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HIGH-GRADIENT BOOSTER FOR ENHANCED PROTON RADIOGRAPHY 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. We propose accomplishing this energy boost with a compact cost-effective linac based on cryo-cooled normal conducting high-gradient (HG) RF accelerating structures. HG structures exceeding 100 MV/m have been developed for electron acceleration and operate with short RF pulse lengths below 1 µs. Though such parameters are unusual for typical proton linacs, they fit perfectly for proton radiography (pRad) applications. The pRad limits contiguous trains of beam micro-pulses to less than 80 ns to prevent blur in images. For a compact pRad booster at LANSCE, we develop a staged design: a section to capture and compress the 800-MeV proton beam is followed by the main HG linac. Our beam dynamics study addresses the beam magnetic focusing and minimizing its energy spread, which are challenging in high-gradient structures but very important for successful pRad operation.

INTRODUCTION

Proton radiography employs high-energy proton beams to image material behavior under extreme conditions. It was invented and developed at LANL. By now the pRad program at the Los Alamos Neutron Science Center (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 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 ~10 mA, mainly by the ion source, but also by losses in the linac. On the other hand, the pRad pulses are restricted to 80 ns in length, i.e. contain no more than 16 linac bunches, to prevent image blur.

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. We proposed a much shorter and cheaper booster based on high-gradient (~100s MV/m) normal-conducting RF accelerating structures operating at low duty factors [2].

HIGH-GRADIENT PRAD BOOSTER

High-Gradient Cavities

HG structures with phase velocity $\beta = 1$ were developed for acceleration of electrons [3]. Accelerating gradients up to 150 MV/m have been demonstrated in X-band copper cavities at room temperature. When such cavities are operated at cryogenic temperatures (cryo-cooled), gradients up to 250 MV/m were achieved. HG C-band cavities at room temperature provide gradients 50-60 MV/m, but at liquid-nitrogen (LN_2) temperature one can expect gradients two times higher [4]. The 800-MeV protons at the exit of the LANSCE linac have velocity $\beta = v/c = 0.84$, and at 3 GeV they will have $\beta = 0.97$. Therefore, HG cavities have to be modified for protons to cover this velocity range.

Operating the HG pRad booster at liquid-nitrogen (LN_2) temperatures makes structures more efficient, which reduces the required RF power. The cryo-cooled operation of pRad booster can be practically implemented. The pRad needs only a few short beam pulses per event, typically one or a few events per day. Even if some nitrogen evaporates due to heating caused by RF losses in cavity walls during one event, it can be easily refilled before the next one.

Requirements for pRad Booster

There are additional requirements for HG structures for pRad booster. First, they have to accept the large proton bunches out of the existing linac both longitudinally – this limits RF frequency from above – and transversely, which limits the cavity aperture from below. Second, high accelerating gradients lead to strong beam defocusing by RF fields, so a strong focusing is required. Finally, there are important requirements to the output beam: energy stability pulse-to-pulse, pulse timing, and low energy spread. For better quality of radiographic images, it is highly desirable not just to keep the relative momentum spread $\Delta p/p = 8.8\cdot10^{-3}$ at the exit of our 800-MeV linac but to reduce it as 1/p, down to $3.4\cdot10^{-4}$ at 3 GeV. This last requirement cannot be achieved with a compact two-stage booster proposed in [2], which starts with S-band cavities and continues with HG structures in X- or C-band.

In fact, since LANSCE operates with five different beam types [5], and it is important to preserve this flexibility, the closest point where a new booster can start is about 38 m away from the 800-Mev linac exit. The exiting beam spreads in this drift, so we need to lower RF frequency in the first cavities to capture it longitudinally. All the above requirements lead to a modified design of the booster.

Modified pRad Booster Design

Beam losses are determined by acceptance of accelerating structures. To ensure small losses, the transverse acceptance of new structures should not be lower than that of

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the existing LANSCE linac, which is 3.5 π cm·mrad at 800 MeV. Limitations on acceptance are translated into limitations on accelerator aperture, which, in turn, defines the choice of RF frequency to provide high value of shunt impedance of the accelerator sections. The minimal aperture that satisfies this requirement is plotted as a function of beam energy in Fig. 1.

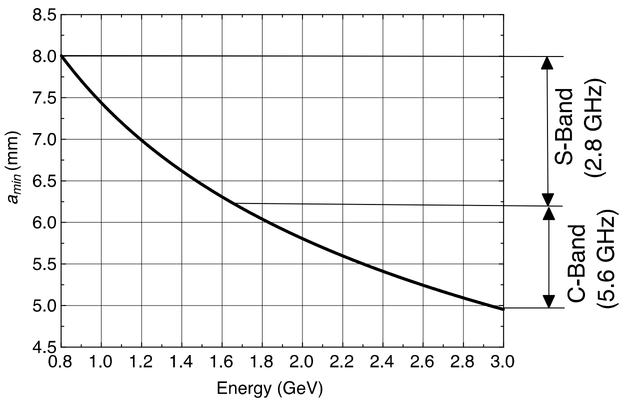


Figure 1: Minimal cavity aperture vs beam energy.

Another important consideration is the focusing strength to mitigate RF defocusing in HG structures. Phase advance of longitudinal oscillations per focusing period S is usually limited by the value of ~70° (1.2 rad). This limits the focusing period $S\,[\mathrm{m}] < 20.7(\beta\gamma)^{3/2}(\lambda\,[\mathrm{m}]/E\,[\mathrm{MV/m}])^{1/2}$, where λ is the RF wavelength and E is the accelerating gradient. These limits are plotted in Fig. 2 for two HG cavities. Adding focusing quadrupoles increases the length of HG structures and reduces the linac real-estate gradient. One should keep S reasonably long to prevent a noticeable reduction; this defines minimal energy for transition from S-band to C-band cavities, cf. Fig. 2.

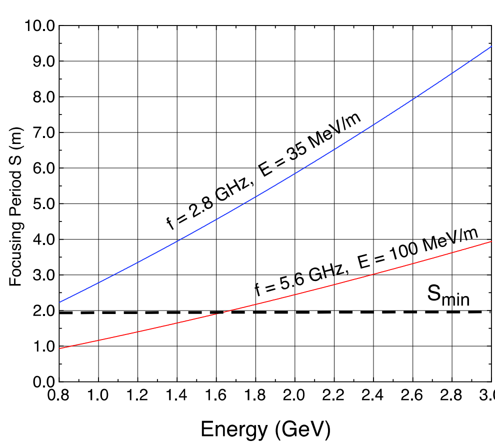


Figure 2: Maximal focusing period vs beam energy.

In [2] our choice for the S-band cavity RF frequency was 2817.5 MHz, which is the 14th harmonic of the linac bunch frequency 201.25 MHz. In C-band cavities, this frequency is doubled, to 5635 MHz. In the modified design, we add an L-band buncher at 1408.75 MHz at nearest possible distance, 37.6 m after the LANSCE linac, to capture 800-MeV linac bunches. Correspondingly, an L-band de-buncher section at 3 GeV is used to reduce the momentum spread to the required value. The resulting modified layout of HG pRad booster is shown in Fig. 3.

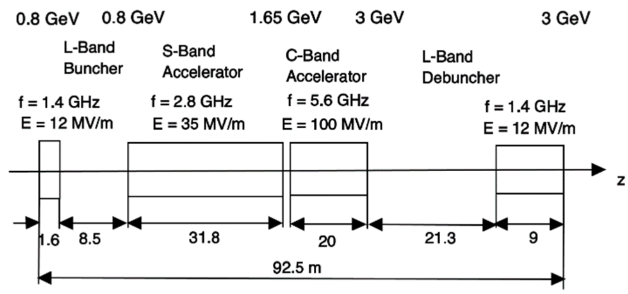
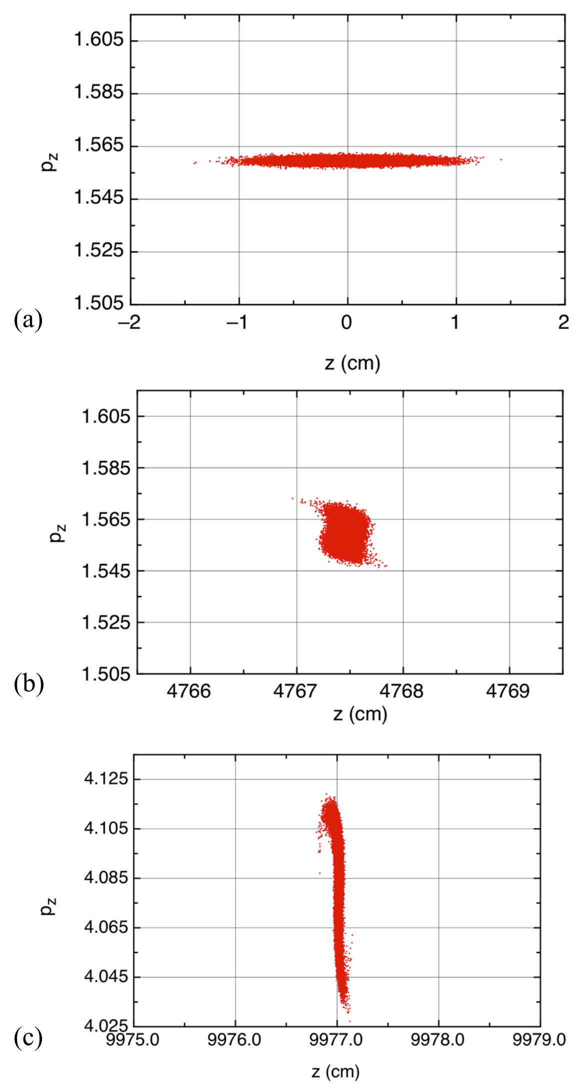


Figure 3: Layout of 3-GeV HG pRad booster.

Beam dynamics in the booster was modeled with Beampath [6]. Some phase-space snapshots from simulations that illustrate the booster operation are presented in Fig. 4.



Beam focusing in the booster will be provided by regular FODO magnetic quadrupoles with the quadrupole focusing strength GL gradual increasing from 6.3 T at the initial energy of 800 MeV to 13.8 T at the final energy of 3 GeV.

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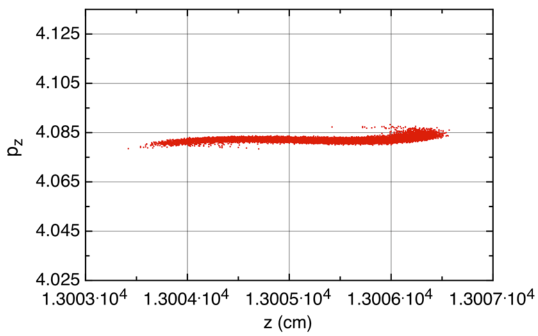

Figure 4: Longitudinal phase-space evolution in HG pRad booster: (a) at the 800-MeV linac exit; (b) after buncher at the S-band section entrance; (c) at the exit of C-band section; (d) after L-band de-buncher at 3 GeV.

Such strengths can be realized with either electromagnetic (EMQ) or permanent-magnet quadrupoles (PMQ). EMQs allow more flexibility with tuning while PMQs are more compact and simple. Mixing both types is also possible.

High-Gradient RF Cavities for pRad Booster

The RF structures for HG pRad booster are planned to be standing-wave (SW) structures with distributed RF coupling [7]. The shape of individual RF cavities will be reentrant and optimized to maximize the structure shunt impedance and reduce the required peak RF power. A bare S-band cavity at 2817.5 MHz for $\beta = 0.84$, without RF couplers and waveguides, is illustrated in Fig. 5.

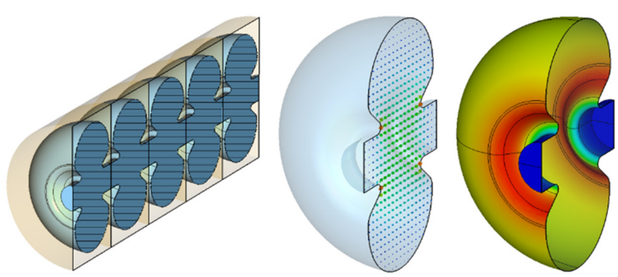

Figure 5: S-band structure for β=0.84 (left to right): 5-cell structure section; electric field within a cell; current distribution on the cell inner surface.

While the cavity shapes still need further optimization, some preliminary results for the cavities in L-, S-, and C-band with the required beam apertures are summarized in Table 1. Here *f* means RF frequency: L 1408.75 MHz, S 2817.5 MHz, and C 5635 MHz; *a* is the beam aperture; *Z′* is the structure shunt impedance, and RF power per unit length *P′* at the room temperature is given for the reference gradient *E*. Using these values, we estimate the total required peak RF power for the booster at about 2 GW. With cryo-cooled operation, the required power will be reduced below 1 GW.

CONCLUSION

We developed a preliminary design of HG pRad booster at LANSCE. It captures and compresses the 800-MeV proton (H^-) beam from the LANSCE linac using an L-band buncher. The captured beam is accelerated to 3 GeV in a high-gradient linac consisting of S- and C-band structures. After that an L-band de-buncher is used to reduce the relative beam momentum spread of the 3-GeV beam below its value at the exit of 800-MeV linac. Beam dynamics study with Beampath addresses the beam magnetic focusing. It also demonstrates the required relative momentum reduction for the accelerated beam, which is very important for successful pRad operation.

Table 1: Cavity Parameters

f	β	*a* mm	*E* MV/m	E_{max}/E	*Z′* MΩ/m	*P′* MW/m
L	0.84	8	18	4.3	68.6	4.7
S	0.84	8	36	4.23	69.9	18.5
S	0.93	6.5	36	4.1	83.4	15.5
C	0.93	6.5	80	3.63	76.9	83.2
C	0.97	5	80	3.63	96.9	66
L	0.97	5	18	4.6	77	4.2

ACKNOWLEDGEMENTS

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