Design of 3-GeV High-Gradient Booster for Upgraded Proton Radiography at LANSCE

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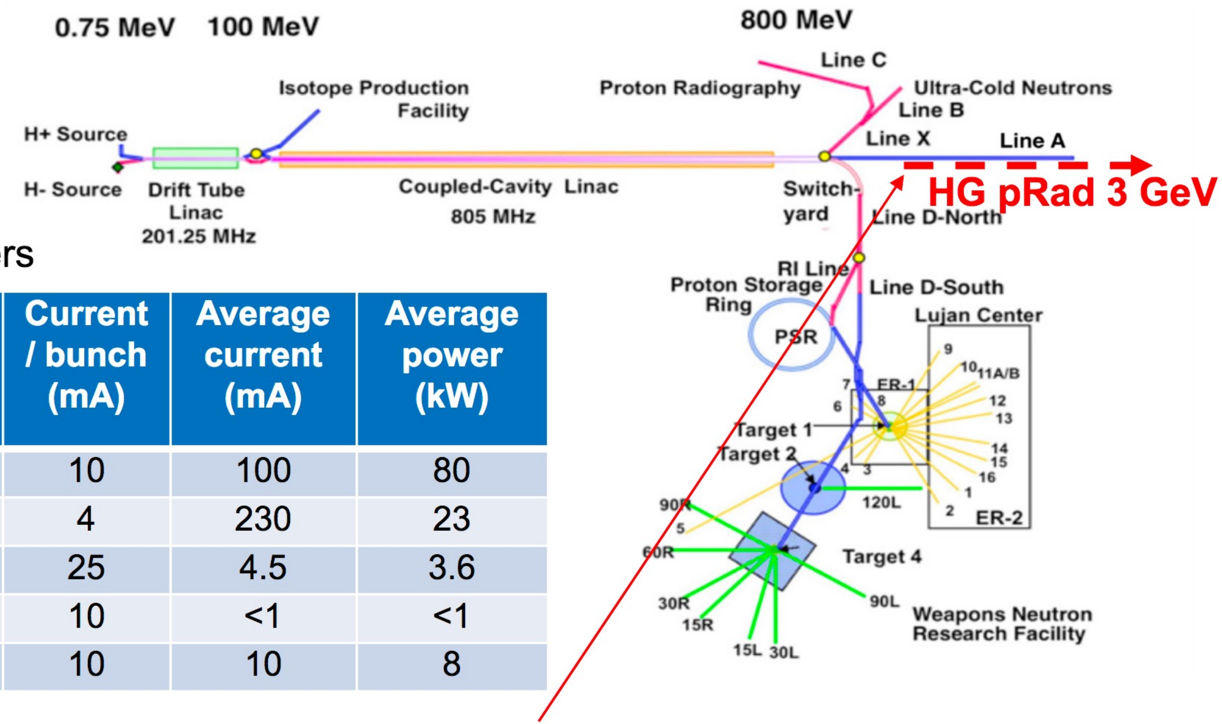
Los Alamos Neutron Science Center (LANSCE)



LANSCE Beam Parameters

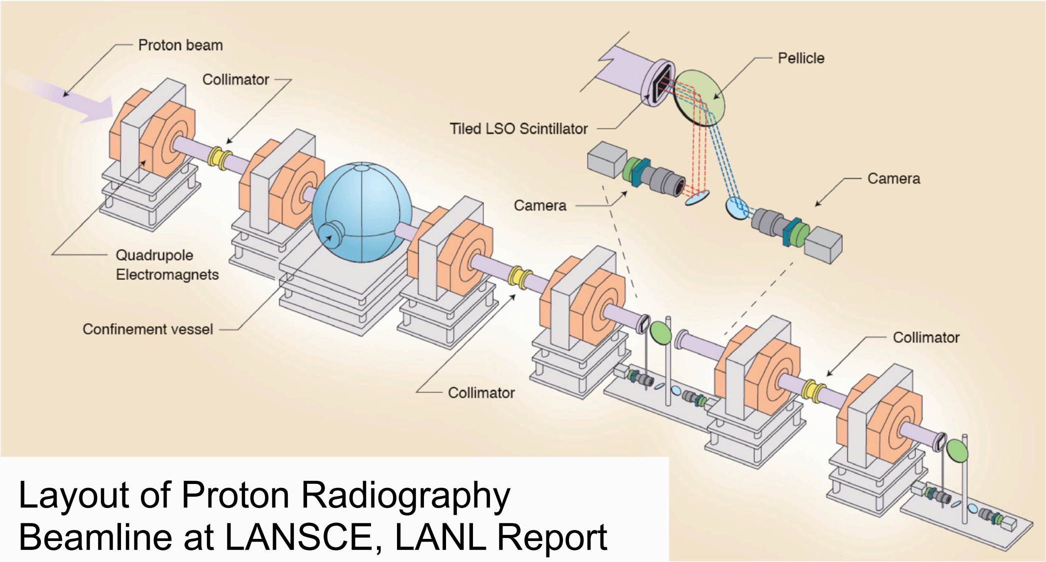
Area	Rep. Rate (Hz)	Pulse Length (ms)	Current / bunch (mA)	Average current (mA)	Average power (kW)
Lujan	20	625	10	100	80
IPF	100	625	4	230	23
WNR	100	625	25	4.5	3.6
pRad	1	625	10	<1	<1
UCN	20	625	10	10	8

Potential Location of High-Gradient pRad booster to 3 GeV at LANSCE

Proton Radiography at LANL

Proton Radiography (pRad) was developed at the Los Alamos National Laboratory in the mid-1990s as a multi-pulse flash technique for deep-penetrated hydro test objects study. It utilizes an 800-MeV proton beam from Los Alamos linear accelerator with a beamline for beam imaging.

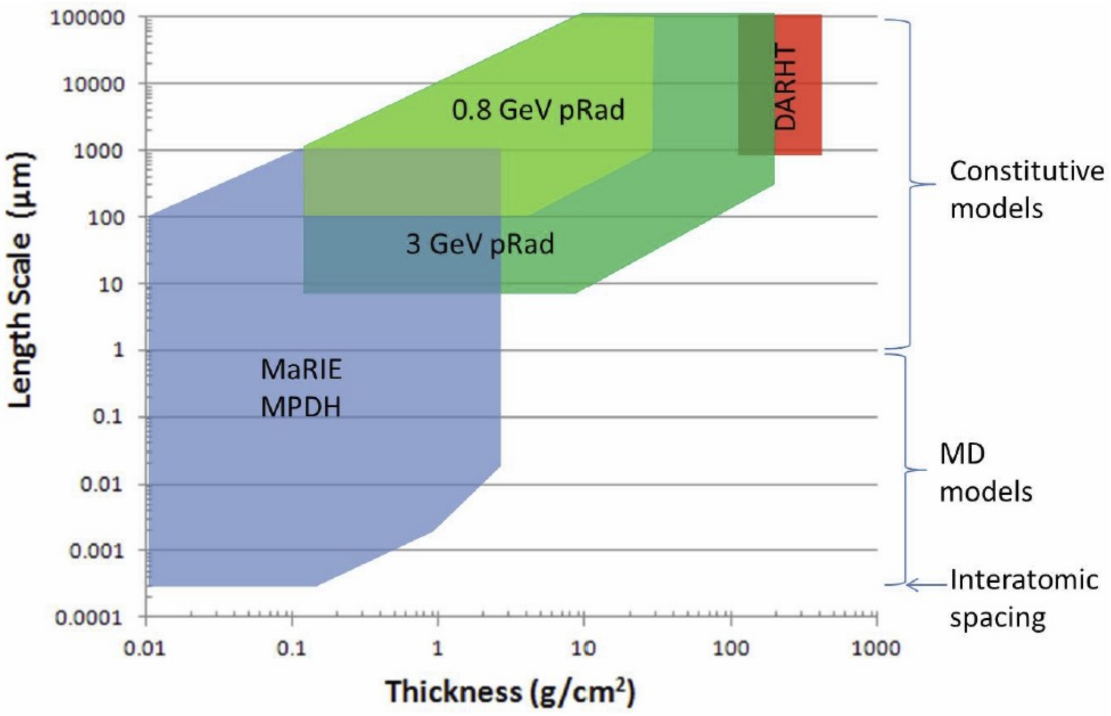
Experimental area of the 800-MeV LANSCE Proton Radiography Facility



Layout of Proton Radiography Beamline at LANSCE, LANL Report LA-UR-13-24376 (2013).

Radiographic Capabilities of the 3-GeV Proton Radiography

Increasing the proton energy from the present 800 MeV to 3 GeV improves the radiography resolution by a factor of 10. It will bridge the gap between the existing DARHT facility, which covers large length scales for thick objects, and future high-brightness light sources like MaRIE and DMMSC, which can provide the finest resolution.

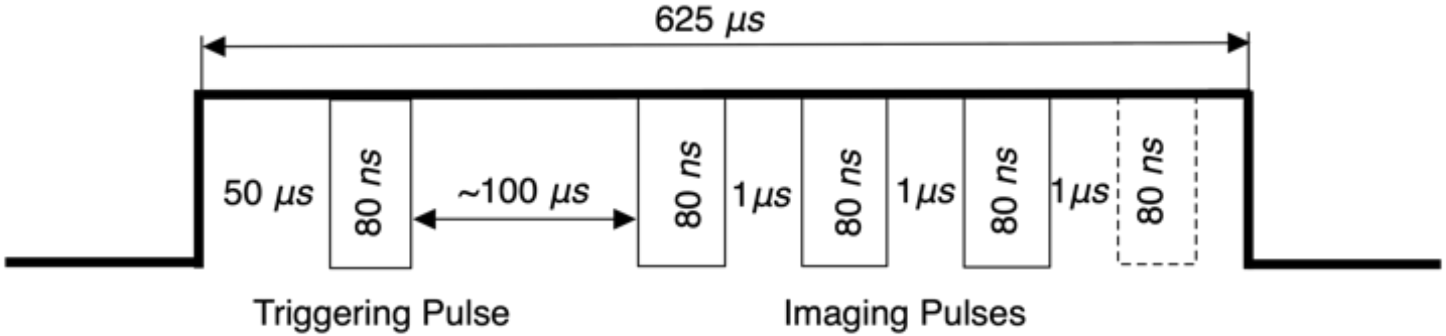


Design of 3 GeV pRad booster is supported by LDRD 20210004ER.

The object thickness and length scale regimes at existing and planned LANL facilities [LANL Report LA-UR-13-24376 (2013)].

Parameters of Existing and Upgraded pRad Beams

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



Time structure of LANSCE pRad beam

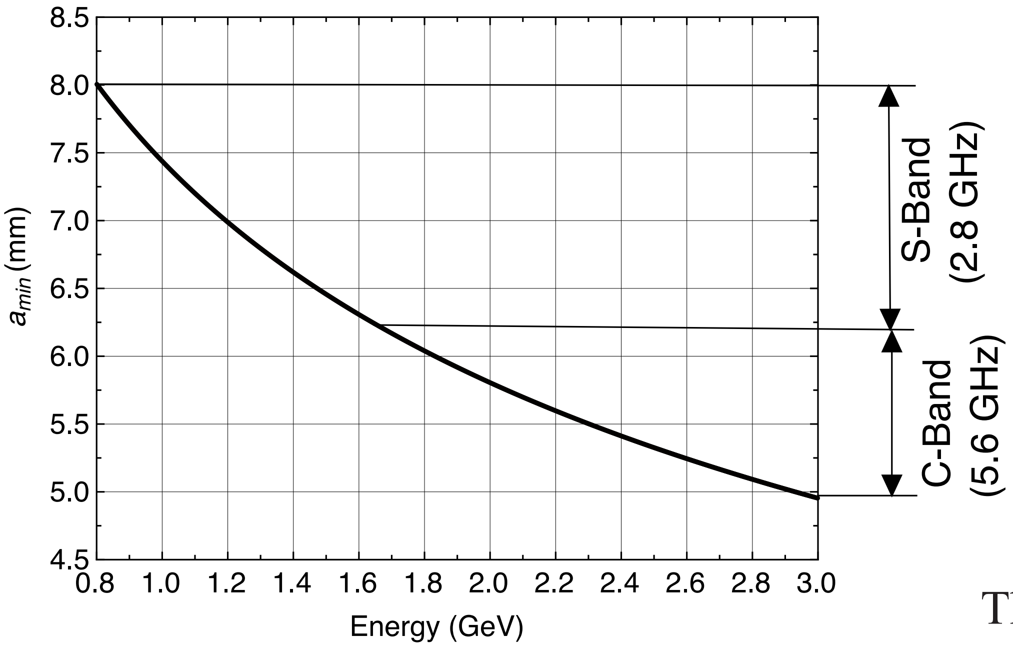
Beam Loss and Transverse Acceptance

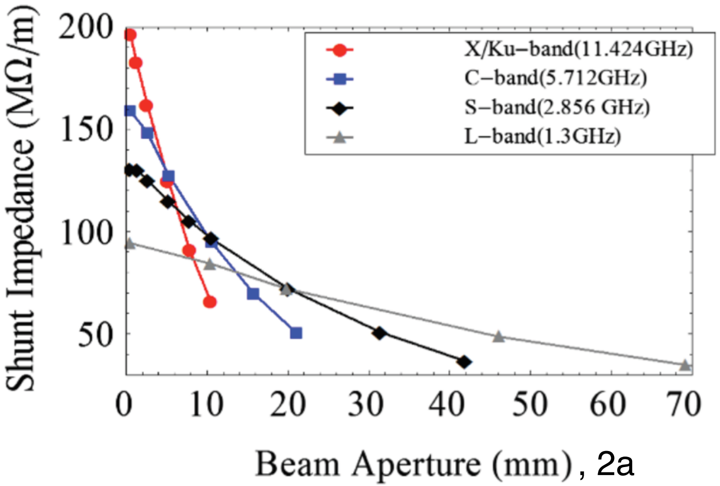
Utilization of high RF frequencies (short RF wavelength λ) results in reduction of beam aperture *a* (typically, in accelerators, a/λ ~0.1). This results in reduction of accelerator acceptance and possible beam losses. To insure small beam losses, transverse acceptance of the proposed structure should not be smaller than that in existing LANSCE.

Normalized (energy-independent) transverse acceptance of accelerating structure	$\varepsilon_{ch} \approx 0.7\,\beta\gamma\,\frac{a^2\mu_s}{S} \geq \varepsilon_{LANSCE}$
Particle momentum	$\beta\gamma$
Aperture radius of accelerator channel	a
Focusing period	S
Phase advance of transverse oscillations per focusing period	μ_s
Acceptance of LANSCE at 800 MeV	$\varepsilon_{LANSCE} \approx 3.5\pi\, cm\, mrad$

Selection of RF Frequency

Limitations on acceptance are translated into limitation on accelerator aperture, which, in turn, is translated into selection of RF frequency to provide high value of shunt impedance of the accelerator sections.

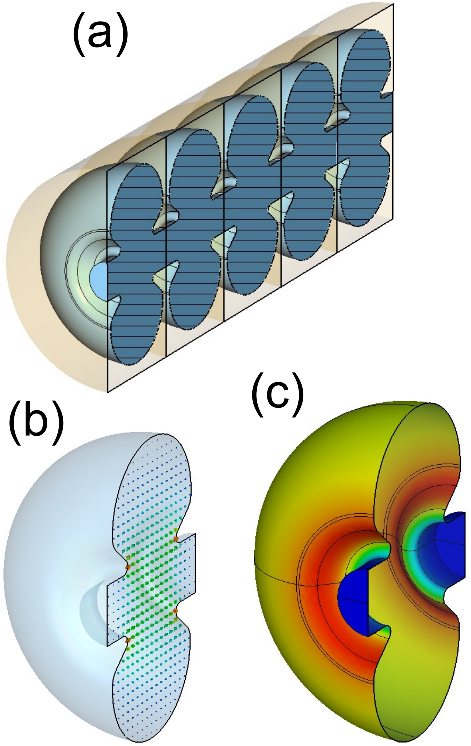




Minimal aperture $a_{\min} \approx \frac{10}{\sqrt{\beta\gamma}}\ [mm]$

The shunt impedance $Z_{eff}=E^2L/P$ for various accelerating structures [S.Tantawi et al, PRAB 23, 092001 (2020)].

Parameters of RF Structures

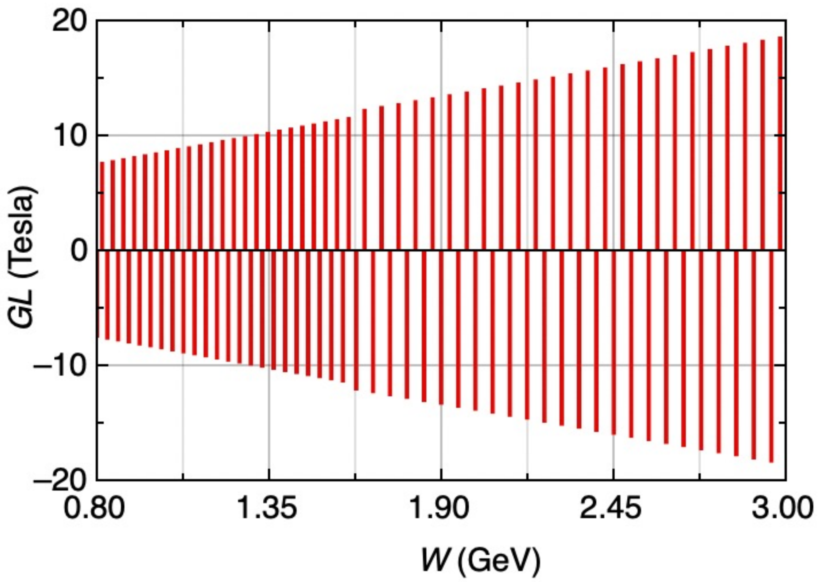


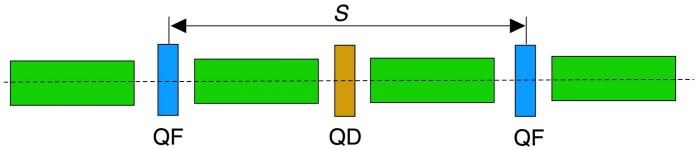
S-band 2.8 GHz cavities for β=0.84: (a) 5-cell structure, (b) electric field (c) surface current

Frequency f (GHz)	Velocity β	Aperture radius, a (mm)	Accel. gradient, E_oT (MV/m)	Shunt Imped., $R_{sh}T^2/L$ (MΩ/m)	RF Power, P/L (MW/m)
1.40875	0.84	8	12	68.6	4.7
2.8175	0.93	6.5	25	83.4	7.5
5.635	0.97	5	40	96.9	16.5

Detailed description of RF structures: S.S. Kurennoy, Y.K. Batygin and E.R. Olivas, "Accelerating Structures for High-Gradient Proton Radiography Booster at LANSCE", NAPAC 22, THZD4, this conference (2022).

FODO Focusing Structure





Phase advance of longitudinal oscillations per focusing period *S* is selected to be limited by the value of ~ 70° (1.2 rad):

$$\mu_{oz} = \sqrt{2\pi\left(\frac{qE\lambda}{mc^2}\right)\frac{|\sin\varphi_s|}{(\beta\gamma)^3}}\left(\frac{S}{\lambda}\right) < 1.2$$

It is translated into limitation of focusing period:

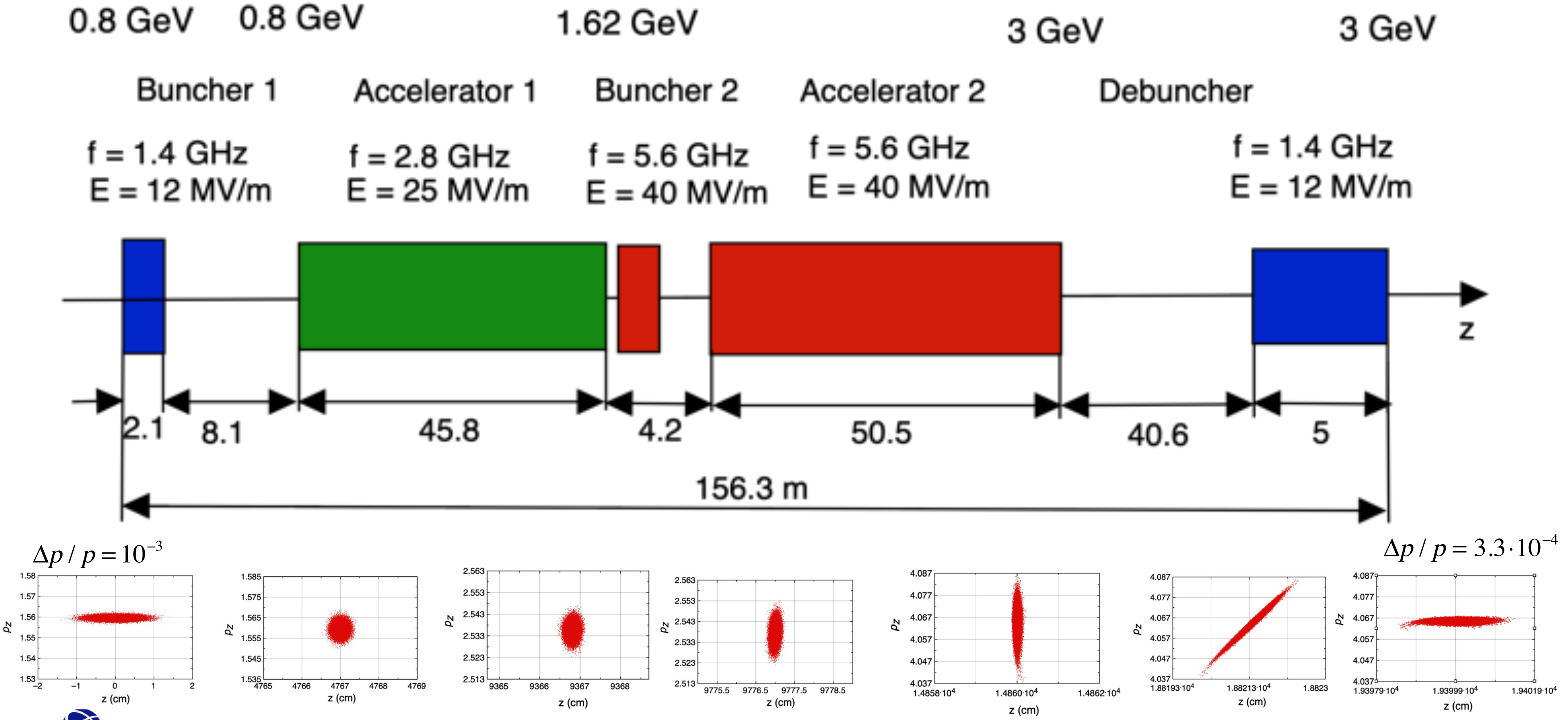
$$S\,[\mathrm{m}] \le 20.7\,(\beta\gamma)^{3/2}\sqrt{\frac{\lambda\,[\mathrm{m}]}{E\,[\mathrm{MV/m}]}}$$

Focusing strength versus beam energy

$$GL = \mu_o \frac{mc\beta\gamma}{qS}\frac{1}{\sqrt{1-(4/3)(L/S)}}$$

Reducing of the focusing period results in decrease of the average accelerating gradient. Final selection: *S* = 2 m. Average gradient: $\bar{E} = 0.8 E_o T \cos\varphi_s$

Layout of 3-GeV Booster



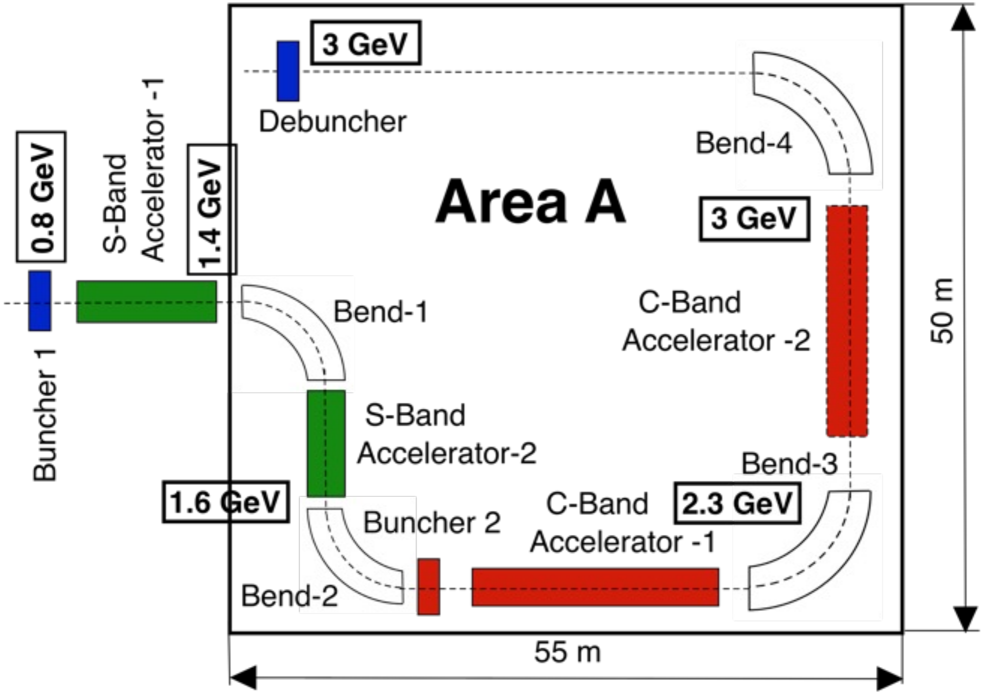
Transformation of Longitudinal Phase Space

LANSCE Line A and Area A

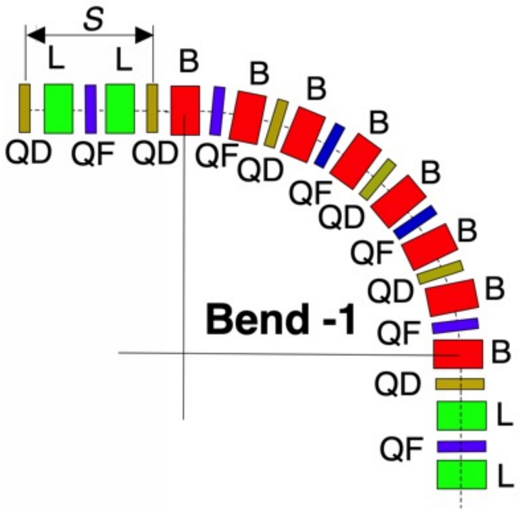
Line A after the linear accelerator

Experimental Area A

Placement of the Booster in Experimental Area A



Placement of pRad booster in existing experimental area A.



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.

Summary

1. High-energy accelerator for 3 GeV pRad enhancement is proposed.

2. Accelerator consists of 1.4 GHz buncher, two accelerators based on 2.8 GHz and 5.6 GHz high-gradient accelerating structures and 1.4 GHz debuncher.

3. Utilization of buncher-accelerator-debuncher scheme allows us to combine high-gradient acceleration with reduction of beam momentum spread dp/p from 10^{-3} to 3.3×10^{-4} .

4. Requirement to provide small beam momentum spread beam results in an accelerator of total length of 156.3 m. Possible location of the pRad booster is in the existing experimental Area A.