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DESIGN OF 3-GeV HIGH-GRADIENT BOOSTER FOR UPGRADED PROTON RADIOGRAPHY AT LANSCE*

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Abstract

Increasing the proton beam energy from the present 800 MeV to 3 GeV will improve the resolution of the Proton Radiography Facility at the Los Alamos Neutron Science Center (LANSCE) by a factor of 10. It will bridge the gap between the existing facilities, which covers large length scales for thick objects, and future high-brightness light sources, which can provide the finest resolution. Proton radiography requires a sequence of short beam pulses (~ 20 x 80 ns) separated by intervals of variable duration, from about 300 ns to 1-2 µs. To achieve the required parameters, the high-gradient 3-GeV booster is proposed. Utilization of buncher-accelerator-debuncher scheme allows us to combine high-gradient acceleration with a significant reduction of beam momentum spread. Paper discusses details of linac design and expected beam parameters.

INTRODUCTION

Proton Radiography (pRad) was developed in the Los Alamos National Laboratory in the mid-1990s as a multi-pulse flash technique for deep-penetrated hydro test objects study [1]. It utilizes an 800-MeV proton beam from Los Alamos linear accelerator with a beamline for beam imaging (see Fig. 1). Increasing the proton energy from the present 800 MeV to 3 GeV will significantly improve the resolution of radiography. Such an improvement can bridge the gap between the existing LANL DARHT facility and future high-brightness light sources like MaRIE and DMMSC [2]. One important requirement to the 3-GeV booster is a significant reduction of beam momentum spread from the existing value of $dp/p = 1\cdot10^{-3}$ to the new value of $dp/p = 3.3\cdot10^{-4}$. The proposed booster is based on high gradient (HG) cavities. Stepwise increase of the RF operating frequency in the booster from S-band to C-band allows us to combine high accelerating gradient with high beam capture and low emittance growth. This paper discusses a layout of the proposed accelerator for 3 GeV pRad enhancement.

TIME STRUCTURE OF PROTON BEAM

The time structure of the LANL proton radiography beam is presented in Fig. 2, and parameters of existing and future pRad beams are presented in Table 1. Proton radiography pulse contains 60 ns triggering beam pulse followed by 100 µs time interval and by a sequence of beam imaging pulses. These pulses are of the length of 60 - 80 ns containing up to 16 linac bunches with bunched beam current $I = 10$ mA. Bunches follow with the RF period of 5 ns defined by the linac RF frequency $f = 201.25$ MHz.

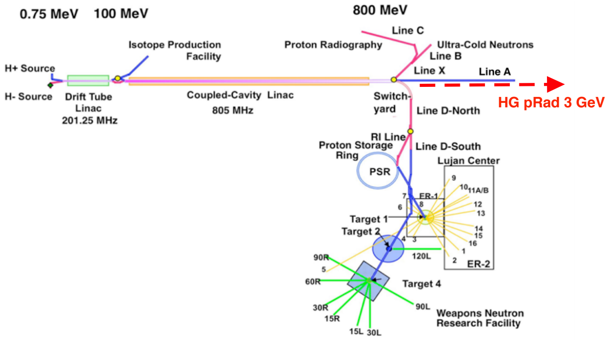

Figure 1: LANSCE accelerator facility and potential location of 3 GeV High-Gradient pRad booster.

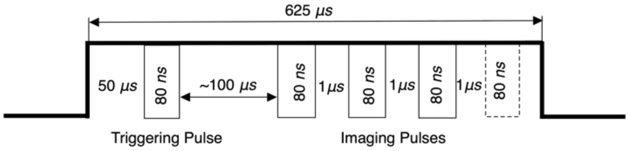

Figure 2: Time structure of LANSCE pRad beam.

Table 1: Parameters of Proton Beam

Parameter	Existing	Upgraded
Energy (GeV)	0.8	3
Momentum spread, dp/p	1 x 10^{-3}	3.3 x 10^{-4}
Beam current / bunch (mA)	10	19
Protons per pulse	5 x 10^{9}	9.5 x 10^{9}

Each bunch contains a charge of $Q = I/f = 4.9\cdot10^{-11}C$ which corresponds to $3\cdot10^{8}$ protons per bunch. The 16 bunches work cumulatively to produce one image with the total number of protons ~ $5\cdot10^{9}$. For multiple images (movie of a dynamic event), pRad uses a few such pulses separated by a time interval of about 1 µs. Peak beam current per bunch in LANL accelerator is limited by the value of ~ 20 mA which, in turn, is limited by the power of 805 MHz klystrons. The number of protons per imaging session can be doubled in the existing LANL accelerating facility.

DESIGN OF HIGH-GRADIENT PRAD BOOSTER

High-gradient booster for pRad expansion at LANL was proposed in Ref. [3], and a preliminary design was per-formed in Ref. [4]. One of the main issues in the design is the minimization of the size of the accelerator with high beam capture and low emittance growth. Beam

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losses are determined by the acceptance of an accelerating structure. Normalized (energy-independent) transverse acceptance of accelerating structure is given by

$$\varepsilon_{ch} \approx \beta\gamma \frac{a^2 \mu_s}{S\,(1+\upsilon_{\max})^2}, \qquad (1)$$

where a is the radius of aperture, S is the focusing period, $\beta\gamma$ is the particle momentum, $\upsilon_{\max}$ is the ripple factor in envelope oscillations, $\mu_s = \mu_o \sqrt{1-\mu_{oz}^2/(2\mu_o^2)}$ is the phase advance of transverse particle oscillations per period S in presence of RF field, μ_o is the phase advance of transverse oscillations in quadrupole channel, μ_{oz} is the phase advance of longitudinal oscillations per focusing period:

$$\mu_{oz} = \sqrt{2\pi(\frac{qE\lambda}{mc^2})\frac{|\sin\varphi_s|}{(\beta\gamma)^3}}\,(\frac{S}{\lambda}), \qquad (2)$$

$E = E_o T$ is the accelerating gradient, λ is the wavelength, and φ_s is the synchronous phase. At the end of LANSCE accelerator, the value of transverse normalized acceptance is $\varepsilon_{ch} \approx 3.12\,\pi$ cm mrad. In order to avoid beam losses, the value of booster transverse acceptance should be equal to, or higher than that at the end of LANSCE accelerator.

From Eq. (1), the acceptance of the channel is increasing with the increase of phase advance, aperture of the channel, and decrease of focusing period. Within separatrix, the transverse phase advance of particle oscillations is varied within $\mu_s \le \mu \le \mu_o$. The value of $\mu_o < 90^o$ is limited to avoid envelope resonances. Selecting $\mu_{oz} \le 60^o$, the value of transverse phase advance is maximized, $80^o \le \mu_s < 90^o$. With such selection of longitudinal phase advance, μ_{oz}, the focusing period from Eq. (2) is limited by

$$\mathrm{S\,[m]} \le 12.22\,(\beta\gamma)^{3/2}\sqrt{\frac{\lambda\,\mathrm{[m]}}{\mathrm{E[MV/m]}|\sin\varphi_s|}} \qquad (3)$$

Decrease of the focusing period results in decrease of the average accelerating gradient along the booster. Assuming the focusing is provided by FODO quadrupole structure, the average accelerating gradient along the booster, $\bar{E}$, is

$$\bar{E} = E_o T\,[1 - 2(D+2d)/S]\cos\varphi_s \qquad (4)$$

where D is the quadrupole lens length, and d is the distance from the lens to accelerator structure. Selecting the value of focusing period $S = 2$ m and $D + 2d = 0.2$ m, the average accelerating gradient is $\bar{E} = 0.8 E_o T \cos\varphi_s$. With chosen parameters, Eq. (1) gives the minimal value of the aperture of the channel $a_{\min} \approx 10/\sqrt{\beta\gamma}$ [mm].

Shunt impedance of accelerating structures quickly drops with the increase of accelerator aperture. From that consideration, the initial part of booster acceleration from LANSCE exit energy of 800 MeV to energy of 1.6 GeV is selected to be S - band with frequency $f = 2.8175$ GHz (14th harmonics of the primary LANSCE accelerator frequency of 201.25 MHz), while the subsequent acceleration can be performed in C-band structures with frequency $f = 5.635$ GHz (28th harmonics of primary frequency) [4]. In order to operate pRad booster with RF pulse length 50 – 100 µs, the accelerating gradient in S-band accelerating structure is selected to be to 25 MV/m, and that in C-band 40 MV/m. Parameters of the RF structures of the booster are discussed in Ref. [5]. The focusing strength of quadrupoles in FODO structure

$$GD = \mu_o \frac{mc\beta\gamma}{qS} \frac{1}{\sqrt{1-(4/3)(D/S)}} \qquad (5)$$

is varied from 6.3 T at the initial energy of 800 MeV to 18.4 T at the final energy of 3 GeV.

The structure of the booster is presented in Fig. 3. Beam leaving LANSCE 800 MeV linac has transverse normalized rms emittance $\varepsilon_{t\_rms} = 0.07\ \pi$ cm mrad and longitudinal normalized rms emittance $\varepsilon_{z\_rms} = 0.25\ \pi$ cm mrad with momentum spread $dp/p = 1\cdot 10^{-3}$. After linac, the beam is transported through the Swithyard at the distance of ~ 37 m. The buncher section is required to compress the beam out of Switchyard to that matched with S-band accelerating structure. The value of synchronous phase $\varphi_s = -30^o$ was selected in both S-band and C-band accelerators to avoid distortion of longitudinal beam emittance. S-band accelerator with energy gain $\Delta W = 800$ MeV and gradient $E_o T = 25$ MV/m has a length of 45.8 m, and C-band accelerator with energy gain $\Delta W = 1.4$ GeV and gradient $E_o T = 40$ MV/m has a length of 50.5 m. Together with the bunchers before and after S-band accelerator, the length of 3 GeV accelerator is 110.7 m. Debuncher section with drift space of 40.6 m and 5 m long RF section is required to rotate the longitudinal phase space of the beam in phase space, and to reduce momentum spread up to $dp/p = 3.3\cdot 10^{-4}$. The length of the accelerator is 156.5 m.

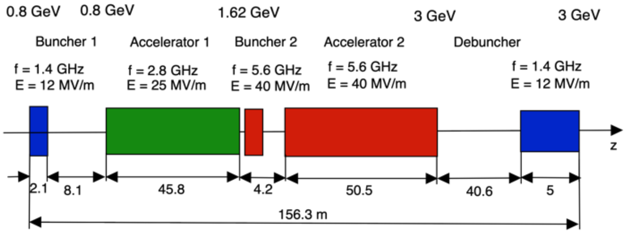

Figure 3: Layout of 3 GeV linear accelerator.

Figure 4: Line A connecting LANSCE Switchyard and experimental Area A.

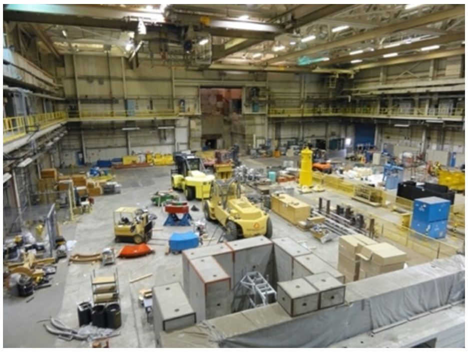

Figure 5: Experimental area A.

BOOSTER IN THE EXPERIMENTAL AREA A

Possible location of the pRad booster is in the experimental Area A, connected with LANSCE Switchyard by Line A (see Fig. 4 and Fig. 5). Area A is a large, 50 x 55 m^2 experimental building, which was used for the medium energy research program, and currently is not used. The perimeter available for placement of the accelerator is 160 m with additional 40 m of line A before Area A.

The layout of pRad booster in Area A is presented in Fig. 6. There are four arcs filled with bending magnets. The bending areas were selected to be achromats, containing four FODO cells separated by bending magnets, with phase advance of transverse oscillation per FODO cell $\mu_o = 90^o$. Therefore, the arc of the $\pi / 2$ bend contains eight $\theta = 11.25^o$ bending magnets separated by quadrupole lenses (see Fig. 7). The focusing period in bending areas is expressed as $S = 2(R\theta + D + 2d)$, where $R = \beta\gamma mc / (qB)$ is the dipole bending radius. With limited bending field $B = 1.5$ T, the focusing period is increasing along the linac.

The distance from the Switchyard to the first bend is around 40 m, where the beam extends its energy from 800 MeV to 1.4 GeV. The first bending arc is followed by the rest of the S-band linac at the available length of 10 m, where the beam reaches an energy of 1.6 GeV. After the second bend and C-band buncher, the beam is accelerated in C-band linac up to 2.3 GeV at the length of 25 m. The focusing period is gradually increases from 2 m to 3 m to be matched with 3rd bend at the energy of 2.3 GeV. The last part of the linac is the C-band linac of 25 m long accelerating beam up to final energy of 3 GeV. The focusing period is increasing from 3 m to 3.6 m to match the fourth bend. The momentum spread of the 3 GeV beam after the fourth bend is $dp / p = 2.7 \cdot 10^{-3}$. The rest of the perimeter of Area A after the fourth bend can be used as a debuncher to reduce beam momentum spread up to $dp / p = 3.3 \cdot 10^{-4}$, or to be filled with imaging equipment.

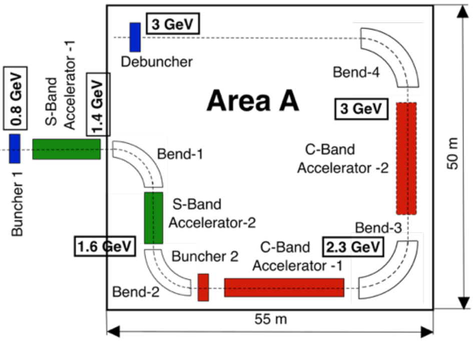

Figure 6: Placement of pRad booster in existing experimental area A.

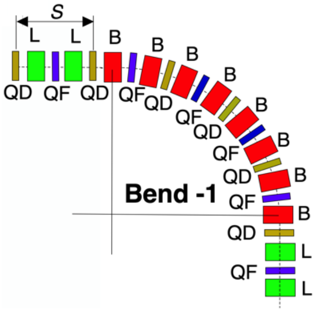

Figure 7: Bending arc containing four FODO cells with transverse phase advance per cell 90°: (L) linear accelerator, (B) bending magnet, (QF) x-focusing quadrupole, (QD) x-defocusing quadrupole.

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