Update: RF Projects at JLab

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Facilities

- CEBAF – Continuous Electron Beam Accelerator Facility
  - Originally designed as a 4 GeV, 200 uA superconducting machine.
  - Energy has been pushed to 6 GeV, and will have to run at that energy by 2008.
  - There is a planned upgrade to get to 12 GeV.
- FEL
  - Uses same SC technology to reach 10 kW IR (with planned upgrades including UV).

Site View

Projects

- IOT-based amplifiers for beam separation
- 13 kW RF source options for the 12 GeV upgrade
- New HPA controller
- FEL Injector Test Stand RF sources
- LLRF upgrade for 12 GeV
- Maintenance Items

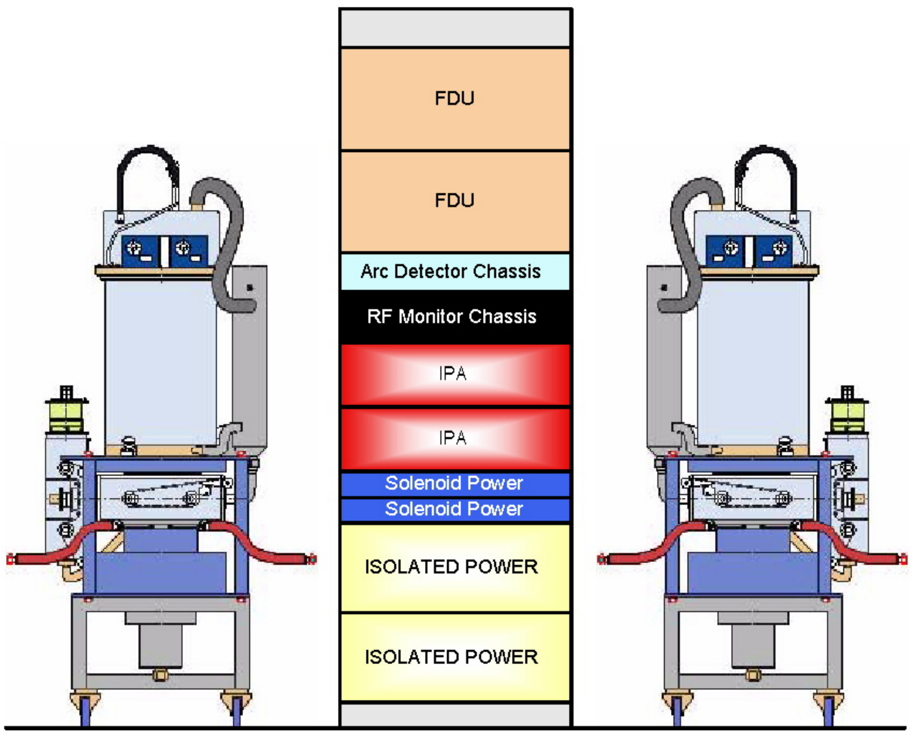
499 MHz IOT Amplifiers

- Information about these amplifiers was presented at CWHAP04
- The goal was to replace 6 aging solid state amplifiers with IOT-based amplifiers
  - —Output transistors were no longer in production ; the original design had reliably issues at the required 1 kW output per amplifier
  - —Higher power will be needed in the future running with machine upgrades to 12 GeV
- Basic requirements:
  - —Supply up to 10 kW CW at 499 MHz to each of 4 outputs

499 MHz IOT Amplifiers

- 2 systems were operational in 2004, the remaining 2 being commissioned.
- All 4 systems are now usable and have been in use for almost 2 years.
- Normal output power ranges from ~1kW to 3 kW though capability is 10 kW per channel if required.
- Reliability has been good
  - —No problems with the IOTs – some with other chassis
  - —Some undefined trips appear to be related to the remote PLC I/O.
  - —One “high” power coaxial phase shifter burned during commissioning.

499 MHz IOT Amplifiers



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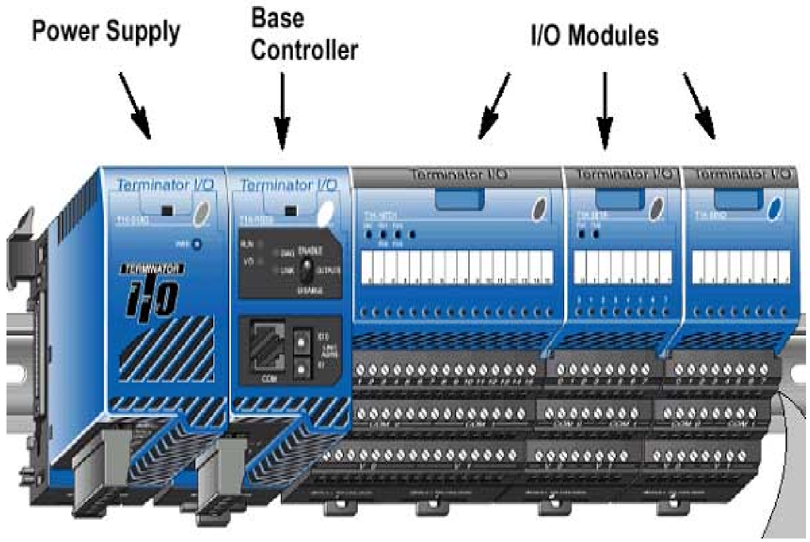
499 MHz IOT Amplifiers

- The FDU contains the filament, bias, ion pump power supplies, and communication between the floating remote I/O and host PLC (fiber).
- Those few system trips seem to point to a loss of communications between these systems since all 4 IOTs dropped out and no other faults were annunciated.



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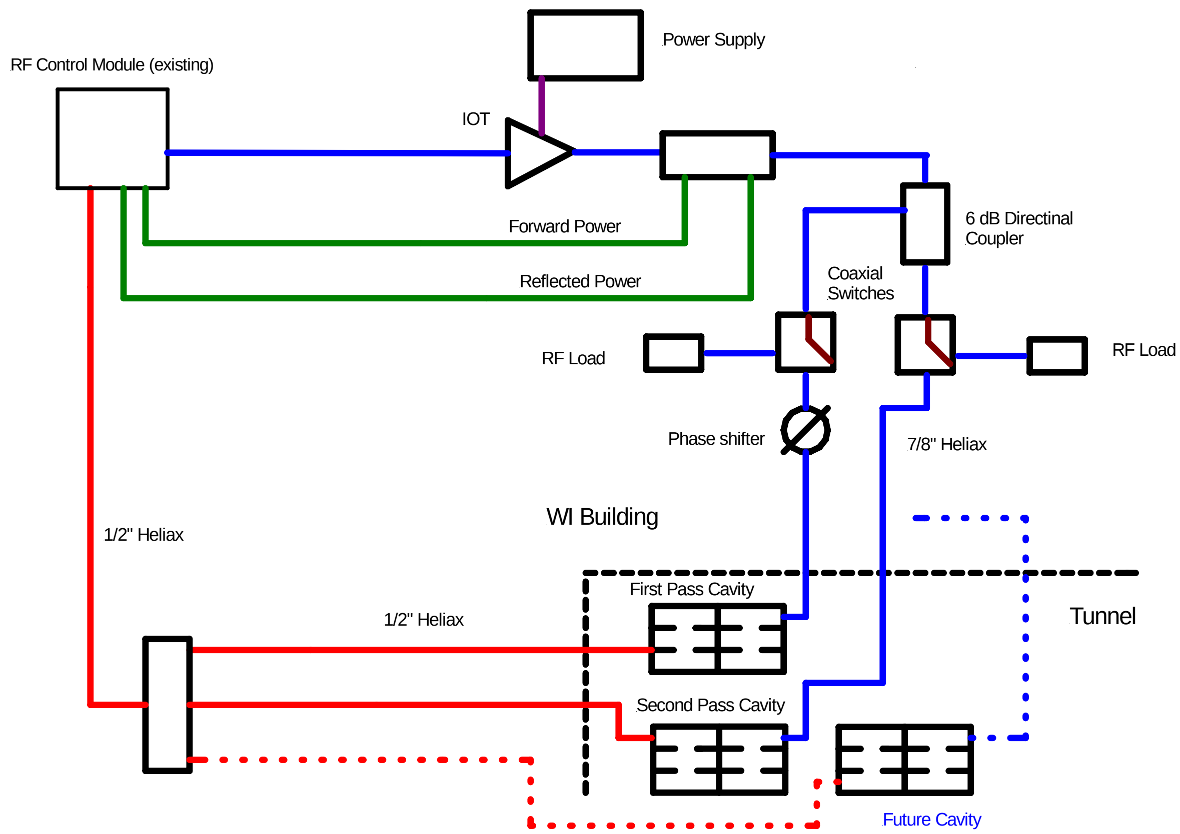
4 IOTs / 5 Passes

- A single IOT normally drives each of the higher passes (3,4,5). (1 or more cavities per pass).
- The 1^{st} and 2^{nd} passes can be handled by a single IOT with power divider and phase shifter.
- Pass 2 requires 4X the power of pass 1 and power for both passes is supplied by 1 IOT.
- Given the proper power split, only the phase between them needs to be adjusted for acceptable separation.
  - A remotely operable phase shifter is in one leg.
  - A dummy load for the leg not being used can be connected.
  - Higher energy may ultimately require a second cavity on pass 2 so the split would change.

Pass 1-2 Configuration



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Testing

- A test plan was written, beam time was made available, and power was applied.
- After several hours, an odor indicated something wasn't right.
- Discoloration was found on the outside of the phase shifter, and the housing was a hotter than we thought it should be at 2 kW.
- The phase shifter is a 7/8" coaxial unit.
- The system was shut down and reconfigured to run the only the pass required.
- The phase shifter was removed and dissected.
- Something sounded familiar about the problem…
  - —something I'd heard in a 2004's talk…

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…no fire department was called

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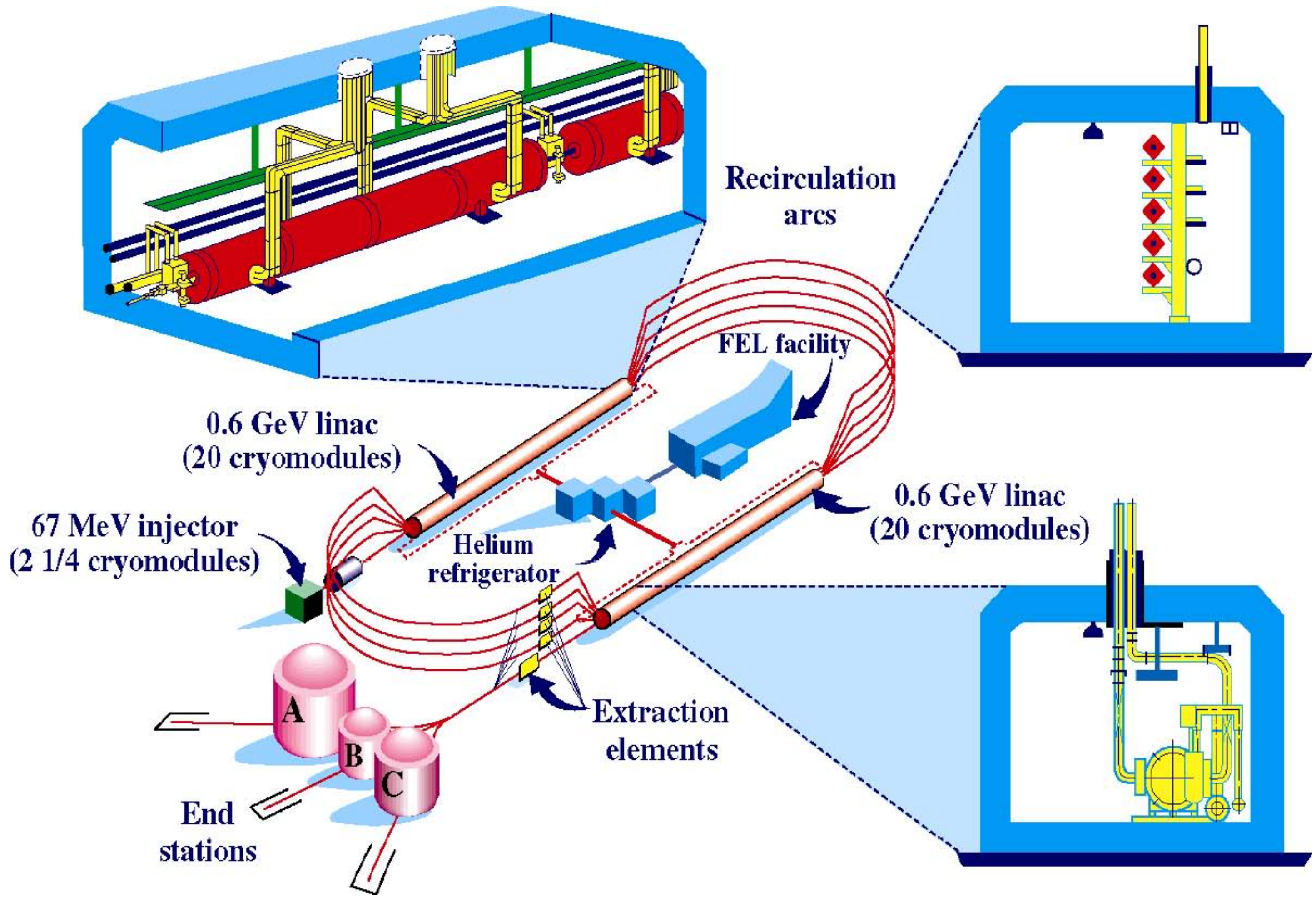
Resolution

- The unit as returned to Mega for repair – at no cost.
- As part of the repair, Mega opted for a higher grade G-10 for the actuator rod.
- Due to significant arcing, the aluminum housing was also replaced.
- What happened?
  - Never conclusively determined.
    - Could have been some (lossy) foreign material in the original fiberglass.
    - No problem with the connecting pin (it was fiberglass as designed).
    - The metal drive screw or coupling did not penetrate the enclosure.
- The problem has not reoccurred.

Upgrading to 12 GeV

- **Planning for a major upgrade continues following two announcements:**
  - **2004: Jefferson Lab's 12 GeV Upgrade achieved Critical Decision-Zero (CD-0), a DOE designation that recognizes the "mission need" for the Upgrade and allows the Lab to develop conceptual, acquisition and project execution plans.**
  - **2006: The Secretary of Energy announces that President Bush's Fiscal Year 2007 budget request includes $7 million for the upgrade.**

Present Configuration



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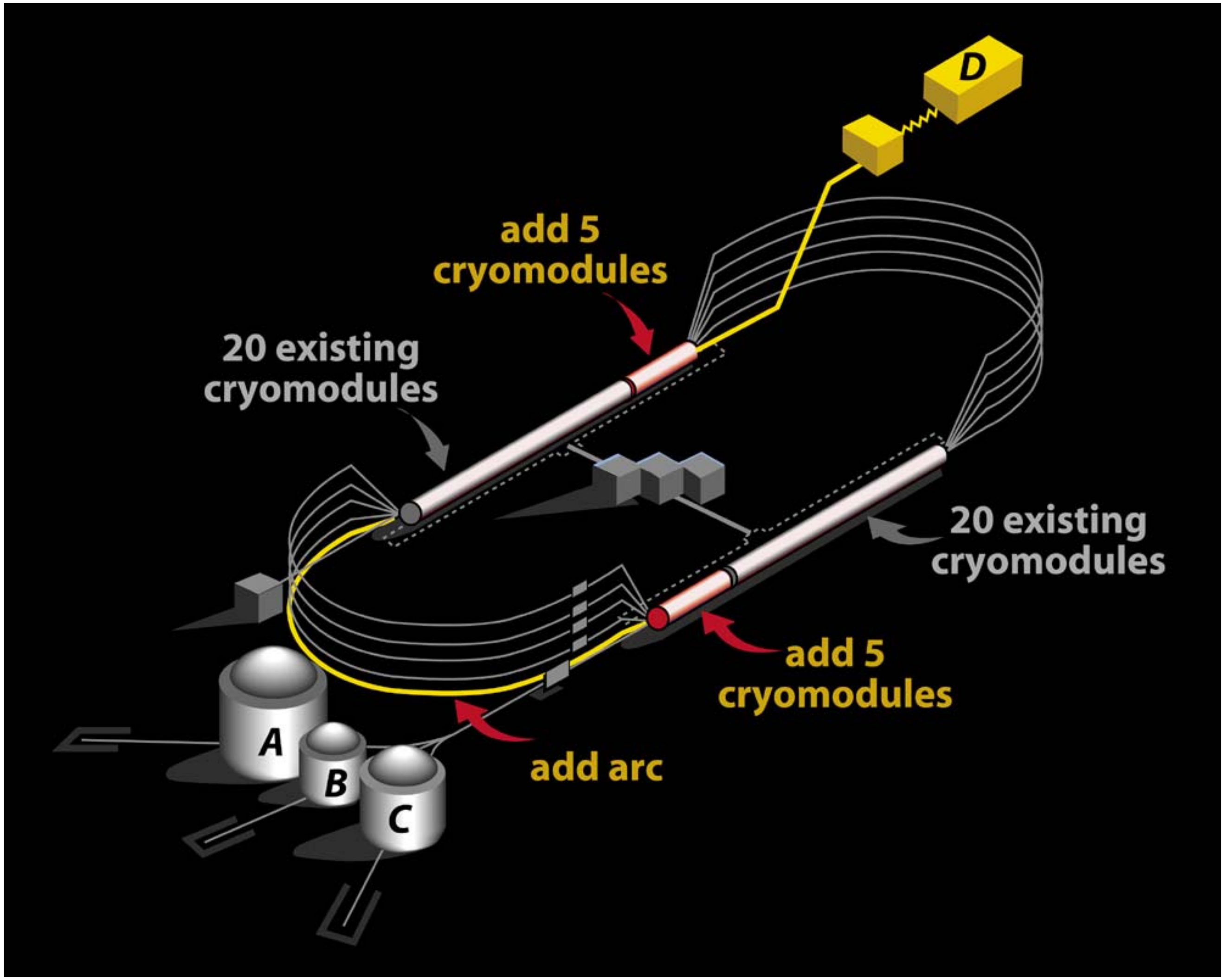
Upgrade to 12 GeV



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First Stop: Robust 6 GeV

- CEBAF was designed as a 4 GeV machine
- It met that goal easily
- To achieve 12 GeV it must first operate as a robust 6 GeV machine.
- Brief runs have been made near 6 GeV
  - The first time killing a klystron a day for 9 days.
  - More running at near 6 GeV is planned in the timeframe of 1 year plus.
  - To achieve 6 GeV several cryomodules must be refurbished.
  - Numerous klystrons will be rebuilt and/or replaced.

Upgrade to 12 GeV

- **80 additional superconducting cavities will be added which will require 80 additional RF sources**
  - **—Our present RF system uses 5 kW klystrons (or 8 kW for later purchases, though only operated at that level in the FEL)**
  - **—These new, higher gradient cavities will require 13 kW**
    - **Too far to push the existing klystron**
  - **—So, we need a higher power tube: klystron or IOT**
    - **… higher power circulators, a different HPA configuration, HVPS, and new controls to support it all…**

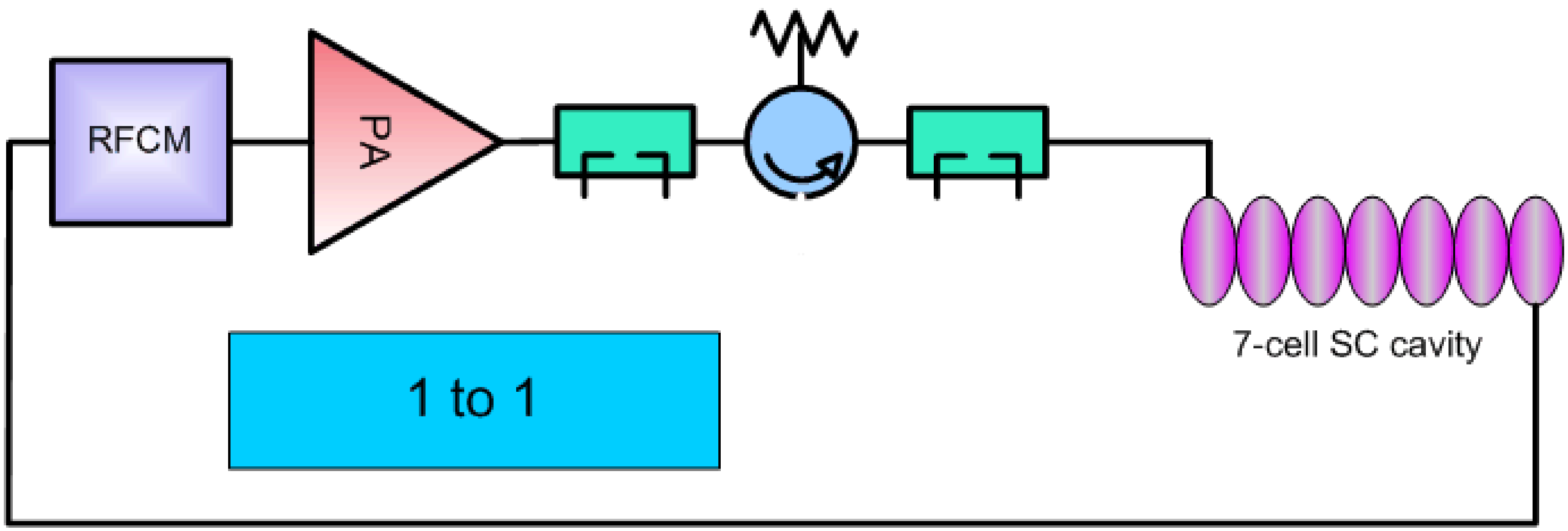
Powering the Cavities

- Two main approaches were suggested
  - —Option 1. As it's always been done at JLab: One klystron (or IOT) driving One cavity
    - 1 RFCM and klystron per cavity, HVPS powering 8 tubes…
  - —Option 2. Use a higher power klystron, split the output power equally and drive more than one cavity (8 since that makes a compete zone).
    - One RFCM per cavity, a bigger klystron, and a_lot_more_stuff

One to One

- **Option 1: our preferred method**
  - **It's the way we do it now**
  - **Makes controlling each cavity individually to the tight amplitude and phase control specs necessary easier/possible**
  - **Minimizes the impact to availability should a single tube fail (results in the loss of a single cavity)**
- **Standard Zone: 8 klystrons, 1 HV PS, 8 RFCM and associated components powering 8 cavities for one zone**

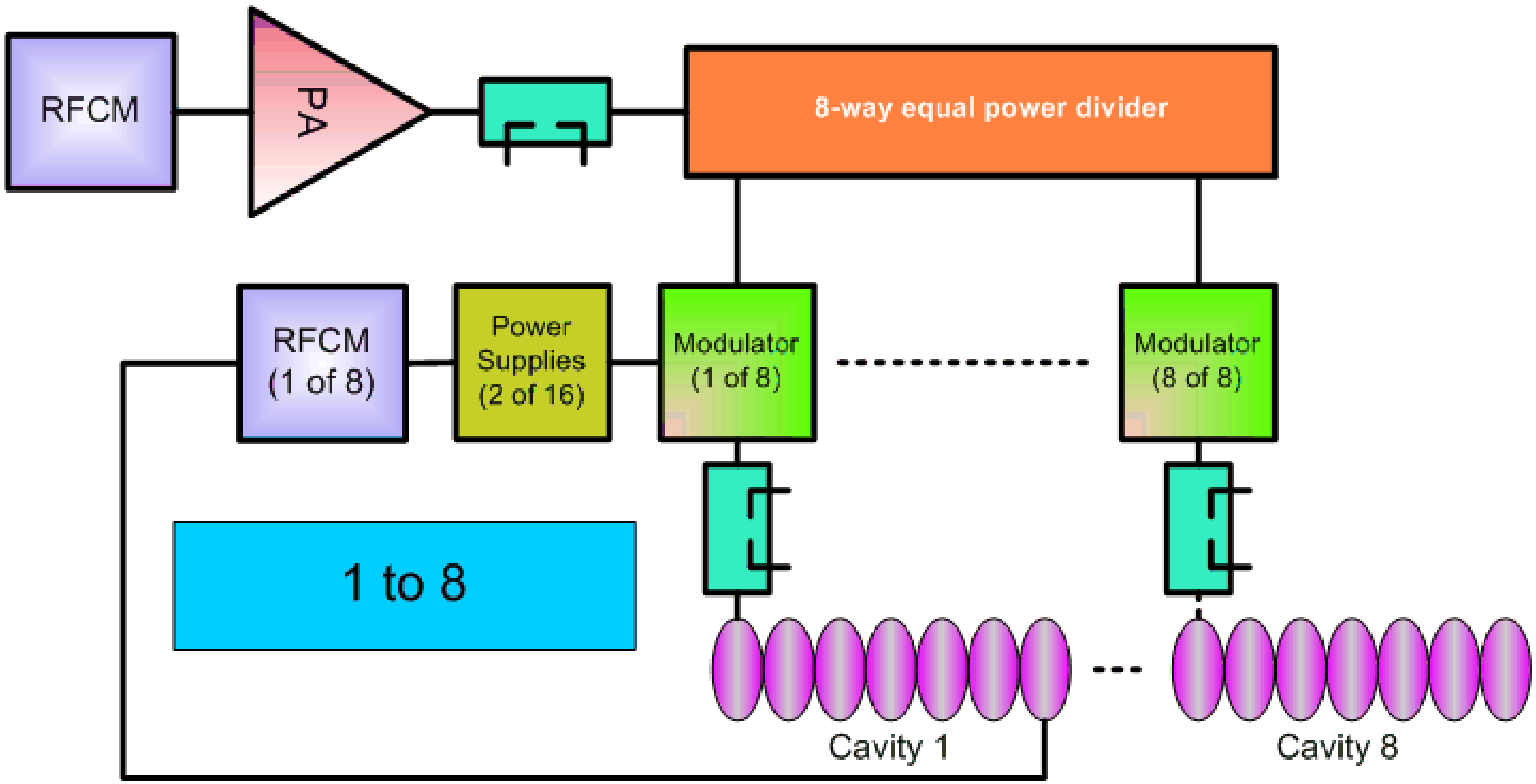
1:1 Block Diagram (single cavity)



1 to 8

- **Option 2: A higher power klystron, output is run through an 8-way splitter.**
  - **Each output feeds one SC cavity.**
- **Problem: phase & amplitude must now be controlled in each of the high power feeds.**
  - **One approach is to use fast ferrite amplitude & phase modulators (AFT is one source)**

1:8 Block Diagram



Requirements

- Simulations for controlling a 1:8 configuration haven't yet started, but will begin soon
- Field control stability requirements:
  - 0.5° phase settable to 0.1°
  - $4.5x10^{-4}$ amplitude with control over a range of 0.5 to 25 MV/m
- Control of individual cavities is required to deal with microphonics, detuning, to because cavities within a given cryomodule may have different gradients -- down to zero if a cavity needs to be bypassed
- Based on the control ranges suggested by AFT, wide amplitude control seems difficult or expensive
- This option has higher cost, higher risk
  - but we were asked to consider this option

1.497 GHz Tube Options

- Klystrons or IOTs (not here yet)
  - Klystron has good gain (= low driver cost)
    - Lower efficiency
    - In our experience, offer long life
  - IOT has lower gain (=higher driver cost)
    - Higher efficiency
    - Cost of IOT can be lower but when driver cost is factored in overall cost could easily be higher
  - Tradeoff of higher initial cost vs. long term energy savings is not my decision alone
  - Also, there's the issue of service life
    - 1.5 GHz IOTs don't exist at all and 1.3 GHz IOTs haven't really seen any service yet
    - UHF IOTs have reported a range of lifetimes like any other tube.

Pros & Cons

- IOT
  - Pro: good efficiency
  - Con: low gain/high drive power required
  - Lifetime unknown
- Klystron (1:1)
  - Con: lower efficiency
  - Pro: low drive required
  - Good lifetime experience (our own)
- Between IOT and Klystron the choice may be between higher initial cost and lower operating cost

Klystron 1:8

- Con: lots of extra pieces required – more complicated
- Budgetary pricing suggests the cost of 1 higher power tube is roughly 5X cost of a lower power tube.
  - Everything else needed to use this approach must essentially be had for the cost of 3 smaller tubes.
- Con: a single failure has more impact
- Con: more difficult to bypass a "bad" cavity (isolating shutters could be added at additional cost).
- The tube is cheaper than 8 lower power units, but the extra hardware makes it uneconomical.

Add-ons for 125 kW Option

- 8-way power divider
  - —26.5k each (magic tees, loads, etc. for quan=10)
- Fast ferrite modulator for amplitude & phase control
  - —39-75k each depending on required specs
    - 0-3dB/±80° to 0-10dB /±180° control range
    - 1 or 10 kHz response times
  - —Power supplies for the modulators (fast and rated for CW)
  - —Maybe waveguide shutters

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Cost Comparison 1:1 vs. 1:8

- Assumption: All combinations require the essentially the same circulators, couplers, and comparable HV power supply costs, so those costs are not included here.
- 1:1 configuration using single klystrons (lowest priced)
  - 43k per channel = 3.45M$ for 80
- 1:8 using HP klystron and lowest performing modulator (simulations not done to show if this is even feasible)
  - 71.1k per channel = 5.60M$ for 80
- Plus all the parts & pieces necessary for either approach

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HPA Controller

HPA Controller

- High Power Amplifier (klystrons, HV PS, etc.)
- Control is presently handled by
  - Our present RF control module
  - CAMAC, interfaced to EPICS
- Main function is to control & monitor the 8 klystrons, HV PS, auxiliary power supplies, etc.
- Klystron reflected power is presently interlocked through the RFCM, though the it doesn't need to know about it, nor does it need to know much about klystron status in general

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Division: Per Zone/Per Cavity Functions

- RFCM looks at "per cavity" items -- klystron parameters
  - Heater voltage/current x 8
  - Cathode current x 8
  - Body current x 8
  - Modulating anode voltage x 8
  - Klystron reflected power x 8
- CAMAC looks at "per zone" signals
  - Auxiliary power (120/1P & 208/3p)
  - WG pressure interlock (also a safety interlock)
  - Cooling
  - And late additions like modulating anode current
- The new RFCM won't look at klystrons at all, and CAMAC won't be used in any new zones. CAMAC is mature.

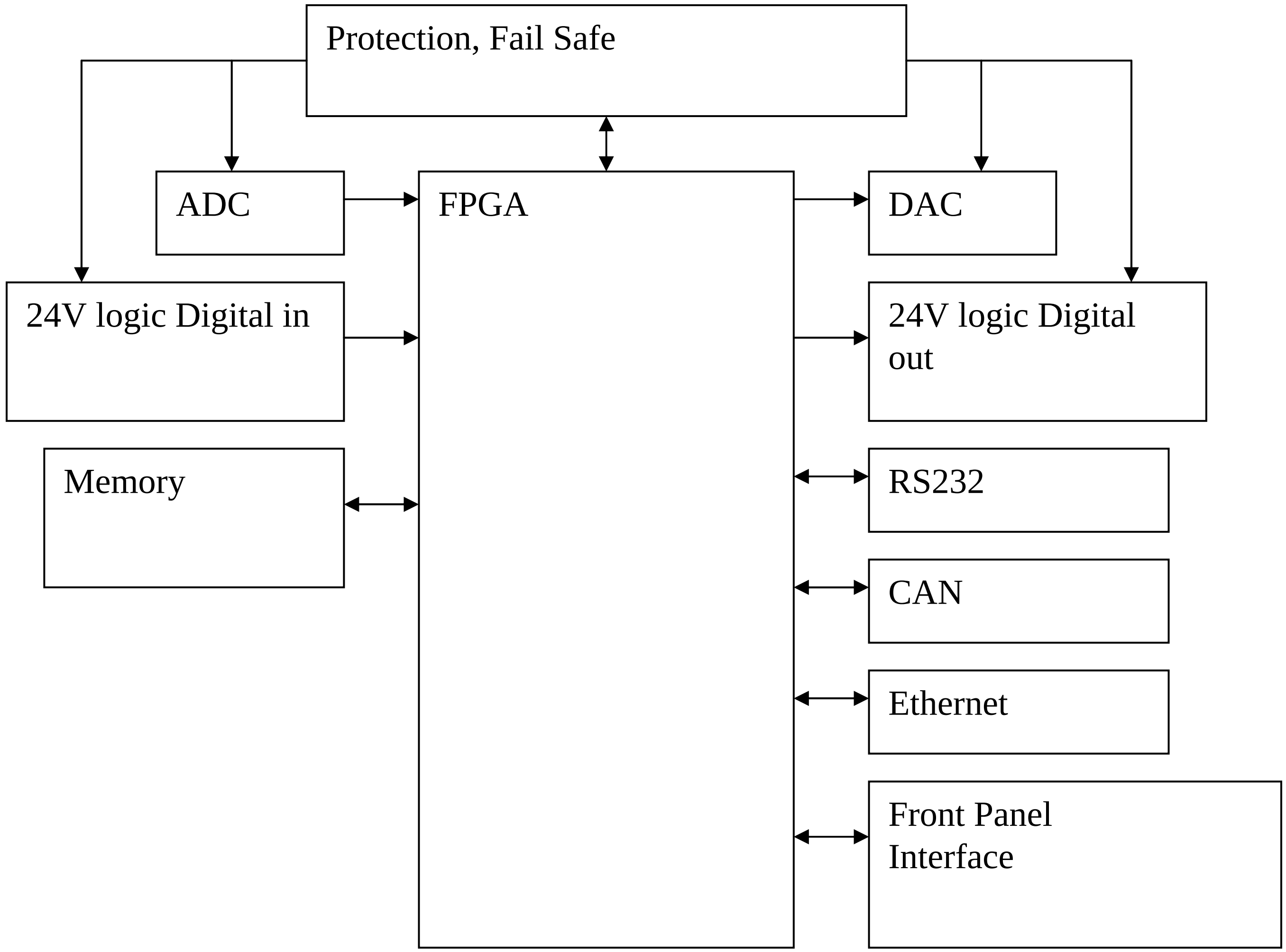
CAMAC is older than I thought…

- **"First found in Cumberland where they were seated from very ancient times, some say well before the Norman Conquest and the arrival of Duke William at Hastings in 1066 A.D."**

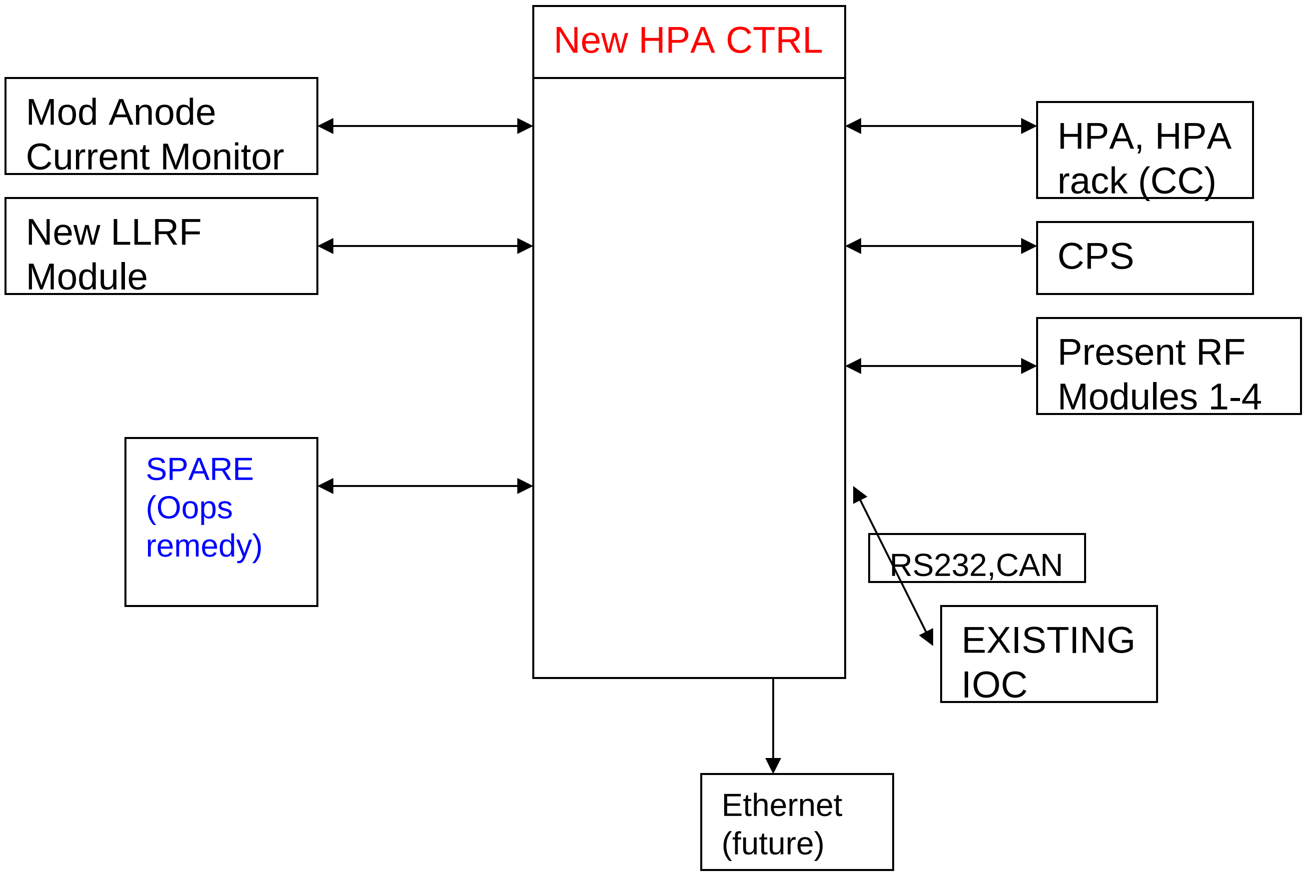
12 GeV Upgrade Problems

1. CAMAC has been eliminated in the upgrade design
   — Tasks presently assigned to them must be picked up by other hardware
     - A new controller for klystrons and HVPS is being developed and will be tested in an existing half-zone (first destination for new 1497 MHz RFCM)
2. The new LLRF (RFCM) will concern itself strictly with RF signal functions only – no housekeeping or klystron interlocks
   — Functions presently handled by the old RFCM will be handled the new controller

Block Diagram

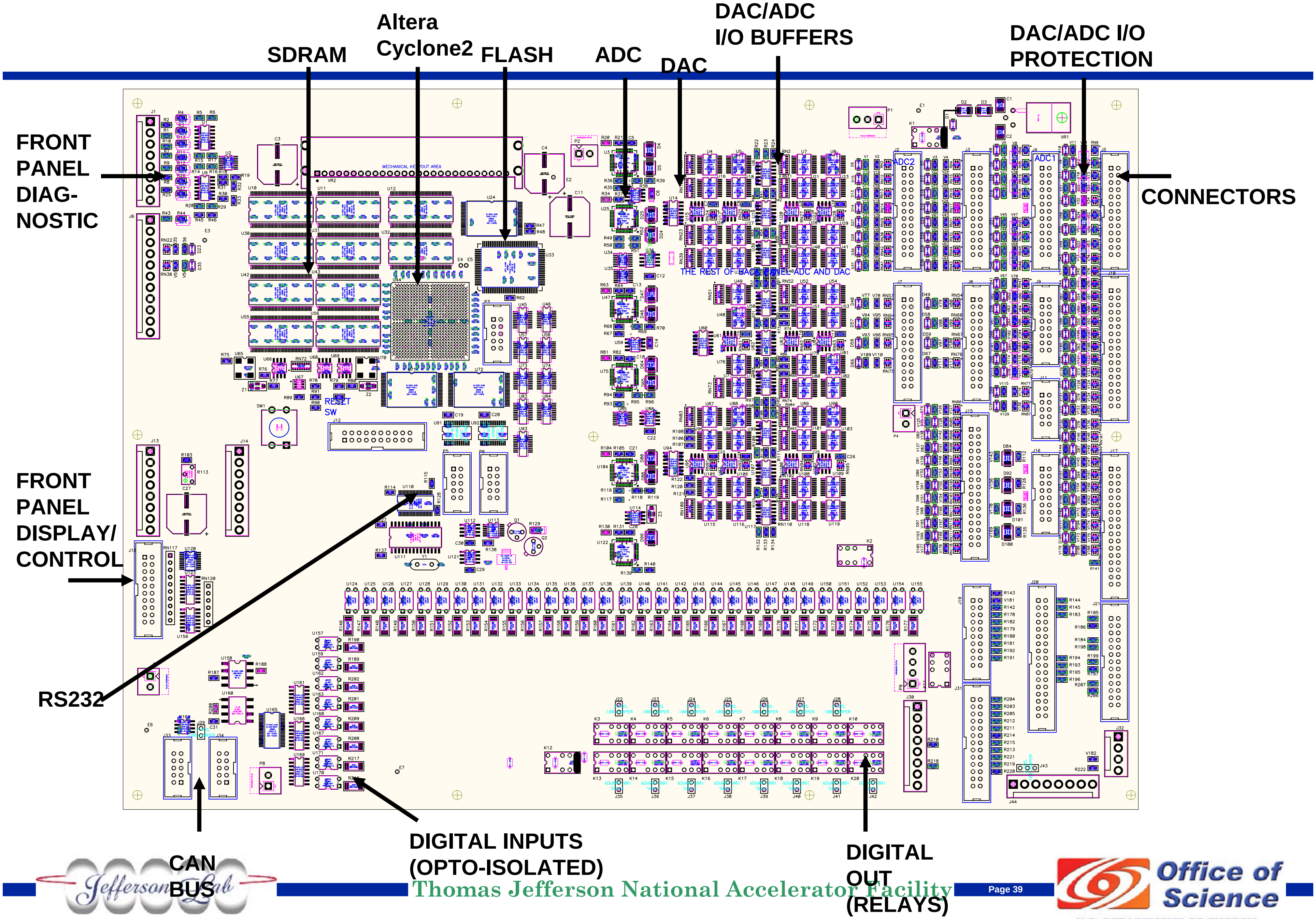


External Connections



The Basics

- Altera Cyclone EP2C70F672 FPGA with resources to support two soft core NIOS processors
- 88 ea, 16 kHz throughput ADC channels
- 32 ea, 100 kHz throughput DAC channels
- 32 opto-isolated digital input channels (5-24 VDC)
- 16 digital output channels (relay contacts)
- Interface: RS232, CAN Bus (Controller Area Network) for connection to EPICS
- 2 SDRAM Memory Banks
  - 32 Meg x 32
  - 8 Meg x 32
- 2 FLASH Memory Banks
  - 16 Meg x 8
  - 8 Meg x 8
- And includes ring buffers with fault recording for downloading and analysis



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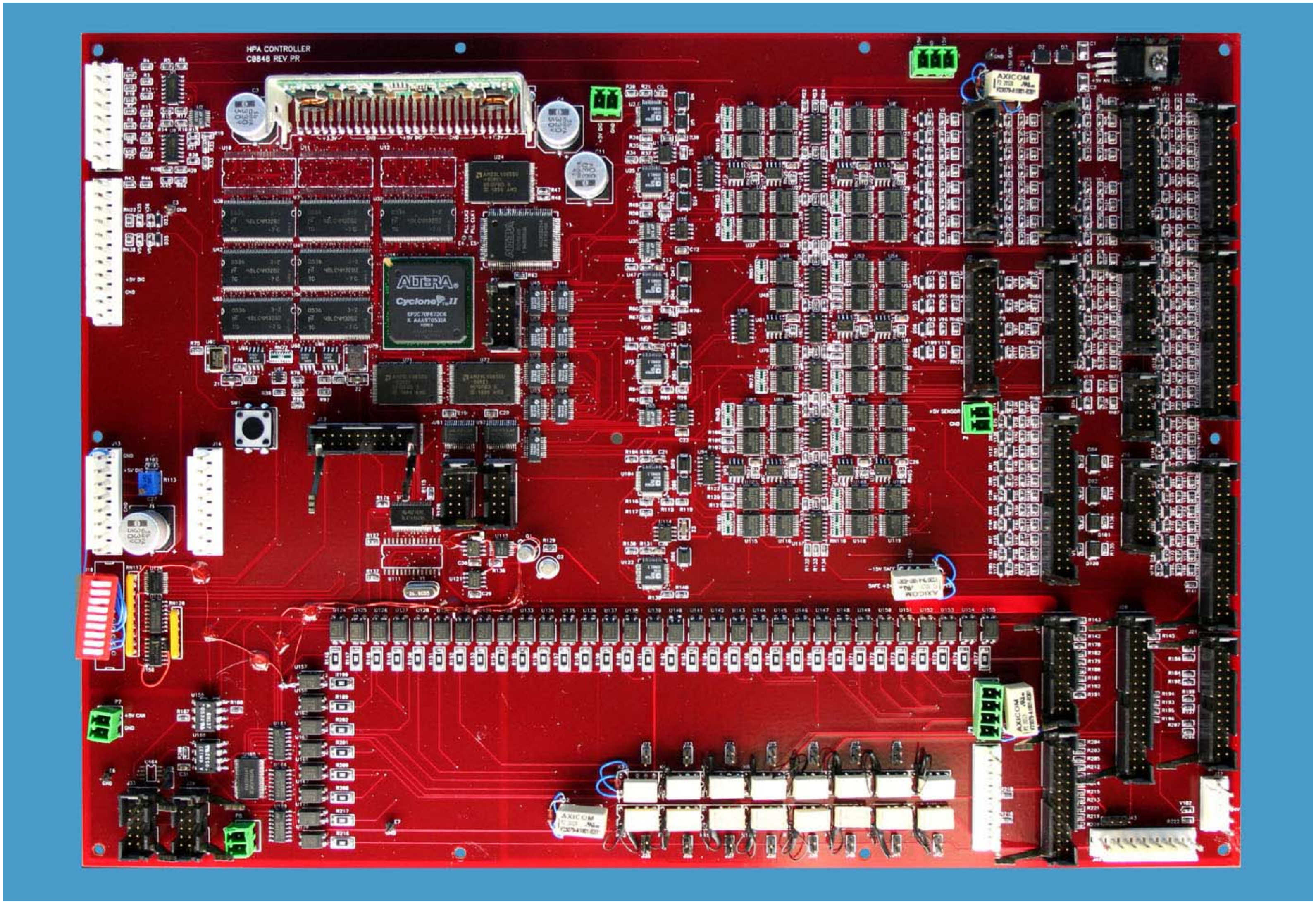
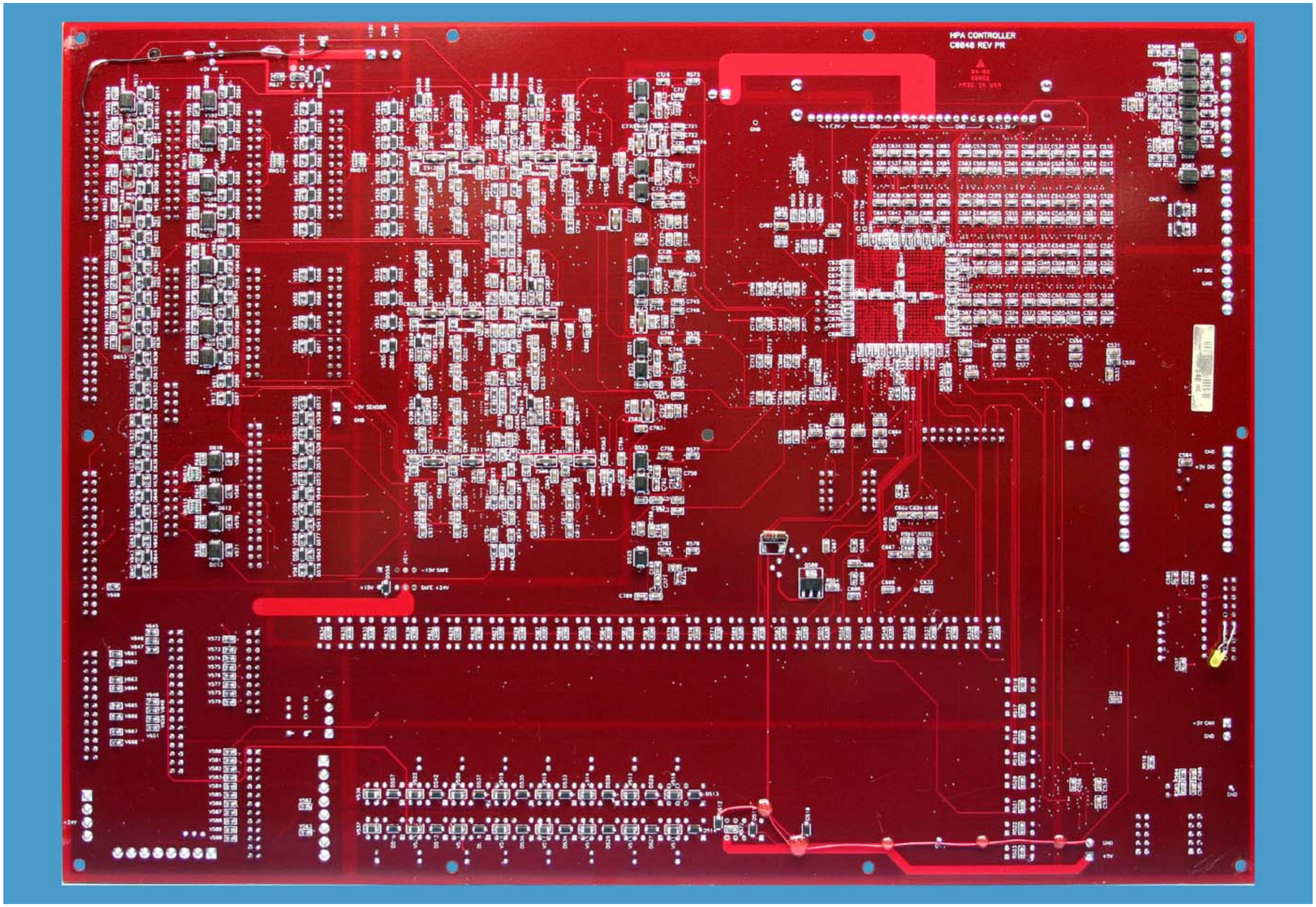
Main Side



Back Side



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Putting it Together

- **A single board with over 1000 components.**
  - **—Which will probably be revised to a mother/daughter configuration.**
    - **Easier troubleshooting**
    - **More convenient replacement & upgrade if required**
- **The prototype board took 96 hours to stuff.**
- **The chassis it mate with existing cabling where possible.**
- **A revised configuration will probably be necessary for the upgrade zones.**
- **Local controls will be minimal but all functions fully accessible through plug-in local PC.**
  - **—<u>Not</u> designed to be a stand-alone transmitter.**

FEL Injector Test Stand

FEL Injector Test Stand

- **Goal: deliver three identical systems capable of supplying at least 80 kW CW at 748.5 MHz (half CEBAF frequency)**
- **2005: Bid process was started – funding was reallocated to another need.**
- **2006: Bid process was *almost* started – funding reallocated to another need.**
- **This year we also *almost* went out for bid on the IOTs, and… funding was reallocated to another need.**

Design

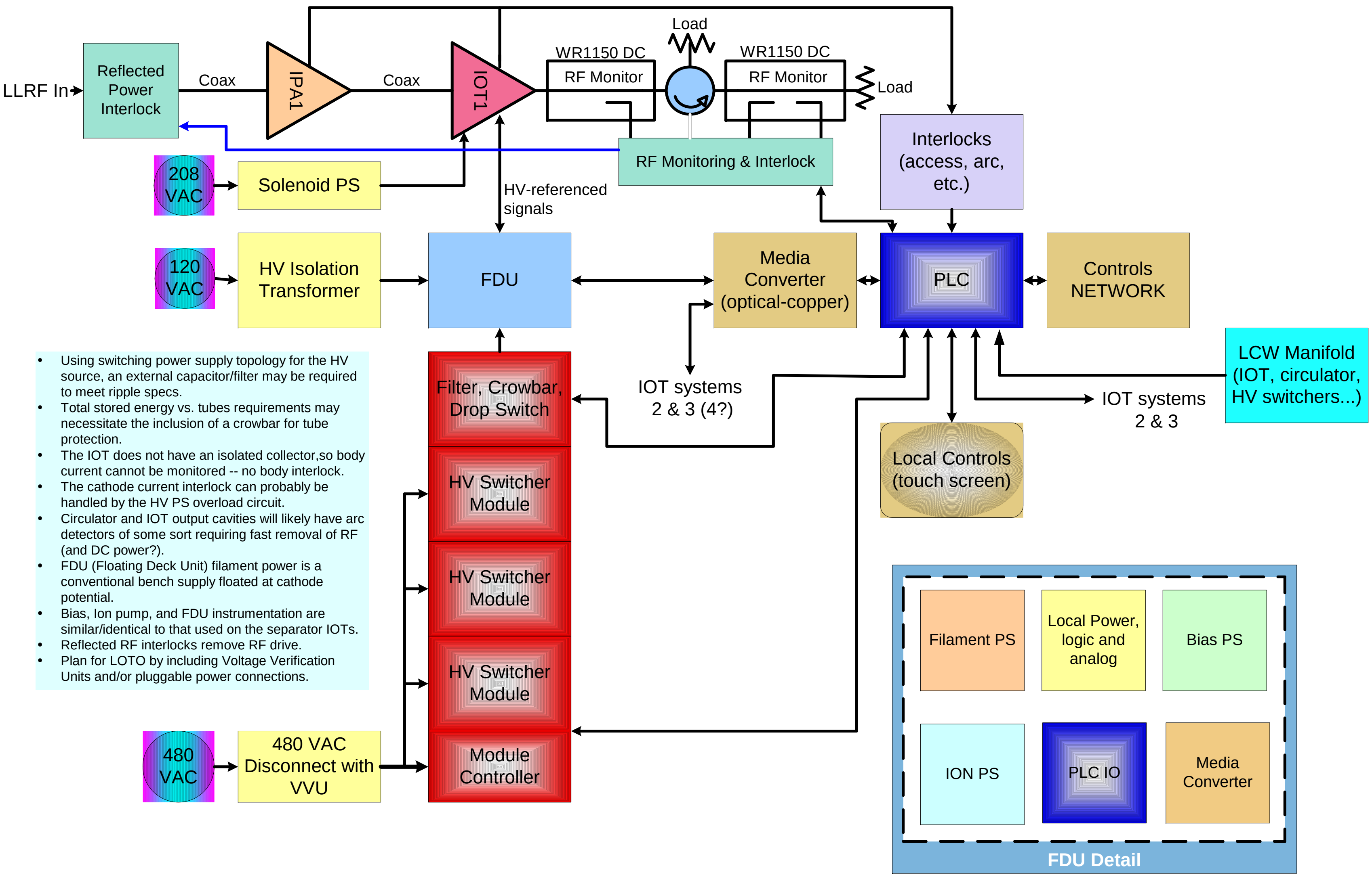
- **Richard Walker, tasked with the project had a first thought to buy a turn-key system.**
  - —**Price wasn't supposed to be an issue**
  - —**until the prices came in far too high**
    - **…and the funding was reallocated to something else**

- **The next approach was to buy the IOT and build everything else (including HV PS)**

- **The current direction is to buy the IOT, driver amp, HVPS and build it that way.**

Block Diagram: FEL 748.5 MHz IOT RF System

March 6, 2006



- Using switching power supply topology for the HV source, an external capacitor/filter may be required to meet ripple specs.
- Total stored energy vs. tubes requirements may necessitate the inclusion of a crowbar for tube protection.
- The IOT does not have an isolated collector,so body current cannot be monitored -- no body interlock.
- The cathode current interlock can probably be handled by the HV PS overload circuit.
- Circulator and IOT output cavities will likely have arc detectors of some sort requiring fast removal of RF (and DC power?).
- FDU (Floating Deck Unit) filament power is a conventional bench supply floated at cathode potential.
- Bias, Ion pump, and FDU instrumentation are similar/identical to that used on the separator IOTs.
- Reflected RF interlocks remove RF drive.
- Plan for LOTO by including Voltage Verification Units and/or pluggable power connections.

Lambda-EMI ALE 303

- 30 kJ/S cap charging, 50 kW DC
- 13 models from 1 to 50 kV
- 200# in a 7U rack package
- 30 kHz switcher
- Water-cooled
- Computer interface available
- Master-Slave configuration for higher power (separate combiner chassis available)
- Isolated return
- $43k each

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Present Status

- Close to issuing a procurement for a driver amplifier (1kW).
- Purchase of 9 power supplies: pushed off until…
- Purchase 3 IOTs: pushed off until…

Low Level Controls

Low Level Controls

- 10 new upgrade zones will require 80 new control modules
- Present RFCM is ~15 years old and would be difficult (and undesirable) to duplicate.
- Old design has many obsolete components!
- New Design:
  - Digital, FPGA-based
  - Additional diagnostics built-in
  - Interfaces to EPICS (old unit interfaced through CAMAC)
  - Smaller, mother/daughter arrangement

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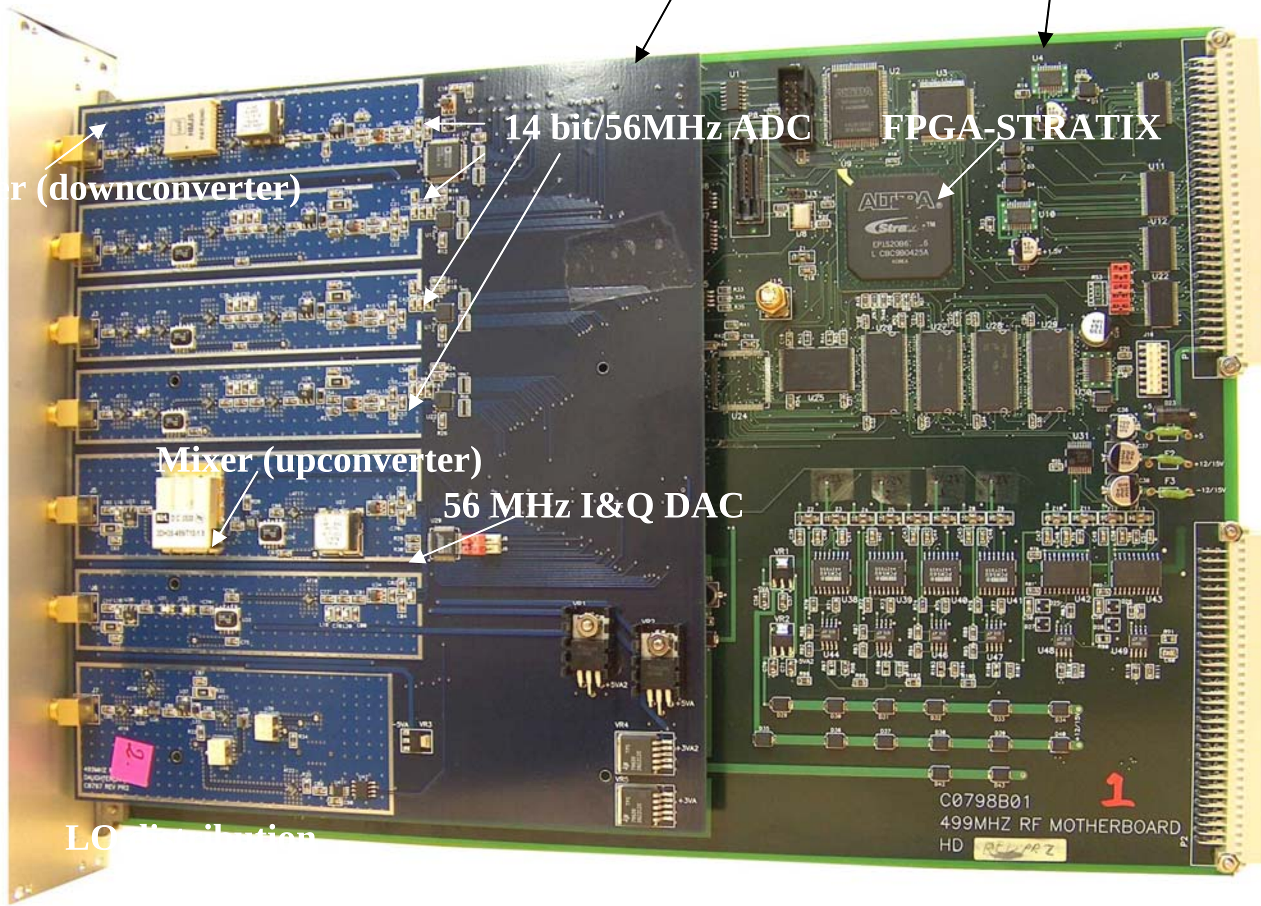
New LLRF system : Daughterboard & Motherboard



Motherboard – generic platform for all type of LLRF systems

Daughterboard – specified for cavity frequency

VHDL code – specified for cavity type : NC/SC

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Status

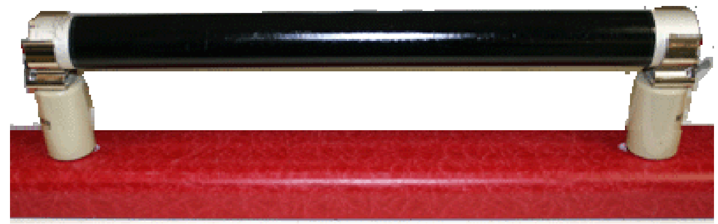
- Nine of the new units have been commissioned for 499 MHz on warm cavities (5-separator and 4-injector).
- Installation was done in parallel with existing systems for easy back-out (not necessary)
- Systems are performing as designed and were turned over for regular use
- 1497 MHz version has already received preliminary testing on a SC cavity
  - — Gradient was cavity-limited to below the desired 17.5 MV/m
  - — Field control better than specification was achieved.
  - — Due to time restraints, resonance control tests were limited to stepper motor and not piezo tuners (ultimately required)
    - Present tuners are controlled through CAMAC
  - — Goal is to install with the HPA controller in the injector with the new RFCM (date indeterminate).

Misc. Reliability Projects

- **Klystron Care**
  - — **LCW flow reductions were noticed in some locations, typically at one end of the distribution system.**
  - — **Reduction had gotten so bad in some areas that we were actually boiling water in collectors.**
  - — **Hose deterioration due to high temperature.**
- **Acid flushing of systems (dilute citric acid).**
  - — **Problem zones only initially; will continue this summer.**
  - — **L-3 experience was good… except with plate heat exchangers.**
- **Replacement of flow monitoring and interlocks planned for summer '06.**
  - — **Present system of plastic rotameter and DP switch**
  - — **Replace with all metal, dial-type with built-in switch.**
- **Normal PM plus klystron "screening".**

Modulating Anode Load Banks

- 11.6 kV / 168W
- 8 x 100k, 50 watt w-w
- Glastic type channel



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End