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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.

Objectives of the Commissioning Process

By commissioning of the accelerator, we refer to the process whereby the components that have already been individually tested, installed, and (if they are in the beam line) optically aligned, are brought into operation with beam for the first time as a functioning integrated accelerator system. In principle, 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 is the acquisition of data 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 codes. 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 the 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.

Special Considerations for Commissioning APT

The experience gained from operating and restarting the LANSCE linac, a pulsed machine with multiple beam operation that includes a 6%-duty-factor, 1-mA average current, 800-MeV proton beam, will be our reference point. LANSCE experience has shown that minimizing beam loss is very important, because beam loss produces radioactivity that restricts hands-on maintenance, and can cause equipment damage. Beam loss and activation when commissioning a section of the accelerator in a staged commissioning scenario can complicate the subsequent installation of higher energy sections of the machine. Beam loss is a concern during commissioning because the parameters are adjusted over a wide range and at times can deviate substantially from the design values. This means that beam tests should be carried out only when necessary. 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 peak current chosen varies depending 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 tests the peak current will be increased to 100 mA, again with pulsed-beam, 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. Downstream of the diagnostic package, a beam stop is installed, which prevents the commissioning beam from inducing radioactivity in the accelerating and focusing structures 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 to allow the installation of the next section.

To meet the schedule, it is desirable to commission the linac in no more separate sections than is necessary, consistent with the requirement that a simple operational procedure 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.

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. These parameters will be set using a phase-scan method, in which the phase of each accelerating cavity relative to the input beam is varied by adjusting the phases of the RF drive signals that deliver power to the cavity. A pair of beam-image-current probes downstream of the accelerating structure is used to obtain timing signals induced by a string of beam bunches, and the output beam energy is related to the measured phase difference of the signals induced in the two detectors. In the normal-conducting linac at relatively low energies, plots of either the output beam energy or the phase of 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 design code, the RF parameters that produce the design values of the cavity amplitude and phase can be determined. The design amplitude can be determined by searching for the curve corresponding to a particular amplitude for which the output energy or output phase is approximately independent of cavity phase, and the design cavity phase can be obtained from a nearly common intersection point of the curves. Except at very low energies, there is generally plenty of available space and flexibility for placement for the beam-diagnostic components.

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. 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 (using mechanical tuners) 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 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. For example, if the phases of the cavity fields relative to the beam for two cavities within the same module are supposed to be equal, the correct phase shift between the two cavities is just $\omega L/v$, where $\omega=2\pi f$ is the cavity frequency, v is the design velocity, and L is the center-to-center spacing between the cavities.

After presetting these parameters, we use the beam to determine the required RF drive phase ϕ_{kly} 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 V versus ϕ_{kly} (or instead versus the phase shift between the cavity RF pick up voltage and a beam-image-current probe), where V is a digitized output signal proportional to the phase shift between the two beam detectors. The curve is a skewed sinusoid, and by comparing the phase locations of the peak and valley from the measured curve with those predicted by calculation, we can set the klystron phase to the correct value relative to the beam. 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.

The beam energy at the output of the module 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 two beam detectors, L is the spacing of the two detectors, 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

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

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%. 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.

Characterization of the Accelerator System

Experience obtained 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. More detailed measurements are possible during the commissioning, when plenty of space is available at each section's output to install a variety of beam-diagnostic equipment. Measurements made at the low-velocity end of the linac 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, particularly the centroids and rms beam properties? Because the space charge effects are negligible, these measurements will depend primarily on the applied focusing fields. 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 accurately predicted by numerical simulation codes. 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 bunched, peak, and average beam currents, beam loss, transverse beam profile, transverse phase-space distribution and rms emittance, transverse beam halo, final beam energy centroid, and bunch length at the output of each commissioning section [4]. The measurement of the three types of current will allow us to monitor and quantify the micropulse and macropulse structure of the beam. 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. Additionally, beam-halo measurements will be obtained in which we acquire the transverse projected profiles of the beam from 3-rms-widths to approximately 5-rms-widths at multiple locations similar to the beam profile measurements. Since beam mismatches cause beam halos, these halo measurements will be sensitive to beam mismatches. Finally, for the longitudinal dynamics, we depend primarily on beam-centroid phase and energy measurements, and bunch length or phase spread measurements. For further details of how these measurements are performed, refer to reference [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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