RF Workshop and Parallel Session

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For the RF Group

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Smith, Sheffield

DeMello, Li, LBNL, Fermilab

Torun, Hanlet, Illinois Institute of Technology

RF Workshop

- Held at Daresbury in April
- Address RF Review Panel Comments
  - Elimination of the dynamic phase control between cavity pairs
  - Simplification of distribution network
  - Improve accessibility of Amplifier Stations
  - Address risk of overvolting the transmission lines
  - Consider risk posed by exposure of tetrode valves to the magnetic field
  - Define specification for MICE RF system
  - Provide feedback control of phase (and amplitude?)
- Allow specification of components to enable purchase by Univ. Mississippi MRI (by mid 2013)
- Address measurement of Muon transit RF phase

Cavity Parameters

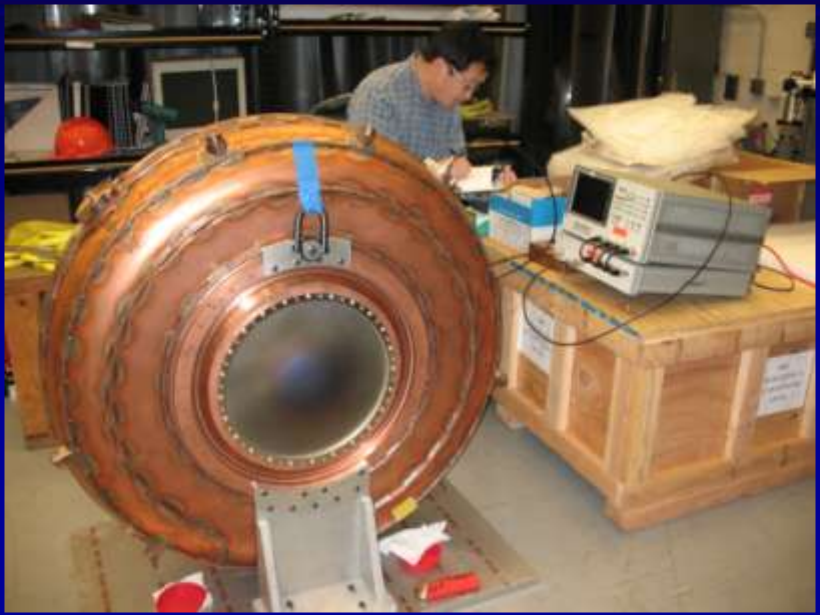
- Each cavity
  - 430mm pitch, 410mm gap, Resonance at 201MHz,
    - Dynamically tuneable by 230kHz (deformation)
    - This tuning is slow, to compensate for long term thermal expansion (due primarily to RF heating)
  - Gradient 8MV/m target, Driven by 1MW RF power
  - Q of 44,000
    - Instantaneous spectral width ~5kHz
    - Charging energy 1kJ per pulse, average heating power 1kW
  - Energy into any given particle ~e.E.d is very small

Progress with Cavities

- Cavity dimension measurement in progress
- First cavity electropolished
  - 9 cavities to be polished in next FY
- After polishing, cavities subject to RF measurement and tuning
- Single cavity test stand completed at MTA
  - First cavity to move to MTA for testing
  - Autumn 2012 suggested date
  - No magnetic field at this time?
- Automated actuator driver to tune cavity being developed
  - Will require interfacing to LLRF

Cavity Measurements

Cavity physical measurement

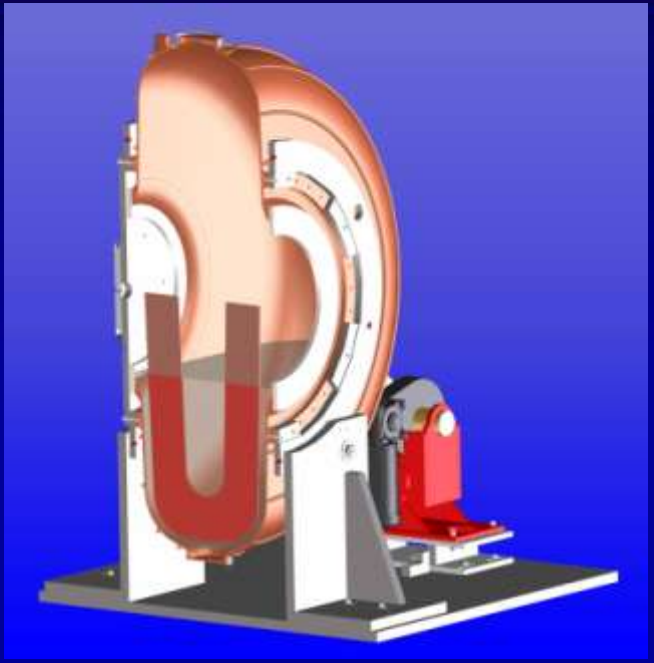


Cavity frequency measurement

- Physical measurements for the six remaining cavities expected to take approximately 1-1/2 weeks (60 hours)
- RF measurements and tuning to a center frequency after the EP of all ten cavities (two spares) at LBNL.
- This activity will begin in the next fiscal year

Cavity Electropolish at LBNL

EP rotation fixture



Cavity section view

- The inner surface of each cavity will be mechanically smoothed and then electropolished at LBNL using the techniques developed at JLab for the prototype cavity
- Electropolishing process will take approximately 1- 2 days for each cavity or 4 weeks to complete all 10 cavities

Cavity Electropolish at LBNL

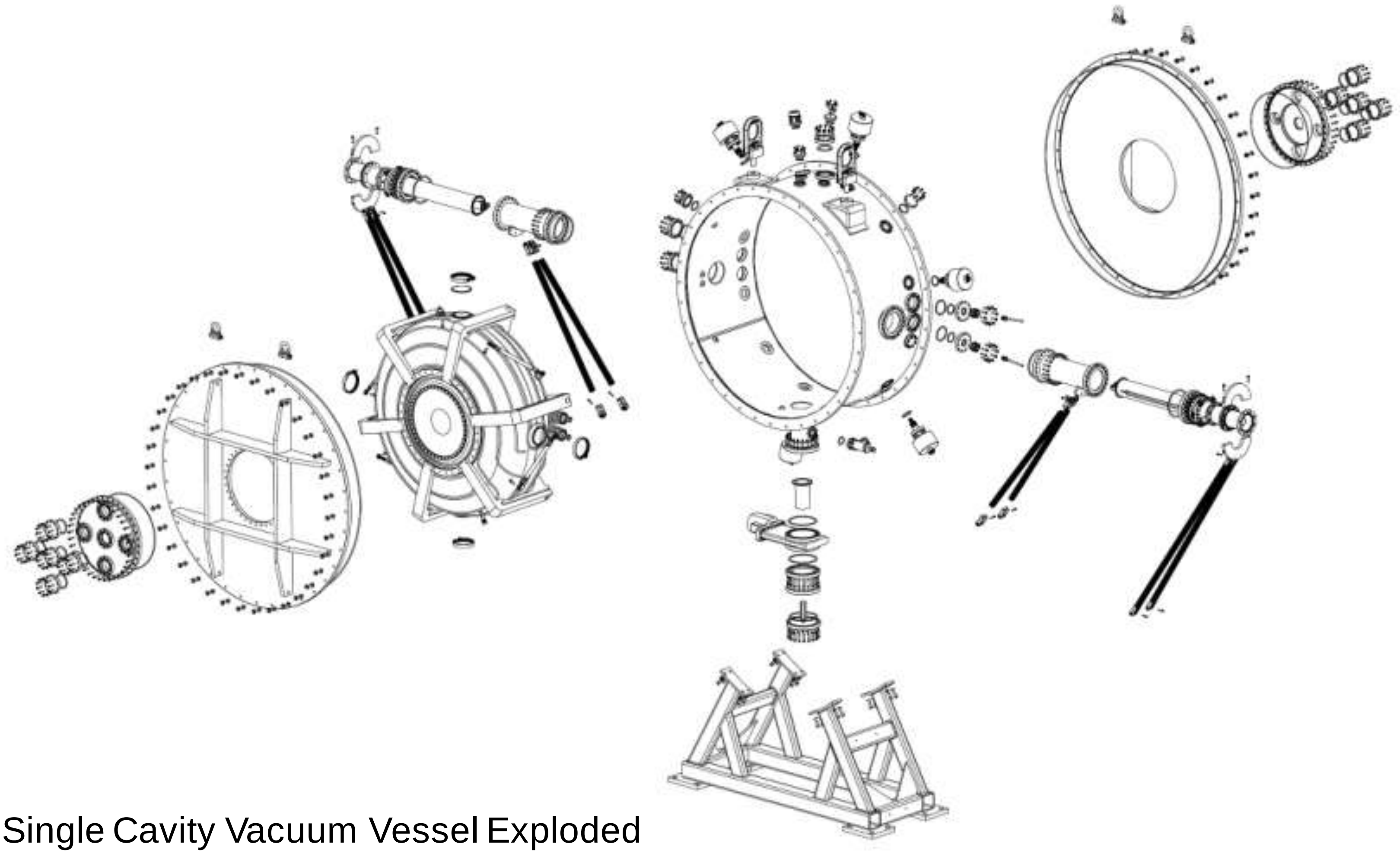
EP setup in plating shop at LBNL

EP finished

View inside of finished cavity

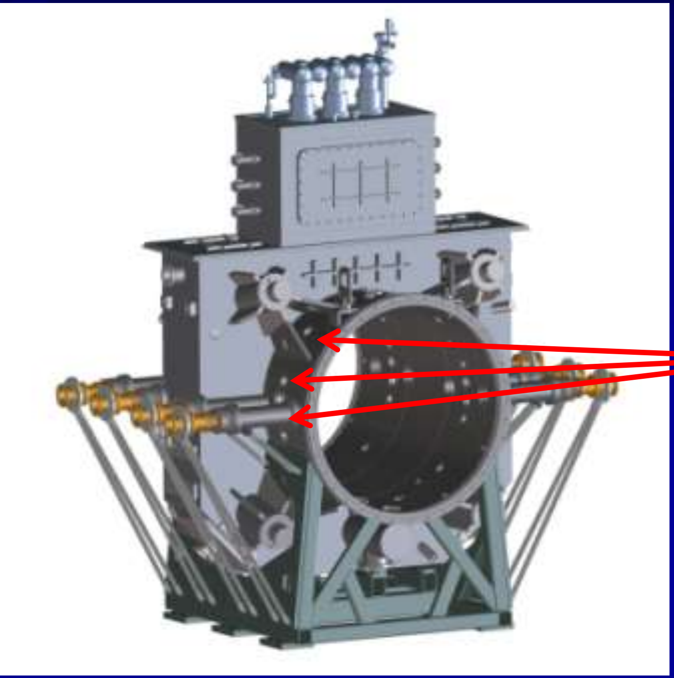
- Fabrication of EP fixturing is complete and approved for use by EH&S
- Electropolishing has been done on one cavity
- Electropolishing of the remaining nine cavities will resume in the next fiscal year at LBNL

Single RF Cavity Vacuum Vessel



Single Cavity Vacuum Vessel Exploded View

Single Cavity Vacuum Vessel



MICE Vacuum Vessel (cavities removed)

Single cavity vacuum vessel is designed with all of the same ports that the MICE RFCC vacuum vessel will have

The single cavity vacuum vessel is complete and at Fermilab

Phasing of adjacent Cavities

- Match phase delay to the transit time
  - The phase should be delayed by the transit time
  - Allowing for the loss of momentum in the first H_2 cell

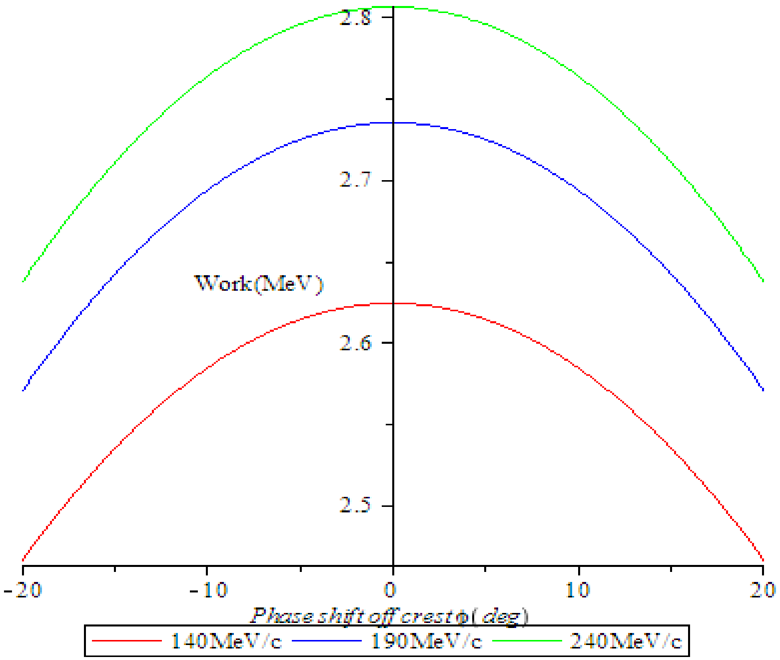
140MeV/c	190MeV/c	240MeV/c
1.88ns	1.67ns	1.58ns
135^o	120^o	114^o

$\Delta f_{max}=21^o$

- Ideal phase delay is significant function of the momentum
  - The issue is exaggerated at lower energies/momenta
  - Each adjacent pair of cavities is driven from a single amplifier chain
    - These pairs have a fixed phase relationship which must be determined
    - The separate pairs can be controlled by the LLRF system
      - Easily adjusted electronically

Impact of Shift in Transit Phase

- Particles may not be on crest in transit
- Work is reduced
- The effect is limited
  - For small phase offsets
  - Slight increase in sensitivity with energy
  - Impact on total acceleration over cavity pairs is small

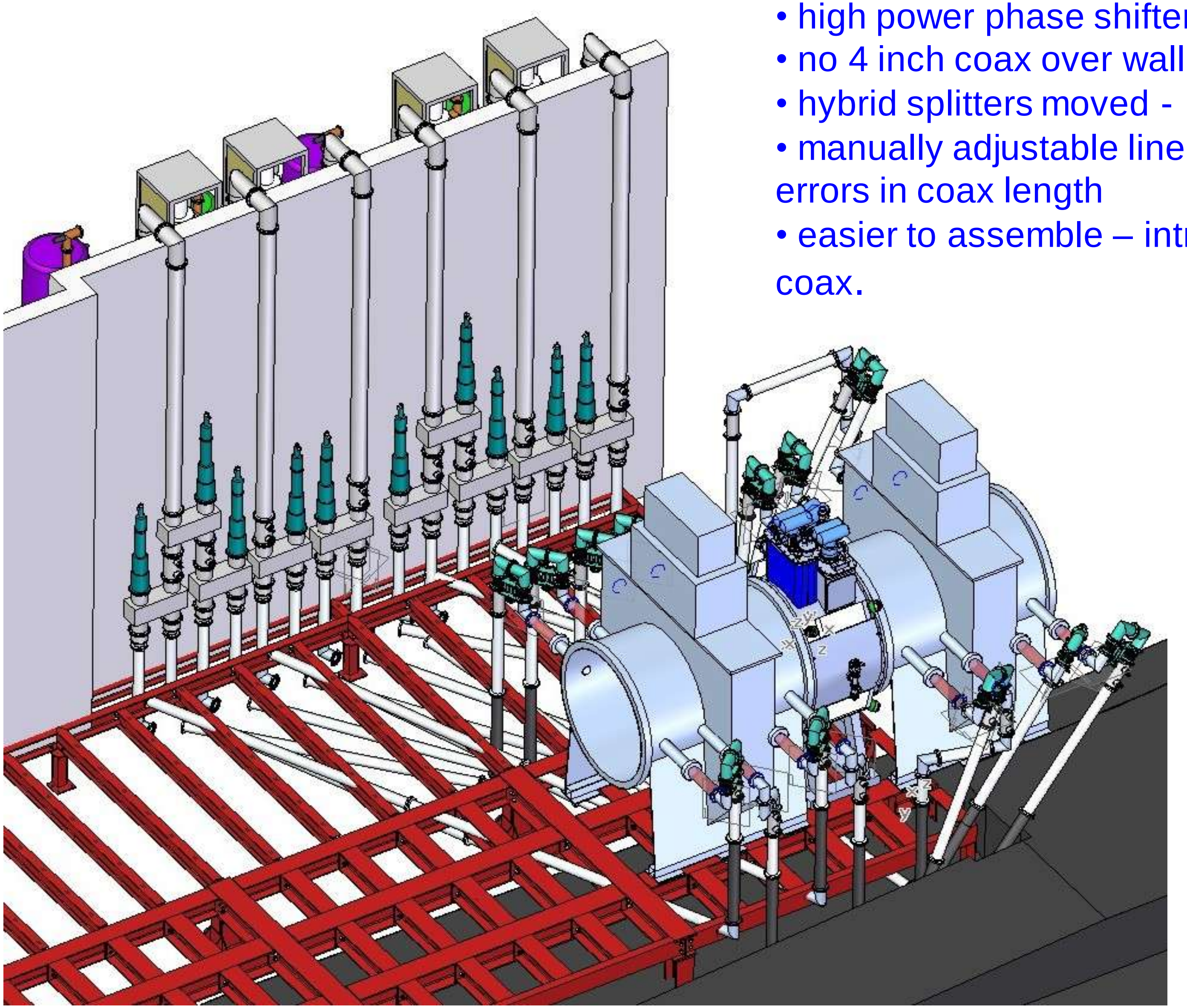


Ek_{in}(C-1)	Ek_{out}(C-1)	v_{out}(C-1)	Ek_{out}(C-2), 135°	Ek_{out}(C-2), 120°	Ek_{out}(C-2),114°
57.9MeV	60.5MeV	$2.31.10^8 ms^{-1}$	63.1MeV	63.0MeV	62.95MeV
99.5MeV	102.2MeV	$2.58.10^8 ms^{-1}$	104.8MeV	105MeV	104.9MeV
146MeV	148.8MeV	$2.73.10^8 ms^{-1}$	151.4MeV	151.6MeV	151.6MeV

Revised Layout of components

- It seems that fixing the phase shift over a pair of cavities does not substantially affect the achievable acceleration
  - Providing the phase is not more than 20^{o} from optimum for any particle
    - Suggest the coupled pairs be set at 124^{o}, the lowest energy particles would then be 10^{o} late and the highest 10^{o} early
    - The third cavity in the chain should be set at 228^{o}-270^{o} as the energy is reduced
- Mechanical Line Trimmers
  - Installed in 3 of the lines to each pair of resonators
  - Primarily to take up the assembly uncertainty
  - 82mm of travel, implies +/- 10^{o} of trimming might be available
    - Dependant on how much has been take up in the trimming of the line
- Elimination of dynamic phase control between cavity pairs
  - Enables simplification of distribution network

RF Layout – view from cooling



- high power phase shifters removed.
- no 4 inch coax over wall.
- hybrid splitters moved - more accessible
- manually adjustable line trimmers to take up errors in coax length
- easier to assemble – introduced flexible coax.

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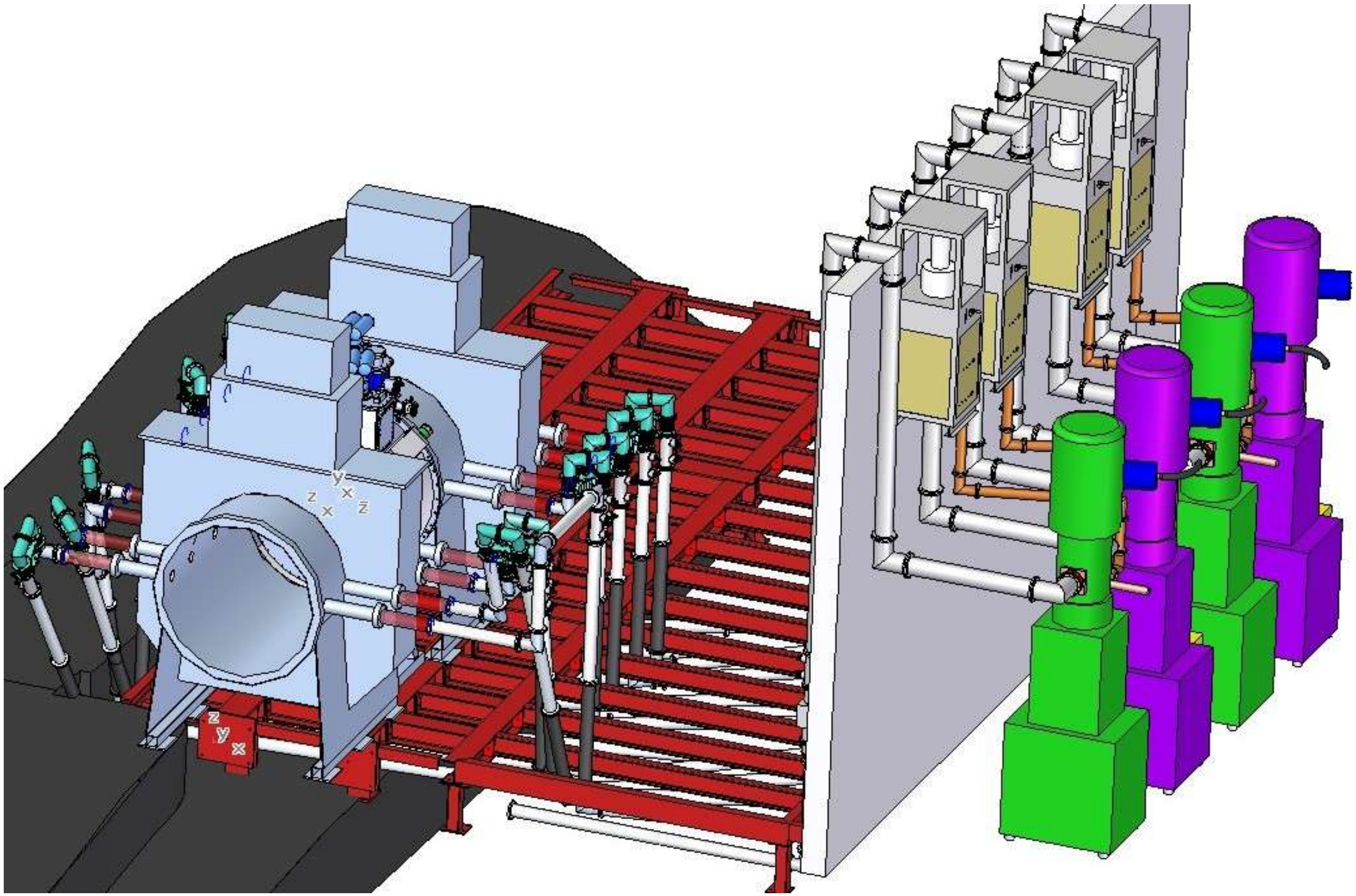
RF Layout – view behind shield wall



- hybrid splitters moved – space freed up behind wall.
- no coax distribution going under the wall.
- 6 off 6 inch coax over the top of wall.
- Coax length matching now takes place other side of wall – space less of a constraint.
- improved access for installing amplifiers.

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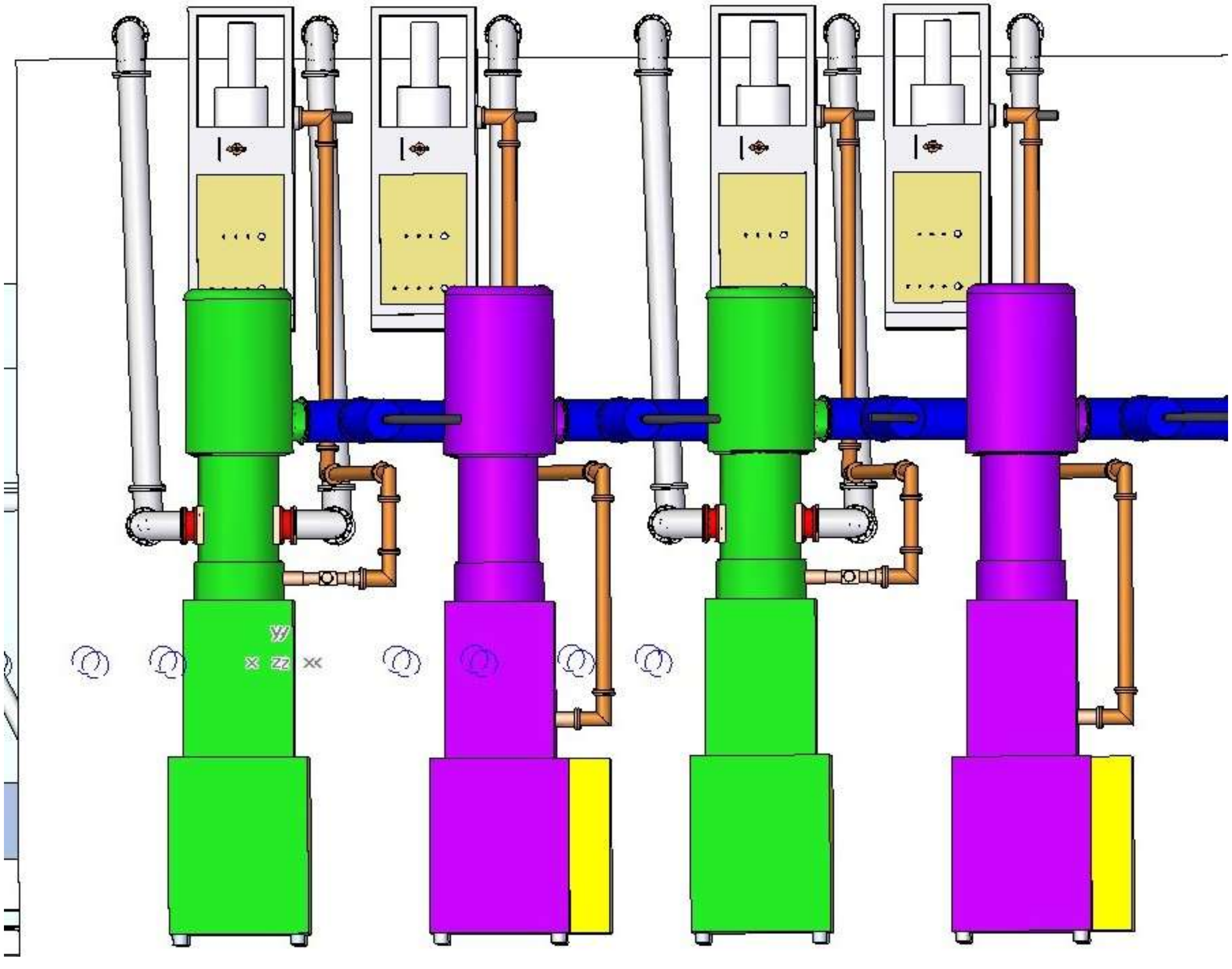
RF Layout – view behind shield wall



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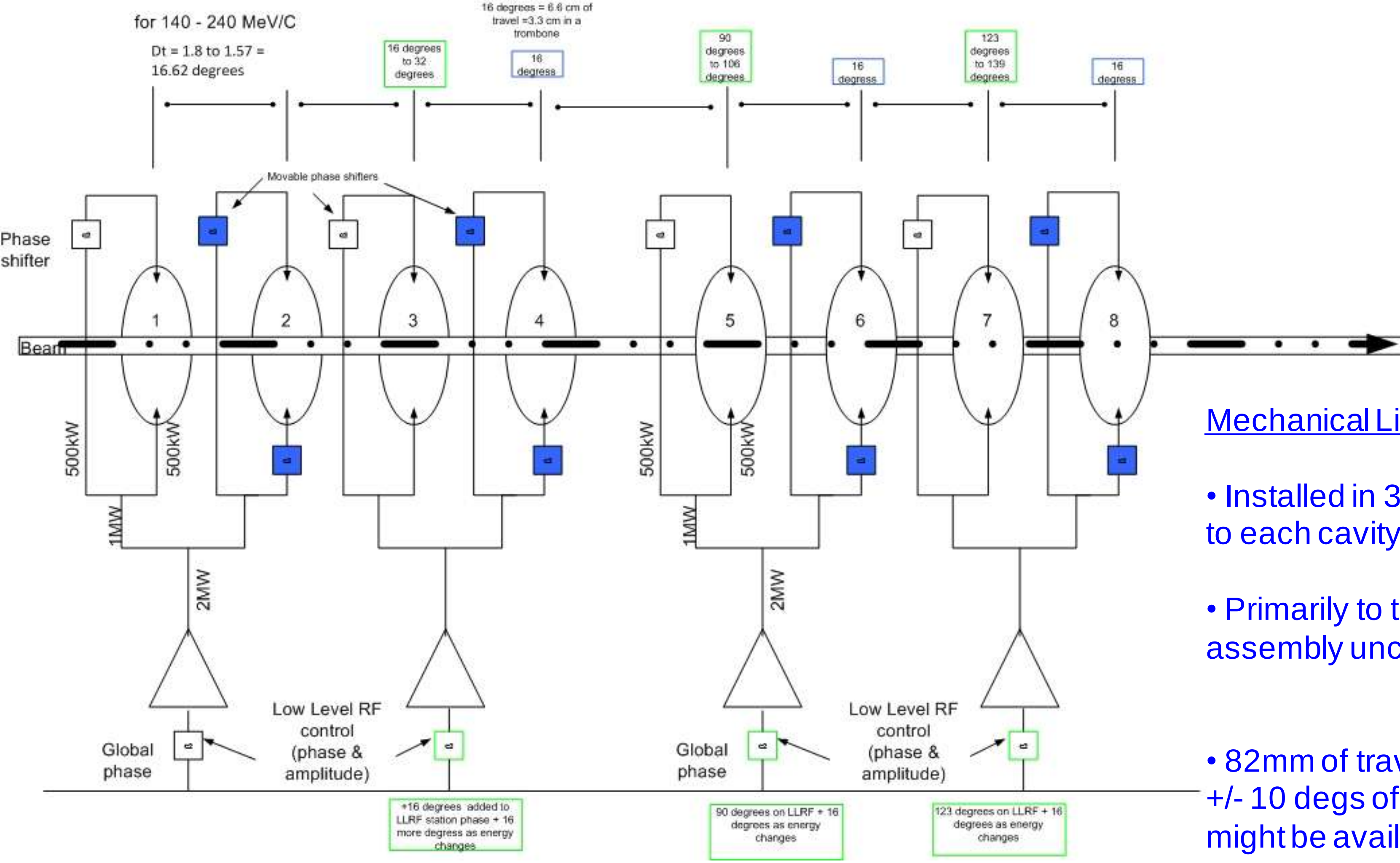
Fixed Phase Operation Schematic
Mechanical Line Trimmers for assembly uncertainties.



Mechanical Line Trimmers

- Installed in 3 of the lines to each cavity pair.
- Primarily to take up the assembly uncertainty.
- 82mm of travel, implies +/- 10 degs of trimming might be available.

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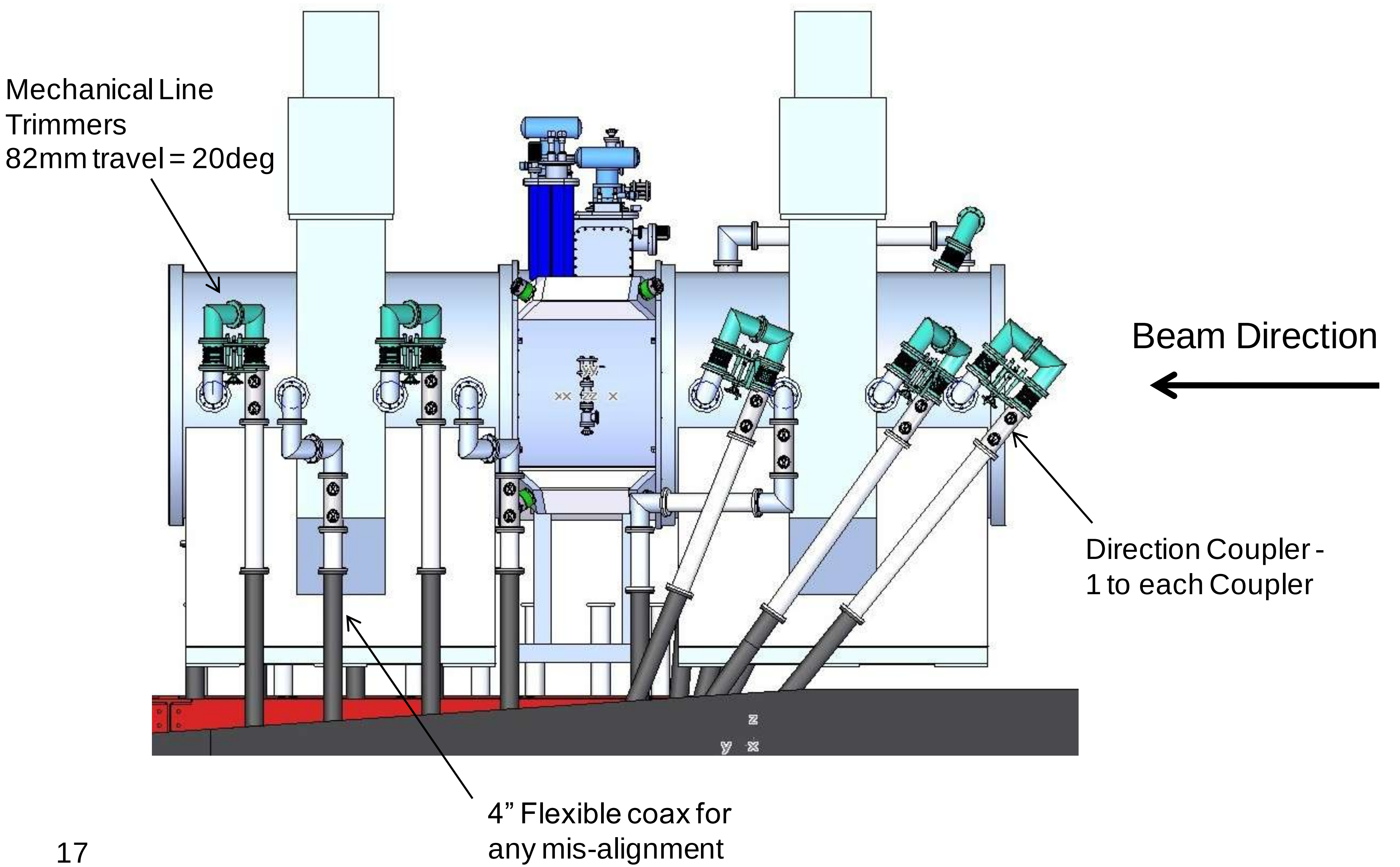
Line Trimmer Arrangement to South Side RF Couplers



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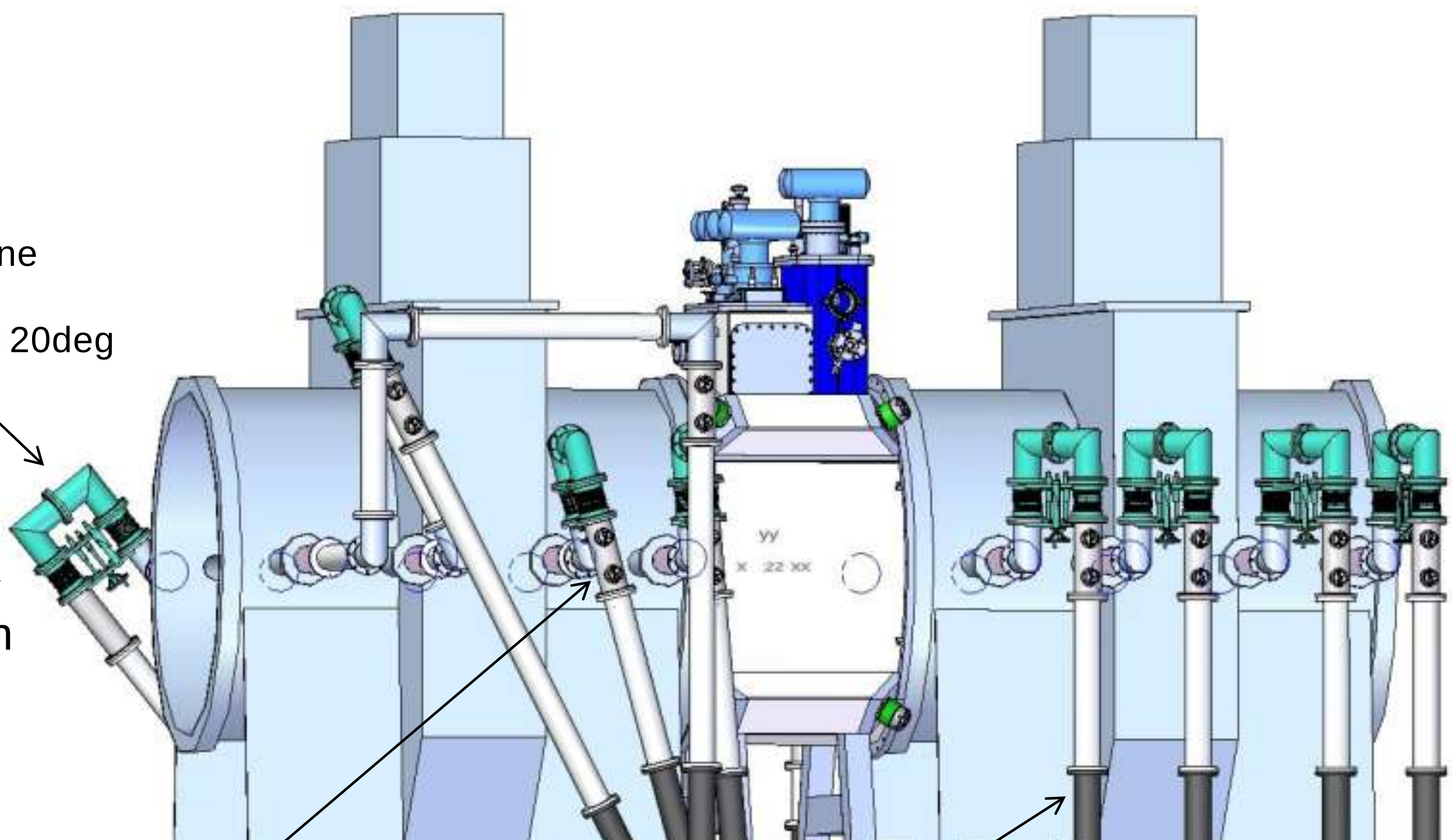
Line Trimmer Arrangement to North Side RF Couplers

Mechanical Line Trimmers
82mm travel = 20deg

Beam Direction



Direction Coupler - 1 to each Coupler

4" Flexible coax for any mis-alignment

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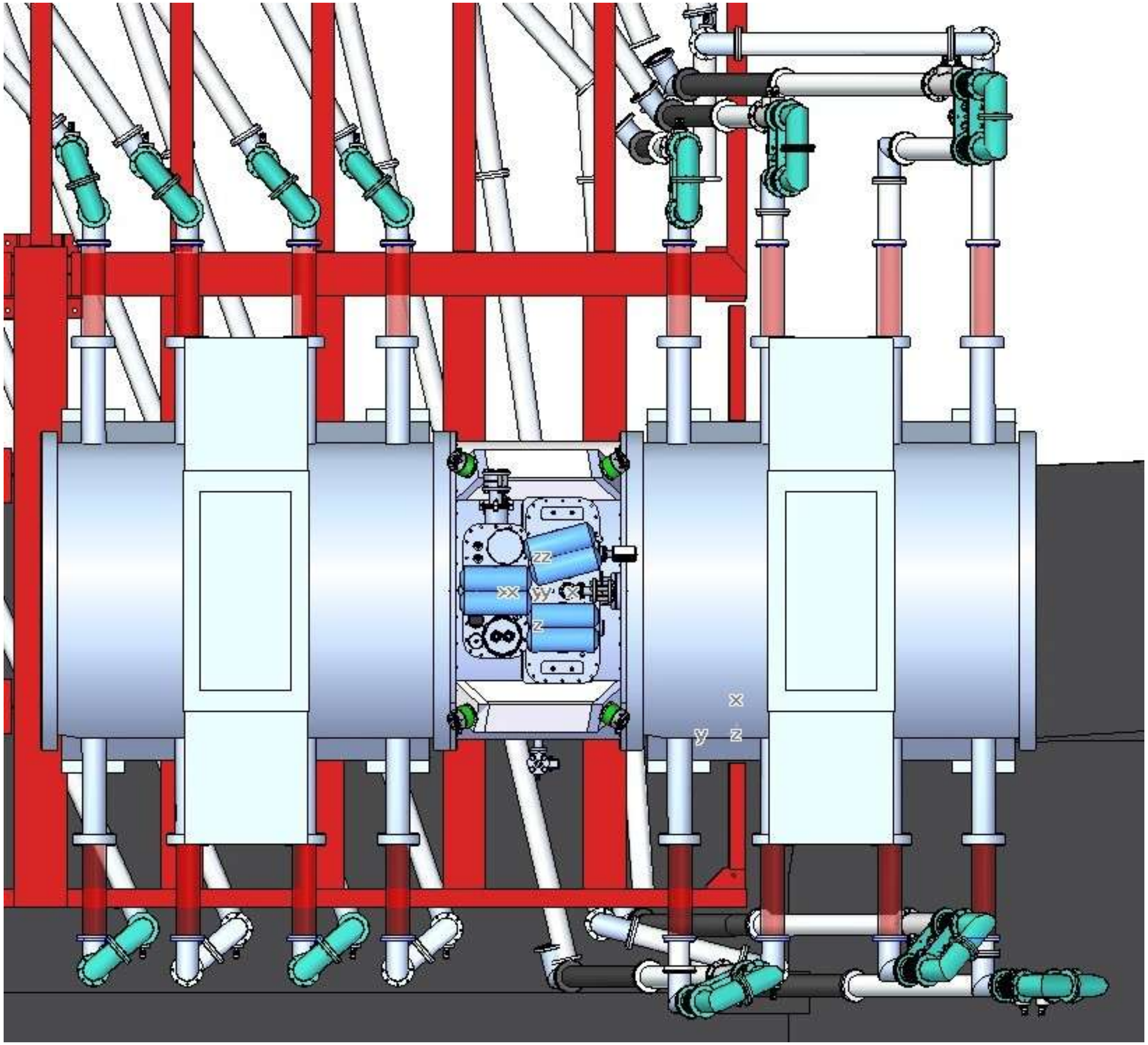
Clear Access for removal of AFC



AFC's can be removed without having to dismantle any of the RF coax system

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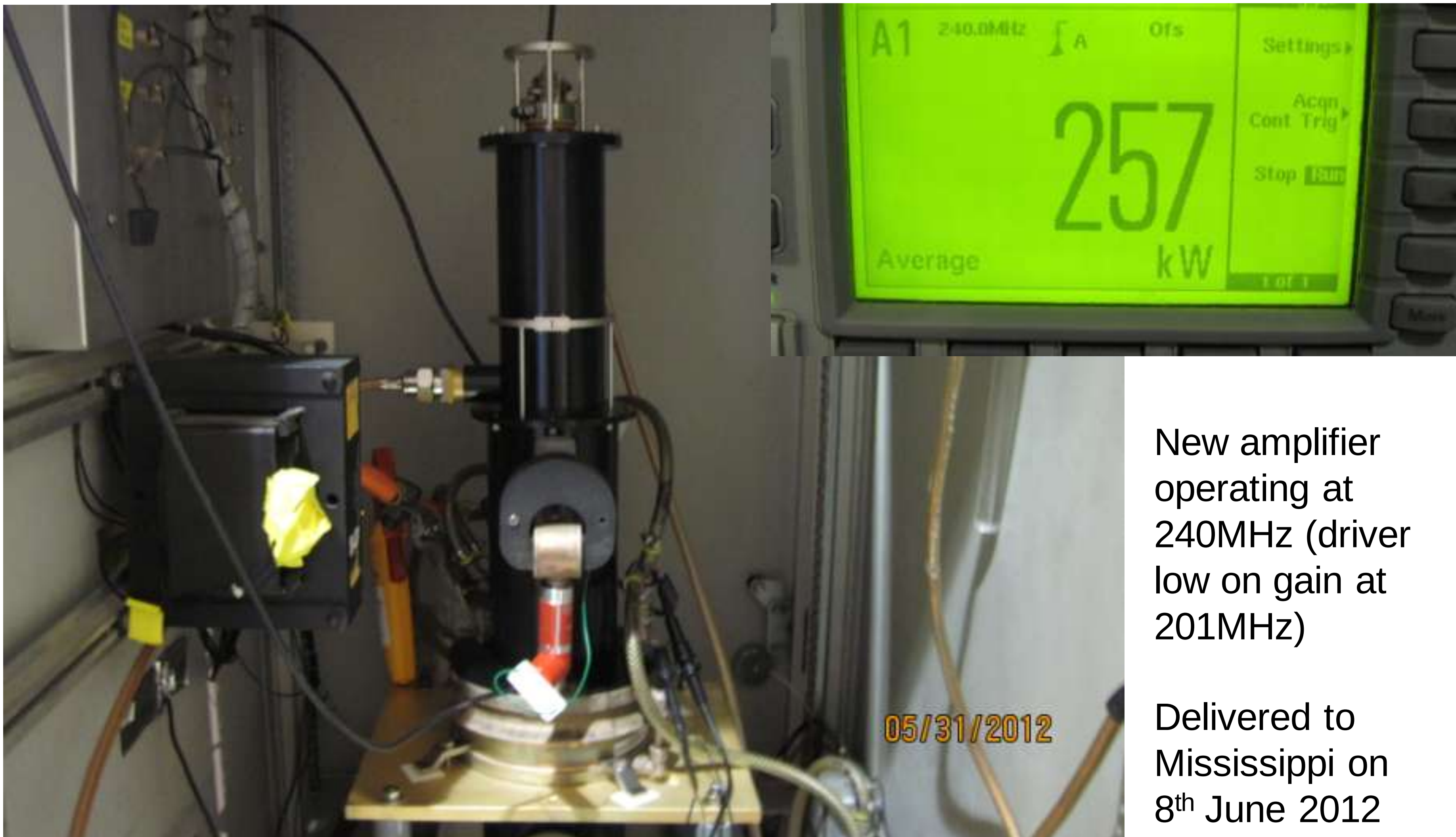
RF Power Systems

- Substantial progress on medium power valve amplifiers
  - DL have 240kW from first 4616 system using new valve after suitable conditioning and input match adjustment
  - 'Missing' tetrode amplifier system procured through Mississippi (MRI?)
    - Also operating at > 240kW
  - DL have advanced significantly in the refurbishment of 2 other amplifiers
- High Power Amplifiers
  - High power amplifier No 1 ready for full power test
  - Using new TH116 Triode valve
- Co-Axial lines and 'Slow' fill of cavities
  - Co-axial lines have limited voltage capacity and exhibit losses
  - Initially cavities present a perfect reflect to driver
  - Reflection signal can superpose on input signal, doubling line voltage
  - Strong reflection can disturb triode
  - Mitigate with slow cavity fill and pressurisation of the transmission lines

New amplifier in test bay at Photonis USA

Andrew Moss

New 250kW amplifier cavity



New amplifier operating at 240MHz (driver low on gain at 201MHz)

Delivered to Mississippi on 8th June 2012

Andrew Moss

New tetrode tube in DL test amplifier number 1

- Tube needed to be conditioned after spending 3 years on shelf
- Input matching set far to high (S21 45dB), eventually this was optimised at around 20dB
- After 20 hours running, with a lot of adjustments to amplifier and electrical parameters, system is stable and predictable with linear response
- Still some issues with screen power supply to sort out – loading of screen is moving with beam current and output loading

Drive (dBm)	ct 100mv per amp	HT (kV)	Electric power in tube (kW)	Grid 1 (V)	Screen Grid (V)	Drive (W)	Forward power (kW)	Reflected power (W)	Reflected Power Percentage (%)	Gain (dB)	Efficiency (%)	Ion Pump Current (μA)
0	8.1	19	153.9	170	1740	1086	48	243	0.5	16.5	31.2	0.11
1	9.9	19	188.1	170	1740	1376	69.2	320	0.5	17.0	36.8	0.17
2	12	19	228	170	1740	1740	102	307	0.3	17.7	44.7	0.3
3	14.9	19	283.1	170	1740	2200	158	311	0.2	18.6	55.8	0.39
3.5	17	19	323	170	1740	2480	208	314	0.2	19.2	64.4	0.55
3.7	17.7	19	336.3	170	1740	2580	236	364	0.2	19.6	70.2	0.98
3.5	17.5	19	332.5	170	1740	2480	234	287	0.1	19.7	70.4	0.64

250kW amplifiers numbers 2 and 3

- One amplifier is now completed and assembled in rack
- Small number of parts left to source from the manufacturer because they are missing – may need modification to suit much older design of amplifier cavity
- final 250kW amplifier will be assembled back into rack in the next few months

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High Power Amplifiers

- Amplifier 1 tested at 1MW
  - Used old valve
- Amplifier 1 ready for testing to 2MW - imminently
  - Using new TH116 valve
- Next 2MW amplifier refurbishment CERN type
- Very similar electrical design philosophy for the heater and control functions etc
- Some modifications may be required to make these work with current PSU design
- Operation test should be made within the next year

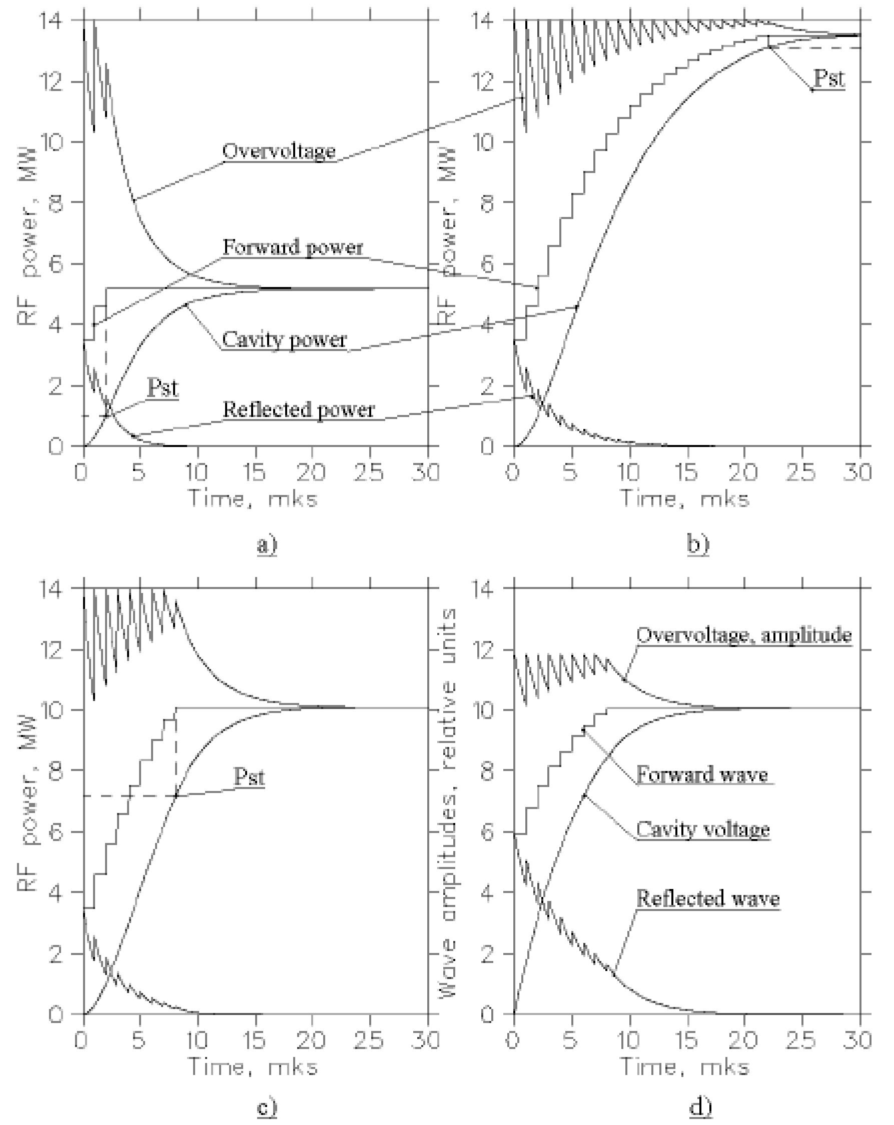
Andrew Moss

Slow Ramp of Input RF

- Co-Axial 4” line rated to 5960V and 700kW of power
  - Transmission Losses ~10%
  - Our input power of 500kW is 5kV RMS or
  - Full reflect, transient peak field ~10kV on SW maximum
  - Likely to arc the line
- Use slow ramp of RF power, slightly extending pulse duration
  - Reduce reflected field to keep SW maximum below rating of the line
- Use pressurisation with N_2 gas at 1 Bar
  - Increases tolerable power by 20%
  - Avoids issues associated with SF_6
- May make the triode more controllable during start up
- Implement ramp in LLRF control circuit
  - This is the most ‘unusual’ feature of the LLRF control

Cavity Filling (feed forward)

- Because MICE does not use circulators / Isolators to protect the amplifiers, large reflections can cause damage.
- Large reflections may occur during initial cavity filling.
- This can be eased by ramping the input power using constant reflection condition.
- On the FPGA, we need to code a programmable ramp with variable duration, so that we can use the shortest ramp length possible, whilst still avoiding overvoltage in the coax.



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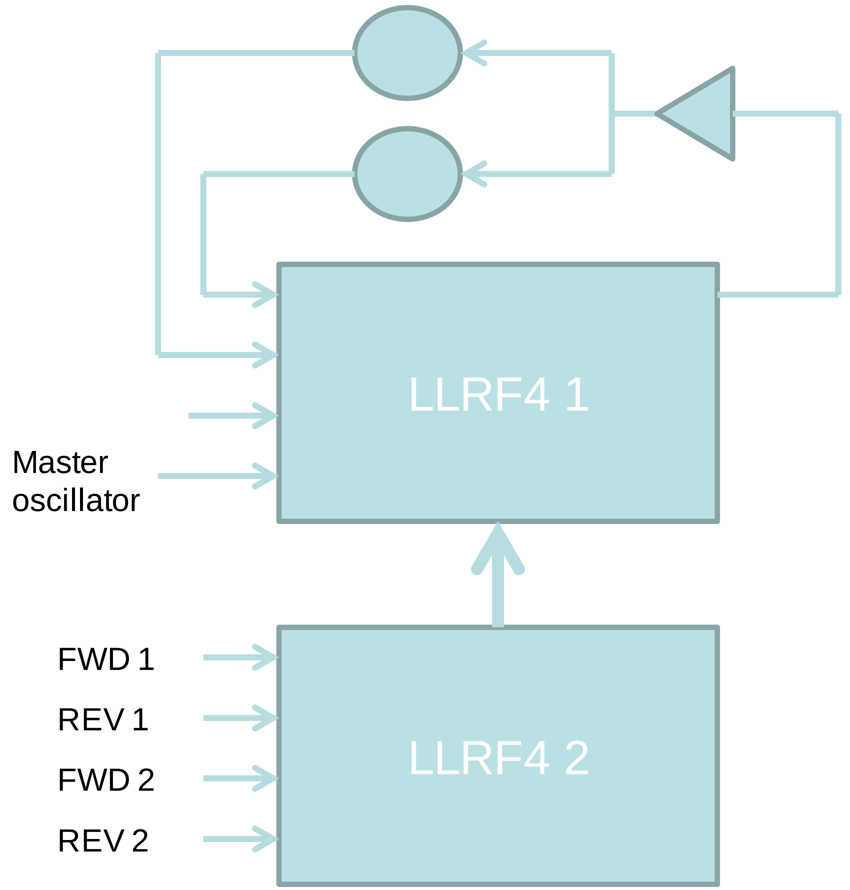
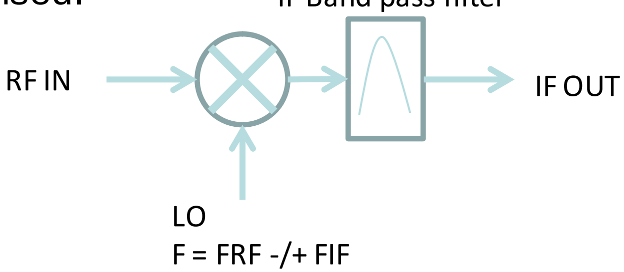
Control of RF system

- From discussion at RF workshop
  - LLRF system with feedback favoured for regulation of phase (and amplitude?)
  - Suggested specification is 1% in amplitude and 0.5^{o} in phase (7ps) within suggested limits for phase accuracy needed
  - Known technique with experience in implementation
- Could mitigate the phase-history recording
  - If the relative phase of the cavities is well known, the ToF system need interface with only one representative RF reference signal
- If no phase control, then the phase of cavities could wander significantly during pulse
  - Frequency shift of ~1kHz would be enough to move cavities into antiphase at some point during a pulse
  - Triode is non-linear and may distort in electrical length at heavy load
  - Reflected signal may impact on triode output phase
  - Even if phase is being measured, this would be detrimental to the acquisition of good data
  - LLRF Phase control required to compensate by fettling the input signal

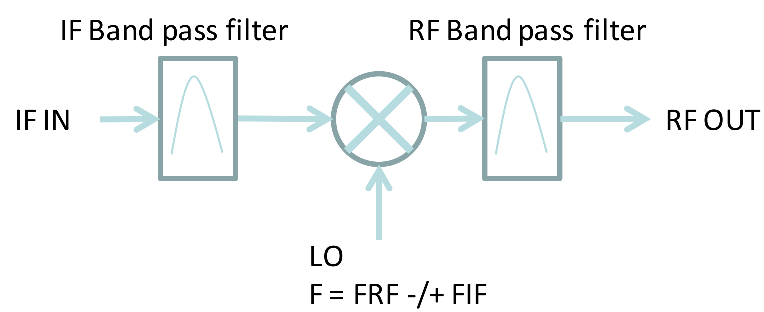
Proposed Hardware

- For each cavity pair, we use 2 x LLRF4
  - One board samples the 2 cavity probes, plus the reference oscillator.
  - Second board samples the FWD and REV powers for each cavity.
  - Sample data is continuously streamed from the second FPGA to the first.
  - All clever control is performed by the first LLRF4 card.
- Inputs are mixed down to an IF frequency
  - Somewhere between 30 and 60 MHz
- Outputs are mixed up from the same IF frequency.
- Analogue Up/Down conversion components are temperature stabilised.



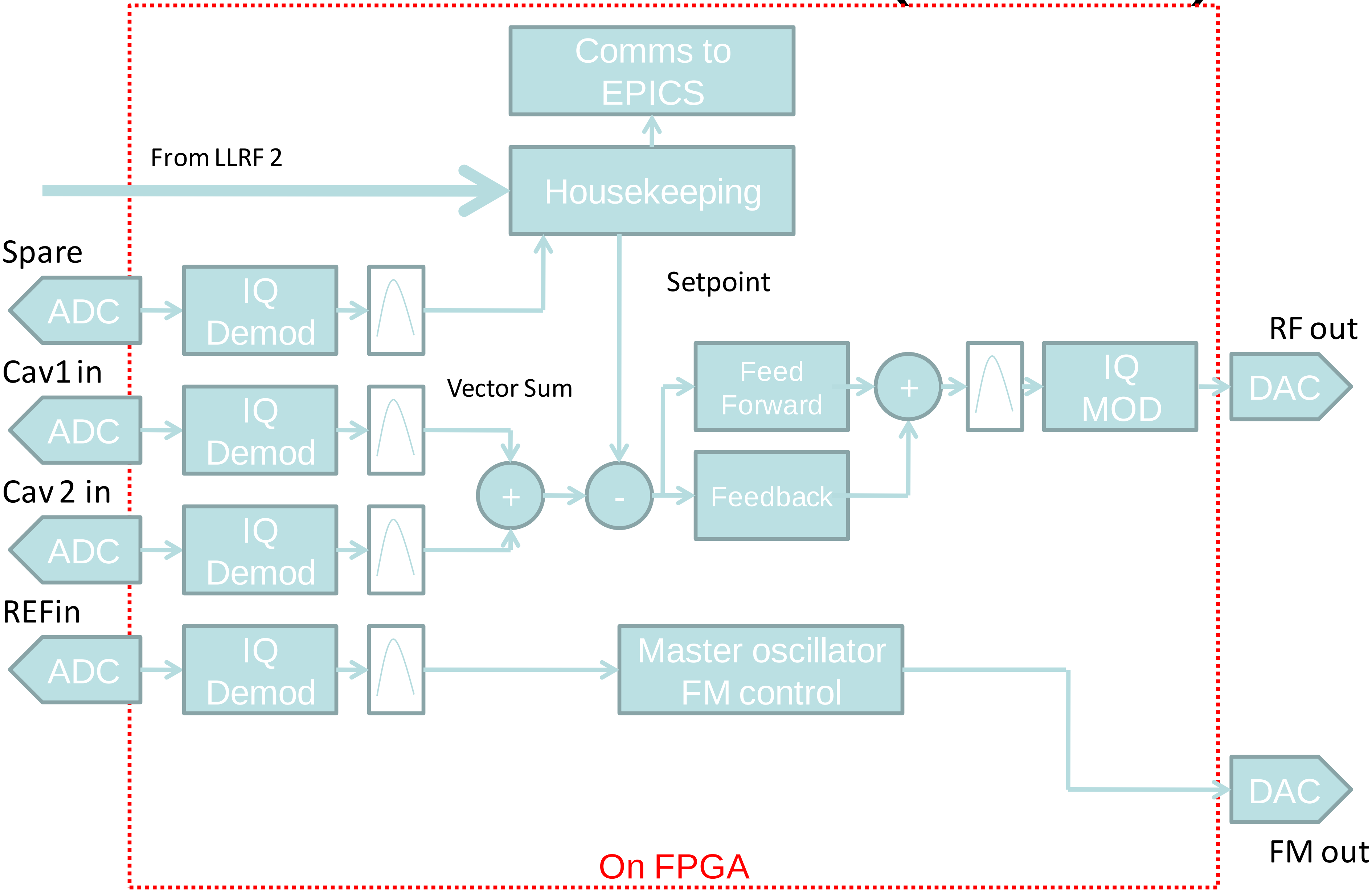


INPUT DOWNCONVERSION



INPUT DOWNCONVERSION

Firmware structure (FPGA1)



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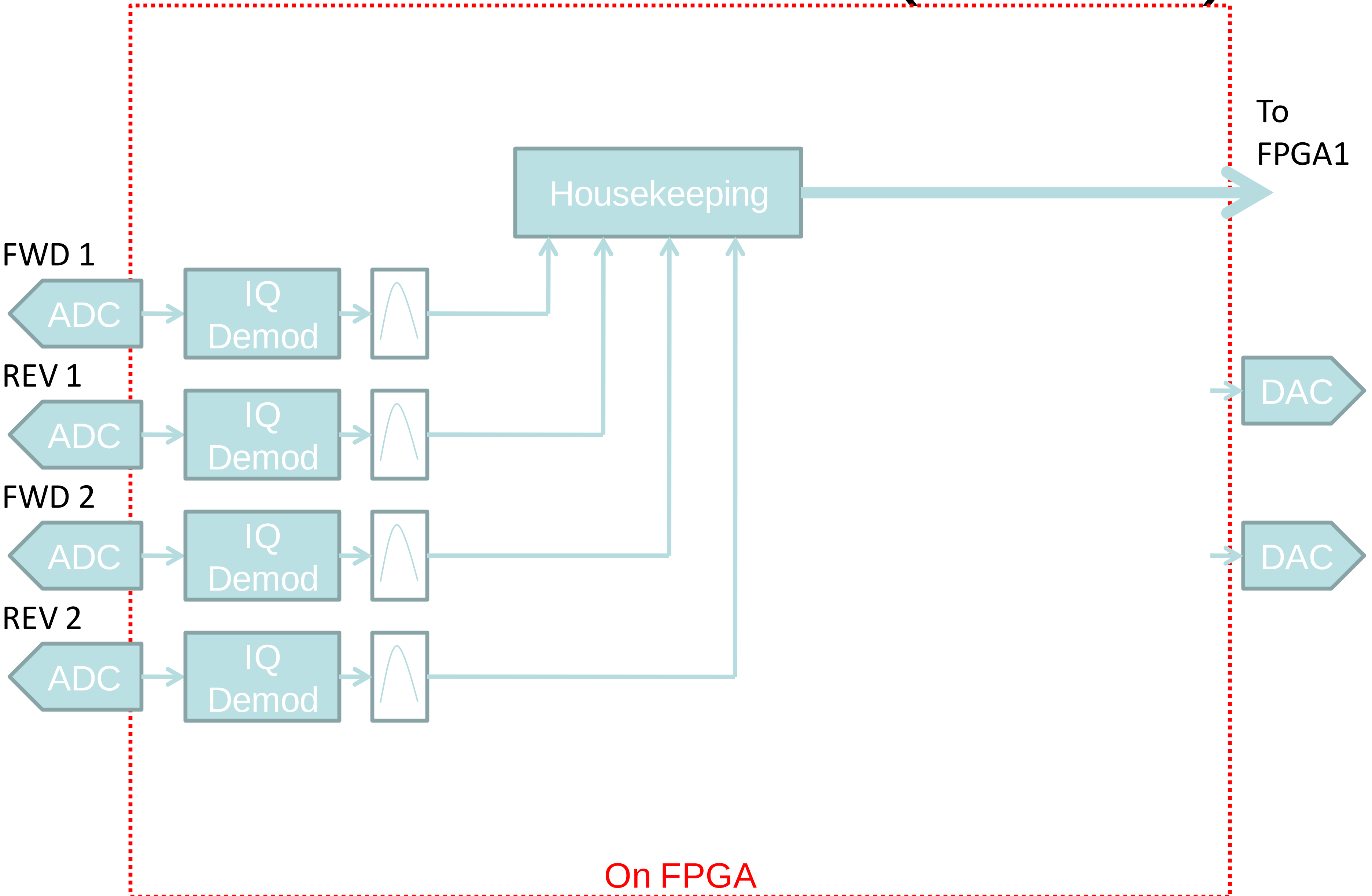
Firmware structure (FPGA2)



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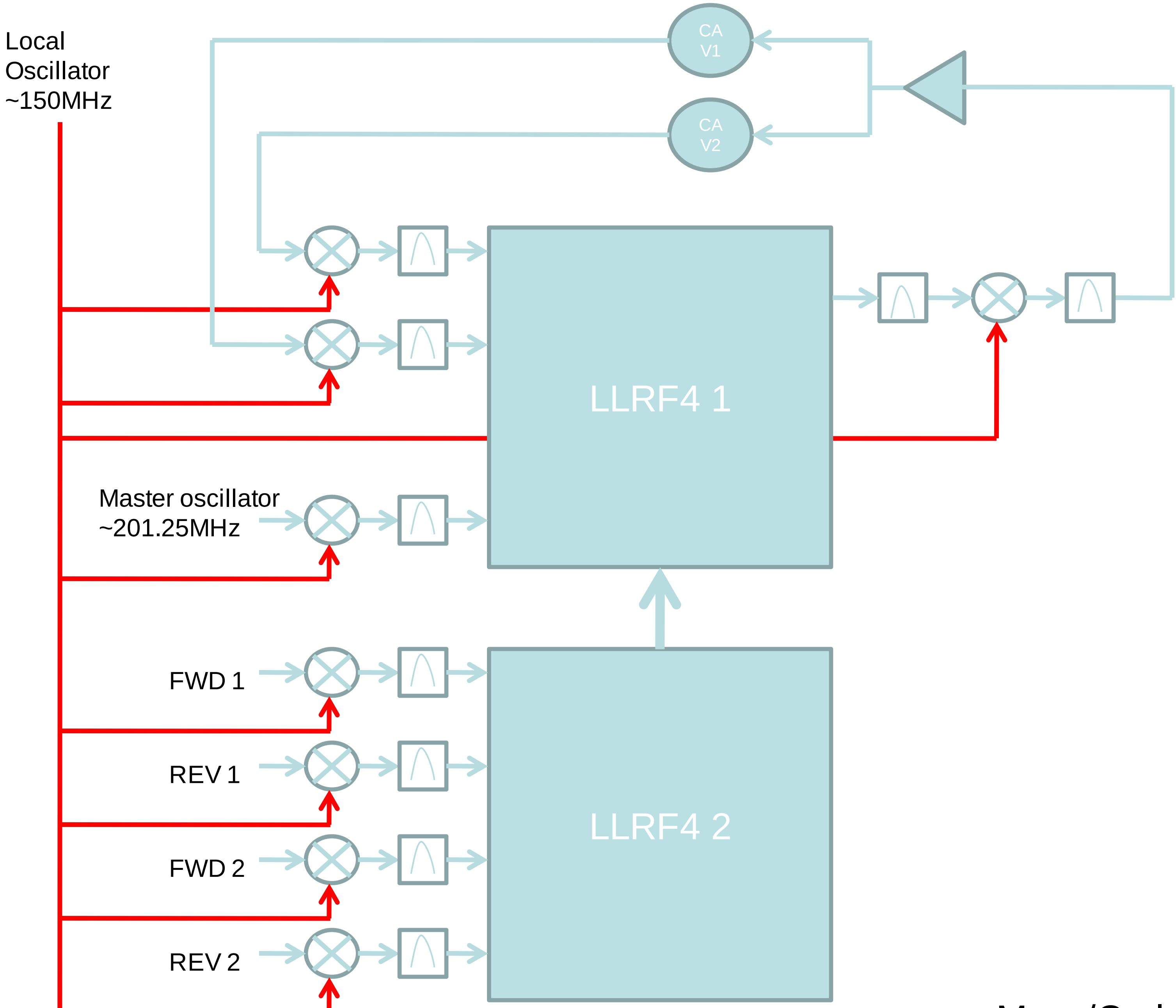

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Control and Measurement of RF Gradient & Phase

- From discussion at RF workshop
  - Amplitude control will (and phase control may?) demand an overhead allowance
  - Suggested overhead allowance is 15-20% of tube power
  - Implication is loss of gradient down to 7.4-7.15MV/m
    - This needs to be combined with the 10% power loss anticipated in the co-axial feed circuit
  - Recovery would require configuring valves for service at ~2.4MW
    - Implications for the amplifier assemblies?
    - Implications for valve lifetime (could be significant)
  - Reduce overhead allowance at price of some amplitude stability
- If no control then droop will arise
  - Level unknown, about 10%? Will drop acceleration to 7.6MV/m
- Options for measuring the acceleration gradient
    - If LLRF regulation is not used then this will be required, with reproducibility of 1%
    - Amplitude cannot change much in less than 10us (due to the Q), Frequency is well known
    - Digitise the waveform completely, sub-sampled or in bursts and reconstruct waveform to obtain amplitude (requires data on each channel)
    - Mix the 201MHz signal down with a well calibrated mixer
    - Rectify the waveform and measure the DC signal with a relatively slow digitiser.

Outline of the Proposed Solution

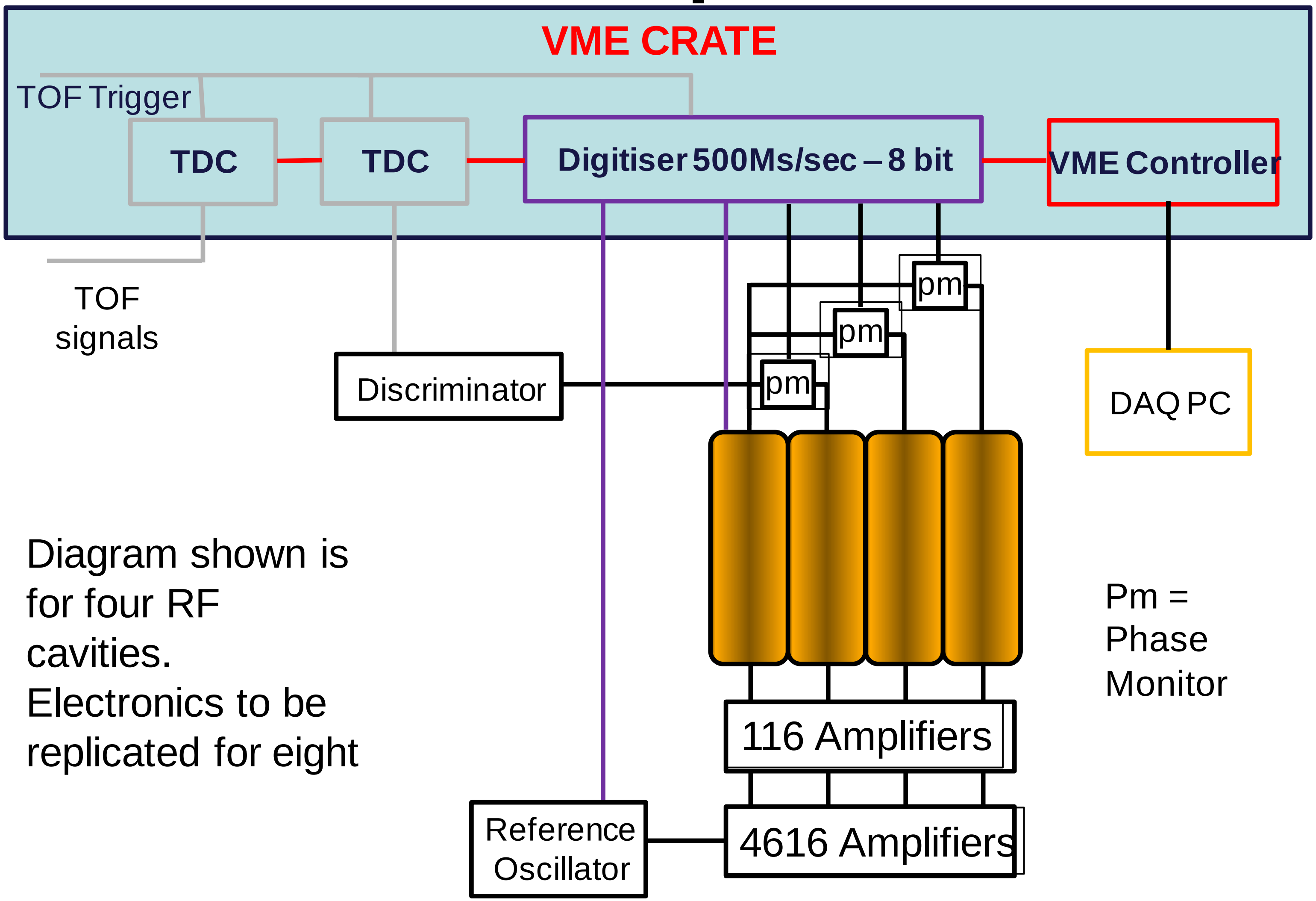


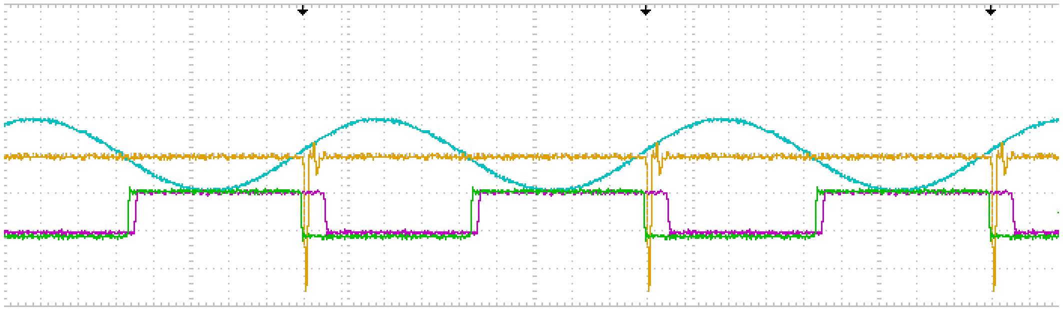
Diagram shown is for four RF cavities. Electronics to be replicated for eight

Pm = Phase Monitor

Discriminator - Function

- A fast discriminator (level/zero crossing/fraction) will provide a series of timing pulses that would provide a mechanism to lock a given phase value of the RF to the TOF triggers.

- By logging these triggers in a TDC synchronised to the TOF TDCs we should be able to time correlate the phase of the RF to events registered by the TOF TDCs. With this information it should be possible to reconstruct what the phase of the RF was when the muon traversed a cavity.



Note: This is a composite Image of LF Sine Wave (Few MHZ) with a discriminator to demonstrate the principle of generating regular timing pulses from the RF.

Other items from Review

- Impact of B-field on 4616 not thought to be severe
  - Tube gap is short, tube below shield wall (0.16m) and 0.5m back
  - Possibly worth doing quick trajectory PiC models and analytical estimates
- Procurement of Components
  - In addition to the new tetrode amplifier Don Summers has now started procurement of a list of passive components including:
    - Line trimmers (mechanical adjustment)
    - Dummy Loads
    - Hybrid Splitters
    - Reducers
    - Directional Couplers
    - Circulators
    - Elbows
- Response document prepared detailing how the issues raised in the RF review were addressed

Ongoing Activity

- Testing of 2MW amplifier with new valve
- Assembly of cavity in MTA
- Testing of Cavity in MTA (Autumn)
- Procurement of RF test gear where this is not already available
- Recruitment of personnel in UK
- Firming up of the LLRF scheme
- Firming up of the strategy for determining Muon transit phase

Forward Timescales and Plans

- Tiara funding
  - Requires an amplifier set to be operational in MICE hall
  - By Sept 2013
  - Interaction of this test with STEP IV programme?
  - Opportunity to define how some of the RF requirements will link to the MICE control
- If PSU's move to MICE, then commissioning of amplifiers stops at DL unless more PSU's are built
  - This could delay further roll out of the RF system
- Testing of Cavity in MTA (Autumn)
  - Followed by testing of cavity with B-field
  - Timescale dependent on arrival of Coils
- Planning for future
  - Need to define resources required to both build the systems for and operate the RF systems in the Hall to move towards STEP VI
- Important to keep in mind that the TH116 valves are irreplaceable