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

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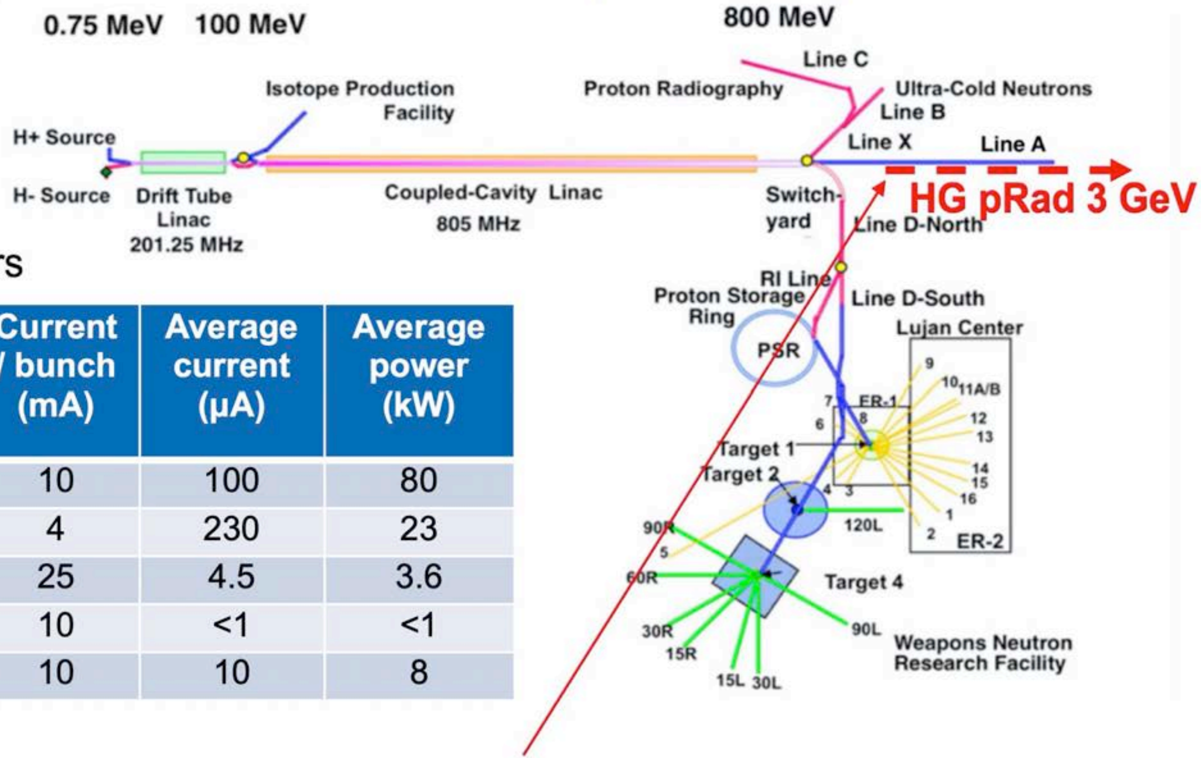
Los Alamos Neutron Science Center (LANSCE)



LANSCE Beam Parameters

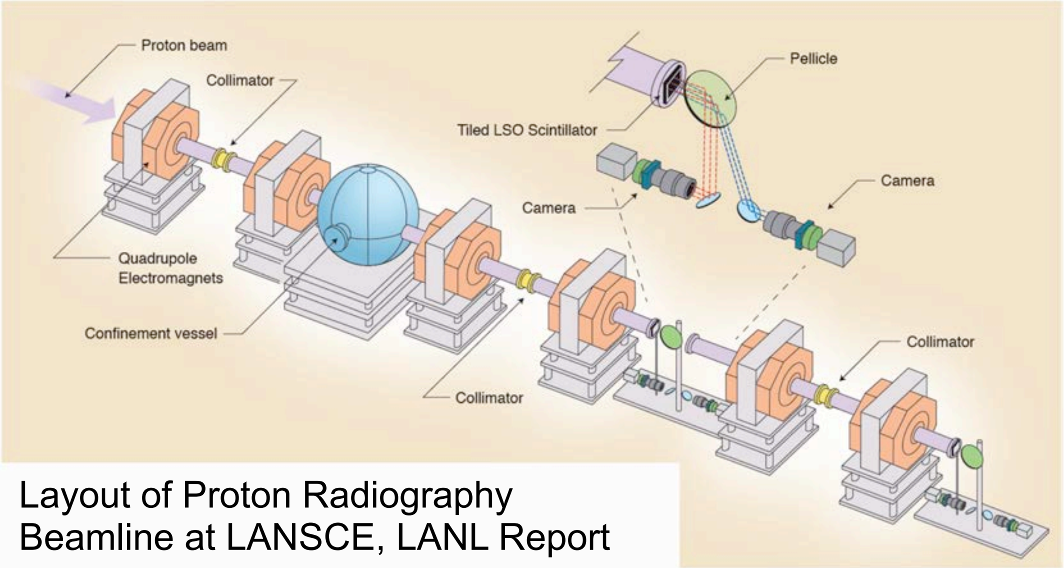
Area	Rep. Rate (Hz)	Pulse Length (μs)	Current / bunch (mA)	Average current (μA)	Average power (kW)
Lujan	20	625	10	100	80
IPF	100	625	4	230	23
WNR	100	625	25	4.5	3.6
pRad	1	625	10	<1	<1
UCN	20	625	10	10	8

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

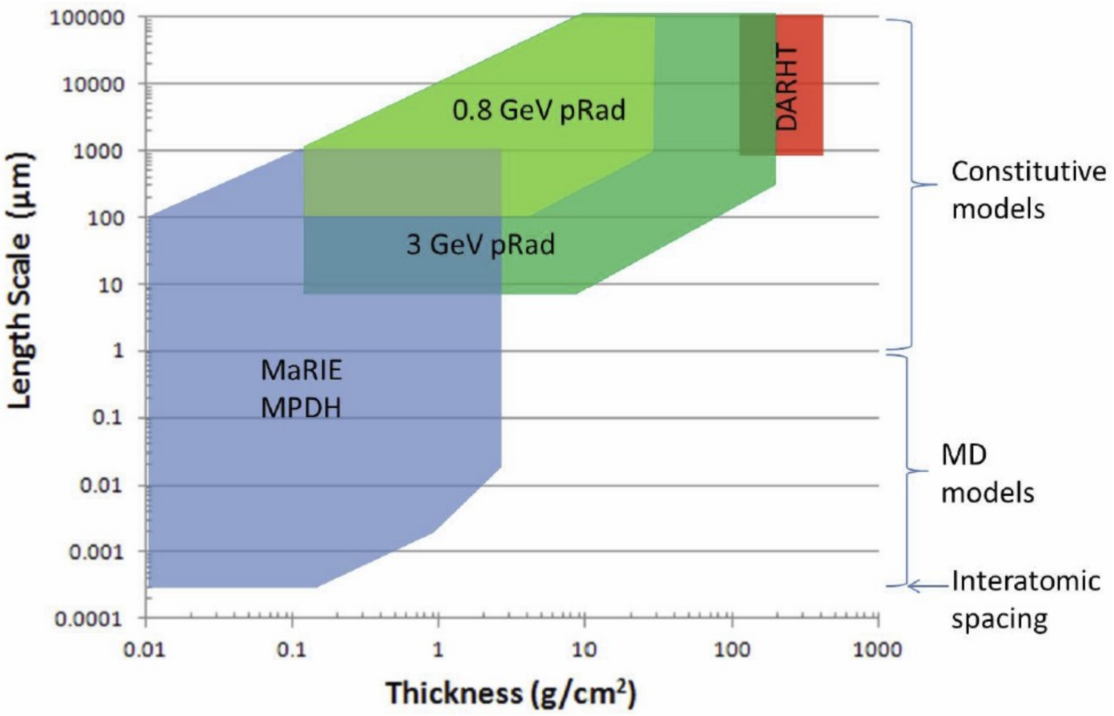


Layout of Proton Radiography Beamline at LANSCE, LANL Report LA-UR-13-24376 (2013).

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.

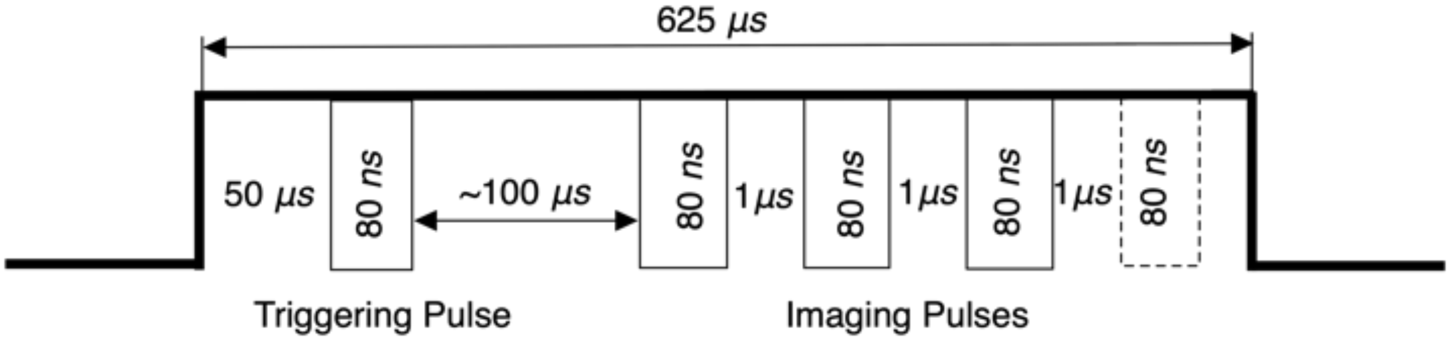
Design of 3 GeV pRad booster is supported by LDRD 20210004ER.



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

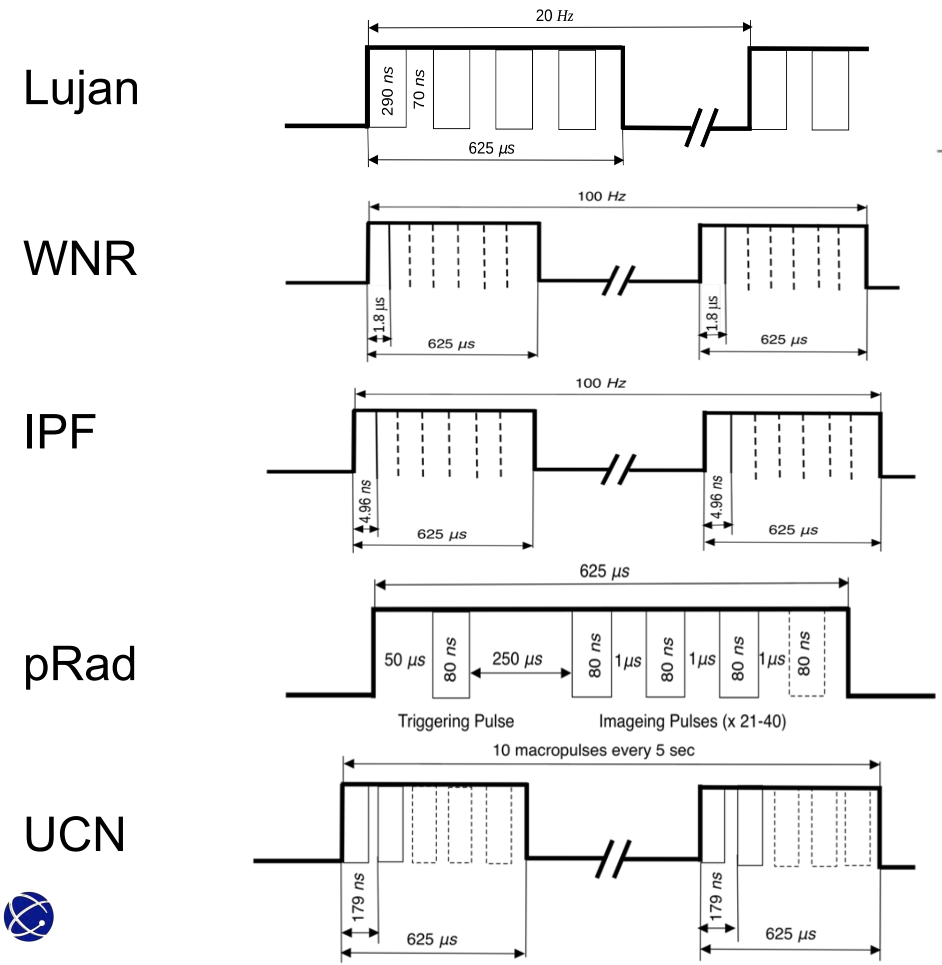
Parameters of Existing and Upgraded pRad Beams

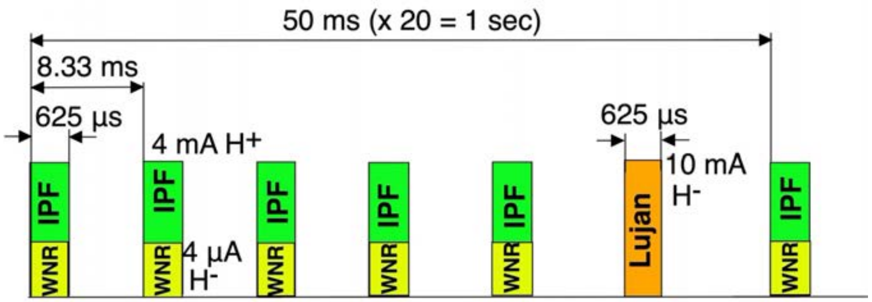
Parameter	Existing	Upgraded
Energy (GeV)	0.8	3
FWHM momentum spread, dp/p	1×10^{-3}	3.3×10^{-4}
Beam current / bunch (mA)	10	19
Protons per pulse	5×10^{9}	9.5×10^{9}



Time structure of LANSCE pRad beam

Time Structure of LANSCE Beams





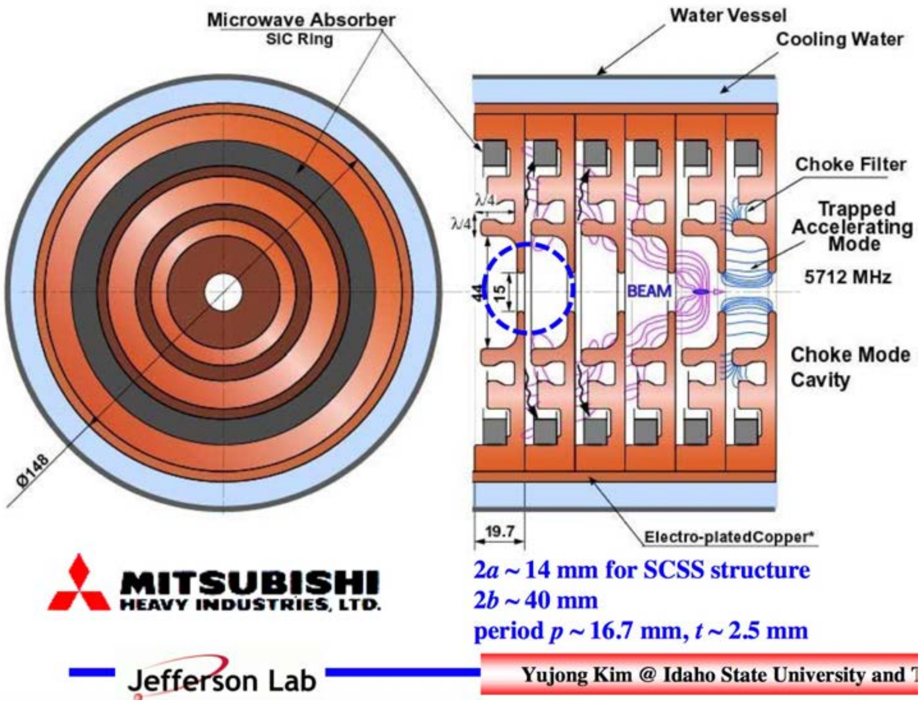
Layout of Lujan/WNR/IPF beams. Beams delivered to pRad or UCN facilities “steal” their time cycles from WNR beam.

LANSCE slow-wave chopper

Design Issues for High-Gradient pRad Booster

1. Adaptation of high-gradient structures for protons
2. Prevention of beam loss and preservation of transverse acceptance
3. Mitigation of strong RF defocusing due to high gradient
4. Selection of appropriate magnetic focusing
5. Matching of the 800-MeV output LANSCE beam to high gradient structure
6. Beam debunching after linac is required to ensure low-momentum spread of the beam

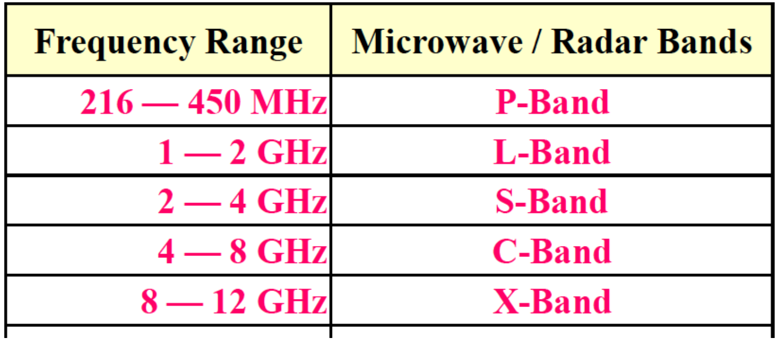
Application of High-Gradient Accelerating Structures



$2a \sim 14$ mm for SCSS structure
$2b \sim 40$ mm
period $p \sim 16.7$ mm, $t \sim 2.5$ mm

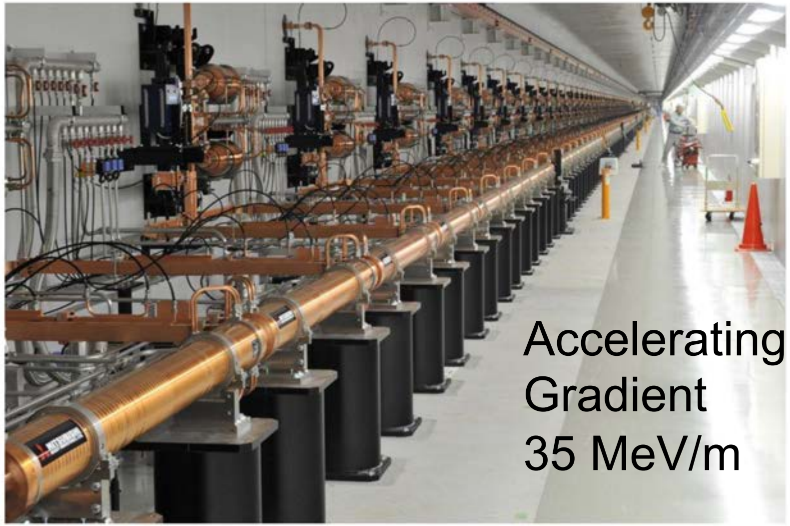
Yujong Kim @ Idaho State University and T

Mitsubichi 5.7 GHz C-Band Accelerating Structure.



Frequency Range	Microwave / Radar Bands
216 — 450 MHz	P-Band
1 — 2 GHz	L-Band
2 — 4 GHz	S-Band
4 — 8 GHz	C-Band
8 — 12 GHz	X-Band

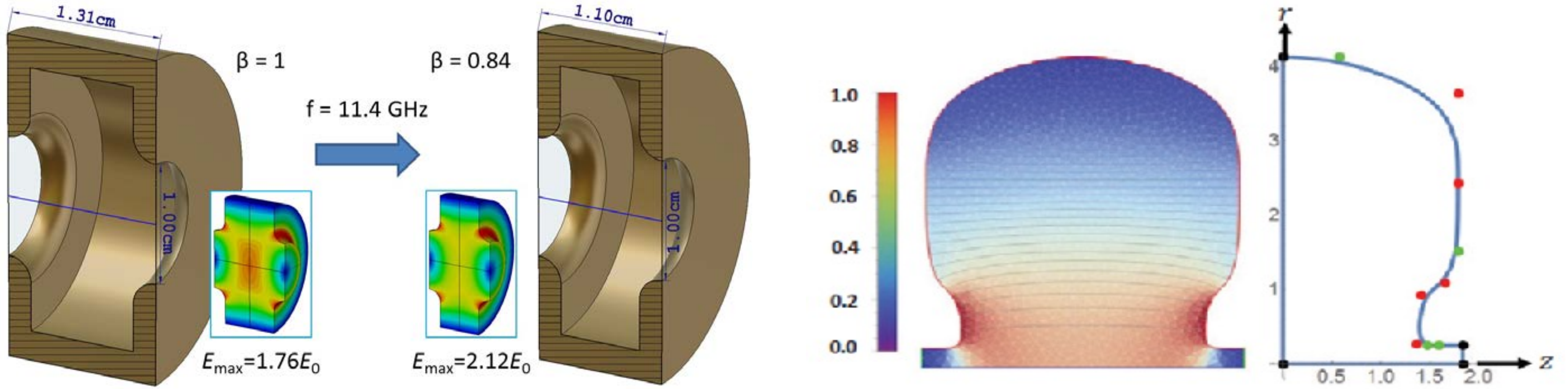
260 m long C-band RF LINAC for XFEL/SPring-8



Accelerating Gradient 35 MeV/m

Adaptation of High-Gradient Structure for Protons

The HG structures with β=1 have been developed for electrons. Accelerating cell length is βλ/2. Reducing the cell length from β=1 to β=0.84 significantly increases the maximum surface field (risk of RF breakdown). Optimization of the shape of cavities is required.



Adapting of High Gradient electron cavities for protons: (a) cell length adjustment; (b) shape optimization (M. Nasr, S.Tantawi, IPAC2018).

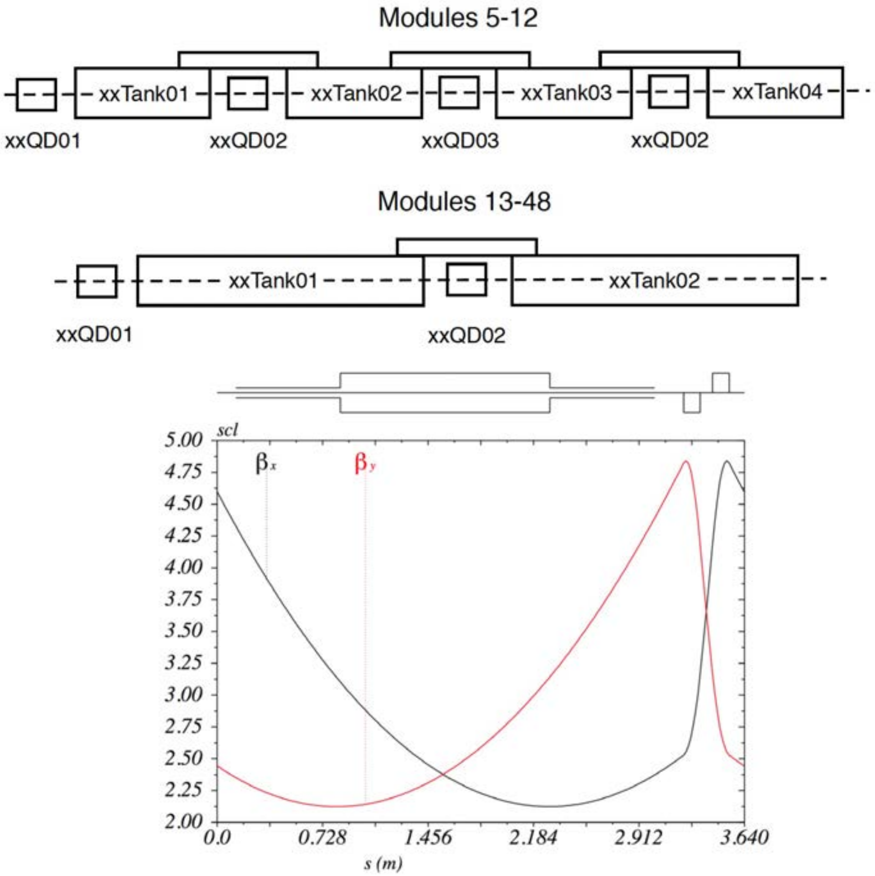
Beam Loss and Transverse Acceptance

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

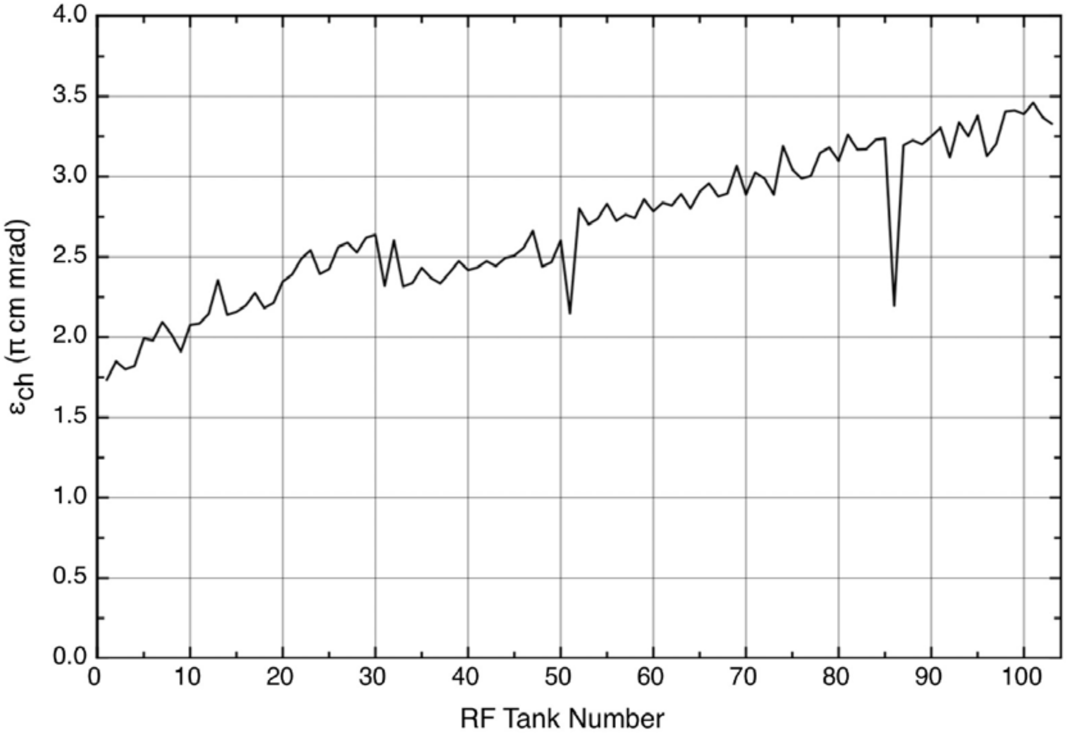
Focusing Structure of Existing 805 MHz Coupled Cavity Linac

LANSCE Coupled Cavity Linac



LANSCE CCL Module Layout and beta-functions.

Normalized Transverse Acceptance of 805 MHz Coupled Cavity Linac



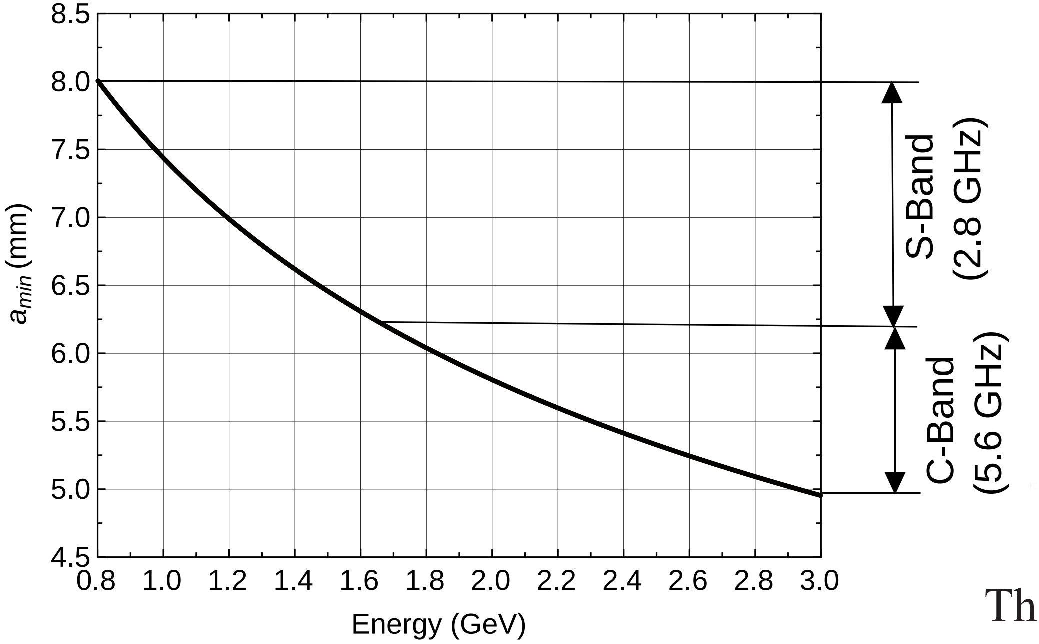
Transverse acceptance of LANSCE at 800 MeV:

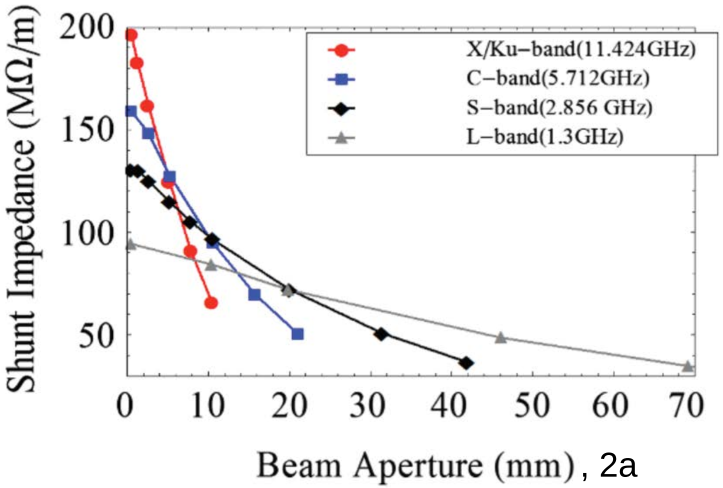
$$\varepsilon_{LANSCE} \approx 3.5\pi\, cm\, mrad$$

LANSCE CCL normalized transverse acceptance
(T. Fronk, MS Thesis, Indiana University, 2018)

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.

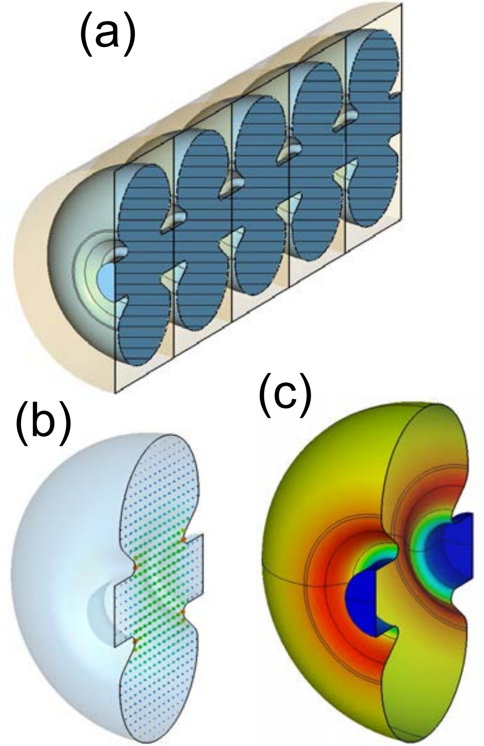




The shunt impedance $Z_{eff}=E^2L/P$ for various accelerating structures [S.Tantawi et al, PRAB 23, 092001 (2020)].

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

Parameters of RF Structures



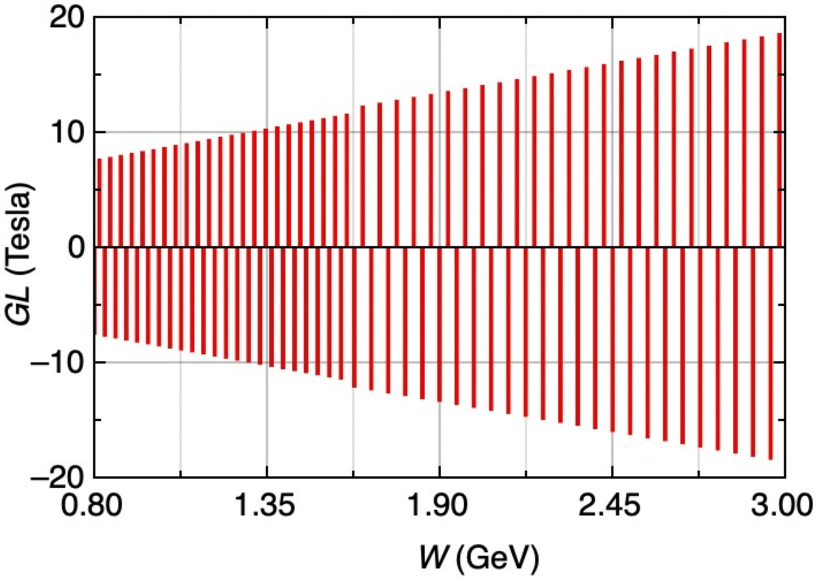
Frequency f (GHz)	Velocity β	Aperture radius, a (mm)	Accel. gradient, E_oT (MV/m)	Shunt Imped., $R_{sh}T^2/L$ (MΩ/m)	RF Power, P/L (MW/m)
1.40875	0.84	8	12	68.6	4.7
2.8175	0.93	6.5	25	83.4	7.5
5.635	0.97	5	40	96.9	16.5

Total RF Power ~ 0.75 GW

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

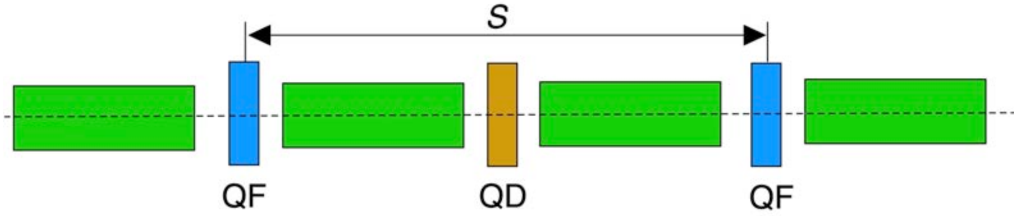
High-peak-power klystrons (>20 MW) with a variable pulse length 2-50 μs at very low duty factor (single pulse) are feasible but require development. Available S-and C-band klystrons produce up to 50-MW peak with pulses 1-3 μs and rep rates ~100 Hz. Multi-beam L-band (1.3 GHz) klystrons at DESY produce 10-MW peak with 1.5-ms pulse at 10 Hz. Modulators for such klystrons will also need development.

FODO Focusing Structure



Focusing strength of quadrupoles versus beam energy

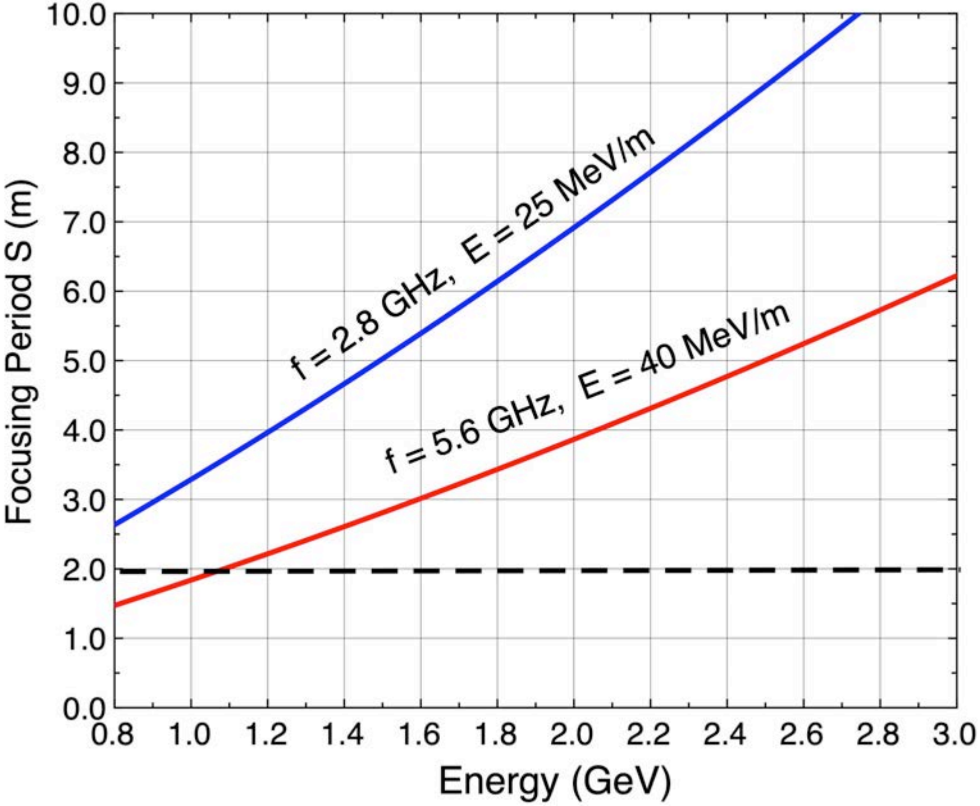
$$\boxed{GL = \mu_o \frac{mc\beta\gamma}{qS} \frac{1}{\sqrt{1-(4/3)(L/S)}}}$$



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

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

Selection of Focusing Period



Required focusing period versus beam energy to mitigate RF defocusing

Selection of phase advance is translated into limitation of focusing period:

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

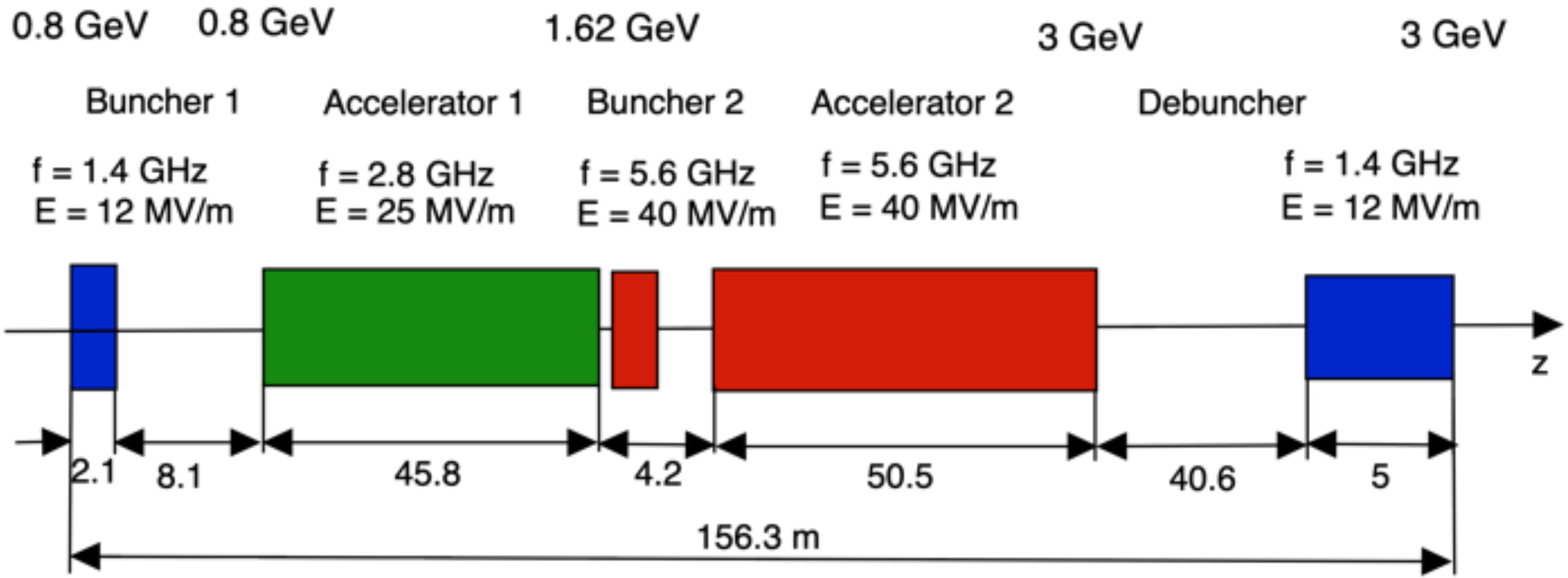
Reducing of the focusing period results in decrease of the average accelerating gradient:

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

Final selection: *S* = 2 m. Average gradient:

$$\bar{E} = 0.8 E_o T\cos\varphi_s$$

Layout of 3-GeV Booster



0.8 GeV 0.8 GeV 1.62 GeV 3 GeV 3 GeV

Buncher 1 Accelerator 1 Buncher 2 Accelerator 2 Debuncher

f = 1.4 GHz
E = 12 MV/m

f = 2.8 GHz
E = 25 MV/m

f = 5.6 GHz
E = 40 MV/m

f = 5.6 GHz
E = 40 MV/m

f = 1.4 GHz
E = 12 MV/m

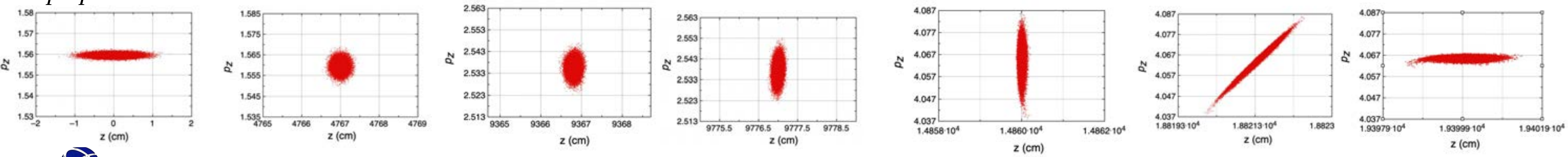
2.1 8.1 45.8 4.2 50.5 40.6 5

156.3 m

z

$\Delta p / p = 10^{-3}$

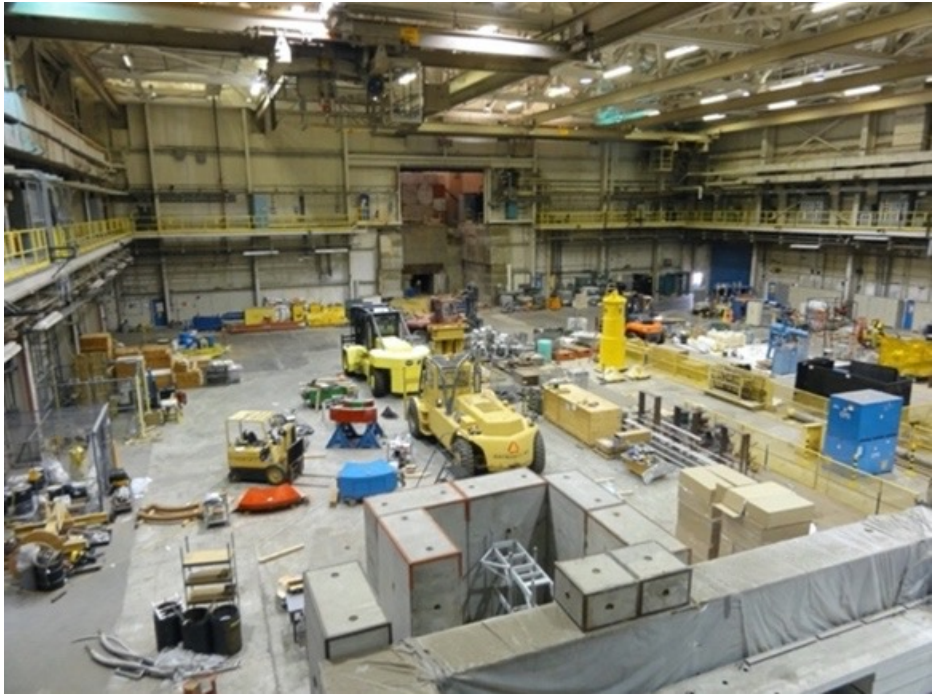
$\Delta p / p = 3.3 \cdot 10^{-4}$



Transformation of Longitudinal Phase Space

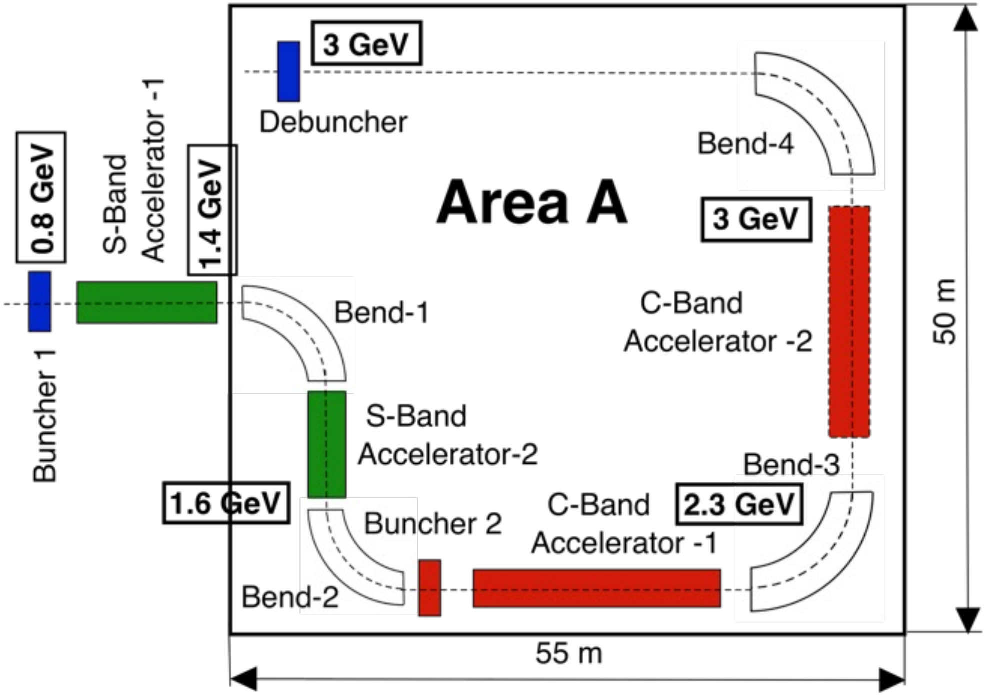
LANSCE Line A and Area A

Line A after the linear accelerator

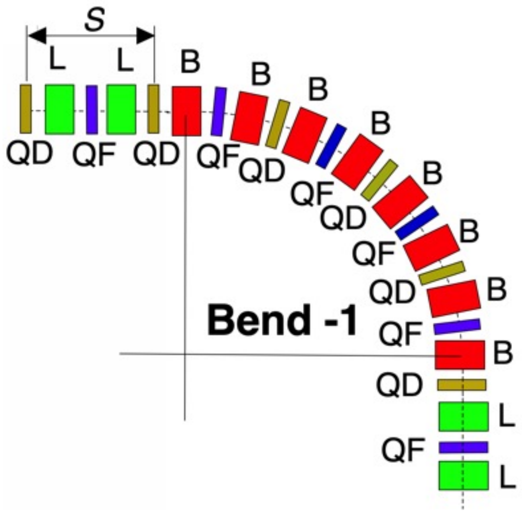


Experimental Area A

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.

Publications

Journal Articles

- Batygin, Y. K. Beam dynamics in independent phased cavities. 2022. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment.* 167192. (LA-UR-22-25550 DOI: 10.1016/j.nima.2022.167192)

Conference Papers

- Batygin, Y. K. Longitudinal Beam Dynamics in Array of Equidistant Multicell Cavities. Presented at *International Linear Accelerator Conference 2022 (LINAC2022)*. (Liverpool, United Kingdom, 2022-08-28 - 2022-09-02). (LA-UR-22-28774)
- Batygin, Y. K. and S. S. Kurennoy. Design of 3-GeV High-Gradient Booster for Upgraded Proton Radiography at LANSCE. Presented at *North American Particle Accelerator Conference (NAPAC)*. (Albuquerque, New Mexico, United States, 2022-08-07 - 2022-08-12). (LA-UR-22-27594)
- Kurennoy, S. S., Y. K. Batygin and E. R. Olivas. Accelerating Structures for High-Gradient Proton Radiography Booster at LANSCE. Presented at *North American Particle Accelerator Conference (NAPAC)*. (Albuquerque, New Mexico, United States, 2022-08-07 - 2022-08-12). (LA-UR-22-27859)
- Kurennoy, S. S., Y. K. Batygin and E. R. Olivas. Development of High-Gradient Accelerating Structures for Proton Radiography Booster at LANSCE. Presented at *Linear Accelerator Conference (LINAC)*. (Liverpool, United Kingdom, 2022-08-28 - 2022-09-02). (LA-UR-22-28838)
- Kurennoy, S. S. and Y. K. Batygin. High-Gradient Booster for Enhanced Proton Radiography at LANSCE. Presented at *12th International Particle Accelerator Conference - IPAC'21(virtual)*. (Campinas, Brazil, 2021-05-24 - 2021-05-28). (LA-UR-21-24609)