Beyond Bulk Niobium R&D: SIS Multilayer Studies for a New Generation of SRF Cavities

Lea Preece - on behalf of the SRF R&D Team Hamburg

11. Annual MT Meeting, 3.-6. Nov. 2025

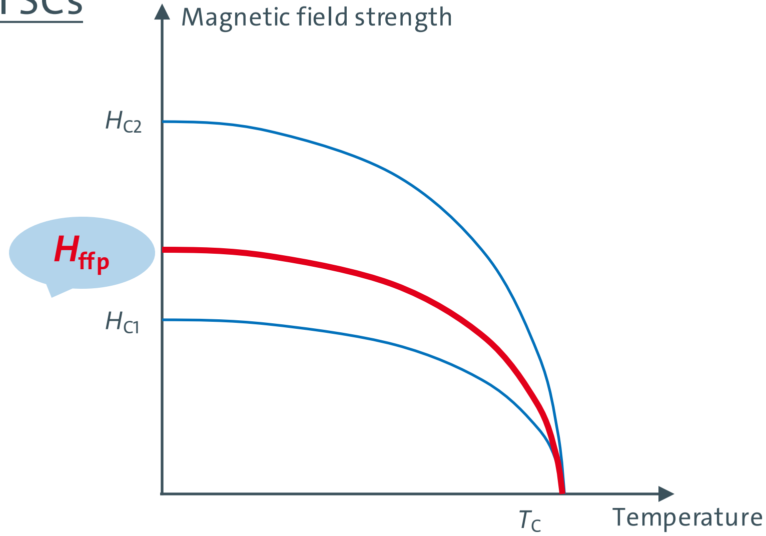
Bundesministerium
für Forschung, Technologie
und Raumfahrt

Superconductivity in Particle Accelerators

Niobium as material of choice for SRF cavities

- ✓ Highest known T_C of **9.27 K**
- ✓ Highest known H_{C1} of **180 mT**

Type II SCs



Upper limit for rf vortex penetration is even higher:

Superheating field

$H_{sh,Nb}$ ~ 200 to 250 mT

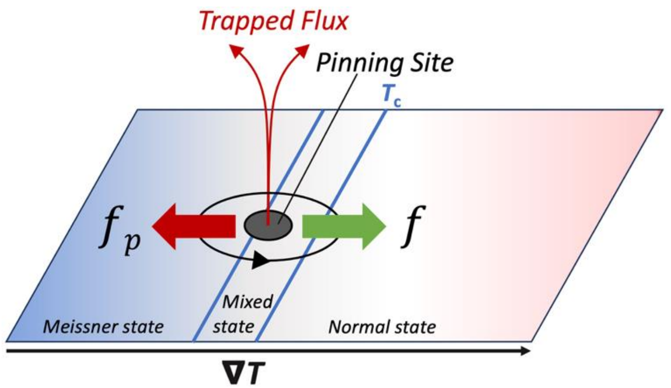
Limiting Performance Factors

Surface Resistance

$$R_S = \underbrace{A\frac{\omega^2}{T}\exp\left(-\frac{\Delta}{k_B T}\right)}_{R_{BCS} \text{ vanishes for } T \to 0\text{ K}} + R_{res}$$

Everything *except* R_{BCS}

- Weakly coupled grain boundaries, surface oxides etc.
- Trapped magnetic flux



Quality Factor

$$Q_0 \sim \frac{1}{R_S}$$

- ➢ Magnetic Quenching when $H_{applied} > H_{C1}$
- ➢ Dissipation becomes unmanagable!

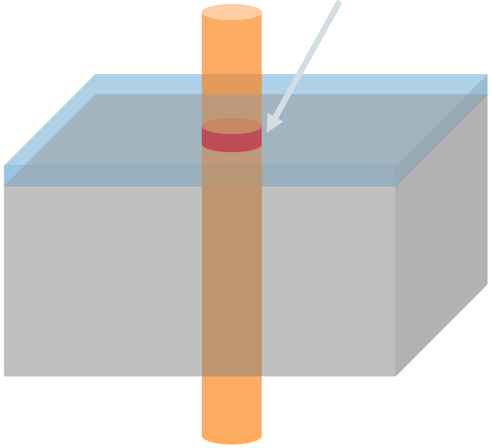
E_{acc} is limited by dissipation because of high surface magnetic fields!

Thin Films and Pancake Vortices

- Vortices energetically supressed in SC thin film
  - ➢ Thinner than the London penetration depth $d < \lambda_{L,NbTiN}$ **(~ nm)**
- Coat inner cavity surface with higher-T_c superconductor

NbTiN T_C = 17.8 K

- **Superconductor-<u>Insulator</u>-Superconductor** (SIS) multilayers
  - ➢ Insulator as vortex barrier

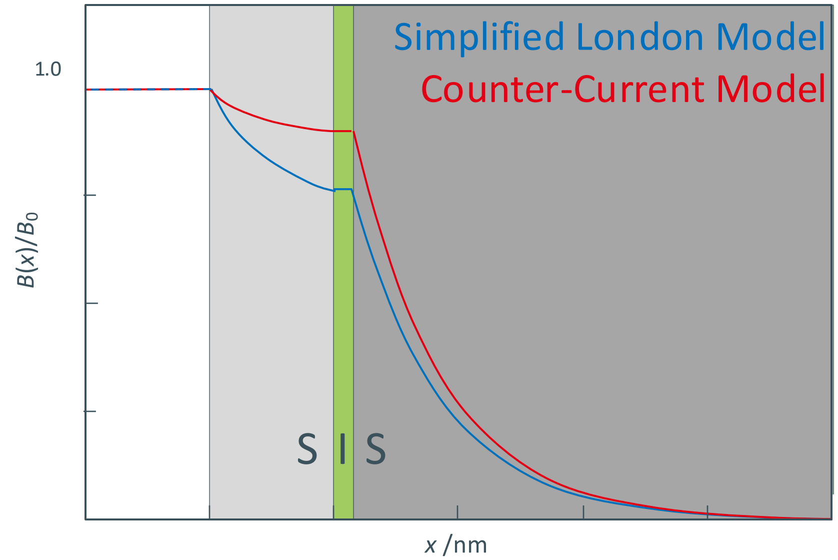


Vortex dissipation becomes energetically unfavourable

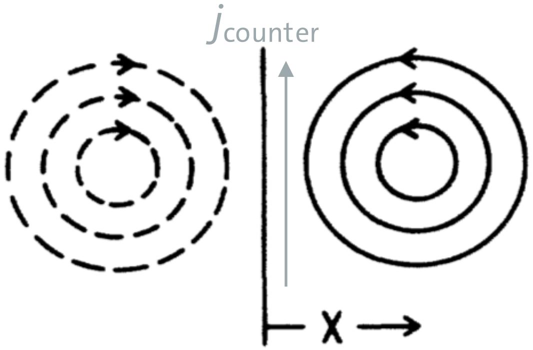
For more detail see:
A. Gurevich, APL 88 (2006)

Counter Currents at the Interfaces

- Vortex penetration shifts to higher H_{ffp} through "**counter currents**" at interfaces



Bean-Livingston Barrier

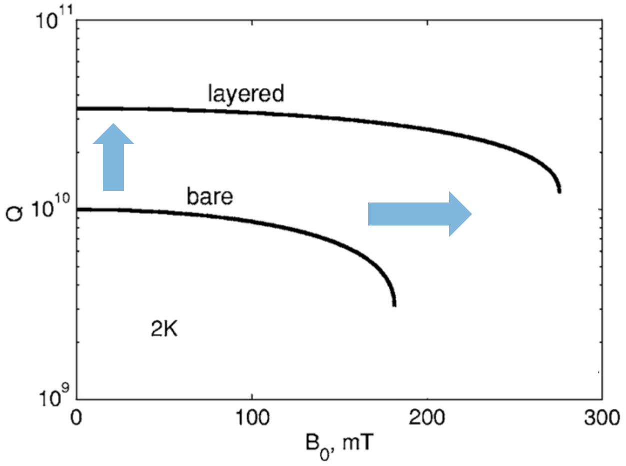


For more detail see:
T. Kubo, SUST 30 (2017)

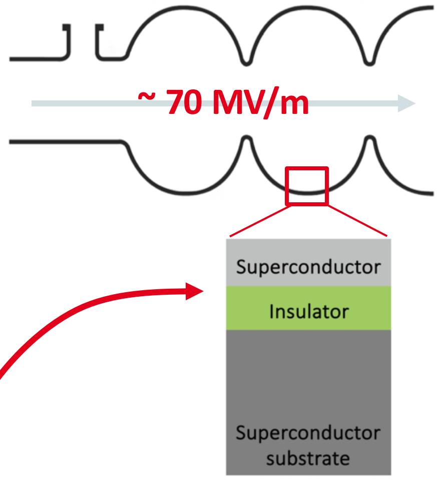
The Need for SIS Multilayers in SRF

SRF cavities approach thermodynamic limit of niobium

Superconductor-**I**nsulator-**S**uperconductor multilayer theory shows **potential to enhance E_{acc}** and achieve **lower rf losses**



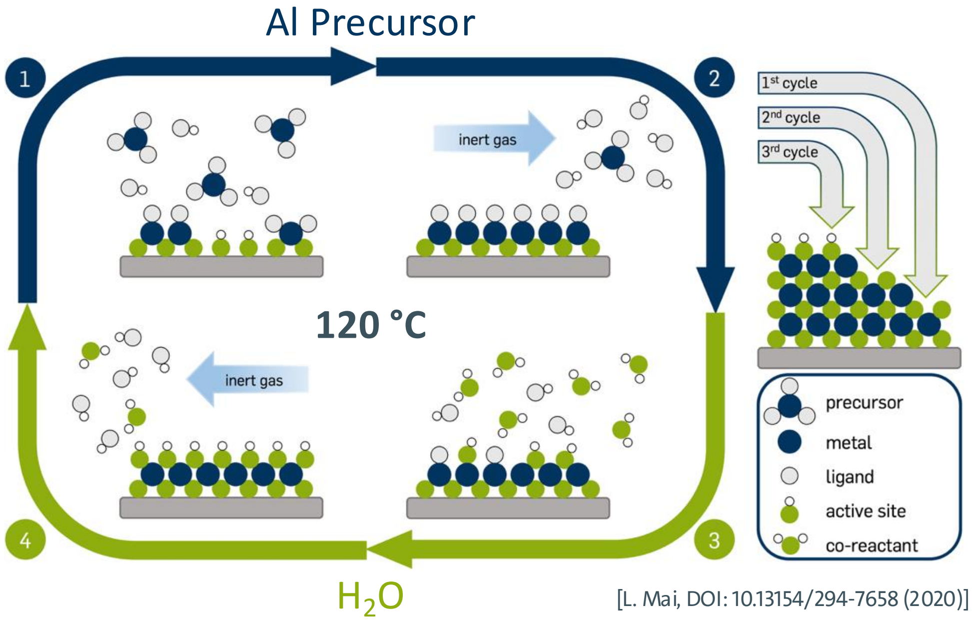
[A. Gurevich, Appl. Phys. Lett. 88, 012511 (2006)]



Realization of thin multilayer coating on the inner cavity surface is challenging!

ALD is the Key to Success

Thermal Atomic Layer Deposition



[L. Mai, DOI: 10.13154/294-7658 (2020)]

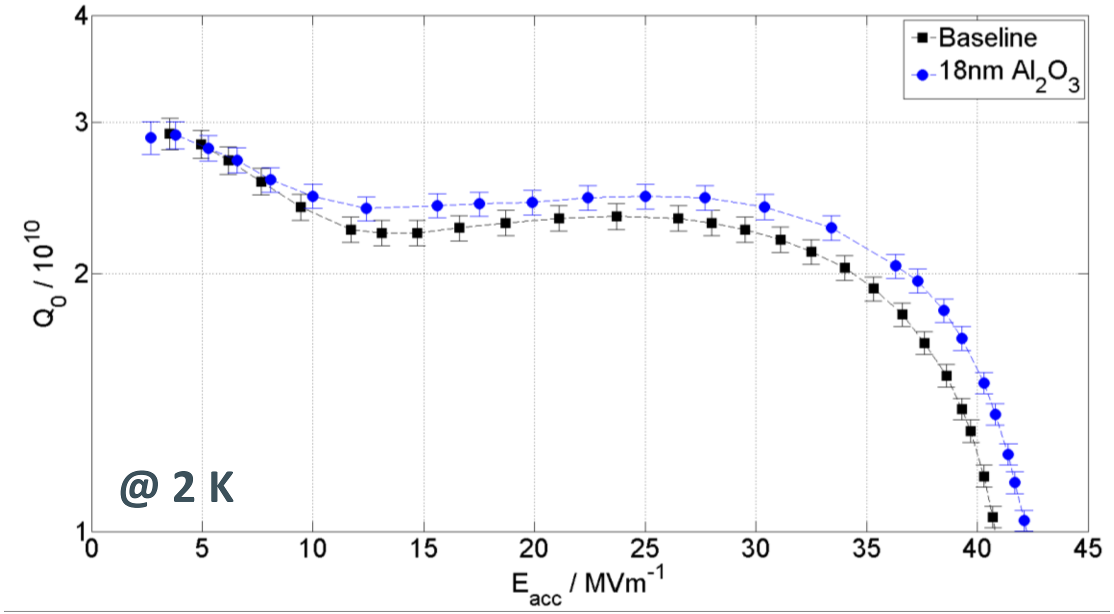
⇒ **forms Al_2O_3 atomic layers**

- Uniform deposition of high quality and high conformality
- Surface-controlled process
- Sub-nm thickness control

Thermal ALD System at University of Hamburg

Successful Al_2O_3 Cavity Coating

Thermal ALD coating on a 1.3 GHz cavity



[Wenskat, M., Deyu. G. et al., Supercond. Sci. Technol. 36.1 (2022): 015010.E.]

- ✓ Uniform and conformal surface coverage through ALD
- ✓ Preserved cavity performance

Successful Al_2O_3 Cavity Coating

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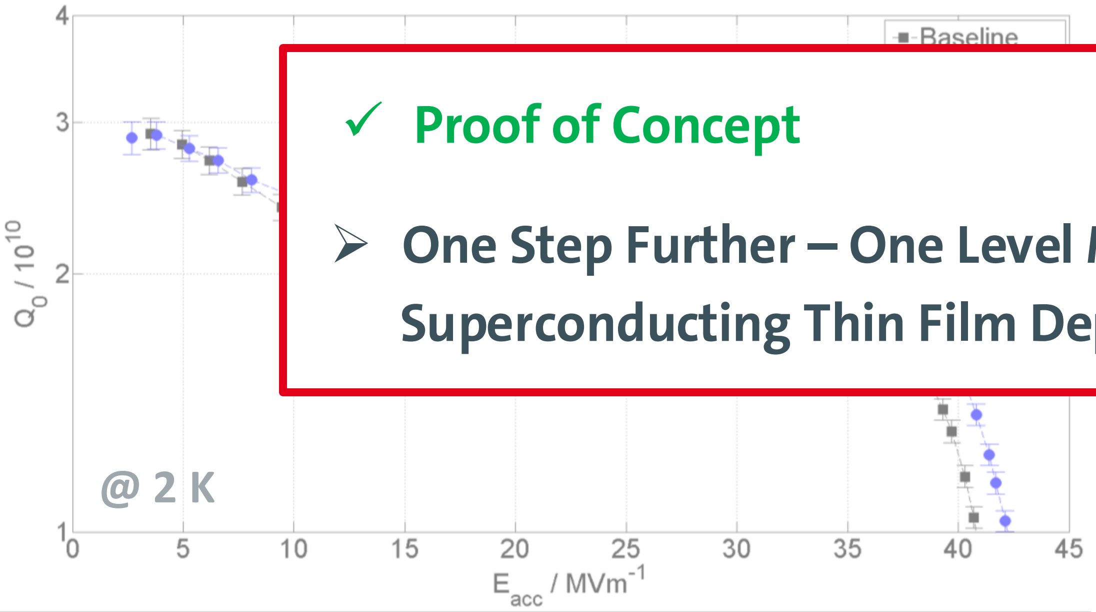

[Wenskat, M., Deyu. G. et al., Supercond. Sci. Technol. 36.1 (2022): 015010.E.]

rmal surface
LD
rformance

✓ **Proof of Concept**

➢ **One Step Further – One Level More Challenging: Superconducting Thin Film Deposition!**

Benefits of PEALD for SIS Multilayers

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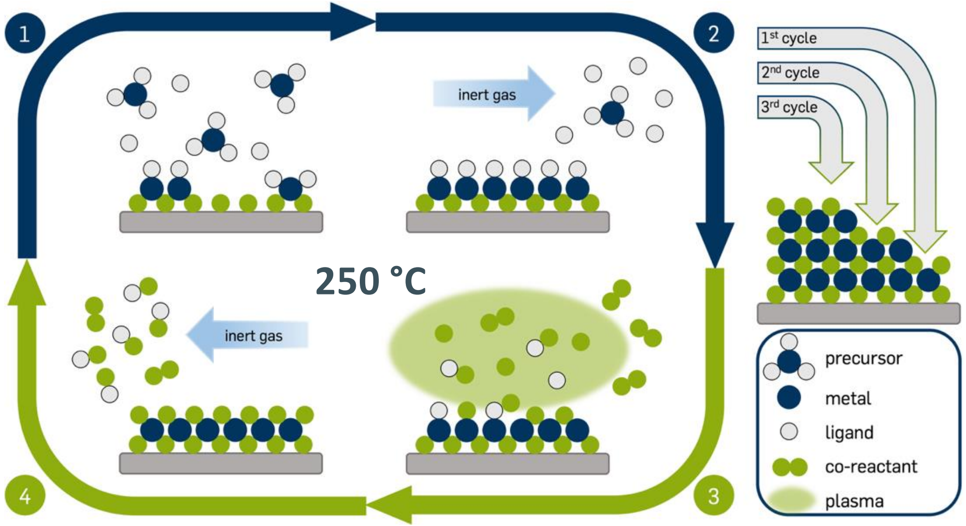
Plasma-Enhanced Atomic Layer Deposition

Al, Nb, Ti Precursor

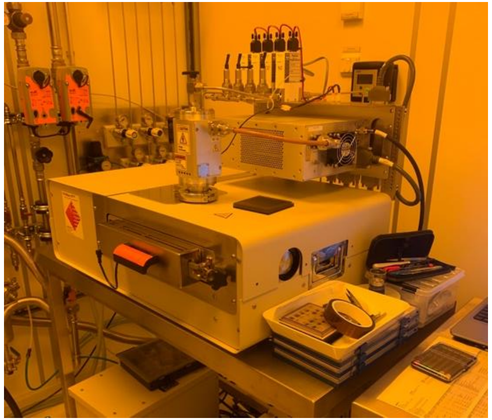


Plasma mix of H_2 and N_2 [L. Mai, DOI: 10.13154/294-7658 (2020)]

⇒ **forms AlN, TiN + NbN = NbTiN**

- ✓ Lower deposition temperature
- ✓ **No** acidic chemicals
- ✓ Higher crystalline order expected
- ✓ High precision thickness control

Plasma-Enhanced ALD System at University of Hamburg



Sample deposition device…

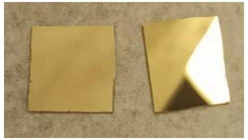
… a cavity will <u>not</u> fit in there!

Comprehensive PEALD-Coated Sample Study

Deposition of

- ☞ NbTiN only (**SS** Sample) ~ 60 nm
- ☞ AlN + NbTiN (**SIS** Sample) ~ (15+60) nm

On planar substrates:

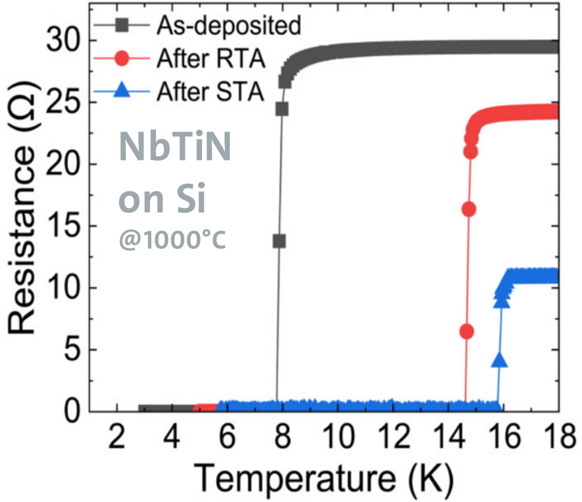


Si wafer

Nb substrate

Standard cavity surface preparation

1 hour **high temperature annealing** to enhance superconducting material properties



$\mu_0 H_{C1}$ = 15 mT

$\mu_0 H_{C1}$ = 81 mT

$\mu_0 H_{C1}$ = 98 mT

$\mu_0 H_{C1,bulk} \approx$ 33 mT

[González.I. et al., J. Appl. Phys. 134, 159902 (2023), 035301 (2023)]

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What have we learned about multilayers so far?

	SIS: Si	SIS: Nb	SS: Si	SS: Nb
As-deposited	✓ Well-defined layers × No high-Tc × Small grains, impurities			
Annealed	✓ T_c ~ 16 K ✓ δ-NbTiN phase ✓ Impurities degassing • Material interfaces become diffuse • Al atoms diffuse into NbTiN ~ few nm	✓ T_c ~ 14 K ✓ δ-NbTiN phase ✓ Impurities degassing • Material interfaces become diffuse • Al atoms diffuse into NbTiN ~ few nm	✓ T_c ~ 16 K ✓ δ-NbTiN phase ✓ Impurities degassing	× No enhanced T_c × No δ-NbTiN phase ✓ Impurities degassing × Inhomogeneous × Nb and Ti cluster × Oxygen uptake into NbTiN

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	Si — SIS — Nb	Si — SS — Nb
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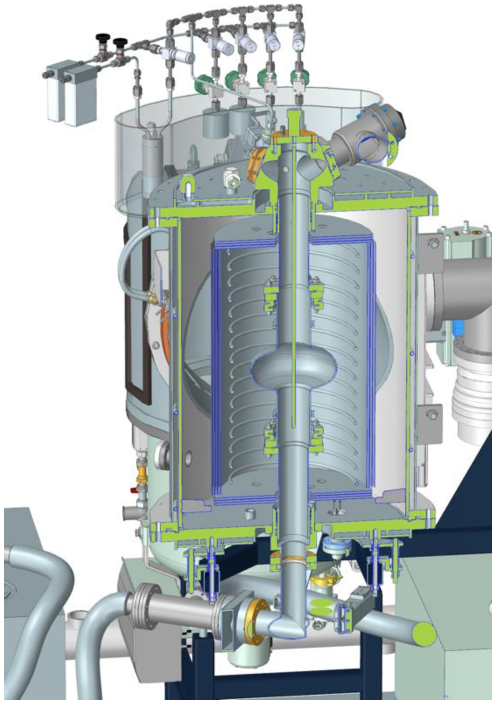
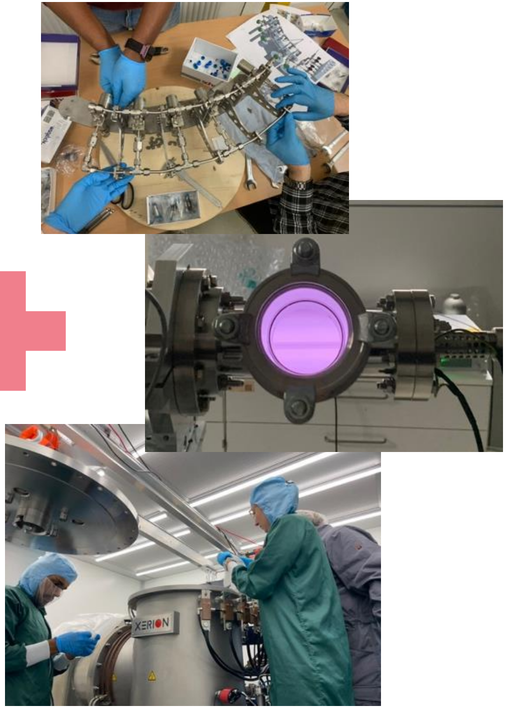
! Annealing is crucial for high T_c

! Insulating layer is vital

New PEALD SIS Cavity-Coating System



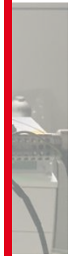
A sophisticated design...



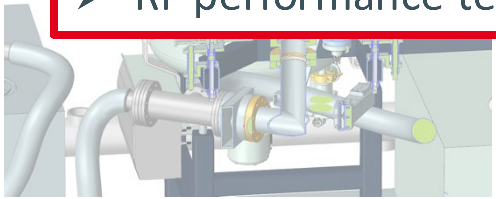
A lot of hard work by a great team!

... becomes reality!

New PEALD SIS Cavity-Coating System



- ➢ Scaling-up sample deposition parameters to **single-cell cavity** deposition
- ➢ Coating **single-cell cavities** with AlN-NbTiN SIS multilayers
- ➢ RF performance tests on the **coated cavities**



A sophisticated design… *A lot of hard work by a great team!* **… becomes reality!**

Summary

- ✓ **PEALD** is the **key technique** for **SIS cavity-coating**
- ✓ Expertise for successful PEALD coating and process optimisation
- ✓ Vital importance of thermal annealing and insulating layer proven
- ✓ Further investigation ongoing

Operation of the new Cavity-Coating System will begin soon!

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