Conduction-Cooled SRF Cavities: Opportunities and Challenges

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Cornell Laboratory for Accelerator-based ScienceS & Education (CLASSE)

21st International Conference on Radio-Frequency Superconductivity (SRF 2023)

Outline

- *Foundation: Conduction-Cooled SRF Cavities*
- *Overview: Compact Cryomodules*
- *Implementation: Key Challenges & Solutions*
- *Summary*

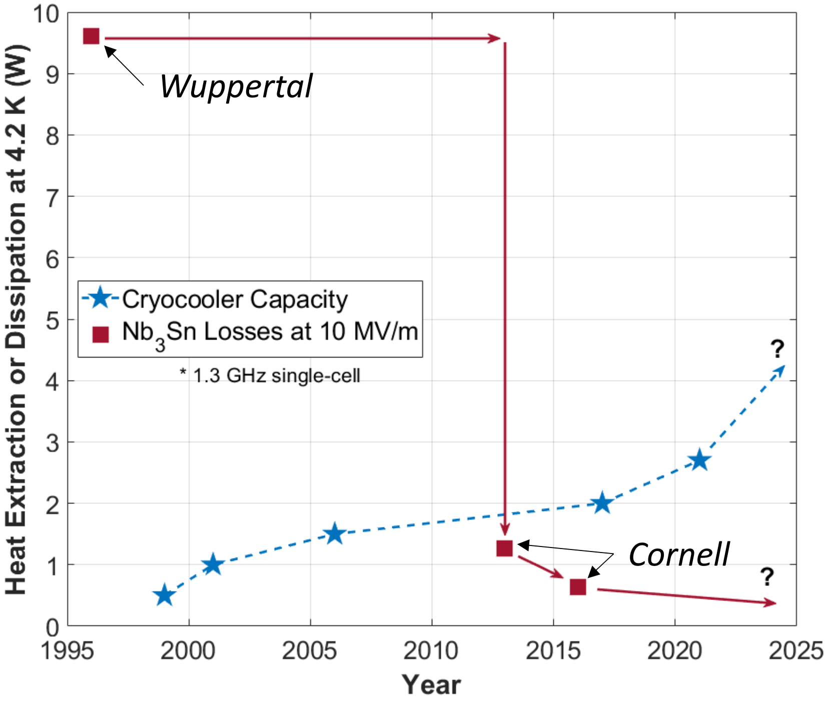
FOUNDATION

Conduction-Cooled SRF Cavities

A New Frontier

- *1.3 GHz Nb_3Sn cavities reliably dissipate* **< 1 W at 10 MV/m at 4.2 K**
- *Cryocoolers can now extract* **2+ W at 4.2 K** *(turn-key)*

→ **Cryocooler-based cooling** *is now possible!*



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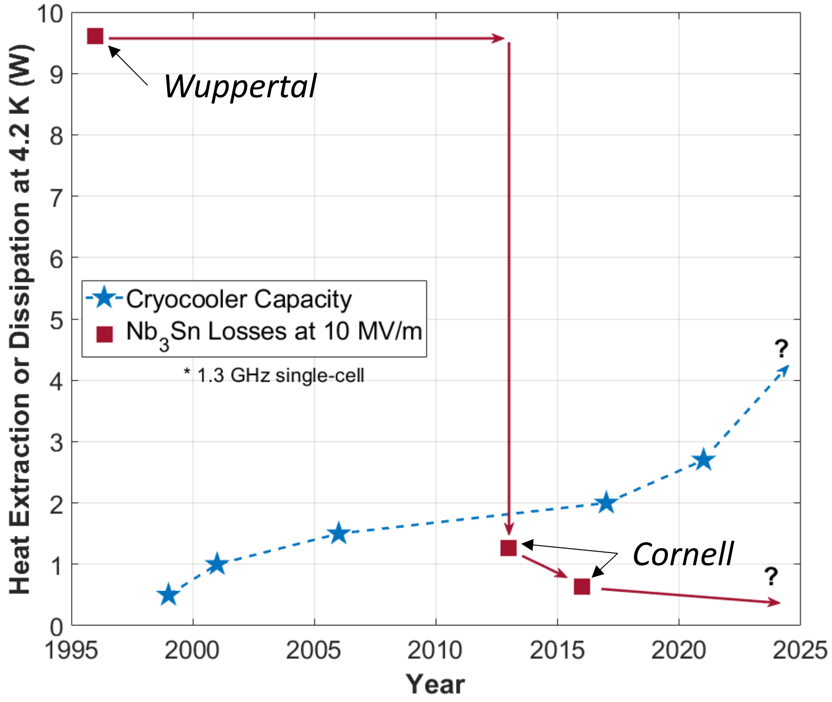

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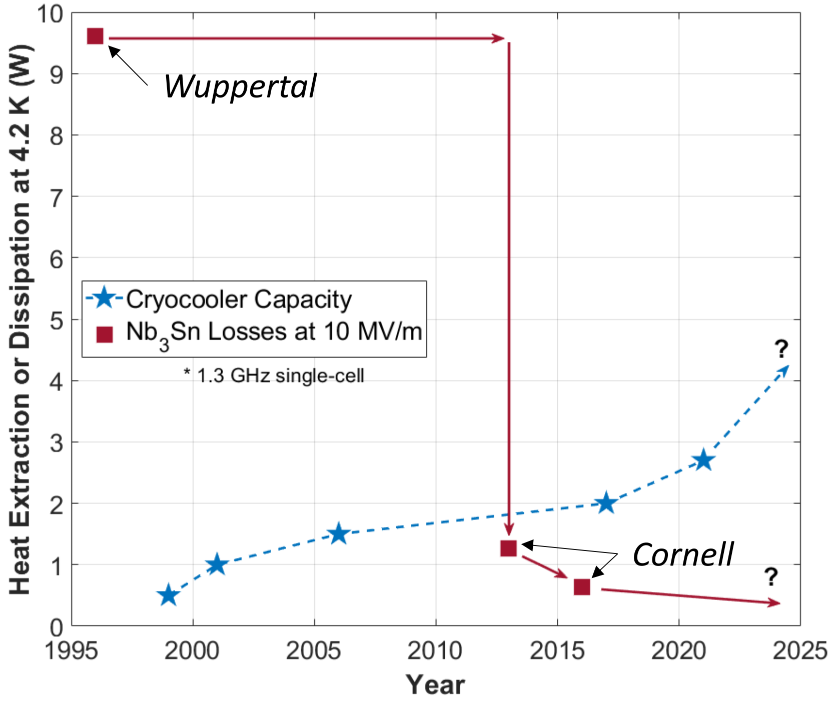
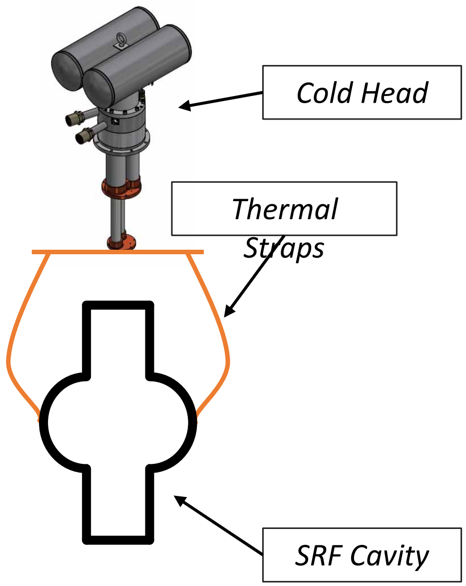
Direct conduction cooling





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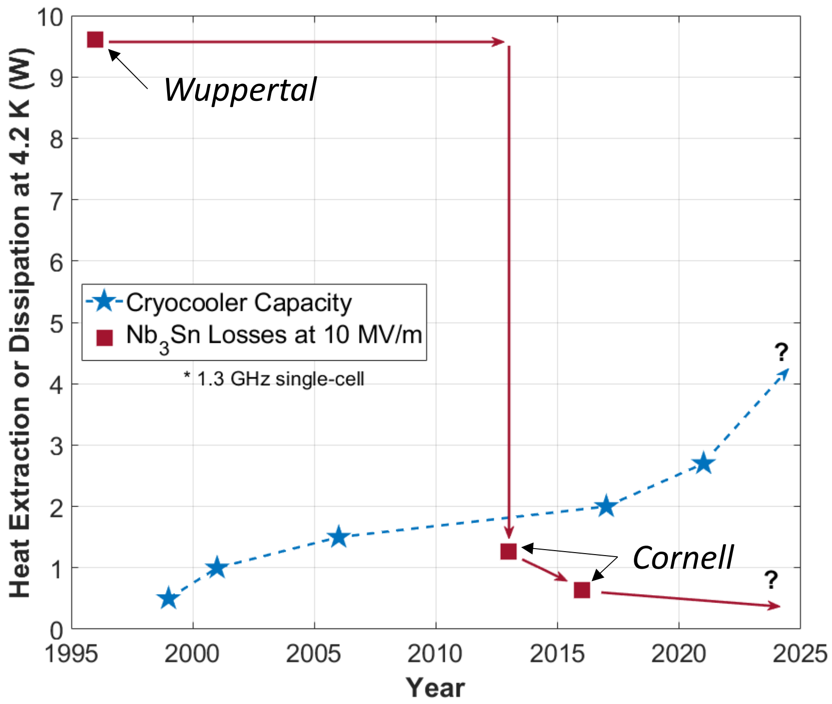

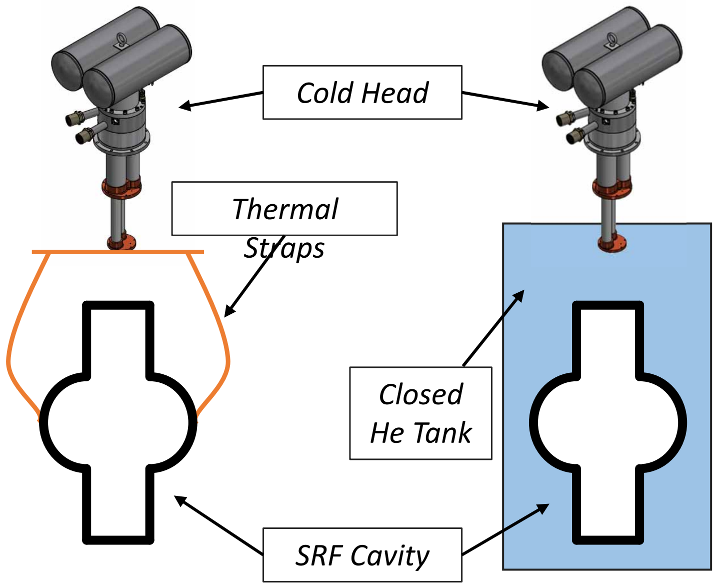

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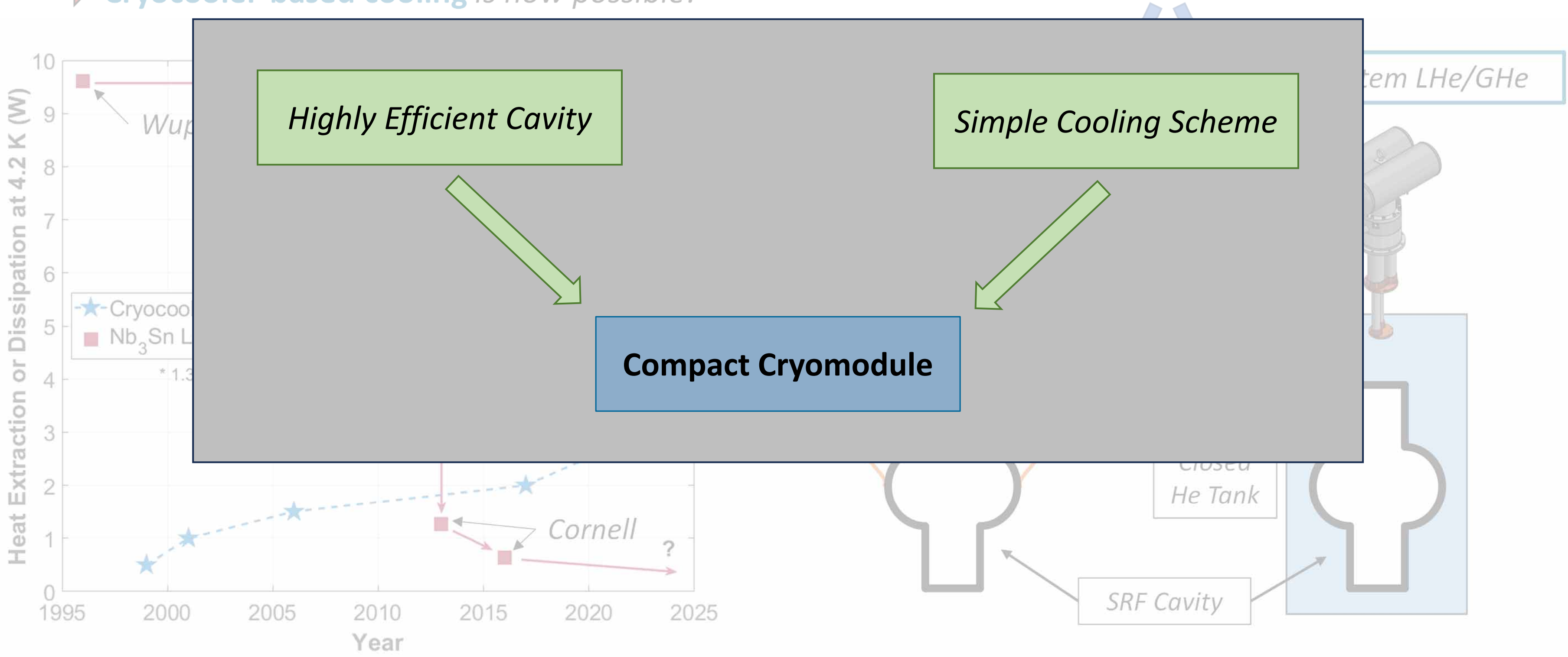
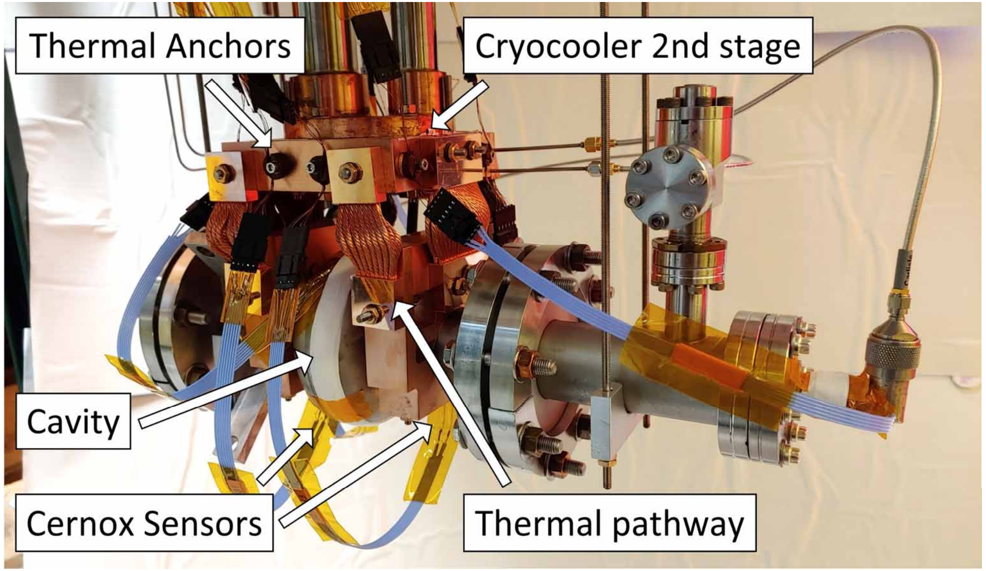
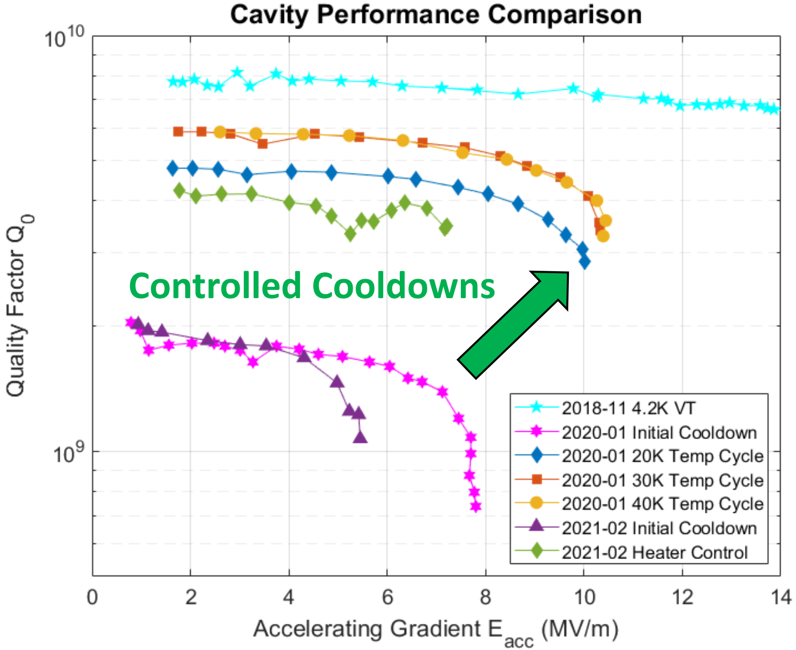


Proof-of-Principle Demonstrations

Initial studies completed at Cornell, Fermilab, JLab: Cornell University

- *2.6 GHz Nb_3Sn cavity*
- *Beam clamp design for* **thermal gradient control**
- **First demonstration** *of stable RF operation at* **10 MV/m***!*
- **Controlled cooldown** *required*





N.A. Stilin et. al, doi:10.1088/2631-8695/acdd51

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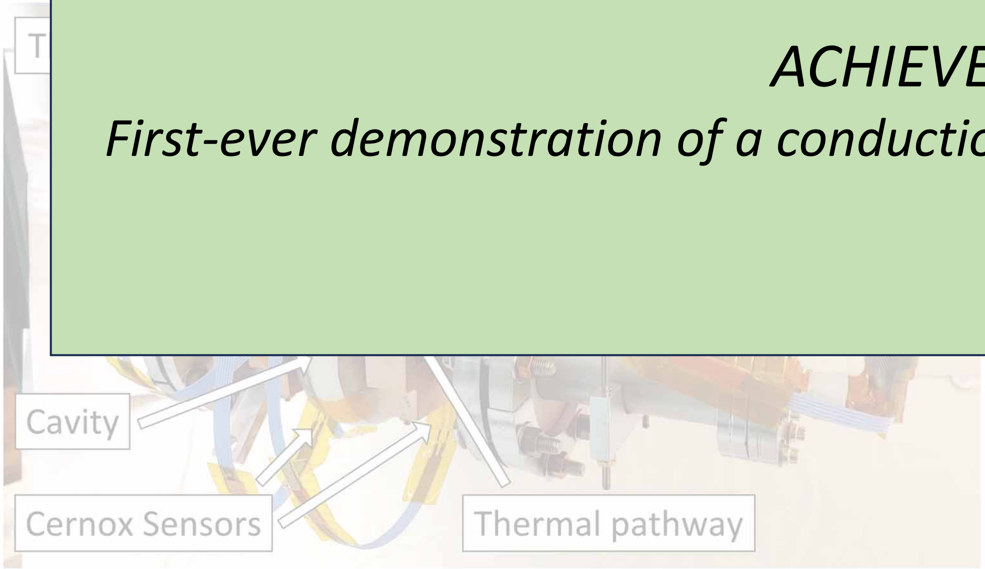
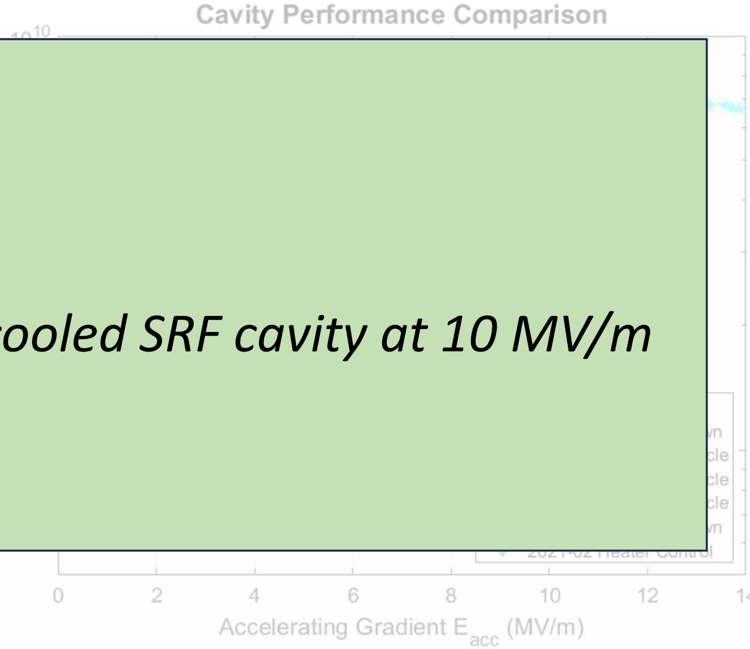




ACHIEVED:

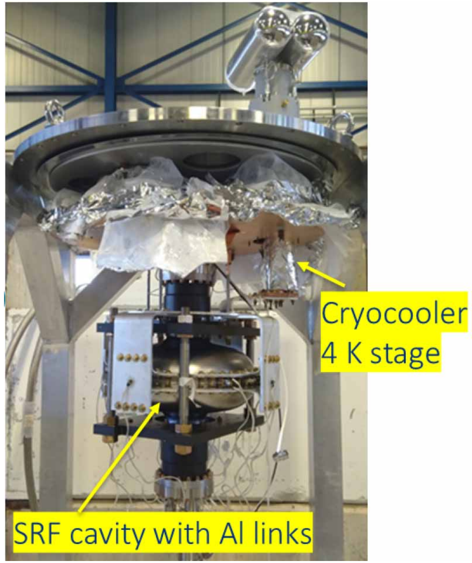
First-ever demonstration of a conduction-cooled SRF cavity at 10 MV/m

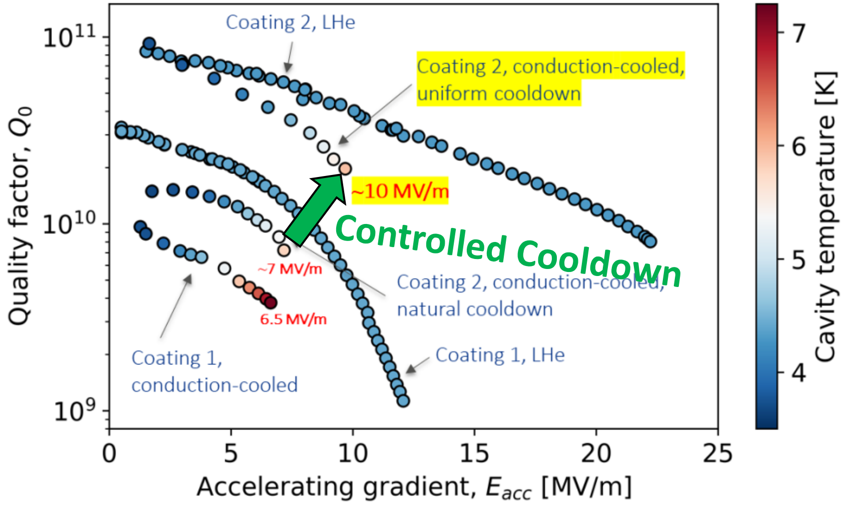
N.A. Stilin et. al, doi:10.1088/2631-8695/acdd51

Proof-of-Principle Demonstrations

Initial studies completed at Cornell, Fermilab, JLab: Fermilab

- *650 MHz Nb_3Sn cavity*
- *Nb rings welded at equator for heat extraction*
- *Reached 10 MV/m after* **controlled cooldown**



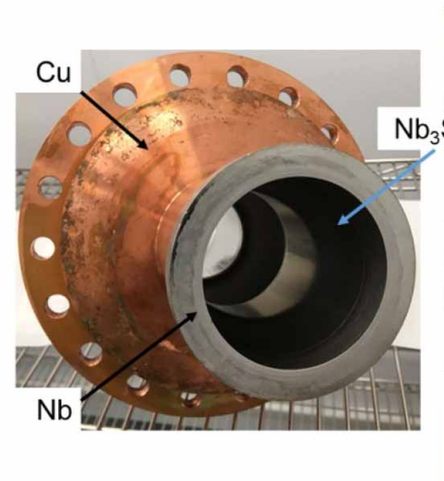


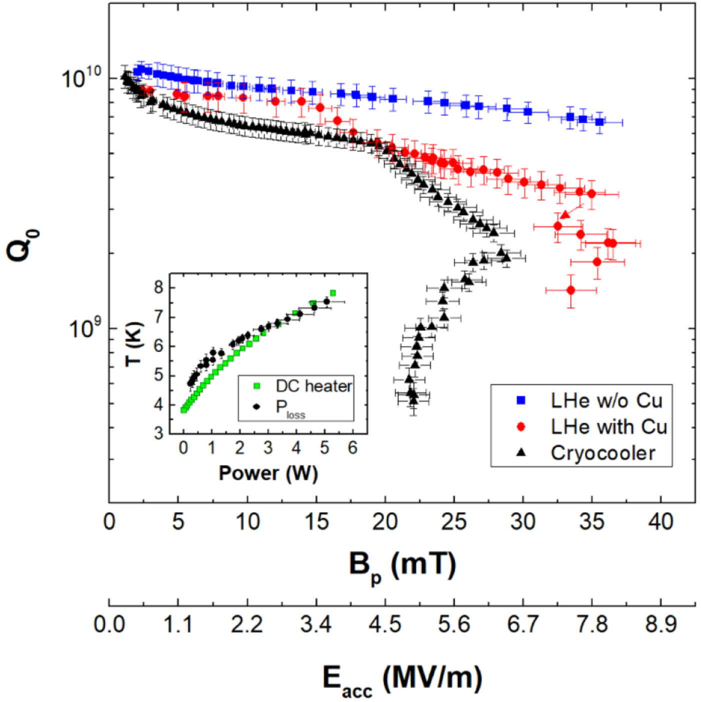
R.C. Dhuley et. al, doi:10.1088/1361-6668/ab82f0

Proof-of-Principle Demonstrations

Initial studies completed at Cornell, Fermilab, JLab: Jefferson Lab

- *1.5 GHz Nb_3Sn cavity*
- *5 mm* ***copper layer electroplated*** *to cavity exterior*
  - *Offers better thermal conduction across cavity*
- *Performance possibly limited by strain on Nb3Sn layer*





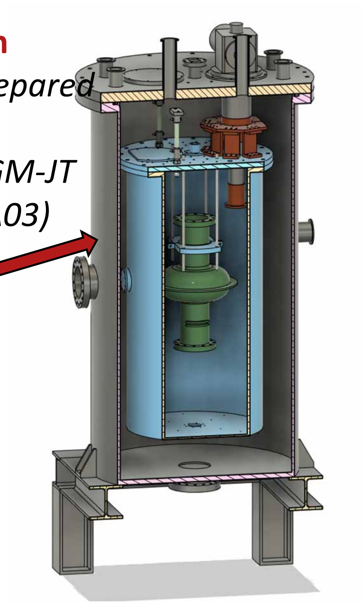
G. Ciovati et. al, doi: 10.1088/1361-6668/ab8d98

Proof-of-Principle Demonstrations

Similar studies ongoing at KEK & IMP:

Cavity cooling test under construction

- *Chamber and components were prepared for conduction cooling R&D*
- *Applying prototype high-capacity GM-JT cryocooler from SHI (see talk THIXA03)*



Poster WEPWB081

Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

Courtesy of Kensei Umemori

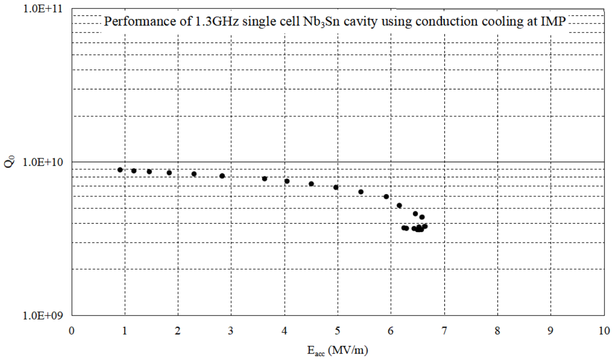
First test performance:

- *Q_0 at low field ~9E9*
- *$E_{acc,max}$ ~6.6 MV/m*

Structural optimization and improvement of the conduction cooling is ongoing

Good thermal stability at the dissipation power of below 3.2W

Precise slow-cooling of **2-10min/K**



Courtesy of Ziqin Yang

Motivation

We've shown conduction-cooled cavities are possible… why bother?

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→ *Makes SRF technology accessible to small-scale operations*

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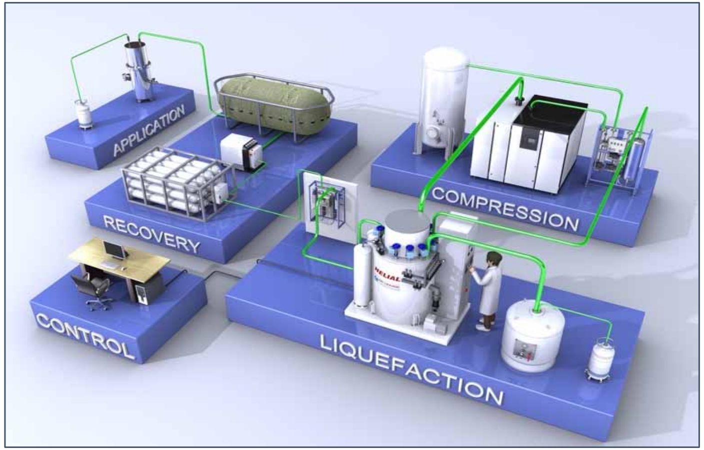
Current infrastructure requirements:



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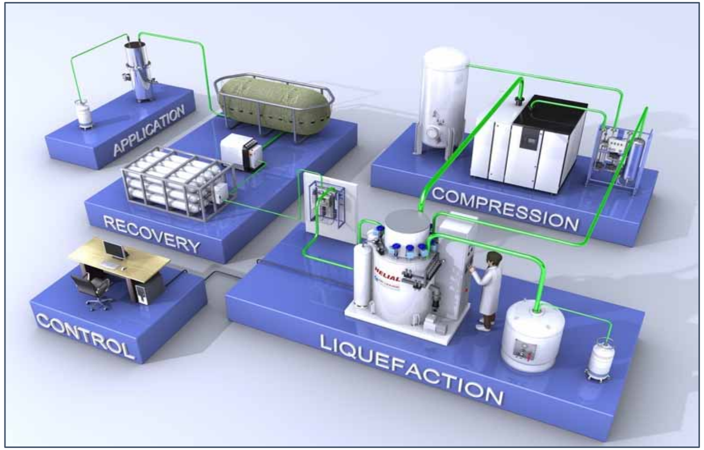
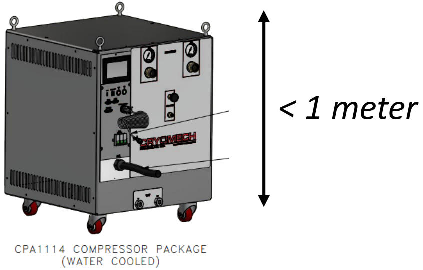


Conduction cooling



Significantly lower costs, very low-maintenance (robust), turn-key operation (no expertise)

Motivation

Applications for small-scale operations:

- **Energy and environment**
  - *Sterilizing waste water, sludge, medical waste*
  - *Flue gas treatment*
  - *Remediation of contaminated soil*
  - *Asphalt treatments (durability)*
- **Medicine**
  - *Radioisotope production*
- **Security & defense**
  - *Cargo inspection*
- **Industry**
  - *Producing biofuel*
  - *Curing carbon fiber composites*
- **… and many more!**

Typical beam parameters

- *Moderate Energy:* 1 – 10 MeV
- *High Current:* ≥ 100 mA
- *High Avg. Power:* ≥ 1 MW

Decontamination cross section for a 10 MeV beam into a high-clay-content 5% contaminated soil

U.S. DOE Report, "Accelerators for America's Future"
U.S. DOE Report, "Workshop on Energy and Environmental Applications of Accelerators"

OVERVIEW
Compact Cryomodules

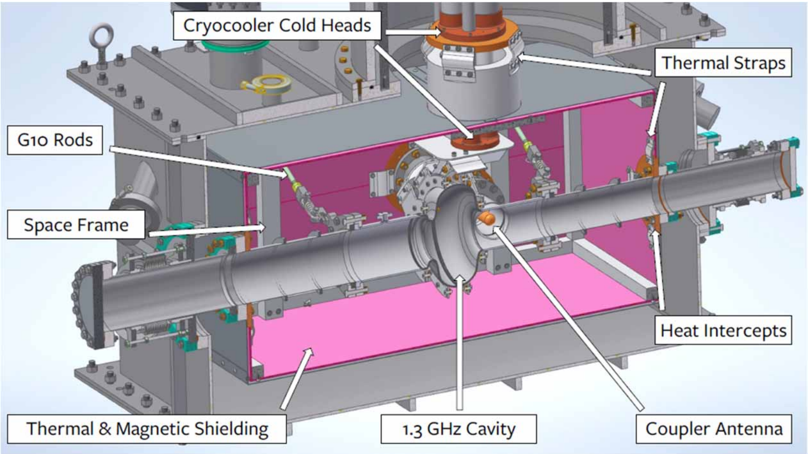
8 Examples

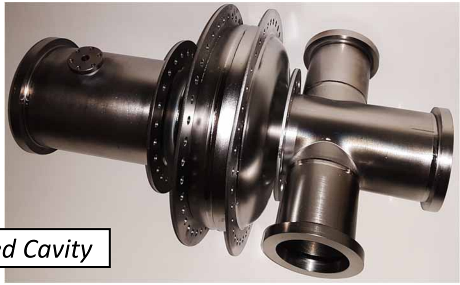
Cornell University

R&D Project – **General Application**

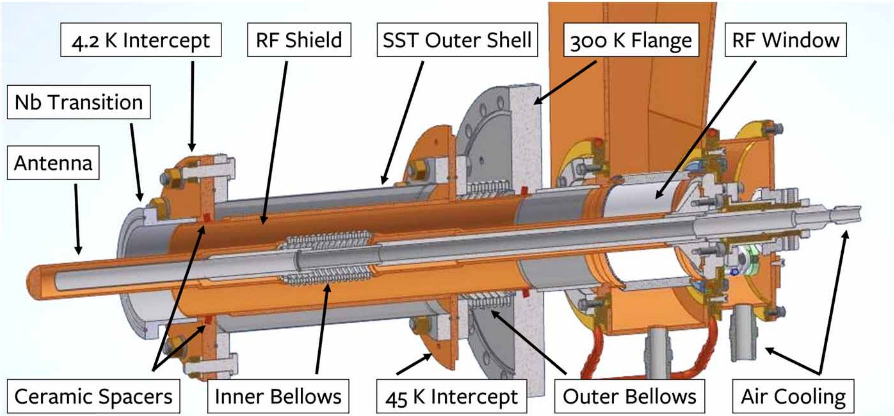
Energy Gain	*1 MeV*
Beam Current	*100 mA*
Average Power	*100 kW*

- *Single-cell* **1.3 GHz** *Nb_3Sn cavity*
- **Nb rings** *at cavity equator (2) and near cavity irises (2)*
- *1 PT420 + 1 PT425 cryocoolers (Cryomech)*
  - *Total capacity: 4.15 W at 4.2 K and 100 W at 45 K*





Finalized Cavity



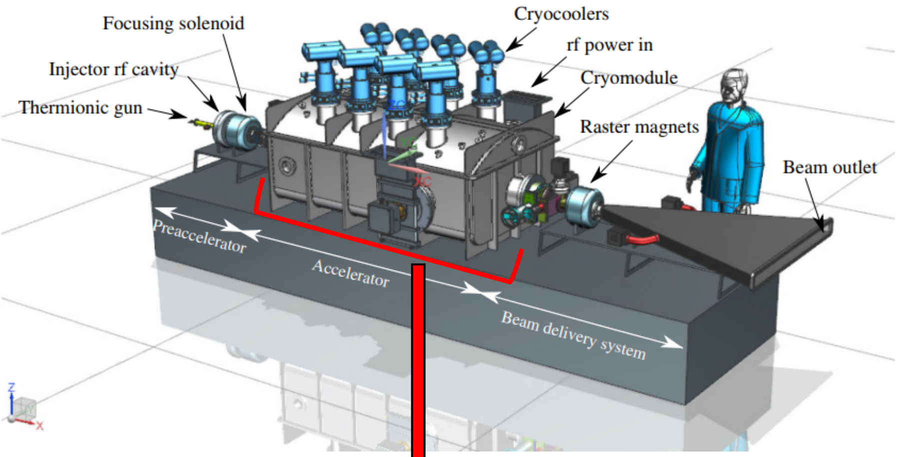
IARC @ Fermilab

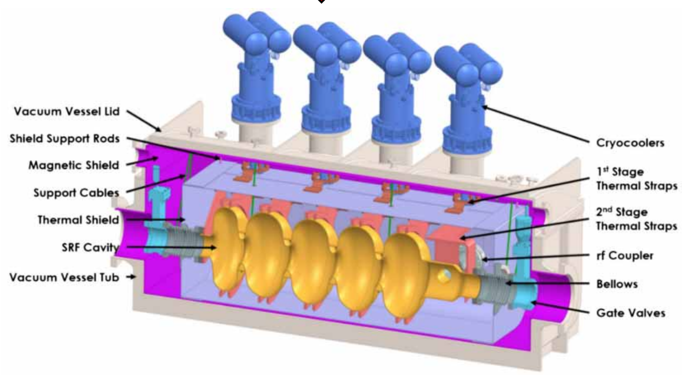
Talk THIXA07

Application: Wastewater Treatment

Beam Energy	*10 MeV*
Beam Current	*100 mA*
Average Power	*1 MW*

- *Design: treat up to 12 million gallon / day*
- *Pre-accelerator (RT gun + injector cavity + sol.)*
- *Accelerating cryomodule*
  - *5-cell 650 MHz Nb_3Sn cavity*
  - *Twin coaxial FPC*
  - *6 PT420 + 2 PT425 cryocoolers (Cryomech)*
- *Beam delivery (raster magnet + beam horn)*





See: R.C. Dhuley et al., Phys. Rev. Accel. Beams ***25****, 041601 (2022)*
"Design of a 10 MeV, 1000 kW average power electron-beam accelerator for wastewater treatment applications"

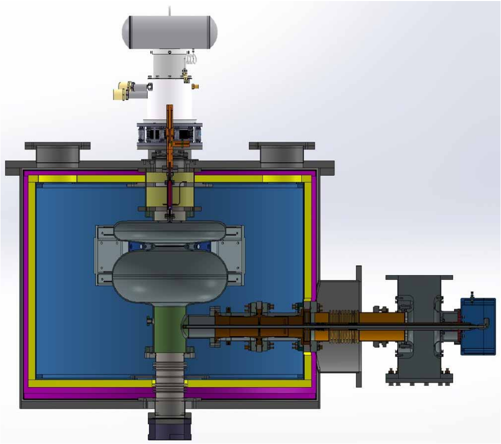
IARC @ Fermilab → *Core Team: Ram Dhuley, Christopher Edwards, Jayakar Thangaraj, Tom Kroc*

Talk THIXA07

See also: C2Po1B-10 at CEC in July

Application: Medical Device Sterilization

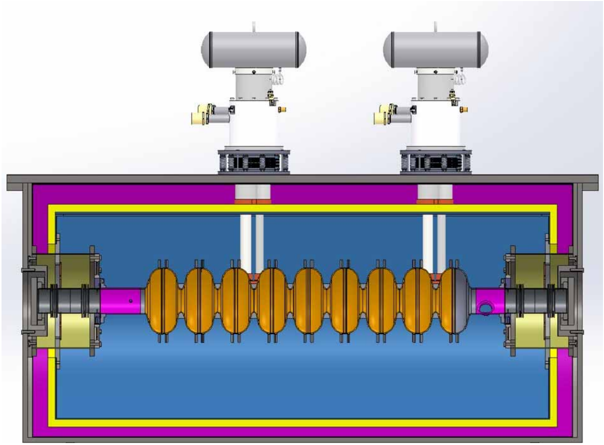
- *Beam power: 20 kW*
- *1.5-cell 650 MHz Nb_3Sn cavity*
- *Multi-year funded program, looking to replace Co-60 with accelerator-based ionizing radiation*



Cryomodule Design – Tom Nicol

Application: Improved Pavement Processing

- *Beam power: 200 kW*
- *9-cell 1.3 GHz Nb_3Sn cavity*
- *Multi-year funded program, interested in the ability to modify pavement in-situ*



Cryomodule Design – Tom Nicol (under development)

Courtesy of Chris Edwards

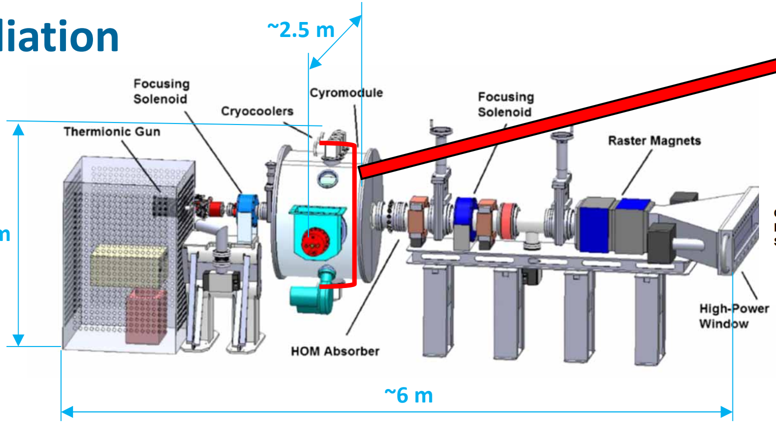
Jefferson Lab

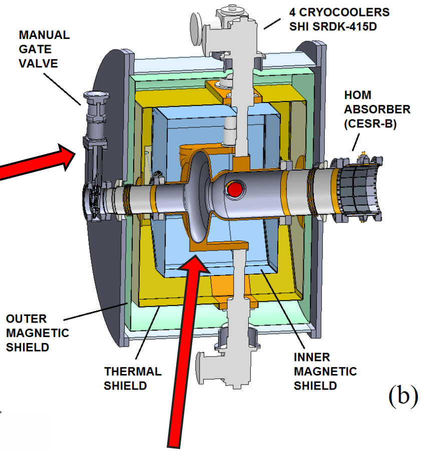
GENERAL ATOMICS

Talk THIXA04

Application: Environmental Remediation

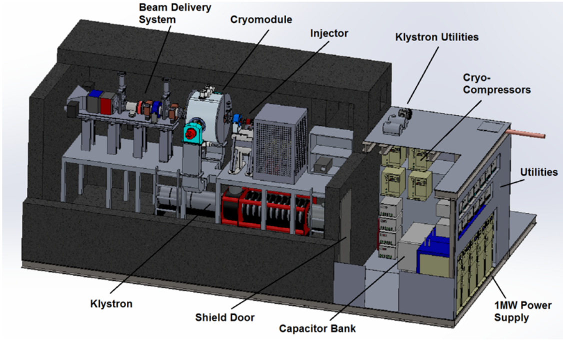
Beam energy	*1 MeV*
Beam current	*1 A*
Beam power	*1 MW*





Cu/Nb/Nb_3Sn SRF cavity

- *Single-cell 750 MHz Nb_3Sn cavity (β=0.5)*
  - *Cu electroplated exterior*
- *Twin coaxial FPC*
- *4 GM cryocoolers (each 1.5 W at 4.2 K)*
- *Beam generation and delivery systems*
- *Possible use in flue gas treatment*



Example of a facility layout using a 1 MW CW commercial klystron

G. Ciovati et al., Phys. Rev. Accel. Beams ***21****, 091601 (2018)*
US Patent 10,932,355 High-current conduction cooled superconducting radio-frequency cryomodule

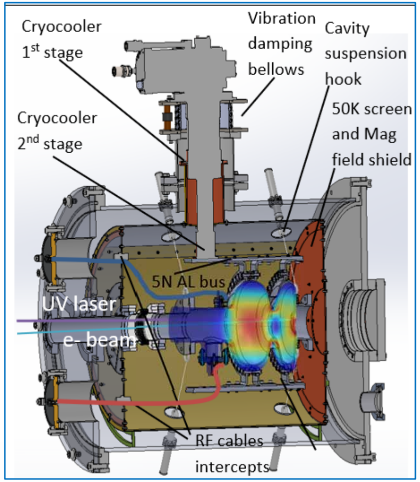
euclid BEAMLABS

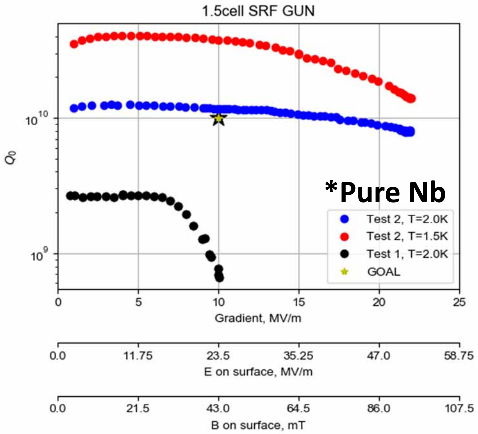
Application: SRF Photogun for MeV UED/UEM

Beam energy	*1.655 MeV*	*1.655 MeV*
Charge	*5 fC*	*0.5 pC*
Laser pulse length, rms	*6.4 fs*	*6.4 fs*
Beam bunch length, rms	*167 fs*	*741 fs*

- *1.5-cell 1.3 GHz Nb_3Sn cavity*
- *One cryocooler is enough to cool Nb3Sn gun at 4K*
- **Final goal** – *user facility at BNL Accelerator Test Facility*

- *Successful test of pure Nb photogun at 2 K*
- *4 K test of Nb_3Sn photogun had low Q_0 and HFQS*





Assembled cryomodule

See: R.Kostin et al., "Conduction cooled SRF photogun for UEM/UED applications", UED 308081, 23-rd ATF user meeting, 2020.

R.Kostin et al., "Status of Conduction Cooled SRF Photogun for UEM/UED", proc. of IPAC21, TUPAB167.

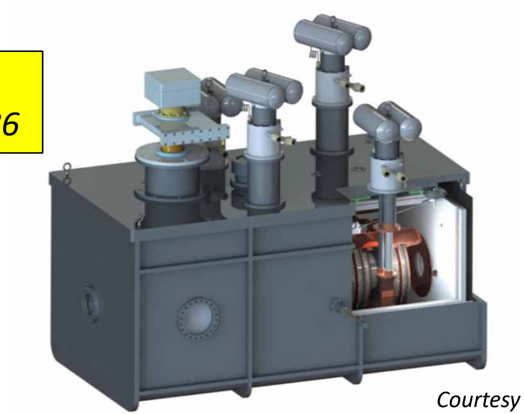
*DoE SBIR Phase II Grant #DE-SC0018621

RadiaBeam + IARC Fermilab

Application: **Deployable Conductively Cooled Cryostat**

- *Small, mobile cryostat with no cryoplant requirement*
- *Target design: 4.5-cell 650 MHz Nb_3Sn Cavity*
- *Utilizes 4 PT420 cryocoolers (Cryomech)*
- *Currently in fabrication to test with a single-cell 650 MHz cavity in the last quarter of this year*

Poster WEPWB086



Courtesy of Sergey Kutsaev

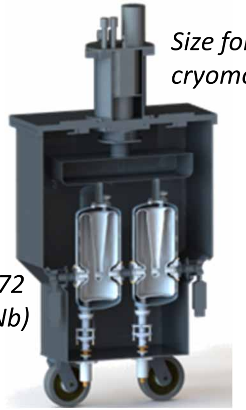
RadiaBeam Argonne NATIONAL LABORATORY Fermilab

Application: **Standalone Cryomodule for SC Nb_3Sn QWRs**

- *Current QWRs for ion linacs are ~ 1 m long*
- *Nb_3Sn enables higher frequency (small) & lower loss*
- *ATLAS upgrades, medical isotope production*

218 MHz cavity (Nb_3Sn)

ATLAS 72 MHz (Nb)



Size for a two-cavity cryomodule (218 MHz)

Courtesy of Mike Kelly

IMPLEMENTATION
Key Challenges & Solutions

Focus: Cavity & Coupler

Conduction Cooling

Challenge #1: *effective* **conduction cooling** *of cavity*

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What makes this difficult?

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1) Limited cooling power → **2 – 2.5 W** *per cryocooler at* **4.2 K** *(Cornell:* **4.15 W** *total)*

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3) *Uniform cooling of cavity assembly* → *good conduction* **around entire cell**

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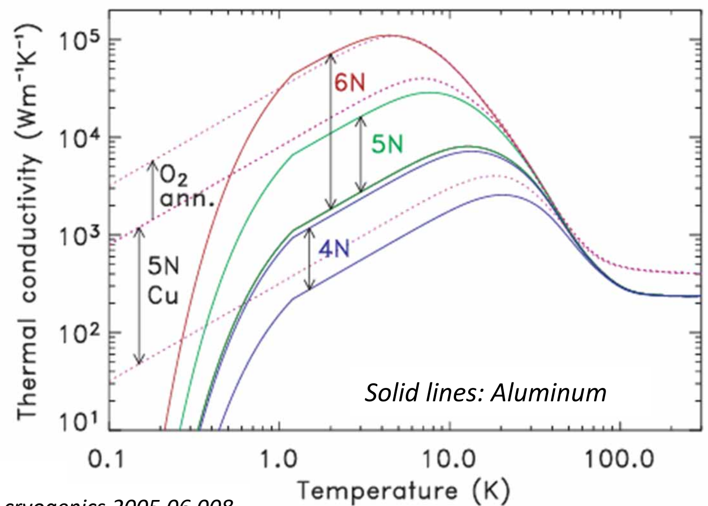
3) *Uniform cooling of cavity assembly* → *good conduction* **around entire cell**

→ *Very high thermal conductivity is necessary*



A. Woodcraft, doi:10.1016/j.cryogenics.2005.06.008

Conduction Cooling

Challenge #1: *effective* **conduction cooling** *of cavity*

→ *Different approaches being examined:*

Conduction Cooling

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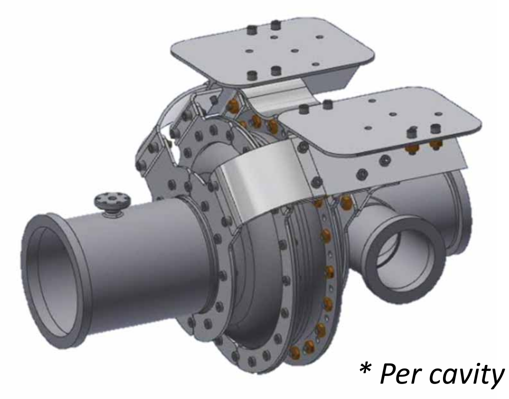
Cornell University

*a) Four intercepts**
b) Nb + 5N Al
c) 5N Al foil straps



** Per cavity cell*

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Challenge #1: *effective* ***conduction cooling*** *of cavity*

→ *Different approaches being examined:*

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*a) Four intercepts**
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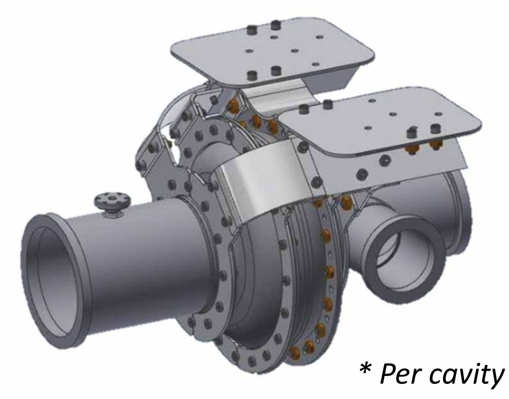
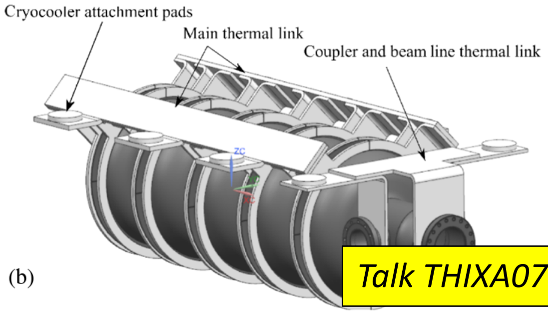
c) 5N Al foil straps

Fermilab

*a) Two intercepts**
b) Nb + 5N Al
c) 5N Al bent sheet





Talk THIXA07

** Per cavity cell*

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Challenge #1: *effective* **conduction cooling** *of cavity*

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Cornell University

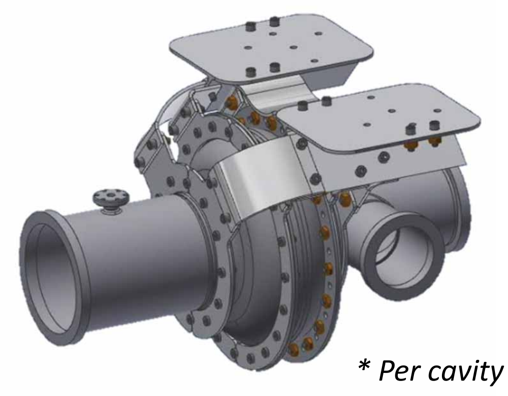
a) *Four intercepts**
b) *Nb + 5N Al*
c) *5N Al foil straps*

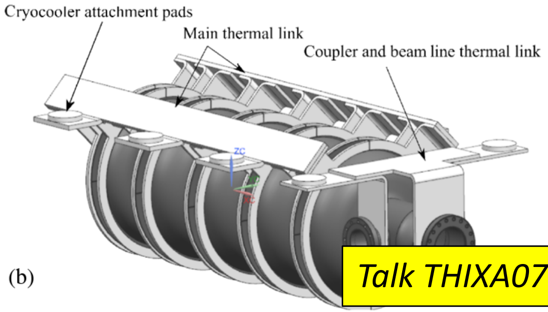
Fermilab

a) *Two intercepts**
b) *Nb + 5N Al*
c) *5N Al bent sheet*

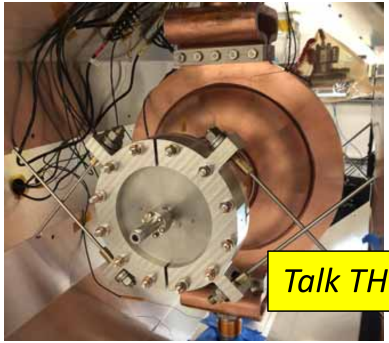
Jefferson Lab

a) *One intercept**
b) *Cu (cold-spray & plated)*
c) *C103 foil straps*





Talk THIXA07



Talk THIXA04

* *Per cavity cell*

Conduction Cooling

Challenge #1: *effective* ***conduction cooling*** *of cavity*

→ *Different approaches being examined:*

Cornell University ★

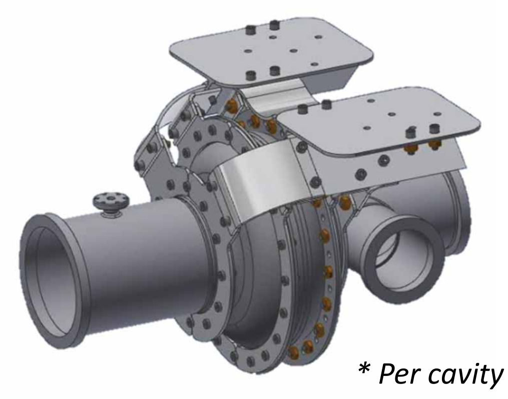
*a) Four intercepts**
b) Nb + 5N Al
c) 5N Al foil straps

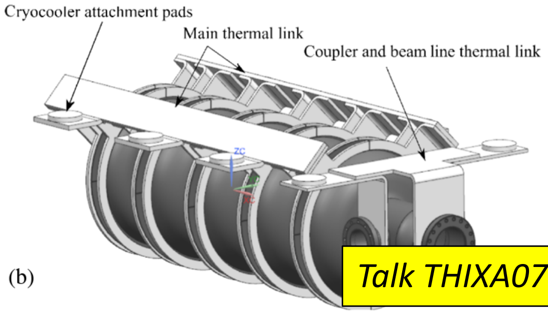
Fermilab

*a) Two intercepts**
b) Nb + 5N Al
c) 5N Al bent sheet

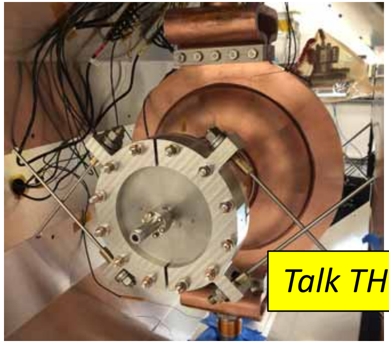
Jefferson Lab

*a) One intercept**
b) Cu (cold-spray & plated)
c) C103 foil straps





Talk THIXA07

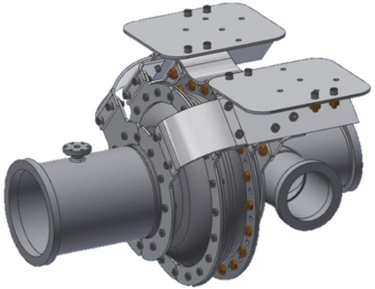


Talk THIXA04

** Per cavity cell*

Heat Extraction

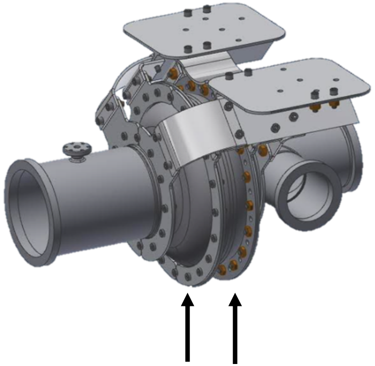
Question: *Is my design effective?*

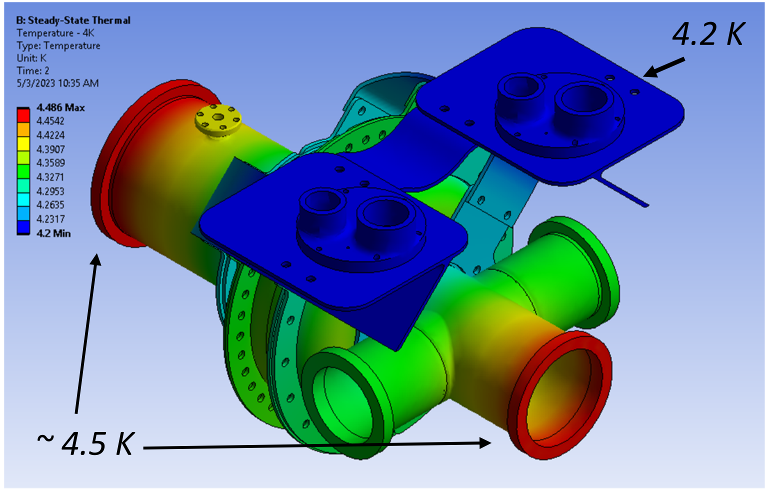


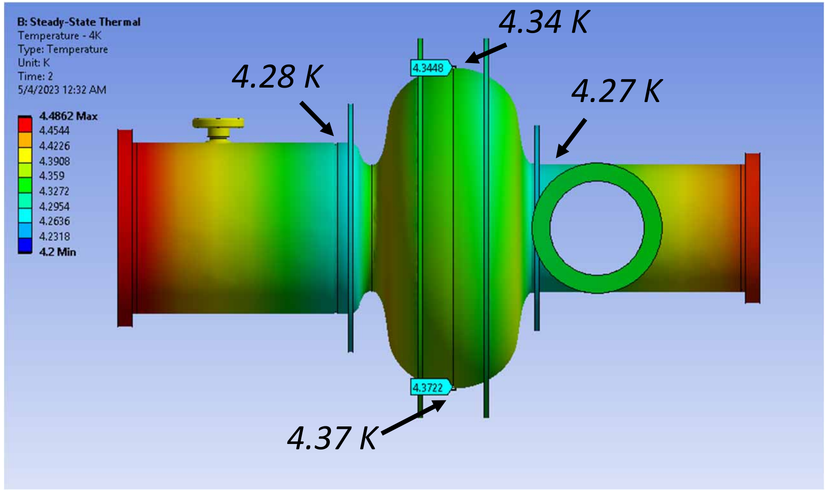
Heat Extraction

Question: *Is my design effective?*

- *Perform thermal modeling corresponding to* **10 MV/m operation**
- *Primary RF heat load extracted by* **equator intercepts**
- *Temperature results show* **small thermal gradients** *across cavity assembly*
- *Total of* **1.65 W** *at* **4.2 K** *(0.16 W static / 1.49 W dynamic)*







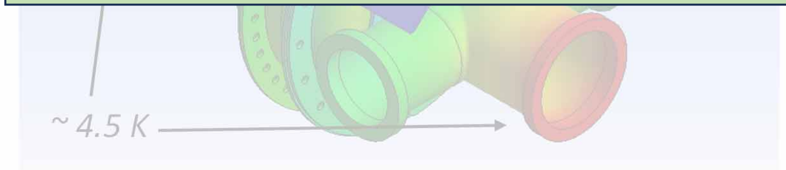
Heat Extraction

Question: *Is my design effective?*

- *Primary RF heat load extracted by* ***equator intercepts***

ACHIEVED:

Effective heat extraction with small gradients during RF operation



Experimental Comparison

Question: *Is this realistic?*

Experimental Comparison

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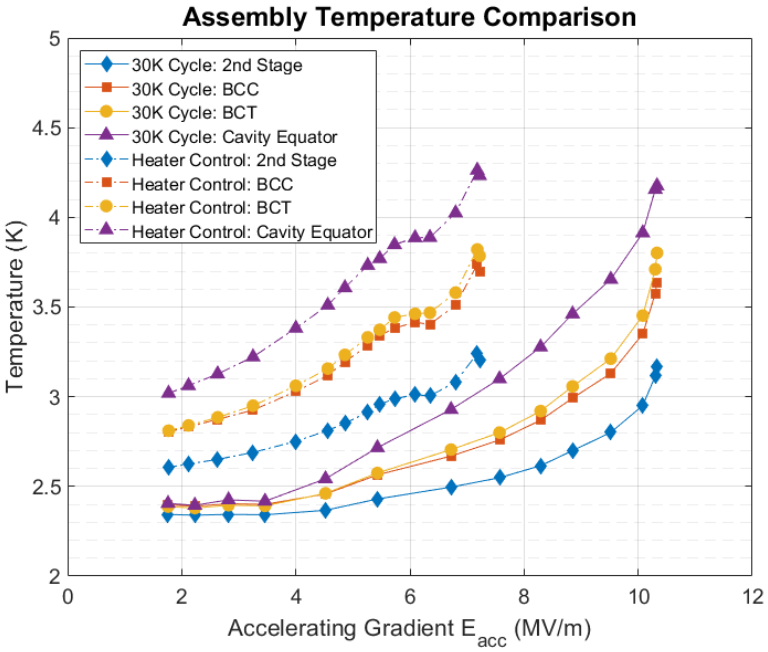
Recall **proof-of-principle demonstration***:*



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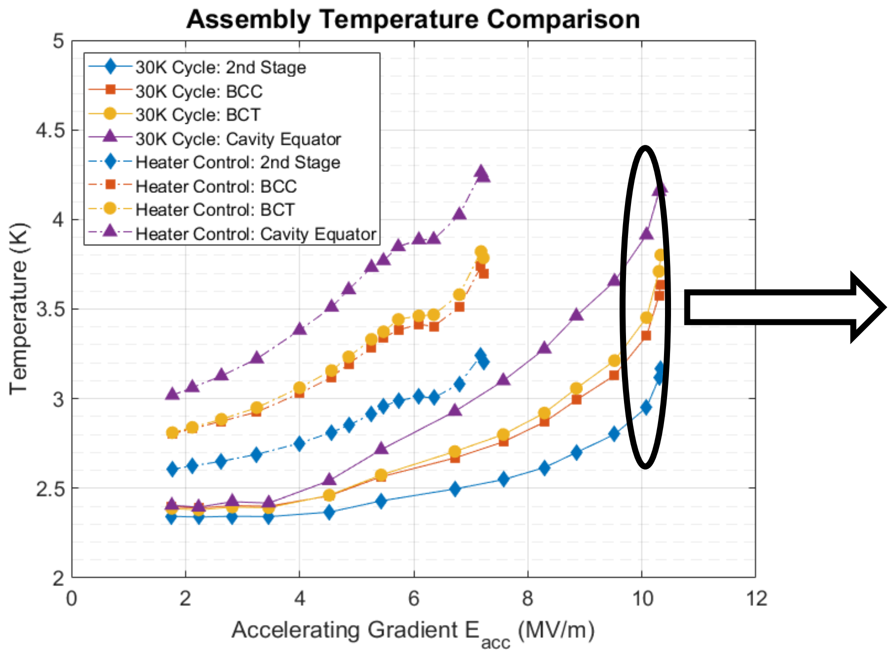

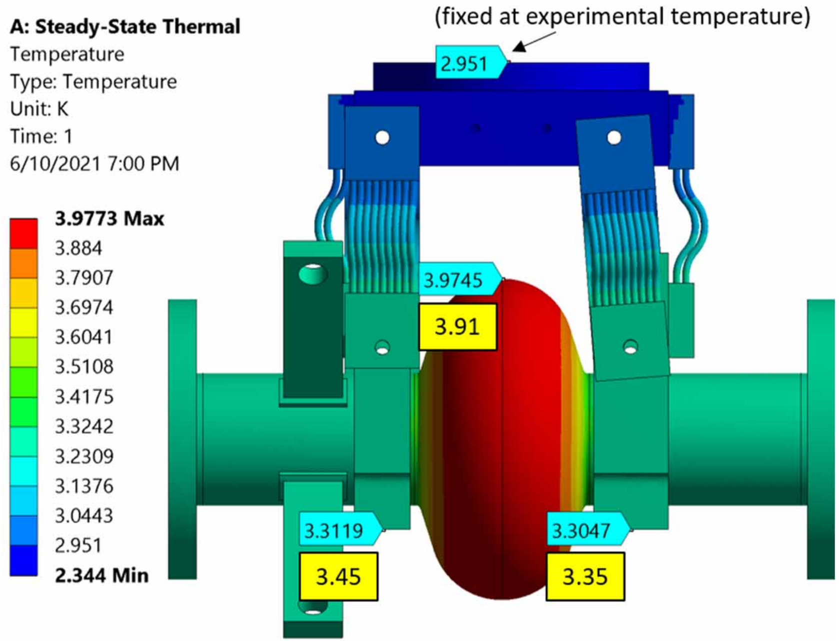

Experimental Comparison

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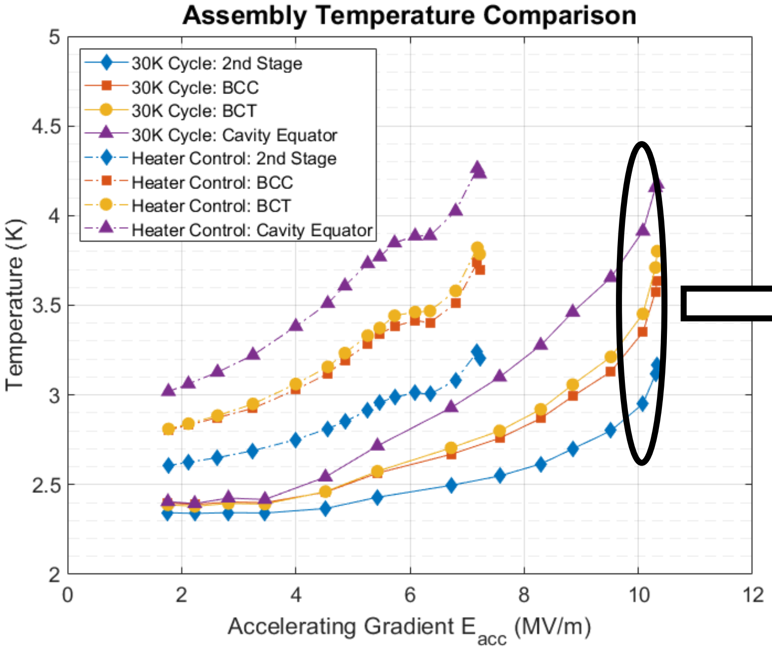
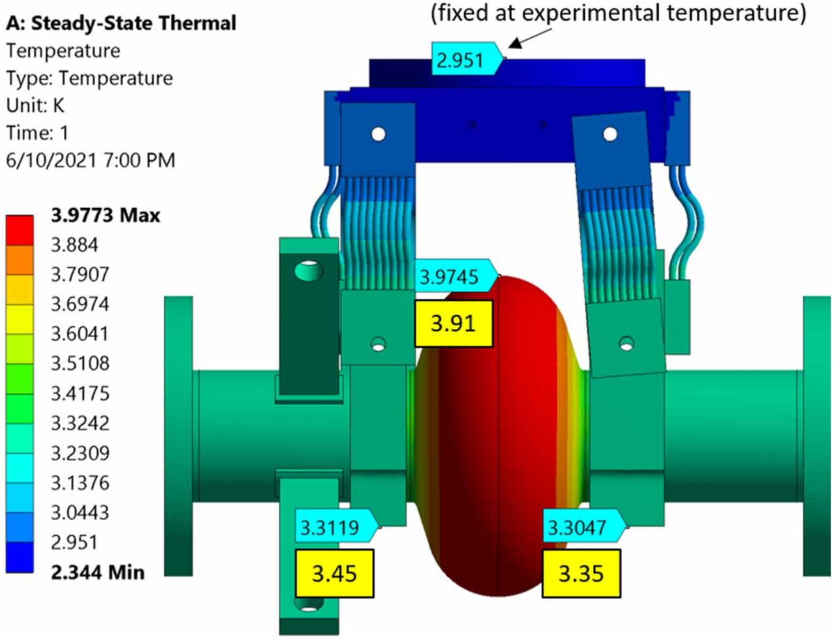
Recall **proof-of-principle demonstration***:*

Good agreement *between simulation and experiment!*





Cavity Cooldown

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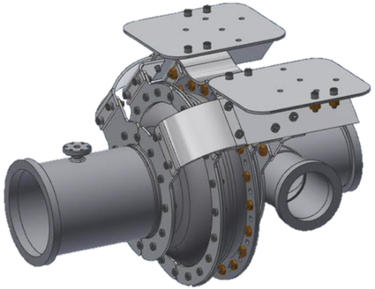
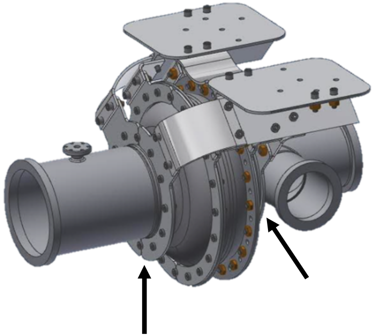
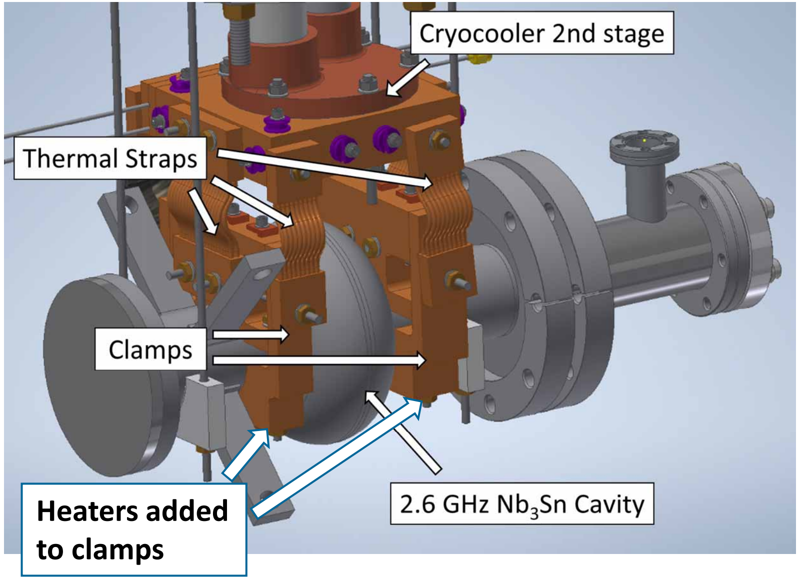


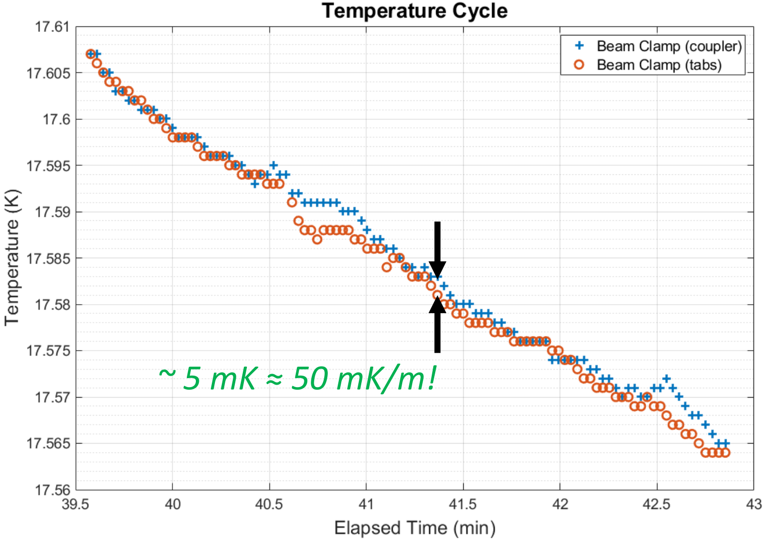
Cavity Cooldown

Question: *Is my design effective?*

- *Nb_3Sn requires* **small thermal gradients during cooldown** *for optimal performance*
  → *Aim for* **< 200 mK/m** *to reduce thermocurrents (Seebeck) during transition at T_c*
- *Proof-of-principle study demonstrated effectiveness of* **independent heater control**
- *Same capability enabled by use of additional intercept rings near* **cavity irises**







Cavity Cooldown

Question: *Is my design effective?*

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ACHIEVED:

Ability to optimize cavity cooldown to improve RF performance

High Power, Low Heat

Challenge #2: *design a* **simple, high-power** *input coupler with* **low 4.2 K heat load**

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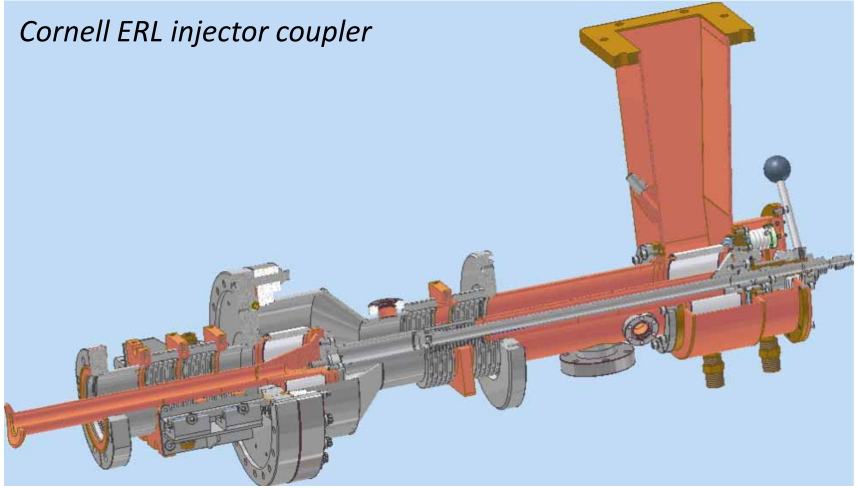
- *Max forward power:* **75 kW**
- *Heat load at 5 K:* **~ 3 W**

Cornell ERL injector coupler



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100 kW
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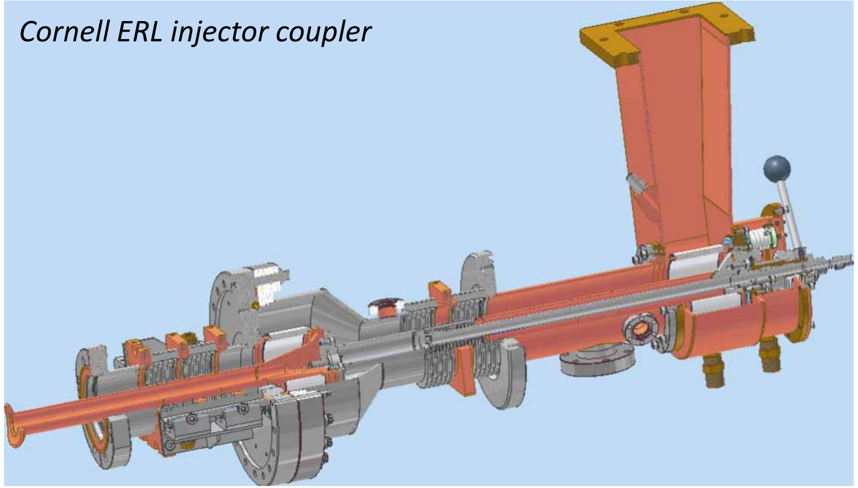

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100 kW
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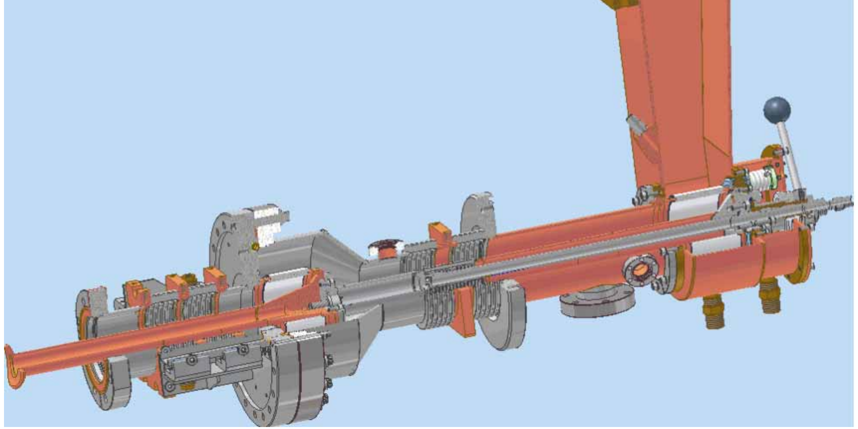
Factor of 10^5 difference between RF and dissipated power required!

Cornell ERL injector coupler



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→ *Optimize heat load distribution, enable conduction cooling, reduce cost & complexity*

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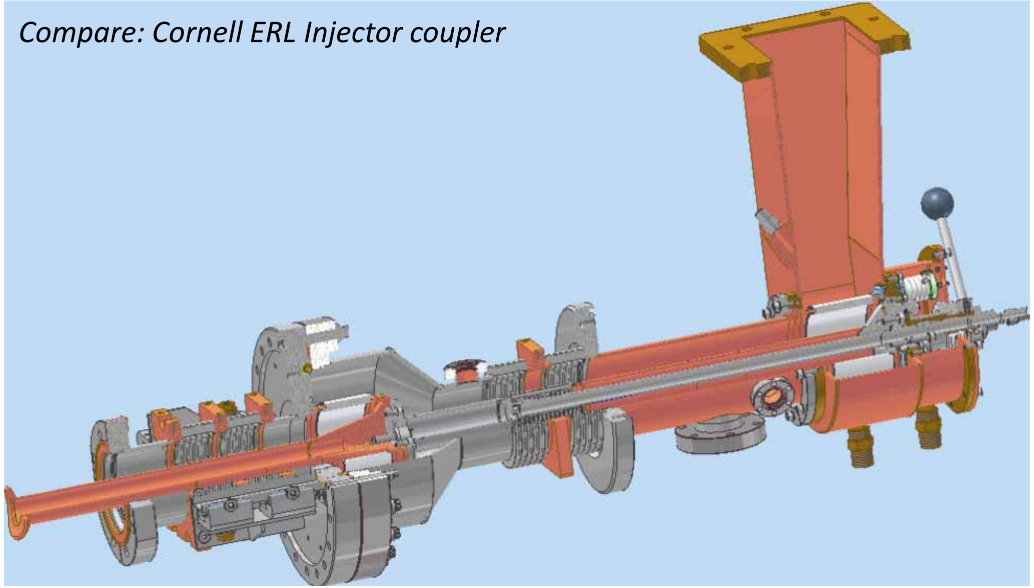

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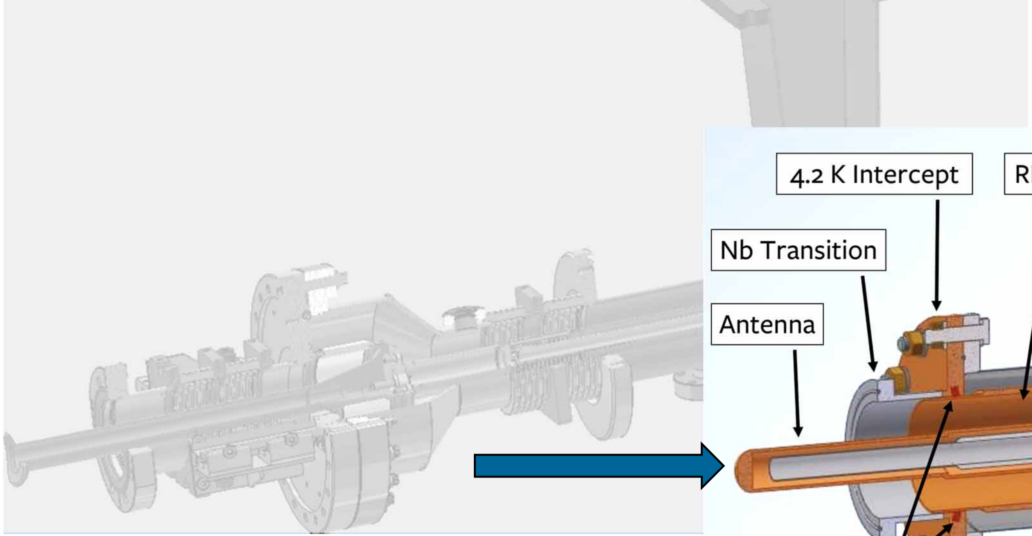
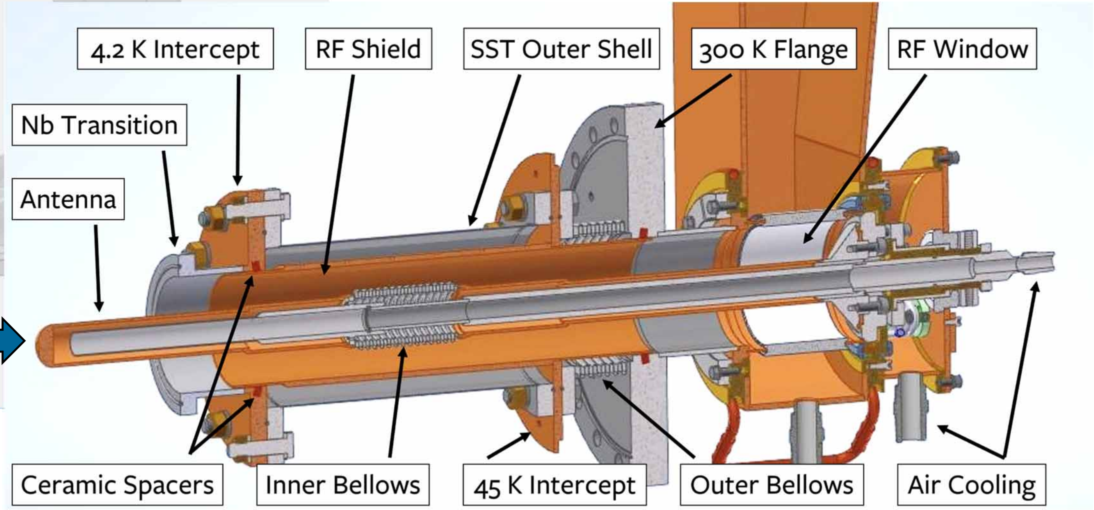


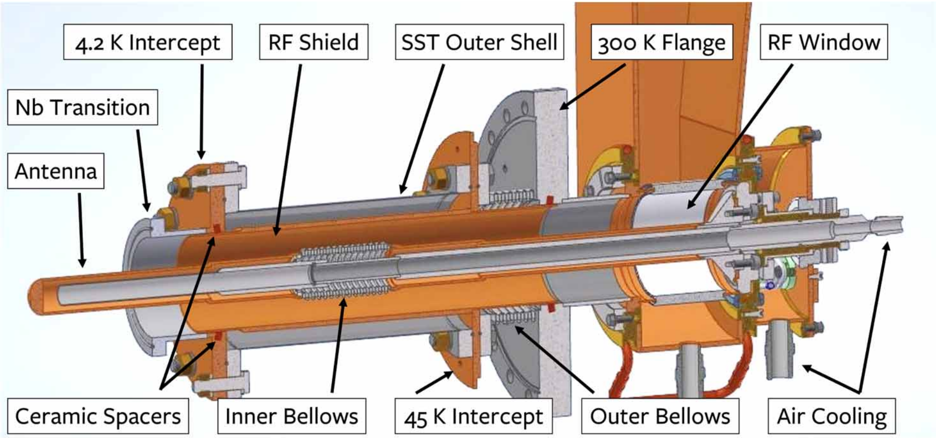


Coupler Design

Heat Load Distribution

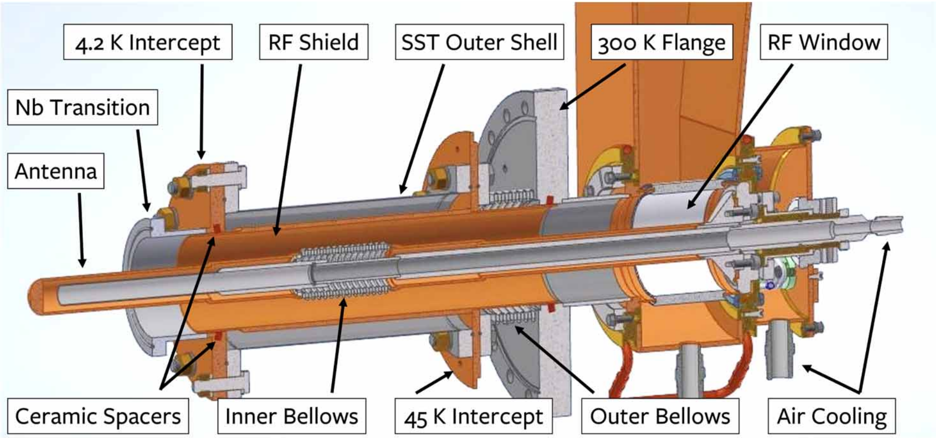
Conduction Cooling

Cost & Complexity



Coupler Design

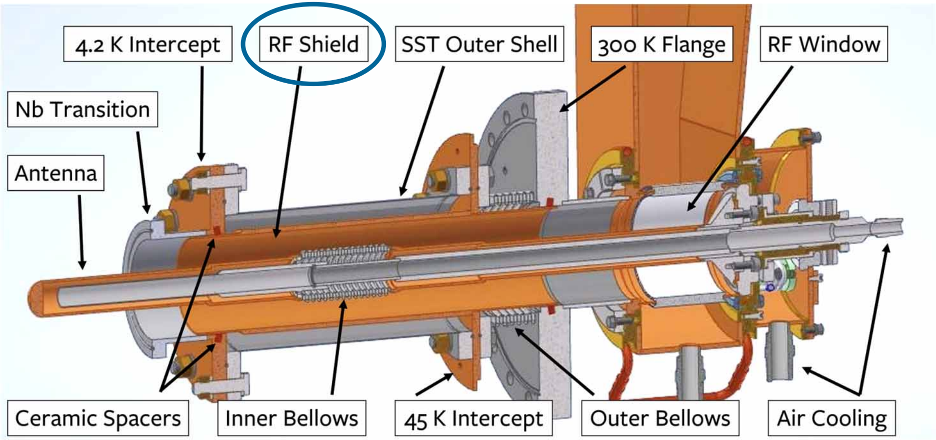
Heat Load Distribution | Conduction Cooling | Cost & Complexity



Coupler Design

Heat Load Distribution | Conduction Cooling | Cost & Complexity

1) *Implement* **"RF shield,"** *inspired by Fermilab design*[1] *& further modified*
   → *Protects 4.2 K components from high fields*

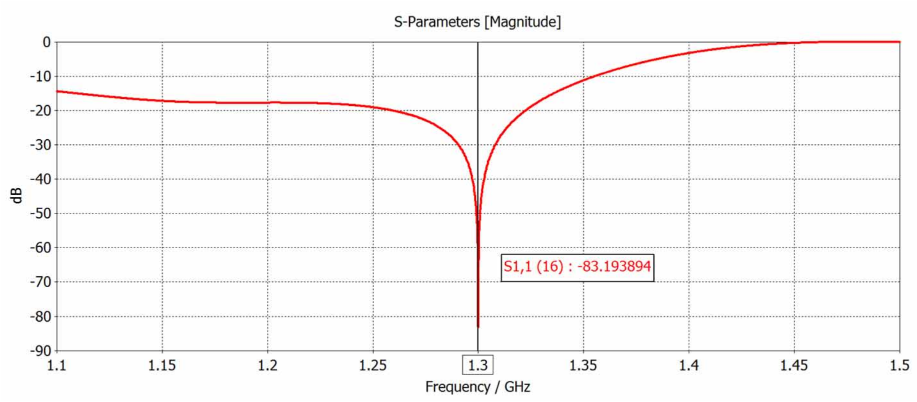


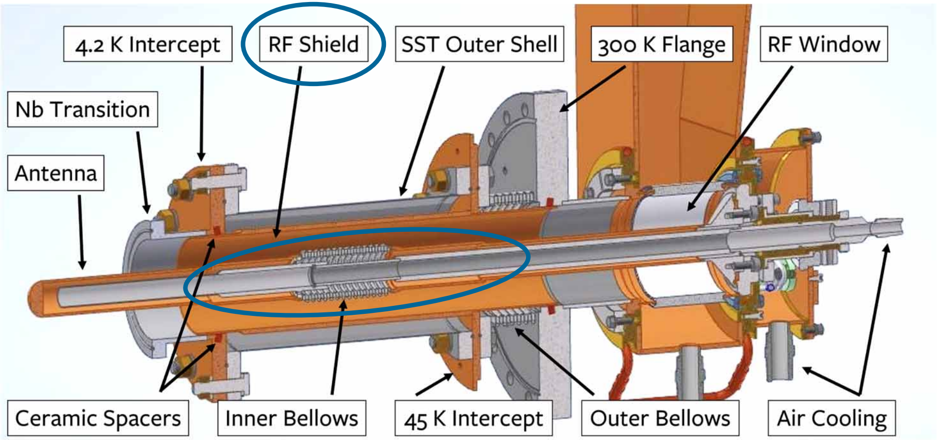
[1]*R.C. Dhuley et al., Phys. Rev. Accel. Beams* **25**, *041601 (2022)*

Coupler Design

Heat Load Distribution | Conduction Cooling | Cost & Complexity

1) *Implement* **"RF shield,"** *inspired by Fermilab design*[1] *& further modified*
   → *Protects 4.2 K components from high fields*
2) *Add* **quarter-wave transformer** *to inner bellows*
   → *Optimizes RF behavior for ± 8mm throw*





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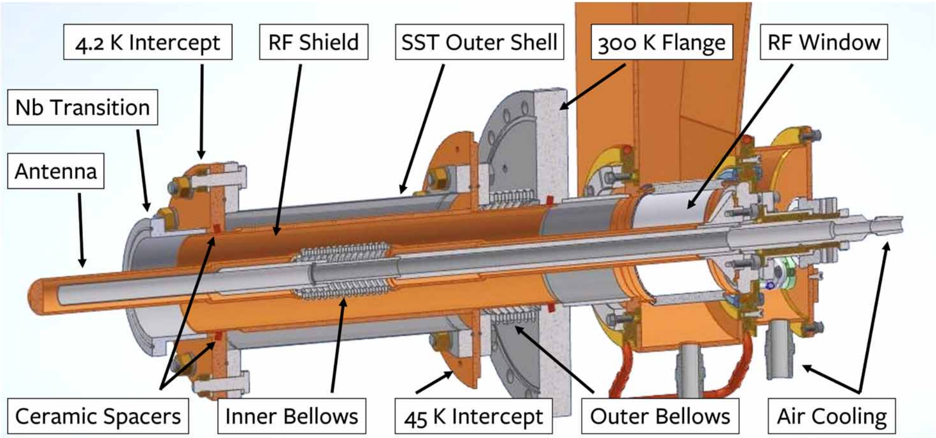
Coupler Design

Heat Load Distribution

Conduction Cooling

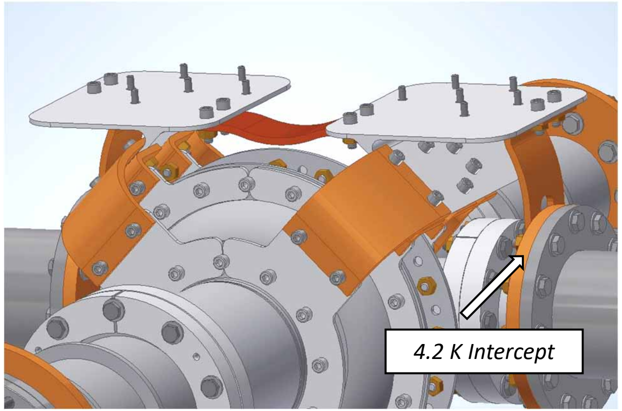
Cost & Complexity

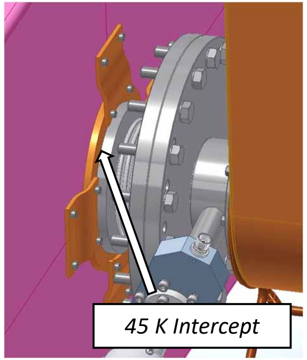


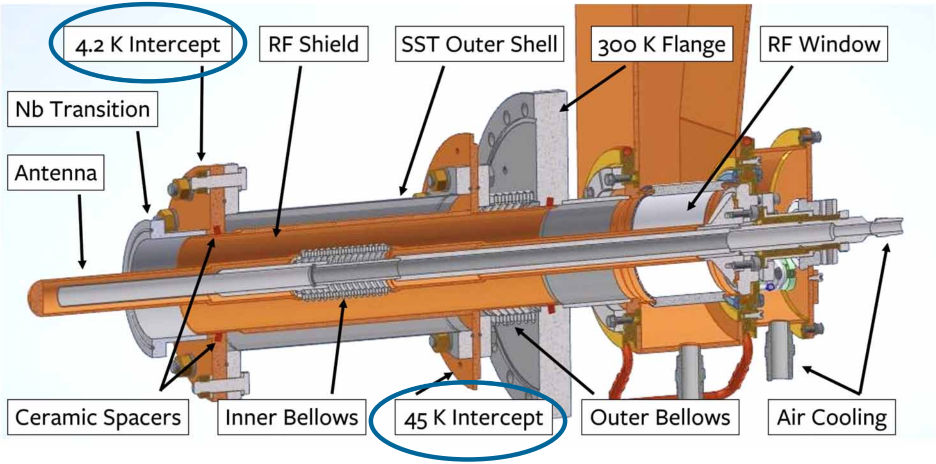
Coupler Design

Heat Load Distribution | **Conduction Cooling** | Cost & Complexity

1) *Extract heat via* **flexible thermal straps** *mounted to coupler intercepts*
   → *Replace typical cooling pipe intercepts with copper disks and flanges*







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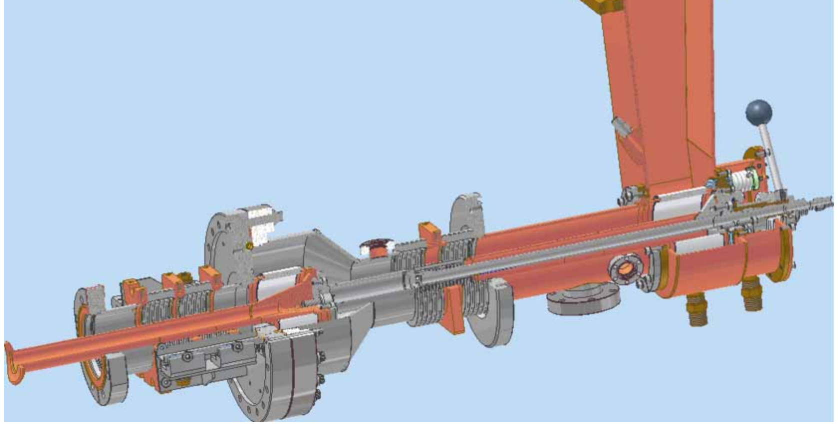
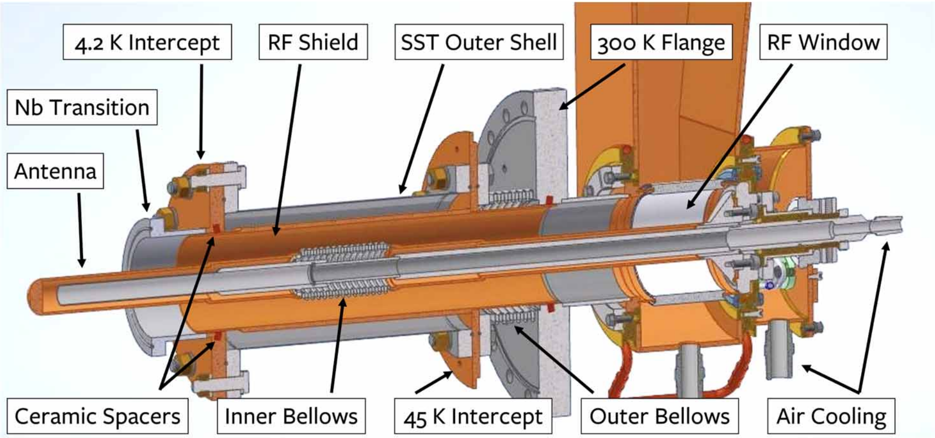
Coupler Design

Heat Load Distribution | Conduction Cooling | **Cost & Complexity**

Compare: Cornell ERL Injector coupler



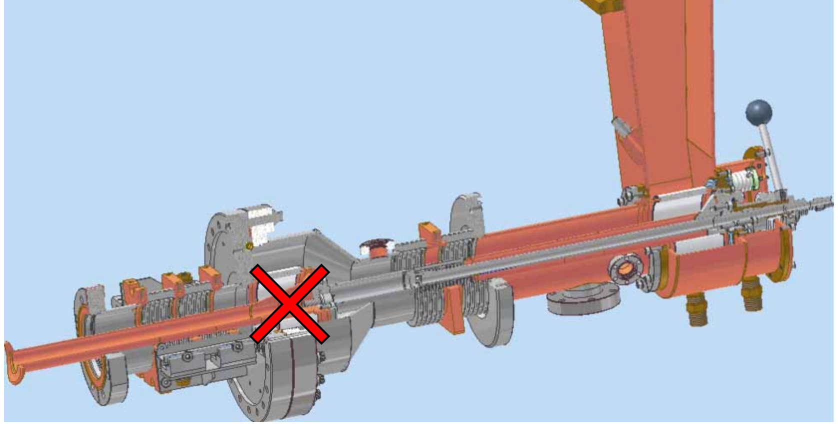


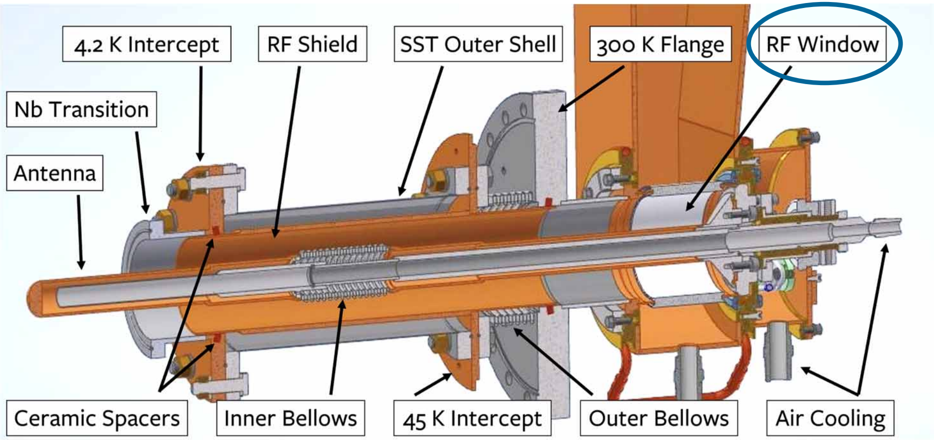
Coupler Design

Heat Load Distribution | Conduction Cooling | **Cost & Complexity**

1) *Remove cold RF window, use* ***warm RF window only***
   → *Greatly simplifies cold portion of coupler*

Compare: Cornell ERL Injector coupler



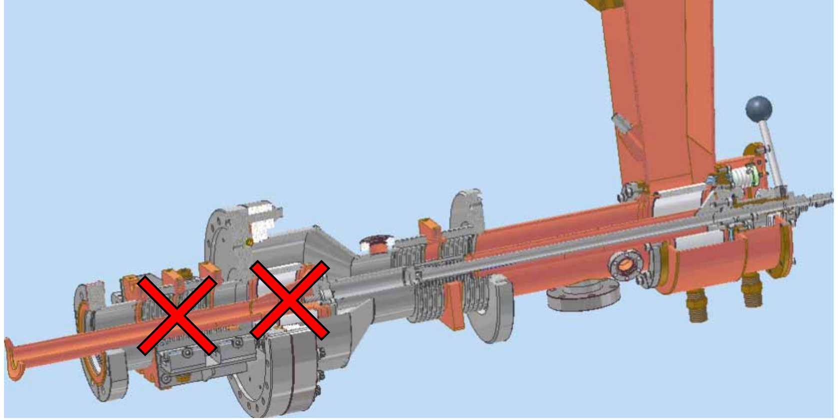


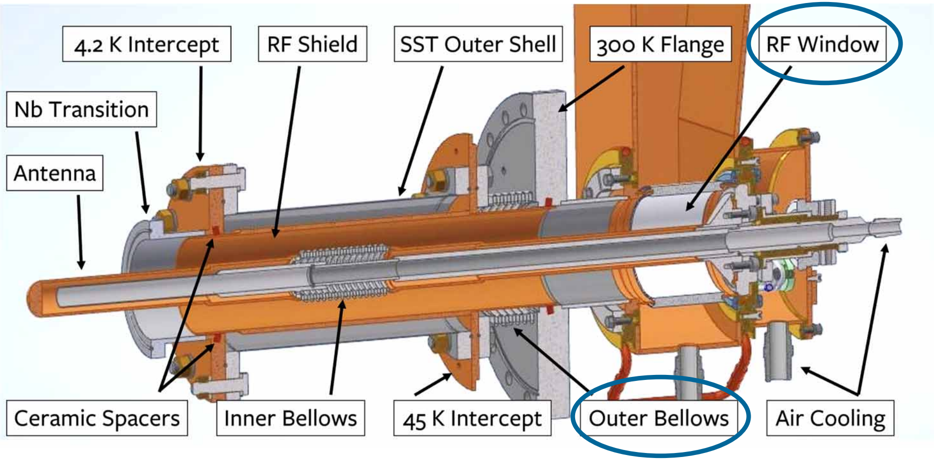
Coupler Design

Heat Load Distribution | Conduction Cooling | **Cost & Complexity**

1) *Remove cold RF window, use* **warm RF window only**
   → *Greatly simplifies cold portion of coupler*
2) *Remove all but* **one outside bellows**
   → *Only needed for thermal contraction*

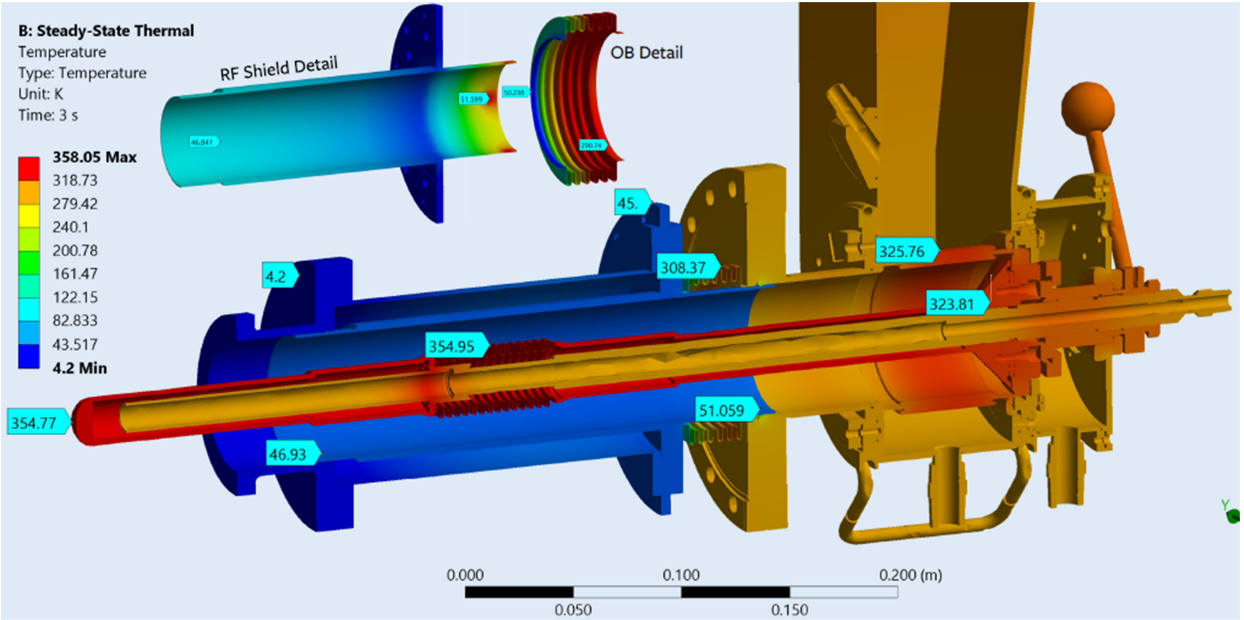
Compare: Cornell ERL Injector coupler





Thermal Results

- *Perform thermal modeling for up to 100 kW forward power*
- *Air cooling* **prevents overheating** *on inner conductor and RF window*
- *Resulting heat loads:*
  - *Total of* **21.1 / 29.5 / 37.9 W** *at* **45 K** *for 0 / 50 / 100 kW operation*
  - *Total of* **0.46 / 0.80 / 1.11 W** *at* **4.2 K** *for 0 / 50 / 100 kW operation*



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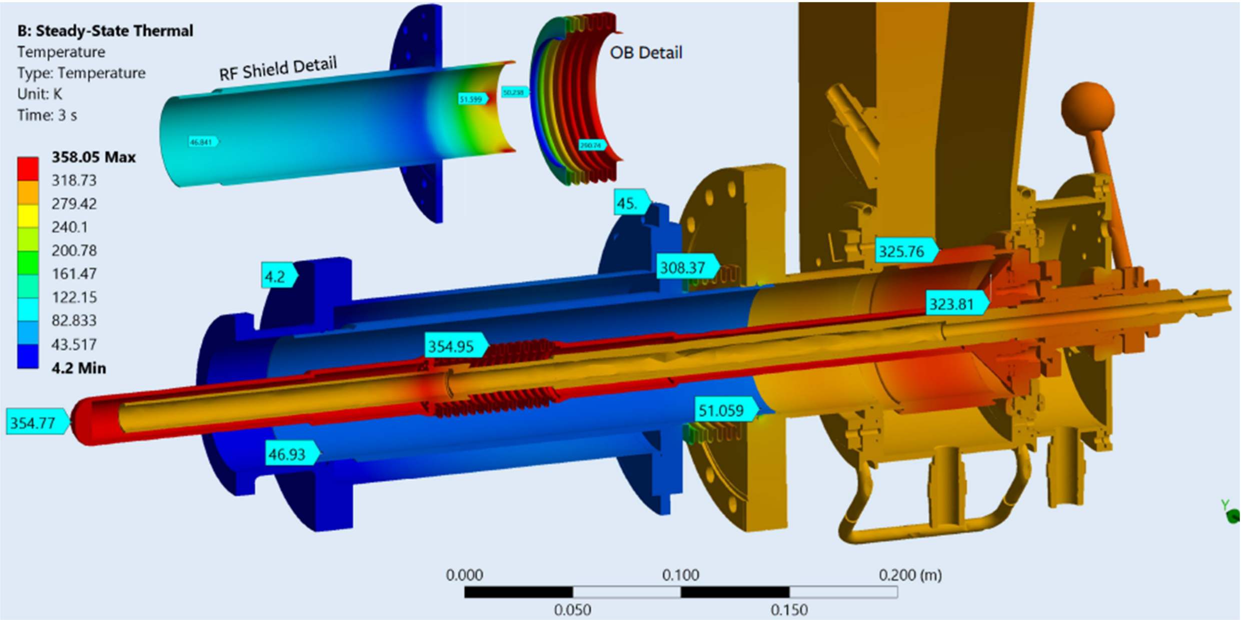
- *Recall ERL injector heat loads:*
  - **75 W** *at 80 K*
  - **3 W** *at 5 K*



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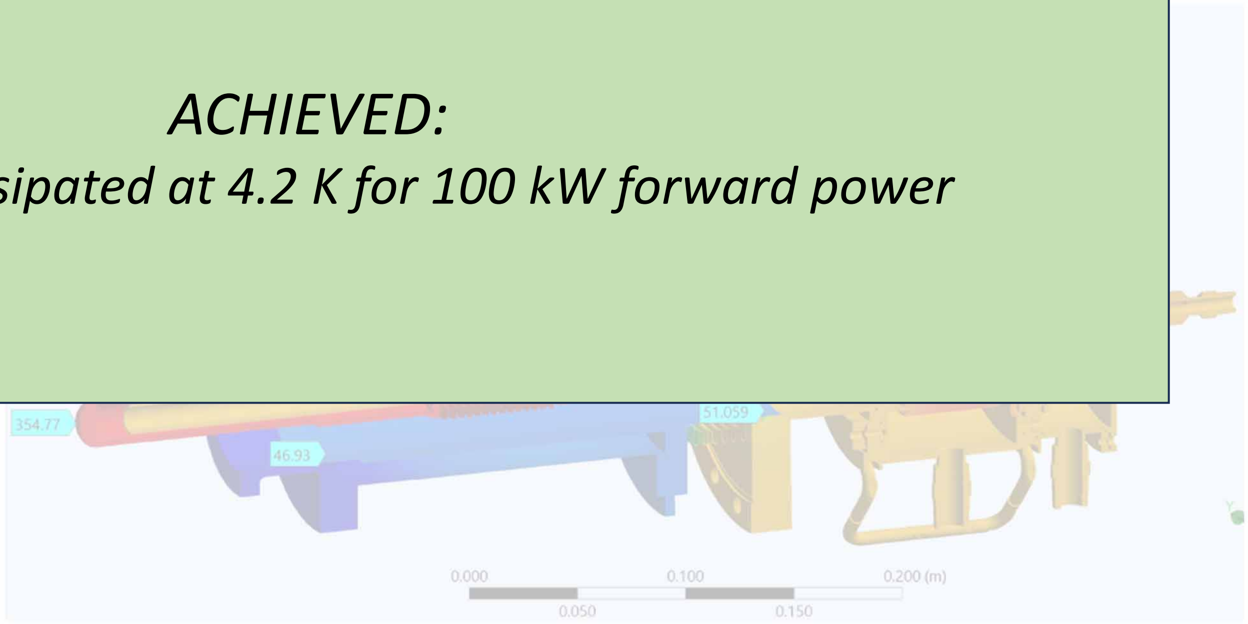
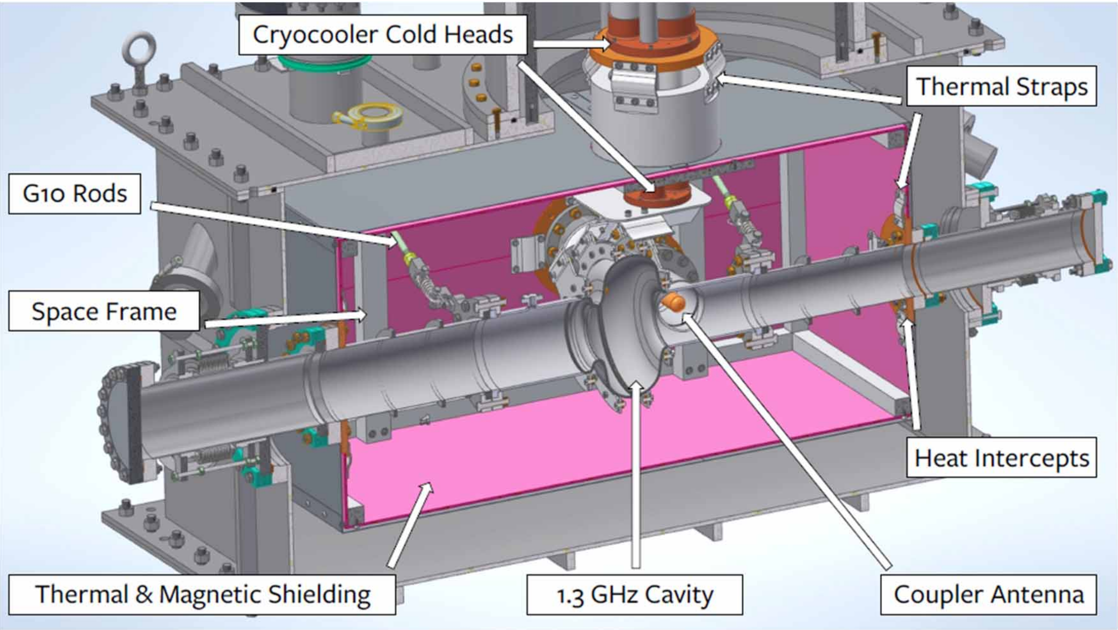


ACHIEVED:

Only 1.1 W dissipated at 4.2 K for 100 kW forward power

Full System Example: My Cryomodule



Source	45 K Heat Load	4.2 K Heat Load
Cavity & Beamline	*15.2 W*	*1.65 W*
Coupler	*37.9 W*	*1.11 W*
Support Rods	*0.34 W*	*0.02 W*
Thermal Rad.	*4 W*	*0.1 W*
TOTAL	**95.34 W**	**3.99 W**
Cryocooler Limits	**100 W**	**4.15 W**

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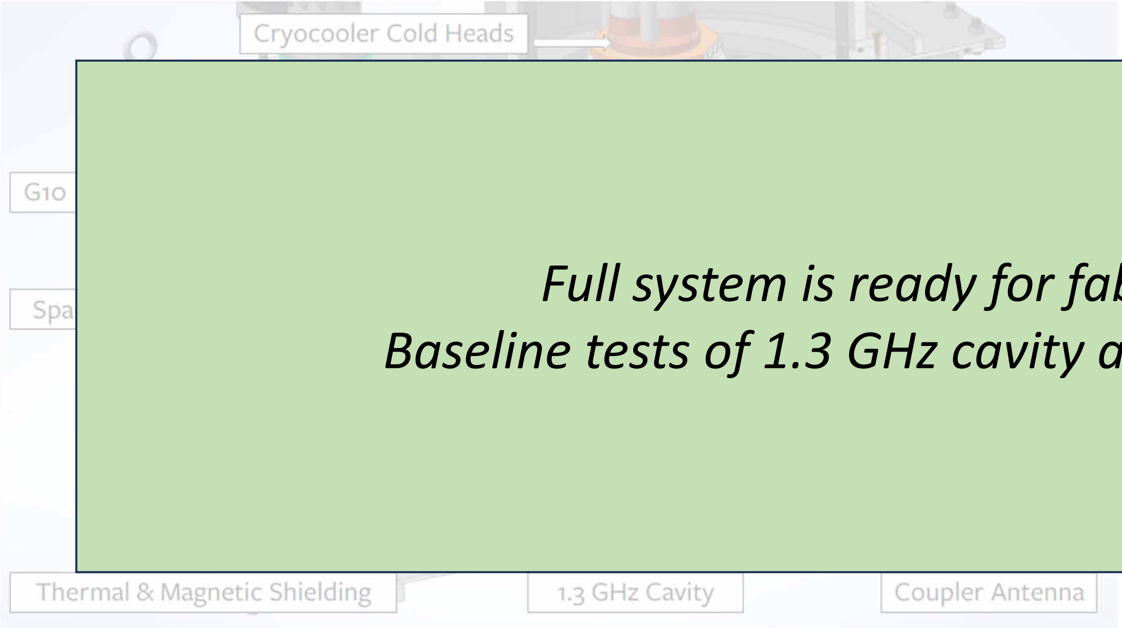

Full system is ready for fabrication!
Baseline tests of 1.3 GHz cavity are coming soon!

SUMMARY
What have I shown?

My Contributions

- *Achieved first-ever operation of a conduction-cooled SRF cavity at* **10 MV/m***!*
- *Designed a conduction cooling assembly with effective performance both during* **RF operation** *and* **cavity cooldown**
- *Designed a high-power (***100 kW***) coupler which dissipates only* **1.1 W** *at 4.2 K*
- *Designed a complete cryostat capable of operating with only* **two cryocoolers***.*

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- *Designed a complete cryostat capable of operating with only* **two cryocoolers**.

Cool **future for this technology!**

Acknowledgements

Thank you *to the following people for their significant contributions:*

Fermilab: Grigory Eremeev, Sam Posen, Jayakar Thangaraj, Ram Dhuley, Christopher Edwards, and Tom Kroc
Jefferson Lab: Gigi Ciovati, John Vennekate
KEK: Kensei Umemori
IMP: Ziqin Yang
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