BEAM QUALITY AT JEFF ERSON LAB

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Abstract
The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab is a $600M CW electron accelerator in Newport News, Virginia. The machine is a recirculating, superconducting 5-pass linac initially commissioned for 4 GeV with a maximum beam power of 1 MW. With improvements in our RF cavity performance and an upgrade to magnet power supplies we are now capable of reliable operations at u p to 5.7 GeV. We employ a three-laser photocathode gun to provide a CW electron beam with 80% polarization to three experimental endstations in currents ranging from 100 pA to 200 μA. Establishing clear criteria for beam quality and developing the means to verify and maintain beam quality is essential to a successful physics program.

1. INTRODUCTION

Beam quality criteria are developed early in the life cycle of an experiment and are realized through a coordinated effort between the various departments within the Physics and Accelerator Divisions. I'll discuss the overall experiment approval process, in the context of the identification of beam quality specifications, and the realization and maintenance of these criteria through the development and implementation of diagnostics, feedback systems and communication mechanisms.

2. EXPERIMENT APPROVAL PROCESS

Experiments are awarded beam time as a result of a careful review of overall scientific merit, technical feasibility, and manpower requirements. All experiment pr oposals come under the review of the Program Advisory Committee (PAC). The PAC is an advisory group to the Lab Director. It consists of members external to Jefferson Lab appointed by the Director, plus the current Chair of the User Group Board of Directors .

The PAC solicits input from the Technical Advisory Committee (TAC). The TAC reviews an experimental proposal from the perspective of challenging technical issues, unusual demands on Jefferson Lab resources, and unusual Environmental Health and Safety iss ues. Specific beam quality criteria are contained in the body of the proposal and the TAC evaluates these on the basis of the present capabilities of the accelerator and decides if additional hardware or diagnostics are required to meet the beam quality specifications.

When technical challenges are evident for an approved experiment the effort is managed by the Accelerator Division Experiment Coordinator. A much broader audience is now exposed to the experiments needs and meetings are scheduled with members of Mechanical Installation, Electrical Installation, Cryogenics, Diagnostics, Radiation Control, Personnel Safety, Survey and Alignment, Software, Accelerator Electronics Support, and Operations Groups as necessary.

A key step in the process of communicat ing beam quality specifications to the Operations Group is the assignment of an Operations Experiment Liaison. The liaison is either a crew chief or operator who is responsible for facilitating information exchange between the experimenter and Operations staff during an experiment as well as during the planning stages. The liaison works closely with the Accelerator Division Experiment Coordinator in streamlining the flow of information between the Operations Group and the Experimental Collaboration. Standar d forms have been developed as tools to aid in the information exchange.

- **Physics/MCC Experiment Planner Form** – This form is completed by the Accelerator Division Experiment Coordinator (this is a full-time position that should not to be confused with the Experiment Liaison, which is a temporary responsibility). The form provides a brief description of the experiment, contact names and information, beam quality requirements, run times, and any special concerns related to the Machine Protection System (MPS) or the Personnel Safety System (PSS).
- **Experiment Liaison Check List** – This form is completed by the Accelerator Division Experiment Coordinator prior to the start of an assigned experiment. The form consists of a list of questions that help identify areas of special concern (e.g., additional procedures, new MPS interlocks, additional magnets…).
- **Experiment Liaison Binder** – The binder is located in the MCC control room and includes a specific section for each upcoming experiment. The Experiment Liaison is res ponsible for adding the completed *Physics/MCC Experiment Planner For*m, the *Experiment Liaison Check List,* and any other important experiment-specific information to the binder, prior to the start of the experiment.

Having clearly defined the flow of inform ation to Operations staff regarding beam quality specifications, we then need to focus on mechanisms for maintaining beam quality and overall facility efficiency. This is accomplished through implementation of diagnostics, software, communications feedback mechanisms, and time accounting systems.

3. BEAM TIME ACCOUNTING

JLAB is operated by the Southeastern Universities Research Association (SURA) under a performance-based contract with the Department of Energy (DOE). The DOE employs a 1000 -point system to rate our performance in the following key areas for overall success.

• Science and Technology Peer Review	300
• Reliable Operations (Simultaneous Availability)	250
• Production of Scientific Manpower	75
• Corporate/Community Citizenship	75
• Environmental Heath and Safety Peer Review	100
• Fiscal Responsibility Peer Review	100
• Institutional Management Peer Review	100
	1000

The category for Reliable Operations specifically addresses our accountability with regards to maintaining the highest level of beam quality and efficiency of operations and counts for 25% of our overall assessment. A system of time accounting has been developed to keep us apprised of the overall facility efficiency, and helps us utilise our resources wisely when it comes to i mproving machine availability and beam quality.

3.1 Accelerator/End Station Status Definitions

The time accounting system is defined by the following categories:

- Acceptable Beam in Use (ABU) - Both the accelerator and experimental end station are meeting program requirements.
- Beam Available but Not in Use (BANU) – The accelerator is considered to be able to meet program requirements, but the experiment is not in an *Experiment Ready* status and therefore cannot make productive use of the beam.
- Beam Not Available or Unacceptable (BNA) – The accelerator is unable to meet program requirements which may include beam quality issues.
- Accelerator Configuration Change (ACC) – The accelerator is making a planned configuration change in the beam(s) being delivered.
- Experiment Ready (ER) – The experimental equipment is meeting program requirements or is considered capable of meeting program requirements if the Accelerator is in a BNA status.
- Planned Configuration Change (PCC) – The experimental end station is making a planned change to the software or hardware configuration, and this activity interrupts data taking or other activities in progress.
- Unplanned Experiment Down (UED) – The experimental equipment is unable to meet program requirements because of an unplanned system or administrative failure.

3.2 Metrics Definitions

Simple relations can be developed from these definitions to determine the overall success of the program. If T is defined as the total time in the run period planned for physics activities then by definition:

$$T = ABU + BANU + BNA + ACC$$

$$T = ER + PCC + UED$$

The Accelerator Availability (AA), Experiment Availability (EA) and the Simultaneous Availability (SA) are then defined as follows:

$$AA = \frac{ABU + BANU}{ABU + BANU + BNA} = \frac{ABU + BANU}{T - ACC}$$

$$EA = \frac{ER + PCC}{ER + PCC + UED} = \frac{ER + PCC}{T}$$

$$SA = \frac{ABU}{T - ACC}$$

The most relevant metric with regards to beam quality is Beam Not Available or Unacceptable (BNA). In most cases this means that the accelerator is unable to deliver acceptable beam to the user. This includes time required for investigating, troubleshooting, and repa iring a software or hardware problem. It also includes time used for unplanned beam tuning. This is the time spent tuning the accelerator after an unexpected event, such as an equipment failure or when beam characteristics have drifted out of specification so that the beam is no longer useable. It also includes time when an accelerator configuration change takes longer than planned.

BNA events involve two major categories. The first is *Downtime*, which is relatively straightforward to track and is related to a hard subsystem failures or Fast Shutdown (FSD) events (beam trip). The second is *Tunetime*, which is related to events where nothing is apparently broken but the accelerator is still unable to meet program requirements due to unacceptable beam quality at one or more experimental end stations.

4. DOWNTIME AND TUNETIM E TRACKING

Our electronic logging system is used by Operations staff to record lost beam time due to Downtime and Tunetime events. These entries are automatically entered into a database designed to track such instances. The entries are also emailed to relevant system owners, the Operability Manager and the Operations Group Leader.

The Operability manager is responsible for tracking Downtime while the Operations Group Leader is responsible for trac king Tune Time. Both are reported on at the weekly scheduling meeting, which is attended by senior staff from the Physics and Accelerator Divisions as well as members of all of the associated support groups.

The Downtime report includes lost time for each system failure and indicates if there are any trends associated with the failure. Top-level categories for Downtime reporting are hardware, software, tuning, FSD, and End Stations. Major sources of downtime are specifically called out with responsible parties identified, and action items are developed to deal with improving recovery from such events and minimizing the chance of the incident reoccurring. Failure statistics are kept on a system-by-system basis and long-term trends are presented during monthly and semi-annual reports.

The Tunetime report indicates lost time due to unscheduled tuning. Events are tracked until sufficient improvement in procedures, software, hardware, or diagnostics make it unlikely that the event will reoccur. The particular prob lem is stated as well as proposed solutions and responsible parties for each tuning event. These incidents are usually related directly to the accelerator being unable to deliver beam to an end station according to one of the experiment's beam quality crit eria.

Both Downtime and Tunetime reporting are our primary means of ensuring that the accelerator availability remains acceptable and that we are able to maintain beam quality within specification.

5. RUN COORDINATOR WEEK LY REPORT

Each experiment assigns the role of Run Coordinator to a collaboration member for a period of two weeks. This person is responsible for attending our morning summary meeting and providing a weekly beam availability report at the scheduling meeting. The Run Coordinator Weekly Report i s used to indicate beam time accounting metrics, major causes of downtime in the hall, percentage of data collected to date, percentage of scheduled time the experiment has been running, special task results (e.g. energy measurement, spin measurement...), an y potential problems related to beam quality or communications with Operations staff, as well as plans for the upcoming week.

This feedback mechanism is relatively new but has proven quite effective in bridging the gap between experimenters and Accelerator Division staff.

6. BEAM QUALITY MONITOR S

A program of beam quality control relies heavily on diagnostic implementation, software development, feedback mechanisms, and communication. Following are some of the beam quality criteria with a description of the me thod used to monitor and communicate the information to the User.

6.1 Beam Position Stability

Beam Position Monitors (BPM's) are used to indicate position stability in Halls A and C. These devices are strip line detectors with 4 orthogonal electrical pickups . The resolution of these BPM's is on order 10 microns with an absolute accuracy of ± 1 mm in the current range of 2 – 200 μAmps. The critical points as far as the experiment is concerned are the two BPM's located immediately in front of the nuclear physics target. These two are used to indicate the position and angle of the beam as it enters the target chamber.

Position stability in Hall B is indicated by the nA BPM system since their typical beam current is well below the resolution of the style of BPM's u sed in the accelerator and Halls A and C. There are three such devices, each of which is composed of three pillbox cavities. One cavity is used to indicate horizontal position, one is used to indicate vertical position, and the third is a current monitoring normalization cavity. They have 10-micron position resolution and a 50 pA current resolution.

A slow feedback system is used to lock position and angle in Hall B since the response time of the nA BPM system is slow. We employ a Fast Feedback System (FFB) to keep beam position and angle stable at harmonics of 60 Hz. with an additional slow lock to keep the FFB system actuators in the center of their range.

All three Halls have direct access to the BPM information as well as calibration factors that go into beam position calculations. The operations staff monitors beam position as well, and are alerted to errors in the relative beam orbit as they occur.

6.2 Momentum

The relative momentum error in our 9 main accelerator arcs and 2 of the experimental endstation transport arcs is provided by a model-based software application. The application reports the total energy error as well as the integral contributions from the beam orbit, correctors, and earth's field. This application is presently being redesigned with a better calculation engine and the output will be made available to the experimenter.

6.3 Momentum Stability

Momentum stability is monitored at high dispersion points in the transport arcs for Halls A and C. We use Optical Transition Radiation (OTR) monitors a nd pipe the image to a digitizer system to measure the width of the spot due to energy error. Halls A and C have dedicated digitizers so they can monitor the energy error online. The operations staff has access to the same information and can easily respond to errors in momentum. We use synchrotron light monitors in arcs 1 and 2 to monitor the stability of our linacs with a resolution of 1e-5 and minimum detection current of ~ 1 nA. The data from the OTR systems is readily available to the user and typicall y is part of their data stream. We are presently designing a synchrotron light monitor for the injection region.

The Fast Feedback System is used to suppress any power line harmonics that may be present on the beam by modulating an RF vernier system while monitoring BPM's in dispersive locations.

6.4 Emittance

At present we have no way of monitoring the beam emittance online, but we are in the midst of developing a solution. In the meantime we perform harp swipes at multiple locations in Halls A and C and calculate the emittance based on the beam aspect ratio at five locations. We also have the capability of measuring the emittance in the injection region using a similar multiple harp technique.

The measurement results are posted in the electronic log and are ac cessible by the experimenter and all accelerator staff.

A system that monitors beam transfer functions from the injector to the experimental end - station is under development for improving optics reproducibility and monitoring at Jefferson Lab. The measurements are based on small amplitude excitation of the transverse beam motion using four correctors in the injector and subsequent observation of beam motion in Halls A and C. Using four correctors allows one to extract a full set of betatron transfer functio ns. Four different frequencies of less than 1 kHz are used to distinguish each of the four correctors' excitations. The excitation amplitude is far less than the beam size, so there is no beam quality deterioration. This diagnostic will utilize hardware from two existing systems – the Beam Scraping Monitor (providing excitation) and the Fast Feedback System (providing beam position monitoring). The two systems lack inherent phase synchronization; however using more monitors than correctors allows one to det ermine the excitation's amplitudes and relative phase for each of the four frequencies. These are used in a least squares fit against the optics model, which yields the amplitude and phase of the incoming betatron motion from each of the four correctors. T he output will be monitored by operations staff and provided to the experimenter.

6.5 Current Stability

Beam current is monitored with cavity based systems in the injector and Halls A and C. Hall B uses a photmultiplier based measurement to monitor beam curren t as well as the output from the nA BPM system. The operations staff and experimenters both have access to the data. Feedback systems are used to stabilize the beam current by adjusting the intensity of three independent lasers at the injector photocathode.

6.6 Helicity Correlated Current Stability

The Polarized Electron Source is typically configured to flip the sign of the polarization at a 30 Hz. rate. Any changes in beam current as a function of helicity are undesirable as it adds an additional error term for the experimenter. We minimize this effect by monitoring a photmultiplier system in Hall B, which is fed back to optical elements on the Polarized Source laser table. Operations and Hall B staff monitor this error signal from their control rooms.

6.7 RMS Spot Size

The beam spot size on target is measured with Harp systems in all three experimental end stations. The measurement and correction process is invasive and slow. We are presently developing solutions to minimize the time for optimising the beam aspect ratio. We will be using an OTR system in Hall A and insertible scintillators in Halls B and C. All three monitors will be fed to digitizers with automated quadrupole adjustments to optimise the spot size. Monitoring will be part of the Emittance monitoring application. The information will be provided to both the experimenter and Operations staff.

7. AREAS OF CONCERN

While we would like to believe that we have a good handle on providing quality beam to the experimenter there is always room for improvement.

7.1 Specification Creep

A process of continuous improvement of beam stability is what we strive for. We identify as early as possible reasonable beam quality criteria. When we meet a particular specification consistently there is a tendency for the User to want to tighten the acceptable error window. Getting all parties to agree to the extent to which we tighten specifications is challenging. We could do a better job of providing a more consistent process for identifying when specifications can be changed.

7.2 Operations Liaison Program

The success of the Operations staff member as a liaison to an experiment depends on the availability of collaboration members for meetings and the operator's schedule. With a distinct person assigned to each experiment the Accelerator Division Experiment Coordinator winds up working with many people for a relatively short duration, which can yield inconsistent results. We have recently changed the program by assigning one Operations Liaison to each experimental end station for a one or two year term. This person will have the opportunity to develop a working relationship with the Accelerator Division Experiment Coordinator and will also work closely with technical staff from each experimental end station.

7.3 Visibility of Beam Quality Crite ria

We could benefit from making beam quality specifications more apparent through the development of a web-based tool. This would allow easy access to the information for all staff and enable specific persons to change specifications remotely as required. This level of consistency and availability of information will ensure that the Users and Operations staff are in agreement as to what the expectations are. More timely reviews can then occur at our morning summary and weekly scheduling meetings.

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