HIGH-GRADIENT BOOSTER LINAC FOR MULTI-GeV PROTON RADIOGRAPHY AT LANSCE

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Abstract

Increasing energy of proton beam at the Los Alamos Neutron Science Center (LANSCE) from 800 MeV to 3-5 GeV will improve radiography resolution ten-fold. This energy boost can be achieved with a compact cost-effective linac based on normal-conducting high-gradient (HG) RF accelerating structures operating at liquid nitrogen temperatures (cryo-cooled). Such an HG booster is feasible for proton radiography (pRad), which requires short beam pulses at very low duty. The pRad booster starts with a short L-band section to capture and compress the 800-MeV proton beam from the existing linac. The main HG linac will be based on S- and C-band cavities. An L-band debuncher at the booster end can reduce the beam energy spread if needed for pRad experiments. We are developing proton cryo-cooled HG standing-wave structures with distributed RF coupling for the booster. Prototype cavity structures at S- and C-band are designed and will be tested cryo-cooled to measure breakdowns at high gradients. The booster linac beam dynamics design is also discussed.

INTRODUCTION

Proton radiography (pRad) was invented at LANL in the 1990s. It employs high-energy proton beams to image material behavior under extreme conditions. Since then, the pRad program at the Los Alamos Neutron Science Center (LANSCE) has performed hundreds of successful experiments, both static and dynamic. The LANSCE pRad now uses 800-MeV H$^-$ beam. For dynamic experiments, multiple pulses from the linac 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 following with 201.25-MHz repetition frequency, to prevent image blur, e.g., see Ref. [1].

Increasing the beam energy for pRad at LANSCE from present 800 MeV to 3-5 GeV would provide significant improvements: for thin objects, the radiography resolution will increase about 10 times, and much thicker objects can be also imaged. We aim to develop the most efficient way to provide proton beams at energies of 3-5 GeV for enhanced proton radiography at LANSCE. A high-gradient (HG) proton booster linac after the existing LANSCE linac offers a viable cost-efficient solution [2]. Its potential location is shown in Fig. 1; the booster (red line) will be much shorter than the existing linac. The booster linac will be based on normal-conducting RF accelerating structures operating cryo-cooled at liquid-nitrogen (LN2) temperature, 77K, at very low duty required for pRad.

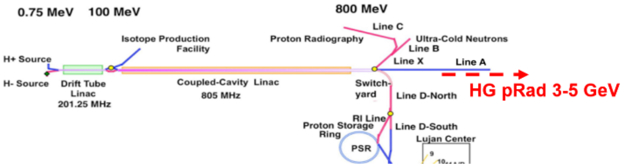

Figure 1: Location of the pRad booster linac (red dashed line) at LANSCE. The existing linac is on the left.

The Laboratory Directed Research and Development (LDRD) program at LANL supported our work on the HG pRad booster as an Exploratory Research (ER) project in 2021-2023. The ER results were presented in [2-4] and summarized in [5]. A larger LDRD Directed Research (DR) project started in Oct. 2025 with the main goal to develop accelerator technology of cryo-cooled HG structures for protons applicable to the pRad booster at LANSCE.

HIGH-GRADIENT PRAD BOOSTER

Requirements for pRad Booster

High-gradient structures for relativistic electrons with velocity $\beta = v/c = 1$ demonstrated accelerating gradients $E_{\mathrm{acc}} = E_0 T$ up to 150 MV/m in X-band copper cavities at room temperature [6]. Here E_0 means the average on-axis electric field in the structure cell and T is transit-time factor. 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 LN2 temperature one can expect gradients two times higher. 800-MeV protons at the exit of the LANSCE linac have velocity $\beta = 0.84$; at 5 GeV $\beta = 0.987$. Therefore, HG cavities must be modified for protons to cover this velocity range. HG structures for pRad booster must 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. High accelerating gradients lead to beam defocusing by RF fields, so strong focusing is required. For good quality radiographs, it is important to control the relative momentum spread of the beam. It is $\Delta p/p = 10^{-3}$ at the exit of our 800-MeV linac, and in [2] the beam dynamics design reduced it as $1/p$, i.e., to $3.3 \cdot 10^{-4}$ at 3 GeV. However, this requirement depends on specific pRad experiment.

Operating the HG pRad booster at 77K makes structures more efficient and reduces the required RF power by a factor of 2-3. In addition, it is expected that the RF breakdown rates are reduced in cryo-cooled cavities, though the data for C- and S-band is insufficient. One of our goals is to get additional breakdown rate data, which would help to advance understanding of high gradient RF cavities. The cryo-cooled operation of pRad booster is practical because pRad needs only 1-20 beam pulses spread by about 1 μs per event, and there are only a few events per day. We estimate the fraction of nitrogen evaporated due to heating caused by RF losses in cavity walls during one event to be below 0.1%, so refills will be rarely needed [4].

Further considerations are related to the LANSCE layout and operations. The facility delivers five different beam types [1] to multiple users, and it is important to preserve this capability. The closest point where a new booster can start is about 38 m away from the 800-MeV linac exit, after the existing switchyard. 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 led to a multi-stage compact booster design [2, 3].

pRad Booster Design

The booster starts with an L-band buncher operating at 1408.75 MHz, the 7th harmonic of the linac bunch frequency 201.25 MHz, to capture 800-MeV linac bunches. The linac includes S-band structures at 2817.5 MHz up to the energy of 1.6 GeV and continues with C-band structures at 5635 MHz (28th harmonic). For the booster design with the final energy of 3 GeV [2], an L-band de-buncher at 3 GeV reduced the momentum spread to the required value, see Fig. 2. The transition energy S-C was defined by beam focusing requirements and cavity apertures. That design had the total length of the booster 92.5 m, but it assumed a high real-estate gradient, $E_{\rm acc}$ = 100 MV/m, in C-band structures. High RF fields cause strong beam defocusing, which is prevented by strong quadrupole focusing with permanent-magnet quadrupoles. Considering quadrupole lengths, the C-band cavity gradients should be around 120 MV/m. For room-temperature linac operation, the required total peak RF power was very high: 1.9 GW in C-band and 0.42 GW in S-band.

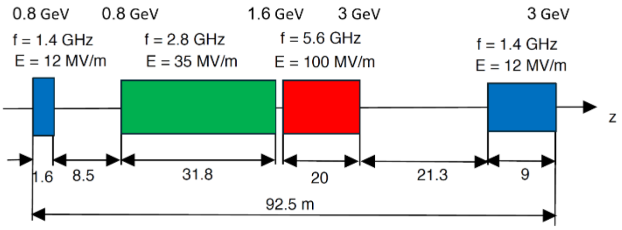

Figure 2: Layout of booster linac to 3 GeV. Drifts are for bunching / de-bunching. Section lengths are not to scale.

The peak RF power is the major cost driver for a room-temperature booster linac. A modified design [3] with moderate gradients, $E_{\rm acc}$ = 25 MV/m in S-band and 40 MV/m in C-band, made the booster longer, 156.3 m, which required achromatic bends to fit the folded linac in the existing buildings. The total peak RF power became noticeably lower, 0.75 GW in C-band and 0.3 GW in S-band. The RF costs would be reduced, but bend achromats significantly complicated the linac layout. Operating the booster linac structures at LN2 temperatures allows us to reduce both the required RF power and linac length, because cryo-cooled accelerating structures need less RF power at a given gradient due to lower surface losses. They are also expected to have lower RF breakdown rates at high gradients compared to room-temperature structures. One of the goals of our project is to confirm that experimentally.

Our previous beam dynamics efforts [2-4] assumed that the normalized transverse acceptance of the pRad booster linac should be no less than that at the exit of the LANSCE linac, 3.12 π cm·mrad. However, this assumption, typical for high power applications, can be relaxed for the unique low duty operation of pRad booster. We plan to explore alternative beam dynamics designs to have a more compact and efficient booster linac.

Accelerating Structures for pRad Booster

The booster linac will use multi-cell accelerating structures with distributed RF coupling originally developed for electrons [7]. Such structures were modified for protons in the energy range required for the booster [2-5]. The structures operate in a standing-wave π-mode. A short 2-cell C-band prototype was fabricated and tested at the HG RF test stand – the C-band Engineering Research Facility in New Mexico (CERF-NM) [8] at LANL. We measured RF breakdown rates (BDR) at accelerating gradients up to 100 MV/m in that room-temperature test structure [5]. It is worth mentioning that the test cavities are designed for the frequencies matching the available klystron frequencies. For example, the 2-cell prototype structure was designed for and tested at 5712 MHz, standard for C-band klystrons. This frequency is close enough to 5635 MHz that will be needed for the booster C-band section, so we received meaningful test results. The klystrons for the pRad booster linac will have the required custom frequencies.

Based on this experience, we optimized the design of the accelerating structures for the pRad booster linac. The test structures for S- and C-band will contain 4 cells with distributed RF coupling. The number of cells is limited by the available peak RF power to bring the cavities to the desired high gradients. We plan to fabricate and test the 4-cell S-band structure at RadiaBeam [9], where an S-band klystron can provide 5 MW peak RF power at 2856 MHz with pulse lengths up to 13 μs. The C-band 4-cell test structure will be tested at the LANL HG RF test stand, where the klystron can deliver up to 50 MW peak power but with shorter pulses, up to 1.5 μs. However, the peak power for the tests will be limited by 12 MW due to the installed circulator.

A 4-cell C-band test structure with distributed RF power coupling was designed for protons at 1.6 GeV (β = 0.93). It corresponds to the beginning of the C-band section in Fig. 2 and has a beam aperture radius of 6.5 mm, the largest one in the C-band section, so we expect it to have the most stringent RF conditions. Figure 3 shows the vacuum volume of the 4-cell C-band test structure. RF power is delivered through the port (on the back in Fig. 3) connected to a standard WR187 waveguide and is split into two waveguide manifolds, above and below the cells. The manifolds distribute RF power to the accelerating cavities (cells) with correct phases to support the operating π-mode.

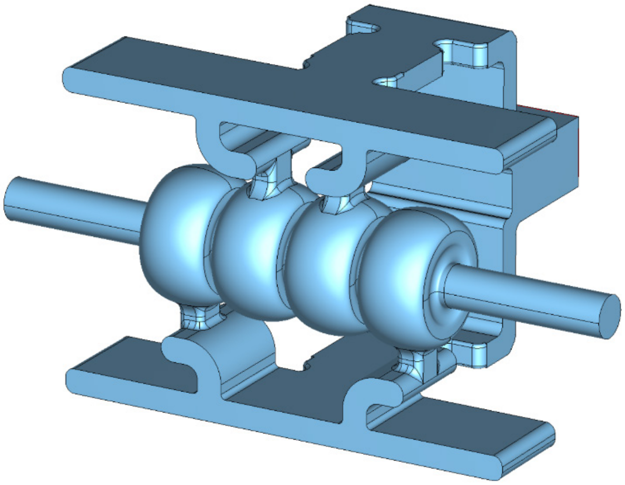

Figure 3: Vacuum volume of the 4-cell C-band test structure with distributed RF coupling.

The cell shape was optimized using multiple objectives: minimizing the maximum surface electric and magnetic fields as well as the maximum value of the Pointing vector, while maximizing the shunt impedance. The multi-objective optimization and detailed parameters of the C-band test structure are described in [10]. For scale, in Fig. 3 the cell length is 2.438 cm and radius 2.085 cm. These cavity dimensions should be achieved at LN2 temperature. The structure model for fabrication has calculated temperature-corrected dimensions at room temperature, see [10]. The test structure at 77K was analyzed with CST frequency domain solver [10] and eigenmode solver. Electromagnetic parameters of the structure are summarized in Table 1, where $Z'_{\mathrm{eff}} = Z'T^2$ is the effective shunt impedance per unit length and $Z_0 = 120\pi\ \Omega$ is the impedance of free space.

Table 1: C-band 4-cell Test Structure Parameters

Parameter	**Value**	**Units**
Frequency	5712.0	MHz
Unloaded Q @ LN2	32,496	
Z'_{eff} @ LN2	190	MΩ/m
$E_{\max}/E_{\mathrm{acc}}$	2.59	
$Z_0H_{\max}/E_{\mathrm{acc}}$	1.72	
$(\lvert\boldsymbol{E}\rvert \text{ x } Z_0\lvert\boldsymbol{H}\rvert)_{\max}/(E_{\mathrm{acc}})^2$	1.93*	

* Calculated in accelerating cells without RF couplers.

The maximum field values are slightly higher than those in [10], but it is likely due to numerical effects in resolving hot spots. It is important to emphasize that the maximum surface magnetic field in the 4-cell structure, which is reached on the walls of RF couplers, is higher than that in the cell without coupler, but not very high: the ratio 1.18 becomes 1.72 in Table 1, cf. [10]. This is important for reducing RF breakdown rate and was achieved by the coupler design that was inspired by work on HG structures at SLAC. The calculated fields of the structure are depicted in Fig. 4, where red means the high field values and blue the low ones.

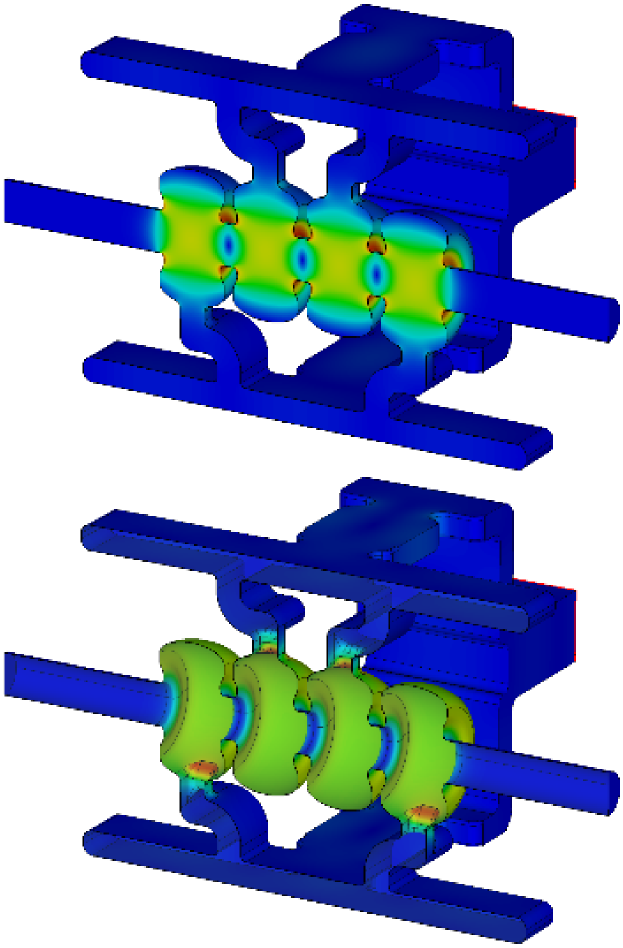

Figure 4: Contours of electric field (top) and surface current magnitude of π-mode in C-band test structure.

CONCLUSION

We outlined the goals and status of our research project developing accelerator technology for a high gradient (HG) booster linac to enable multi-GeV proton radiography (pRad) at LANSCE. The pRad booster will use normal-conducting cryo-cooled HG accelerating structures with distributed RF coupling adapted for protons in the energy range from 800 MeV to 5 GeV. We already have two options of beam dynamics design for the booster linac [2, 3]. The optimization of linac design continues aiming to find the most compact and efficient solution satisfying stringent pRad beam requirements.

A prototype C-band 4-cell structure is designed [10]. Another test structure, for S-band, will also have four accelerating cells and distributed RF coupling. The prototypes will be fabricated and tested at high gradients at liquid nitrogen temperatures. We continue preparing the high gradient C-band RF test stand at LANSCE [8] for cryo-cooled operations. The S-band prototype will be built by and tested cryo-cooled at RadiaBeam [9]. In both cases, cryostats for LN2 operations will be built.

The authors acknowledge useful discussions with and help from our LANL colleagues, both in Accelerator Operation and Technology and in Physics Divisions.

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