KSC Operation

- Control of Cavity Gradients
- Failure Analysis
- Near and Long Term R&D
- Effect on Beam Emittance

Chris Adolphsen
SLAC
9/7/2010

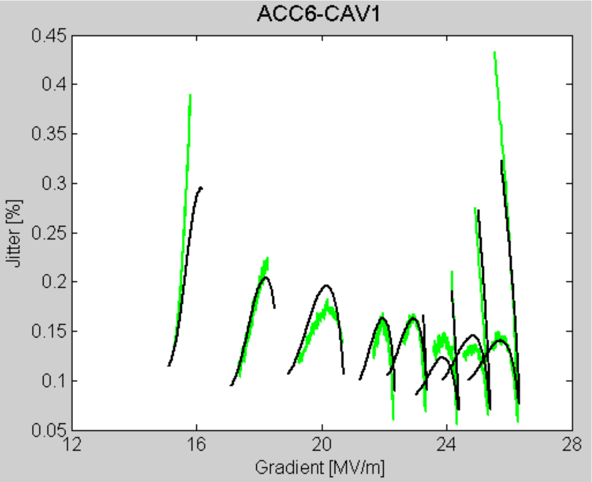
Going Native in the Mekong Delta, Vietnam

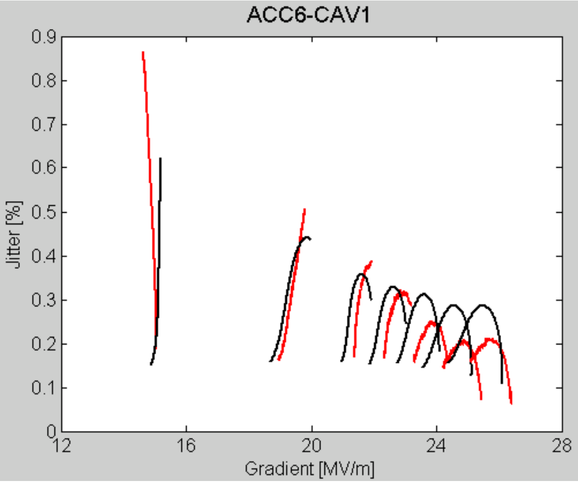
Gradient Control Overview

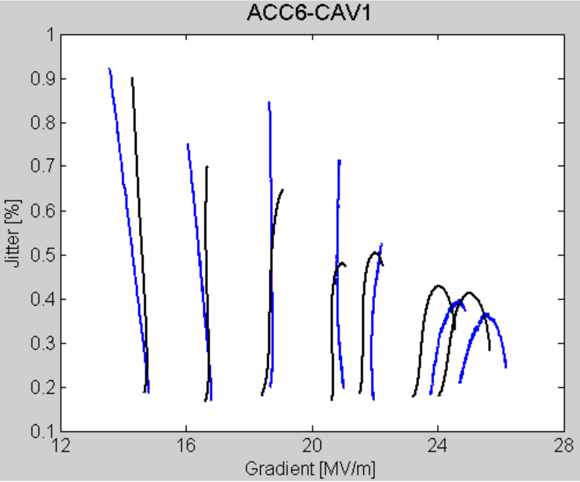
- The beam energy profile along the bunch train will only be measured at the beginning and end of the linac – but the gradient profile in each cavity will be monitored.
- A FB system that controls the rf pulse shape will be used to achieve a flat gradient profile over particular length scales (2 cavities in DRFS, 26 in the RDR and 728 in the KCS).
- All cavity signals will be processed the same way so if they are biased, the effect on the beam can be corrected globally
- The gradient 'flattop' needs to be flat mainly so cavities do not exceed operation limits (quench, Q, radiation)
- From FLASH data, the pulse-to-pulse gradient variation from input rf jitter and microphonics is small (few tenths of percent) if the cavities are tuned properly. It is also uncorrelated so vector sum variation should be even smaller.

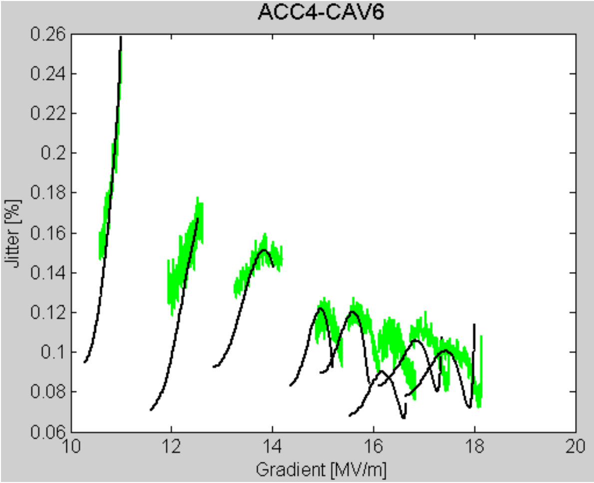
FLASH Cavity Gradient Stability

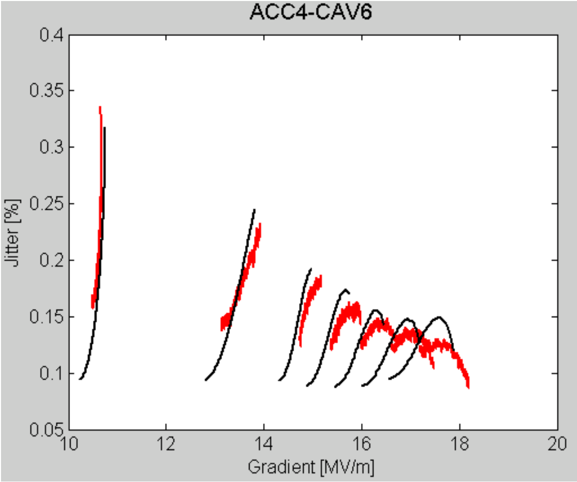
Comparison of beam-off measurements of pulse-to-pulse cavity gradient jitter during the flattop period for different gradients and initial cavity detuning (green, red and blue lines) to a cavity fill model including Lorentz force detuning (black lines) with two degrees of freedom (initial and initial rms detuning)

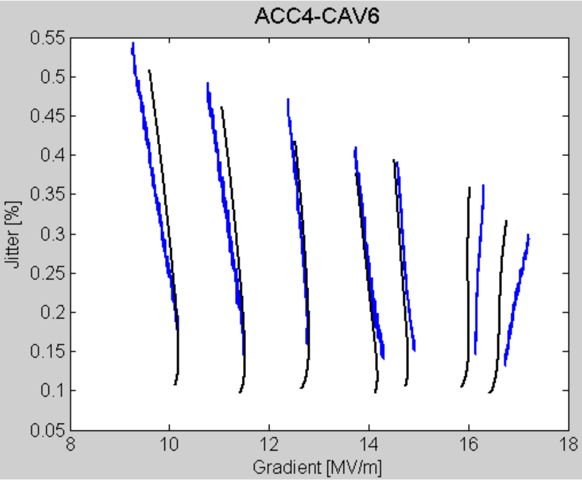








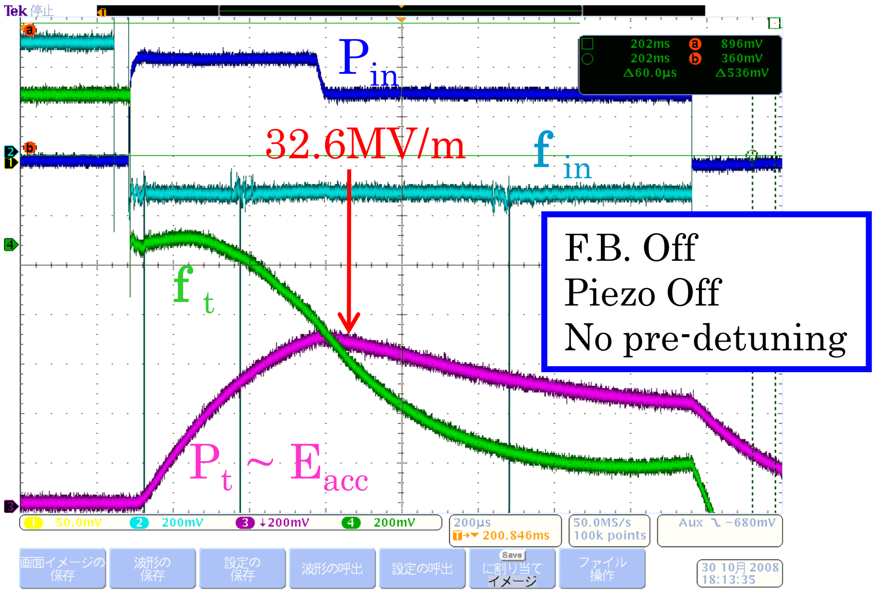




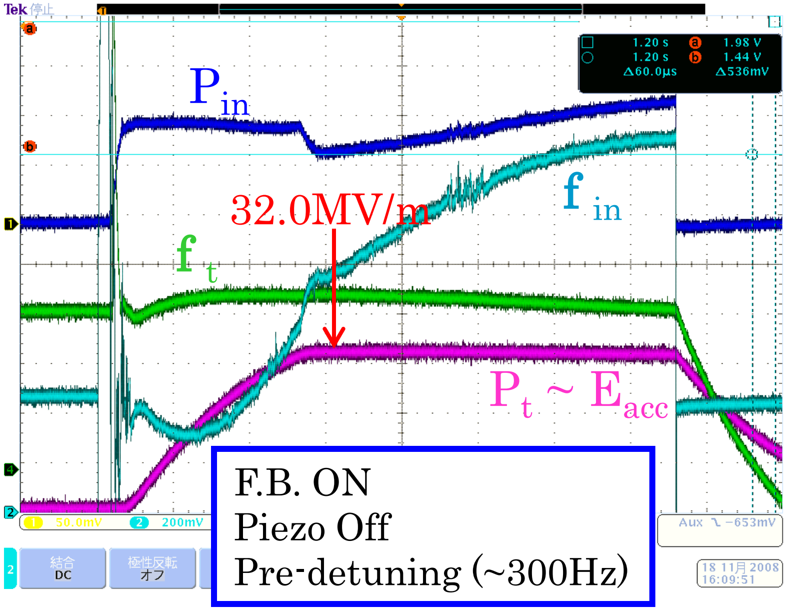
Gradient Control Overview (Cont)

- Expect the largest gradient profile distortion to be from Lorentz Force Detuning (LFD), which scales as gradient squared and differs cavity to cavity due to cavity stiffness variations.
- Piezo compensation of LFD has been studied in individual cavities but no multi-cavity test has been done at high gradient with proper setup and FB control to gauge the resulting flatness of individual cavities.
  - FLASH relies on a significant gradient and power overhead, letting the FB system correct for all 'sins' (wrong cavity freq, Qext, power, klystron pulse shape and incomplete or no LFD compensation) since they are more worried about the bunch energy variations than the operational overhead.
  - ILC cannot afford to be so generous, especially with gradient overhead, and we need to better evaluate the compensation effectiveness given the spread in cavity gradients and properties.

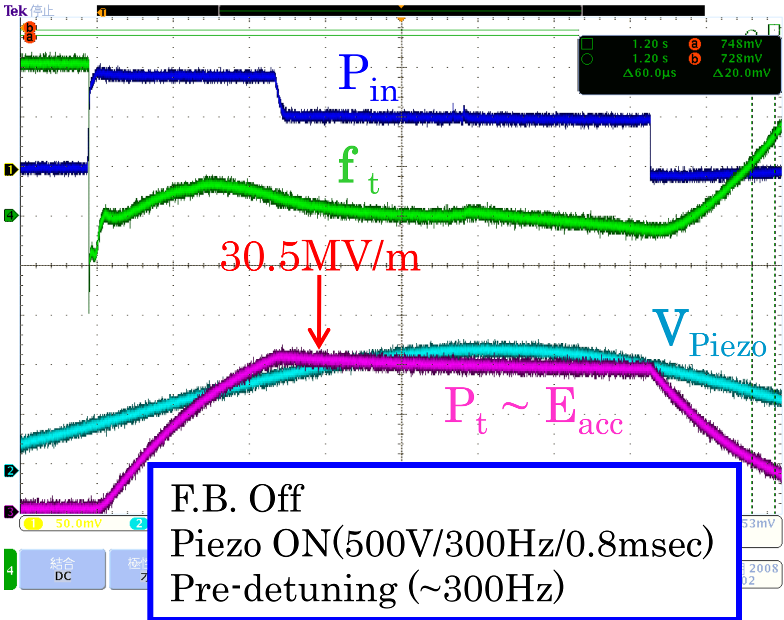
KEK: Compensation of Lorentz Detuning



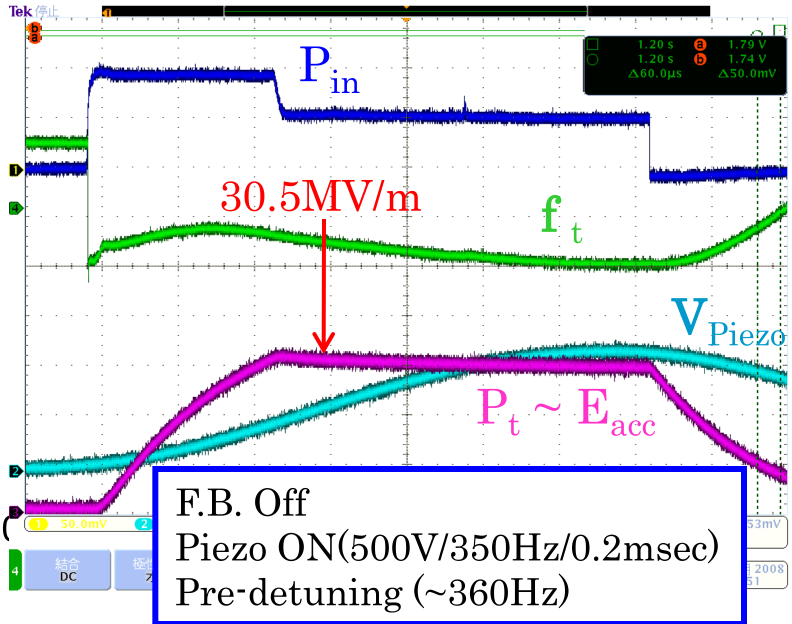
F.B. Off
Piezo Off
No pre-detuning



F.B. ON
Piezo Off
Pre-detuning (~300Hz)



F.B. Off
Piezo ON(500V/300Hz/0.8msec)
Pre-detuning (~300Hz)

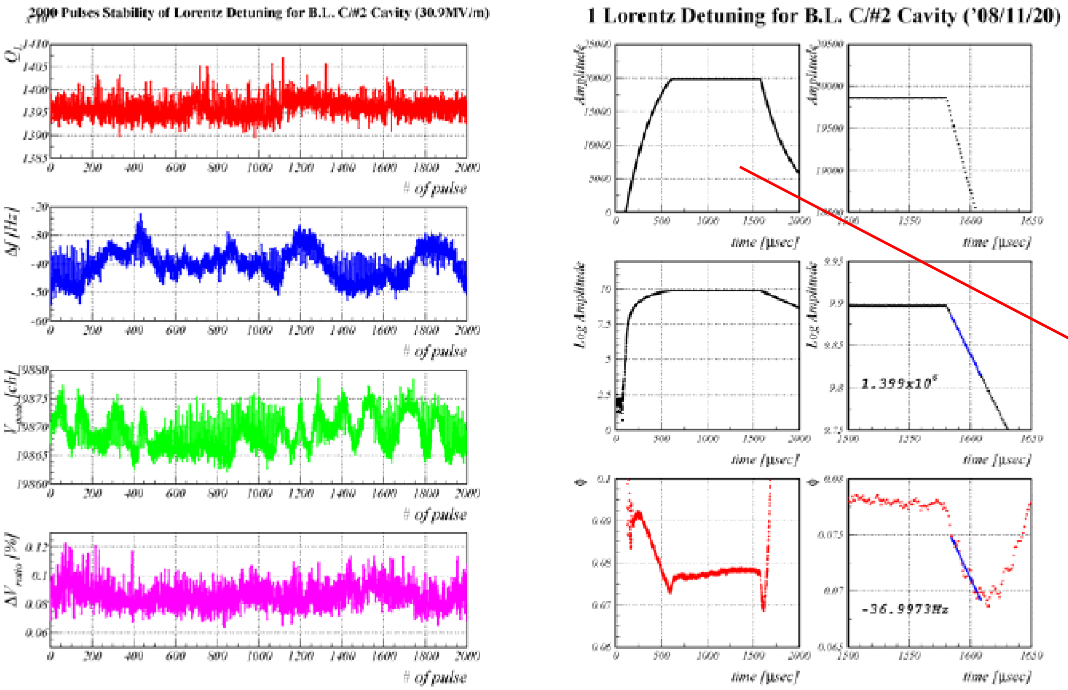


F.B. Off
Piezo ON(500V/350Hz/0.2msec)
Pre-detuning (~360Hz)

Pulse Stability Test

The pulse stability test was carried out for a long time around 30MV/m. The operation by Piezo compensation was stable for several hours. Figure 8 shows the example of the pulse stability for 16 minutes. The r.m.s. of the detuning frequency was about 5Hz and the peak-to-peak of the cavity field at the flat-top was below 0.1%.

FB OFF ?



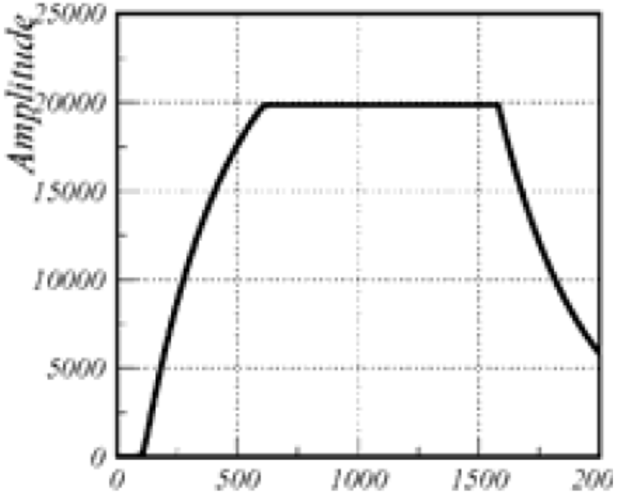
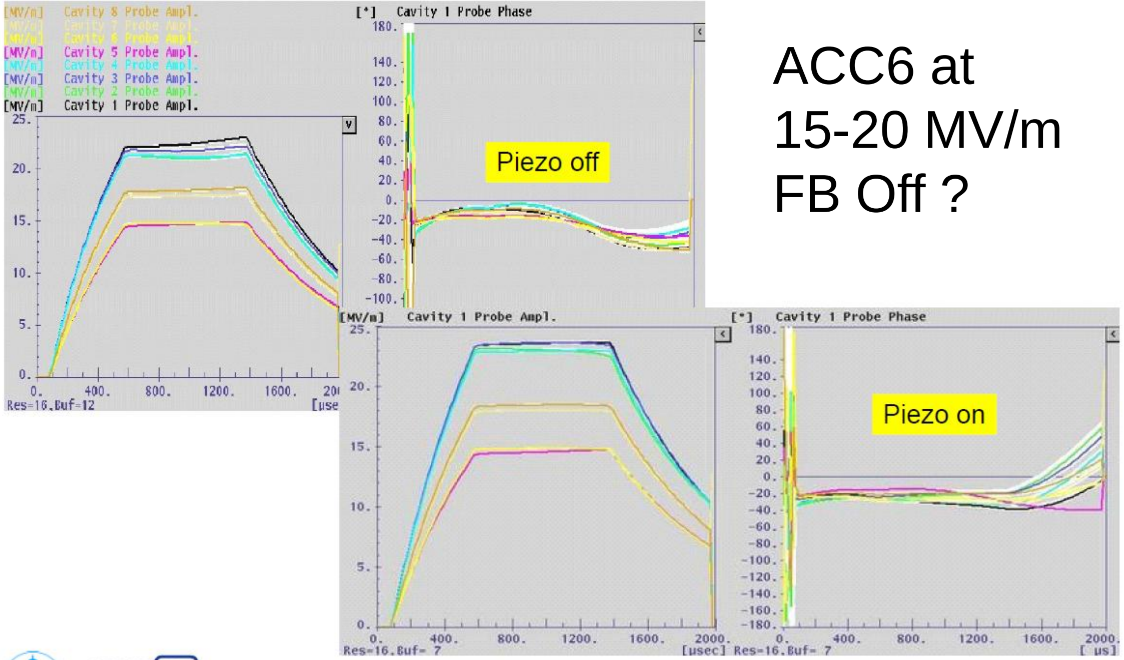
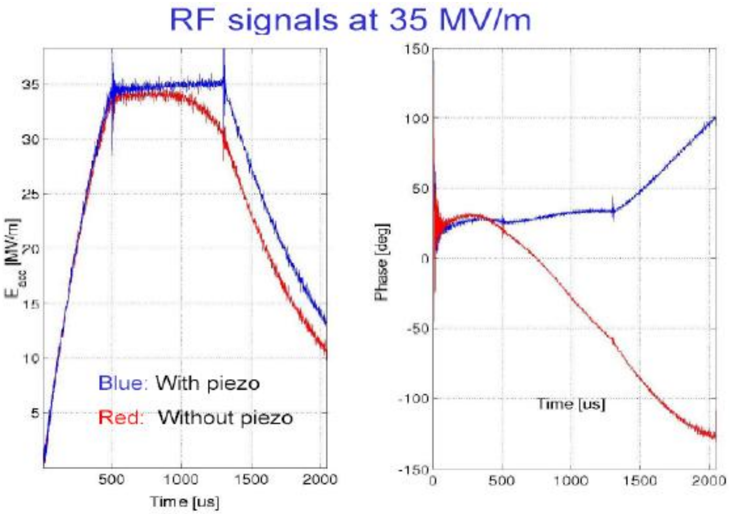


Figure 8: Result of the pulse stability test around 30MV/m. Left shows the time trend and right shows the status of one pulse.

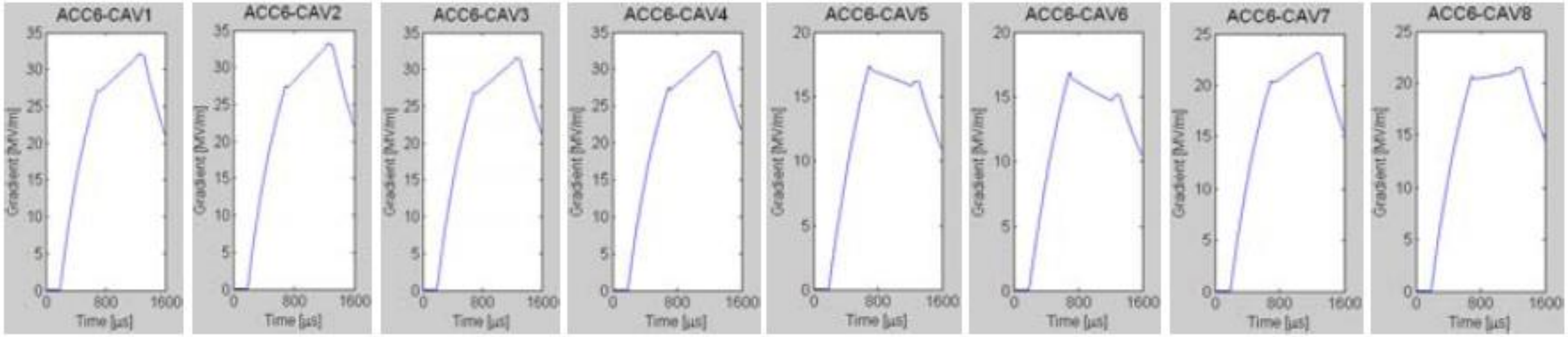
DESY: Compensation of Lorentz Detuning



ACC6 at
15-20 MV/m
FB Off ?



ACC6 Cavity Flattops During the 9 mA Tests – No Compensation

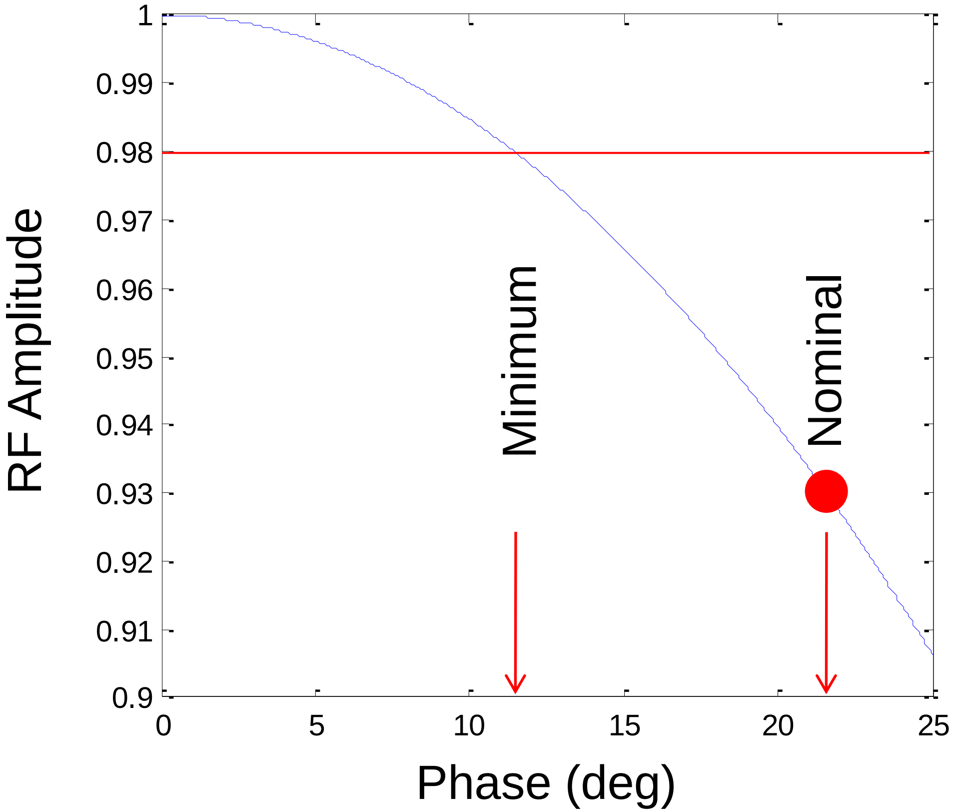


Gradient Control Overview (Cont)

- A common effect on all cavities is beam current variations, which may be at the 1% rms level pulse-to-pulse and probably smaller within the pulse. The beam current profile will be known well in advance (200 ms) of the beam arrival so the rf pulse shape can be pre-programmed to compensate for the loading variation
  - A 1 % current change requires a 1/2 % input rf change during the flattop period
  - This compensation is independent of the cavity gradient if the input power and Qext are setup to nominally produce a flat pulse (?)
- For the KCS, we assume a 5% rf overhead to correct for beam current variations and any systematic gradient errors after LFD compensation (which are likely constant pulse to pulse). Uncorrelated gradient errors will ‘wash out’ in the vector sum. Thus there should be no need for fast corrections and the FB gain can be low (> 50 us response time: KCS min ~ 10 us)

Gradient Control Overview (Cont)

Assume modulator voltage can be shaped to achieve a flat rf pulse (the Marx has ~ 100 timing time controls on the vernier board), and that a FB system would be used to regulate the KCS rf output to < 0.1% level. Run klystrons saturated and use alternate phasing scheme to control amplitude



Assumptions for Availability Study

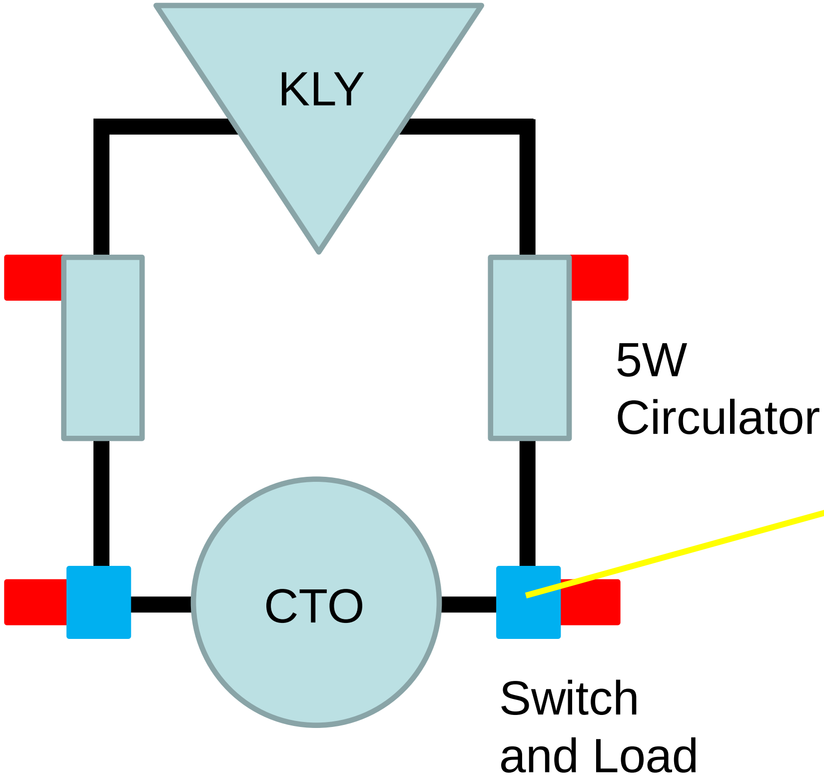
- No downtime from rf breakdown in the main rf distribution waveguide – will gauge reliability during the R&D program.
- Include 2 spare klystrons – no downtime if any source fails (klystrons can be repaired/replaced while cluster operational).
- Can also quickly (seconds) turn off power to cryomodules. Failures in local distribution system and cryomodules the same as for the RDR.
- Vector sum control system for each cluster would have redundancy so it would be rare to lose cluster control (OK if input from a few of the cryomodules are missing).

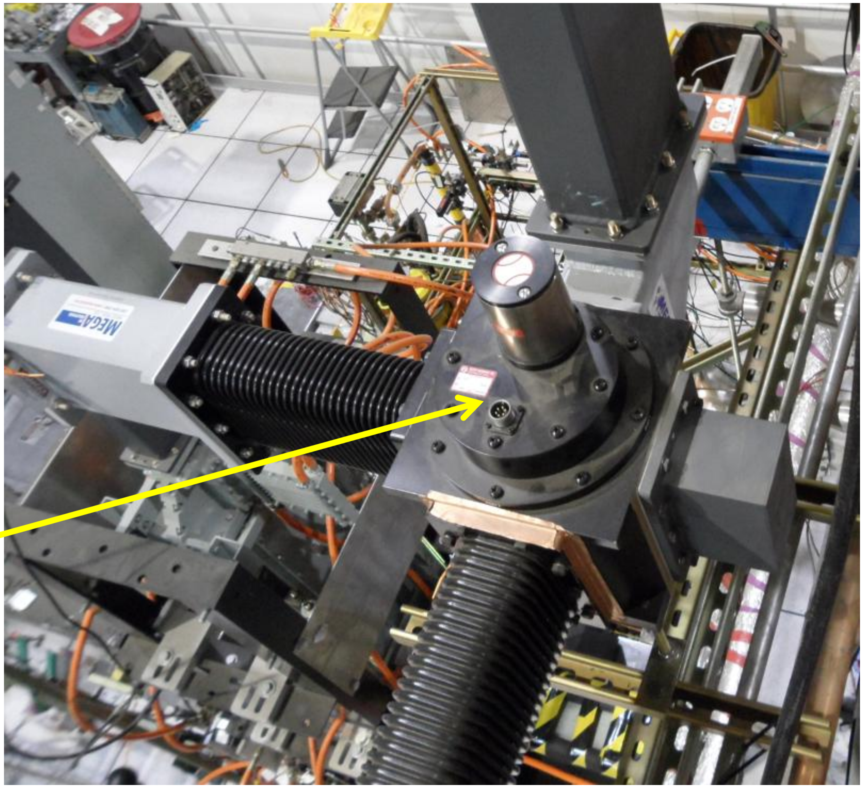
LLRF System Redundancy

- Digitize and sum cryomodule (CM) probe signals locally and transmit in real time to the associated cluster building.
- Here the digital signals from each of the ~ 100 CMs are split three ways and sent to three identical Drive Processors
- The output rf from each of the klystrons are also digitized and split three ways, one going to each Drive Processor.
- Each Drive Processor uses the CM sum signals, the klystron output signals and dynamic FF tables to compute the digital drive signal to each of the klystrons (one digital output per klystron).
- At each klystron, the three digital signals from the Drive Processors go through 2-of-3 majority logic before being used to generate a klystron drive signal.
- The clock signals and LO for this system are provided by redundant sources so that if one source fails, the signals would still be provided by the others.
- With this scheme, individual CMs or klystrons may have to be turned off due to LLRF failures, just as in the baseline design, but rarely the entire cluster.

Failure Points: Klystron to CTO

Use remote-controlled mechanical rf switches to isolate region upstream of CTO if failure of klystron or circulators

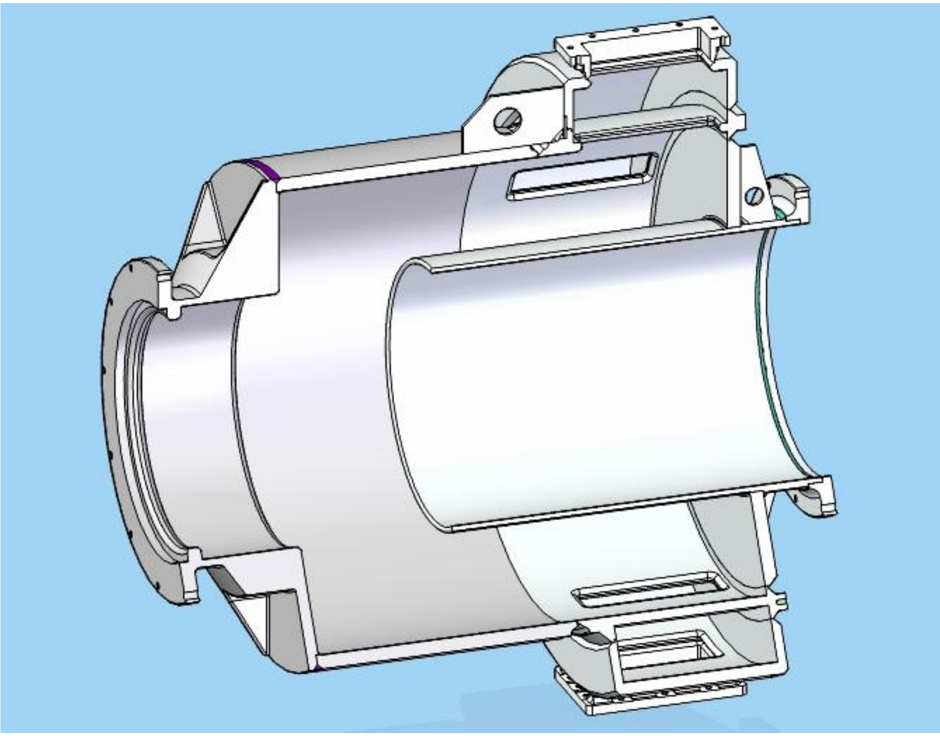


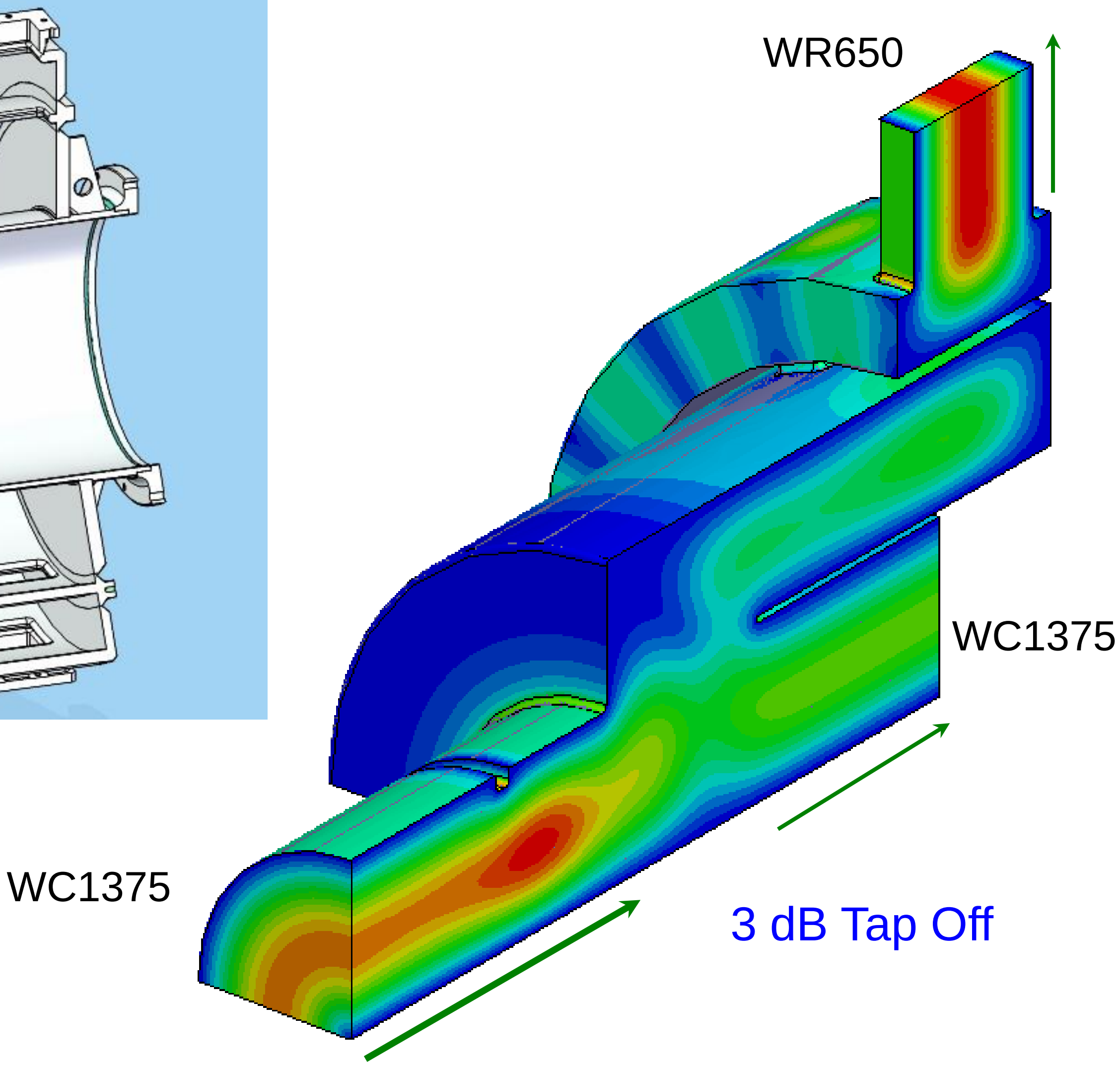


Failure Points: CTO to CTO

- The peak surface electric field in the CTO of 1.6 MV/m is lower than in the Aluminum VTO (variable tap-off) operating at 5 MW (1.9 MV/m), which has run for hours with 1ms pulses at 14 psig N2 with no rf breakdowns.
- Running the CTO under vacuum (< 1e-6 Torr) should be breakdown free based on operational experience with SS and copper (if Al worse, would Cu coat it). E.g., our 5-cell,1.3 GHz SW structure runs reliably with 20 MV/m surface fields with 1 ms pulses.
- The peak surface magnetic field for the maximum 340 MW (full current) flowing through a CTO is 15 kA/m on the edge of the tube defining the gap. The pulsed heating temperature rise of 3 degC in this case is considered negligible.
- In the tapers and main 0.48m waveguide, the surface electric fields are non-existent. SLAC has decades of experience running high power in overmoded X-band TE01 mode waveguide. The mode can basically only break down by gas ionization (Emax ~ 4 MV/m), so need to have a good vacuum or high gas pressure.
- The two bends required in each main waveguide may be the most risky part of the system, as they carry the maximum power and must depart from the pure TE01 field pattern.

Coaxial Tap Off (CTO)

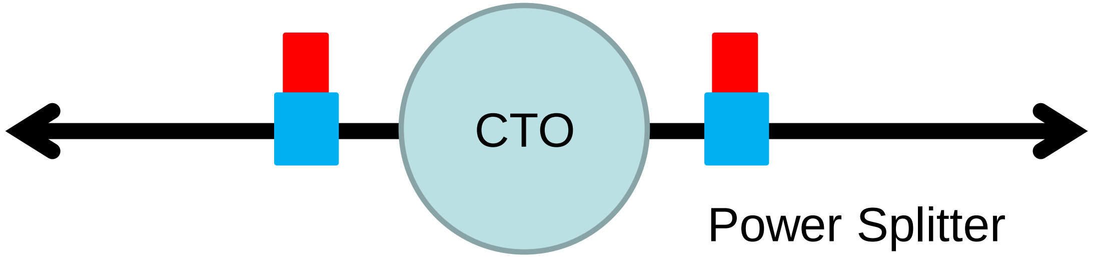




Failure Points: CTO to Cavities

Use remote-controlled phase shifters in combination with magic tee’s to control power to upstream and downstream 1.5 cryomodules segments – the surface fields in these power splitters are lower than in the CTO.

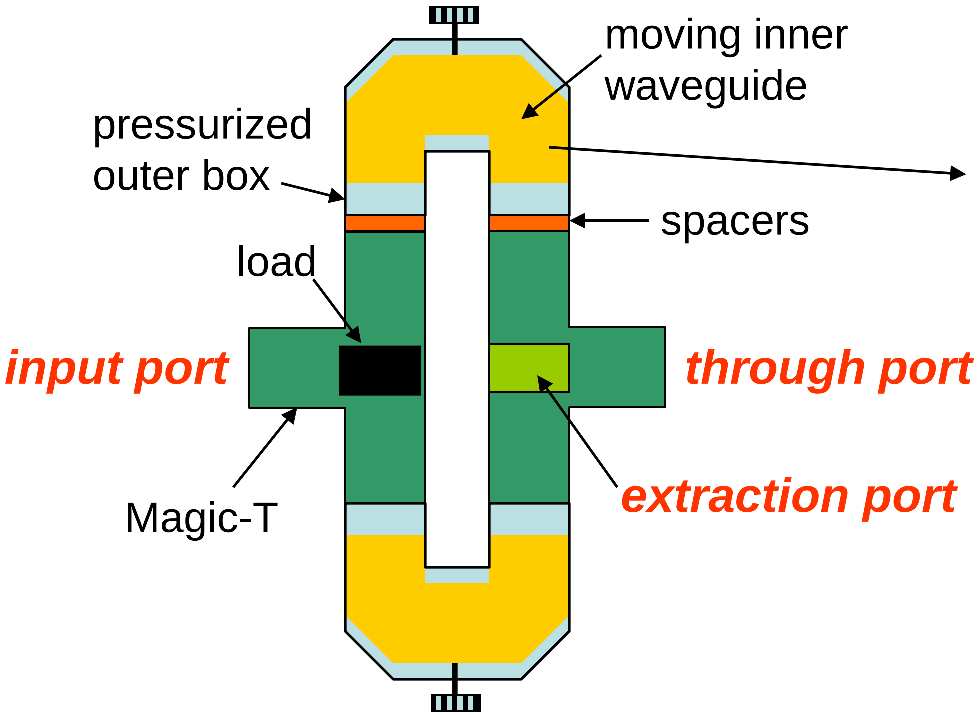
Thus the power can be reduced or shut off in the event of a problem with the cryomodule, such as coupler breakdown



0 to 5 MW to 13 cavities

Power Splitter
and Load

Power Splitter for FNAL CM2

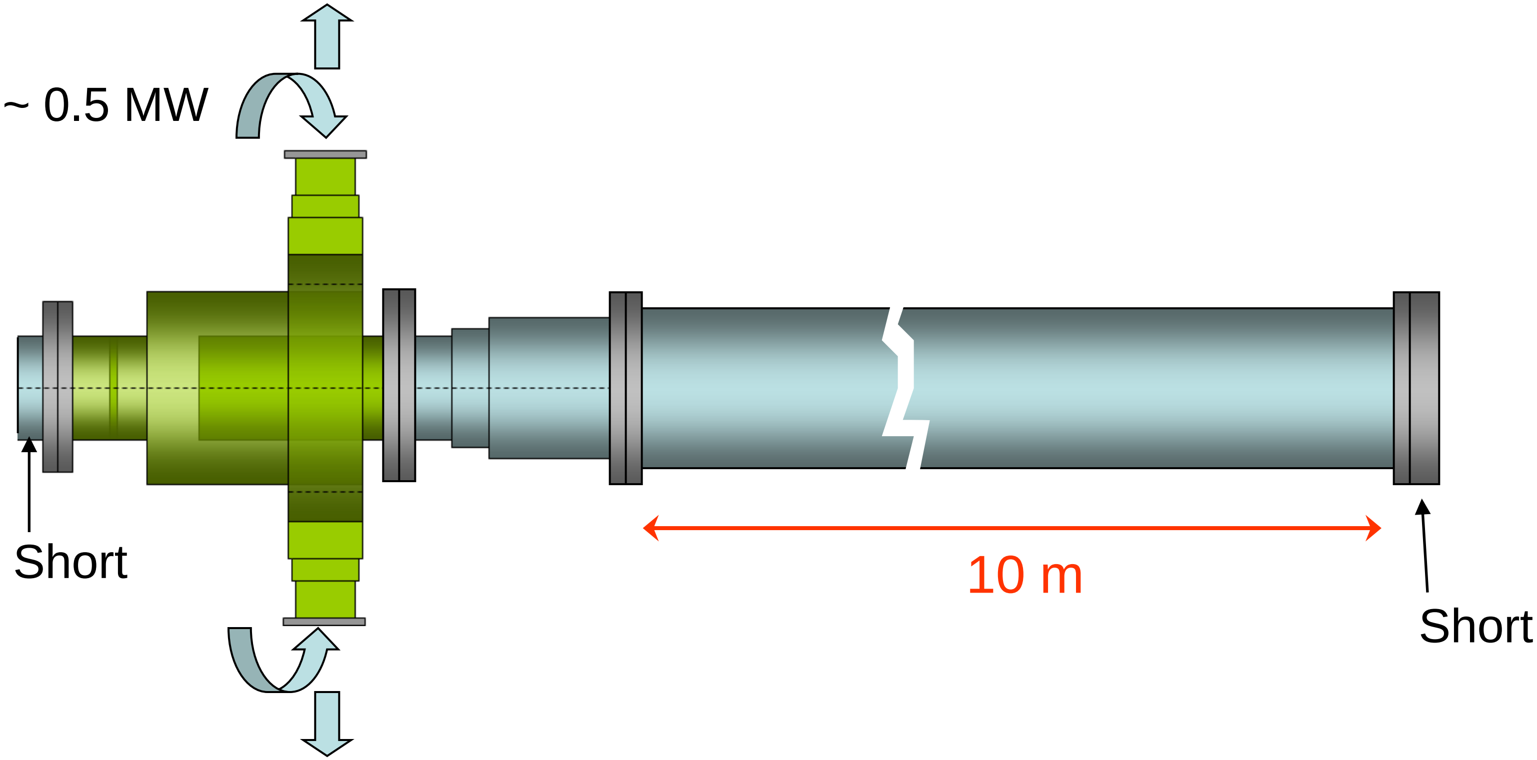


- Input and through ports are in-line
- Trombone phase shifters take advantage of required U-bends
- Match of phase shifters nominally unaffected by position

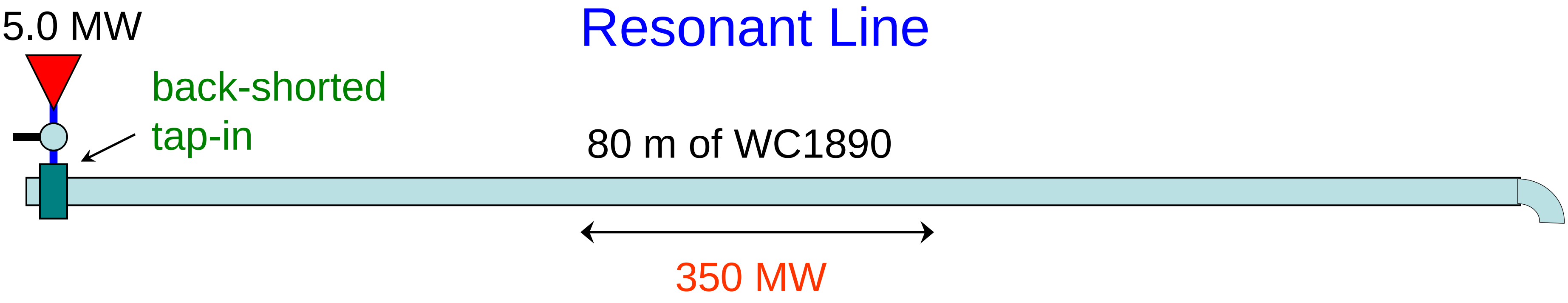
R&D Status: Testing Pipe Power Handling

Currently: testing resonant system at fields equivalent to 350 MW transmission with pipe under 15 psig N2, and if need be, under vacuum. Also add second CTO to do transmission test at 4 MW (2 MW per port).

In FY11, do transmission tests at 10 MW (5 MW per port) with 10 us rf shut-off time (= ILC)



In FY11: Also extend pipe system to 80 m and add bend prototype



Resonant Line

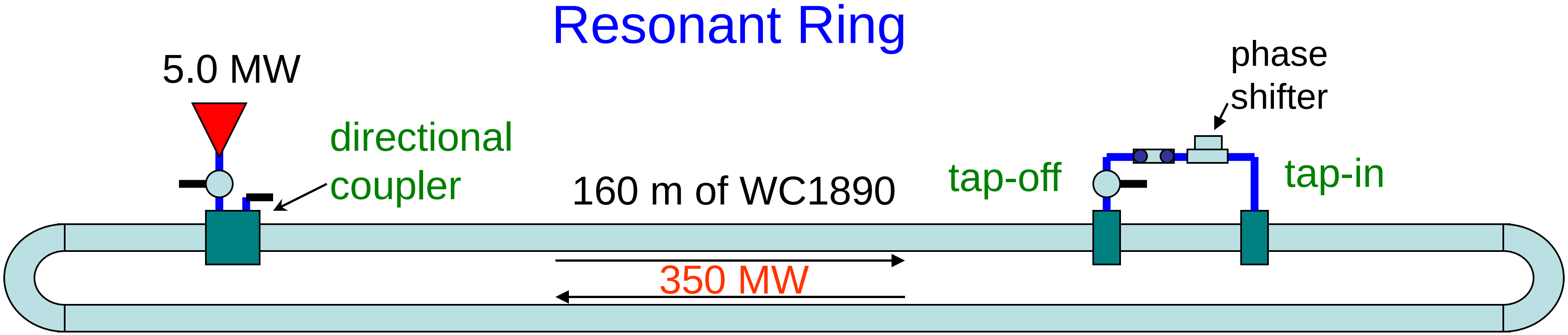
5.0 MW

back-shorted
tap-in

80 m of WC1890

350 MW

In FY12: Use resonant ring to test ‘final design’ bends and tap-in/off



Resonant Ring

5.0 MW

directional
coupler

160 m of WC1890

350 MW

tap-off

phase
shifter

tap-in

Quantifying the CTO-to-CTO Reliability

- Want to verify that each 1.25 km CTO-to-CTO region either breaks down rarely (< 0.1/year) if the repair time is long (24 hours), or break downs modestly (< 1/day) if the recovery is quick (1 minute).
- The former requires a long running time with many CTOs while the latter requires a system with a similar shut-off time as ILC so the effect of the continued power flow into an arc can be evaluated.
- For ILC
  - Power in tunnel (P) = Po*(L – z)/L, where z is distance from first feed and L = distance from first to last feed
  - RF shut off time (t) = (zo + z)*2.25/c where zo is the distance from the cluster to first feed
  - Max of P*t/Po = 4.1 us for zo = 100 m, L = 1.25 km
  - Max t = 10 us for zo = 100 m, L = 1.25 km

Quantifying the CTO-to-CTO Reliability

- For the waveguide that runs at 10 MW, easy to assess the effect of the ILC rf shutoff time by running the test setup in a 10 MW transmission mode and increasing the shut-off time after an arc from our current value of 2 us to10 us.
- For the pipe that runs at up 350 MW, increasing the klystron shut-off time for our resonant test setup does not help since the power likely decreases rapidly each rf round-trip time.
- For the 160 m resonant ring, t is at minimum equal to the rf roundtrip time = 0.66 us, so P*t would be at least ~ 1/6 of the max at ILC.
- Would need ~ 1 km of pipe and thee 10 MW klystrons to ensure the maximum energy absorption (P*t) of ILC
  - But it would be delivered at ~ twice the power in ~ half the time

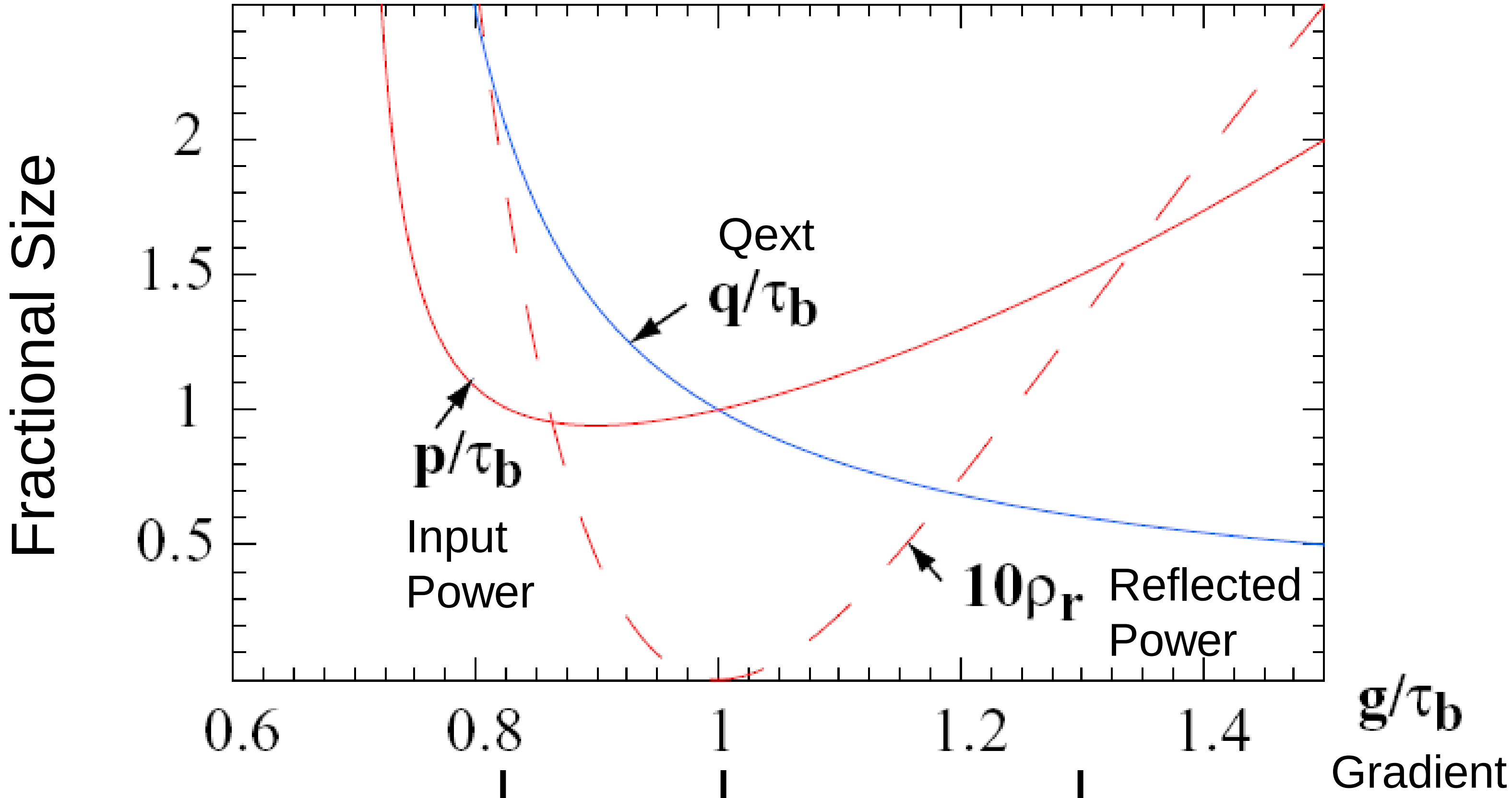
Summary

The flatness the gradient profile in each cavity will depend largely on the effectiveness of LFD compensation – this is true for XFEL (32 cavities powered by one klystron) as it is for ILC (RDR or KCS), so XFEL will likely invest heavily to make piezo compensation work effectively.

Expect the breakdown rate in the KCS system to be low based on experience to date – at minimum, want to asses the effect of breakdown in the pipe with a 4 us effective shutoff time – the R&D program through FY12 will reach 1/6 of this level (and the full 10 us shut-off time for the 10 MW waveguide). Need three klystrons and 1 km of pipe to reach the full effective level for the pipe.

The energy errors introduced with the coarser KCS energy control should not increase the beam emittance.

Flattop Operation with a Spread of Cavity Gradients



31.5 MV/m
Average

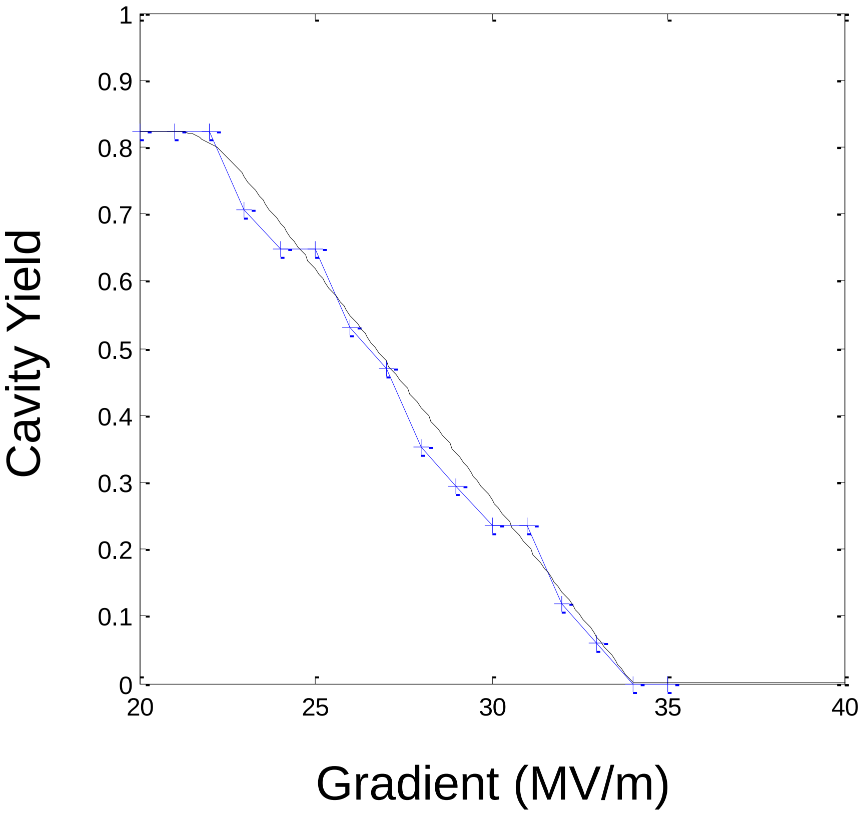
24.5
MV/m

29.8
MV/m

38.5
MV/m

Production Performance and R&D (2007)

In last DESY production run when cavities processed only a few times, average sustainable gradient about 28 MV/m: World-wide R&D focused on improving the yield

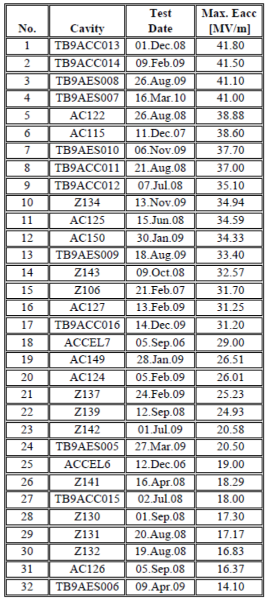


Recent TTC Meeting Cavity R&D Summary

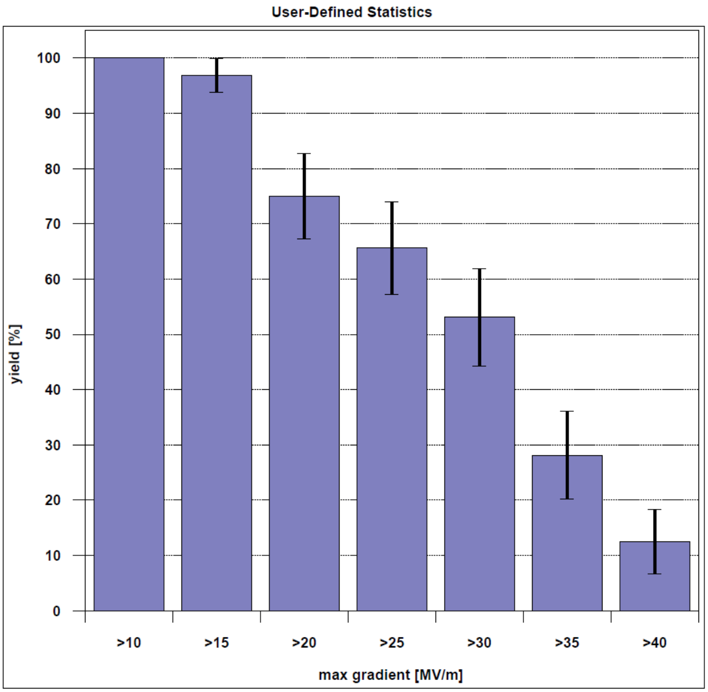
- In most cases quenches are reached in vertical qualifying tests – good news !
- What is disturbing is the spread in performance and the majority are below ILC specifications
- It is not clear that we understand what these limits really are (MP or FE induced) and there is an inconsistent approach in the testing methods to quantify this type limit
- Need to focus effort on better understanding of mechanism and develop solution (new cleaning method ?)

Compare 1st and 2nd pass yields (updated!) (2010)

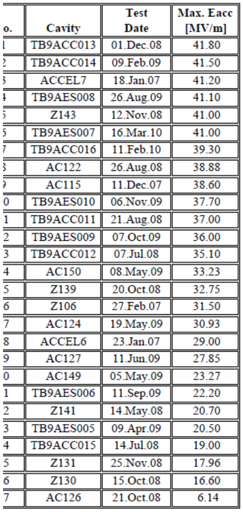
1st pass



No.	Cavity	Test Date	Max. Eacc [MV/m]
1	TB9ACC013	01.Dec.08	41.80
2	TB9ACC014	09.Feb.09	41.50
3	TB9AES008	26.Aug.09	41.10
4	TB9AES007	16.Mar.10	41.00
5	AC122	26.Aug.08	38.88
6	AC115	11.Dec.07	38.60
7	TB9AES010	06.Nov.09	37.70
8	TB9ACC011	21.Aug.08	37.00
9	TB9ACC012	07.Jul.08	35.10
10	Z134	13.Nov.09	34.94
11	AC125	15.Jun.08	34.59
12	AC150	30.Jan.09	34.33
13	TB9AES009	18.Aug.09	33.40
14	Z143	09.Oct.08	32.57
15	Z106	21.Feb.07	31.70
16	AC127	13.Feb.09	31.25
17	TB9ACC016	14.Dec.09	31.20
18	ACCEL7	05.Sep.06	29.00
19	AC149	28.Jan.09	26.51
20	AC124	05.Feb.09	26.01
21	Z137	24.Feb.09	25.23
22	Z139	12.Sep.08	24.93
23	Z142	01.Jul.09	20.58
24	TB9AES005	27.Mar.09	20.50
25	ACCEL6	12.Dec.06	19.00
26	Z141	16.Apr.08	18.29
27	TB9ACC015	02.Jul.08	18.00
28	Z130	01.Sep.08	17.30
29	Z131	20.Aug.08	17.17
30	Z132	19.Aug.08	16.83
31	AC126	05.Sep.08	16.37
32	TB9AES006	09.Apr.09	14.10



2nd pass



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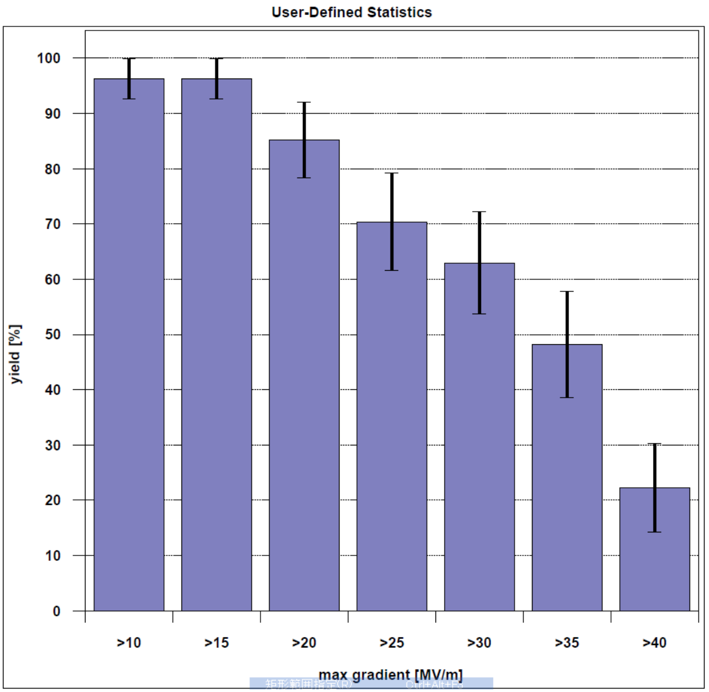
5	Z143	12.Nov.08	41.00
5	TB9AES007	16.Mar.10	41.00
7	TB9ACC016	11.Feb.10	39.30
3	AC122	26.Aug.08	38.88
9	AC115	11.Dec.07	38.60
0	TB9AES010	06.Nov.09	37.70
1	TB9ACC011	21.Aug.08	37.00
2	TB9AES009	07.Oct.09	36.00
3	TB9ACC012	07.Jul.08	35.10
4	AC150	08.May.09	33.23
5	Z139	20.Oct.08	32.75
6	Z106	27.Feb.07	31.50
7	AC124	19.May.09	30.93
8	ACCEL6	23.Jan.07	29.00
9	AC127	11.Jun.09	27.85
0	AC149	05.May.09	23.27
1	TB9AES006	11.Sep.09	22.20
2	Z141	14.May.08	20.70
3	TB9AES005	09.Apr.09	20.50
4	TB9ACC015	14.Jul.08	19.00
5	Z131	25.Nov.08	17.96
6	Z130	15.Oct.08	16.60
7	AC126	21.Oct.08	6.14



Beam-to-RF Timing

Relative beam (c) to rf (vg) travel times for each feed

$$v_g = \frac{c^2}{v_p} = \sqrt{1-(k_g/k_0)^2}\; c = 0.8103\; c$$

Upstream: 1.25 km × ($1/v_g$ + 1/c) = 9.32 μs

Downstream: 1.25 km × ($1/v_g$ - 1/c) = 0.98 μs

For the upstream feed, the RF-to-beam timing will vary by 9.32 μs. Centered, this represents ± 0.8% of nominal fill time.

As a remedy, the cavity Q_L's and powers will be tweaked to vary the desired t_i accordingly. This will be done anyway to deal with the gradient spread.