Machine Protection at the 1MW CEBAF Electron Accelerator and Free Electron Laser Facility

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Continuous Electron Beam Accelerator Facility - CEBAF

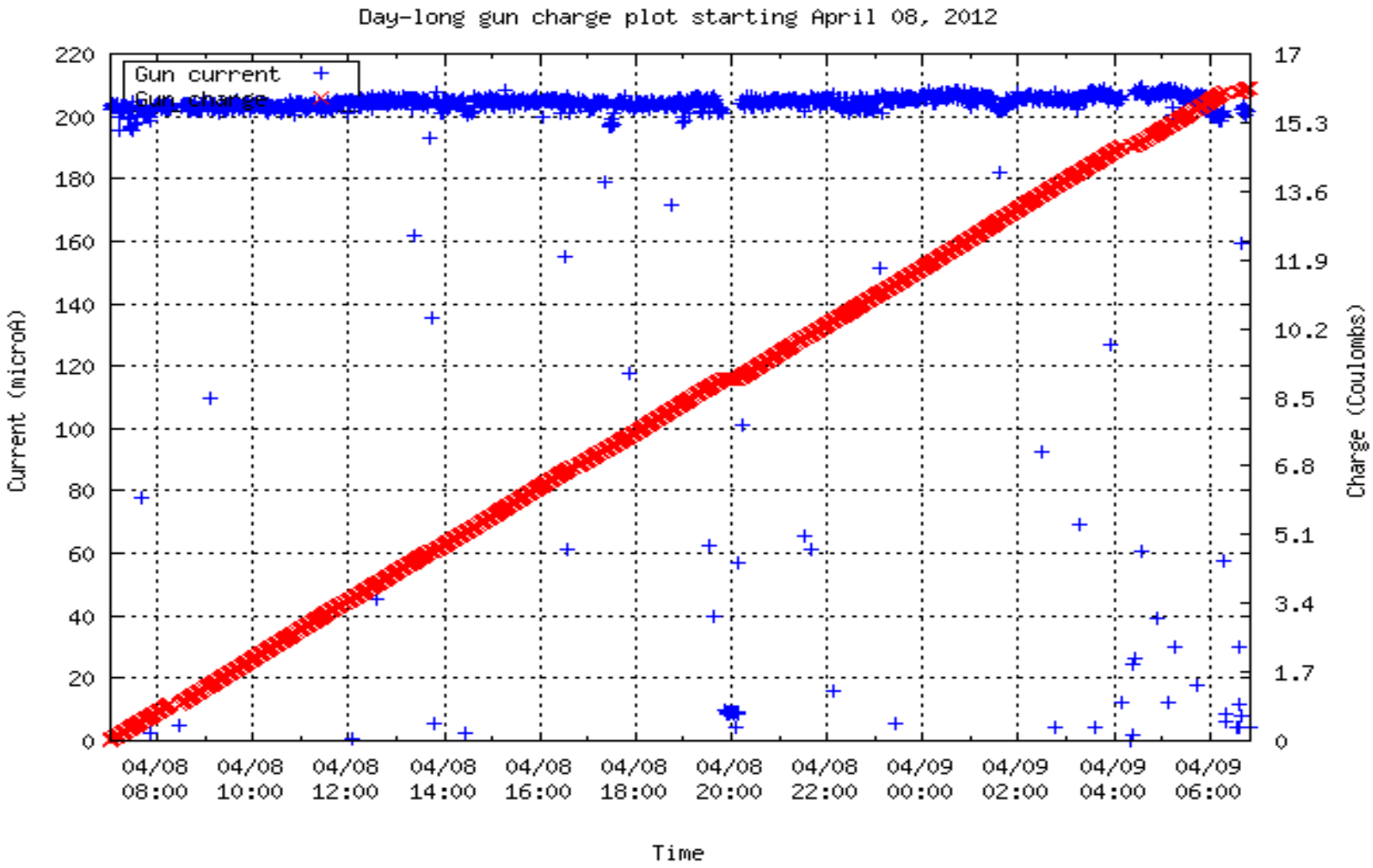
- 1MW, 100 % duty factor, (Limited by Dump Cooling System)
- Two Superconducting Linacs with Recirculation
- 3 Fixed Target Experiments Operating Simultaneously
- Completed 6 GeV running in May, 2012
- Currently shutdown for upgrades to double energy to 12GeV

CEBAF Beam – Recent Beam Runs

3 Simultaneous Fixed-target Experiments

- 0.7 to 6 GeV
- 10 fA - 200 μA CW
- Up to 750 kW beam power (350 kW typical)
- Polarization > 90%

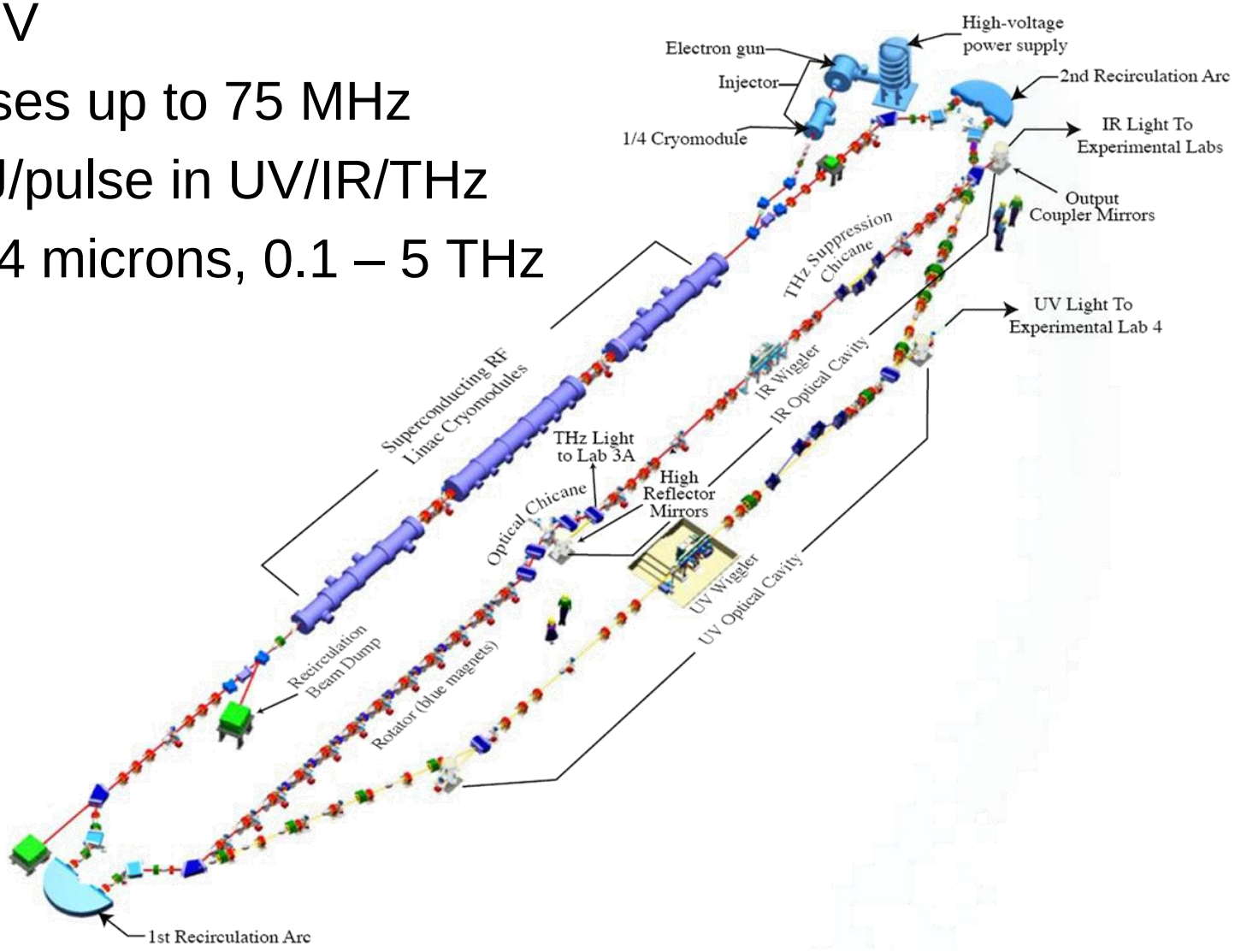
Recent CEBAF Operation



24 Hours

JLab Free Electron Laser

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



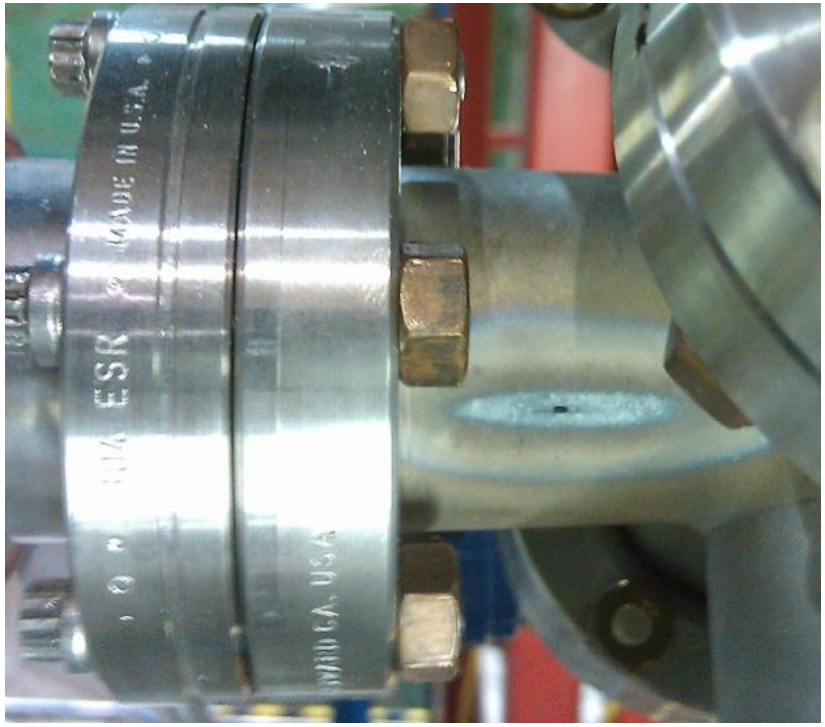
Superconducting Cryomodule

- Existing Injector and Linacs
  - 42 ~20 MeV cryomodules
- Upgrade
  - +10 100 MeV cryomodules
  - Two tested as part of last physics run

- SC Cavities have unique Machine Protection Issues
  - Highly beam loaded – Beam couples to RF systems.
    - Can Create kilo-watts of RF in unpowered cavity
  - High Energy Field Emission/Dark Current Source
  - Many Interlocks related to avoiding/detecting quench

High Power Machine Protection Issues

- Catastrophic Beam Loss
- Halo/Dark Current
- Vacuum Interaction
- Complex Beam Transport

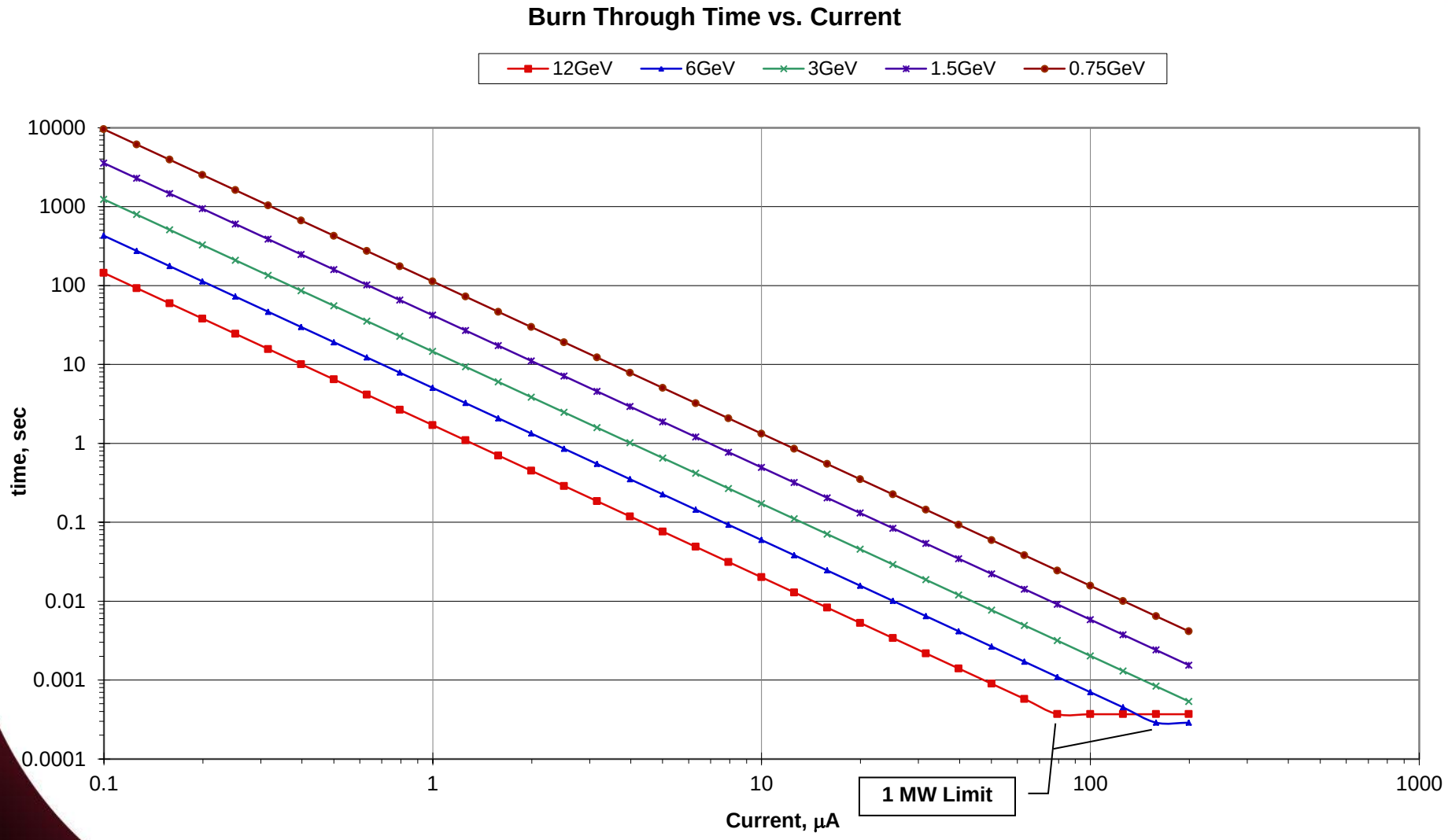


JLab Beam Loss Protection Philosophy

- Identify Precursors, correct before MPS shutdown required
- Major Beam Loss detected by Zero Sum beam accounting
  - $\Sigma_{iabc} = i_{INJECTED}$
- Point Loss detection for small apertures
- Diagnostic Loss Detection coverage for whole machine

- Beam Loss protection threshold is in terms of integrated loss
  - Ampere-seconds
  - Integrated Charge deposited (Q)
  - Typical integration constant is 15,000 μA-μs

e^- Burn-through time vs. Current



Issues

- What is the value/benefit of detecting Watts out of MW?
  - Especially in high background regions
- Need to define protection in terms that mean something to hazard awareness and mitigation – NOT Health Physics terms.
  - Random failure and component reliability are orders of magnitude better than when MPS paradigm was developed.
    - Controls equipment can be designed to be highly reliable and available.
  - Effort Needs to go in to integrated systems and components
    - Emphasis on detecting precursors to beam loss and taking corrective action before loss crosses damage threshold.

Systems Approach

- Top-Down
- Accelerator is a system of systems
  - Injection Systems
  - Accelerating Systems
  - Beam Transport Systems

- Focus of MPS is to ensure maximum machine availability – not to shut it OFF
  - Linear Accelerators typically have surplus accelerating capacity
  - Fail-safe mode may be to abort/dump but also to auto diagnose and recover
    - CEBAF SW auto-recovery has beam ON in < 9 seconds per trip.

Systems Approach

- Loss aware Beam Transport/other components (System knows when components are not doing their job)
  - Evaluate Failure Modes and Effects of functions
    - Assign risk level to each
  - Define compensating measures
  - Automate compensating measures to the greatest extent possible
  - Alert Operations Staff
    - (Note – the complexity of accelerators makes the effectiveness of operations intervention questionable. Some catastrophic events due to operator misunderstanding.)

Systems Approach

- Focus on machine mission
  - What is required to maintain beam availability and quality?

- Focus on identifying and delegating availability impact of machine functions. Establish functional requirements for all equipment
  - Self test and diagnostics
  - Cross compare available information/diagnostics
  - Self healing SYSTEM

  RF, BPMs, Magnets,… know when energy is OFF by 1E-5 – why is it left up to MPS to detect?

- When MPS intervention is required, automate recovery
  - Coordinate actions of MPS and other controls to recover as soon as practicable.

Machine Protection as a System Property

- Machine Modes/Beam Modes
  - Machine Mode – Specific Machine Configuration
    - Source and destination
    - All Beam transport systems ready to support a given machine configuration
  - Beam Mode – Predefined Beam Properties
    - Includes peak current, pulse structure, duty factor

- MAINTAIN beam ‘awareness’ - non-linear effects, e.g. wakefield, SRF fill, Energy Recovery by keeping high charge per bunch but reducing duty factor.

Machine Protection as a System Property

- Allows MPS to fall-back to lowest Beam Mode that will not increase damage
  - CEBAF presently has 3 Beam Modes
    - Will increase to 5 in 2013
  - FEL has multiple modes that are integrated in to the fundamental operating parameters of the machine.
  - Pre-programmed into gun controls

- All RF, diagnostic, and feedback systems remain locked to beam
  - e.g. position and energy
  - Allows real-time diagnostics of problem areas

Conclusions

- Cost-benefit for stand-alone MPS for high power accelerators is reaching asymptote
- Machine Protection is a System Property
- Random HW Failure is Extremely Small Part of Failure Modes
  - Requires emphasis on SW assurance
- Identify and allocate ‘machine availability’ functions to all equipment and controls
  - Machine/Beam Modes
  - Pre-cursor MPS functions for other systems
  - Cross Comparison/Verification Functions
  - Auto-recovery
- MPS as a system function takes on an arbitration role