STATUS OF SPIRAL2 AND RFQ BEAM COMMISSIONING

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Abstract

The SPIRAL2 project beam commissioning is started and the superconducting linac installation is being finalized. In parallel with the installations, the first proton beam was extracted in 2014 and the expected beam performances were achieved from both light and heavy ion sources. The conditioning of the RFQ started in October 2015, and the beam commissioning soon after that. After having briefly recalled the project scope and parameters, the present situation of the RFQ beam commissioning is presented.

INTRODUCTION

GANIL is significantly extending its facility with the new SPIRAL2 project based on a multi-beam Superconducting CW linac driver [1, 2].

This new SPIRAL2 facility has two dedicated experimental areas in the fields of Neutron for Science (NFS) and very heavy and super heavy element production (S3). The SC linac is composed of 12 low β and 7 high β cryomodules, including a β=0.07 cavity and two β=0.12 cavities respectively. The status of the installation and commissioning is explained.

PROJECT STATUS

Beams Requirements

The layout of the SPIRAL2 driver takes into account a wide variety of beams to fulfill the physics requests. It is a high power CW superconducting linac delivering up to 5 mA proton and deuteron beams or 1 mA ion beams for Q/A > 1/3 (Table 1). Our major challenges are to handle the large variety of different beams due to their different characteristics (in terms of particle type, beam currents – from a few µA to a few mA - and/or beam energy), a high beam power (200 kW, CW) and to answer correctly to the safety issues, especially with the deuteron beam.

Table 1: Beam Specifications

Particles	H^+	D^+	ions	option
Q/A	1	1/2	1/3	1/6
Max I (mA)	5	5	1	1
Max energy (MeV/A)	33	20	15	8.5
Max beam power (kW)	165	200	45	51

Injector

The injector is composed of two specialized ECR ion sources and of a warm RFQ connected to the superconducting LINAC. Both ECR sources and their Low Energy Beam Transport lines (LEBT) have been successfully tested and qualified at an earlier stage [3] in the past years at LPSC Grenoble and IRFU Saclay. The two ion sources and their respective LEBT are now installed in the SPIRAL2 building (Fig. 1). The first proton beam was extracted on December 19, 2014. The First heavy-ion beam at was obtained in July 10, 2015 (230 µA argon 9+).

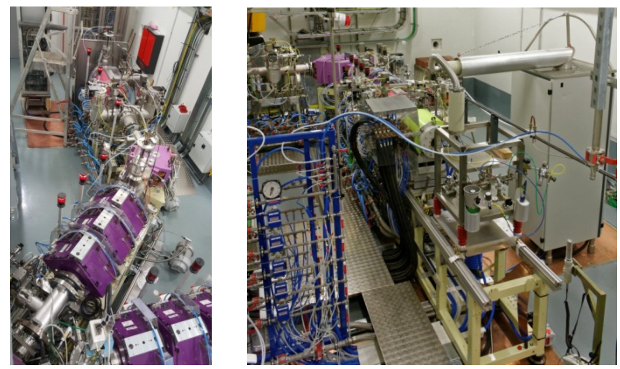

Figure 1: sources and LEBT at GANIL/SPIRAL2. Left : light ion source (H^+, D^+), right : heavy ions (Q/A=1/3).

On December 03, 2015 the 88.0525 MHz RFQ cavity was ready for beam, and the first proton beam was successfully accelerated. The theoretical 100% transmission was obtained after a few hours.

The next step will be to accelerate the Q/A=1/3 heavy ions after completion of the full RF power RFQ conditioning.

LINAC

Eighteen of the nineteen superconducting cryomodules are installed (Fig. 2). The last cryomodule is currently under maintenance (small helium leak).

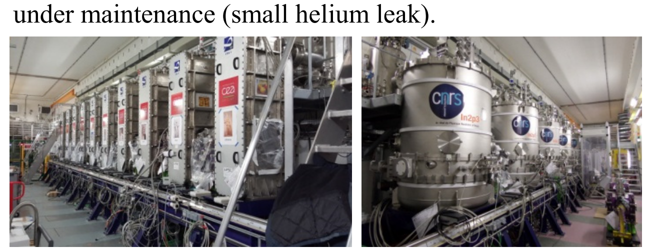

Figure 2: Cryomodules in the linac tunnel.

Warm sections including two quadrupole magnets and a BPM are located between the cryomodules. The first five warm sections also include a longitudinal bunch extension monitor (BEM) to allow a complete beam tuning.

All the valve-boxes needed to be repaired. It was a very long process to manage that delayed the installation by one year.

BEAM COMMISSIONING STRATEGY

The SPIRAL2 beam commissioning is managed in four phases:

Phase 1: qualification of the ion sources and LEBT in the laboratories in charge of the development. The project decided to pre-install the ECR ion sources and the LEBT in the two French laboratories where they were designed (CEA-Saclay and LPSC-Grenoble), in order to commission them *with beam* before the SPIRAL2 building availability. These successful tests were achieved by late 2012.

P*hase* 2: qualification of the injector on a diagnostic plate (D-Plate). This is a very important step with the achievement of various goals:

- Reproduce the results from the pre-commissioning of the ion sources, i.e. validate the source performances on SPIRAL2 site,
- Validate the RFQ performances for the various main reference particles (see below): transmission, beam energy, output emittances in the three planes, and bunch extension,
- Provide a development platform for various beam diagnostics required either to validate the RFQ beams or later to tune and validate the linac beams,
- Measure the beam characteristics at the RFQ exit, to serve as input parameter for the next stage.

Phase 3: SC linac beam commissioning up to the main beam dump, in order to validate the objectives of Table 1.

Phase 4: “day-1” experiment, with beam delivered to NFS and S3 experimental halls, including commissioning of NFS and/or S3 tuning procedures.

Strategy for the Multi-Particle Commissioning

The reference particles mentioned above in the phase 2 are related to an increasing stress for the RFQ cavity (increasing vane voltage). We started with the proton beam (A/Q=1), which is also the easier particle to produce. This validated the light ion source, its LEBT and the RFQ at 50 kV vane voltage. The second beam was the $^{4}He^{2+}$ beam, up to 2mA (A/Q=2), chosen to mimic the future deuteron beam. The RFQ vane voltage is then 80kV. It also allowed us to start validating the heavy ion source performances. The third beam is chosen to demonstrate the ultimate performances of the injector: 1mA, CW, A/Q=3 ion beam. For this, the $^{18}O^{6+}$ ion beam has been chosen as the more convenient to produce. The RFQ will have to work at its maximum vane voltage of 113 kV. The following beam would ideally been a 20 µA Ni ion beam to facilitate the future tuning of the accelerator and to prepare for the first experiments. It is unfortunately cancelled due to a lack of time on the D-Plate. The last beam will be the 5-mA deuteron beam. This will be the ultimate beam during the tests and requires the final authorizations from the French nuclear safety authority office, due to the activation of the internal components of the injector, expected by the end of 2016. The D^{+} beam commissioning is required in order to obtain the SC linac input parameters for the most sensible beam.

All the other A/Q particle tunings will be extrapolated from these four reference beams.

The injector commissioning will last until the linac is ready (installation and administrative authorizations). Metallic beams will be also measured if time is left.

The SC linac commissioning will start after disassembly of the D-plate and installation of the MEBT. It will follow a classical path of beam power ramping.

LINAC Commissioning

With the knowledge acquired during the injector commissioning, the high quality performances of the TraceWin code [4] and of our 3D electromagnetic maps, the MEBT can be precisely tuned for each reference beam. The Linac quasi periodic channel will be tuned to its theoretical value and the beams will be matched to this channel. The scheme will be

- Adjust all the quadrupoles of the linac and HEBT according to the RFQ-MEBT beam parameters,
- Match the MEBT beam to the linac channel, keeping constant transverse and longitudinal beam sizes in the first 4 lattices, while keeping the beam centered in the warm sections.
- Tune the first linac cavity (amplitude & phase) using the BPMs for Time of Flight measurements, keeping the beam centered in the warm sections.
- Re-adjust all linac and HEBTs quadrupoles,
- Operate the same way for the next 25 cavities…

During this process, the beam will be lost in the linac. The safety rules and the machine protection allow losing a maximum beam power of 1 W/m. As a consequence, our power ramp-up strategy is described in Fig. 3. Linac tuning will be first done with a low intensity (150 µA) low duty cycle (DC 400 µs/ 500 ms) proton beam. As the cavities are progressively tuned, the beam energy will be increased to its nominal value. The beam current will then be increased (matching with space charge) before the final duty cycle ramp-up.

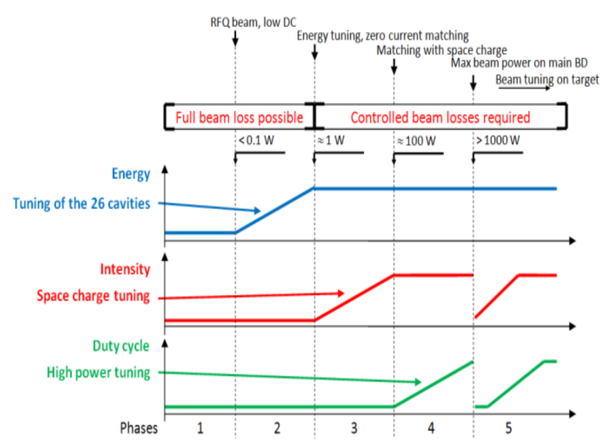

Figure 3: Power ramp-up strategy.

The linac tuning is highly depending on the accuracy of the BPMs inserted in the first quadrupole of each warm section; they must allow a precise control of the beam positions, phases and energies (@ ToF measurements) and shapes (@ transverse profile ellipticity measurements).

INJECTOR RESULTS

Sources Results

Both sources perform in GANIL as in their respective development lab. Up to 11 mA beam current can be extracted from the light ion source (70% proton fraction). The permanent magnet positions have been retuned in order to minimize the current noise and maximize the source tuning repeatability. Argon, helium and oxygen have been extracted from the heavy ion source.

Especially with the heavy ion source, the LEBT emittance may show some strong filamentations. Figure 4 shows rms normalized emittances equal to 0.5 and 0.7 π.mm.mrad, larger than the expected 0.4 π.mm.mrad. These values measured for an A/Q = 2 helium beam are mainly due to the fact that the line is optimized for the A/Q = 3 beams. Whatever, three pairs of H and V slits are located in the common LEBT to define the emittances. We usually tune the line and optimize the transverse emittances to get the highest beam current on the final LEBT Faraday cup, then cut the halo (few % of the total intensity) to get a 100% transmission through the RFQ.

The performances measured at the end of the LEBTc are given in Table 2.

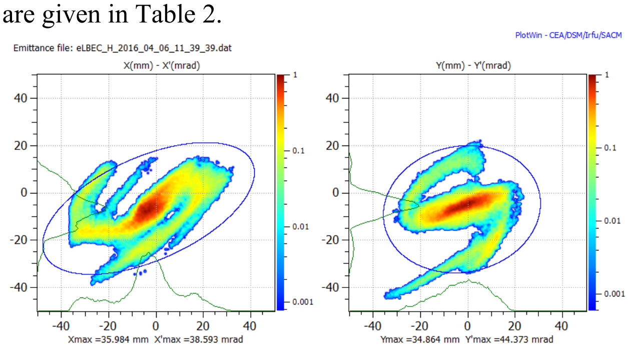

Figure 4: LEBTc emittance measurement for a 1.35 mA He beam, open slits, before hexapole tuning optimization.

Table 2: Measured Performance at the LEBT End

Particle	Beam current (mA)	Emit X (π.mm.mrad)	Emit Y (π.mm.mrad)
H^+	5.2	0.18	0.2
$^4He^{2+}$	1.35	0.54	0.43
$^{18}O^{6+}$	0.75	0.44	0.41

Emittances have also been measured in pulsed mode operation, to measure and optimize the neutralization time. For example, the characteristics of a 5.8 mA proton beam are stabilised after about 400 µs with a residual pressure of 10^{-6} mbar (uncorrected value).

RFQ Conditioning

The RFQ was assembled in Sept 2014. The voltage law tuning [5,6] was ended in March 2015 (Fig. 5). Final measured voltage errors are smaller than 2.1% for the quadrupole component, 0.5% and 1.1% for the dipole S and T components. Toutatis [4] simulation with the resulting voltage law *AND* the manufacturing errors showed that the expected transmission is still 100% and above 99.7% of accelerated particles.

The cavity RF conditioning started on November 15th, 2015 with only three out of four RF amplifiers. The conditioning in CW mode up to the maximal possible accelerating field level (85 kV for 110 kW within the cavity) went smoothly. The cavity voltage measurement was calibrated using an X-ray energy measurement technique. The 16 pick-ups located along the 5-m long RFQ allow controlling the voltage law in operation, making a comparison with the last beadpull measurement. The relative errors are less than ±0.2% as the vane voltage is varied from 20 kV to 80 kV (Fig. 6). Moreover, this is a stable long-term behavior.

Up to now, various technical difficulties do not allow us to condition the RFQ cavity at its ultimate performance (CW, 113 kV). They reside in RF amplifier reliability and performances, difficulties with the LLRF, and a long response time of the cooling circuit used to tune the cavity resonance frequency. The behavior of the cavity itself is good up to now since we have reached the nominal voltage in pulsed mode with a 20% DC.

Figure 5: RFQ during the bead pull measurement.

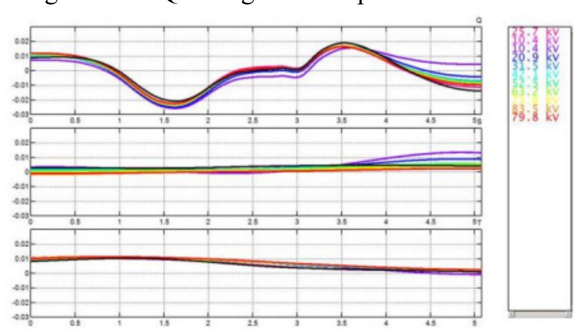

Figure 6: Voltage error versus accelerating voltage.

Injector Diagnostic Plate

The D-Plate is installed in the Medium Energy Beam Transport Line (MEBT, Fig. 7) in order to validate the RFQ performances, to develop and qualify the diagnostics and to measure the following beam characteristics:

- Intensity with faraday cups, ACCT and DCCT
- Transverse profiles with classical multi wire profilers and ionisation gas monitor (MIGR)
- H and V transverse emittance with Allison type scanners
- Energy with a Time of Flight (TOF) monitor
- Phase with the TOF and the BPM

- Longitudinal profile with a Fast Faraday Cup (FFC), a fast current transformer (FCT) and a Beam Extension Monitor (BEM)
- Beam position and ellipticity ($\sigma_x^2 - \sigma_y^2$, with σ_x and σ_y the standard deviations of the beam transverse sizes) with the BPM.

The performances of the diagnostics are given in [7,8,9]

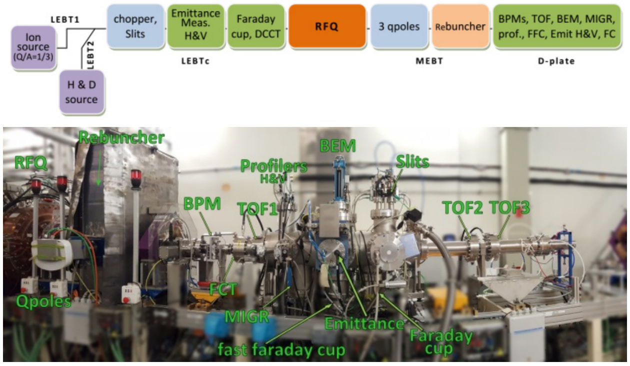

Figure 7: Injector scheme and Diagnostic Plate picture.

RFQ Beam Commissioning

On December 3, 2015, the first proton beam was accelerated at 0.73 MeV (200 µA of proton, 200 µs/250 ms, 50 kV vane voltage law). By noon the same day, 100% transmission was demonstrated and within a few days, a 5.2 mA CW proton beam was successfully accelerated (Fig. 8).

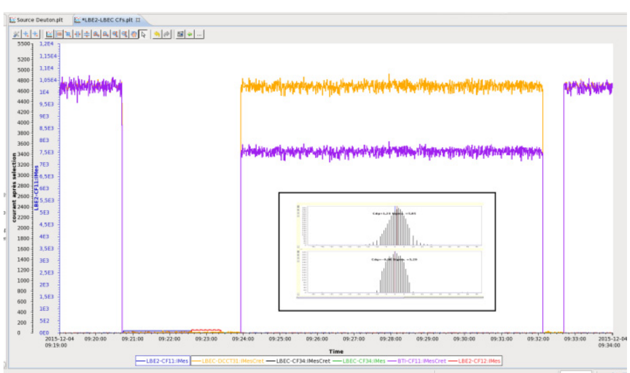
Figure 8: 4.8 mA proton beam current measured before (orange) and after (magenta) the RFQ. The 2 curves superimposed at both ends show the 100% transmission. In the middle, a profiler inserted just after the RFQ intercepts a part of the accelerated beam.

On February 2016, a 1.34 mA, CW $^4He^{2+}$ beam was accelerated with up to 98.5% transmission in spite of a bigger than expected input transverse emittance (see Table 2). The 100% transmission was obtained with a slight closing of the LEBT slits.

The beam transmission as a function of RF vane voltage and the beam characteristics were measured. There is a very good agreement between these measurements and the beam dynamics simulations performed using the TraceWin/Toutatis code. This is illustrated by Fig. 9 for the RFQ transmission and by Fig. 10 for the RFQ output horizontal emittance.

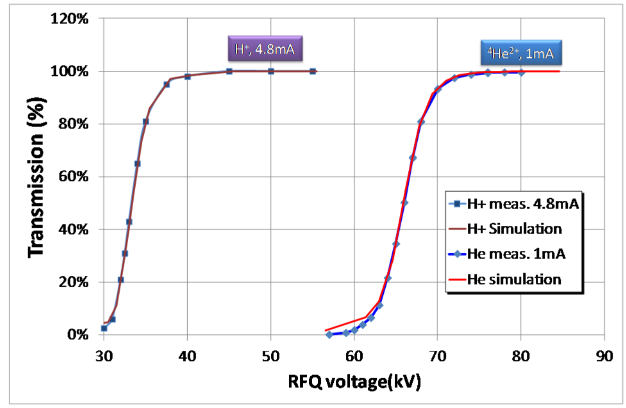

Figure 9: Comparison between measurement and TraceWin/Toutatis simulation (p and He beams).

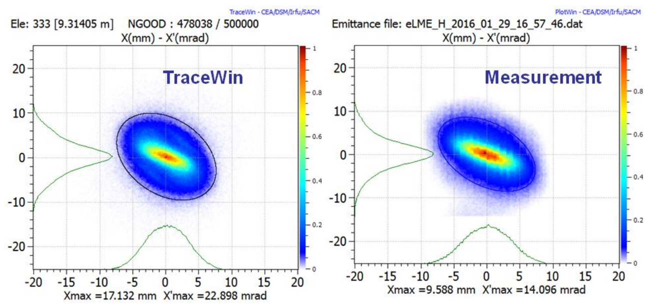

Figure 10: 5 mA proton beam in the D-plate.

The RFQ beam energy is measured using 3 ToF pick up electrodes [7]. The proton beam was measured from 10 µA to 5 mA (pulsed and CW), helium beam from 10 µA to 1.5 mA. (see Table 3 below)

Table 3: RFQ Measured Beam Energy

Energy (keV/nucleus)	Toutatis simulation	TOF buncher off	TOF buncher on
Proton	730	729.3	
Helium	727.2	728.1	727.3

The longitudinal bunch parameters were characterized using two tools: a Fast Faraday Cup (FFC) and the Beam Extension Monitor (BEM). The FFC is a coaxial Faraday cup limited to 400 W beam power. It has a minimum possible measurement of σ_{rms}= 320–330 ps due to bandwidth limitation (2 GHz).

The BEM is a 150 µm tungsten wire interacting with the beam (limited beam power), the measurement is done analyzing the emitted X-rays using µchannel plates coupled with a fast readout anode [9]. The estimated temporal resolution σ = 47 ps corresponds to 1.5° of phase resolution at 88 MHz.

Fig. 11 shows again a good agreement between the two measurements and the TraceWin simulations.

Using the rebuncher, the 3 gradient method has been used to measure a longitudinal emittance of 0.077 π.deg.MeV. This value which is two times smaller than expected needs to be validated.

The bunch profile measurements done with helium beam current from 0.1 to 1 mA showed very interesting behaviors. The longitudinal bunch shapes are quasi

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Gaussian at high intensity but have a fine structure at low intensity (Fig. 12). The same behavior is observed with protons (quasi Gaussian shape from 0.5 mA to 5 mA). The TraceWin simulations give the explanation (Fig. 13): at low beam current the S-shape particle distribution in the longitudinal phase-space is not scrambled by the space charge force.

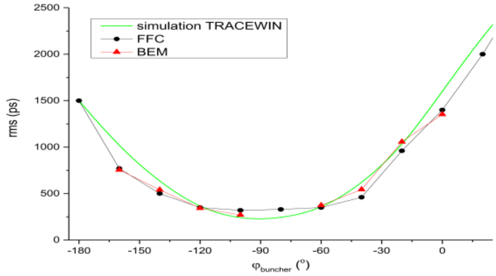

Figure 11: Comparison of the bunch width between FFC, BEM and TraceWin simulations.

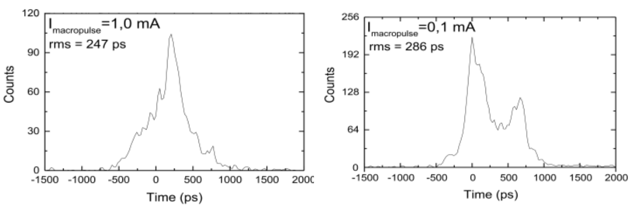

Figure 12: $^{4}He^{2+}$ longitudinal bunch shape for 1 and 0.1 mA.

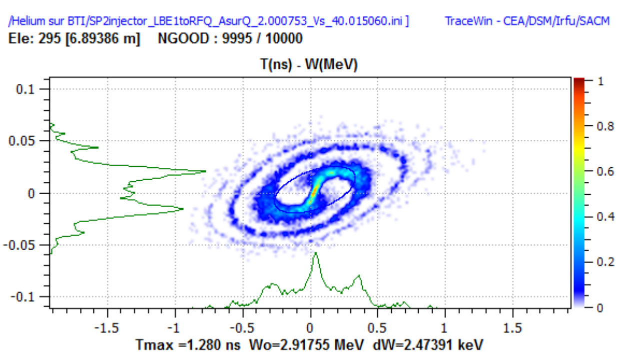

Figure 13: TraceWin simulation of a 0.15mA He beam at the BEM location.

LINAC First Cool Down

In July 2016 all the conditions were gathered to allow a partial cool down of the SC Linac. The tests consisted of cooling down three cavities in two different types of cryomodules (one high and one low β). This stage allowed to test a major part of the cryogenic installation (cryoplant, cryodistribution) as well as the preliminary version of the PLCs and C/C. The cryomodules were selected at both ends of the helium distribution lines (CMA1 and CMB7) in order to validate the whole cryogenic line at once. Due to an instrumentation failure in first valve box, the tests were done with CMA3 and CMB7. It was the very first time that liquid helium flowed in the cryogenic lines in linac tunnel. Both cryomodules were regulated at 4K after about 20 hours of cool-down (Fig. 14).

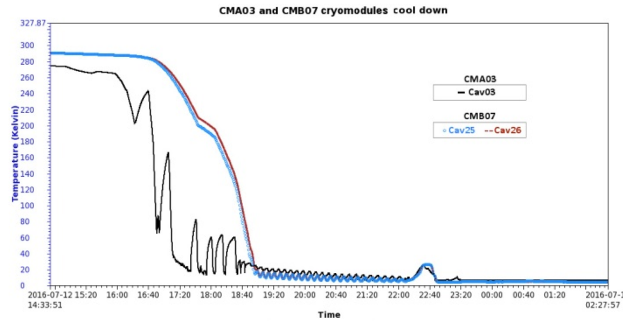

Figure 14: Very first cool down of linac cryomodules.

The next stages aim at increasing the cool down speed, and to achieve and optimize the effective regulation of helium pressure and level.

CONCLUSION

We are facing exciting days, with the first accelerated beams in the injector, and a great 100% transmission through the RFQ. The preliminary results are very similar to the expected theoretical results, illustrating the good design of the machine, and giving us confidence for the next phases. We are working to solve the technical problems to validate the A/Q=3 beam at the RFQ exit, hopefully before the end of 2016. Next step will be the SC linac RF conditioning in early 2017, D-plate replacement with the MEBT and linac beam commissioning hopefully by mid 2017.

ACKNOWLEDGEMENT

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