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Progress on a High-Gradient Booster Linac for Multi-GeV Proton Radiography at LANSCE

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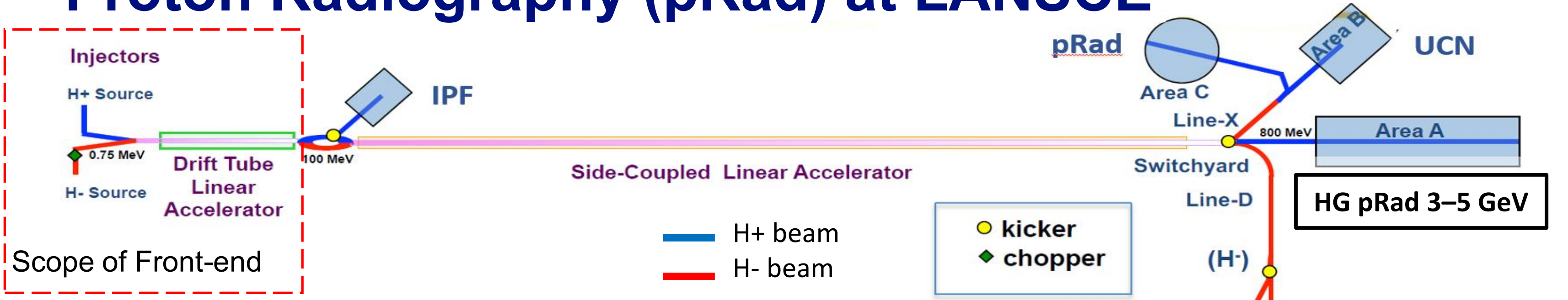
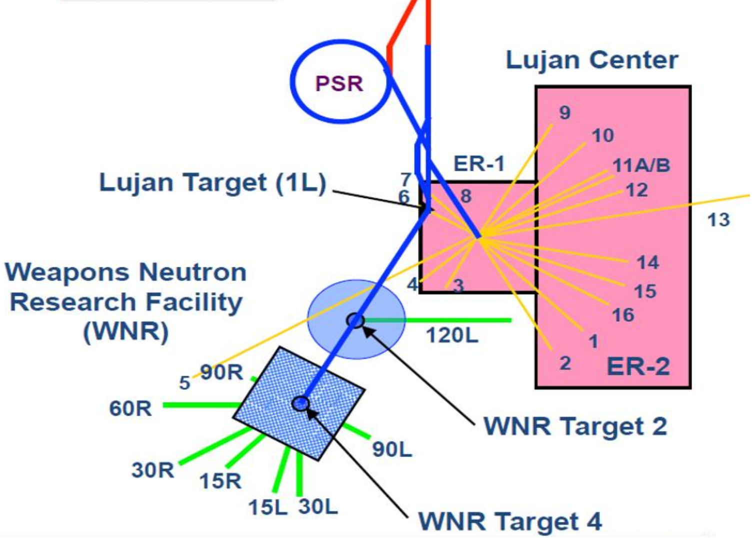
DYMENSO

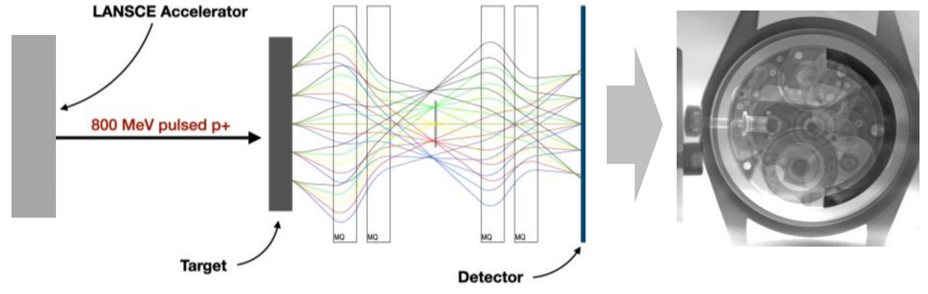
Outline

- Proton Radiography at LANSCE
- High-energy booster linac
- Theory and cavity prototyping
  - Room-temperature test
  - Liquid-nitrogen-temperature test

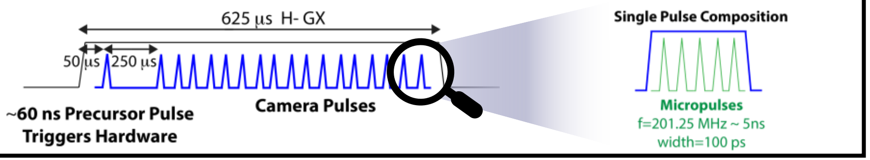
Proton Radiography (pRad) at LANSCE





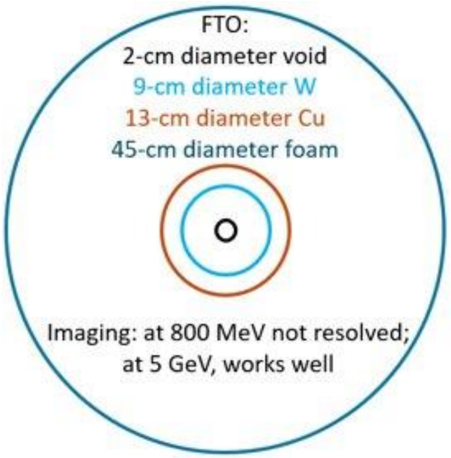


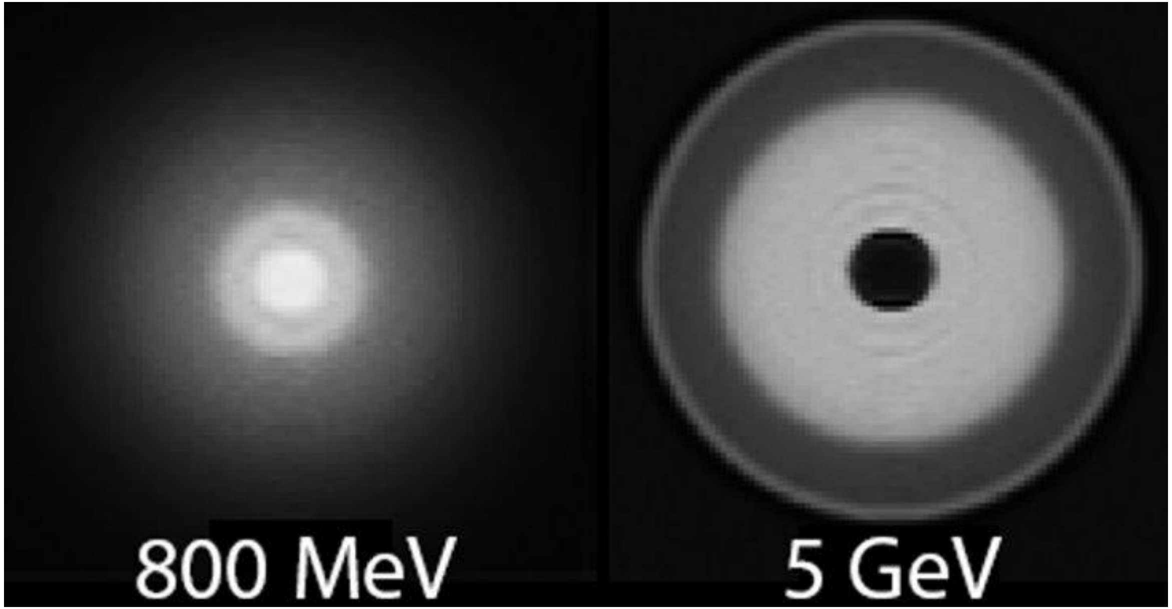
pRad: Multi-frame film; very low duty: a few events per day.



Proton Radiography vs Beam Energy

- “French Test Object”



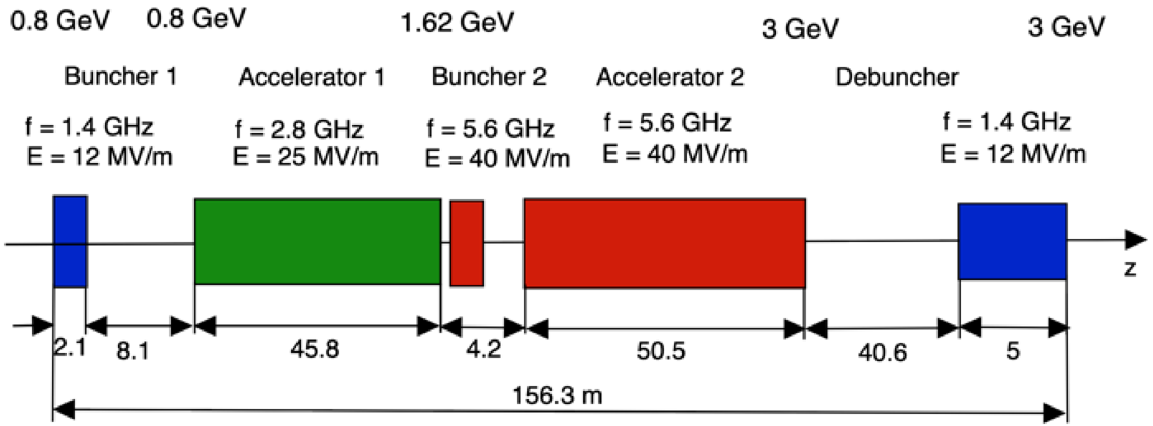


Beam energy increase from 800 MeV to 3–5 GeV enhances pRad resolution by one order of magnitude

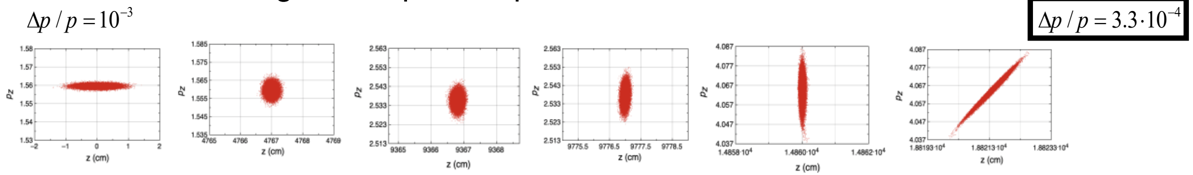
* J. L. Schmidt *et al.*, “Adjustable collimation for dark-field proton radiography contrast enhancement,” *Rev. Sci. Instrum.* 97:053304 (2026).

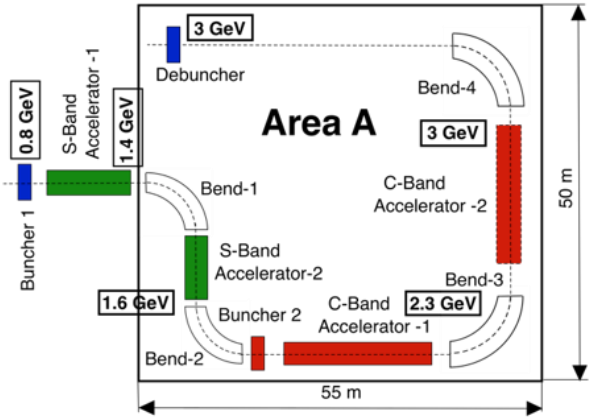
pRad Energy Booster Linac: 3 GeV

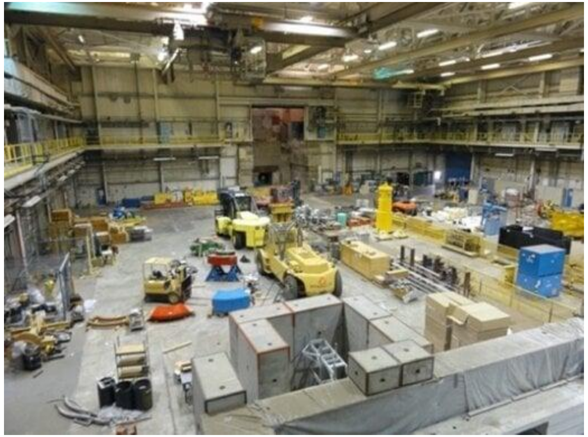
- Beamline layout



Evolution of longitudinal phase space:





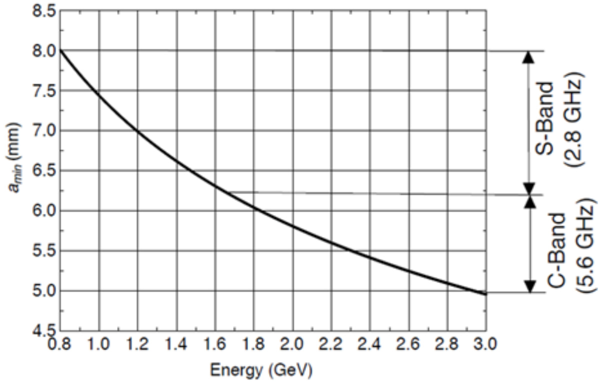


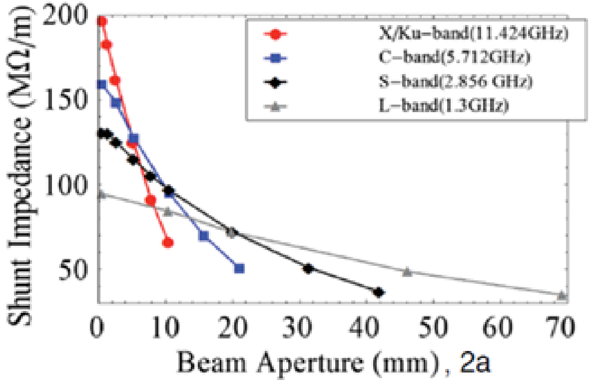
Experimental Area A

* S. S. Kurennoy *et al.*, "Accelerating structures for high-gradient proton radiography booster at LANSCE," in *Proc. NAPAC2022*, pp. 894-896 (2022).

pRad Energy Booster Linac: Design Considerations

- Shunt impedance and acceptance:
  - Beam aperture
  - RF frequencies

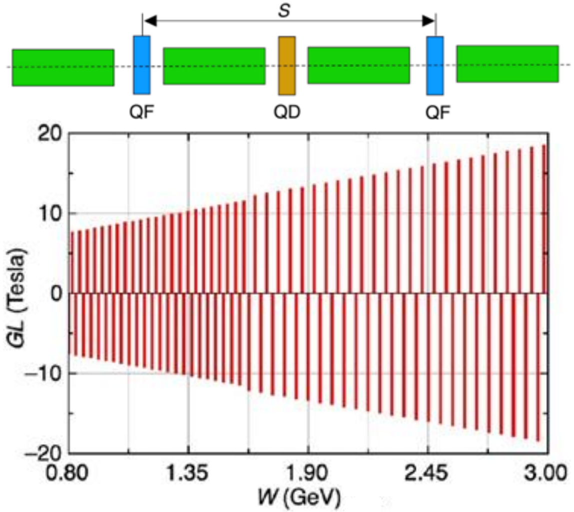




Transverse acceptance at LANSCE CCL exit: 3.5 π·cm·mrad

Minimum aperture: $a_{min} = 10 \cdot (\beta\gamma)^{-1/2}$ [mm]

- FODO focusing (S = 2 m)



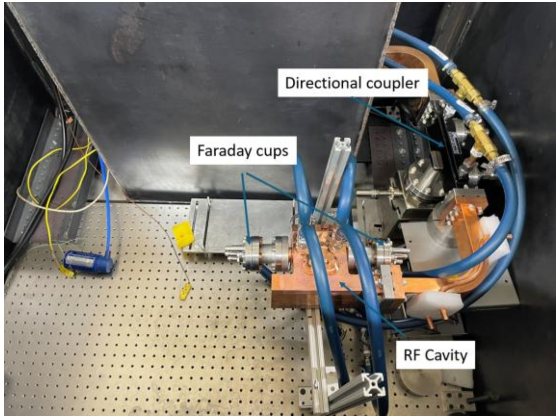
$$GL = \mu_o \frac{mc\beta\gamma}{qS} \frac{1}{\sqrt{1-(4/3)(L/S)}}$$

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

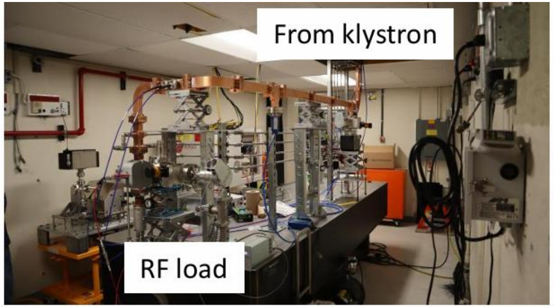
* Y. K. Batygin and S. S. Kurennoy, "Design of 3-GeV high-gradient booster for upgraded proton radiography at LANSCE," in *Proc. NAPAC2022*, pp. 891-893 (2022).

LANL C-Band Test Stands

CERF-NM



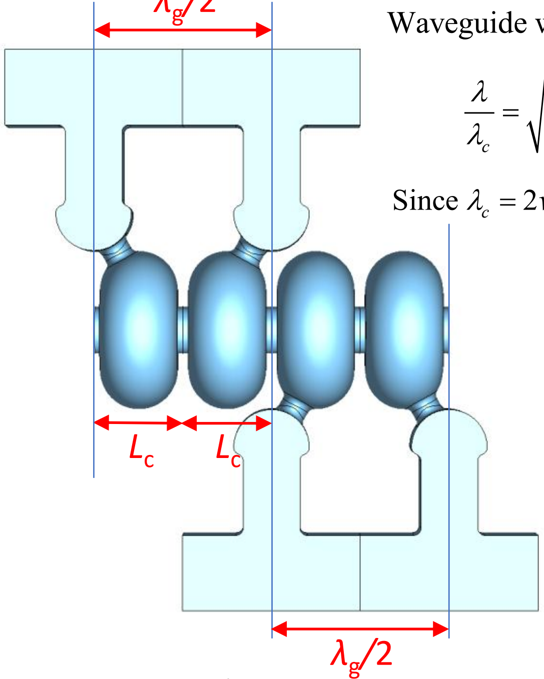
CARIE



* E. I. Simakov *et al.*, “Status of the CARIE high gradient photocathode test facility at LANL,” in *Proc. IPAC2026*, pp. 1731–1734 (2026).
* E. I. Simakov *et al.*, “High gradient testing of a two-cell C-band accelerator cavity with NiCr higher-order mode absorbers,” in *Proc. IPAC2026*, pp. 1727–1730 (2026).

Prototyping: Theory and Room-Temperature Test

Distributed coupling
Subrelativistic structure



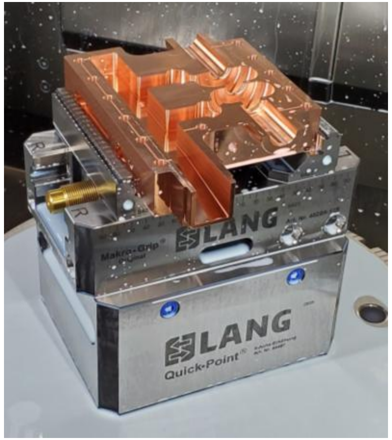
$L_c = \beta\lambda/2; \quad \lambda = c/f$ - free-space wavelength

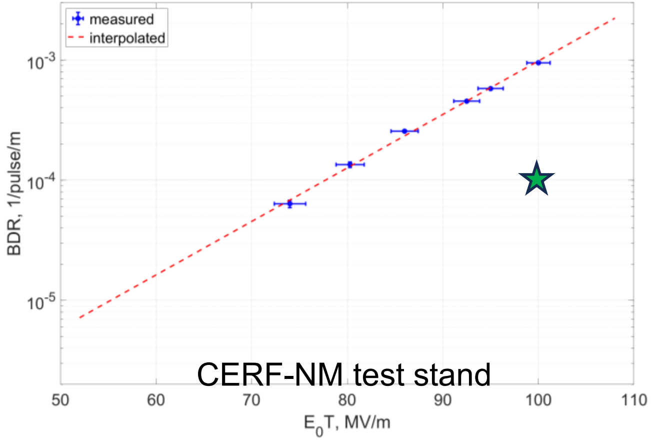
$\lambda_g/2 = 2L_c = \beta\lambda$ - to excite π-mode & ensure periodicity

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

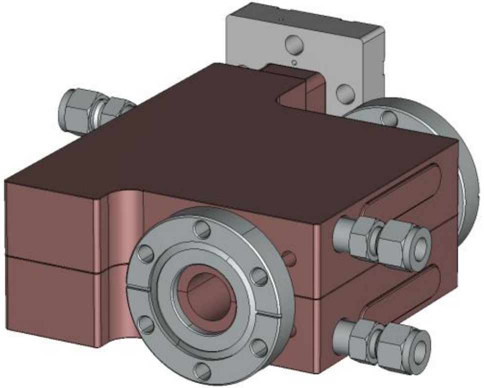
$$\frac{\lambda}{\lambda_c} = \sqrt{1-\frac{1}{4\beta^2}} \text{ – only possible for } \beta > 1/2.$$

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





CERF-NM test stand

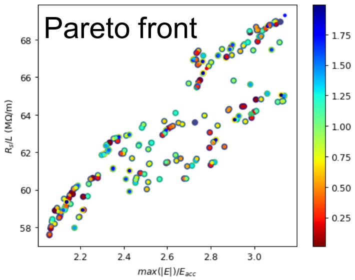


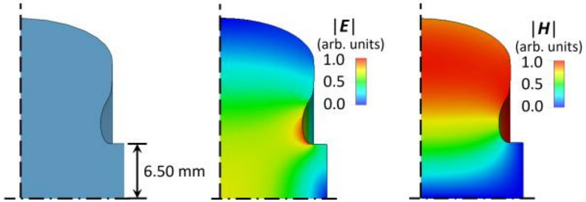
* M. Zuboraj *et al.*, "High-gradient performance of a prototype accelerator cavity for a 3 GeV proton radiography booster," *Phys. Rev. Accel. Beams* 27:021001 (2024).

Prototyping: S- and C-Band for Liquid-Nitrogen T.

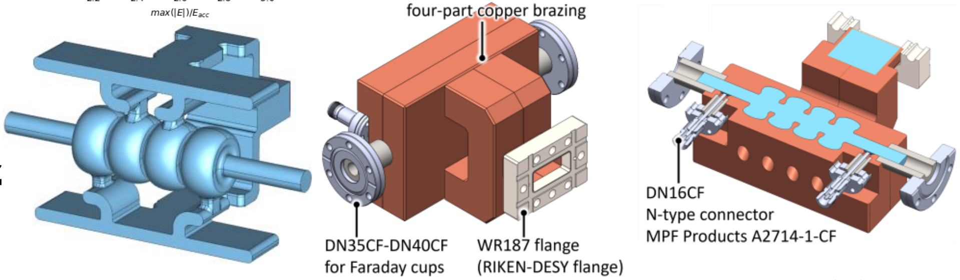
- Anomalous skin effect (C-band example)
  - Assumption: $RRR = \frac{\rho(293\text{K})}{\rho(4.2\text{K})} \approx 100^*$
  - Bloch–Grüneisen model
    - $\sigma_{\text{ASE}}(77\text{ K}) = \frac{1}{\rho(77\text{ K})} = 4.42 \times 10^8$ S/m
  - Stupakov/Reuter–Sondheimer method
    - $Z_{s,\text{ASE}}(77\text{ K}) = \zeta \cdot Z_0 = (7.43 - 8.95i)\ \text{m}\Omega$
  - CST setup (assuming normal skin effect)
    - $\sigma = 4.09 \times 10^8$ S/m
- Thermal contraction
  - NIST fit equation and coefficients
  - $\alpha_L = 0.9970$
  - $f_0(293\text{K}) = 5.712\text{GHz} \times \alpha_L = 5694.65\text{GHz}$

- RF design at LANL (four-cell)
  - Multi-Objective Genetic Algorithm (Xopt) driving Superfish on LANL HPC.
  - CST Eigenmode & High-Frequency Solvers





individual-cell profile



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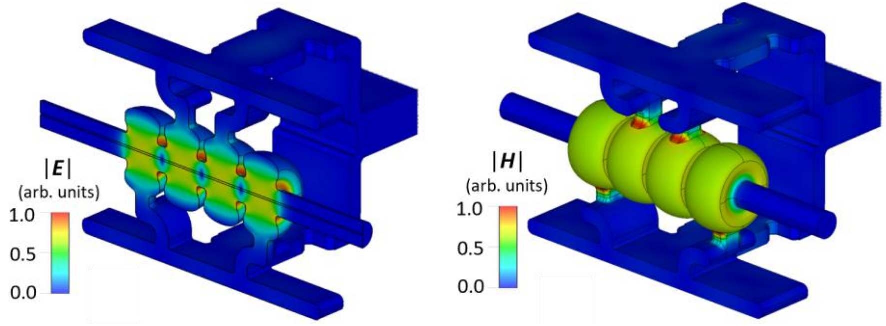
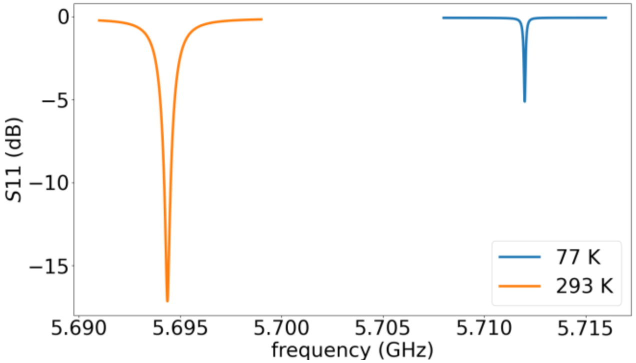
* M. Kaemingk *et al.*, “Genetic optimizations of RF cell profile using Superfish,” in *Proc. IPAC2026*, pp. 473–476 (2026).

Prototyping: S- and C-Band for Liquid-Nitrogen T.

C-band example





- S-band (0.8-GeV H⁻): eng., fab., and tests at RadiaBeam Technologies, LLC.

reso. freq.	2.856 MHz	shunt imp.	172 MΩ/m
293K-70K R_s fac.	2.69	power avail.	5 MW
CST elec. cond.	4.21e8 S/m	max gradient	69 MV/m
unloaded Q	46259	norm. peak E-fld	2.41
coupl. fac.	1.00	norm. peak H-fld	1.30

- C-band (1.6-GeV H⁻): eng. and fab. at Dymenso, LLC; tests at LANL's CARIE.

reso. freq.	5.712 MHz	shunt imp.	187 MΩ/m
293K-70K R_s fac.	2.65	power avail.	12 MW
CST elec. cond.	4.09e8 S/m	max gradient	121 MV/m
unloaded Q	32605	norm. peak E-fld	2.50
coupl. fac.	3.49	norm. peak H-fld	1.63

* S. S. Kurennoy *et al.*, "High-gradient booster linac for multi-GeV proton radiography at LANSCE," in *Proc. IPAC2026*, pp. 2428–2431 (2026).
* H. Xu *et al.*, "Plans for cryogenic C-band prototype tests for LANL pRad booster linac," in *Proc. IPAC2026*, pp. 2410–2413 (2026).

Summary

- Higher-energy Proton Radiography is desired for enhanced imaging resolution.
- Cryo-cooled RF linac is under investigation as a candidate technology for increasing Proton Radiography beam energy from 800 MeV to 3–5 GeV at LANSCE.
- A 3-GeV energy booster linac was conceptualized for fitting inside LANSCE Area A.
- Room-temperature 2-cell C-band prototyping and testing was successful.
- Liquid-nitrogen temperature 4-cel S- and C-band prototyping and testing are underway, at LANL and with industrial partners.