Capacitive Impedance ~~Space-Charge~~ Compensation at the LANL PSR

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(February 28, 2000)

I SPACE CHARGE PROBLEM

II FERRITE COMPENSATION

III INSTABILITY FROM COMPENSATION

IV SOLUTION

Fermilab - LANL Collaboration (starting from 1997)

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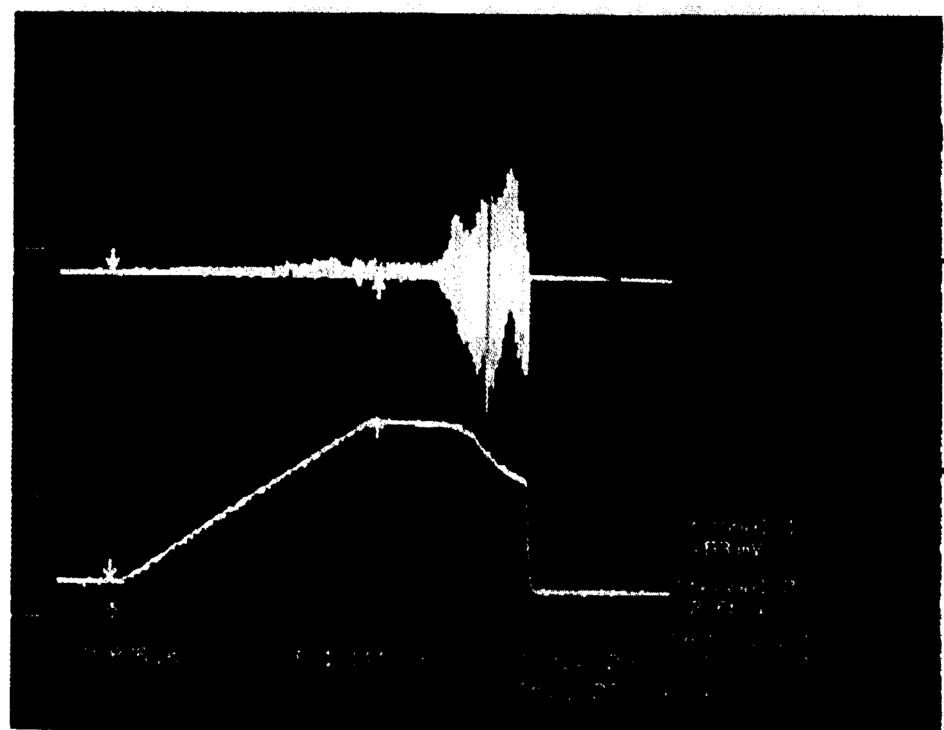
INTRODUCTION

- Electron rings are troubled by the inductive impedance.
- For example, the inductive impedance of the damping rings is mostly eliminated by smoothing the chamber walls. ~~are compensated with capacitive wall cavitie~~s.
- This introduces undesirable real impedance which lowers the coupled-mode instability.
- Low-energy proton rings are below transition. we are therefore troubled by space charge force instead.
- Here, I am going to talk about the compensation of space charge force at the PSR at Los Alamos.
- We also come across instability due to the real part.
- This instability has been eliminated now.

- Some information of the PSR at Los Alamos.

Kinetic Energy	0.797 GeV, $\gamma = 1.85263$, $\beta = 0.841811$
Cycle rate	12 Hz
Circumference, C	90.2 m
Rf harmonic, h	1
Transition, γ_t	3.1, $(\eta = -0.18830)$
No. per bunch, N_B	< 1997: 3.2×10^{13} ($5.2\,\mu$C), upgrade goal (1998): 4.2×10^{13} ($6.7\,\mu$C)
	6.5×10^{13} ($9.7\,\mu$C)
95% bunch area, A	3.64 eV-s (parabolic)
Half bunch length, $\hat{\tau}$	133.5 ns
Energy spread, $\Delta E/E$	± 0.005
Bunching factor B	0.498
95% emittance, ϵ_{N95}	$50 \times 10^{-6}\,\pi$ m

Unstable Beam Signals



- Space-charge impedance:

  With $g_0 = 1 + 2\ln(b/a) = 3$,

$$\left.\frac{Z_\parallel}{n}\right|_{\rm spch} = i\frac{Z_0 g_0}{2\gamma^2\beta} = i196\ \Omega$$

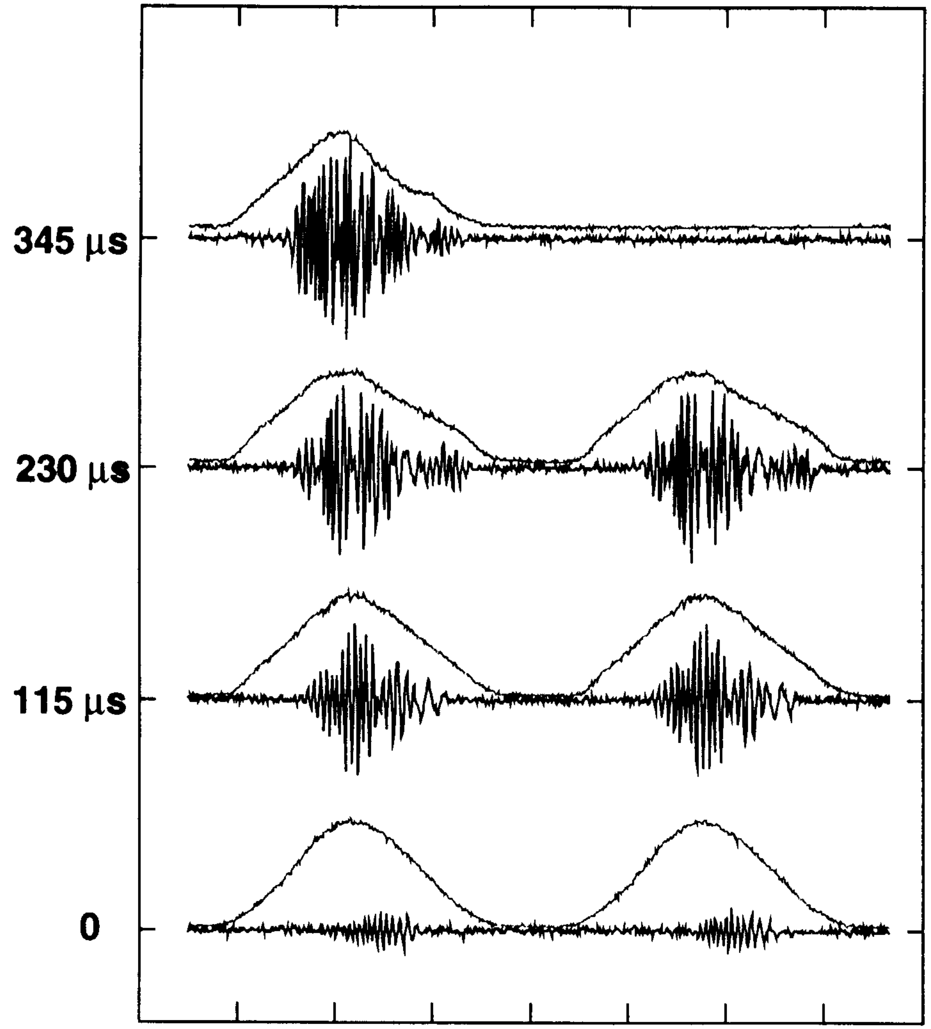
- This is an accumulation ring that stores injection of a chopped bunch from the linac for 1000 to 2000 turns. Then the beam is extracted.

- To preserve the bunch length from phase drift and space charge repulsion, there is a rf buncher with $V_{\rm rf}$ up to $18 \sim 20$ kV. gap is required to get rid of trapped electrons.

- The intense longitudinal space-charge repulsive force acts against the rf focusing.

- Potentail well distortion is big and more rf voltage will be necessary.

Vertical Oscillations Compared with Beam Density



- **Vertical difference signals (blue) from a short stripline BPM and beam pulses from a wall current monitor (red).**
  - **WM41VD.4B**
  - **WC41.4B**
  - **Data taken Apr. 14, 1997**
  - **Data at t, t+115 µs, t+230 µs, t+345 µs**

A. Alexandrov's talk will cover a more detailed analysis of BPM signals and the question of obtaining absolute values of the beam centroid motion.

- A particle at distance s from bunch center sees a longitudinal space-charge $E_{z\,\mathrm{sp\;ch}}$ field and a potential drop per turn (assuming 5.1μC bunch):

$$E_{z\,\mathrm{sp\;ch}} = -\frac{eg_0}{4\pi\epsilon_0\gamma^2}\frac{d\lambda}{ds}, \qquad g_0 = 1 + 2\ln\frac{b}{a}$$

$$V_{\mathrm{sp\;ch}} = E_{z\,\mathrm{sp\;ch}}C = \left(\frac{3\pi I_{\mathrm{av}}Z_0 g_0}{2\gamma^2\beta}\right)\left(\frac{R}{\hat{\ell}}\right)^2\frac{s}{\hat{\ell}} = 4.82\,\frac{s}{\hat{\ell}}\;\mathrm{kV}$$

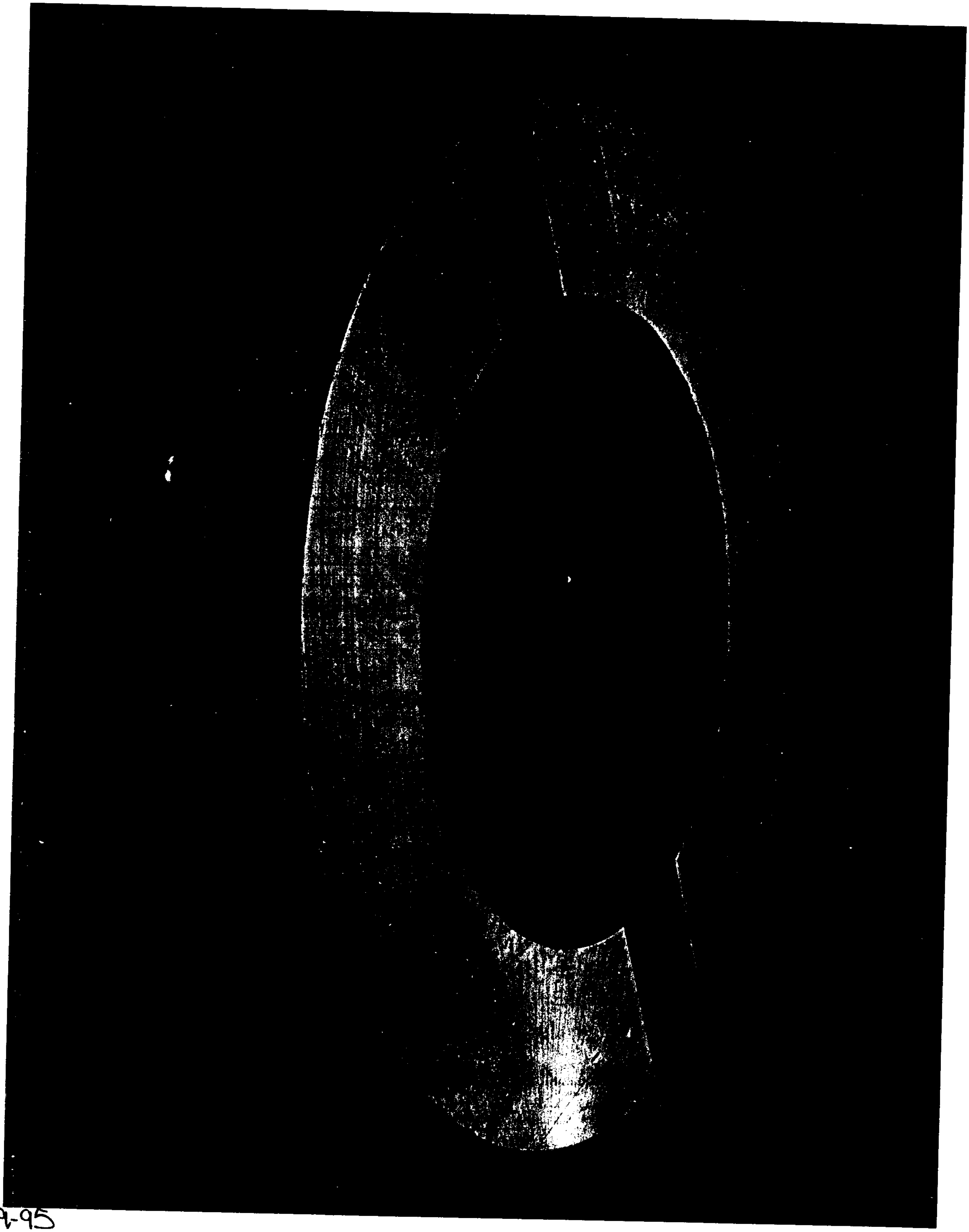
- On the other hand, neglecting space charge, the synchrotron tune and required rf are

$$\nu_s = \frac{|\eta|\hat{\delta}}{\omega_0\hat{\tau}} = 0.000402 \qquad V_{\mathrm{rf}}\cos\phi_0 = \frac{2\pi\beta^2 E}{|\eta|h}\nu_s^2 = 6.60\;\mathrm{kV}$$

- We see that the space-charge force is a big portion of the rf force.

- We want to compensate this intense space charge force by an inductive force from ferrite.

- Note that we wish to compensate potential-well distortion here at $f_{\rm rf} = 2.79$MHz.
- There is no intention to compensate space-charge impedance at the GHz frequency range, since space-charge force will not lead to microwave instability if ReZ/n is small.
- For this reason, ferrite rings can be used.



99-95

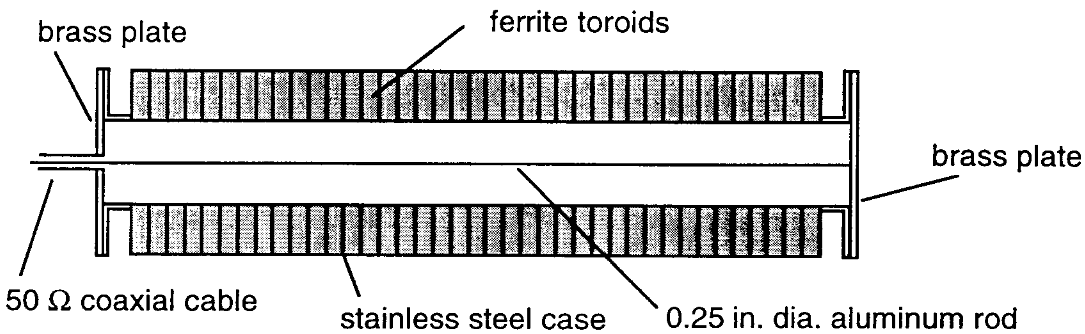


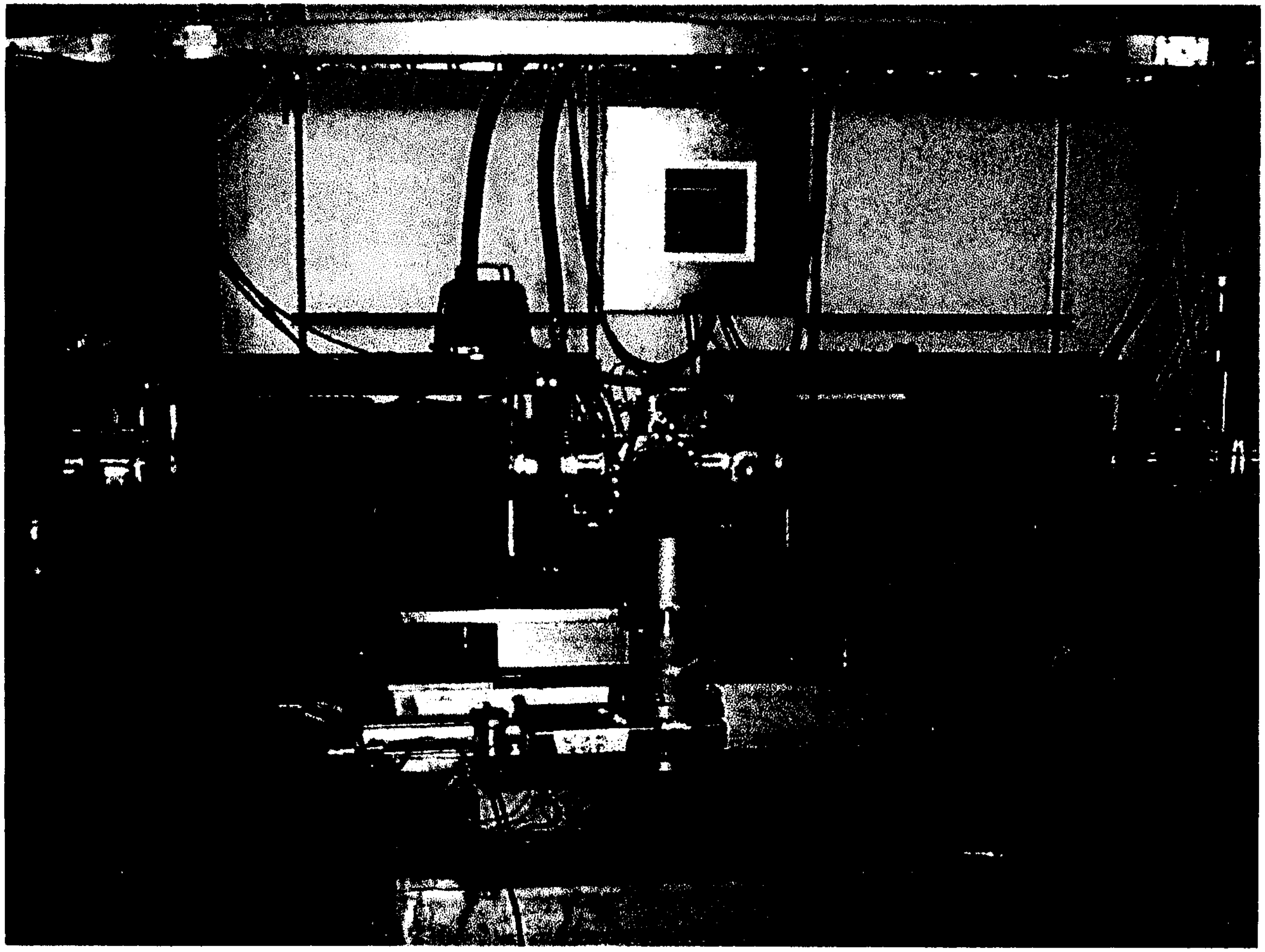
FIG. 6. Schematic cross section of the measurement setup with test fixtures.

3 of this ferrite tuner will suppose to cancel

Space charge $\left.\frac{Z}{n}\right|_{spch} \sim 150 - 200\ \Omega$

Inductive Insert

Beam Loading Studies
1997 FNAL-LANL Inductor Experiment (cont.)



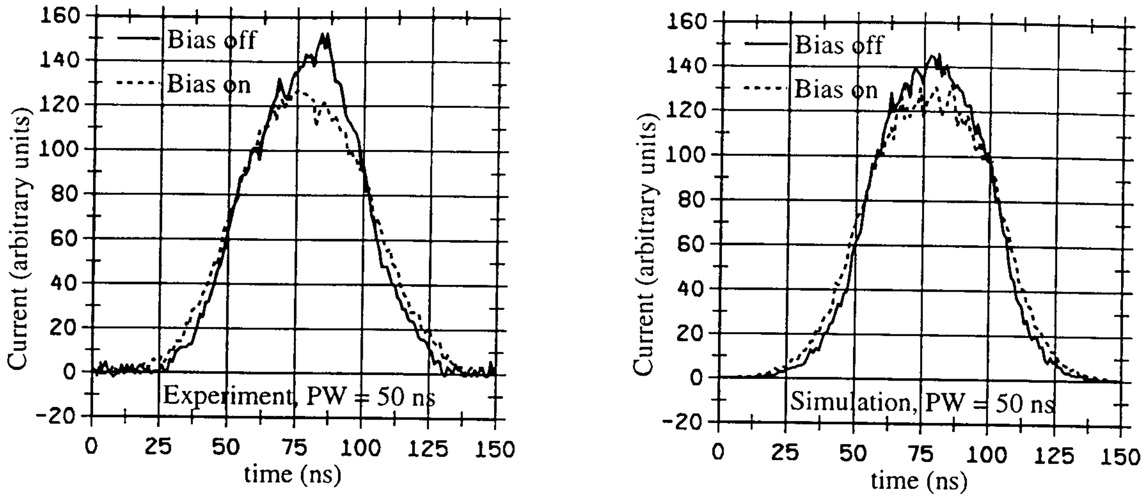


FIG. 3. Measured (left) and simulated (right) pulse shapes after 625 μs for an injected pattern width of 50 ns. The simulations used 4×10^{12} protons. Solid curves represent the shape with no bias on the inductor (7.29 μH in the simulation). Dotted curves represent the shapes with a 900-A bias applied to the inductor (2.49 μH in the simulation). Buncher voltage was 7.500 kV.

μ is about 3 times smaller.

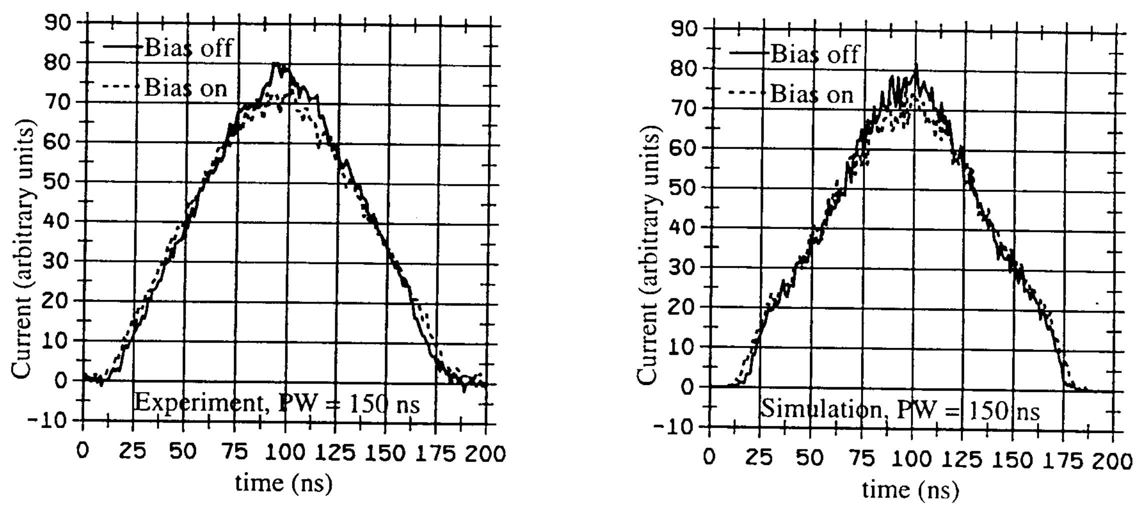


FIG. 4. Measured (left) and simulated (right) pulse shape after 625 μs, with an injected pattern width of 150 ns. The simulations used 1.2×10^{13} protons. Solid curves represent the shape with no bias on the inductor (7.29 μH in the simulation). Dotted curves represent the shapes with a 900-A bias applied to the inductor (2.49 μH in the simulation). Buncher voltage was 7.500 kV

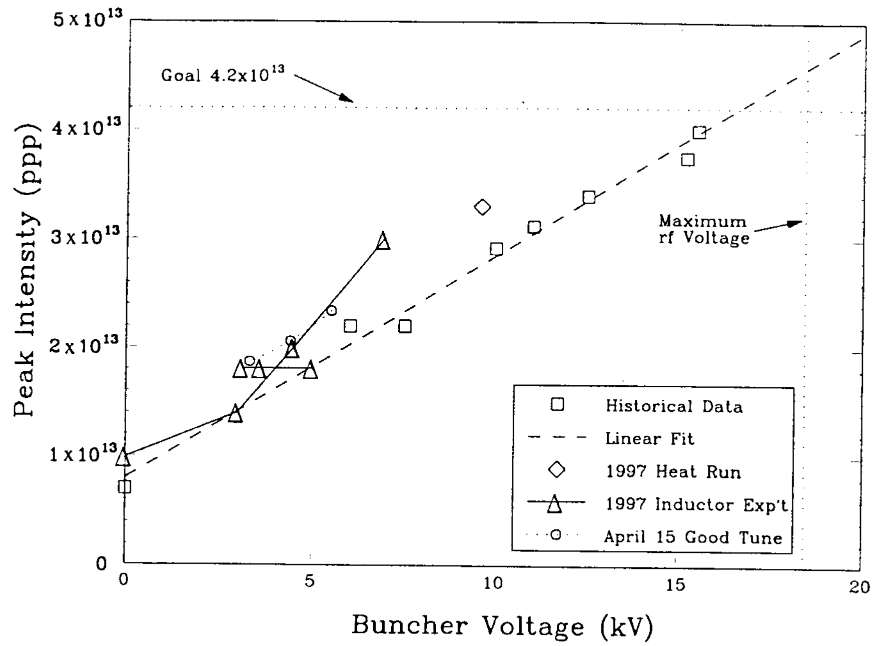


FIG. 5. Stability threshold versus rf voltage improvement. Results of this experiment are depicted by triangles.

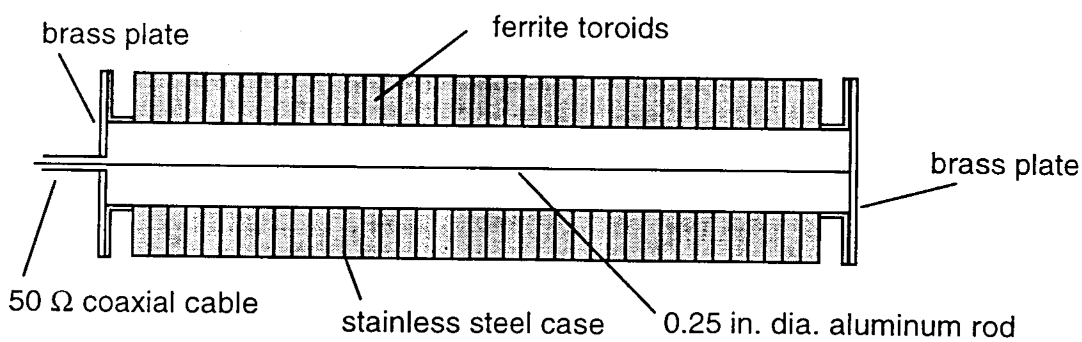


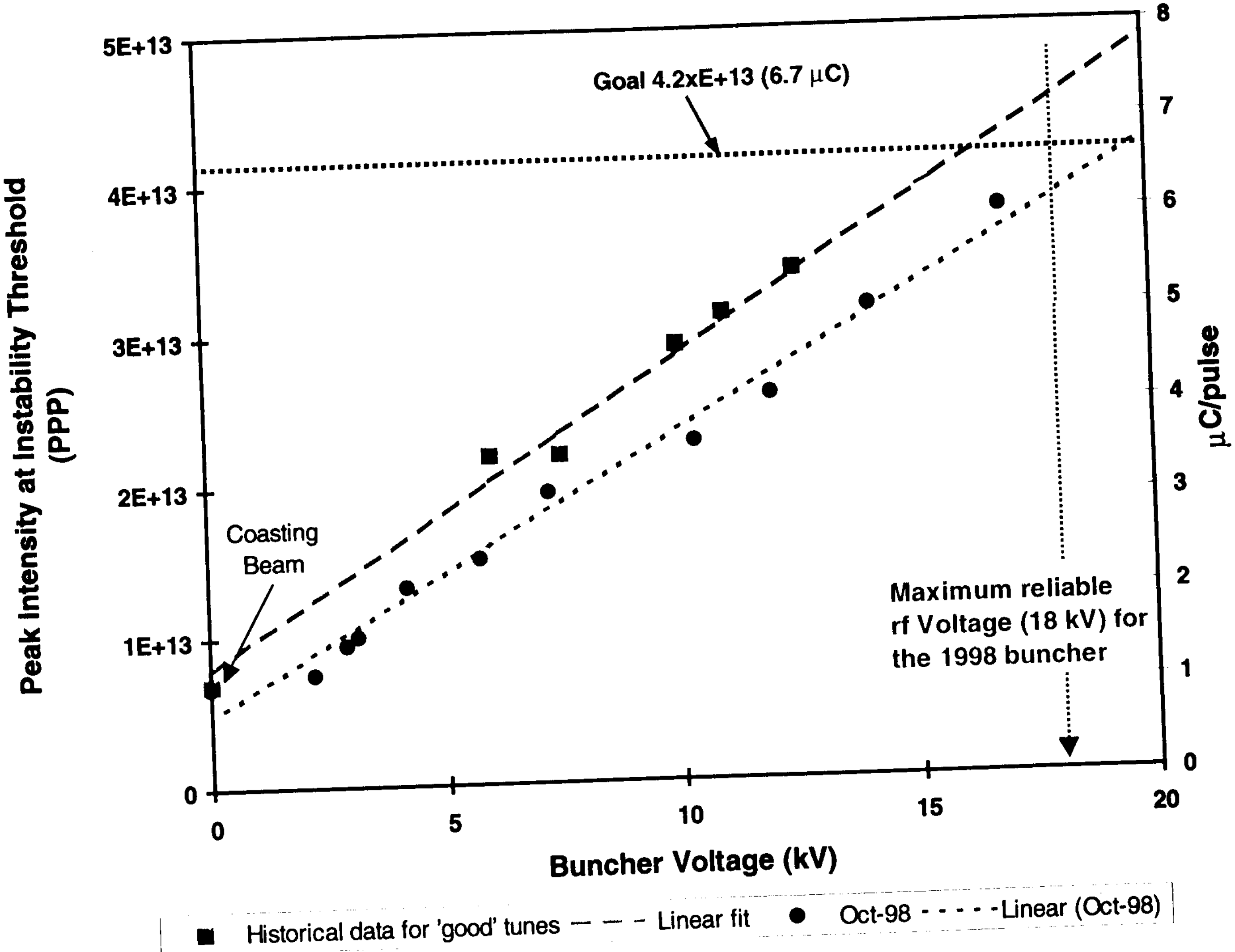
FIG. 6. Schematic cross section of the measurement setup with test fixtures.

Results

1. Bunch lengthens when ferrites are biased (μ decreases).
2. About only $\frac{2}{3}$ of former V_{rf} is required.
3. It appears that the gap is the cleanest ever seen.

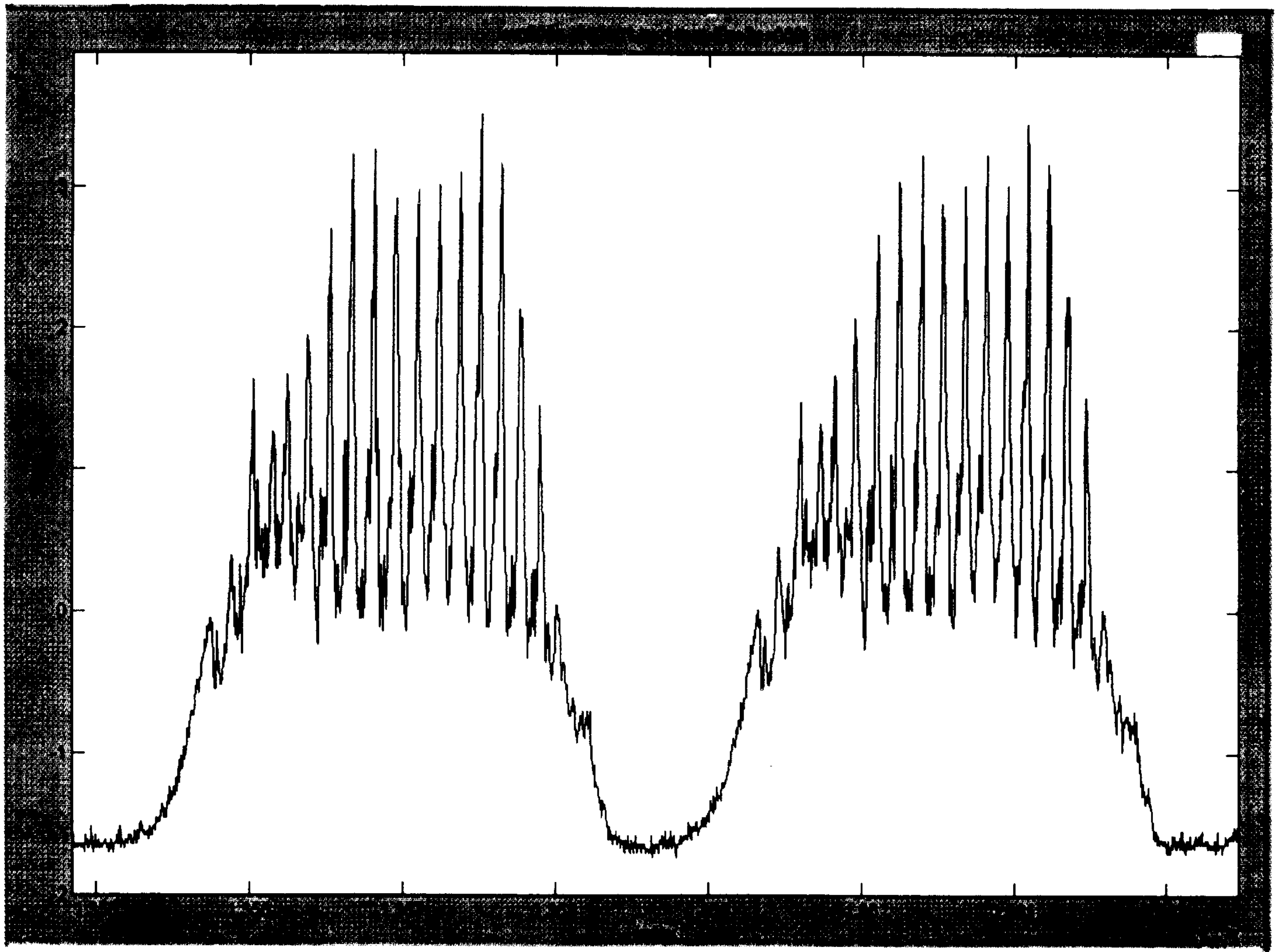
August 1977, then upgrade, started again October 1998.

Updated Instability Threshold Curve



Longitudinal Instability

Two turns displayed



RF off, Injected bunch width 250 ns, accumulate 125 μs, 500 μs store, Inductor Bias=0

~ 4.0 μC

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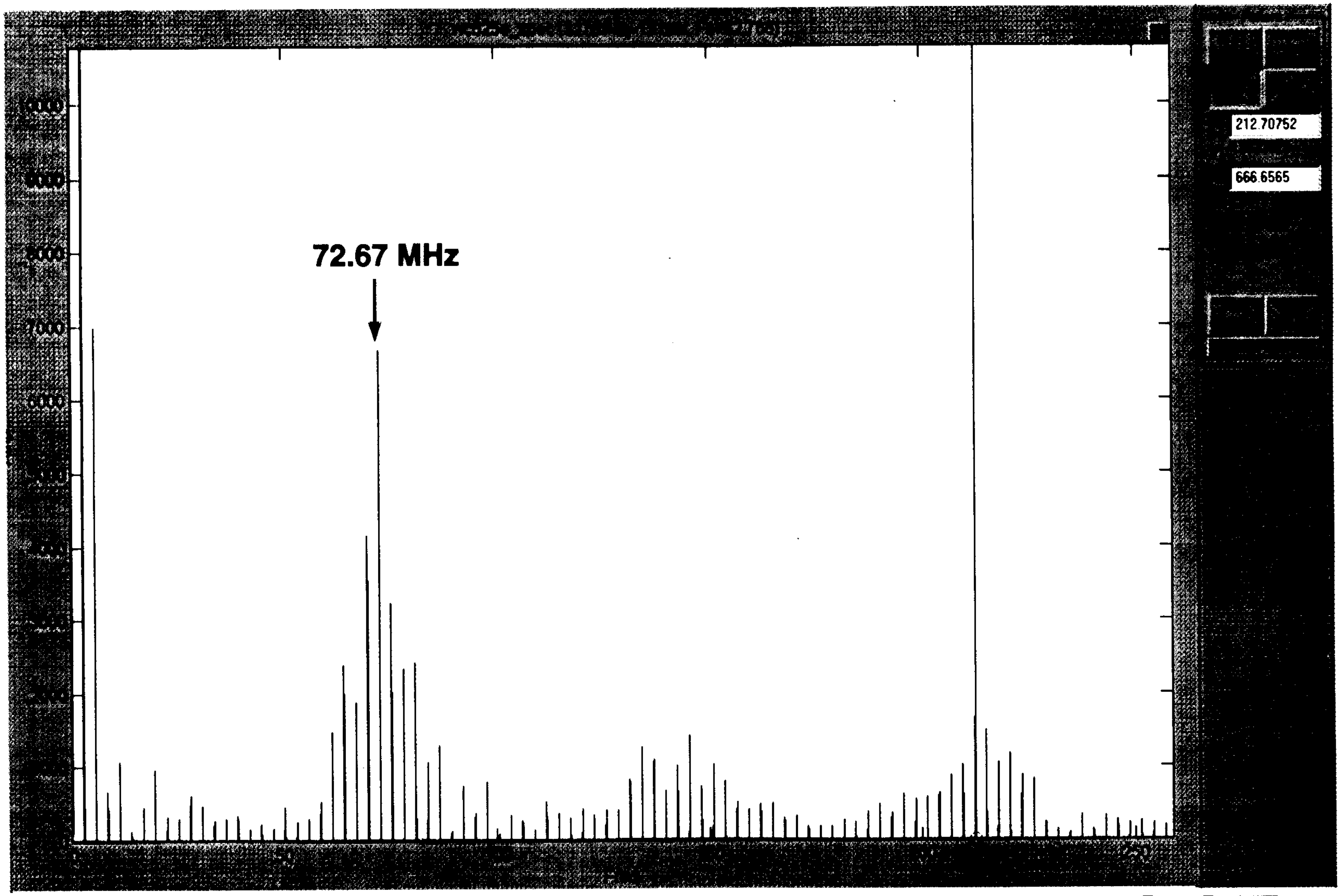
Frequency Spectrum



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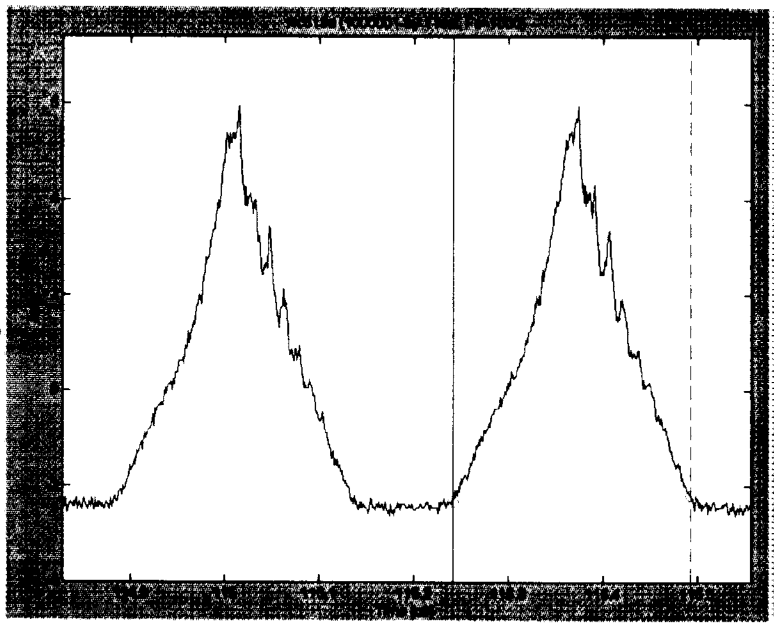
Effect of Inductors on Bunched Beam Pulse

- Injected bunch width = 250 ns (standard injection width)
- Longitudinal modulation may be tolerable at 250 ns bunch width.

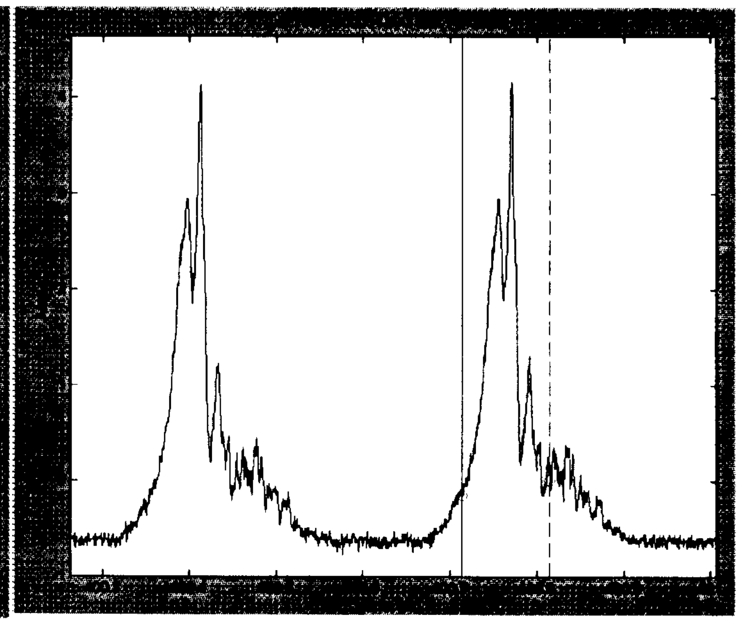
- Injected bunch width = 100 ns
- Here beam pulse is too badly distorted to be very useful for potential short-pulse applications.

3 modules used, bias =0, room temperature

Wall Current Monitor



Bk86, p78



Bk87, p56

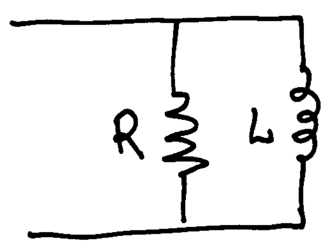
For a ferrite, the permeability is $\mu = \mu' - j\mu''$

Both μ' & μ'' must be functions of frequency.

Simplest model

lower freq. $\longrightarrow$ a pure inductance L

high freq $\longrightarrow$ a pure resistance R



$$\therefore \quad Z = \frac{j\omega L}{1 + j\frac{\omega L}{R}} = \frac{j\omega L}{1 + j\frac{\omega}{\omega_r}} \qquad \omega_r = \frac{R}{L}$$

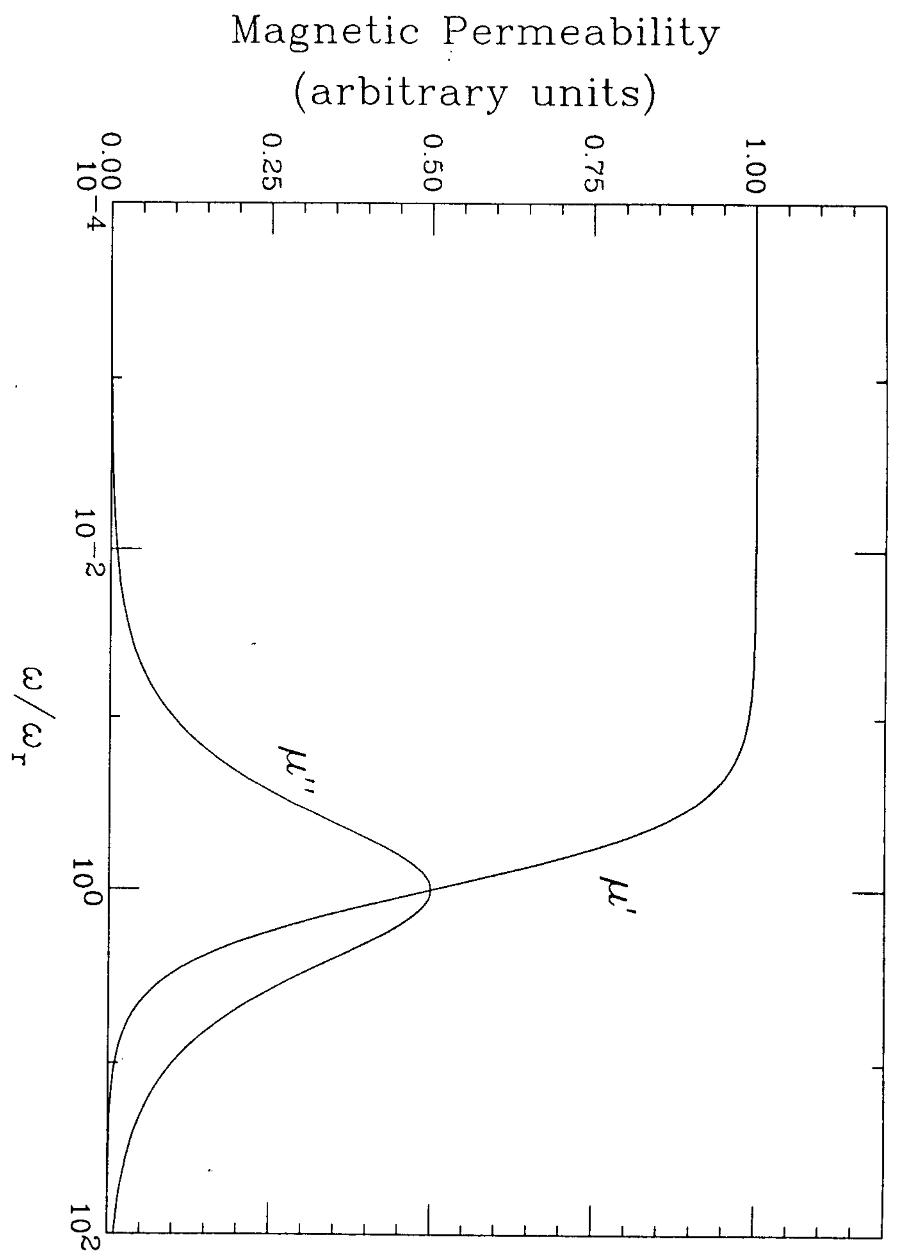
$$\therefore \quad \mu' = \frac{1}{1 + \frac{\omega^2}{\omega_r^2}} \qquad \mu'' = \frac{\frac{\omega}{\omega_r}}{1 + \frac{\omega^2}{\omega_r^2}}$$

With a bias current,

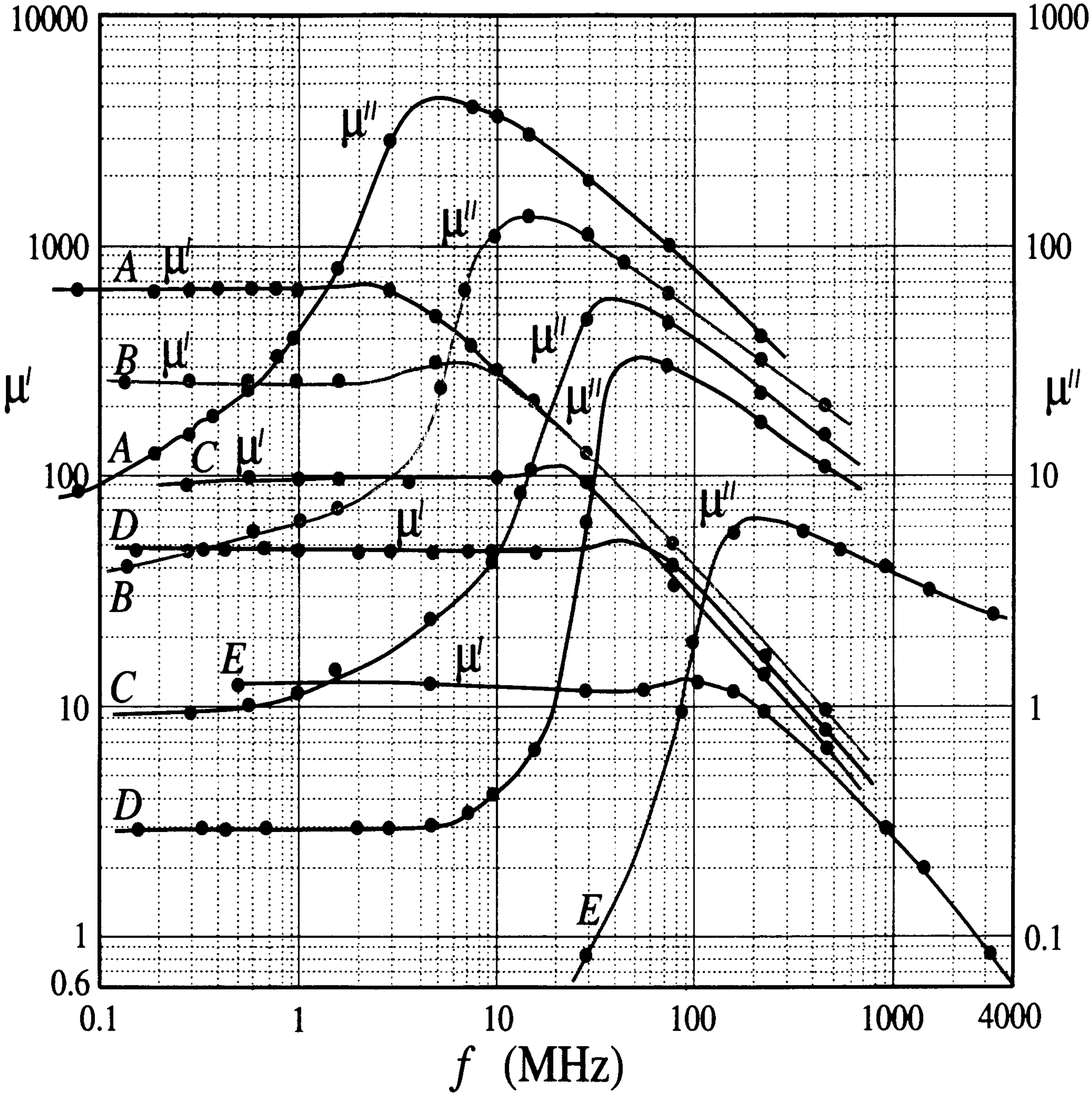
L is reduced but not R $\Longrightarrow$ ω_r increases
(or μ')

$\frac{\mu''(\omega_r)}{\mu'(0)}$ unchanged

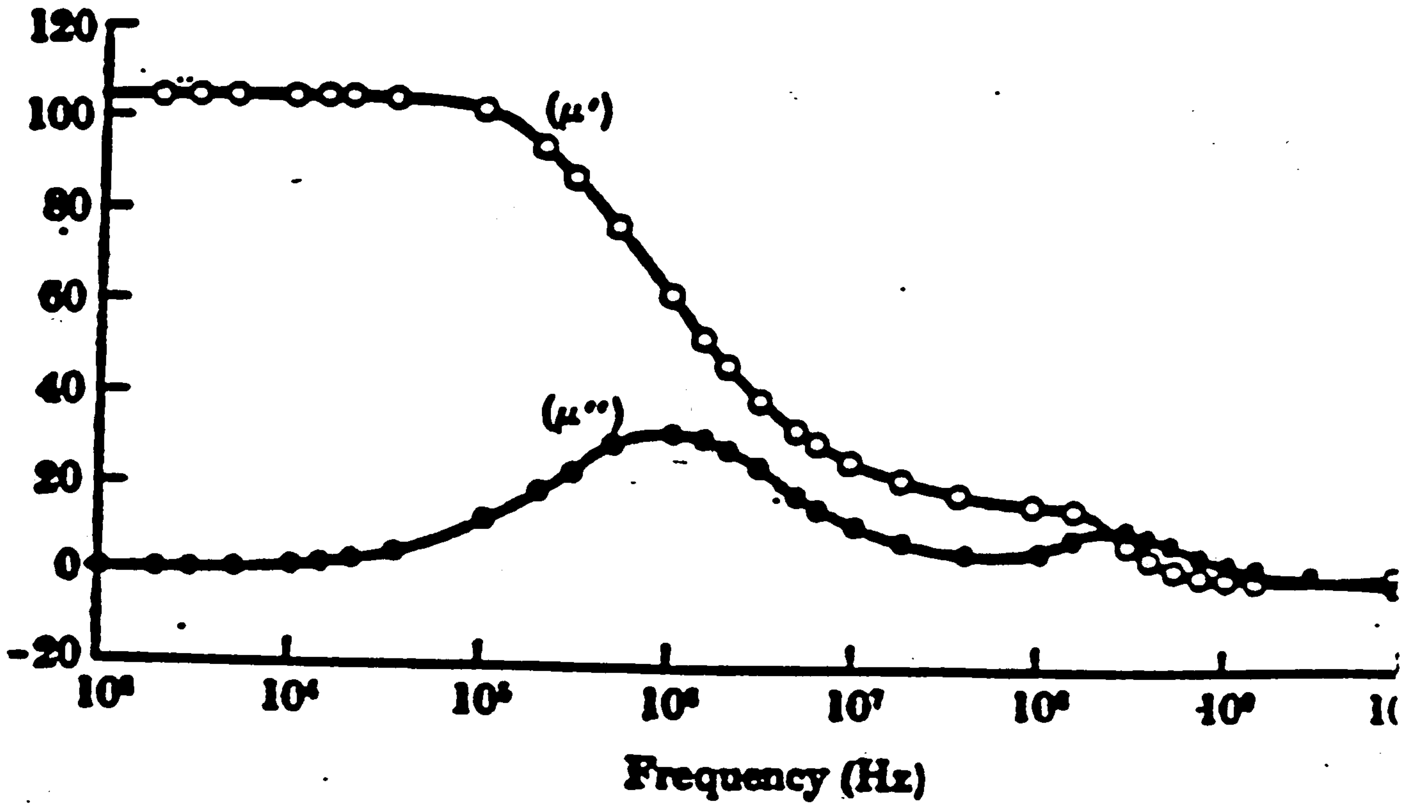
Experiments do show that ω_r increases with bias current.



Magnetic Permeability
(arbitrary units)
0.00
0.25
0.50
0.75
1.00
10^-4
10^-2
10^0
10^2
ω/ω_r
μ''
μ'



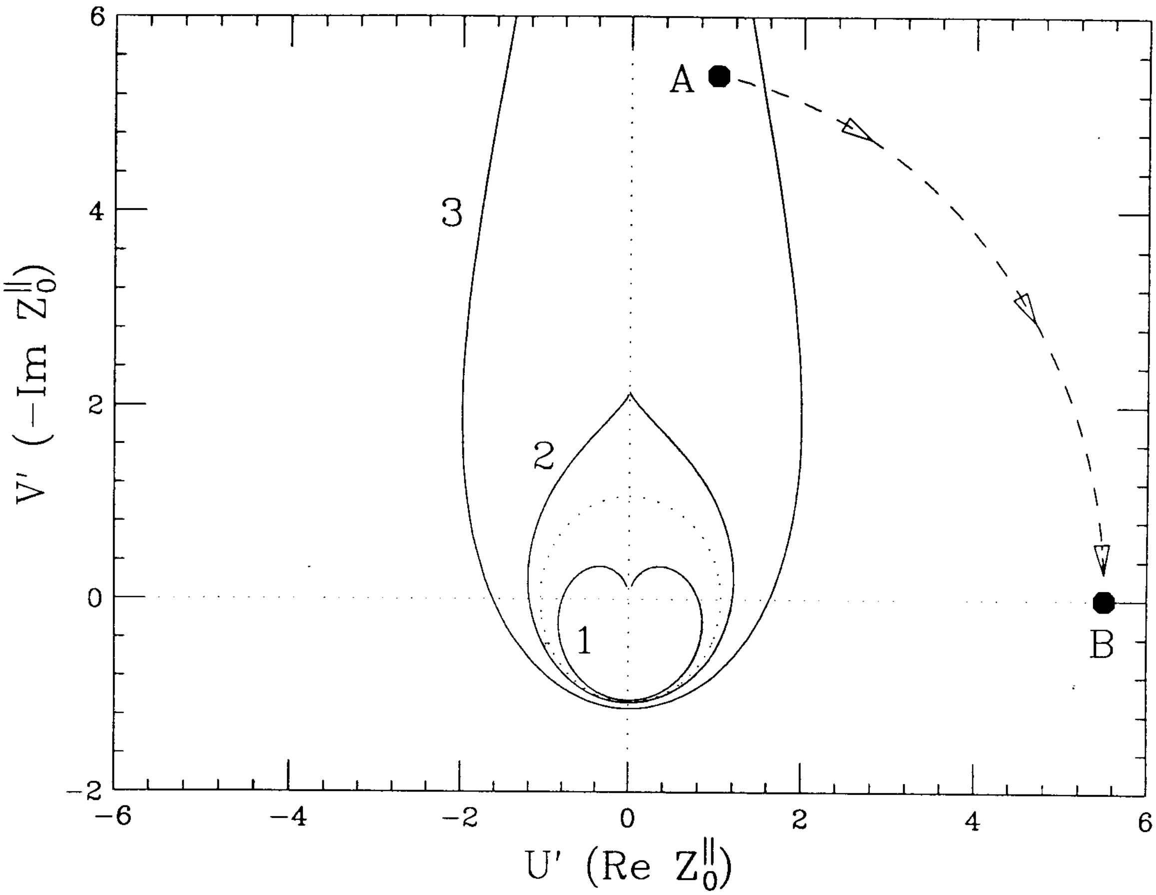
Commercial nickel-zinc ferrite, Ferroxcube IV



3. 5.8. The initial permeability of polycrystalline YIG as a function frequency (after Epstein and Frackiewicz 1959).

higher $\frac{\mu'_{max}}{\mu''_{max}}$ ratio

but μ' rolls off at too low freq. ~ 100 kHz

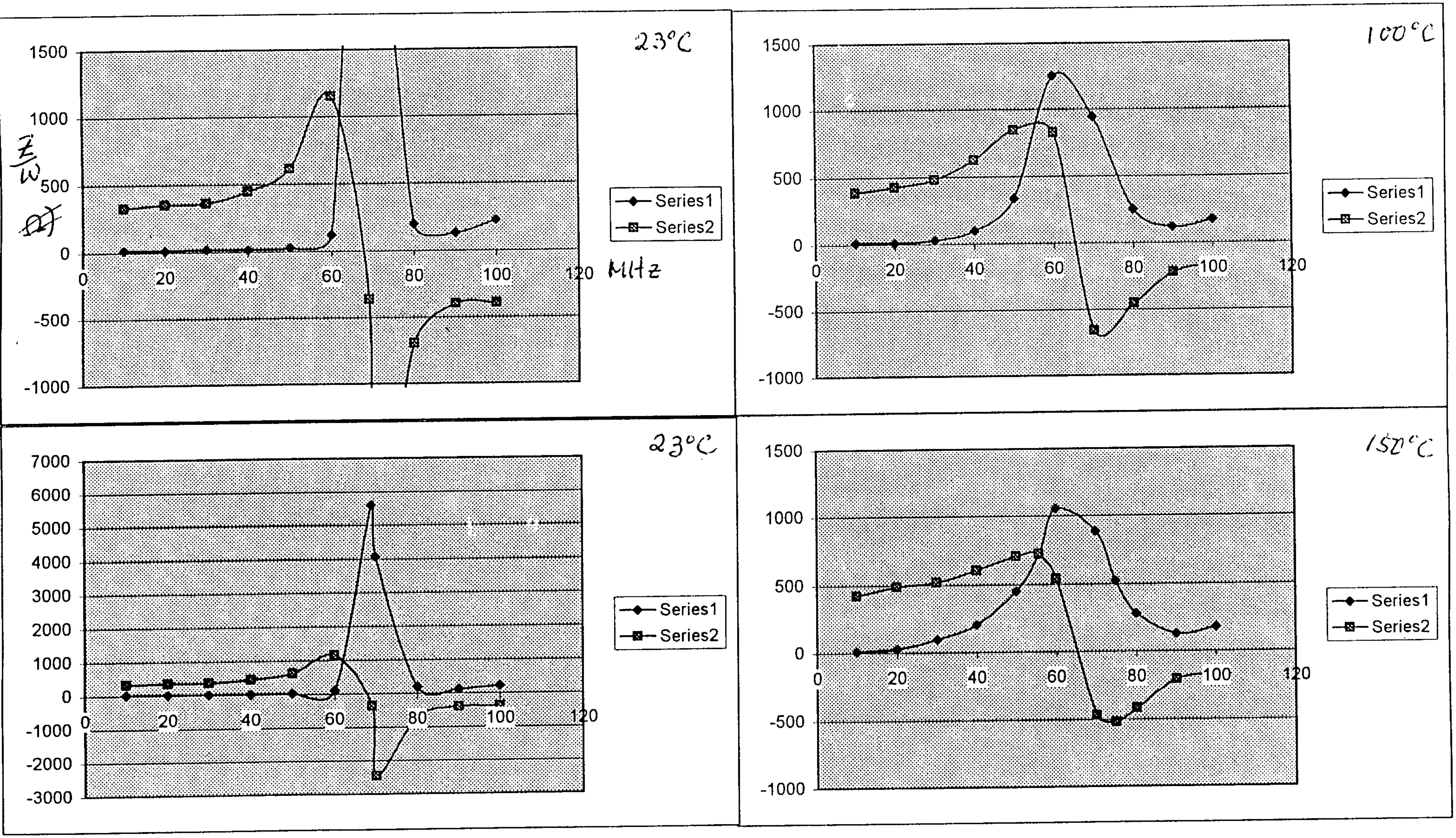


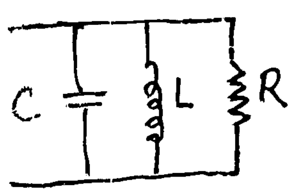
For highly space-charge limited machines, full compensation of space charge by ferrite must lead to microwave instability

(1) Therefore only partial compensation is possible unless there is a way to lower μ''

(2) Or choose a ferrite with $\frac{\mu'_{max}}{\mu''_{max}}$ is <u>very</u> large

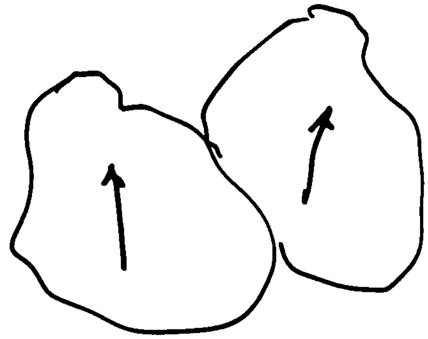
Idea of Milorad popovic





somehow as temperature increases L increases (~30%)
ferrite becomes lossy, R decreases 4 times
∴ $Q = R\sqrt{\frac{C}{L}}$ decreases 5 times

Why μ' increases with temperature ?



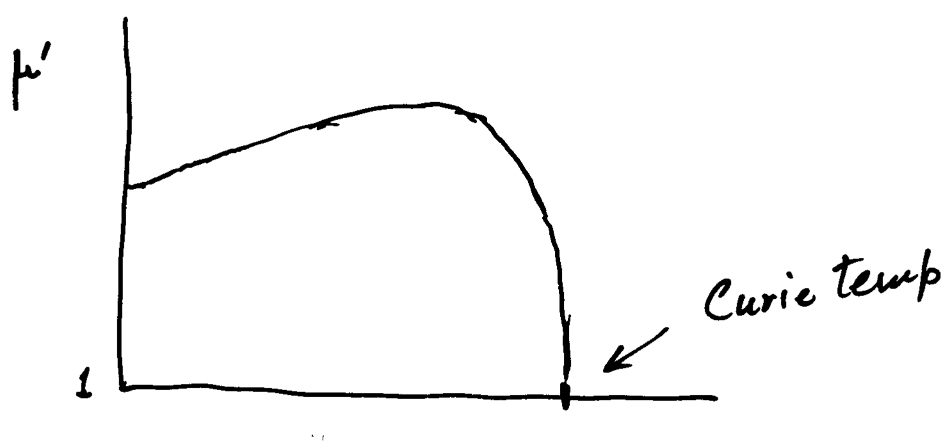
Domains with magnetizations

Total magnetization = vector sum of magnetization of domains

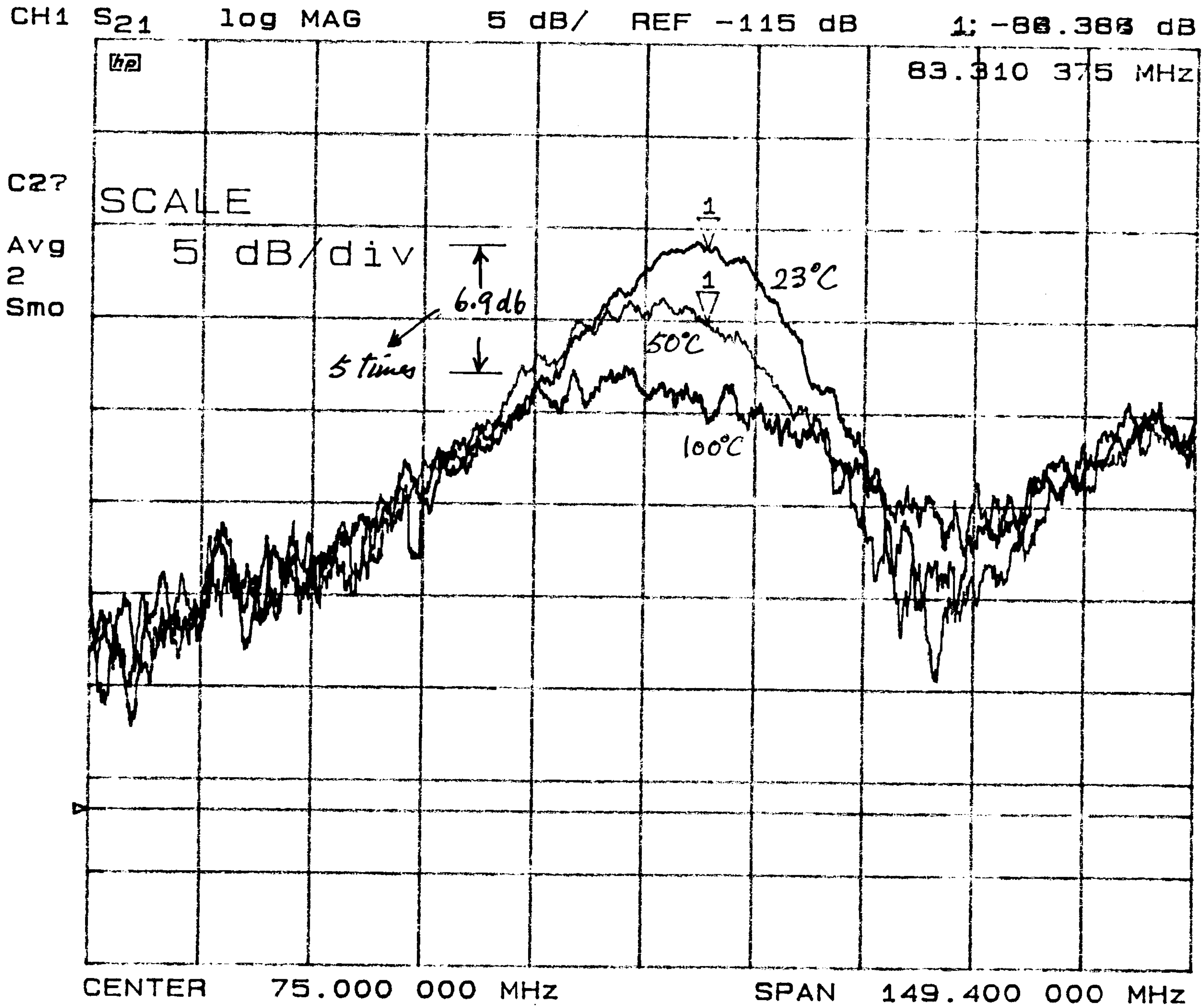
Increase temp, domain magnetizations are freer to move or line up $\Rightarrow$ higher μ'

However, if temp is too high, spin of individual atoms or molecule are random.

$\Rightarrow$ magnetization of a domain $= 0$



Changing temperature of Cores 7/24/99 15:57



At PSR, They put back 2 tuners

remove bias solenoid wiring & put on heating tapes

At 130°C

1. The troublesome longitudinal resonance (70-75 MHz) was eliminated

2. The measured low frequency inductance was enough for complete compensation of sp. ch.

   Or μ' increases by ~ 50%

Also heat to 160°C. Inductance was enough to overcompensate sp. ch. & no long. instability

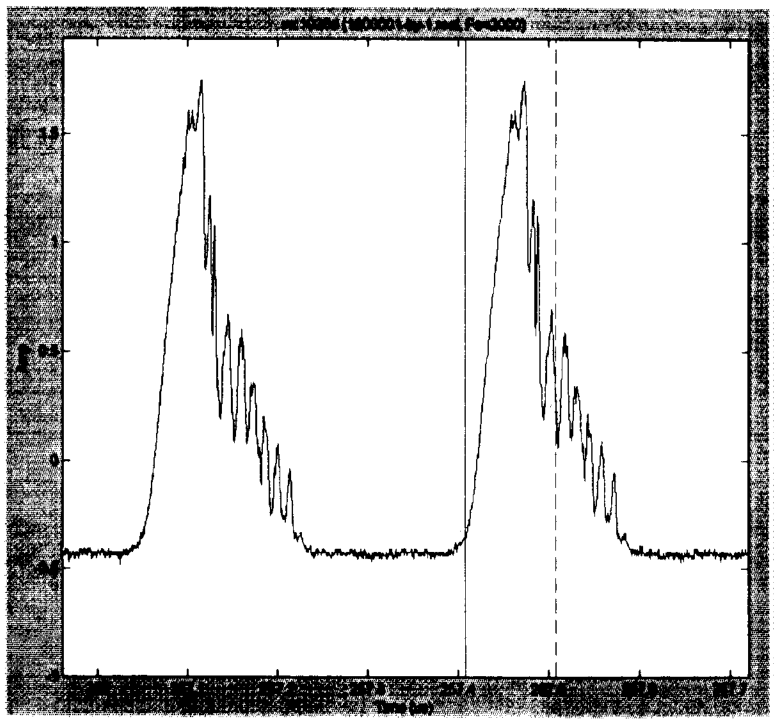
- gap is very clean
- only operational issue of outgassing & stress on the ion pumps.
- also see beam pulse more sharply peaked than with no inductors, implying that the inductance has not been reduced.

Effect of Heating the Inductor Ferrite

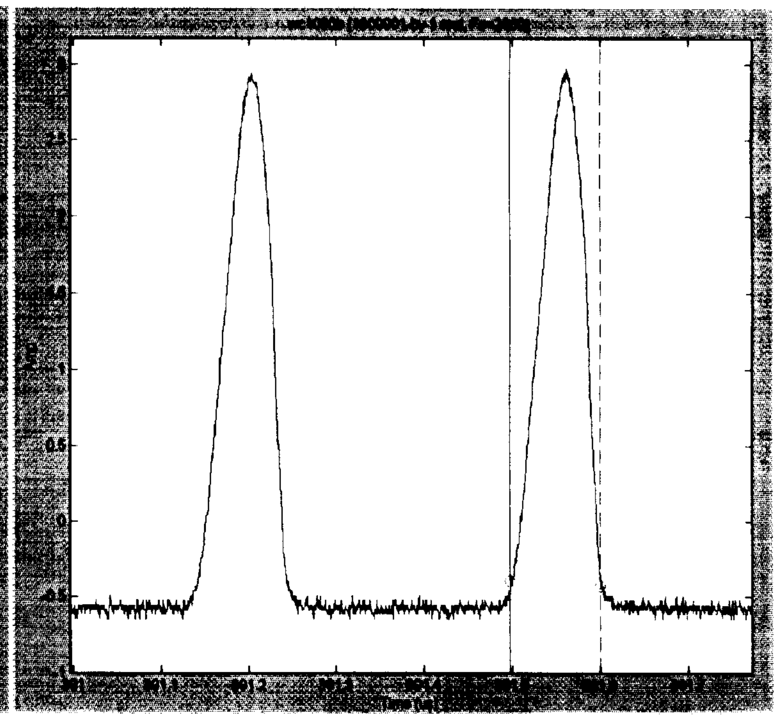
- Ferrite Inductor (2 modules) at room temperature
- 3.3 μC accumulated

- Ferrite at 130º C
- 3.3 μC accumulated
- Longitudinal signal at cavity resonance down 30db from room temperature case

Wall Current Monitor



Bk91, p150



Bk92, p10

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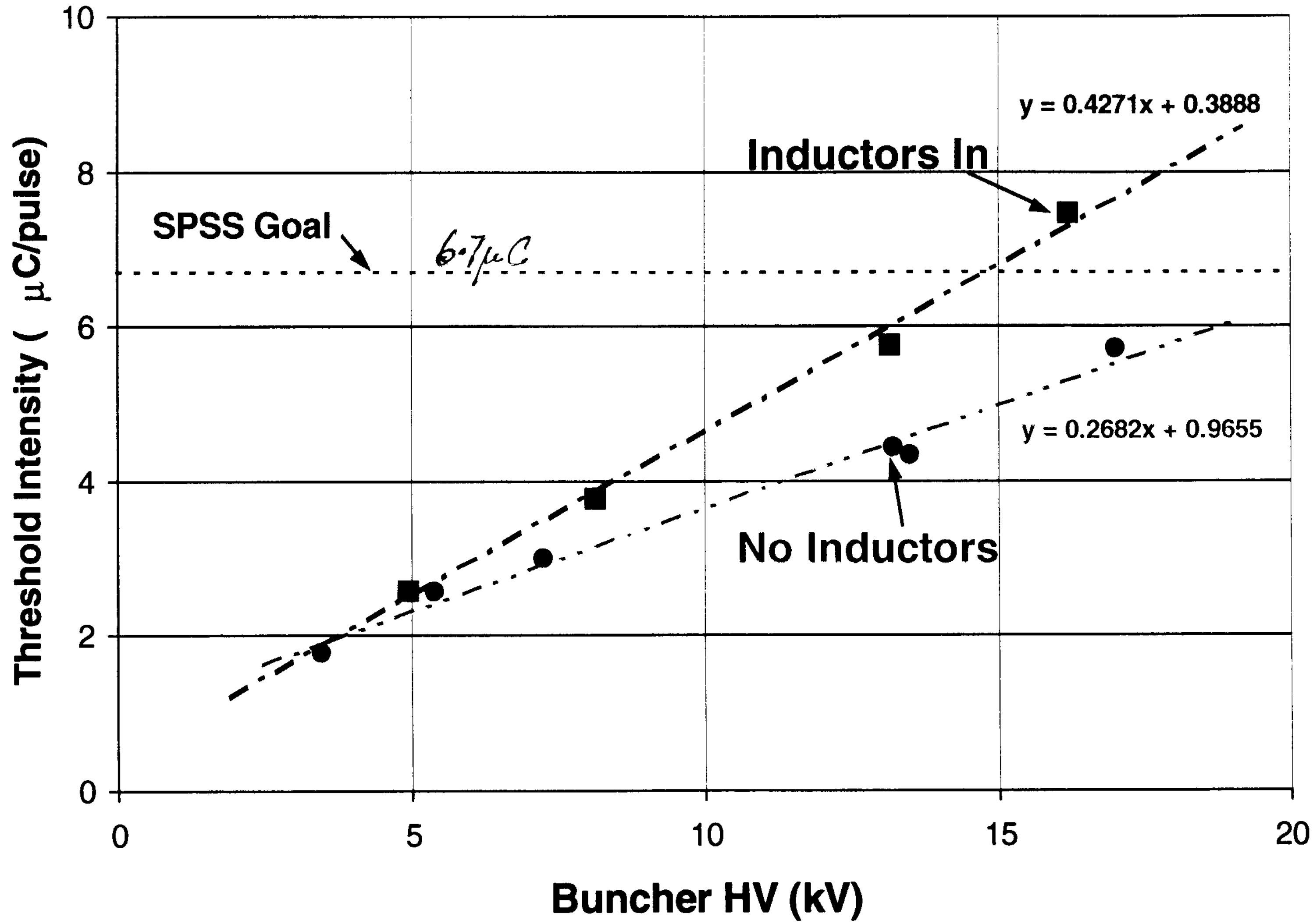
Effect of Inductors On Instability Threshold Curves



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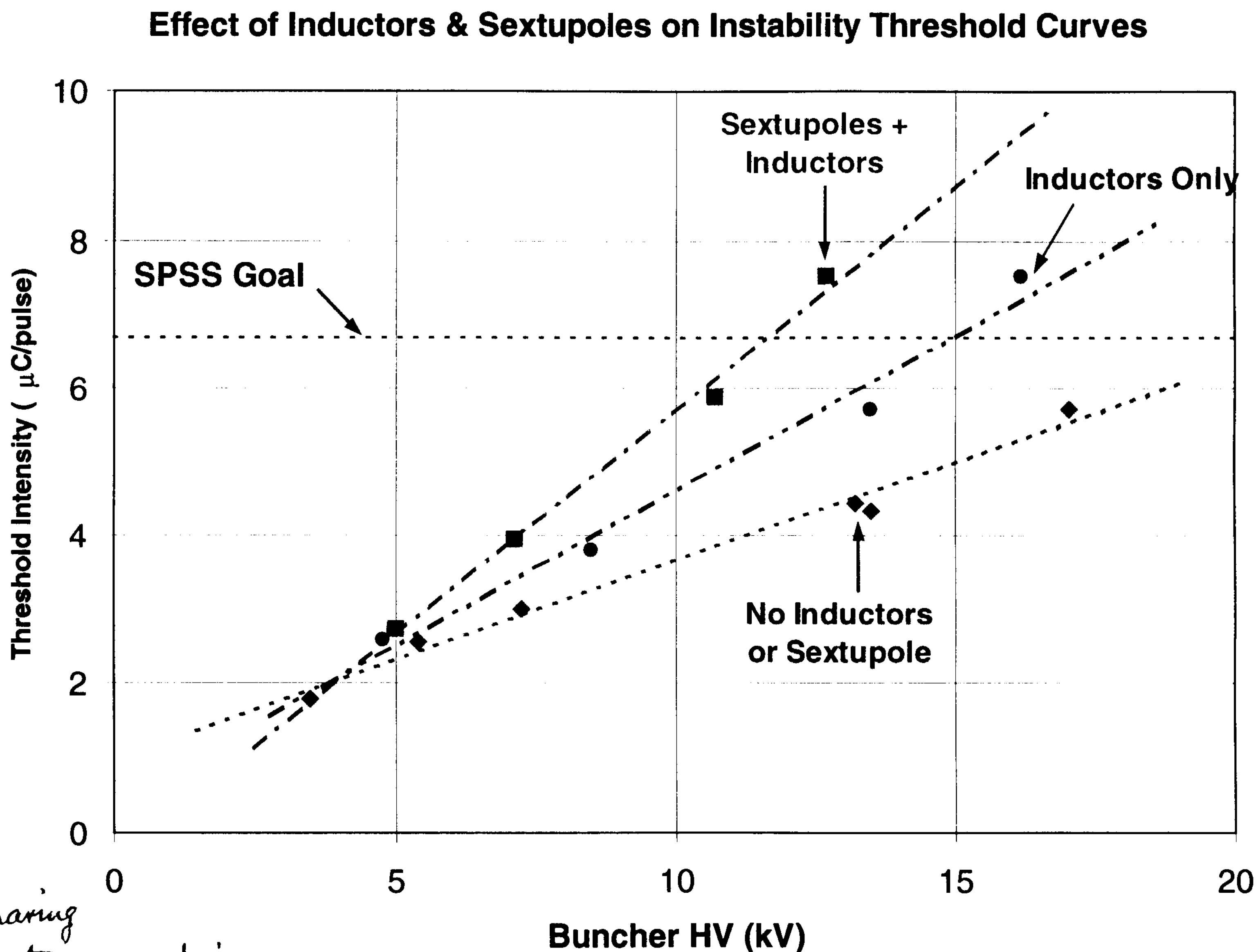


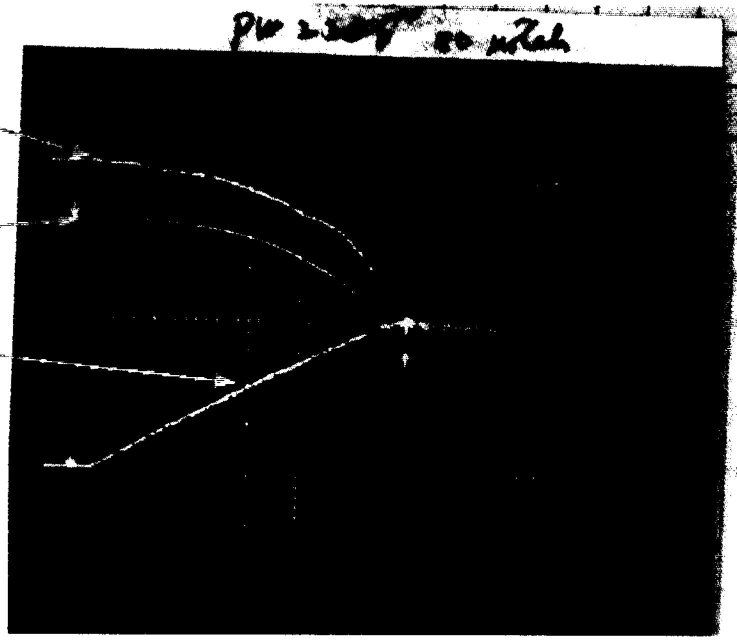
X-Y coupling produces a sharing of stabilizing time spread in both plane for extra damping But there is more loss.

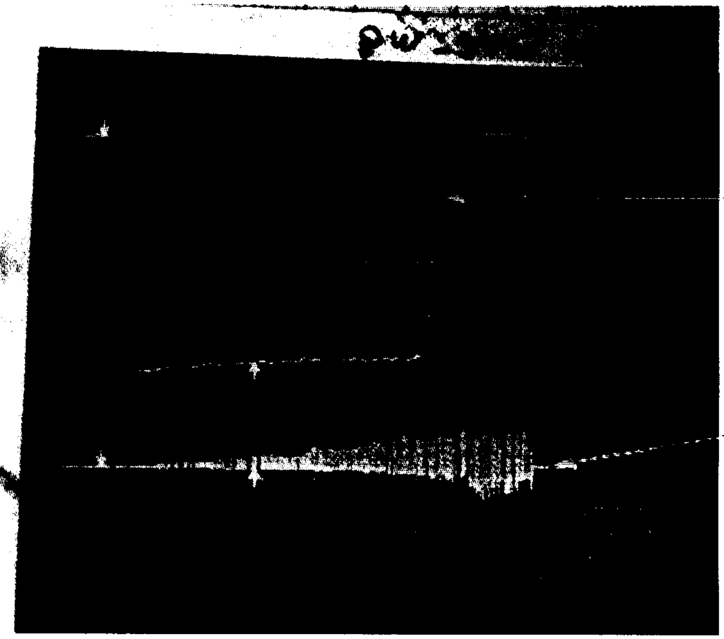
A Record Accumulated Charge of 9.7 μC/pulse

Losses

⇩loss

CM42

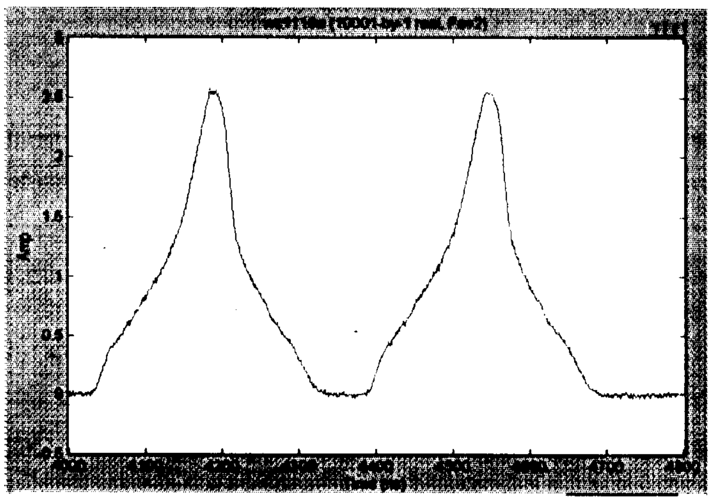




Injected Beam

Vertical BPM Sig

Wall Current Monitor



- **Beam & Ring Conditions**
  - **Accumulation time = 1.225 ms**
  - **Bunch Width 305 ns**
    - — greater than possible with no inductors
  - **Skew Quad = - 8.6 A, Sextupoles off**
  - **Inductors at 190º C overcompensate longitudinal space charge by ~ 50 %**
  - **rf Buncher Voltage = 18 kV**
  - **Peak Current in Ring = 82A**
  - **Bunching Factor = 0.33**

loss ~ 5%