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High-Gradient Accelerating Structures for 3-GeV Proton Radiography Booster

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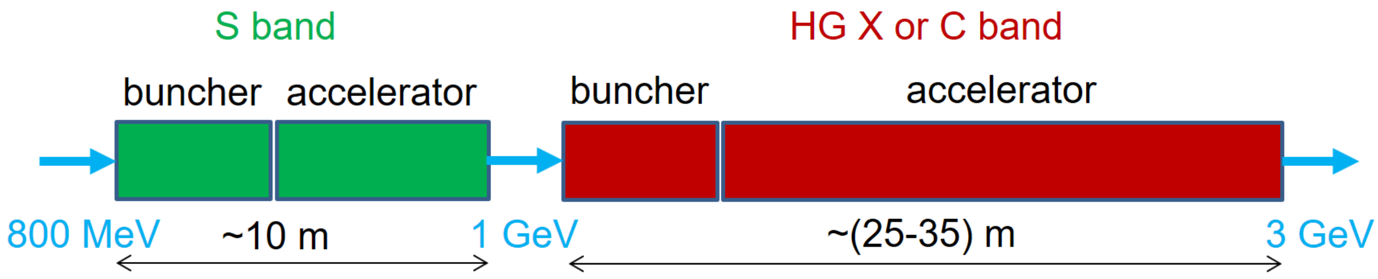
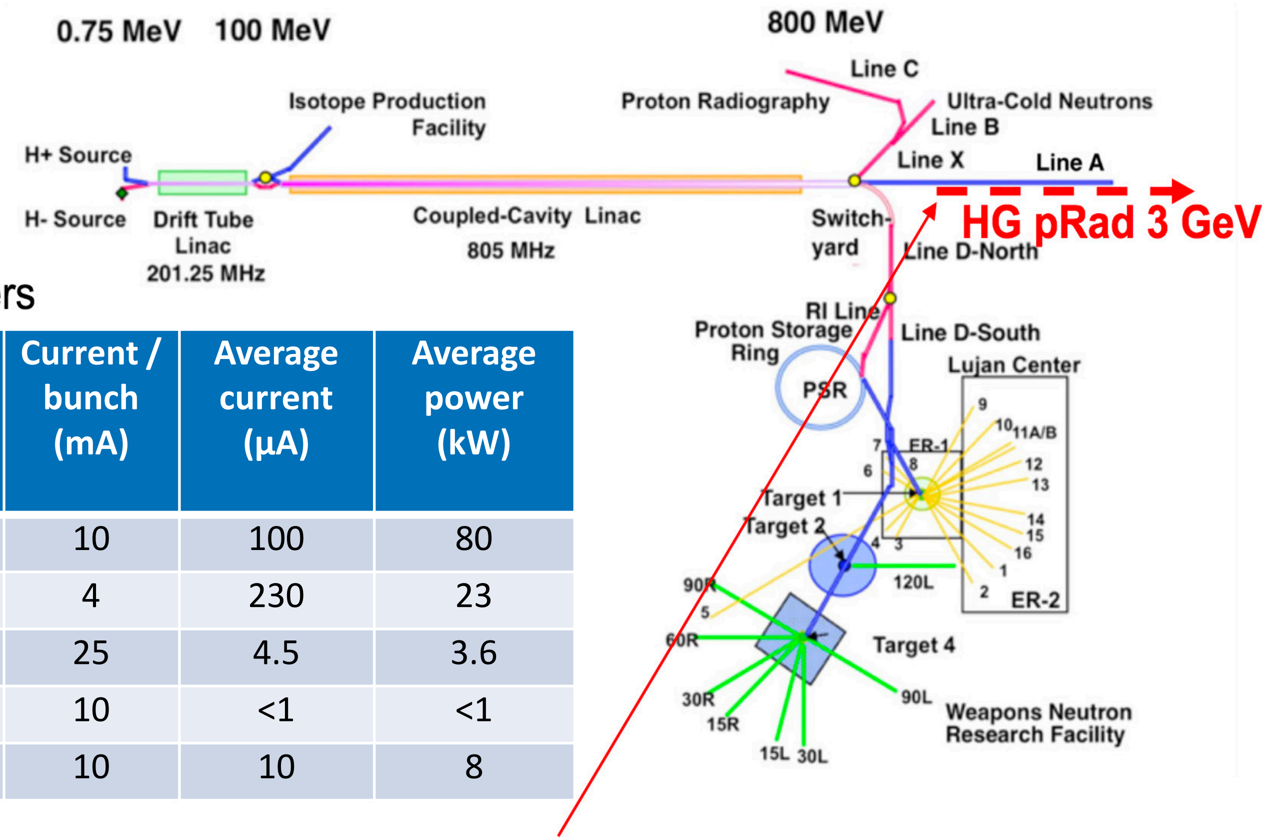
Compact High-Gradient Booster for Enhanced Proton Radiography

- What: High-gradient (HG) linear accelerator (linac) after the existing LANSCE linac to increase the proton beam energy from 800 MeV to 3 GeV.
- Why: This increases proton radiography (pRad) resolution 10 times.
- How: Compact 3-GeV high-gradient pRad booster:
  - Will be based on S- & C-band HG structures adapted for protons (v/c = 0.84 – 0.97). Prototype high-gradient proton C-band cavities will be tested at LANL.
  - Will have an optimal beam-physics design based on front-to-end modeling.
  - Fits the site and can be used in parallel with the existing 800-MeV pRad.
  - Can be the first-ever high-gradient normal-conducting proton linear accelerator.



(Linac16)

Los Alamos Neutron Science Center (LANSCE)



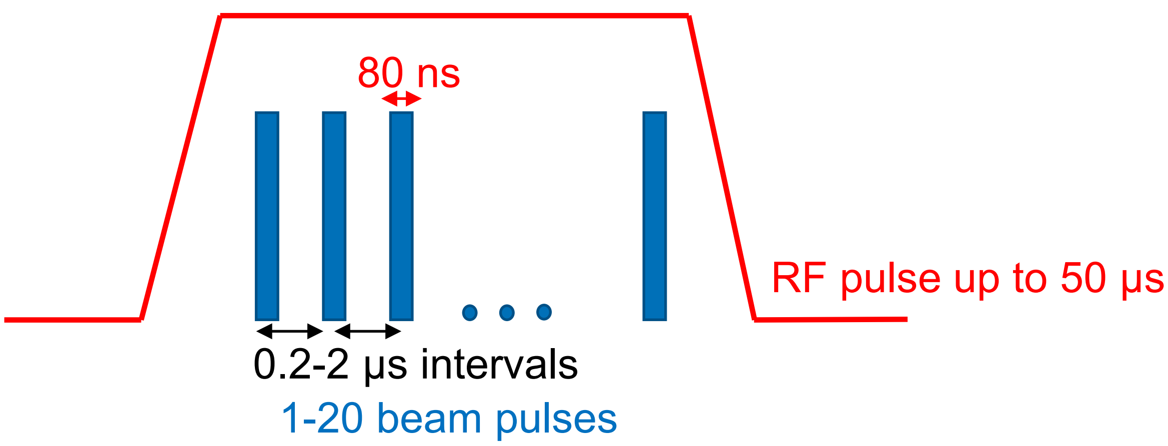
LANSCE Beam Parameters

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

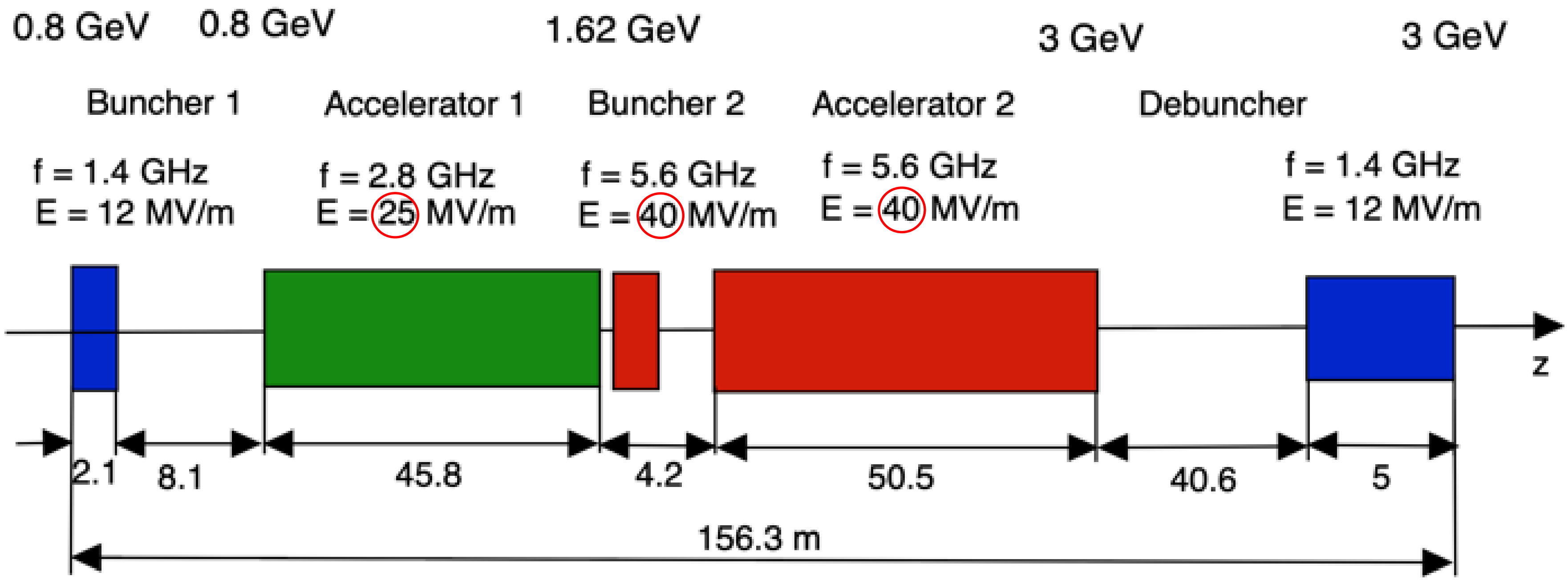
Potential Location of High-Gradient pRad booster to 3 GeV at LANSCE

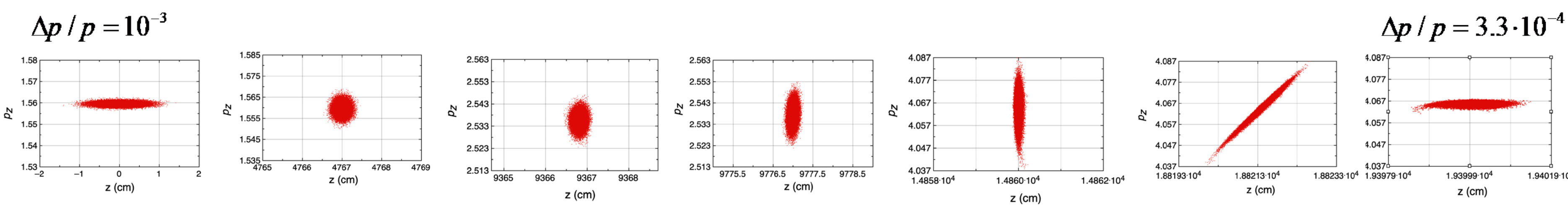
HG pRad Booster – Requirements

- Booster must satisfy pRad needs and fit the LANSCE site:
  - provide 1 to 20 short beam pulses (<80 ns) separated by variable intervals of 0.2-2 μs. Each short beam pulse contains proton bunches following at 5 ns (f_b = 201.25 MHz bunch repetition frequency) and produces one radiograph.
  - very low duty: one pulse train per event; a few events per day.
  - reduce relative energy spread at 3 GeV as ~1/p for good radiography quality: from $\Delta p/p = 10^{-3}$ at 800 MeV → $3.3 \cdot 10^{-4}$ at 3 GeV.
- Development of accelerator structures that support such a design:
  - HG structures so far have only been designed for electrons -> adapt for protons.
  - beam magnetic focusing scheme defines minimal allowable cavity apertures.
  - added L-band buncher & de-buncher + drifts to reduce beam energy spread.
  - standing-wave accelerator structures with distributed coupling are chosen.
- High peak power (~10s MW) RF sources (klystrons) that can support the required beam structure. Variable single RF pulse up to 50 μs.



Layout of 3-GeV Booster



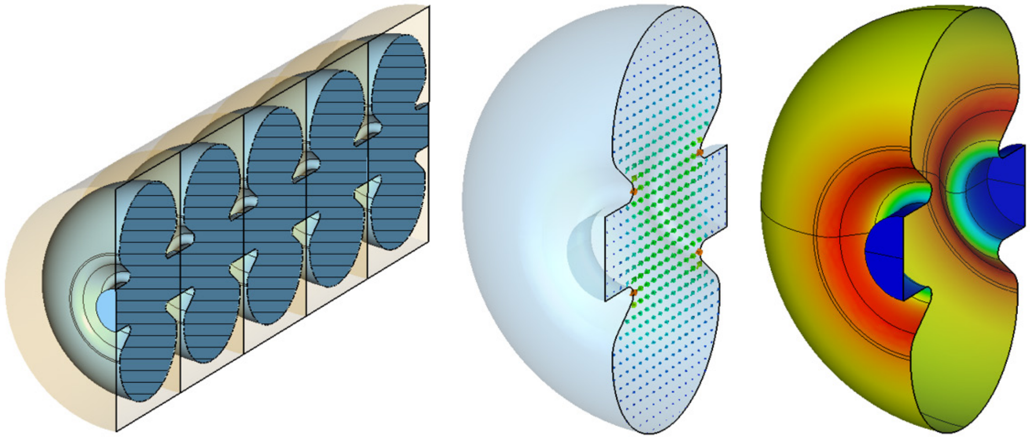


Evolution of Longitudinal Phase Space

The booster with reduced gradients needs bends to fit into existing buildings but saves RF

High-Gradient Structure Development

- Re-entrant cavity shapes were optimized to achieve high efficiency.



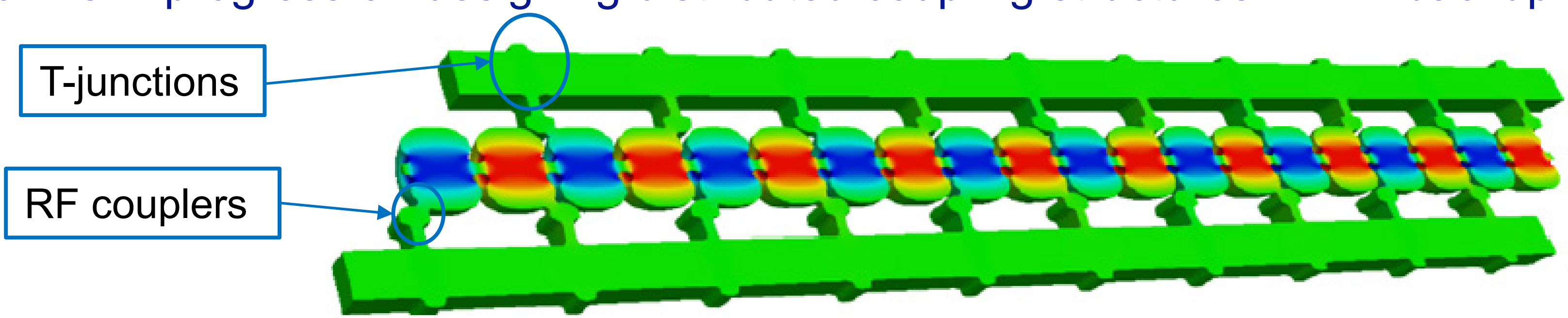
Bare S-band (14 f_b = 2817.5 MHz) structure for β=0.84: 5-cell structure section (left); electric field within a cell; current distribution on the cell inner surface (right).

Cavity Parameters at Gradient *E*

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

Reducing gradient saves RF($)!

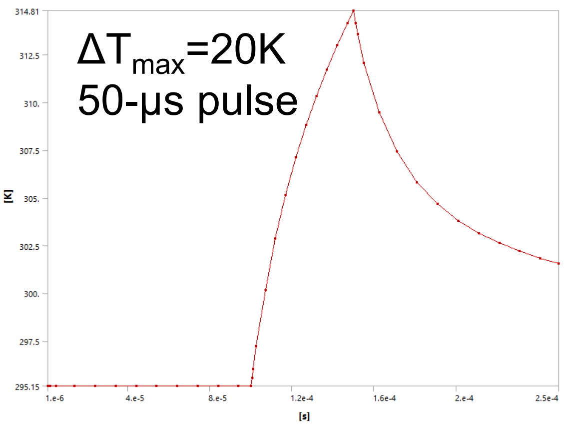
- Work is in progress on designing distributed coupling structures. TW – backup.

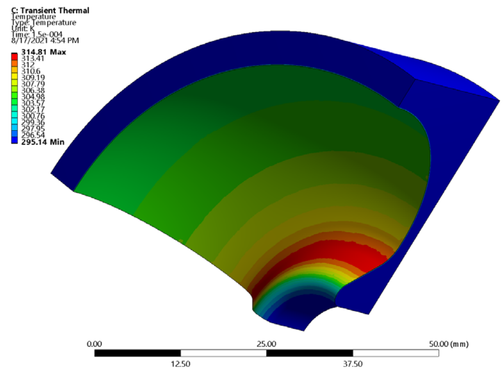


Ref: S. Tantawi *et al*. PRAB, **23**, 092001 (2020)

HG Cavity Thermal-Stress Analysis

- Preliminary thermal-stress analysis was performed for S-band cavity. Nominal frequency f = 2817.5 MHz (L: 1408.75 MHz; C: 5635 MHz)

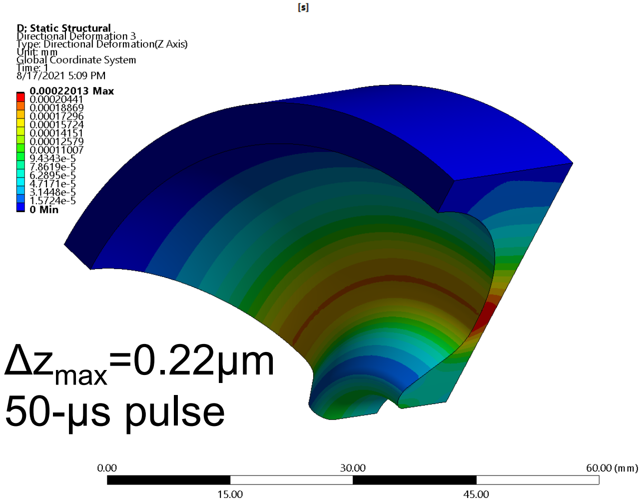




Cavity Parameters at Gradient E

f	β	a, mm	E, MV/m	E_{max}/E	Z', MΩ/m	P', MW/m
L	0.84	8	18	4.3	68.6	4.7
S	0.84	8	36	4.23	69.9	18.5
S	0.93	6.5	36	4.1	83.4	15.5
C	0.93	6.5	80	3.63	76.9	83.2
C	0.97	5	80	3.63	96.9	66
L	0.97	5	18	4.6	77	4.2

$P \sim E^2$



Δt_{pulse}, μs	ΔT_{max}, K	Δz_{max}, μm	Δf_{max}, MHz
50	20	0.22	-
100	28	0.44	-
1000	88	4.6	-0.48

Thermal-structural analysis of S-band cavity for β=0.84: temperature distribution and deformation after 50-μs pulse.

HG pRad Booster – RF power

Total peak RF power estimates (room temperature operation)

Booster	*L*, m	E_S, MV/m	P_S, GW	E_C, MV/m	P_C, GW
Design 1	92.5	36	0.42	100	1.9
Design 2	156.5	25	0.3	40	0.75

IPAC21

NAPAC22

Cryo-cooled operation (LN_2) can reduce the RF power by factor 2-3 and is well suited for pRad booster: < 50-μs single RF pulse, a few events per day. If some nitrogen is evaporated due to structure heating (we estimated this fraction below 10^{-3}, even after full 50-μs pulse); if needed, it can be refilled before the next event. Cool!

- 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.

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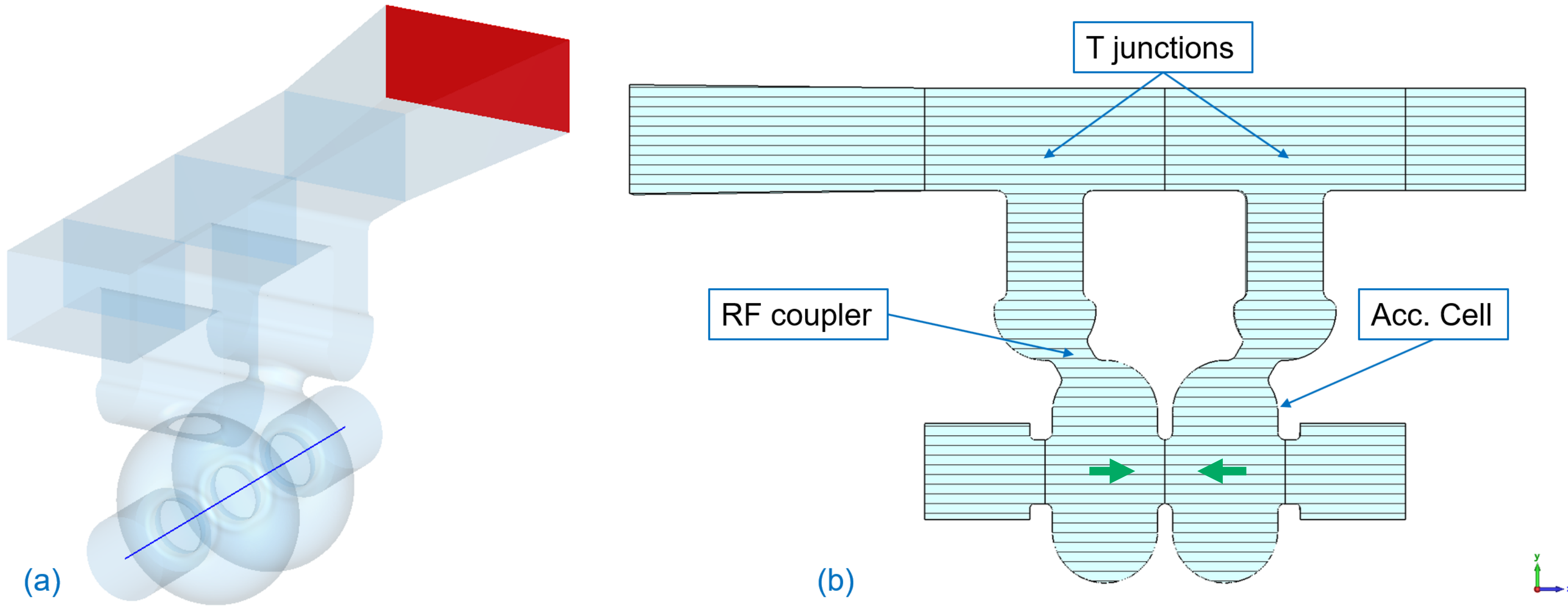
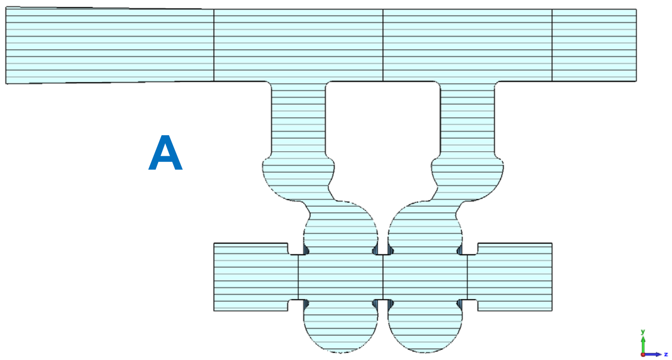
Test cavity with distributed coupling

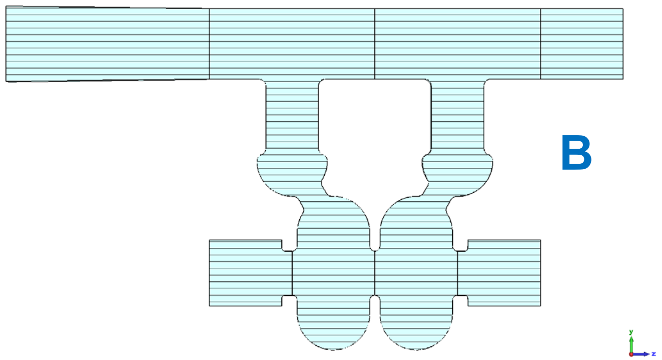


C-band 2-cell π-mode test cavity for β = 0.93 (1.6-GeV protons): (a) inner vacuum volume with standard WG187 port (red); (b) vertical cross section.

- The test cavity was designed for 5.712 GHz (not 5.635 GHz), to be tested at the existing LANL C-band RF test stand: 50-MW klystron with <1 μs pulse at 100 Hz.
- Simplified cell shape – no noses (not efficient for large beam apertures: a = 6.5 mm, r = 21.9 mm; a/r = 0.3); reduces E_{max} by 37%.
- Large RF couplers: each delivers one-half of the RF power fed into waveguide.

Test cavity with distributed coupling – parameters





Comparison of two cavity types. f = 5.712 GHz; ideal Cu; E_0T = 80 MV/m

Re-entrant cavity, A	EM quantity, unit	Simple cavity, B
0.7429	T	0.7346
12,746	Q_0	13,150
10,764	Q_{ext}	11,006
3.98	P, MW	4.37
3.67	E_{max} / E_0T	2.32
2.10	Z_0H_{max} / E_0T	2.29
78.6	Z'_{eff}, MΩ/m	71.4
81.5	P', MW/m	89.6

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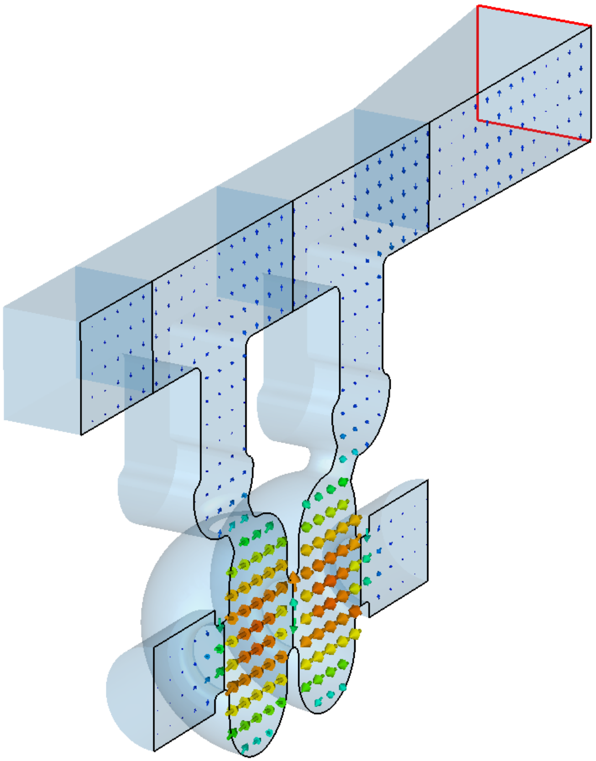
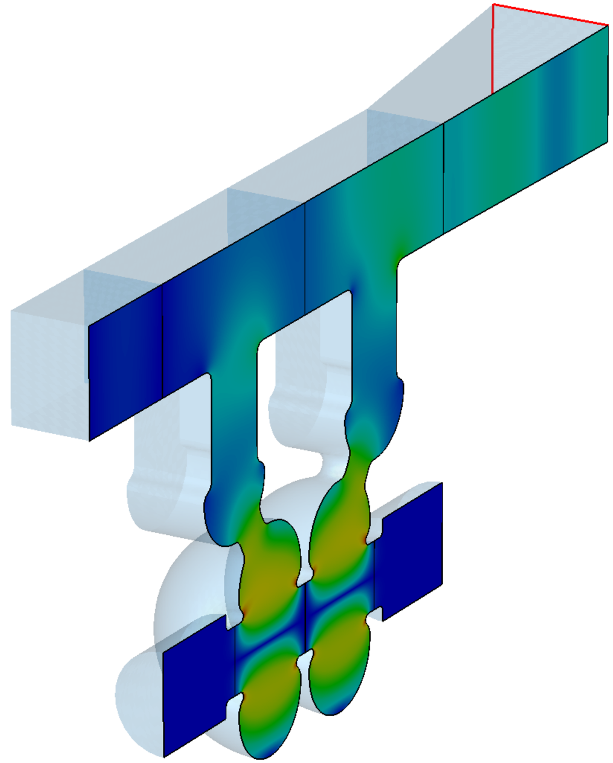
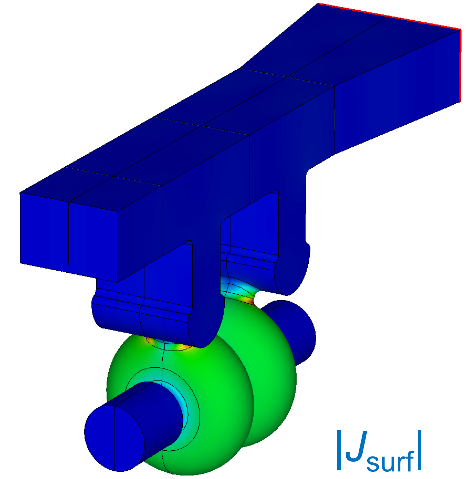
Fields and power flow in the test cavity

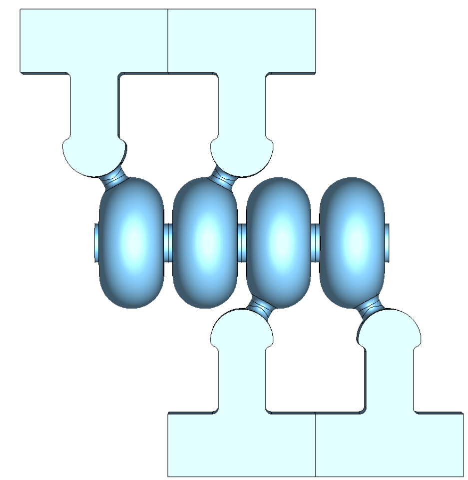


E-field in cut plane



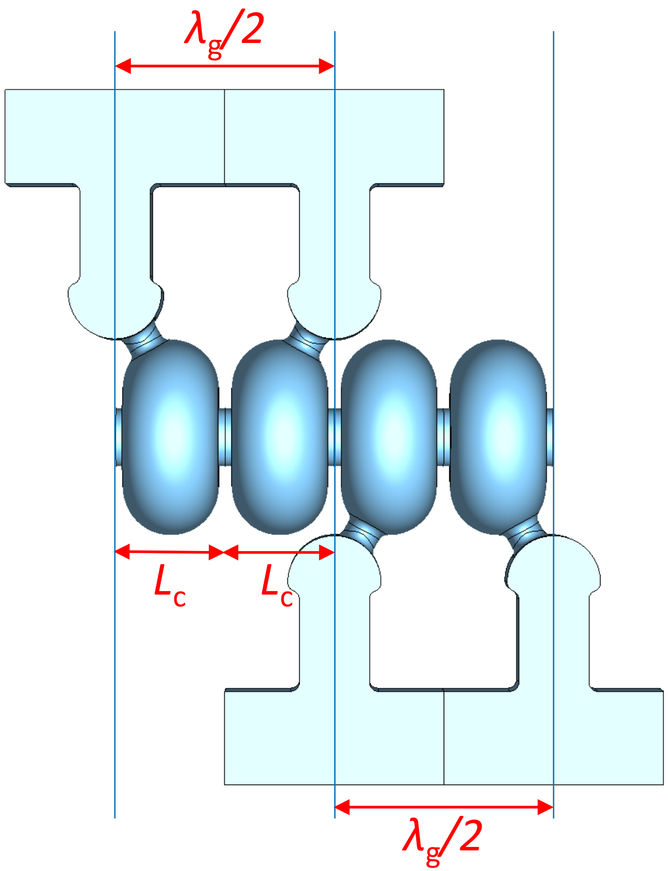
Power flow snapshot





CST calculated fields and power in the test cavity

Structure with distributed RF coupling – one period



$L_c = \beta\lambda/2; \quad \lambda = c/f$ - free-space wavelength

$\lambda_g/2 = 2L_c = \beta\lambda$ - to excite π-mode & ensure periodicity

Waveguide wavelength $\lambda_g = \lambda / \sqrt{1-(\lambda/\lambda_c)^2} \quad \Rightarrow$

$$\frac{\lambda}{\lambda_c} = \sqrt{1-\frac{1}{4\beta^2}}$$ – only possible for $\beta > 1/2$.

Since $\lambda_c = 2w, \quad w = \lambda / \sqrt{4-\beta^{-2}}$ - defines the WG width.

WG width *w* changes with *β*

WG width *w* is chosen to feed the *π*-mode and to match the structure and WG periods

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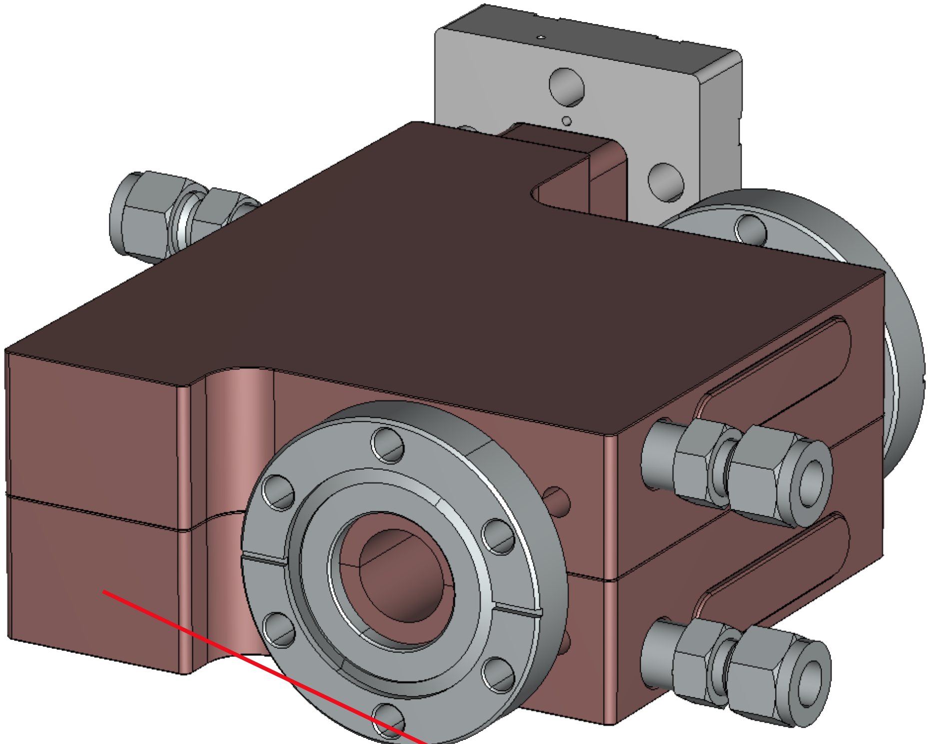
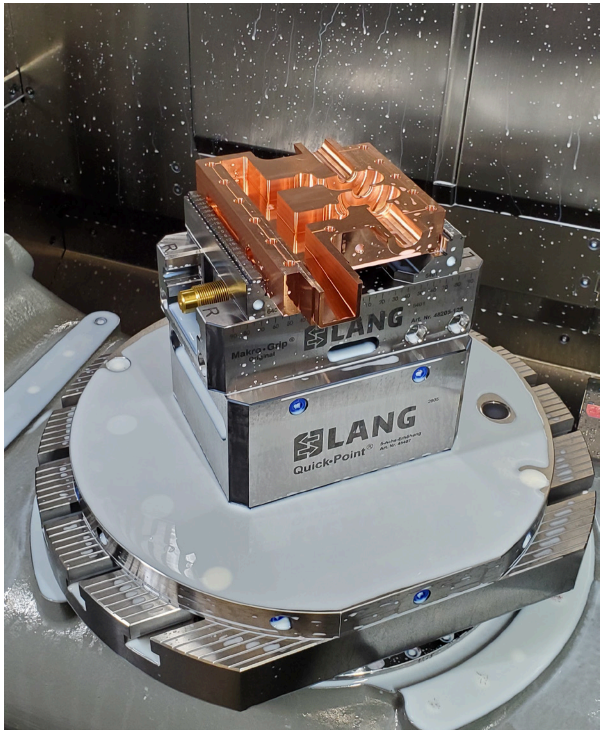
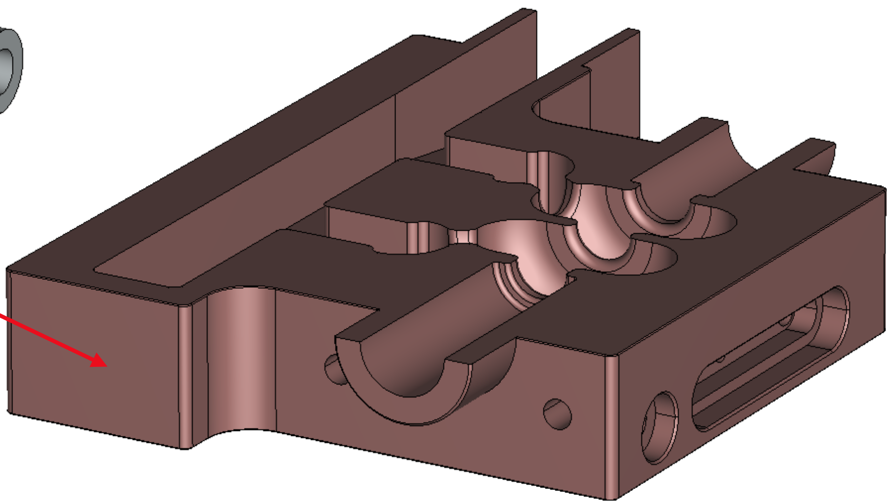
Test cavity is fabricated







Ph. Borchard, Dymenso, LLC

C-band test cavity: CAD model and machined half-structure (picture top right)

Summary

- A high-gradient (HG) booster linac for enhanced proton radiography (pRad) at LANSCE is designed to increase the beam energy from 800 MeV to 3 GeV. It is a unique application of HG normal-conducting cavities for protons made possible by pRad requirements of very short beam pulses at low duty.
- We continue development of high-gradient structures for the pRad booster. Our focus is on standing-wave π-mode S- and C-band structures with distributed RF coupling adapted for protons with β = 0.84-0.97 (beam energy from 800 MeV to 3 GeV).
- A short 2-cell C-band test cavity for β = 0.93 with distributed coupling was designed for frequency 5.712 GHz. The cavity is fabricated and delivered to LANL, and it will be tested soon at the LANL C-band RF test stand.

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