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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.

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 μs up to 100 μs.

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 additional 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 design [2] 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 Fig. 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 μs. For either the eRad or XFEL beams, the maximum macropulse average current is 87 mA based on their respective minimum microbunch spacing.

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 μs. For reliable operation, a 10-μs 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

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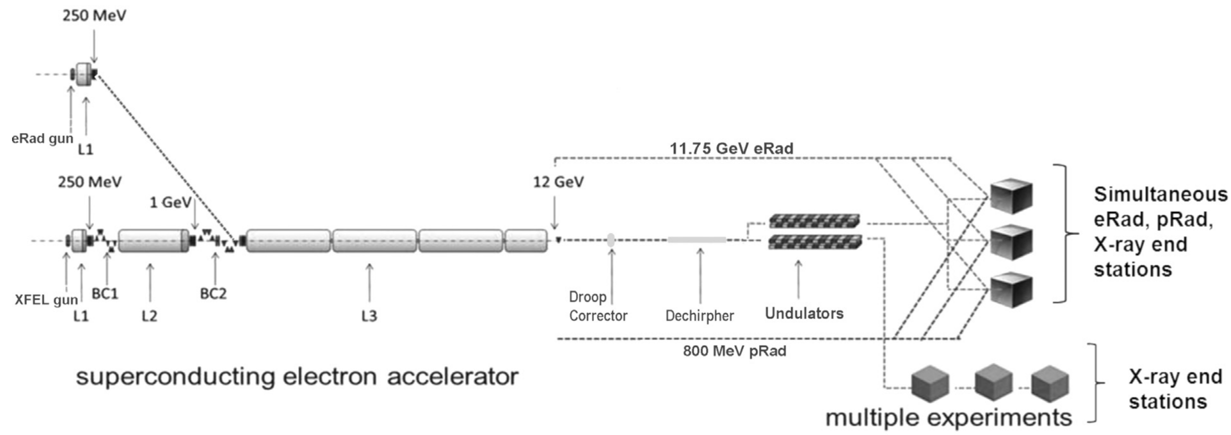

Fig. 1. Cartoon of the major components of the proposed MaRIE reference design. The XFEL normal conducting photoinjector produces micropulses that are accelerated to 250 MeV through 1.3 GHz and a 3.9 GHz cryomodules, compressed in time in BC1, further accelerated to 1 to 2 GeV before another micropulse compression stage, accelerated to 12 GeV, pass through the droop corrector, pass 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 3.9 GHz cryomodules, 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 GeV 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.

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, and 1.3-GHz SC [3] 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 is approximately the same cost as 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 μs 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 10 × 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 two 0.2 nC micropulses and a single eRad micropulse as shown in Fig. 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.

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 $Q_{ext}=2.9 \times 10^6$ 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, shown in Fig. 2; thus the planned SC RF can provide power for macropulses longer than 3.3 μs.

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.