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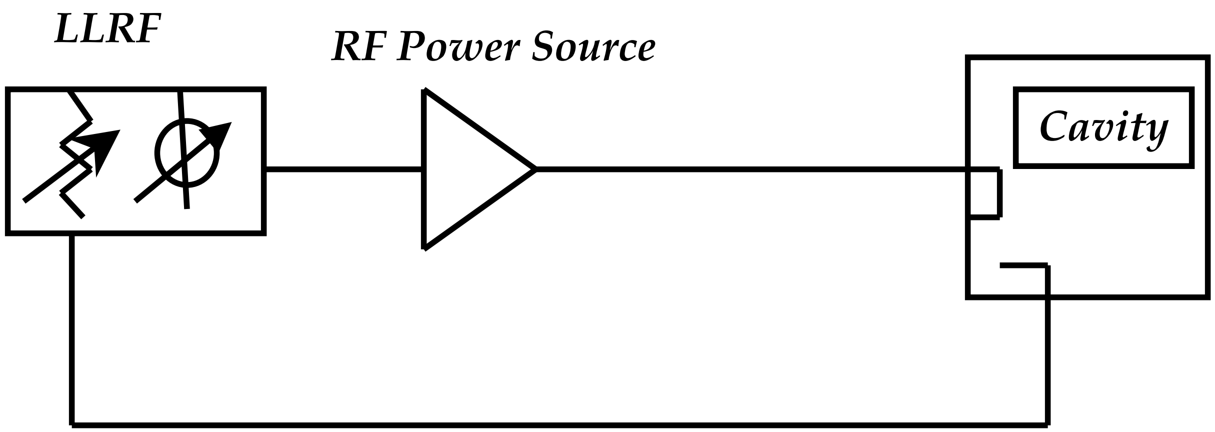
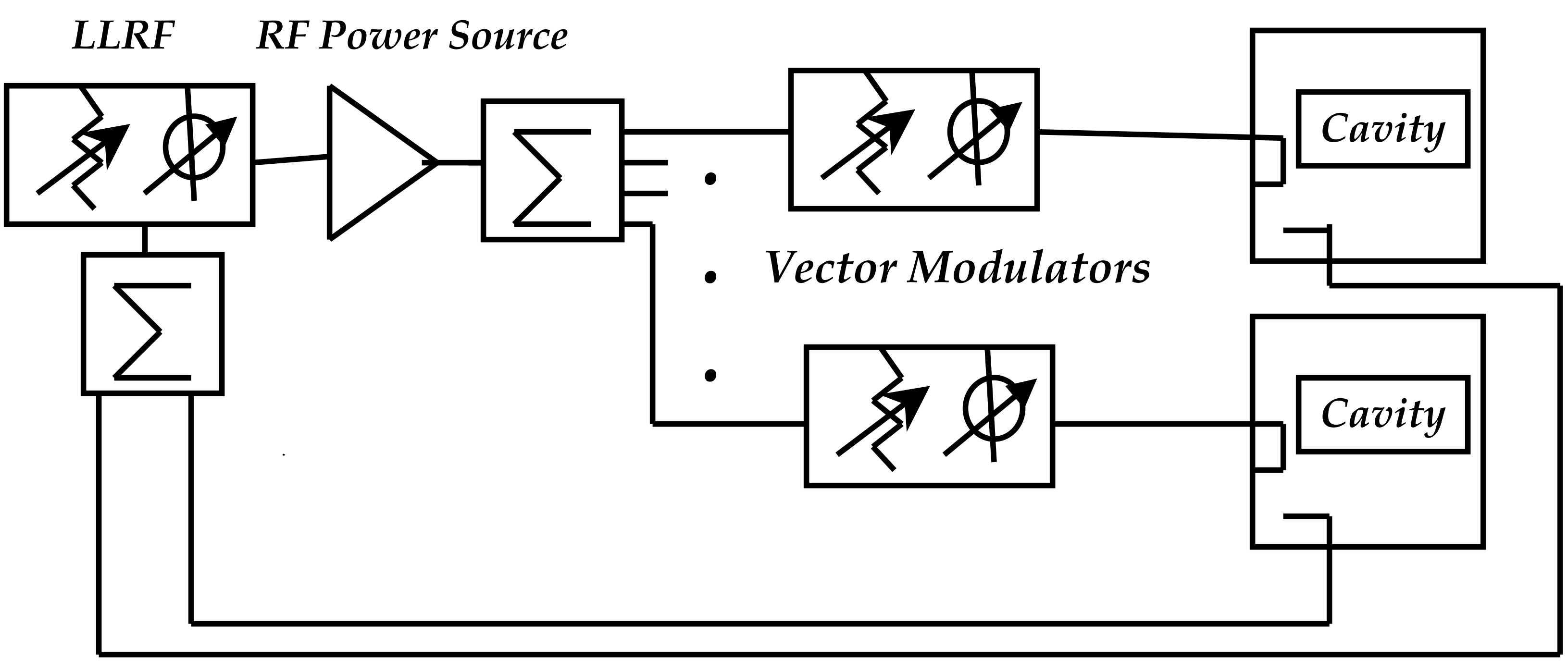
RF Power Distribution from Single Power Source to Multiple Loads

Ralph J. Pasquinelli
Accelerator Division
Fermilab

Vector Control in Low Level RF (LLRF)
Single power source for each load
Vector control cost low, performance high



Vector Control in High Level RF (HLRF)
Allows multiple loads on a single power source
Vector control cost high, performance unproven



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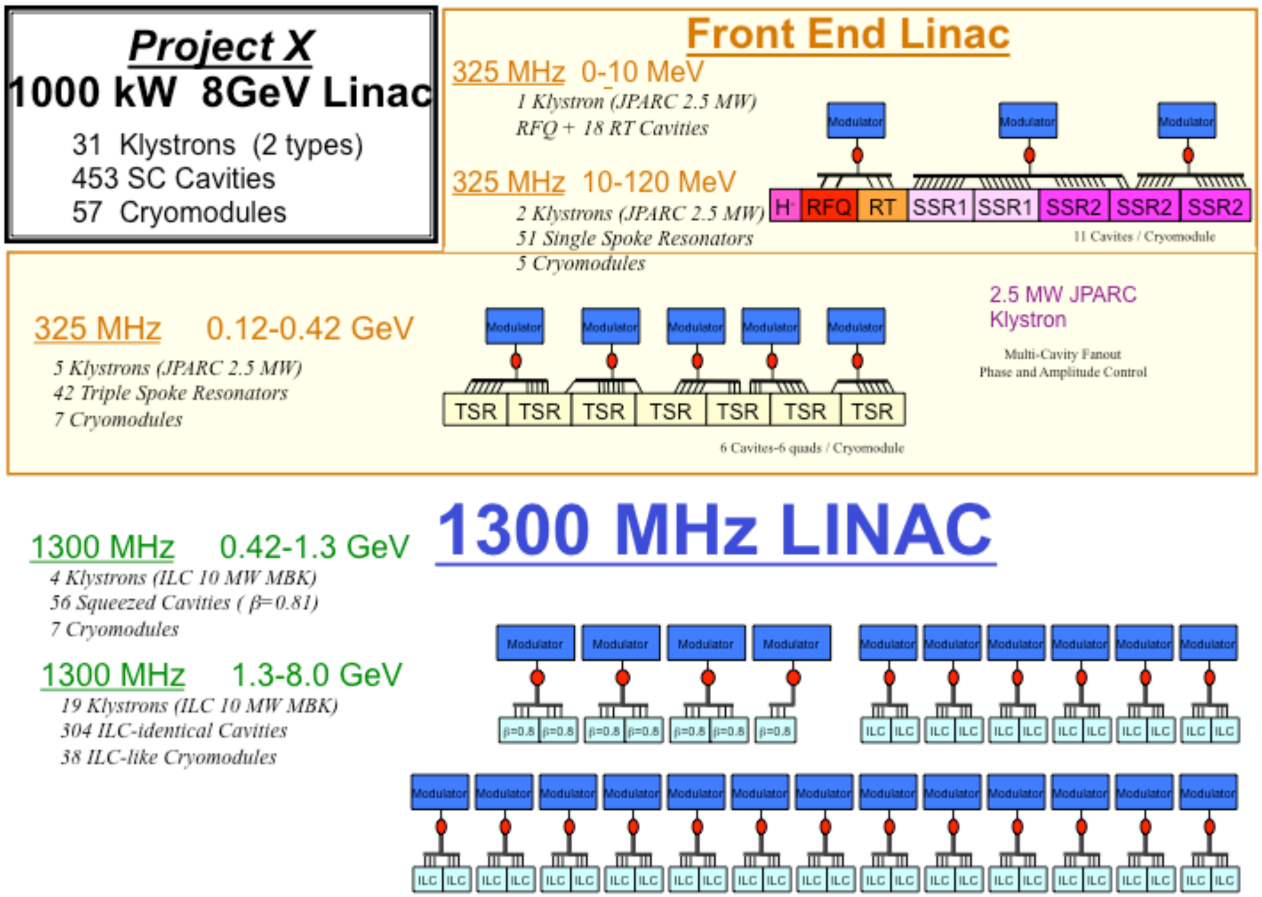
Project X



Cost of RF power!

Manufacturers of High Power RF Sources

Continental Electronics

TOMCO TECHNOLOGIES

HARRIS

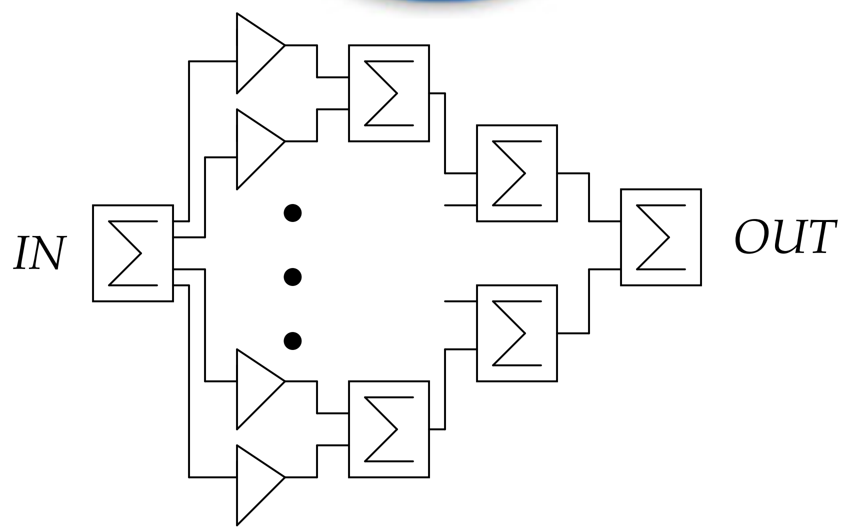
THALES

CPI
Communications & Power Industries

L3 communications

TOSHIBA
Leading Innovation

50 KWatts 325 MHz solid-state
$5.50 per Watt - Turn Key



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90 KWatts 1.3 GHz $5.27 per Watt
IOT alone $1.36 per Watt - Turn Key

CPI
Communications & Power Industries

VKL-9130 IOT Amplifier

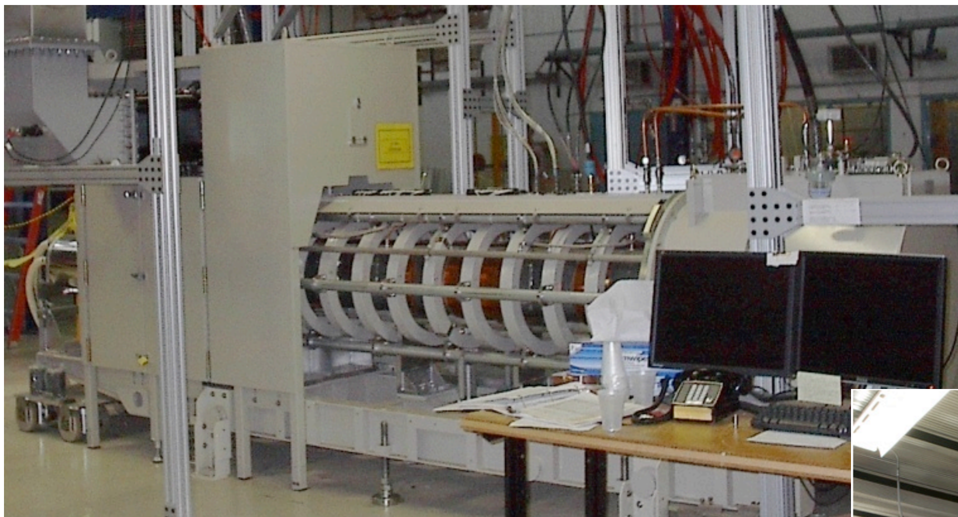
VIL-409
(NEMA 4X type of enclosure option shown)

500 KWatts 325 MHz
$3.20 per Watt - Turn Key

Tetrode/Triode Amplifier

Continental Electronics

2.5 MWatts 325 MHz
$0.35 per Watt + Modulator Labor



Toshiba 325 MHz klystron

Fermilab Bouncer Modulator

10 MWatts 1.3 GHz
$0.14 per Watt + Modulator Labor

CPI VLK8301

Toshiba

TH 1801

Multi-Beam Klystron

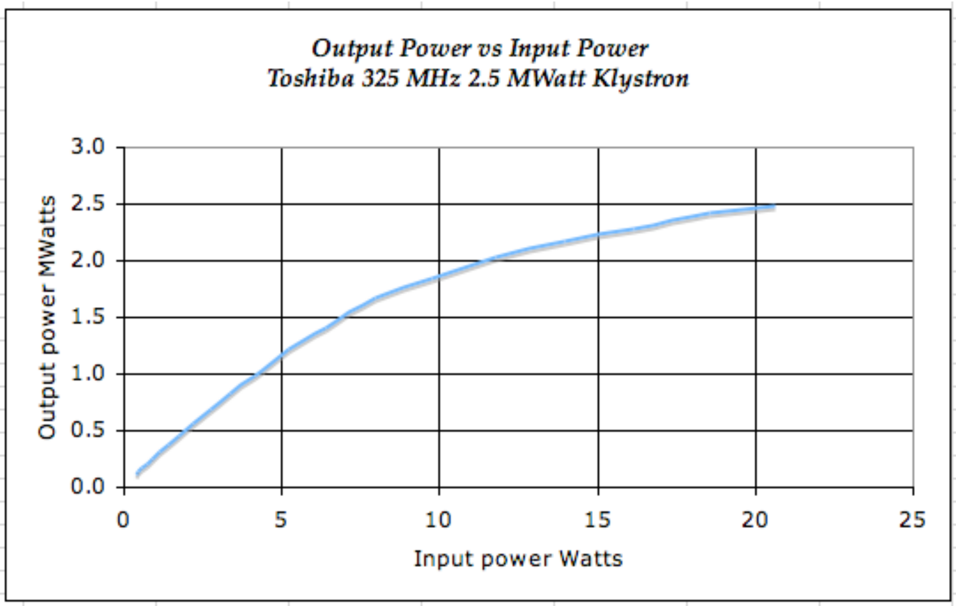
10 MW peak - 150 kW av.
at 1.3 GHz

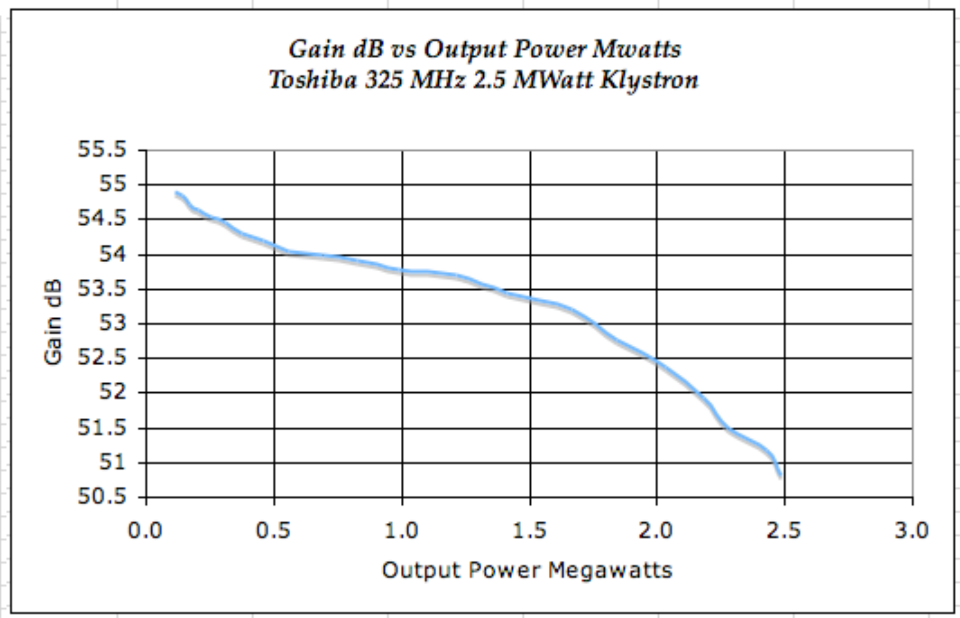
THALES

325 MHz 2.5 MWatt Toshiba Klystron Gain and Power Characteristics

1 dB compression occurs around 1.5 MWatt output power

Necessary to operate below saturation for feedback control
True of all amplifiers; increasing the cost per Watt





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HINS Meson Test Facility

May 8, 2009

R. J. Pasquinelli

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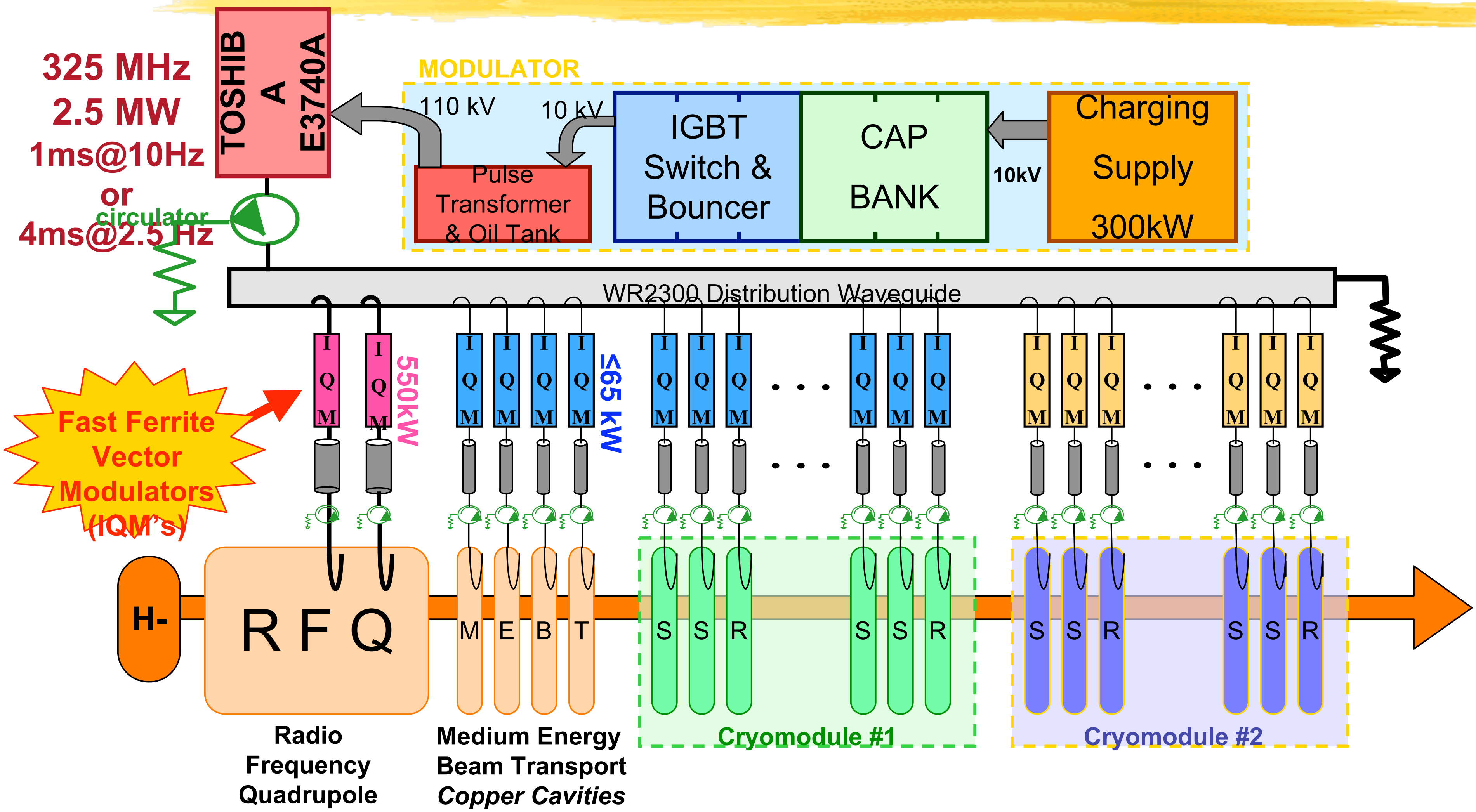
High Intensity Neutrino Source (HINS) 325 MHz Linac @ Fermilab



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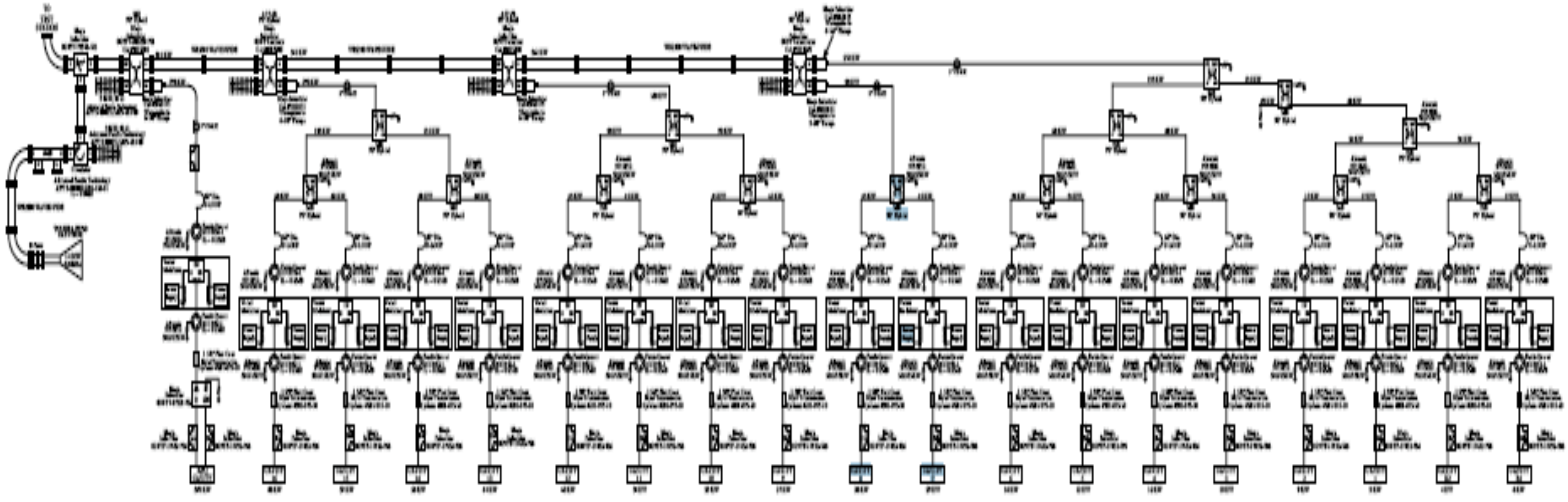
Power table HINS Warm Cavities

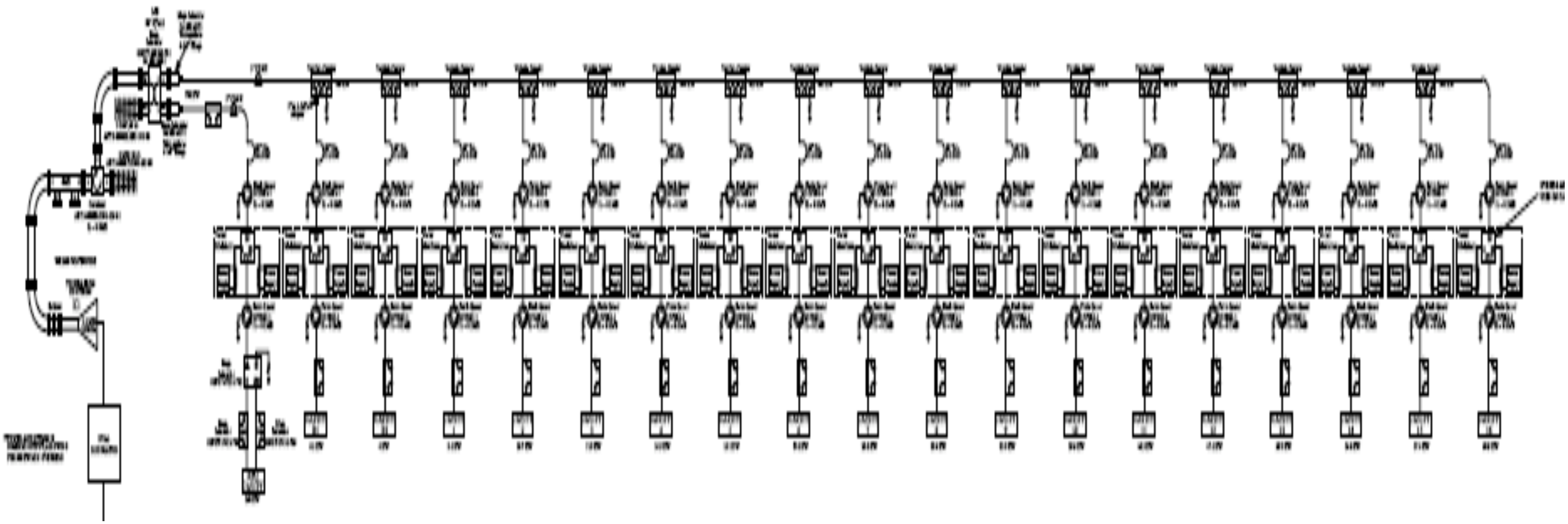
Cavity number	design type	β geom.	β particle	Rsh MOhm	Veff MV	φ_S deg	dW MeV	W MeV	P_{copper} kW	P_{beam} kW	P_{total} kW
1	1	0.0744	0.0729	10.45	0.1807	-90	0.000	2.5	3.1246	0	3.1246
2	2	0.0771	0.0741	10.55	0.277	-50	0.178	2.678	7.2729	1.78	9.0529
3	3	0.0804	0.0767	10.994	0.2994	-50	0.192	2.871	8.1536	1.92	10.074
4	4	0.0842	0.0795	11.15	0.3336	-50	0.214	3.085	9.9811	2.14	12.121
5	5	0.0882	0.0825	15.64	0.3877	-50	0.249	3.334	9.6107	2.49	12.101
6	5	0.0882	0.0861	16.96	0.459	-45	0.325	3.659	12.422	3.25	15.672
7	8	0.1015	0.0905	14.38	0.5929	-45	0.419	4.078	24.446	4.19	28.636
8	8	0.1015	0.0955	17.16	0.6061	-40	0.464	4.542	21.408	4.64	26.048
9	8	0.1015	0.1008	18.62	0.6387	-35	0.523	5.065	21.909	5.23	27.139
10	11	0.116	0.1064	17.78	0.6983	-33	0.586	5.651	27.425	5.86	33.285
11	11	0.116	0.1121	19.77	0.7412	-33	0.622	6.273	27.788	6.22	34.008
12	11	0.116	0.1181	20.31	0.8216	-33	0.689	6.962	33.236	6.89	40.126
13	14	0.1316	0.1244	20.88	0.9425	-33	0.790	7.752	42.543	7.9	50.443
14	14	0.1316	0.1308	22.12	0.9071	-33	0.761	8.513	37.198	7.61	44.808
15	16	0.1422	0.1368	22.59	0.94	-33	0.788	9.301	39.115	7.88	46.995
16	16	0.1422	0.1426	23.29	1.0172	-40	0.779	10.081	44.427	7.79	52.217
								Total :	370.06	75.79	445.85

Binary Distribution Scheme



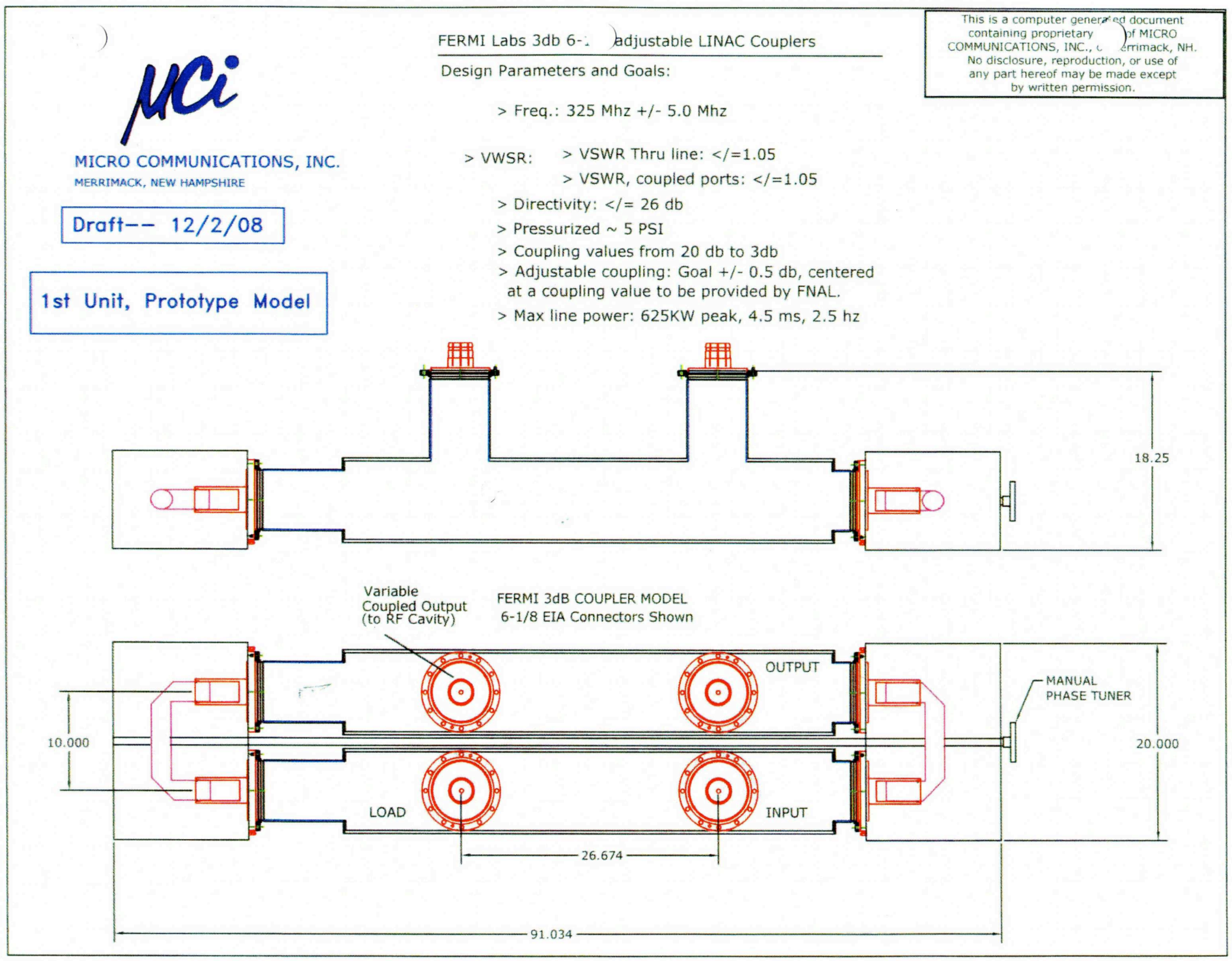
This technique utilizes standard components: Cost Effective
But requires more insertion loss with the VM, i.e. wasted power

Variable Coupler Distribution Scheme



This technique utilizes custom coupler: Expensive
Minimizes power loss, preferred to be remote controlled for efficient commissioning

Variable Coupler



Project X 325 MHz RF Distribution
8 klystrons, 112 cavities, 400 MeV

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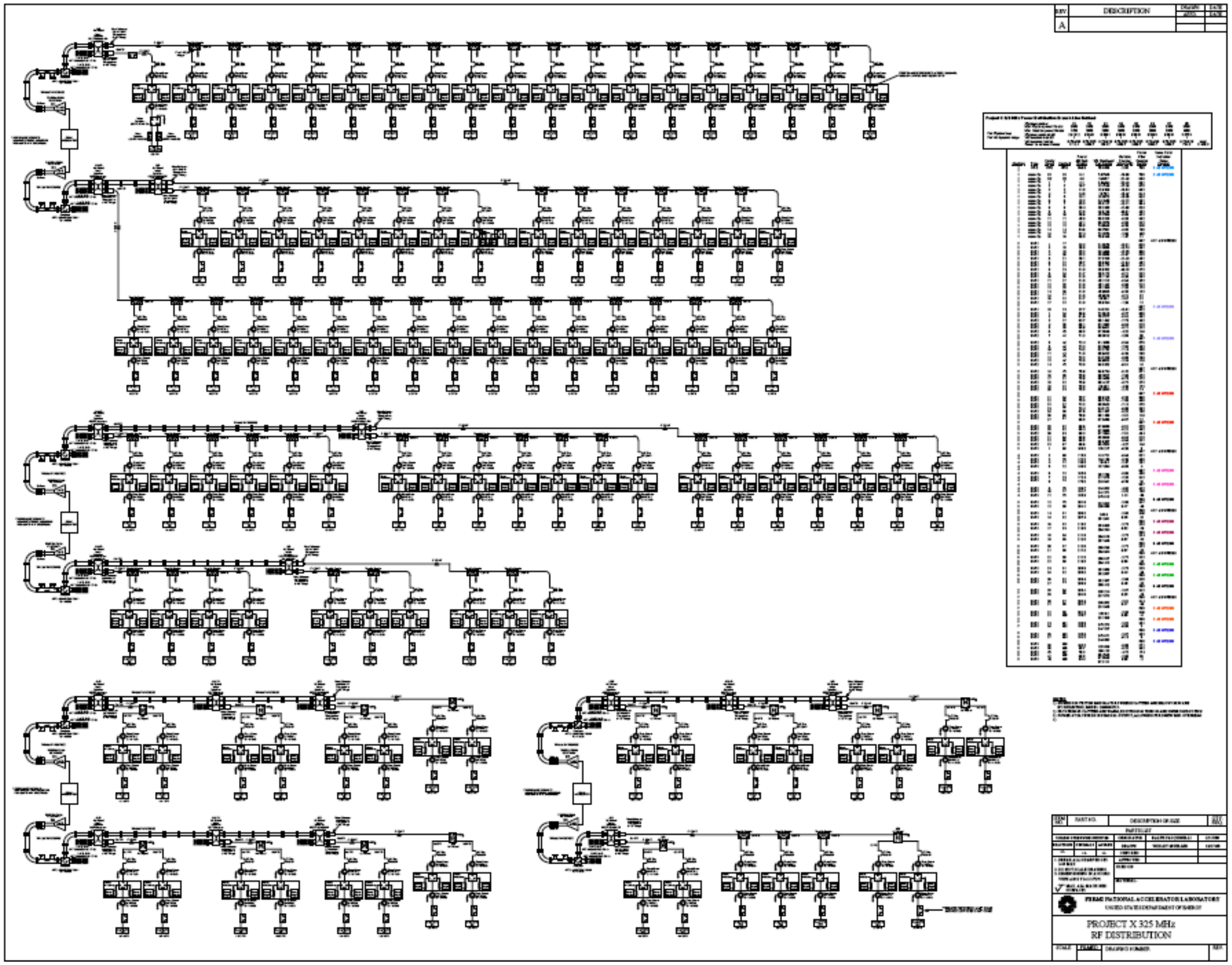
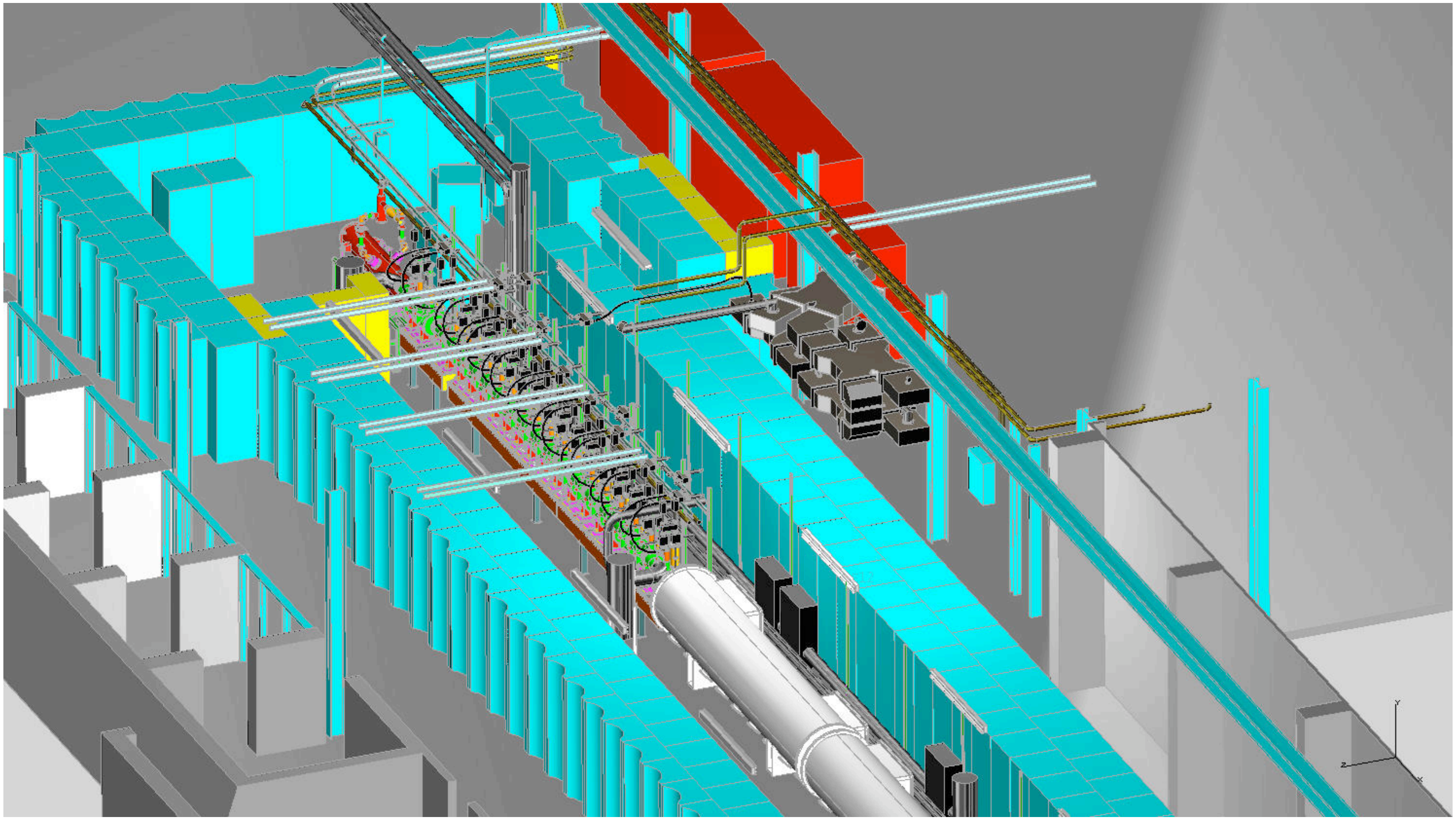
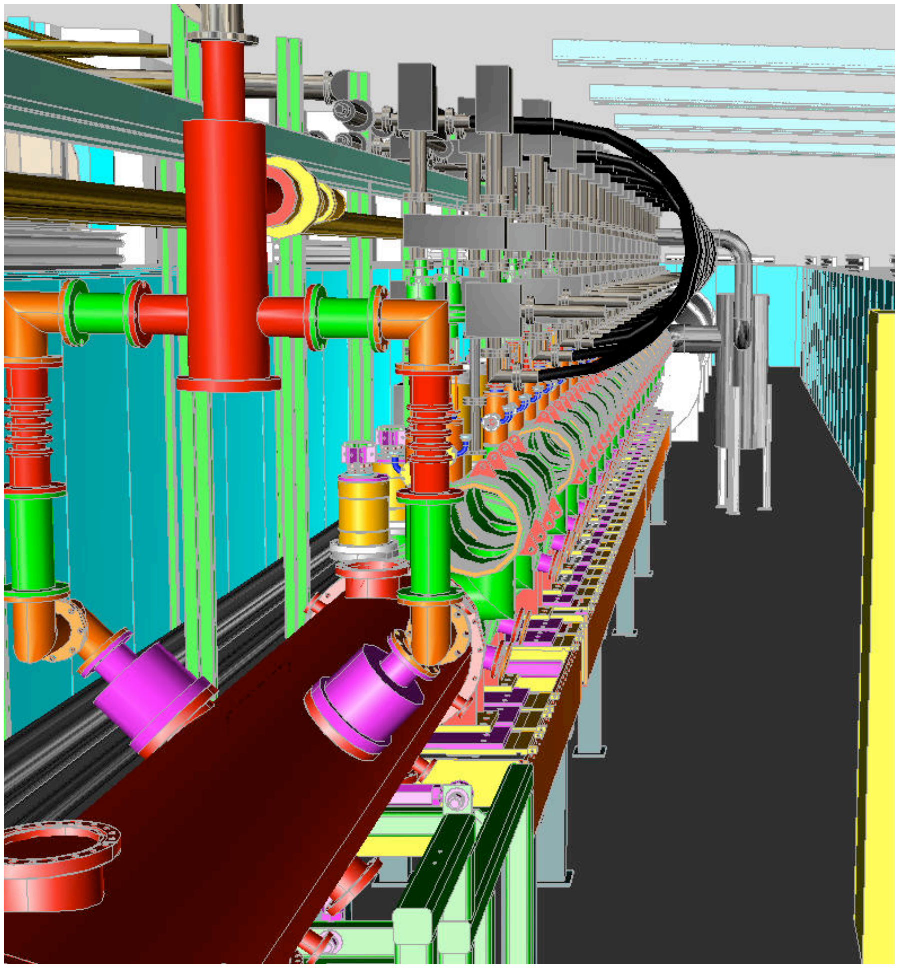
Klystron loads range from 7 to 32 cavities

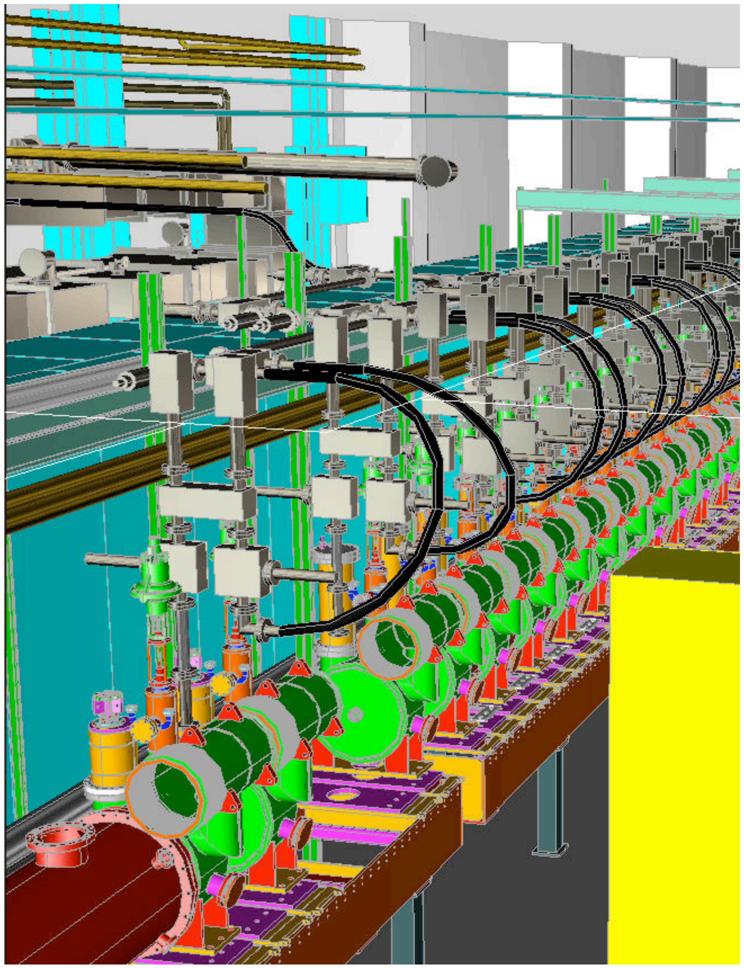


HINS 325 MHz RF Distribution
3-D Model

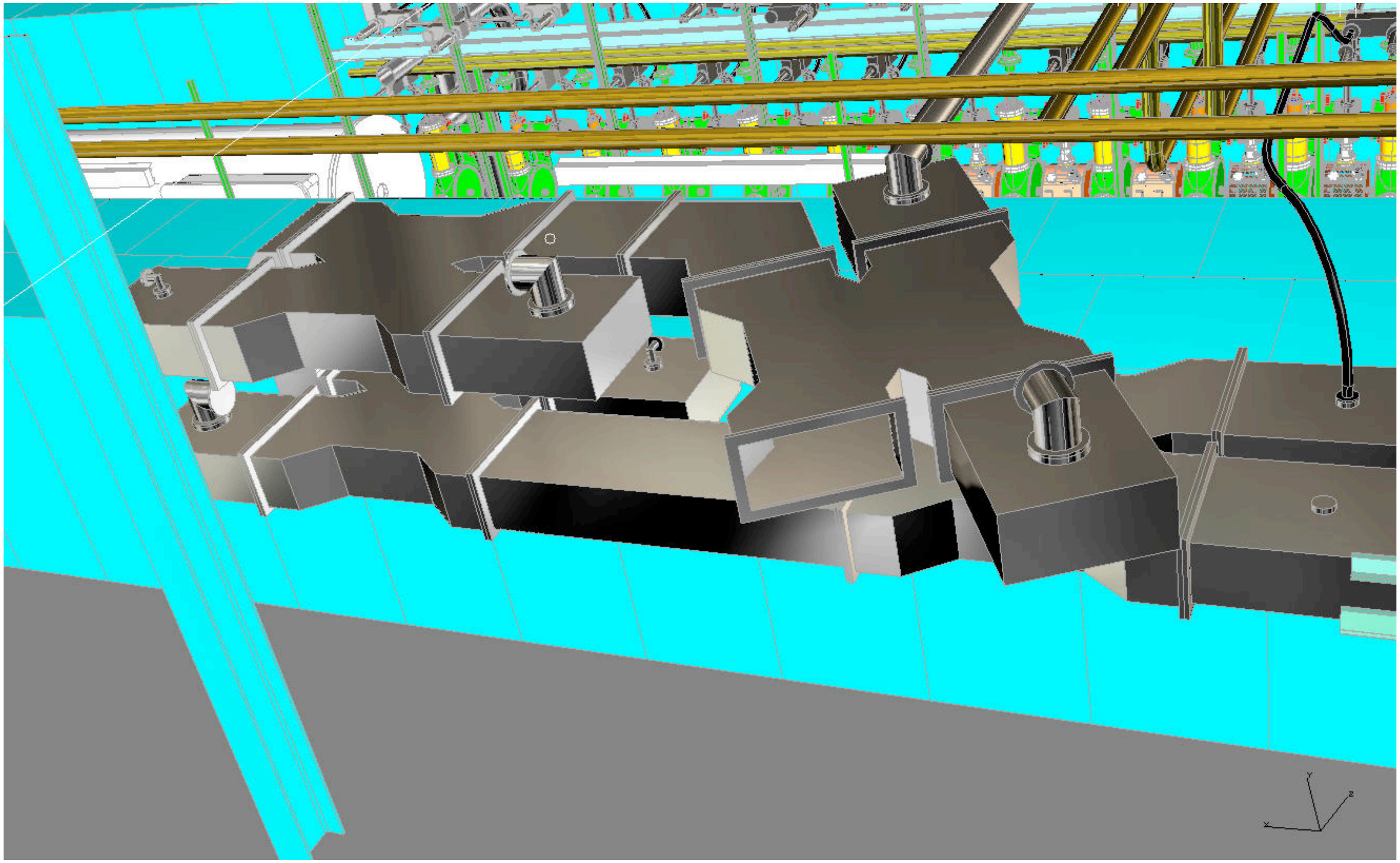


HINS 325 MHz RF Distribution
3-D Model





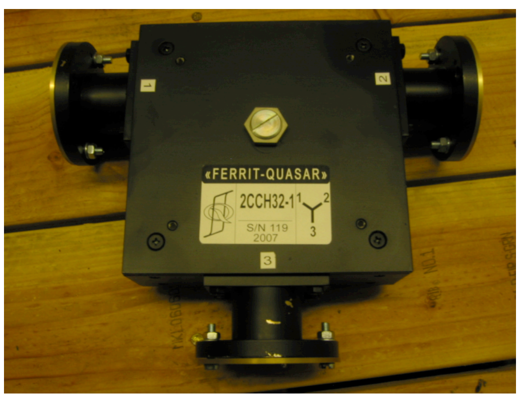
HINS 325 MHz RF Distribution
3-D Model



Fermilab High Power Components

Directional Coupler

Power Hybrids



Circulator

Loads

Many commercial manufacturers, but most do not have high power testing capabilities at your frequency of interest.

Poor match between components means higher VSWR and reduced power handling

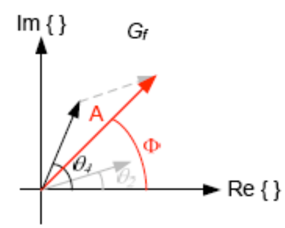
Check track record to see if similar components have been fabricated for other customers.

Establish a close working relationship with manufacturers. Devise means to include high power testing as part of the procurement process.

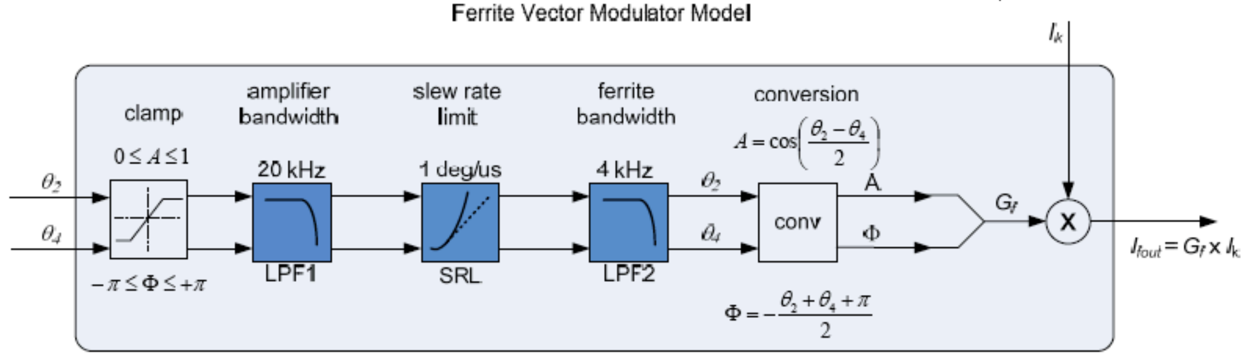
Beam loading compensation: Approach A

Using high power ferrite vector modulators (FVM)

- each cavity has its own: Q_0, V_0, Φ_s, ψ, Q_L
- P_{fwd} A/Φ modulation is unique to each cavity
- using one FVM for each cavity

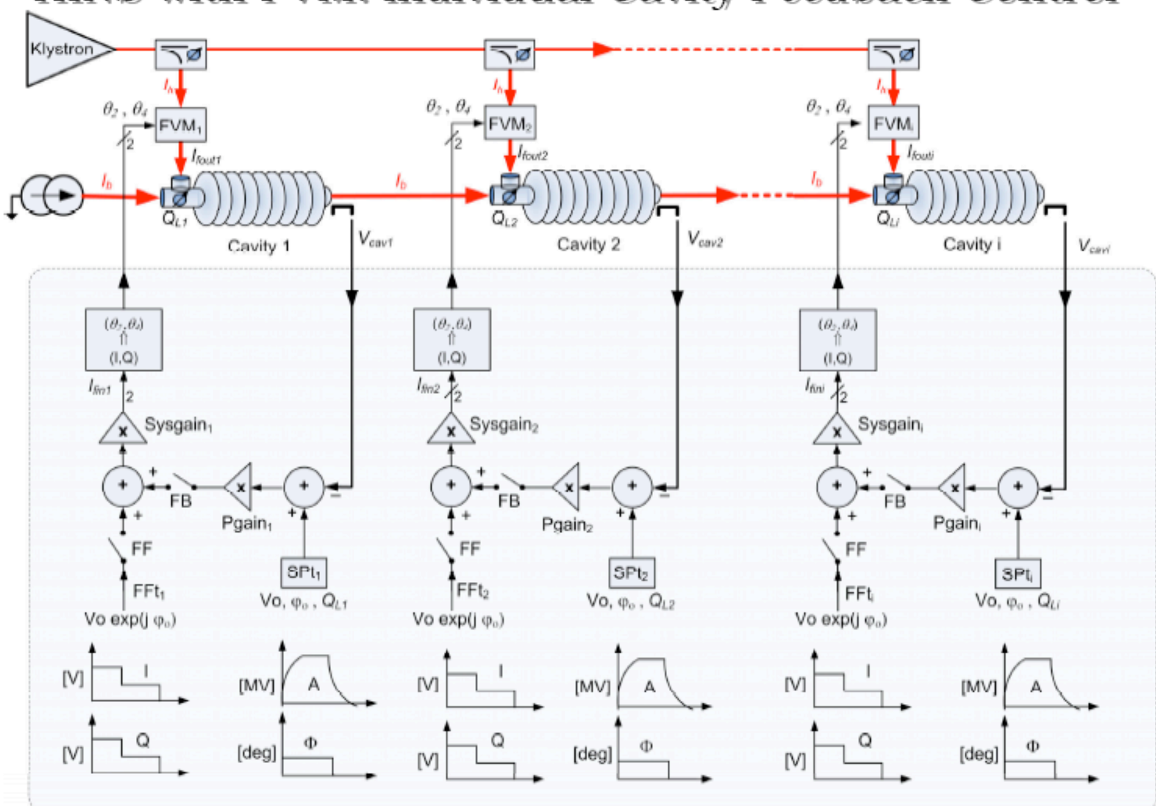


Ferrite Vector Modulator Model



System Model

HINS with FVM: individual Cavity Feedback Control

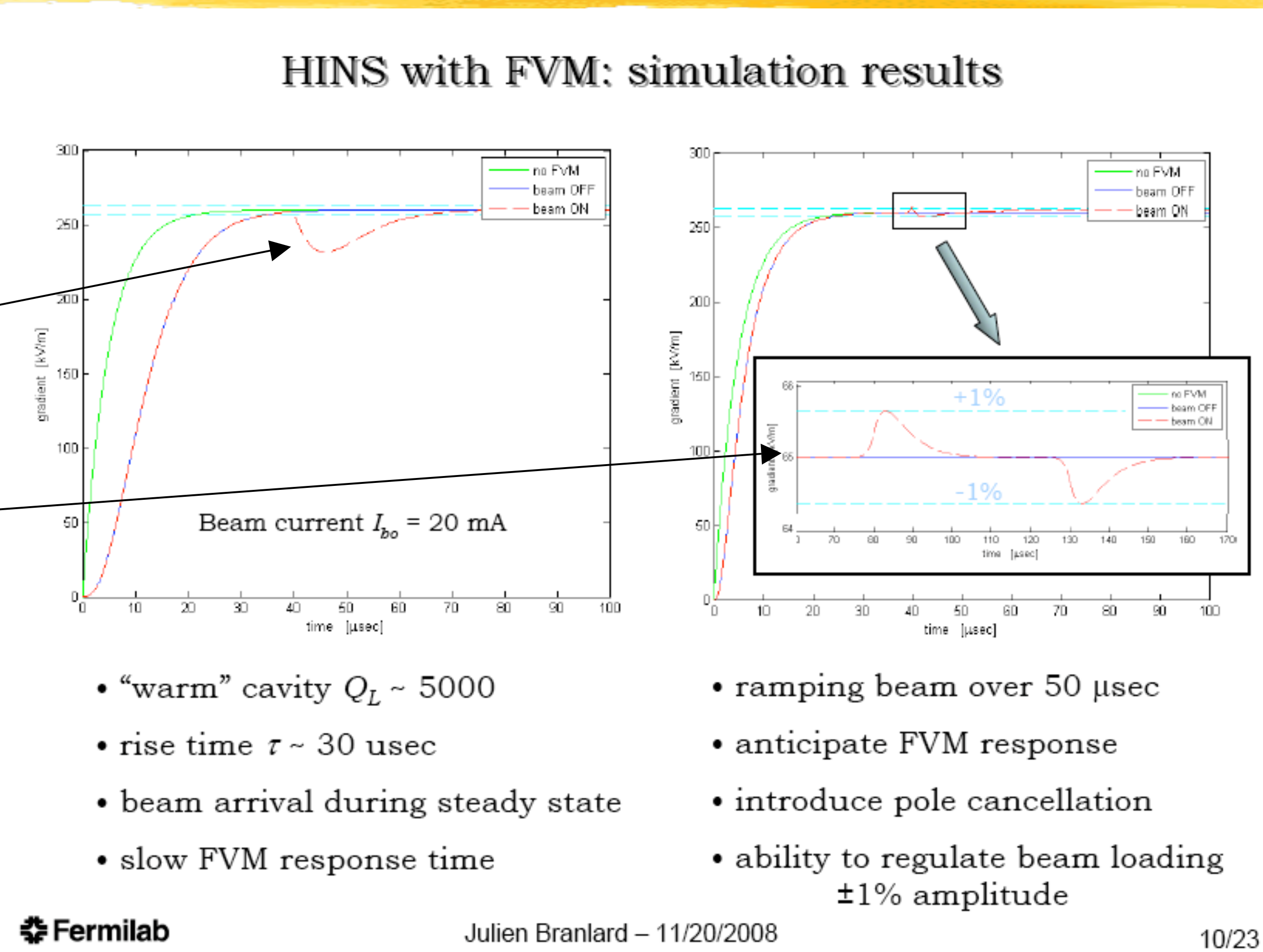


VM Simulation Results

VM alone with step in beam current does not regulate adequately

VM with ramped beam appears better

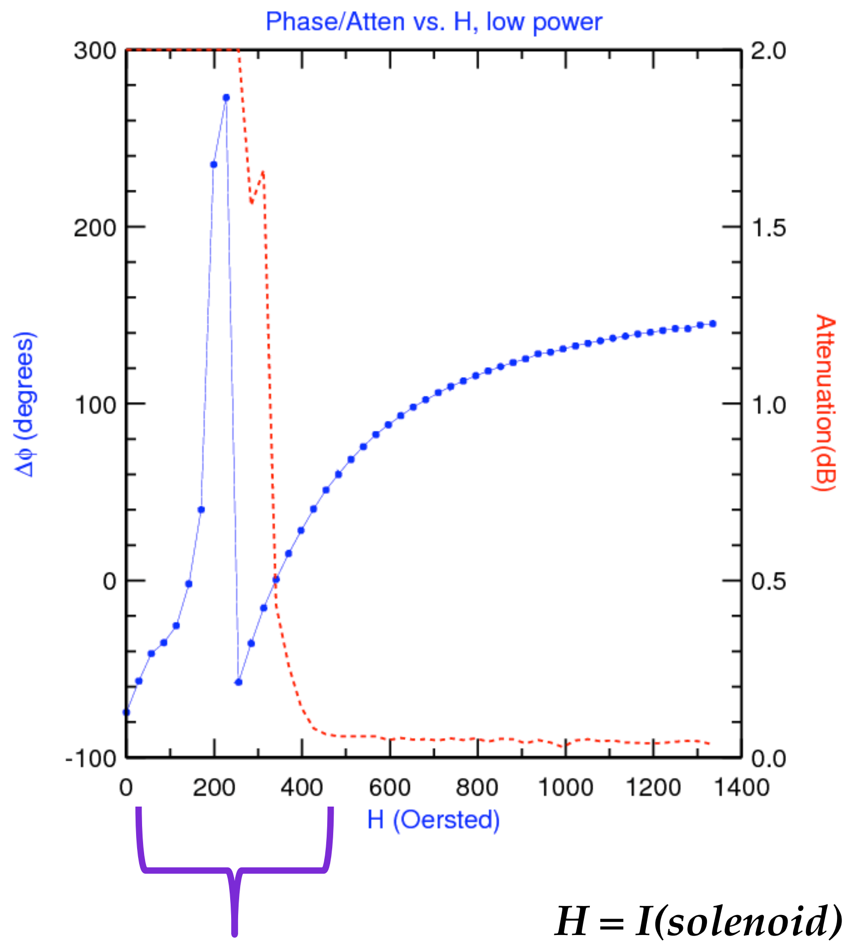
Best solution klystron feedback and VM feedback plus feed forward



Fermilab *HINS 325 MHz 75 KWatt Coaxial Vector Modulator*

May 8, 2009 *R. J. Pasquinelli*

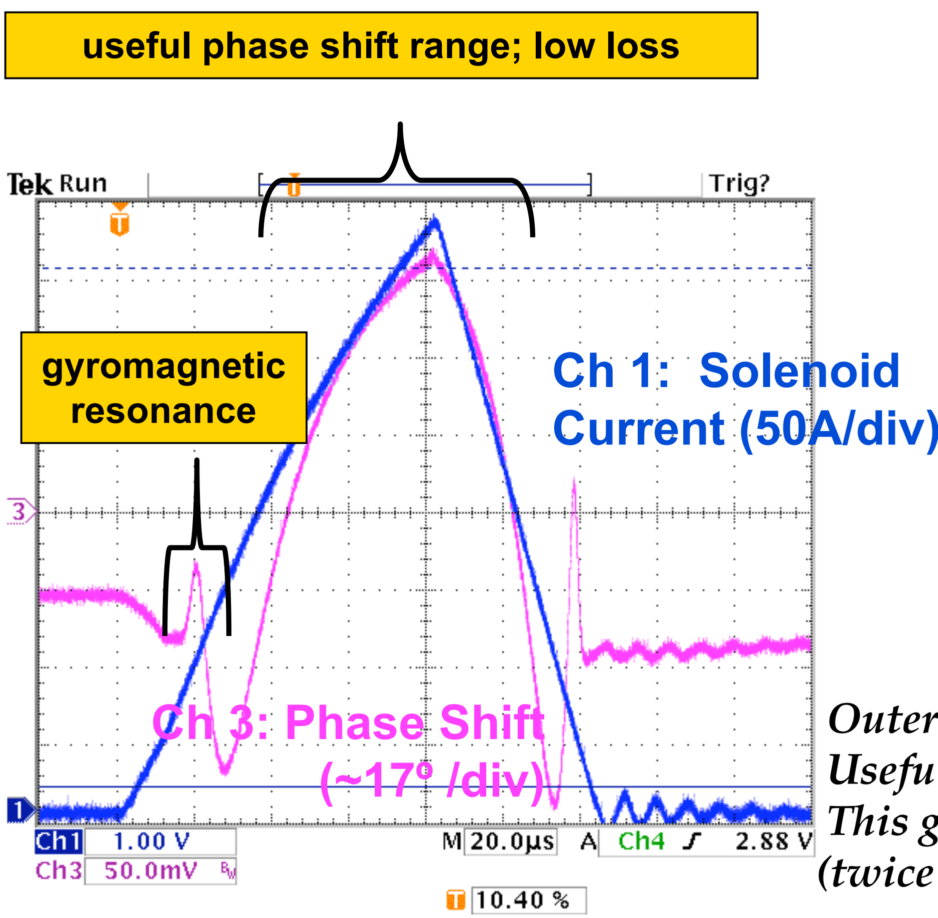
Fermilab 325 MHz Single Phase Shifter Response

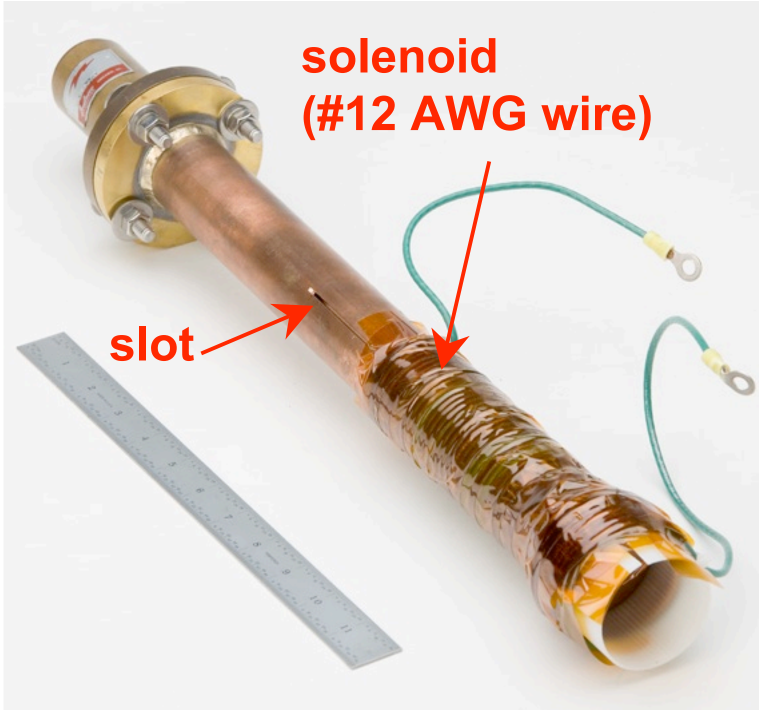


*H = I(solenoid) * (#turns/cm)*4pi/10*

Gyromagnetic resonance (lossy region)

325 MHz Phase Shift Response





Outer conductor is slotted to eliminate eddy currents
Useful phase shift range above resonance: ~50us, 110°
This gives an average slew rate of 2.2°/us
(twice as fast as design spec)

325 MHz Vector Modulator Test

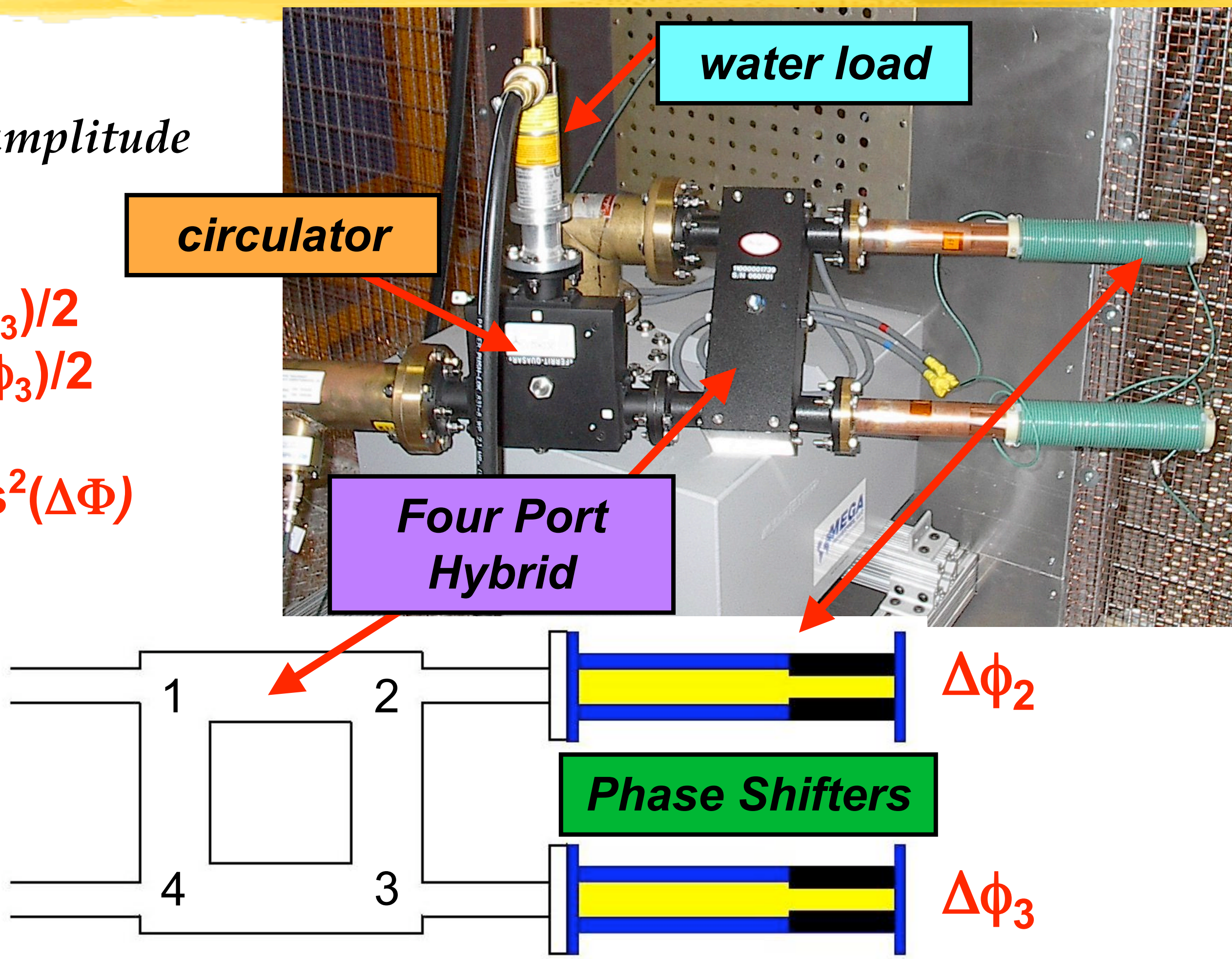
Modulates phase and amplitude independently:

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



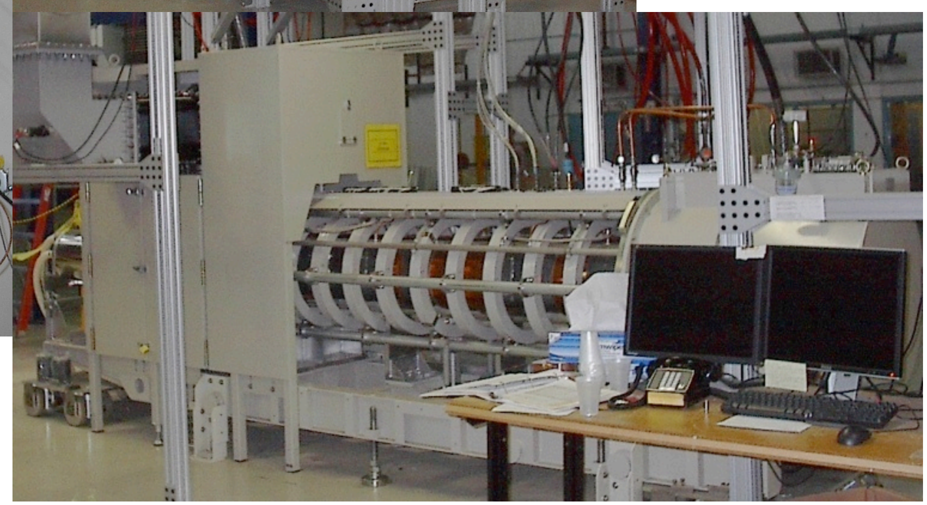
Input →

Output :← to circulator and cavity

Fermilab 325 MHz High Power Tests at Meson Lab

RF component test cage up to 2.5 MW

Cavity test cave
25 kW line,
250 kW line



325 MHz klystron

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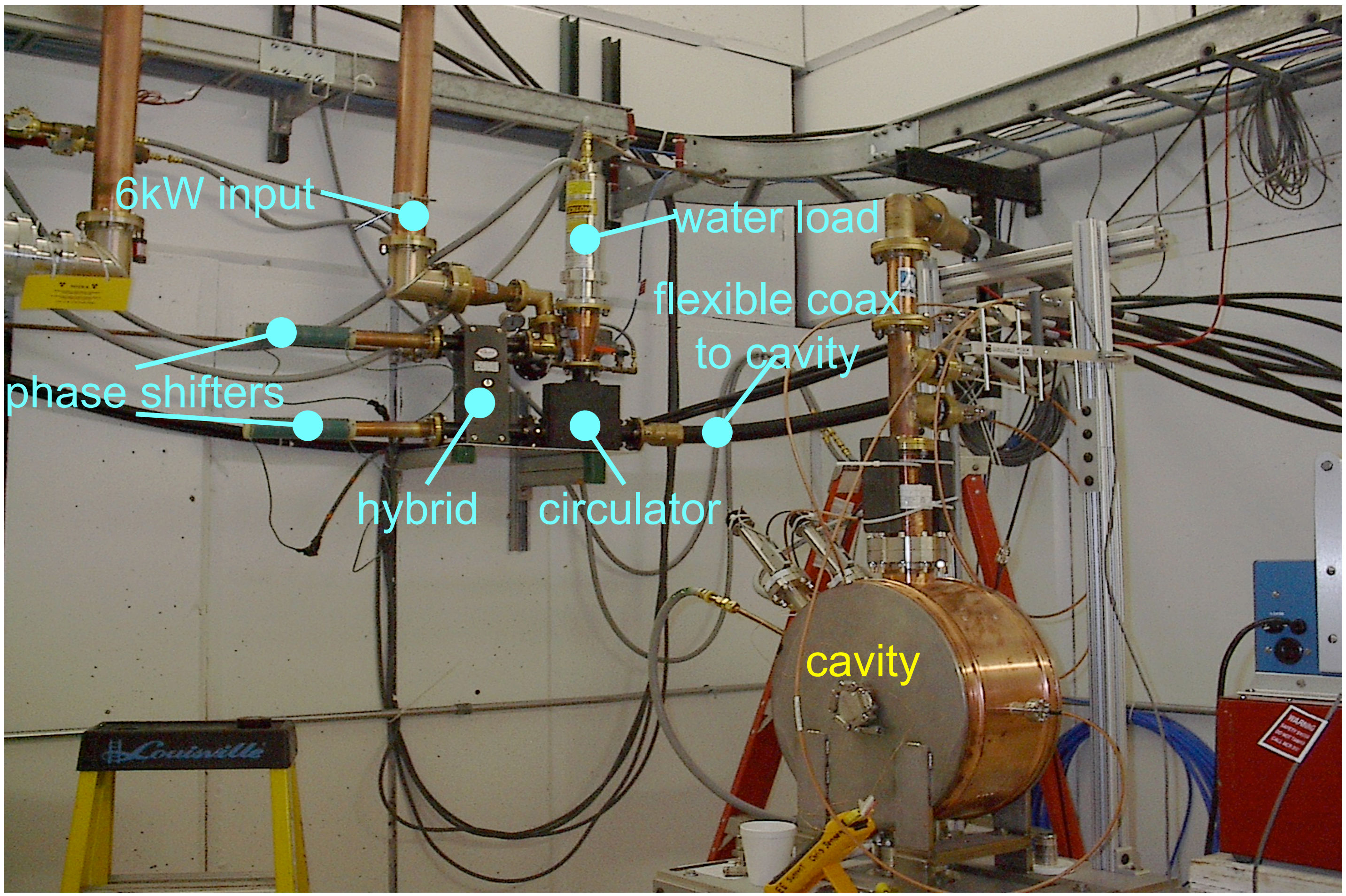
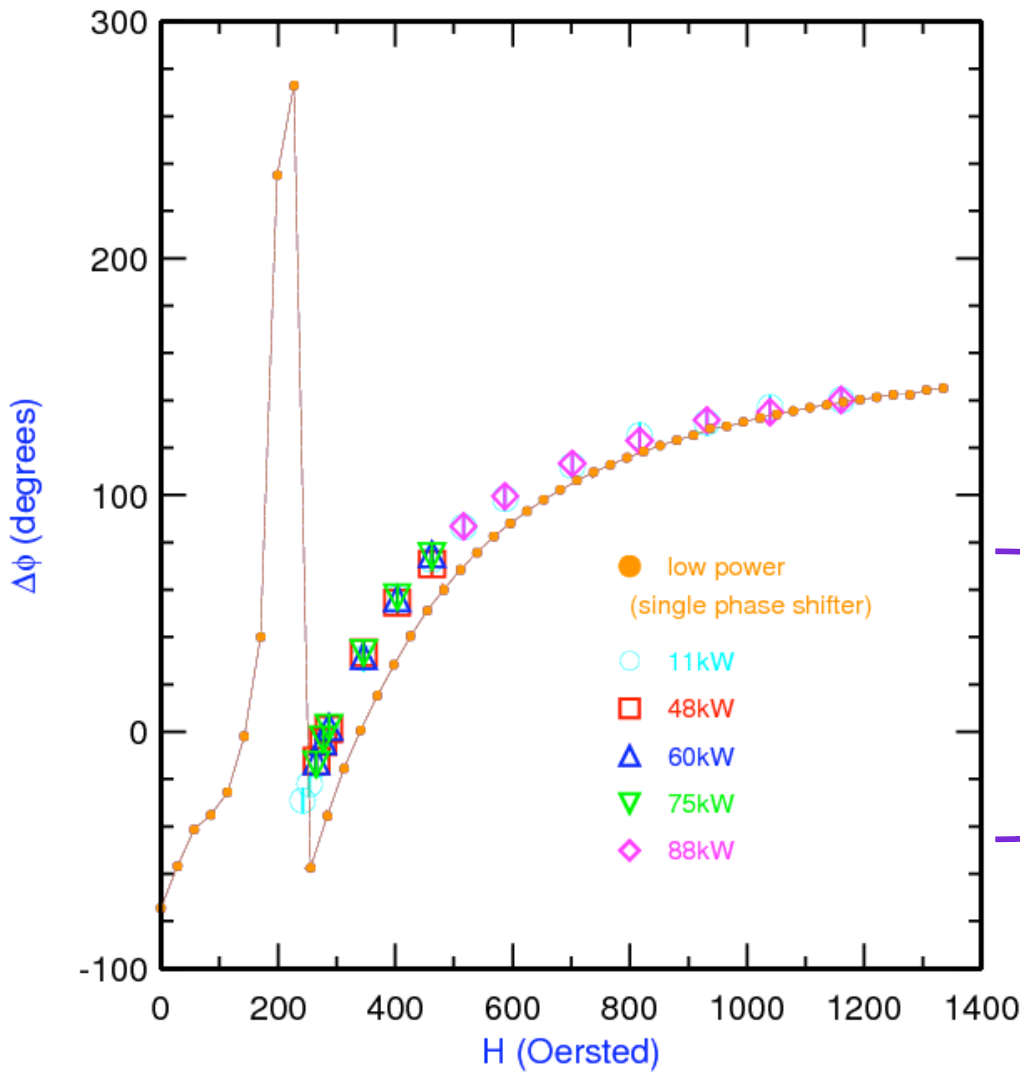
325 MHz Vector Modulator with Cavity @ 6 KWatts



Fermilab 325 MHz Vector Modulator High Power Test



→ *Vector Modulators work well to > 75 kW*

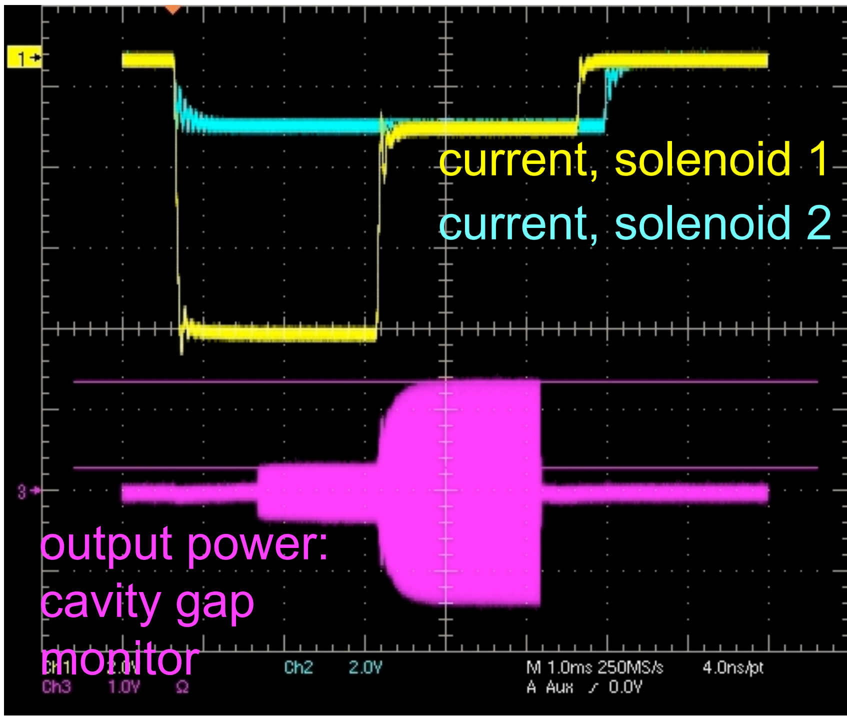
here, solenoids on both phase shifters driven by one power supply

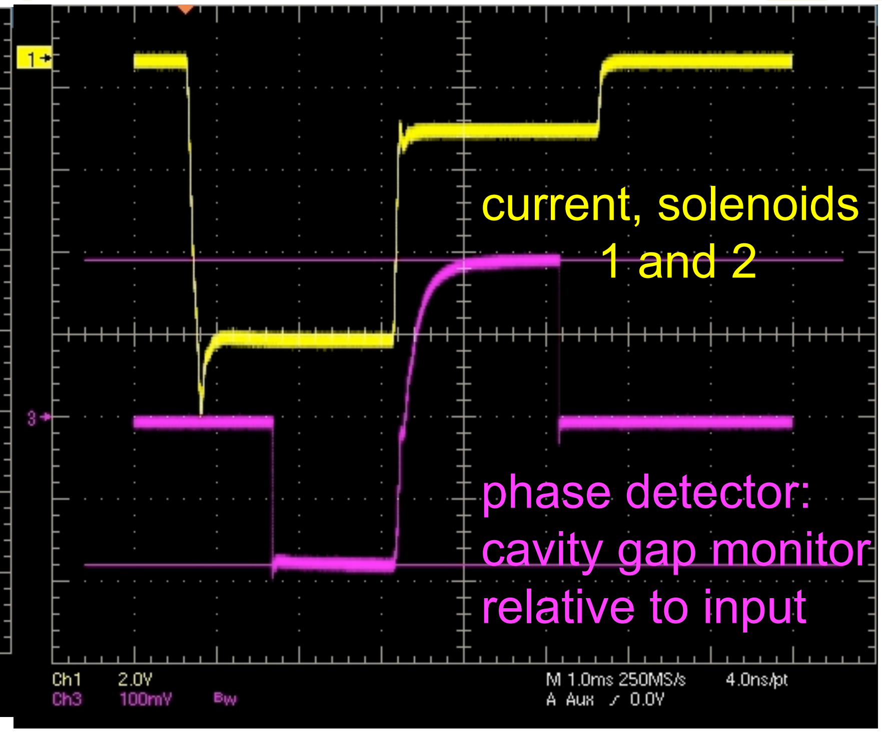
$(\Delta\phi_1 = \Delta\phi_2)$

phase ~ **$(\Delta\phi_1 + \Delta\phi_2)/2$**

R. J. Pasquinelli

325 MHz Vector Modulator with Cavity @ 6 KWatt

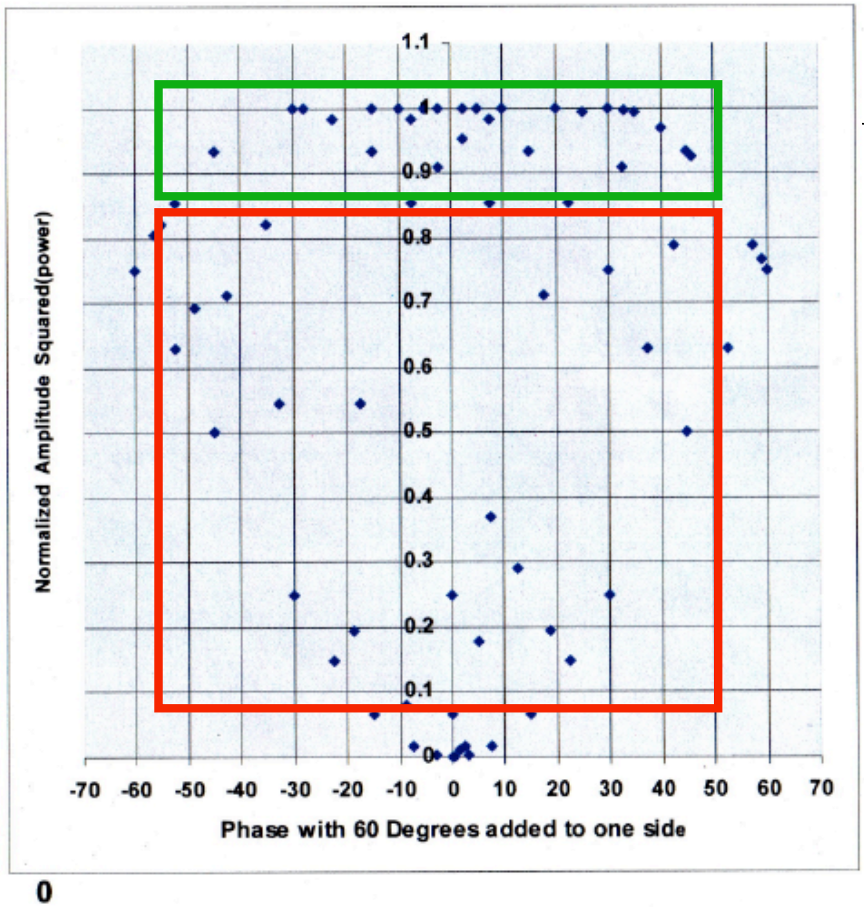




- *Phase shifters (solenoids) driven independently by 2 supplies*
- *Output power ~ cos2 [(Df1 -Df2)/2]*
- *Relative levels (range) = 13.6 dB*

- *Phase shifters (solenoids) driven in series by 1 supply*
- *phase ~ (Df1 + Df2)/2*
- *phase range ~ 155 degrees*

Fermilab 325 MHz Vector Modulator Dynamic Range

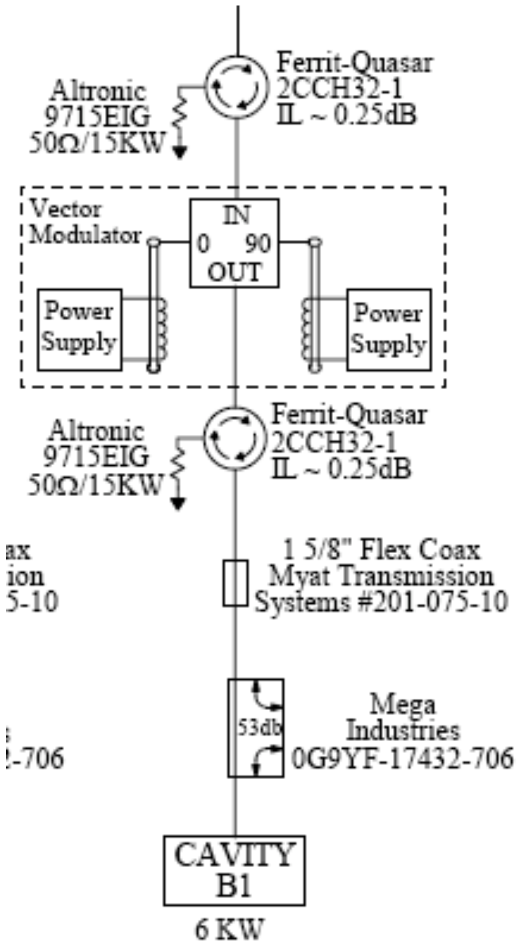


VSWR~2:1

VSWR >2:1

Power output vs Phase.

Vector Modulator Schematic



Circulator on input necessary due to poor VSWR

Circulator near Cavity essential for SRF cavities

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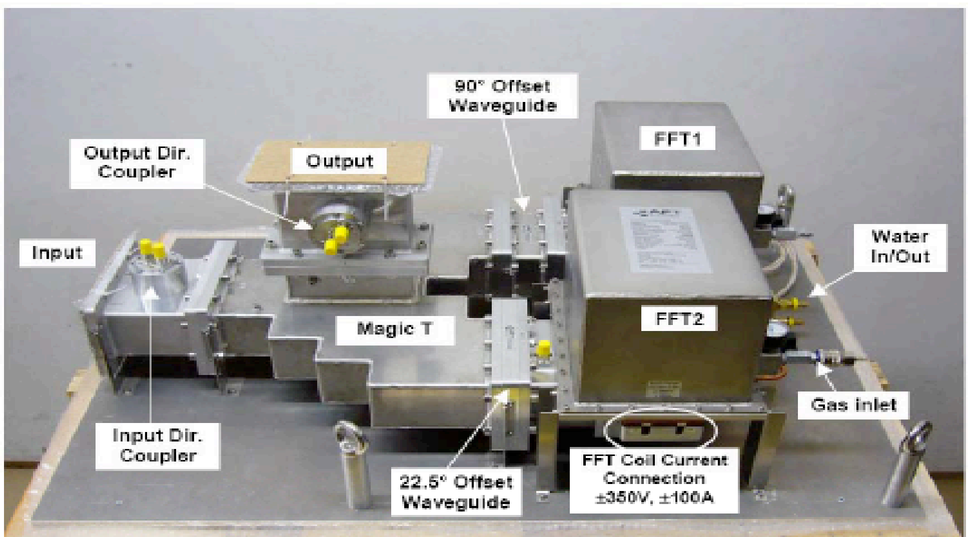
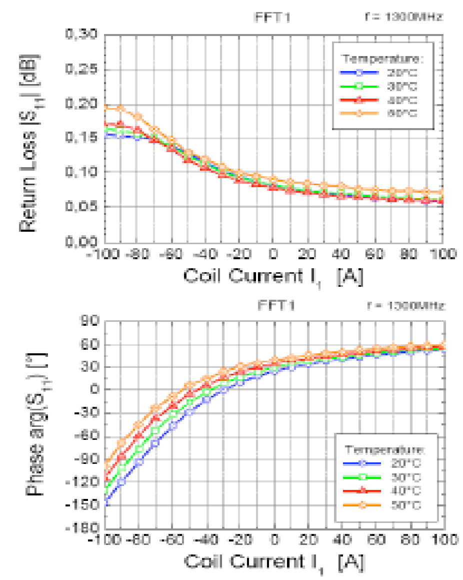
325 MHz Vector Modulator Costs

all prices in $K			
	Quantity	unit cost	line cost
HP Vector Modulator >75KW			
circulator	1	$40.00	$40.00
90 degree coax hybrid	1	$3.20	$3.20
reactive loads	2	$4.00	$8.00
power supplies	2	$9.00	$18.00
coax load	1	$3.00	$3.00
total cost			$72.20
LP Vector Modulator <75 KW			
circulator	1	$3.00	$3.00
90 degree coax hybrid	1	$1.50	$1.50
reactive load	2	$2.00	$4.00
power supplies	2	$9.00	$18.00
coax load	1	$1.00	$1.00
total cost			$27.50

Fast Amplitude and Phase Control
(AFT prototype for FNAL PD)

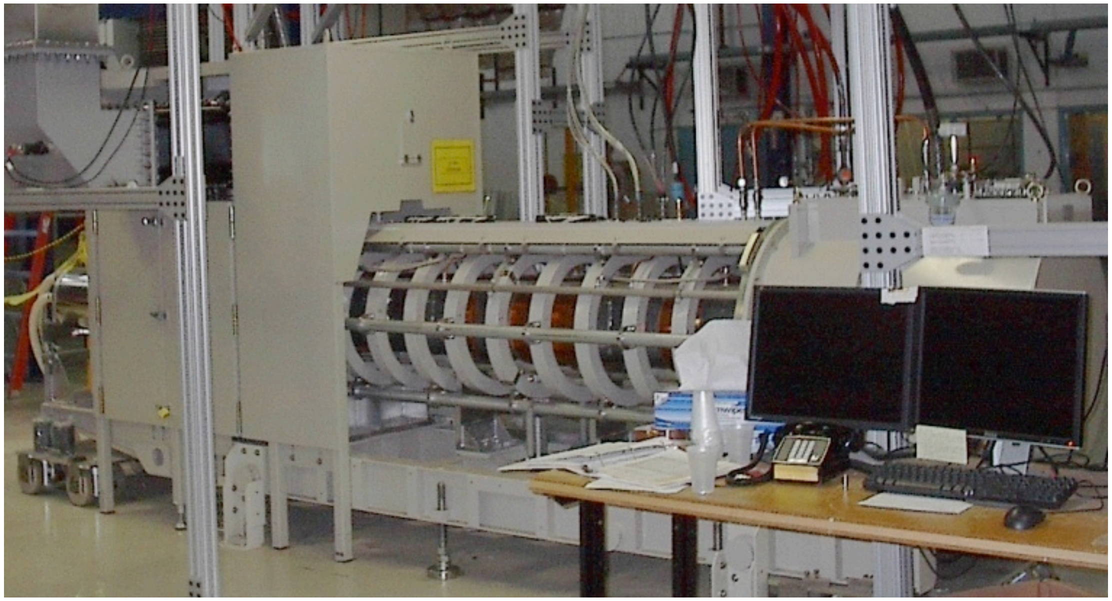




1 meter

Rated for 550 kW at 1.3 GHz and has a 30 us response time

8 Klystrons deliver 14.4 MWatts with Distribution System
Total cost is $21 million dollars for hardware $1.46 per watt
Plus the cost of Engineering and Technical Manpower
still viable and worth the pursuit



Toshiba 325 MHz klystron

Summary

High Power RF distribution deals with expensive components

Need to maximize efficiency and reliability at minimal cost

Close cooperation between vendors and Laboratory

Put high priority on prototyping system


Thank You