DEVELOPMENT OF A COMMISSIONING PLAN FOR THE APT LINAC

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Abstract

The Accelerator Production of Tritium (APT) facility [1,2] is based on a linac which incorporates both normal-conducting and superconducting RF technology and accelerates a 100-mA cw proton beam to an energy of 1030 MeV or higher, depending on the desired production rate. Commissioning plans to achieve full power operation with minimum beam-induced activation of components have been evolving [3]. This paper presents the main issues and the basic approaches that are now being discussed.

1 COMMISSIONING OBJECTIVES

By commissioning of the accelerator, we refer to the process whereby the components are brought into operation with beam for the first time as a functioning integrated accelerator system. Commissioning need not await the complete installation and alignment of all the accelerator components, but may be done in stages. Two main activities make up the commissioning process. First is the initial setting of parameters, which includes the focusing and steering fields, and cavity-field amplitudes and phases, to values determined by the physics and engineering design. Second are the measurements to characterize the functioning of the integrated system, especially the beam and the RF system. These data will be compared with the predictions of simulation code. Discrepancies that are outside of error tolerances must be understood and, if appropriate, used to update the codes. The commissioning process is the time to detect and resolve any unanticipated performance problems that might arise. Also needed for evaluation of the overall performance are tests of different operating modes. For APT this includes operation with some superconducting cavities turned off, simulating fault conditions, where the rest of the linac is reset to continue beam operation.

2 SPECIAL CONSIDERATIONS FOR COMMISSIONING APT

The experience gained from operating and restarting the LANSCE proton linac, a pulsed machine with multiple beam operation that includes a 6%-duty-factor, 1-mA average current, and 800-MeV final energy, will be our reference point. LANSCE experience has shown that minimizing beam loss during normal operation is important, because beam loss produces radioactivity that restricts hands-on maintenance, and can cause equipment damage. Beam loss could be a concern during commissioning because the parameters are adjusted over a wide range and at times can deviate substantially from the design values. Many steps, including alignment, polarity setting, and calibration of focusing quadrupoles and steering dipoles, alignment and calibration of beam-diagnostic components, and relative phasing of multiple power feeds should be carried out prior to the start of beam tests. Also, commissioning operations that require beam should be done using pulsed beam with as small a beam duty factor and as small a peak current as is practicable, consistent with the capabilities of the beam diagnostics and the ion source. Beam-pulse lengths should be long compared with the transients in the low-energy beam transport and the RF system. We anticipate using cw RF power and pulsed beams with approximately 200-μs pulse length and a repetition rate from 1 to 10 Hz. Depending on the beam current, an RF-system settling time of 30 to 100-μs is expected before steady state is reached. The choice of peak current depends on the procedure. We expect a peak current of about 1 mA to be adequate for measuring the transverse beam-centroid alignment and setting the transverse beam steering. The 1-mA peak current, for which the space-charge forces are small, is suitable for phase scans used to set the phases and amplitudes of the cavity fields. After the 1-mA procedures are completed, the peak current will be increased to 100 mA to evaluate beam and system performance at full space charge and with full beam loading. To limit the beam losses during the commissioning, LANSCE experience suggests that the commissioning procedures should be as simple as possible, and should be done one section at a time, where each section to be commissioned consists of one of more accelerating modules.

After all the parameters have been set, beam measurements will be made to characterize the output beam from that section, using a commissioning beam-diagnostic package placed at the output. After the diagnostic package, a beam stop is installed, which prevents the commissioning beam from inducing radioactivity downstream of the section being commissioned. The beam stops must have sufficient cooling capability to absorb the beam power at 100-mA peak current with materials chosen to minimize long-lifetime activation. After the commissioning of a given section is completed, the diagnostic package and the commissioning beam stop are removed, making room for installation of the next section.

Although dividing the linac into sections helps to locate and fix problems, to keep the commissioning time within reasonable bounds, it is desirable to commission the linac in no more separate sections than is necessary, consistent with the requirement that simple operational procedures be used. For practicality and simplicity, LANSCE experience suggests that all the commissioning steps, including the cavity phase scans, during which the beam energy varies over a large fractional range, be carried out with fixed quadrupole gradients. This requirement leads to a preliminary estimate of perhaps six commissioning-section final energies: 6.7, 10, 21, 54, 211 MeV, and 1030 MeV. A systematic study to determine the optimum number of sections and their final energies is now in progress.

3 SETTING THE PARAMETERS

Setting the parameters affecting the transverse beam dynamics, primarily quadrupole gradients and beam-steering fields should be straightforward except for outright mistakes or possible component failures. Quadrupole gradients can be set accurately to values determined from the physics design by using magnetic-field calibrations. Beam-profile measurements made near the major focusing-lattice transitions can be used to make adjustments in the quadrupole gradients if needed to improve the beam quality. As the beam energy increases, the apertures increase and good transmission can be expected over a wide range of the amplitudes and phases of the accelerating cavities.

The main task for the parameter-setting part of the commissioning process is expected to be setting the amplitudes and phases of the cavity fields. Beam measurements are required for this because direct RF field-measurement methods are not accurate enough. Cavity-field parameters can be set using a phase-scan method, in which the phase of each accelerating cavity relative to the input beam is varied, and for each phase, corresponding output beam parameters are measured. The beam measurements for commissioning can be made using both an interceptive method, such as the absorber/collector technique at low energies that measures the accelerated beam intensity above an energy threshold set by the thickness of a copper absorber, or a non-interceptive method based on beam-image-current probes in which signals are induced by the string of beam bunches. Advantages of the absorber/collector method for setting phase and amplitude at low energies are simplicity, and the ability to measure directly the phase width of the bunch from the shape of the curve of accelerated-beam intensity versus input phase.

The beam-probe method allows a measurement of beam arrival time or phase using a single probe, or beam-energy using a pair of probes separated by a drift distance. The non-interceptive beam-probe method allows more accurate measurements over the full range of beam energies and at full peak current. In the normal-conducting linac, plots of either the output-beam energy from a pair of probes or the output-beam phase from a single output probe, versus cavity phase are made as a function of the cavity amplitude. By comparing these curves with corresponding curves predicted by the simulation code, the RF parameters that produce the design values of the cavity amplitude and phase can be determined. The method based on a plot of output-beam phase versus cavity phase gives greatest accuracy when the longitudinal phase advance between the beginning of the cavity and the output probe is near an odd-integer multiple of 90°. The method involves plotting the curves for two amplitudes, one for the amplitude corresponding to 90° phase advance, and one for the design amplitude, which is known from simulation relative to the former amplitude. The two curves intersect at a known phase near the design phase. This method has the advantage that intertank spaces will generally be available allowing us to install an output probe near a location within the accelerating module corresponding to an odd-integer multiple of 90° phase advance. The other method based on a plot of output energy versus cavity phase is most accurate when the longitudinal phase advance is an integer multiple of 180°, a property that is not generally satisfied if the probes are installed in the drift space after the module.

A phase-scan procedure is also planned for the cavities in the high-energy superconducting linac. In this case the RF modules consist of either two or three independent superconducting cavities, driven by one klystron, and the longitudinal phase advance is small compared with 90°. Each cavity has an RF pickup probe that samples the field in the cavity, and whose amplitude can be calibrated in the laboratory using measurements of power and quality factor Q to an accuracy of about ±5%. After the cavities are installed in their cryostats in the tunnel, and before beam is injected into the linac, the cavity resonant frequencies are set by calculation to compensate for beam loading, the cavity fields are set to approximate values based on the laboratory calibrations, and relative phases of the cavities within the same module are set using low-power RF measurements and by adjusting mechanical phase shifters. This one-time setting of the mechanical phase shifters is determined by the design values of the cavity phases relative to the beam and the nominal value of the beam velocity at that location.

After presetting these parameters, we use the beam to determine the required RF drive phase that gives optimum phasing of the whole RF module relative to the beam, using a phase-scan measurement. In this case we obtain from the measurements a curve of output energy from a pair of beam probes versus RF drive phase. The curve is a skewed sinusoid, and using the phase locations of the peak and valley from the measured curve, we can set the RF drive phase to the design value. A complete analysis of tolerances has yet to be completed, but if uncertainties are limited to those from the beam diagnostics, the phase can be set to within a degree of the design value.

Because of the accuracy of the beam-energy measurement, the klystron amplitudes can be adjusted at each stage to minimize cumulative energy errors as we proceed down the linac. The beam energy from the pair of beam probes is obtained from the relation $\phi(\text{deg})=360L/\beta\lambda$ and solving for β, where ϕ is the measured phase difference of the signals induced by the beam in the probes, L is the spacing of the two probes, β is the beam velocity relative to the speed of light, and λ is the wavelength at the bunch frequency of 350 MHz. For example, at 1 GeV (β = 0.875), L = 8.54 m (using the spacing of two detectors separated by a lattice period), and λ = 0.857 m, we find that ϕ = 4102° or 142° (mod 360°). We are more interested in the energy uncertainty ΔW from the measurement. This can be calculated from

$$\Delta W = mc^2\gamma^3\beta^3\left(\frac{\lambda}{L}\right)\left(\frac{\Delta\phi(\deg)}{360}\right).$$

If we use mc^2=938.3MeV, L=8.54m, γ=2.066, β=0.8750, λ=0.857m, and $\Delta\phi$ =±3.1° (a conservative estimate of the "accuracy" from the beam diagnostics) we obtain a corresponding uncertainty in the beam-energy of ±4.8 MeV, which is only ±0.48%, sufficient to prevent a significant accumulation of an energy error.

4 CHARACTERIZATION OF THE ACCELERATOR SYSTEM

Experience from commissioning accelerators over the years has shown that as new parameter regimes are explored, new and unanticipated effects can appear. Especially because of the need to control beam loss to maintain high availability, carrying out a comprehensive set of measurements of the beam properties after setting the parameters of each stage is an important requirement. Such data taken at the end of each newly commissioned section will be compared with the predictions of the numerical simulation code. Discrepancies can be used to identify problems, which may include either component errors or physics effects that may not be included in the beam-dynamics model. Measurements made at the low-velocity end of the linac, where space-charge is important, are particularly important because discrepancies between measurements and simulation can provide an early warning of possible problems that could lead to beam loss at the high-energy end of the machine.

Measurements should be chosen so that, by comparison with the simulation code, we can answer three main questions. First, do we observe the expected low-peak-current beam characteristics, where space-charge effects are negligible? Second, do we observe the expected rms properties of the beam at the full peak current? These rms properties depend on the space-charge force, and should be compared with the numerical simulation code. Finally, do we understand the observed beam distribution including the beam halo, its density profile and its extent?

Using a commissioning beam-diagnostic package placed at the output of the section being commissioned, we plan to measure the beam current, beam loss, transverse beam profile, transverse rms emittance, transverse beam halo, final beam energy centroid, and bunch length at the output of each commissioning section [4]. Beam-loss measurements depend on the beam-halo characteristics, which depend on beam mismatches in either the longitudinal or transverse phase space [5]. Multiple transverse profile measurements using permanently installed beam-profile monitors will be compared directly with the simulations, and will also be used to determine the rms emittance during both commissioning and nominal operation. Because of its interceptive nature, a separate phase-space measurement using a conventional slit and collector device will provide beam-emittance measurements during low peak current operations. Comparison of the emittance measurements from the two methods will provide a calibration of the multiple profile measurements, which will be used to characterize beam operation after the commissioning process. Also, transverse beam-halo measurements will be obtained in which we acquire the transverse projected profiles of the beam from 3 to 5 rms-widths at multiple locations. Finally, for the longitudinal dynamics, we depend primarily on beam-centroid phase and energy measurements, and bunch length or phase spread measurements [4].

Prior to implementing supermodule RF systems in the normal conducting linac, klystron phase calibration measurements must be performed. These measurements are made to ensure that the RF phase of the klystrons have a unique and fixed relation to one another. In addition, the low-level RF (LLRF) control system has built in some on-line system-characterization capabilities [6]. These enable the operator to inject a signal of known frequency characteristics and measure the system response. After the RF parameters are set, measurements will be made to characterize the RF system performance under full beam-loaded conditions. These measurements will include the reflected power, and the errors signals associated with phases and amplitudes of the cavity fields, which are controlled by the LLRF system.

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6 REFERENCES

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