Operational Experience with Jefferson Lab ERL/FEL Machine Protection System (MPS)

ERL 2011

the 50th ICFA Advanced Beam Dynamics Workshop
on Energy Recovery Linacs

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& the FEL Team

October 18, 2011

Outline

- Machine layout
- Sources of losses
- How to detect losses - BLMs
- How to decide if there is a problem - MPS
- How to stop the beam - DLPC
- New design choices with COTS

Jlab UV FEL

- Photo cathode source; (320KV, Gallium Arsenide, doubled YAG)
- SRF injector (10 MeV) & linac (~135 MeV)
- We operate this ERL with incomplete energy recovery
- There is no chicane anywhere in the UV transport
- The wiggler aperture is quite small - comparable to the Dark Light aperture in angular extent.
- Very high peak brightness for a CW machine.
- Can operate CW or with pretty much any pulse structure you can imagine
- Uses parallel to point longitudinal focus so the bunch length at the wiggler is very short (100 fsec rms)

Key Concepts in ERL Design

Some obvious to remind oneself when designing an ERL:

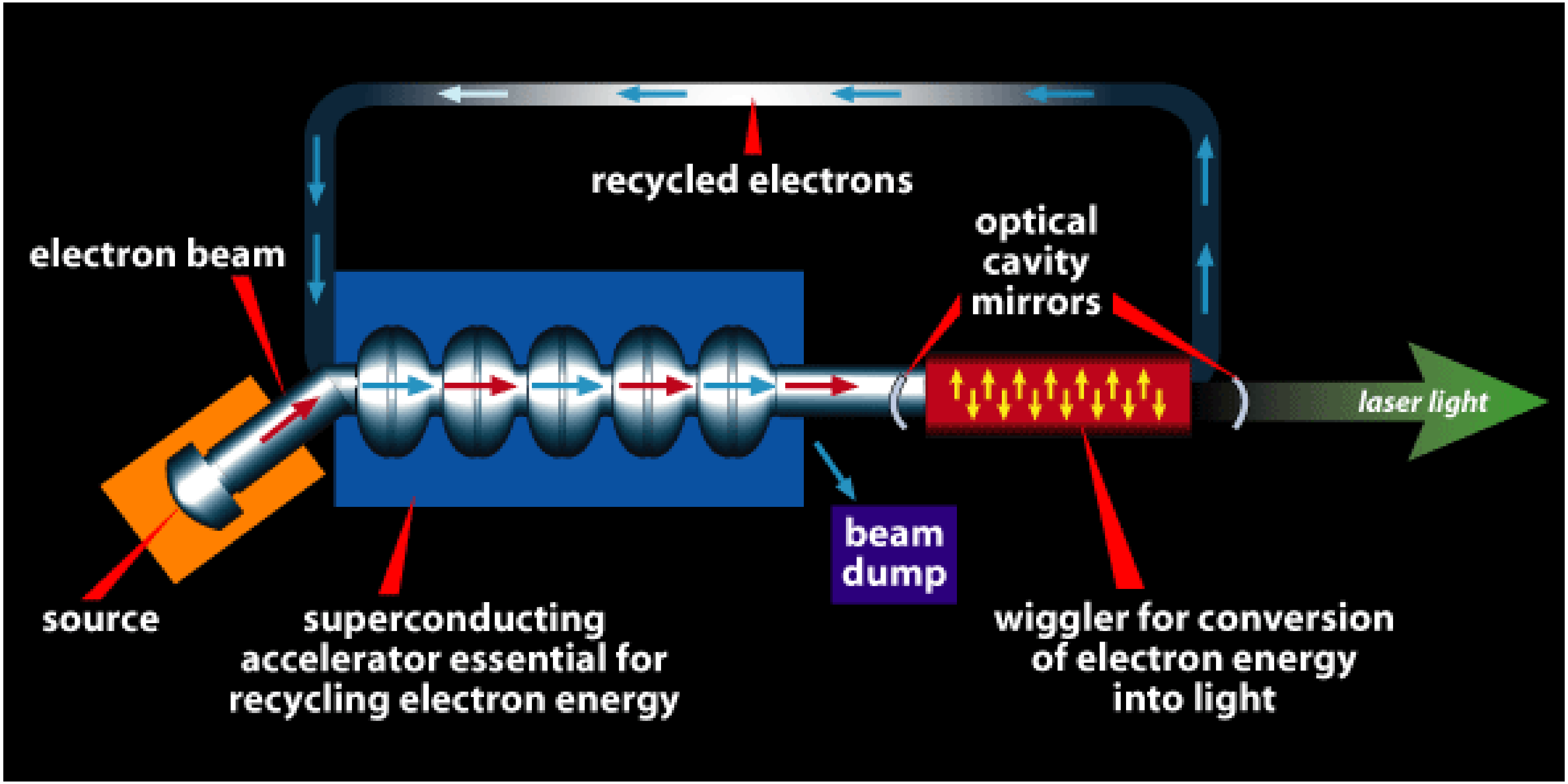
- ERLs are 6-dimensional systems
  - essentially time-of-flight spectrometer (well, maybe turned inside-out)
  - natural home for "emittance exchange"
- They are transport lines (not rings)
  - beam does not achieve equilibrium
  - "σ" not meaningful, in the sense of "I have 25 σ clear aperture"
    - designs must be observant of halo-imposed limitations
- ERLs do not have closed orbits
  - multiple passes may be in the same place - *but not at the same energy and/or time*
  - overall transport may/need not be betatron stable – no guarantee there are unique "matched" Twiss parameters

"beam envelopes" ⇎ "optimized lattice functions" not the same!

- ERLs do not recover energy, they recover RF power – and power flow management is critical to their operation
  - Put power where you want it, avoid putting it where you don't!

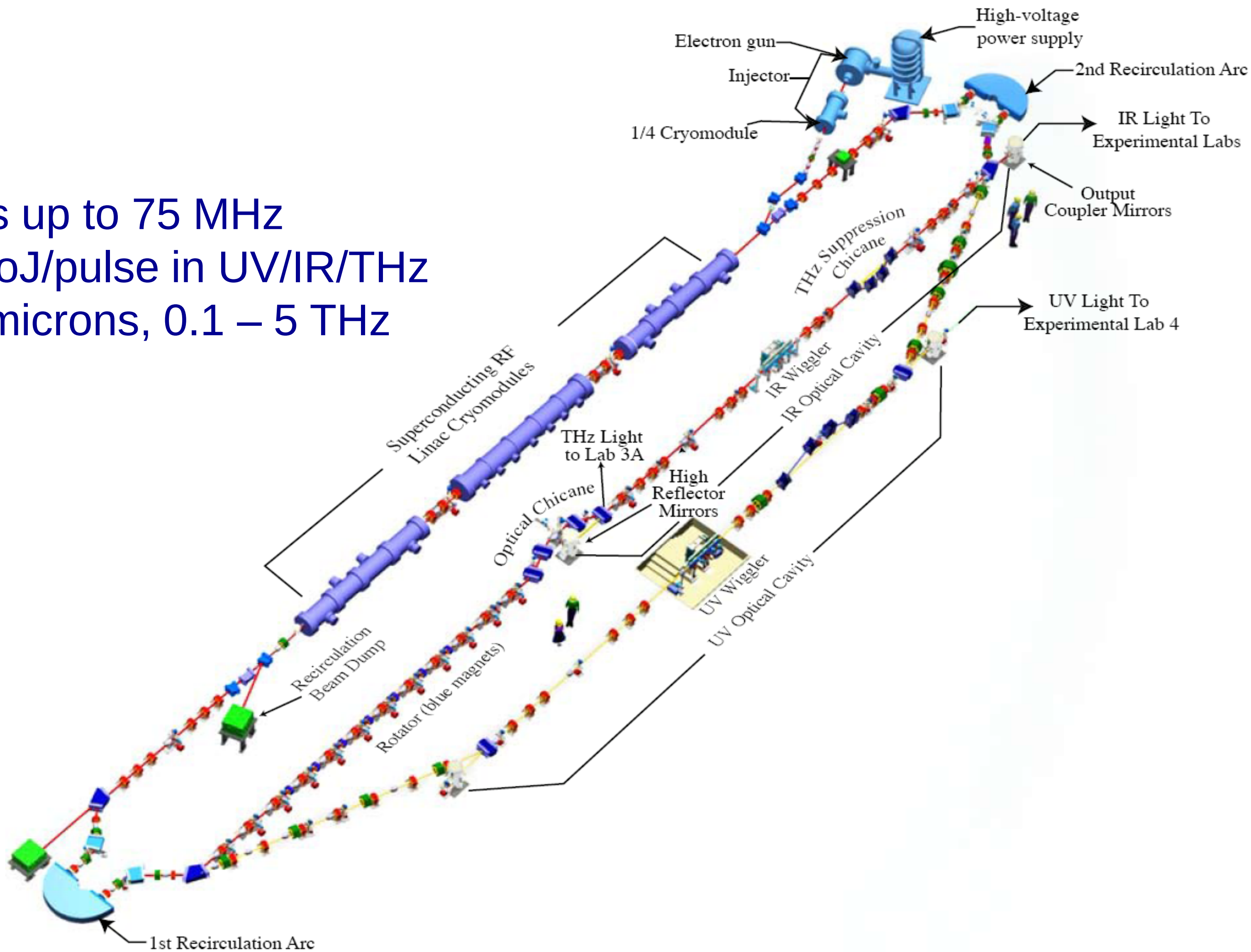
Slide courtesy Steve Benson

FEL Cartoon


recycled electrons
electron beam
optical cavity mirrors
laser light
beam dump
source
superconducting accelerator essential for recycling electron energy
wiggler for conversion of electron energy into light

Jlab IR/UV ERL FEL

E = 120 MeV
135 pC pulses up to 75 MHz
20/120/1 microJ/pulse in UV/IR/THz
250 nm – 14 microns, 0.1 – 5 THz



Widely Available Pulse Structure

Any time structure produced by the drive laser can drive the FEL

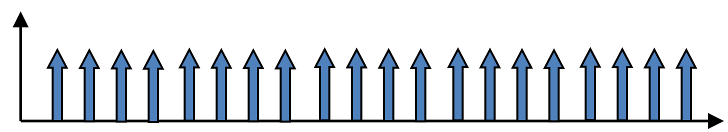
single shot (one pulse)

pulsed

(micropulse rep rates 4.8 MHz-75 MHz, macropulse rep rates essentially at user definition, macropulse duration from single shot to CW)

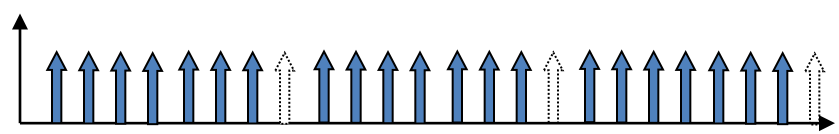
CW

75 MHz (and 2nd subharmonics thereof – on a good day to 584 kHz…)



“vernier mode”: fill in the blanks at subharmonics of 75 MHz

e.g. “7 of 8:

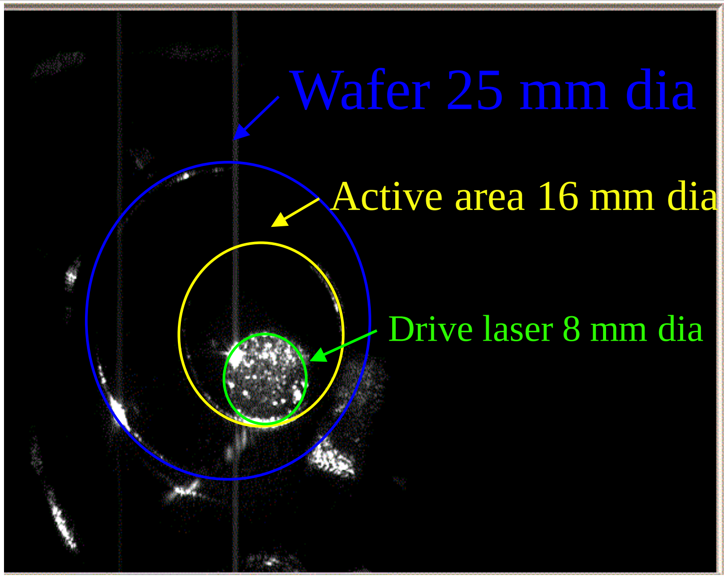


Courtesy David Douglas

Sources of the "Underachievers"!

- Halo: No, more like the deviants!
- There are 2 classes of non-productive electrons; those near & far from the phase space of the core of the beam

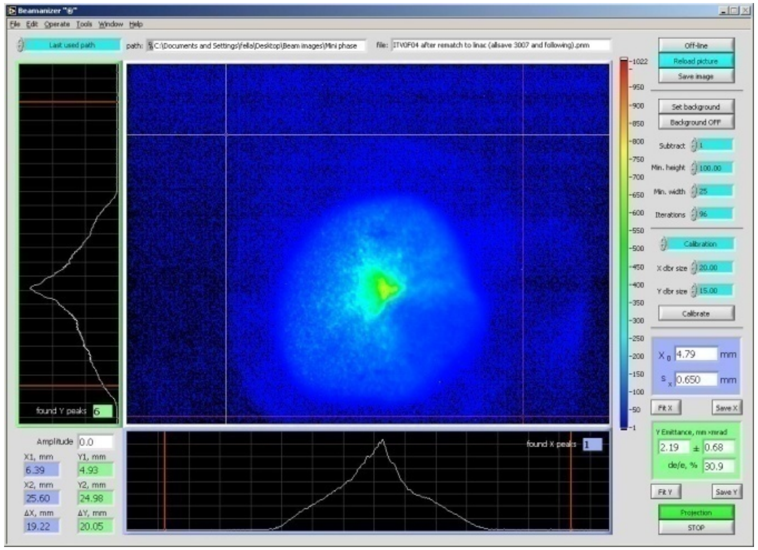
  (thanks Alan!)



- Photo-Cathode Source
  - Irregular Photo-Cathode Surface
  - Reflections (near nλ) from drive laser that creates mismatched beam
- "Ghost Pulse" (low charge) beam that is mismatched from lack of space charge
- DC field emission from gun that gets captured and accelerated
- RF field emission form the SRF injector cavities that propagates through machine (at least to 1st bend)

Halo

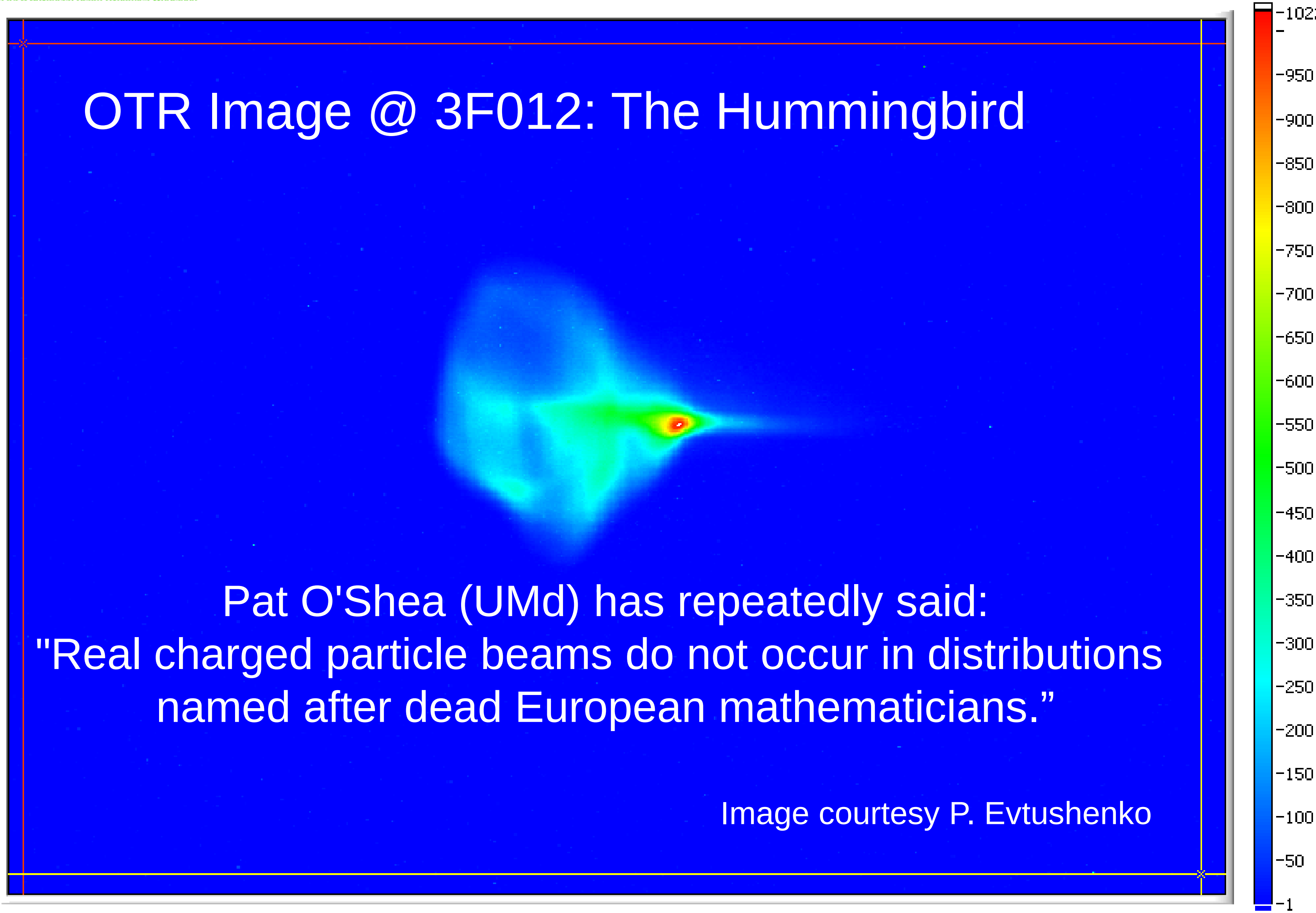
- Huge operational problem
- Many potential sources
  - Ghost pulses from drive laser
  - Cathode temporal relaxation
  - Scattered light on cathode
  - Cathode damage
  - Field emission from gun surfaces
  - Space charge/other nonlinear dynamical processes
  - Dark current from SRF cavities…



- We see multiple sources
  - CW beamlets at various energies (even with beam off)
  - large-amplitude energy tails
  - spatial halo (e.g. at wiggler)
  - Tends to be mismatched to, out of phase with, core beam
- Much tune time spent getting halo to “fit”
  - can’t throw it away – get activation & heating damage;
  - can’t collimate it, (“it just gets mad…”)
  - We “tweak” it through –this might not work a large system….
    - Look at activation patterns, beam loss, tune on BLMs

Slide courtesy Steve Benson

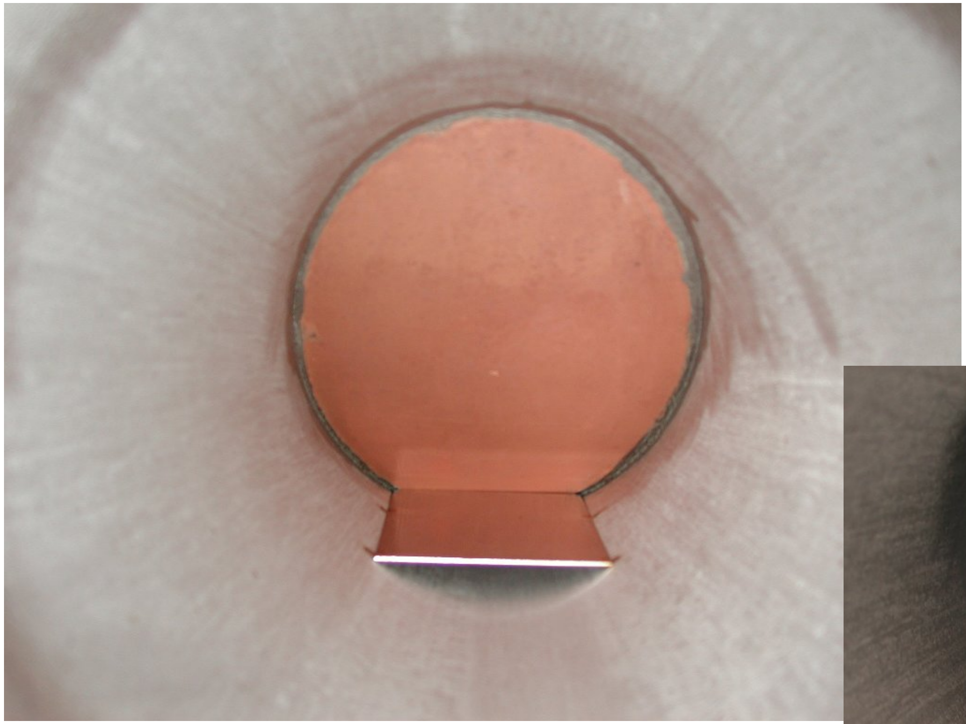
OTR Image @ 3F012: The Hummingbird



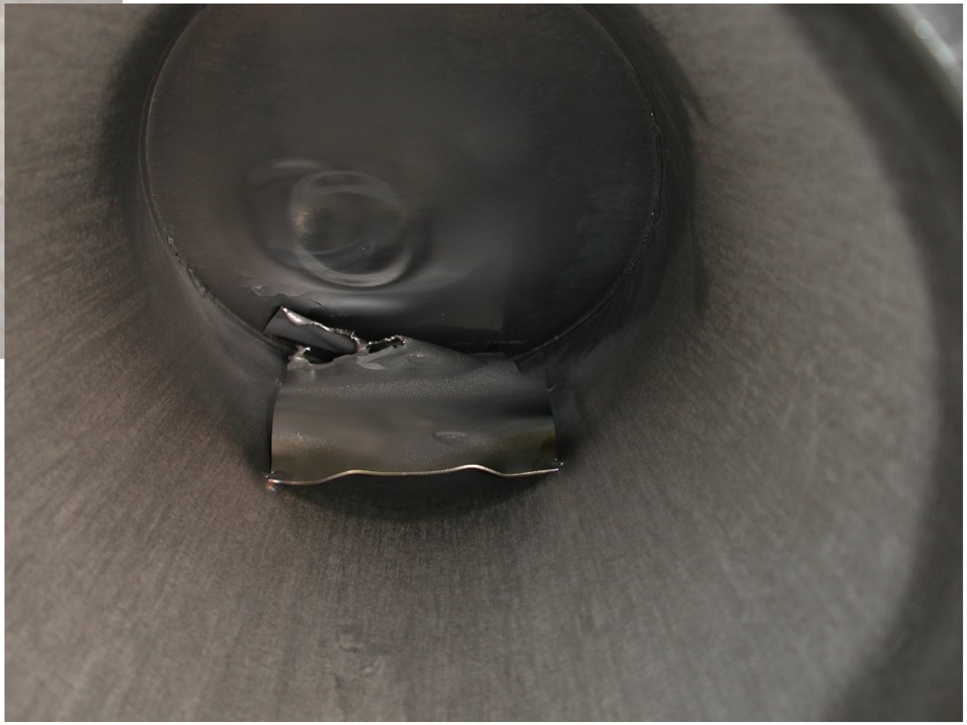
Pat O'Shea (UMd) has repeatedly said:
"Real charged particle beams do not occur in distributions named after dead European mathematicians."

Image courtesy P. Evtushenko

JLab IR Demo Dump



core of beam off center,
even though BLMs showed
edges were centered
(high energy tail)



MPS Design Philosophy

- Consider all modes of operations and design the system to accommodate them!
- Seamless integration with drive laser is key to success!
  - It can not be an after-thought - DLPC
- Machine Modes; there are 8 choices of where one can terminate the beam
- Beam Modes; there are also 8 choices of maximum beam power
- A single VME board was designed to provide this functionality
  - 64 channel input/output configuration
  - Data is passed through ‘P2’ connector to rear of crate
  - Multiple *transition* modules for interfacing both 24 volt level signals as well as fiber input & outputs

Beam Modes

- Beam Modes describe the limits placed on the average beam current
  - These limits are to prevent damage to insertion devices
  - They are flexible in the fact the mode is a duty cycle limit
- Beam Mode 0 – “0” microamp ave.; No Beam Allowed
- Beam Mode 1 – 0.005 microamp ave.; Ceramic Viewer Mode ITV0F02
- Beam Mode 2 – 0.5 microamp ave.; IR Beam Viewer Mode
- Beam Mode 3 – TBD microamp ave.; UV Beam Viewer Mode
- Beam Mode 4 – 2 microamp ave.; High Power Viewer Mode
- Beam Mode 5 – “0” microamp ave.; Laser Alignment Mode
- Beam Mode 6 – TBD microamp ave.; Laser Mode
- Beam Mode 7 – 10,000 microamp ave.; No Restrictions; Full Power Mode
  - Note that modes 4,5, &6 can be used by the Laser Safety System to limit the Laser power

Machine Modes

The Beam Dump Determined by Magnet Current and Switch Settings (partial examples give below)

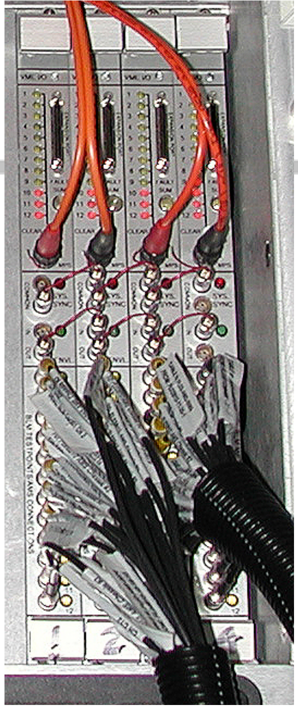
- Machine Mode 0 – No Beam Allowed; Settings not valid.
- Machine Mode 1 – Injector Dumplet; Inj. & SW=ON
- Machine Mode 2 – 2G Strait Ahead Dump, Inj ON & SW=OFF, Ext OFF, Arc1 OFF;
- Machine Mode 3 – IR Recirculate to 1G Dump; Inj ON & SW=OFF, Ext ON, Arc1,2 ON, SW OFF
- Machine Mode 4 – UV Recirculate to 1G Dump; Inj ON, Ext ON, Arc1,2 ON, SW=ON,
- Machine Mode 5, 6, 7 – TBD, spare
  - Note that ON is Power Supply ON + Current OK (window comparator)

Beam Loss Monitors

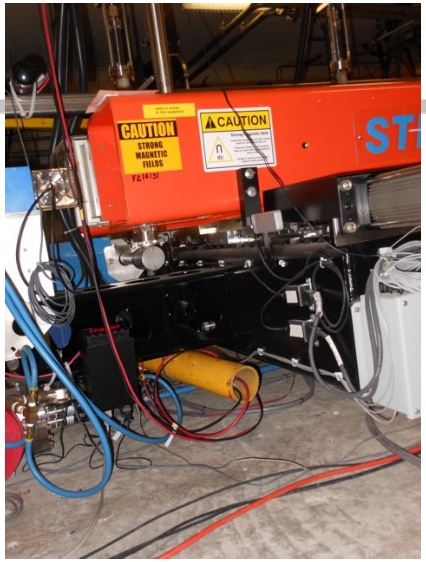
- The primary BLM at the JLab is a 931B Hamamatsu photo-multiplier tube
  - These are operated with a fixed integrator and individually variable HV power supply
- The BLM electronics are 12 channel VME boards.
  - VME was re-designed from earlier CAMAC version
  - There is a single FSD fiber output to the MPS for each VME board
  - All 12 channels have analog monitors that are connected to the Analog Monitoring System (AMS)
    - These are used as tune-up diagnostics in the control room
  - Feature that did not work was "Auto-Blanking"
    - The system was supposed to ignore *tolerable* events like beam loss from thin OTR foils, the reason this did not work was that the beam would occasionally strike the support frame of the foils and the recovery from saturation. This could be done with a more prompt detector.
- Calibration procedure
  - Machine is *locked* into 1 microAmp CW operation, beam is driven into chamber and detector gain is varied by changing HV. The HV is adjusted until the system trips. This new "gain" setting is saved in EPICS and accounts for aging of tube.

BLM Hardware

BLM 48 Channel Programmable HV
Power Supply front & rear

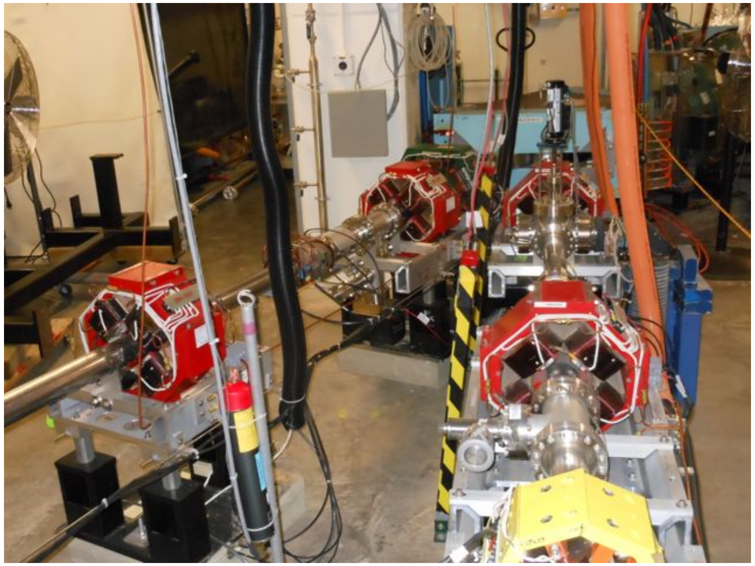


BLM VME



Rate detector;
Wiggler protection

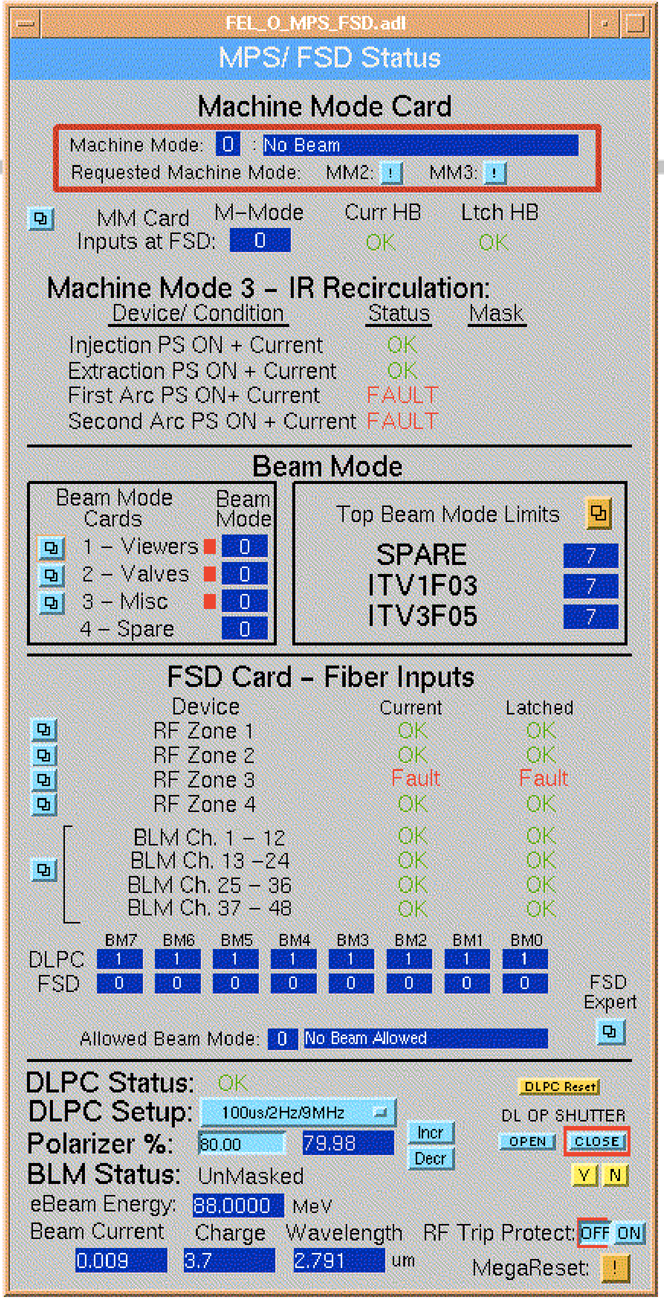
"Rapid Access"
Gamma detector

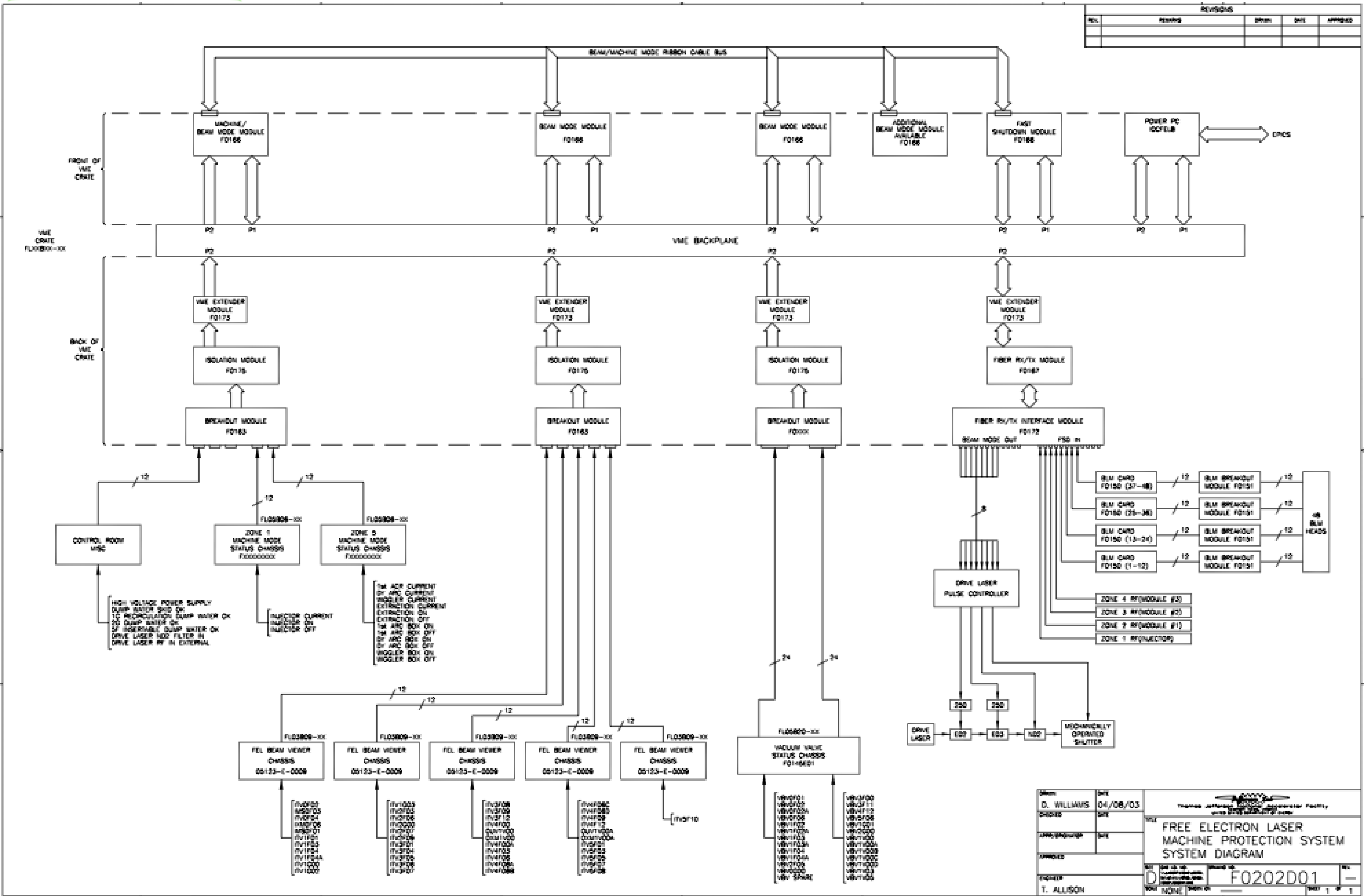


BLM at exit Arc 1

Operational Screens

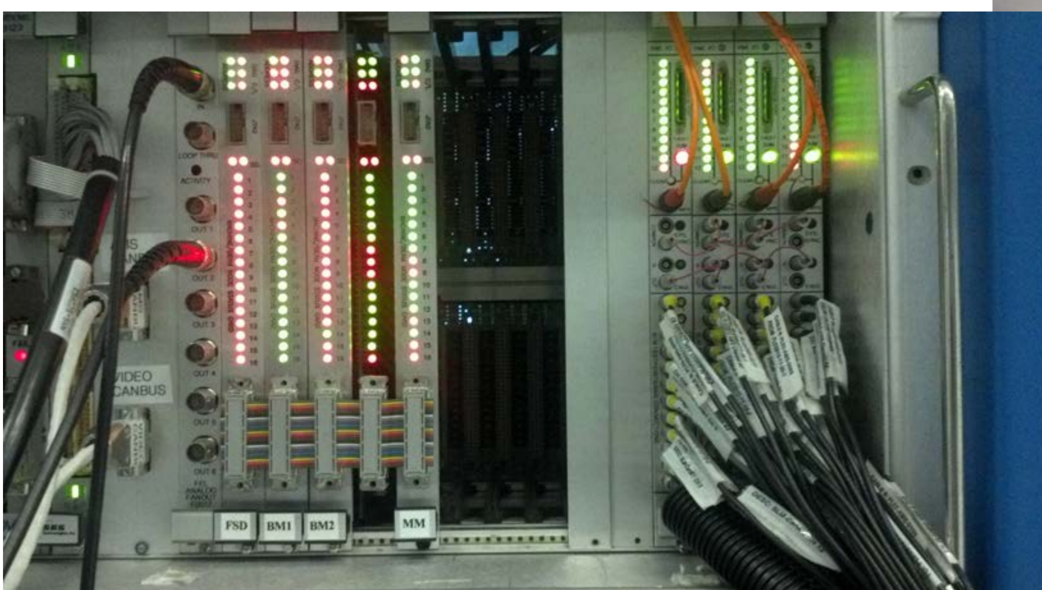
- High level ops screen
- Shows Machine Mode & Beam Mode
- Status of *Fast* inputs
  - RF & BLMs
- Shows status of DLPC
  “Drive Laser Pulse Controller”
  - Able to adjust current & pulse structure
- We created the “Top 10 List” to aid the operator in restoring beam
- Buttons to get to other relevant screens




BEAM/MACHINE MODE RIBBON CABLE BUS
MACHINE/ BEAM MODE MODULE F0166
BEAM MODE MODULE F0166
ADDITIONAL BEAM MODE MODULE AVAILABLE F0166
FAST SHUTDOWN MODULE F0168
POWER PC IOCFEL8
EPICS
FRONT OF VME CRATE
VME BACKPLANE
BACK OF VME CRATE
VME EXTENDER MODULE F0173
ISOLATION MODULE F0176
FIBER RX/TX MODULE F0167
BREAKOUT MODULE F0163
FIBER RX/TX INTERFACE MODULE F0172
CONTROL ROOM MISC
DRIVE LASER PULSE CONTROLLER
VACUUM VALVE STATUS CHASSIS
FEL BEAM VIEWER CHASSIS 05123-E-0009
MECHANICALLY OPERATED SHUTTER
DRIVE LASER
FREE ELECTRON LASER MACHINE PROTECTION SYSTEM SYSTEM DIAGRAM
F0202D01
D. WILLIAMS
04/08/03
T. ALLISON

VME Hardware

The image below is the implementation of the MPS & BML hardware. The 5 VME boards (left side) are the MPS I/O & the other 4 (right) are the BLM boards. All MPS inputs & outputs are done through the "P2" connectors. The ribbon cables on the front pass the 3 bit Machine Mode & Beam Modes between cards.



The image above is the 12 channel BLM board. The BML connections are on the rear panel (12 -9 pin "D" connectors). The front panel has the Analog Monitoring System (AMS) and FSD fiber outputs. As a diagnostic the gain (HV) can be raised on any tube and monitored in the control room for study of losses.

What is the DLPC?

- Drive Laser Pulse Controller (DLPC) - Integrated Controls Hardware that defines the time structure of electron beam pulses.
  - Micropulse Frequency – Electron bunch rep-rate (75 MHz – 512 kHz)
  - Macropulse Structure – Pulse width and frequency micropulse
- Limited average current as defined by the Machine Protection System (MPS)
- Remote interface via EPICS control system

Slide courtesy Daniel Sexton

Design Philosophy

The DLPC is treated as two separate systems in the same package that work together but are not dependant on each other.

1. <u>E.O. Cell Pulse Generator Electronics</u>
    - Maximize the flexibility in time structure
        - rep-rate, pulse width, micropulse frequency, synchronization, etc.
    - Provide other accelerator components beam sync and timing options

2. <u>Average Current Limiting Hardware</u>
    - Operate the given interlock devices
        - MPS Shutter, ND2 filter, Pockel Cells (E.O.) & others
    - Duty Factor Calculation
        - Feed forward to inhibit faulting combinations based on E.O. Cell Pulse Generator

Slide courtesy Daniel Sexton

E.O. Cell Pulse Generator Electronics

- Line Locked Trigger Source (60Hz) -------------------------- VME Crate Power
  A simple circuit is attached to an AC source to produce the line-locked 60Hz TTL logic
- Rep-Rate and Pulse Width Selection ----------------------- F0080 Timing Cards
  One timing card to handle Pulse Repetition Rate and another to handle Pulse width.
- Beam Sync, Beam Envelope and Diagnostic Timing ----- F0080 Timing Cards
  Other timing boards will be used to provide precision delays after beam sync for look ahead triggers and miscellaneous functions.
- Line-Sync vs. Asynchronous Mode ------------------------ Handled by EPICS
  As 60Hz will be provided to the ‘Rep-Rate’ timing card, EPICS can easily notice the desired requests and make the switch transparent
- One Ping Only Mode --- Handled by EPICS
  The timing cards have an external sync input that the ‘Pulse Width’ card can use a digital I/O bit from EPICS to drive.
- Micropulse Frequency -- Conoptics305
  A modified 305 is controlled by digital I/O lines to determine the 2^n+1 division of the micropulse frequency.
- EO-Cell Drivers --- Conoptics M25Ds
  The output of the 305 is to 25Ds so the front end EO Cell can gate the laser pulse.

Slide courtesy Daniel Sexton

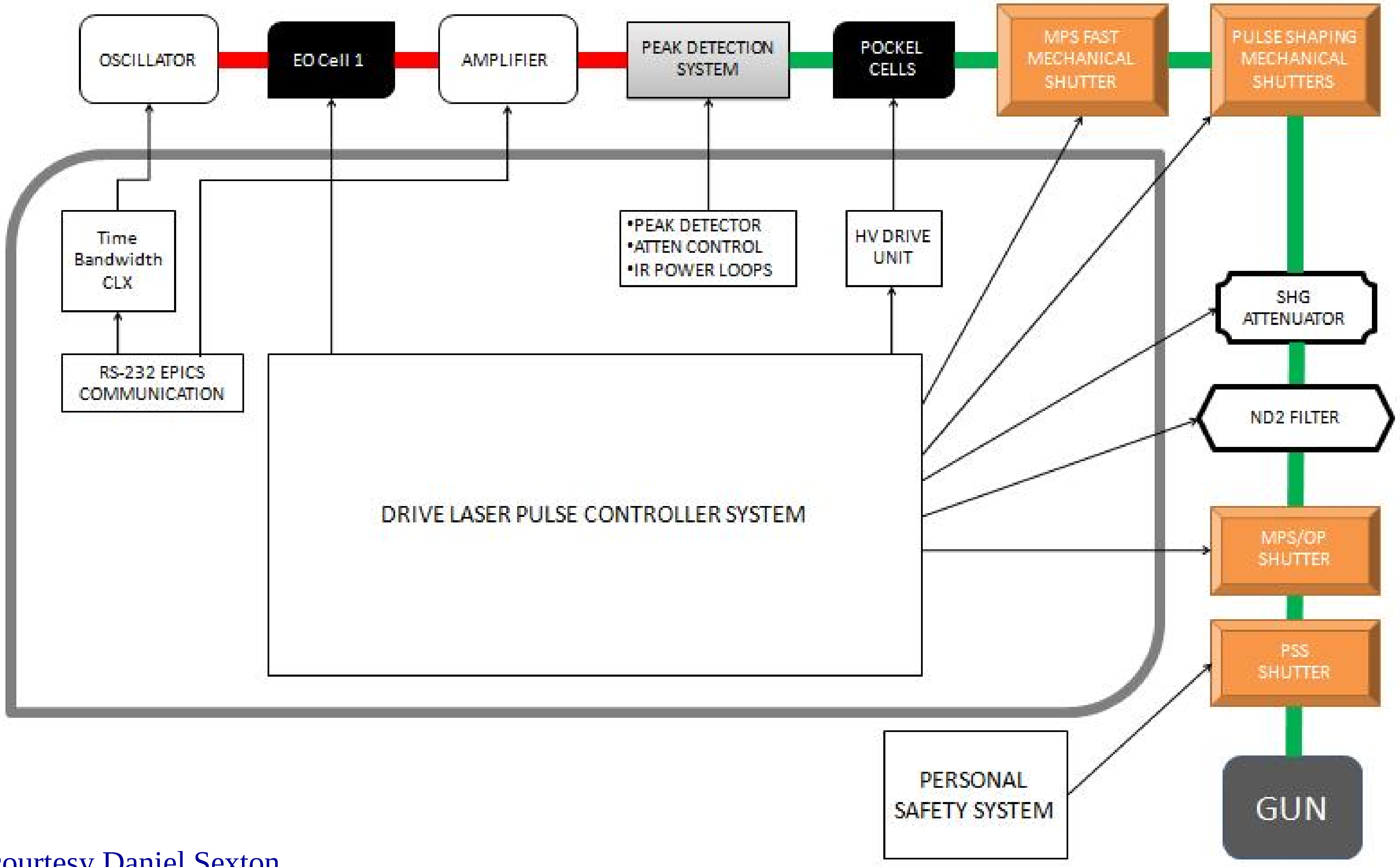
- External Trigger -- F0080 Timing Cards
  A 50 ohm TTL input is available to allow external synchronization and/or triggering from an external source

Average Current Limiting Hardware

- Fiber-Optic Beam Mode Inputs --------------------------- DLPC MPS Board
  A simple board that converts the 5MHz fiber based permits into TTL logic for the DLPC MPS Board.
- MPS (Operators) Shutter ----------------------------------- DLPC MPS Board
  The MPS Shutter is controlled using a Beamviewer control channel, but the activating signal is interlocked on the DLPC MPS Board
- ND2 Filter --- DLPC MPS Board
  The ND2 filter is also operated by a Beamviewer control channel but insertion of the device is interlocked to the DLPC MPS board
- Pockels Cell Driver -- DLPC FSD MPS Board
  Intercedes Beam Mode 0 Fiber and generates the triggers to open and close the Pockel Cell
- Fast MPS Shutter -- DLPC FSD MPS Board
  Uses the same Beam Mode 0 Fiber to latch the shutter opened or closed depending on the presence of 5MHz fiber signal
- Peak Detection System ------------------------------------ Peak Detector Chassis
  Monitors the IR pulses and closes a fast shutter to protect the SHG Crystal. Includes feed-back and feed-forward systems

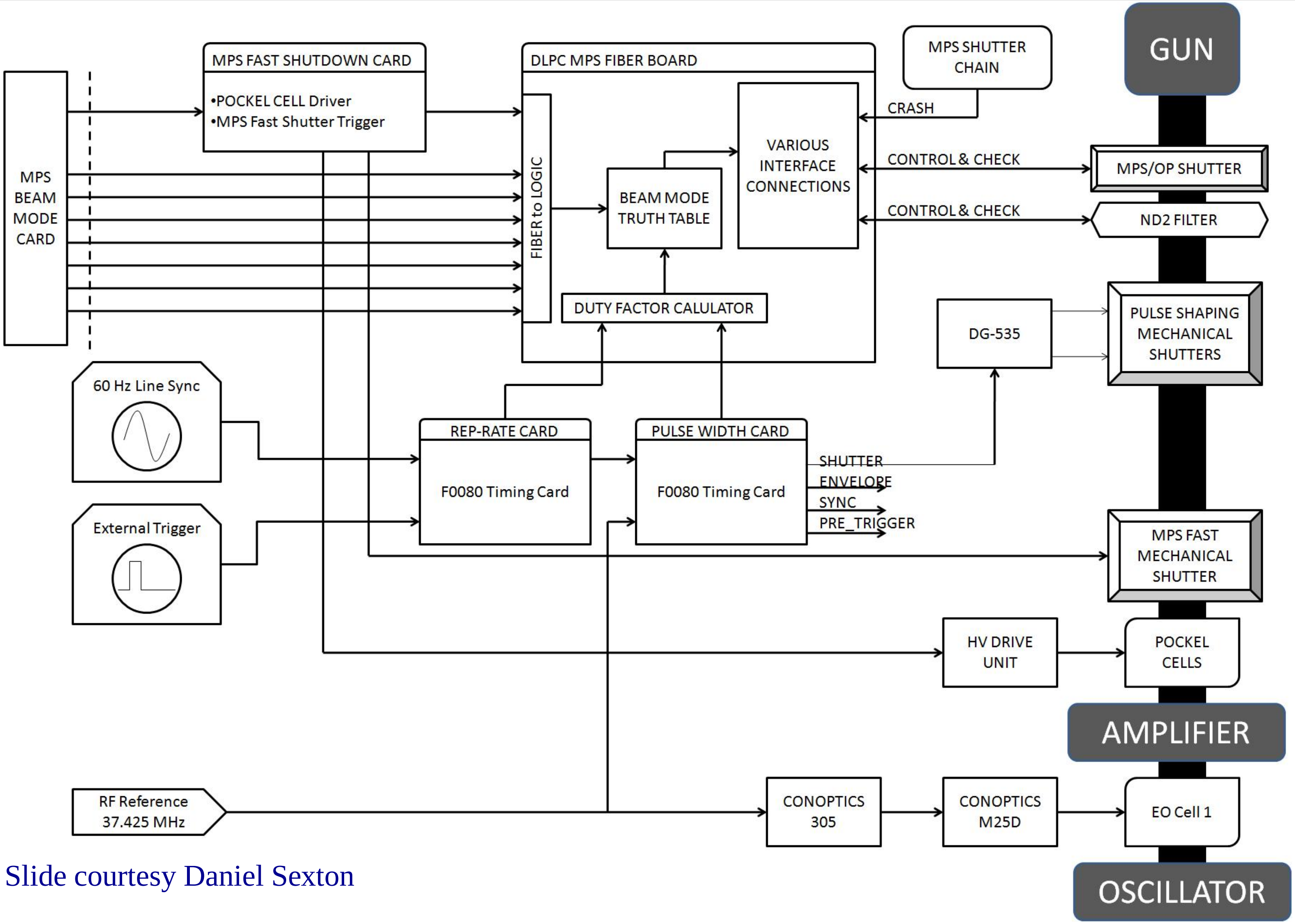
Slide courtesy Daniel Sexton

Drive Laser System Overview



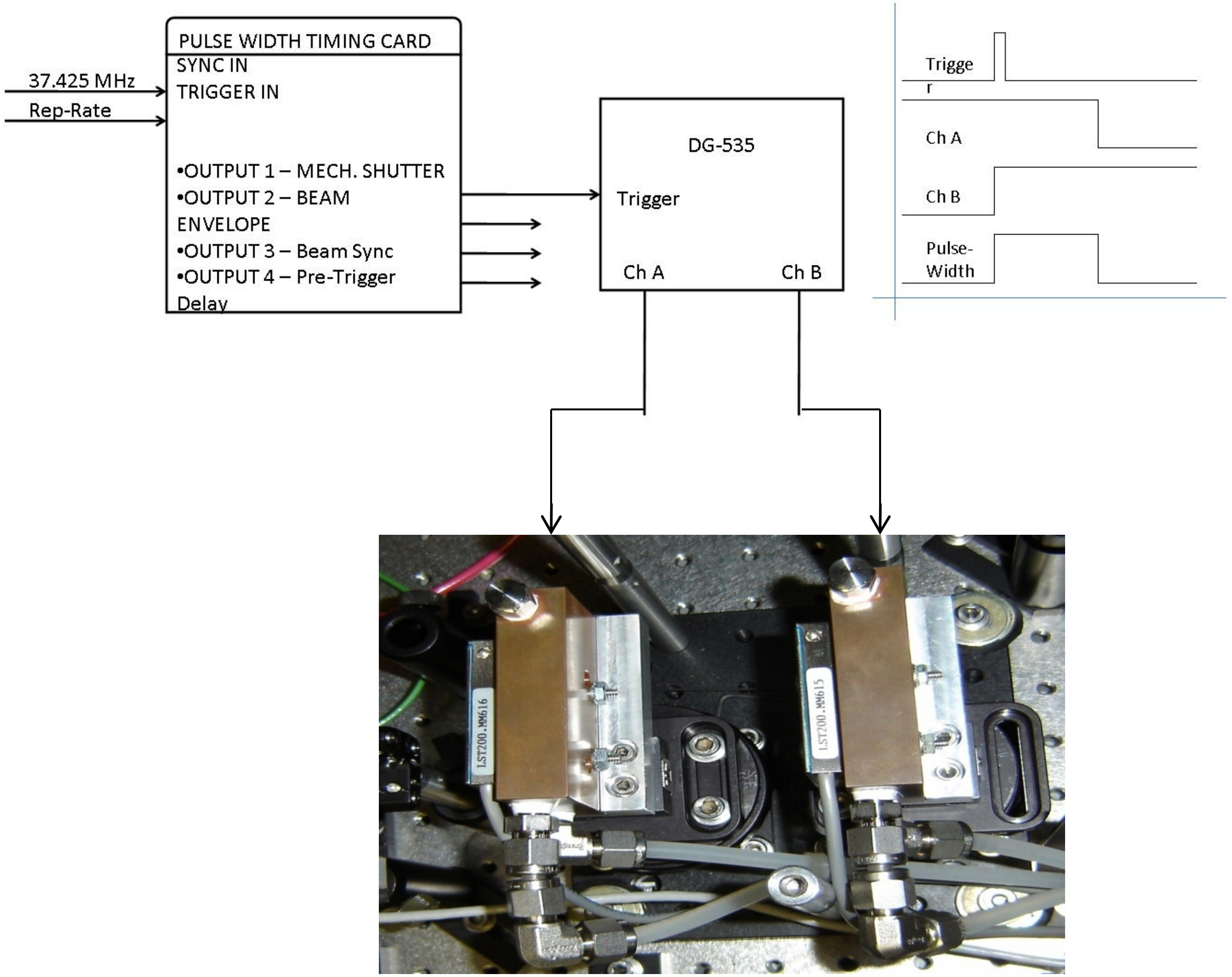
Slide courtesy Daniel Sexton

DLPC Overview



Slide courtesy Daniel Sexton

Twin-Shutter Scheme

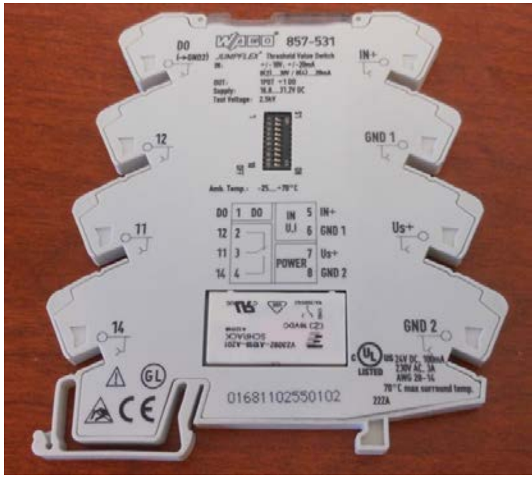


S. Zhang, etc., “A simple gating technique for high-average-current photo-injectors”, NIMA 629 (2011) 11-15

PLC vs VME

- Our MPS design philosophy has always been to avoid the need for jumpers. This requires the *system* to be aware of many different *classes* of devices; some fast some slow.
- The slow devices are commonly those operated by pneumatic cylinders or motors
  - These limit switches are well suited for interlocking through a PLC
- Fast devices such as Beam Loss Monitors or loss of RF power require a more prompt response time
  - At the JLab FEL this signal distribution is done by passing 5 MHz on a fiber optic cable (FSD-Fast Shut Down) from device to VME gate array
    - The ‘5MHz on fiber’ was partly legacy from existing RF designs & we stuck with it

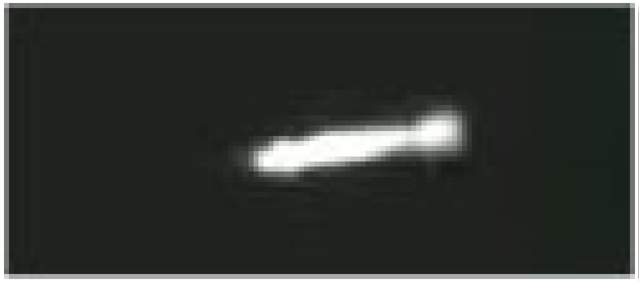
Progression to COTS

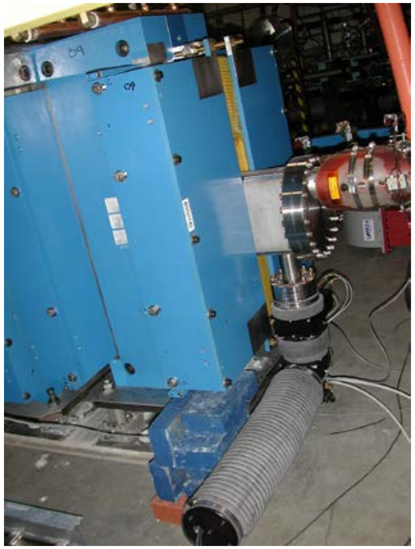


- COTS; Commercial-off-the-Shelf
  - 12 years ago I was a skeptic about using PLCs for MPS; I was wrong
    - Or perhaps the recent increases in performance has sold me…
- When I first designed the systems in mid '90s there were a number of interface chassis that we simply designed & built
  - An example of this was the need to know the current in a magnet string; the transducer output was sent to a chassis with a custom designed window comparator which generated the permit signal to be passed on to the VME board
  - Below is the chassis (>$5K) that can be replaced by the WAGO DIN mount window comparator ($150 each)
    - This din mount device runs off 24 volts & is ideally suited for connecting to a PLC

Synchrotron Light Monitors

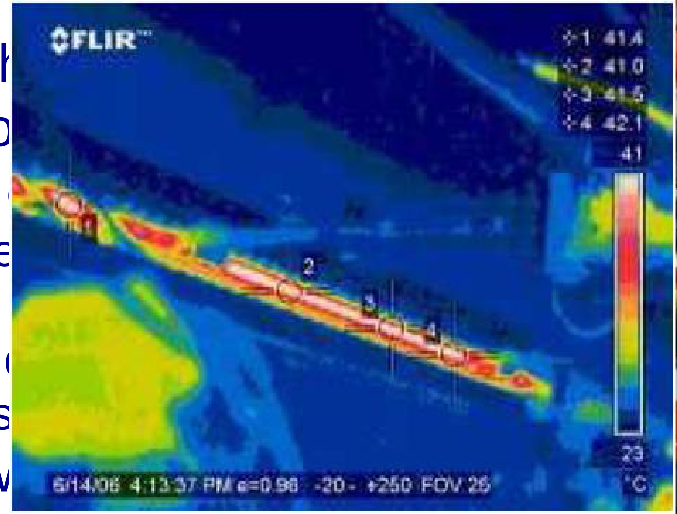
- SLM ports are installed even in unlikely locations
- Large dipoles were built with telescopes to bring out light
- THz chicane has a mirror in vacuum to *peek* into magnet
- All locations have insertable neutral density (ND) filters to attenuate signal, SLM bright even at 88MeV pulsed beam
- OD1 (10x) and OD2 (100x) filters extend dynamic range of cameras 3 orders of magnitude



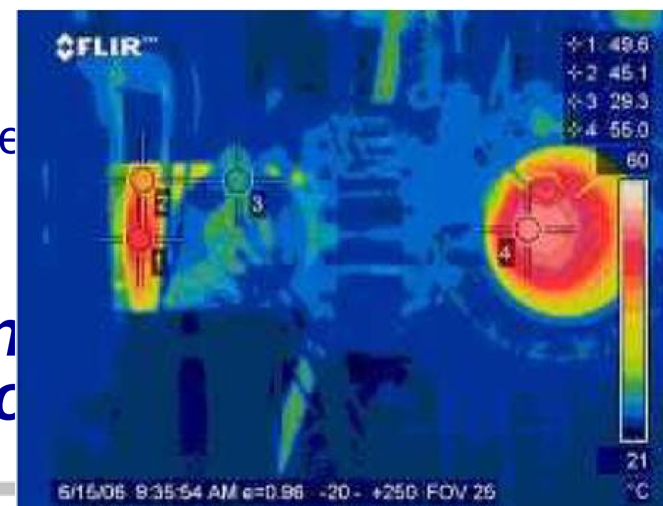


The above image on the left is from Arc 2 with NO Lasing, the right side is the same conditions but with strong Lasing

Collective Effects

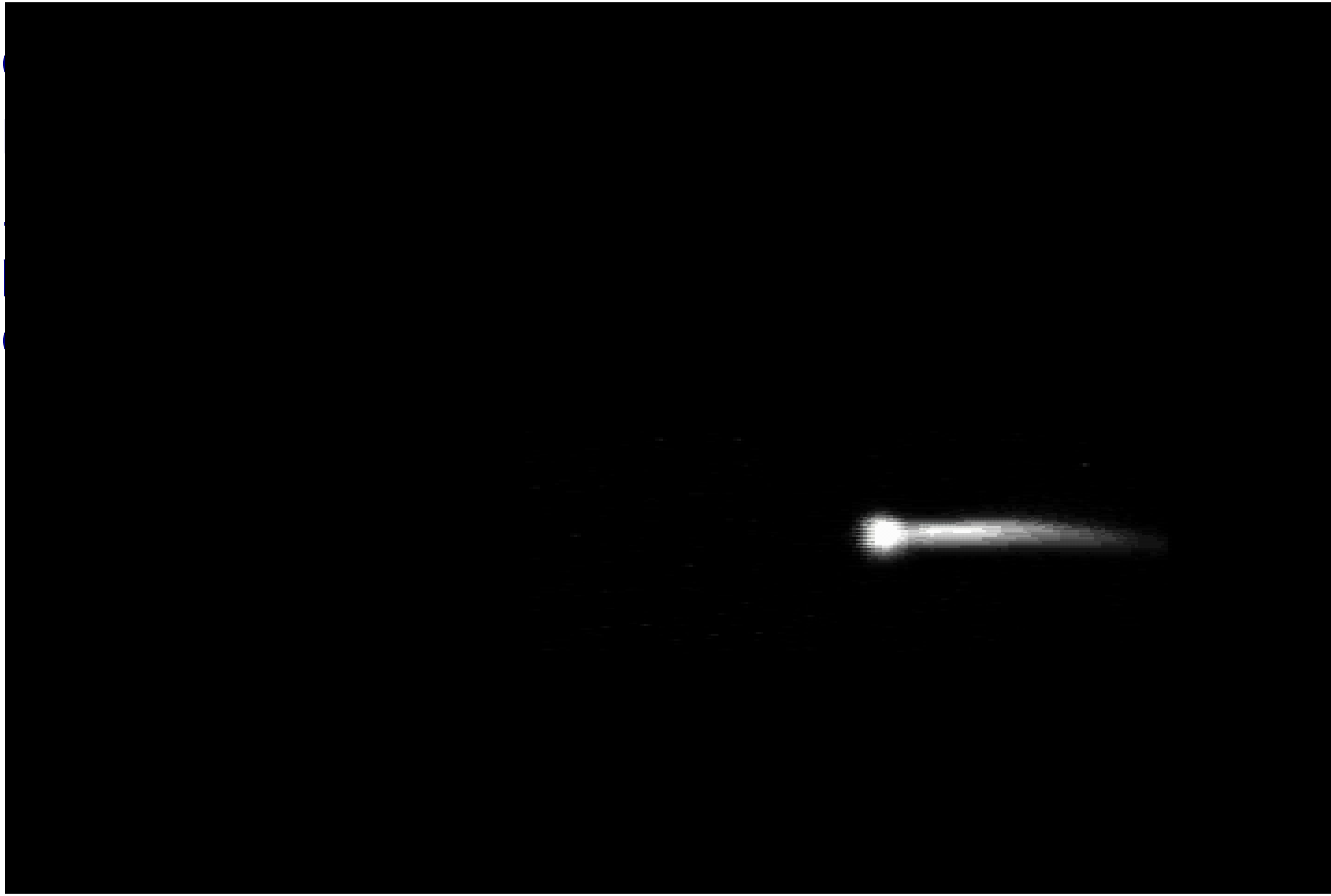


- ERLs live to generate high
- Collective effects are a "lo
- JLab systems have been
  - Longitudinal space charge
  - BBU (limited current)
  - CSR (potential emittance
  - Enviromental wakes, resis
- Larger/brighter systems w
  - Intrabeam scattering, Touschek effect, beam/gas scattering formation, beam loss)
- Must be able to observe, characterize, quantify effects
  - e.g. power into HOMs for BBU
  - Disentangle source of inappropriate behavior
    - e.g. poor dispersion suppression vs. lattice energy shift from CSR…



Lattice must support diagnosis, con compensation, and suppression c

CSR/LSC



Acknowledgements

- I would like to thank the organizing committee for the opportunity to present the Jlab FEL Team's work!
- Special thanks to Steve Benson & David Douglas – it is a pleasure to work with such insightful people
- And to our funding agencies
  - Please do not forget us…