RUNTIME ACCELERATOR CONFIGURATION TOOLS AT JEFFERSON LABORATORY

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Abstract

RF and magnet system configuration and monitoring tools are being implemented at Jefferson Lab to improve system reliability and reduce operating costs. They are prototype components of the Momentum Management System [1] being developed. The RF is of special interest because it affects the momentum and momentum spread of the beam, and because of the immediate financial benefit of managing the klystron DC supply power. We describe present and planned monitoring of accelerating system parameters, use of these data, RF system performance calculations, and procedures for magnet configuration for handling beam of any of five beam energies to any of three targets.

1 INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) consists of two 1497 MHz recirculating electron linacs and the associated beam transport lines. Each linac provides a nominal energy gain of 400 MeV, for a final beam energy of 4 GeV after five acceleration passes. The injector provides three interleaved 499 MHz electron pulse trains, one for each of the three experimental halls. The machine typically operates at a fixed linac energy for weeks at a time, with most of the magnets in the system held at a constant field during such times. The major exceptions are orbit feedback correctors and the magnets and RF separators used for selecting the number of acceleration passes for the pulse train destined for each hall.

The present implementation is file-based, using a collection of awk, perl, and tcl scripts [2]. The user interface unifies these from an operator's perspective, but has been used so far only for generating RF and magnet parameters. Configuration data generated is downloaded by operators with the standard tools used during accelerator operations.

2 TYPICAL CONFIGURATION TASKS

The configuration needs of the accelerator, generally in order of frequency of execution, are:

- Configure linac gradient distribution respecting:
  - RF cavity performance
  - RF system line power consumption
  - available klystron power
- Switch beam destinations
- Switch pass count of beam to a hall (coarse momentum control)
- Provide variable acceleration per pass (fine momentum control)

We have delivered beam from our polarized source for checkout of the source and polarimeters, and will soon be adding polarization to the configuration tasks.

The overall goal is to provide a unified interface with minimal execution time and error rate for:

- RF reconfiguration
- changing beam destination or pass count
- changing acceleration per pass
- setting on-target polarization

The most mature of the configuration tools is the RF gradient calculation. It is used to determine usable gradients for the RF cavities at the expected total beam loading, which are then used to distribute gradient along the linacs.

3 REGIONS OF THE ACCELERATOR

The accelerator is naturally divided into regions successively occupied by the beam as it is accelerated and extracted (see Figure 1). Interlocks for devices such as valves and vacuum pumps must be enabled while carrying beam, but may be disabled for maintenance. Information defining the active portions of the machine for system configuration is exactly that needed to support an advisory (and possibly control) interface with the machine protection system.

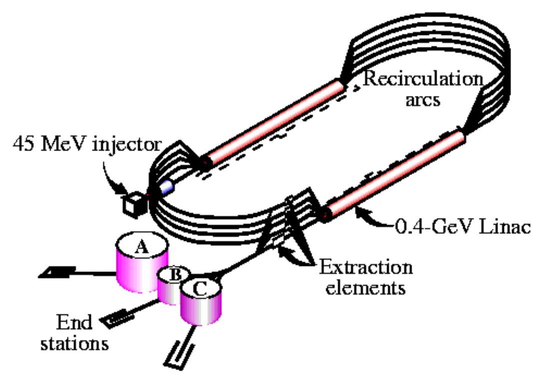

Figure 1: The accelerator is naturally divided into the segments between branch points occupied by the beam on its path to the experimental halls.

With respect to magnet configuration (generally parallel to the machine protection system), these regions are:

- injector (momentum, current, polarization on target)
- linac quadrupoles (matched to RF acceleration profile)
- beamline for each of the first four acceleration passes to the extraction septum

- extraction line (with RF separators) for each of the first four passes
- fifth pass transport including the final extraction line
- destination switching in the beam switchyard
- hall transport lines (variable momentum)

4 RF HANDLING

The primary goal of line power management is provision of adequate beam power within constraints set by the electrical utility's demand charge schedule, rather than incremental reduction of energy use. Excessive power demand increases the billing rate for all site power usage. The power usage is adjusted by a combination of reducing the klystron DC supply voltage and reducing the cathode current (using the klystron modulation electrode). The system characterization required for efficient use of the available capacity also results in early identification of weak components. Reducing the klystron cathode current also allows reduction of the filament temperature without running the cathode in emission-limited conditions. This increases tube lifetime and decreases maintenance costs and frequency of online failures.

4.1 Limitations on RF Gradient

The calculation of maximum gradient for each RF system outlined below uses both generic and individually measured characteristics. Measurements for individual RF systems include the rms acoustic vibration level and loaded Q. Generic dependences on klystron voltage and cathode current are used to extrapolate from measured conditions to other configurations. The information required for RF configuration is:

- Klystron DC HV and cathode current
- Active cavity complement
- Required energy gain per linac
- Anticipated beam loading
- Limiting gradient for each cavity

Assuming that the cavity accelerating voltage $\vec{E}$ itself is fixed, the fields in the cavity satisfy the vector equation:

$$\left(1 - j\frac{\omega_d}{\omega_f}\right)\vec{E} = 2\vec{K}\sqrt{\frac{R_c}{l}} - R_c\vec{I} \qquad (1)$$

where $\vec{K}$ is the incident wave amplitude in $\sqrt{\mathrm{Watts}}$, R_c is the coupling impedance $Q_L \cdot (r/Q)$, ω_d is the (time varying) frequency error, and $\omega_f = \omega_0/2Q_L$. The detuning angle ϕ is given by

$$\tan(\phi) = \frac{-\omega_d}{\omega_f}$$

The circulating beam current $\vec{I}$ (the sum of current for each experimental hall times the pass count) is used to calculate the maximum gradient each RF system can support.

For any given machine setup, the available gradient $|\vec{E}|$ is computed on a cavity by cavity basis, given an assumed current $|\vec{I}|$. The power available from the Klystron is derived by scaling from available measurements by (cathode voltage)$^{5/2}$, and then derated if the cathode current is reduced by use of the modulation electrode of the klystron. The value of ω_d/ω_f is conservatively estimated to cover three sources of detuning: 1.) 3.5 times the measured rms acoustically driven detuning for that cavity, 2.) a $10°$ allowance for the deadband of the mechanical tuner control and 3.) an $8°$ allowance for drift and other tuner control loop errors. The machine is assumed to be operated with perfect cresting ($\vec{I} \parallel \vec{E}$).

The final value for available $\vec{E}$ for each cavity is limited to the maximum rated gradient for that cavity. These maximum usable gradients are downloaded into the control system as limits on the gradient setpoint for each RF system. The actual gradient setpoints are subsequently calculated online [3] as needed, the operators providing any additional limits appropriate from time to time (due to 2K region waveguide vacuum degradation, or instability of the RF regulation, as common examples). All operational cavities not used for feedback energy stabilization are set to the same fraction of their available gradient. An empirical scaling factor input by the operators for all cavities in a linac (typically between 1 and 1.01) allows for beam setup even with some of the cavities off-crest. The total energy available from all cavities in the linac is compared with the desired machine setup; we call any available E beyond that required for setup of each linac our headroom. Headroom values less than 10% of the desired linac energy gain have been operationally difficult, given the remaining uncertainty in the calculations and demands on this reserve as cavities are taken offline for maintenance.

4.2 Additional RF Optimizations

Minimizing the momentum spread of the beam delivered to the experimental halls requires on-crest acceleration of the beam in each RF cavity. Once the crested phase setpoint is determined, the cavity must be run near resonance for greatest efficiency of coupling RF power into the beam. Both of these parameters are measured periodically at CEBAF [4, 5], as the regulation systems for both have residual drifts from thermal effects and aging of components.

The relative phase of the RF drive field $\vec{K}$ and cavity field probe signal $\vec{E}$ in Eq. 1 is a monitored as the detuning angle. For cavities properly crested and on resonance, $\vec{K}$, $\vec{E}$, and $\vec{I}$ are aligned. The beam loading dependence of the detuning angle allows for passive monitoring of the difference of these two parameters during normal operation. Interruption of the delivery of as little as 100 μA of total circulating current, whether due to a system fault or deliberately, causes a shift in detuning angle from which the phase relationship of the beam loading and the klystron drive power may be calculated. This provides individual monitoring for each cavity in the system. Independent drift of either parameter can be detected, and the periodic cresting and cavity tuning measurements mentioned above will detect accidentally coincident drifts. Shifts in both of these parameters have been observed in the past due to degraded cabling or to internal RF module faults. Early detection and correction are very desirable.

5 MAGNET HANDLING

The control parameter used for the magnets is the straight-line path integral of magnetic field (G cm) for dipoles or of gradient (G) for quadrupoles. Future plans are to provide a beam momentum value for each point in the system, so that the control system can calculate the required magnet current from geometrical parameters such as lens strength or bending angle. Scaling the system to various energies is expected to be possible using a master template. As we develop experience with the machine at different energies, we expect to be able to separate the corrections required for static perturbations like the earth's field. We have had ia few occasions to use linac energy gains other than 400 MeV, and scaling all magnetic fields with the beam momentum has provided a good starting point for final tuning.

5.1 Beam Switchyard and Recombiners

During most accesses to the experimental halls, we divert beam to the beam switchyard (BSY) tuning dump for use in commissioning tests or in system checkout and retuning. At other times, we prepare for delivery of beam of a different energy to an experimental target by changing the number of acceleration passes for the beam before it is directed to the BSY dump. These switchings of beam destination and pass count are simple in concept but have been demanding in practice. The switchyard consists of a vertical recombiner mirroring the spreader near the extraction elements at one corner of the main accelerator (see Fig. 1) and a 3-aperture Lambertson magnet which directs the beam to the three experimental hall transport lines.

By design, the vertical dipoles of the recombiner should be set for fixed bending angles for the beam, with switching among the various destinations effected by referring to a lookup table for the necessary settings. We have found anomalous steering variations of the scale of 50 microradians at the exit of each of the similar recombiners feeding the linacs, potentially associated with variations in the relative timing of cycling the drive currents of these closely spaced dipole strings for remanent field control. These (along with distributed but identified problems with the individual quadrupole and steering magnet channels) are the largest remaining sources of irreproducibility in the machine setup. We are presently searching for sources of coupling between the various magnet strings in these areas, and hope soon to have fixed steering settings for these critical regions.

6 SUMMARY

The CEBAF accelerator will be delivering beam simultaneously to all three experimental halls in the coming weeks, and needs comprehensive system monitoring and reliable setup tools. We are identifying the remaining uncontrolled parameters in the system, instituting monitors for early identification and correction of systems which are prone to drifts, and removing the last major obstacles to high reliability operation of CEBAF for nuclear physics research. The processes unifying the configuration interface for major accelerator subsystems (magnets, RF, and the machine protection system) will ultimately be greatly improved over the prototypes being implemented, but those future developments will be significantly aided by the multi-system integration being done now.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] "Mom-management.doc" by B. Dunham, G. Krafft, and R. Legg, and "Software Requirements for the Momentum Management System" by Michael Tiefenback; CEBAF internal development specifications.

[2] Awk, perl, and Tcl/Tk are standard Unix scripting and interfacing tools, freely available. Perl and Tcl are becoming available on DOS/Windows platforms, as well.

[3] "Rapid Application Development Using the Tcl/Tk Language," J. van Zeijts, Proceedings of the 1995 Particle Accelerator Conference and International Conference on High-Energy Accelerators.

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[5] "Parallel SRF Cavity Tuning by MO Modulation," L. Doolittle, CEBAF internal procedure.