RF Control Requirements for HINS at Fermilab

Jim Steimel
Bruce Hanna

Motivation

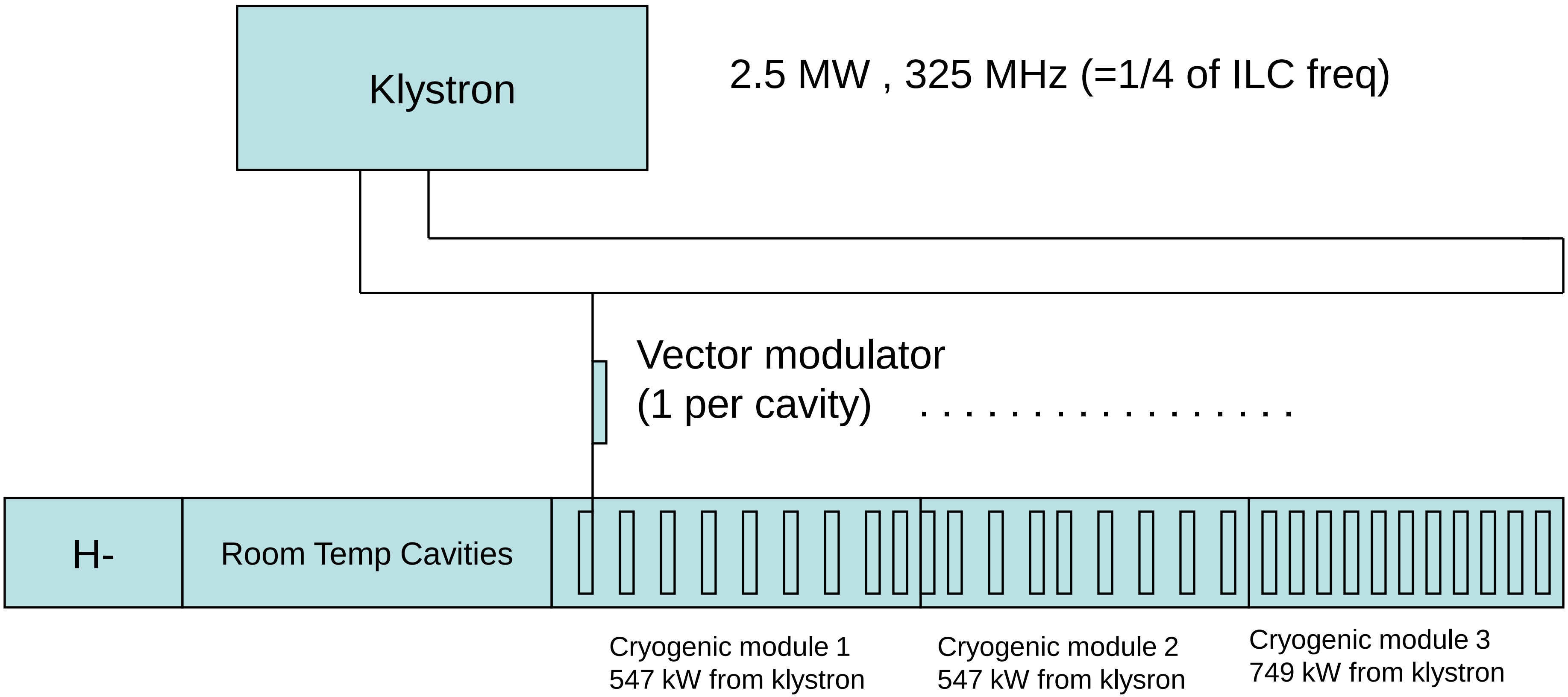
– To demonstrate key technologies in RF power distribution and control, accelerating structures, and beam optics as applied to a high intensity, low-energy Linac that might serve as the front-end for a proposed 8 GeV H- Linac

- The H- ion source, RFQ Room temperature cavities and the first 3 cryo modules comprise HINS

The Linac Parameters

Parameter	Quantity	Unit
Particle Species	H- ion	
Output Beam Energy	8.0	Gev (kinetic)
8-GeV Beam Power	360	kW
Particles per Pulse	5.625	E13
Pulse Repetition Rate	5	Hz
Beam Pulse Length	1	msec
Average Pulse Beam Current	9	ma
Beam Chopping at 2.5 MeV	- 6% at 89 kHz for 700 ns MI abort gap - 33% at 53 MHz 'pre-bunching' for RR	
Particles per Linac bunch	2.73	E8
Nominal Bunch Spacing	4 / 1.3 = 3.1	nsec
8-Gev Transverse Emittance	$\varepsilon_H = \varepsilon_V = 0.4$	mm-mrad RMS
8-GeV Longitudinal Emittance	2.5E-6	ev-sec/bunch RMS
8-GeV Energy Spread	At Linac output – 2.7 At RR injection – 0.3	MeV RMS
8-GeV Bunch Length	At Linac output – 1.0 At RR injection – 8.6	psec RMS

HINS Layout



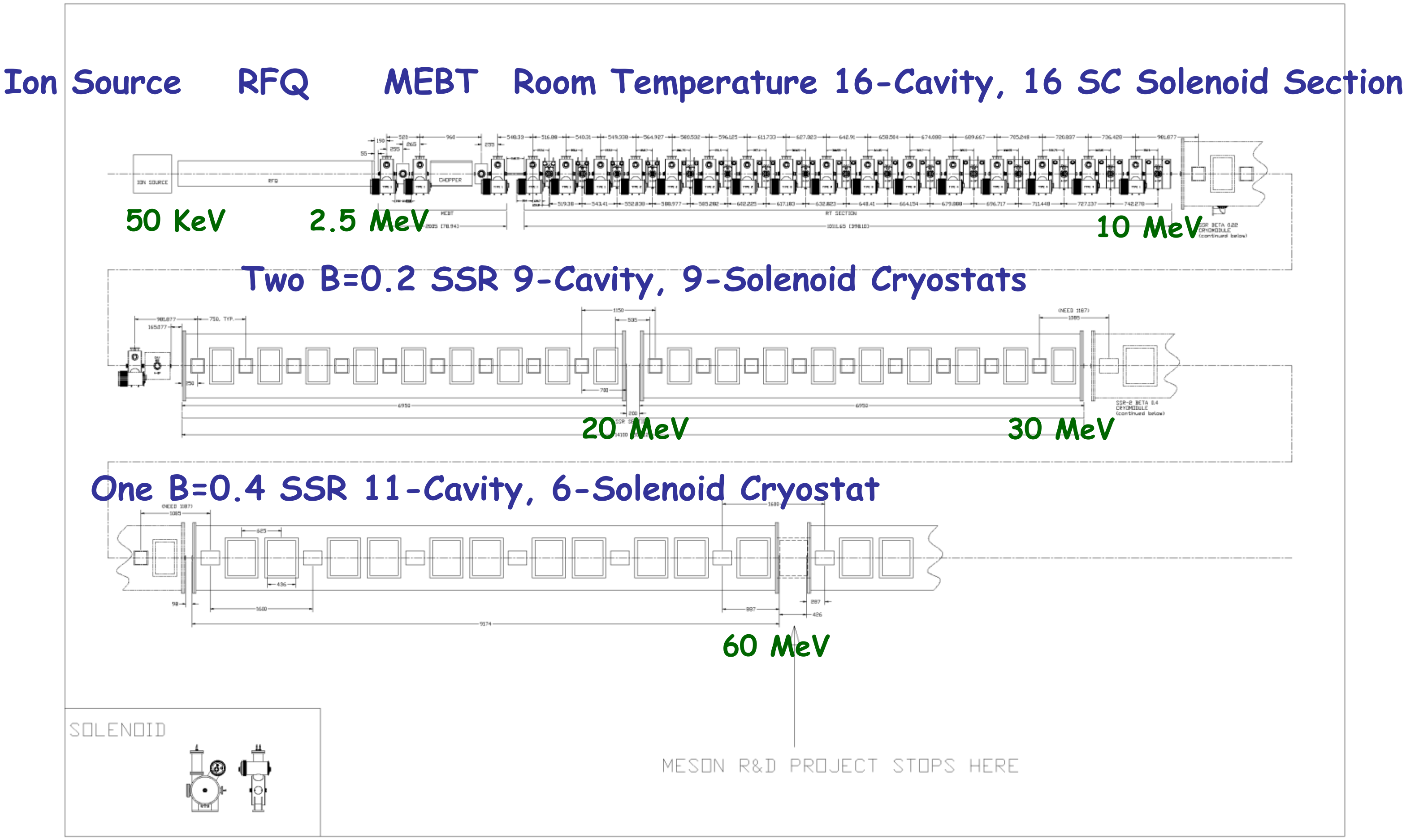
-Cavities operate at 325 MHz
-SCRF cavities are single spoke cavities
-1 msec pulse at 10 Hz or 3.5 msec pulse at 2.5 Hz
-Beam current ~ 10 mA
-29 Single Spoke Cavities
-60 MeV energy

325 MHz HINS Toshiba Klystron

Why 325 MHz?

- Both TESLA (1300 MHz) and SNS (805 MHz) compatibility were considered back in 2004. TESLA compatibility was chosen for the following reasons:
- - only 2 klystron types were needed
- - fewer klystrons
- -no klystron R&D needed
- -there exists a useable coupler design.
- -waveguide components are smaller and cheaper
- These overrode the SNS advantages:
- -successful models existed for 3 out of 4 cavities
- -only 3 beta ranges were required to cover the beta<1 region. (6 cell 805 MHz
- cavities have larger vertical acceptance than 9 cell 1300 MHz cavities)
- - waveguide losses are lower
- -Accelerator physics is well documented
- 325 chosen because fewer cavities needed and acceptance ~1/freq^3

Layout Through Second β=.4 Cryostat



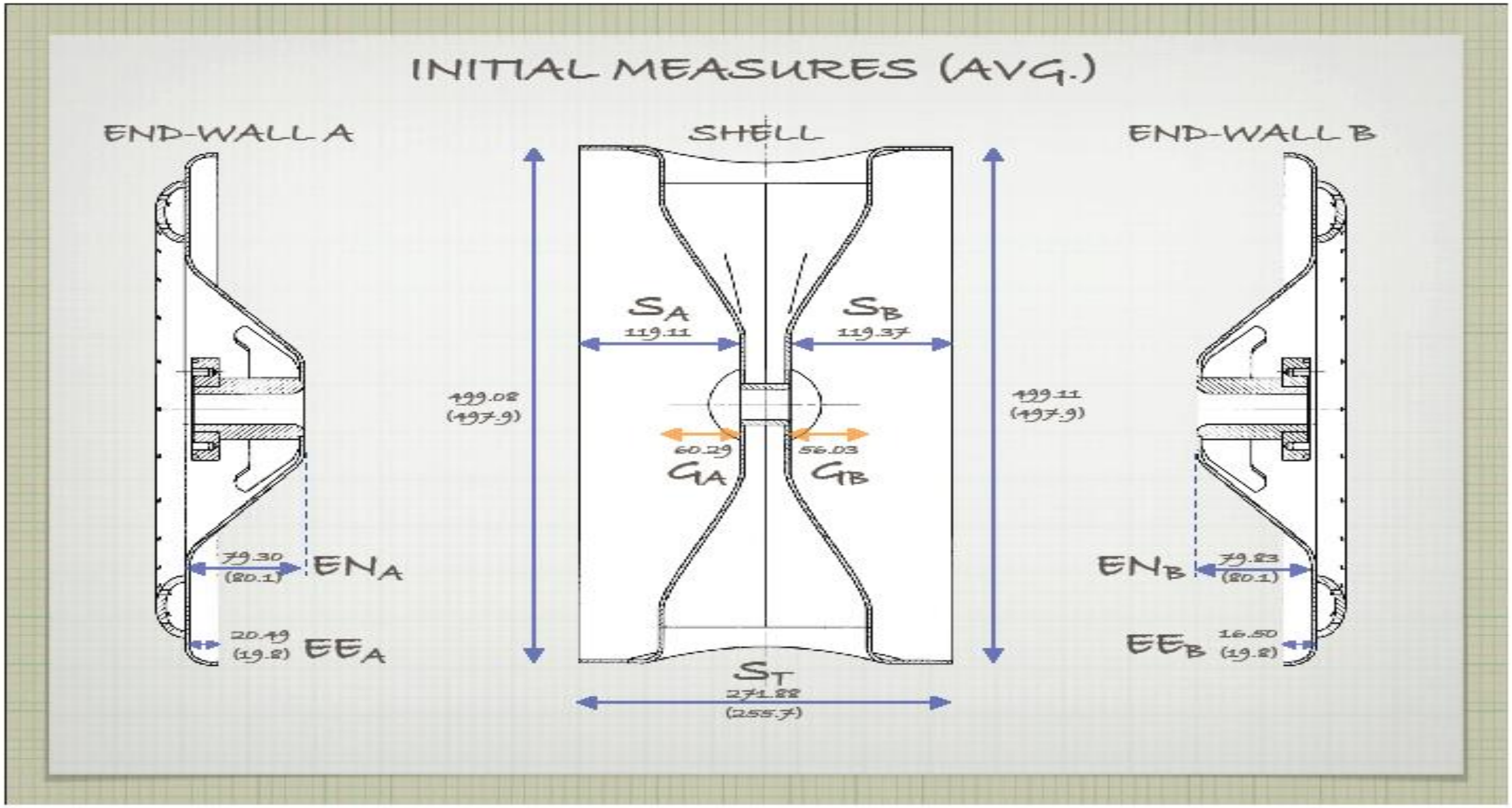
Experimental Program

- Project X will deliver 2 MW of proton beam power for Neutrino production.
- Graphite target is planned:
  - expect 1 year lifetime due to rad damage
  - Cooling design work needed
- Protons also available for study of rare processes.

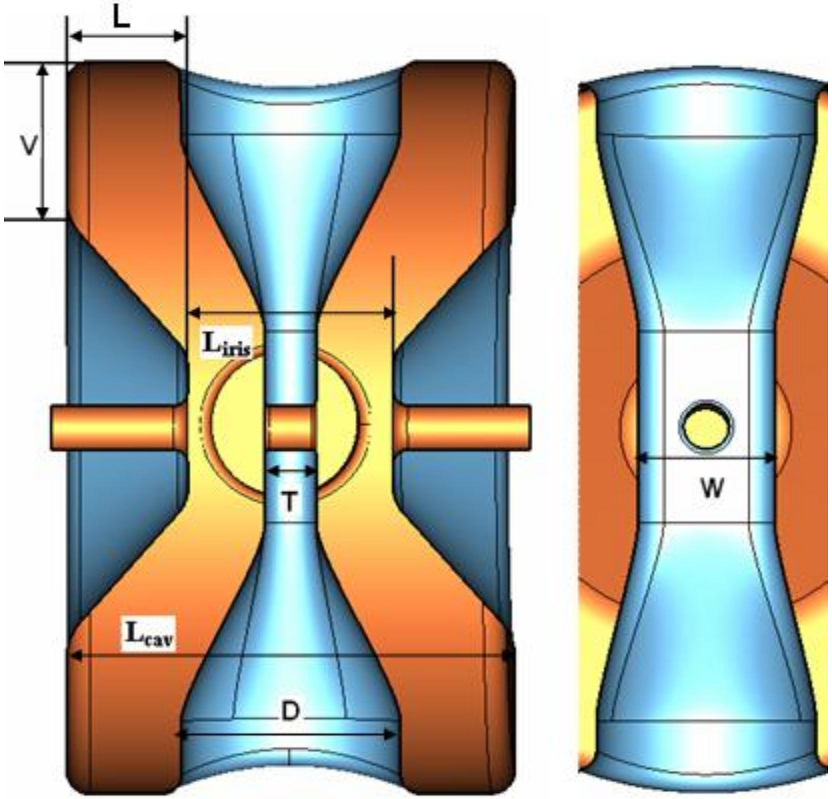
Superconducting RF Componenets

- Single Spoke Resonators: one on hand and tested in vertical test stand, 1 more being processed, need 27 more
- Cryostats and cryogenics: In process of being designed by outside vendors
- Non adjustable coupler design is complete and 3 are being built
- Spoke resonators will operate at E (peak)=32MV/m and E (acc)= 10 MV/m. The synchronous phase =-30 degrees and the effective cavity length = 9.2 cm

Initial mechanical measurements for SSR1-01



Optimization of cavity shape



	R/Q			
V \ L	50	60	70	80
30	234.19	236.89	238.16	239.8
55	240.67	243.76	246.19	249.14
80	248.41	251.77	256.2	259.61
105	257.27	262.66	267.63	272.24

	Epeak/Eacc			
	50	60	70	80
30	2.86	2.83	2.73	2.69
55	2.83	2.74	2.72	2.66
80	2.84	2.69	2.64	2.62
105	2.69	2.64	2.61	2.55

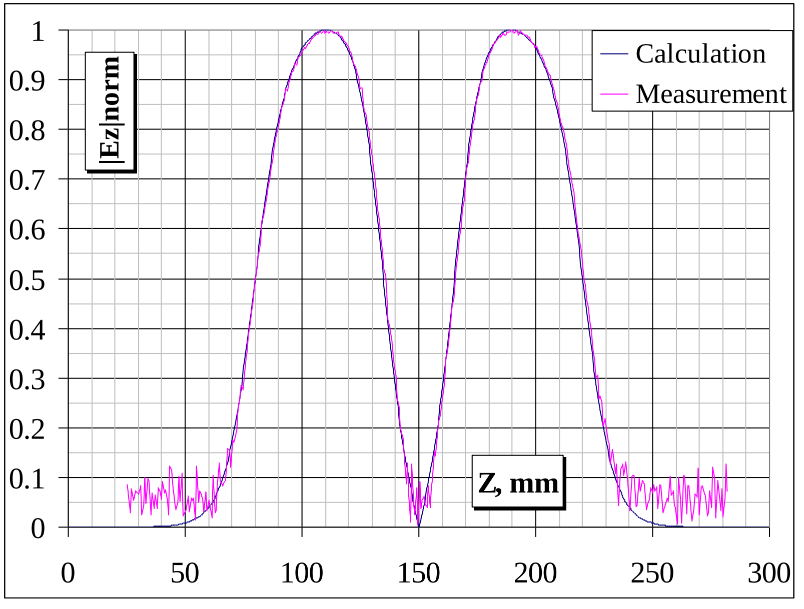
	Q			
	50	60	70	80
30	1.41E+09	1.44E+09	1.39E+09	1.45E+09
55	1.44E+09	1.50E+09	1.55E+09	1.51E+09
80	1.49E+09	1.53E+09	1.60E+09	1.65E+09
105	1.52E+09	1.58E+09	1.65E+09	1.71E+09

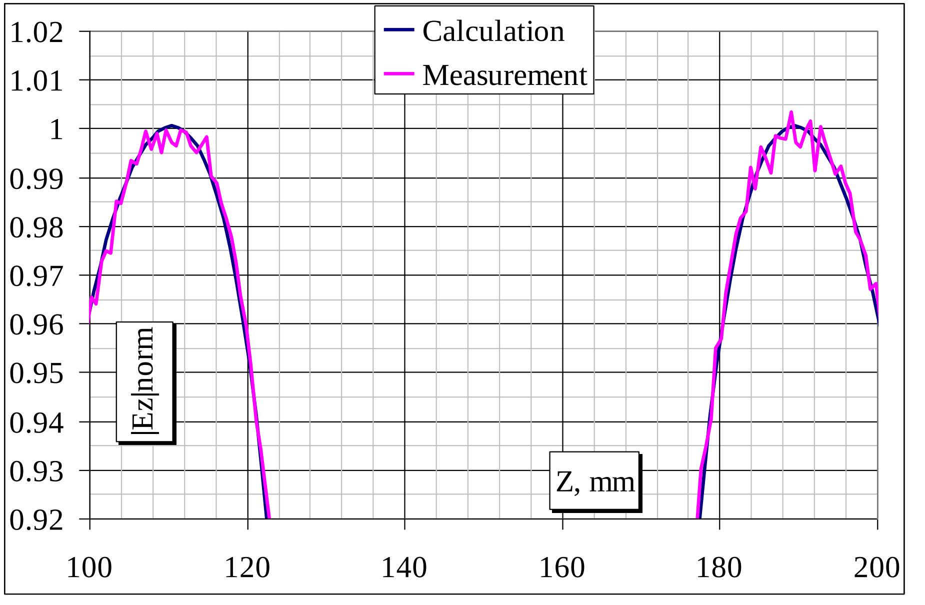
	Bpeak/Eacc			
	50	60	70	80
30	7.06	6.30	5.83	5.35
55	6.86	6.22	5.71	5.23
80	6.65	6.02	5.52	5.08
105	6.50	5.88	5.36	4.87

Typical Chart of the Meson Linac Cavities

	RT Cavity #8	SSR1 Cav#8	SSR2 Cav#8
β	2.624719	7104.275	5616.088
Q_L	3,222.32	2.6741E5	4.4507E5
Τε	0.991 us	261.91 us	435.91 us
Beam time **Beam Time = .6931 τε**		Need Apply Attenuation so it arrives same Beam time	302.13 us

Bead pull results for SSR1

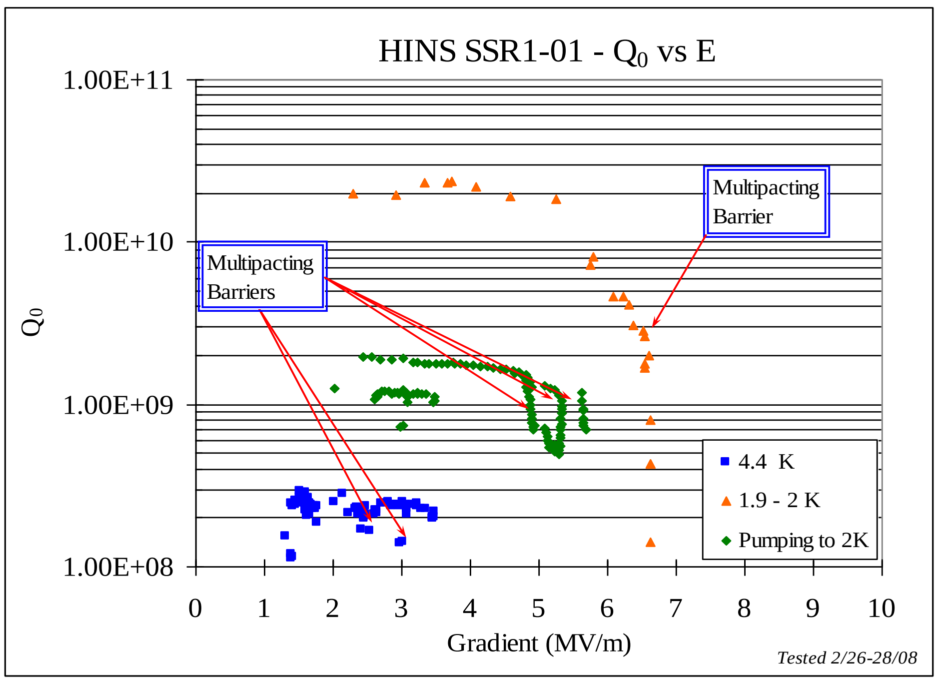




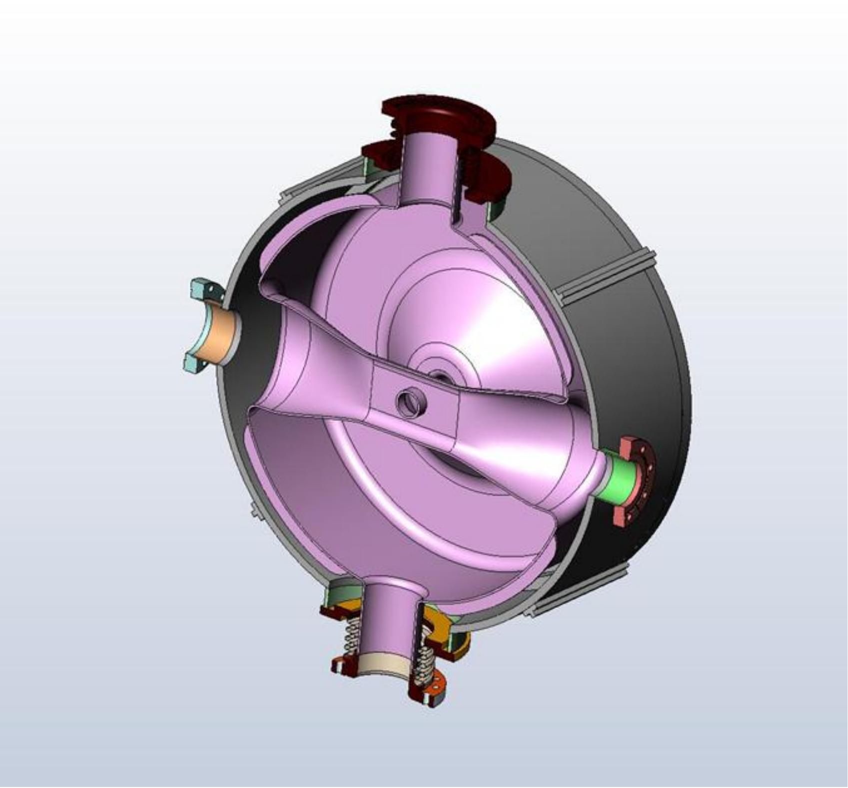
These show a cell spacing = 80 mm
(As built after fourth trim has 85 mm)

Recent results from vertical test stand

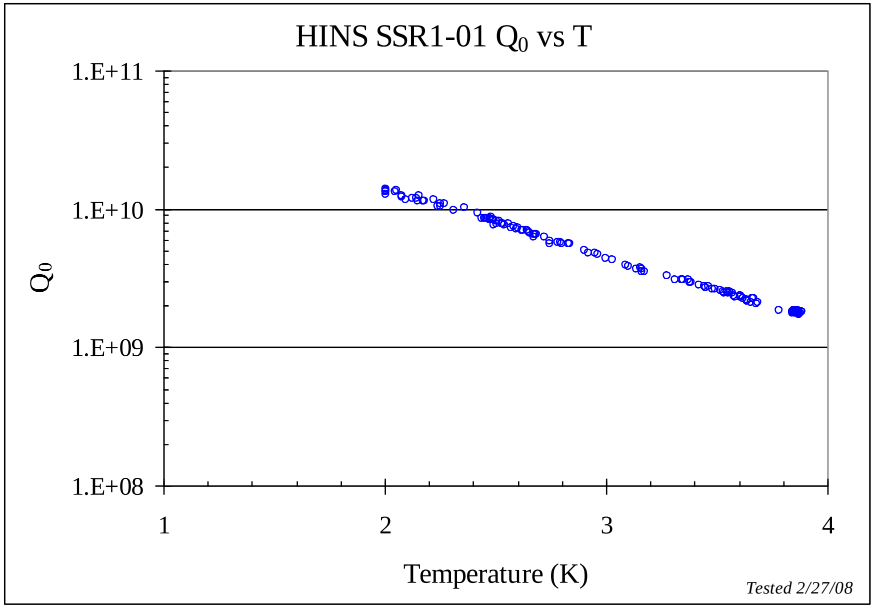
- HINS SSR1 Vertical Test Summary
- Data taken 2/26-2/28/08

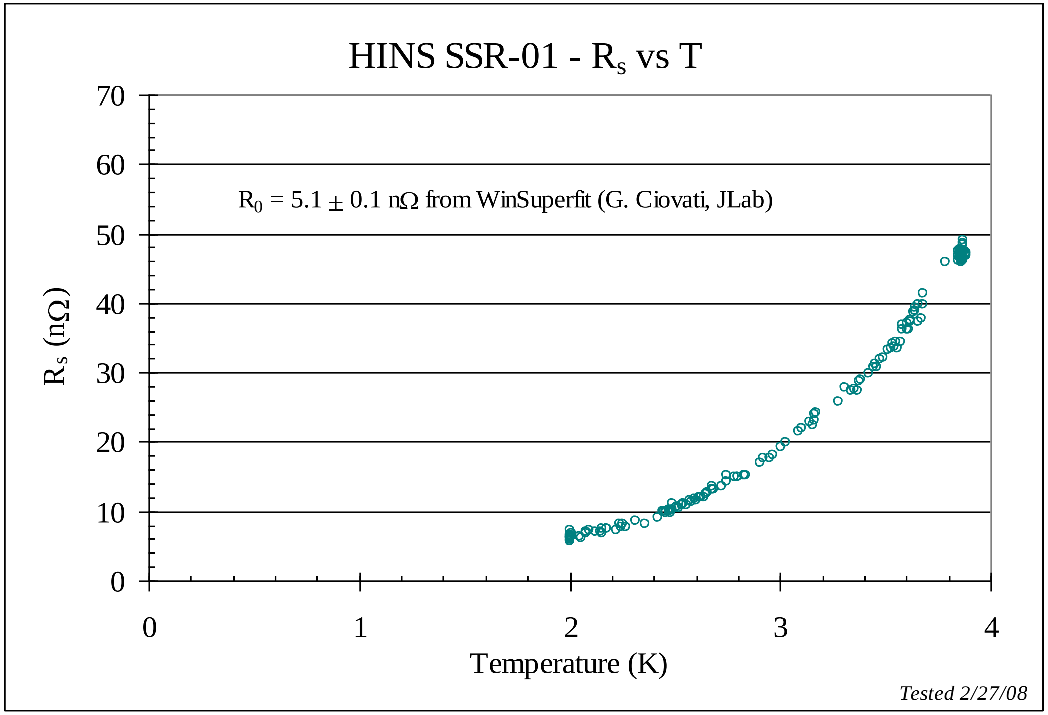


Single spoke resonator drawing



More HINS SSR1-01 vertical Test Summary From 2/27/08





Plans for SSR1-01, 5-15-08

- Hasan Padamsee was at Fermilab for an accelerator review, and we talked with him about the completed tests of the SSR1-01 in the VTS and plans for a test in the near future (before a high temperature bake):
- **Previous VTS tests:**
  - Mid-range E_{acc} (2 to 10 MV/m): No evidence for non-multipacting x-rays, and the Q drop is possibly (probably?) due to hydrogen (Q disease).
  - High E_{acc} (10 to 13.4 MV/m): x-ray evidence beyond multipacting indicates the likelihood of field emission. The Q drop here may be due to Q disease, field emission, or a combination.
  - Condensates due to "bad" vacuum could definitely have exacerbated the multipacting problem.
- Also suggested: Another HPR and 120 degree bake

Purpose of Accelerator RF Control System

- Maintain proper gradient and synchronous phase angle in every RF cavity to preserve beam longitudinal emmitance and energy as specified by the lattice design.
- Make efficient use of available klystron power for accelerating beam.
- Protect the RF cavities and equipment from damage due to RF power.
- Provide beam and RF diagnostics.

RF Control Devices

Device	Speed	Individual Cavity	Range
Klystron	100ns	No	Full Power/Full Phase
FVM	10us	Yes	***
Tuners	1s	Yes	???

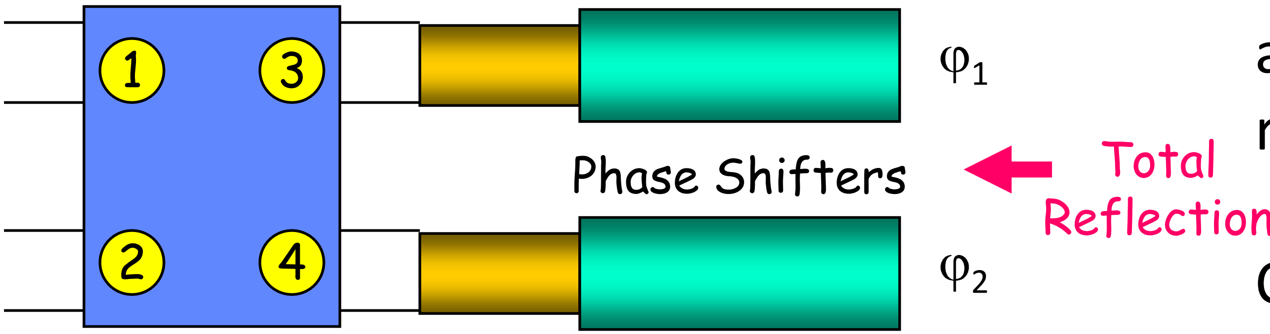
*** FVM has an amplitude range of about 10dB or a phase range of +/- 100˚.

- We would like to maximize the use of the klystron for RF control with its flexibility.
- FVMs are used to compensate for cavity-to-cavity differences that require tuning within a RF pulse.
- Tuners are adjusted slowly and cannot be used for tuning within a RF pulse.

Limitations of FVMs

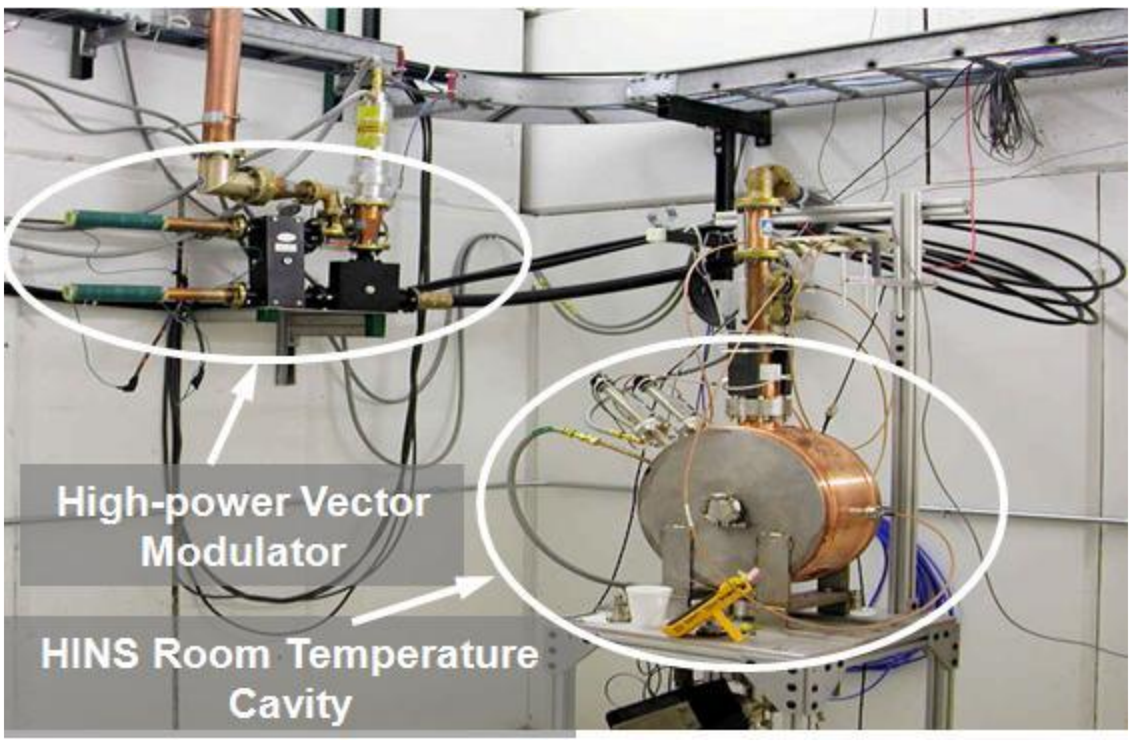
- Tuning range is limited. Large attenuation values limit phase range and visa-versa.
- They cannot act as RF stops. At best, they can attenuate by about 20dB.
- They are not very fast. Currently about 2.2 degrees per us.

Vector Modulator



Vector Modulator controls the phase and amplitude of the rf to the cavities.

Control is done by adjusting the current in solenoids on the phase shifters.



Modulates phase and amplitude independently:

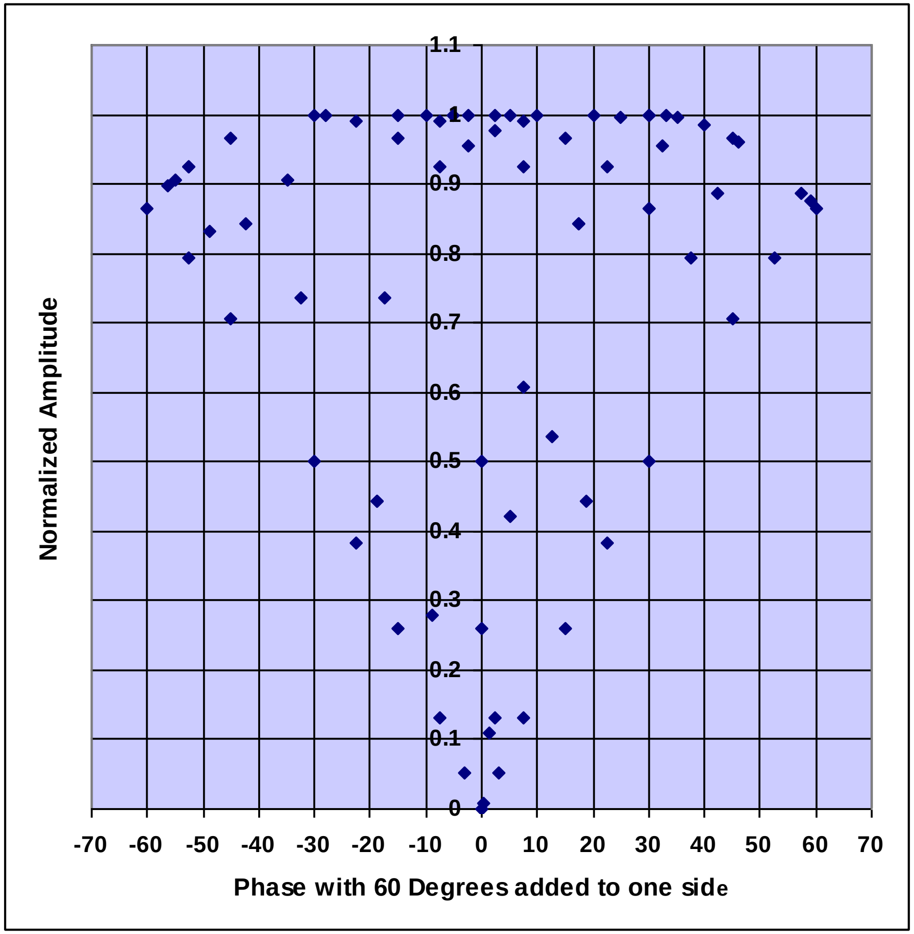
With $\Delta\Phi = (\Delta\phi_2 - \Delta\phi_3)/2$

$\Phi = (\Delta\phi_2 + \Delta\phi_3)/2$

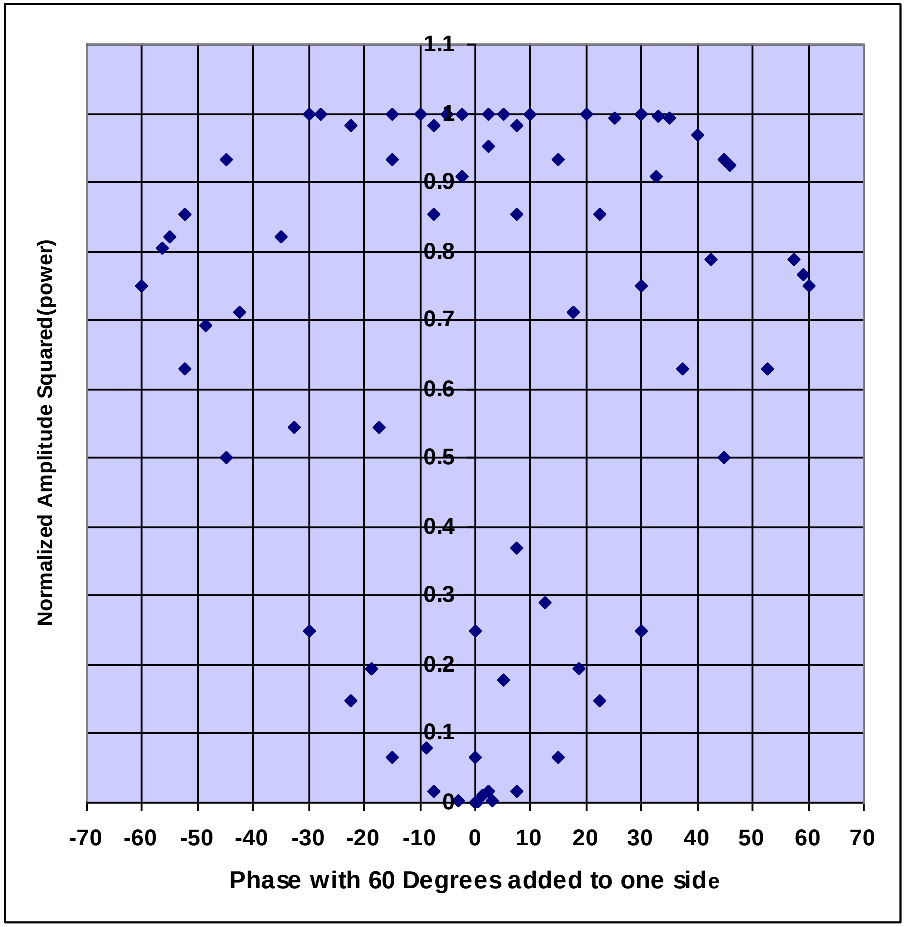
Output power ~ $\cos^2(\Delta\Phi)$

Output phase ~ Φ

Hybrid Output with 60 Degree Section Added to One of the Ferrite Phase Shifters



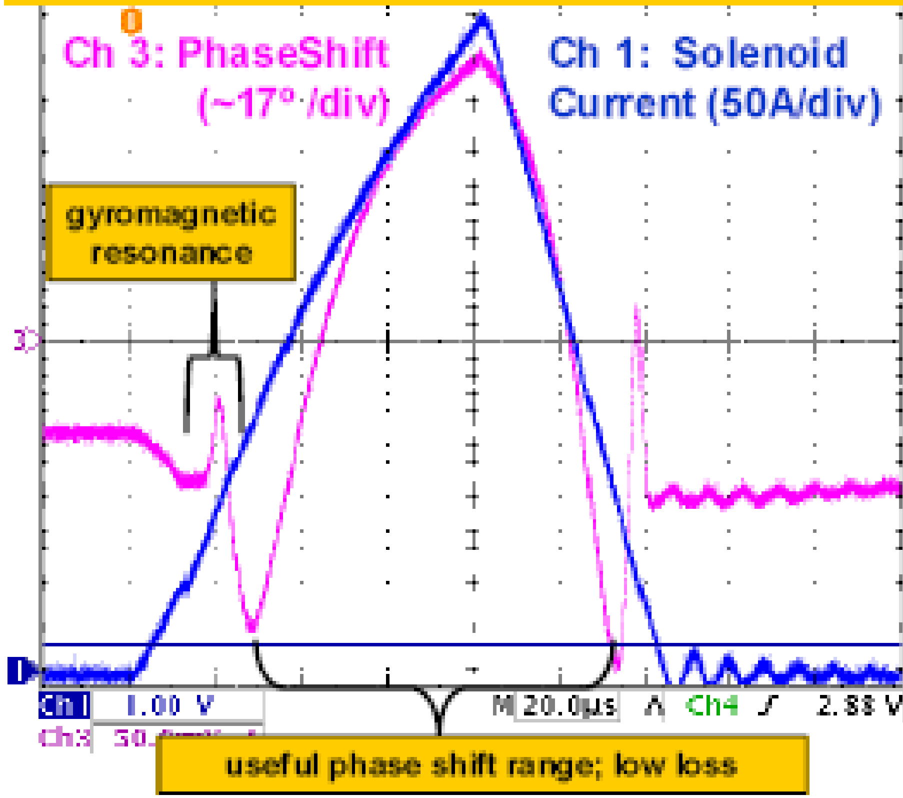
Amplitude vs Phase

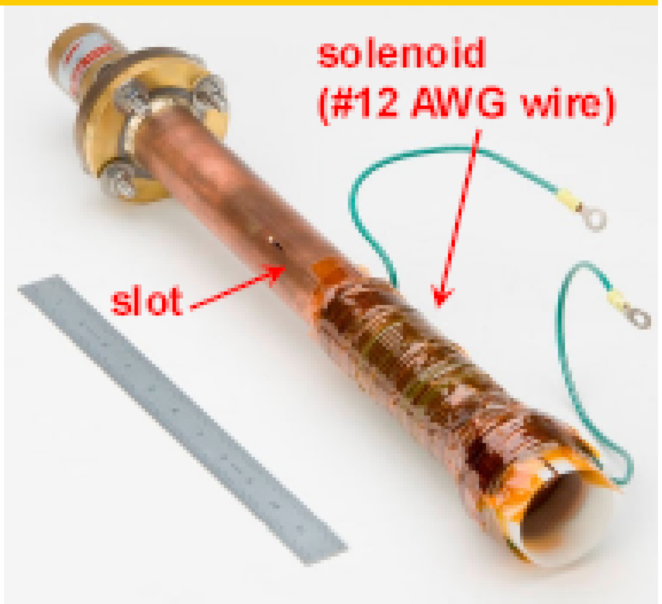


0

Power output vs Phase.

Fast Response Measurements: 1⅝" OD





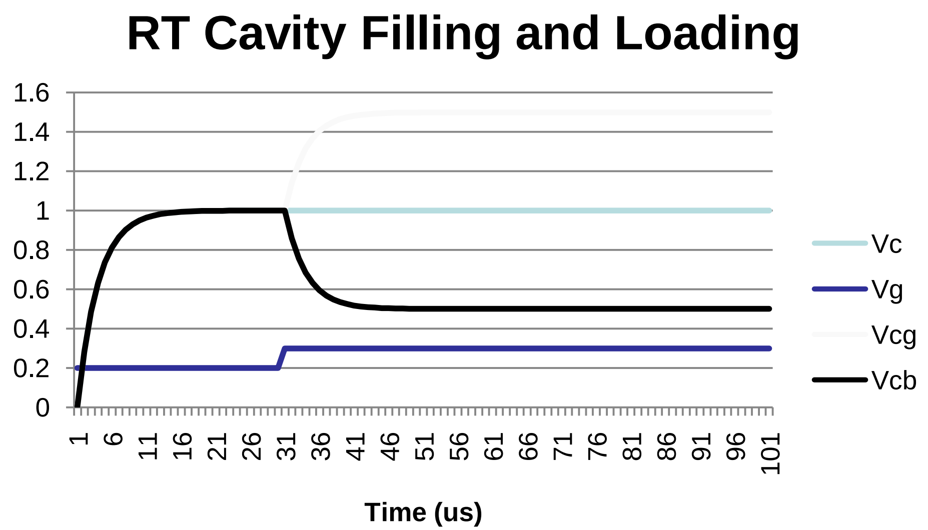
- *Outer conductor is slotted to eliminate eddy currents*

- *Useful phase shift range above resonance: ~50µs, 110°*

- *This gives an average slew rate of 2.2°/µs*
(twice as fast as design spec)

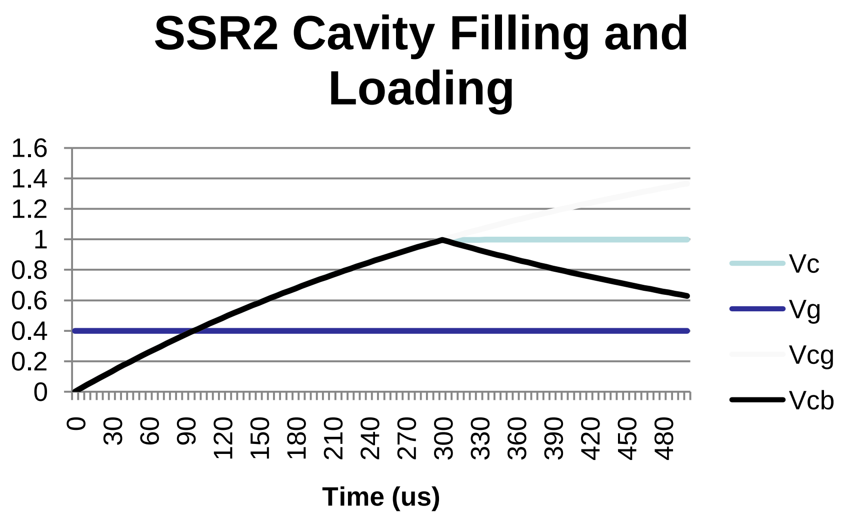
Cavity Filling

- All cavities require a certain amount of filling time.
- The time constant is about 2Q/ω0.
- Copper cavity time constant is about 3us.
- Cavity drive is set to bring cavity voltage up to nominal value.
- Drive is increased at beam injection to compensate for beam loading.



Cavity Filling

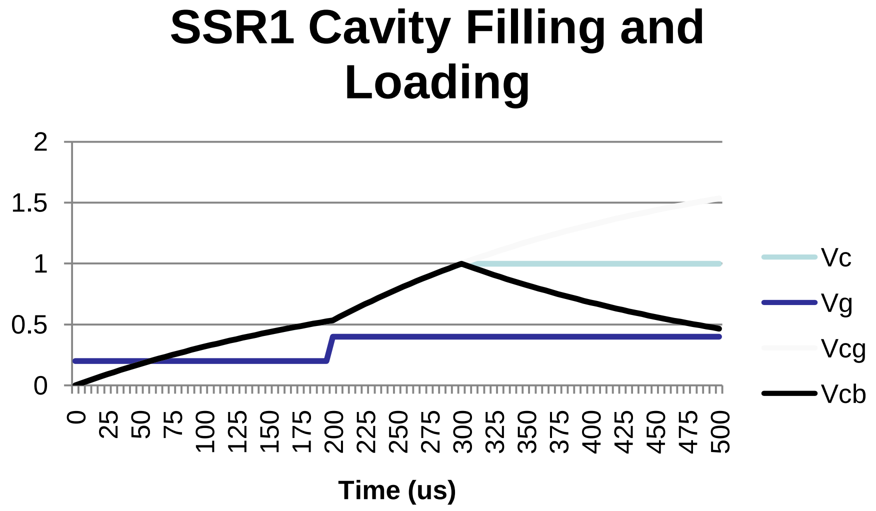
- Cavity filling time of SSR2 cavity is prohibitively long (~500us).
- Don’t want to waste very expensive klystron duty cycle on filling.
- Solution: Drive cavity at full beam loading power and inject beam when voltage is at nominal accelerating gradient.

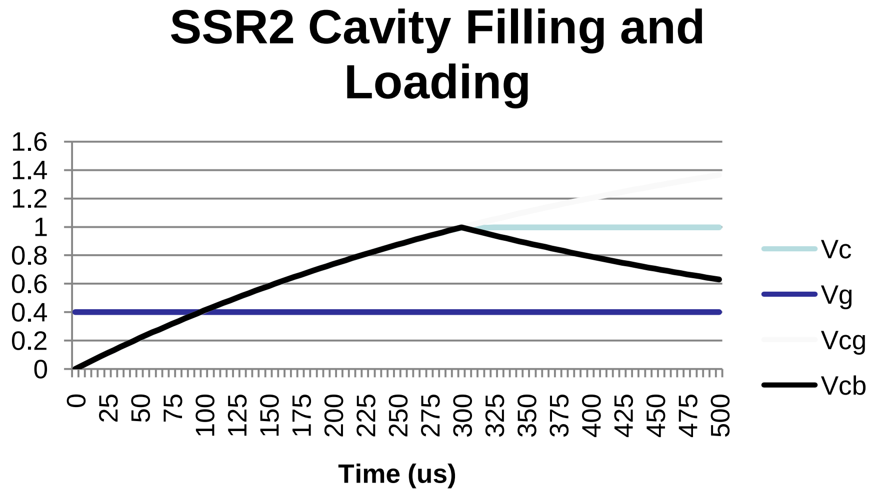


Cavity voltage reaches ½ max when t=τ/ln(2)

Cavity Filling

- Cavities do not fill with the same time constant.
- SSR1 cavities have time constants that are about ½ the SSR2 constants.
- Need to utilize FVM to reduce power drive and increase filling time.
- Use a feedforward algorithm to adjust amplitude and/or timing of FVM change to maintain a smooth beam on transition.



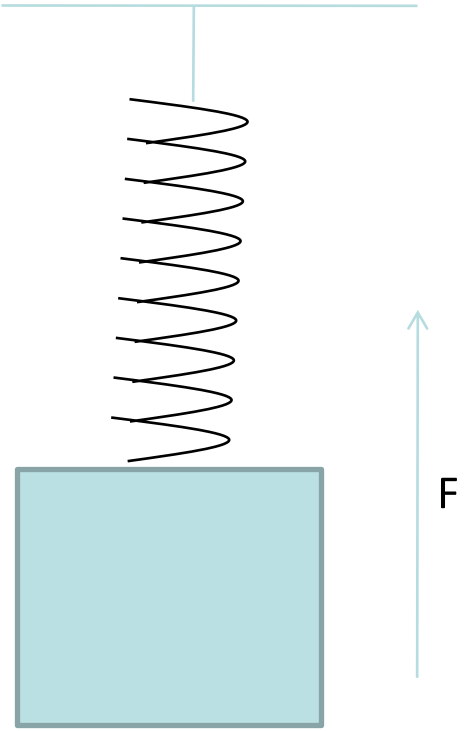


Lorentz Detuning

- SSR1 spoke resonator has measured Lorentz detuning coefficient of ~4Hz/(MV/m)^2.
- Cavities will be run with a gradient of about 10MV/m.
- Lorentz detuning will be ~400Hz from zero to full gradient.
- Bandwidths of loaded SSR1 and SSR2 cavities are 1220 Hz and 730 Hz respectively.
- Lorentz detuning will cause significant changes to cavity impedance which could be difficult for the FVMs to compensate.

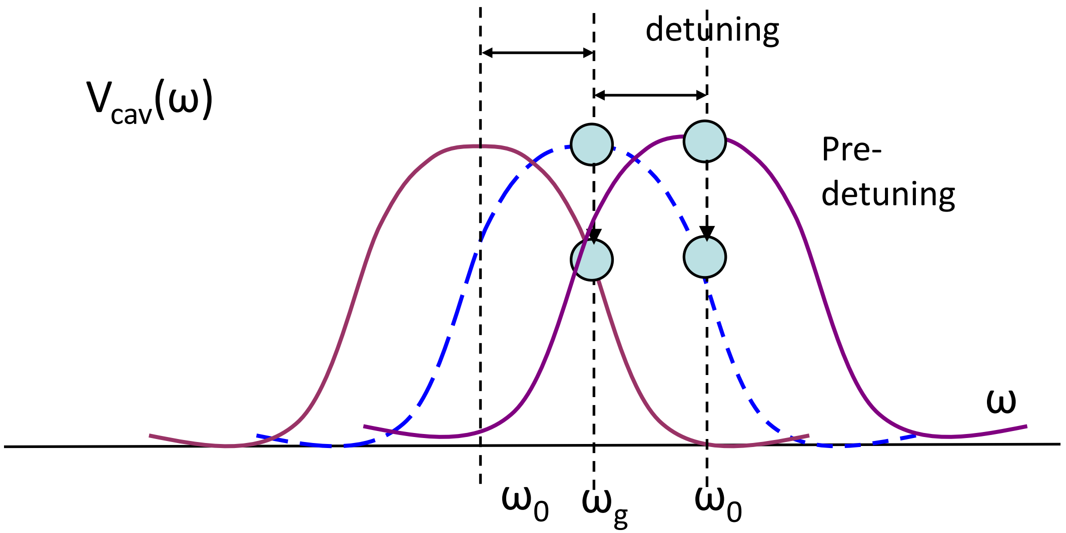
Dynamic Lorentz detuning

- Lorentz detuning is not instantaneous.
- If a sudden force is applied to a harmonic system, the mass takes time to find its equilibrium.
- This time is a function of resonant frequency and damping constant.
- Time constant is probably on the order of the RF pulse width.



Dynamic Lorentz Detuning

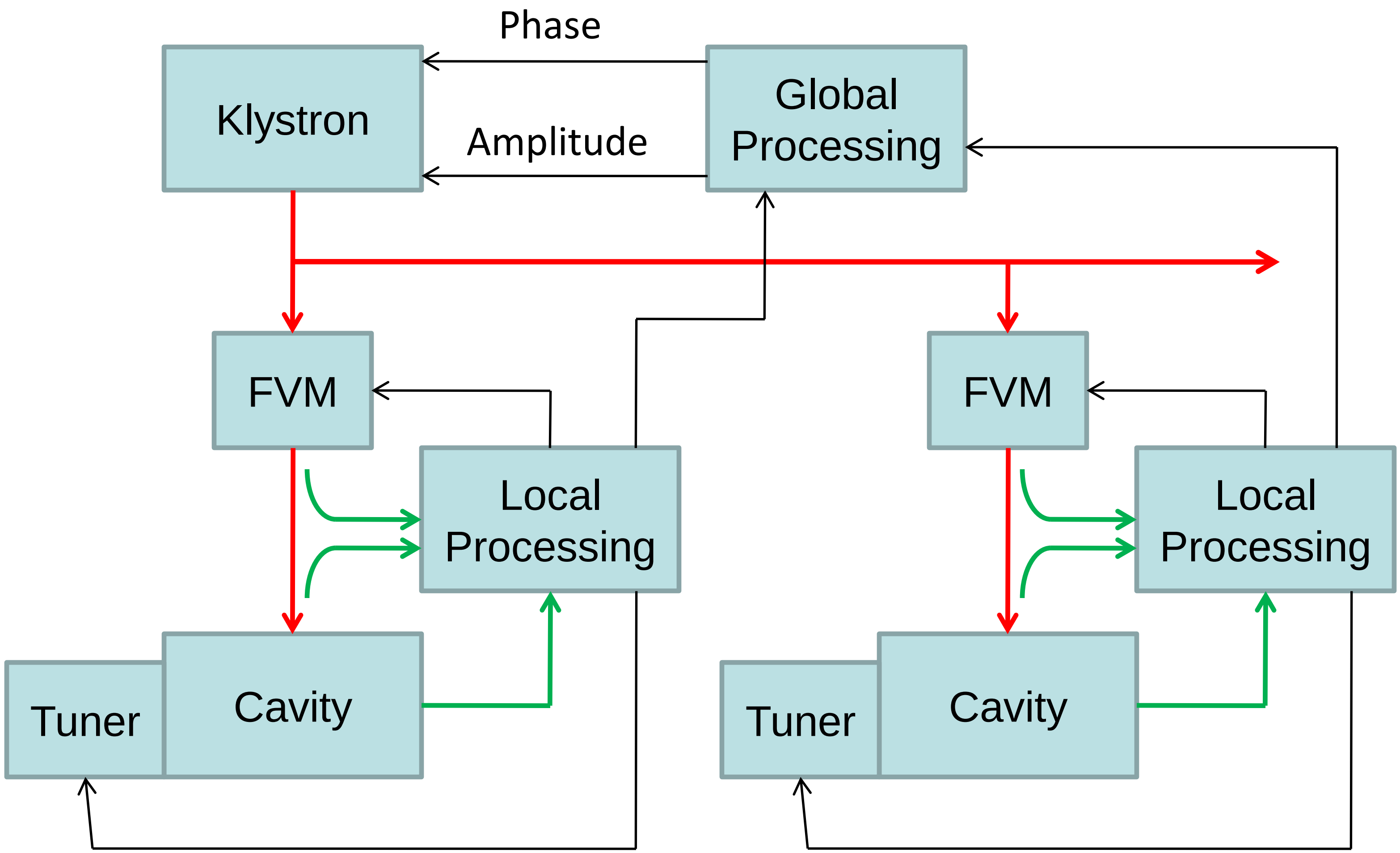
- The cavity tuners should be set to minimize the cavity excursion from resonance during the beam pulse.
- The tuners should sample the frequency error at the median Lorentz detuning point during the beam pulse.



RF Instrumentation

- The local processors at each cavity must be able to capture and store the phase and amplitude of the forward, reflected, and cavity power monitors.
- With the phase and amplitude informa-tion, other parameters can be calculated, such as resonance frequency error and beam synchronous phase.
- Information can be used to control tuners, correct for microphonics, correct for global energy errors, etc.

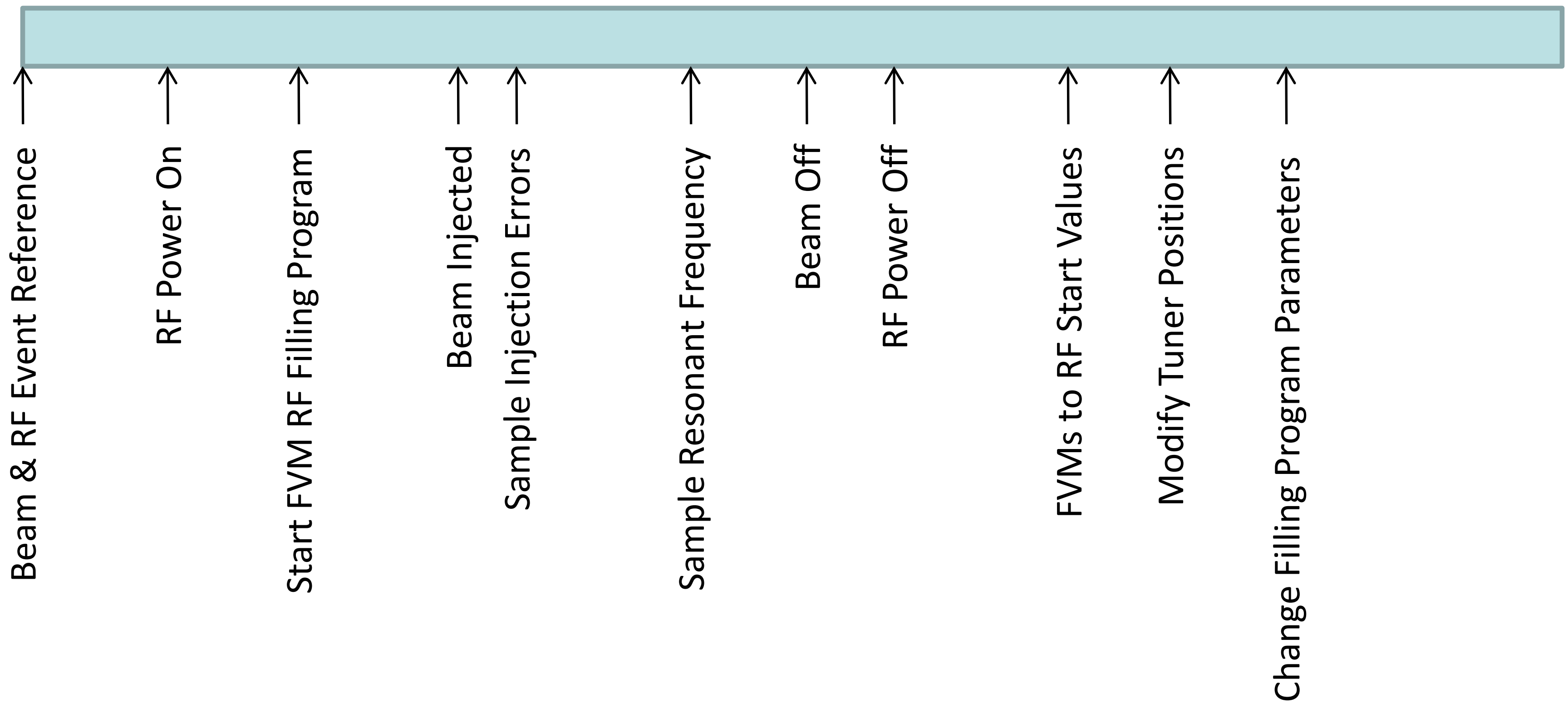
Block Diagram of RF Control



Interlocks

- A dedicated control path must be used between the power detectors and the klystron.
- FVMs cannot protect cavities. All cavity protection must involve cutting off power to the klystron.
- Each local processor will have a dedicated comparator on the three RF amplitude signals (forward, reflected, and cavity).
- The logical and of these signals will go directly to some cavity interlock fanback circuit that will disable the RF gate and beam permit.

Timing Diagram



Beam Current Stability

- The control issues with the FVMs discussed so far assume that the beam current is relatively stable.
- It is not apparent that the FVMs could respond to unexpected changes in beam current fast enough to preserve a pulse.
- May need to rely on klystron for global energy monitoring and adjustment.

Conclusions

- Still a lot of work to do.
- Control system needs to be constructed before room temperature cavity section is commissioned. (We don’t want two separate systems).
- Need to more carefully design control loops and their parameters.