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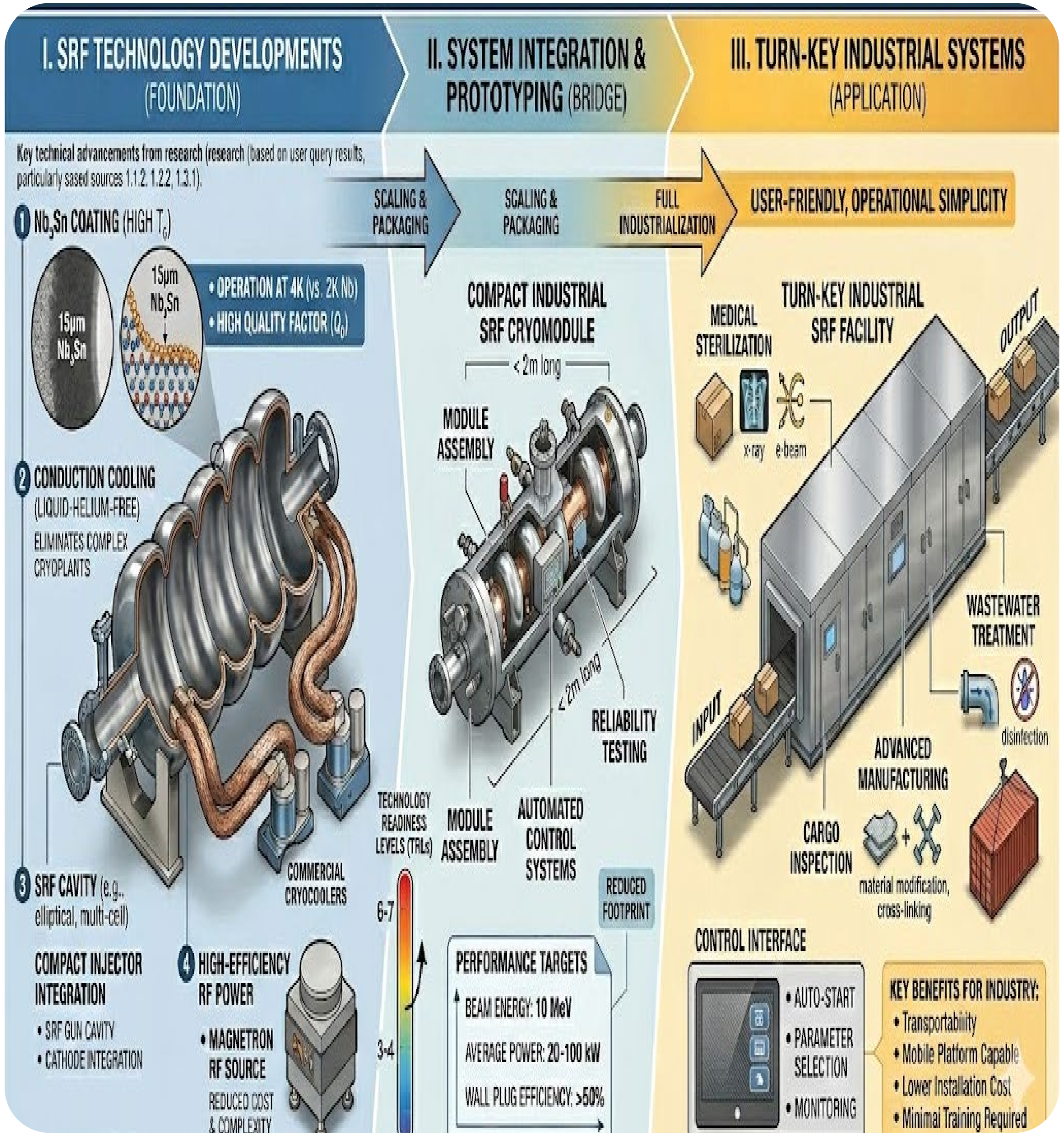
Hot topic Session

Developing SRF towards Turn-Key Industrial Systems

6/11/2026

***Panelists**: Cristian Pira, Teng Tan, Reza Valizadeh, Florian Hug, Andrew Burrill, Lucas Zweibaumer, Nikki Tagdulang*



Hot topic Developing SRF towards Turn-Key Industrial Systems

Session Outline

- ❑ Introduction
- ❑ Grey Enid: operation of a Nb3Sn based cryomodule — A-M Valente-Feliciano
- ❑ Proving Conductive Cooling: 10,000 Hours of Trouble-Free Operation, Beam-Loss Design, and Degradation Recovery at IMP — Teng Tan
- ❑ High-Gradient "Turn-Key" SRF Systems for the MESA ERL Project — Florian Hug
- ❑ Engineering Gaps for Industrial SRF Adoption — Nikki Tagdulang
- ❑ Reliability for EUV FEL based systems — Andrew Burrill
- ❑ Nb3Sn based “Turn-Key“ SRF Systems – When is the technology ready for industrial ramp-up? — Lucas Zweibaumer

Discussions

- ❑ Technical Frontier
- ❑ Engineering path for reliability
- ❑ Strategic democratization
- ❑ Preliminary considerations for a Roadmap towards an SRF "plug-and-play"

Session Charge

Developing SRF towards Turn-Key Industrial Systems

The landscape of SRF technology is shifting beyond large instruments, specifically with advances with Nb3Sn and conduction cooling, enabling the perspective of SRF-based standalone industrial machines. However significant developments remain for repeatable production of consistent Nb_3Sn performance, successful application on various cavity shapes and for successful integration into compact, high-duty-cycle accelerators. The discussion should address the critical R&D and engineering required to move from promising R&D into a mainstream technology for the next generation of cryomodules. This session should also focus on the "vulgarization", or the strategic democratization, of SRF technology by transitioning from specialized laboratory physics to robust, mainstream industrial engineering. The hot-topic session should address the roadmap for making SRF "plug-and-play." What are the standardizations and simplifications that would be required to allow for industrialization and operation by non-specialist technicians in non-laboratory environments.

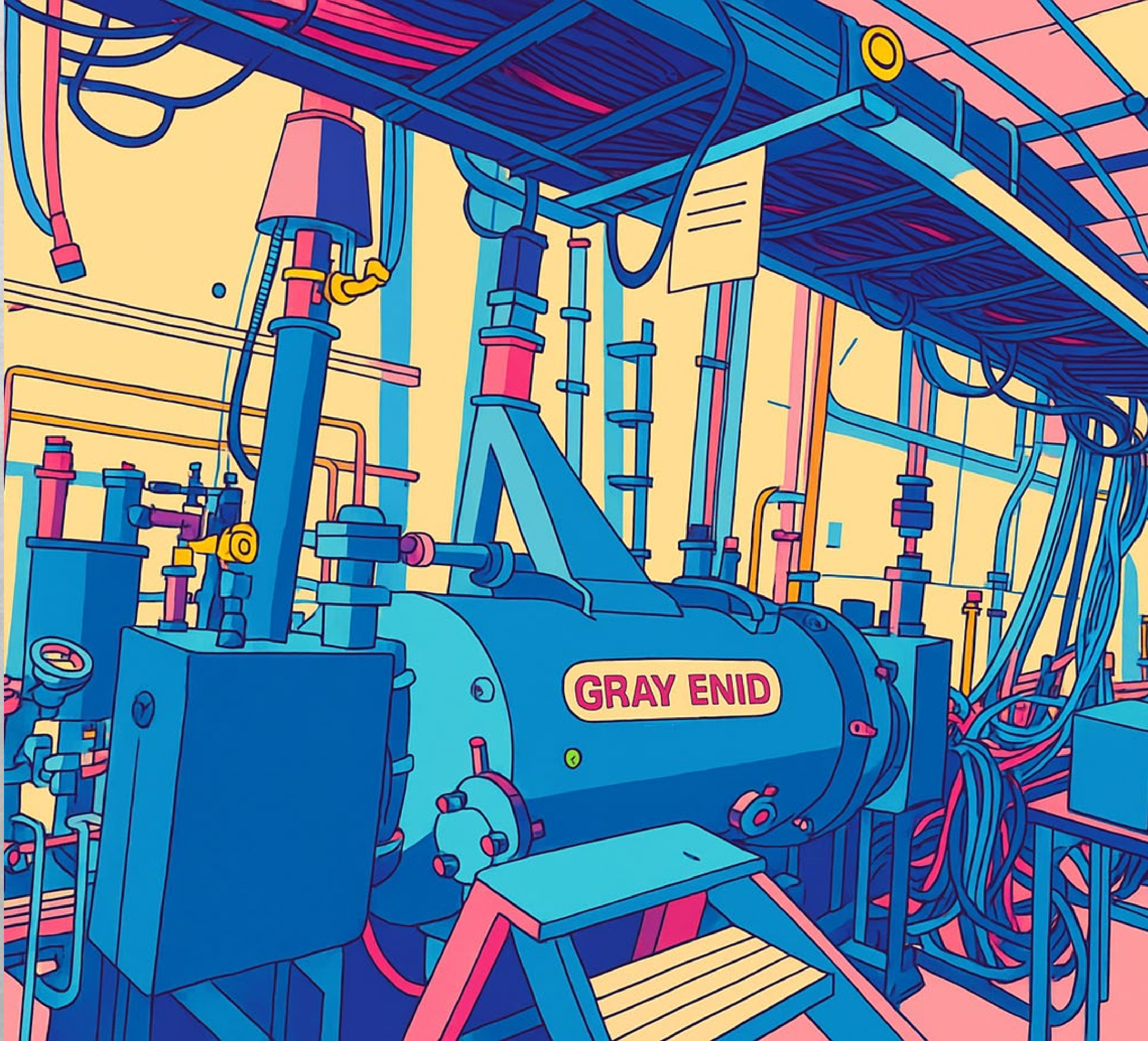
Keywords:

Nb_3Sn, SRF Industrial applications, conduction cooling, roadmap, strategic democratization, mainstream acceptance, turn-key

Google Form to gather input: https://forms.gle/65V3VwZnUgRfmVxHA

“Gray-Enid I” : Beam Acceleration with a Nb_3Sn cryomodule at JLab

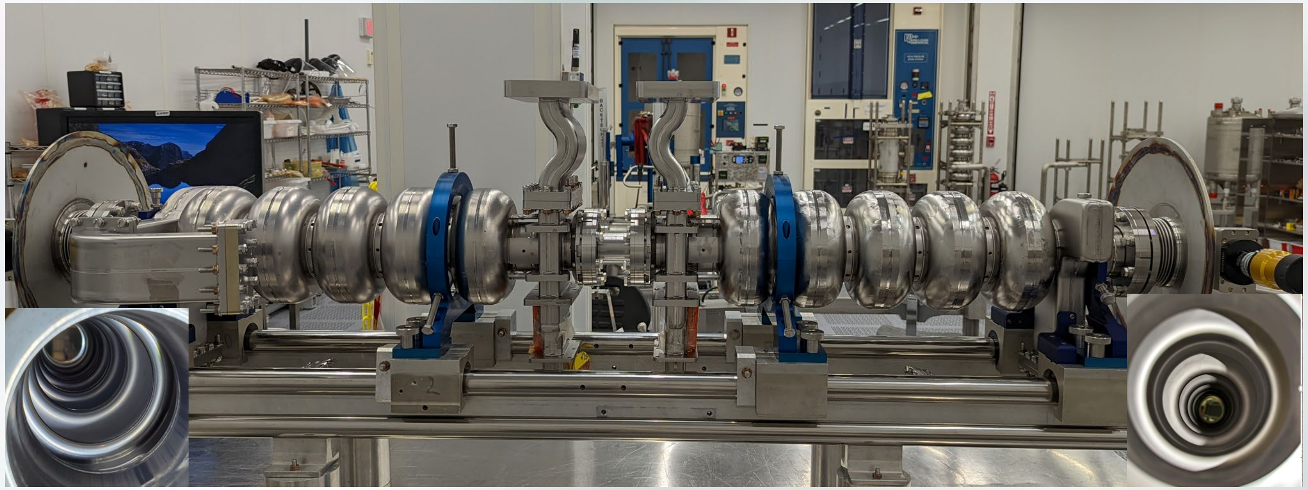
Jefferson Lab

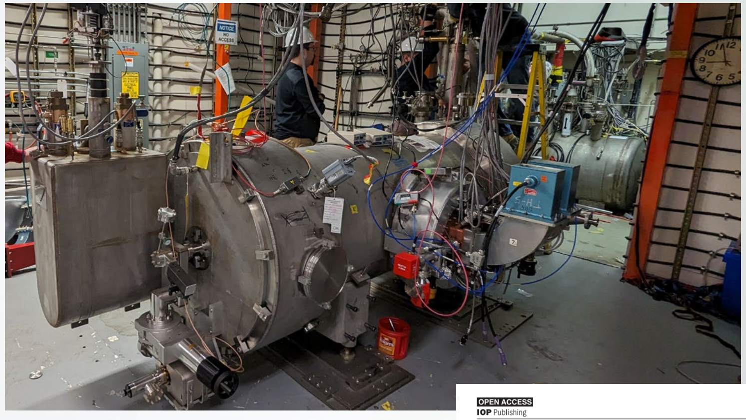


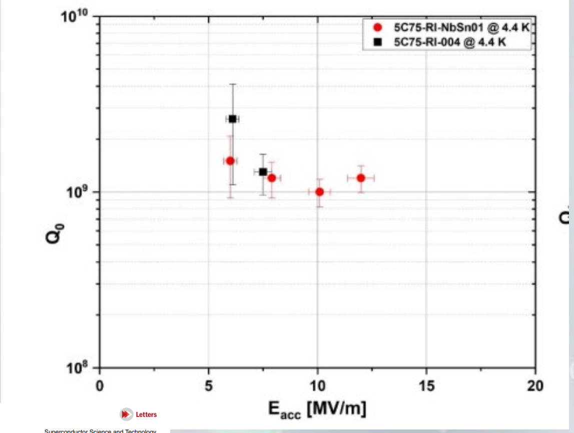
Background

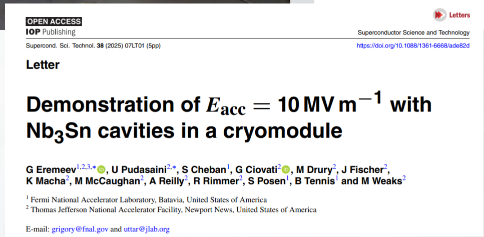
Jefferson Lab

- Cryomodule development started in 2018, aiming for beam acceleration at UITF
- One cavity coated at JLab, another at FNAL; both >13 MV/m, Q ~10^{10} @ 10 MV/m.
- Pair assembled but disassembled due to RF window leak → one cavity degraded to 8 MV/m but accepted.
- Cryomodule Assembled and tested
    - Demonstrated >10 MV/m gradient in a cryomodule for the first time: lower Q_0 due to limiting cooldown control









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https://doi.org/10.1088/1361-6668/ade82d

Letter

Demonstration of $E_{acc} = 10\,\mathrm{MV\,m^{-1}}$ with Nb_3Sn cavities in a cryomodule

G Eremeev[1,2,3,*], U Pudasaini[2,*], S Cheban[1], G Ciovati[2], M Drury[2], J Fischer[2], K Macha[2], M McCaughan[2], A Reilly[2], R Rimmer[2], S Posen[1], B Tennis[1] and M Weaks[2]

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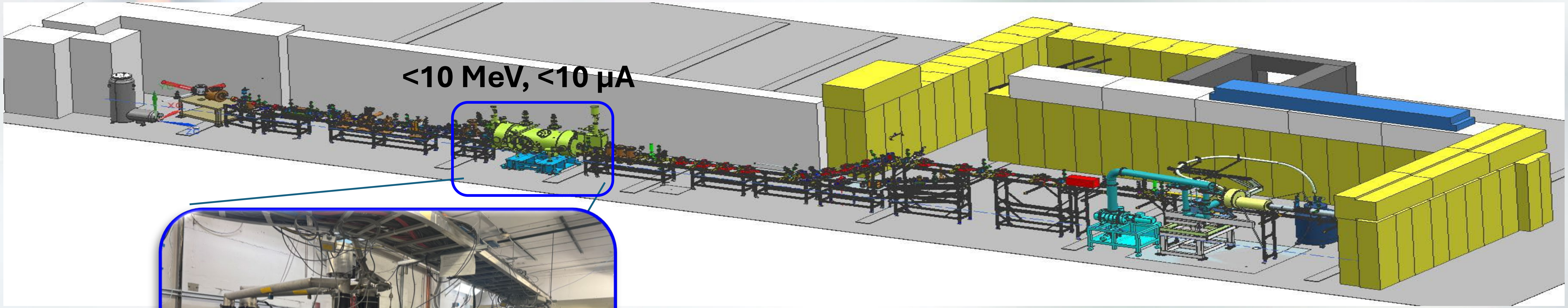
[2] Thomas Jefferson National Accelerator Facility, Newport News, United States of America

E-mail: grigory@fnal.gov and uttar@jlab.org

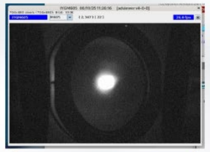
Beam Acceleration with Nb_3Sn Quarter Cryomodule in UITF

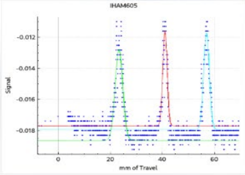


Beam Acceleration Test at UITF

2 K

Metric	Value
Beam energy	6.9 MeV
Cavity 1 Eacc	10 MV/m
Cavity 2 Eacc	6 MV/m



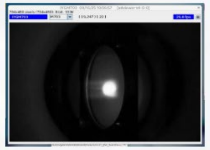


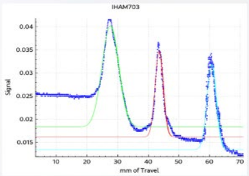
Beam spot on viewer

Beam cross-section profiles

4 K

Metric	Value
Beam energy	5.1 MeV
Cavity 1 Eacc	7 MV/m
Cavity 2 Eacc	4 MV/m





"Beam Acceleration with A Nb3Sn Cryomodule at JLab" SRF 2025, R. Geng et al.

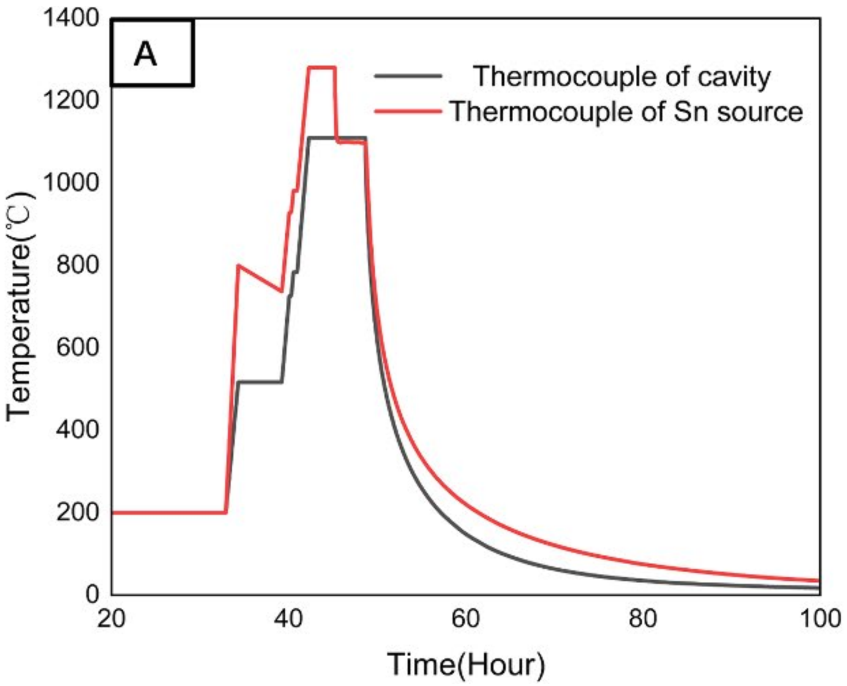
- First electron beam acceleration experiment at 2 K and 4.3 K in Sept. 2025, both cavities actively tuned with tuners and phase locked to the beam bunch rep rate of 1496.5 MHz
- Phase II beam acceleration experiment, Feb – May, 2026, greatly improved the phase stability at 4.3 K
  - achieving record beam energy up to 7.6 MeV –stay tuned!!
- First user experiment carried out with a 1-hour beam delivery to a sample from industry

Proving Conductive Cooling at IMP

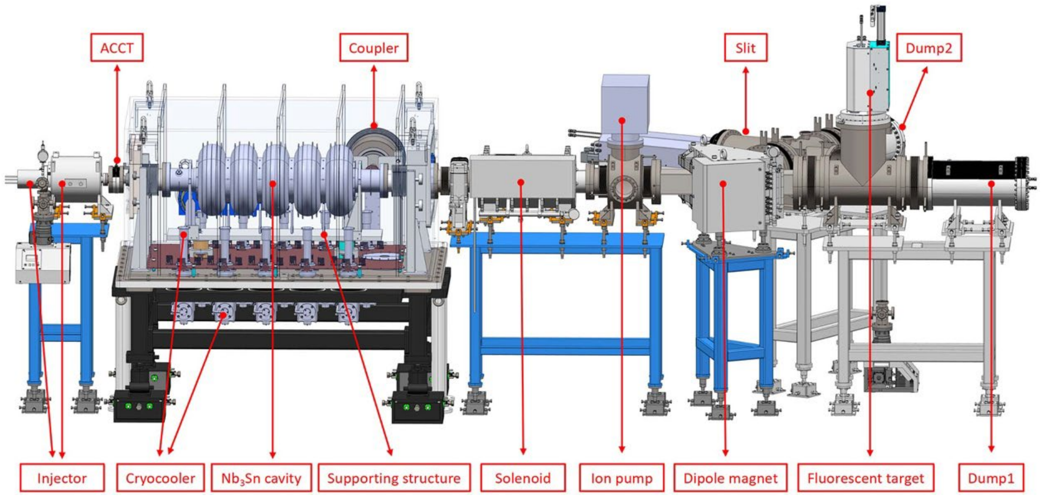
10,000 Hours of Trouble-Free Operation, Beam-Loss Design, and Degradation Recovery at IMP

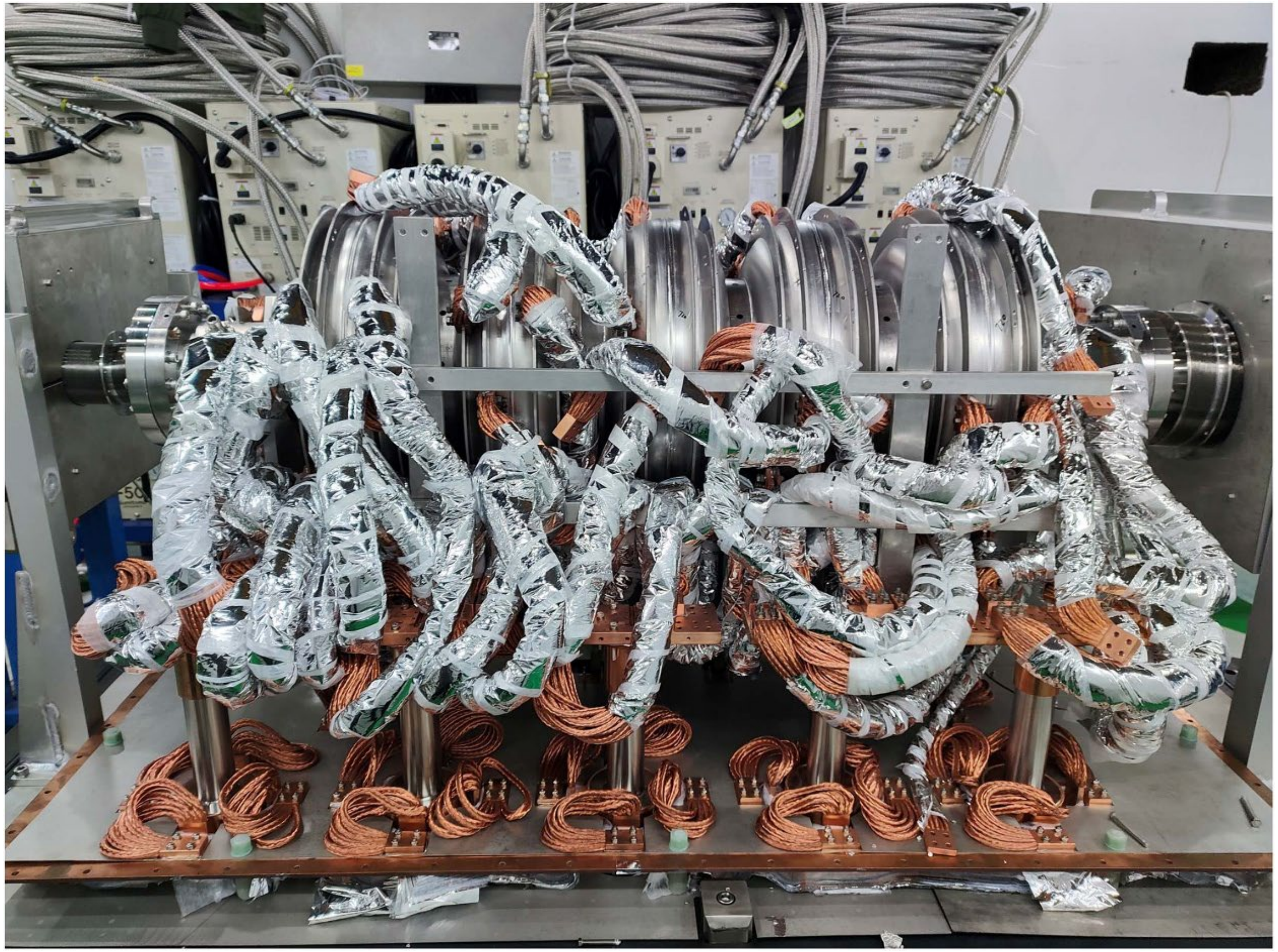
Teng Tan, on behalf of the SRF team of IMP

Basic information about the machine



Basic information about the machine





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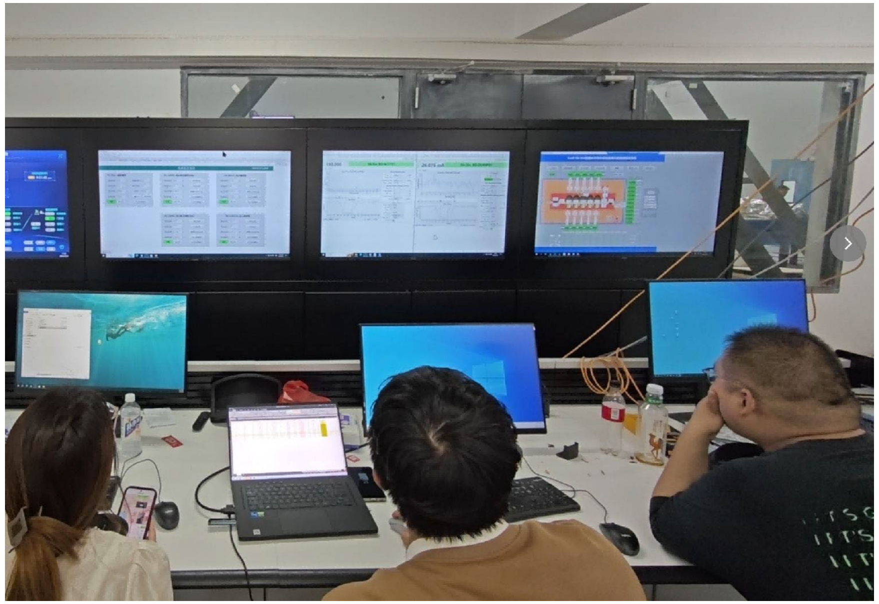
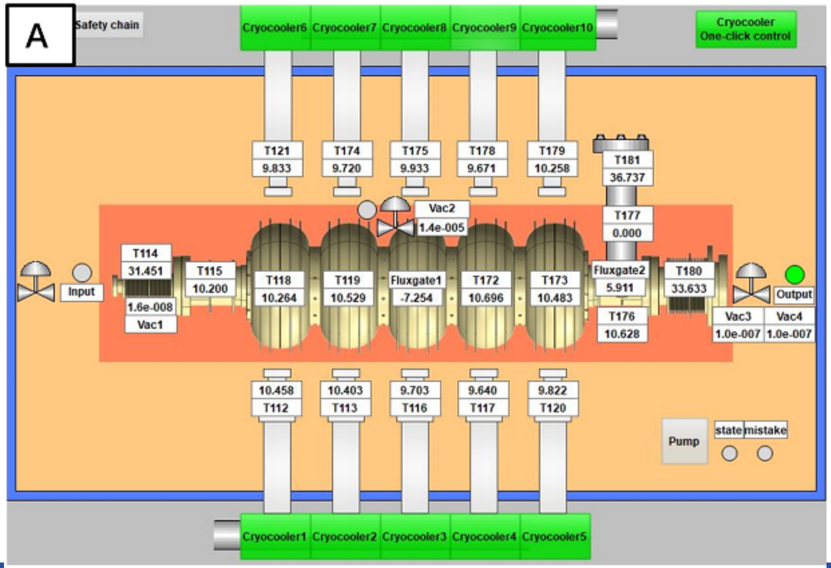
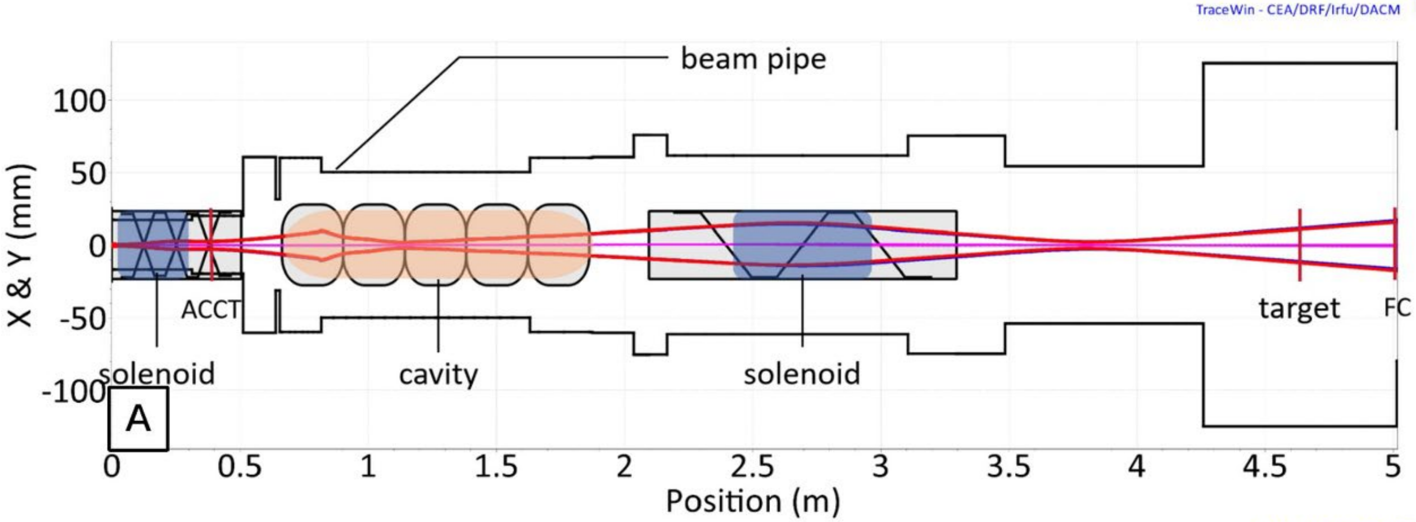
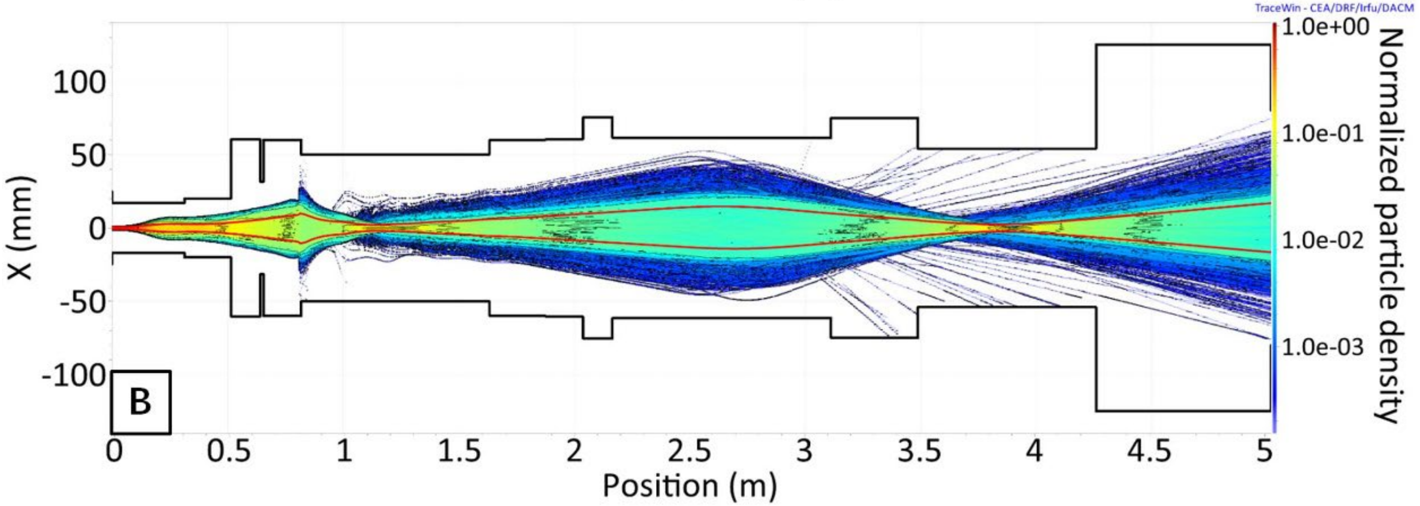


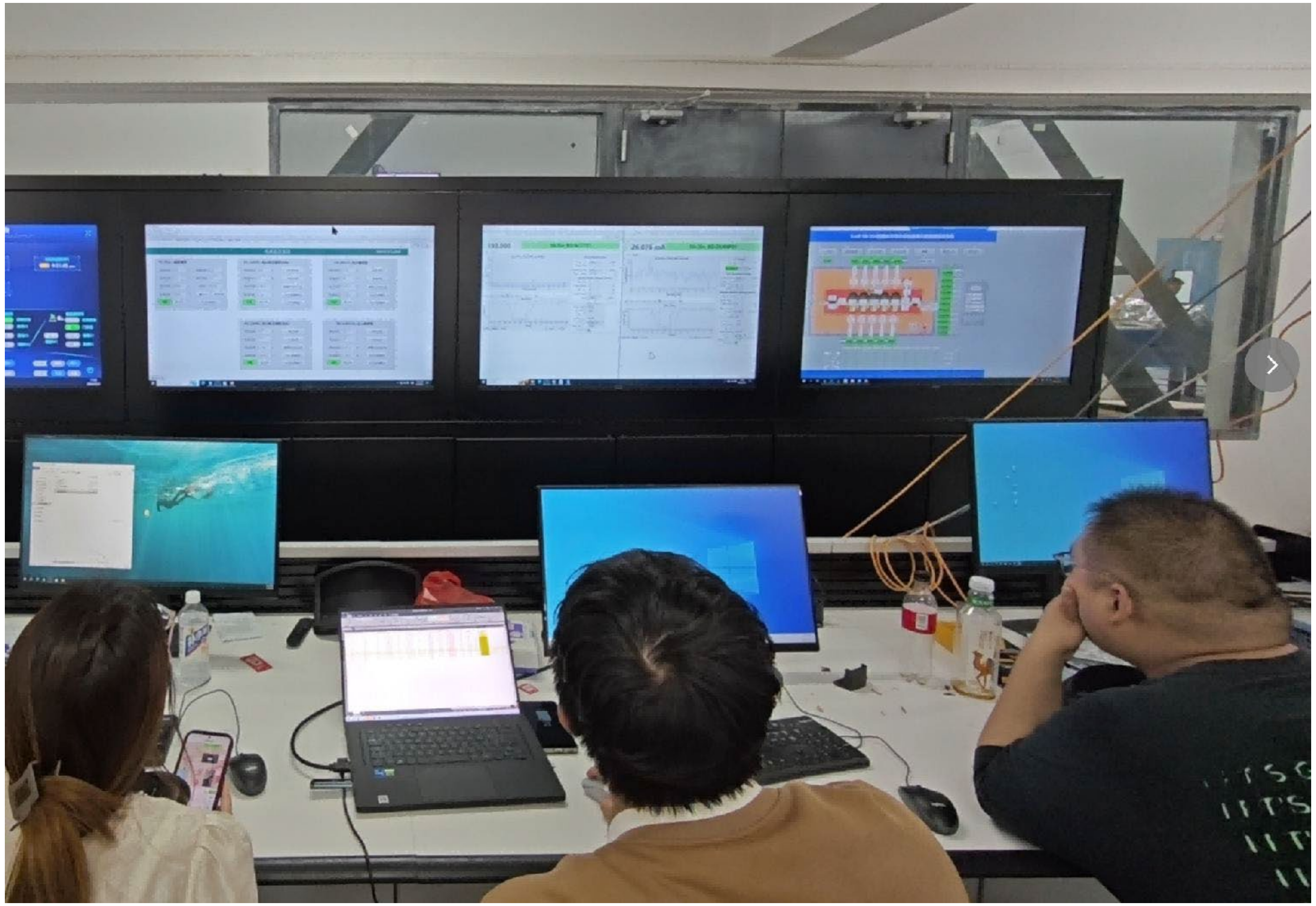






Operational Experience and Stability Assessment

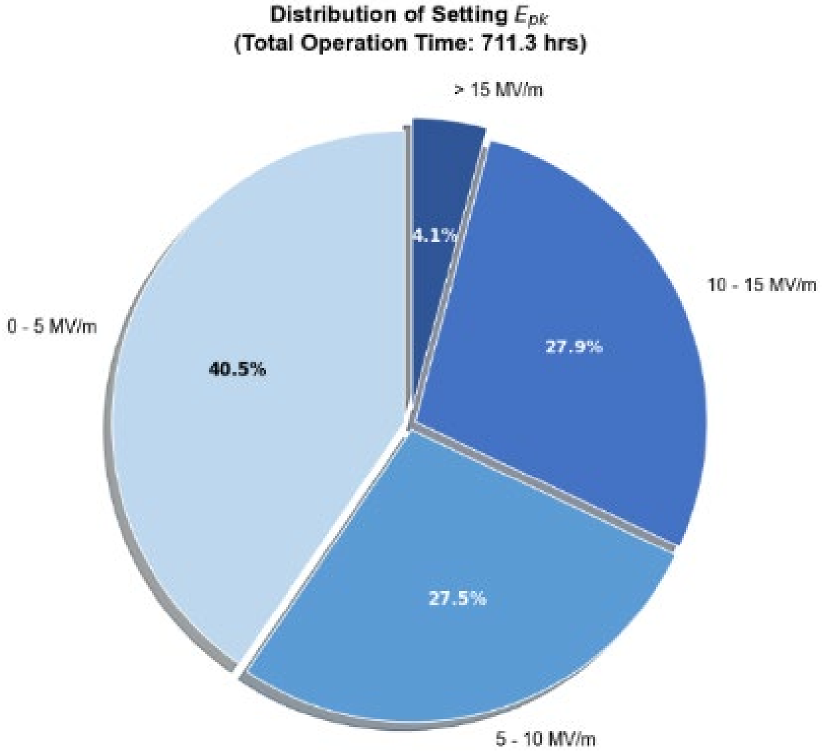
The cryogenic system has been in operation for over 10,000 hours without any failures

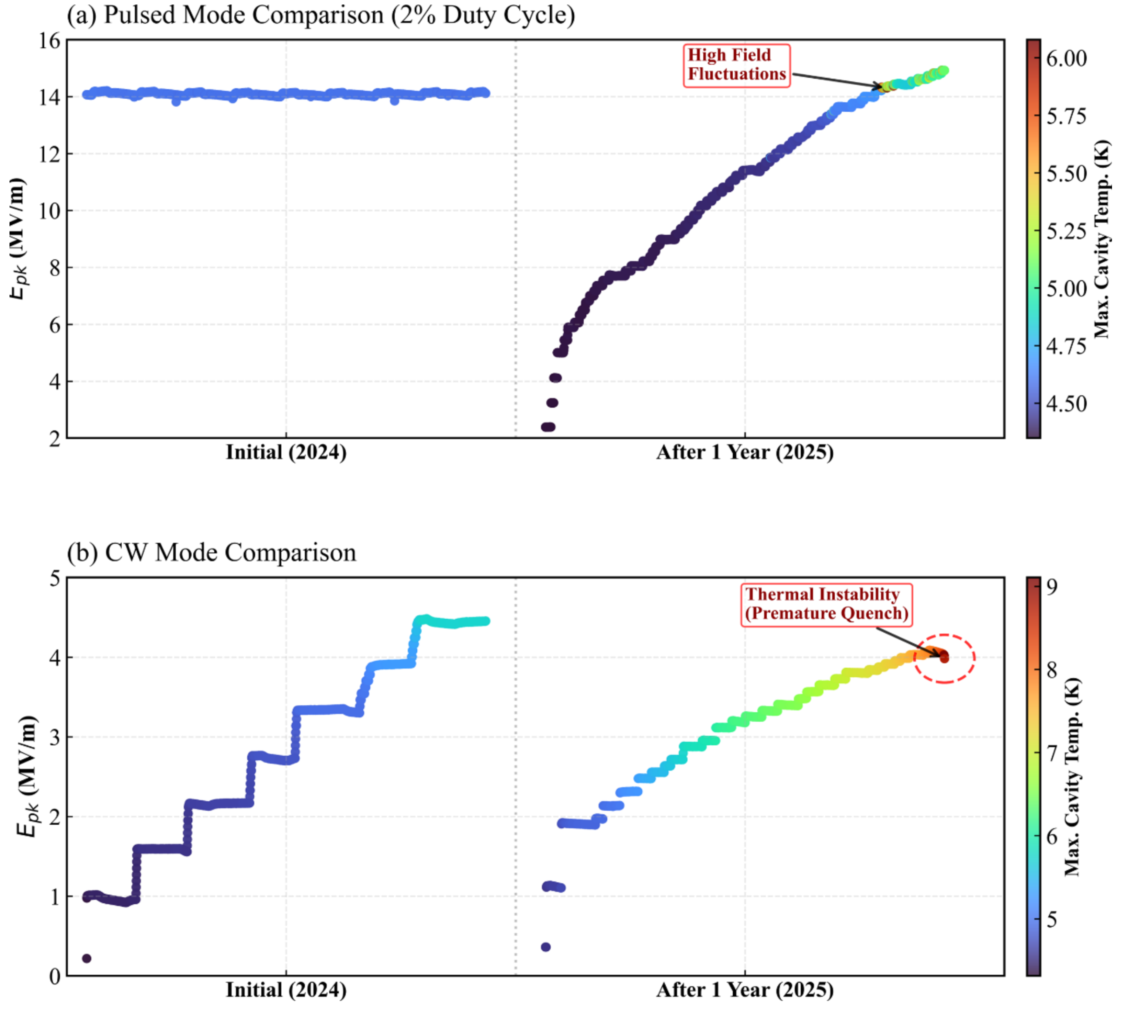


After brief training, daily operation of the accelerator can be managed by only one person

- **Demonstrates excellent operational stability and convenience, which lower the application threshold of SRF technology**

Possible reasons for performance degradation





1. The higher cavity temperature observed at the same gradient after one year of operation suggests degradation of the Nb_3Sn thin film;

2. Field emission behavior remained stable;

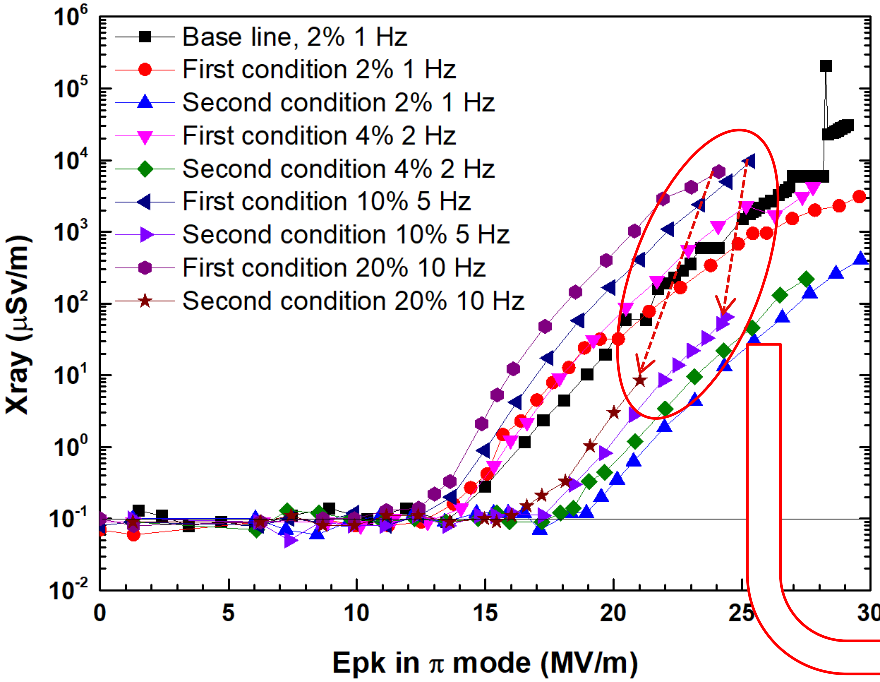
3. primarily caused by electron beam irradiation from escaping beam loss.

Longitudinal statistics of acceleration gradient and macropulse average beam current

☐ **Highlighting the necessity of loss-free physical design**

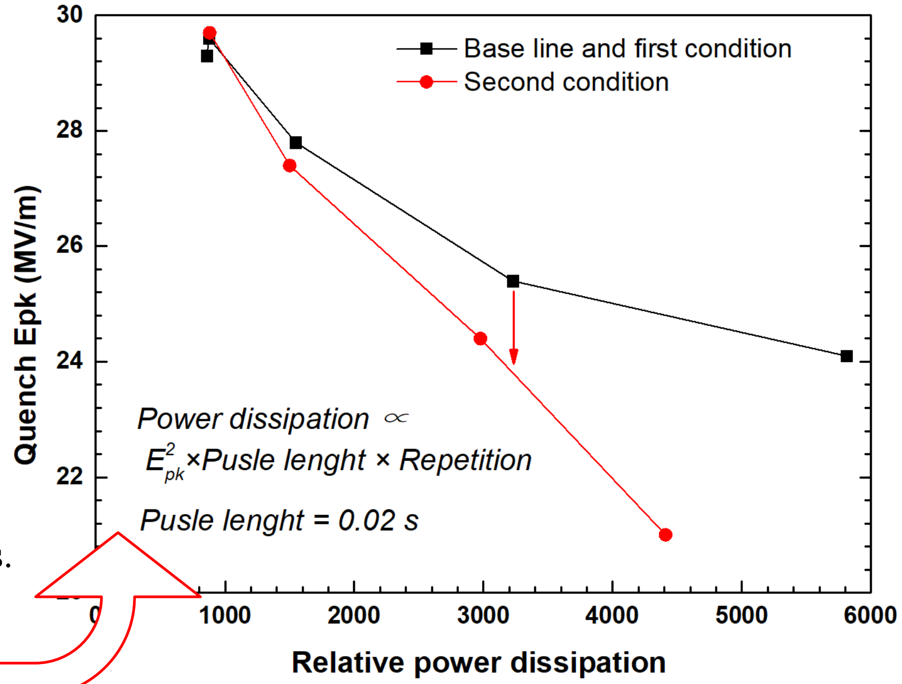
Nb_3Sn in-situ surface processing

Surface modification of the cavity interior was performed via helium condition



- **First Condition:** 2 Hours, Field electron emission remained **largely unchanged**;
- **Second Condition:** 8 Hours, Field emission performance showed a **dramatic enhancement**.

Reason: Improved surface conditioning depends on **RF pulse count**, not breakdowns. *(arXiv:2502.03967v1)*



At high repetition rates, field emission was improved while **the maximum achievable gradient decreased**. The correlation between heat load and gradient was characterized using the relative power dissipation method.

Observation

Second helium processing reduced the maximum gradient at identical heat load.

Possible Cause

Film damage from prolonged He-processing reducing thermal conductivity.

- **Helium processing suppresses FE of Nb_3Sn films, with film damage risk dependent on cleaning strength.**

Experience with High-Gradient "Turn-Key" SRF Systems for the MESA ERL Project

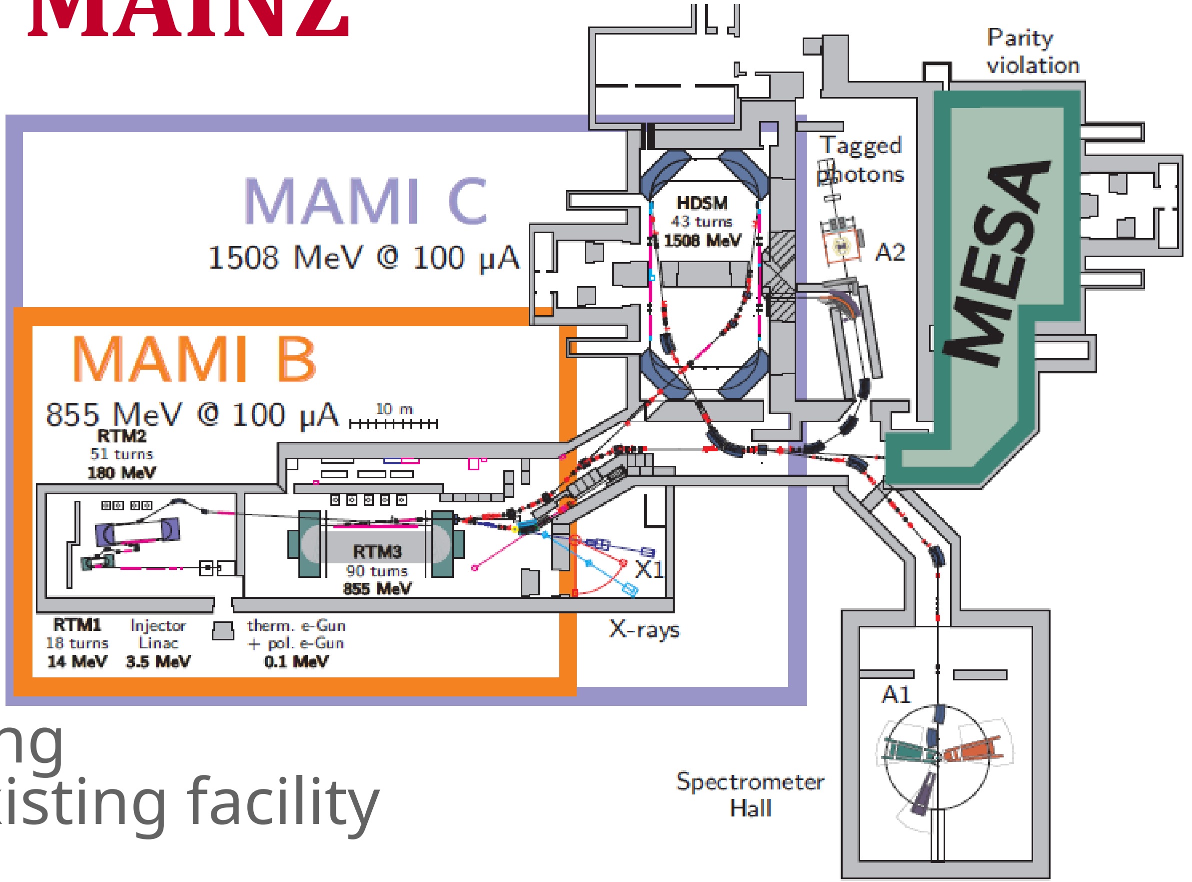
F. Hug for the MESA group
Institut für Kernphysik
JGU Mainz
11.06.2026

MAMI AND MESA AT KPH MAINZ

- MAMI microtron is operating since >25 years at KPH

- In **2012** funding of PRISMA cluster of excellence has been granted including a new accelerator project:

  Mainz **E**nergy Recovery **S**uperconducting **A**ccelerator (MESA) to be built in the existing facility



- In June 2015 DFG granted a research building to JGU „Center for Fundamental Physics (CFP)“ including an extension for MESA halls

MAMI AND MESA AT KPH MAINZ

Main challenges in 2012 (regarding SRF plans):

- A lot of experience in running normal-conducting cw accelerators was present at Mainz but **almost no SRF knowledge**

- State-of-the-art ERL layouts (in 2012) were aiming on 100 mA beam current and required special cavities and cryomodules

→ Out of any reach for MESA group at university level

→ Decision: go for a turn-key cryomodule, not reaching highest beam current in ERL operation and build up a SRF group in parallel

PRODUCTION OF 2 CRYOMODULES

- 2015: Ordered at RI Research Instruments GmbH
- All changes incl.
  - **Cryogenic Components** (valve box, 2K heat exchanger and JT valve, transfer line)
  - Stand alone **control system** (for cryogenics/RF interlocks and connectable to EPICS)
  - With expertise of DESY, HZDR and industry partners
- Milestones
  - VT at DESY AMTF
  - FAT at Mainz
  - SAT at Mainz

PRODUCTION OF 2 CRYOMODULES

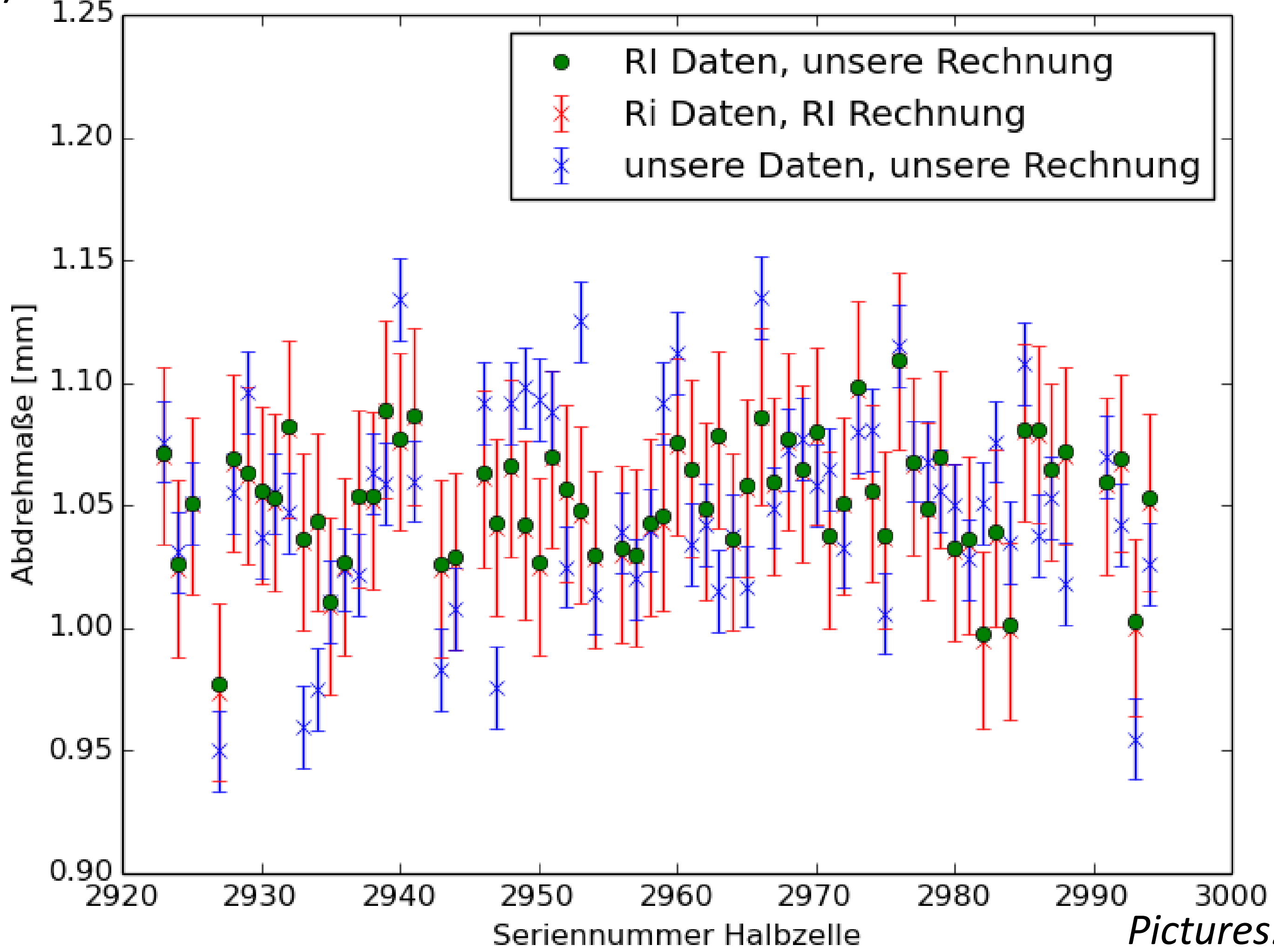
- Close cooperation between RI and Mainz University

  - Weekly **conference calls**
  - **Personal meetings** if necessary approx. **3 per year**
  - **Approval** of all changes
  - Quality control: All RF **measurements** verified by JGU

➢ Effective cooperation between RI and JGU
➢ Close cooperation needed for project coordination

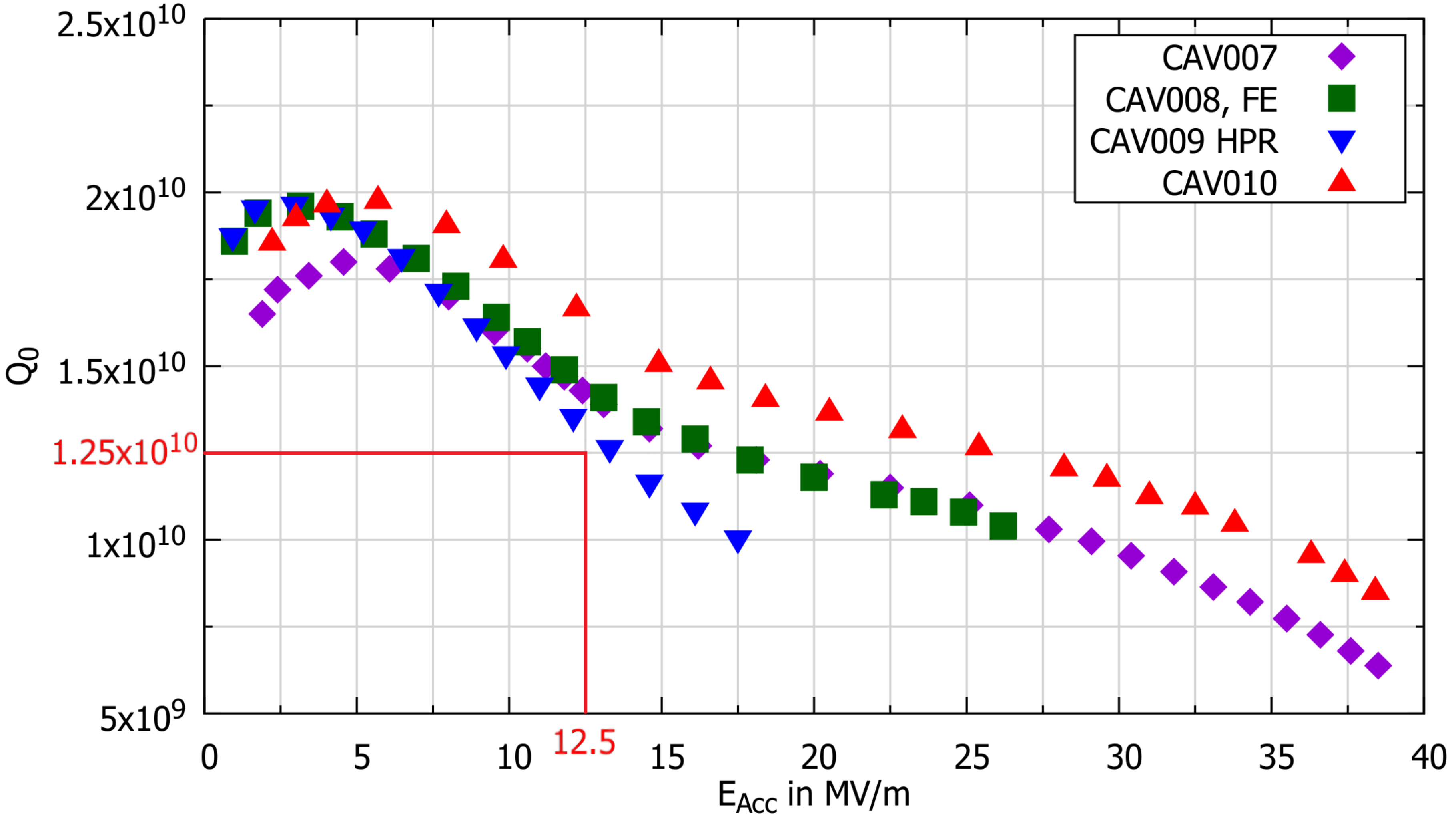
QUALITY CONTROL OF CAVITY PRODUCTION BY JGU

Trimming measures calculated by using the different datasets show good consistency between the two calculations (RI and JGU):



Pictures: P. Weber

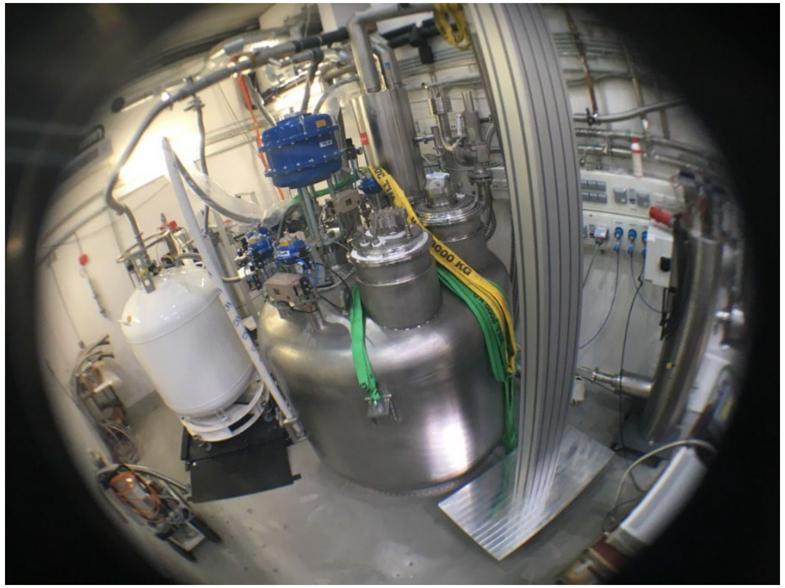
VERTICAL TESTS WERE DONE @ DESY AMTF

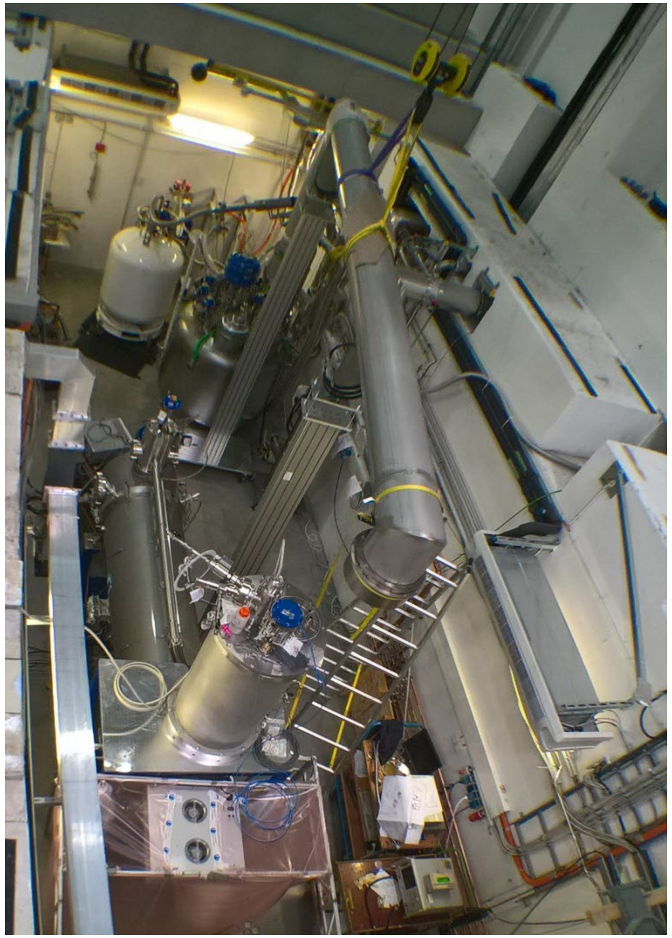


SITE ACCEPTANCE TESTS AT HIM

Helmholtz-Institut Mainz

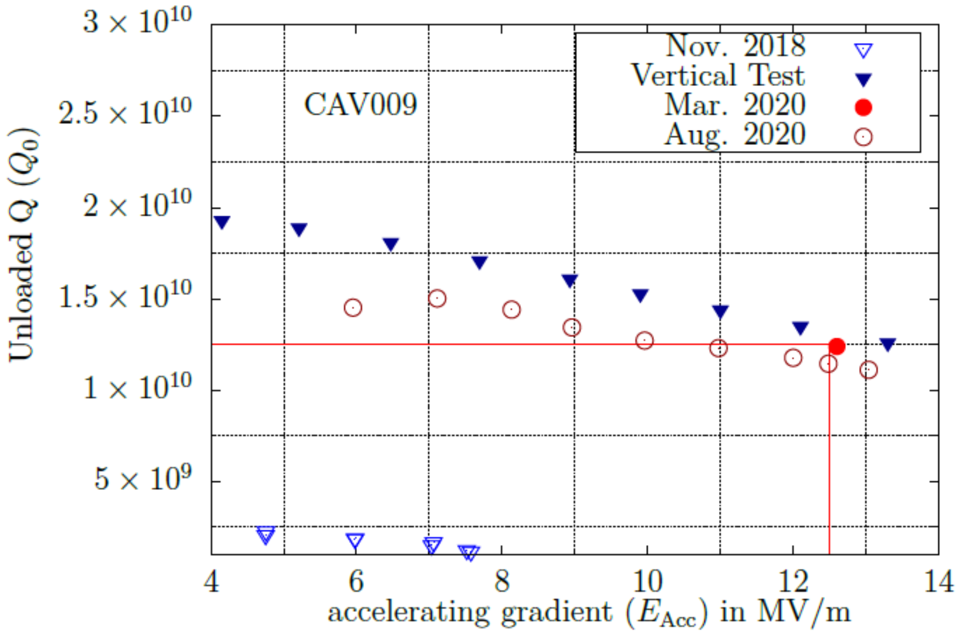
- → Several successful cooldown cycles to 1.8 K at the HIM RF bunker with both cryomodules
- → CW measurements up to 12.5 MV/m
- → Static heat load more than 30% better than design value for both modules
- → **SAT for module #1 approved 30.4.2019**

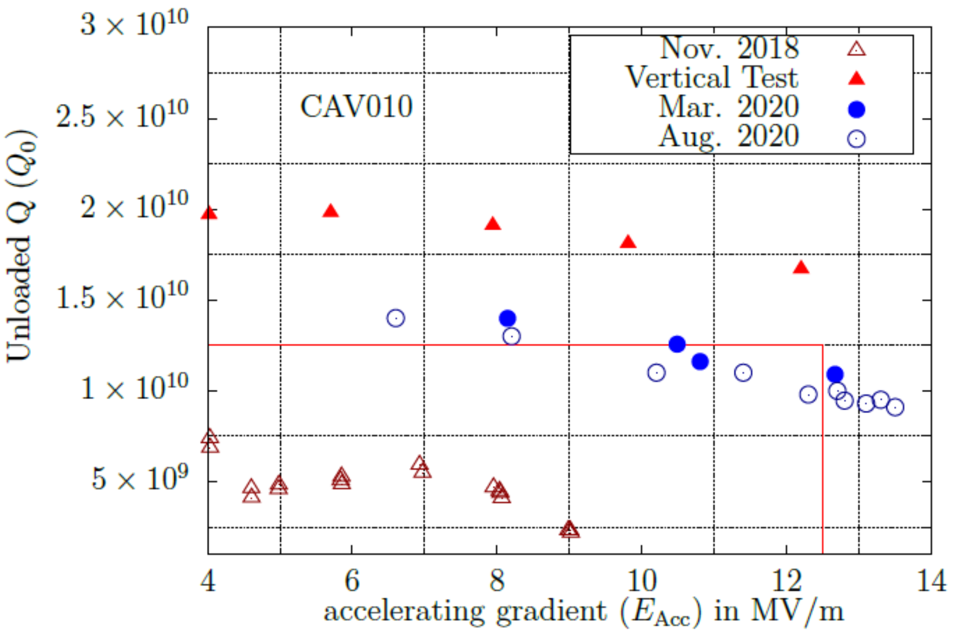




PRODUCTION OF 2 CRYOMODULES FOR MESA IN SUMMARY

- 2015: 2 MEEC's ordered at RI Research Instruments GmbH
- Until 2017 SRF testing infrastructure became available at HIM
- 9/2018: First cryomodule does not meet specs at HIM → refurbishment by vendor,
- 3/2019: Second tested cryomodule achieves specs during test at HIM/Mainz
- 8/2020 :refurbished cryomodule tested and fulfills specs.
  (25 MeV Energy gain at <40 Watt thermal loss at 2 Kelvin)





PhD thesis Timo Stengler
See also: T. Stengler et al.
Proc. SRF 2019
doi:10.18429/JACoW-SRF2019-TUP041

Both Cryomodules fulfill specs→ On average the Helium consumption is estimated to be less than anticipated.

SUMMARY AND LESSONS LEARNED

Cryomodule production:

- Built up an SRF group at Mainz from scratch within a few years
- Successful „turn key“ CM production by industry
- CM1 with 2x 12.5 MV/m @ Q_0=1.2·10^{10}
- CM2 successfully refurbished and accepted

„Turn key“ experience:

- Need of close contact to vendor and collaborative work
- Successful project in the MESA case. Both partners gained a lot of experience
- Modules and cavities might not be the ultimate ERL devices but good compromise for universities/small labs
- This type of modules (medium gradient, cw possible, based on XFEL cavities) allows smaller groups to run SRF systems at all

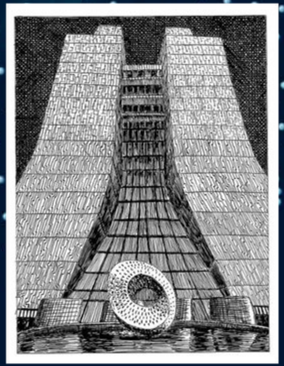
Additional needs for “real” turn key systems:

- LLRF systems and Amplifiers
- Other labs maybe not capable/willing to contribute that much

Engineering Gaps for Industrial SRF Adoption

Nikki Tagdulang

on behalf of
CHarles Thangaraj, Fermilab
Chris Edwards, Fermilab



Fermilab

IARC at Fermilab

Building Real Industrial SRF Machines — Today

What We Are Building

Machine	Notes (all conduction cooled)	Application
1.5-cell 1.3 GHz	**20 kW, internal injection**	compact e-beam
5-cell 650 MHz	**100+ kW, external injection**	env. Remediation
9-cell 1.3 GHz	**20 kW, external injection**	Emerging application

Achievements at IARC

- First CW gradients in a conduction-cooled Nb_3Sn cavity — no liquid helium needed reaching 10 MeV/m with a “ringed” cavity
- A technology development group focused on commercialization and industrialization of SRF accelerators

Where We Stand: Technology Readiness

TRL 4–5
Conduction-cooled cavity demo
◄ *We are here*

TRL 6
Prototype in a real environment
Next 3 years

TRL 7–9
Commercial system, field operation
This session

What stands between TRL 5 and a real product is repeatability and standardization!

R&D Gap #1 — Nb_3Sn Reproducibility

High Q at 10 MV/m, every time, guaranteed

The Gap

Typical outcome:

10 MV/m, 1e10

Variation!!

A — Nb_3Sn Process Database + AI Model

▶ ***Converts process into a recipe anyone can follow.***

Every coating run, track variables such as temperature, tin pressure, and time into a shared database. A simple AI model predicts the result before you coat. This turns artisanal coating into a data-driven process. Every new run at any lab improves the shared model.

B — Defined Coating Protocol (like an EP recipe)

▶ ***Industry cannot buy what it cannot specify.***

A step-by-step standard that can be used for a quality check criterion → pass/fail decision. In such a way that any vendor can follow.

C — Community Data Sharing + Coordinated Runs

▶ ***The faster we accumulate coatings, the cheaper and more reliable they get for everyone.***

All labs sharing coatings data multiply experience without multiplying cost.

R&D Gaps #2 & #3 — Standardize, Then Prove Reliability

An MRI magnet is operated by a hospital technician — not a physicist. SRF must get there too.

Gap #2 — Standard Cryomodule Platform

STANDARD CRYOMODULE
Nb_3Sn cavity + cryocooler + LLRF tuner + diagnostics

RF power in
Cryo in
Thermal links

Same design. Same vendors. Same manuals.

Two standard frequencies: 650 MHz and 1.3 GHz

Every non-standard frequency is a custom project — custom projects do not industrialize. Modularity helps us learning curve.

Gap #3 — Reliability Demonstration

⚠ No published dataset exists on a conduction-cooled Nb_3Sn cavity operating for more than a few hundred hours — or surviving repeated thermal cycles under controlled conditions.

What industrial customers require:

- MTBF data (mean time between failures)
- Documented failure modes ….so field techs know what to expect

Three suggestions to close the industrialization gap

1

Shared Nb_3Sn Process Database

Open coating database + AI surrogate model shared across institutions. Active learning identifies the best next experiment. Compresses the learning curve community-wide.

2

Standard Cryomodule Platform

Agreed design with defined external interfaces. Two frequencies: 650 MHz and 1.3 GHz. Modular design enables standardization and field serviceability.

3

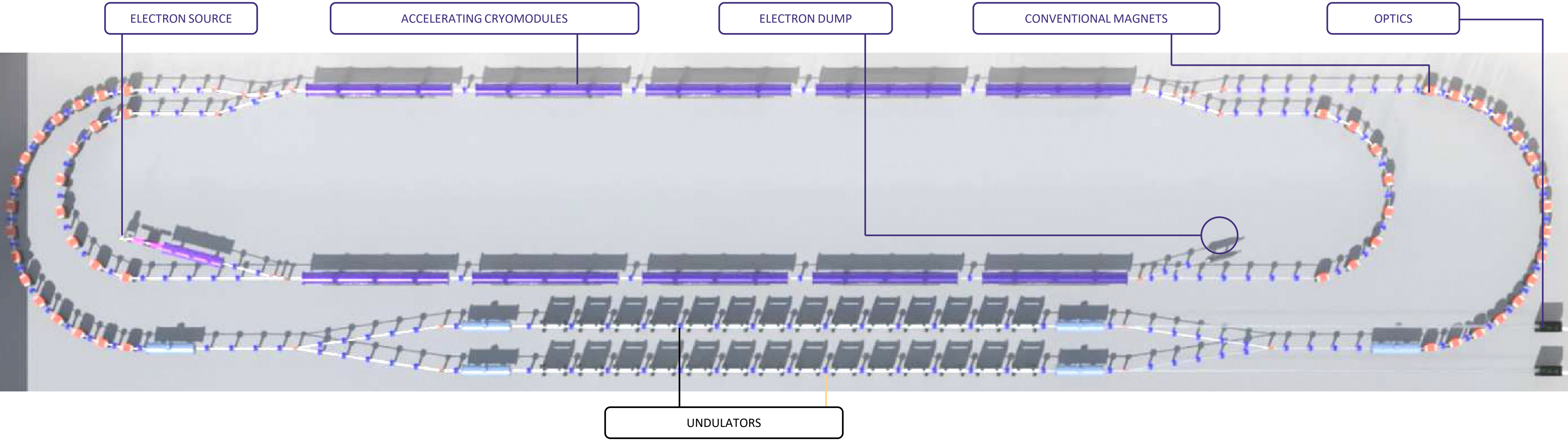
Published Reliability Specification

Systematic failure-mode catalogue. Result: an MTBF number that gives confidence.

Reliability for EUV FEL based Systems

xLight

NEW APPLICATION OF PROVEN TECH



Reliability Drivers

Customer Requirements

- 99% uptime – 87.6 hours/year not delivering photons to scanners

Internal Demands

- We must move quickly
  - No time to design everything from scratch
  - No time to ramp up vendors on a new design
- True prototypes must come before production designs are locked down, adding years to a project
- Ability to utilize existing designs
  - cavities, couplers, infrastructure

Reliability Challenges

Customer Demands

- 99% uptime – 87,6 hours/year not delivering photons to scanners
- **How much planned maintenance do you need?**

High Power, High Current operations of an ERL

- How hard do you push your systems?
- Incomplete energy recovery implications
- Multi-alkali photocathode operations

Electrical Grid

- How many dips in electrical supply can the system stand before it trips?

Recovery

- If you trip the machine, how fast can you get back online?

Reliability Solutions

- Use existing demonstrated designs whenever possible
  - Cavities
  - Couplers
  - Amplifiers
- Keep operating point for cavities, couplers, magnets in very stable region
- Include redundancy where necessary
- Carry out detailed reliability analysis for every component based on previous operating experience

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Hot topic Developing SRF towards Turn-Key Industrial Systems

Discussion

- Technical Frontier
- Engineering path for reliability
- Strategic democratization
- Preliminary considerations for a Roadmap towards an SRF "plug-and-play"

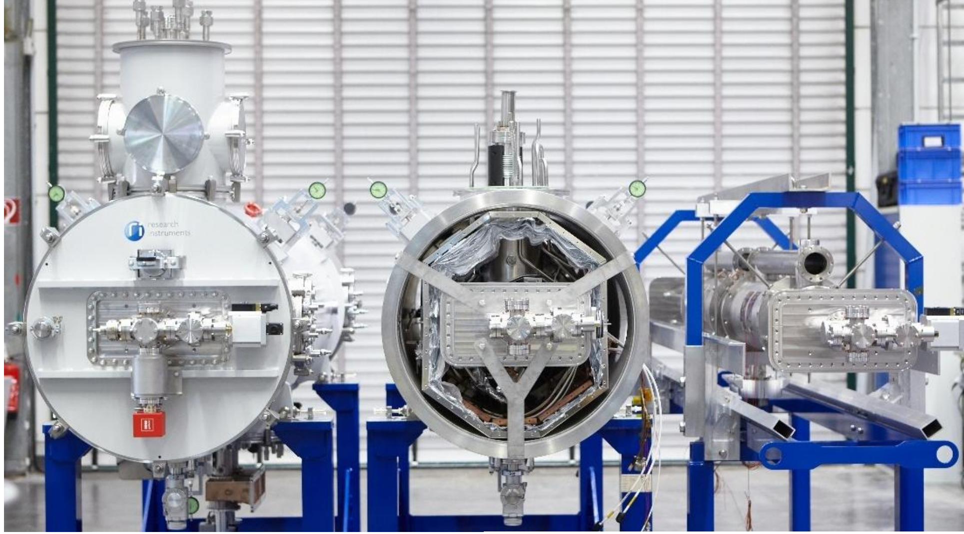
research instruments

TTC 2026 Meeting, Gif sur Yvette, France

Nb_3Sn based “Turn-Key“ SRF Systems – When is the technology ready for industrial ramp-up?

Lucas Zweibäumer

June 11, 2026



RI Research Instruments

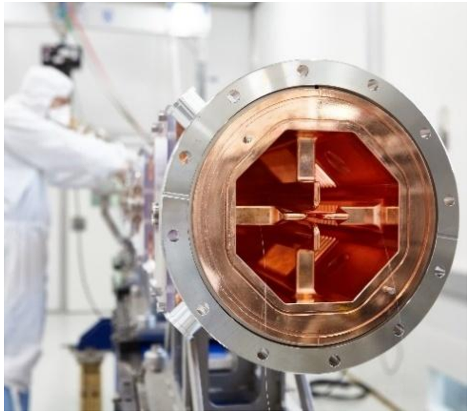
RI at a glance

- Founded in 1994 as ACCEL Instruments GmbH – since 2009 named RI Research Instruments GmbH
- Annual revenue of 90 million EUR
- Majority (52%) owned by Bruker EST, Management team are additional shareholders
- Headquarters in Bergisch Gladbach, Germany, very close to Cologne
- 3 main high-tech business fields
  - Particle accelerators: Super and normal conducting
  - Fusion: Systems and components supplier
  - Semicon: EUV tools and Semicon supply chain

Bergisch Gladbach & Dortmund, Germany

Customers in >25 countries

30 years of innovation



Our Customers

Diversified high-tech portfolio

„Big Science": 70%

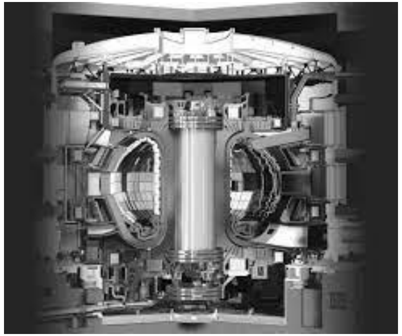
1. Superconducting RF cavities and accelerator modules
2. Normal conducting RF cavities, RFQs, linacs, accelerators for medical isotopes & radiation therapy including pulsed power equipment
3. Fusion equipment (ITER, JT60...)

"High-tech industry" (partly confidential): 30%

4. EUV metrology tools including photon instrumentation
5. Components for EUV lithography machines

Others e.g. Nuclear, Pulsed Power, Space

- Worldwide leading company in SRF cavities production
- The only company in the world that can deliver turn-key SRF modules including controls and cryogenic supply valve boxes



Hundreds of Experts / Dozens of Technologies

Large enough to do complex projects & small enough to be flexible

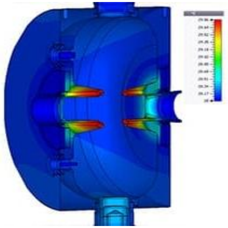
400 Experts

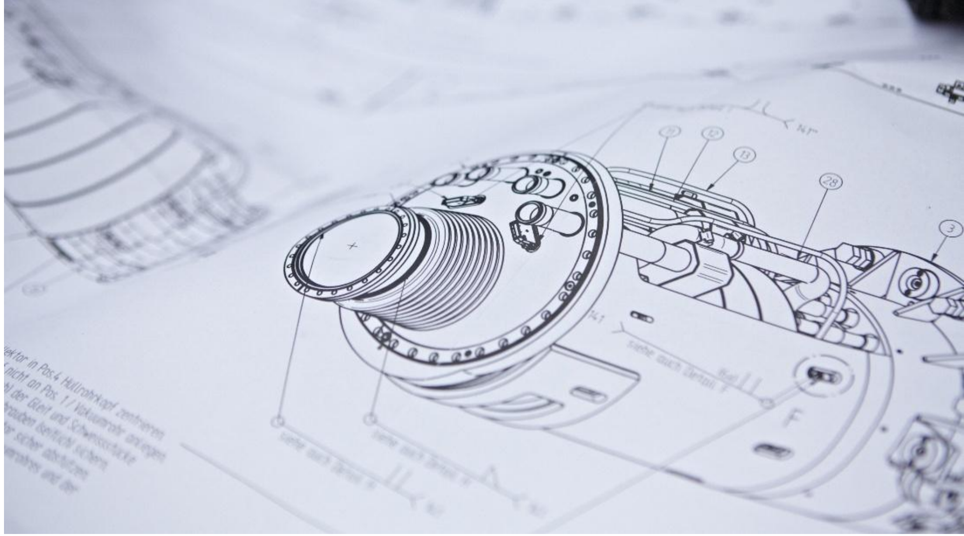
- 140 Engineers & physicists
- 220 Craftspeople
- 40 Finances, HR, IT, …

400
and growing

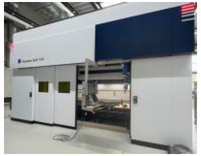
End-to-end Engineering and Manufacturing Solutions

- R&D
- Engineering
- Precision Manufacturing
- Qualification & Testing
- Assembly, Integration & Service
- Series production



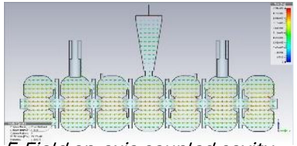


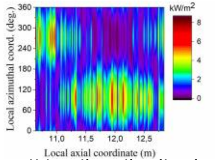
Deep Dive production capabilities

Discipline	Technologies	Pictures
CNC Milling & Turning	- 10 5-axis precision milling machines - 6 turning machining centers - 5 CAM programmers, 20 CNC machine operators - All relevant materials can be processed (from plastic to titanium, with niobium as a unique selling point)	 
Welding	- TIG welding, Orbital Welding - 1 Cobot Welding Machine - 1 CNC laser welding TruLaser Cell 7040 with 4000W - 2 CNC Electron-beam welding systems (Probeam, PTR), each with 30 kW (max. 150 kV, 200 mA) power - Certified according to DIN EN ISO 3834-2 (and DGRL)	 
Leak Test	- Leak testing with high sensitivity (< 1x10-11 mbar*l/s) - Pressure testing - Certificates: DIN EN ISO 20485 & DIN EN 1779	
Surface Treatment	- Various cleaning and pickling basins, flexibly adjustable in size to suit project requirements, with and without ultrasound	
Dimensional Control	- Measurement room classes 2 and 3 - 6 tactile portal measuring devices for component measurements with a length of up to 3 meters and an accuracy of up to (1.4 + L / 350) µm (L in mm), e.g. Zeiss Prismo ultra - 2 optical stationary CMMs, GOM (Length deviation: 0.02 mm) + Zeiss O-Inspect - >10 mobile CMM systems, e.g. Hexagon measuring arms (length deviation: 0.064 mm), Zeiss T-Scan (length deviation: 0.03 mm)	 
Final Inspection	- Visual inspection with UV, white and ambient light - Dark room - VT testing	

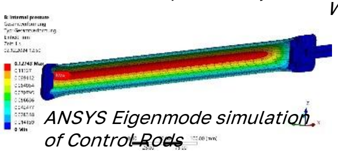
Deep Dive engineering capabilities

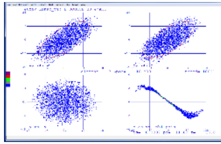
Discipline	Technologies	Pictures
Electro-magnetic design	- Development of accelerator components like electromagnets, kickers and cavities incl. the magnetic field design (Poisson Superfish (2D) or CST Microwave Studio (3D)	
Structural design & thermal simulations	- Analyzes of stresses, displacements or mechanical eigenmodes, thermal problems using such software packages like ANSYS Workbench, CST Studio Suite incl. MPhysics Studio which contains structural mechanics as well as thermal solvers	
Beam Dynamics simulation	- Ray-transfer-matrix analysis-based code Trace3D is employed for fast bunched-beam envelope calculations (incl. linear space-change forces) of standard beam manipulating elements (solenoids, quadrupoles, bends, etc.) - Detailed beam dynamics calc. by Tstep/PARMELA (multi-particle tracking + beam optics from SUPERFISH), ELEGENT (for e⁻ simulations), GPT, CST Particle Studio (multi-particle tracking + particle-in-cell (PIC) simulations	
3D-CAD Design	- 3D modelling and preparation of manufacturing drawings utilizing Autodesk Inventor Professional 2022	
Control System Design	- Development of control systems/software for own equipment & turn-key accelerators. - Building Programable Logic controllers (PLCs) for hardware control (valves, pumps, power supplies) like Beckhoff TwinCAT, EPICS or Siemens SIMATIC, NI LabView	
Cryogenic engineering	- Process calculations, definition of pressure relief/safety systems, calculation of thermal insulations, heat load optimisation, choice of materials, testing at LT	


E-Field on-axis coupled cavity

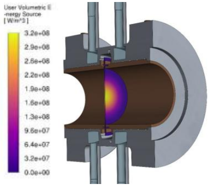


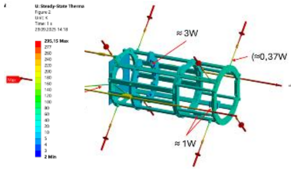
WG wall loading distribution


ANSYS Eigenmode simulation of Control Rods

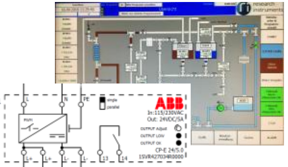

STEP Multi particle simulation


Cryopump in Autodesk Inventor Professional


Heat in diamond window



Heat load optimisation



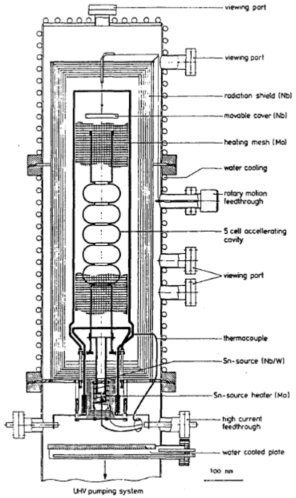
EPlan and PLC of BCP system

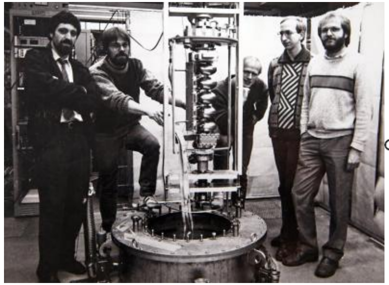
Nb_3Sn related facts from our story

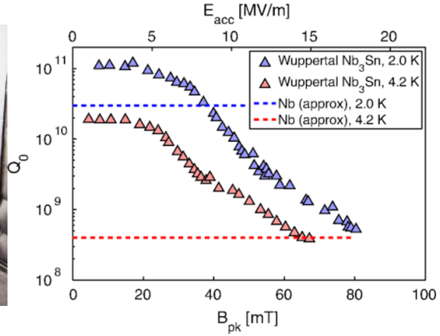
1980s: Cooperation with Uni. Wuppertal

“RI team” was involved into pioneering experiments with Nb_3Sn coating of high-purity Nb cavities at Uni. Wuppertal.

M. Peiniger et al. **1987** *Proc. Workshop on RF superconductivity* https://jacow.org/srf87/papers/SRF87E04.pdf



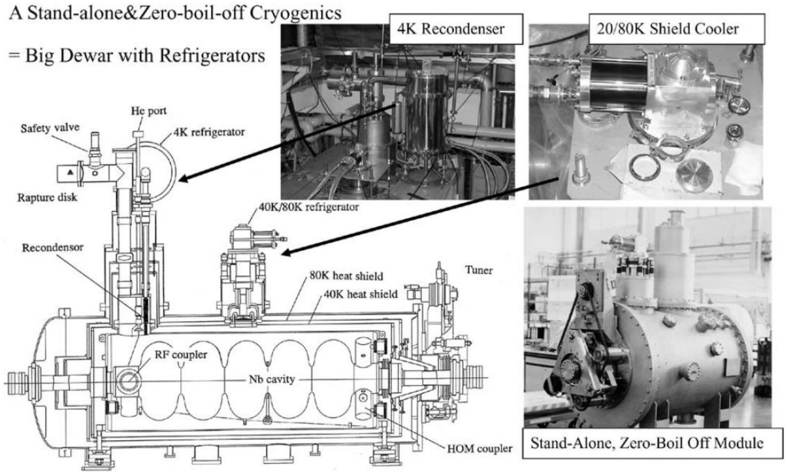




1990s: Turn-key superconducting cryomodules for the JAERI FEL

“RI team” performed final design, manufacturing, assembly and testing of 4 modules equipped with compact 40K/80K shield-cooler and 4K He-recondenser refrigerators.

E.J. Minehara **2002** *Nucl. Instrum. Methods Phys. Res. A* https://doi.org/10.1016/S0168-9002(02)00277-2

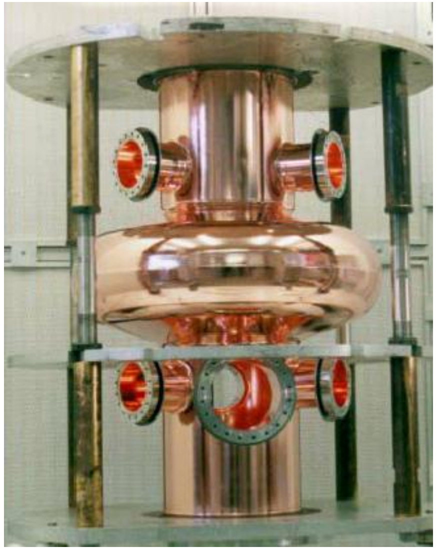


Nb_3Sn related facts from our story

1990s: Cooperation with CERN on Nb sputtering

For the Large Hadron Collider (LHC) at CERN, 21x superconducting 400 MHz single cell cavities have been produced by ACCEL (later RI) using the technology of magnetron sputtering of niobium on copper cavities. This technology was developed by CERN and transferred to industry within the scope of the LEP 200 project.

S. Bauer et al. **1999** *Proc. Workshop on RF superconductivity*
https://proceedings.jacow.org/SRF99/papers/wep016.pdf?n=SRF99/papers/WEP016.pdf



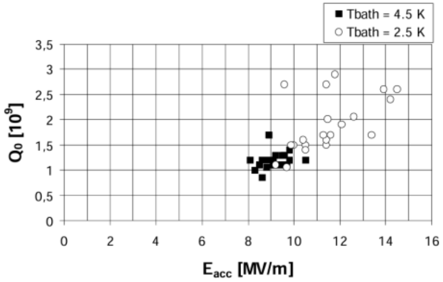


Figure 3: Highest gradients E_{acc} and quality factors Q_0 at the highest gradients achieved at bath temperatures of 4.5 K and 2.5 K in the LHC 400 MHz single cell cavities. The tests were carried out at CERN. The preparation of the cavities prior vertical test was done at ACCEL.

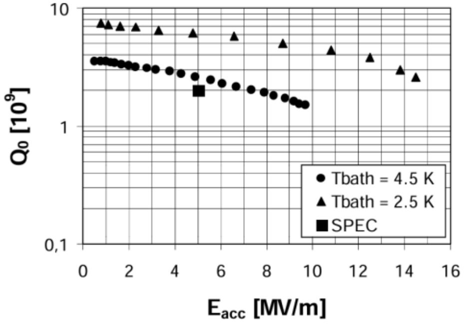


Fig. 4: Performance of cavity A11 at 2.5 K and 4.5 K bath temperature.

What we bring to the Table

research instruments

1. Experience in R&D, Prototyping, Series manufacturing & Industrialization

Contributor to: ITER, CERN, SLAC, DESY, and more

2. Cross-Domain Expertise

SRF, NCRF, Vacuum, Cryogenics, Fusion,
Pulsed Power, Welding,

Manufacturing, Testing.....

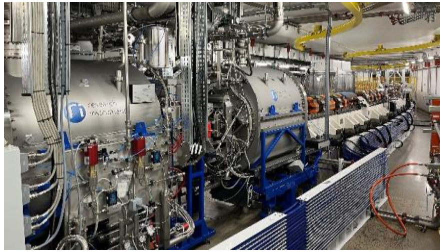
3. Vertically Integrated

One Partner for the entire project:
Design, Development, Manufacturing, Supply Chain, Assembly, Integration, Service

4. Strategic Positioning & Heritage

With roots in European mega-projects like CERN, ITER, GSI, and DESY, our work

bridges scientific innovation and industrial reliability.



Enabling technologies

Technologies to enable industrial Nb_3Sn-based "Turn-Key" SRF Systems:

- Reliable coating technique (diffusion, PVD, ...) of high-quality Nb3Sn coating on Nb or Cu cavities

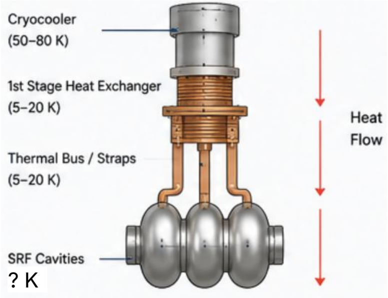
Mature ?

- Low Heat-Leak RF Couplers

Thermal load for 2K cryogenic zone	< 0.2 W
Thermal load for 5 K cryogenic zone	< 3.7 W
Thermal load for 80K cryogenic zone	< 75 W

Too high ?

- Method of efficient helium-free conduction cooling / High-purity thermal links



- Powerful reliable Cryocoolers

Example:
CryoMech PT450
– 40 W @ 45 K
– 1.5 W @4.2 K

Enough cooling?

Industrialization roadmap (TBD)

research instruments

Industry scope

- Provide cavities for coating
- Engineer and design He-free cryomodules

↓

- Find business opportunities and first customers
- Mature systems for market entry

↓

- Industrialized coating facility
- Provide turnkey cryomodule systems

short term → long term

Science scope

- Mature recipes for coating (reliability & repeatability)
- Coating and qualification of industry cavities for CM production

↓

- Technology transfer/licensing to industry
- Support to industry on special topics

↓

Continue technology improvement ;-)

- *Questions?*

Feel free to contact us.

+492207-7674-100

www.research-instruments.de

TESLA TECHNOLOGY TTC COLLABORATION

Hot topic Developing SRF towards Turn-Key Industrial Systems

Technical Frontier

Performance Metrics

- What performance level should we realistically consider today as a ***reproducible benchmark*** for Nb_3Sn-coated cavities at 4 K: **$Q_0 \approx 10^{10}$ at 15 MV/m** is still a best-case result and **$Q_0 \approx 10^{9}$ at 10 MV/m** remains a more honest metric for routine production?
- ***Have we reached a plateau*** where further improvements in Q_0 and accelerating gradient require fundamentally new approaches, or are we still limited mainly by coating process control?

Substrate & Deposition

- Is compositional control of the A15 phase still the dominant obstacle preventing uniform Nb_3Sn coatings on complex geometries (e.g., non-elliptical or high-frequency structures), or are other factors now equally limiting performance?
- How would you address the stoichiometric variations in A15 phase growth to ensure consistent thermal and electromagnetic performance across batch production?

Lifetime Performance

- Most Nb_3Sn discussions focus on initial performance. Based on the data available, do you observe evidence of performance degradation under prolonged RF operation or repeated thermal cycling?
  If so, what are the dominant degradation mechanisms? How do you characterized it? How confident are we about long-term reliability under realistic operating conditions?

TESLA TECHNOLOGY COLLABORATION

Hot topic Developing SRF towards Turn-Key Industrial Systems

Technical Frontier

Thermal Link Optimization

- Which thermal-link technologies have demonstrated the **best compromise** between low thermal resistance, mechanical compliance, and long-term reliability: **high-purity Al straps, Cu braids, rigid Cu links**, or alternative architectures?
- Many groups report practical heat extraction limits of only **1–3 W at 4 K. Is this a fundamental limitation of today's conduction-cooling** approach, or simply an engineering challenge that has not yet been fully addressed?
  - Does your experience differ?
  - What is currently the main bottleneck: the cavity, the thermal link, the interfaces, or the cryocooler itself?

Vibration Mitigation

- Are mechanical vibrations introduced by pulse-tube or GM-type cryocoolers a major concern for conduction-cooled cryomodule operation?
- What decoupling techniques or damping strategies are required to preserve the phase and amplitude stability of superconducting cavities?

Cryocooler Duty Cycle Impact

- How do you manage the transient thermal load on the cryocooler during the start-up phase compared with the steady-state load encountered during high-duty-cycle industrial operation?

TESLA TECHNOLOGY TTC COLLABORATION

Hot topic Developing SRF towards Turn-Key Industrial Systems

Engineering path for reliability

Operational Stability: What are the critical "failure points" when transitioning from a controlled laboratory environment to a high-duty-cycle industrial accelerator?

Key concerns revolve around long-term process repeatability, high-standard cleanliness, and power grid stability. Specific engineering vulnerabilities include the high brittleness of the Nb_3Sn layer during assembly, strict low-magnetic hygiene requirements, narrow cryogenic tuning margins, and sensitivity to pressure or microphonic fluctuations. The transition also faces human and environmental friction points like robust transportability and training non-expert industrial operators.

Cooling & Integration: Given the push for conduction cooling, what are the primary engineering bottlenecks in maintaining stable cryogenic temperatures under varying industrial load conditions?

The primary bottlenecks are the high capital cost of higher-capacity cryocoolers and the raw material quality of the Nb_3Sn coating. Designing specialized thermal links that support a controlled, uniform cooldown profile (as opposed to natural, uneven cooling) is vital to operate effectively within the tight power constraints of standard commercial cryocoolers.

Quality Control: What standardized diagnostic protocols (e.g., RF testing, surface inspection) should be adopted to ensure industrial-grade reliability before system deployment?

The community relies almost exclusively on comprehensive RF testing backed by strict manufacturing process controls and material analysis. There is a strong collective interest in developing predictive diagnostic tools capable of verifying cavity performance without requiring a full vertical or cryogenic test.

TESLA TECHNOLOGY COLLABORATION

Hot topic Developing SRF towards Turn-Key Industrial Systems

Engineering path for reliability

Cryostat Design: What are the most significant obstacles to reducing the footprint and complexity of the cryostat/cryogenic distribution system while maintaining high-duty-cycle performance?

Major obstacles involve mitigating the coating's mechanical sensitivity, preventing magnetic flux trapping, and optimizing the integration of thermal links. Furthermore, the massive physical footprint of commercial compressors (often designed for standard MRI applications) means that the entire system needs a clean-sheet redesign optimized around conduction-cooled SRF requirements.

Vibration & Microphonics: For compact, industrial-grade accelerators, what vibration mitigation strategies (passive or active) are currently being validated to ensure stable operation in non-lab environments?

The community relies on a blend of active and passive methods, with passive methods taking priority. These include physical vibration decoupling, such as locating pumps and compressors on isolated slabs away from the cryomodule, though field validation data remains relatively scarce.

Power Couplers: Are current power coupler designs capable of handling the high average power required for industrial applications without frequent maintenance or failure?

Perspectives are split. Some express confidence that Fundamental Power Couplers (FPCs) can rapidly meet industrial demands (handling up to hundreds of kW with low maintenance overhead (less than once per year). Others note that true high-power capability remains unproven in commercial settings and that specialized couplers developed specifically for conduction cooling need more validation.

Hot topic Developing SRF towards Turn-Key Industrial Systems

Engineering path for reliability

Serviceability & Maintenance: What is the industry standard for the "Mean Time Between Maintenance" (MTBM) that would be considered acceptable for a turn-key industrial system (e.g., >20,000 hours)?

The minimum acceptable threshold is cited around 5,000--10,000 hours, while ambitious expectations for a competitive commercial commodity range from 30,000 to 60,000 hours.

Redundancy Models: For industrial environments where downtime is costly, what level of cryocooler redundancy (e.g., N+1 configuration) is required to ensure continuous operation without manual intervention?

While some models suggest fractional dependencies, the dominant sentiment points to an N+2 configuration to ensure continuous, hands-off industrial operation

TESLA TECHNOLOGY T T C COLLABORATION

Hot topic Developing SRF towards Turn-Key Industrial Systems

Strategic democratization

Cost Reduction: What specific component or process (e.g., vacuum systems, cryostat design, power couplers) represents the largest cost barrier to widespread commercial adoption?

The largest financial barriers are driven by the RF power source (dominating both Capex and Opex), the power couplers, reactor/vessel design, and the technical scaling up of the Nb_3Sn coating and cavity processing to a high-throughput industrial standard.

Skill-Set Barrier: What are the most essential features required to allow operation by technicians who are not specialized in accelerator physics?

True turn-key functionality is mandatory, relying on high automation, well-defined step-by-step procedures, and highly constrained manual interventions. Simplifying the control logic to a standardized framework would allow technicians from adjacent fields (e.g., radar technicians) to operate the hardware easily.

Regulatory Hurdles: Are there specific safety or regulatory standards (e.g., pressure vessel codes, radiation shielding certifications) that currently hinder the deployment of SRF systems in non-laboratory settings?

High-mass radiation shielding represents the largest logistical and regulatory bottleneck for new installations outside labs. Additionally, there is a lack of standardized mechanical design codes for next-generation SRF structures, though regulatory pressure may ease at modest energy outputs (e.g., 10 MV).

TESLA TECHNOLOGY COLLABORATION

Hot topic Developing SRF towards Turn-Key Industrial Systems

Strategic democratization

Manufacturing Scaling: What manufacturing processes (e.g., additive manufacturing, automated welding, or robotic cavity processing) are necessary to shift from "one-off" production to "batch" production?

Shifting to industrial batch production demands automated assembly and welding lines alongside a simplified, robust recipe for cavity coating. While robotic processing and AI-driven automated coatings are highly desirable, the general consensus is that the technology is not yet mature enough for deployment.

Chain Maturity: Where do you identify the greatest bottlenecks in the supply chain for high-purity materials, specialized vacuum hardware, or cryo-component manufacturing?

The primary constraint is a systemic lack of reliable "market pull" from industry. This creates a highly specialized and fragile supply chain characterized by constrained high-purity material sources, custom cavity processing pipelines, and a minimal pool of commercial vendors for specialized cryocooler components.

On-Site Maintenance: What is the minimum level of on-site diagnostic equipment (e.g., remote monitoring, automated gas analysis) required to avoid the need for dedicated SRF expert personnel at industrial sites?

Robust, continuous remote monitoring is unanimously considered the most critical tool. The community envisions a commercial model similar to Transmission Electron Microscopes (TEMs)—combining general on-site maintenance with structured annual service contracts—enabling a single remote expert to manage compact accelerator installations.

Hot topic Developing SRF towards Turn-Key Industrial Systems

TESLA TECHNOLOGY TTC COLLABORATION

Preliminary considerations for a Roadmap towards an SRF "plug-and-play"

•Modular Standardization: Which elements of an SRF cryomodule (e.g., interface dimensions, control logic, vacuum connectivity) are the most critical to standardize across the community?

Input points to a comprehensive need to standardize physical and system-level boundaries across the community, highlighting mechanical interface dimensions, control logic, vacuum connections, and standard operating frequencies.

•Plug-and-Play Integration: What level of "autonomous operation" is realistically achievable in the next 5 years (e.g., automated cryo-management, self-tuning RF systems)?

High levels of autonomy are deemed achievable within a 5-year window. Driven by advancements in machine learning and AI, systems should be fully automated across cryo-management, RF conditioning, and tuning, requiring human intervention only for choosing top-level parameters like beam energy and current.

•Standardized Control Architectures: Should the community move toward a common, open-source control platform (e.g., a specific EPICS implementation or PLC-based standard) to facilitate "plug-and-play" integration?

The community favors standardization, noting it would significantly aid system integration. However, experts raise concerns that industrial adopters typically prefer integrating hardware into their own proprietary, pre-existing control frameworks, and current open-source alternatives may lack industrial robustness. Early stakeholder input is heavily recommended.

Hot topic Developing SRF towards Turn-Key Industrial Systems

Preliminary considerations for a Roadmap towards an SRF "plug-and-play"

•Transportability: What design changes are needed to ensure an assembled, vacuum-sealed cryomodule can withstand the rigors of transportation and installation without requiring a full re-commissioning/re-processing phase?

This topic received no definitive comments or expert feedback in this round of input, identifying it as an open question requiring further study.

•System "Startup" Logic: If you were to design a "turn-key" system, what automated sequences (e.g., automated cool-down, auto-RF conditioning) are most essential to minimize the human element in operation?

The most essential automated operational blocks are automated cooldown sequences, auto-RF conditioning, automated fine-tuning, and robust automated recovery logic following a sudden power loss.

The 10-Year Vision: From your perspective, what are the top three milestones required to transition SRF from a custom-engineered scientific asset to a standardized industrial commodity?

Collective community vision highlights three overriding milestones:

1. Establishing a reliable industrial supply chain for mass-produced Nb_3Sn cavities with predictable performance.
2. Enforcing rigorous standardization across cryomodule designs, operating frequencies, physical interfaces, and processing recipes.
3. Achieving a repeatable, high-duty demonstration of continuous MW-class operation (running >200 days/year) to definitively validate machine-grade reliability in an industrial environment.

Science and Technology Facilities Council

12th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity

21–25 Sept 2026
Chester, United Kingdom

Innovative thin films and related technology to advance future generations of superconducting RF accelerators. Present superconducting RF accelerator technology is based on predominantly bulk niobium, for which the state of the art in performance is reaching the theoretical limit. Thin film technology offers the prospect of considerable savings in fabrication costs and opens the way with innovative technologies to the use of alternative superconducting materials with enhanced intrinsic properties such as critical temperature and critical field. Intensive and coordinated R&D effort is of decisive importance for the scientific community. The primary aim of the workshop is to support this initiative by providing an opportunity to bring together individuals and institutions working in this effort and infusing expertise of specialists from related disciplines (superconductivity, plasma physics, material science, nanotechnology, RF engineering and industry). Reports on work from each participating group and extensive discussions on existing problems, new ideas and programs for the future constitute the primary focus of the program.

Registration deadline is **July 27th**
Register: cvent.me/rZdPOP

Core Mission: Provide a dynamic forum to advance the next generation of superconducting RF (SRF) accelerators by focusing on innovative thin films and emerging technologies with enhanced superconducting properties (e.g., higher critical temperatures and fields).
Primary Objective: Foster international, cross-disciplinary collaboration by uniting experts from superconductivity, materials science, plasma physics, nanotechnology, RF engineering, and industry.
Program Focus: Share progress reports from global research groups, address current technical challenges through in-depth discussions, and strategically plan future R&D initiatives.

- **Setting the Horizon: welcome address, global perspectives & technical roadmaps**
- **Pushing SRF thin films limits: theoretical advances, deposition modeling & DFT** *(Eliashberg, ..).*
- **Latest advances in Nb thin film technology**
- **Conventional PVD, energetic condensation from highly ionized plasmas** *(HiPIMS, Arc Deposition, ECR plasma deposition ...), CVD...*
- **Nb_3Sn Technology: recent technical advances & scaling horizons**
- **Beyond Nb & Nb3Sn: alternate materials, multilayer SIS structures and functional layers – (***B1 compounds (NbN, NbTiN...), A15 materials other than Nb_3Sn (V_3Si,Nb_3Al ...), MgB_2 and other high-Tc superconductors (oxypnictides, FeSe monolayer...), SIS multilayer, cap, barrier layers and nano-engineered structures)*
- **Tailored substrates for advanced film growth – (***Surface cleaning, atmospheric plasmas; cavity substrate fabrication (electroplating, seamless cavities, 3D-manufacturing...))*
- **Emerging frontlines in characterizion methods: advanced imaging & novel probes** *(ptychography (TEM), ...)*
- **Emerging Frontiers & Synergies in SRF Thin Films: from quantum sensing to AI-driven materials** *(including detector cavities and quantum and superconducting logic & sensing applications, perspectives for AI enabled material development)*

Details concerning the program, registration and other practical details can be found on the dedicated Indico site: https://indico.stfc.ac.uk/event/1671/

Abstract Submission is open!

Deadline July 17th