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Accelerating Structures for High-Gradient Proton Radiography Booster at LANSCE

Sergey Kurennoy, Yuri Batygin, and Eric Olivas
LANL, AOT Division

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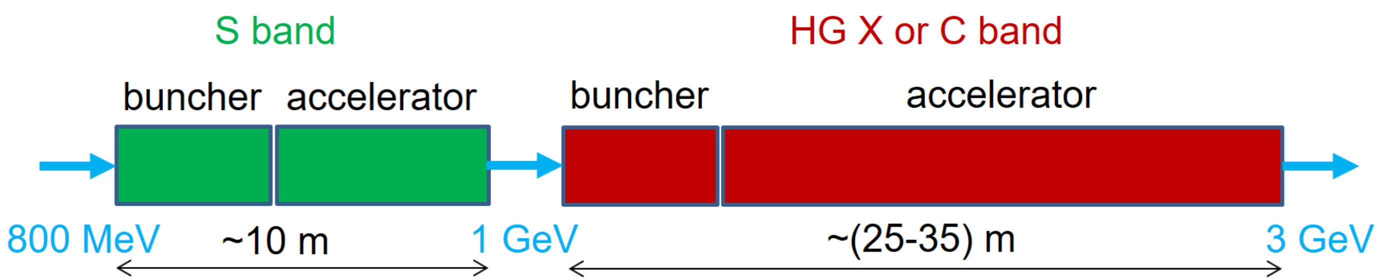
Compact High-Gradient Booster for Enhanced Proton Radiography

- 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.
  - Will be the first-ever high-gradient normal-conducting proton linear accelerator.

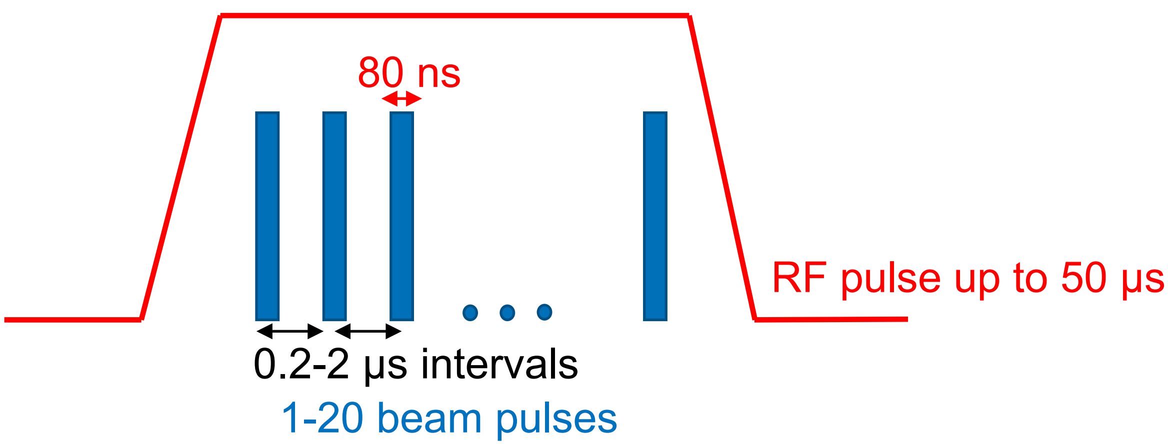


(Linac16)

HG pRad Booster – Requirements

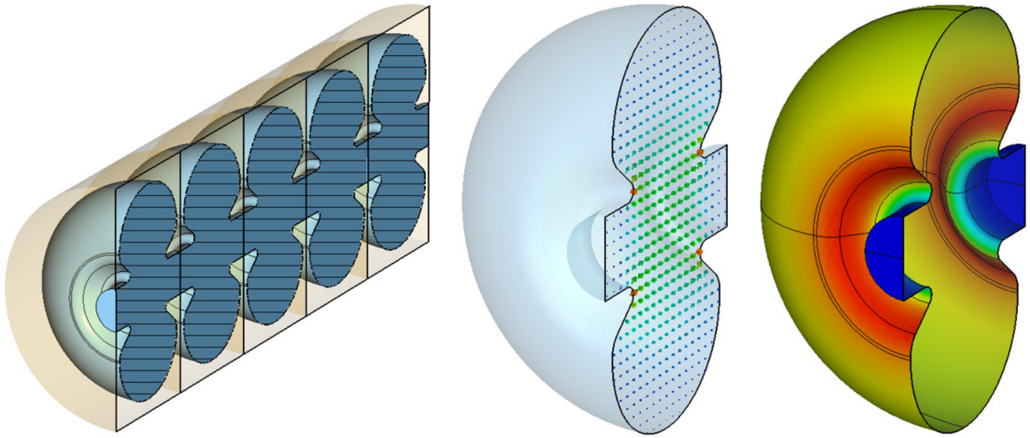
- Booster must satisfy pRad needs and fit the LANSCE site:
  - provide 1 to 20 short beam pulses (<80 ns) separated by variable intervals of 0.2-2 μs. Each short beam pulse contains proton bunches following at 5 ns (f_b = 201.25 MHz bunch repetition frequency) and gives one radiograph.
  - very low duty: one pulse train per event; a few events per day.
  - reduce relative energy spread at 3 GeV as ~1/p for good radiography quality: $\Delta p/p = 10^{-3}$ 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?

THZD3



High-Gradient Structure Development

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



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).

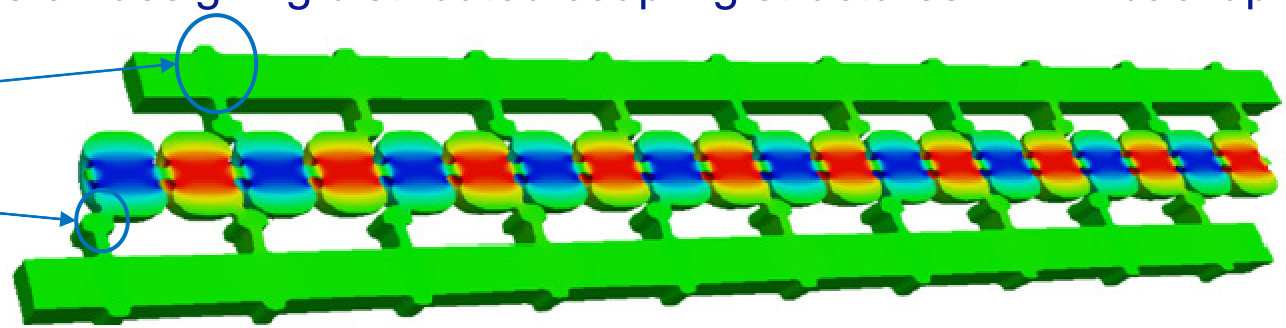
Cavity Parameters at Gradient *E*

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.

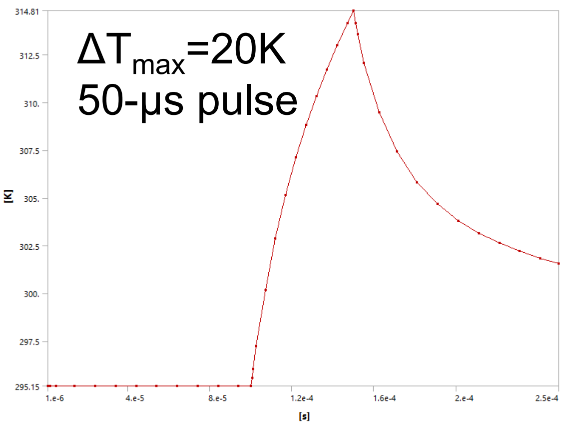
MDZE1

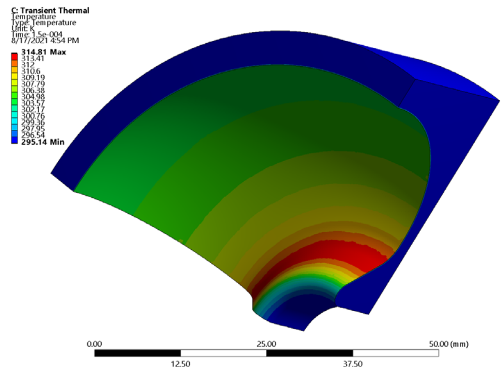


Ref: S. Tantawi *et al*. PRAB, **23**, 092001 (2020)

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)

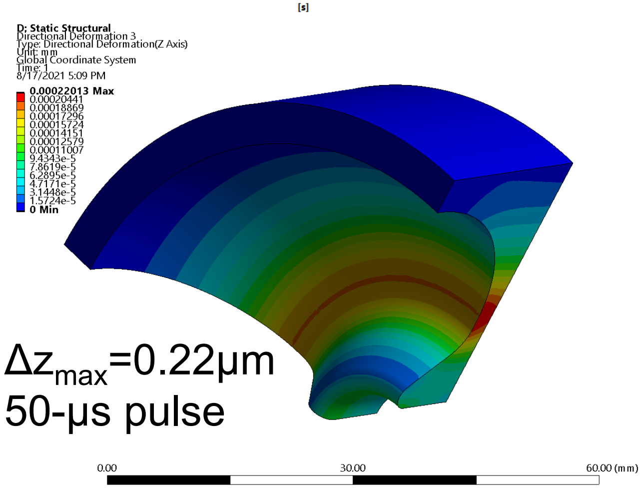




Cavity Parameters at Gradient *E*

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)

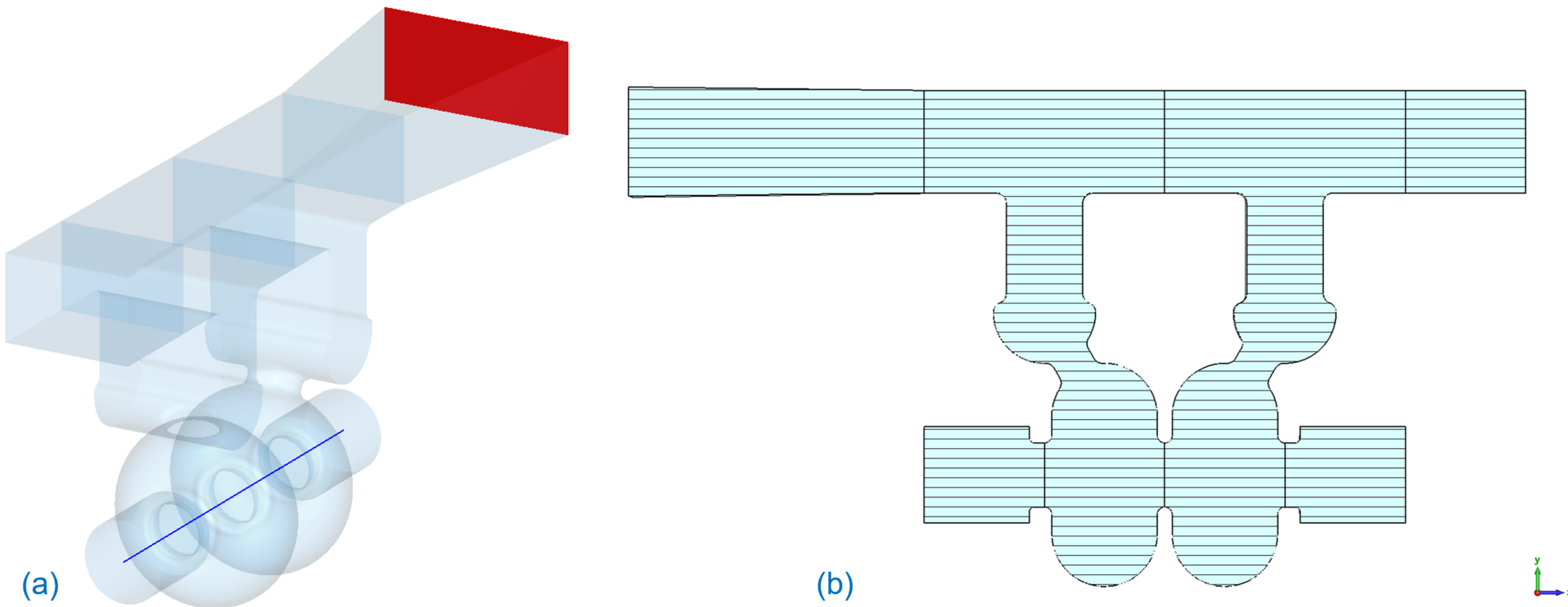
Booster	*L*, m	E_S, MV/m	P_S, GW	E_C, MV/m	P_C, GW
Design 1	92.5	36	0.42	100	1.9
Design 2	156.5	25	0.3	40	0.75

IPAC21 THZD3

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, it can be refilled before the next event. Cool!

- We will need high-peak-power klystrons (>10 MW) with a variable pulse length 2-50 μs at very low duty factor (single pulse). 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 require development.

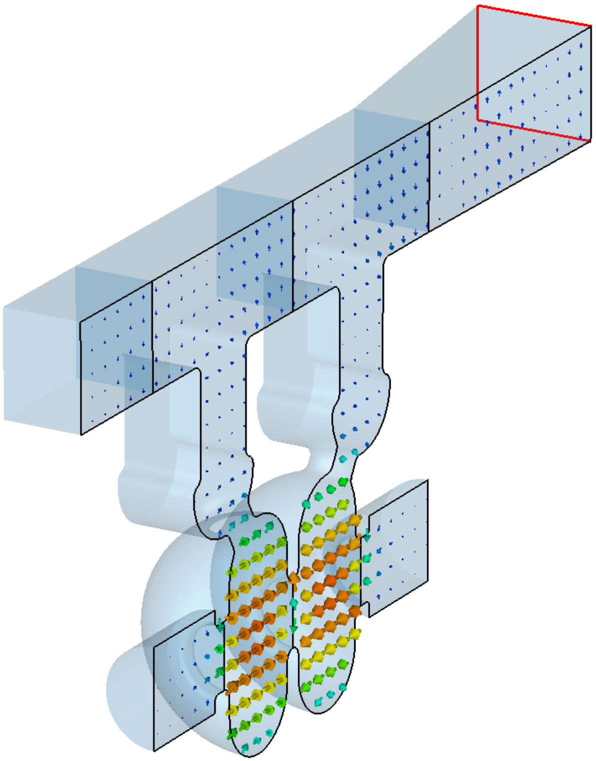
Test cavity with distributed coupling



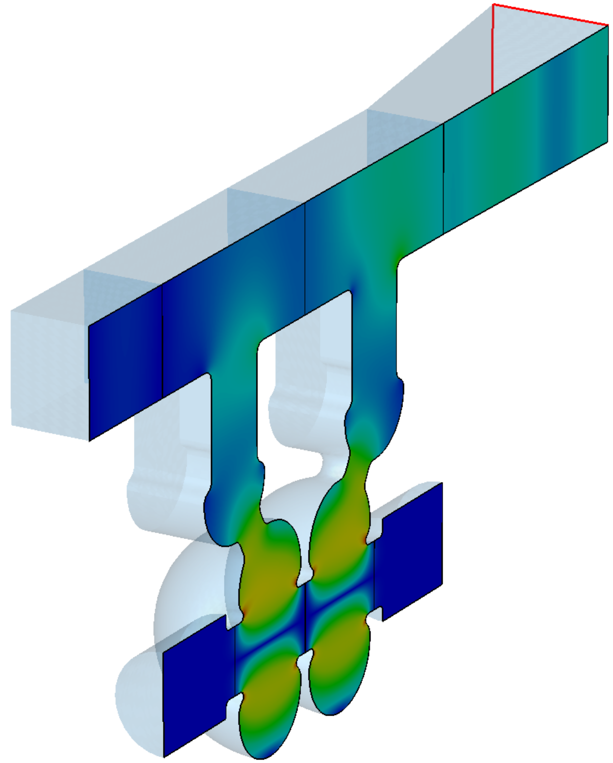
C-band 2-cell test cavity for β = 0.93: (a) inner volume with WG187 port (red); (b) vertical cross section (room temperature operation)

- 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 45%.
- Large RF couplers: each delivers one-half of the RF power fed into waveguide.

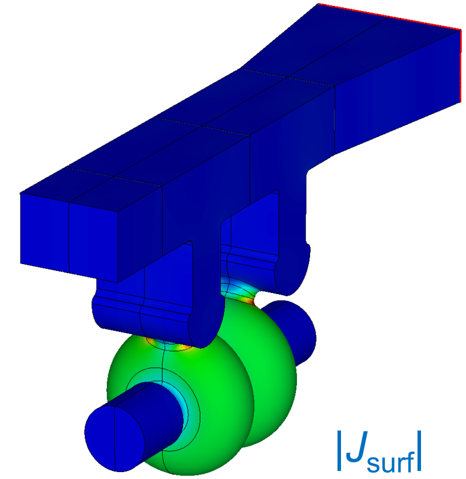
Fields and power flow in the test cavity



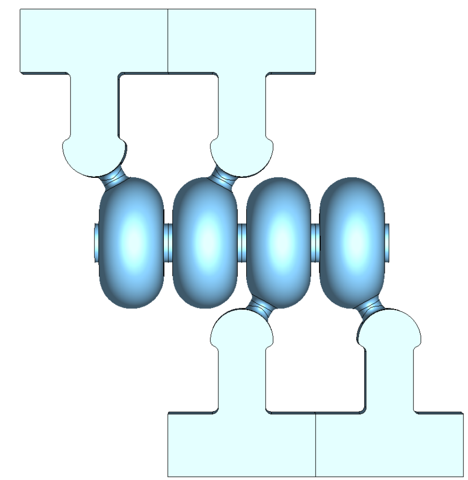
E-field in cut plane



Power flow snapshot

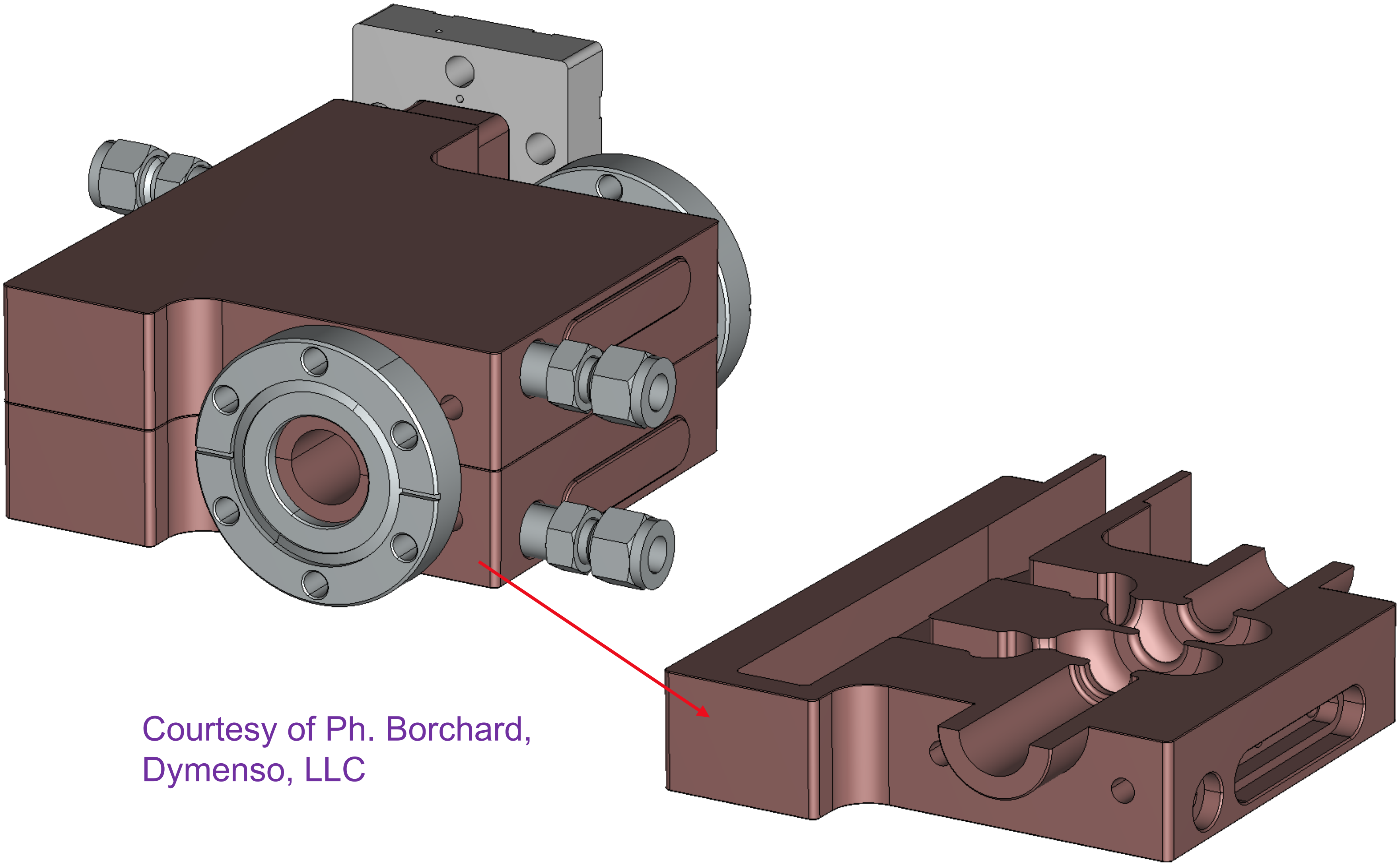


$|J_{surf}|$



CST calculated fields and power in the test cavity

Test cavity is being fabricated



Courtesy of Ph. Borchard, Dymenso, LLC

CAD model of C-band test cavity for fabrication

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 S- and C-band structures with distributed RF coupling adapted for protons with β = 0.84-0.97 (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. It is being fabricated and will be tested soon at the LANL C-band RF test stand.

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