Studies of niobium thin films deposited by coaxial energetic deposition*

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Introduction

Superconducting RF cavities are traditionally constructed from pure niobium metal

There are several problems with this approach:

Niobium is expensive and difficult to manufacture

- large fabrication and material costs

Majority of the metal is wasted

- London penetration depth (λ) of the SC current is thin compared to the wall of the cavity
- Wall must be thick to provide mechanical strength

Introduction

Alternative approach: Niobium thin film on copper cavities

Some advantages:

Copper is less expensive and easier to manufacture than niobium

- Reduces material and manufacturing costs

Copper has better heat transfer properties than niobium

- allows locally generated heat to be more effectively removed from the cavity

Copper is less sensitive to external magnetic fields than is niobium [1]

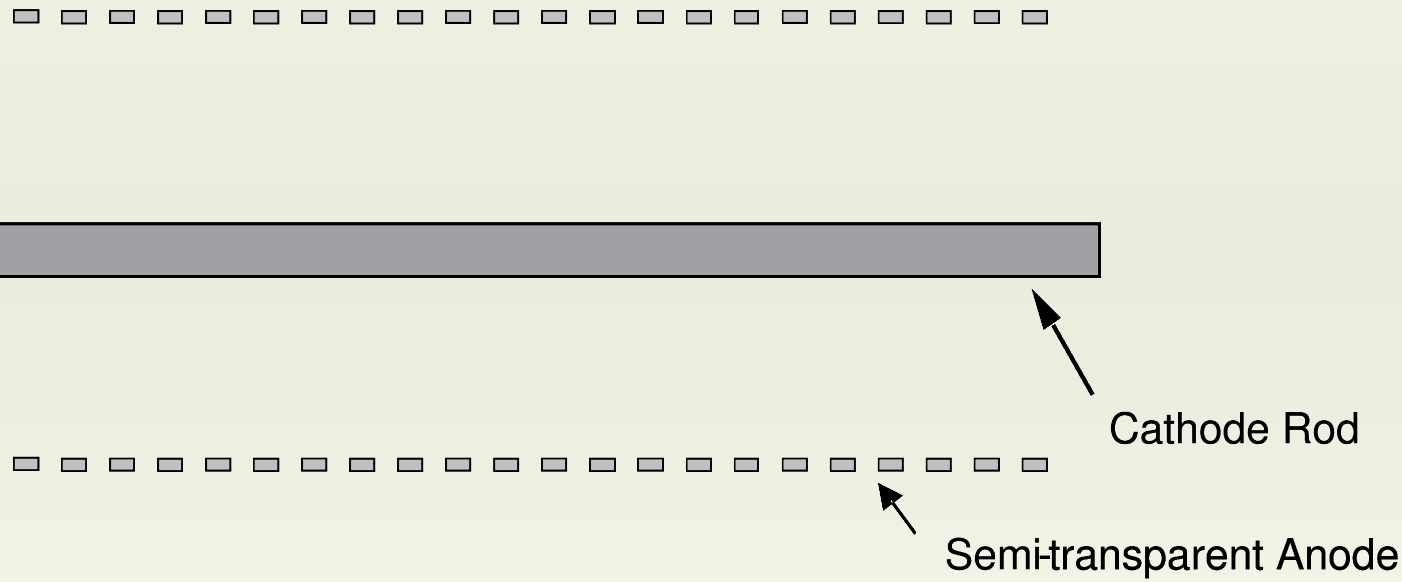
Potential for alternative superconductive materials with higher critical temperatures (*Tc*) and critical RF magnetic field strengths (*Hc*). [3]

- MgB_2
- Nb_3Sn

Coaxial Energetic Deposition (CED) is a cathodic arc process

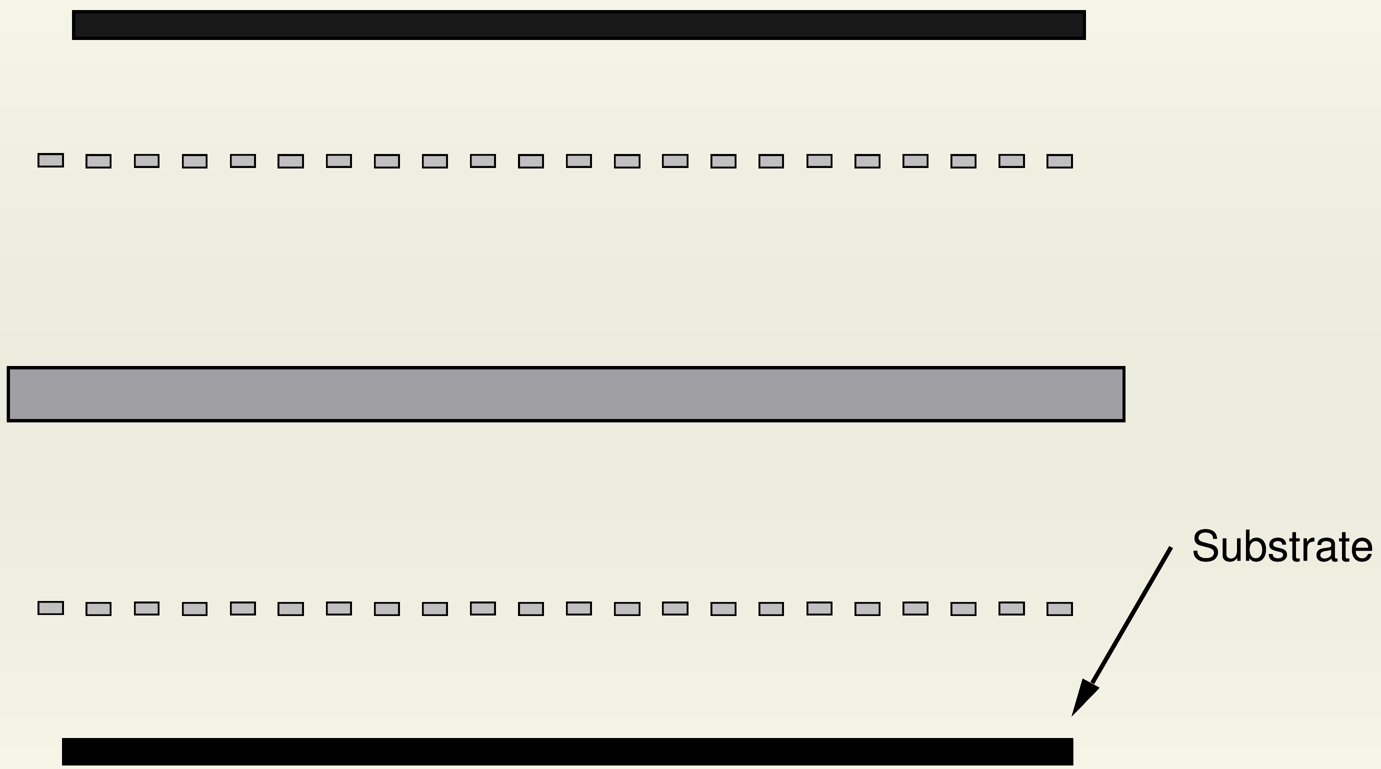
The CED Process

A rod-shaped cathode is positioned co-axially within a semi-transparent anode



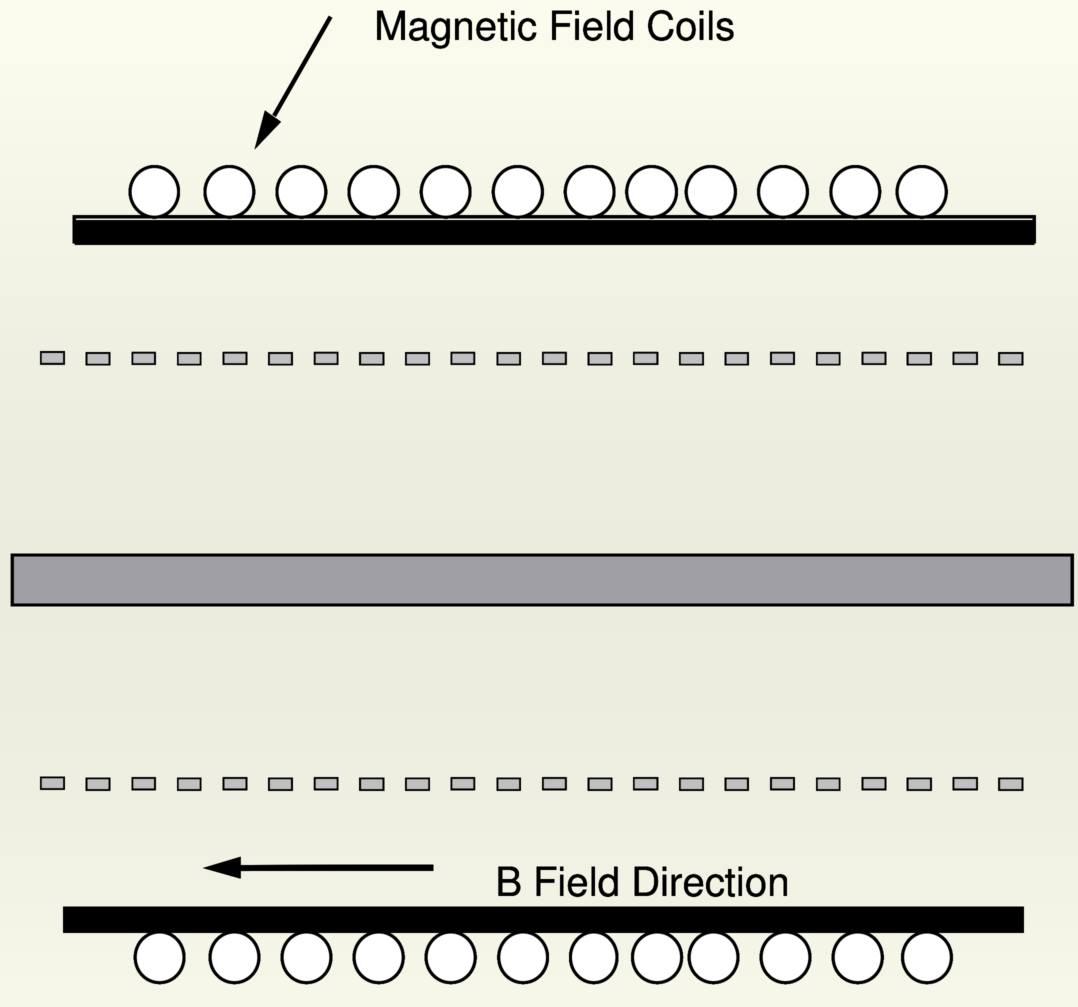
The cathode is the source of the material to be deposited

The CED Process



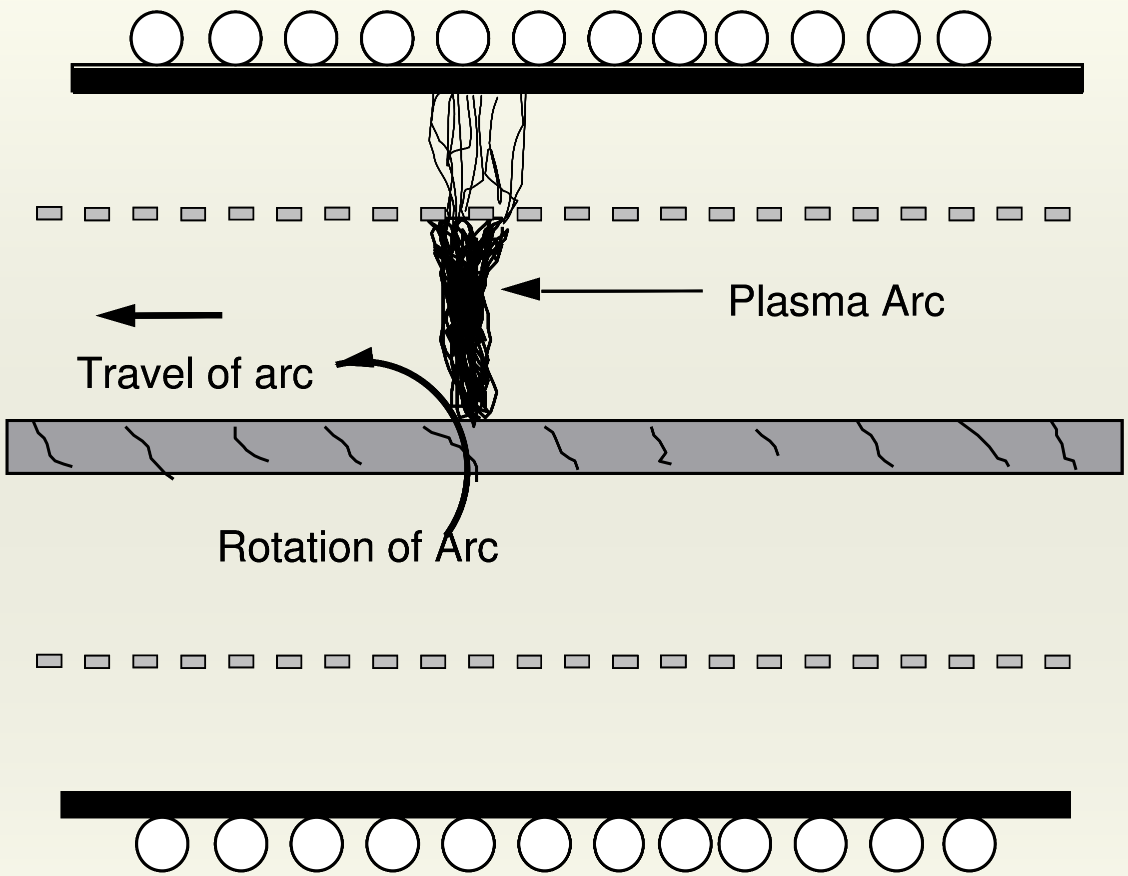
The electrode assembly is positioned coaxially within the cylindrically-symmetrical substrate

The CED Process



An axial B-field is applied by current through an external solenoid

The CED Process



Arc is triggered, axial B-field and arc-current return path cause location of arc spots to “spiral” along length of cathode

The CED Process

Ionized cathode material passes through the semi-transparent anode and deposits on the substrate surface. Multiple passes build up a high-quality, uniform coating.

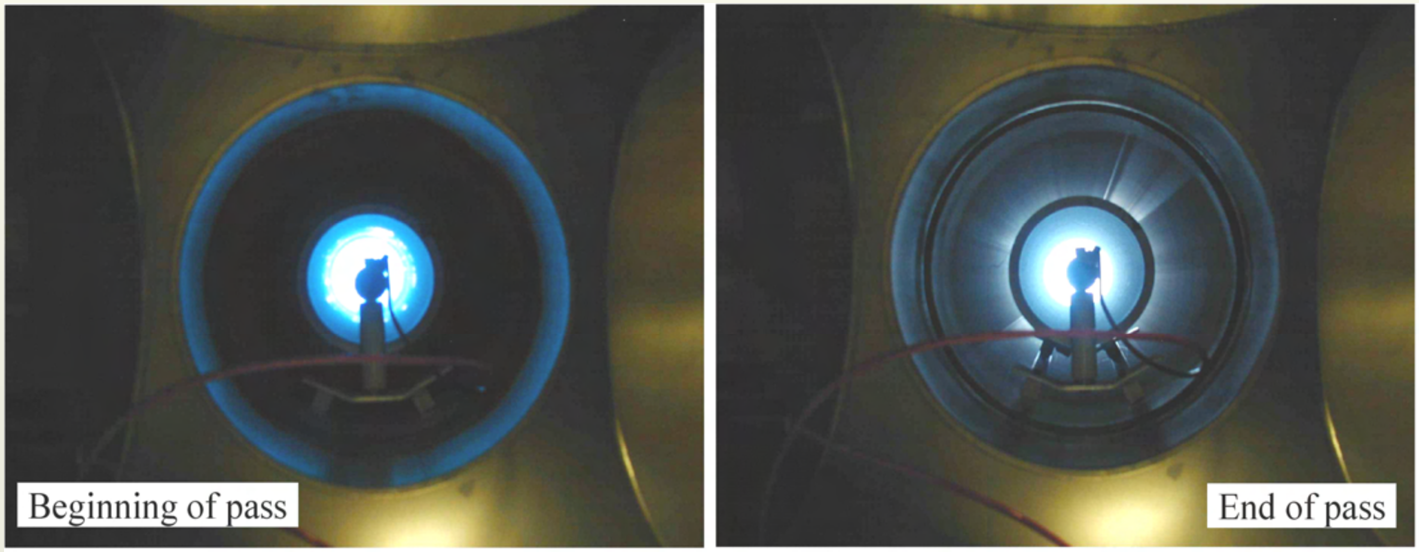
The CED process requires no working gas to deposit pure metals

- Can perform depositions under UHV conditions.
- Extremely high purity can be achieved in the deposited films.

The CED Process

CED deposition chamber at AASC

The CED Process



End-on view of arc spiraling along cathode length

Note: Camera shutter speed insufficient to resolve plasma “spoke” so arc appears as “disk”

Why CED?

Numerous methods have been investigated for depositing superconducting Nb films on copper substrates:

- Sputtering
- Magnetron Sputtering
- Filtered Cathodic-Arc Deposition (FCAD)
- Electron Cyclotron Resonance (ECR) deposition [4]

Magnetron Sputtering has been used to coat copper SRF cavities

- Both ECR and FCAD have displayed superior film characteristics on flat coupon substrates

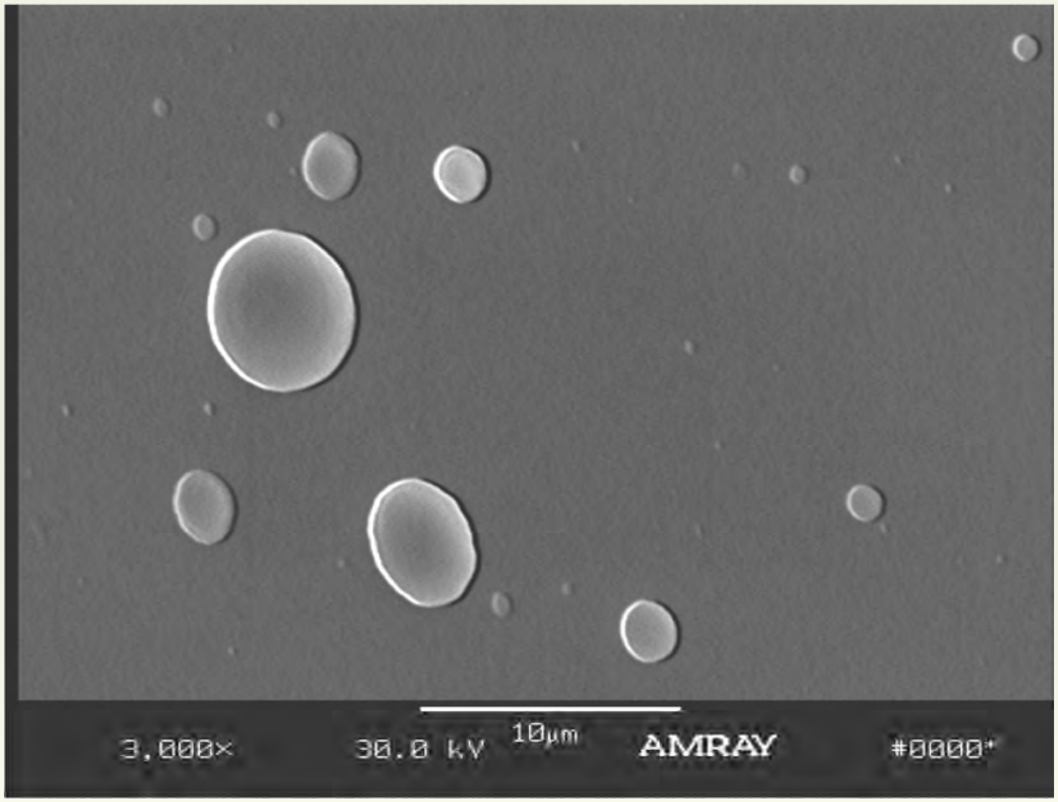
The unique geometry of RF cavities poses a challenge to scale-up of either ECR or FCAD to coat actual cavities.

CED uses physics similar to that of FCAD, but is well-suited to coating the insides of cylindrically symmetric structures

Macro-particles

One drawback of cathodic arc processes (including CED): macro-particles

- Macro-particles: sub-micron to ~10 micron sized particles of cathode material formed at the cathode arc-spots



SEM of Nb film deposited on sapphire substrate showing ~1-10 µm macro-particles. (Note 10 µm scale line).

Macro-particles

Macro-particles and other irregularities in the film surface cause localized field enhancements.

Sufficiently strong fields emit electrons.

- Electrons can impact the cavity walls and heat them,
- Can lead to multipacting

Macro-particles are believed to be the single biggest hurdle for CED to produce successful cavity coatings

The Macro-particle Filter

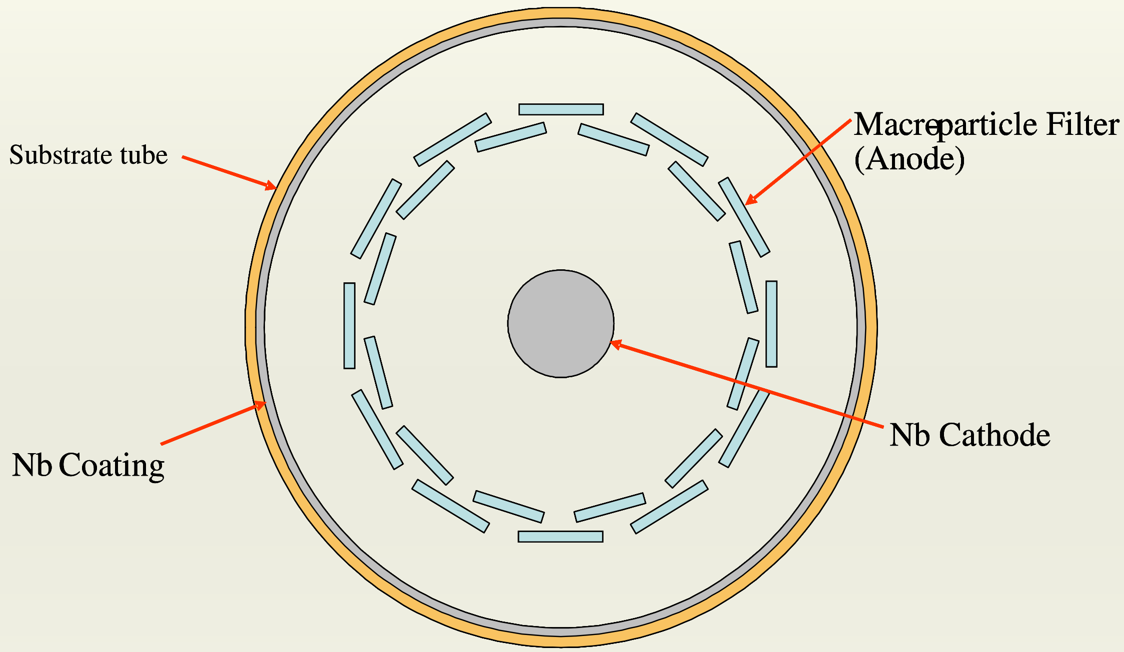
A coaxial Venetian-blind type macro-particle filter was developed by AASC

- Blocks line-of-sight between the cathode and the substrate to stop macro-particles from reaching the substrate
- Ions have wider distribution of velocity vectors and a fraction passes through
- To average out any periodic thickness variation or “striping” the substrate is rotated

In addition to removing macro-particles, the filter also acts as the anode so the substrate can be independently biased to control ion energy at the deposition surface.

Our Filters are based on the Venetian-blind design, which has been shown to reduce the macro-particle content for planar cathodic arc depositions.[5], [6]

The Macro-particle Filter

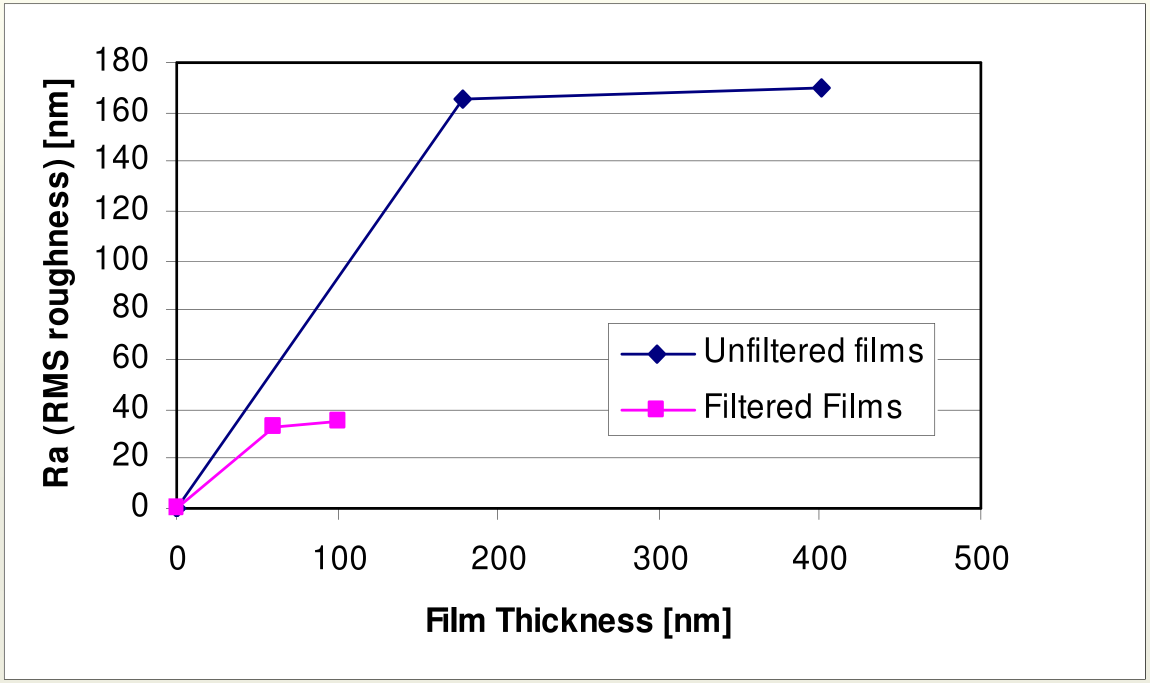


Schematic drawing of AASC macro-particle filter for CED process

The Macro-particle Filter

Macro-particle Filter used in CED Nb depositions

Filtering Results



Filter has demonstrated ability to reduce macro-particle content of films, but:

- Plasma throughput is significantly reduced compared to non-filtering anodes
- Maximum film thickness achieved with filter is reduced significantly

Filter redesign will be performed to enhance throughput

RRR and T_c Results

Deposition	Chamber Base Pressure [torr]	RRR
8	3.4E-6	1.1
9	8.8E-8	2.7

Initial results showed slow transition, low T_c and low RRR

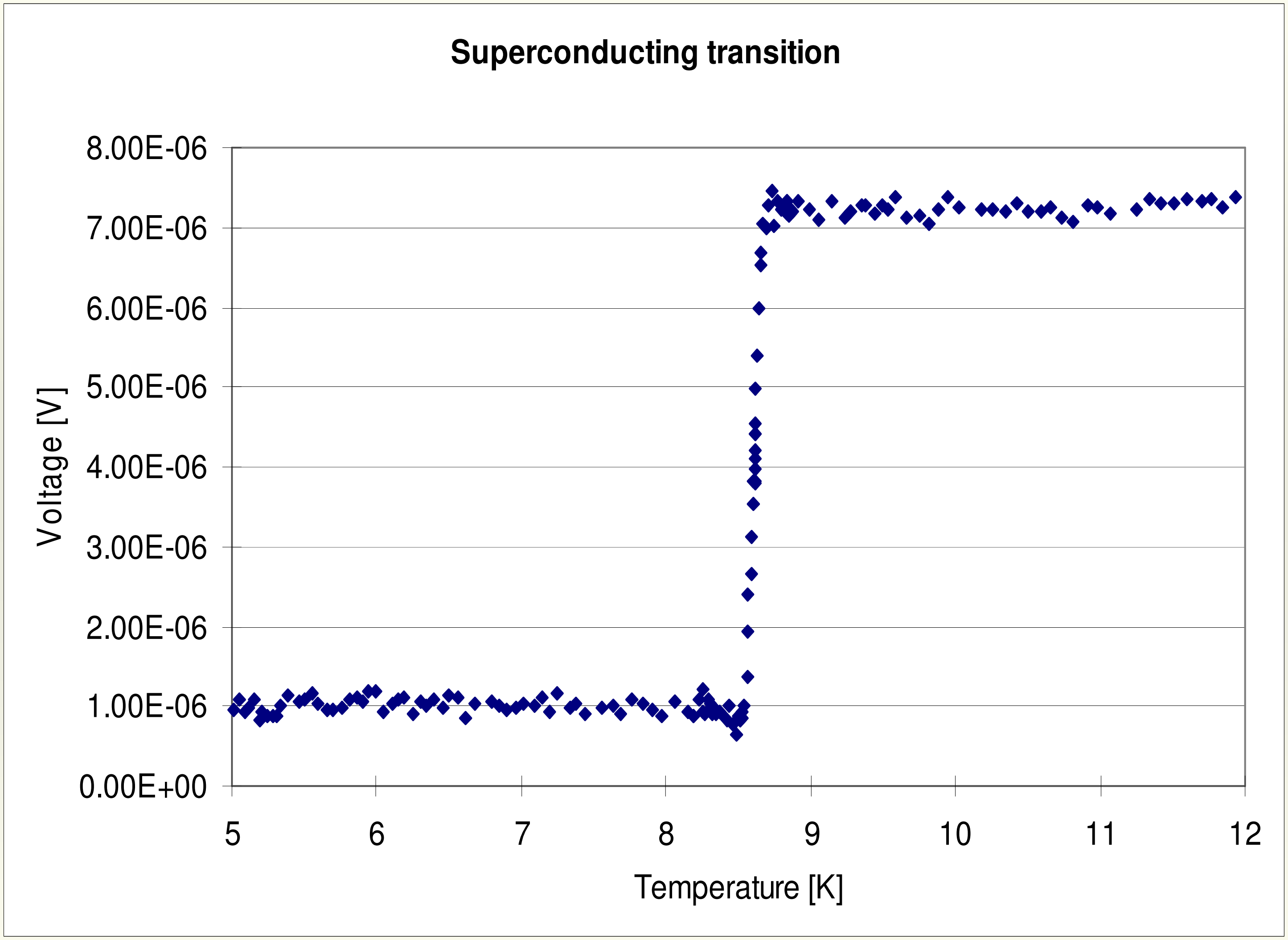
- SIMS revealed significant oxygen contamination
- Steps taken to reduce chamber pressure from HV to UHV

Efforts yielded improvements in both RRR and T_c

<u>Pressures will be reduced further in future efforts</u>

All film characterization measurements performed by JLAB

RRR and T_c Results



T_c data for Nb film deposited with chamber base pressure of 8.8E-8 torr

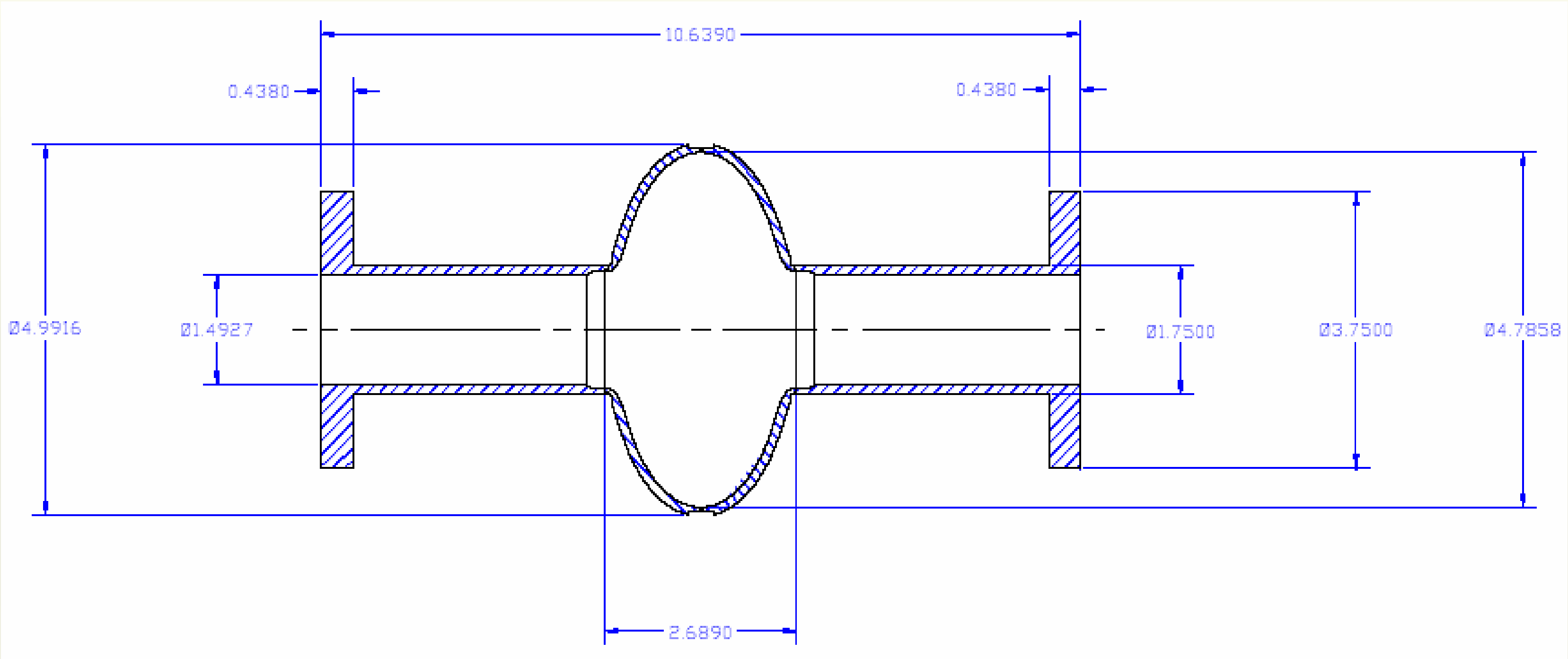
Half-cavity Coated

2.2 GHz copper half-cavity coated with Nb using CED process.

No measurements were performed to determine film properties, but basic film coverage of cavity geometry demonstrated.

It is believed that there will be no substantial difficulties to scale up to whole cavities and eventually to multi-cell structures.

Half-cavity Coated



Dimensions of 2.2 GHz single cell Copper cavity (units in inches)

AASC has recently won a Phase II DOE SBIR grant to continue this research

- **Will reduce oxygen contamination in the films**
  - Upgrade vacuum system to achieve lower base pressures
  - Improve process parameters and hardware to enable increased pulse repetition rate
    - Will increase the rate of niobium ion impingement at the substrate surface relative to the rate of residual chamber contaminant impingement
- **Macro-particle filter design will be improved**
  - increase filtering as well as ion throughput
  - increase filter robustness
- **Arc current and axial B-field will be optimized to minimize macro-particle production at cathode surface [6].**
- **The process will be transitioned to coat single-cell and eventually multi-cell copper RF cavities.**

Future Efforts

AASC has also recently won phase I DOE SBIR funding to deposit MgB_2 films as an alternative to niobium films in SRF cavities.

- MgB_2 has a higher transition temperature that niobium
- Grain boundaries in MgB_2 are more transparent to SC current than in niobium

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