Performance of Ferrite Vector Modulators in the LLRF system of the Fermilab HINS 6-Cavity Test

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FERRITE VECTOR MODULATOR

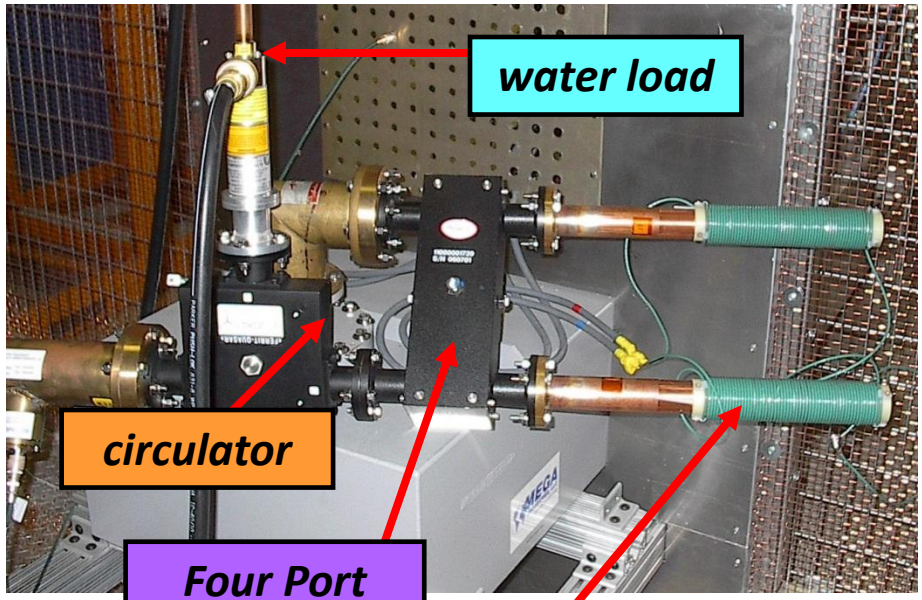
Modulates phase and amplitude independently:

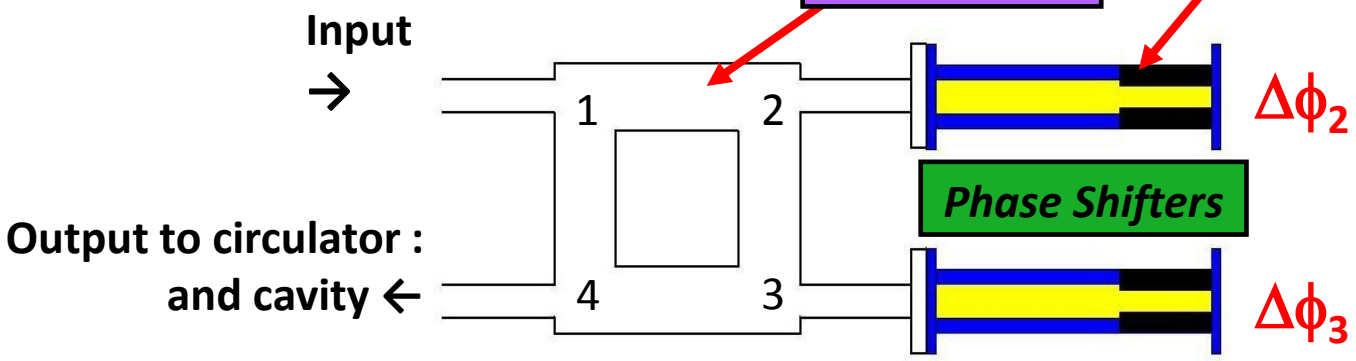
With $\Delta\Phi = (\Delta\phi_2 - \Delta\phi_3)/2$

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

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

Output phase ~ Φ

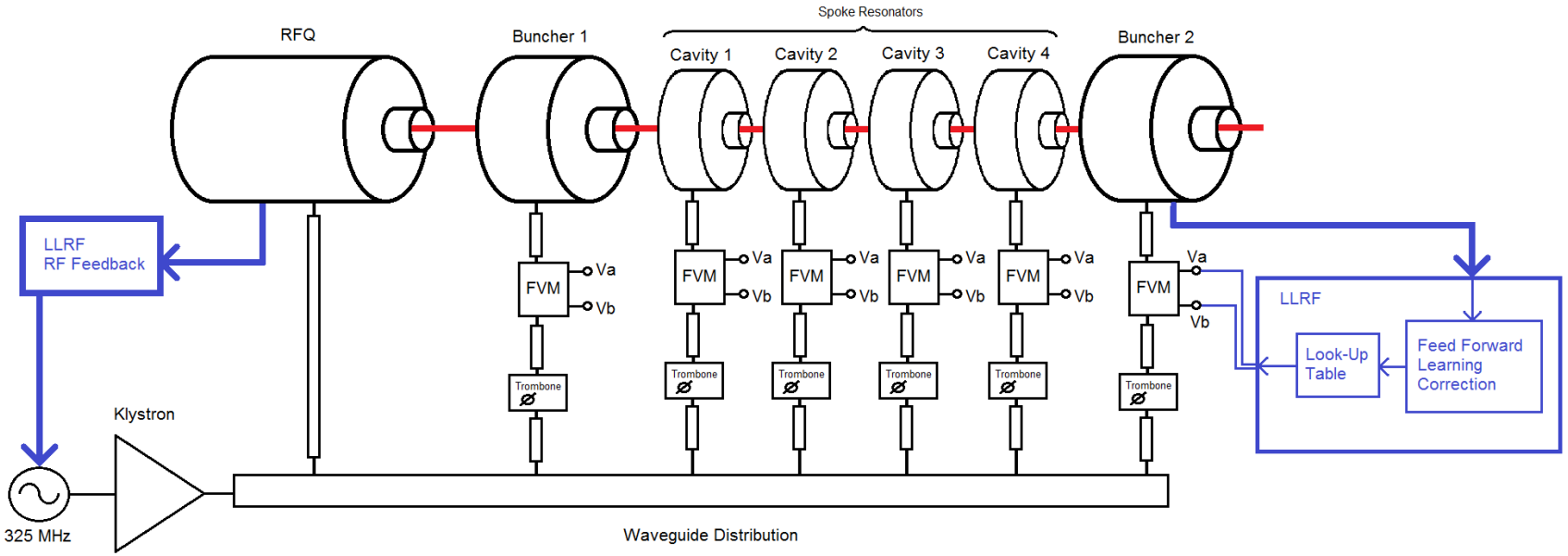




0	0.69	0.73	0.77	0.8	0.84	0.87	0.91	0.94	0.97	1
-35	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	1.75
-30	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	1.85
-25	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	2.15	1.94
-20	NaN	NaN	NaN	NaN	NaN	NaN	NaN	2.42	2.24	2.04
-15	NaN	NaN	NaN	NaN	NaN	2.91	2.73	2.56	2.38	2.15
-10	NaN	NaN	NaN	NaN	3.32	3.12	2.92	2.73	2.54	2.26
-5	NaN	NaN	4.18	3.87	3.61	3.36	3.14	2.93	2.69	2.42
0	5.49	5.03	4.66	4.3	3.95	3.68	3.41	3.15	2.88	2.57
5	NaN	5.74	5.25	4.81	4.4	4.03	3.72	3.42	3.12	2.74
10	NaN	NaN	NaN	5.44	4.93	4.48	4.1	3.73	3.38	2.96
15	NaN	NaN	NaN	NaN	5.65	5.07	4.57	4.12	3.68	3.2
20	NaN	NaN	NaN	NaN	NaN	NaN	5.17	4.62	4.07	3.49
25	NaN	NaN	NaN	NaN	NaN	NaN	NaN	5.22	4.59	3.86
30	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	5.19	4.3
35	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	4.87
40	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	5.64

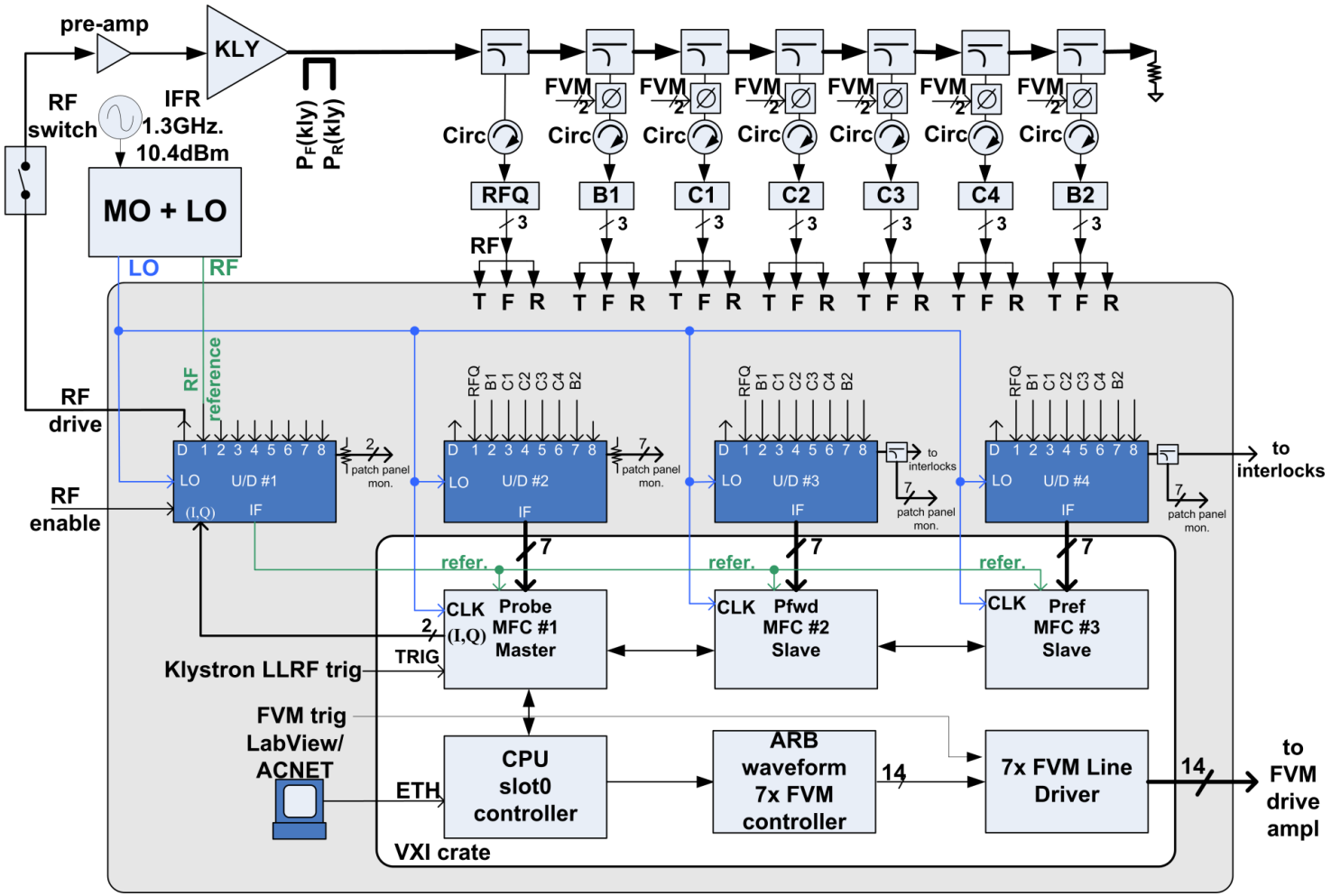
0	0.69	0.73	0.77	0.8	0.84	0.87	0.91	0.94	0.97	1
-35	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	1.6
-30	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	1.64
-25	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	1.56	1.69
-20	NaN	NaN	NaN	NaN	NaN	NaN	NaN	1.55	1.62	1.74
-15	NaN	NaN	NaN	NaN	NaN	1.52	1.57	1.62	1.69	1.82
-10	NaN	NaN	NaN	NaN	1.54	1.58	1.63	1.69	1.76	1.89
-5	NaN	NaN	1.53	1.57	1.61	1.65	1.7	1.76	1.85	1.98
0	1.52	1.56	1.6	1.64	1.68	1.72	1.77	1.84	1.93	2.08
5	NaN	1.62	1.67	1.7	1.74	1.8	1.86	1.93	2.01	2.18
10	NaN	NaN	NaN	1.78	1.83	1.88	1.95	2.02	2.12	2.29
15	NaN	NaN	NaN	NaN	1.91	1.97	2.03	2.13	2.23	2.41
20	NaN	NaN	NaN	NaN	NaN	NaN	2.14	2.23	2.36	2.57
25	NaN	NaN	NaN	NaN	NaN	NaN	NaN	2.35	2.49	2.72
30	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	2.64	2.91
35	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	3.11
40	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	3.36

HINS RFQ + 6 Cavity System

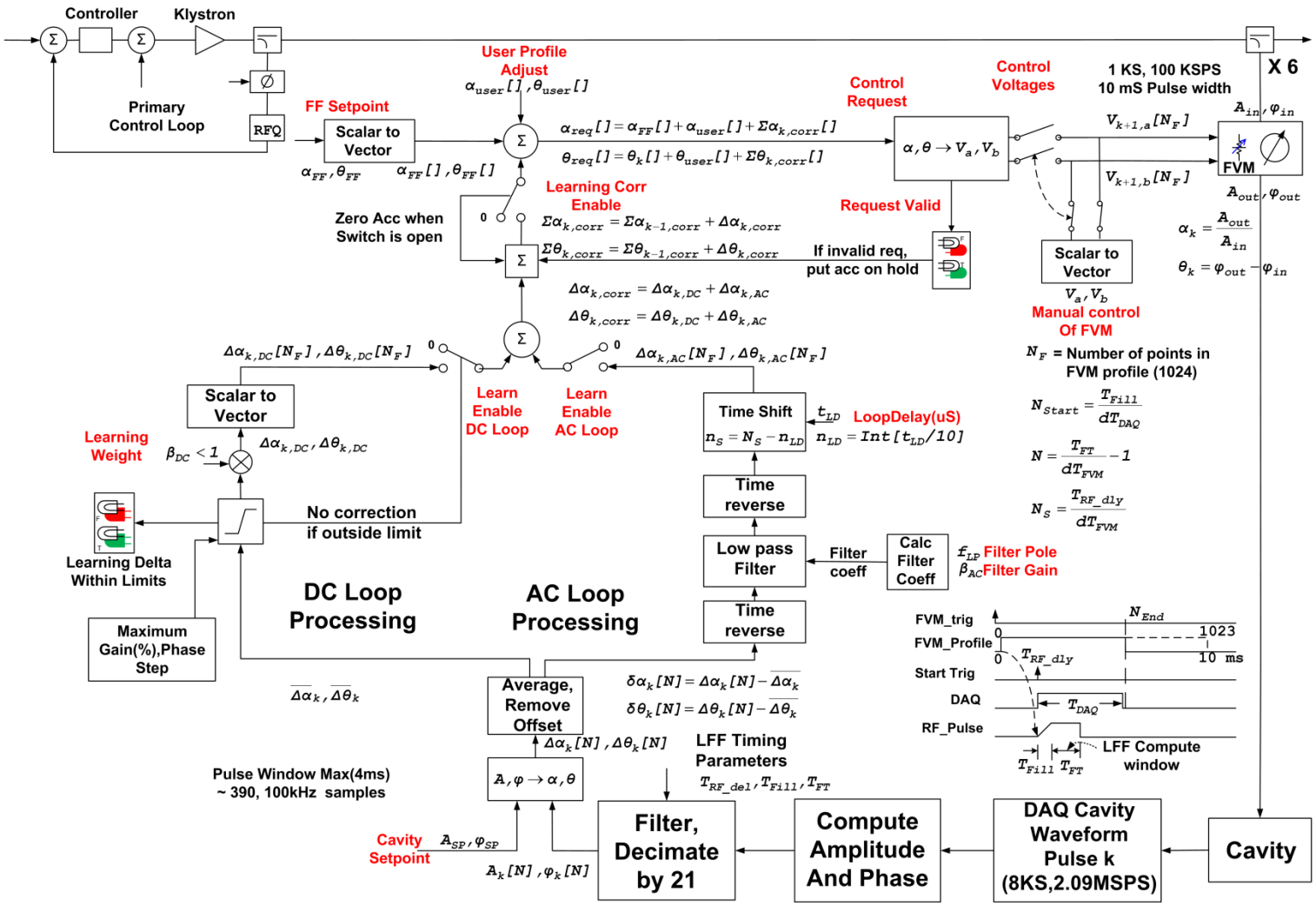


- Driving multiple cavities with a single klystron reduces RF system costs
- An adaptive control system for the HINS 6-cavity system was developed and tested with a regulation target of 1% / 1°

LLRF system configuration

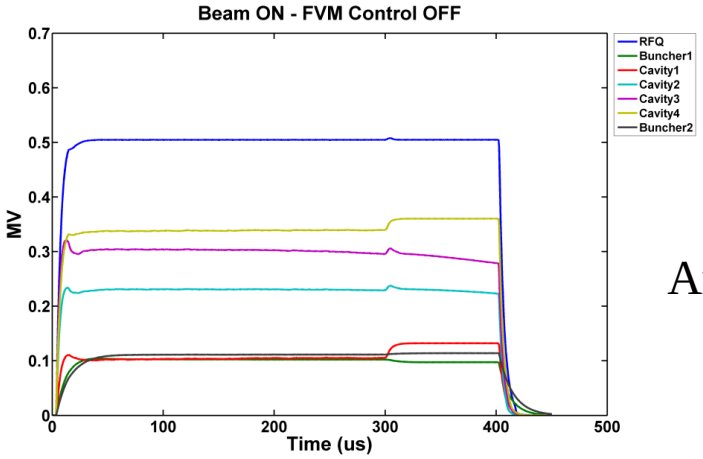


Learning Feed-forward Algorithm

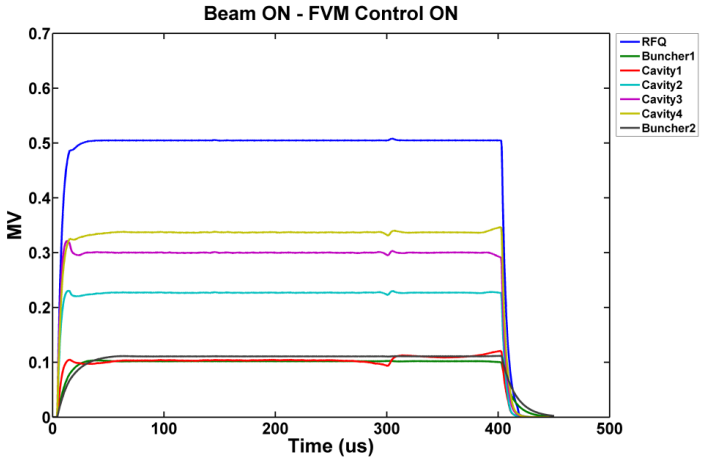


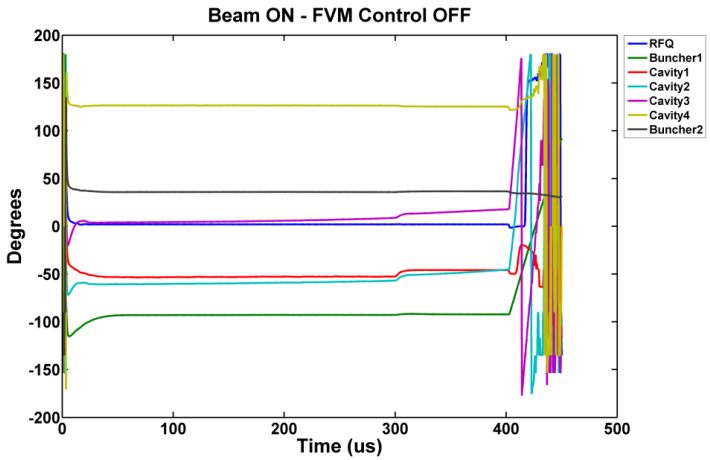
Beam Loading Response

RFQ feedback ON

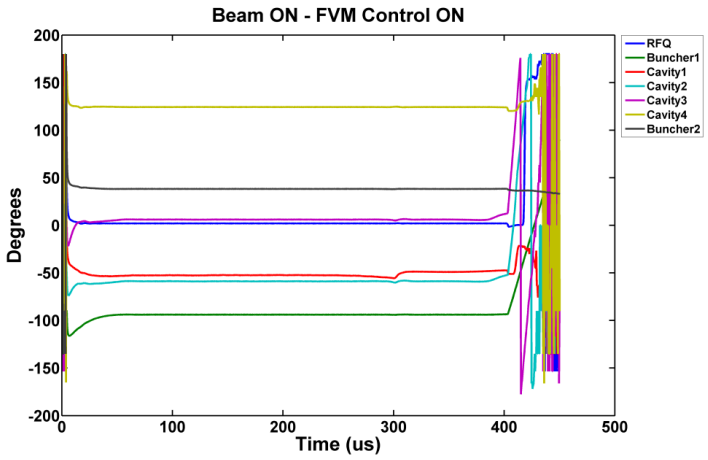


Amplitude





Phase



REGULATION

No Beam

Description	Mag. Reg. (%)	Phase Reg. (deg)
RFQ	**0.0107**	**0.027**
Buncher 1	**0.108**	**0.065**
Cavity 1	**0.099**	**0.136**
Cavity 2	**0.100**	**0.106**
Cavity 3	**0.098**	**0.112**
Cavity 4	**0.099**	**0.104**
Buncher 2	**0.191**	**0.098**

With Beam

Description	FVM Control OFF		FVM Control ON	
	Mag. Reg. (%)	Phase Reg. (deg)	Mag. Reg. (%)	Phase Reg. (deg)
RFQ	**0.021**	**0.015**	**0.021**	**0.015**
Buncher 1	**0.605**	**0.945**	**0.142**	**0.089**
Cavity 1*	**2.254**	**0.435**	**1.664**	**0.647**
Cavity 2	**1.737**	**1.200**	**0.203**	**0.209**
Cavity 3	**1.070**	**1.434**	**0.201**	**0.145**
Cavity 4	**0.543**	**1.887**	**0.159**	**0.149**
Buncher 2	**0.457**	**2.314**	**0.190**	**0.113**

* FVM control dynamic range limit reached

SUMMARY

- FVM Control with a pulse to pulse adaptive algorithm was tested with beam on the HINS 6-cavity system

- Independent control of individual cavities with different characteristics and set-points was achieved

- Regulation of the cavity fields within the specification of 1°/ 1 % range was met

- Despite limited range and non-linear characteristics FVMs can be successfully used to control multiple cavities with a single Klystron

Thank You !