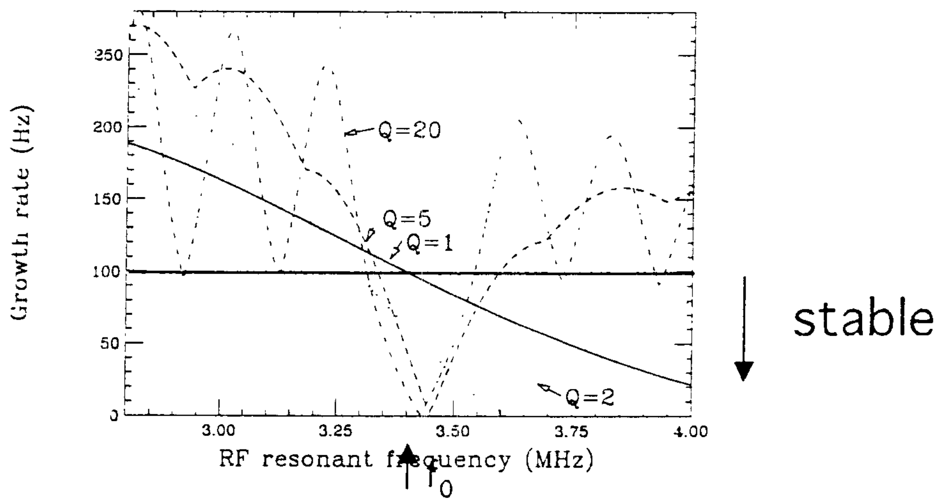
Fundamental Mode in the 50-GeV Ring

- Dipole instability

σ_t=30nsec, fc=3.43MHz



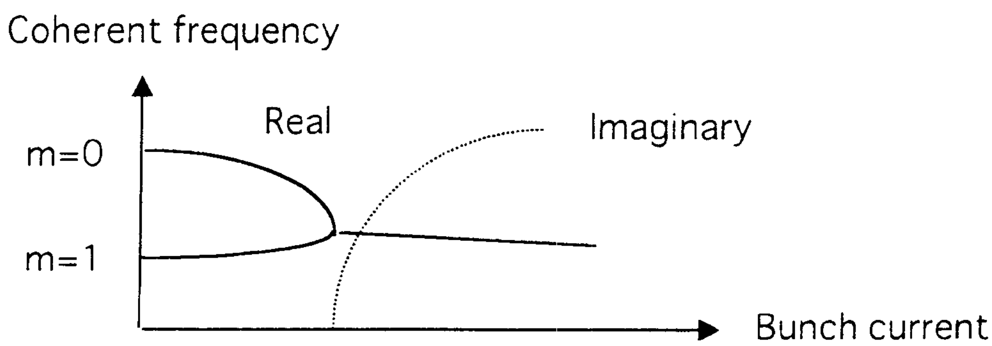
σ_t=50nsec, fc=3.43MHz



Conclusion 4
Dipole instability due to the fundamental mode can be tolerated both in the 3-GeV and 50-GeV rings.

Transverse Single-Bunch Instability

- Transverse Mode-Coupling Instability (TMCI)
  - TMCI has been observed in many electron machines and imposes a limitation on the single-bunch current.
  - But, it has been never observed in proton machines.
- What is TMCI?
  - It arises when the frequencies of two head-tail modes are coupled.
  - A clear threshold
  - Very fast



Conclusion 7
We do not consider at this stage that TMCI is a major limiting factor.

Transverse Multibunch Instability

- Growth rate for
  - a resistive-wall type instability
  - a very small negative chromaticity (3-GeV)
  - the half-corrected chromaticity ($\xi Q_T = -10$) (50-GeV)

3-GeV ring

$$\tau^{-1} \approx 3.1 \times 10^{-3} R_T$$

at 0.2 GeV

50-GeV ring

$$\tau^{-1} \approx 9.1 \times 10^{-5} R_T$$

at 3 GeV

R_T = transverse impedance at $\omega=(1-\Delta Q_T)\omega_0$

- If the same stability condition (head-tail mode)

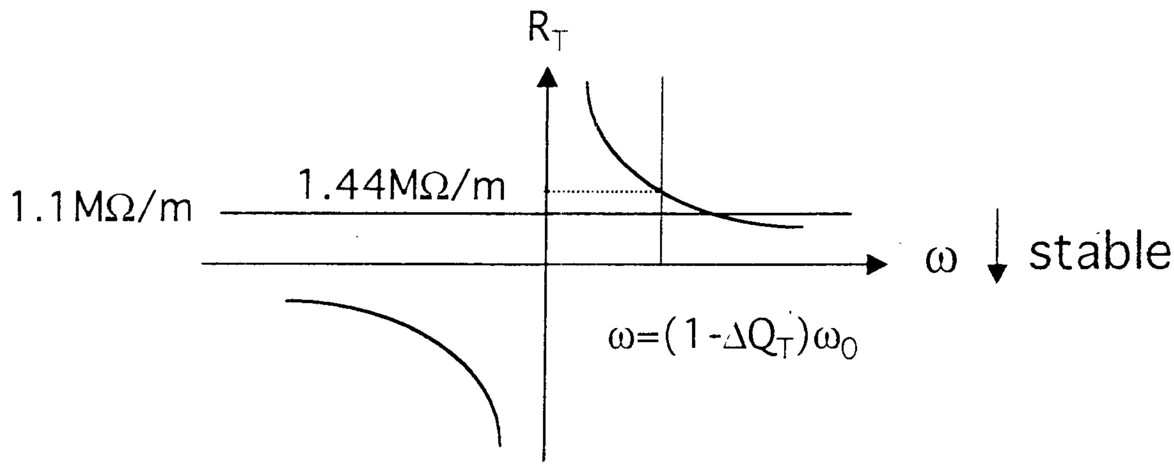
$$\tau^{-1} \leq 900 Hz \qquad \tau^{-1} \leq 100 Hz$$

is applied, the tolerance for R_T is

$$R_T \leq 0.29 M\Omega / m \qquad R_T \leq 1.1 M\Omega / m$$

Resistive-Wall in the 50-GeV Ring

- The resistive-wall instability is believed to dominate the transverse coupled-bunch instability.



- When the stain-less steel 316 chamber is used,

$$R_T = 1.44 M\Omega / m \geq 1.1 M\Omega / m$$

Conclusion 8.2
A dedicated narrow-band transverse feedback system is needed to damp the dipole mode due to the first harmonic .

Kicker Magnets

- The kicker magnets are under design.
- If we use the fast extraction kicker of PS 12-GeV ring, the total impedance will be

tolerance

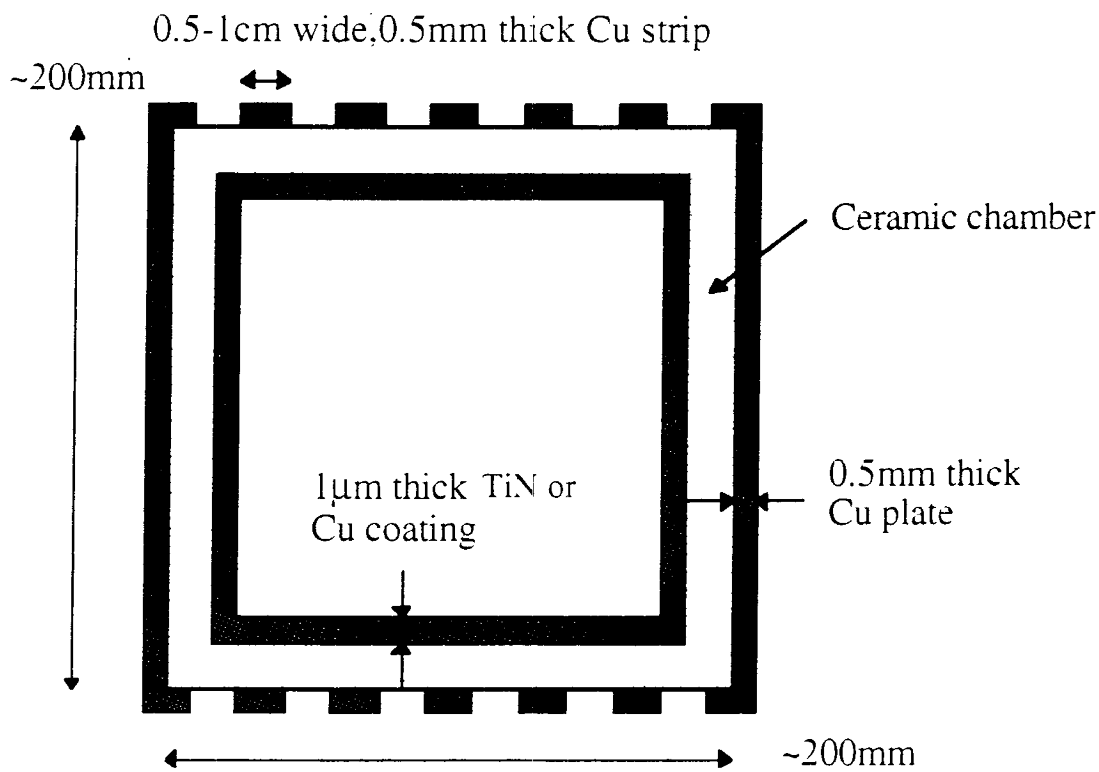
- At 3-GeV ring
  - 0.4/7 MΩ/m x13 kickers =0.74 MΩ/m ≫ 0.29 MΩ/m
- At 50-GeV ring
  - 0.4/7 MΩ/m x18 kickers =1.0 MΩ/m < 1.1MΩ/m

Conclusion 9

Low impedance kicker magnets need to be designed. The present design (or its alike) will create a transverse impedance well above the tolerance in the 3-GeV ring, (it is marginal at 50-GeV ring) and thus a transverse feedback system is necessary to damp dipole oscillations.

RF Shieldings for a Ceramic Chamber (3-GeV Ring)

- The high repetition rate (20-50Hz) raises concerns on the eddy current on the chamber in dipole magnets, and strongly favors a ceramic chamber.
- RF shieldings are needed to reduce the resistive-wall impedance.



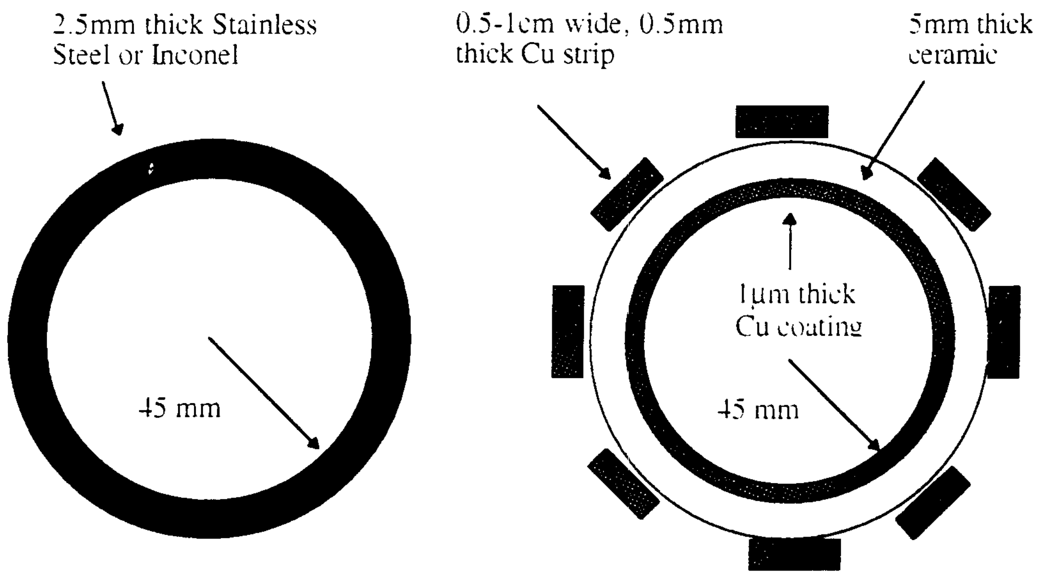
- Exterior thick Cu strips
  - a path of low-frequency impedance for the image current
  - the largest aperture for a beam
  - an easy check of any damage
  - careful designing of the end connection with flanges necessary to reduce the inductance
- Interior thin TiN or Cu coating
  - a path of high-frequency impedance for the image current
  - precludes a charge buildup
  - precludes a heating due to dielectric loss inside the ceramic
- The merit of matching the RF shieldings with the beam envelop should be investigated.

Conclusion 10
The design of RF shieldings is still under way.

Choice of Chamber Material (50-GeV Ring)

- Comparison among different chamber materials

	Stainless steel 316	Inconel	Ceramic
Eddy current	OK if $f_{rep} < 3$Hz	OK if f_{rep}=1-10 Hz	OK even f_{rep} >10Hz
Impedance	OK with feedback	OK with feedback	OK
Cost	Most inexpensive	Inexpensive	Expensive
Fabrication	Easy	Easy	Complicated
Magnetization	OK	OK	OK
Residual radiation	Problem	Problem	OK
Damage by a beam	Possible melting	Possible melting	OK



Sketches of the stainless steel 316, the Inconel and the ceramic chambers.

Summary of the Findings (3-GeV Ring)

Longitudinal	
Single-bunch instability	
Space charge	Better to be reduced by impedance tuner
Inductance	OK
Cavity fundamental	Beam-loading should be compensated at present impedance of R=10.5 kΩ and Q=1~2. No feedback is needed if the impedance is reduced to 5kΩ, and Q ~ 2
Multibunch instability	
Fundamental mode	Well controllable
Parasitic resonances	Probably OK
Stability in double RF system	
Transverse	
Single-bunch instability	
TMCI	Probably OK
Multibunch instability	
Resistive-wall	Should be OK
Kicker magnets	Low impedance design is needed
RF shieldings for a ceramic chamber	Should be designed and tested

Summary of the Findings (50-GeV Ring)

- Longitudinal
  - Single-bunch instability
    - Space charge — OK
    - Inductance — Blow up the longitudinal emittance to 3 eVs before acceleration
    - Cavity fundamental — Beam-loading effect is not significant at injection, but it should be compensated during acceleration
  - Multibunch instability
    - Fundamental mode — Well controllable
    - Parasitic resonances — Probably OK
- Transverse
  - Single-bunch instability
    - TMCI — Probably OK
  - Multibunch instability
    - Resistive-wall — Needs a feedback to damp a dipole instability due to the first harmonic
    - Kicker magnets — Marginal. But, low impedance kicker should be designed.
    - SS 316 chamber — OK