FLASH X-RAY (FXR) ACCELERATOR OPTIMIZATION BEAM-INDUCED VOLTAGE SIMULATION AND TDR MEASUREMENTS *

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Abstract

Lawrence Livermore National Laboratory (LLNL) is evaluating design alternatives to improve the voltage regulation in our Flash X-Ray (FXR) accelerator cell and pulse-power system. The goal is to create a more mono-energetic electron beam. When an electron beam crosses the energized gap of an accelerator cell, the electron energy is increased. However, the beam with the associated electromagnetic wave also looses a small amount of energy because of the increased impedance seen across the gap. The beam-induced voltage at the gap is time varying. This creates beam energy variations that we need to understand and control.

A high-fidelity computer simulation of the beam and cell interaction has been completed to quantify the time varying induced voltage at the gap. The cell and pulse-power system was characterized using a Time-domain Reflectometry (TDR) measurement technique with a coaxial air-line to drive the cell gap. The beam-induced cell voltage is computed by convoluting the cell impedance with measured beam current. The voltage was checked against other measurements to validate the accuracy.

I. FXR ENERGY REGULATION AND TEST STAND

The FXR accelerator generates a 3 kA electron beam with 17 MeV of energy. Our present pulse length is about 70 ns. The x-ray dose at 1 m is over 400 Rad, and the current spot-size is 2 mm (full-width half-maximum).

There are two sources of beam energy variations: the pulse-power system and the beam interaction with the cell and pulse-power system. The first two terms of the target energy equation (1) includes the voltage that is generated by the Marx and Blumlein, along with their interactions with the time-isolation and power feed coaxial lines and cell features. The injector voltage has added complexity because of the reflections in the cathode and anode stalks. The third term is defined as the beam-induced gap voltage that launches an electromagnetic (EM) wave into the cell and pulse-power system. A portion is reflected back from the different cell components and appears in the gap again. This is related to beam loading, but the impedance mismatches in the cell and pulse-power system creates a much more dynamic process than the name "loading" implies. This report focuses on the beam-induced energy variation.

$$E_{V\,injector} + E_{V\,accelerator} - \boldsymbol{E}_{\boldsymbol{V}\,\textbf{beam-induced}} = E_{target} \quad (1)$$

Alternative designs for improving voltage regulation could not be easily evaluated on FXR. Instead, a Single-cell Test Stand was constructed that would allow new designs to be studied without interfering with the shot schedule or jeopardizing FXR reliability [1]. On the Test Stand, a low-voltage TDR high-fidelity measurement generated the transfer function for calculating the induced voltage. Identification of cell components that generate the time varying induced gap voltages is possible. By opening ports we can safely and easily insert shorting bars to associate features in the TDR voltage waveform with cell locations.

II. TDR Measurements

The low-voltage test setup for studying beam-induced potentials is shown in Figure 1. A 50 Ω air-line is attached to the cell. The air-line is driven from the right with the pulser of a Time-domain Reflectometry system. This emulates the effect of the electron beam passing through the cell. The other end of the air-line is terminated with a 50 Ω load. While the impedance between the beam and beam-pipe varies, the 50 Ω test components were chosen because 50 Ω pulsers, cables, and terminations are readily available. The effect of the

* This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2005	**N/A**	**-**

4. TITLE AND SUBTITLE
Flash X-Ray (Fxr) Accelerator Optimization Beam-Induced Voltage Simulation And Tdr Measurements

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lawrence Livermore National Laboratory, PO Box 808, L-153 Livermore, CA, 94551

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

50 Ω impedance of the air-line will be removed from the measurements to obtain the cell impedance.

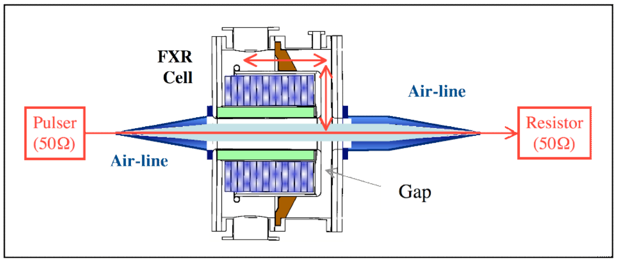

Figure 1. A cross section of the cell interior and air-line shows the power flow from the pulser and reflections.

The measured cell impedance is shown at the bottom of Figure 2. The first two peaks are created in the acceleration gap and corner. The back wall impedance is located between 5 ns and 6 ns and appears to be a short.

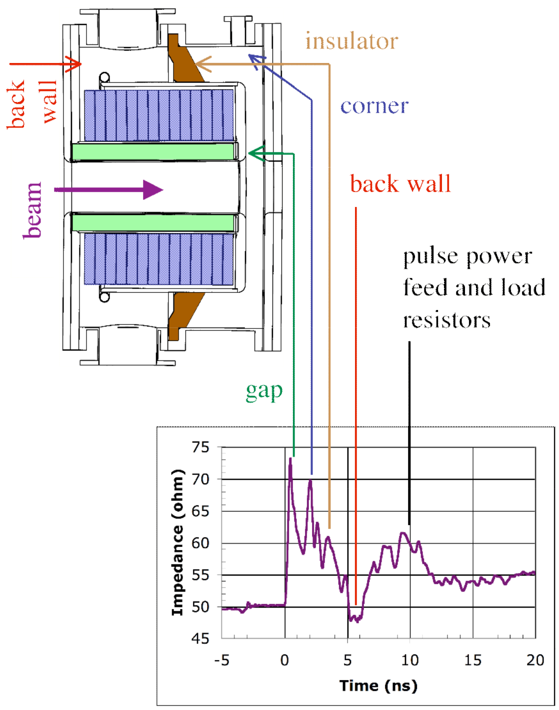

Figure 2. Cell impedance as a function of time starting at the gap.

III. Computer Simulation of Beam-induced Cell Voltage

The gap voltage is computed by convolving the impulse cell response (see right plot of Figure 3) with the beam current (see left plot).

$$V_{gap\text{-}induced}(t) = [\, I_{beam} * Z_{impulse\text{-}gap} \,](t) = \int I(\tau)\, Z(t-\tau)\, d\tau$$

The TDR instrument excites the cell with a step function. To obtain the impulse response of the cell, the step response is differentiated. The result is shown in the right plot of Figure 3.

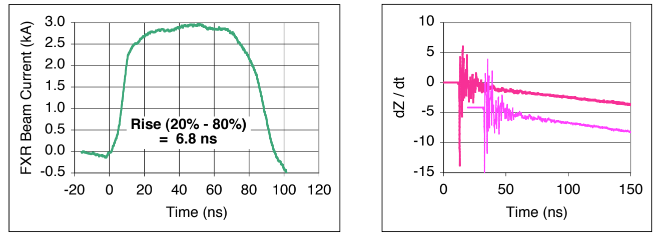

Figure 3. Beam current and impulse response of FXR cell derived from TDR measurements.

The convolution was performed with MATLAB. The sample interval for the beam current was 0.2 ns, which very accurately represents the rise-time. The TDR data was taken at 40 ps intervals, and de-sampled to 0.2 ns. Low-pass filtering greatly reduced the random noise in the measured reflected voltage and allowed a more accurate differentiation.

The simulated gap voltage is shown in Figure 4 and is overlaid with the current. The voltage is really negative and has the opposite polarity of the accelerating voltage.

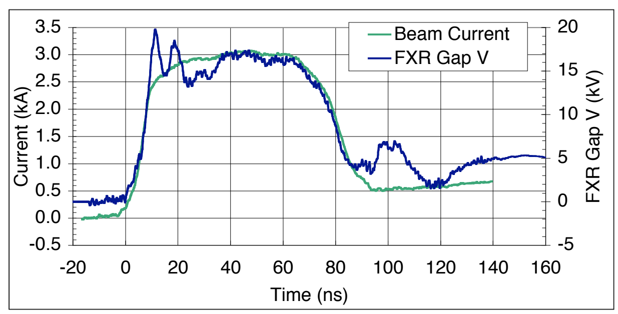

Figure 4. Beam current and computed beam-induced gap voltage have the same duration.

Ideally, the voltage profile would be the same as the current profile if the impedance were a constant 7.2 Ω. Based on theory, the induced voltage at the middle of the beam should be 22 kV (3 kA x 7.2 Ω). The simulation predicted 17 kV because the measured "steady-state" impedance was about 6 Ω. This beam loading causes the acceleration voltage to drop about 5%.

The validity of the simulations was checked against three types of measurements: energy analyzer at the end of the accelerator, cell voltage from pulse-power system with and without beam, and beam-induced voltage in the cell. They all support the simulation results.

In the spring of 2000, LANL loaned FXR their energy analyzer. The analyzer was installed in the drift section after the accelerator. A carbon collimator blocked most of the FXR beam, and a precision magnet bent the beamlet that was allowed to pass. The electrons were converted to light photons with a fast scintillator. The vertical position of the spot on the scintillator depended on the energy of the electrons. An image of energy variation as a function of time was created with a streak camera. The image from the streak camera was saved to a computer with a CCD camera. (See upper image in Figure 5.)

The data from the energy analyzer is compared with the computed gap voltage in Figure 3. The energy analyzer data include voltage variations caused by the injector, accelerator, and beam-induced voltage in the cells. Nonetheless, the gap-voltage and beam-energy have matching peaks and valleys for most of the beam. Mismatches are denoted by first and last two dotted lines, and the remaining lines are good matches. The first line does not have a match on the image because of the limited range of the analyzer. At about 40 ns, the match is poor. This could be explained by a voltage drop in the injector, accelerator, and cell mis-timing after 40 ns.

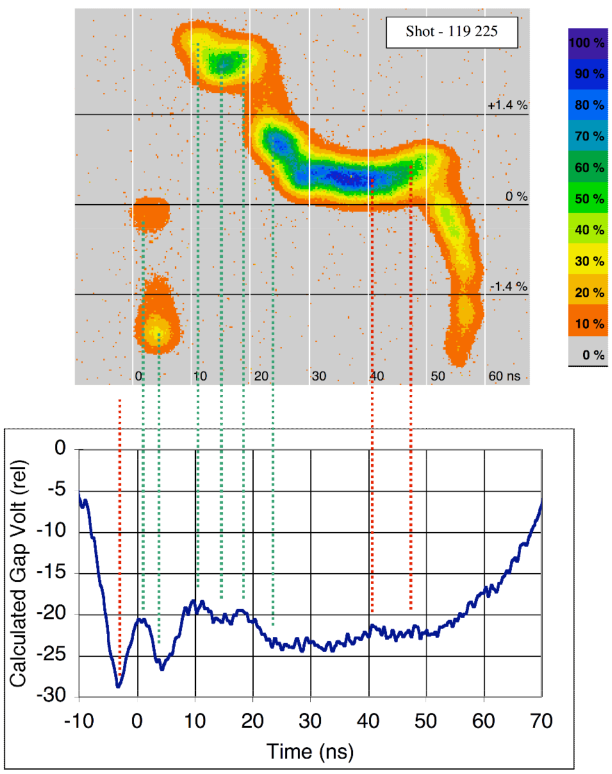

Figure 5. The image from an energy analyzer shows a similar pattern from the computed gap voltage for most of the beam.

FXR has cell voltage monitors that can measure the beam-induced voltage by passing a beam across the gap with the pulse-power system off. The results from three cells located throughout the accelerator are shown in Figure 6 along with the computed gap voltage. Their trends are similar.

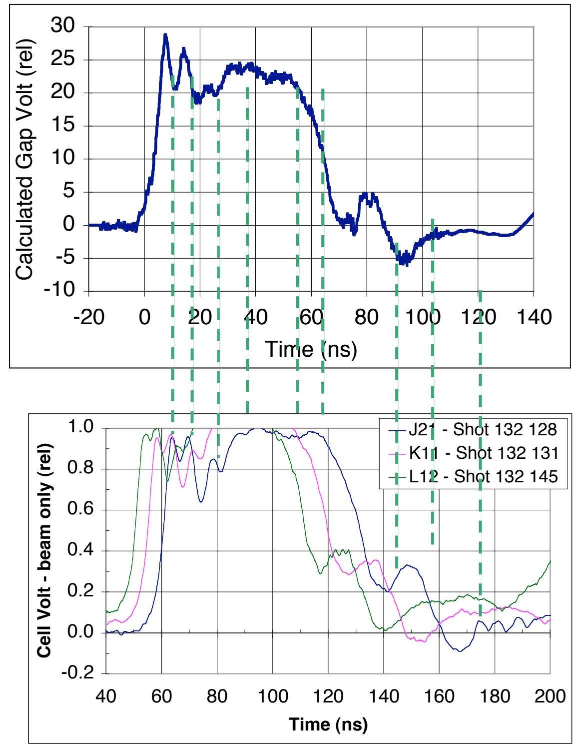

Figure 6. Computed gap voltage and measured beam-induced voltage have similar trends.

The agreement is extremely good in spite of the fact that the cell voltage monitor is not close to the gap. We believe that the computed gap voltage is a better predictor of beam energy variation caused by reflected electromagnetic waves in the cell.

IV. EVALUATION OF ALTERNATIVE CELL DESIGNS

Minimizing beam energy variations requires compromises in accelerator and cell design. A large number of alternative designs are being studied including better control of the Marx voltage, flatter Blumlein pulse, better impedance matching of the components including the cell, longer ferrite operation, and reduced timing jitter. Three types of alternative design will be evaluated to determine their effect on the induced cell voltage: slower rise-time beam, corner reflectors, and different load resistance.

The only the result from a simulation of a slow rise-time will be presented. The beam oscillations in the cell impedance occur very quickly for the first 20 ns. (See Figure 5.) By slowing down the rise-time of the beam, we can “average” out these faster impedance changes. The FXR beam rise-time is 9 ns. (See Figure 7.) If we slow the rise-time to 18 ns, the induced voltage should be appreciably reduced.

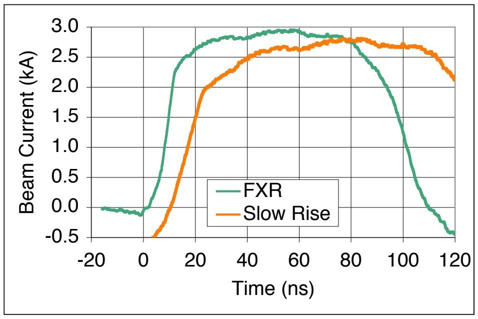

Figure 7. FXR beam rise-time is 9 ns, and the hypothetical slower beam has a rise-time of 18 ns.

When the cell impedance is convolved with the slower rise-time current, the resulting variation in beam-induced voltage is much less for the first half of the beam. (See Figure 8.) The induced voltage has a longer duration. This is explained by the longer beam duration. (See Figure 9.)

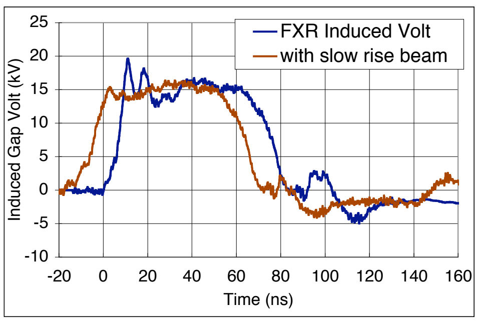

Figure 8. Computed beam-induced gap voltage for slower rise-time beam has less variation.

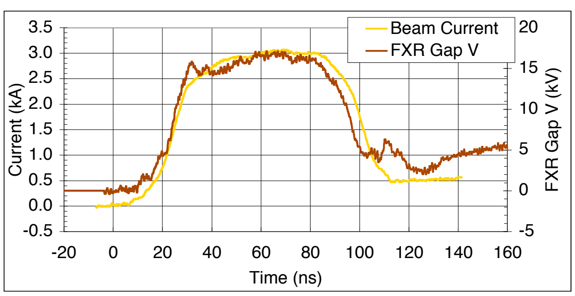

Figure 9. Waveforms of the slow rise-time beam current and induced gap voltage have the same duration.

Slowing down the rise-time of the beam may have detrimental effects on x-ray spot-size. The head of the beam has more off-energy electrons, and the result would be larger low-dose "wings" or ring around the main x-ray spot. The slower beam may also be more difficult to transport.

V. ACKNOWLEDGMENTS

We want to acknowledge the contributions of Blake Kreitzer, Jim Bowman, Ken Griffin and other mechanical and electronic personnel who worked hard to build the Test Stand and support the TDR measurements. The ideas for improving voltage regulations came from many people including Ron Kihara, Dave Goerz, and Bill DeHope. We want to especially thank B-Program, Dave Goerz and Ray Scarpetti for funding this work.

VI. REFERENCES

[1] Ong, Mike, George Vogtlin, Dave Goerz and Ray Scarpetti, "Flash X-Ray (FXR) Accelerator Optimization", 14th IEEE International Pulsed Power Conference, Dallas, TX, June 2003, pp. 909-12.

[2] Ong, Mike and George Vogtlin, "Flash X-Ray (FXR) Accelerator Optimization – Injector Voltage-variation Compensation via Beam-Induced Gap Voltage", Lawrence Livermore National Laboratory, UCRL-TR-205798, April 2004 (full report).