

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

T. Berenc, J.Reid

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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, $V_{a \text{ lim}}$, is:

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

where:

- $\alpha_{apg} = 0.75$ is the nominal individual station Anode Program scaling adjustment
- $\kappa_a = 3 \text{ kV/V}$ 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.

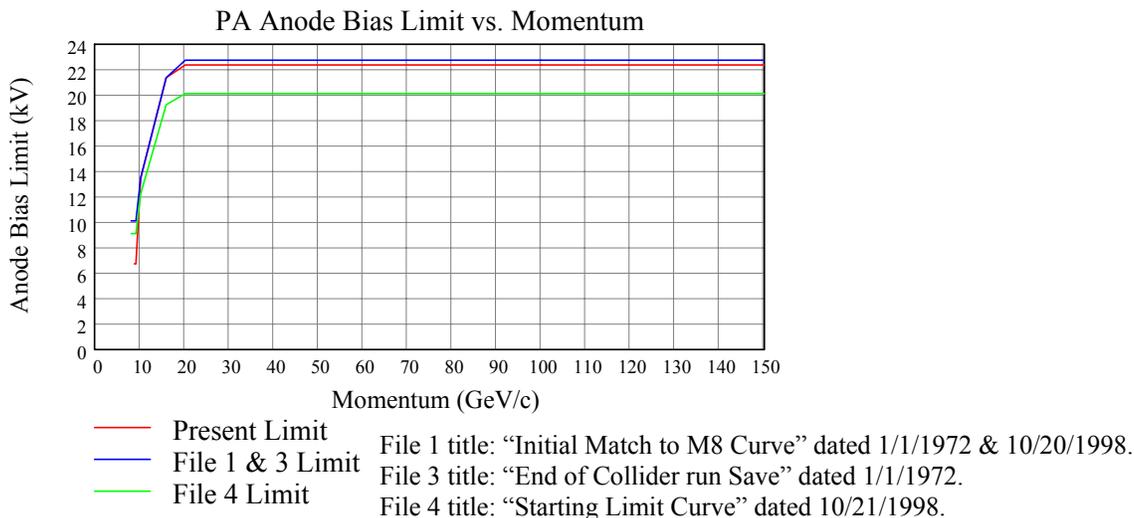


Figure 1: Present and past ALP files on application page I3.

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:

$$V_{cav\ lim} = (\alpha_{app} \kappa_a \cdot ALP - V_{screen}) \cdot N_{Gap}$$

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, $L = 3.322\ km$ 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.

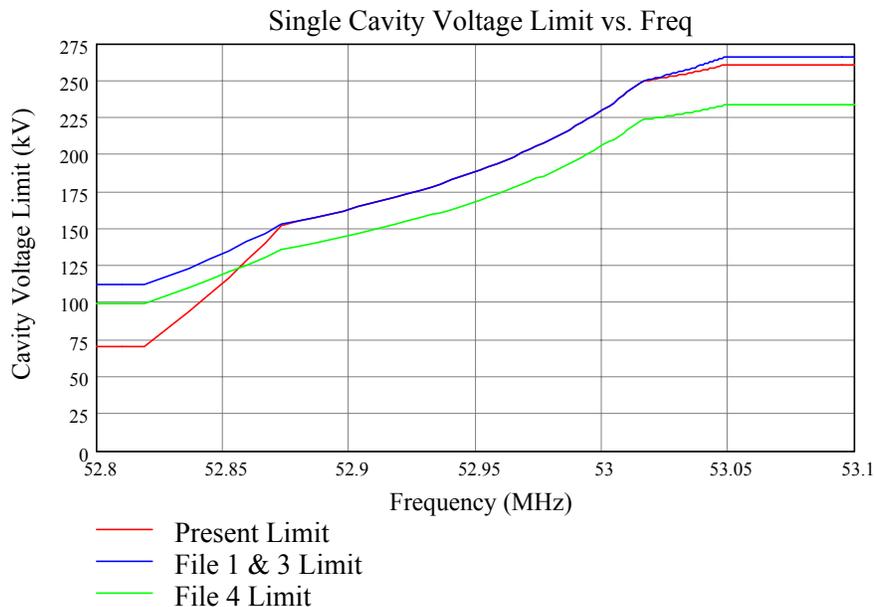


Figure 2: Single station cavity-gap voltage limit implied by the ALP files on I3.

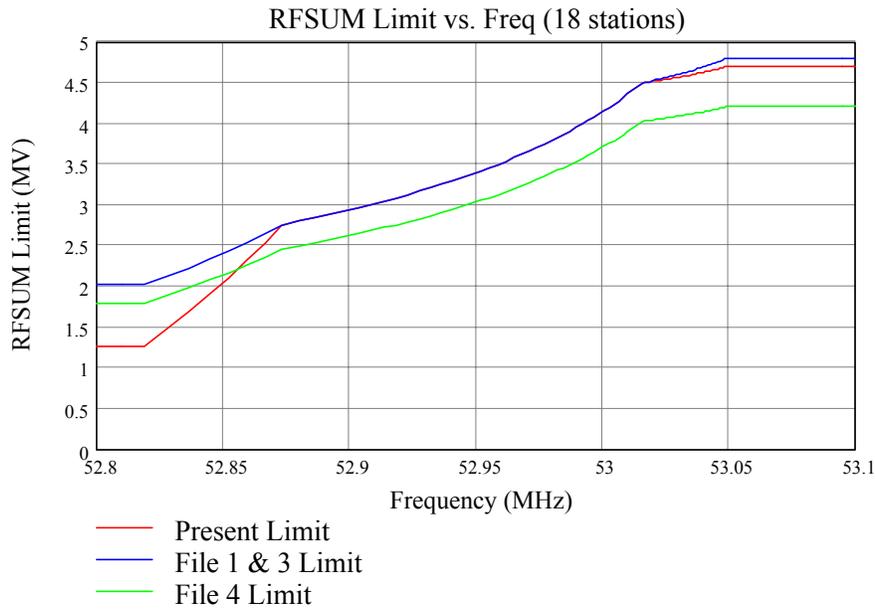


Figure 3: HLRF RFSUM limit implied by the ALP files on I3.

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:

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

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.

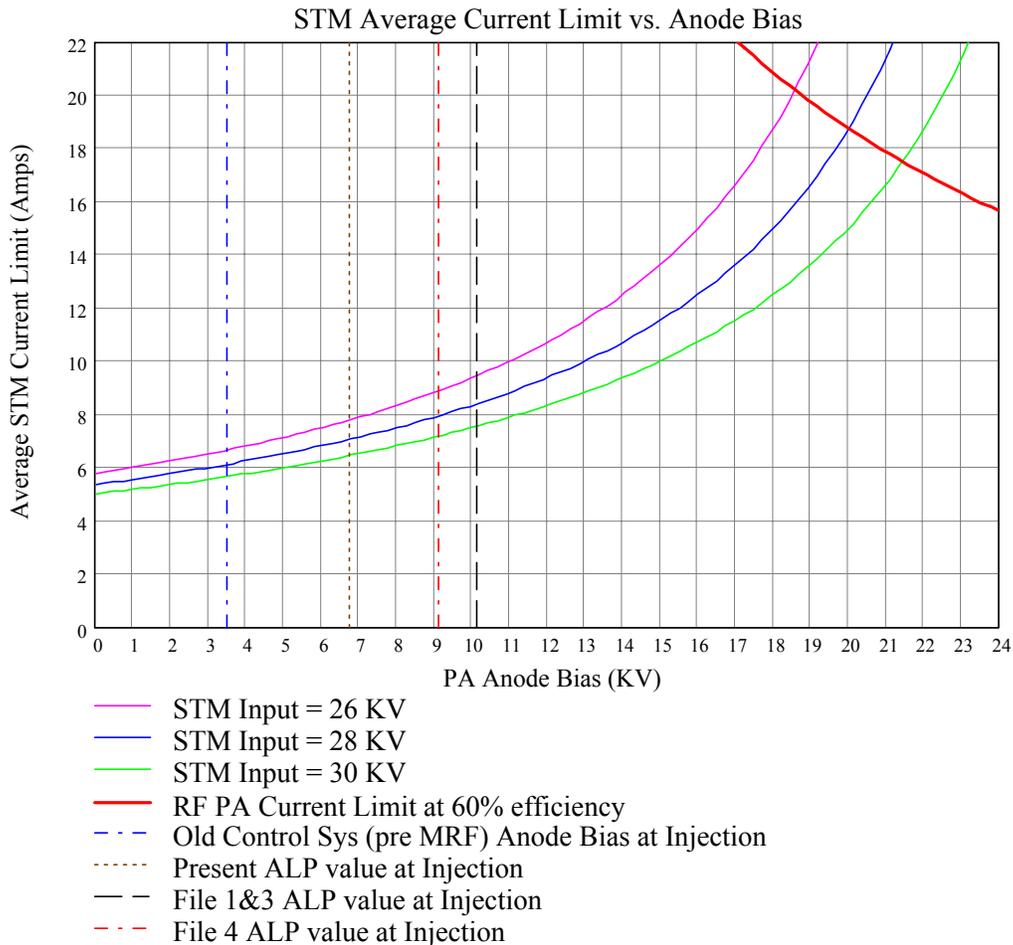


Figure 4: Series Tube Modulator average current limit vs. anode bias for various anode supply voltages (STM input). The current also cannot exceed the RF PA current limit which is shown for a PA efficiency of 60%. Various anode bias values at injection are shown as vertical lines.

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.

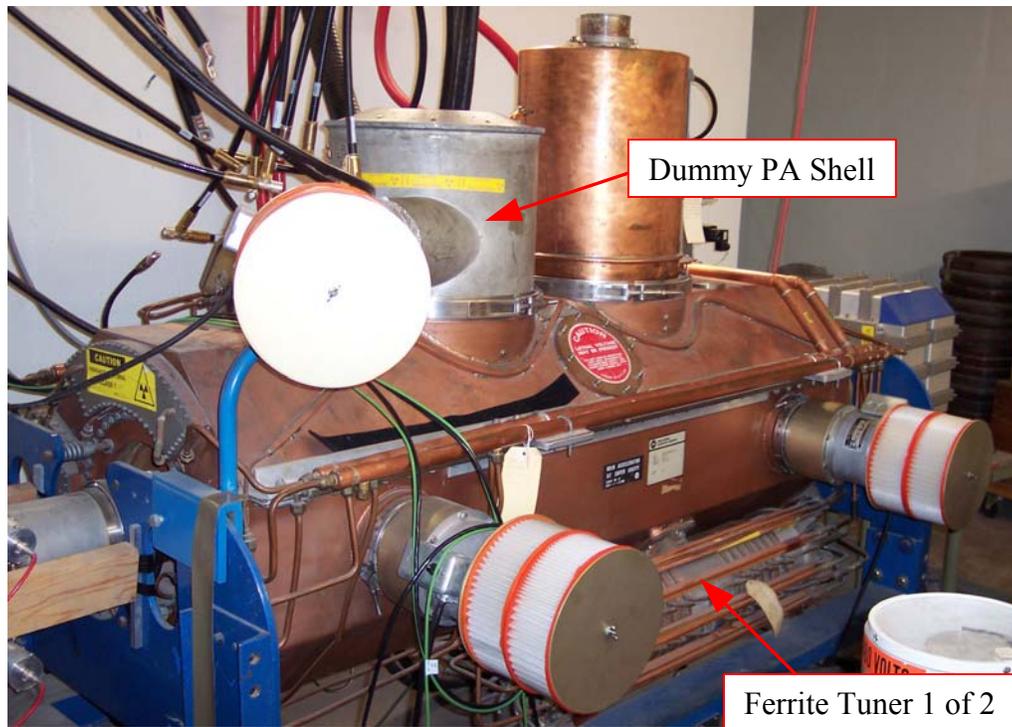


Figure 6: MI Cavity S/N 17 at the MI-60 test station with the dummy PA shell installed.

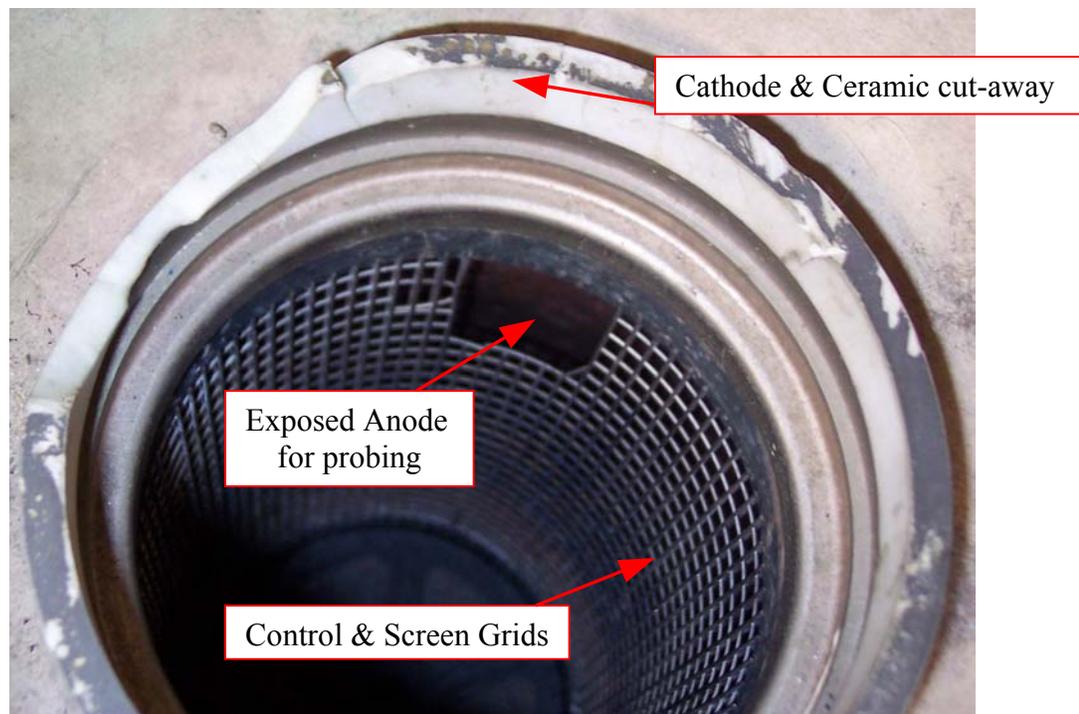


Figure 5: Dummy PA shell's cut-away Y567 tube.

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)	$ Z_{\text{anode}} $ k Ω	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)	$ Z_{\text{anode}} $ @ f_o k Ω	RF Drive Frequency f_{rf} (MHz)	$ Z_{\text{anode}} $ @ f_{rf} k Ω	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:

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

The result is shown in Fig. 7:

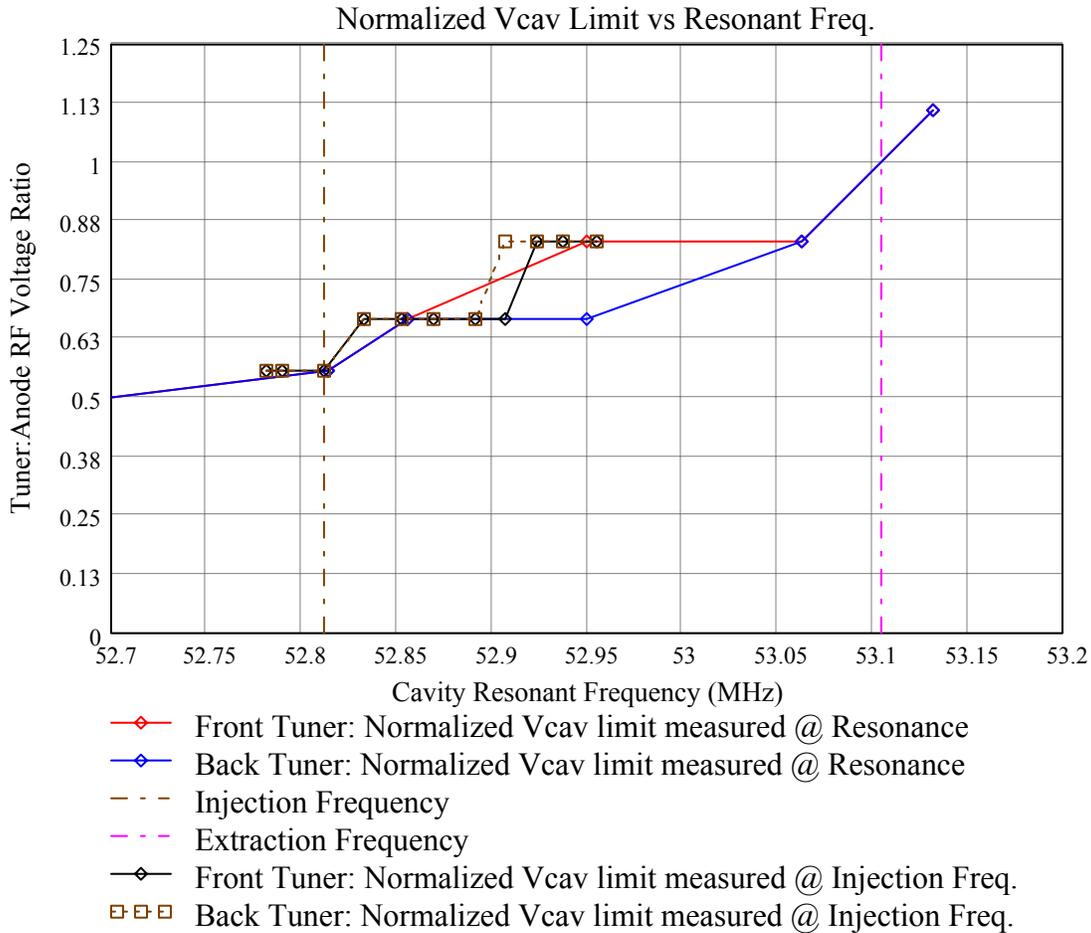


Figure 7: MI Cavity S/N 17 normalized cavity voltage limit (wrt extraction freq.) vs. resonant frequency for both measurement sets.

Based upon the small signal measurements at the test station, it appears that the ALP value at injection could be raised to at least $\frac{1}{2}$ 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’)

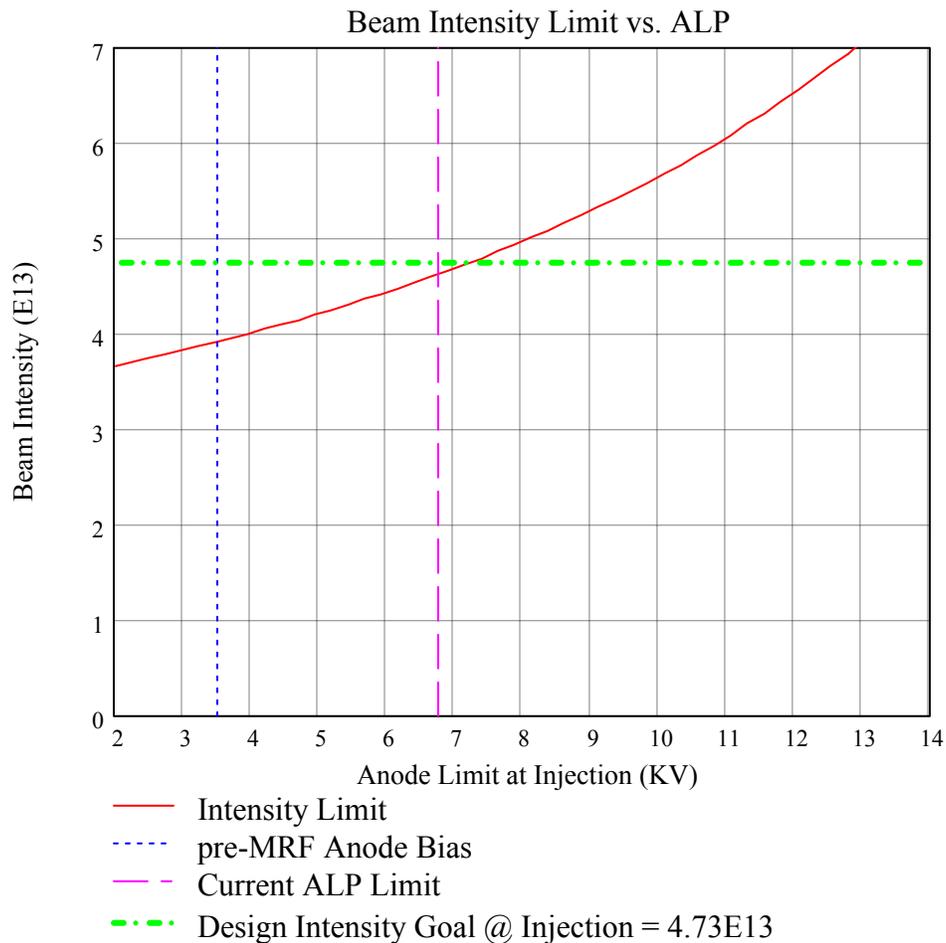


Figure 8: Beam Intensity limit as a function of ALP injection value in order not to exceed STM power dissipation.

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 of cavity gap voltage per station at injection frequency until it was pointed out that the ALP limit of 70.5 KV was being exceeded. 110 KV 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 ~140 KV 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 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

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 a MI cavity (S/N 17) at 140 KV gap voltage with an anode bias of 12 KV. This is almost twice the value implied by the current ALP file. Raising the ALP limit would allow the Series Tube Modulator dissipation for Proton Plan to be relaxed during the slipping process [2]. Additional measurements of the actual cavity tuner RF breakdown voltage would benefit the decision of raising ALP at injection.

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>.