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Stronger and durable pavement infrastructure using accelerator technology

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Challenges on the 'roads ahead':

- 94% of road in the US are asphalt.

- > 50 B$/year in renewing asphalt pavement

Source: http://asphaltmagazine.com/94percent/

- Asphalt pavement damage is largely due to cracks of the bitumen binder under heavy load. Oxidation, water freezing and thawing in cracks all create a continuous and expensive cycle of renewal, exacerbated in colder climates

- Despite attempts to improve asphalt pavement, the materials and fabrication method have changed little for several years.

Accelerator technology for pavement life extension

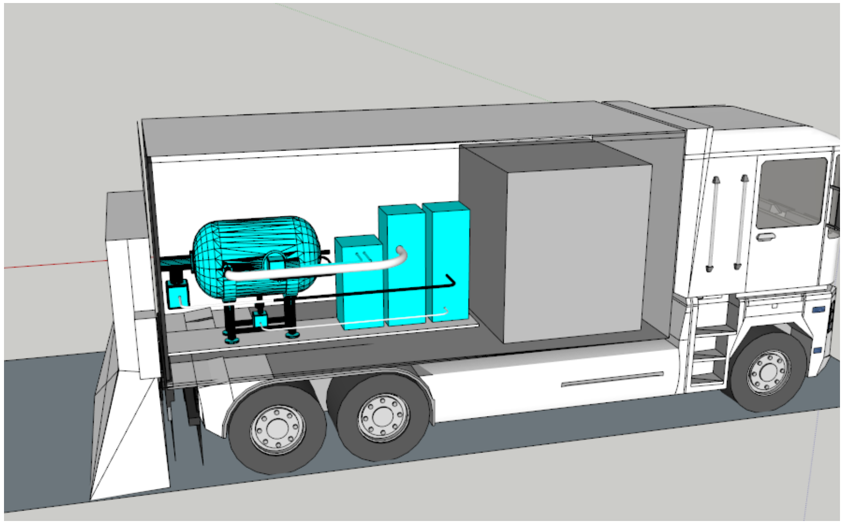
- Modern accelerator technology now enables fundamental change in paving technology using electron beam induced polymerization.

- Dramatically improve pavement performance leading to lifetime extension

- Potential reduction in a large carbon footprint from this industry. Directly reduces energy consumption due to
  - Reduced need for heavy machinery
  - Reduced transportation cost in material moves
  - Reduced energy need to make asphalt-bitumen mix at elevated temperatures

Currently on-going project

- Activity: Fermilab and US Army Engineer Research and Development Center (Vicksburg, Mississippi) are working together to
  - Create a tough, strong binder with improved temperature performance vs bitumen to extend pavement lifetime (a radiation chemistry-driven material science research work: Fermilab & ERDC)
  - Develop a prototype of a modern high-power compact electron accelerator (technology development work: Fermilab)

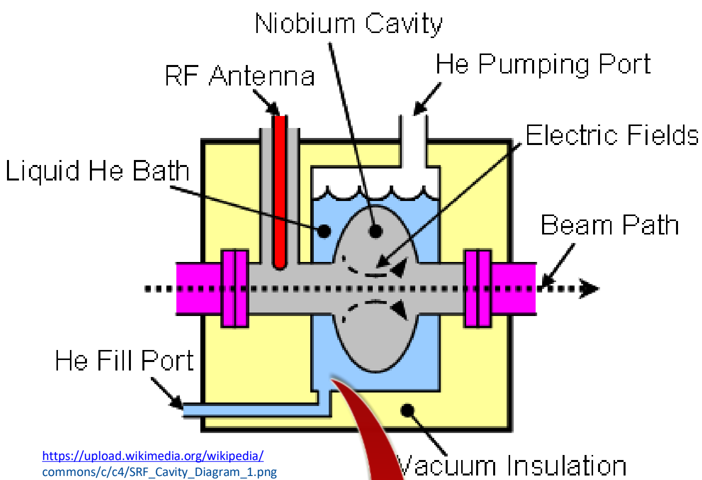


IARC@Fermilab

IARC, previously Illinois Accelerator Research Center, was established with a goal of exploiting technology developed in pursuit of science to enable new industrial accelerator applications

Current "science" accelerators are large and complex

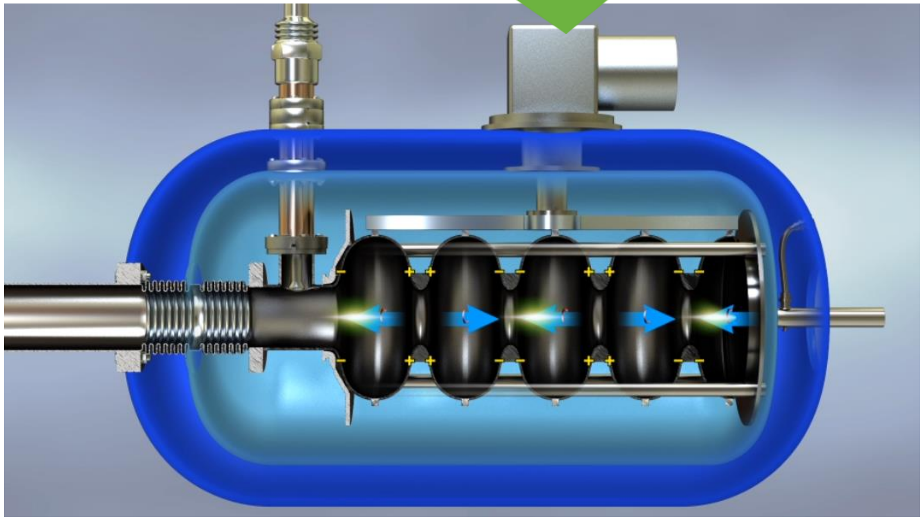
Vision: Access superconducting technology minus the complexity



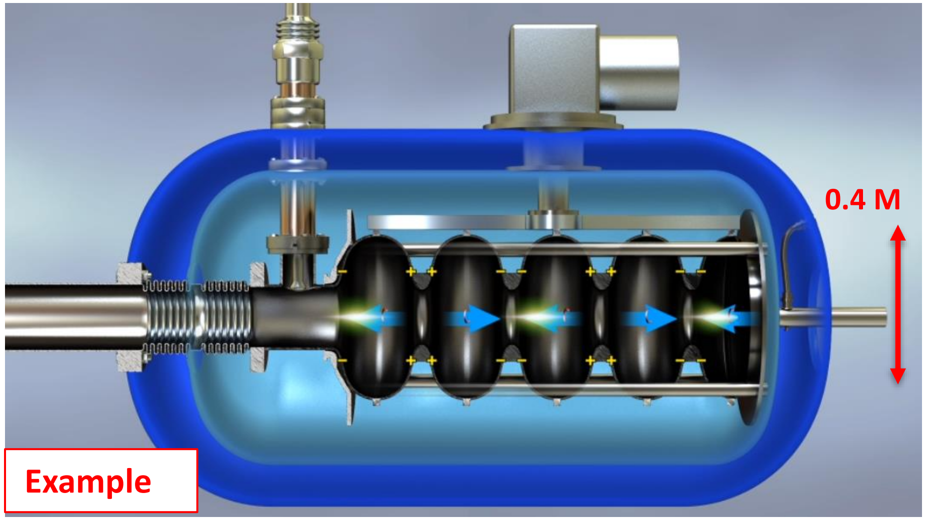
https://upload.wikimedia.org/wikipedia/commons/c/c4/SRF_Cavity_Diagram_1.png

Take out liquid helium
(and its complexities)

Cool with a cryocooler
(simpler refrigerator)



Ideas integrated into a simple SRF accelerator



- Energy: ~ 10 MeV
- Power: 250 KW
- Compact
- Simple, reliable
- Affordable

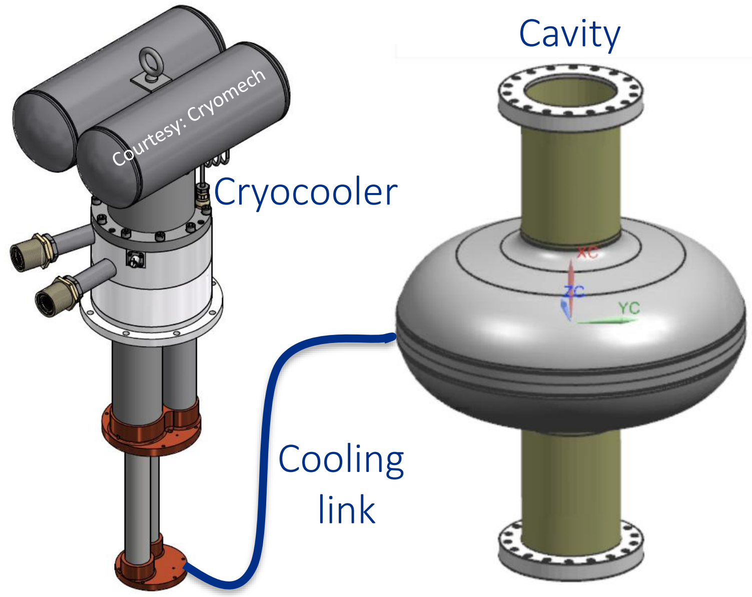
- Elliptical niobium cavity (well understood from $1B+ science projects)
- Patented conduction cooling technology
- Low cost power sources
- Accelerator system <3000 lbs ➔ mobile applications

Conduction cooled Nb_3Sn SRF development

Goal: demonstrate 10 MV/m cw on an Nb_3Sn cavity with cryocooler **conduction** cooling

Our choice:

- Single cell 650 MHz, <u>Nb_3Sn coated niobium</u> cavity
- Cryomech <u>PT420 cryocooler</u> (2 W @ 4.2 K with 55 W @ 45 K)
- <u>High purity aluminum</u> for the conduction cooling link



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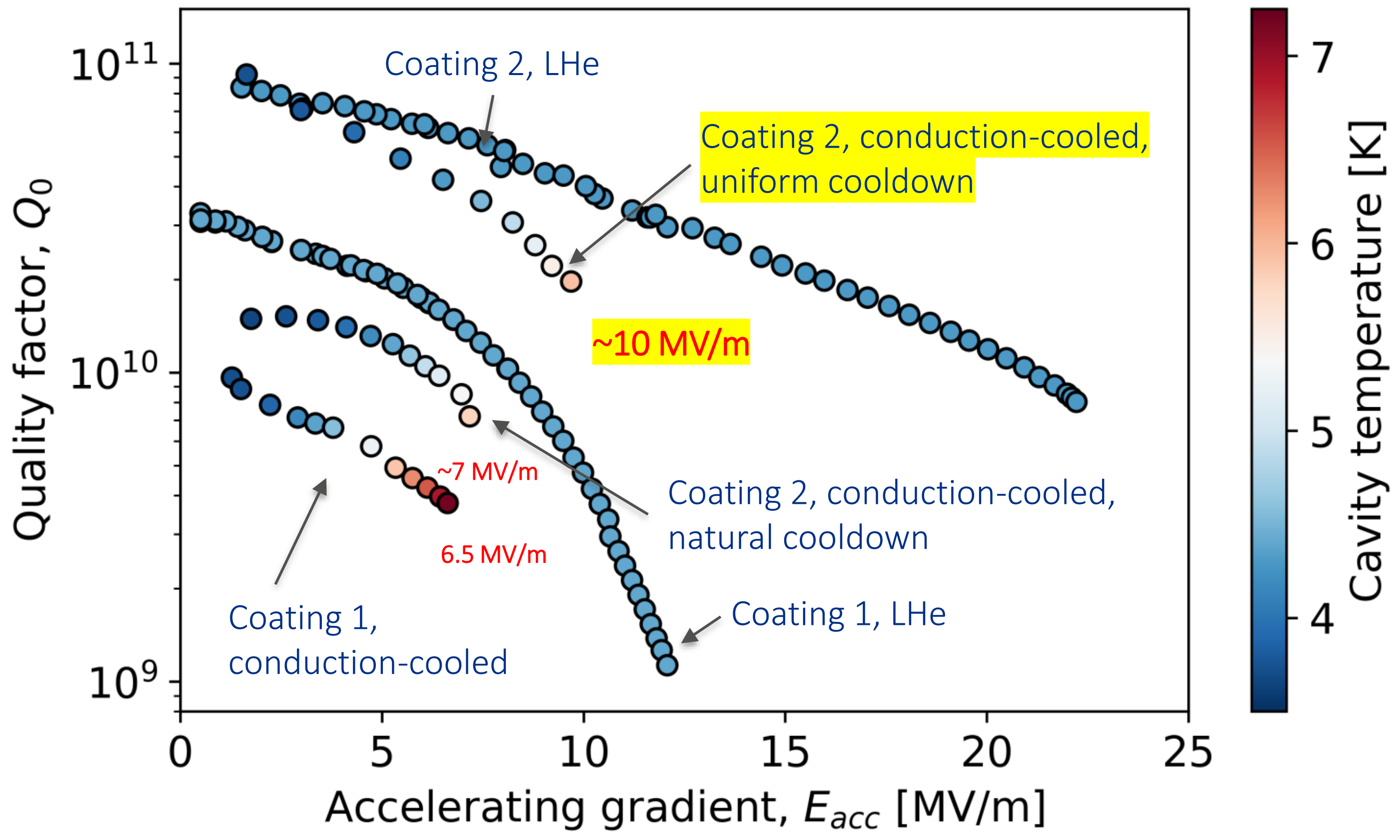
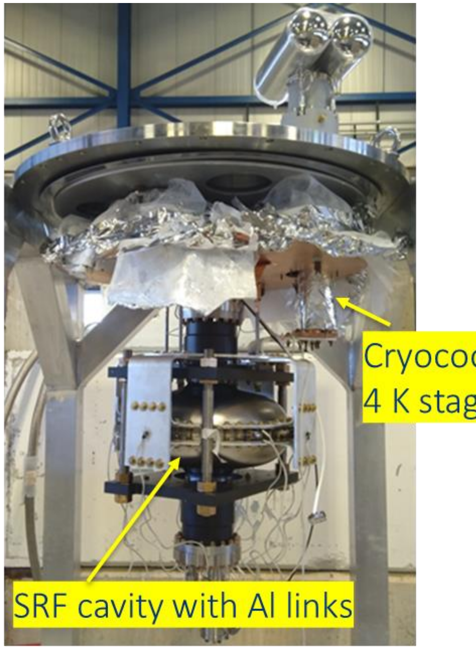
Recent results with Nb_3Sn coating (R.C. Dhuley arXiv:2108.09397v1)



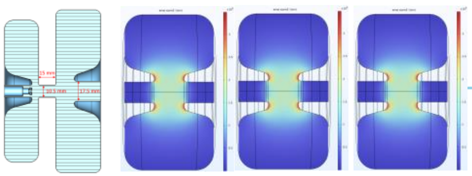


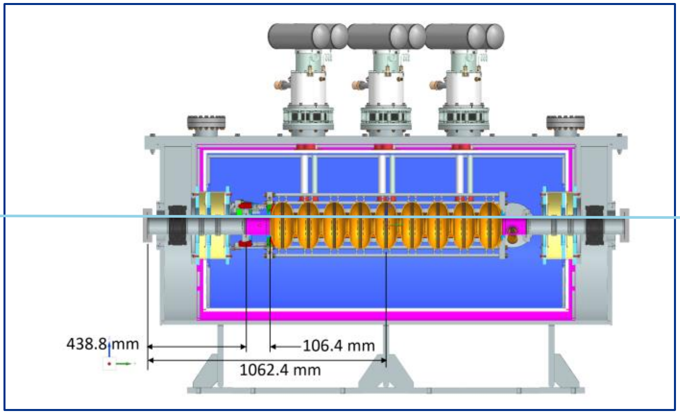
This is the technology that underpins our accelerator.
Controlling losses (beam + RF+ static) is imperative!

Approach: Using an external NC injector for SRF cryomodule

Injector (NC)

Conduction cooled cryostat

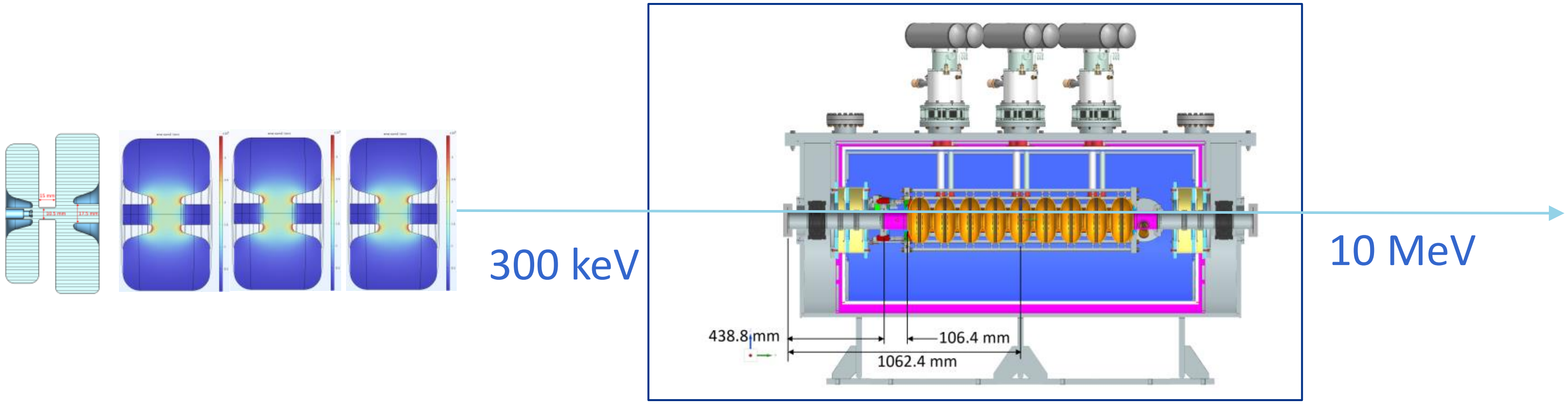




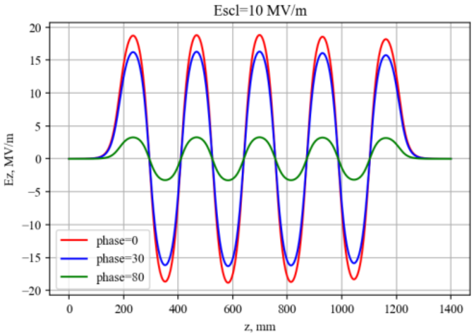
10 MeV

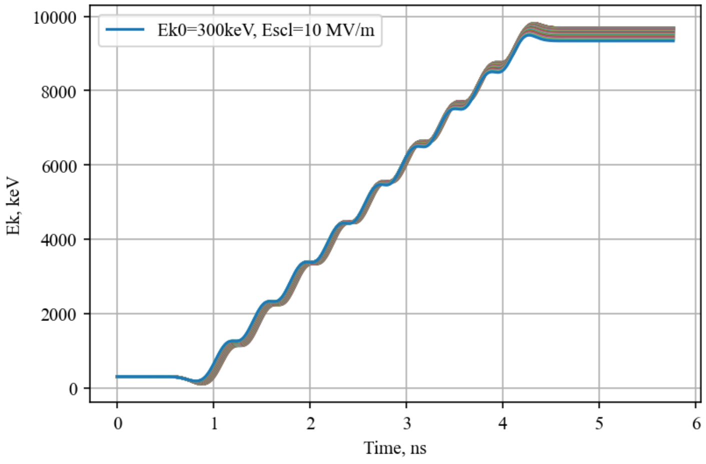
- Modular design allows parallel development
- 1.3 GHz TESLA-style cavity
- Beam loss control inside the cryostat less stringent
- Leveraging experience from LDRD, SBIR, industry and Fermilab SRF linac (FAST-IOTA)
- SSA amplifiers
- Simple Blinky-lite control
- Mobile-friendly

What injection energy to choose? Affects control



- Goal: 10 MeV
- 300 keV gives 10 MeV out
- 300 keV preferred
  - Wider phase capture
  - Higher energy
  - Higher beam power





euclid TECHLABS

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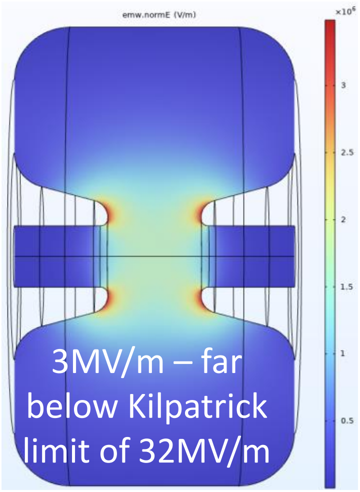
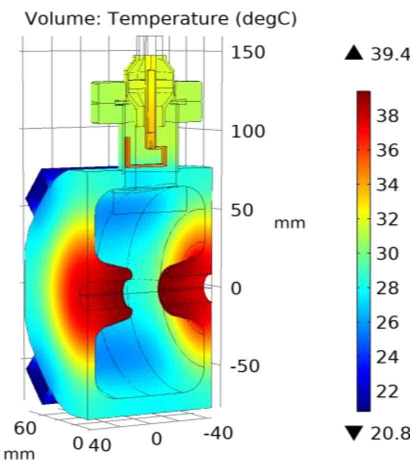
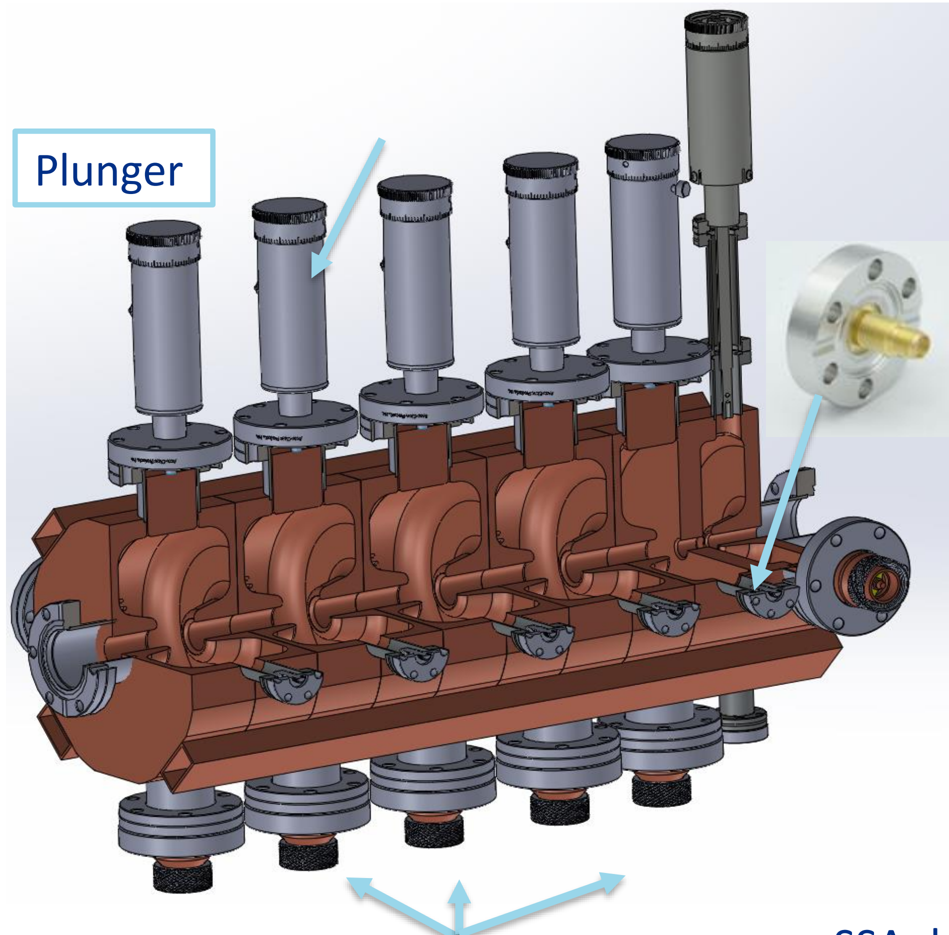
Our injector development using NC-RF is proceeding…



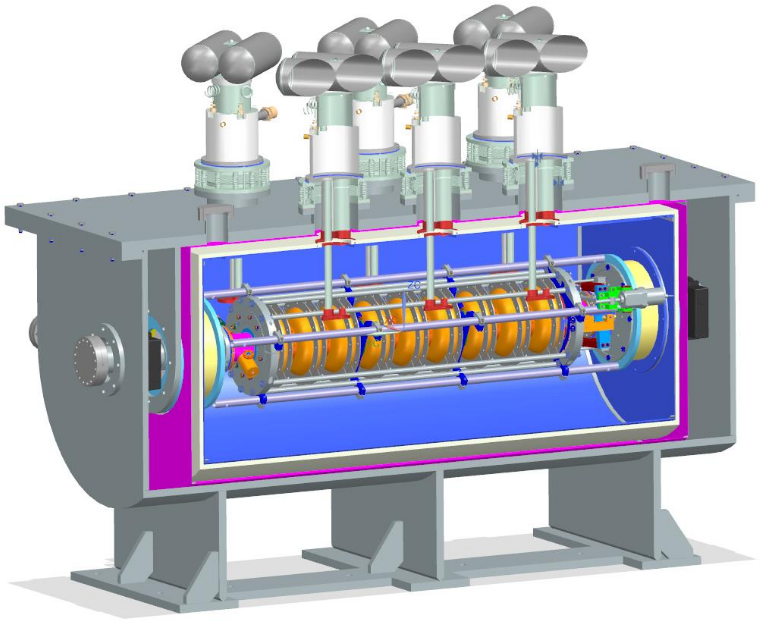


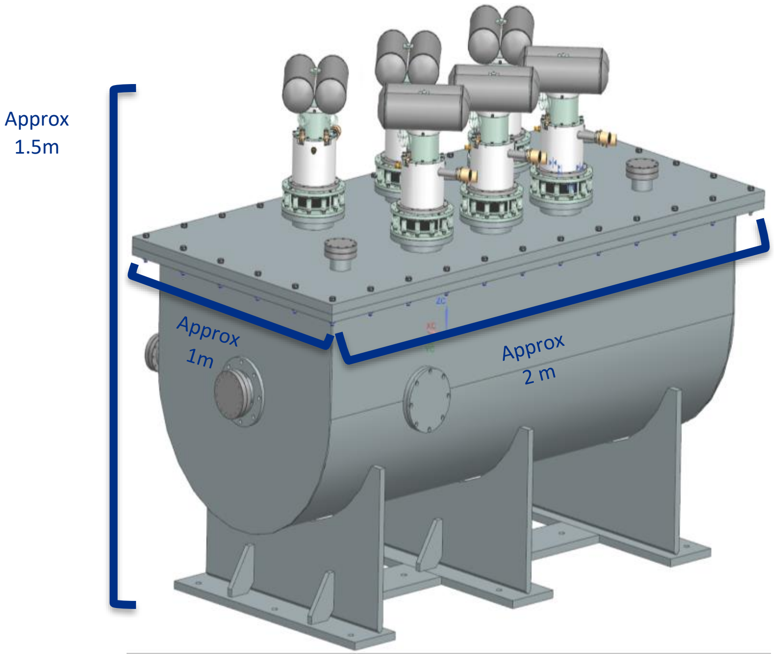


FPC

- SSA design (custom)
- Much lower E-fields
- Temperature control
- Engineering Design complete

Current and Future design



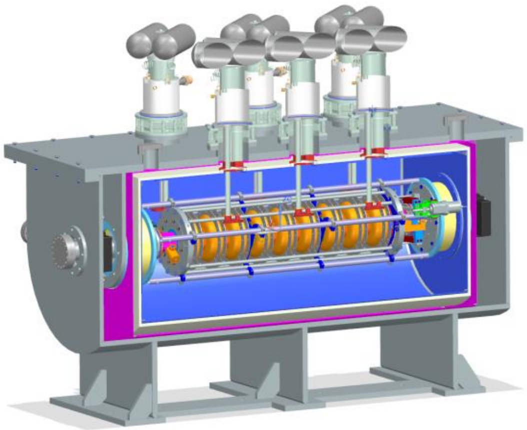


Future design:

- Truck mountable design constraints
- SRF technology constraints
- Maintenance needs
- Application requirements

…. all are being included

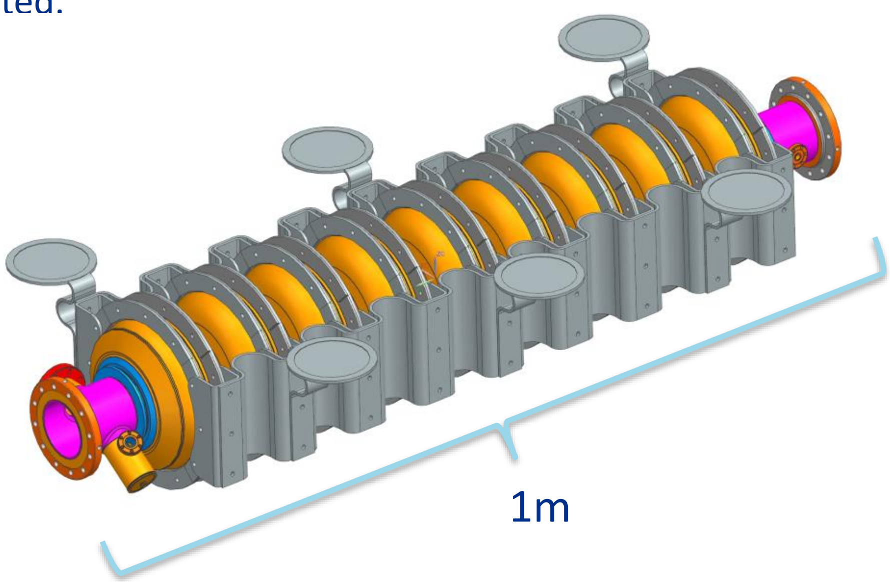
Cryomodule design components and status

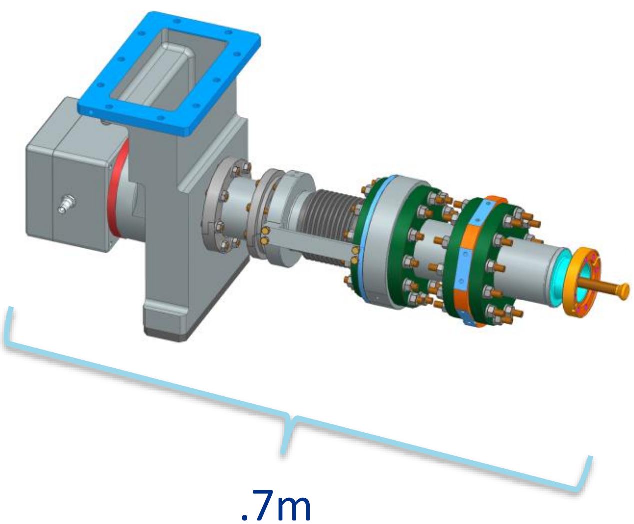


Cryostat: The conceptual design of the cryostat is complete, and the project team is working on finalizing the model so procurement can begin. Cryocoolers are being procured.

RF Coupler: The RF and mechanical design of the coupler is complete, and FNAL engineers have undergone a final design review. This will go out for fabrication of this assembly.

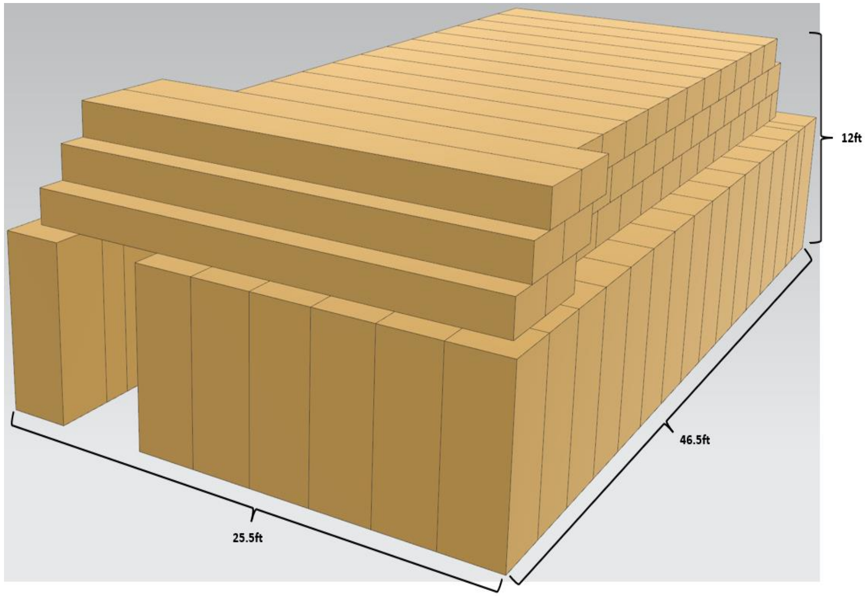
Cavity: The project team has obtained a 9-cell cavity and has a design for the conduction cooling scheme that will be used. The cavity will be tested.

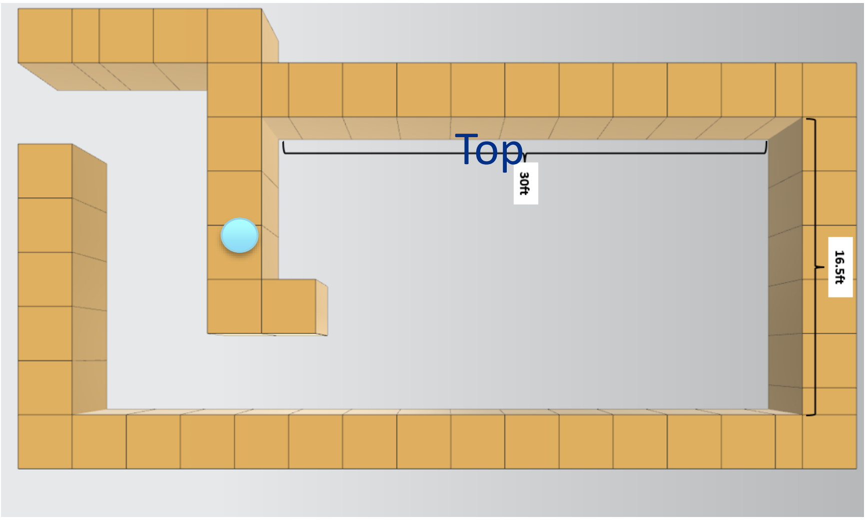




ERDC accelerator cave (on-going)

16’x30’x12’





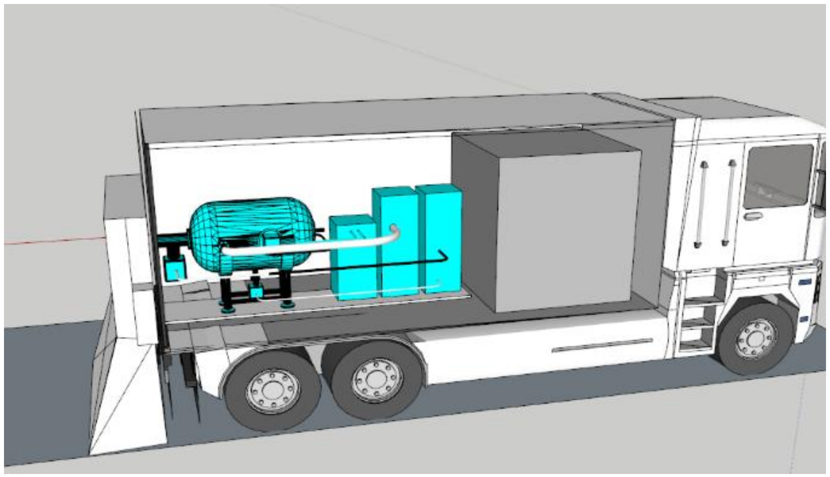
E-beam Pavement Studies

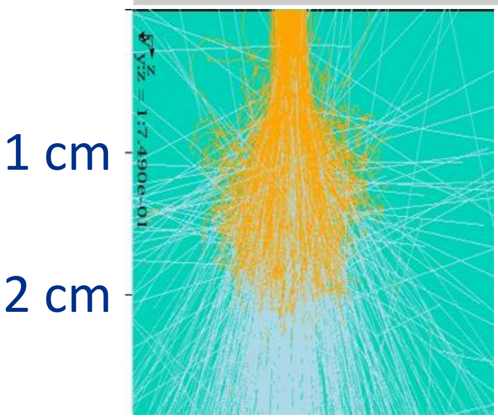
- Proof of principle work with ERDC & Univ of Illinois
  - Univ of Illinois prepares and analyzes samples, has good analytical capabilities.
  - Fermilab treats bitumen-polymer formulations at various dose rates, total doses and higher temperatures to promote diffusion.
  - Currently looking at recycled PE as an additive and other polymer formulations that would not “self-crosslink”.

- Optimizing e-beam conditions at Fermilab’s A2D2 (Accelerator Application Development & Demonstration)
  - E-beam energy – 10 MeV high standard for industrial apps to satisfy higher penetration depth while no activation
  - Dose rate – lower dose rate is usually better for limit scission degradation.

Courtesy: Charlie Cooper, Slavica Grdanovska

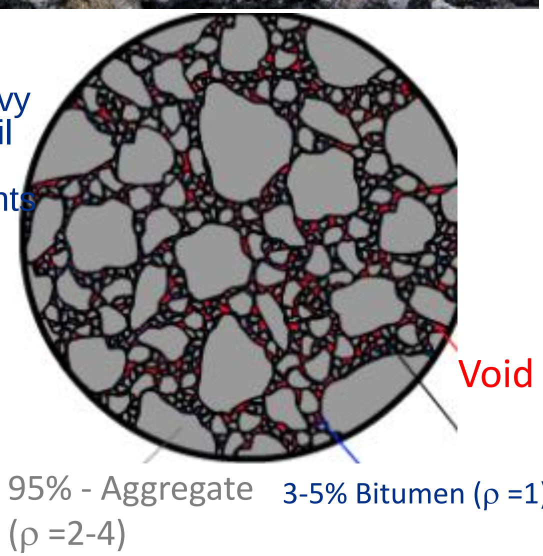
Use of Electron Beam to Improve Asphalt Pavement





Kephart, R. Method and System for In-Situ Cross Linking of Polymers, Bitumen and Similar Materials to Increase Strength, Toughness and Durability via Irradiation with Electron Beams from Mobile Accelerators. US 9,340,931 B2, May 17, 2016.

- Bitumen is the heavy remains of crude oil after all other valuable components have been distilled out
- Thousands of compounds
- Sulfur rich



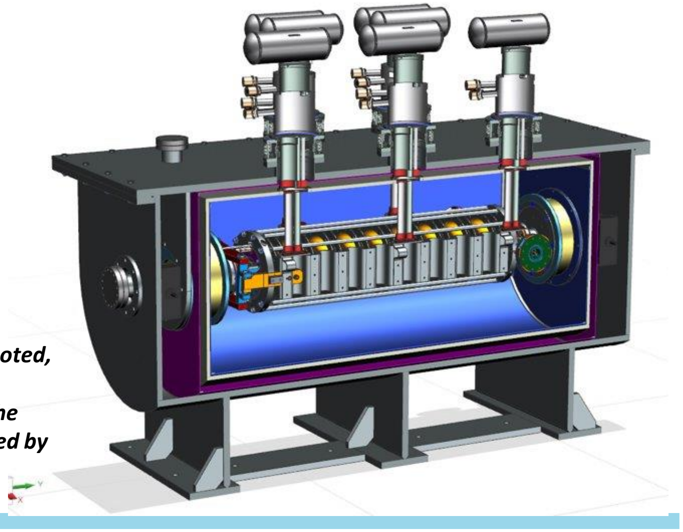
Courtesy: Charlie Cooper, Slavica Grdanovska

Thank you!

To deliver the high-power accelerator for ERDC for the pavement application, Fermilab has taken an <u>external injector approach followed by a conduction-cooled cryostat</u>

1. Built a prototype (20 kW)
    1. De-risk key technology – Nb3Sn, conduction cooling
    2. Design a cryomodule based on results
    3. Secure cryogenic, microwave power sources
    4. Build the electron source
    5. Commission the prototype

we are here



Acknowledgment to US Army Corps of Engineers (ERDC), IARC-ETD, APSTD, AD and several others at Fermilab

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Backup

Recent SRF Technology Breakthroughs:

- Higher temperature superconductors: Nb_3Sn coated cavities dramatically lower cryogenic losses and allow higher operating temperatures (e.g. 4 K vs 1.8 K)
- Commercial Cryocoolers: new devices with higher capacity at 4 K enables turn-key cryogenic systems
- Conduction Cooling: possible with low cavity losses➔ dramatically simplifies cryostats (no Liquid Helium !)
- New RF Power technology: injection locked magnetrons allow phase/amplitude control at high efficiency and much lower cost per watt
- Integrated electron guns: reduce accelerator complexity

- **Enable compact industrial SRF accelerators at low cost**

Accelerator Applications enabled by modern advancements

Energy and Environment

- Treat Municipal Waste & Sludge
  - Eliminate pathogens in sludge
  - Destroy organics, pharmaceuticals in waste water
- In-situ environmental remediation
  - Contaminated soils
  - Spoils from dredging, etc

Industrial and Security

- In-situ cross-link of materials
  - Improve pavement lifetime
  - Instant cure coatings
- Medical sterilization without Co60
- Improved non-invasive inspection of cargo containers
- Additive manufacturing refractory metals

These new applications need cost effective, energy efficient, high average power electron beams.

New technology can enable new applications (including mobile apps)

Impact: publications, talks, and media coverage

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

ELSEVIER

Thermal resistance of pressed contacts of aluminum and niobium at liquid helium temperatures

R.C. Dhuley*, M.I. Geelhoed, J.C.T. Thangaraj

Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

IEEE — IEEE Transactions on Applied Superconductivity

Thermal link design for conduction cooling of SRF cavities using cryocoolers

R. C. Dhuley, R. Kostin, O. Prokofiev, M. I. Geelhoed, T. H. Nicol, S. Posen, J. C. T. Thangaraj, T. K. Kroc, and R. D. Kephart

U.S. DEPARTMENT OF ENERGY | Office of Science — Science Highlights

Cryogen-free Superconducting RF Cavity

A team from Fermilab has demonstrated cryogen-free operation of a niobium superconducting radiofrequency cavity.

TechConnect WORLD INNOVATION CONFERENCE & EXPO — 20th ANNIVERSARY — MAY 13-16, 2018 ANAHEIM, CA

ColdFacts INTERNATIONAL — The Magazine of the Cryogenic Society of America, Inc.

Towards cryogen-free SRF particle accelerators