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DEVELOPMENT OF HIGH-GRADIENT ACCELERATING STRUCTURES FOR PROTON RADIOGRAPHY 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. We propose accomplishing this energy boost with a compact cost-effective linac based on normal conducting high-gradient (HG) RF accelerating structures. Such an unusual proton linac is feasible for proton radiography (pRad), which operates with very short beam (and RF) pulses. For a compact pRad booster at LANSCE, we have developed a multi-stage design: a short L-band section to capture and compress the 800-MeV proton beam from the existing linac followed by the main HG linac based on S- and C-band cavities, and finally, by an L-band de-buncher. Here we present details of development, including EM and thermal-stress analysis, of proton HG structures with distributed RF coupling for the pRad booster. A short test structure is designed specifically for measurements at the LANL C-band RF Test Stand.

INTRODUCTION

Proton radiography employs high-energy proton beams to image material behavior under extreme conditions. It was invented and developed at LANL. 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]. With a real-estate gradient of 15 MV/m, it leads to a rather long booster, more than 150 m only in accelerating structures. This option is also expensive because it requires a new cryogenic plant and significant tunnel modifications. We proposed a shorter and cheaper pRad booster based on normal-conducting RF accelerating structures with higher gradients operating at low duty factors [2].

HIGH-GRADIENT PRAD BOOSTER

Requirements for pRad Booster 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. 800-MeV protons at the exit of the LANSCE linac have velocity $\beta = v/c = 0.84$, and at 3 GeV $\beta = 0.97$. Therefore, HG cavities must be modified for protons to cover this velocity range.

Operating the HG pRad booster at liquid-nitrogen temperatures makes structures more efficient and reduces the required RF power by a factor of 2-3. Such operation of pRad booster seems practical: the pRad needs only 1-20 beam pulses per event spread by about 1 μs; no more than 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.

There are additional requirements for HG structures for pRad booster. First, they 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. Second, high accelerating gradients lead to beam defocusing by RF fields, so a strong focusing is required. There are also important requirements to the output beam: energy stability pulse-to-pulse, pulse timing, and low energy spread. For better quality of radiographs, it is desirable to reduce the relative momentum spread, $dp/p = 10^{-3}$ at the exit of our 800-MeV linac, as $1/p$, i.e., to $3.3\cdot10^{-4}$ at 3 GeV.

Further considerations are related to the LANSCE layout and operations. The facility delivers five different beam types [4] 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 [5].

pRad Booster Design

The booster starts with an L-band buncher operating at 1408.75 MHz, the 7^{th} harmonic of the linac bunch frequency 201.25 MHz, to capture 800-MeV linac bunches. The booster includes S-band structures at 2817.5 MHz to the energy of 1.6 GeV and continues with C-band struc-

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tures at 5635 MHz. An L-band de-buncher at 3 GeV reduces the momentum spread to the required value. The transition energy is defined by beam focusing requirements and cavity apertures [5]. The total length of the HG pRad booster is 92.5 m, but the C-band structure gradient $E = E_0T = 100$ MV/m is rather high. This leads to high required total peak RF power: 1.9 GW in C-band and 0.42 GW in S-band. Reducing gradients makes the booster longer but also reduces the required peak RF power.

Therefore, we developed another design, with moderate gradients, $E = 25$ MV/m in S-band and 40 MV/m in C-band [6]. It makes the booster longer, 156.3 m, see Fig. 1, and will require bends to fit in the existing buildings [6]. The estimated total peak RF power is noticeably reduced: 0.75 GW in C-band and 0.3 GW in S-band.

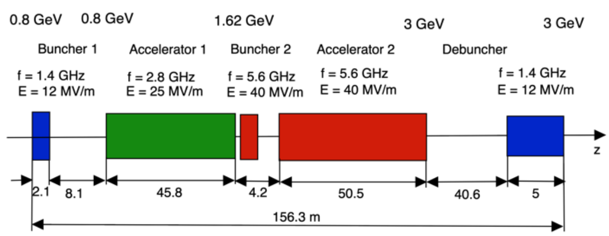

Figure 1: Layout of 3-GeV pRad booster.

Beam focusing will have a FODO scheme with magnetic quadrupoles of the focusing strength *GL* gradually increasing from 6.3 T at the initial energy of 800 MeV to 18.4 T at the final energy of 3 GeV [6]. Such fields can be realized with either electromagnetic (EMQ) or permanent-magnet quadrupoles (PMQ). EMQs allow more flexibility with tuning while PMQs are simpler and more compact. The most attractive option is to use mainly PMQs, with some EMQs near the ends of different linac sections. It can reduce the packing factor – the ratio of accelerating structure length to the length of the focusing period – which we now assume to be 0.8 for estimates, see in [6].

High-Gradient RF Cavities for pRad Booster

The RF structures for HG pRad booster are planned to be standing wave (SW) π-mode structures with distributed RF coupling [7]. The shape of individual RF cavities will be re-entrant 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. 2.

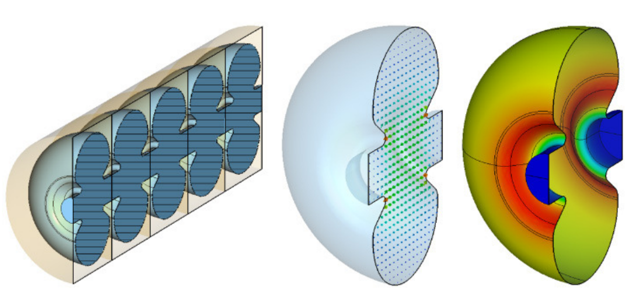

Figure 2: S-band structure for β=0.84 (left to right): 5-cell structure section; electric field within a cell; current distribution on the cell inner surface.

The parameters of the cavities in L-, S-, and C-band with the required beam apertures are summarized in Table 1. Here *f* indicates the RF frequency: L=1408.75 MHz, S=2817.5 MHz, and C=5635 MHz; *a* is the aperture radius; *Z′* is the structure shunt impedance. RF power per unit length *P′* at the room temperature is given for the reference gradient *E*; the power values scale with gradient as E^2. These values were used for estimates of the total peak RF power.

Table 1: Booster Cavity Parameters

f	*β*	*a*, mm	*E*, MV/m	E_{max}/*E*	*Z′*, MΩ/m	*P′*, MW/m
L	0.84	8	12	4.3	68.6	2.1
S	0.84	8	25	4.23	69.9	8.9
S	0.93	6.5	25	4.1	83.4	7.5
C	0.93	6.5	40	3.63	76.9	20.8
C	0.97	5	40	3.63	96.9	16.5
L	0.97	5	12	4.6	77	1.9

One should note that the booster cavities will work in an unusual regime defined by pRad operation, at very low duty. The RF system can provide just a single RF pulse of variable length, 1-50 µs. This allows all required pRad beam patterns ranging from a single 80-ns beam pulse, which consists of 16 LANSCE linac bunches spaced by 5 ns, to a sequence of 20 such pulses separated by intervals that vary from 0.2 to 2 µs, depending on the pRad experiment; see [6]. The cavity fill times are on the order of 1 µs.

A preliminary thermal-stress analysis was performed for a few cavities in Table 1. The CST-calculated surface loss power density was imported into ANSYS as heat load. For S-band cavities at $\beta = 0.84$ (row 2 in Table 1) with gradient 36 MV/m, one 50-µs RF pulse increases the surface temperature by maximum $\Delta T = 20$ K at the pulse end, and the largest surface deformation is only 0.22 µm. Even for a 100-µs RF pulse, ΔT is only 28 K. For C-band cavities at $\beta = 0.97$ (row 5 in Table 1) at 80 MV/m, a single 50-µs RF pulse causes $\Delta T = 101$ K, which may be acceptable but large. At 50 MV/m in this cavity, $\Delta T = 40$ K and maximum deformation becomes 1.2 µm.

With LN_2 cryo-cooled operation, the structure RF power is reduced 2-3 times. We estimate the fraction of LN_2 evaporated after one pRad event using a single 50-µs pulse to be 10^{-3} or less, depending on the cooling design.

Unlike widely used traveling-wave cavities, accelerating structures with distributed coupling have not yet been implemented in operation, only tested as insertions in electron linacs. They offer some advantages, such as enforcing the π-mode in the structure and simple fabrication. An important step for the pRad booster project is to develop and test such a structure with distributed coupling for protons.

C-band Test Cavity with Distributed Coupling

A simple two-cell test cavity with distributed coupling was designed for the frequency of 5.712 GHz, to be tested at the existing LANL C-band RF test stand [8]. The test

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stand is equipped with a 5.712-GHz klystron having max peak power 50 MW, pulse length <1 µs, and repetition rate up to 200 Hz. The RF power is delivered to test cavities via a standard WR187 waveguide (WG). The klystron frequency is close to our design frequency of 5.635 GHz.

The test cavity includes a custom RF-feed WG, which contains two T-junctions and RF couplers, and provides a transition to a port for connecting to the WR187 WG at the test stand, see in Fig. 3. The feed WG is shorted on the other end by an added quarter-wave section. For scale, the length of each of the two accelerating cells is 2.44 cm, their inner radius is 2.19 cm.

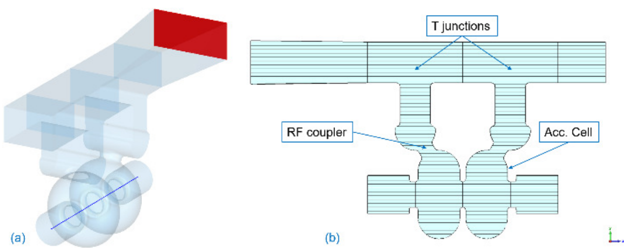

Figure 3: C-band 2-cell test cavity for $\beta = 0.93$: (a) inner volume with WG187 port (red); (b) vertical cross section.

The C-band cavity for $\beta = 0.93$ with $a = 6.5$ mm (row 4 in Table 1) was modified for the test cavity by removing noses. The effect of noses on efficiency with this relatively large aperture is small but they noticeably increase maximum electric field. This modified cavity (M, no noses) is compared to the original re-entrant cavity tuned to 5.712 GHz (O) in Table 2. Power values here are given for the gradient $E = 80$ MV/m at room temperature.

Table 2: Comparison of Cavity Parameters

Cav	T	E_{max}/E	Z_0H_{max}/E	Z', MΩ/m	P', MW/m
O	0.743	3.67	2.10	78.6	81.5
M	0.731	2.51	2.27	73.2	87.4

The height of the RF-feed WG in the cavity of Fig. 3 is selected such that the WG wavelength λ_{wg} is twice the period of the accelerating structure, which is equal to two cell lengths, i.e., $\lambda_{wg} = 2{\cdot}2(\beta\lambda/2)$, where $\lambda = c/f$. This ensures that the structure can be repeated periodically, with RF couplers for the next two cells connecting from a second RF-feed WG on the opposite side of the accelerating structure, cf. [7]. The two RF couplers are separated by one-half of the WG wavelength, so they feed two cells in opposite phases, exciting the operating π-mode in the accelerating structure. Note that the RF couplers here are rather large, because each coupler diverts into its cavity one-half of the total RF power fed into WG. In a typical structure with distributed coupling [7], which contains $N = 20$-40 cells, the fraction of RF power diverted by one coupler from each of the two WGs is much smaller, $2/N$. The sizes of T-junctions and couplers become smaller in that case.

The C-band test cavity is now being fabricated [9]. We plan to test it at the LANL C-band RF Test Stand this year.

CONCLUSION

We continue to develop HG pRad booster at LANSCE. It is designed to capture and compress the 800-MeV proton (H^-) beam from the existing LANSCE linac with an L-band buncher. The captured beam is then accelerated to 3 GeV in a high-gradient linac consisting of S- and C-band structures. An L-band de-buncher is used to reduce the relative beam momentum spread of the 3-GeV beam 3 times below its value at the exit of 800-MeV linac. However, the debuncher with drift adds about 46 m of length, see Fig. 1.

The modified booster design [6] significantly reduces the required peak RF power. A short C-band test cavity with two accelerating cells for protons at 1.6 GeV and distributed RF coupling was designed. It is being manufactured and will be tested at LANL later this year.

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