OBSERVATION OF SELF-STEERING EFFECTS ON THE ITS 6-MeV LINAC

Paul Allison, David C. Moir, Gary Sullivan
Los Alamos National Laboratory
Thomas P. Hughes
Mission Research Corporation, Albuquerque

Abstract

Beam centroid oscillations were induced in the ITS eight-cell linear induction accelerator (LIA) by steering the beam near the entrance, and position measurements were then made at four locations through the linac. Measurements were in good agreement with code predictions, using the nominal accelerator values, for a collimated beam of ~ 0.3 kA, but to get reasonable agreement for the full 3-kA beam, it was necessary to increase the code value of injection voltage from its known value of ~ 3.7 MeV by ~ 300 kV, approximately the edge beam-potential depression (bpd). Subsequent simulations with the 3D PIC code LSP showed that centroid steering is described more accurately by the total rather than the kinetic energy of the beam. Modification of the beam dynamics code to eliminate the bpd resulted in good agreement with measurement for both 0.3- and 3-kA beams.

PURPOSE

The Integrated Test Stand (ITS) is the first part of the DARHT linac[1] and consists of a 3.75-MeV injector and eight 250-kV induction-linac cells. We are making various beam measurements to compare with design predictions to validate codes and to gain confidence in our ability to predict performance for the full linac. Accurate prediction of centroid motion is important for interpretation of BBU gains[2]. Agreement between position measurements, made at downstream beam position monitors (bpms), and code predictions requires accurate

1. bpm calibrations
2. bpm waveform digitizers
3. bpm analysis programs
4. steering and focusing magnet fieldmaps, polarities, locations, calibrations, readouts
5. beam voltage and current, cell voltage.

Good machine reproducibility and beam roundness[2] are also essential. Code physics must include proper modeling of centroid deflection in the cells caused by image-current effects, a.k.a. imaginary transverse impedances and hereafter called $Z_\perp$. Since these deflections are proportional to $i_b Z_\perp$, then $Z_\perp$ can be inferred by comparing steering experiments (runs) for high- and low-current beams, i_b ~ 3- and ~ 0.3-kA, with otherwise identical linac and injector settings. The goals of the steering experiment were to

1. demonstrate ability to model beam steering
2. deduce $Z_\perp$.

We did six different runs (#1-#6, summarized in the table below) at three injection energies and several currents. The same magnet settings and gap voltages (233 kV) were used for all runs, except for #4 and #6, for which solenoid magnet #7 (Fig.1) was off.

EXPERIMENT

The layout of the experiment (Fig.1) shows the location of the bpms and the steering magnet pair (smx and smy, before the linac), which were used for steering in either the X- or Y- planes. Deflections dx and dy were measured at bpms 3,4,5,6. A 2-cm diam. collimator was placed upstream of the steering magnet for the low-current measurements. The drift-tube solenoid was turned off for all runs.

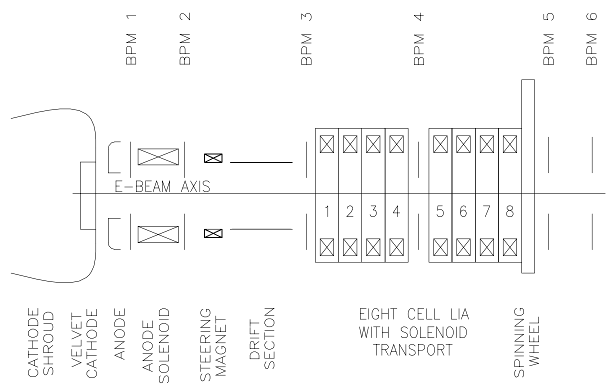
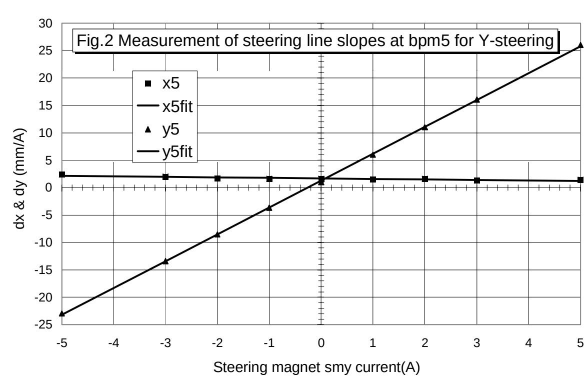


Fig.1 Layout of the ITS steering experiment

For a typical run, smy was varied in steps of 1 A from -5 to +5 A, and the bpm data were analyzed over the central 50 ns of the 60-ns pulse flattop with correction for bpm non-linearities for deflections of up to 30 mm. The steering waveforms were digitized at 700 MS/s with accuracies of a few percent. The deflections dx and dy (Fig.2 shows a sample) were generally quite linear with steering currents and reproducible. The sixteen slopes of the steering lines dx and dy in mm/A for the four bpms



0-7803-4376-X/98/$10.00 © 1998 IEEE

with steering in the two X- and Y- planes constitute a dataset of 16 values that the code must predict for a single run, with the figure of merit fom(mm/A) being defined as the rms difference between the predicted and the measured values. The injector beam energy and the cell $Z_{\perp x,y}$ in both planes were varied to find the minimum fom. The injector energy was known to ~ 2% from other measurements, consistent with the values determined here. A common pair of $Z_{\perp x,y}$ values was used for all six runs.

For the ~ 0.3-kA runs, we initially found good agreement with code using the nominal values of the energy and current (Fig.3 shows run #4). The labels sxm and sxc refer to the eight measured and calculated dx and dy deflections (mm/A) for steering in the X-plane and similarly for sym and syc. Typically the fom for the sixteen measurements for one run was ~ 0.25 mm/A (table), equivalent to ~ 10% accuracy.

#	phi(MeV)	Magnet#7	ib(kA)	fom(mm/A)
1	3	on	.55	0.34
2	3.5	on	.26	0.35
3	3.7	on	.22	0.24
4	3.7	OFF	.22	0.29
5	3.7	on	3.2	0.18
6	3.7	OFF	3.2	0.19

The injector was operated at nominally 3, 3.5 and 3.7 MeV for the low-current runs, which were of course not very sensitive to the gap impedances.

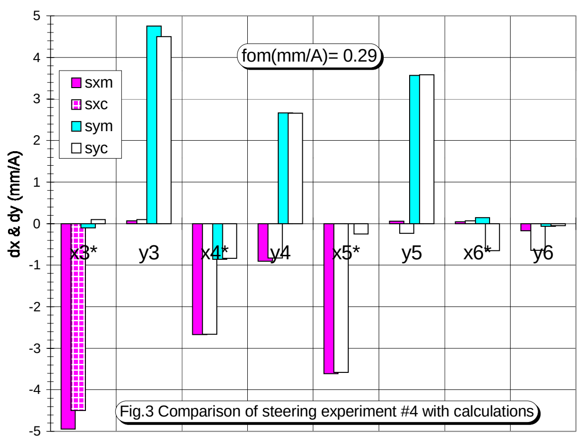


Fig.3 Comparison of steering experiment #4 with calculations

The injector was operated only at 3.7 MeV when the collimator was removed and the 3-kA beam was steered. The agreement with code was poor until we increased the injector energy in the code by ~ 300 kV, approximately the value of the edge bpd = $(i_bZ_0/2\pi\beta)\ln(R_w/r_b)$, where R_w is the wall radius (74 mm) and r_b is the beam radius. We then simulated[3] steering in a solenoid using the 3D electromagnetic PIC code LSP and discovered that steering indeed scaled closely with the total (nominal) beam energy rather than with the depressed (kinetic) energy. Evidently, the forces on the beam on a curved trajectory from ahead and behind act to nearly cancel the effect of the bpd, hence the beam is self-steered.

An estimate of this effect[3] is obtained by considering a section of beam with a stationary trajectory which has local radius of curvature R. We compute the transverse force at a given position due to nearby beam charge and current. The electric and magnetic forces reinforce to give a total self-force of

$$F_\perp^s \approx (ei_bZ_0/2\pi R)\ln(R_w/r_b) \qquad (1)$$

where logarithmic divergences have been cut off at R_w (shielding effect of wall) and r_b (finite beam radius). The curved beam orbit due to a transverse magnetic field $B_\perp$ satisfies

$$-m\gamma v^2/R = evB_\perp + F_\perp^s \qquad (2)$$

If γ_0mc^2 is the undepressed energy, then γ at the edge of the beam is $\gamma_0 - 2(i_b/\beta I_0)\ln(R_w/r_b)$, where I_0 = 17.045 kA, so that Eq. (2) can be rewritten for $\beta \sim 1$ as

$$-\gamma_0/R + (2i_b/I_oR)\ln(R_w/r_b) = eB_\perp/mv + (2i_b/I_oR)\ln(R_w/r_b) \qquad (3)$$

There is an approximate cancellation between the space-charge depression of γ and the beam self-force. Experiment and simulation confirm this cancellation within an uncertainty of ~ 20%. The beam is deflected by $B_\perp$ as though its energy were approximately the total energy γ_0mc^2. Similar effects have been calculated[4] for beams in circular accelerators.

The physics in our beam dynamics code xtr for steering had included

1. beam potential depression
2. higher-order space-charge corrections[5] to account for non-uniformity of β across the beam and the diamagnetic B_z enhancement at the beam edge
3. image steering in the gaps, in the constant-radius beam pipe, in bellows, and in bpms

Without having a complete theoretical formulation of the steering, the code has now been modified so that all steering fields act on the centroid as if bpd = 0.

For the 3-kA beam, only the 3.7-MeV energy was used, since it would have been necessary to retune the linac magnets to transport a lower-energy beam. The measurements for run #6 (Fig.4) agree well with code and are quite different from those shown in Fig.3, even though all ITS settings are nominally identical. The only

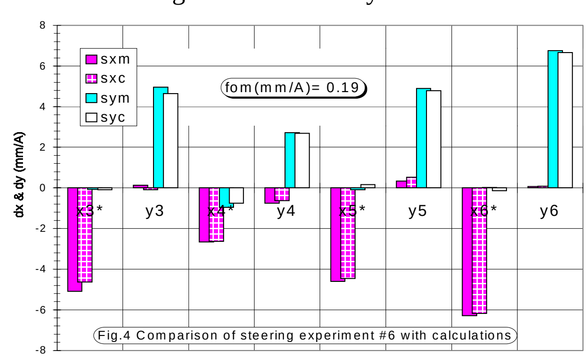


Fig.4 Comparison of steering experiment #6 with calculations

difference was removal of the collimator and readjustment of the pulsed-power drive to produce the same gap voltages with the different beam loading. The centroid trajectories through ITS for Y-steering for #5 are shown in Fig.5 (solid curves dy, dashed dx), with the measurements overplotted. The trajectories are quite different (Fig.6) if the edge energy is depressed by the bpd. The relative magnetic fields (1150 G max) are also overplotted.

The image-steering effects on the centroid x_c are proportional to $i_b Z_\perp$, that is

$$\Delta x'_c/x_c = -e i_b Z_\perp/\beta\gamma mc^2$$

so that the fom depends mainly on this product for the gaps, bpms, and bellows. For the bpms and bellows, $Z_\perp$ = -.2 and -1 Ω/cm were used. A value of $Z_\perp \approx$ -3 Ω/cm for the gaps was

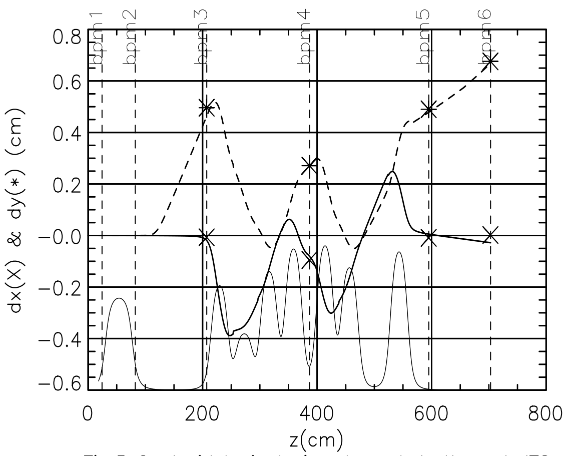


Fig.5 Centroid trajectories dx and dy through ITS

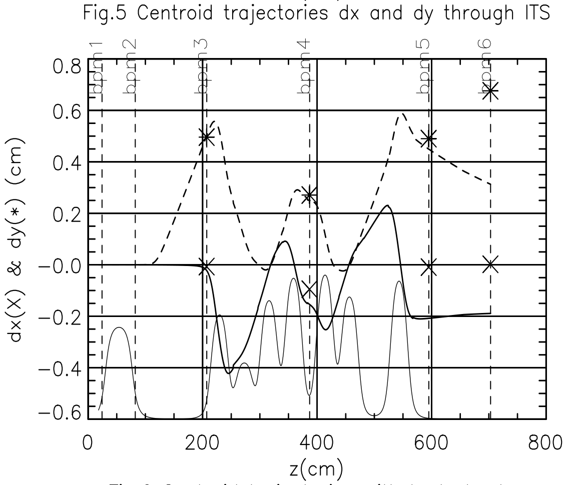


Fig.6 Centroid trajectories with bpd at edge

calculated with the Briggs model[6], compared with a more realistic calculation of -3.6 Ω/cm by Hughes[7]. This value should be modified to $Z_\perp$ = -3.3, -3.9 Ω/cm for the X- and Y- planes by the quadrupole effect[8] for the cells, $\int \nabla_\perp Bdz \approx$ 3G for a 3-kA beam, since it is not taken into account elsewhere in xtr. Except for this quadrupole effect, steering should be symmetric in X and Y. The best xtr fit for all runs gives

$$Z_{\perp\,x,y} = -3.5\pm0.5,\ -4.9\pm0.7\ \Omega/\text{cm},$$

as determined by the sensitivity of the fom. The strongest image effect is found to be in the gaps.

CONCLUSIONS

Steering measurements and code xtr predictions are in reasonable agreement, using the total, rather than the kinetic, energy at the beam edge for the centroid dynamics. We are unaware of other measurements demonstrating this effect. Six different runs with very different beam conditions were matched to ~ 10% with nominal linac settings and injector parameters. The greatest source of experimental uncertainty may be individual bpm calibration, perhaps ± 5%. Defining sensitivity S as that parameter change which increases the minimum fom by 20%, this set of experiments determines S = 0.7% (phi), 8% (i_b), 12% ($Z_\perp$), and 4% (V gap).

REFERENCES

[1] M. Burns, P. Allison, R. Carlson, J. Downing, D. Moir, and R. Shurter, “Status of DARHT”, XVIII International Linac Conference, Geneva, August, 1996

[2] Paul Allison and David C. Moir, “BBU Gain Measurements on the ITS 6-MeV, 4-kA Linac”, *Proc. PAC97 Conference.*

[3] T. P. Hughes, “Self-Steering Effects in ITS Experiments”, MRC/ABQ-N-576, Mission Research Corp., Albuquerque, July, 1996.

[4] C. A. Kapetanakos, S. J. Marsh, and P. Sprangle, “Dynamics of a high-current electron ring in a conventional betatron accelerator”, Particle Accelerators Vol. 14 (1984) p.261, and Edward P. Lee, “Cancellation of the centrifugal space-charge force”, Particle Accelerators Vol.25 (1990), p.241.

[5] M. Reiser, “Laminar-flow equilibria and limiting currents in magnetically focused relativistic beams”, Phys. Fluids 20, 477 (1977), and T. P. Hughes, T. C. Genoni, et al., Computational Support for ITS and REX, MRC/ABQ-R-1735, April, 1995.

[6] R. J. Briggs, D. L. Birx, G. J. Caporaso, V. K. Neil, T. C. Genoni, “Theoretical and Experimental Investigation of the Interaction Impedances and Q Values of the Accelerating Cells in the Advanced Test Accelerator”, Part. Acc. Vol. 18 (1985), pp.41-62.

[7] T. P. Hughes, R. E. Clark, D. R. Welch, and R. L. Carlson, “Computational Support for REX and ITS”, MRC/ABQ-R-1797, Mission Research Corp., Albuquerque, June 1996.

[8] Paul Allison and David C. Moir, “Quadrupole Image-Current Effects in the ITS 6-MeV, 4-kA Linac”, *Proc. PAC97 Conference.*