PROGRESS OF THE SUPERCONDUCTING LINEAR ACCELERATOR PROJECT AT IUAC

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Abstract

The superconducting (SC) linac system of IUAC, to boost the energy from the existing Pelletron accelerator, is on the verge of completion. Presently, the superbuncher, the first linac accelerating module and the rebuncher are operational. Different ion beams from Pelletron accelerator were further accelerated by all the eight resonators of the first accelerating module and delivered for months together to conduct experiments with the Hybrid Recoil mass Analyzer (HYRA) and the National Array of Neutron Detectors (NAND). During the linac acceleration, the operation of linac was made nearly automated. The remaining two linac cryostats are already installed and aligned in the beam line. The cold tests of the in-house fabricated resonators are currently going on in the test cryostat. On completion of the cold tests, installation of the resonators in the cryostats will be started. An alternate frequency tuning mechanism by Piezo actuator has also been tried out successfully on a SC resonator.

INTRODUCTION

The Pelletron accelerator of IUAC has been delivering ion beams for experiments since early nineties in the energy range of few tens to few hundreds of MeV [1] corresponding to ~ 1 to 8 MeV/nucleon for most of the ion species (figure 1). A Superconducting Linear Accelerator (Linac) was chosen to augment the energy of the ions from the existing Pelletron accelerator. The linac was designed to have a superbuncher cryostat having a single niobium Quarter Wave Resonator (QWR) followed by three accelerating modules, each containing eight QWRs and a rebuncher cryostat housing two QWRs. The complete layout of the Pelletron and linac is given in figure 2. The prototype niobium resonator and the first batch of twelve identical resonators were built by the IUAC personnel in collaboration with Argonne National Laboratory, USA [2]. The remaining resonators for cryostat 2 and 3 are being built in-house with the help of local vendors and using the in-house facilities of electron beam welding, high vacuum annealing furnace and surface preparation laboratory [3]. The fabrication work is almost complete and cold tests of the cavities are going on in test cryostat. Soon the indigenous resonators will be installed in the last two cryostats and beam will be accelerated through the complete linac. Meanwhile, different beams have been accelerated by the first module of linac and delivered to perform experiments with HYRA, NAND and other detection systems.

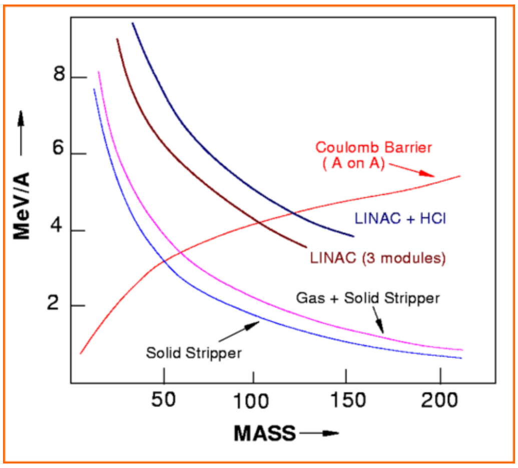

Figure 1. The energy per nucleon curve of the different ion species accelerated through Pelletron (light blue and pink), Pelletron + Linac (brown) and HCI + Linac (deep blue)

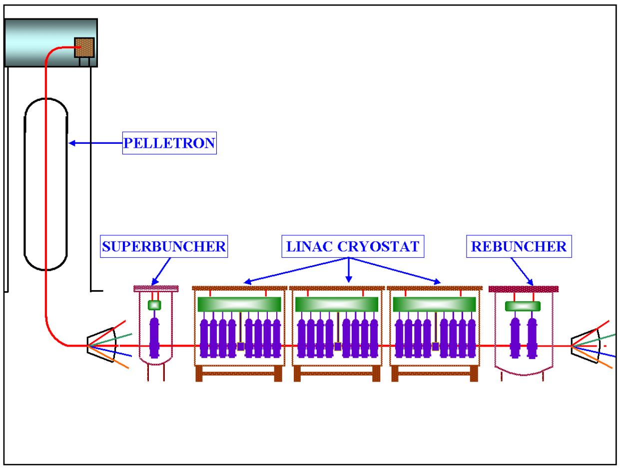

Figure 2. The schematic layout of Pelletron and Linac

Significant progress has been accomplished towards automation of linac operation and a stage is reached where the operational task can be handed over to the operational staff of Pelletron and linac. In a parallel development, an alternate tuning mechanism with Piezo-actuator was tried out successfully on a superconducting resonator [4].

BEAM ACCELERATION THROUGH LINAC

Cold test of the resonators after mounting them in linac cryostat had been started about 4 years back. However the initial problems faced during the tests led to the modification of power coupler design, development of a technique to damp the microphonics picked up by the resonator from its ambience, design change of the SS-jacket to increase the buffer volume of liquid helium at the top of the resonator and fabrication of a more rugged fixture for the mechanical tuner [5, 6]. Thereafter, the linac operation became smooth and in April-May 2009, for the first time at IUAC, all the eight resonators in linac-1 along with the single resonator in SB and two resonators in RB were made operational [7]. During this period, different beam starting from ^{12}C to ^{107}Ag were accelerated and the beam was delivered to conduct experiments for almost two months. Again in July-September 2010, different Pelletron beams accelerated by all the eight resonators of linac-1 were delivered to conduct experiments with the Hybrid Recoil mass Analyzer and the National Array of Neutron Detectors for a period of two and half months.

Steps before accelerating beams through linac

Prior to the acceleration of the beam through linac, the resonators in SB, linac and RB are cooled down initially with LN_2 and then with LHe. Once the resonators become superconducting, they go in to multipacting (MP) and it takes almost two days to perform the MP conditioning for the eight resonators in linac cryostat, whereas for the resonators in SB and RB, one day is sufficient to overcome the MP barriers. The extra time to clean up the MP levels in linac is required due to the close proximity of the eight QWRs installed in the cryostat for which the multipactor electrons can enter easily from one cavity to another inducing fresh MP barrier. During the initial operation of linac, large amount of RF cross talk was also observed which was greatly reduced after replacing the 95% shielded RF cables by 100% shielded cables.

After the MP barriers are conditioned, the resonators undergo high power RF pulse conditioning where RF power of ~100 watts is used with a duty factor of 10-20%. During the pulse conditioning, the drive coupler is kept in the critical coupling condition, so approximately 10-20 watts are used to generate the accelerating field in the cavity. Usually 50-100% improvement in the field levels has been observed after performing the RF pulse conditioning. Recently RF pulse conditioning in presence of pure helium gas after deteriorating the cryostat vacuum from $\sim 1 \times 10^{-8}$ to $\sim 5 \times 10^{-5}$ has also been done in addition to the usual RF pulse conditioning. An additional field improvement of 5-8% was observed by the helium conditioning. The quality factor (Q-value) of the resonator is then measured as a function of the accelerating field. During a recent linac operation, the accelerating fields of the resonators achieved at 4W and 6W of helium power is shown in Figure 3.

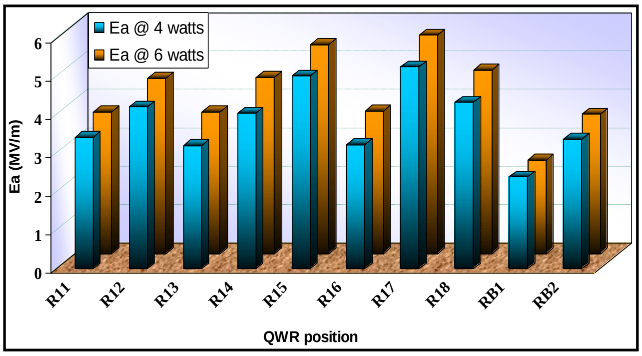

Figure 3. The accelerating field obtained at 4 and 6 watts of helium power. (R11-R18 and RB1-RB2 denote the eight and two QWRs of linac-1 and Rebuncher cryostat)

Problems faced during initial linac operation

During the initial operation of resonators in linac-1, two major problems were faced. The first one was that the accelerating fields obtained during the Q-measurements for most of the resonators in linac-1 were in the range of 1-2 MV/m, lower by a factor 2-3 compared to the fields obtained during their individual tests in test cryostat. This problem seemed to be solved by installing a dome shaped structure at the top of the resonator [5,6]. Secondly, a large forward power (250-300 watts) was required to phase lock the resonators at higher accelerating fields. This was due to the high level of microphonics picked up by the resonators from the ambience. To solve this problem, SS-balls (4 mm diameter) were introduced in to the central conductor of the resonator to act as a mechanical damper [8]. This has reduced the power requirement for phase locking of the cavities by $\geq 50\%$. But still the requirement of RF power to lock the resonators at the similar field obtained at 6 watts of input power is ~ 125-150 watts. It had been observed in the past that the use of high RF power (~ 250-300 watts) at the time of phase locking caused heating of the drive coupler, and that resulted many operational problems. It was further noticed that even if the resonator was phase locked with a forward power of ~ 150 watts or so, temperature of the drive coupler kept on increasing slowly. So to operate the linac for long duration extending for a few months, it was decided that the resonator would be phase locked without exceeding the forward RF power beyond 100 watts with an optimized power coupling coefficient. Consequently, at the time of beam acceleration, the resonators could not be phase locked at the accelerating fields corresponding to 6W of input power. The field levels achieved for the eight resonators installed in linac cryostat # 1 in phase locked condition during beam acceleration and at 6 watts of power during Q-measurements are shown in figure 4.

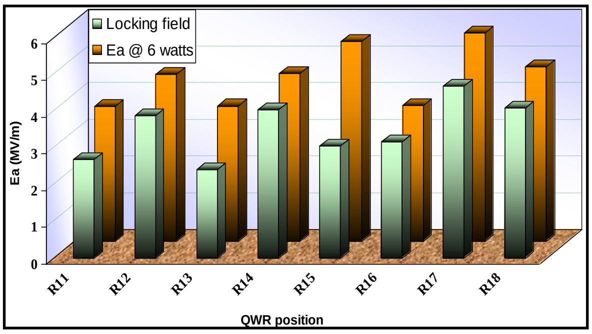

Figure 4. The accelerating field in phase lock condition obtained at ≤ 100 watts of forward RF power.

Beam	Energy from Tandem (MeV)	Δt by MHB (ns)	Δt by SB (ps)	Energy gain LINAC (MeV)
$^{12}C^{+6}$	87	0.95	250	19.2
$^{16}O^{+8}$	100	0.95	150	26
$^{18}O^{+8}$	100	0.96	182	20
$^{19}F^{+9}$	115	1.08	140	25.1
$^{28}Si^{+11}$	130	1.2	182	37.5
$^{30}Si^{+11}$	126	1.2	140	40
$^{48}Ti^{+14}$	162	1.68	176	51.2
$^{107}Ag^{+21}$	225	1.7	232	74.6

Table 1. Beam species accelerated through the first accelerating module of linac

Phase optimisation of the linac resonators during beam acceleration

The ion beams in the range of ^{12}C to ^{107}Ag from the Pelletron accelerator are pre-bunched by the beam chopper and multi-harmonic buncher and a time width of 1-2 ns is injected in to the Superbuncher (SB). After optimizing the bunching field and phase of the SB, a time width of ~150-250 ps is produced at the entrance of linac. With the help of Surface Barrier detectors along with gold foils mounted in a scattering chamber at the exit of linac, the energy centroid of the bunched beam from SB is measured when all the resonators are off. Then the first resonator is turned on and its phase was varied and kept at a value in such a way that the energy centroid of the beam coincides with the value of the centroid when all the resonators are off. Thus the zero cross over of the RF field of the first resonator is found out. The RF phase is then advanced by 70° or decreased by 110° depending upon whether the zero cross over is the bunching or the de bunching one. This can be determined by changing the RF phase in any one direction (increasing or decreasing) and observing the shift of the energy centroid of the beam. In this way, all the remaining seven resonators are optimised to maximise the energy gain of the beam. Few parameters of the different beams accelerated through the linac are presented in table 1.

Role of random phase focussing on the time width of the beam bunch at the exit of linac

At the time of beam acceleration through linac, usually the phase of the synchronous particle at the middle of the first accelerating gap of a QWR is always kept at sin(70) (or cos(-20)) to ensure phase focussing in the longitudinal phase space along with the acceleration. But if the beam is to be transported a long distance after linac, then changing the synchronous phase of a few resonators from 70° to 110° is found to be more beneficial to accomplish the time focussing of the beam bunch. To understand this phenomenon, a simulation code was written to calculate the combination of synchronous phases to be applied on the resonators to obtain the minimum time width of the beam bunch at the target location which is ~ 30 metres from the exit of the first linac module [9]. The calculation showed that for 96 MeV $^{16}O^{+8}$ beam from Pelletron, the minimum time width of the beam bunch would be obtained when the fourth resonator of linac-1 is kept at 110° with the remaining resonators kept at 70°. During the linac acceleration, the time width of the same beam with same energy was measured at the final scattering chamber when all the resonators are kept at 70^0 in one case and with only the fourth resonator kept at 110^0 in the other case. In the latter case, a reduction of ~ 20% in the time width of the beam bunch was measured at the target.

Use of last accelerating resonators as the re-buncher

During the last linac operation concluded few months back, the rebuncher could not be operated due to shortage of liquid helium. So the simulation code was used to find out whether the last linac resonator could be used as a rebuncher to control the time width of the beam bunch at the target. For $^{16}O^{+8}$ and $^{19}F^{+9}$ beams with fixed energy from Pelletron and variable energy gain from linac, a reduction of time width in the range of 33% to 62% was measured after applying the calculated bunching field on the last linac resonator acting as a rebuncher. Without this provision, the time width of the beam bunch increased to ~ 2.2 ns, which was too large to conduct the experiments. However, with the help of the last resonator as rebuncher, the time width was restricted to a value of 0.5 to 1.5 ns on all the occasions [9].

Status of automation of linac operation

To ensure a safe operation of linac with minimum human intervention, a number of steps were taken to automate the linac operation. The different developments in the automation of linac operation are as follows:

(a) Remote control of the phase/amplitude locking of a superconducting resonator was implemented. This had helped to control linac and Pelletron simultaneously with reduced effort at the time of beam delivery [10].

(b) During the phase locking of the resonator, the amount of forward power going to a resonator is monitored in a module and displayed in the control console kept at the control room and other places [11].

(c) In the event of the resonator going out of phase lock, RF power going to the resonator from the amplifier reaches its maximum value which may damage the power cables. A code in python is written to monitor the status of the phase lock condition and to sense the amount of power going in to the resonators. Whenever a resonator goes out of lock and RF power from amplifier goes high for more than a minute, the phase and amplitude locks of the resonator are switched off by the code to reduce the RF power and to protect the power cable [12].

(d) The movement of the drive coupler to feed the power in to a resonator is now controlled by computer with a position read back of the power coupler [11].

(e) An electronic device containing multiple outputs of pulse signal necessary for conducting simultaneous RF pulse conditioning of the resonators was fabricated and used during last linac operation. Each channel of the module is computer controlled with an option to vary their duty cycle etc. [11].

Figure 5. The remaining two cryostats 2 and 3 are installed in the beam line

FUTURE PLAN

The in-house fabrication of the resonators is nearing completion and the cold tests of the resonators to be installed in the cryostats 2 and 3 are going on at present. The performances of most of the resonators measured in the test cryostat are encouraging and the best accelerating field achieved was 6.4 MV/m at 6 watts of helium power. The details of the test results and the improvements in the surface preparation techniques of the resonator are presented in this conference proceeding [13]. At present, cryostat 2 and 3 are installed in the beam line as shown in figure 5. The installation and cold test of the resonators in those two cryostats will begin in early 2011. It is expected that the beam will be accelerated through the complete linac around the middle of 2011.

To phase lock the resonators at the same fields what was obtained at 6 watts of power into helium, forward RF power must be increased to ~ 150 watts. To handle the higher power, use of a semi rigid cable to carry the RF and possibility of electronic damping of the microphonics present in a resonator are being planned.

The present phase locking mechanism of the resonators consists of a helium gas operated mechanical tuner [14] which is quite complicated, less reliable and expensive in long term operation. To replace this existing tuning mechanism, a Piezo based scheme has been devised and successfully tested on a few resonators in the test cryostat [4]. It is planned to incorporate the new tuning mechanism on the resonators of cryostat 2 and 3.

CONCLUSION

Ion beam from the Pelletron accelerator were further accelerated for scheduled experiments by the first accelerating module of linac along with the superbuncher and rebuncher. The remaining two cryostats are already installed in the beam line and the resonators are undergoing cold tests prior to their installation in the cryostats. Off-line cold tests of the resonators in the new linac modules will start soon and subsequently beam will be delivered through the complete linac. The automation process for the linac operation will be further improved and a Piezo-actuator based tuning mechanism will replace the existing helium gas based arrangements.

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