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Flash X-ray (FXR) Accelerator Optimization Injector Voltage-variation Compensation via Beam-induced Gap Voltage

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FLASH X-RAY (FXR) ACCELERATOR OPTIMIZATION INJECTOR VOLTAGE-VARIATION COMPENSATION VIA BEAM-INDUCED GAP VOLTAGE *

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Abstract

Lawrence Livermore National Laboratory (LLNL) is evaluating design alternatives to improve the voltage regulation in our injector and accelerator cells of our Flash X-Ray (FXR) machine. The operational peak electron beam current and energy at the x-ray generating target are 3.2 kA and 17 MeV. The goal is to create a more mono-energetic electron beam with variation of less than 1%-root-mean-squared (rms). This would allow the beam to be focused more tightly and create an x-ray source with a smaller spot-size. Our injector appears to have significant voltage-variation, and this report describes a technique to appreciably correct the deviations.

When an electron beam crosses the energized gap of an accelerator cell, the energy increases. However, the beam with the associated electromagnetic wave also loses a small amount of energy because of the increased impedance seen across each gap. The phenomenon is sometimes called beam loading. It can also be described as a beam-induced voltage at the gap which is time varying. The polarity of this induced voltage is the opposite of the voltage in the injector. The time varying profiles of the injector and induced gap voltage are related through the beam current. However, while the change in magnitude is similar, they are not exactly the same. With the right choice of cell and pulse-power system impedance, the injector variations can be greatly reduced by cancellation, but not totally eliminated.

The FXR injector voltage is estimated to be 2.5 MV-peak. The variation is estimated to be about 3.0%-rms for an interval of 60 ns. A simplified mathematical explanation of voltage compensation is given, and an idealized injector profile is used to quantify the effectiveness in a computer simulation. The result calls for a constant cell and pulse-power system impedance of 12.1 Ω. For this impedance, the compensated injector voltage-variation is less than 0.1%-rms.

I. FXR ENERGY REGULATION AND INJECTOR VOLTAGE

The LLNL FXR is an induction linear accelerator that produces pulsed x-rays and is used regularly and reliably on explosive experiments since its completion in 1982. In recent years, FXR has been incrementally improved, adding double-pulse capability, increasing dose, and reducing x-ray spot-size [1, 2].

FXR generates a 3.2 kA electron beam with 17 MeV of energy. Our present beam duration is 70 ns full-width half-maximum (fwhm). The forward x-ray dose at 1 meter is over 400 Rad, and the current spot-size is about 2 mm-fwhm. The peak energy of the injector is estimated to be 2.5 MeV.

Beam energy at the electron to x-ray converter target (eq. 1) is proportionate to the voltage of the injector and accelerator, minus the voltage lost as beam loading [3]. This report focuses on a technique to compensate for injector voltage-variations with the beam-induced voltage in the cells indicated in gray in the equation.

$$E_{V\ injector} + E_{V\ accelerator} - E_{V\ beam\text{-}induced} = E_{target} \quad (1)$$

This equation has been greatly simplified by eliminating the distributed nature of the acceleration process; nonetheless it represents the concept. The first two terms includes the gap voltage generated by the Marx and Blumlein, along with their interactions with the time-isolation and power feed coaxial lines, and the cell features. The injector voltage has added complexity because of the reflections in the cathode and anode stalks. The accelerator term denoting the unloaded cell voltage is not a part of this discussion.

The third term is derived from the beam-induced gap voltage that launches an electromagnetic (EM) wave into the cell and pulse-power system. Reflections are created at components with different impedances, and they

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eventually affect the voltage in the gap. To concentrate on the compensation analysis, we will assume that the cell and pulse-power system impedance is constant.

The FXR injector diode uses two voltage adders, the cathode is driven by six cells, and a hollow anode stalk is driven by four cells. Adding up the individual cell voltages to get the injector voltage will not be accurate because of the reflections in the stalks. Fortunately, the beam current is routinely and accurately measured. By reversing the diode equation (2 and 3) we can estimate the voltage profile, $V_{cath\text{-}anode}$, from the beam current, I_{beam}. The constant k is a conversion number and equal to 8.1 10^7 for I_{beam} = 3.2 kA and $V_{cath\text{-}anode}$ = 2.5 MV.

$$I_{beam}(t) = k\, V_{cath\text{-}anode}(t)^{3/2} \quad (2)$$

$$V_{cath\text{-}anode}(t) = I_{beam}(t)^{2/3} / k \quad (3)$$

The beam current at the head and tail of the beam is reduced about 16% from the peak. The upper portion of the inferred injector voltage is shown in Figure 1, and the beginning and end of the pulse is down about 11%. For precision accelerators, this is a large variation. The average voltage is estimated to be 2.4 MV.

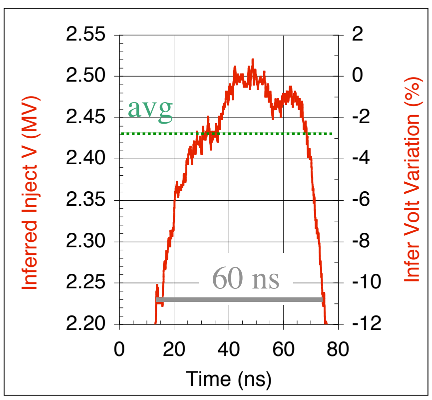

Figure 1. The inferred injector voltage shows a large drop of 11% for a 60 ns interval.

The variation is 73 kV-rms, or 3.0%-rms for the 60 ns interval. If we scale this variation by the energy at the target of 17.5 MV, the variation is 0.43%-rms. The estimated injector characteristics are shown in Table 1.

Table 1. Characteristics of inferred injector voltage.

for 60 ns Beam current Δ at head and tail	 100% -16%	 3.2 kA 0.47 kA
$V_{cath\text{-}anode}$ Δ at head and tail	100% -11%	2.5 MV **270 kV**
$V_{cath\text{-}anode}$ mean variation (V-rms) variation (%-rms)*		 2.43 MV **73 kV** **3.0%**
$V_{cath\text{-}anode}$ / V_{FXR} variation (%-rms)**		**0.42%**

* normalized to 2.4 M
** normalized to 15 MV for accelerator

II. INJECTOR VOLTAGE-VARIATION COMPENSATION

A. Theory

In this section, the mathematical basis for injector variation compensation will be presented. The goal is to determine the best cell and pulse-power system impedance that will minimize injector voltage-variation. The target energy equation (1) can be rewritten as a simplified voltage equation (4) by removing the electron charge

$$V_{injector}(t) + V_{accelerator}(t) - V_{induced}(t) = V_{target}(t) \quad (4)$$

Each term is time varying and spatially distributed. The spatial nature of the acceleration process is not important in this discussion. To focus on the voltage-variation compensation concept, we will assume all the voltage sources are collocated.

The beam-induced gap voltage is simply the beam current times the gap impedance. If we assume a constant impedance in the gap, cell and pusle-power system, the induced voltage for a cell is

$$V_{induced\text{-}cell}(t) = I_{beam}(t) * Z_{cell} \quad (5)$$

The objective is to balance the change in the injector with the opposite change in the gap. Focusing on just the injector and gap voltage, the difference between the injector and induced voltages, applying equation (5), for n cells is

$$V_{injector\text{-}induced}(t) = V_{injector}(t) - I_{beam}(t) * Z_{cell} * n \quad (6)$$

Substituting for the current from equation (1), we get

$$V_{injector\text{-}induced}(t) = V_{injector}(t) - k\, V_{injector}(t)^{3/2} * Z_{cell} * n \quad (7)$$

This difference does not have to be zero, only a constant, but the variation needs to be minimized.

$$V_{injector}(t) - k\, V_{injector}(t)^{3/2} * Z_{cell} * n = \text{constant} \quad (8)$$

We do this by differentiating the difference equation (8) and setting the result equal to zero.

$$\{dV_{injector}(t)/dt\} - \{(k\,n\,Z_{cell})\,(3/2)\,V_{injector}(t)^{1/2}\,(dV_{injector}(t)/dt)\} = 0 \quad (9)$$

$$\{1-(k\,n\,Z_{cell})\,(3/2)\,V_{injector}(t)^{1/2}\}\,(dV_{injector}(t)/dt) = 0 \quad (10)$$

There will be injector voltage-variations, so $dV_{injector}(t)/dt$ cannot be equal to zero. Therefore, to minimize the variation in the difference the term, $V_{injector\text{-}induced}(t)$, the result in the { } of equation (10) must be zero.

$$1-(k\,n\,Z_{cell})\,(3/2)\,V_{injector}(t)^{1/2} = 0 \quad (11)$$

$$Z_{cell} = 1/\{(k\,n)\,(3/2)\,V_{injector}(t)^{1/2}\} \quad (12)$$

The optimal cell and pulse-power system impedance depends on the diode conversion constant, the number of cells, and the injector voltage. Because the injector voltage is time varying, the value of Z_{cell} must also change to make the variation of the difference zero. In theory, perfect compensation is possible, but changing Z_{cell} in time is extremely difficult. Instead we will choose a single value for Z_{cell} and use a simple computer simulation, to quantify the effectiveness of compensation.

For an average injector voltage of 2.4 MV and with 44 cells in the accelerator, the gap impedance should be **12.1 Ω**. (See Figure 2.) Fortunately, we are operating at a high voltage where the slope of the curve is not very steep, and our uncertainty about the injector voltage will not seriously change the optimal impedance.

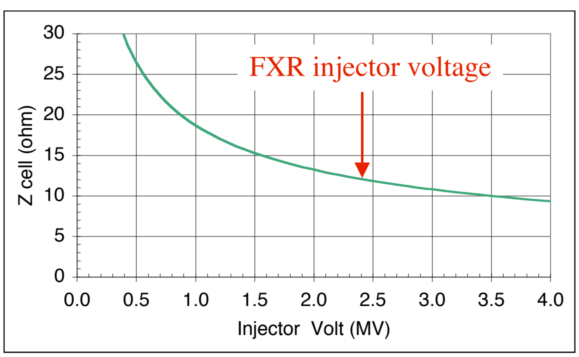

Figure 2. The optimal gap impedance for an injector voltage of 2.4 MV and 44 cells is 12.1Ω

B. Simulation

A simplified computer simulation is used to quantify the effectiveness of injector voltage-variation compensation. An idealized injector voltage profile is put forth because the real data has noise that would degrade the accuracy of the analysis. The idealized injector voltage is shown in Figure 3 denoted with a dashed line. The 60 ns waveform is composed of a portion of a sine wave and an offset. The maximum amplitude is set at 2.5 MV, sine wave amplitude was chosen to provide a variation of 3%-rms to match the inferred variation discussed in the previous section. This profile should reasonably represent the injector voltage.

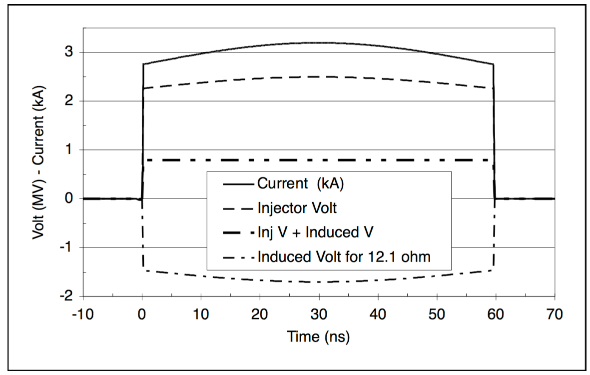

Figure 3. Injector voltage-variation compensation works extremely well for 12.1 Ω.

The calculated beam current is shown in the top curve. The total beam-induced voltage for all the cells is negative and is shown in the bottom curve, and to a high degree it has the reverse profile of the injector voltage. The compensated injector voltage is very flat.

The compensated voltage-variation is very low, less than 0.1%-rms. The percentage of variation normalized to the peak injector voltage is shown Figure 4. While not every point can be perfectly corrected, compensation does work exceptionally well.

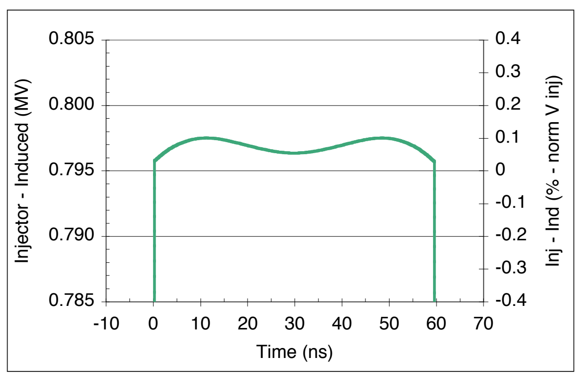

Figure 4. Expanded near perfect compensated injector voltage shows very little variation.

III. EVALUATION OF ALTERNATIVE GAP IMPEDANCES

In this section, the effectiveness of compensation with different cell and pulse-power system impedances will be evaluated. Using our model for determining the voltage-variation with an average injector voltage of 2.4 MV, the percentage of compensated injector voltage-variation for a range of impedances is given in Figure 5. Without compensation, the variation is simply the variation of the injector voltage, 3%-rms. As expected, the optimal impedance of 12.1 Ω derived in the previous section produces the minimum variation. Compensation works fairly well on FXR, but this could still be improved.

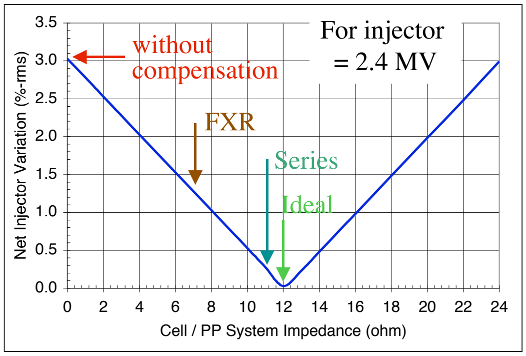

Figure 5. Compensation works on FXR but it could be better.

A comparison of the effectiveness of compensation for four impedances is given in Table 2. Note that the average injector voltage is lowest when compensation works best. There is no free lunch.

Table 2. Comparison of compensation effectiveness for various impedances.

Z_{cell}	FXR 0.0 Ω	FXR 7.2 Ω	Series 11 Ω	Ideal 12.1 Ω
V_{inj} - $V_{induced}$				
max	2.5 MV	1.49 MV	0.95 MV	0.80 MV
average	2.4 MV	1.45 MV	0.94 MV	0.80 MV
Δ-max/min-%	9.3 %	6.4 %	2.3 %	0.1 %
Δ-rms	73 kV	30 kV	7 kV	< 1 kV
Δ-rms-%	3.0 %	1.2 %	**0.3 %**	**< 0.1 %**

An assumption was made at the beginning of the analysis about the value of the injector voltage. A sensitivity study is presented using the optimal impedance of 12.1 Ω. The results are shown in Figure 6. With the optimal cell and pulse-power system impedance, compensation will work over a range of injector voltages. A 10% change from our estimated average injector voltage of 2.4 MV will increase the compensated variation only 0.15% to 0.2%. Therefore, the compensation technique requires only a modestly accurate measurement of injector voltage.

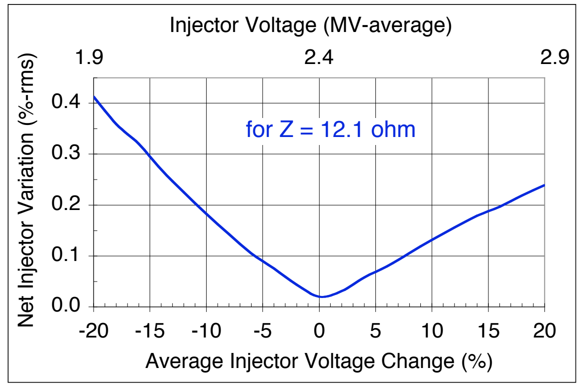

Figure 6. With the optimal impedance, compensation will work well over a range of injector voltages.

The results from this study will be incorporated into a larger accelerator system-model to quantify their effect on total beam energy variations. The compensated injector voltage-variation is reduced to about 40% of the injector variation.

IV. ACKNOWLEDGMENTS

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V. REFERENCES

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