

# HIGH-GRADIENT STRUCTURES FOR PROTON ENERGY BOOSTERS

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## Abstract

Increasing the proton beam energy at LANSCE from 800 MeV to 3 GeV can improve radiography resolution ~10 times. The best current practice to achieve this energy boost is to employ superconducting (SC) RF cavities with gradients about 15 MV/m after the existing linac, which results in a long and expensive booster [1]. We propose accomplishing the same with a room-sized booster based on high-gradient (100s MV/m) room-temperature RF accelerating structures operating at low duty factors. Such high-gradient (HG) structures at very high RF frequencies have been demonstrated for electrons. However, they have never been used for protons because typical RF wavelengths are smaller than the proton bunch length. This is not a problem for proton radiography (pRad): a train of very short proton bunches with the same total length (10s ps) and charge as the original proton bunch will work as well, i.e., will create one radiography frame. Such a compact HG pRad booster can also be about an order of magnitude cheaper than the SC one. We explore feasibility of HG structures for protons and their application for a compact pRad booster at LANSCE.

## INTRODUCTION

Proton radiography (pRad) employs a high-energy proton beam to image the properties and behavior of materials under extreme conditions. Invented at LANL, the pRad program at the Los Alamos Neutron Science Center (LANSCE) performed hundreds of successful experiments, both static and dynamic. While the LANSCE 800-MeV linac accelerates both protons and H<sup>-</sup> ions, the pRad uses H<sup>-</sup> beam, which is presently the only beam species that can be chopped in the front end by a fast traveling-wave chopper and directed to the pRad facility. For dynamic experiments, pRad uses multiple pulses from the LANSCE 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<sup>-</sup> 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 on a new injection line with a chopper that will deliver higher bunch currents, up to 30 mA. The new 750-keV 4-rod RFQ [2] has been recently delivered to LANL; its high-power tests will be performed within next few 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 HG 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]. Even much higher gradients, up to 300 MV/m were measured at 115-140 GHz, though with very short RF pulses of a few ns [4]. Important to notice that at such high RF frequencies, the structure aperture sizes are tiny, ~1 mm; in X band, the aperture diameter can be as large as 1 cm. The structure gradients are limited by various factors, most important of them are the maximal surface electric field, pulse heating, and energy transfer in the cavities as defined by the modified Pointing vector, see in [3, 4].

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. It should be recalled that 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<sup>-</sup> 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 (tens of ps) linac bunch will make the same contribution to a single radiography frame. Let us consider now if a HG proton booster can work 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<sup>-</sup> 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  $\sim 50$  pC (10 nA at 201.25-MHz bunch repetition frequency). At 800 MeV, the acceptable losses [5] are about 10 nA average current lost per RF module, which is 15-m long. This translates to lost charge of approximately 1 nC per meter per second. 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  $\beta = 0.97$ . For an RF cavity (one cell of a  $\pi$ -mode structure), the length should vary with beam energy as  $\beta\lambda/2$ , where  $\lambda$  is the RF wavelength. Figure 1 illustrates how a simple X-band  $\beta = 1$  cell with a relatively large beam aperture is modified for  $\beta = 0.84$ . The cavities are analyzed with CST Studio [6]. The cavity frequency is kept fixed by adjusting the cavity inner radius.

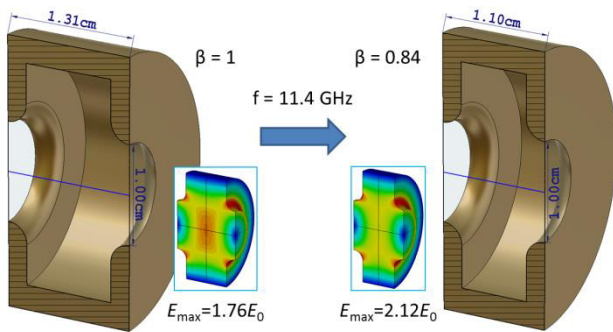


Figure 1: Modification of X-band RF cavity for  $\beta = 0.84$ .

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  $\beta$  increases the maximal surface field for a given accelerating gradient  $E_a = E_0 T$ , where  $E_0$  is the cell averaged on-axis electric field and  $T$  is the transit-time factor. This disadvantage can be amended to some extent by modifying the cavity shape.

### pRad Booster Scheme

If we try to apply HG X-band structures directly at 800 MeV, the linac bunch would occupy  $\sim 215^\circ$  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 rather 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 14<sup>th</sup> 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  $52^\circ$  longitudinally. While this is not small, it can be accepted with minimal losses, especially if one runs the initial part of the S-band stage in a buncher mode, with RF phases in cavities starting near  $-90^\circ$  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 small modifications. It is very likely that again we will need to use the initial part of the X-band section in a buncher mode and gradually move to an efficient HG accelerator. The layout of such a two-stage pRad booster is schematically shown in Fig. 2.

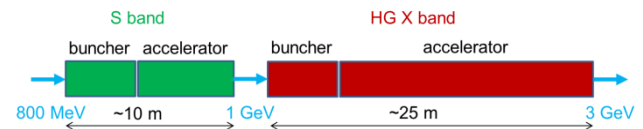


Figure 2: Conceptual scheme of HG pRad booster.

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

### 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  $V_{tot} = E_a L$  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  $P_{tot} = E_a V_{tot}/R'_{sh}$ . Assuming for HG X-band section  $E_a = 100$  MV/m, and using typical value of the structure shunt impedance  $R'_{sh} = 100$  M $\Omega$ /m [3, 7], we obtain  $P_{tot} = 2$  GW, since  $V_{tot} = 2$  GV for that section. This peak power can be delivered by 20 X-band klystrons with SLED pulse compression. Similar crude estimates for the S-band section with  $E_a = 25$  MV/m and  $R'_{sh} = 40$  M $\Omega$ /m give  $P_{tot} = 125$  MW, which requires 3 S-band klystrons.

One should note very promising recent experiments at SLAC with cryogenically cooled HG X-band structures

[7]. They achieved gradients up to 250 MV/m and shunt impedance as high as 200 M $\Omega$ /m, though only with very short pulses so far, using copper cavities at 45K. If future experiments confirm that with longer pulses, using such cryocooled structures would allow us either making the booster 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 would be very 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 a cryoplant.

### Preliminary Beam Dynamics Results

We performed simplified beam dynamics simulations for the pRad booster shown in Fig. 2 using linac design and beam dynamics code PARMILA [8]. A few simple cavities in S-band and X-band covering the  $\beta$ -range 0.84-0.97 were designed to calculate and interpolate  $T$ -factors for PARMILA runs. For these simulations we neglect the beam transverse distribution to focus completely on the longitudinal beam dynamics, which is more challenging.

Our preliminary results 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 uses RF phases from  $-80^\circ$  to  $-50^\circ$  in the S-buncher,  $-80^\circ$  to  $-60^\circ$  in the X-buncher, and  $-40^\circ$  in the both S- and X-band accelerating sections. The total booster length in this case becomes somewhat longer, 43 m. The output beam parameters from PARMILA simulations with a narrow input beam distribution are shown in Fig. 3. The number of exiting particles at 3 GeV is 9945 out of the initial 10000 at 800 MeV.

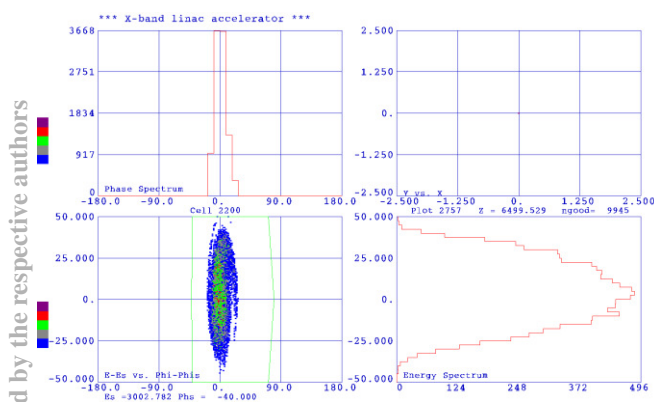


Figure 3: 3-GeV beam parameters after HG pRad booster.

### CONCLUSION

We proposed a compact booster based on high-gradient (HG) normal-conducting RF accelerating structures to

increase the energy of the H<sup>+</sup> beam exiting the LANSCE linac from 800 MeV to 3 GeV for proton radiography (pRad). Such an energy boost would improve the pRad resolution  $\sim 10$  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 structures for electrons. These HG  $\beta = 1$  structures operate at very high frequencies using short RF pulses. Our results indicate that HG structures, slightly modified to accommodate proton beams with  $\beta < 1$ , fit quite well for a pRad energy booster. This is mainly because the pRad uses very short beam pulses and operates at low duty factors.

A high-gradient pRad booster at LANSCE would be significantly (3 to 5 times) shorter and a few times cheaper than a SC one. In the particular case of LANSCE, we consider a two-stage booster: a short S-band section to capture and compress the 800-MeV linac beam, which is followed by the main X-band booster. This two-stage design was chosen mainly to minimize the intensity loss for the Rad beam pulses.

Hopefully there are other applications of proton beams or experiments where similar HG energy boosters can be beneficial. Such applications are clearly limited, mainly by rather short pulses of the energy-boosted beam and overall by low-duty operation.

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### REFERENCES

- [1] R.W. Garnett *et al.*, "A Conceptual 3-GeV LANSCE Linac Upgrade for Enhanced Proton Radiography," IPAC12, New Orleans, LA, p. 4130 (2012); www.jacow.org
- [2] R.W. Garnett *et al.*, "LANSCE H<sup>+</sup> RFQ Status," IPAC15, Richmond, VA, p. 4073 (2015); www.jacow.org
- [3] V. Dolgashev *et al.*, "Status of High Power Tests of Normal Conducting Short Standing Wave Structures," IPAC11, San Sebastian, Spain, p. 241 (2011); www.jacow.org
- [4] M. Dal Forno *et al.*, "RF breakdown tests of mm-wave metallic accelerating structures," *Phys. Rev. AB*, v. 19, p. 011301, 2016.
- [5] Y.K. Batygin *et al.*, "Operation of LANSCE Linear Accelerator with Double Pulse Rate and Low Beam Losses," TUOAA01, these proceedings.
- [6] CST Studio Suite, CST, www.cst.com
- [7] V. Dolgashev, private communication, 2016.
- [8] Los Alamos Accelerator Code Group, laacg.lanl.gov