BBU GAIN MEASUREMENTS ON THE ITS 6-MeV, 4-kA LINAC

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Abstract

The amplification of transverse beam motion by the ITS eight-cell linear induction accelerator (LIA) was measured with a 4-kA beam at frequencies between 710- and 950-MHz. The 3.75-MeV injector beam was deflected with amplitudes of ~ 1 mrad by an RF-driven tunable cavity 84 cm before the linac. The centroid-position waveforms from calibrated B-dot loops were recorded with 5-GS/s digitizers at the linac entrance, exit, and after a further free drift of 108 cm. The FFT amplitudes of the waveforms were used to compute the gains. The code LAMDA, an envelope and BBU model for the linac, was used to interpret the gain curves, using the transverse impedances of the cells as adjustable parameters. The results compare favorably with cell impedances previously measured with a two-wire TSD method.

PURPOSE

Beam-breakup (BBU) was first observed and described at SLAC, where the beam current disappeared (broke up) after going partway down the linac[1] because of the excessive amplitude of transverse motion. This amplitude grows approximately[2] as $\exp(ni_b\omega Z/c^2B)$ for a beam of current i_b in a linac of n cells with peak transverse impedance $\omega Z/c$ and solenoidal magnetic field B. We require for DARHT[3] that the transverse motion at the X-ray target be a small fraction of the inherent spot size of ~ 1 mm. DARHT cells were designed for low transverse impedance, which we measured[4] using the two-wire through-short-delay (TSD) method. The purpose of our BBU experiment is to measure amplification with a 4-kA beam, deducing the frequency dependence of $\omega Z/c$ using our beam dynamics code LAMDA[5], to compare with the TSD measurements.

EXPERIMENT

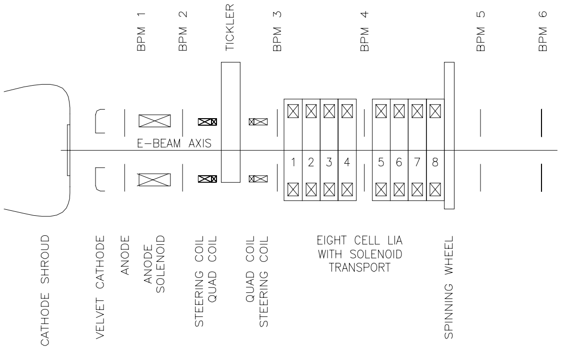

Fig.1 Layout of ITS for BBU experiment

Beam was deflected in the Y-plane before the ITS linac (Fig.1) entrance with a tunable "tickler" box[6]. Centroid deflections in the X- and Y-planes were measured with beam-position monitors (bpms) at the linac entrance (bpm3), exit (bpm5), and after a field-free drift of 108 cm (bpm6). In effect, the angles at bpm5 are determined by the positions at bpm6 and bpm5, therefore a complete measurement of the centroid motion at bpm5 is made. The tickler box had a single mode below pipe cutoff frequency of ~ 1.2 GHz, with the pipe offset so that RF-deflection of the beam would occur. The bpms were precision B-dot loop types[7], individually calibrated. Each bpm was connected, without integrators, to Tektronix TDS-684 5-GS/s digitizers through 30-db attenuators with cables time aligned through the digitizers to ~ 20 ps. The waveforms were clean but damped by beam loading as it is deflected in the 8-cm length of the box. Since the frequency was not an exact multiple of the bin spacing of 20 MHz, the power spectral density (PSD) of the waveforms over 50 ns was summed over ± 3 bins around the peak, adequate to include ~ 99% of the signal. A waveform for bpm6x is shown in Fig.2, along with the FFT analysis, converted approximately to μ. Gains are defined as gx5 = $[\,\mathrm{PSD(bpm5x)/PSD(bpm3y)}\,]^{1/2}$, and similarly for gy5, gx6, and gy6.

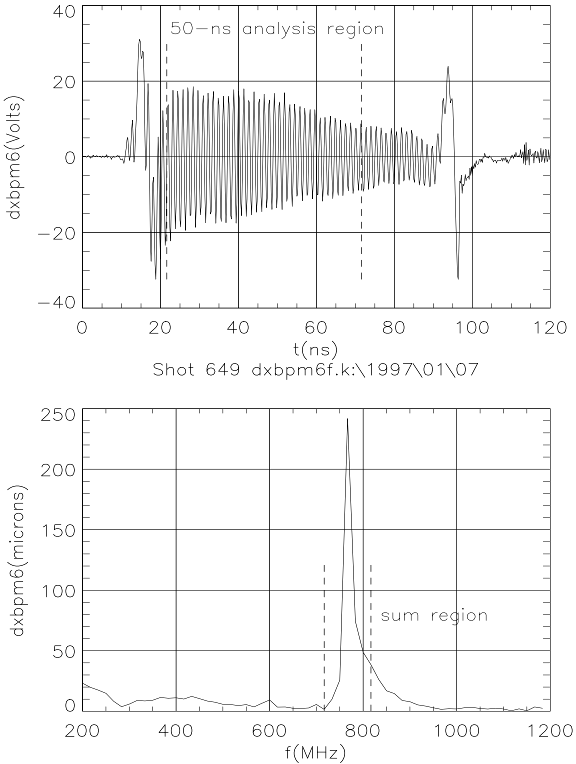

Fig.2 Digitized waveform (upper), FFT(lower)

The injector was operated at 3.75-MeV, 3.8-kA, the linac at 224-kV/cell. The eight linac magnets had a total phase advance of 2.48π with B ~ 700 to 900 G. There

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was no observable current loss to bpm6, 734 cm from the cathode, to within our 2% accuracy. Field maps were made of all linac magnets in situ, so that the effects of ferrites and mu-metal shielding on the fields were included, and accurate models of these fields were then used in the codes. We drove the tickler with a 25-W RF amplifier to stabilize the deflection amplitude to ~ 20%.

We did steering experiments[8] at low (~0.3 kA) and at high (3-kA) currents to verify overall accuracy of calibrations of magnets and bpms, data capture and analysis, and code physics. Besides verifying basic calibrations, this led to the discovery that for steady-state steering, the centroid steers as if the beam-potential depression bpd = $(i_b Z_0/2\pi\beta)\ln(R_w/r_b)$ from the wall, $R_w = 7.41$ cm, to the beam edge r_b were zero. We also discovered that the quadrupole image-field of the beam in the tickler box, $\int\nabla_\perp B dz \approx 5$ G/kA, made the beam highly elliptical (up to ~ 3x at bpm3). Analysis shows that the fractional bpm response error = $3(r_y^2-r_x^2)/4R_w^2$ ~ 20% in some cases (beam radii r_x, r_y). To eliminate this error, we added quadrupole corrector coils (Fig.1) around the tickler box and measured ellipticity near bpm3 as a function of the frequency of the tickler and the corrector settings, then used this data to set the corrector currents for the BBU experiment. Over its full range of ± 20 A, we found that apparent gains at bpm5 and bpm6, near the BBU gain maximum at ~ 760 MHz, varied up to 30% but were not very sensitive to uncertainties around the proper setting of about 6.5 A. To eliminate the quadrupole effect entirely, we measured gains with a circular cavity with TM_{110} modes at 764 MHz. The results closely matched those with the rectangular tickler.

The TSD-measured impedances showed that the TM_{120}-like modes near 800 MHz would dominate over those near 300 MHz. We made our measurements with excitation in the Y-plane only, from 710 MHz up to 950 MHz in 20-MHz steps, then back down at intermediate frequencies. During the downward steps, there was an injector energy shift of about 100 keV, which shifted the up/down gain curves by 5-20%. We took a smooth average of the data, about 250 shots at 23 different frequencies. Out of ten shots at each frequency, typically two were discarded because of low amplitude, the remainder then having gains with a standard deviation of only ≈ 4%.

ANALYSIS

Simulations[9] with the PIC code ISIS show that at 800-MHz, as for steady-state steering[8], the bpd is essentially zero for the centroid dynamics, therefore LAMDA was modified accordingly. The LAMDA model for the centroid has the image-displacement steering of the pipe and of the gaps. We neglected the effect of impedance of three bellows, ~ 1 Ω/cm each. The TSD-measured impedance values for all cell modes were used initially in LAMDA, then the eight values of Q, f, and reZ and imZ at resonance f were varied for the two ~ 800-MHz modes. During the TSD measurements we had observed that with ferrite bias current of 500 A, the impedances declined by ~ 10% and the frequency changed by a few percent, so it is expected that cell parameters under beam conditions may differ slightly from the TSD values.

We define fom = $[\Sigma(gm-gc)^2/\Sigma gc^2]^{1/2}$, summed over all frequencies, as a convenient figure of merit for comparing the measured and calculated gains gm and gc. The fom was calculated for each of the four gains gx5, gy5, gx6, and gy6 and for the magnitudes g5 (= $[gx5^2 + gy5^2]^{1/2}$) and g6. Generally, g5 and g6 are less affected by the imaginary impedances or the energy (phase advance) than the other four gains. We tried to minimize all six fom's simultaneously. Positive fom means that the weighted gm > gc and vice-versa.

The best match of LAMDA to the BBU measurements is shown in Fig.3, having adjusted the injected beam energy to 3.62 MeV, 130 keV or 3.5% below the nominal value. This could mean that the bpd cancellation is not complete under all conditions of our measurements. The magnetic fields are probably accurate to better than 1%, otherwise a possible source of the discrepancy. There is a clear determination from LAMDA of the energy to ~ 1%, however, from the ratio of X- and Y- gain amplitudes at bpm5 and at bpm6. The best values of LAMDA model parameters are shown in the table for the X- and Y-planes, along with the TSD-measured values. The LAMDA values are lower by 5% and 27% in X and Y. The average $reZ_{X,Y}$(Ω/cm) are 7.6 (TSD) and 6.2 (LAMDA). If the code energy is increased to the nominal 3.75 MeV, then only g5 and g6 can be matched well, in which case the optimum average is 6.8 Ω/cm. We believe that the TSD measurements determined reZ to ±20%, imZ to ±2 Ω/cm. LAMDA fits reZ to ~5%, imZ to ±1 Ω/cm. We might expect the imZ to be near their zero-frequency values[8] of ~ -3.5 and -4.5. Neglect of bellows impedances and other modeling omissions or errors may influence the fit values of any of the parameters, of course, but the BBU experiment determines that reZ is 10-20% lower than the TSD values.

	TSD	LAMDA
f_X(MHz)	760	790
Q_X	4.5	4.6
reZ_X(Ω/cm)	6.35	6.03
imZ_X(Ω/cm)	-1.8	-1.
f_Y(MHz)	785	780
Q_Y	5.3	5.5
reZ_Y(Ω/cm)	8.8	6.45
imZ_Y(Ω/cm)	1	-5.5

CONCLUSIONS

Measurements of the BBU gains and their theoretical interpretation give results that are close those expected from the TSD measurements but more favorable for DARHT operation. The cancellation of the bpd for centroid motion observed for steering[8] appears to be ~ 1/3 incomplete for our RF frequencies. Beam performance predictions at the DARHT X-ray target used the higher TSD impedances, therefore BBU motion at the target should contribute negligible spot blur.

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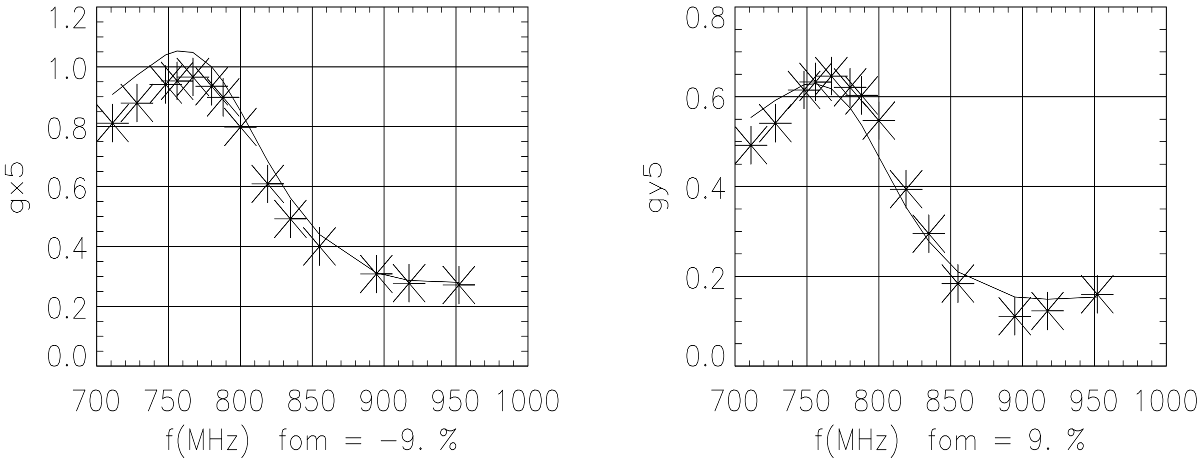

Fig.3 Measured(*) and Calculated(lines) Gains vs f, fom5 = −6.6 % & fom6 = −1.8 %