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"REAL-LIFE" PULSE FLATTENING ON THE LLNL FLASH X-RAY (FXR) MACHINE*

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Abstract

High-resolution radiography using high-current electron accelerators based on the linear induction accelerator principle requires the linac's final spot on the X-ray target to be millimeter-sized. The requisite final focusing solenoid is adjusted for a specific beam energy at its entrance, hence, temporal variation of entrance beam energy results in a less than optimal time-averaged spot size.

The FXR (Flash X-Ray) induction linac facility at Lawrence Livermore National Laboratory will be briefly described with an emphasis on its pulsed power system. In principle, the pulsed Blumleins at the heart of the system output a square pulse when discharged at the peak of their charging waveform so that, with correct cell timing synchronization, the effective beam output into the final focusing solenoid should be optimally flat.

We have found that real-life consideration of transmission line and pulse power details in both the injector and accelerator sections of the machine results in significant energy variations in the final beam. We have implemented methods of measurement and analysis that permits this situation to be quantified and improved upon. The improvement will be linked to final beam spot size and enhancement in expected radiographic resolution.

I. BACKGROUND

Although direct application of Faraday's Induction Law as a means to accelerate particles in a circular orbit in a changing magnetic field [1] was utilized early in the history of accelerators, the technique was not successfully applied to linear acceleration at high energy [2] until the mid 1960's. Advances in pulsed power technology [3] have enabled this field to steadily develop. Modern induction linacs find application [4] in fields such as heavy ion fusion, advanced radiography, and advanced rf sources for next-generation linear colliders.

The Flash X-Ray (FXR) induction linac (see Fig. 1) at Lawrence Livermore National Laboratory (LLNL) is one of the few early [5] linear induction accelerators (LIAs) to still be in daily use at a working radiography user facility. To bring its spatial resolution capabilities up to the standards of modern radiography LIAs such as DARHT and DARHT-II [6], FXR began an upgrade effort focused on the accelerator and its pulsed power. A sizable investment in a new Contained Firing Facility [7] had been made and, along with an aggressive radiographic test schedule, peak accelerator performance would become increasingly important.

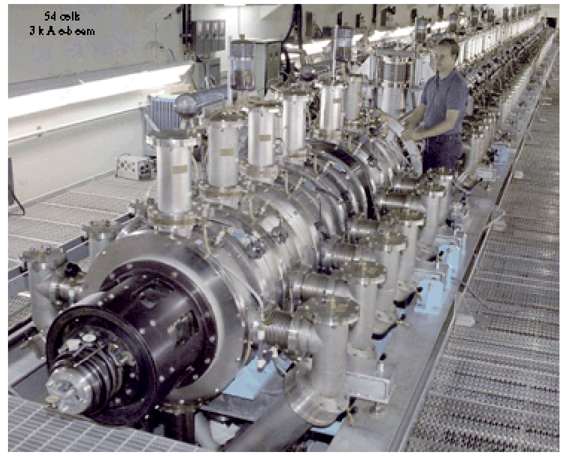

Figure 1. The FXR induction linac at LLNL

II. MOTIVATION

A. Pulsed Power

Energy transfer and pulse compression in FXR takes place in 3 stages, as shown schematically in Figure 2. First a Marx generator is charged to ~70 kV in a period of 1-3 seconds. Its 300kV output is then resonant-charge transferred to a coaxial Blumlein in a 2 us period. At that point, sulfur hexafluoride (SF6)-insulated trigger switches discharge the Blumlein into the accelerator cell in a 100 ns pulse. There are 54 such cells and high-voltage closing switches in FXR.

Flat top adjustment

The resonant charge waveform that represents the charging of the Blumleins is well-represented by a "one-minus-cosine" pulse shape. Peak energy transfer to the

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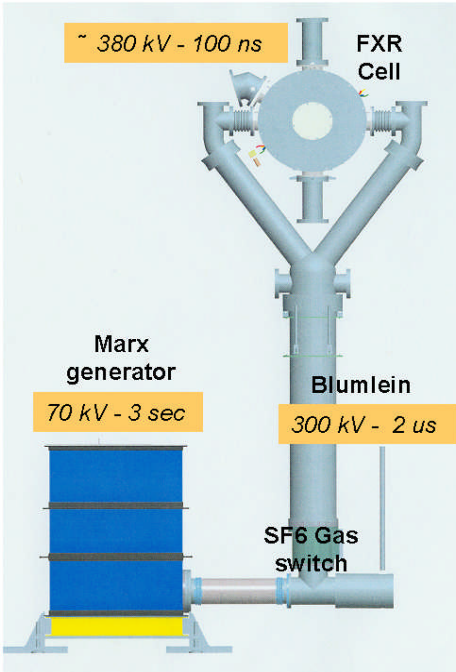

Figure 2. Pulsed Power for FXR

Blumleins is accomplished at 180 degrees of phase in this inverted cosine, which occurs at 1.8 us after start of charge (the discharging of the Marx generator.) This should also result in the squarest output wave shape from a discharged Blumlein to a cell. A flat (zero-slope) cell voltage pulse should then result in uniform acceleration of the beam in time and permit the tightest temporal beam spot to be achieved at the X-ray conversion target.

It had long been recognized that early or late discharging of the Blumlein relative to its Marx charge is a way to produce a slightly positive- or negative-sloped, respectively, output pulse to the cell. This approach was appropriated on a cell-by-cell basis in this work.

B. Timing

The absolute timing of the Blumlein discharges must be such as to ensure synchronism between the accelerator's electron bunches and the individual cell voltage pulses. This has traditionally been performed by time-aligning the rising edge of each cell pulse, with appropriate time-of-flight correction made based on cell spacing and beam energy at that point.

A key aspect of this work is the realization that the effective X-ray output pulse, based on several different diagnostics, is 60 ns, not 100 ns, the shortening due mostly to the width and transport of the electron beam pulse. Hence, the most uniform final spot size at the target, which will give best radiographic resolution, will be generated by determining the flattest 60 ns of each cell pulse and time-aligning the cells based, not on rising edge or a fiducial based on full-width-at-half-max or something similar, but based on that optimal 60 ns piece of beam.

III. APPROACH

A. Diagnostics

Each FXR cell is fitted with a thin-disc capacitive divider (Figure 3) fitted to the outer cell wall. These "D-dots" are connected to integrator networks that permitted direct viewing of voltage waveshapes on the analog oscilloscopes that made up the bulk of early FXR diagnostics.

Three years ago, FXR was upgraded [8] with a fast 128-channel array of digitizers so that each cell voltage is acquired on each FXR pulse. To ensure our beam energy flattening exercise described here was operating on true cell voltages, routines were implemented in the subsequent data handling to correct for the RC droop introduced by the real-time integrators.

Furthermore, each cell monitor is now calibrated against a precision voltage monitor that is separately calibrated on a NIST-traceable network analyzer.

B. Algorithm

Each corrected cell voltage pulse is fitted with best-linear fits for 60-ns segments for varying starting points within the pulse, which is essentially statistical regression analysis. The degree of error in these linear fits is used as an indicator of the beam energy variation that would be expected if the beam were time-aligned at that starting point.

The cumulative accelerating effect (cell summation with time-of-flight correction) is tracked by section and for the entire accelerator. Figure 4 illustrates a display of this analysis that is available on every shot.

C. Data

Approximately quarterly, a sweep of Marx charge to Blumlein trigger time (CT time) is performed (Figure 5) to ensure the cumulative effect for this minimal error approach. Note that achieving a "flat-top" with minimal

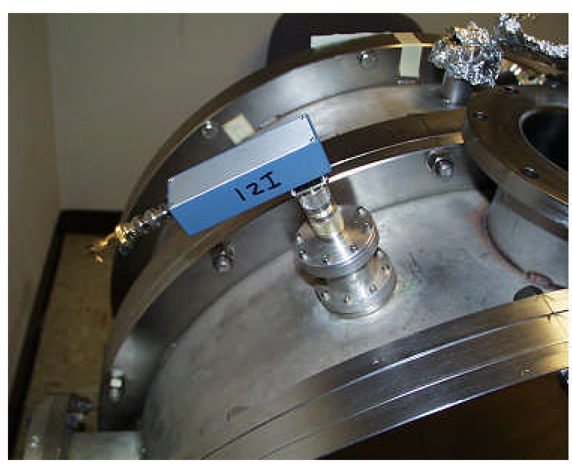

Figure 3. An FXR cell capacitive voltage monitor and signal integrator.

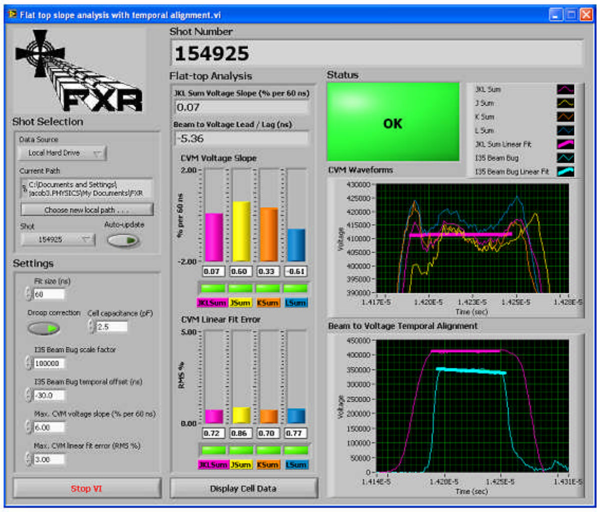

Figure 4. 60-ns linear fit and slope analysis.

error occurs significantly off (~20 degrees of phase) from the 1.8 us value expected for idealized pulse power components. These cell summation results are also validated by our recently-fielded [8] scattering-wire energy spectrometer."

IV. RESULTS

Using a rolled edge and integrating the edge spread function of the resulting radiograph, the radiographic spot size can be directly determined. Figure 6 shows that since this pulse-flattening methodology was adopted in 2005, the spot size has improved significantly with an acceptable cost in dose.

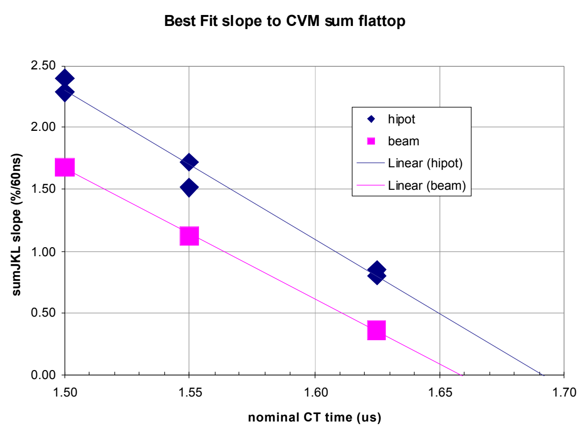

Figure 5. A sweep of CT time to minimize slope of flattop.

V. SUMMARY

An improvement in X-ray spot size and radiographic resolution was achieved on FXR using a simple algorithm based on linear curve fitting and by employing timing modifications to minimize energy variations in the final beam delivered to target. It is based on time-aligning the beam and individual accelerator cells to the recognition that the X-ray pulse can be significantly less than individual pulsed voltages delivered to the accelerator's cells..

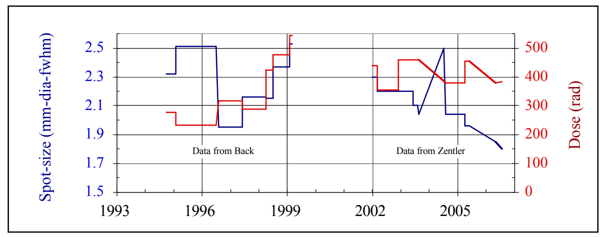

Figure 6. Improvement of FXR spot size and dose with time.

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