REDUCING LOSSES AND EMITTANCE IN HIGH INTENSITY LINAC AT BNL *

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Abstract

BNL 200 MeV linac has been under operation since 1970 and gone through several changes during its 40 year lifetime. The latest (2009-10) reconfiguration in low and medium energy (35 and 750 keV) beam transport lines resulted in about a factor of 2 reduction in the transverse emittance for the accelerated polarized proton beam, and a several fold reduction in the radiation levels due to beam losses throughout the linac and isotope production facility complex with 30% more beam current for the un-polarized H^- beam for BLIP.

INTRODUCTION

The Brookhaven National Laboratory (BNL) 200 MeV drift tube linac (DTL) has been operating since November 1970 and was designed for 100 mA of peak current with 200 μs of pulse length at 10 Hz. During last 40 years of operation, linac has gone through many changes to accommodate changing requirements of the BNL accelerator complex for higher average beam current, better beam quality, or higher reliability. To satisfy present requirements, linac now provides H^- beam at 6.67 Hz, 200 MeV for the polarized proton program at Relativistic Heavy Ion Collider (RHIC) and 66-200 MeV for Brookhaven Linac Isotope Production (BLIP) [1]. The requirements for these programs are quite different and are the following. (1) RHIC: 200 MeV, 200 μA beam current, 400 μs pulse length, polarization as high as possible and emittance as low as possible, (2) BLIP: 66-200 MeV, 450 μs pulse length, current as high as possible (~40 mA), uniform beam distribution at the target, and losses as low as possible. In this article, we will discuss only the high intensity aspects of the linac.

BNL 200 MEV LINAC HISTORY

Table 1 summarizes changes of the last 40 years. There are several points worth noting. In 1982 switching to H^- operation increased the intensity in the AGS, while decreasing the linac output. In 1989 switching to RFQ preinjector provided high reliability and lower cost of operations. The changes in 1996 included shorting 35 keV line by removing diagnostics and adding PMQ in the flange of the RFQ at the high energy end to better match the beam line. These changes resulted in a 50% higher peak beam current and about 45% lower emittance. In 2009, the medium energy beam line length was reduced to 70 cm from 7 meters, resulting in an emittance reduction for high current by a factor of 4 and for the polarized H^- by a factor of 2. The reduction in emittance for polarized H^- was translated into emittance reduction in RHIC by 25% at the collision energies. But due to longer 35 keV line, the beam current for BLIP was not increased as expected. In 2010, the beam current for BLIP was increased by 30 % by reducing the length of 35 keV line to two meters. Now linac is delivering the highest average current to BLIP while maintaining minimum losses since it was built in 1970.

Table 1: BNL 200 MeV Linac History

Year	Rep Rate Hz	Pulse Length μs	Peak Current mA	Avg. Curret μA
Design	10	200	100	200
1972	10	80	55	44
1975	10	100	60	60
1976	Switch to 5 Hz operation			
1979	5	220	70	77
1982	Switch to H- acceleration			
1984	5	200	25	25
1984	Add polarized H- operation			
1986	5	470	30	71
1989	Switch to RFQ pre-injector			
1990	5	500	25	63
1996	Switch to 6.67 HZ and changes in LEBT/MEBT			
1996	6.67	400	38	90
2000	Add Polarized source OPPIS			
2009	LEBT/MEBT reconfiguration (short MEBT)			
2009	6.67	430	32	80
2010	Shorten LEBT			
2010	6.67	430	38	110
2011	New Buncher and einzel-lens solenoid combo			

The linac was designed for 100 mA and smaller emittance since it was designed for protons. Particle simulations showed that transverse and longitudinal matching and the quadrupole focusing laws are essential for controlling the emittance growth in transverse as well as longitudinal planes. All the emittance growth occurs within the 1st tank (10MeV).The beam was pre accelerated with Cockeroft-Walton (C-W) to 750 keV than followed by an 8.5 meter long line consisting with eight triplets and two bunchers. To minimize the emittance growth in the 750 keV line, the beam size was kept small and the emittance growth in the line was about 50%. The beam was matched to DTL in all three planes. The capture efficiencies in the DTL were about 65-70%. It was recognized that longitudinal beam size was the key contributor in the transverse emittance growth, and the

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quadrupoles laws in the DTL played a significant role in controlling emittance growth for high currents.

In 1989 when Cockeroft-Walton was replaced with an RFQ, a new transport line at 35 keV (LEBT) was introduced between the ion source and the RFQ, which provided space for a chopper. The transport line between RFQ and linac was 7 meters long and had fast and slow choppers, a dipole to accommodate polarized protons, ten quadrupoles, three bunchers, four emittance probes, five current toroids, five segmented and a fast faraday cup [2]. This 750 keV line is named the medium energy beam transport (MEBT). The beam was matched into DTL in all three planes. The importance to keep the longitudinal beam size as small as possible was realized, but the given constraints in the MEBT, longitudinal beam size grew up to +/- 120 degrees at buncher locations, although about 75% of the beam fit in the longitudinal bucket of the DTL [3]. There were no measurable improvements in transmission or beam losses, but noticeable sensitivity of amplitude and phase of the RFQ and bunchers were noted at 200 MeV while producing no observable effect on the beam in the 750 keV lines [4].

In 1996 the linac rf power supplies and high power transfer lines were upgraded to operate at 7.5 Hz and 550 μs long beam pulses. At the same time LEBT length was reduced from 2.1 meters to 1.4 meters by removing the fast chopper and emittance probe. To capture more beams into the LEBT from the ion source, the first solenoid was moved closer to ion source and the second solenoid moved closer to RFQ to provide a better match into the RFQ. These changes resulted in a 20% reduction of the emittance at the RFQ entrance and about a 10% improvement in transmission of the RFQ [5]. The 7 meter long MEBT transmission was about 75%. The first quadrupole was too far from the RFQ; by the time the beam reached the first quadrupole, it had gone through a waist in the x plane, hence it was diverging in both planes. Also the longitudinal beam size was very big by the time the beam reached the first buncher. To improve the capture and transmission of the beam in MEBT, the RFQ end flange at the high energy end was modified to accommodate a permanent magnet quadrupole (PMQ). The PMQ was similar to one used in the SSC DTL [6]. In addition, this PMQ can be moved transversely while running the beam via micrometer adjustment outside vacuum in order to steer the beam. A picture of the RFQ end flange with PMQ is shown in Figure 1. The gate valve and current transformers also rearranged to bring the buncher close to RFQ. Last quadrupole quadruplet was converted to quadrupole triplet. These changes resulted in a 50% higher transmission at 200 MeV with 45 % lower emittance [7]. But still there were 40% beam losses in tank1 and emittance growth of several fold at the end of linac. In 2000, a new high intensity polarized source OPPIS was added in the LEBT before the RFQ and the dipole in the MEBT was replaced with a spin rotator solenoid [8]. The resulting layout is shown in Figure 2.

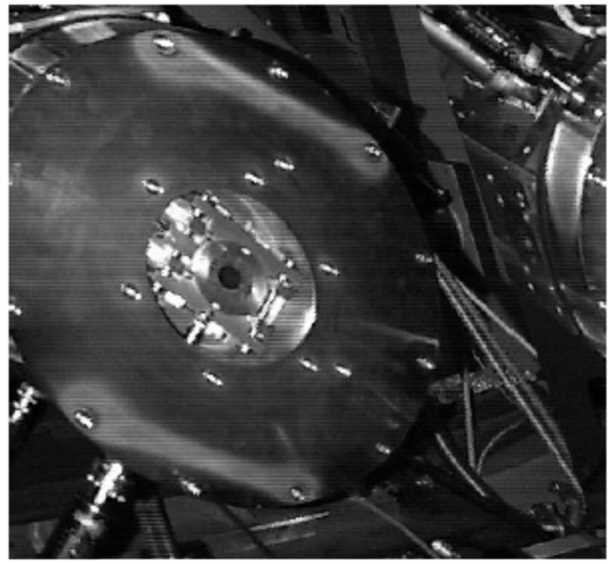


Figure 1: RFQ end flange with PMQ.

There were no measurable changes in the high intensity operation except about a 5% drop in the intensity at 200 MeV.

EMITTANCE GROWTH AT BNL 200 MEV LINAC

Several observations can be made for the changes that occurred from1970 to 2000. (1)The replacement of Cockeroft -Walton by RFQ did not result in an improved transmission of linac. Amplitude and locations of beam losses were the same as when the cw beam from Cockeroft- Walton was bunched by two bunchers. (2) Any improvement in LEBT was translated to the output of the linac, keeping the transmission efficiencies of linac the same.(3)The phase and amplitude of RFQ and bunchers were most sensitive to the output of 200 MeV and not at MEBT.

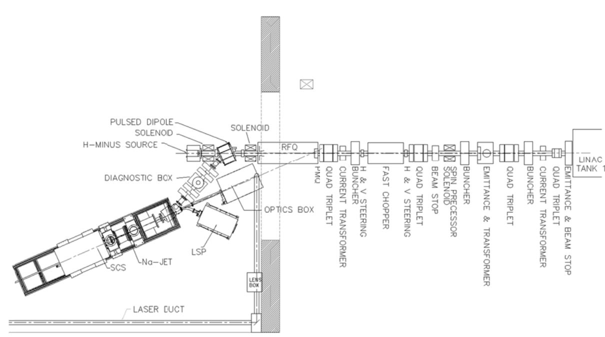


Figure 2: LEBT-MEBT layout in 2000 after adding polarized source in the LEBT.

The ideal match between RFQ and DTL could have been obtained with a 5 βλ long FODO lattice with quadrupoles spacing about one βλ and at least two bunchers [9]. But the requirements of beam chopping and the polarized beam dictated a triplet solution. Indicating problems lie at the MEBT in the longitudinal plane not in the transverse plane, because there were enough degrees of freedom (knobs) available to match into the linac. Moreover, tanks quadruples can be tuned independently. The MEBT resulted in a lattice mismatch in both the transverse and longitudinal direction. The RFQ (βλ ~ 6 cm) and DTL (βλ ~ 6 cm) both have a FODO lattice (period of 6-12 cm) but MEBT had 15 to 20 times longer drift spaces to accommodate chopper, dipole and diagnostics. For the given emittance, the transverse beam size roughly scales as drift length between focusing elements. The MEBT aperture grew 10 cm in diameter from 1 cm in RFQ, and back to 2 cm in DTL. During this process, the external focusing forces remained linear in nature, and not much damage occurred in transverse emittance in the MEBT, consistent with the observation.

Similarly, in the longitudinal direction, the focusing period in RFQ and DTL is much smaller than the space between unevenly distributed three bunchers. The bunch length grew faster than transverse beam size since the longitudinal focusing period is half of the transverse focusing period in RFQ. But restoring forces (sinusoidal rf) are non-linear in nature and this non linearity embedded in the particle distribution results in particle losses at higher energies [10]. Figure 3 shows the longitudinal phase spaces at (a) RFQ, (b) buncher 1, (c) buncher 2, (d) buncher 3, (e) end of MEBT, and (f) at cell 20 of DTL.

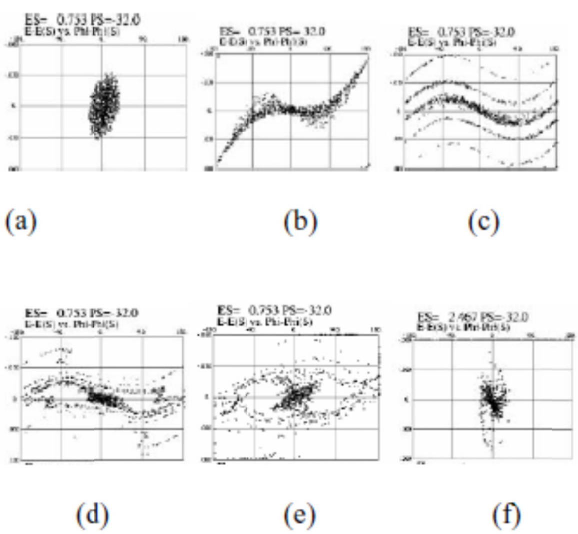


Figure 3: Longitudinal phase space plots (a) at end of RFQ, (b) after buncher 1, (c) after buncher 2, (d) after buncher 3, (e) at end of MEBT, and (f) at cell 20 of DTL.

These PARMILA simulations indicate that bunch length was too big when it reached to buncher 1, 2 and 3 and the beam is only partially bunched as it reaches the DTL. Figure 4 shows the corresponding transverse space (x-y), there is no apparent effect on the transverse space in MEBT, but it is quite clear in the DTL. There is inherent mismatch between DTL Tanks. This mismatch is due to the fact that there is 0.6 – 1meter drift space between the tank causes discontinuities in the longitudinal focusing pattern. In the modern linacs, these discontinuities are compensated by shifting the synchronous phase of the first and last few cells in each tank [15].

The primary mechanism of emittance growth for BNL linac lies in the coupling of the longitudinal and transverse oscillation and consists of (a) the dependence of the transverse rf defocusing impulse on the longitudinal phase and (b) the dependence of energy gain on the transverse displacement in the rf gap.

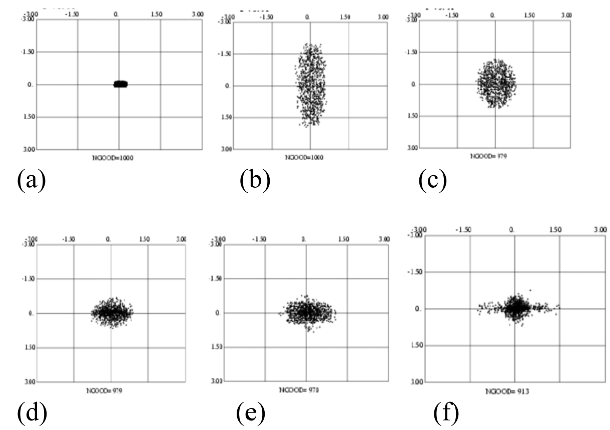


Figure 4: Transverse space (x-y) plots (a) at end of RFQ, (b) after buncher 1, (c) after buncher 2, (d) after buncher 3, (e) at end of MEBT, and (f) at cell 20 of DTL.

The coupling between transverse and longitudinal space lies in the equation of motion given by

$$\frac{1}{\beta\gamma}\frac{d}{ds}\left(\beta\gamma\frac{dx}{ds}\right)+k_t^2x=-\frac{k_l^2}{4}x(2g\delta\varphi+(\delta\varphi)^2)$$

$$\frac{1}{(\beta\gamma)^3}\frac{d}{ds}\left((\beta\gamma)^3\frac{d(\delta\varphi)}{ds}\right)+k_l^2(\delta\varphi)$$
$$=g\frac{k_l^2}{2}(\delta\varphi)^2-k_l^2\left(\frac{\pi x}{\beta\gamma\lambda}\right)^2(g+\delta\varphi)$$

where β,γ are the relativistic parameters, k_t,k_l are the transverse and longitudinal wave number, $\delta\varphi=\varphi-\varphi_s$, φ_s is the synchronous phase and $g=\cot\varphi_s$.

The maximum amplitude growth due to phase difference from synchronous phase is given by

$$\frac{(\delta X)_{max}}{X}=\frac{k_l^2}{4k_t|2k_t-k_l|}\frac{(\delta\varphi)_{max}}{|\varphi_s|}$$

Emittance growth will be order of square of the amplitude growth.

It can be shown that the emittance growth due to the different displacement in the rf gap, excited in TM_{010} mode, is given by

$$\Delta\epsilon=\frac{c_1}{\beta^2\gamma}x^2+\frac{c_2}{\beta^2\gamma}x^4$$

where c_1 and c_2 are constant and depend on the cavity parameters like accelerating gradient, length and frequency.

It is essential to keep the transverse as well as longitudinal beam size as small as possible in the buncher. If the longitudinal beam size is large enough, it will see non linear part of the sinusoidal rf field in the gap. The emittance growth and particle loss may not be immediate, but it tends to show up at higher energies. If the transverse beam size is big enough, then non linear field (r-dependence) will cause non linear relative velocity distribution in the longitudinal as well as transverse plane and emittance growth shows up immediately.

EMITTANCE GROWTH MITIGATION

In 2008 the LEBT and MEBT were reconfigured, driven by the aim to reduce the emittance growth for polarized proton to increase luminosity in the RHIC [10]. Figure 5 depicts the LEBT and MEBT after reconfiguration. The MEBT length was reduced from 7 meters to 70 cm. It has three quadrupoles, two pairs to steerers in each plane, one buncher and a current transformer. Due to physical constraints, the polarized source could not be moved, and linac tanks could not be moved, therefore we ended up with a long LEBT. The LEBT for the high intensity beam was about 4.5 meters long and had two solenoids, two sets of steerers and collimator in each plane, a beam stop, a slow chopper, and an einzel lens before the RFQ. The einzel lens was tested with the RFQ for the transmission in 2007, and gave about a 80% transmission through the RFQ for high intensities and a 90% for the polarized H-. .

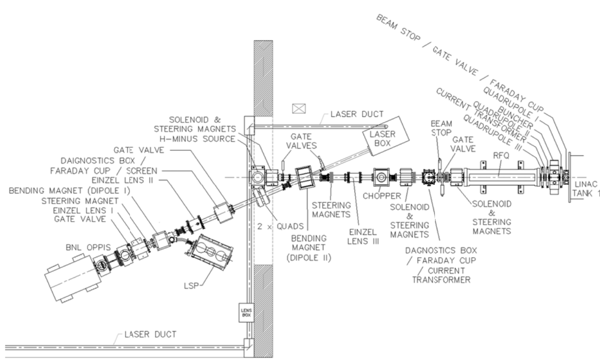


Figure 5: Layout of LEBT and MEBT after the reconfiguration.

In the MEBT (see Figure 6), we have used the quadrupoles from the LEDA [15] project with a solid core. The power required for the buncher was about 10 kW, but the buncher RF power source was capable of only a maximum of 5 kW. The buncher was modified by adding an additional feed loop to each of the cavity's two-¼ wave resonator arms. The buncher was powered by two 7651 tetrode, 5 kW power amplifiers. Each amplifier system is independently phase adjusted and power combined in the buncher. One of the additional loops is used for feedback for both phase and amplitude stabilization loops about both amplifiers. We have successfully operated the buncher at 8 kW's of RF power, 4 from each amplifier system. During previous operating years up to 3 bunchers were required with the highest power requiring 3.5 kW.

In 2009[11], with up to 100 mA out of the ion source, we measured only 30 mA in front of RFQ and about 17 mA out of RFQ, and big current fluctuations during the 400 µs long pulse. Similar instability has been seen earlier [12, 13]. Various configurations were then tried, by changing second solenoid location, but neither current transmission efficiencies nor the current fluctuations improved. The transmission efficiencies were almost the same for a wide range of currents (source current 50 mA to 100 mA) and energy (20 keV to 35 keV).

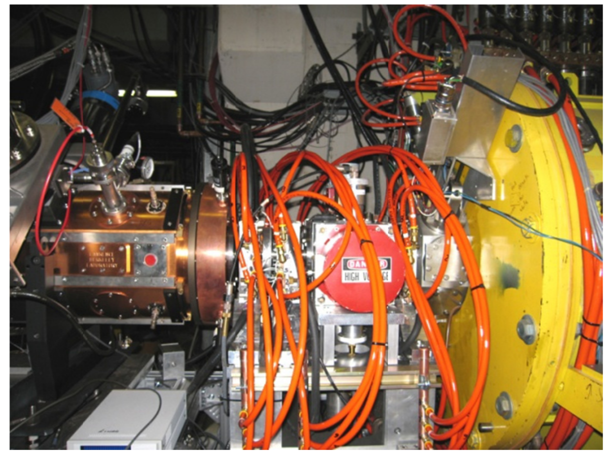


Figure 6: Photo of 70 cm long MEBT.

One more solenoid was added, now having three solenoids and an einzel lens in front of RFQ. With this configuration, one got about 45 mA in front of the RFQ and 22 mA after the RFQ. With einzel lens #3 turned on (supposed to be used for the polarized beams only) we got 50 mA in front of the RFQ and 25 mA after the RFQ. Finally, the einzel lens before the RFQ was replaced with one of the solenoids, and the other solenoid reconfigured such that the distance between the RFQ and the 2nd solenoid was approximately the same as before the reconfiguration. This configuration resulted in 35 mA after the RFQ. When Xe gas was introduced into the beam pipe, one got 65 mA in front of the RFQ and 42 mA out of the RFQ. The LEBT had an average pressure of 3.7 x 10^{-6} Torr. The ionization cross section for the Xe gas is 8 x 10^{-16} cm^{-2} and the required pressure for the Gabovich critical density [12] for complete neutralization is 3.6 x 10^{-6} Torr (Xe gas density of 1.2 x 10^{11} cm^{-3}). We measured a neutralization rise time about 40 µs, and the calculated value is about 38 µs. The stripping cross section for 35 keV H- is about 4 x 10^{-15}, which gives about a 20% stripping loss for the 4 meter long LEBT, while about a 32% loss in the LEBT is measured. Table 2 summarizes commissioning of LEBT for high intensity.

Table 2: Summary of LEBT Commissioning for High Intensity

Configuration	Before RFQ	After RFQ
2 sol. + ein. lens	30 mA	17 mA
3 sol. + ein. lens	45 mA	22 mA
3 sol. + ein. lens#	50 mA	35 mA
3 sol. + ein. lens + Xe gas	65 mA	42 mA

#Solenoid in front of RFQ and Einzel lens before chopper

The transmission though linac was limited by buncher power. At 8 kW power, the maximum current out of linac was about 32 mA (76% transmission), in agreement with simulations. We measured no beam losses in the MEBT.

In 2010, the high intensity source was moved upstream with a bend angle of 45 degrees as shown in Figure 7. The new length of the LEBT is now 2 meters and has two solenoids, two quadrupoles, and two steerers in each plane, a chopper and one 45 degree dipole. The transmission through linac was increased by 30%. Average beam current on the BLIP target was increased to 110 µA in 2010 from 80 µA in 2009. Radiation in the BLIP transport line was further reduced.

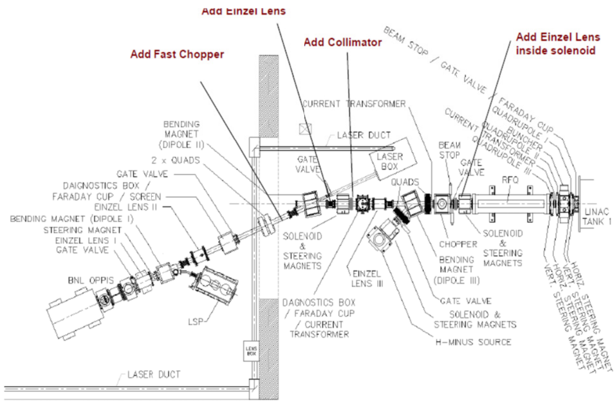


Figure 7: Layout of LEBT and MEBT in 2009.

RESULTS

Table 3 compares the emittance and linac transmission efficiencies before and after the upgrade in 2009

Table 3: Emittance and Transmission Efficiencies of the Linac. Transmission Efficiencies Measured as Ratio of Linac Output Current to Source Current.

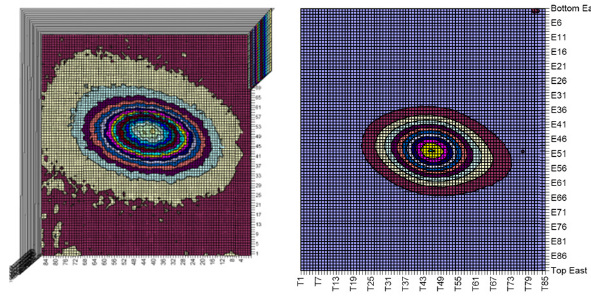
Year	ε_X, N, 95% (π mm mr)	ε_Y, N 95% (π mm mr)	Trans. (%)
2008	10.7	15.9	50-55
2009	4.5	5.5	65-70

The reduction in emittance is seen in every step of the RHIC accelerator chain and translated to about a 25% reduction in emittance in the RHIC at collision energies.. Table 4 show the linac performance for high intensity for the last three years

Table 4: BNL Linac Performance for High Intensity H- for Last Three Years.

Parameters	**2008**	**2009**	**2010**
Average Current within 2" target	71µA	80µA	110µA
Beam outside 2"	8%	0%	0%
Collimator temp.	160°C	70°C	65 °C
Radiation	Normal	Low	Lower

Figure 8 shows a comparison of the beam foot-print at the target before and after the upgrade. Radiation due to beam losses has been reduced everywhere, compared to before the upgrade.



(a) (b)

Figure 8: Beam foot print at the BLIP target (a) before and (b) after reconfiguration of LEBT/MEBT showing the same number of contours.

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