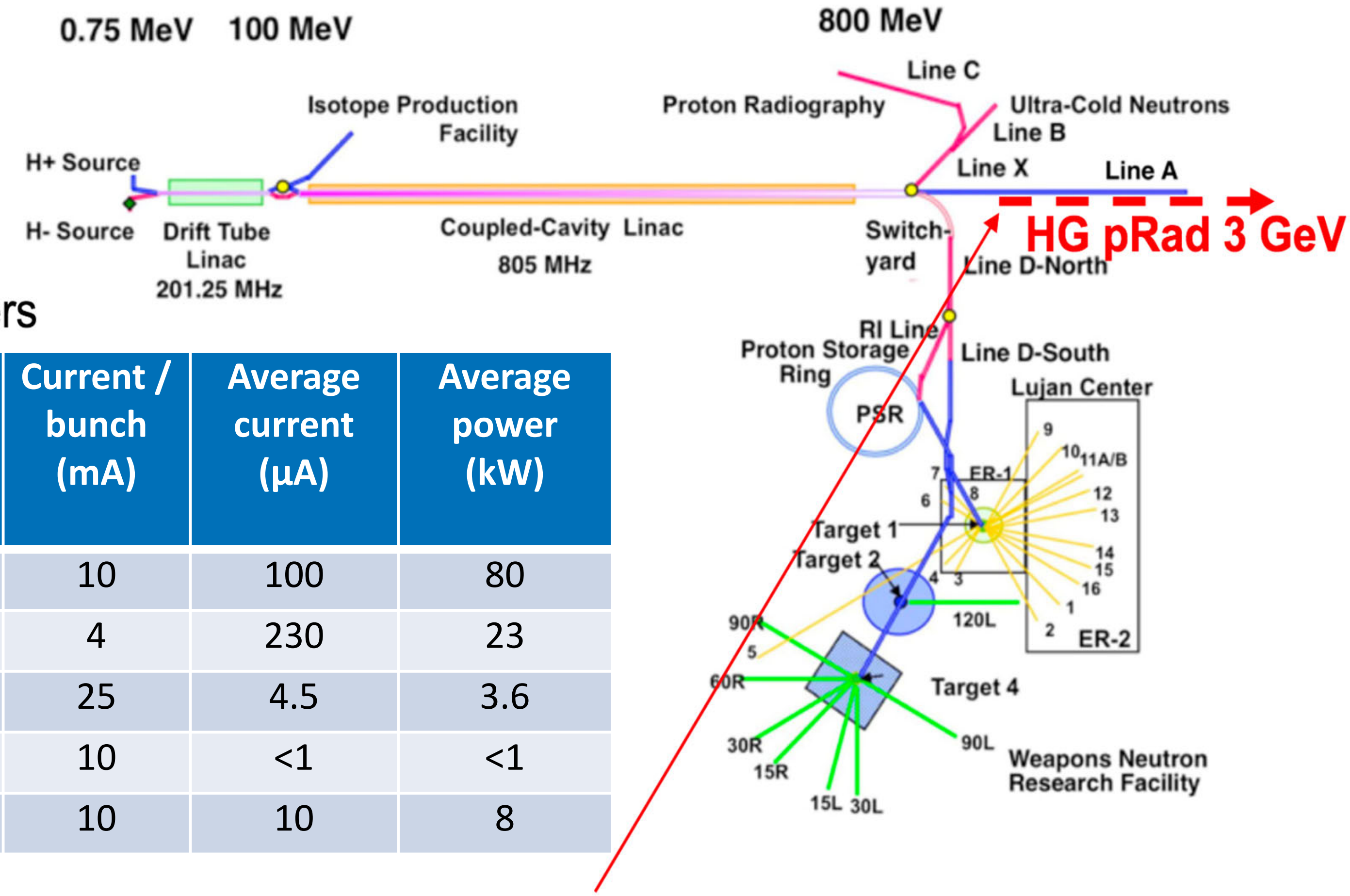
High-Gradient Booster Linac for Enhanced Proton Radiography at LANSCE

Evgenya Simakov, Sergey Kurennoy, Yuri Batygin, Eric Olivas, Haoran Xu, and Muhammed Zuboraj

Los Alamos National Laboratory, Los Alamos, NM, U.S.A.

HG 2023, Frascati, Italy
October 16-20, 2023

Los Alamos Neutron Science Center (LANSCE)



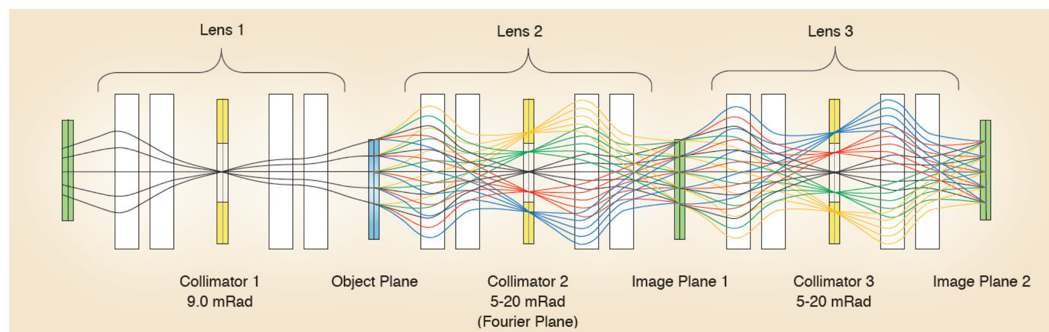
LANSCE Beam Parameters

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

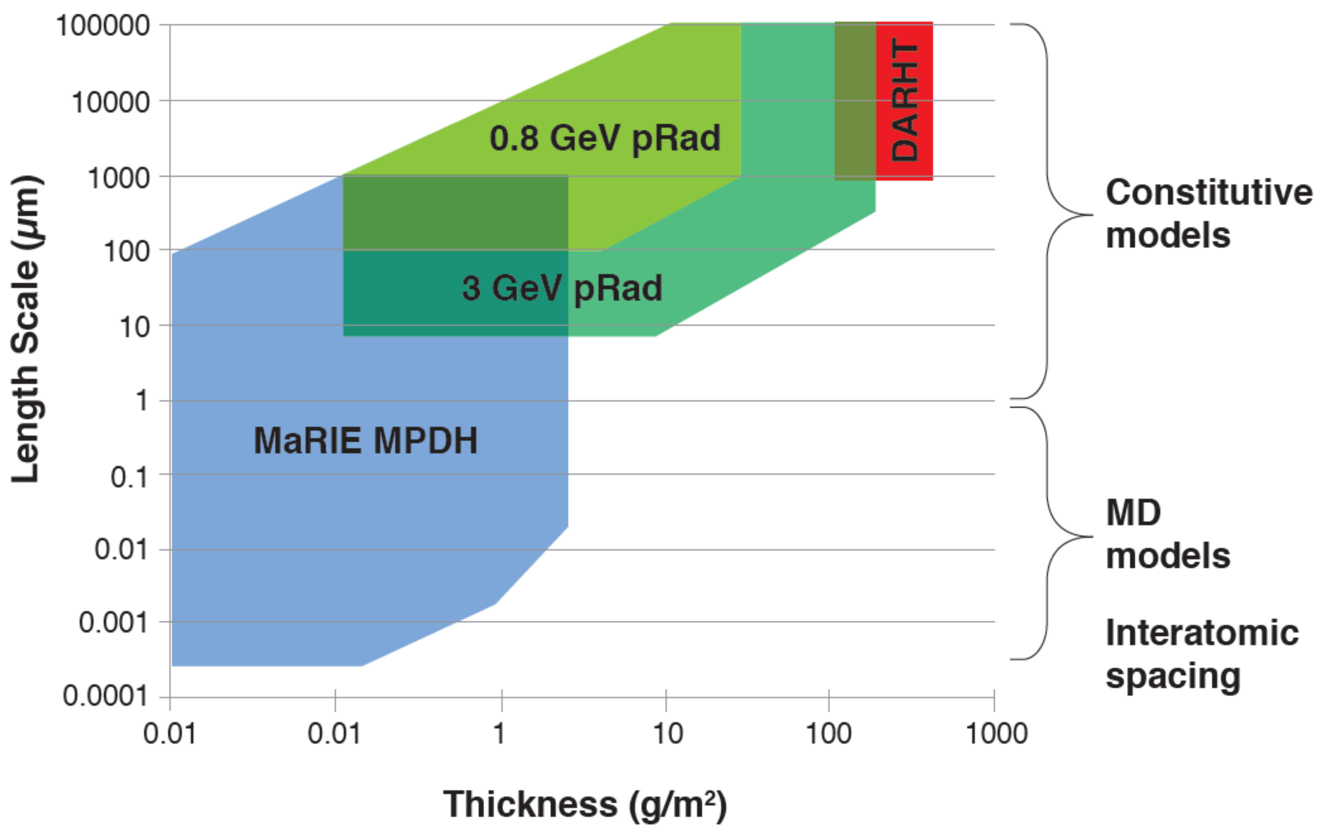
Proton radiography at LANSCE

- Uses 800 MeV proton pulses generated by the LANSCE linear accelerator.
- Capable to produce up to 42-frame movies in a dynamic event with frames separated by 200 ns.
- Capable of radiographing experiments with up to 50 g/cm^2 of line-integrated density through the object.
- The unique experimental capability for mission-relevant tests and fundamental discoveries.



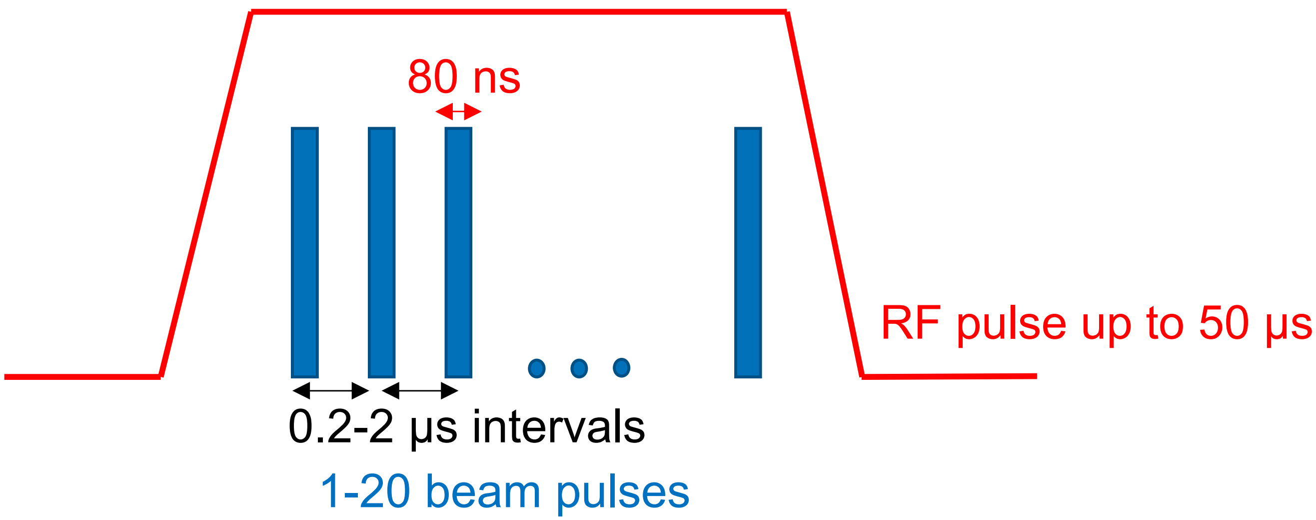
Compact High-Gradient Booster for Enhanced Proton Radiography

- Compact high-gradient linear accelerator boosting the energy of the existing LANSCE linac from 800 MeV to 3 GeV.
- Increases proton radiography resolution by 10 times.

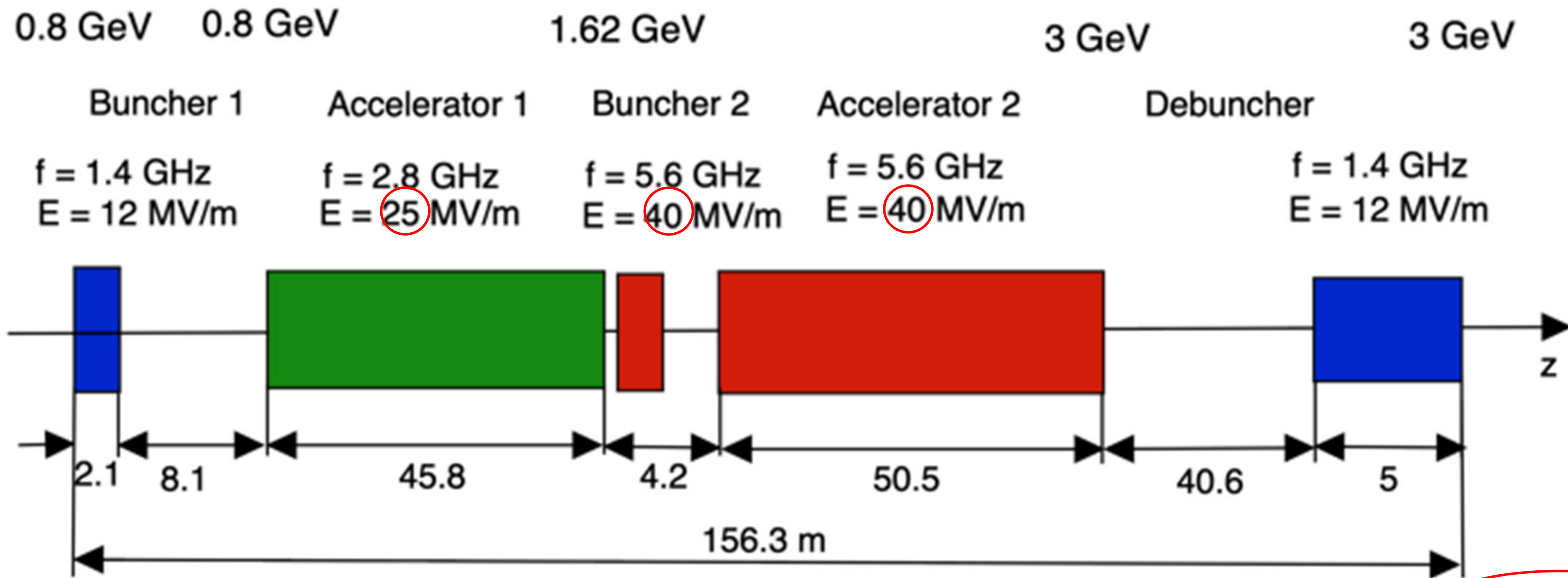


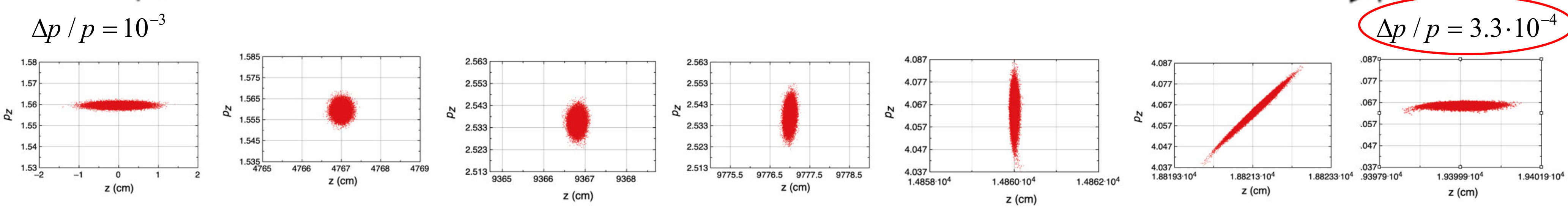
HG pRad Booster – Requirements

- 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 → $3.3\cdot10^{-4}$ at 3 GeV.
- Development of accelerator structures that support such a design:
  - HG structures have mostly been developed for electrons -> adapt for protons.
  - beam magnetic focusing scheme defines minimal allowable cavity apertures.
  - add L-band buncher & de-buncher + drifts to reduce beam energy spread.
  - standing-wave accelerator structures with distributed coupling are chosen.
- Single RF pulse up to 50 μs with power up to 10 MW.



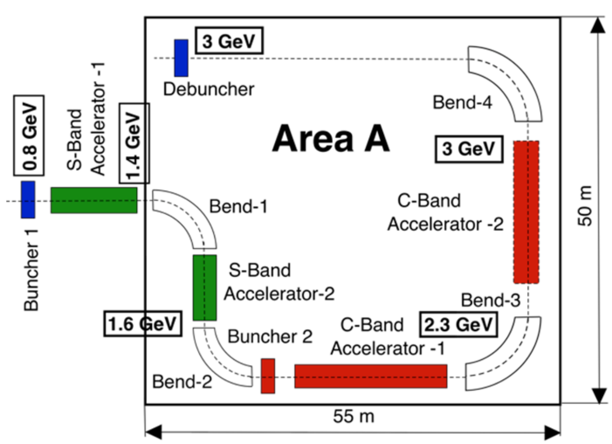
Proposed layout of the 3-GeV Booster





Evolution of Longitudinal Phase Space

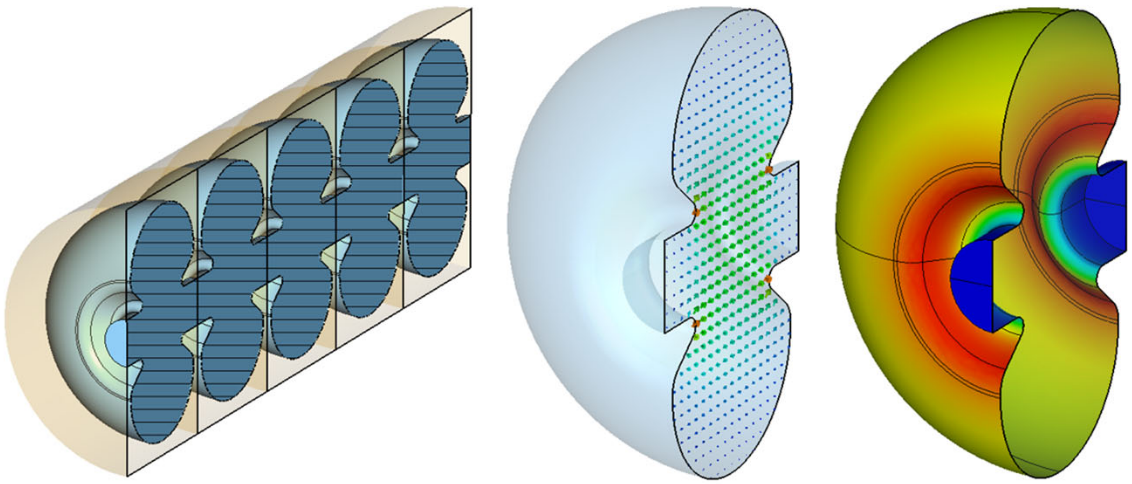
The booster with reduced gradients needs bends to fit into existing buildings but saves RF!



Los Alamos
NATIONAL LABORATORY

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($)!

Using distributed coupling structures increases shunt impedance and reduces required power. Example for β=0.93 C-band structure:

	a/λ	E_{max}/E	Z_0H_{max}/E	Z, MΩ/m	P, MW/m for 80 MeV/m
TW structure (2π/3)	0.122	3.15	1.31	37.3	171
Distributed-coupling structure (π/2)	0.122	2.32	2.32	71.4	89.6

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

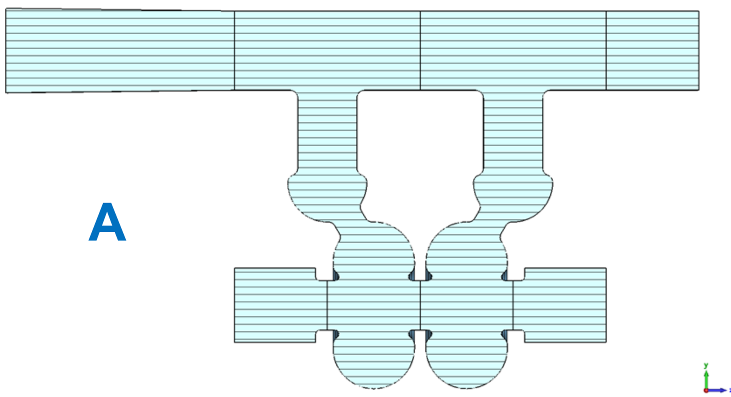
NAPAC22

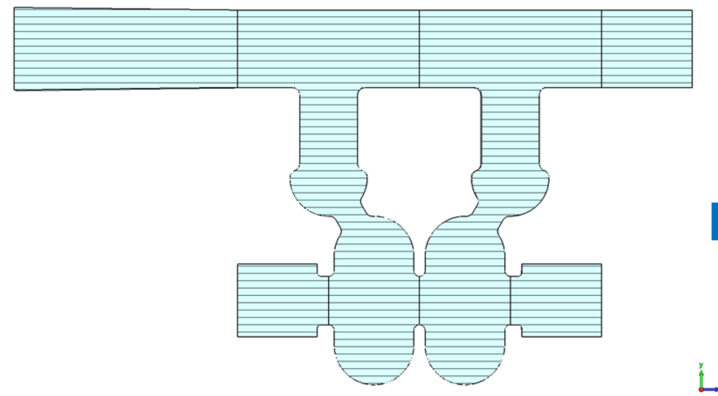
Cryo-cooled operation (LN_2) can reduce the RF power by a factor 3 and is well suited for pRad booster: < 50-μs single RF pulse, a few events per day.

- 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.

Selection of the test cavity shape

A





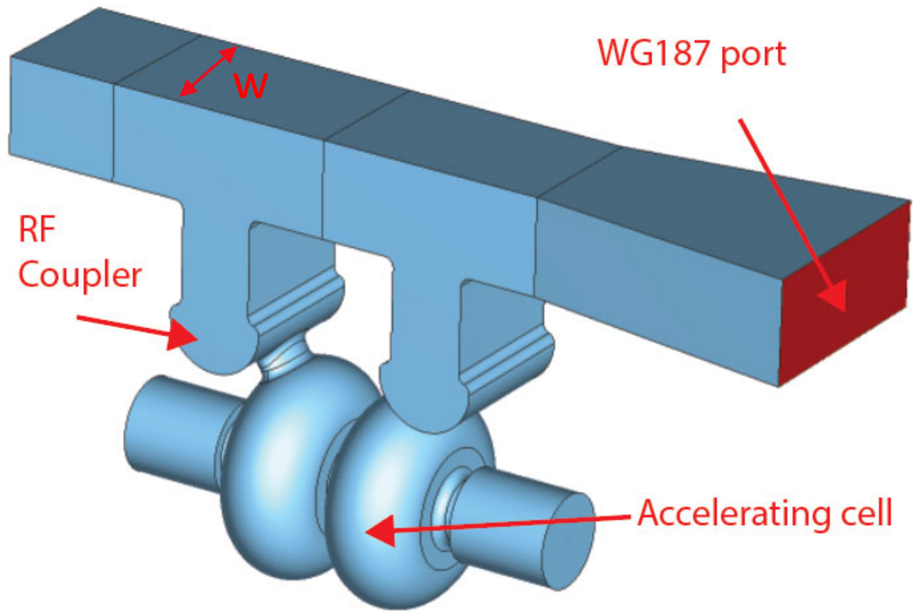
B

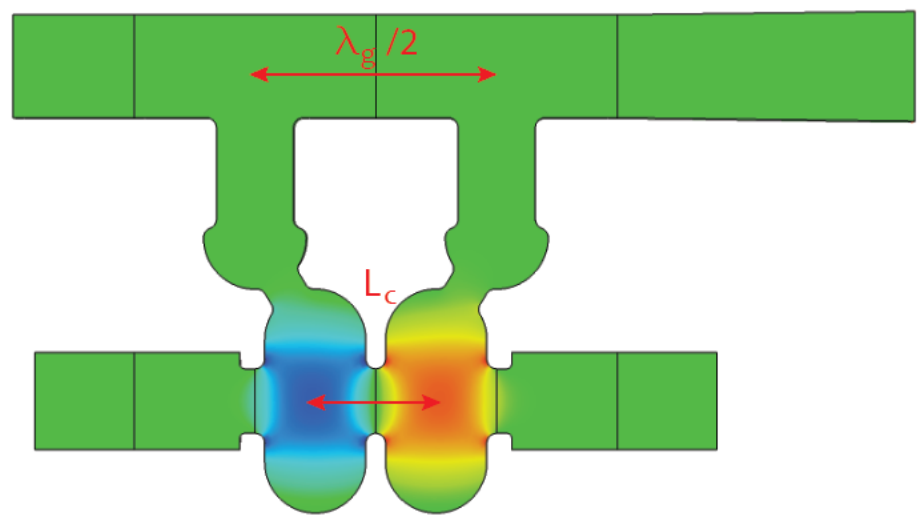
Comparison of two cavity types. f = 5.712 GHz; ideal Cu; E_{acc} = 80 MV/m

Re-entrant cavity, A		Simple cavity, B
0.7429	T	0.7346
12,746	Q_0	13,150
3.98	P, MW	4.37
3.67	E_{max} / E_{acc}	2.32
2.10	Z_0H_{max} / E_{acc}	2.32
78.6	Z'_{eff}, MΩ/m	71.4
81.5	P', MW/m	89.6

Two-cell test cavity with distributed coupling

- The test cavity was designed for 5.712 GHz (not 5.635 GHz), to be tested at LANL's CERF-NM.
- Two cells operate in a π-mode. Cell length adjusted for β = 0.93 (1.6-GeV protons).





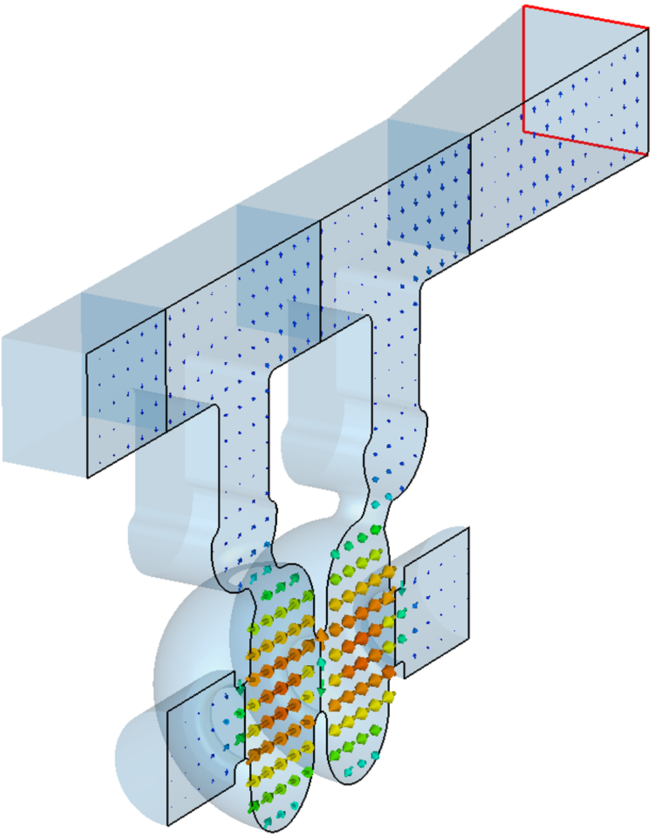
WG's width, w, is chosen to couple into the π-mode

Waveguide wavelength $\lambda_g = \lambda/\sqrt{1-(\lambda/\lambda_c)^2} = 4L_c$ for a long periodic structure.

$$L_c = \beta\lambda/2; \quad \lambda = c/f - \text{free}-\text{space wavelength.} \qquad w = \frac{\lambda}{\sqrt{4-\beta^2}}\ .$$

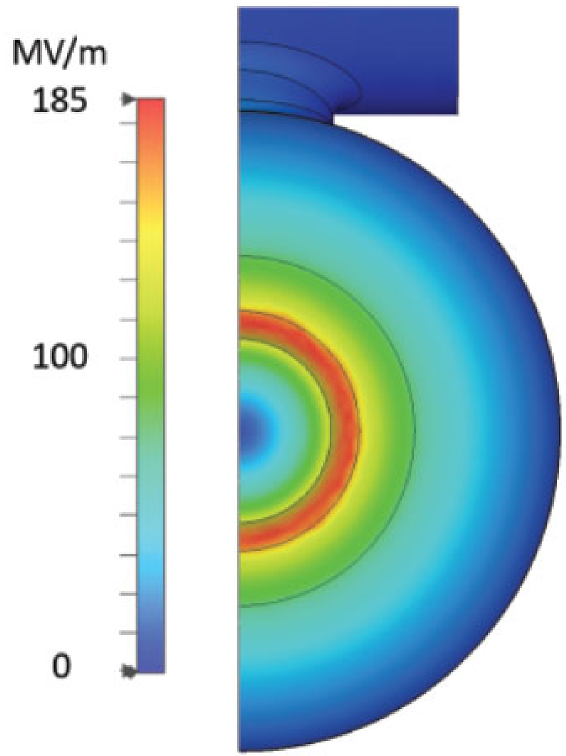
Fields in the test cavity

Electric field distribution in the longitudinal cross-section

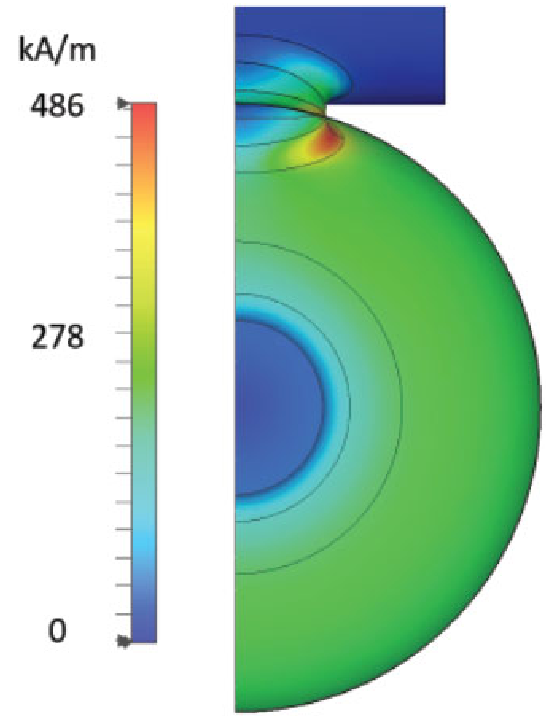


Peak surface fields for 100 MeV/m accelerating gradient

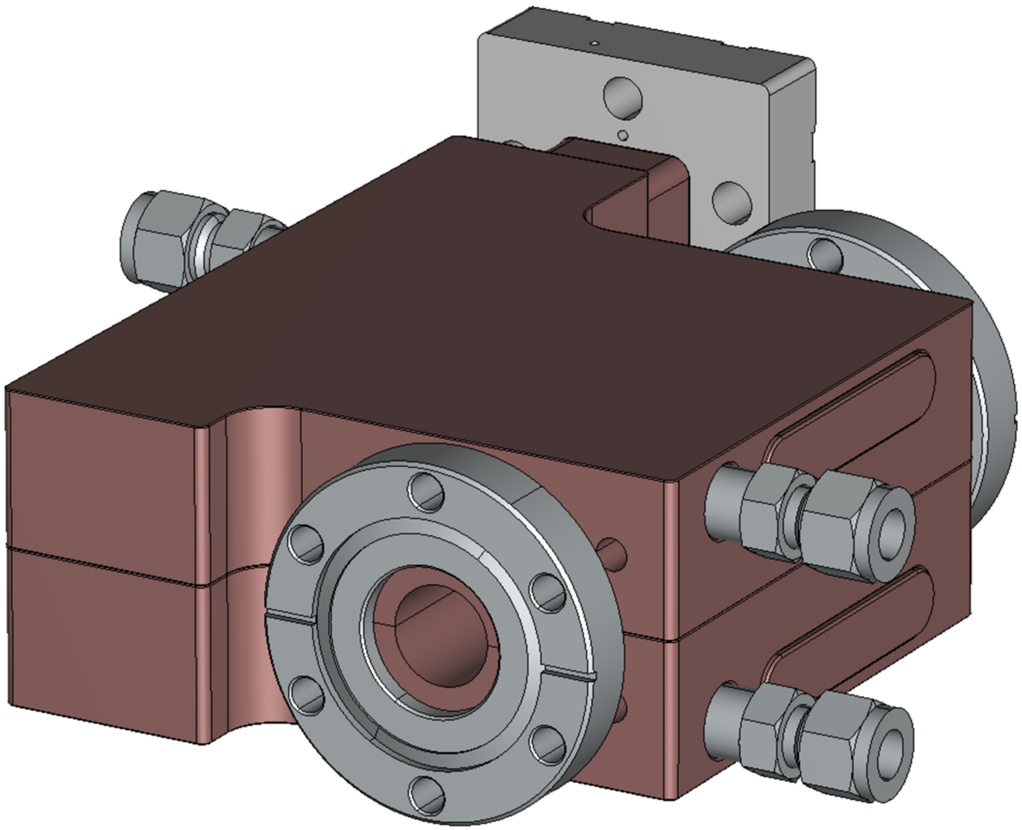
Electric field

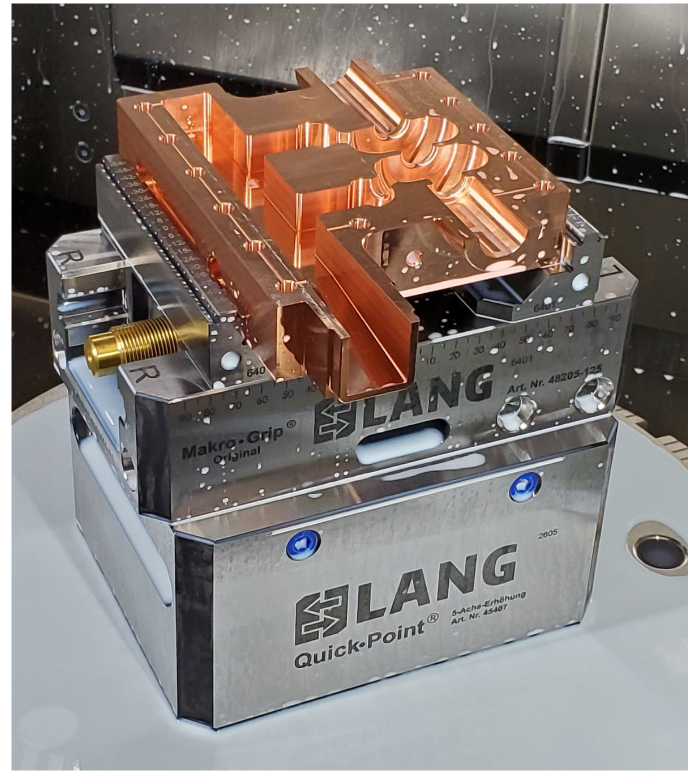


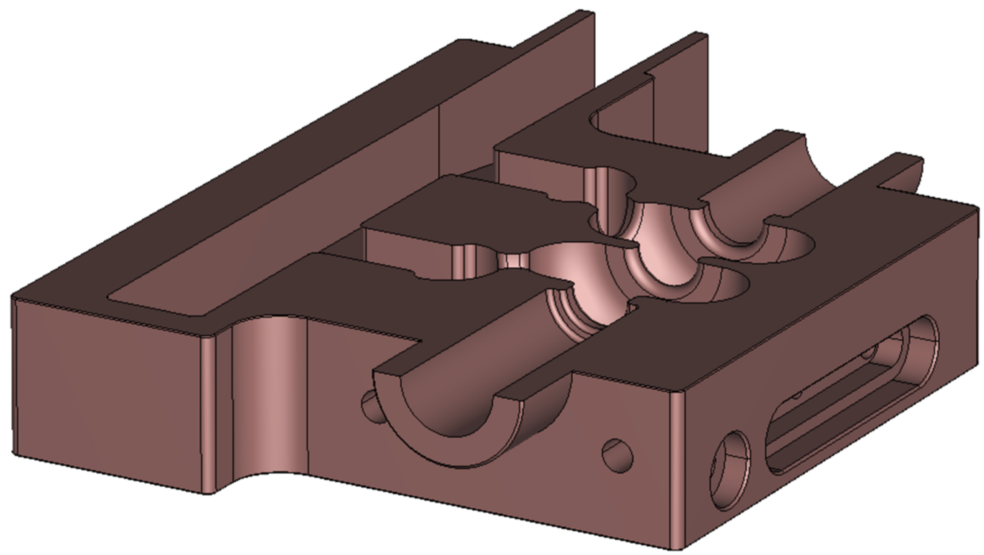
Magnetic field



Fabrication of the two-cell test cavity



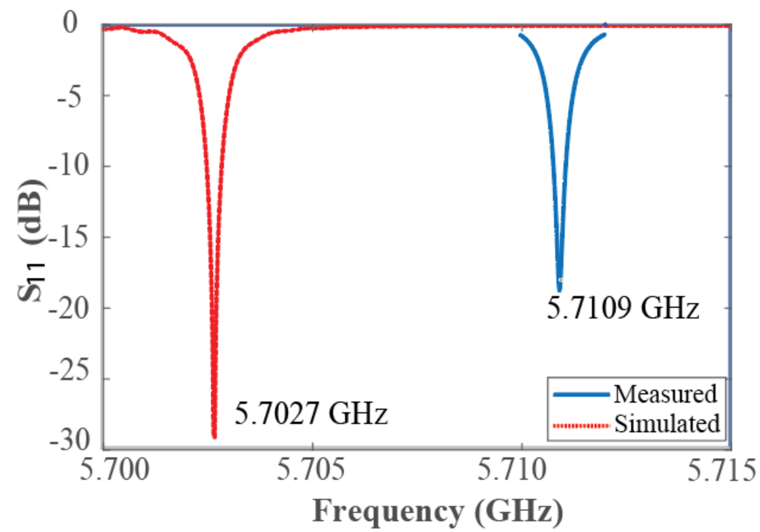


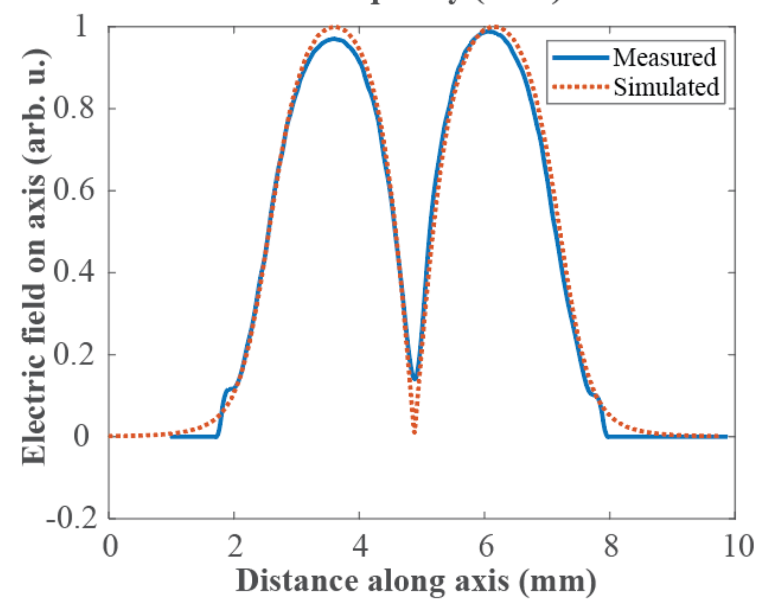


Fabrication was performed by Dymenso, LLC

Cavity tuning

- The cavity design resulted in the initial cavity's frequency of 5703.4 MHz in air, very close to MWS simulations of 5702.7 MHz in air.
- The cavity was tuned to 5710.9 MHz in air. Field profile was tuned to balance the field in two cells.



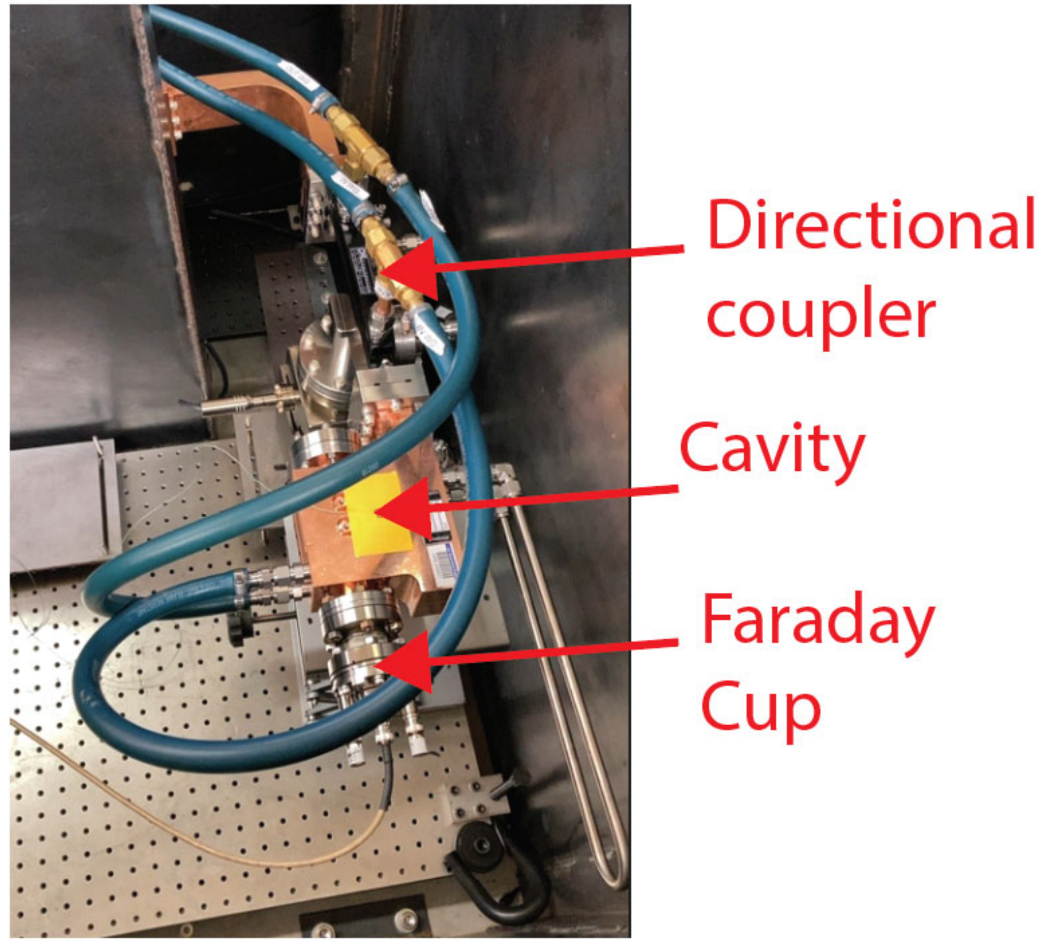


	Calculated	Before tuning	After tuning
Frequency in air	5702.7 MHz	5703.4 MHz	5710.9 MHz
Frequency in vacuum	5704.4 MHz	5705.1 MHz	5712.6 MHz
Ohmic Q-factor	13150	12820	13238
External Q-factor	11000	10815	10137

High gradient testing at CERF-NM

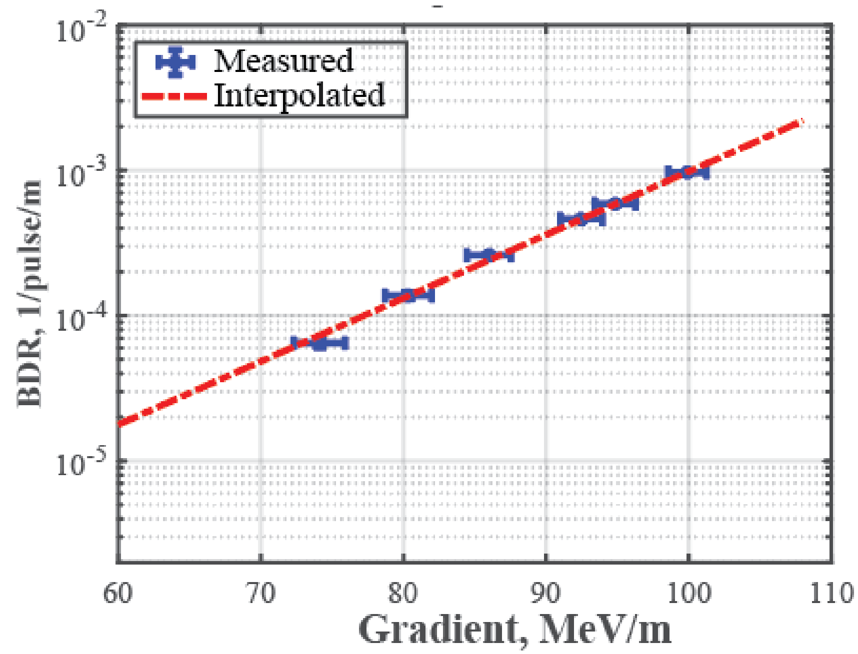
CERF-NM was built with $3M of LANL's internal infrastructure investment.

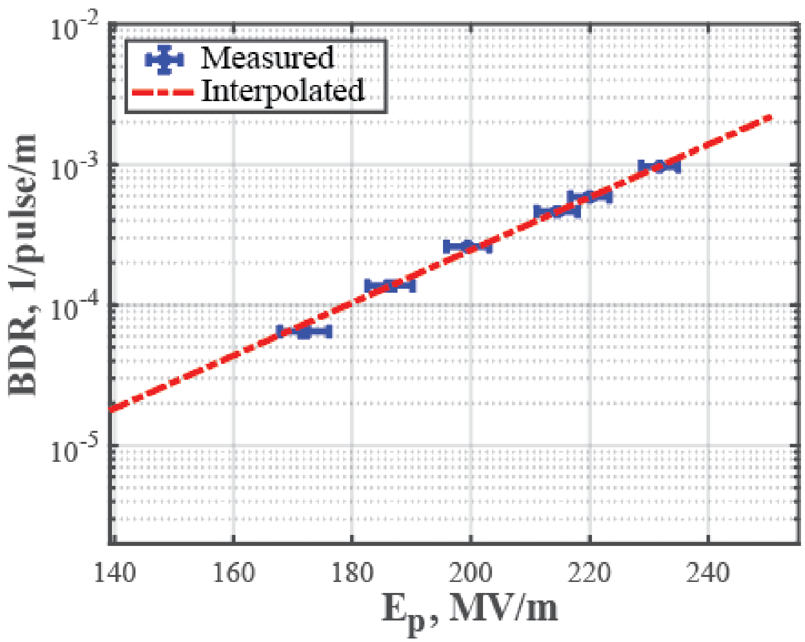
- Powered with a C-band Canon klystron
- Conditioned to 50 MW
- Frequency 5.712 GHz
- 300 ns – 1 μs pulse length
- Rep rate up to 200 Hz (typical 100 Hz)
- Nominal bandwidth 5.707-5.717 GHz

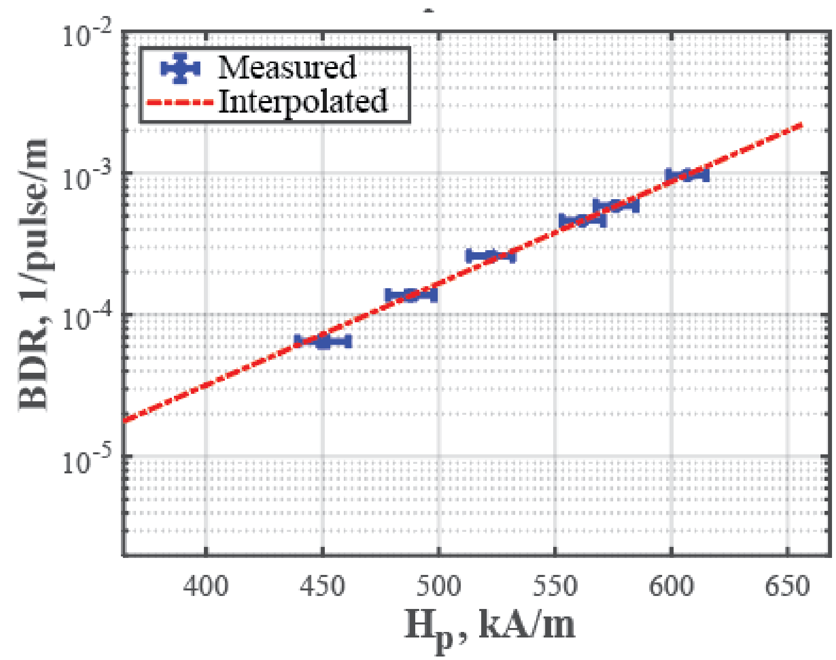


High gradient testing results

- Breakdown rates were mostly dominated by peak surface magnetic fields.
- Cavity's post-mortem exam is pending.

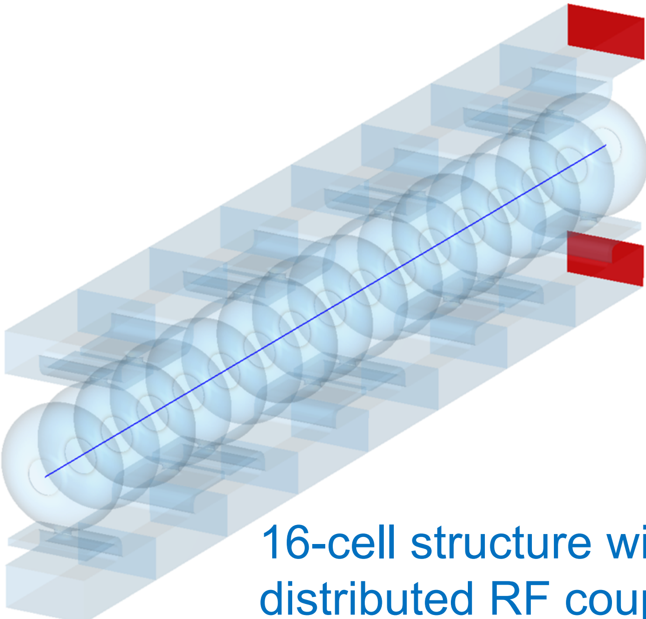




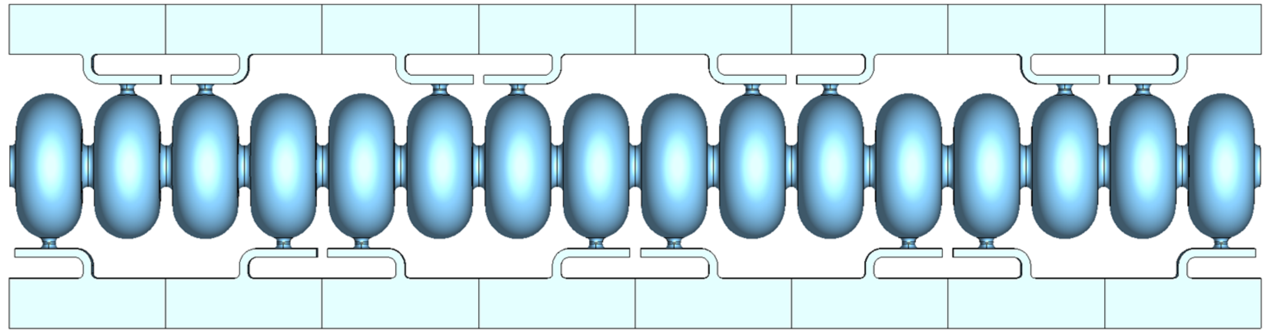


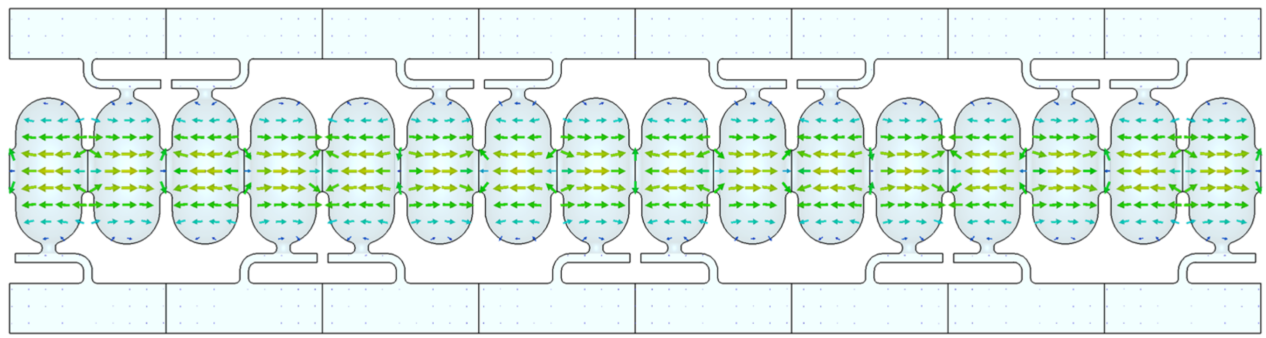
Los Alamos NATIONAL LABORATORY

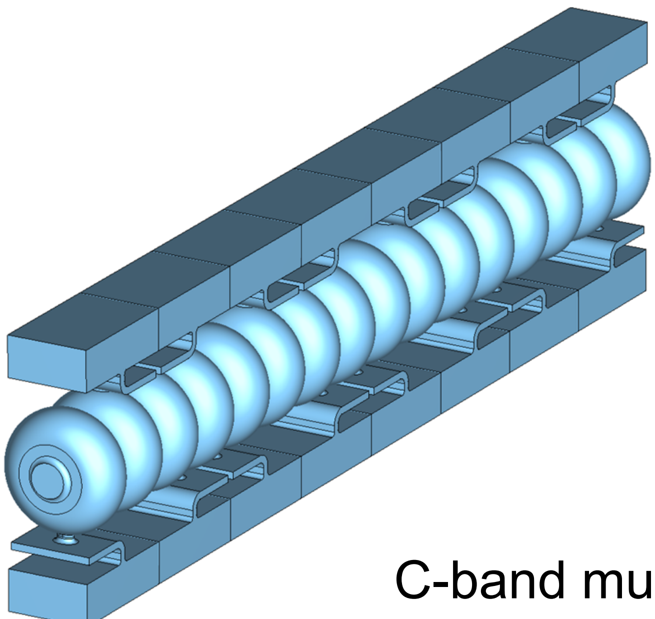
Work in progress: multi-cell structure modeling with CST



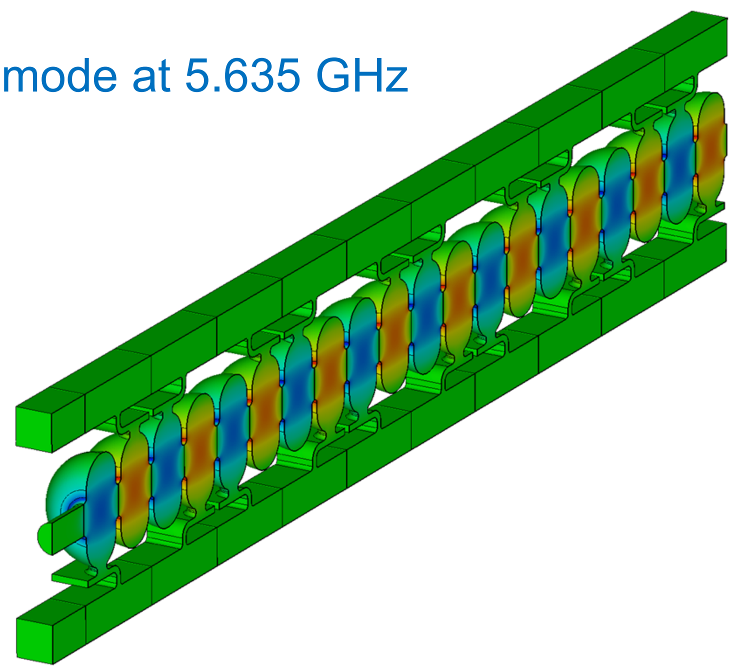
16-cell structure with distributed RF coupling







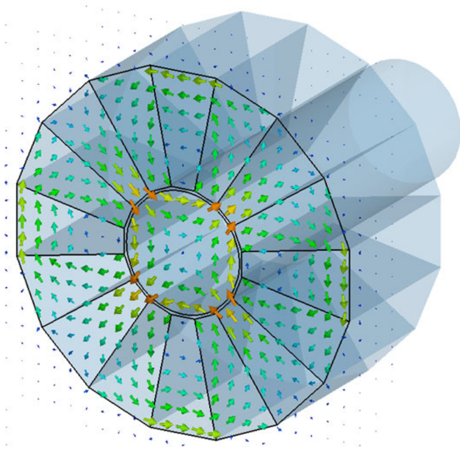
Electric field of the π-mode at 5.635 GHz



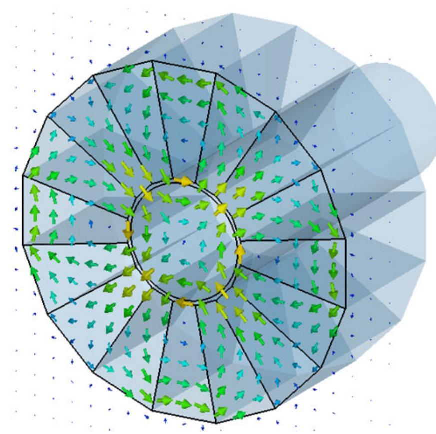
C-band multi-cell structure modeling
(β = 0.93, 1.6 GeV protons)

Los Alamos
NATIONAL LABORATORY

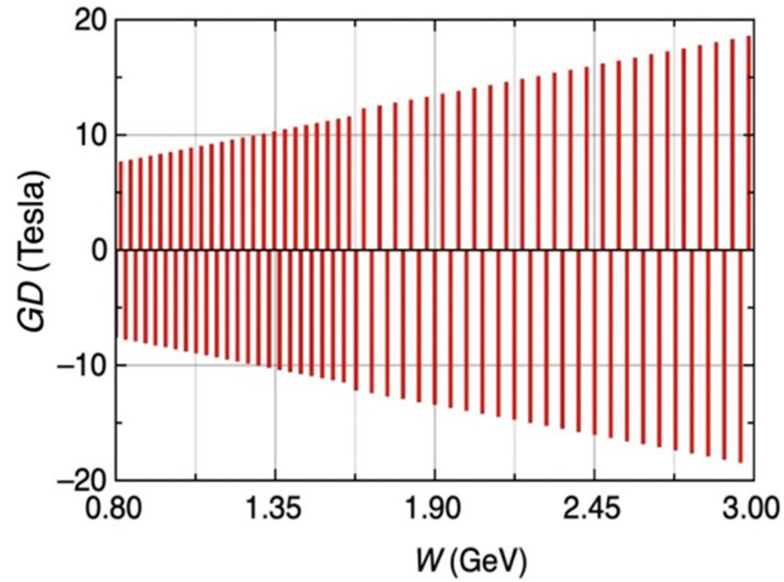
Work in progress: beam focusing with PMQs



800 MeV (β = 0.84)
a = 0.8 cm, L = 4.6 cm
GL = 6.3 T

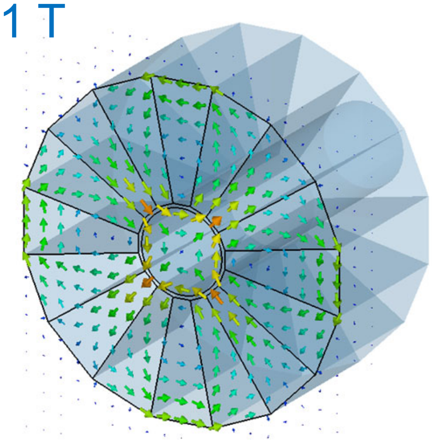


1.6 GeV (β = 0.93)
a = 0.65 cm, L = 6.8 cm
GL =11.4 T



Quad focusing strength GL vs proton beam energy

SmCo, B_r = 1 T



3 GeV (β = 0.97)
a = 0.5 cm, L = 7.7 cm
GL = 18.4 T

CST modeling of 16-segments PMQs for L-, S-, C-band accelerating structures

Summary

- An HG booster linac for enhanced pRad at LANSCE is designed to increase the beam energy from 800 MeV to 3 GeV.
- A unique application of HG normal-conducting cavities for protons.
- A 2-cell C-band test cavity for β = 0.93 was designed for frequency 5.712 GHz.
- The cavity was fabricated, tuned, and high-power tested at the LANL's CERF-NM test stand.
- We continue development of HG structures for pRad, focusing on standing-wave π-mode S- and C-band structures with distributed RF coupling for protons with β = 0.84-0.97.
- Multi-cell accelerating structures with distributed RF coupling and magnetic focusing elements (PMQs) – work in progress.

This work is supported by the LANL LDRD program