Main Injector HLRF Anode Limit Program & Cavity Tuner RF Voltage Limit

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Introduction: Presently the Main Injector (MI) cavity ferrite tuners are protected from RF sparking by taking advantage of the natural saturation of the RF power amplifier (PA). The protection is implemented through an anode limit program (ALP) that limits the PA anode bias. Since the Series Tube Modulator (STM) and RF PA form a series circuit, this ALP function also places a constraint on the STM voltage drop and hence the maximum current that the circuit can withstand before exceeding the power dissipation limits of the STM. The Proton Plan intends to perform multi-batch slip-stacking at injection which will require increased average STM current at the highest STM voltage drop. The STM power dissipation could be relaxed if ALP is raised at injection. This note documents the present and past status of ALP as well as MI-60 test station measurements made on a MI cavity to understand the cavity tuner RF voltage limit.

Present & Past ALP Files:

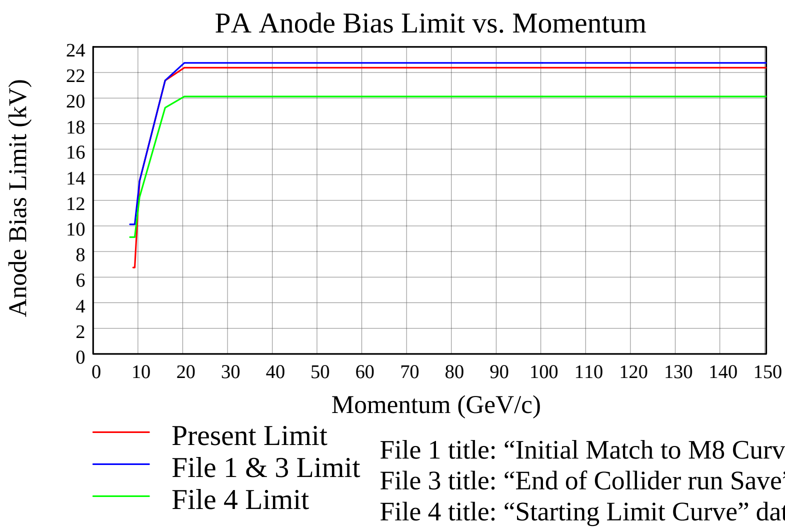
The STM output voltage is identical to the PA anode bias; thus for this note the two will be referred to only as the PA anode bias. The ALP function is defined on application page I3 as a function of momentum. It is in arbitrary units of Camac 465 card DAC output volts; however its relationship to a single station PA anode bias limit, $V_{a\ \mathrm{lim}}$, is:

$$V_{a\ \mathrm{lim}} = \alpha_{apg} \kappa_a \cdot ALP \quad (1)$$

where:

$\alpha_{apg} = 0.75$	is the nominal individual station Anode Program scaling adjustment
$\kappa_a = 3\ kV/V$	is the modulator program scaling ratio of output:program
ALP	is the Anode Limit Program

A graph of the STM output voltage limit as a function of momentum is shown in Fig. 1 below for the present I3 ALP definition and for three other previous I3 files.



File 1 title: “Initial Match to M8 Curve” dated 1/1/1972 & 10/20/1998.
File 3 title: “End of Collider run Save” dated 1/1/1972.
File 4 title: “Starting Limit Curve” dated 10/21/1998.

Figure 1: Present and past ALP files on application page I3.

Clearly, past ALP files have had a higher limit at injection than the present ALP file. The 1972 dates on the files don't necessarily make sense and may have to do with database timestamp problems. The title of the files may be more descriptive.

The single station cavity-gap RF voltage limit, $V_{cav\,\lim}$, implied by these files can be found from the relationship between the PA anode bias and the cavity gap voltage; which is approximately given as:

$$V_{cav\,\lim} = \left(\alpha_{apg}\kappa_a \cdot ALP - V_{screen}\right) \cdot N_{Gap}$$

where:

$V_{screen} = 1\ kV$ is the nominal PA screen bias voltage

$N_{Gap} = 12.25$ is the nominal cavity gap:anode voltage step-up ratio

This formula assumes that the maximum RF anode voltage swing is given by the DC anode bias less the screen bias voltage. This is approximately the point at which the tube begins to saturate and draw screen current. The resulting single station cavity-gap RF voltage limit for the present and past ALP files is shown in Fig.2 where there momentum variable has been converted to frequency, f_{RF}, via the formula:

$$f_{RF} = \frac{h\beta(p)c}{L}$$

where $h = 588$ is the harmonic number, $L = 3.322km$ is the MI circumference, c is the speed of light, and $\beta(p)$ is the velocity factor as a function of momentum. The total HLRF voltage sum limit (RFSUM) assuming there are 18 HLRF stations active is simply 18 times the single station limit. This is shown in Fig. 3.

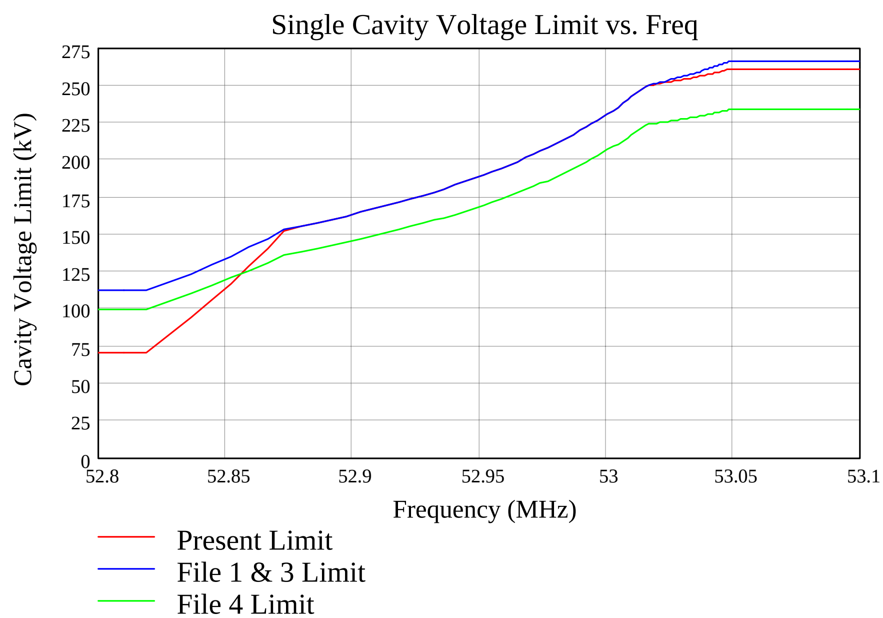


Figure 2: Single station cavity-gap voltage limit implied by the ALP files on I3.

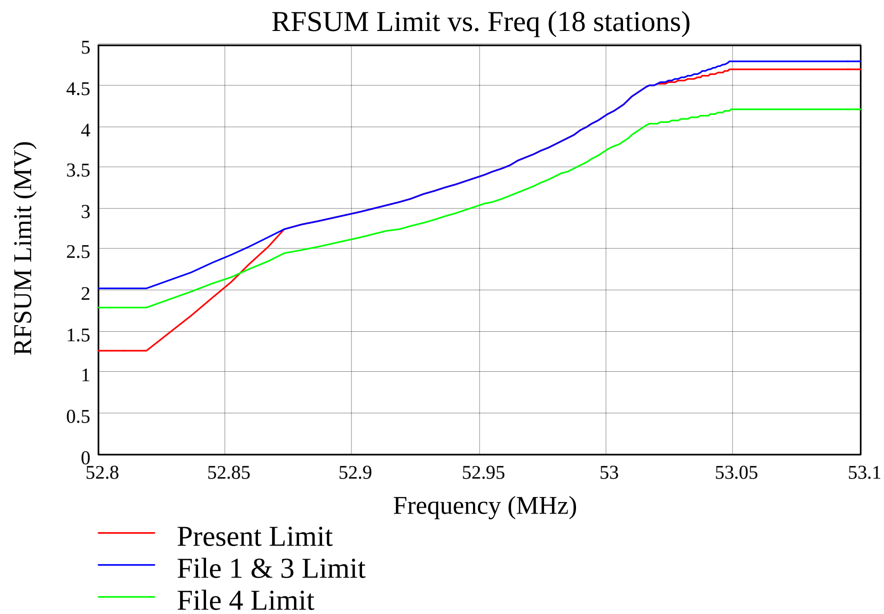


Figure 3: HLRF RFSUM limit implied by the ALP files on I3.

Average Anode Current Limit:

The STM tube voltage drop is given as the difference between the STM input voltage and the PA anode bias. The STM input voltage is determined by the Anode Power Supply (APS). Present unloaded measurements (week of 4/24) of the output voltage of the Main Injector Anode Power Supplies were:

Table 1: Anode Power Supplies – Unloaded Output Voltages

Supply	Voltage (KV)
South APS	28.25
Center APS	30.25
North APS	27.1

The South APS powers stations 1-6. The Center APS powers stations 7-12. The North APS powers stations 13-18.

In order not to exceed the STM power dissipation limit of 150 kW, the average anode current cannot exceed the following:

$$I_{\lim} = \min\left(\frac{150kW}{V_{aps} - V_a} \ , \ \frac{150kW}{(1-\eta_{PA}) \cdot V_a} \right)$$

The first term ensures that the STM dissipation limit is not exceeded; while the second term ensures that the RF PA dissipation limit is not exceeded given that the PA is operating with an efficiency of η_{PA}%. Figure 4 plots the first term for 3 different APS voltages (STM input), V_{aps}, as a function of the anode bias voltage, V_a. Also shown is the second term assuming the RF PA is operating with 60% efficiency. Furthermore, the injection anode bias voltages for the previous screen current regulation control method (pre-MRF) and the present and past ALP limit files are notated on the plot.

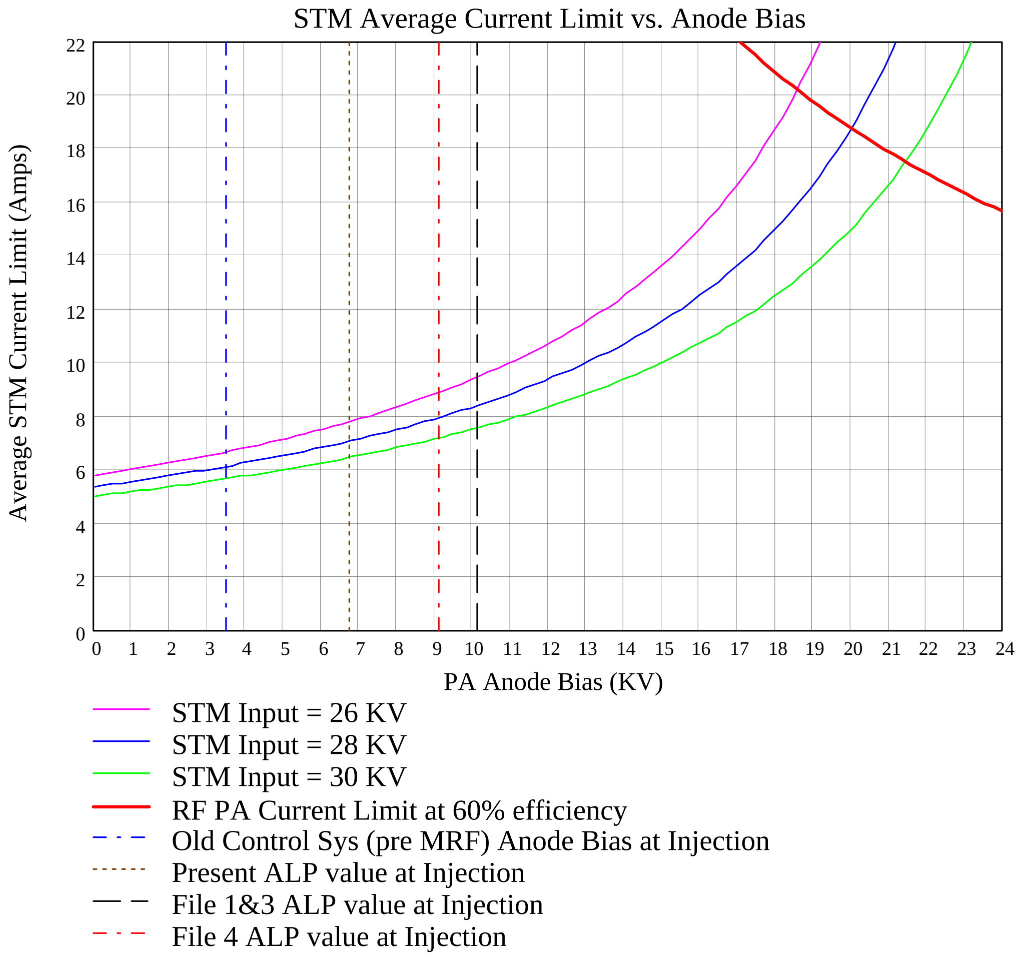


Figure 4: Series Tube Modulator average current limit vs. anode bias for various anode supply voltages (STM input). The current also cannot exceed the RF PA current limit which is shown for a PA efficiency of 60%. Various anode bias values at injection are shown as vertical lines.

MI Cavity Tuner:Anode RF Voltage Ratio:

In order to understand the shape of the ALP curve, small signal measurements of the cavity tuner:anode RF voltage ratio were taken on MI cavity S/N 17 at the MI-60 test station. This was done by installing a dummy PA shell on the cavity, exciting it with an RF source, and measuring the cavity tuner and anode RF voltages with a vector voltmeter to determine the ratio. The dummy PA shell has a PA tube whose cathode has been cut away; thereby exposing the anode, control grid, and screen grid. Since the dummy PA shell comes complete with control grid and screen grid bypass capacitors, the cavity can be probed and driven directly across the anode to control grids. Each tuner's hub was probed via the tuner ventilation holes. Measurements were taken at various cavity resonant frequencies by changing the ferrite tuner biasing current. The resonant frequency was measured with a frequency counter and a vector impedance meter at the anode. A picture of the MI cavity with the dummy PA shell is shown in Fig. 5. An image of the cut away tube is shown in Fig. 6.

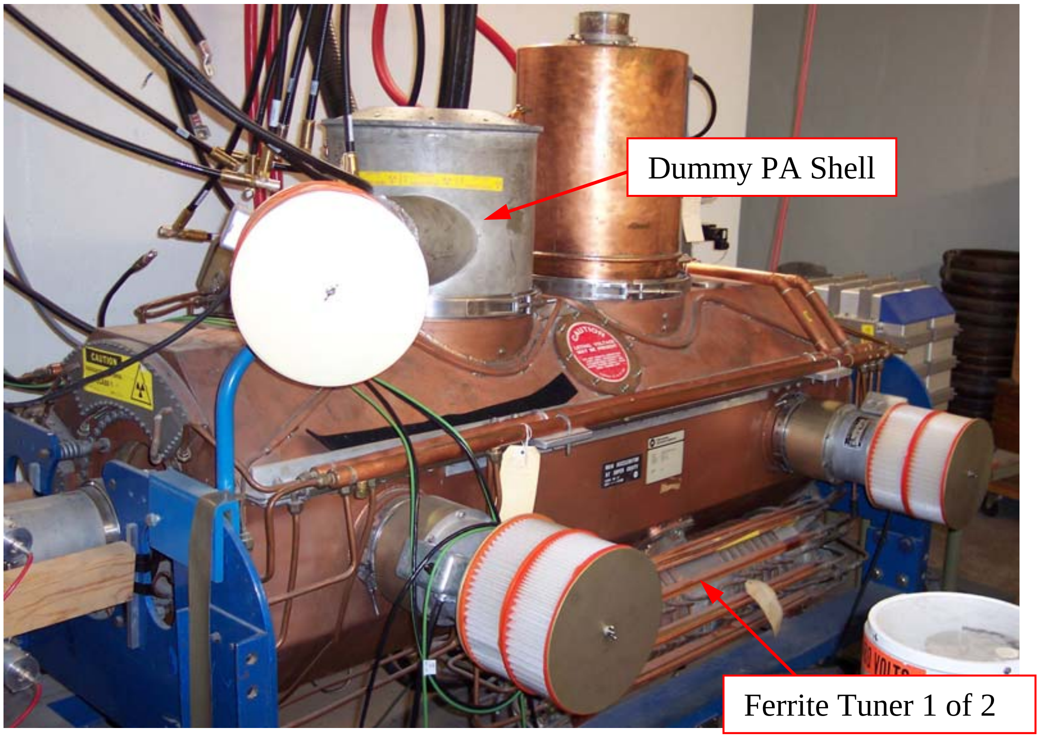


Figure 6: MI Cavity S/N 17 at the MI-60 test station with the dummy PA shell installed.

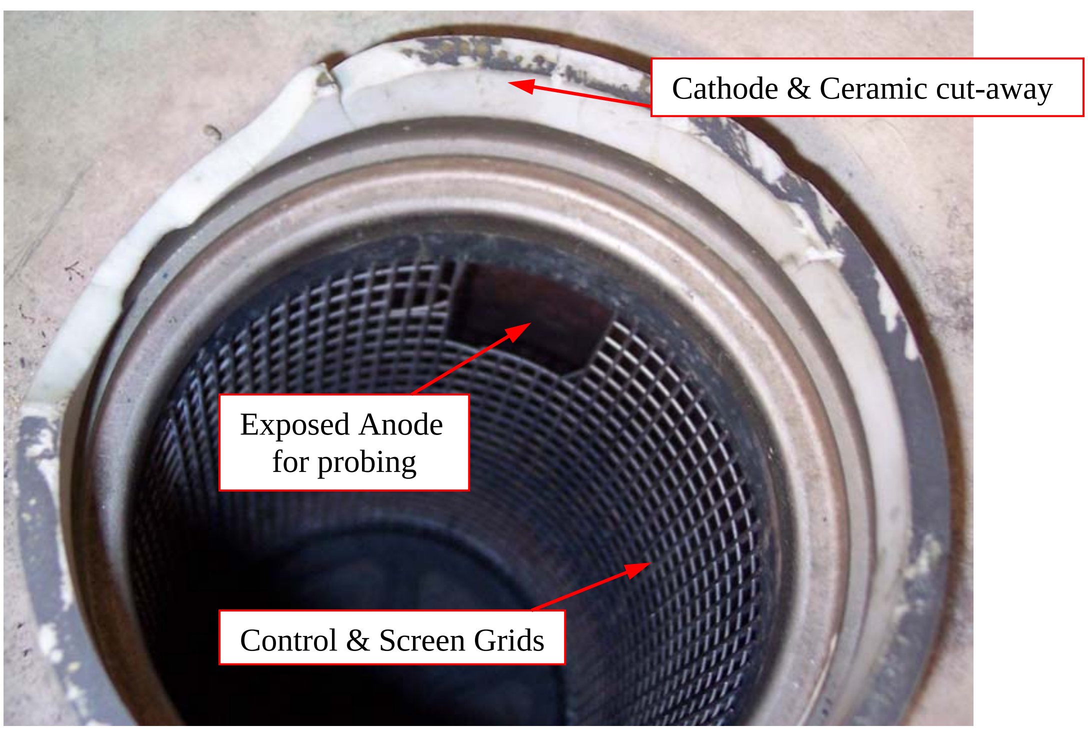


Figure 5: Dummy PA shell’s cut-away Y567 tube.

There were two sets of small signal measurements. The first set measured the tuner:anode voltage ratio at the resonant frequency; i.e. the anode was driven with an RF source set to the same frequency as the resonant frequency of the cavity. The results of this first set of measurements are shown in Table 2.

The second set of small signal measurements measured the tuner:anode voltage ratio at the injection frequency while the cavity resonant frequency was varied; i.e. the anode was driven with an RF source fixed at 52.8114 MHz while the cavity resonant frequency was varied to simulate cavity detuning. These measurements were made to confirm that the tuner:anode ratio follows a similar pattern as the first set of measurements as the cavity is detuned but driven at injection frequency. The results of these measurements confirm that detuning the cavity at injection would allow the ALP value to be raised at injection. The second set of measurements are shown in Table 3.

Table 2: MI Cavity S/N 17 Tuner:Anode RF voltage ratio @Resonance vs. Resonant Frequency

Frequency (MHz)	$\lvert Z_{anode} \rvert$ kΩ	Left Gap:Anode	Right Gap:Anode	Front Tuner:Anode	Back Tuner:Anode	Q	Ferrite Bias Current (Amps)
52.534	1.85	12.6	11.8	0.8	0.8		0
52.8137	2.75	12.9	11.7	0.6	0.6		70
52.855	2.8	12.6	11.4	0.5	0.5	3109	90
52.949	3.2	12.2	11.5	0.4	0.5		150
53.062	3.8	11.1	11.5	0.4	0.4		250
53.132	4.2	12.4	11.4	0.3	0.3	4787	350

Table 3: MI Cavity S/N 17 Tuner:Anode RF voltage ratio @Injection Freq. vs. Resonant Frequency

Resonant Frequency f_o (MHz)	$\lvert Z_{anode} \rvert$ @ f_o kΩ	RF Drive Frequency f_{rf} (MHz)	$\lvert Z_{anode} \rvert$ @ f_{rf} kΩ	Angle of Z_{anode} @ f_{rf} (deg)	Left Gap Mon. Meas.	Right Gap Mon. Meas.	Front Tuner Meas.	Back Tuner Meas.	Bias Current (Amps)
					Gap:Anode	Gap:Anode	Tuner:Anode	Tuner:Anode	
52.781	2.60	52.8114	0.65	-77	13.2	12.1	0.6	0.6	50
52.789	2.62	52.8114	0.93	-71	13.5	12.0	0.6	0.6	60
52.8137	2.75	52.8137	2.75	0	12.9	11.7	0.6	0.6	50
52.832	2.80	52.8114	0.96	68	12.7	11.5	0.5	0.5	80
52.852	2.87	52.8114	0.52	78	12.2	11.6	0.5	0.5	90
52.869	2.95	52.8114	0.35	80	12.0	11.0	0.5	0.5	100
52.891	3.03	52.8114	0.25	82	11.7	10.9	0.5	0.5	110
52.907	3.07	52.8114	0.20	84	11.7	10.7	0.5	0.4	120
52.923	3.15	52.8114	0.21	85	11.3	10.5	0.4	0.4	130
52.937	3.20	52.8114	0.19	85	11.3	10.3	0.4	0.4	140
52.955	3.23	52.8114	0.18	86	11.1	10.2	0.4	0.4	150

To understand what the cavity voltage limit should look like as a function of frequency, based upon the small signal measurements, both measurement sets were normalized with respect to the ratio at the extraction frequency via the following formula:

$$V_{cav\,\lim\,normalized} = \frac{(tuner : anode)\big|_{extraction}}{(tuner : anode)\big|_{f}}$$

The result is shown in Fig. 7:

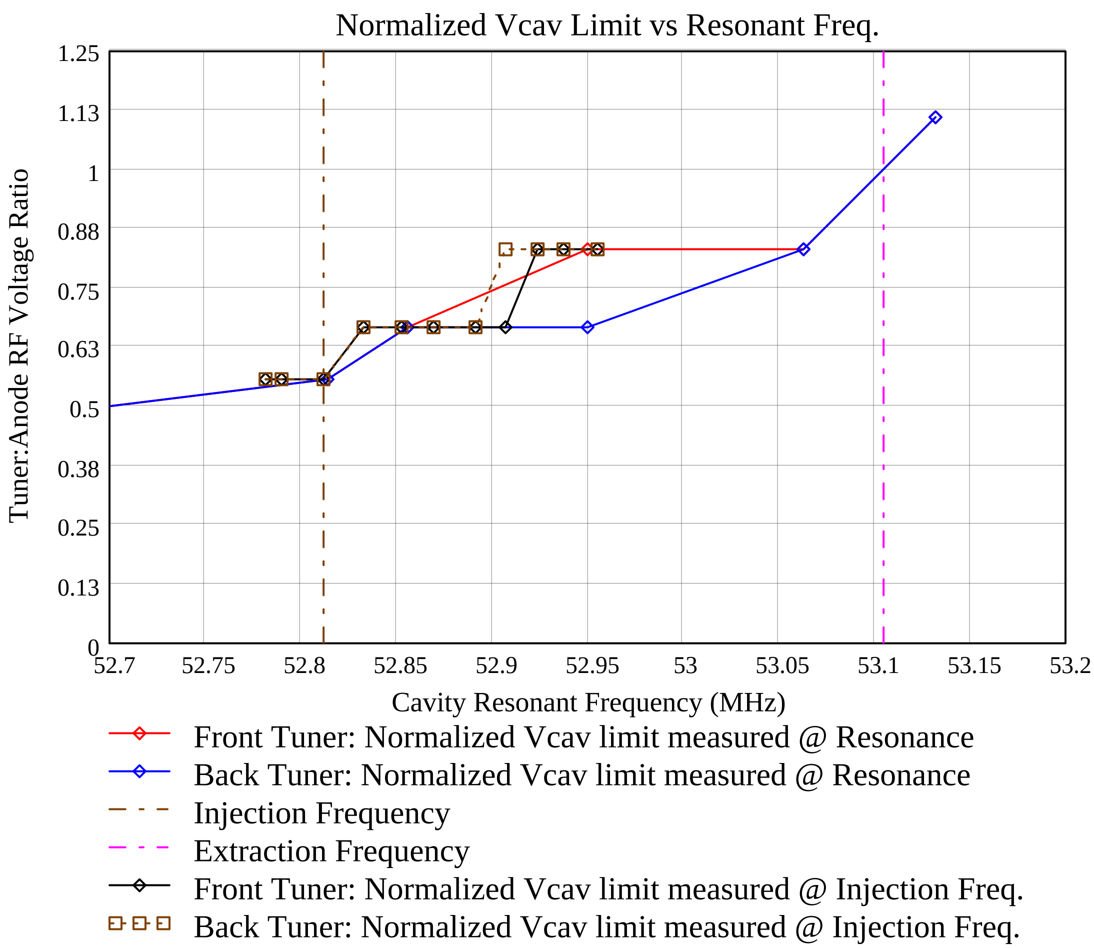


Figure 7: MI Cavity S/N 17 normalized cavity voltage limit (wrt extraction freq.) vs. resonant frequency for both measurement sets.

Based upon the small signal measurements at the test station, it appears that the ALP value at injection could be raised to at least ½ the ALP value at extraction if no cavity detuning is implemented and even higher if cavity detuning is implemented.

Impact of ALP on Beam Intensity

In order not to exceed the STM power dissipation of the 'OFF' stations, the total beam intensity becomes a function of the ALP injection value as depicted in Fig. 8. The assumptions for generating Fig. 8 were:

(1) twice the bunch form factor is 2; implying that the 'instantaneous' RF component of the beam current is twice the 'instantaneous' DC component (see Ref [2] for further details). This is an approximate 18% to 30% overestimate to compensate for possible errors in the PA tube current curve fit of Ref [3] which was used for simulating the PA tube response.
(2) the cavity gap:anode voltage ratio is 12.25
(3) the STM input voltage is 26 kV
(4) the STM power dissipation limit is 135 kW; this is a 10% reduction from the datasheet rated value of 150 kW.
(5) The 'moving average' during slipping is formed from the single batch intensity (see Ref [2] for further details about the 'moving average')

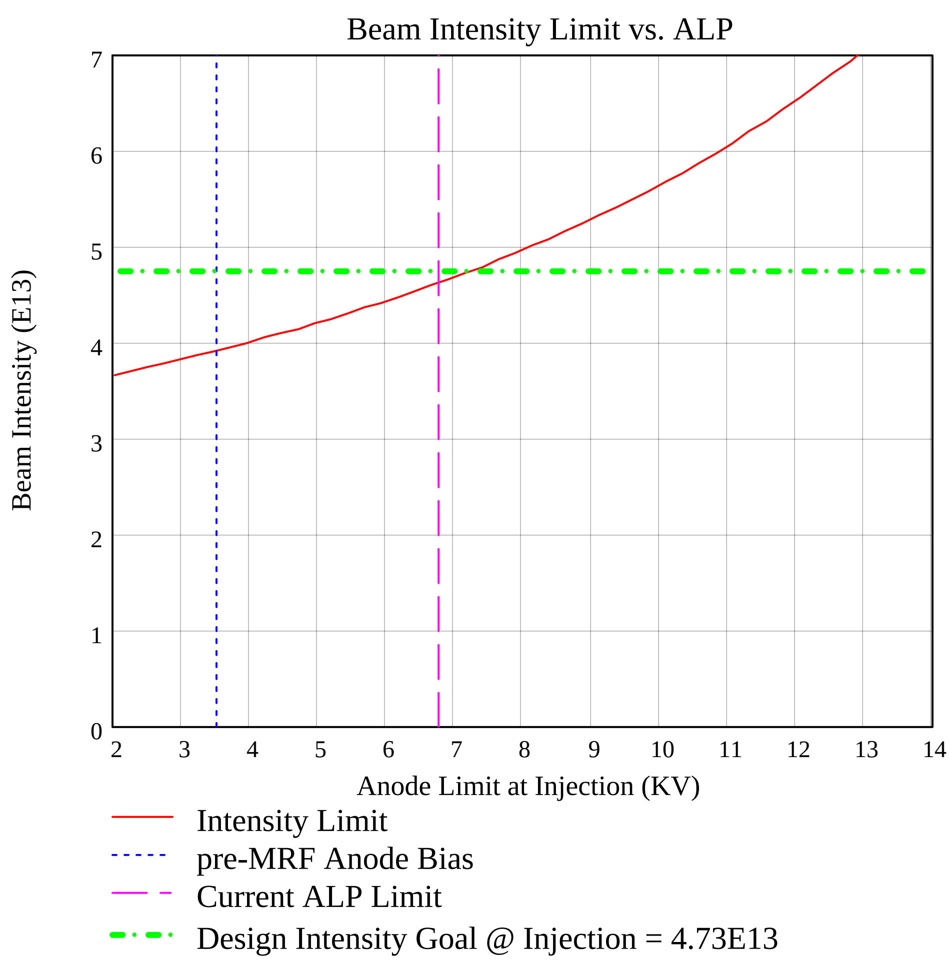


Figure 8: Beam Intensity limit as a function of ALP injection value in order not to exceed STM power dissipation.

Previous Examples of Exceeding Present ALP Limit:

The small signal tuner:anode ratio measurements suggest that the present ALP anode bias limit of 6.75 KV can be exceeded. In fact there are three cases in which the cavities have been run with a PA anode bias higher than the present ALP limit. These cases are:

1. When slip-stacking was first implemented only 2 stations (one from each Group) were being used to create the slip-stacking voltage. Initial slip-stacking studies were using up to 110KV peak of cavity gap voltage per station at injection frequency until it was pointed out that the ALP limit of 70.5 KV peak was being exceeded. 110 KV peak of gap voltage corresponds to ~ 9 to 10 KV of PA anode bias. The number of stations was then changed to 4 stations (two per Group). The present number of slip-stacking stations is now 6 since this is required to create the 1.2 MV bunch rotation voltage.

2. MI cavity S/N 17 has been run in the test station up to ~140 KV peak of cavity gap voltage at a PA anode bias of 12 KV near injection frequency without any incidents of sparking. This was done during initial test station measurements that were mimicking the slip-stacking stations during studies for the SSD upgrade. Raw data from measurements made with 12 KV of anode bias at the injection frequency are shown in Table 3. These measurements are also included in the documentation of Ref [1].

3. Before the APG-A and APG-B overdrive watchdog modules were installed, there were a number of occasions when the cavities would be driven to extraction voltages at the injection frequency. This would happen when MECAR was not sending momentum data to the LLRF system and the RF drive frequency would be kept at injection frequency throughout an entire RF cycle.

Table 4: Raw measurement data of 140 KV peak gap voltage at 12 KV anode bias at injection frequency from 2/2004

System Bias Conditions	**Frequency (MHz)**	**52.814**	**52.85**	**52.9**	**52.95**	**53**	**53.05**	**53.1**	**53.104**
	Grid Bias Voltage (V)	-292	-292	-292	-292	-292	-292	-294	-292
	Anode Voltage (KV)	12	12	12	12	12	12	12	12
	Anode Current (A)	2.76	2.62	2.52	2.3	2.16	2.1	1.952	1.96
	Anode Current (NO RF) (A)	0.92	0.932	0.992	0.992	0.972	0.992	0.992	0.992
	Screen Current (mA)	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0
	Anode-to-Cathode Phase Det. Error (deg)	1.8	2.7	0.36	0.9	-0.9	1.08	4.5	-4.5
	Bias Supply Program (V)	0.375	0.454	0.548	0.704	0.884	1.107	1.444	1.498
	Bias Supply Current (A)	80	103	126	164	206	263	345	355
Station RF Controller	**RF Drive Program (V)**	6.88	6.88	6.88	6.88	6.88	6.88	6.88	6.88
	RFOLG Program (V)	9.26	9.04	8.56	8.20	7.9	7.60	7.40	7.43
	RF Input Level (dBm)	-11.32	-11.3	-11.3	-11.31	-11.32	-11.32	-11.32	-11.32
	RF Drive Level @ J1 (mW)	14.1	13.9	13.9	13.9	13.9	14.1	14.1	14.1
	RF Output Level (mW)	4.9	4.7	4.2	3.9	3.6	3.3	3.2	3.2
System RF Power Levels	**Cathode Drive FWD Pwr from diode (Watts)**	697	660	596	535	497	466	441	441
	Cathode Drive FWD Fund (Watts)	675	650	580	536	497	460	443	426
	Cathode Drive FWD Fund x2 (Watts)	0.84	0.78	0.81	0.72	0.72	0.78	0.67	0.72
	Cathode Drive FWD Fund x3 (Watts)	1.32	0.77	0.39	0.14	0.07	0.04	0.03	0.03
	Cathode Drive REF Pwr from diode (Watts)	44	43	42	40	39	41	48	50
	Cathode Drive REF Fund (Watts)	36	36	30	36	35	35	39	41
	Cathode Drive REF Fund x2 (Watts)	1.91	1.77	1.84	1.52	1.64	1.64	1.64	1.52
	Cathode Drive REF Fund x3 (Watts)	1.94	1.23	0.66	0.31	0.18	0.12	0.09	0.09
	Cathode RF Voltage from diode (Vpk)	152	150	144	140	137	135	132	133
	Cathode Fundamental Voltage (Vpk)	146	143	140	137	135	130	130	127
	Cathode Fund x2 Voltage (Vpk)	21	20	19	17	15	15	12	12
	Cathode Fund x3 Voltage (Vpk)	6	5	6	5	5	6	5	6
	Anode RF Voltage from diode (KVpk)	11.5	11.5	11.5	11.5	11.6	11.7	11.7	11.7
	Upstream Gap Voltage (KVpk)	135.6	135.6	133.9	134.4	133.9	133.4	133.4	133.4
	Downstream Gap Voltage (KVpk)	142.9	142.9	142.9	142.9	142.9	142.9	142.9	142.9

High RF Cavity Gap Voltage at the Test Station:

Due to the above presented evidence, it was decided to perform additional high RF cavity gap voltage testing on the MI test station cavity (S/N 17). Three series of tests were performed:

1. The cavity gap voltage was successfully increased up to ~240 KV peak at injection frequency (52.8114MHz) with an anode bias voltage of ~22 KV using 40 usec short pulse testing. Proof of operation under these conditions is shown in Fig. 9 below. No evidence of sparking, neither internally (vacuum region) nor at the tuners was witnessed.

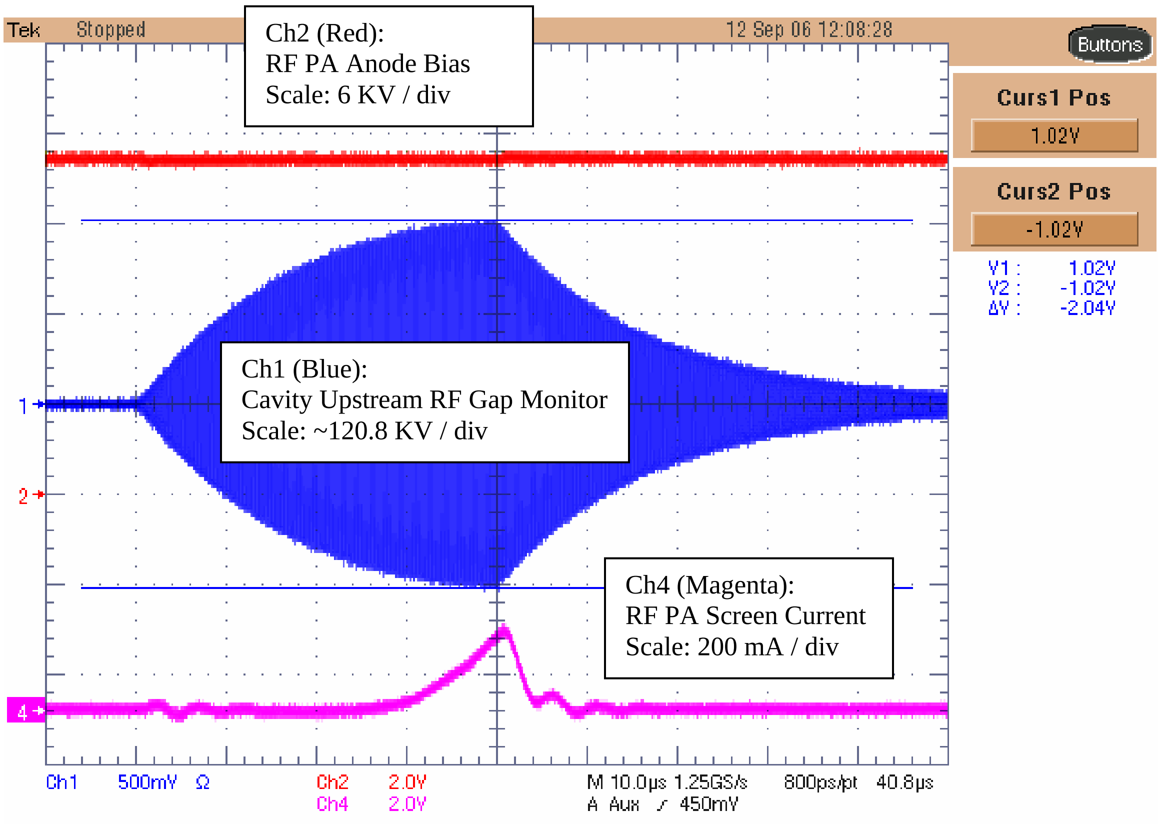


Figure 9: Proof of MI Test Station Cavity (S/N 17) achieving ~240KV peak of RF gap voltage at injection frequency (52.8114 MHz) at an anode bias voltage of ~22KV. The RF pulse width was 40usec, just enough to fill the cavity which has a Q of ~3000 at injection.

2. With the success of the first test, it was decided to run at high cavity RF gap voltage with longer pulses and sweep both the RF drive and resonant frequency of the cavity similar to a typical MI operational cycle. The RF drive signal and the Ferrite Bias Supply program (cavity tuning program) signals from the operational MI RF system were used to drive the test station. The MI test station cavity was successfully run at ~200 KV peak of cavity RF gap voltage at an RF PA tube anode bias of ~18 KV during a typical MI RF operating cycle which lasts for ~1 second. No evidence of sparking, neither internally nor at the tuners was witnessed. Proof of operating under these conditions is shown in Fig. 10 below.

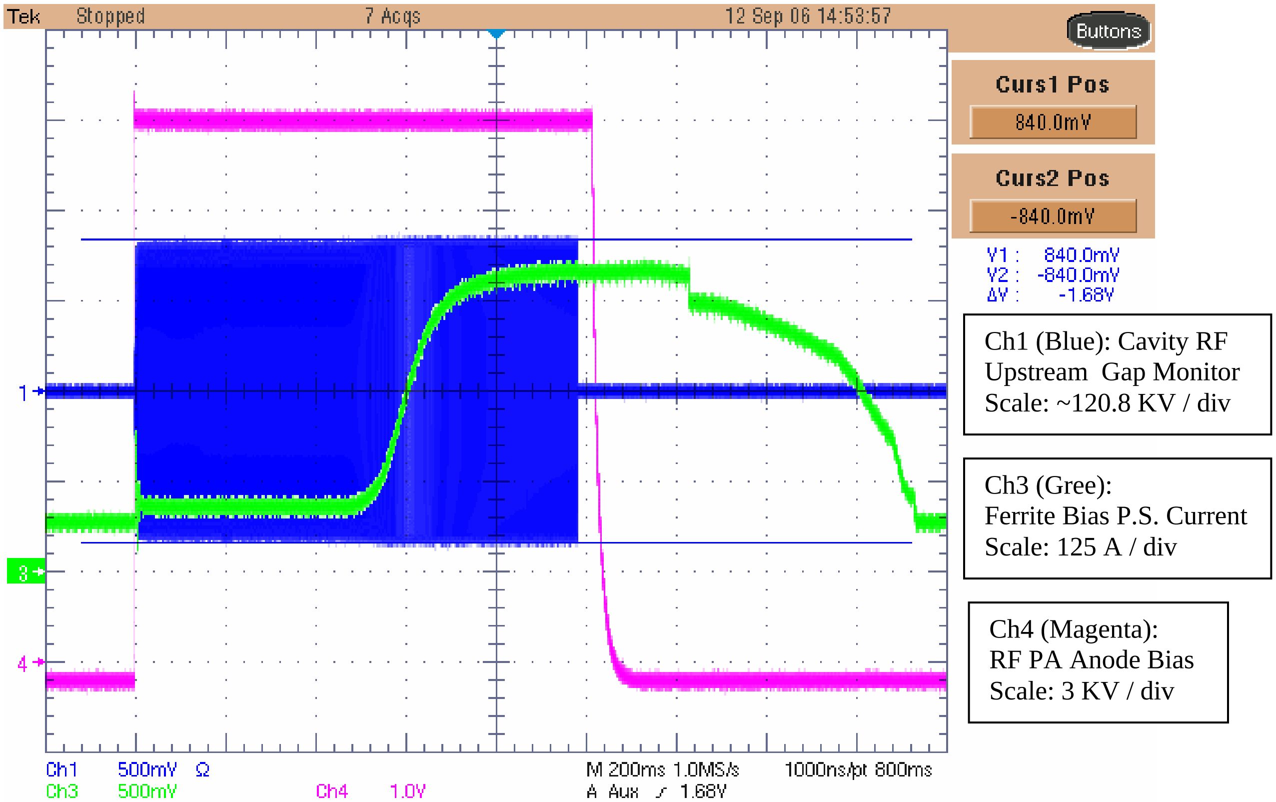


Figure 10: Proof of the MI Test Station cavity (S/N 17) operating at ~200 KV peak across a typical ~1 second MI RF operational cycle with the RF drive and the cavity resonant frequency sweeping from injection (~52.8114 MHz) to flat top (~53.104 MHz). The Anode Bias Voltage used was ~ 18KV. Note shown here is that the RF PA tube reached saturation at this Anode Bias level with a RF PA screen current of ~200mA at injection and ~400mA at flat top. Notice that the cavity is sitting at ~200 KV peak of RF gap voltage for the entire front porch (at injection frequency) which lasts for ~0.5 sec. No evidence of sparking, neither internally nor at the cavity tuners, was witnessed. Although the scope sampling time is 1 usec, the observed peak to peak values of the RF Gap Monitor are valid. This was confirmed by reducing the time span and sampling time.

When attempting to push to 240 KV across the cycle, evidence of internal sparking (inside the vacuum region) was observed just before flat top (~53.1 MHz). Since the cavity Q increases as a function of frequency, once the anode bias voltage was increased above 18 KV and the tube was taken out of saturation, the RF gap voltage increased as a function of frequency. Thus voltages greater than ~200 KV at injection were not able to be achieved under this scenario because of the internal sparking at voltages near 240 KV at flat top. Evidence of the internal sparking was seen from both the dV/dt sensor circuit in the RF spark detector module and in the vacuum level as measured with the vacuum ion pump power supplies. The vacuum level increased from ~10^{-8} to 10^{-7} torr while attempting to condition the cavity to operate at 240 KV across the cycle.

3. Finally, to test the worst case scenario, the same short pulse testing as in (1) was made at the lowest achievable cavity resonant frequency. This was achieved by turning off the Ferrite Bias Supply so there was no bias on the cavity tuners. The minimum resonant frequency of the test station cavity (S/N 17) was ~52.525 MHz. A cavity RF gap voltage of ~220 KV peak was achieved with an anode bias voltage of ~20 KV. No evidence of sparking, neither internal nor at the cavity tuners, was witnessed. Proof of these operating conditions is shown in Fig 11 below. Since the RF PA tube was already saturated at an anode bias voltage of ~20 KV and the amount of RF drive was limited in the test configuration, it was not pushed to 240 KV at this frequency.

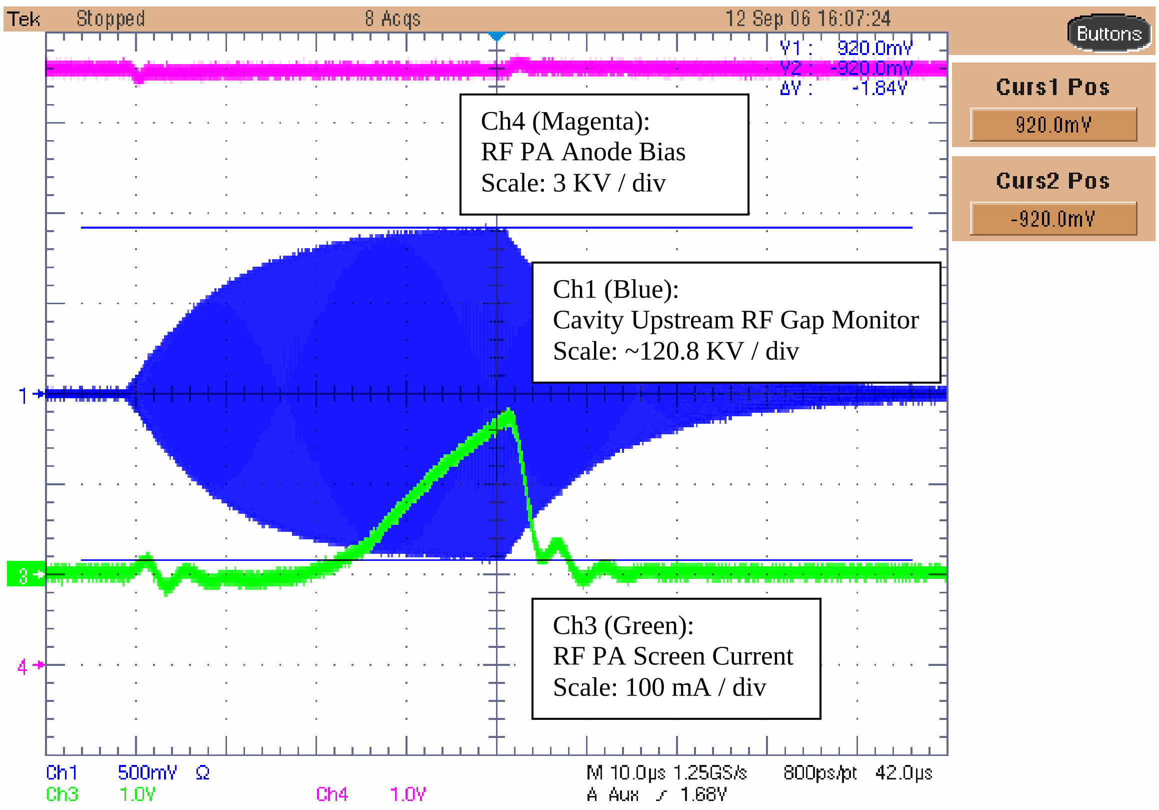


Figure 11: Proof of operating at ~220 KV peak of RF gap voltage at the lowest cavity resonant frequency (~52.525 MHz) on the MI Test Station cavity (S/N 17) with an RF PA Anode Bias Voltage of ~20 KV.

Summary:

There is supporting evidence that the present ALP limit at injection can be raised. This is supported by small signal measurements of the tuner:anode voltage ratio, examples of exceeding the limit in the past, and real data of running the MI test station cavity (S/N 17) at 240 KV peak gap voltage for short pulses with a PA tube anode bias of ~22 KV and at 200 KV peak gap voltage with an anode bias of ~18 KV for an entire typical MI operational cycle. This evidence suggests that ALP can be comfortably raised to at least 9 KV, enough for ~10% headroom from the Proton Plan design beam intensity with regards to the Series Tube Modulator power dissipation. If more headroom is needed once Proton Plan begins approaching design intensities, this data can be used to evaluate a decision and the necessary steps to increase ALP further. Raising the ALP limit would allow the Series Tube Modulator dissipation for Proton Plan to be relaxed during the slipping process [2].

References:

[1] T.Berenc, "Main Injector HLRF Station Gain Measurements", Fermilab RF TechNote #070, 6/2005. http://www-rfes.fnal.gov/global/technotes/TN/TN070.pdf .

[2] T.Berenc, D.McGinnis, I.Kourbanis, J.Reid, "Main Injector RF Power Calculations for the Proton Plan", Fermilab Beams-doc-2311, 6/2006. http://beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=2311 .

[3] D.McGinnis, "Main Injector RF Requirements for a 1.3 Megawatt 120 GeV Proton Source", Fermilab Beams-doc-2253, 4/2006. http://beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=2253 .