Fermilab

February 5, 2025

New cavity shapes and types: Potential and further R&D directions

Kellen McGee
FNAL/APS-TD

U.S. DEPARTMENT of ENERGY
Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

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Outline

- Motivating SRF structures for HEP accelerators
- Tunable SRF cavity for synchrotron applications
- Crabbing cavity for collider applications (QMiR)
- Travelling wave cavity for compact high-gradient machines
- Summary & Outlook for GARD SRF structures

Developing new SRF structures for HEP

Novel SRF structures enabling future machines pushing energy and luminosity frontiers

- SRF structures optimized for Q_0 or gradient in novel ways will enable next-generation HEP experiments, and support accelerator stewardship
- Is the future of SRF increasingly sophisticated impurity doping/RF surface processing?
  - Other kinds of impurity doping, Nb3Sn, SIS multilayers, etc. Production challenges: How to move from small test-cases/samples to full-size SRF cavities? How to scale to ~100s of cavities for a production run?
- What else can we optimize? Nb material is likely sticking around, we've been perfecting fabrication and processing techniques for decades…

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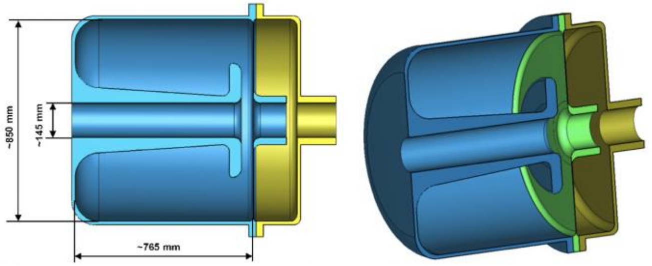
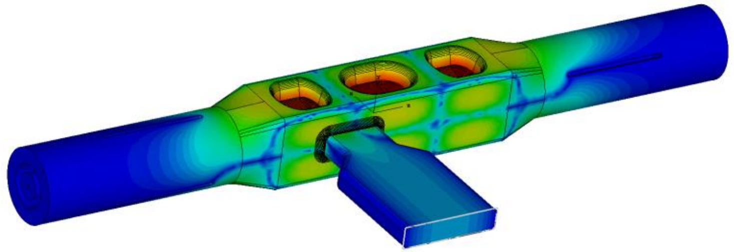
Using well-developed Nb fabrication/processing techniques, we can exploit new cavity geometries to unlock transformational performance improvements.

Tunable SRF cavity for RCSs



QMiR Cavity for EIC



Travelling wave cavity

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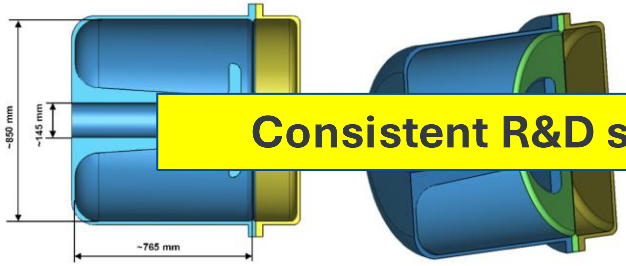

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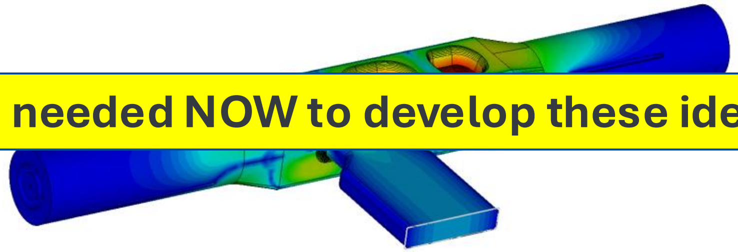


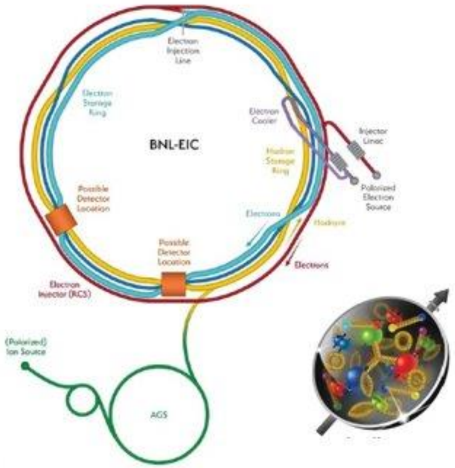
Travelling wave cavity

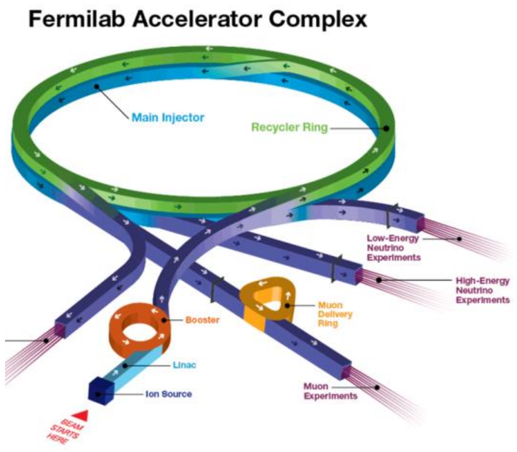
Consistent R&D support is needed NOW to develop these ideas in a timely manner.

Tunable SRF cavities for rapid-cycling synchrotrons

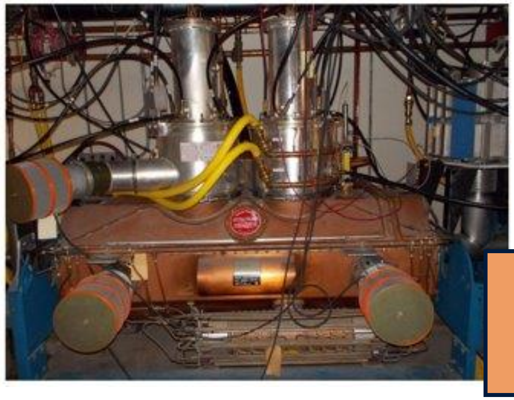
SRF has a leading place in next-generation HEP machines

- Rapid-cycling synchrotrons are key components of accelerator complexes
- Despite order-of-magnitude cost-saving benefits of SRF, it has yet to be developed for RCS
- FNAL MI must be upgraded to support LBNF/Dune
  - Current baseline plan adds 17 NC cavities to the existing 20
  - Higher beam impedance, significant RF power losses/draw, increased facility complexity, limited tunnel space
- Instead, with tunable SRF cavities:
  - **Replace 37 NC cavities with just 6 SRF cavities!**
  - Reduced beam impedance, save physical space, RF power
- Novel SRF technological development opportunity
  - Successful demonstration in a facility like the MI will pave the way for adoption of tunable SRF technology by the accelerator community

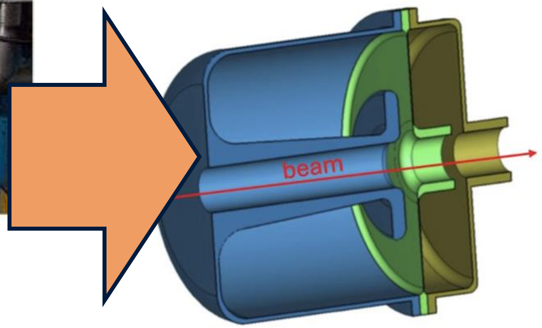




Current MI cavity:



Proposed tunable concept:



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Primary tunable SRF technical challenges

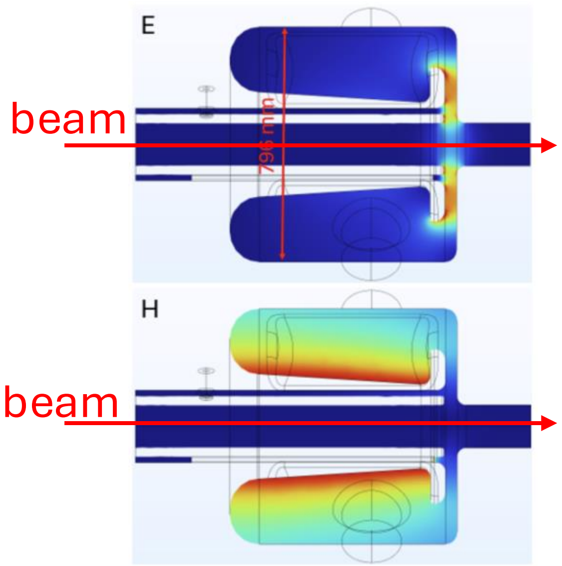
In context of FNAL Main Injector…

MI parameters:

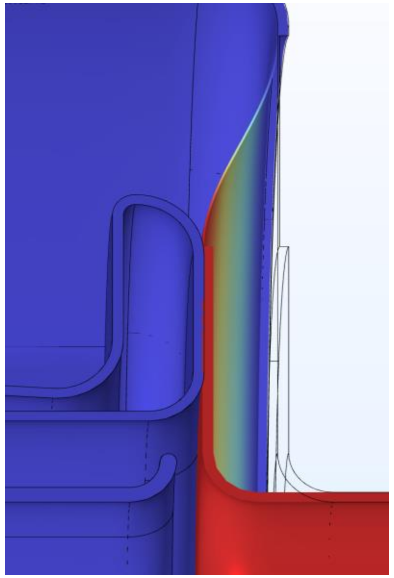
Parameter	Value
Beam energy	8 – 120 GeV
MI ramp	0.65 s
Protons on target per cycle	7.5×10^{13}
Beam power at 120 GeV	2.22 MW
Maximum accelerating rate	500 GeV/s
Acceleration time	~0.22 s
Beam accelerating power	6 MW
RF frequency	52.808 – 53.104 MHz
RF frequency change	0.296 MHz
Required acceleration ($V_c \sin \phi_s$)	5.54 MV
Total operating voltage	7.8 MV
Number of SRF cavities	6
Operating peak voltage	1.3 MV
Peak RF power per cavity	1 MW

- Tuning range & speed
  - MI: ~300 kHz (0.6% tunability) at 5.2 MHz/sec maximum
- HOM damping
  - Sufficient HOM damping over discrete (CBM) and continuous spectrum, minimize multipacting areas
- Other challenges
  - Large forward-power needs (~1MW), low-temperature Nb fatigue studies (underway), surface processing
- Preliminary design studies favor an axisymmetric quarter-wave resonator concept

Field distribution



Tuning membrane



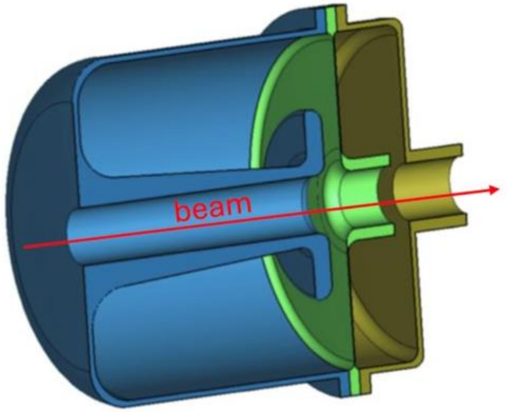
Current and future work at FNAL

- Initiated flexible membrane tuning concept development
  - Precedent: RHIC storage cavity. Nb fatigue studies underway.
- Proof-of-concept 1/3-scale tunable cavity in development
  - Establish fabrication techniques, validate Q, gradient, processing techniques, measure HOM modes, bench-test tuning/frequency range
- Derisked by 1/3-scale development, full-scale cavity development becomes much more feasible!

Parameter	Value
$R/Q = \frac{V_c^2}{\omega U}$	104.8 Ω
Cavity stored energy, U, at 1 MV	28.7 J
Geometry factor, G	38.7 Ω
Q_0 at $R_s = 10$ nΩ	3.9×10^9
Cavity wall power dissipation at 1 MV	2.5 W
Q_{ext}	9,540
Cavity bandwidth	5.56 kHz
Frequency tuning range	$\sim$ 0.5 MHz
Maximum frequency slew rate	5.2 MHz/s
Maximum surface E field at 1 MV	31.1 MV/m
Maximum surface B field at 1 MV	29.6 mT

Table 2: Tentative 53 MHz MI QWR parameters

MI: 0.6% tunability



RHIC: 0.06% tunability*

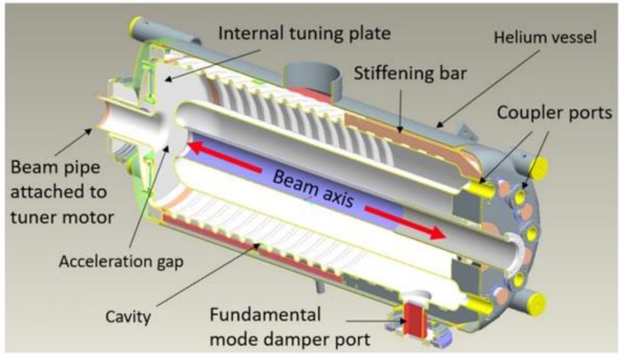
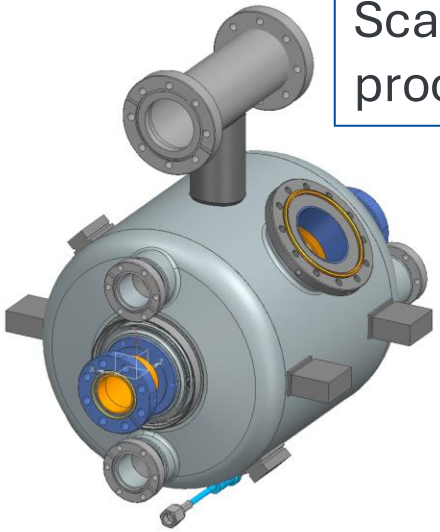


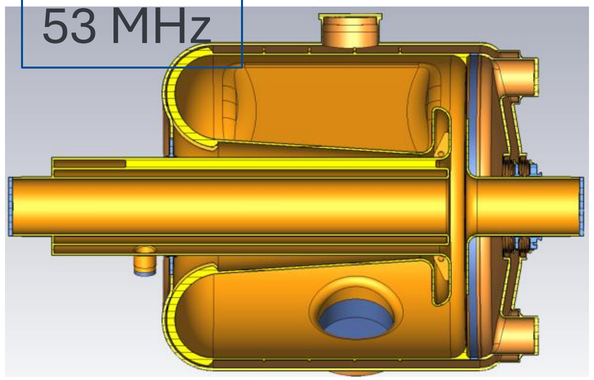
FIG. 1. 56 MHz SRF cavity with a total length of 1.3 meters.

*Qiong Wu et al., Phys. Rev. Accel. Beams, 22:102001, October 2019.

Scaled 159 MHz proof-of-concept



53 MHz



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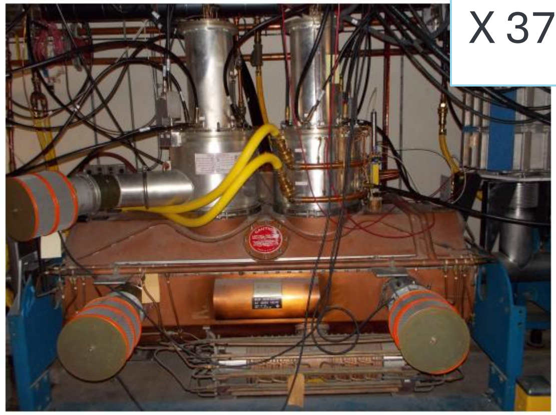
Future outlook for tunable SRF

- Transformational improvement in facility performance, efficiency, and flexibility!
- Next-generation machines pursuing high-current operations struggle with dangerous instabilities, significantly reducing beam impedance by employing small # of SRF cavities will be critical
- Timeline for ACE-MIRT is aggressive, supporting accelerated DUNE project (P5 report). R&D *now* is critical. Tunable cavity proof-of-principle must be demonstrated in a timely manner to become a viable candidate for ACE-MIRT
- Other Tunable SRF cavity applications for synchrotrons: Brookhaven's AGS, Hadron Storage Ring for EIC, & more.



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R&D

- Cryogenic Nb fatigue testing
- 1/3 scale proof-of-principle cavity
- Fabrication/procurement for full-scale cavit
- HOM, FPC, and tuner testing/validation
- 1-cavity cryomodule design
- Cryomodule procurement and fabrication
- Full horizontal cold testing

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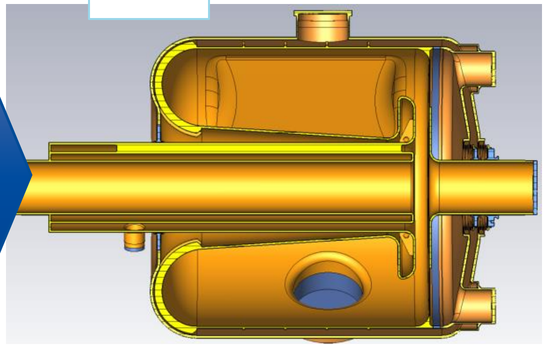


02

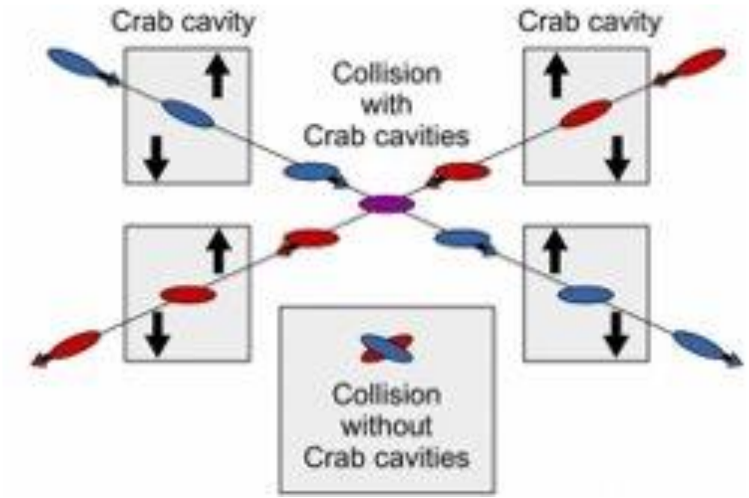
QMiR Crab Cavity for EIC

QMiR Cavity for EIC

Quasi-waveguide Multicell Resonator

*A. Lunin, V. Yakovlev, FNAL

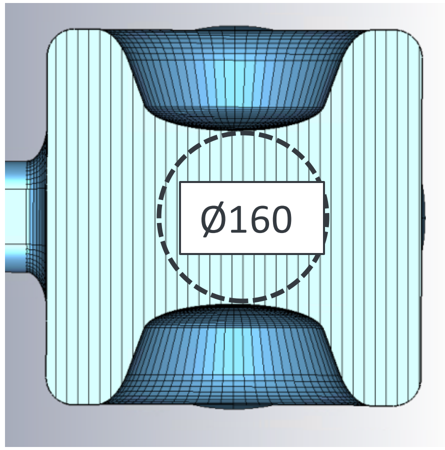
- “Crabbing” to directly increase collider luminosity
  - Trapped dipole mode introduces a transverse kick to beam
- Compact and efficient single crab cavity for EIC
  - Optimized for low surface fields
  - Strong HOM damping, simplified design with no additional couplers

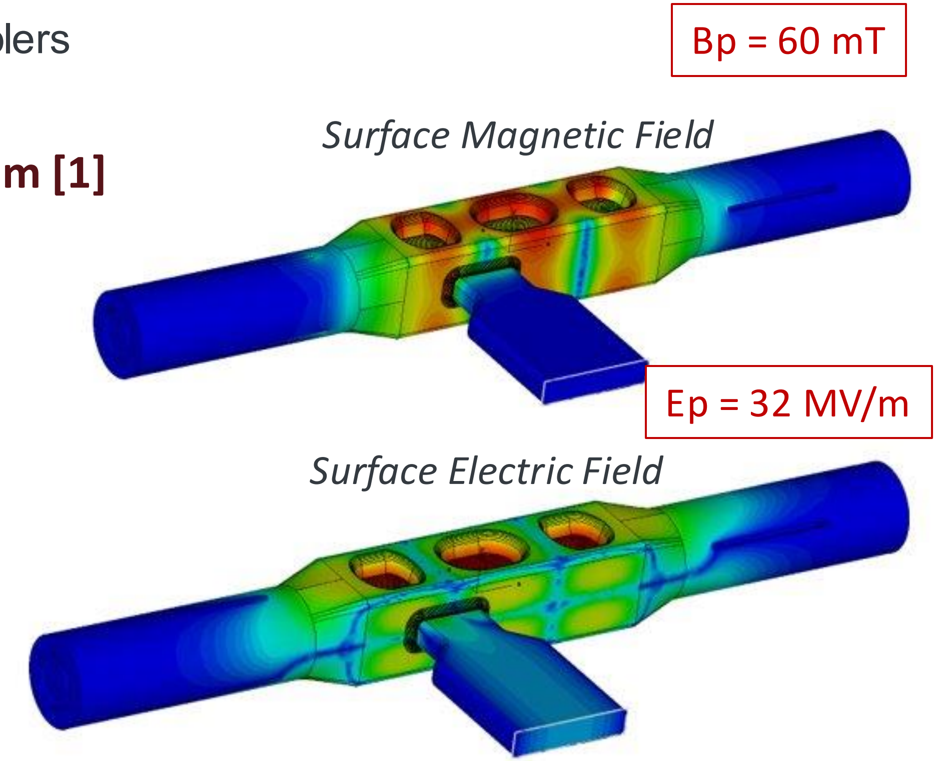


Operating Mode	
Freq	400 MHz
V_{kick}	4.75 MV
$(R/Q)_{\perp}$	225 Ω
G-factor	160
Bp, max	60 mT
Ep, max	32 MV/m
W_{STORED}	40 J
Length	3000 mm

EIC Crab Cavity Aperture Limit: Ø103 mm [1]

[1] BNL-221006-2021-FORE

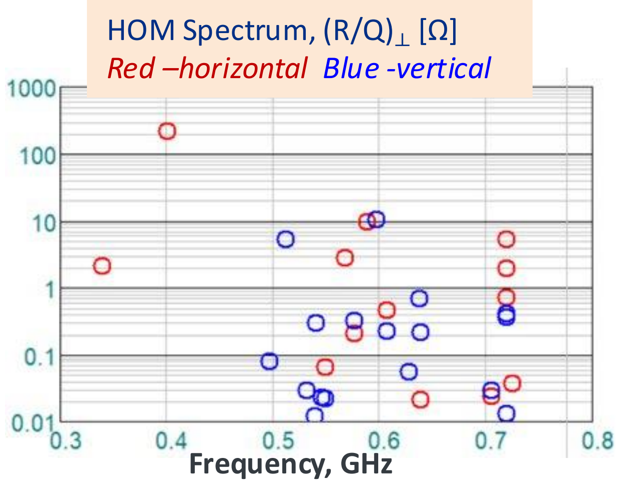


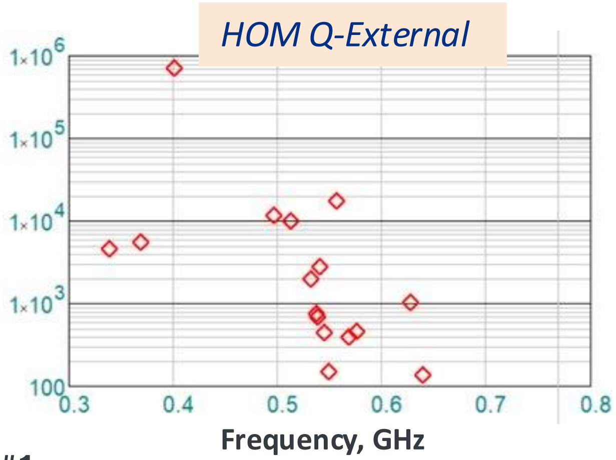


Advantages of QMiR for EIC

*A. Lunin, V. Yakovlev, FNAL

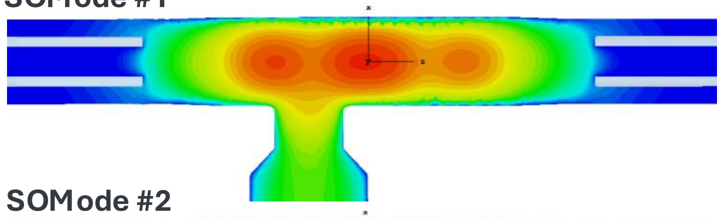
- In CW RF operation, nominal cryo-load is expected to be as low as 6W
- Same-order modes are coupled only to the input waveguide port, no need for additional coupling
- Monopole HOMs are mostly loaded into the coaxial line
- Est. 40 kW solid state amplifier will be sufficient to maintain crabbing voltage, and compensate for beam ON and microphonics





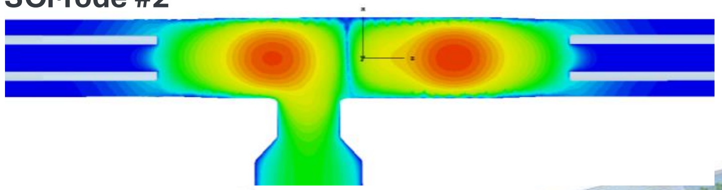
SOMode #1

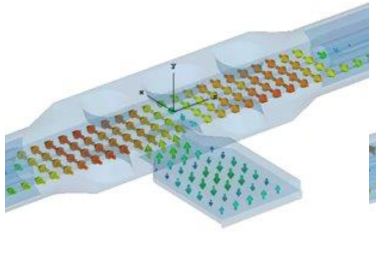
1st Dipole SOM
F = 0.340 GHz
QE = 4500
$(R/Q)_\perp$ = 2 Ω



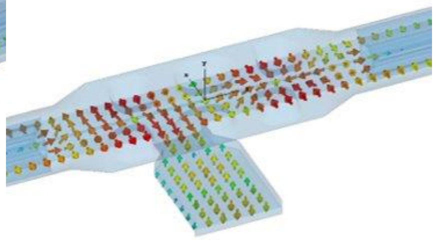
SOMode #2

2nd Dipole SOM
F = 0.370 GHz
QE = 5500
$(R/Q)_\perp$ = 0.01 Ω

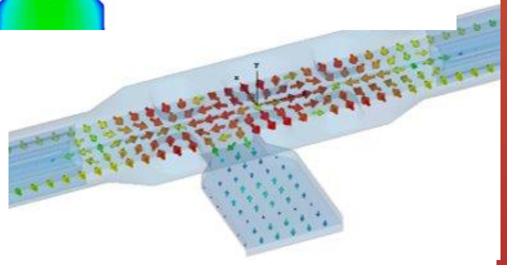




Dipole HOM
F = 0.512 GHz
QE = 1.0E4
$(R/Q)_x$ = 5 Ω



Monopole HOM
F = 0.545 GHz
QE = 440
$(R/Q)_z$ = 120 Ω

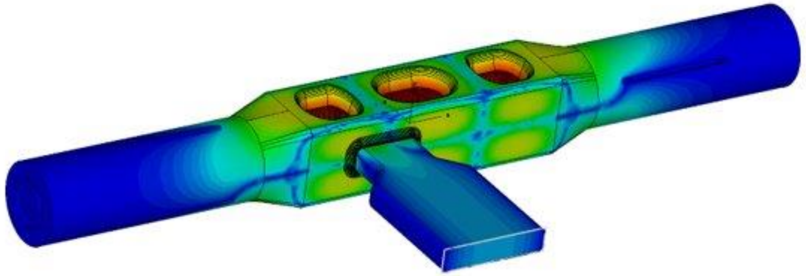


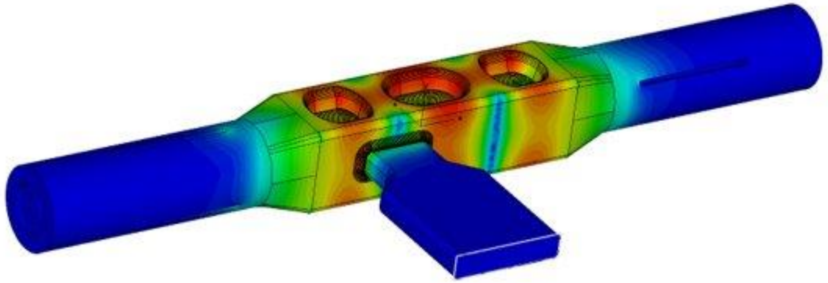
Monopole HOM
F = 0.556 GHz
QE = 1.8E4
$(R/Q)_Z$ = 14 Ω

*A. Lunin, V. Yakovlev, FNAL

Future and outlook for QMiR

- **QMIR is a good option for the EIC Crab Cavity**
  - Design is radially compact (<0.35 m) and simple;
  - Sparse HOM spectrum and small loss/kick factors;
- **QMiR re-optimized for 400 MHz with an aperture of 160 mm**
  - 1 QMiR can provide nominal 4.75 MV kick for EIC proton bunch;
  - Cavity has low operating surface fields: Ep < 32 MV/m and Bp < 60 mT
  - SOM/HOM are damped below EIC specifications!
- **Fermilab can design, build and test the QMIR cavity for EIC**
  - Further design optimization is possible to meet detailed requirements





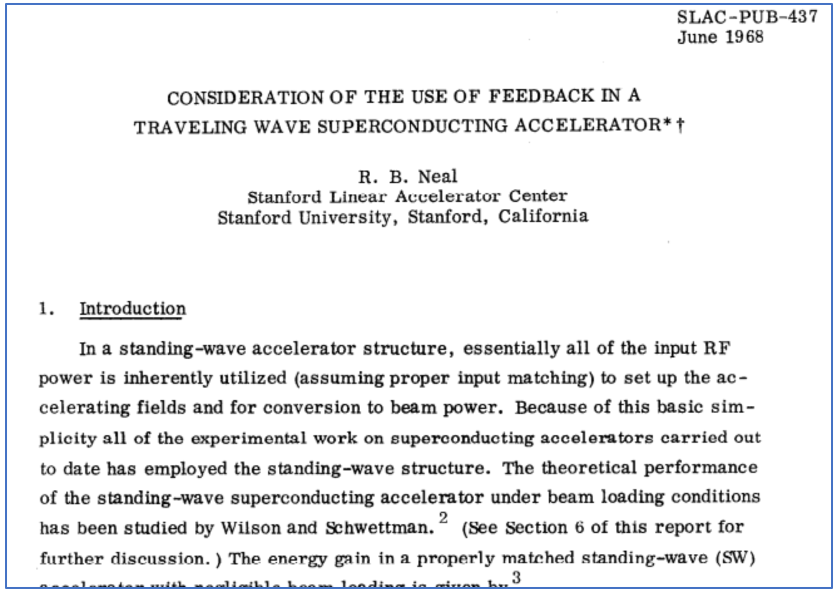
03

Traveling wave cavity

Advantages of Traveling Wave structures

Journey towards high-gradient SRF...

- SC traveling wave structures (considered since ~1968!)
- Transformational advantages: ~40% higher accelerating efficiency than SW
    - Increase in transit time factor, *T:* Standing wave ~0.7, TW~0.9
    - Lower surface magnetic field: 20% increase in E_{acc}
    - Larger V_{group} is more tolerant of manufacturing defects => longer cavities
    - Use resonant feedback waveguide to not waste RF power
- Significant cost-reductions possible for linear machines*
    - HELEN achieves 250 GeV CM energy in 7.5 km



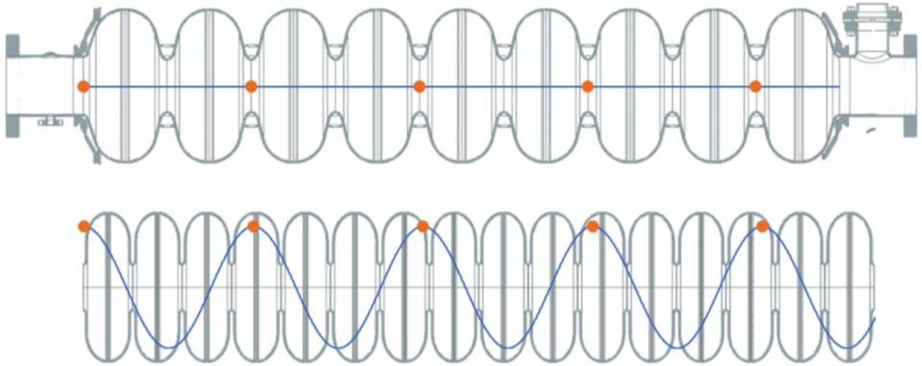
SLAC-PUB-437
June 1968

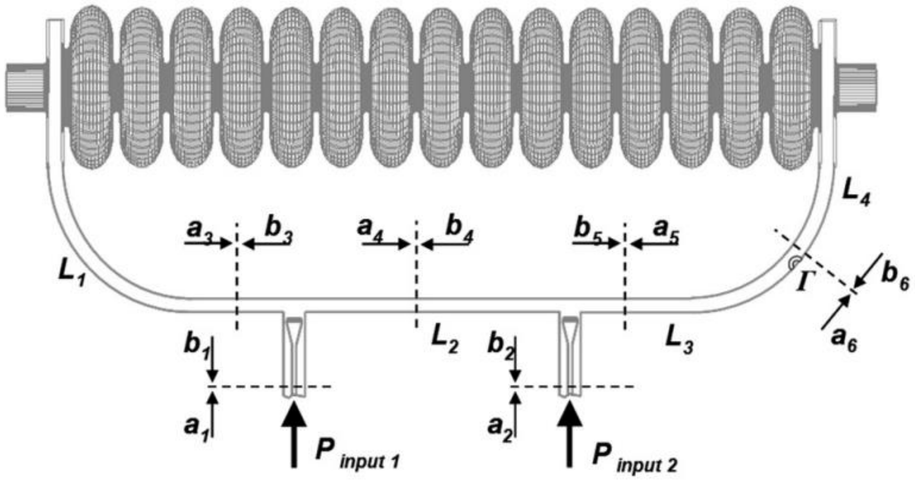
CONSIDERATION OF THE USE OF FEEDBACK IN A TRAVELING WAVE SUPERCONDUCTING ACCELERATOR* †

R. B. Neal
Stanford Linear Accelerator Center
Stanford University, Stanford, California

1. Introduction

In a standing-wave accelerator structure, essentially all of the input RF power is inherently utilized (assuming proper input matching) to set up the accelerating fields and for conversion to beam power. Because of this basic simplicity all of the experimental work on superconducting accelerators carried out to date has employed the standing-wave structure. The theoretical performance of the standing-wave superconducting accelerator under beam loading conditions has been studied by Wilson and Schwettman.[2] (See Section 6 of this report for further discussion.) The energy gain in a properly matched standing-wave (SW) accelerator with negligible beam loading is given by[3]



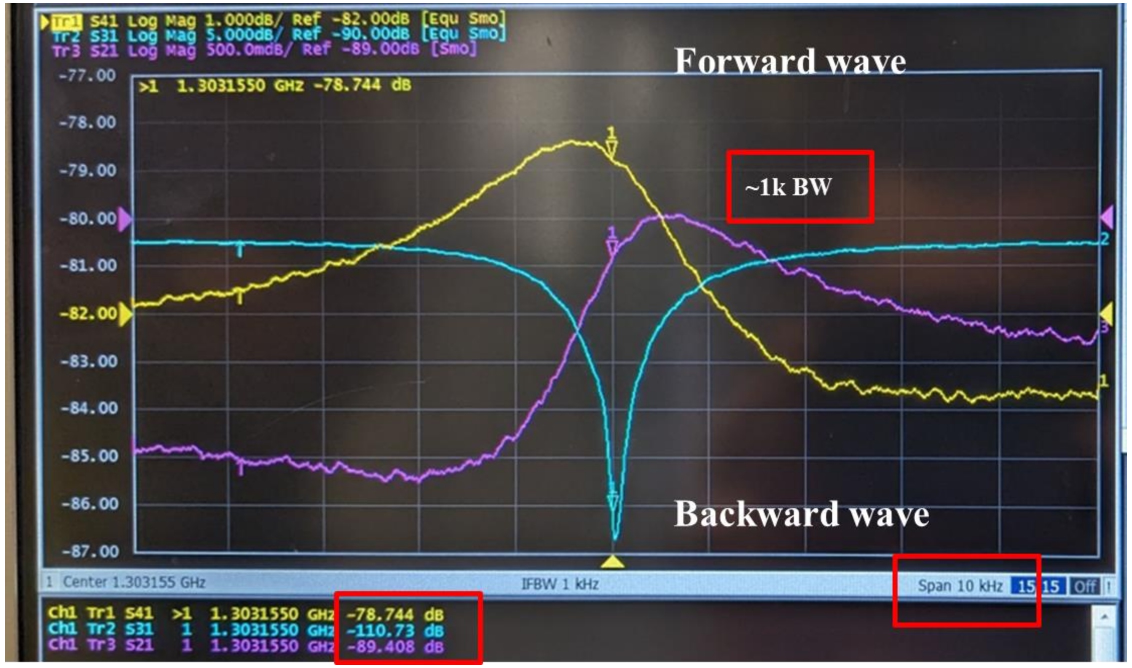


*S. Belomestnykh et al., "Superconducting radio frequency linear collider HELEN," *JINST* **18**, P09039 (2023)

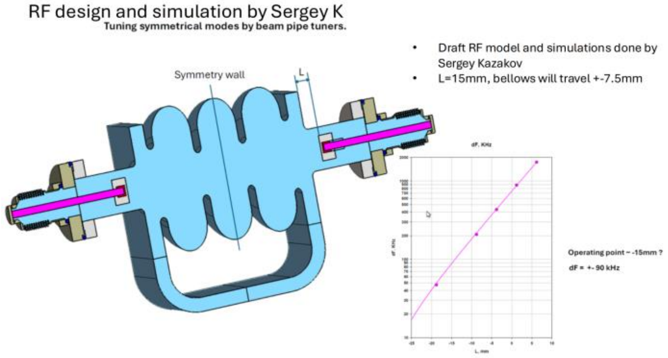
3-cell cold tests

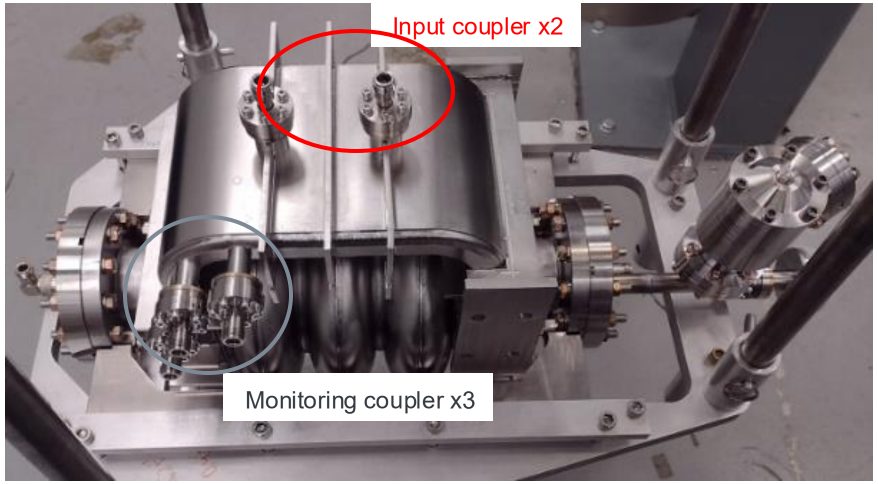
First demonstration!

- Low-power (<10W) cold test with existing circuitry
  - Input coupling (Qext1) ~10^6
- TW signals at 1303.155 MHz successfully tuned at 2K!
  - Yellow: forward wave signal
  - Blue: suppressed backward wave signal (30dB less)
  - Purple: a signal from the calibration pick up.



- High-power testing (>500W) ongoing
- Higher Qe1 hoping to demonstrate higher gradient.
- Improving cold-temperature tuning methods to demonstrate high-power traveling wave (Spring 2026)

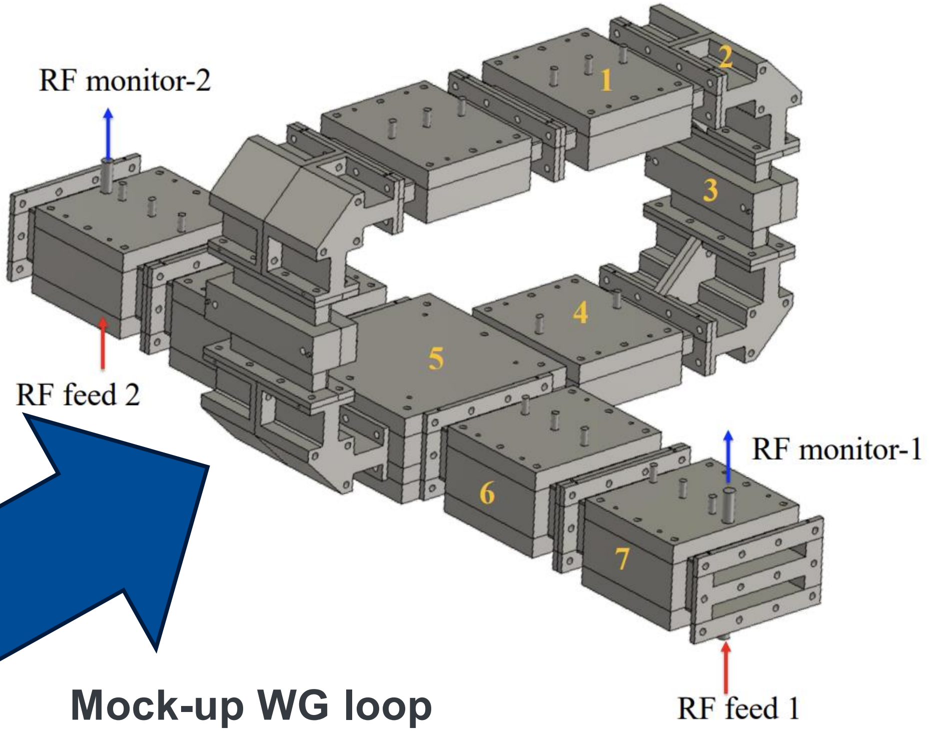




The 3-cell cavity on VTS support structure

Half-meter scale waveguide innovation

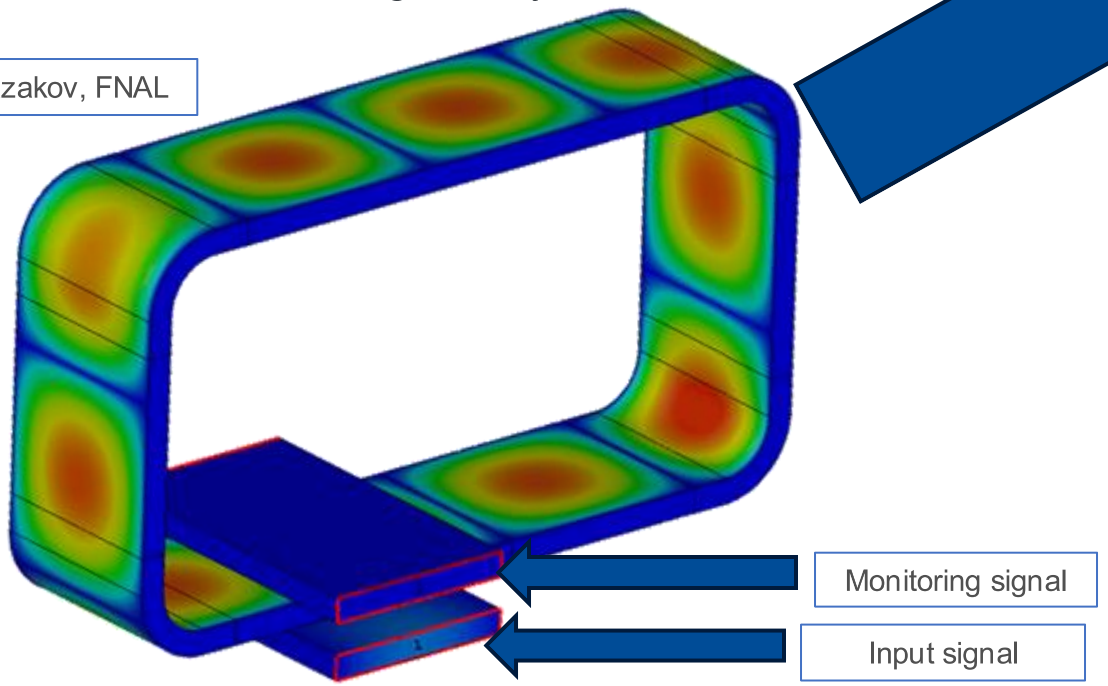
- Design and evaluate double-directional coupler concept
  - DDs to greatly simplify input and calibration coupler system used on 3-cell cavity
  - Low-cost aluminum model allows benchtop investigation and nice modular configurability



Mock-up WG loop with launchers and attenuators

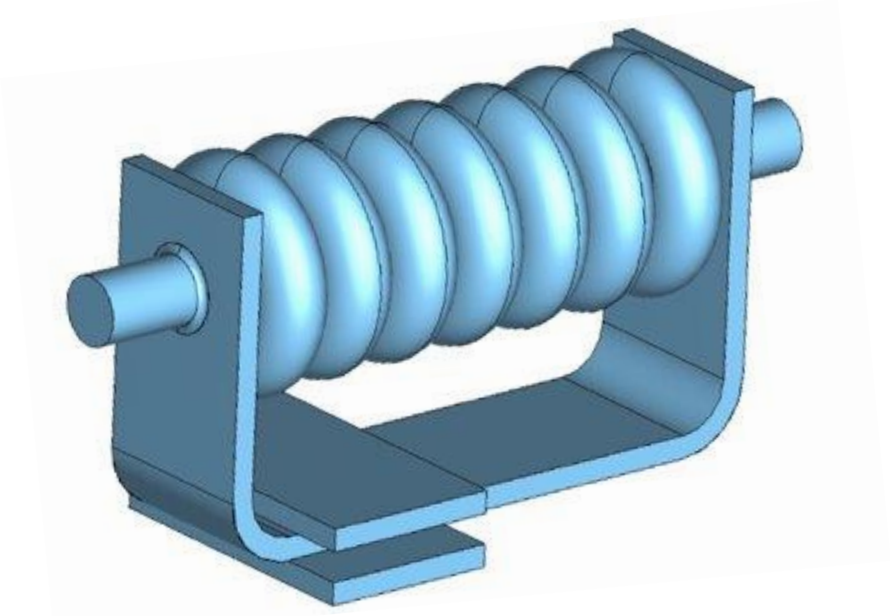
1. Single attenuator
2. 90-bend
3. Spacer waveguide
4. Tuner equivalent
5. DD coupler
6. Double attenuator
7. Double launcher

RF simulation by S. Kazakov, FNAL



Future and outlook for Traveling wave

- Traveling wave structures are an attractive prospect for compact, high-gradient linacs offering ~40% improvement in accelerating efficiency with mature Nb technology
- Successful proof-of-principle trials
- Technical hurdles remain
  - Cold-test at high-power to demonstrate pure traveling wave mode in 3-cell prototype
  - Demonstration of coupling/tuning methods
- Other practical questions
  - How to clean/process these cavities? Flanged waveguide loops?
  - Fabrication: feasible weld maps for larger-scale structures?
  - Handling?
- The good news: these appear to be “easier” problems!



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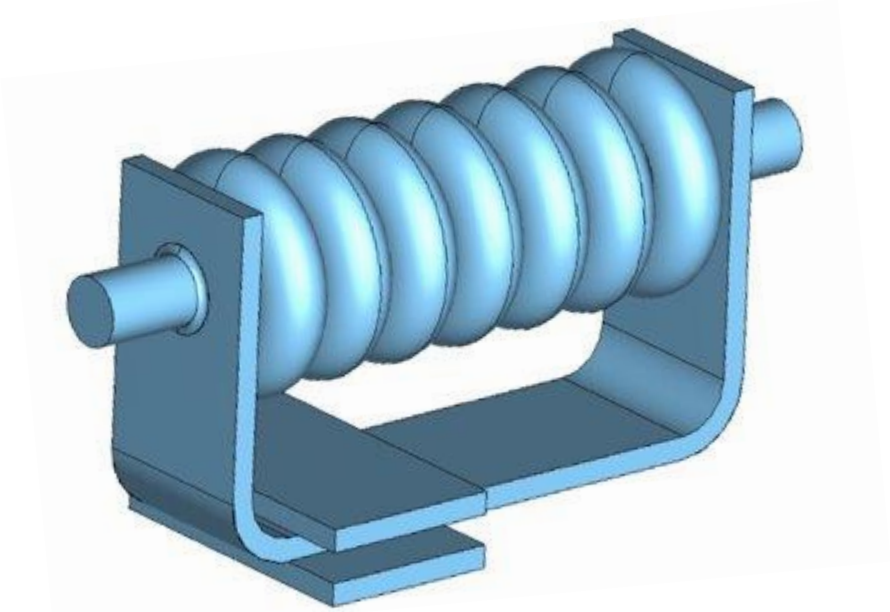
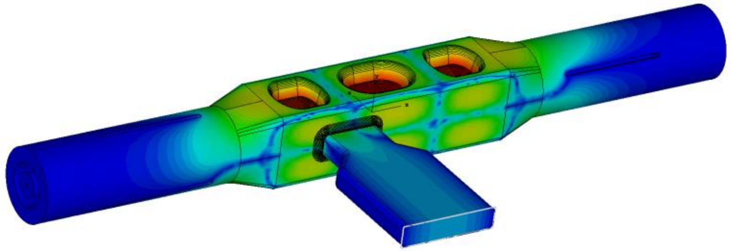


Pathway towards 70 MV/m!

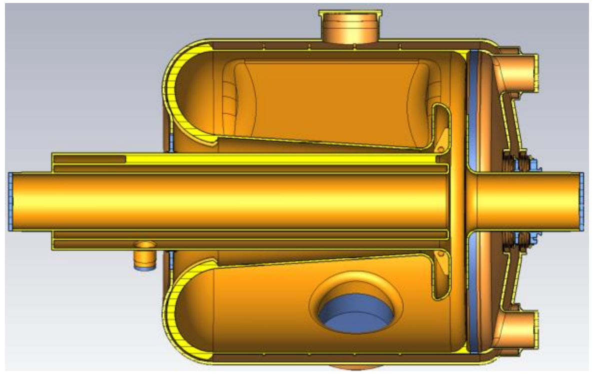
04

Summary & future outlook

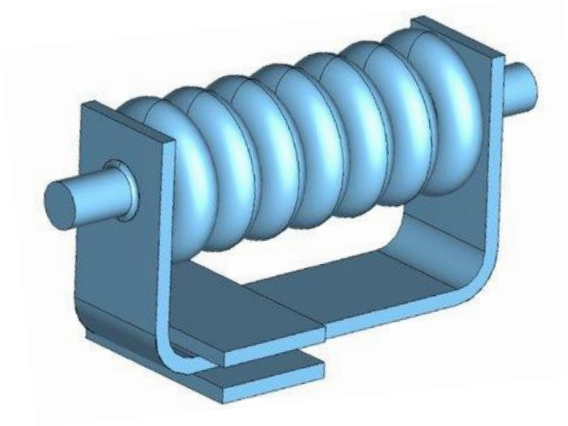
Summary and outlook for SRF structures



- Nb structure optimizations can also deliver immediate performance benefit to next generation machines without waiting for surface processing methods to mature further
- Novel SRF structures are enabling technologies for:
  - High gradient devices: linear higgs factories, compact devices
  - Next-generation SRF for RCS to reduce beam impedance/instabilities
- Improved facility efficiency and flexibility is a key component of accelerator stewardship, expanding experimental reach
- Consistent R&D is critical to ensure these options are well developed for adoption by future projects



Thank you! Questions?



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