# TIME-OF-FLIGHT, BEAM-ENERGY MEASUREMENT OF THE LANSCE 805-MHz LINAC [*]

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## *Abstract*

Control of the beam-energy ramp along the length of a proton linear accelerator is required to keep the accelerator tuned according to design. Historically, the values of the field amplitudes and phases of the side-coupled, 805-MHz LANSCE linac modules are maintained using a well-known delta-t tuning procedure [1]. Time-of-flight measurements of the proton beam energy are now also being used to confirm and improve the overall control of the energy ramp along the linac. The time-of-flight method uses absolute measurements of beam energy using direct signals from beam at an oscilloscope, as well as the difference in RF phases measured as the beam passes installed delta-t pickup loops. A newly developed BPPM data acquisition system is used. Details of the procedure and results of measurements are presented.

## INTRODUCTION

The LANSCE accelerator facility is equipped with two independent injectors for $H^+$ and $H^-$ beams, merging at the entrance of a 201.25 MHz Drift Tube Linac (DTL). The DTL performs acceleration up to the energy of 100 MeV. After the DTL, the Transition Region beamline directs a 100 MeV proton beam to the Isotope Production Facility, while the $H^-$ beam is accelerated up to the final energy of 800 MeV in an 805 MHz Coupled Cavity Linac (CCL). The $H^-$ beams, created by different time structure of a low-energy chopper, are distributed in the Switch Yard (SY) to four experimental areas: Lujan Neutron Scattering Center equipped with Proton Storage Ring (PSR), Weapon Neutron Research Facility, Proton Radiography Facility, and Ultra-Cold Neutron Facility.

The Drift Tube Linac consists of 4 tanks, which amplitudes and phases are selected through absorber-collector phase scans. Coupled Cavity Linac includes 44 accelerating modules (modules 5-48), which amplitudes and phases are tuned using the “delta-t” method [1]. This classical method is based on measurement of time of flights between two pairs of delta-t pickup loops while accelerating module is on and off. Delta-t method uses only a small phase range (~ $10^o$) for tuning because the procedure is based on a linear model. Delta-t tuning procedure works well when particles perform significant longitudinal oscillations within RF tanks. Accuracy of the method unavoidably drops with energy. In order to independently control tuning of the machine, the time of flight method for beam energy measurement was added.

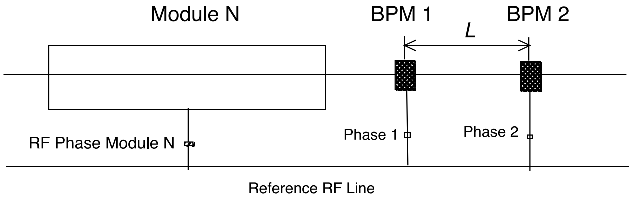

Figure 1: Measurement of beam energy by difference in BPM RF phases.

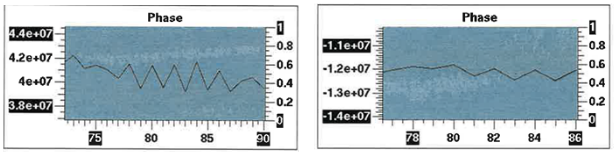

Figure 2: Beam RF phases measured at delta-t loops (in micro degrees).

## BEAM ENERGY MEASUREMENT BY TIME OF FLIGHT

Energy measurement of the beam is usually performed through measurement of time of flight (TOF) of beam $t = L/\beta c$ between 2 pickup loops (see Fig. 1), separated by distance $L$, where $\beta c$ is the beam velocity [2]. Time of flight can be represented as

$$t = N\frac{\lambda}{c} + \Delta t\,, \tag{1}$$

where $N$ is the integer number of RF periods during time of flight, $\lambda$ is the wavelength, and $\Delta t$ is the fractional part of time of flight. The change of RF phase during time of flight is

$$\omega t = 2\pi N + \Delta\varphi\,, \tag{2}$$

where $\Delta\varphi = 2\pi c\Delta t/\lambda$ is an actual measured fractional part of phase change (see Fig. 2). Expressing beam velocity from Eqs. (1), (2):

$$\beta = \frac{L}{\lambda(N + \dfrac{\Delta\varphi}{2\pi})}\,, \tag{3}$$

the beam energy is determined as

$$W = mc^2\left(\frac{1}{\sqrt{(1-\beta^2)}} - 1\right), \tag{4}$$

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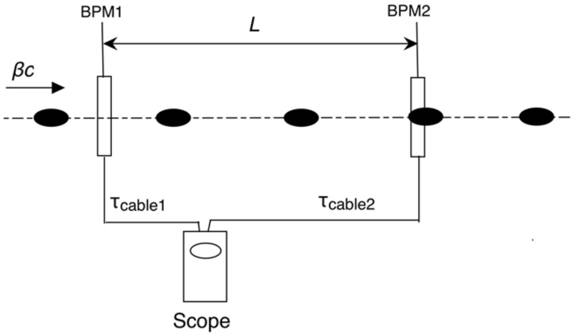

Figure 3: Time of flight measurement of absolute beam energy.

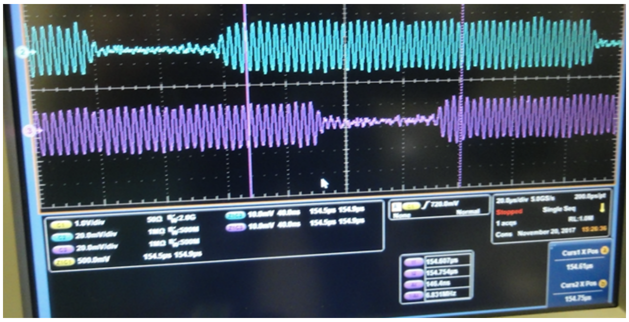

Figure 4: Measurement of time of flight of bunch train between two delta-t loops.

where $mc^2$ is the ion rest energy and $N$ is the value of integer number of RF periods during time of flight. The error in determination of beam velocity is

$$\frac{d\beta}{\beta}=\sqrt{(\frac{dL}{L})^2+(\frac{\delta(\Delta\varphi/2\pi)}{N+\frac{\Delta\varphi}{2\pi}})^2} \qquad (5)$$

where $dL/L$ is the error in measured distance between pickup loops, and $\delta(\Delta\varphi)$ is the error in phase measurement, while error in determination of energy is

$$\frac{dW}{W}=\gamma(\gamma+1)\frac{d\beta}{\beta}. \qquad (6)$$

Separation in possible values of energy due to ambiguity in velocity determination is ($N>>1$)

$$\frac{\Delta W}{W}\approx\frac{\gamma(\gamma+1)}{N}. \qquad (7)$$

Determination of beam energy requires knowledge of integer number of RF periods during time of flight. Direct observation of beam pulse trains (see Figs. 3, 4) allows measurement of absolute value of time of flight between two loops [3]. Beam velocity is determined as

$$\beta=\frac{L}{c[t-(\tau_{cable2}-\tau_{cable1})]}, \qquad (8)$$

where $t$ is the observable time of flight at the scope, and $\tau_{cable1}$, $\tau_{cable2}$ are cable lengths measured in terms of time required for signal propagation from pickup loop to the scope. Error in determination of velocity is

$$\frac{d\beta}{\beta}=\sqrt{(\frac{dL}{L})^2+(\frac{dt}{t-\Delta\tau_{cable}})^2+[\frac{d(\Delta\tau_{cable})}{t-\Delta\tau_{cable}}]^2}, \qquad (9)$$

where $\Delta\tau_{cable}=\tau_{cable2}-\tau_{cable1}$ is the cable length difference.

## RESULTS OF MEASUREMENTS

For beam energy measurement, we used existing Δt loops distributed along the linac. Both methods, presented above, included preliminary calibration of cable lengths, which was done using beam with known energy. Final beam energy of the linac 795.46 MeV is determined through operation of LANSCE Proton Storage Ring, which has circumference of 90.26 m and operational frequency of 2.792424 MHz. Final pair of Δt loops after linac (loops 48 – SY) is separated by the distance of $L_{48-SY}$ = 20.029 m. Measured time of flight $t_{48}$ = 146.6 nsec between that Δt loops with known beam velocity $\beta_{48}$ = 0.84073 provides beam-based measured difference in cable length

$$\tau_{SY}-\tau_{48}=t_{48}-\frac{L_{48-SY}}{\beta_{48}c}=67.1337\text{ ns} \qquad (10)$$

For control of beam energy after every accelerating module, each module was subsequently delayed and TOF between loops 48-SY was determined. Measurements started from the last module 48 and performed until module 13, unless the signal from drifting beam was observed. Using Eqs. (4), (8), the particle velocity and beam energy were determined.

The similar technique was used to measure beam energy in the beginning of 805 MHz linac. Beam with known energy of 100 MeV after DTL was used to calibrate cable length difference of Δt loops after modules 11-12. Using distance between loops $L_{11-12}$ = 16.976 m, velocity of 100 MeV particles $\beta_{100MeV}$ = 0.42799, and measured TOF $t_{100MeV}$ = 196.15 ns, the beam-based measured difference in cable length of loops 11-12 is:

$$\tau_{12}-\tau_{11}=t_{100MeV}-\frac{L_{11-12}}{\beta_{100MeV}c}=63.84528\text{ ns}. \qquad (11)$$

Turning on subsequently modules 5-11, we measured TOF and beam energy after modules 5-11. The final determination of energy after module 12 was performed using measured beam energy after module 11, $E_{11}$ = 196.318 MeV, and Δt loops after modules 12-13.

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Typical error in determination of time of flight in absolute measurements is $dt = \Delta\tau_{cable} =$ 0.1 - 0.2 ns. Distances between Δt loops are known with relative error of $dL/L = 5\cdot10^{-5}$. The error in absolute determination of energy is

$$\frac{dW}{W} \simeq (1.4-3.5)\cdot10^{-3}\gamma(\gamma+1)\,. \qquad (12)$$

Absolute energy measurements were used as a reference for more precise energy determination using determination of RF phase difference in Δt loops.

A newly developed BPPM data acquisition system to control the 3D position of the beam centroid ( $x$, $y$ , phase) was used. As in previous method, we started measurements from the end of the linac using 48-SY Δt loops. Measured beam phase difference between loops $\varphi_{SY} - \varphi_{48} = 192^o$ together with expected difference in beam phase

$$\Delta\varphi_{\text{expected\_48\_SY}} = 2\pi\left[\frac{L_{48-SY}}{\beta_{48}\lambda} - INT\left(\frac{L_{48-SY}}{\beta_{48}\lambda}\right)\right] = 357.3^o\,, \quad (13)$$

provides phase correction due to difference in cable lengths $\Delta\varphi_{corr} = \varphi_{\text{expected\_48\_SY}} - (\varphi_{SY} - \varphi_{48}) = 165.3^o$. Using the RF phase difference measurement in loops 48-SY, and known value of integer RF periods for each value of energy from absolute measurements, $N$, the beam energy was determined in modules 35-48.

In order to perform beam energy measurement in modules 5-34, the calibration of each pair of Δt loops was done using measured beam energy from previous module while tested module was off:

$$\Delta\varphi_{corr} = 2\pi\left[\frac{L}{\beta_{in}\lambda} - INT\left(\frac{L}{\beta_{in}\lambda}\right)\right] - (\varphi^{OFF}_{loop2} - \varphi^{OFF}_{loop1})\,, \quad (14)$$

where $\beta_{in}$ is the measured beam velocity from previous module. Then, turning module on, the beam velocity after tested module was determined though measured phase difference $\varphi^{ON}_{loop2} - \varphi^{ON}_{loop1}$ :

$$\beta = \frac{L}{\lambda\left(N + \dfrac{\varphi^{ON}_{loop2} - \varphi^{ON}_{loop1} + \Delta\varphi_{corr}}{2\pi}\right)}\,, \qquad (15)$$

where value of $N$ was known from absolute TOF measurement.

Error in determination of phase in considered method is $\delta(\Delta\varphi) \approx 1^o$. This method appears to be more accurate than the absolute energy measurement method. The estimated error is one order of magnitude smaller than that in absolute method:

$$\frac{dW}{W} \simeq 1.5\cdot10^{-4}\gamma(\gamma+1) \qquad (16)$$

Table 1: Results of Beam Energy Measurements (MeV) of 805 MHz Linac

| module | Design | Absolute Method | Error | RF Phase Method | Error |
|---|---|---|---|---|---|
| 5 | 113.02200 | 112.36600 | 0.30020 | 112.63126 | 0.10571 |
| 6 | 125.92400 | 126.31650 | 0.36160 | 125.64310 | 0.11520 |
| 7 | 139.39500 | 139.43210 | 0.42350 | 139.46410 | 0.13594 |
| 8 | 153.41299 | 152.26030 | 0.48800 | 152.67914 | 0.15129 |
| 9 | 167.95799 | 168.71800 | 0.57600 | 168.56892 | 0.18032 |
| 10 | 182.10600 | 181.66569 | 0.64971 | 181.73358 | 0.19748 |
| 11 | 196.68500 | 196.31799 | 0.73781 | 196.83067 | 0.21872 |
| 12 | 211.67900 | 211.75160 | 0.93160 | 211.42828 | 0.27409 |
| 13 | 226.37399 | 226.10460 | 1.58080 | 226.59654 | 0.30898 |
| 14 | 240.91701 | 240.16010 | 1.74820 | 241.85416 | 0.16909 |
| 15 | 255.77499 | 255.73830 | 1.94260 | 256.77493 | 0.17984 |
| 15 | 270.93399 | 270.06381 | 2.12999 | 270.95114 | 0.19682 |
| 17 | 286.00000 | 285.79910 | 2.34470 | 287.01511 | 0.21618 |
| 18 | 302.11700 | 301.34119 | 2.56681 | 301.75278 | 0.23536 |
| 19 | 317.56900 | 316.40970 | 2.79100 | 317.99795 | 0.25181 |
| 20 | 333.26401 | 330.68899 | 3.01201 | 333.71249 | 0.27355 |
| 21 | 349.19299 | 348.42291 | 3.29769 | 349.39008 | 0.29520 |
| 22 | 365.34698 | 362.83719 | 3.53921 | 365.59720 | 0.31939 |
| 23 | 381.71701 | 378.32379 | 3.80851 | 380.81226 | 0.34025 |
| 24 | 397.70901 | 395.00610 | 4.10950 | 398.26715 | 0.36809 |
| 25 | 413.88901 | 416.17419 | 4.50821 | 417.15771 | 0.39108 |
| 26 | 430.24899 | 432.56021 | 4.82989 | 433.03842 | 0.41787 |
| 27 | 446.78400 | 442.95270 | 5.03970 | 450.17416 | 0.44641 |
| 28 | 463.48700 | 461.29840 | 5.42160 | 465.09152 | 0.47326 |
| 29 | 480.35199 | 472.97269 | 5.67211 | 485.35034 | 0.51056 |
| 30 | 496.75000 | 493.65680 | 6.13070 | 502.63019 | 0.54392 |
| 31 | 513.28802 | 506.87000 | 6.43350 | 516.21478 | 0.57169 |
| 32 | 529.96301 | 525.51880 | 6.87430 | 535.40192 | 0.61105 |
| 33 | 546.76001 | 545.46118 | 7.36282 | 552.31592 | 0.64856 |
| 34 | 563.69897 | 561.35168 | 7.76522 | 570.46838 | 0.68841 |
| 35 | 580.75299 | 578.11871 | 8.20219 | 580.39380 | 0.57266 |
| 36 | 597.27399 | 601.96979 | 8.84691 | 596.78180 | 0.60292 |
| 37 | 613.90002 | 608.22082 | 9.02018 | 612.32794 | 0.63239 |
| 38 | 630.63000 | 621.09338 | 9.38302 | 625.14526 | 0.65725 |
| 39 | 647.45801 | 634.48639 | 9.76931 | 628.55579 | 0.66394 |
| 40 | 664.38300 | 655.62323 | 10.39597 | 662.19958 | 0.73214 |
| 41 | 681.40100 | 670.46771 | 10.84929 | 676.72748 | 0.76276 |
| 42 | 698.50897 | 693.96619 | 11.58931 | 690.29291 | 0.79196 |
| 43 | 715.70502 | 710.52197 | 12.12753 | 711.34650 | 0.83844 |
| 44 | 732.98499 | 719.08539 | 12.41091 | 725.06293 | 0.86955 |
| 45 | 749.66400 | 746.00488 | 13.32762 | 741.95288 | 0.90875 |
| 46 | 766.41699 | 755.41467 | 13.65643 | 761.34784 | 0.95493 |
| 47 | 783.24103 | 774.93658 | 14.35402 | 779.78540 | 1.00009 |
| 48 | 795.46002 | 795.46002 | 15.10951 | 795.46002 | 1.03937 |

Separation in energy due to ambiguity, Eq. (7), is two orders of magnitude larger than error, Eq. (16). Table 1 contains results of measurements performed by both methods. Obtained results create basis for more careful tuning of linear accelerator.

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