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Longitudinal Emittance from the Fermilab 400 MeV Linac

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Abstract. The measurements which characterize the longitudinal emittance of the Fermilab 400 MeV Linac beam are presented. These measurements are made by determining the momentum spread and the bunch length of the beam using wall-current monitors, bunch length detectors and a spectrometer.

1. Introduction

Accurate measurement of the length of a bunched ion beam with velocities less than c is difficult. In the Fermilab 400 MeV Linac (the Linac), we have made this measurement using wall-current monitors (WCM), and with a special-purpose device known as a Bunch Length Detector (BLD). The momentum spread can also be determined from the BLDs, as well as from a spectrometer magnet. These methods are discussed, the resolution of these devices is calculated and/or measured and measurement results on the Linac are presented.

2. Overview of the Linac

The Linac is described in detail in the references [1, 2]. For the purpose of this paper, it is sufficient to know the following. The first half of the Linac, low-energy linac (LEL), is a 201.25 MHz drift-tube structure which accelerates the beam to 116.5 MeV. It is followed by a 4-meter transition section which contains two 805 MHz non-accelerating bunching cavities, the "buncher" and the smaller "vernier." The second half of the Linac, the high-energy linac (HEL), consists of seven 805 MHz modules which each consist of 28 side-coupled cavities in four sections, which accelerates the beam to 401.5 MeV. Each module is followed by a WCM. The Linac beam travels approximately 70 m for injection to the 8 GeV Booster synchrotron. A spectrometer magnet sits at 401 MeV to dump the beam which Booster does not need.

3. Monitoring of Wall Currents

A WCM is multi-purpose device, providing beam toroid signals, beam phase signals and bunch-length information from a resistive gap in the beam pipe. The bandwidth is a compromise between the low-frequency toroid requirements and the high-frequency bunch length requirements. The $\beta=1$ bandwidth of this device is measured to be 6 GHz.

Formulae

For a charged beam with $\beta < 1$, the image charges on a conducting beam pipe spread ahead and behind the beam bunch by an angle $\sim 1/\gamma$. The electric field at the surface of the conducting beam pipe for a particle of velocity β is [3]:

$$D_r(t) \propto \sum_n \left(J_1(\alpha_n r / r_0) / J_1(a_n)^2 \right) e^{-\alpha_n x / r_0}$$

with:

$$x = \gamma\, \beta\, c\, t \quad \text{and} \quad J_0(\alpha_n) = 0 .$$

$D_r(0)$ is taken to be 0.6631. At the energies of the Linac, 116 MeV to 401 MeV:

$0.0154\, t < x < 0.03054\, t$ [cm], t in picoseconds.

Using these formulae, the delta-function response of a 40 mm aperture WCM to a 116.5 MeV beam produces a signal whose apparent length is 100 psec, or about 30° at 805 MHz. A beam length of 100 psec yields a signal on a 116 MeV WCM of about 135 psec, 40°.

Measurements

The WCMs have been used as follows: to observe adjacent buckets for stray beam (only every fourth RF bucket is used at 805 MHz), to estimate the bunch length and to measure the phase of the beam with respect to the RF reference line. During the initial commissioning of the 805 MHz part of the Linac in 1993, beam was observed in adjacent 805 MHz buckets from LEL, and the match was adjusted. Bunch-length changes were observed at WCMs as longitudinal parameters were tuned. Also, the phase and amplitude of the 805 MHz modules was adjusted based on these beam phase signals [1].

For large bunch lengths at higher β, as obtained following the long drift to the Booster, a WCM is satisfactory. The bunch length is accurately measured at a WCM 41 meters downstream of the Linac. Also, the stability of the Linac beam velocity is tracked with this device.

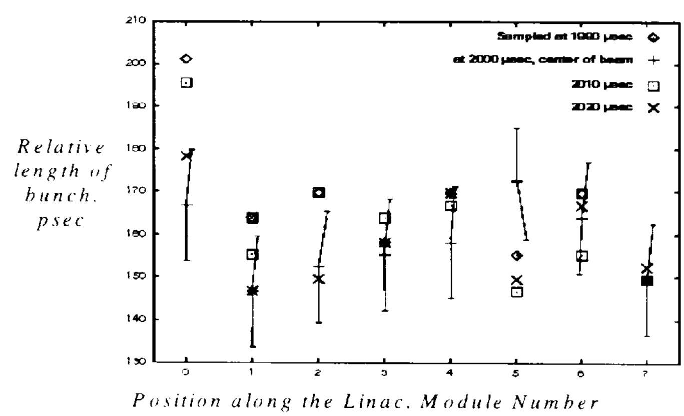

Figure 1, Measurement results from Wall-current Monitors

WCM measurements have been made of the bunch length vs. position in the Linac and time in the Linac 30 µsec macropulse. (The center of the macropulse is called "2000 µsec".) The results are presented in Fig. 1. The average of several measurements of the bunch length is used. The measured WCM signals are compared to a test distribution,

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convolved with the above formulae. These measurements are consistent with a constant bunch length of 159 ± 15 psec (46 ± 4°) through the HEL. This is the average of the measurements, with the uncertainty being the standard deviation on this average combined with the error bars on the measurement. Systematic errors are believed to be large and are not quoted here. The average of the bunch length measurements at the beginning of Module 1 is 185 ± 18 psec (54 ± 5°).

4. The Bunch-Length Detector

A BLD accurately measure the length of a low-β bunched beam. These devices also work well for a high-β beam, but the far simpler WCM is sufficient there. Based on the work of Witkover [3], Feschenko has further perfected this device [4]. Details of the design are presented in the ref. [5]. The BLD gets its signal from a prompt secondary electron beam, created when the primary ion beam hits a target wire, biased to -10 kV. The electrons are collimated by a slit in front of the RF deflector. They are deflected transversely by this RF cavity, which is excited with RF power synchronous to the accelerating RF in the Linac. This time-dependent deflection sweeps the electrons across the detection slit at the far end of the BLD. The RF cavity doubles as a focusing einzel lens. The phase of the deflection is varied, and the resulting electron signal vs. this phase is the longitudinal bunch shape.

Resolution

The resolution of the BLD is predominantly determined by: (a) the temporal distribution of the electron beam when it reaches the deflector (related to the 3D emittances of the beam), (b) the strength of the deflection and (c) by machining tolerances [4].

The transverse emittance of the electron beam is determined by the size of the wire, the size of the collimator slit and the temperature of the electrons as they are ejected from the wire's molecular lattice. The longitudinal emittance is dominated by the time it takes for the secondary electrons to be ejected from the wire—a parameter of some interest to atomic physics. The best measurement to date puts this number at no more than 6 psec [7]. Combined with the other temporal effects, the resolution is degraded less than 10 psec, which corresponds to 2.9° of 805 MHz phase.

The strength of the deflection determines how quickly the image of the wire passes across the detector slit, and this can be measured directly:

$$\delta\phi = 2\arcsin\left(\sqrt{\sigma_{beam}^2 + w_{slit}^2} / 2X_{\max}\right)$$
$$\approx \sqrt{\sigma_{beam}^2 + w_{slit}^2} / X_{\max}$$

for small angle values, where σ_{beam} is the width of the image of the electron beam on the slit, w_{slit} is the width of the slit and X_{max} is the extent of the deflection on the plane of the electron detector and is proportional to the electric field in the RF deflector. Without RF deflection, a DC voltage on one of the einzel lens/deflector plates can be changed until the image of the wire is no longer seen in the detector:

$$V_1 = K\sqrt{\sigma_{beam}^2 + w_{slit}^2}$$

Then, with the RF on, a similar measurement is performed, being careful to measure the maximum deflection of the RF voltage:

$$V_2 = K(X_{\max} + \sqrt{\sigma_{beam}^2 + w_{slit}^2}\ )$$

Therefore, for small angle values,

$$\delta\phi = V_1 / (V_2 - V_1)$$

The resolution of the three BLDs installed in the Fermilab Linac have been measured in this manner:

BLD Position	V1	V2	Res	Est Res	Bandwidth
Transition section, 1	80	1200	4.09	5.02	5.78E+10
Transition section, 2	90	550	11.21	11.58	2.50E+10
400 MeV Area	120	500	18.09	18.32	1.58E+10

V1 and V2 are in Volts, the resolutions are expressed as degrees of 805 MHz phase, and the bandwidth is in Hz. The "Res" column represents the resolution measured here; the "Est Res" column is an estimate of the overall resolution, which is equal to $\sqrt{(Res^2 + (2.9°)^2)}$, taking into account the estimated 10 psec of temporal effects, discussed above.

The resolution on the initial BLD (400 MeV Area BLD) is the poorest, and as we gained experience in building them, the resolution improved. The "Transition section 2" BLD has a smaller, higher-loss cable than "1", and thus a lower value for V2. All measurements are made at the maximum obtainable power in the RF deflector, estimated at tens of watts.

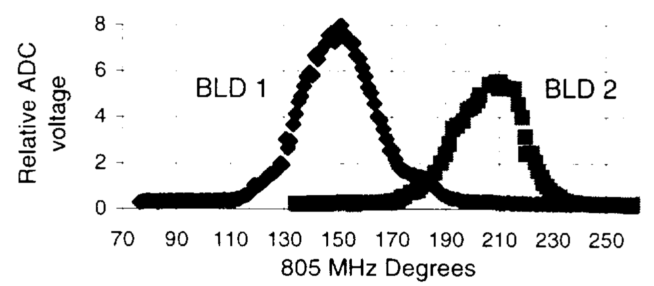

Figure 2. Typical bunch-length measurement.

Measurements

Typical data from the two BLDs in the transition section are shown in Fig. 2. The second BLD has been used to determine the proper gradient of the 805 MHz buncher cavity. The bunch length as a function of the buncher gradient has also been measured. The bunch length at the BLD upstream of module 1 is 25° when the buncher is off, and 11° when the buncher is set optimally.

Another interesting measurement, made with each of the BLDs, is the length variation during the pulse. The bunch length is measured at various intervals through the macropulse by changing the sample time on the A/D module.

These results are shown in Fig. 3.

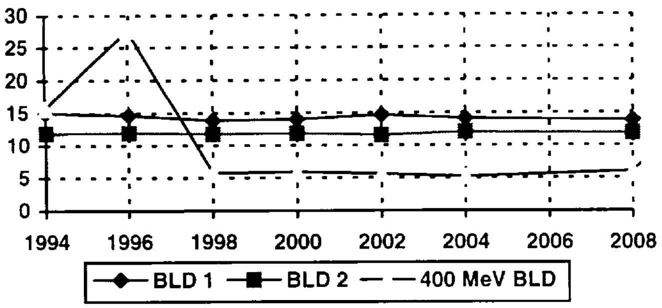

Figure 3, Bunch Length through the macropulse.

Measurement limits

The beam in the Linac has been as high as 50 mA, peak. This corresponds to 1.6×10^9 particles per bunch, or a charge of 2.5×10^{-10} Coulombs. When the BLD target wire is placed in the middle of the beam bunch, the measurement is destroyed. This may be due to a change in the potential seen by the secondary electron beam as the ion beam passed through the target wire. The electrons created in the center of the distribution have a significantly higher potential than the electrons created at the trailing edge. Moreover, the electrons created at the beginning of the bunch are subjected to the passage of the ion beam.

This effect is estimated as follows. The least damaging (and the easiest to calculate) ion beam distribution is a uniform spherical beam. The potential of a test charge along a line is proportional to the distance from the center of the beam, z, and the radius of the beam, R, is:

$$V = \frac{\rho}{2\varepsilon_0}\left[R^2 - \frac{3}{4z}\left((R+z)^3 - (R-z)^3\right)\right]$$

As $z \to 0$, the potential is finite, and for the Linac beam, with R=10 mm, Q = 2.5×10^{-10} C, we have:

$$V_{center} = 339 \text{ volts}$$

With a primary potential on the BLD target of 10 kV, the secondary electron beam has a velocity of β=0.1950. This perturbation produces an electron velocity of β=0.1981 when the ion beam is directly over the wire. Over the 10 cm the electrons must travel to the RF deflector, where their temporal distribution is marked, these faster electrons are 0.75° advanced from the normal electrons.

Further study is needed because (a) there is still a large resolution-killing effect visible on the 400 MeV BLD, (b) the bunch length is much greater than the beam radius and (c) the beam distribution is not uniform. (b) and (c) affect the potential oppositely—longer bunch length lowers the central potential, but non-uniform charge distribution raises it.

5. Momentum Spread

The momentum spread is measured in the Linac by the BLDs at 116 MeV and at 401 MeV, and verified with the spectrometer magnet at 401 MeV.

The bunch length out of Tank 5 is measured by the first BLD to be 14°; the bunch length at the second BLD, 3 m downstream, with buncher cavity off is 25°. This change in the bunch length is due at least partially to the momentum spread, but since the orientation of the longitudinal ellipse is unknown from this measurement, it can only be estimated. Assuming that all of the bunch spreading is from the momentum spread of the beam, $\Delta p/p \approx 0.17\%$. This puts an upper limit on the longitudinal emittance out of the LEL of 1.6×10^{-5} eV-sec. Similarly, the longitudinal emittance is estimated from the change in the bunch lengths from the last BLD to the last WCM, 41 m downstream of the Linac, for the output of the last HEL module to be 7.8×10^{-5} eV-sec.

An upper limit on the momentum spread is obtained with the 401 MeV spectrometer magnet. The edge effects of this magnet are poorly understood. The smallest size beam which can be achieved at the focus of this magnet is 32 mm. If this is all due to momentum spread, then this would correspond to $\Delta p/p = 0.005$. The BLD measurement yields $\Delta p/p = 0.0055$.

6. Conclusions

The length of the Fermilab Linac bunched beam has been measured using wall-current monitors and bunch-length detectors. Both of these devices yield interesting and useful results. A well-constructed and carefully implemented BLD can have a bandwidth of almost 60 GHz. The longitudinal emittance can be estimated with these devices.

7. Acknowledgments

Petr Ostroumov and Alexandr Feschenko, from the Institute for Advanced Studies in Moscow, were fundamental in the construction and assembly of these devices. H. S. Zhang, of the Institute for High Energy Physics in Beijing, China, contributed many of the ideas in the understanding of the resolution of the BLD. Our thanks go out to them.

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