Enabling cost-effective high-current burst-mode operation in superconducting accelerators

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Abstract

Superconducting (SC) accelerators are very efficient for CW or long-pulse operation, and normal conducting (NC) accelerators are cost effective for short-pulse operation. The addition of a short NC linac section to a SC linac can correct for the energy droop that occurs when pulsed high-current operation is required that exceeds the capability of the klystrons to replenish the cavity RF fields due to the long field fill-times of SC structures, or a requirement to support a broad range of beam currents results in variable beam loading. This paper describes the implementation of this technique to enable microseconds of high beam-current, 90 mA or more, in a 12 GeV SC long-pulse accelerator designed for the MaRIE 42-keV XFEL proposed for Los Alamos National Laboratory.

Keywords: Superconducting accelerator, free electron laser, high current, short pulse

1. Introduction

The Matter-Radiation Interactions in Extremes (MaRIE) facilities, the Multi-Probe Diagnostic Hall (MPDH) and the Making, Measuring, and Modeling Materials (M4) Facility, will require a temporal series of closely spaced coherent x-ray beam probes with individual bunches having greater than 2×10^{10} photons in less than 0.1 ps.¹ This probe beam requirement led to designing an XFEL that can provide a series of highly penetrating 42-keV x-rays that will transverse high-Z materials with a low enough absorption to make a “motion picture” of dynamic events lasting from less than 0.1 microsecond up to 100 microseconds.

The highest imaging rate for MaRIE requires up to 30 images in 69 ns. To generate the necessary number of photons simulations show that an XFEL electron microbunch charge of 0.2 nC is needed, which equates to an average electron beam current requirement of up to 87 mA during the macropulse. In addition to the electron micropulses for x-ray imaging, the main section of the linac will also be used to provide ten electron radiography (eRad) pulses. The eRad pulses may be interspersed throughout the XFEL bunch train, but will be subject to a minimum pulse separation constraint imposed by longitudinal wakefields that is discussed later. The highest eRad average current occurs when the eRad bunch train that consists of 2-nC micropulses has a minimum pulse spacing of 23 ns. This gives the same 87 mA average current but over a macropulse length of 230 ns. This high current can significantly reduce the stored energy in a linac during the macropulse that, if uncorrected, can lead to a large energy droop during the

macropulse. An electron beam energy stability of 0.01% is required for both the XFEL and eRad. The tight electron beam energy requirement sets a limit on the allowable energy depletion of an electron bunch on a succeeding bunch, the droop, and any energy loss more than 0.01% during the macropulse must be compensated. The longer eRad macropulse sets the time duration over which the energy droop must be compensated.

2. MaRIE XFEL description

The MaRIE XFEL proposed reference design² is a 12 GeV linac that accelerates 0.2 nC electron bunches for a 42 KeV x-ray FEL and 2 nC electron bunches for eRad, see Figure 1. Due to the wide range of dynamic events to be studied, the pulse format will need to be flexible. The electron beam macropulse length will range from a minimum of 69 ns to a maximum pulse length of 100 μ s. For either the eRad or XFEL beams, the maximum macropulse average current is 87 mA based on their respective minimum microbunch spacing.

Figure 1. Cartoon of the major components of the proposed MaRIE reference design. The XFEL normal conducting photoinjector produces micropulses that are accelerated to 250 MeV through 1.3 GHz and a 3.9 GHz cryomodels, compressed in time in BC1, further accelerated to 1 to 2 GeV before another micropulse compression stage, droop corrected, and then accelerated to 12 GeV before passing through dechirpers to remove the residual energy spread introduced for compression, and then introduced into the undulators. The eRad normal conducting photoinjector produces a beam that is accelerated to 250 MeV through 1.3 GHz and a 3.9 GHz cryomodels, enters the main linac at BC2, accelerated to 11.75 GeV, and passed through the droop corrector linac. The eRad and XFEL beams are then directed to various end stations. Two differing types experimental halls with 3 end stations each are shown. One hall has 11.75 MeV eRad, 800 MeV pRad using the existing LANSCE linac, and 42 keV x-rays illuminating a sample, and the other hall has x-ray only end stations.

Both S-band normal conducting (NC) and L-band SC technology were evaluated for the MaRIE linac using a parametric model spreadsheet. Due to the constraints imposed by the terrain at Los Alamos, the overall accelerator length using either a NC or SC linac must also be considered. The minimum time duration to cover the dynamic events of interest sets a minimum pulse length of 10 μ s. For reliable operation, a 10- μ s macropulse sets a maximum cavity gradient of approximately 15 MV/m for a NC S-band linac, and the resulting estimated length of a 12-GeV NC XFEL, including bunch compressors, undulators, other beam line components and x-ray beam paths, is approximately 1500 m, which does not fit within the site real estate limitations. Using the same parametric model, the length of a 12-GeV, 1.3-GHz SC³ XFEL with a maximum cavity gradient of 31.5 MV/m and the previously mentioned ancillary systems is approximately 1200 m, which does fit within the site limitations and also is less expensive than the NC XFEL. The end result of this analysis is that if either overall accelerator length or cost are issues, SC is the optimal choice for 10 μ s or longer macropulses.

3. Pulse to pulse energy loss problem

Transverse emittance growth and energy spread due to long range wakefields sets a minimum pulse separation for the XFEL 0.2-nC micropulses of 2.3 ns (every third RF period at 1.3 GHz) and 23 ns for eRad micropulses, equating to a very high average-current of 87 mA. The individual 1.3-GHz SC cells have a very large stored energy, calculated to be ~14 J, and a single 0.2 nC pulse is estimated to extract 0.7 mJ or 0.006% of the cell stored energy. This energy depletion gives an overall ~ 0.36 MeV decrease in the final beam energy at 12 GeV. Each succeeding micropulse will reduce the beam energy by another 0.36 MeV. Each eRad pulse causes a 10x larger energy depletion. If no power source replenishes the RF field in the cells between pulses, then electron beam energy loss will exceed the required 0.01% amplitude variation limit after three 0.2 nC micropulses and a single eRad micropulse as shown in Figure 2.

The beam energy loss must be compensated to stay within energy bandwidth requirement. To make up this energy loss by maintaining the cavity fields in the SC linac would require a power flow into a cell of 275 kW, and, including transmission losses and control margin, an RF power of 3.2 MW to drive a single SC cavity that consists of 9 cells. Building an SC accelerator capable of maintaining a peak current of 87 mA and also capable of long pulse operation has very high RF systems costs. Also, this design would be very inefficient since the high peak power is only required for those limited set of experiments that have closely spaced pulses in less than a microsecond; for experiments where the pulse separation is longer than 2.3 ns, much less peak power is required as will be shown below. Further, the power coupling would require readjustment every time the linac pulse format is changed if efficiency is a consideration.

The optimal RF power used to drive the SC cavities is not set by the unloaded cavity Q_0 of $\sim 10^{10}$ but by the external loaded cavity Q (Q_{ext}). The dynamic superconducting cavity losses are due to RF losses, and a low Q_{ext} that reduces the cavity RF fill-time also reduces the RF-induced cryogen loading but at the expense of higher RF power. Using resonant RF filling described in reference 4, the RF input power is minimized when Q_{ext} is $\sim 2.9 \times 10^6$. This Q_{ext} equates to a cavity fill time of ~ 0.9 ms, which is very long compared to the maximum beam pulse length of 100 μs .

Figure 2. Graphical representation of the decrease in final beam energy due to each succeeding eRad pulse up to the final pulse at 230 ns.

The input RF power from the klystrons is high enough to compensate for the energy droop if the average current is low, i.e. if the micropulse spacing is long enough as is now done for pulsed SC linacs.⁵ Using $Q_{\text{ext}} = 2.9 \times 10^6$ and a gradient of 31.5 MV/m gives a required power flow of ~173 kW per cavity. To minimize cost, we are assuming a 6.0 MW multi-beam klystron to power 26 cavities with 17% control margin and 12% losses. We can now make an estimate of the average current capability of this design assuming the above Q_{ext} . Given a matched beam-loaded cavity at this gradient, the energy droop will be compensated when the average current is less than 6 mA, or stated differently, the above klystron and cavity arrangement would allow for long-pulse or CW operation for a beam current less than 6 mA. Since the eRad micropulse charge is 2 nC, then

the beam current limit sets a minimum pulse spacing of more than 330 ns, over an order of magnitude longer than the design requirement. The maximum time the energy droop would have to be compensated is set by the time period required to provide the required 10 eRad pulses, see Figure 2; thus the planned SC RF can provide power for macropulses longer than 3.3 μ s.

4. Energy droop corrector design

One way to maintain a constant 12 GeV beam energy for the high average current of 87 mA over 230 ns is to maintain the SC cavity fields by increasing the RF power into a cavity. This can be done by splitting the RF power among fewer cavities. For our case, this would require using the above 6.0 MW klystron to drive only two cavities each and so result in 13 times the number of high-power klystrons, a very expensive approach.

Another approach is to use a booster linac section located either before, in the middle or after the main SC linac. This “droop corrector” linac can be a low gradient, room temperature copper structure. Since a normal conducting structure has a much lower Q, the RF rise time can be much shorter than for the SC linac, allowing the use of shorter pulse, higher peak power klystrons. This approach incorporates the best features of both room temperature and superconducting technologies. The SC linac efficiently uses the RF to accelerate the beam to 12 GeV, and the room temperature linac is a fast response structure to compensate for droop.⁶

The design of the droop corrector linac will be set by the peak beam current, the time to attain the required cavity field, and the peak available RF power. The peak eRad and XFEL beam current is 87 mA for 230 ns and 69 ns pulse lengths, respectively, so the most demanding application is eRad. The maximum beam energy decrease at 12 GeV after 10 2-nC pulses in 230 ns is 30 MeV assuming no active replenishment of the RF field during the macropulse.

In a constant impedance traveling wave linac, the voltage gain per time is proportional to the cavity fill time.⁷ Using 2-each traveling wave 1.3-GHz 1.3-m long copper linac sections, the field rise time is 230 ns and the two sections will give a total 30 MeV energy gain. For the purpose of this analysis, we assume a Thales 2022A 1.3-GHz tube that has 20 MW peak power and is capable of 8 μ s long pulses.

A 2.6-m long 1.3-GHz NC linac with a 12 MeV/m gradient will have copper losses of 9.9 MW. Assuming an 87 mA maximum beam current requires 2.4 MW for beam loading at 30 MeV. Using 10% waveguide and window losses and 15% control margin gives a total RF power of 15.4 MW, well within the Thales RF tube capability.

To compensate for the increasing cavity energy depletion, the required RF power amplitude must be increased to match the voltage gain required for each succeeding electron micropulse. Each micropulse decrements the stored energy of the SC linac by a fixed amount, so the energy loss for the n_{th} pulse is the energy loss per pulse times the number of pulses. In our case, the cavity fill time is matched to the eRad minimum pulse length. For longer pulses, the klystron power is

varied to match the beam energy loss. Figure 3 shows the required RF power format for two different eRad macropulses, one where the macropulse matches the fill time and another with a macropulse twice as long. Since the droop corrector linac only changes amplitude and not phase, the Cu linac can be placed at any location after the last bunch compressor. For the MaRIE design, the performance of the bunch compressor is not dependent on a 10^{-3} change in beam energy, and elegant⁸ simulations show that an energy correction is not required before either of the bunch compressors.

Thus a relatively inexpensive NC linac will enable short high-current burst mode operation for the MaRIE XFEL. As described above, this linac is a traveling-wave 1.3-GHz copper structure operating at 12 MV/m. The linac has two 1.3-m long sections driven by a single 20 MW peak power klystron. The RF amplitude and phase tolerances of the NC linac are set by maintaining the final beam energy to less than the required 10^{-4} in amplitude. The final beam energy error contribution due to the droop corrector linac, added in quadrature, is set to $< 10\%$ of the overall beam energy error allowance. This requires a NC linac RF control of $< 2\%$ in amplitude and $< 6^\circ$ in phase. Either higher currents or longer macropulses at the same high average current will require adding additional klystrons and/or linac sections. As the eRad 2-nC, 10-micropulse macropulse is extended from the minimum macropulse length of 230 ns, then decreasing peak power is required since the power flow into the SC linac would be compensating for the energy droop up to 3 μ s. For longer than 3- μ s macropulses, the NC linac will not be powered. Since the linac is not powered, it will extract power from each micropulse, but this is not a significant issue since the energy decreases by less than 0.01% and will be easily compensated by the RF tubes that provide power for the SC linac.

Figure 3. RF power flow required to match two representative eRad macropulse formats. The circle and triangle markers are the required beam energy increase. The solid and dotted lines are the RF power temporal profiles that produces the 3 MeV energy gain per pulse for an eRad macropulse that matches the cavity fill time of 230 ns and another for a 460 ns macropulse. The simple examples given in the figure have a constant macropulse current that requires a constant dV/dt , and so a voltage increase that rises linearly with time during the macropulse. For a constant impedance traveling wave linac a pulse length change is accommodated by step function changes in the power.⁷ As given earlier in this section, to attain an energy gain of 30 MeV requires 15.4 MW of klystron power. For the 230 ns macropulse, the klystron output power is set to a constant 15.4 MW for the duration of the macropulse. For the 460 ns pulse, the RF is first fixed at 6.1 MW (Cu loss of 2.48 MW) to reach 15 MeV at 230 ns and then stepped up to 15.4 MW (Cu loss of 9.9 MW) to reach 30 MeV at 460 ns.

5. Conclusion

The addition of a copper traveling-wave linac to a SC linac allows for high-current burst mode operation at any time for CW and pulsed SC-linacs. This droop correction technique might be the least expensive and most flexible linac modification that would enable very flexible short-pulse high-current beam operations.

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Figure 1

Figure 2

Figure 3