OPERATING ATLAS; THE WORLD’S FIRST SUPERCONDUCTING HEAVY-ION ACCELERATOR

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Abstract
ATLAS (Argonne Tandem Linear Accelerator System) has been providing heavy-ion beams for Argonne National Laboratory’s Nuclear Physics Heavy-Ion Program for the past 23 years. Over time we have learned the special needs that this superconducting machine requires, such as; how to cope with power bumps, safety issues involved with cryogens, high-Q resonant cavities, and mechanical vibration. These are just a few of the challenges that must be addressed to operate this superconducting accelerator. This paper shall discuss the nuances that has made ATLAS a world-class accelerator.

1. INTRODUCTION
ATLAS is the world’s first superconducting RF linear accelerator for heavy ions. First beam was accelerated through a portion of the ‘booster linac’ section in 1978. Today ATLAS is a National User Facility. More than 60% of the experiments performed at ATLAS are for groups outside of Argonne National Laboratory. The accelerator operates twenty-four hours a day, seven days a week. Annually ATLAS achieves approximately 6000 hours of beam on target with over 90% reliability.

Fig. 1: Layout of the ATLAS Facility
Heavy-ion beams ranging over all possible elements, from hydrogen to uranium, can be accelerated to energies as high as 17 MeV per nucleon and delivered to one of three target areas. The beams are provided by one of two ‘injector’ accelerators, either a 9 million volt (MV) electrostatic tandem Van de Graaff, or a 12-MV Positive Ion Injector (PII) comprised of a low-velocity linac and Electron Cyclotron Resonance (ECR) ion source. The beam from one of these injectors is sent on to the 20-MV ‘booster’ linac, and then finally into the 20-MV ‘Atlas’ linac section.

The ATLAS accelerator is constructed with six different superconducting resonator designs. The PII section consists of a range of low velocity ($\beta = 0.009 – 0.037 \, c$) quarter-wave resonator structures, and the Booster and Atlas sections are comprised of superconducting split-ring resonators with a $\beta = 0.06 \, c$ and $0.105 \, c$. Figure 2 lists the details of each resonator class. There are sixty-four niobium superconducting resonators at ATLAS, housed in fourteen separate cryostats units.

2. OPERATION ISSUES

2.1 Superconducting Accelerating Resonators

The heart of ATLAS is the superconducting (SC) cavity. The RF linac is based on short, high-gradient SC cavities closely interspersed with short, high field (6-8 T) superconducting solenoids. A benefit derived from a SC linac constructed in this configuration is that the rapid alternation of strong radial and short, high-gradient longitudinal fields maintains the beam quality through the machine [1]. In addition, each accelerating cavity is independently phased. The independent phasing, intrinsic to a SC cavity array, allows the velocity profile to be varied and permits acceleration of a large range of charge-to-mass ratio ions. This makes optimum use of the maximum voltage and enables higher energies for the lighter ions.

Independent phasing also provides the capability to configure the machine in such a way as to compensate for a non-functioning resonator. By the having the ability to skip over a non-functioning resonator, machine reliability is greatly improved. Independently phased resonators are in essence individual accelerators. Each one has to be controlled separately, but must stay phased locked within one degree of each other. The complexity of tuning an accelerator like ATLAS would be very difficult without the use of modern computer systems. In addition, an independently phased array like ATLAS requires many more control elements. When building a control system of this intricacy there must be a high level of reliability if one wants to achieve 6000 hours of beam on target each year.

Because the RF power requirements for SC cavities are low, CW operation is cost effective. The low RF losses of SC cavities also enable large apertures and high field gradients. The accelerating field in these cavities ranges from 2.8 MV/m to as high as 5 MV/m.
Superconducting resonators have several unique characteristics that affect operations. They are vibration, multipacting barriers, and electron loading. The effects of these are discussed below.

2.2 Vibration

In all resonant cavities, ambient acoustic noise will excite mechanical vibration modes that cause fluctuations in the resonator’s eigenfrequency. In room temperature resonant cavities these fluctuations are much smaller than the resonator bandwidth and do not affect the RF phase. However, due to the low RF losses in superconducting cavities the bandwidths are typically a few tenths of a hertz. In an accelerator environment it is difficult to reduce the coupled mechanical vibration below a few tens of hertz, therefore some method must be employed to compensate for the eigenfrequency fluctuation. At ATLAS an electronic ‘fast tuner’ is used to control the RF phase of the resonators. [2]

The fast tuner is mounted on the resonator and is coupled to the cavity’s magnetic field. The circuit is based on PIN diodes that switch, at a rate of 25 kHz, between two different impedance states. The eigenfrequency of the resonator changes when the diodes switch from one impedance to the other. The values of the impedances are chosen so that the frequency shift brackets the operating clock frequency. As the resonator’s eigenfrequency is driven off the clock frequency by microphonic noise, the feedback on the fast tuner drives the resonator frequency the 180 degrees out of phase with the microphonically induced shift. By switching at a fast rate, the frequency error is corrected to less than 1 degree.

From a daily operation standpoint, this means that one must be aware of where portable mechanical equipment is placed. A vacuum pump or out of balance fan may couple acoustic noise into a resonator and drive the eigenfrequency variations beyond the control of the fast tuner. Even certain modes of refrigeration operation may cause vibration problems. Once these noise sources are recognized they are eliminated and normal operation can resume.

Due to the geometry of the very low beta (.009 c) resonators, a damping device has been developed to reduce the amount of mechanical vibration, thereby reducing the control window of the fast tuner. The damper employs a weight mounted in the inner coaxial line. The pendulum motion of the inner line performs work by sliding the weight on a plate thus damping the amount of mechanical motion. The damper has been installed in three of the lowest beta resonators with the effect of reducing the mechanical vibration amplitude by a factor of six. [3]

2.3 Multipacting Barriers

When a resonator is first cooled down from room temperature, it will not immediately achieve high field gradients. Electrons liberated from the surface at low field levels, typically a few kV/m, traverse to another surface and liberate secondary electrons. It is possible to establish an ‘orbit’ of electrons of the right path length so to be in sync with the alternating voltages on the resonator surfaces. These multipacting barriers will inhibit achieving high field levels until emitting objects are sufficiently depleted in that region. This phenomenon is strongly related to the cavity geometry and the cleanliness of the surface. With the application of RF power, and the passage of time, eventually all of the multipacting barriers will go away. To condition the multipacting barriers, ATLAS cavities need anywhere from 1 hour to eight hours, depending on their geometry. Once gone the resonators will operate normally until it is either warmed to room temperature, or has been exposed to poor vacuum conditions. The RF control modules have been designed so that this conditioning process is just a flip of a switch.

2.4 Electron Loading

At high field gradients, the Q of the resonators decreases. Figure 3 illustrates a typical of a resonator Q curve. The high level Q can be increased by pulsing the resonator with short, high power RF. By increasing the Q, the power dissipated into helium is reduced, thereby reducing the overall load on the refrigerator. This conditioning must be repeated from time to time to maintain the lower power losses.
into the helium system. The ATLAS cryogenic system is designed for an average heat load into the helium of approximately 4 to 6 watts per resonator. Pulse conditioning of

![Fig. 3: Typical Q Curve of a Split-ring Resonator. This illustrates the effect of electron loading and the increased load into the helium system.](image)

3. LIQUID HELIUM PLANT

The liquid helium plant is one aspect unique to superconducting machines. At ATLAS, the liquid helium plant is comprised of three separate refrigerators. In total, the refrigerators supply 750 watts of liquid helium cooling. This is distributed between fifteen separate cryostat units. Each cryostat has a dewar that holds approximately 50 to 150 liters of liquid helium. Between the cryostat and the helium distribution system, there is an inventory of approximately 3000 liquid liters of helium.

Utility failure at a superconducting machine is not tolerable. Without electrical power, it is not possible to re-liquefy the boil-off gas from the liquid helium. Since the expansion ratio of liquid to gas for helium is approximately 780:1, an over-pressure situation develops rapidly causing helium to vent from pressure relief devices. Without the proper control systems on the helium plant, a short, two-second-power bump can result in the loss of liquid helium inventory.

Several measures to ensure a reliable system have been taken. The electrical sub-stations that provide power to the facility have automatic switches that will switch over to a secondary feed line in the event the primary feed goes down. This has reduced most power losses to a manageable duration of anywhere from 1 to 10 seconds. At ATLAS, we have installed Uninterruptible Power Supplies (UPS) on the refrigerator control circuits. These UPS units will allow a power loss of up to 15 to 20 seconds without any adverse affects on the refrigerator system. In addition to the UPS units a Programmable Logic Controller (PLC) system controls the sequence of power-up for the compressors. This controlled re-start is necessary because the start-up current on the compressor motors is large compared to the operating current. If all the compressors were allowed to start at the same time, the current draw would overload the substation.

Even with these measures, an operator must respond to a power bump in a swift and correct manner. There is a ‘Power Bump Procedure’ located at the control console, which must be followed immediately upon a power outage. The average recovery time from a short, 2 second, power loss is
from fifteen minutes to one hour. Prior to the installation of the PLC and substation modifications some extended power outages have resulted in a two-week loss of operation.

Contamination of the helium system with air also poses a serious problem. Our refrigerator runs at a positive pressure. This is an advantage in that if there are small leaks in the helium system, air is not drawn in. During maintenance periods, care must be taken to maintain the integrity of the helium system. Both operator error and mechanical failures have resulted in air freezing out in the helium plumbing. This can be a very difficult problem to solve. In some cases it is nearly impossible to get enough heat to the plugged area to melt the blockage. Upon melting, other areas in the system are still cold and the contamination may migrate to the cold sections. These incidents must be dealt with on a case-by-case basis.

4. SAFETY

Most of the safety issues are the same whether the accelerator is superconducting or room temperature. However, there is a need for special safety measures due to the use of cryogens at a SC accelerator. Large quantities of liquid helium and liquid nitrogen are being transported through occupied work areas throughout the facility. A catastrophic failure of one of the cryogenic supply lines can result in both an asphyxiation hazard and an egress hazard. The egress hazard comes from condensation in the room becoming so dense that one simply cannot see the escape route through the fog. Escape lanes have been painted on the floor to assist in guidance to the exits. To address the asphyxiation issue, oxygen deficiency monitors have been installed throughout the facility. If there is an alarm on this system loud claxons and flashing lights are activated to notify personnel to evacuate the area. In addition, all accelerator personnel are required to complete a course in cryogenic safety.

5. THE FUTURE

There is currently a proposal at Argonne National Laboratory for a SC accelerator facility that will produce and accelerate unstable nuclei. The Rare Isotope Accelerator (RIA) will take advantage the unique characteristics of SC cavities. The RIA driver accelerator will be capable of producing a 400 Mev per nucleon uranium beam at abeam power of 400 kW. In order to obtain these beam energies and power SC cavity technology is integral. To take advantage of the large acceptance of SC cavities, multiple charge states of uranium will be simultaneously accelerated through the linac. Accelerating $10^{13}$ uranium nuclei per second to 400 MeV/u requires two stages of stripping. If only one charge state were accepted after each stripping then the intensity at each stage would be reduced by a factor of about five. By capturing and accelerating all of the most populated charge states, the beam intensity will be maintained with only small losses at the final energies. A study has been done at ATLAS to demonstrate this proposal [4].

References


