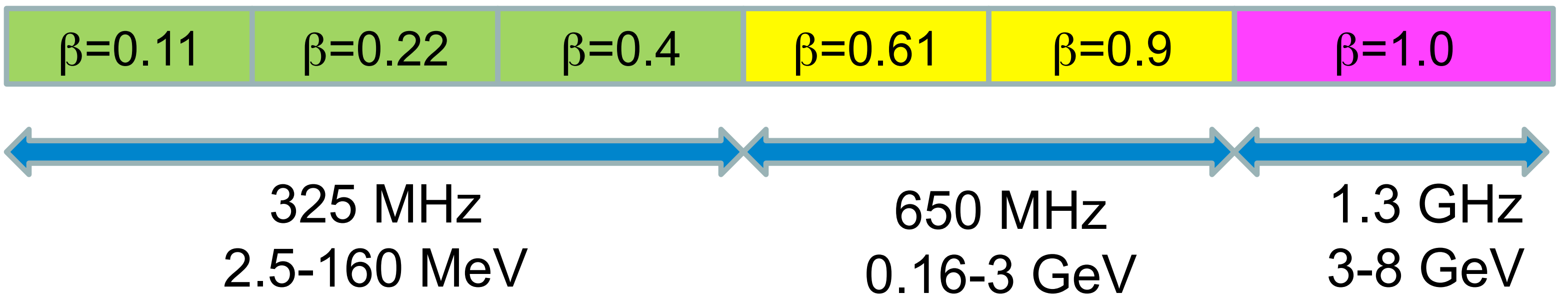
WG 3 RF Summary

Conveners:
Brian Chase FNAL
Yoon Kang SNS

Power Requirements by Cavity Type



$$P = \frac{V^2}{4Q_{ext}(r/Q)}\left[\left(1 + \frac{I\cos\varphi(r/Q)Q_{ext}}{V}\right)^2 + \left(Q_{ext}\frac{2\delta f}{f}\right)^2\right]$$

Section	Freq, MHz	Energy, MeV	Cav/CM	Max gain per cavity (MeV)	RF PA power with overhead (kW)
RFQ	162.5	2.5	1	2.5	100 to 150
SSR0 (β_G =0.11)	325	2.5-10	18/1	0.844	1.2 to 1.5
SSR1(β_G =0.20)	325	10-42	20/2	2.04	2.9 to 3.3
SSR2(β_G =0.40)	325	42-159	40/4	3.32	4.5 to 5.5
LB 650(β_G=0.61)	650	159-457	36/6	11.6	15.5 to 25
HB 650(β_G=0.90)	650	457-3000	160/20	17.7	23 to 27
Pulsed 1.3(β_G=1)	1300	3000-8000	224/28	25	40/640 to 50/800

PA power is topic for discussion

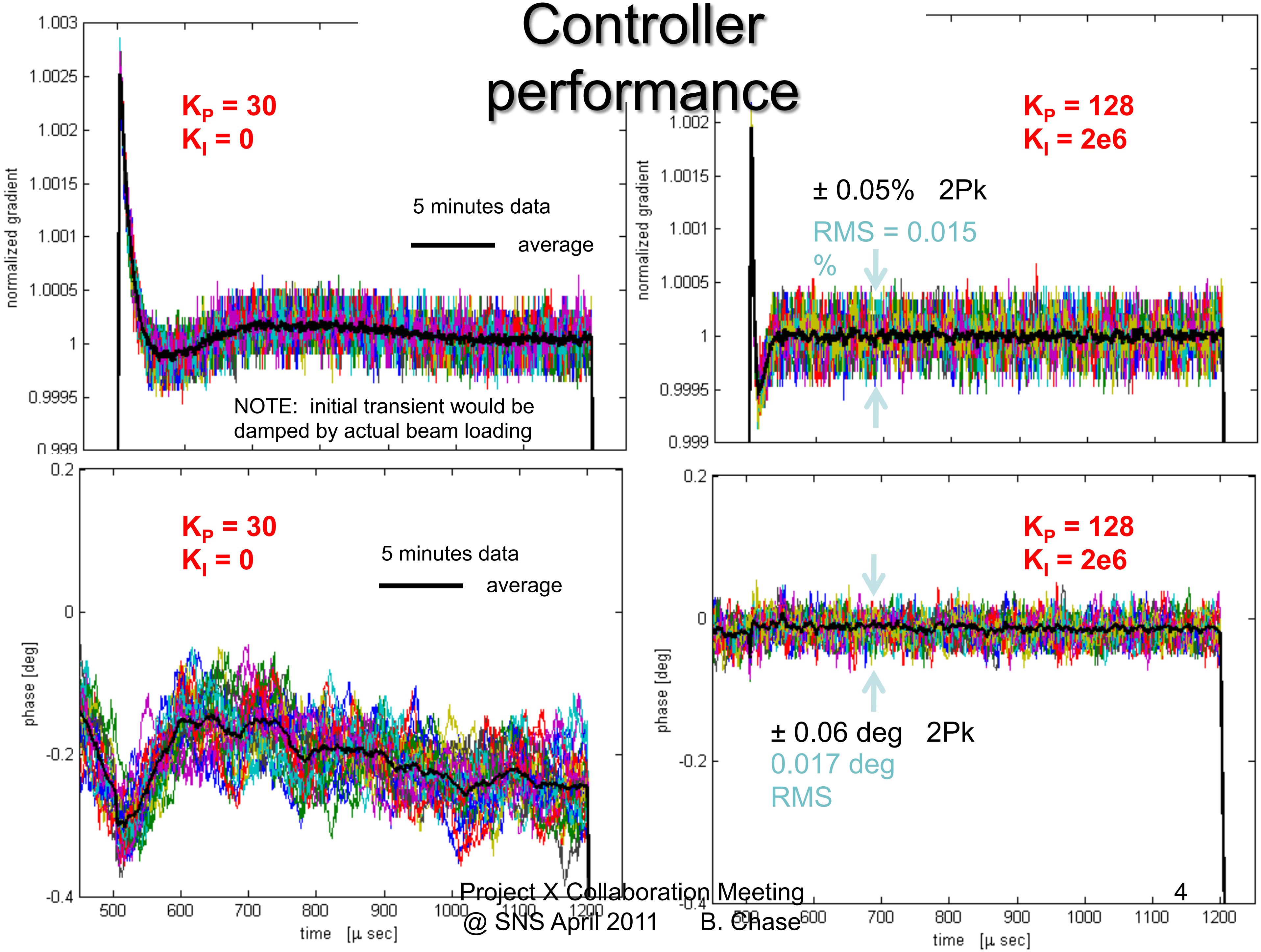
RF Field Error Budget

Physics Requirements are 1%, 1 deg RMS uncorrelated error

- Error terms (RMS) < 1s*
  - Residual controller error (0.05 %, 0.05 deg)
    - Measured at NML (0.015 %, 0.017 deg)
  - Receiver noise (0.02 %, 0.02 deg)
    - Measured at NML (0.009%, 0.005 deg)
  - Reference system noise between RF frequency sections (0.01 %, 0.01 deg)
    - Calculated (0.001 deg)
  - Master Oscillator phase noise 100 Hz to 100kHz @1.3GHz (.005 deg)
    - Measured (.0023 deg)
  - Power Amplifier spurs in CW linac (-55 dBc?)
  - Line generated modulation is coherent across accelerator,
  - Beam loading modulation 100% (peak 0.3%, 0.3 deg)
- Error terms > 1s **B**eam **A**rrival **T**ime monitors reduce LLRF long term requirements
  - Beam based calibration error (1%,1 deg peak?)
    Amplitude dependence on R/Q
  - Cable and Receiver drifts (0.3 deg)
    - Measured at NML (0.125 deg P over 1 week)
  - Phase Reference system drifts (0.1 deg)
    - Measured in lab (< 0.1 deg)

*Measurements made with 500kHz BW, 1.3GHz, Q=3E6, proportional gain = 128, integral gain = 2E6

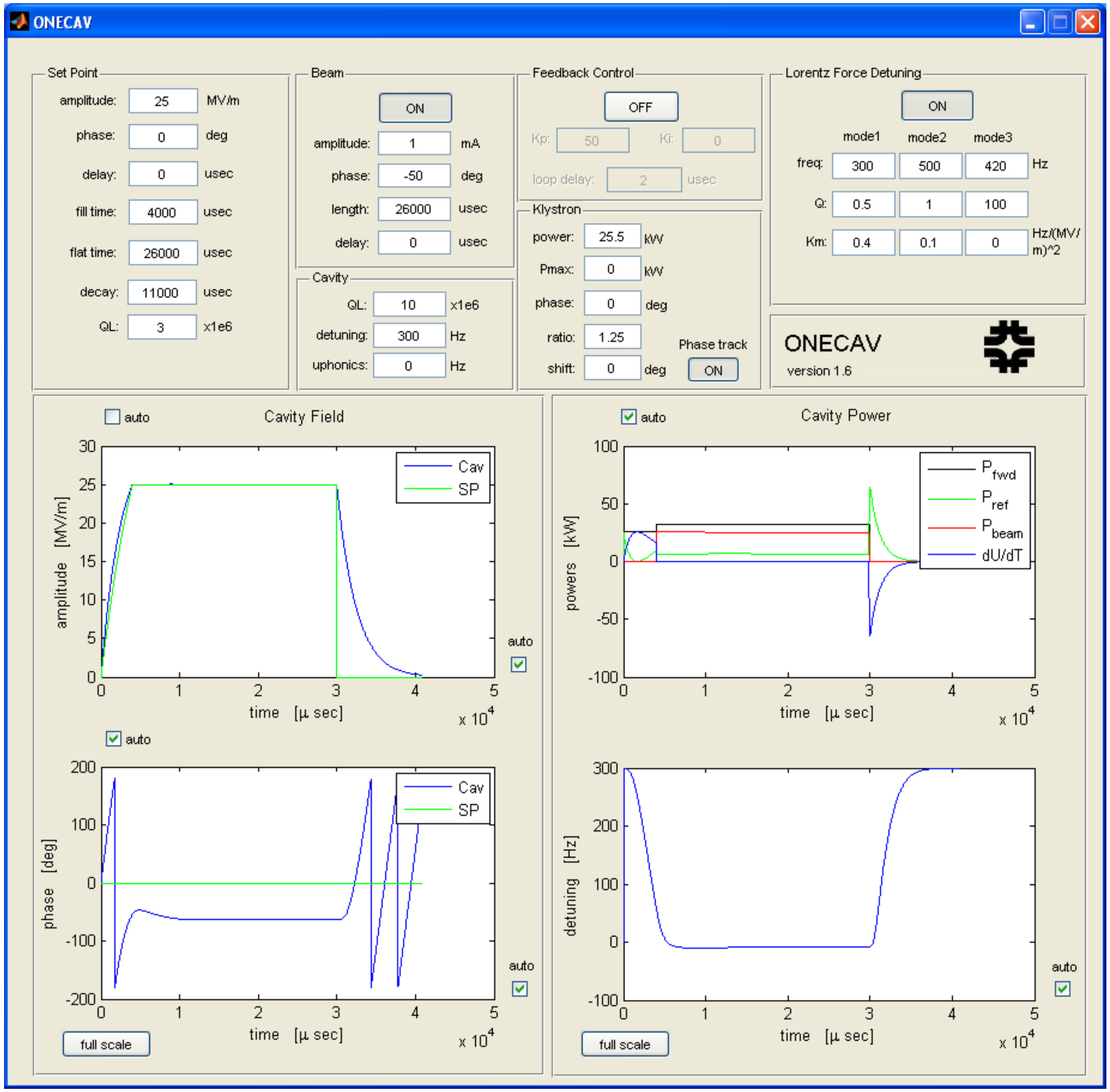
Controller performance



Slow fill
Long pulse
Phase track on

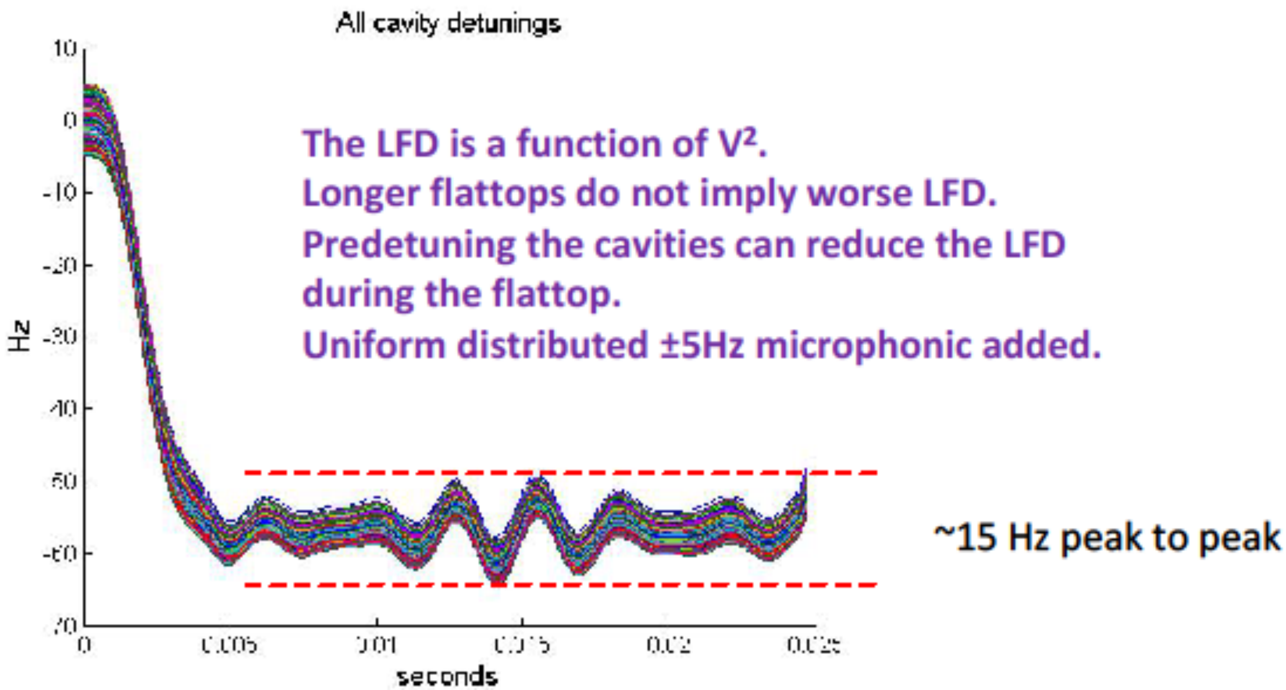
1mA
4 ms fill
13 ms flattop
Phase tracking on
Q_l = 1e7
32kW

Phase trajectory programming with a slow fill allows cavity to detune without ringing



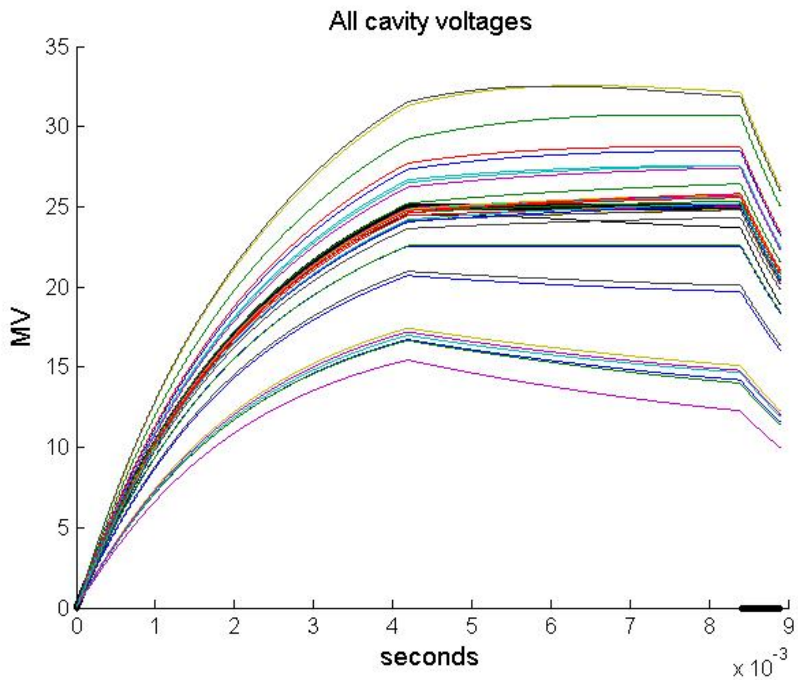
Detuning for 4.2ms fill time

- ILC type 9-cell niobium cavities detune about 600Hz at 25MV by effect of LFD. This number would prohibitive in terms of RF power required. We assume that LFD can be reduced to 60Hz or better.
- In this simulation we assume a cavity to cavity uniform random microphonic detuning of ±5Hz.



A little bit more realistic simulations

Open loop



- 1st RF station is DESY-FLASH ACC6-7
- All other 12 RF stations have 2 low gradient cavities at 18MV and 14 cavities at 26MV.
- LFD: ~ 60 Hz at 25 MV.
- μ-phonics: ±5Hz uniformly distributed.
- Beam errors:
  - Bunch to bunch I_b jitter: 3%.
  - Bunch to bunch Energy jitter: 250KeV.
  - Bunch to bunch time jitter: 1ps.
  - I_b is 3% lower at the end of a 4.2 ms flattop. (cosine function).
- Coupler error: 10% uniformly distributed.

Typical Performance Specs

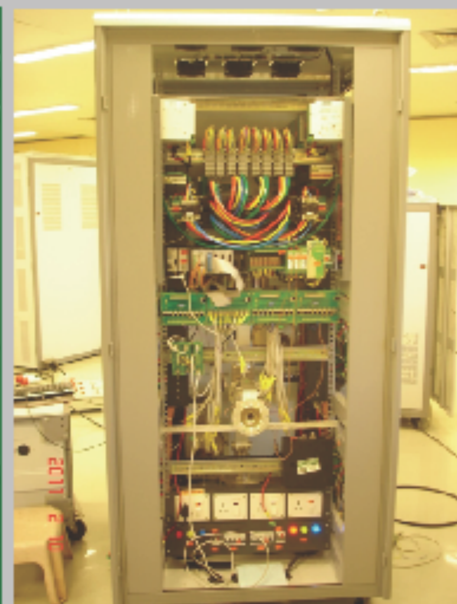
- 60% efficiency at saturated power
- 50% efficiency at -1 dB power minimum
- Water cooled
- Bandwidth 1 MHz minimum
- LLRF drive of 0 dBm for Psat output
- 50 ohms input/output impedance
- Output protected against opens and shorts

RF Sources for Project X

Solid State Development at RRCAT, Indore, India

8 kW ,505.8 MHz Amplifier

Front View of 8 kW SSPA



Rear View of 8 kW SSPA

InPAC - 2011, IUAC, New Delhi Feb 15-18, 2011

RF Sources for Project X

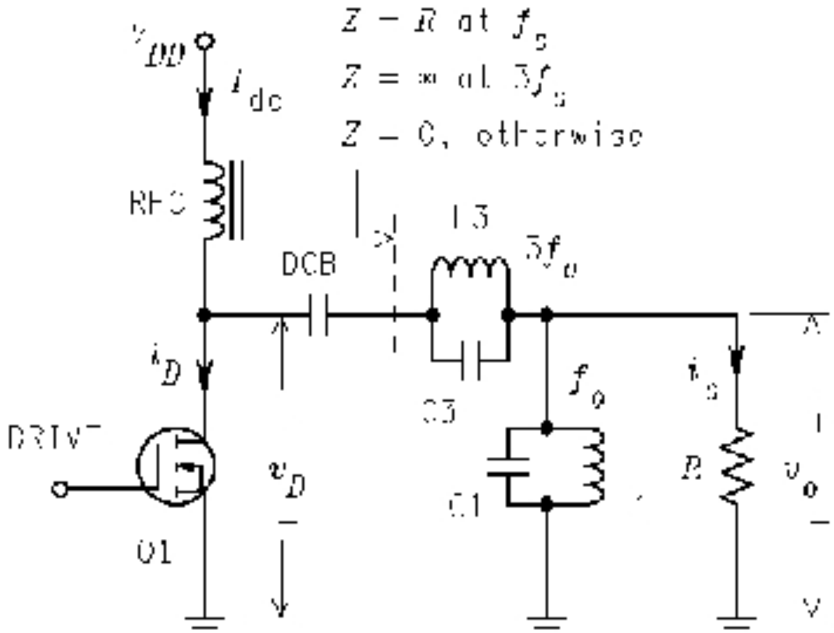
Proposal for long pulse (26msec) 1300 MHz Klystrons

L3 communications	500 kW pk 30 kW ave	1 MW pk 60 kW	2 MW pk 120 kW
Output Power (kW)	554	1163	2336
Beam Voltage (kV)	**70**	90	120
Beam Current (A)	**12**	20	30
Beam Power (kW)	840	1800	3600
Perveance (uP)	0.65	0.74	0.72
Efficiency at Saturation	66%	65%	65%
Output power at 2 dB back-off	349	734	1474
Efficiency at 2 dB back-off	42%	41%	41%
Production quantity	**75 - 125**	**38 - 62**	**19 - 31**

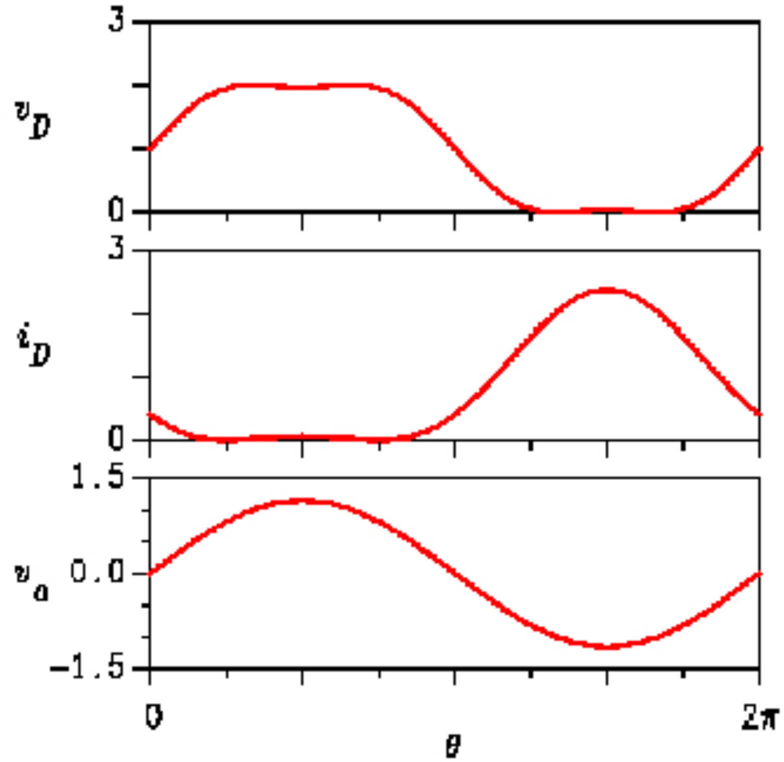
Similar Proposal from Thales Pending

CLASS-F POWER AMPLIFIER

CIRCUIT

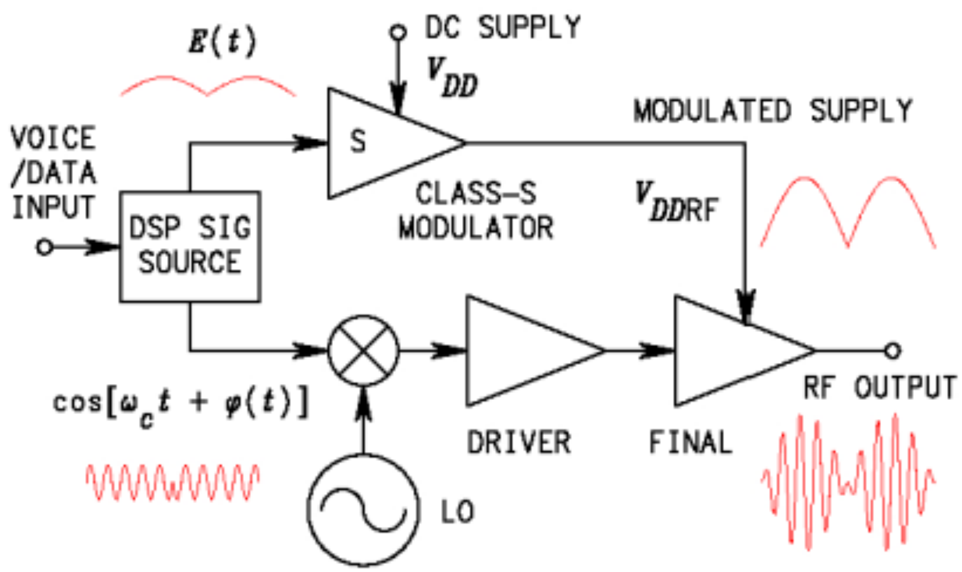


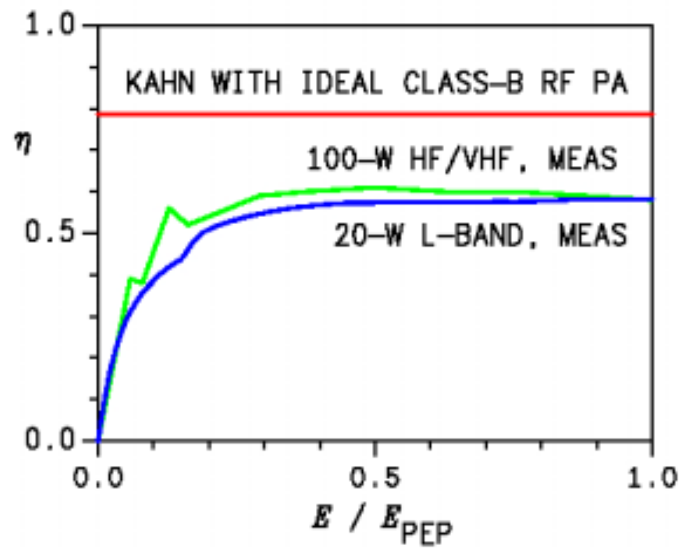
WAVEFORMS



- Voltage ≈ square wave
- Current ≈ half sine wave
- Power and efficiency increased

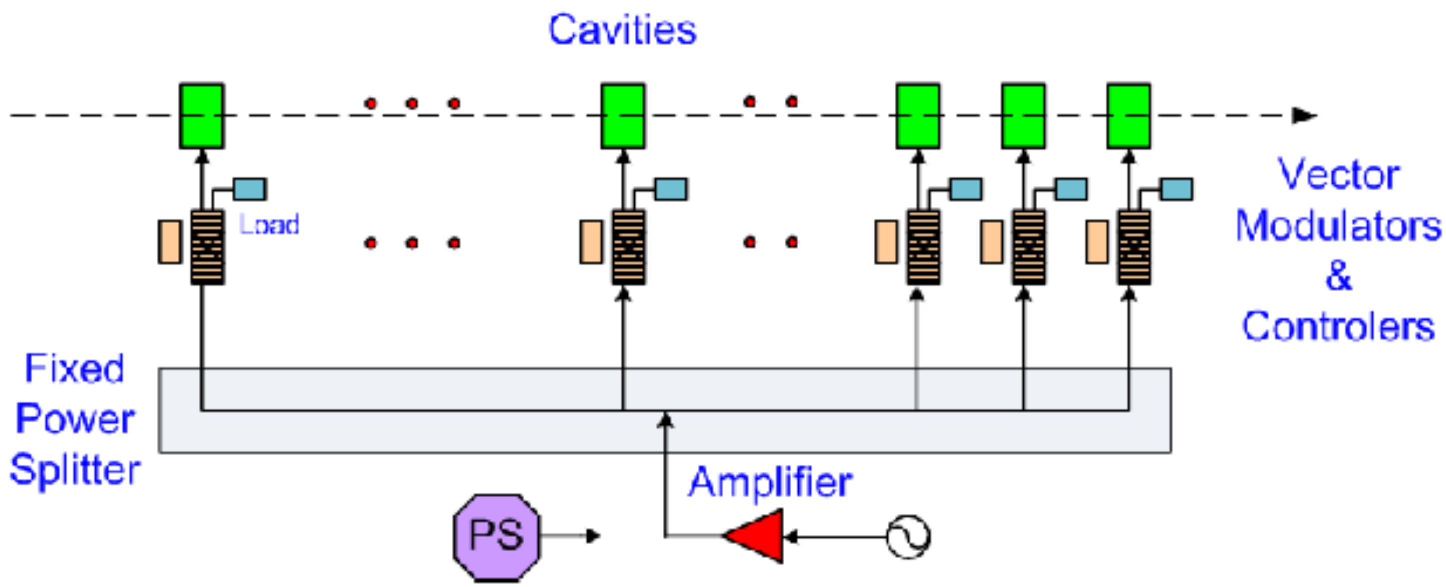
KAHN TECHNIQUE





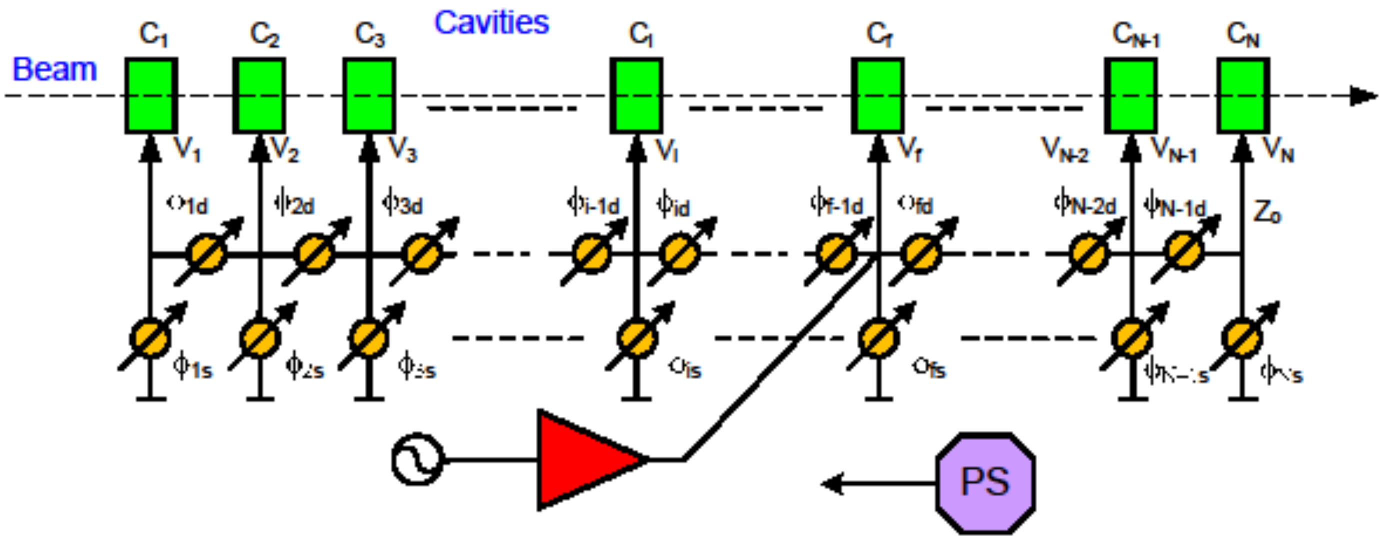
- High-efficiency linear transmitter
- RF signal: Simultaneous AM, ΦM
- Saturated RF PA
- High-level AM
- Average efficiency 3 to 5 times class B

One Amplifier to Multiple Cavities



- RF power splitting network is fixed
- The power splitting ratios are determined for supplying the maximum required power to each cavity
- With a single amplifier input, the individual high power RF vector modulator controls the power delivered to the cavity
  - The input power to each vector modulator is fixed
  - Unused power at the cavity will be dissipated at the vector modulator load or at the circulator load

Realization of One Generator to Many Cavities



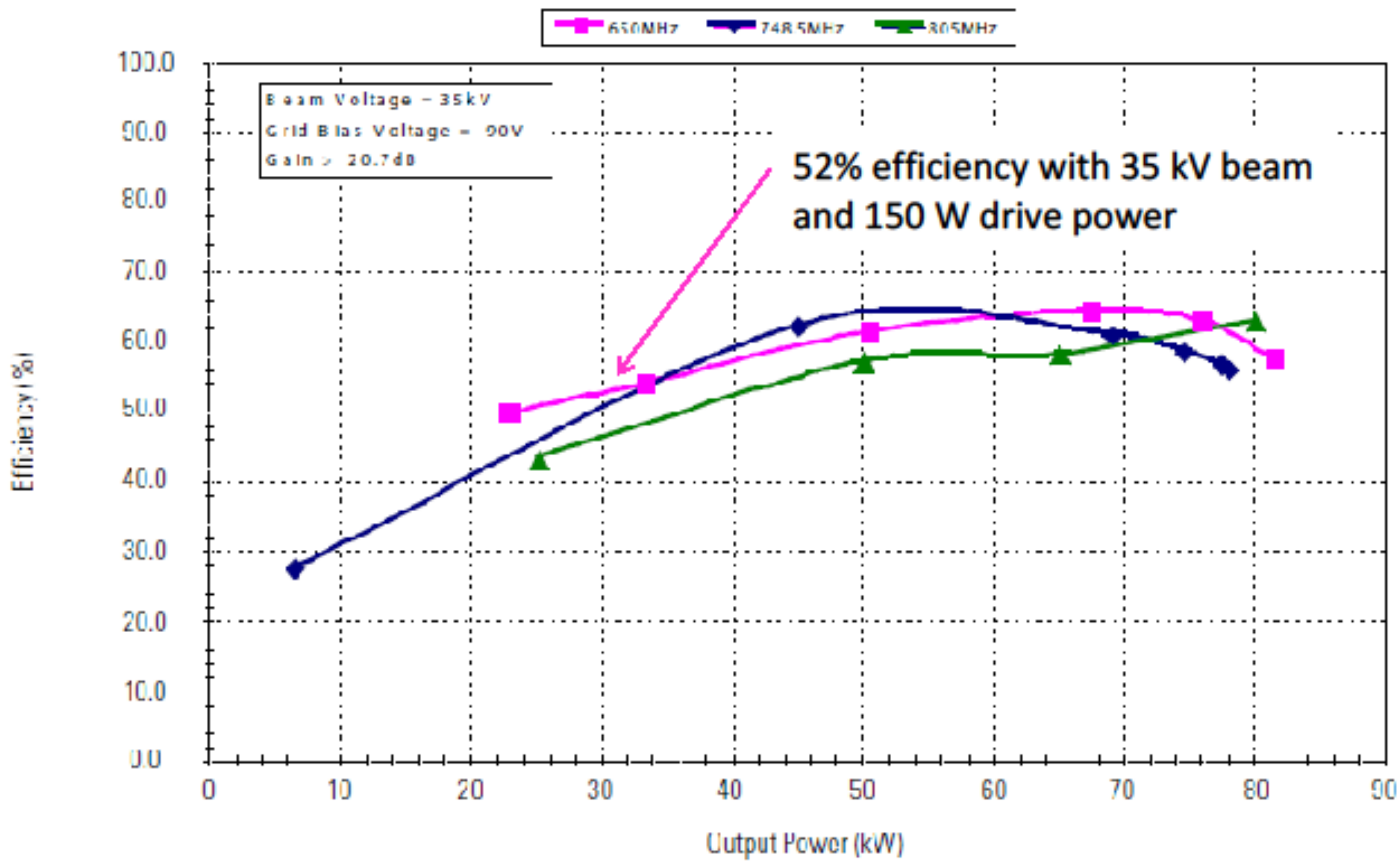
- Using fast high power phase shifters, delivering the power to individual cavity with RF vector control can be possible
  - Use a phase shifter between cavities (as a variable length transmission line section)
  - Use phase shifter with short circuit to provide reactive loading
- The system works as a single system to deliver the RF amplitude and phase in each cavity as needed
  - Only the power needed by each cavity is delivered
- For reduction of construction cost, using a very high power klystron as the RF power generator is favored

Rough Comparison of RF Distribution Schemes for Pulsed Linac (50 kW/cavity)

Amp:Cavity	N:1	1:1	1:N (VM)	1:N
Amplifier	$240,000 (Solid-state)	$50,000 (Klystron)	$37,500 (Klystron)	$37,500 (Klystron)
Power Supply, Modulator, Control	integrated	$70,000	$62,500	$62,500
Waveguide, Splitter/ Combiner	$20,000	$10,000	$10,000	$10,000
Circulator	integrated	$20,000	$5,000	$5,000
Vector modulator, Phase shifter	$0	$0	$20,000	$20,000
Transmitter	$30,000	$50,000	$30,000	$30,000
LLRF	$10,000	$10,000	$6,250	$6,250
Water utilities	$10,000	$20,000	$15,000	$10,000
RF Cost / Cavity	$310,000	$230,000	$186,250	$181,250
Operation Power	**120%**	**100%**	**130%**	**105%**

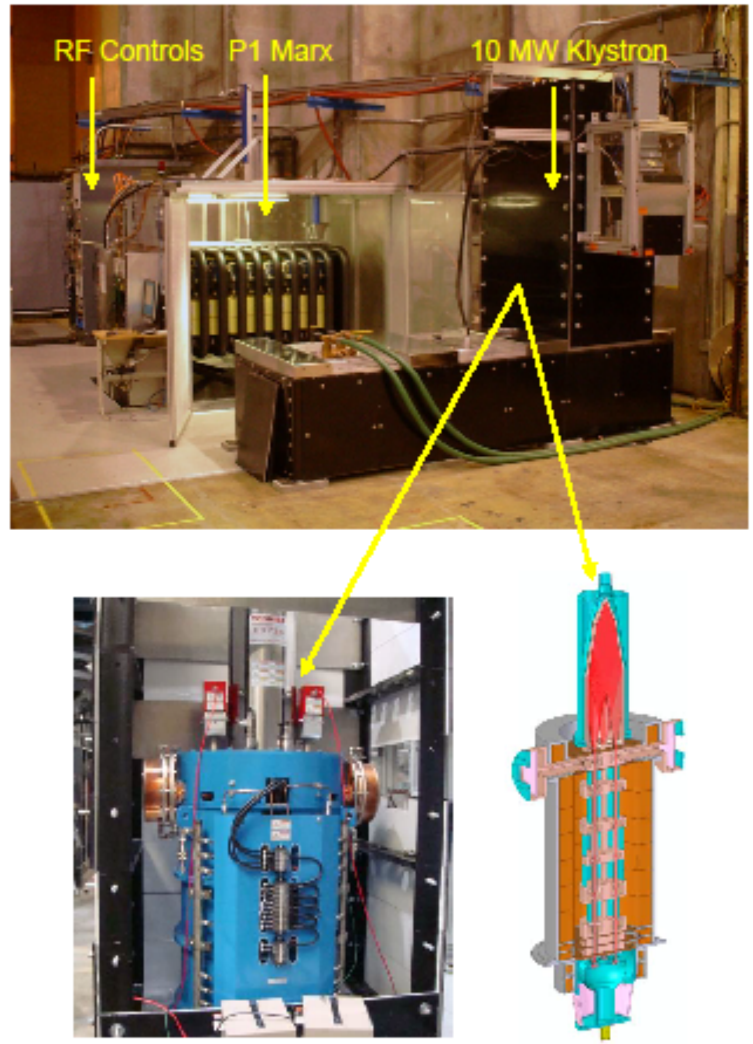
CPI IOT Performance at 30 kW

EFFICIENCY VERSUS OUTPUT POWER

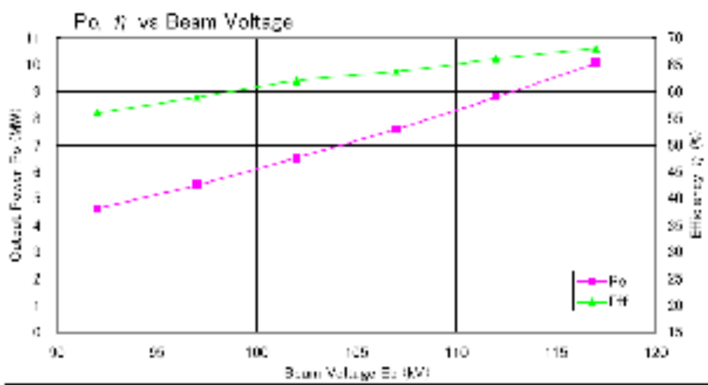


OUTPUT POWER VERSUS DRIVE POWER

P1 Marx Test Stand at SLAC ESB



Toshiba MBK Measurements of Efficiency and Output Power -vs- Beam Voltage



Major points moving forward

- With staging of the project the focus is shifted to the CW Linac
- 95% of the RF power in the CW linac is at 650 MHz. Therefore this should be the primary focus for both cavity and RF development
- Mod anode klystrons could provide dynamic range and efficiency and compete with IOTs
  - Better lifetime
- Benefits of solid state power amplifiers:
  - Possible reliability improvement
  - Low voltage operation is much safer for maintenance
  - Cost is becoming competitive
- The interplay between cavity design, resonance control, RF power technology, power overhead, gradient level, cryogenic loads and beam current peak and average is complex and deserves careful study. The 650 MHz section is the logical starting point as it has the highest cost sensitivity.

Conclusions- Recommendations

- Minimizing cavity df/dp for 650 MHz and LFD coefficient for 1300 MHz will reduce RF costs and improve machine reliability
- Solid state is a strong contender for both 325 and 650 MHz systems and should be pursued
  - SS may be an option for the 162.5 MHz RFQ PA
- In the pulsed linac, low gradient cavities will cause gradient tilts. Tuning errors will cause large phase errors with long pulses
  - Inline phase shifter scheme could correct these errors