MI-0018

RF INTENSITY LIMITATIONS IN MAIN INJECTOR

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RF Intensity Limitation in the Main Injector

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August 18, 1989

1. I believe that the MR cavities should be fitted with Yt-Ga (Al) orthogonal bias ferrite tuners, replacing existing Ni-Zn ferrite tuners, before transfer to MI.

   This should allow higher voltage per cavity and full voltage at any frequency within the tuning range, and increased cavity shunt impedance.

   I assume here: (guess)

   250 kV per cavity
   R_{sk} = 800 k Ohm
   16 cavities - 4 MV

   This should allow broader bandwidth cavity tuning (and detuning) feedback loop. Eliminate the necessity for a "special" or "vernier" cavity for beam-loading compensation of high beam currents.

   Using these values:

   Cavity Excitation Power

$$P_{cav} = \frac{V^2}{2R_s} = \frac{(250\text{x}10^3)^2}{1.6\text{x}10^6} = 39 \text{ kW/cav} \quad (\text{call it } 40 \text{ kW})$$

   $i_o \equiv i_g$ with no beam

$$i_o = \frac{250 \text{ kV}}{800 \text{ k}\Omega} = 0.31 \text{ Amp}$$

   RF power to beam

$$P/\text{proton} = \left[\frac{eV}{\text{sec}}\right] [1.6\text{x}10^{-19}] = (249\text{x}10^9)\ (1.6\text{x}10^{-19}) = 4\text{x}10^{-8} \ \frac{\text{Watts}}{\text{Proton}}$$

   For 10^{13} protons P_{beam} → 400 rW

   or 25 kW/cav

Number of Protons x 10^{13}	Beam Power	B.P./ Cavity	Total RF Power per Cavity
1	400 kW	25 kW	65 kW
3	1.2 MW	75	115 kW
6	2.4 MW	150	190
10	4 MW	250	290

Each cavity now driven by one 100 kW (150) operating at approximately 50% efficiency. So somewhere between 3 and $6x10^{13}$ protons it will become necessary to add an additional rf power source to each cavity. Not difficult to do - we anticipated this need 18 years ago! But water supply may not be adequate and at $6x10^{13}$, total anode power supply drain will be ~6 MW. Existing anode power supplies ~5 MW and larger tubes required in series tube modulators (probably).

Define

i_o = generator current necessary to develop gap voltage V_o with no beam and cavity tuned to resonance, then with beam generator current:

$$i_g = i_o + i_i \sin\Phi s$$

detuning angle:

$$\tan \Phi = - \frac{i_i \cos \Phi s}{i_o}$$

Note: sign of detuning changes with $\Phi_s > \text{or} < \pi/2$ $\gamma > \text{or} < \gamma_t$

$$P \equiv \frac{\text{Power to Beam}}{\text{Power to cavity}} = \frac{i_i \sin\Phi s}{i_o}$$

$$= - \tan \Phi \tan \phi_s$$

The automatic tuning phase detector limits effective detuning angle to about $\pi/3$. Reasonable acceleration rate with adequate "bucket area" establishes ϕ_s near $\pi/4$ or $3\pi/4$. These limits set a practical limit on P of about 3.

At $6x10^{13}$ ($1.2x10^{11}$ protons/bunch).

Beam current

$$i_{bdc} = \frac{(1.2x10^{11}\ (1.6x10^{-19})}{18.8x10^{-9}} = 1 \text{ Amp}$$

Fourier component at rf frequency depending on B.F. ~1.5 A

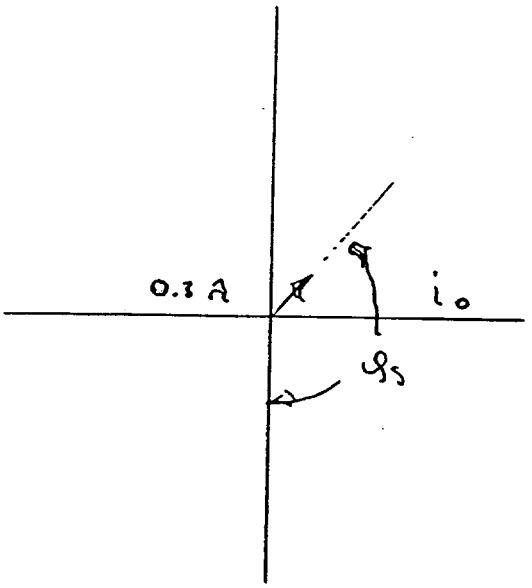
$$\phi_s = 43.6^\circ$$

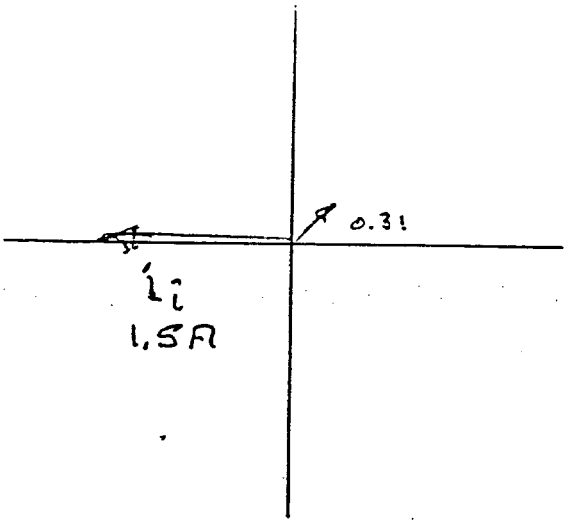
Detuning angle $\text{Tan}\theta = -\dfrac{1.5 \cos 43.6}{0.31} = 3.34$

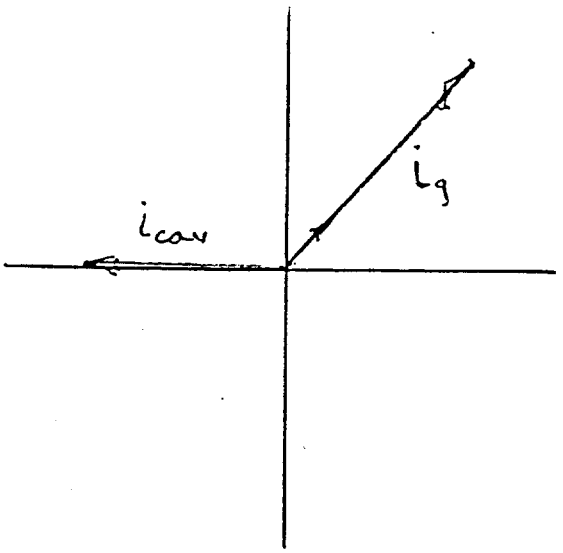
$$\theta = 73^\circ$$

$$\frac{i_1}{i_g} = \frac{1.5}{0.31} = 4.8$$

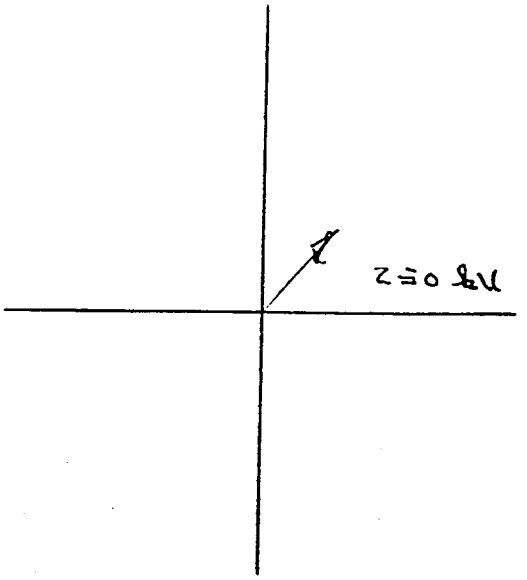
CURRENT

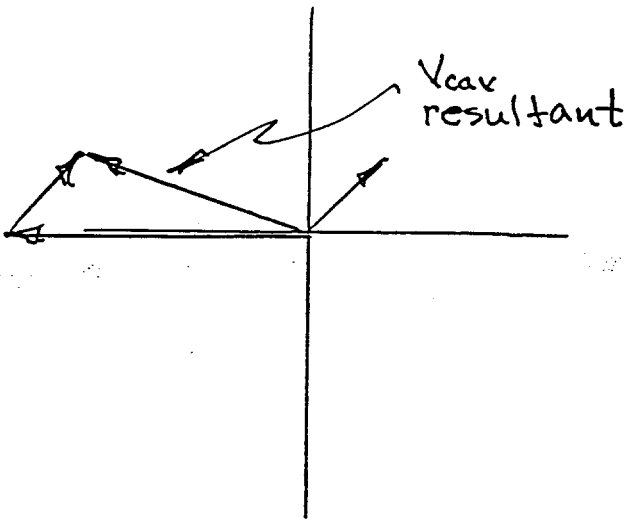


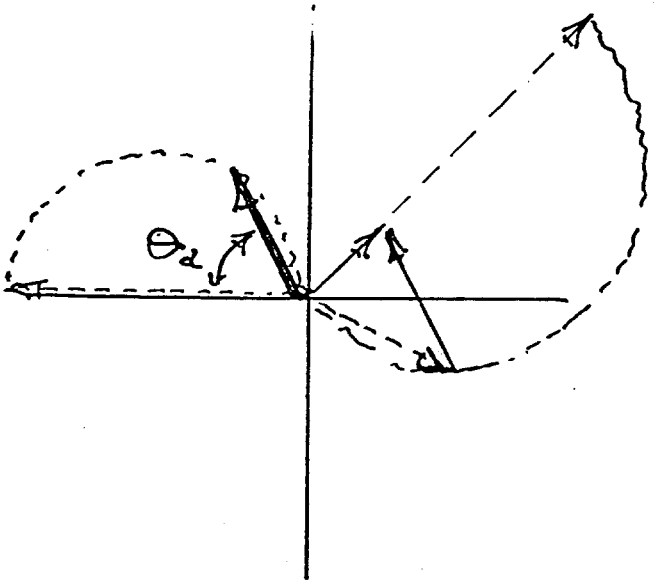


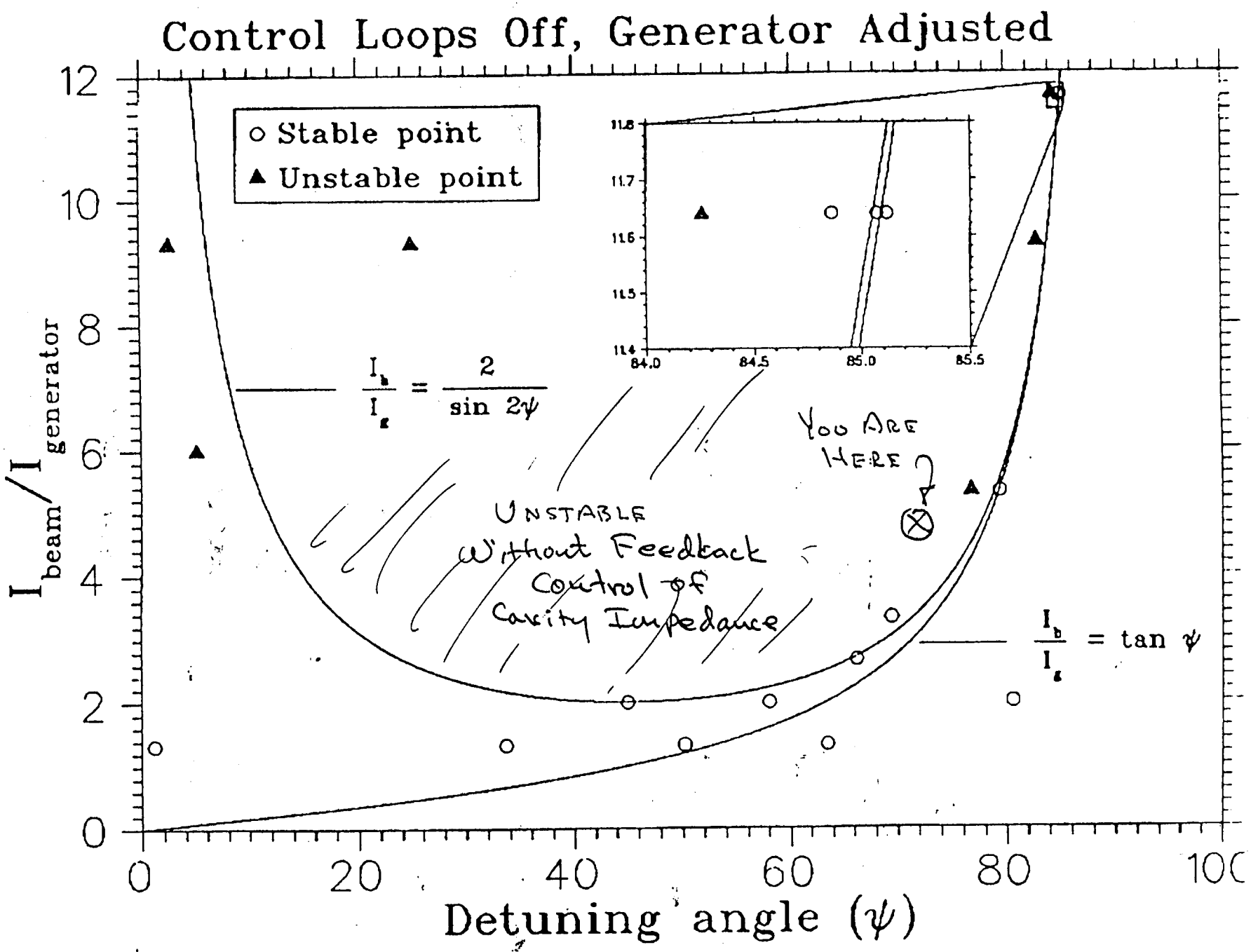


VOLTAGE








Control Loops Off, Generator Adjusted
Stable point
Unstable point
$\frac{I_b}{I_g} = \frac{2}{\sin 2\psi}$
$\frac{I_b}{I_g} = \tan \psi$
You Are Here
Unstable Without Feedback Control of Cavity Impedance
$I_{beam}/I_{generator}$
Detuning angle (ψ)
0
2
4
6
8
10
12
0
20
40
60
80
100
11.4
11.5
11.6
11.7
11.8
84.0
84.5
85.0
85.5

Interim Conclusions

- RF cavities probably okay
- With new tuners voltage limited by breakdown or rf heating of ceramic window
- ~250 kV/cav (more would be nice)
- Additional power tube needed on cavities
- This reflects additional load on series tube modulators, probably larger tube
- More anode power needed - ~ 30 kV @ 50A
- With improved tuners, feedback bandwidth probably (can be made to be) adequate for transient beam loading compensation
- At 6×10^{13} the system is edging into rough ground w.r.t. stability

Proceed carefully!

Recent Developments

Historically rf cavities have been tuned using Mn-Zn ferrite rings. Biassing flux (or current) was parallel to the rf flux (or current).

This created problems.
Ferrite Q ranges 100 -> 1000.
LANL pioneered the use of Yt Ga or other μ-wave ferrite, with orthogonal bias.

The ferrite μ_r is lower - 1.5 to 3.5
but Q is much higher so more
energy can be stored per unit volume

This allows higher gap voltages per cavity - fewer cavities - fewer stability problems. Development condition. Stay tuned.