COMMISSIONING AND OPERATION OF SUPERCONDUCTING LINAC AT IUAC DELHI

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Abstract

The major part of the superconducting (SC) linac at IUAC has been operational for the past few years and the last accelerating module is in the final stage of completion. At present the superbuncher (SB), the first two linac accelerating modules and the re-buncher (RB) are operational and ion beams in the mass range ^{12}C to ^{107}Ag from Pelletron accelerator have been further accelerated and delivered to conduct scheduled physics experiments. A method of random phase focusing to select the accelerating phase of the resonators between 70° and 110° has been successfully tried to reduce the time width of the beam bunch delivered for experiments. Presently, to improve the accelerating fields of the linac resonators in phase locked condition, enhancement of the microphonics damping efficiency with bigger diameter SS-balls, testing of an alternate tuning mechanism based on Piezo Crystal and improvement of the cooling efficiency of the drive coupler are being tried out. The outcomes of all these experiments are being implemented on the resonators of the last cryostat which is under commissioning stage.

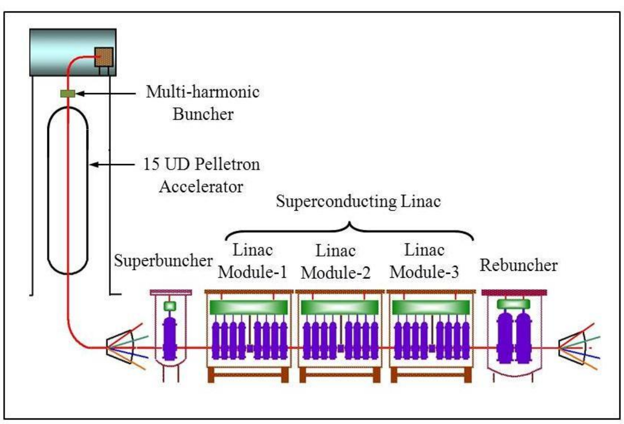

Figure 1: Schematic layout of Pelletron and Linac. The figure is not to scale.

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]. 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 1. The prototype niobium resonator and the first batch of twelve resonators were built by IUAC in collaboration with Argonne National Laboratory [2]. The remaining resonators for module 2 and 3 are indigenously fabricated using the in-house facilities of electron beam welding, high vacuum annealing furnace and surface preparation laboratory [3]. Eight indigenous resonators were installed in the second module and different beams were accelerated through the first two linac accelerating modules with the help of superbuncher and rebuncher. At present the fabrication work for the remaining resonators to be installed in the last linac module is in the final stage.

BEAM ACCELERATION THROUGH THE FIRST TWO LINAC MODULES

The beam acceleration in the mass range of ^{12}C to ^{107}Ag by the first accelerating module with the help of SB and RB resonators are being carried out since last few years [4,5,6]. Recently, the second accelerating module became operational and during this test, beams were accelerated by the sixteen resonators of module 1 and 2. The accelerating field obtained at ~6 watts of power and the phase locked fields at the time of beam acceleration are shown in figures 2 and 3. During linac operation, it was observed that for many resonators, there was a substantial reduction between the phase locked fields and the accelerating fields obtained at 6 watts of input power. A number of steps have been taken to tackle this problem and these are presented in next section.

At the time of operation of the first two linac modules, three beam species from Pelletron accelerator were further accelerated through linac. The final beam was delivered for several months in the beam line of Hybrid Recoil Mass Analyser (HYRA) and National Array of Neutron Detector (NAND) to conduct Nuclear Physics experiment. The beam and their final energies are presented in Table-1.

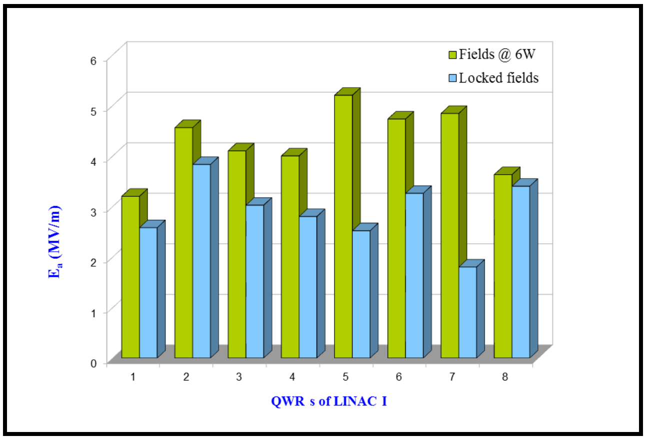

Figure 2: Accelerating field gradients, E_a at 6 watts of input power and phase locked fields at the time of beam acceleration for the resonators in linac-1.

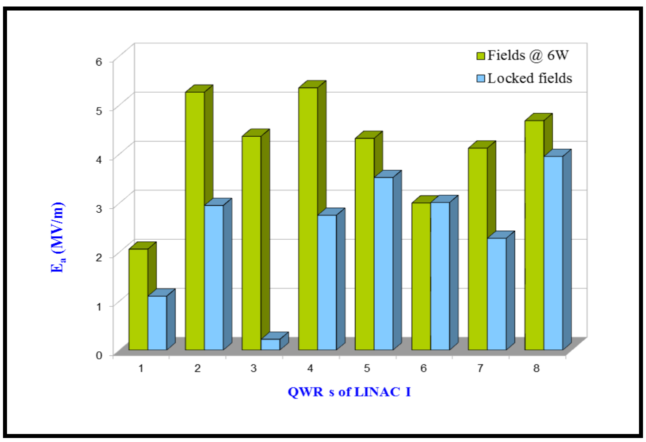

Figure 3: Accelerating field gradients, E_a at 6 watts of input power and phase locked field at the time of beam acceleration for the resonators in linac-2.

Table 1: Beam Species and Energies Delivered for Experiments

Beam	Energy from Tandem (MeV)	Energy gain LINAC (MeV)	Total energy delivered
$^{19}F^{7+}$	100	37	137
$^{28}Si^{11+}$	130	60	190
$^{31}P^{11+}$	130	58	188

EFFORTS TO MATCH THE PHASE LOCKED FIELDS WITH THE FIELDS OBTAINED AT 6 WATTS OF INPUT POWER

For the resonators installed in linac modules, large amount of RF power is required to bridge the gap between the phase locked fields and the fields obtained at 6 watts of input power. However the power coupler, power cable and the other accessories of the resonator are not well equipped to sustain this high power for prolonged duration. The reason for the requirement of high power is that the resonator picks up vibration from the microphonics present in the ambience of the cryostats. This vibration translates in to RF frequency jitter whose maximum value has been measured to be ~ ± 50 Hz. If the Q-value of the resonator at the field of ~ 4 MV/m at 6 watts of input power is typically ~ 2.0×10^8, to accommodate a bandwidth of ± 50 Hz, the coupling coefficient, β will be equal to 200. The forward power required from the amplifier (P_{amp}) is related to β by the following equation:

$$P_{amp} = \frac{(\beta+1)^2}{4\beta} P_{cavity}$$

where,
P_{amp} = RF forward power required from amplifier
β = Coupling coefficient
P_{cavity} = RF power required by the resonator to generate the accelerating field (typically 6 watts).

So the resonator can be locked at the fields obtained at 6 watts of input power but it will be possible only with a supply of huge amount of forward RF power (~ 300 watts). But since the phase locking of the resonator with ~300 watts of power caused several operational problems in the past [4], so it was decided that the resonator would be operated at an accelerating field which could be phase locked with 100 watts of RF power.

The second reason for the lower electric field in phase locked condition with ~100 watts of RF power is the large value of stored energy of the resonator ($0.11J/(MV/m)^2$) which is intrinsic in nature to the cavity. The relationship between the power required from the amplifier (P_{max}), the stored energy (U) and the amount of frequency jitter ($\delta\omega_{shake}$) due to the presence of microphonics, is given by:

$$P_{max} = U.\delta\omega_{shake} \text{ -----(1)}$$

whereas U is related as

$$U = U_o E_a^{\,2}$$

U_0 is the stored energy at 1 MV/m and E_a is the average accelerating fields.

As the intrinsic stored energy at 1 MV/m is reasonably high, the resonator can not be phase locked at a field greater than ~ 3 MV/m for a total frequency jitter of 100 Hz with a forward power of 100 watts. If the resonator is to be phase locked at 4 and 5 MV/m, the amount of forward power required will be 160 and 250 watts respectively for the same amount of frequency jitter. Therefore to lock the resonators at higher fields, three different approaches are being simultaneously implemented in the linac resonators and they are discussed in the following subsections.

Improved Vibrational Damping of the Resonator with Bigger Diameter of SS-balls

Already an innovative vibrational damping mechanism [7] had been adopted and successfully used in all the resonators of module - 1 and 2. However, to extend the success of this mechanism, more extensive experiments are being carried out to improve the efficiency of the damping mechanism.

Table 2: Experimental Results on the Vibrational Damping Mechanism on a Resonator with SS-balls

Dia of SS balls	Decay time with 0 balls (sec)	Decay time with optimum balls	Optimum no. of balls	Factor of reduction in the vibration
1	To be done			
2	3.70	0.60		06.1
3	To be done			
4	3.14	0.40	80	07.8
5	3.03	0.51	75	05.9
6	2.87	0.30	65	09.6
7	3.25	0.39	45	08.3
8	2.98	0.26	35	11.4
9	3.02	0.27	25	11.2
10	2.11	0.29	20	07.3
11	2.61	0.28	20	09.3
12	2.70	0.26	17	10.5

During a recent series of single strike experiments conducted on a niobium resonator kept at room temperature, ball diameter starting from 2 mm to 12 mm had been tried along with a mixture of balls of different diameters. The detail of the experiment has been explained elsewhere [7]. The results of the improvement in the decay time of the vibration have been tabulated in Table-2. Final results with mixture of balls of different diameters are not presented as these experiments are presently underway. In the single strike experiment, the resonator, kept at room temperature, is subjected to a vibration by a single strike from a heavy metal disc swinging like a pendulum. Then the frequency excursion of the resonator about its mean value without any SS-balls present inside the bowl shaped structure of the bottom of the central conductor is recorded with the help of Picoscope and computer. Next, SS balls of a particular diameter in groups of 5 are placed inside the central conductor of the resonator [7] and the frequency excursion of the resonator is measured after the single strike. In this way the experiment is carried over for a total number of balls of around 150-200. The experimental results presented in table-2 show that among the different diameter of balls, 8 and 9 mm are the one which have given the best results. Hence, these diameters and optimum number of balls are being used in all the resonators of module - 2 and 3 in place of 4 mm balls used earlier [7]. However, the performance of the resonators with bigger diameter balls has to be verified at liquid helium temperature during phase locking against the master oscillator. It is expected that with the bigger diameter of SS-balls, there will be more reduction in the total $\delta\omega_{shake}$ and it will be possible to phase lock the resonators at higher accelerating fields.

Alternate Tuning Mechanism by Piezo Actuator

As the Quality factor of niobium resonator is in the range of 10^9, the bandwidth of resonator is around 0.1 Hz. For IUAC QWR, vibration induced fluctuations of the frequency are of the order of few tens to hundred hertz. The frequency fluctuations mentioned here have got two components – one happens in slow time scales (seconds) and the other happens in faster (a few tens to hundreds of μsec) time scale. To tackle the fast frequency drift, power from RF amplifier is fed in over-coupled condition to supply the additional reactive power to the resonator and the whole operation is done electronically (fast tuner). To arrest the slow drift of frequency, a niobium bellow is attached near the high voltage end of the resonator and this is flexed by a few mm with pure helium gas sent from outside of the cryostat. A mass flow control for helium gas is being used to move the niobium bellows. During operation, the tuning scheme operates in a feedback loop to take care of the slow drifts in frequency and thus to reduce the load on the fast tuner. Since this tuning mechanism uses proportional helium gas flow through narrow tubes, the process takes place in the timescale of second. Within this interval of 1 second, all the correction of the loop frequency is being corrected by the fast tuner by supplying more RF power (~100-300 watts). So the average power requirement to maintain the phase lock of the resonator goes up. In addition to this problem, the gas operated tuning system is not so simple and expensive as pure helium gas is being used with partial recovery.

To reduce the average power and to improve the dynamics of control mechansim, an alternate fast tuning mechanism has been tried out successfully [8] and presently being implemented on all the resonators of the last accelerating module of linac. In this scheme, the tuner plate is deflected initially by a mechanical course tuner operated by a stepper motor driven shaft from outside and once the mean frequency is achieved, the control is handed over to the Piezo tuner controller (figure 4). The piezoelectric actuator works in closed loop along with existing resonator control scheme to phase lock the resonator. The response time for the Piezo to correct the frequency deviation is of the order of tens of milli second. So during this short time, the deviation in frequency is very small and the extra power supplied by the amplifier is of negligible amount. Consequently the average power required by the resonator is significantly reduced so the overall power requirement problem gets solved to a major extent.

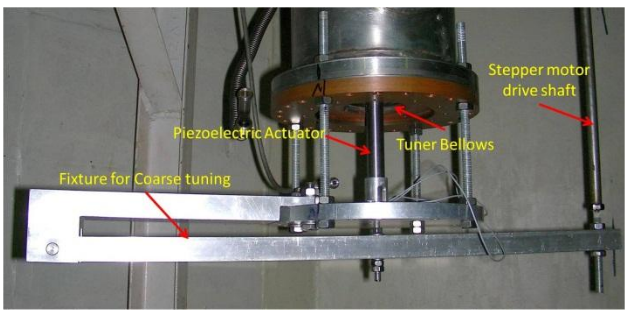

Figure 4: The Piezo-actuators are connected on two resonators of linac-3 prior to loading. The other picture shows the detail of the piezo-actuator and its accessories.

During a recent test of piezo actuator on a resonator in linac module - 3 (figure 4), an excellent and encouraging result was obtained. First, the mechanical shaft of the lever arm of the piezo tuner was adjusted to bring the resonator's frequency approximately 300 Hz above the frequency of the master oscillator as the frequency range of the piezo-actuator was measured to be 600 Hz. The voltage on the piezo actuator was set in such a way that the crystal was at its mid-point of deflection. Forward RF power within the limit of ~ 100 watts was optimized to generate a field of 3.6 MV/m in over-coupled condition. In this condition the resonator was phase locked with piezo actuator as a mechanical tuner along with the electronic tuner. On incorporating of the phase locking of the resonator by the Piezo actuator, the forward power didn't change substantially. Even after intentional induction of mechanical vibration (by mild hammering) into the cryostat housing the resonator, the forward power supplied to the amplifier shot up to 180-200 watts instantly but came down to ~ 100 watts almost immediately. After the success of the piezo actuator as a mechanical tuner on a resonator in linac cryostat-3, it has been decided that all the gas operated slow tuners will be replaced by the piezo actuator in all the resonators in linac module – 2 and 3.

The New Cooling Mechanism to Operate the Drive Coupler at Higher Temperatures

In order to increase the accelerating fields at the time of phase locking, supply of RF power greater than 100 watts may be necessary in future. In the past, when the RF power increases beyond 125 watts or so for continuous operation, a steady increase of the temperature of the drive coupler was observed and that resulted in many operational problems [4]. To eliminate this problem, a separate cooling arrangement was designed to cool the drive coupler. A cold finger was prepared whose one end is kept at LN_2 temperature and the other end is brazed on the brass piece of the drive coupler (figure 5).

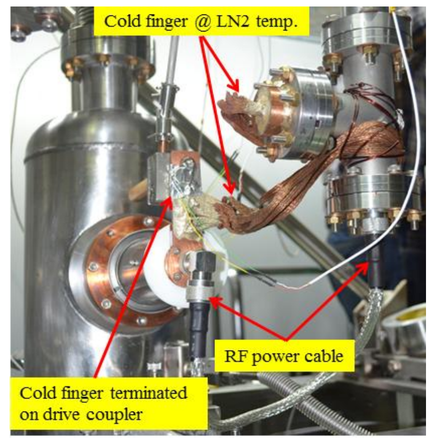

Figure 5: The additional cooling arrangement of the drive coupler at LN2 temperature.

With this arrangement, the drive coupler has been successfully tested with higher RF power through a high temperature RF cable (275°C). With 270 watts of power delivered to the power coupler, the maximum temperature on the drive coupler was measured to be 317 K. When the cold finger is cooled to LN_2 temperature, a decrease of ~ 70 K was observed within eight hours and after that the temperature remained almost constant. In the next step, the RF power was increased to 400 watts up to the maximum capacity of the RF amplifier. With cold finger kept at LN_2 temperature, the maximum temperature recorded on the drive coupler was 268 K. This temperature is sufficiently low for the long term operation of resonators in linac cryostat. The implementation of the new cold finger is underway on all the resonators of linac-3.

IMPROVEMENT IN THE LONGITUDINAL FOCUSSING OF THE LINAC BEAM BY RANDOM PHASE FOCUSSING OF THE RESONATOR

In most of the superconducting linear accelerators operational worldwide, heavy ions are accelerated with the ion beam injected at a phase of 70° (or -20°) into each independently phase locked resonator. Acceleration phase of 70° reduces the acceleration gain by 6% from the case if the beam is accelerated at 90°, but it maintains the narrow time width of the beam bunch within reasonable limits throughout the complete acceleration length of linac. However, if the number of linac resonators are too many (more than 10 or so) and the accelerated beam is delivered at a point which is far off from the exit of linac, then time width of the beam bunch starts to blow up as the beam travels further away from linac. To arrest this problem, a Rebuncher/Debuncher is used approximately halfway between the exit point of the linac and the experimental chamber to squeeze the beam in time or energy. However, the contribution of the rebuncher resonator to bunch the beam in time or energy can be reduced substantially or even eliminated completely by selecting the accelerating phases of a few resonators at 110° instead of 70°.

Table 2: Comparison Between the Reduction of Time Width of Linac Beam Between the Two Cases when all the Resonators were Kept at an acceleration phases of 70 Degree and a Combination of 70 and 110 Degree

Acceleration Phases of resonators in linac-1 and 2	Predicted reduction in delta_t (%) from calculation	Experimentally Measured Time width (ns) at scattering chamber	Experimental reduction in delta_t (%) from Expt.
All 70^0	-	2.88	-
Linac-1: 70, 70, 110, 110, 110, 70, 70, 70 Linac2: 70, 70, 70, 70, 70, 70, 70, 110	38.5	1.73	40

In order to verify this phenomenon which can be called as ‘Random phase focussing’, a simulation code was written to calculate the optimum combination of accelerating phases (between 70 and 110 degree) of the resonators to obtain the minimum time width of the beam bunch at the target location [9]. The simulation was done to inject the beam of 130 MeV $^{28}Si^{11+}$ from Pelletron into the sixteen resonators in module 1 and 2 kept at the different field levels obtained at the time of beam acceleration. The final energy of the ion beam from Linac would be 186 MeV irrespective of the acceleration phases of the resonators kept at either 70 or 110 degree. The value of time width was calculated first at the experimental chamber ~30 meter down the line from linac exit when the accelerating phases of all sixteen resonators were kept at 70 degree. Then the same calculation was repeated for the optimum combination of phases of the resonators between 70 and 110 degree to get the minimum value of the time width of the beam bunch. The calculated value of reduction of the time width between the two cases was verified by the experiment and the results are presented in Table-2. Now the calculation on random phase focussing is being extended to include the remaining eight resonators of the last linac cryostat. It is expected that with the combination of phase focussing on all the resonators, the work load on the rebuncher will be reduced substantially, if not eliminated completely.

USE OF LAST ACCELERATING RESONATOR OF LINAC-1 AS THE REBUNCHER RESONATOR

Table 3: The Measured Time Width of the Linac Beam when the Last Resonator of Module-1 Kept at the Predicted Bunching Field Found by the Simulation Code

Beam	Total energy (Pelletron + Linac)	Bunching field of the last linac resonator	Time width measured at Exp. Chamber (ns)
$^{16}O^{+8}$	113	0	0.84 ns
		0.4	0.5 ns
	106.8	0.0	2.11
		1.7	0.8
	104.5	0.0	2.68
		1.7	1.24
$^{19}F^{+9}$	124	0.0	1.82
		2.08	0.82
	122	0.0	1.75
		0.51	1.09
	118.8	0.0	2.2
		1.35	1.47

The simulation code developed to study the effect of random phase focussing was used to find out whether the last resonator of module-1, could be used as the rebuncher to control the time width of the beam bunch at the experimental chamber. During beam acceleration with only the Superbuncher and linac-1 operational, $^{16}O^{8+}$ and $^{19}F^{9+}$ beams with fixed energy from Pelletron were accelerated through linac module - 1. In the absence of the rebuncher, the time width of the beam bunch at the experimental chamber were too large to be used for the experiments. But by applying the calculated bunching field on the last resonator of module -1, acting as rebuncher, the time width was restricted to a value of 0.5 to 1.5 ns in all the cases [9]. That translates to a time width reduction of 33% to 62% compared to the cases when the last resonator was not used as rebuncher. The theoretically predicted bunching field which was applied on the last resonator of module – 1 and the measured time width of the beam at the experimental chamber is presented in Table-3. During the experiment, the bunching fields of the last linac-1 resonator were intentionally deviated from the calculated optimum values and time width was measured in every occasion at the experimental chamber. But the width measured for the bunching field predicted by the program was found to give minimum values in every cases.

PRESENT STATUS OF LINAC PROJECT AND FUTURE PLAN

Presently, the Superbuncher, the first two accelerating module and the Rebuncher are fully operational and accelerated beam from Pelletron and linac are being delivered to the experimentalists to conduct scheduled experiments. The last accelerating module, linac-3 is under commissioning stage. Recently four resonators were installed in linac-3 (figure-5) and an off-line test was successfully conducted. Piezo-actuators as frequency tuner were incorporated in two out of four resonators in linac-3 and the existing gas operated tuners were connected in other two resonators. Piezo actuators were successfully tested on the resonator of linac-3. Soon, the remaining four resonators will be installed in linac-3 and Piezo tuners will be installed on all of them. Subsequently, in near future, gas operated tuners will be replaced by Piezo tuners in all the eight resonators of linac-2. After installing the remaining resonators in linac-3, an off-line test is being planned in September '12 and the beam acceleration through the complete linac will be followed immediately.

Figure 5. Four resonators installed in linac-3 prior to the cold test. (Figure 6)

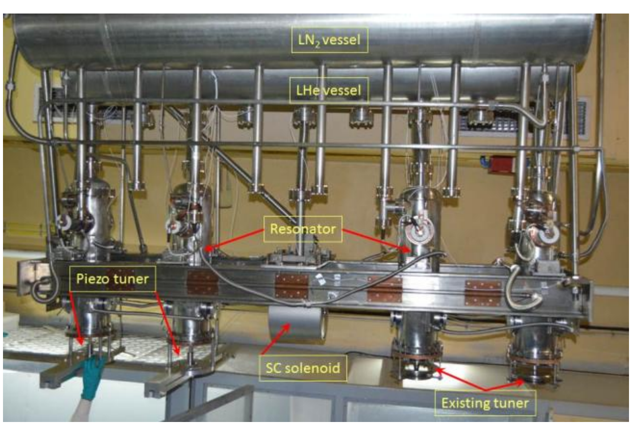

Figure 6: Four resonators installed in linac-3 prior to the cold test.

CONCLUSION

The superconducting linac project of Inter University Accelerator Centre is on the verge of completion. Since last few years, accelerated beams from Pelletron were further accelerated by the first and second module of linac and the beams have been delivered to conduct scheduled experiments in nuclear physics and materials science. Presently the installation of resonators in the last accelerating module is underway. In a parallel development, efforts are on to improve the locking fields of the linac resonators. To achieve this, three approaches are taken up. First the vibrational damping mechanism with larger diameter of balls and their mixture are being tried out to have further reduction of the frequency window at the time of phase locking of resonator. Secondly, Piezo-based actuator is tried out successfully to decrease the correction time to bring back the frequency of a resonator to its mean value. Thirdly, to avoid any kind of heating related problem in the power coupler, a cooling mechanism has been tested successfully and this system is presently used with the commercially available 100% shielded cable which can withstand up to 275°C. With these modifications the complete superconducting linac system is expected to be fully operational by the autumn of 2012.

ACKNOWLEDGEMENT

The authors would like to thank members of the Pelletron, beam transport, magnet and RF groups for their help and cooperation.

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