Measurements of Reduced Corkscrew Motion on the ETA-II Linear Induction Accelerator*

S.L. Allen, H.R. Brand, F.W. Chambers, Y.-J. Chen, F.E. Coffield, F.J. Deadrick, L.V. Griffith,
D.L. Lager, W.J. Mauer, W.E. Nexsen, A.C. Paul, S. Sampayan, W.C. Turner
Lawrence Livermore National Laboratory, Livermore CA 94551

ABSTRACT

The ETA-II linear induction accelerator is used to drive a microwave free-electron laser (FEL). Corkscrew motion, which previously limited performance, has been reduced by: (1) an improved pulse distribution system which reduces energy sweep, (2) improved magnetic alignment achieved with a stretched wire alignment technique (SWAT), and (3) a unique magnetic tuning algorithm. Experiments have been carried out on a 20-cell version of ETA-II operating at 1500 A and 2.7 MeV. The measured transverse beam motion is less than 0.5 mm for 40 ns of the pulse, an improvement of a factor of 2 to 3 over previous results. Details of the computerized tuning procedure, estimates of the corkscrew phase, and relevance of these results to future FEL experiments are presented.

I. INTRODUCTION

The ETA-II is a linear induction accelerator at the Lawrence Livermore National Laboratory designed to produce a high average power electron beam for short-wavelength FELs. FEL performance in 1989 was limited to short (5-10 ns) 0.2 GW pulses at 140 GHz because of a substantial corkscrew motion (~1 cm) of the beam and the nonreproducibility of the electron beam pulse (making empirical wiggler tapering difficult). The corkscrew motion is caused by the energy sweep of the beam during the pulse, coupled with misalignments of the solenoidal transport system of the accelerator [1].

We have implemented several hardware and operational improvements and tested them on a 20-cell version of the whole (60 cell) ETA-II system. The subject of this paper is the resulting reduction of the corkscrew amplitude, and the overall improved operating performance of the ETA-II experiment (e.g., improved pulse-to-pulse reproducibility, lack of insulator damage). Discussion of improved energy flatness during the pulse [2] and a general discussion of the ETA-II system are presented elsewhere [3].

II. DESCRIPTION OF THE EXPERIMENT

A. The ETA-II 20-Cell Experiment

For these "prototype" experiments, ETA-II was assembled with a nine-induction-cell injector and 20 accelerator cells. The injector configuration is similar to previous experiments [4]: a common bus feeds the cells and a thermionic osmium-coated 12.7-cm-diameter dispenser cathode was operated at about 1500 A in the space-charge limited regime. A special coaxial iron shroud was added to minimize transverse magnetic fields in the region where the beam is extracted. A large Helmholtz pair was installed around the ETA-II vault and was adjusted to cancel the earth's magnetic field.

Several improvements were added to ETA-II for these experiments. A new multicable system was installed to feed the 20 cells [5] that minimizes the cell-to-cell coupling of transients. Also incorporated into this system are adjustable fluid resistors for each cell and monitors for current and voltage. The variable resistors allow impedance matching at various operating currents and electrical checkout without electron beam loading. The current and voltage monitors at each cell are coupled to a new system that stops operation in the event of an arc or overvoltage. The power supply firing sequence for the injector and the cell blocks is controlled by a new computerized feedback system. This compensates for timing drifts during the day, and also automatically varies the timing as the current and voltage are brought up at the beginning of the day.

The operating point for these experiments was selected to compensate for the inherent energy and current sweep of the injector [5]. For the ETA-II system, operating at a current of 1500 A, a cell gap voltage of 80-90 kV was shown both experimentally and theoretically to result in minimum energy sweep. This value also provides a nearly impedance-matched pulse distribution system, thereby minimizing voltage reflections and possible insulator damage.

B. Stretched Wire Alignment Technique (SWAT)

A Stretched Wire Alignment Technique (SWAT) [6,7] was used to magnetically align ETA-II. SWAT uses a stretched wire carefully located on the axis of the accelerator. A current pulse is propagated down the length of the wire, and any misalignments in the magnetic field cause forces on the wire that can be detected by a photoelectric sensor at the other end of the wire. The misalignments are minimized by a combination of movement of the components and adjustment of the (sine and cosine) magnetic correction coils that are an integral part of each cell. The largest correction currents were found in the intercell junctions between each 10 cell block. The SWAT technique was used to align the whole accelerator

---

*Performed jointly under auspices of USDOE by LLNL W-7405-ENG-48 and DOD under SDIO/SDC MIPR NO. W42-GBL-0-5007.

including the transport section by compensating for the sag of the wire.

C. Accelerator Tuning System—MAESTRO

After the SWAT alignment, the corkscrew amplitude is further minimized directly during accelerator operations by measurements of the electron beam position as a function of time. A computerized data acquisition and control system called MAESTRO [8] acquires and processes signals from beam position monitors placed between each 10-cell block. From the calculated x and y beam positions (usually defined relative to the mean), MAESTRO can calculate the average corkscrew amplitude (A) for a specified time window :

$$A^2 = \frac{1}{\Delta t} \int_{t_1}^{t_2} (x^2 + y^2)\, dt \quad (1).$$

Because the MAESTRO system can control the current in a particular correction coil, it can determine A as a function of the correction coil current. Beam orbit calculations predict [9] a pronounced single minimum for each coil. This was verified experimentally, as shown in Fig. 1; a time window corresponding to half of the peak electron beam current was used. Note the pronounced minimum in A for each curve.

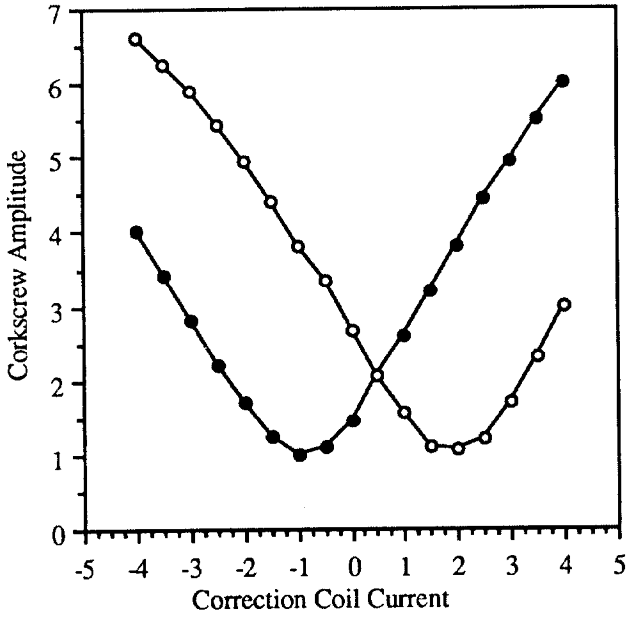

Fig. 1. Corkscrew amplitude A versus the horizontal (solid circle) and vertical (open circle) correction coil current for the last injector cell.

The MAESTRO system was used to determine the settings for the 56 correction coils in ETA-II. First, all the coils were set to the values determined by SWAT. Starting with the injector, MAESTRO then varied each horizontal and vertical compensation coil and found the current that corresponded to the minimum A. When large deviations from the SWAT values were found (or when the minimum corkscrew amplitude increased abruptly for a given coil scan), we found that repeating the previous one or two scans was necessary before the system converged. This procedure was necessary at the intercells, indicating that they are both the largest source of error and the most difficult to measure and adjust with SWAT. Once the minima were found for all of the coils, we found that subsequent passes through the system, using the beam position monitor at the end of the accelerator, resulted in no further reduction in the transverse beam motion. After the procedure was developed, the 20-cell experiment was tuned in about one day, and retuning was not necessary.

III. EXPERIMENTAL RESULTS

A. Measurements of Transverse Beam Motion

The various correction coil currents are stored in the MAESTRO system, so we can easily compare the transverse beam motion with various configurations. Figure 2 compares the beam position versus time at the end of the 20 cells for three cases of correction coil currents:(a) all off, (b) the SWAT values, and (c) the values determined by minimizing A.

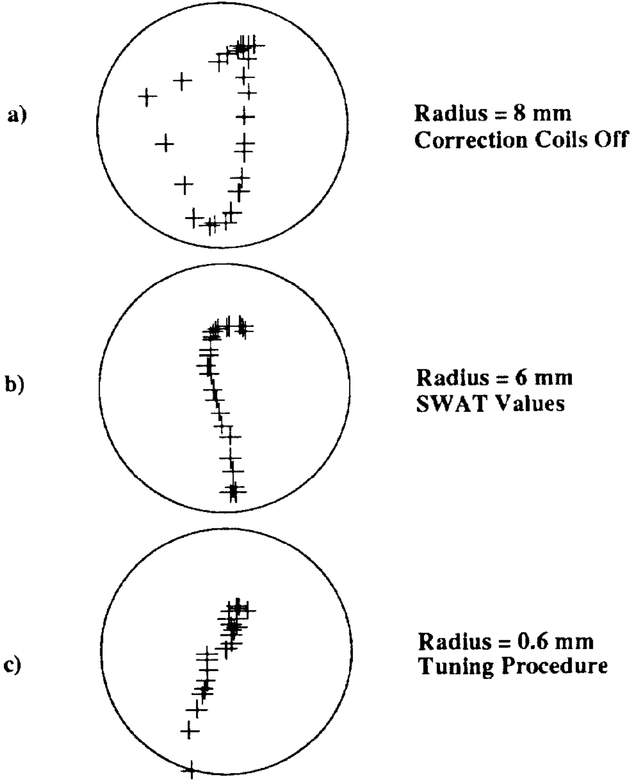

Fig. 2. Measured beam position for 40 ns with (a) all coils off, (b) SWAT values, and (c) the minimization procedure.

Figure 2 shows that there is a modest reduction in the maximum motion using the SWAT values, and nearly an order of magnitude reduction with the values obtained from the MAESTRO tuning procedure. We also determined that these results were reproducible, in that MAESTRO was used to set the correction coil values each day and the maximum motion was nearly the same. The maximum motion (defined as the smallest circle that contains the data) as a function of the width of the pulse for the final tune of ETA-II(case c above) is shown in Fig. 3. Estimates of these 20-cell values scaled to 60 cells have been performed based on previous experimental results and theoretical models. These indicate that the amplitude should be small enough for efficient FEL operations with a 40-50 ns pulse width.

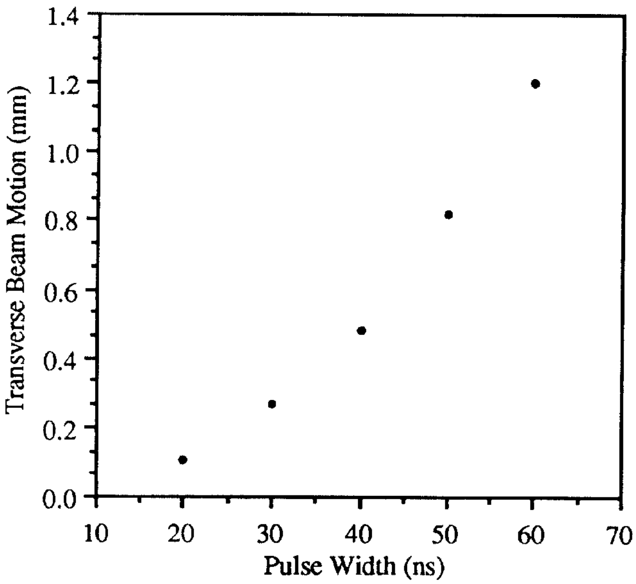

Fig. 3. Transverse beam motion versus pulse width.

B. Characterization of the Beam Motion

In an idealized case, the corkscrew motion can be described as helical motion with a fixed radius and a time-dependent phase. Becasue the phase advance depends on the energy, it is expected to be influenced by the cell voltage and the relative timing between the injector and the cell blocks. For actual experimental data, the characterization of the beam position versus time is more complicated; we have used a radius of curvature ρ defined in terms of the x and y positions and their time derivatives:

$$\rho = \frac{(\dot{x}^2 + \dot{y}^2)^{3/2}}{(\dot{x}\ddot{y} - \ddot{x}\dot{y})} .$$

The phase for a particular time period can then be defined as:

$$\Phi = \int_{t_1}^{t_2} \frac{\left| x\dot{y} - \dot{x}y \right|}{\rho^2} \, dt .$$

Using this formulation, we have compared previous 60-cell experimental data with the present 20-cell results. The major difference is that the calculated phase advance for a ~70 ns section of the pulse (i.e., between the half current points) is nearly 4π for the 60-cell data, compared with 1-2 radians for the 20-cell data. This is most likely due to the greatly decreased energy sweep during the pulse for the 20-cell experiment[2]. The ρ calculated for the 60-cell case varies during the pulse; it is large at the beginning and end (several mm) and small (less than 1 mm) in the middle of the pulse. The calculation of ρ for the 20-cell case is difficult, because the motion is nearly a straight line. (See Fig. 2c, which is a 40–ns section of the pulse.) For the 20- cell configuration, a series of experiments was carried out where the cell voltage and the relative timing between the injector and the accelerator cells was varied. The above analysis indicated that the maximum transverse motion, the radius of curvature, and the total phase advance were insensitive to these variations.

IV. DISCUSSION

We have shown that a combination of the multicable feed, SWAT alignment, and a tuning algorithm implemented with the MAESTRO control system has reduced the corkscrew amplitude for 20 cells of the ETA-II experiment to less than 0.5 mm for 40 ns of the pulse. We are now assembling the whole 60-cell experiment for use in FEL experiments with the MTX tokamak [10]. We are implementing several upgrades to further improve the system, including (1)redesigned intercell magnet support structures, (2)faster MAESTRO processing and control, and (3)improved cell block construction with Rexolite insulators assembled in a clean room. The pulsed power system is being upgraded to allow a burst of about 50 pulses at a repetition rate of ~5 kHz [11]. Burst mode FEL experiments are planned to begin late in 1991.

REFERENCES

[1] Y.-J. Chen, "Corkscrew Modes in Linear Accelerators," Nucl. Instrum. and Meth. in Phys. Res., A292, p 455-464, 1990.

[2] W. E. Nexsen et al., "Reduction of Energy Sweep of the ETA-II Beam," these proceedings.

[3] W.C. Turner, "Control of Energy Sweep and Transverse Beam Motion in Induction Linacs," these proceedings.

[4] J.C. Clark et al., "Design and Initial Operation of the ETA-II Induction Accelerator," in *Proc. 1988 Linear Accel. Conf.*, Williamsburg, VA, October 2-7, 1988.

[5] S.E. Sampayan et al., "Energy Sweep Compensation of Induction Accelerators," in *Proc. 1990 Linac Conference*, Albuquerque, NM, September 10-14, 1990.

[6] L. Griffith and F. Deadrick, "Progress in ETA-II Magnetic Field Alignment Using Stretched Wire and Low Energy Electron Beam Techniques," in *Proc. 1990 Linac Conference*, Albuquerque, NM, September 10-14, 1990.

[7] R.W. Warren, "Limitations on the Use of the Pulsed-Wire Field-Measuring Technique," presented at the *Ninth International FEL Conference*, Williamsburg, VA, 1987.

[8] Darrel L. Lager et al., "Artificial Intelligence Techniques for Tuning Linear Accelerators," these proceedings.

[9] W.C. Turner, S.L. Allen, et al., "Reduction of Beam Corkscrew Motion on the ETA-II Linear Induction Accelerator," in *Proceedings of the 1990 Linac Conference*, Albuquerque, NM, September 10-14, 1990.

[10] B.W. Stallard et al., "ECH by FEL and Gyrotron Sources on the MTX Tokamak," in *Proceedings of the 16th Symp. on Fus. Tech.*, London, Sept. 1990.

[11] S.E. Sampayan, "Performance Characteristics of an Induction Linac Magnetic Pulse Compression Modulator at Multi-Kilohertz Pulse Repetition Frequency," these proceedings.