HIGH-GRADIENT X-BAND STRUCTURES FOR PROTON ENERGY BOOSTER AT LANSCE

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Abstract

Increasing energy of proton beam at LANSCE from 800 MeV to 3 GeV improves radiography resolution ~10 times. Using superconducting RF cavities with gradients ~15 MV/m after the existing linac would result in a long and expensive booster [1]. We propose accomplishing the same with a much shorter cost-effective booster based on normal conducting high-gradient (~100 MV/m) RF accelerating structures. Such X-band high-gradient structures have been developed for electron acceleration and operate with typical RF pulse lengths below 1 μs. They have never been used for protons because typical wavelengths and apertures are smaller than the proton bunch sizes. However, these limitations do not restrict proton radiography (pRad) applications. A train of very short proton bunches with the same total length and charge as the original long proton bunch will create the same single radiography frame, plus pRad limits contiguous trains of beam micro-pulses to below 60 ns to prevent blur in images. For a compact pRad booster at LANSCE, we explore feasibility of two-stage design: a short S-band section to capture and compress the 800-MeV proton beam followed by the main high-gradient X-band linac.

INTRODUCTION

Proton radiography employs high-energy proton beams to image material behavior under extreme conditions. It was invented and developed at LANL, and by now the pRad program at LANSCE has performed hundreds of successful experiments, both static and dynamic. While the LANSCE 800-MeV linac accelerates both protons and H^- ions, the pRad uses H^- beam, which is presently the only beam species that can be chopped in the front end and directed to the pRad facility. For dynamic experiments, pRad uses multiple pulses from the linac, which, coupled with multiple optical viewing systems, produce movies up to a few tens of frames. Each short pRad beam pulse consists of several successive bunches from the linac, which follow at the linac DTL repetition rate of 201.25 MHz, to multiply the pulse total intensity. This is because the H^- bunch current at 800 MeV is limited to about 10 mA, mainly by the ion source, but also by losses in the linac. On the other hand, the pRad pulses are restricted to 60 ns in length, i.e. contain no more than 12 linac bunches, to prevent image blur. The future plans for LANSCE include a proton RFQ in a new injection line with a chopper that will deliver higher proton bunch currents, up to 30 mA. The new 750-keV 4-rod RFQ [2] has been recently delivered to LANL; its initial RF tests will be performed within next several months.

Increasing the beam energy for pRad at LANSCE from present 800 MeV to 3 GeV would provide significant improvements: for thin objects the radiography resolution would increase about 10 times, and much thicker objects could be also imaged [1]. A superconducting (SC) option for a pRad booster to 3 GeV was considered in [1]. Assuming a typical real-estate gradient of 15 MV/m, it leads to a rather long booster, ~150 m. This option is also expensive, in part because it requires a new cryogenic plant at LANSCE. We propose a much shorter and cheaper booster based on high-gradient (~100s MV/m) normal-conducting RF accelerating structures operating at low duty factors.

HIGH-GRADIENT STRUCTURES

High-gradient (HG) normal-conducting structures have been developed for accelerating electrons, e.g. [3]. Such structures operate at very high RF frequencies, usually in X band or higher, with short RF pulses – shorter than 1 μs. The work at SLAC and other labs demonstrated gradients 100-150 MV/m in both traveling-wave and standing-wave X-band cavities at 11.4 GHz with RF pulses of 100s ns [3]. A short standing-wave copper accelerating structure, cut along its axis for autopsy after high power tests, is shown in Fig. 1. Even higher gradients, up to 300 MV/m, were measured at 115-140 GHz, though with very short RF pulses of a few ns [4]. At such high RF frequencies, the structure aperture sizes are tiny, ~1 mm. In X band, the aperture diameter can exceed 1 cm; e.g., the beam aperture diameter of the cavity in Fig. 1 is 11.3 mm. The structure gradients are limited by various factors, most important of them are the peak surface electric field, peak pulse heating, and the modified Pointing vector, see in [3, 4].

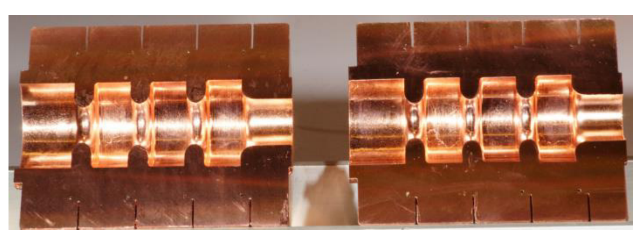

Figure 1: Cut of HG X-band copper accelerator cavity [3].

The HG structures have never been used for protons because their typical wavelengths and apertures sizes are smaller than the usual proton bunch sizes. However, these limitations of HG structures do not restrict their use for pRad applications. The pRad at LANSCE employs up to 12 long bunches from the 800-MeV proton linac to produce a single frame. Obviously, if a linac H^- bunch is sliced by high-frequency RF, the resulting train of very short bunches (slices) with the same total charge and temporal extent as the original long linac bunch will make the same contribution to a single radiography frame. We consider a HG proton booster for the pRad at LANSCE from accelerator viewpoint.

HG PRAD BOOSTER AT LANSCE

Exit Beam Parameters and Losses at 800 MeV

The higher-energy part of the LANSCE accelerator – coupled-cavity linac (CCL) – operates at RF frequency of 805 MHz. From multiple measurements and simulations one can estimate that the H^- beam with peak current of 10 mA exiting the 800-MeV linac is mainly within 15° of 805-MHz RF longitudinal phase space, or about 52 ps. The bunch transverse rms size is typically 2-3 mm, and the beam rms energy spread is about 10^{-3}.

The linac bunch charge is ~50 pC (10 mA at 201.25-MHz bunch repetition frequency). At 800 MeV, the acceptable losses [5] are about 10 nA average current lost per RF module (a CCL section fed by one klystron), which is 15-m long. This translates to the lost charge of approximately 1 nC/m/s. Note that the total charge in 12 bunches (max for 1 pRad frame) is 0.6 nC. From this viewpoint, even significant beam losses in pRad operation will not lead to noticeable radiation, due to its very low duty factor. On the other hand, the resulting loss of beam intensity may compromise the radiographic image quality.

RF Cavity Modifications for Protons

The beam out of the LANSCE linac has energy 800 MeV. Its velocity at this energy is $v = \beta c$, where $\beta = 0.84$ and c is the speed of light. The pRad booster needs to accelerate the linac beam from 800 MeV to 3 GeV, where $\beta = v/c = 0.97$. At that energy the beam becomes close to being ultra-relativistic ($\beta = 1$) though is not quite there. Therefore, the $\beta = 1$ HG structures for electrons have to be modified to cover the proton beam velocity range from $\beta = 0.84$ to $\beta = 0.97$. The cell length of a π-mode standing-wave structure should vary with beam energy as $\beta\lambda/2$, where λ is the RF wavelength. Figure 2 illustrates how an X-band $\beta = 1$ cell with the beam aperture diameter of 1 cm is modified for $\beta = 0.84$.

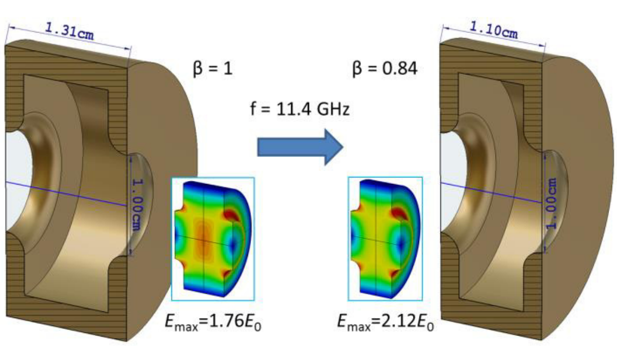

Figure 2: Modification of X-band π-cavity for $\beta = 0.84$.

The cavities are analyzed with CST Studio [6]. The cavity frequency is kept fixed by adjusting the cavity inner radius. The insets show the magnitude of the cavity electric field (red is high, blue is low). Squeezing the cavity longitudinally proportionally to its design value of β increases the maximal surface field for a given accelerating gradient E_a. The increase is relatively small and can be mitigated to some extent by shaping the cell iris.

PRad Booster Scheme

If we try to apply HG X-band structures directly at 800 MeV, the linac bunch would occupy ~215° of the RF longitudinal phase space at 11.424 GHz, since the RF period is 87.5 ps. Clearly, the beam capture efficiency will be low. This is why we suggest introducing an intermediate stage with S-band structures to efficiently capture and compress the 800-MeV beam from the linac. One convenient choice of RF frequency for this stage is 2817.5 MHz, which is the 14th harmonic of the bunch frequency 201.25 MHz. It is also close to the standard SLAC frequency of 2856 MHz, so the existing 5045 klystrons can be used with some modifications. The RF period for such an S-band linac is 354.9 ps, so the linac bunch fits into 52° longitudinally. While this is not small, the bunch can be accepted with minimal losses, especially if one runs the initial part of the S-band stage in a buncher mode, with synchronous RF phases in cavities starting near -90° and gradually increasing. We assume that the S-band section, in addition to beam bunching, will also accelerate the pRad beam to about 1 GeV.

The main beam acceleration to 3 GeV will be performed by HG structures working in X band. The higher frequencies would lead to very small apertures that would scrape the pRad beam. We chose the X-band RF frequency at 4 times that of the S-band section, i.e. 11.270 GHz. This is close to the SLAC X-band frequency of 11.424 GHz, so all the HG structure development results are directly applicable and the XL4 klystrons can be used with some modifications. It is very likely that we will need to use the initial part of the X-band section in a buncher mode and gradually move to an HG accelerator. The layout of such a two-stage pRad booster is schematically shown in Fig. 3.

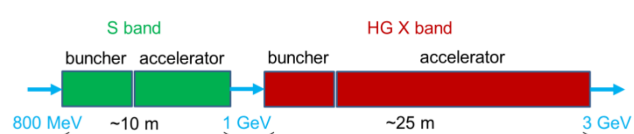

Figure 3: Conceptual scheme of HG pRad booster.

If we assume the accelerating gradients of 25 MV/m for the S-band linac and 100 MV/m for the X-band one, the linac lengths will be approximately 10 m and 25 m, correspondingly. These lengths include from 2 to 5 meters for the buncher.

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RF Power Estimates and System Options

The peak RF power required to operate the HG booster can be estimated as $P_{tot} = (V_{tot})^2/R_{sh}$, where $V_{tot} = E_aL$ is the total voltage along the linac section of length L and $R_{sh} = R'_{sh}L$ is the shunt impedance of the section. It can be written as $P_{tot} = E_aV_{tot}/R'_{sh}$. Assuming for HG X-band linac E_a = 100 MV/m, and using typical value of the structure shunt impedance R'_{sh} = 100 MΩ/m [3, 7], we obtain P_{tot} = 2 GW, since V_{tot} = 2 GV. This peak power can be delivered by 10 X-band klystrons with SLED RF pulse compressor [8]. Similar crude estimates for the S-band linac with E_a = 25 MV/m and R'_{sh} = 40 MΩ/m give P_{tot} = 125 MW, which requires only one S-band klystron with a SLED.

Recent experiments at SLAC with cryogenically cooled HG X-band structures (copper cavities at 45K) achieved the gradients up to 250 MV/m and shunt impedance as high as 200 MΩ/m [7] with the pulse flat part of about 150 ns. Such cryo-cooled structures would allow either making the booster about 2.5 times shorter or reducing the number of klystrons by a factor of two. Operating the X-band pRad booster at liquid nitrogen (LN2) temperature of 77K at LANSCE looks especially advantageous, considering the very low duty factor of pRad operation. Even if a significant portion of LN2 is evaporated during a shot, it can be simply refilled by the next one; there is no need for an expensive cryoplant.

Beam Dynamics Results

In Ref. [9], we performed simplified beam dynamics simulations for the pRad booster using PARMILA code [10]. Cavities in S-band and X-band covering the β-range 0.84-0.97 were designed to calculate and interpolate *T*-factors for PARMILA runs. We neglected the beam transverse distribution to focus on the longitudinal beam dynamics, which is more challenging.

Our results [9] for an idealized two-stage booster are encouraging: by ramping the RF phases in the buncher sections and gradually increasing RF amplitudes along the buncher (amplitude ramp), one can transfer 99% of input particles through the booster. Our first-iteration design used RF phases from -80° to -50° in the S-buncher, -80° to -60° in the X-buncher, and -40° in the both S- and X-band linacs. Though the total booster length in this case was somewhat long, 43 m, the simplified PARMILA simulations with a narrow input beam distribution showed that 9945 particles out of the initial 10000 at 800 MeV exited the booster at 3 GeV. We plan more detailed beam dynamics studies in the future.

CONCLUSION

We propose a compact booster based on high-gradient (HG) normal-conducting RF accelerating structures to increase the energy of the H^- beam exiting the LANSCE linac from 800 MeV to 3 GeV for proton radiography (pRad). Such an energy boost can improve the pRad resolution ~10 times; it also opens possibilities for new experiments with thicker targets. The HG-booster concept takes advantage of the impressive results in development of HG β = 1 structures for electrons, which operate at very high frequencies. We find that HG structures, modified for proton beams with β < 1, fit well for a pRad energy booster, because pRad uses very short beam pulses and operates at low duty factors. A HG pRad booster at LANSCE would be significantly (3 to 5 times) shorter and a few times cheaper than a superconducting one. We propose a two-stage booster: a short S-band section to capture and compress the 800-MeV linac beam, followed by the main X-band booster. This two-stage design was chosen mainly to minimize the intensity loss for the Rad beam pulses.

HG energy boosters can be also beneficial for other applications, for example, to quickly accelerate muons. Though such applications are clearly limited, mainly by rather short pulses of the energy-boosted beam and overall by low-duty operation, it is an auspicious option, especially when high gradients are required or available space is restricted.

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