

HIGH POWER RF REQUIREMENTS FOR DRIVING DISCONTINUOUS BUNCH TRAINS IN THE MaRIE LINAC*

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Abstract

The MaRIE project Pre-Conceptual Referenced Design is based on a superconducting linac to provide 12 GeV electron bunches to drive an X-ray FEL. Dynamic experiments planned for MaRIE require that the linac produce a series of micropulses that can be irregularly spaced within the macropulse, and these patterns can change from macropulse to macropulse. Irregular pulse structures create a challenge to optimizing the design of the RF and cryogenic systems. General formulas for cavities with beam loading can overestimate the power required for our irregular beam macropulse. The differing beam energy variations allowed for the XFEL and eRad micropulses produce cavity voltage control requirements that also vary within the macropulse. The RF pulse driving the cavities can be tailored to meet the needs of a particular beam macropulse because the macropulse structure is known before the pulse starts. We will derive a toolkit that can be used to determine the required RF power waveforms for arbitrary macropulse structures. We will also examine how the irregular RF power waveforms can impact RF and cryogenic system cost trade-offs.

OVERVIEW OF THE PRESENT MaRIE DESIGN

The purpose of the Matter-Radiations Interactions in Extremes (MaRIE) project is to investigate material properties in extreme conditions and record how these conditions evolve over time. Long macropulses are important because the conditions of interest change over a time-scales of 1 ms, but also can change very quickly at any time within this time period.

The Pre-conceptual Reference Design uses a superconducting 12 GeV linac to drive a 42 keV X-ray FEL with a train of up to 0.2 nC electron bunches with an average current of 8 mA over a macropulse of 69ns to 700μs (1000μs goal) [1]. The linac is made up of 1.3 GHz TESLA style cavities operating at the ILC design point of 31.5 MV/m, (implying 32.7 MV/cavity, 121.713 J/cavity, and 367 active cavities).

The main linac will also accelerate electron radiography (eRad) micropulses that will be interleaved with the micropulses driving the X-ray FEL.

CHALLENGES UNIQUE TO PLANNED OPERATION MODES AT MaRIE

The MaRIE linac is a pulsed machine with irregularly spaced micropulses within each macropulse [1]. The irregular spacing provides a particular challenge to the RF system driving the accelerating cavities.

The exact micropulse structures for MaRIE are still subject to modification at this point in the project, but in

general they are as follows: The X-Ray FEL will use a train of up to 0.2 nC electron bunches with an average current of 8 mA over the macropulse, but in the last part of the macropulse the spacing between micropulses decreases dramatically. In the last 230 ns the pulse spacing can be as small as 2.3 ns. The power feeding the main linac cavities is sized for a continuous 8 mA beam, so the concentration of pulses in the last part of the macropulse will cause the cavities in the main linac to lose energy and the accelerating voltage to droop. A 0.01% electron beam energy tolerance sets a limit on the allowable energy depletion of an electron bunch on the cavity voltage for a succeeding bunch [2].

One design option is for simultaneous electron radiography (eRad) with 2 nC micropulses. These larger charge bunches are interleaved in the same macropulse with the smaller charge bunches that drive the X-ray FEL, further complicating the RF drive requirements. Each eRad micropulse is separated from following micropulses with a spacing of at least 23 ns.

CONTINUOUS AND DISCONTINUOUS BEAM LOADING FORMULAS

Continuous Beam Loading Model

The forward RF power required by a cavity with heavy continuous beam loading [3] assuming: $Q \gg Q_e$, on-crest operation and neglecting microphonics simplifies to the well known power requirement formula for flattop operation

$$P_{f_maintain} \approx \frac{V_{eff}^2}{4Q_e \left(\frac{R}{Q}\right)} \left(1 + \frac{I_b \left(\frac{R}{Q}\right) Q_e}{V_{eff}}\right)^2$$

Discontinuous Beam Loading Model

The discontinuous beam loading model essentially applies a piecewise approximation to the continuous beam model. The following assumptions apply: a cavity/coupler system with time constant $\tau_L = 2Q_L/\omega$ and an external coupling $Q_e \ll Q_0$, a micropulse with charge q_n enters the cavity at t_n , then the micropulse decreases the cavity stored energy $U(t_n)$ from the value just before the bunch enters by the energy the bunch removes from the cavity, $V_c(t_n) q_n$; and that this happens instantaneously; finally the forward power between t_n and t_{n+1} is held constant at P_{f_refill} . The cavity stored energy for $t_n < t < t_{n+1}$ is then

$$U(t) = \frac{4P_{f_refill}Q_e}{\omega} \left(1 - e^{-\frac{t-t_n+t_{fill,n}}{\tau_L}}\right)^2$$

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where t_{fill_n} is the time it would have taken to fill the cavity to energy $U(t_n) - V_c(t_n) q_n$ and is given by

$$t_{fill_n} = -\tau_L \ln \left(1 - \sqrt{\frac{U(t_n) - V_c(t_n) q_n}{2\tau_L P_{f_refill}}} \right)$$

The cavity accelerating voltage is then

$$V_c(t) = \sqrt{\omega \left(\frac{R}{Q} \right) U(t)}$$

These equations can be used to calculate the cavity accelerating voltage with time on a pulse by pulse basis for arbitrary micropulse charges and spacings.

Check of the Discontinuous Beam Loading Model for a Beam that Approaches Continuous

The model can be benchmarked by assuming bunches of uniform charge q_0 arriving at frequency $f = 1/(t_{n+1} - t_n)$, a constant average current $q_0 f = I_b$, and a desired cavity voltage V_c . Solving for the value of P_{f_refill} that maintains $U(t_{n+1}) = U(t_n)$ in the above equations gives

$$P_{f_refill} = \frac{V_c^2}{4Q_e \left(\frac{R}{Q} \right)} * \left(\frac{\sqrt{\left(1 - \frac{\omega \left(\frac{R}{Q} \right) q_0}{V_c} \right) - e^{\frac{\omega_0}{2Q_e f}}} - e^{\frac{\omega_0}{2Q_e f}}}{1 - e^{\frac{\omega_0}{2Q_e f}}} \right)^2$$

Reducing to continuous case where $f \rightarrow \infty$, $q_0 \rightarrow 0$, and $q_0 f = \text{constant}$, and taking the first two terms of the Maclaurin series for $\sqrt{1-x}$ and e^x for small x values, the above equation reduces to

$$P_{f_refill} = \frac{V_c^2}{4Q_e \left(\frac{r_{sh}}{Q} \right)} \left(1 + \frac{Q_e f q \left(\frac{R}{Q} \right)}{V_c} \right)^2$$

or

$$P_{f_refill} = \frac{V_c^2}{4Q_e \left(\frac{R}{Q} \right)} \left(1 + \frac{Q_e I_b \left(\frac{R}{Q} \right)}{V_c} \right)^2$$

which is the continuous beam loading formula.

Impacts of RF System Parameters on Cryogenic System Loading

Cryogenic loading of the cavities is proportional to the cavity gradient integrated over time. The impact of fluctuations of a few percent in the cavity field appear to be relatively small compared to the impact of reducing cavity fill time.

Cavity fill time (derived from the lumped parameter model [4]) is a function of P_f and Q_e . The value of Q_e is a compromise between minimizing the required P_f for the average macropulse current and the fill time at that power. The lumped parameter model gives the equation for the power required to fill a cavity to a required accelerating voltage

$$P_f(Q_e) = \frac{V_{req}^2}{4Q_e \left(\frac{R}{Q} \right) \left(1 - e^{-\frac{\omega_0 t_{fill}}{2Q_e}} \right)^2}$$

Setting the derivative of P_f with respect to Q_e to zero yields a transcendental equation with the non-trivial exact solution in terms of the lower branch of the Lambert W function [5]

$$Q_e|_{P_f=\text{minimum}} = \frac{-\omega_0 t_{fill}}{1 + 2W_{-1}\left(-\frac{1}{2\sqrt{e}}\right)} \approx \frac{\omega_0 t_{fill}}{2.512}$$

The value of t_{fill} is chosen as a compromise. High power RF sources suitable for MaRIE have maximum RF pulsewidths on the order of 1 ms. Longer fill times require less power but result in reduced fraction of the RF pulse being used as the beam macropulse and increased heat loading of the RF cavities.

ENERGY DROOP AND COMPENSATION FOR A MARIE MACROPULSE

Simple Estimation of Beam Energy Droop

The average beam current over some 230 ns during the macropulse can be as high as 87 mA [2]. The RF system is designed to refill the main linac accelerating cavities for at most 8 mA, so in this 230 ns during the macropulse there is 79 mA * 230 ns = 18.17 nC of charge that is not corrected for. This much charge passing through a TESLA style cavity at 32.7 MV will decrease each cavity's stored energy from 121.713 J to 121.102 or 0.5% implying a 0.25% drop in cavity accelerating voltage and a 30 MeV drop accelerator beam energy. This 0.25% drop is much greater than the allowed 0.01% electron beam energy tolerance [2].

Calculation of Beam Energy Droop for a More Complex Marie Beam Micropulse Structure

Applying the discontinuous beam loading model in spreadsheet form to the Marie micropulse pattern described above and mixing in 5 eRad pulses with a 23ns empty space after each results in the possible beam pulse pattern shown in fig 1. Figure 2 shows a beam energy droop that occurs within the last 230 ns of approximately 30 MV. Without correction, the linac energy droop exceeds the allowed electron beam energy tolerance

Figure 2 shows the total linac energy deficit caused by the beam loading approaches 30 MV by the end of the beam macropulse. The times where the micropulses exit

the linac are shown as dots. Note that after each eRad pulse, the energy recovers back to the average 87 mA beam loading line during the 23 ns when there are no micropulses.

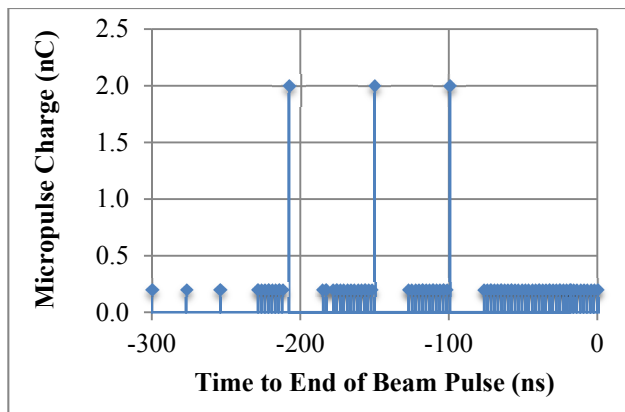


Figure 1: Beam micropulse spacing goes 23 ns to 2.3 ns in the last 230 ns of the macropulse.

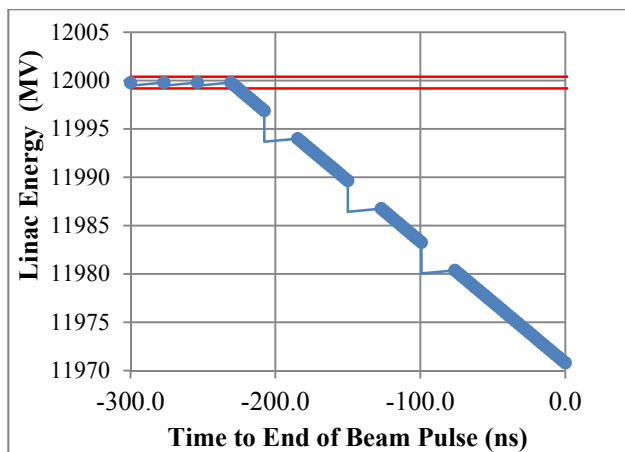


Figure 2: Uncorrected linac beam energy with times of the micropulses marked as dots. Allowed electron beam energy tolerance in red.

Compensation Methods for Beam Energy Droop

One method to maintain the linac beam energy within 0.01% with an average current of 87 mA over the last 230 ns is to increase the RF power into the linac cavities. This can be done by splitting the RF power among fewer cavities. For the MaRIE linac, this would require using 13 times the number of high-power klystrons required for the 8 mA average beam; a very expensive approach. An alternate approach proposed by Sheffield is to use a booster linac section located either before, in the middle or after the main SC linac [2].

Required Energy Profile for a Booster Linac section at MaRIE

The booster linac section must precisely offset this droop with an increasing energy slope of 130 MV/ μ s. A short Normal Conducting linac has been proposed to offset this droop [2].

Figure 3 shows how a simple ramp of booster linac beam energy can compensate for the effect of beam energy droop. A 230 ns risetime to 30 MV is practical for a normal conducting booster linac. In contrast, the high Q of a superconducting linac makes rapid fill times impractical.

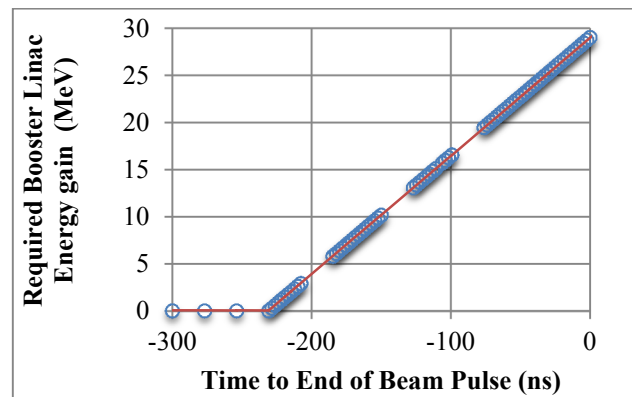


Figure 3: Required booster linac energy gain must be at the circled points to compensate for droop.

More complex pulse patterns (without the 23 ns gap after each eRad pulse) can be compensated for by tailoring the pulse shape of the RF drive to the NC Booster linac.

CONCLUSION

The 12 GeV MaRIE linac will be required to accelerate electron beam macropulses that are very non-uniform in time. The beam power requirements increase more than tenfold in the last part of the macropulse. It is not practical to size the main linac RF systems to accommodate this beam loading, so a booster linac is proposed to make up the energy difference caused by energy droop in the main linac cavities. The methods described are used to calculate the size of this droop and determine the required boost linac fill waveform that exactly offsets the energy droop in the main linac.

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