

Magnetron Sputtering Configuration for Coating 1.3 GHz Cavities with a Nb Film

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Abstract

In the framework of the ARES project and as possible application for TESLA project, we are assembling, in the 2nd University of Rome, a system to study the deposition of Nb film on TESLA type copper cavity. Magnetron sputtering to coat accelerating cavities with superconducting film was developed at CERN for 500 MHz cavities, 3 times larger than TESLA cavities; while it's relatively easy to scale the technique up to larger cavities (as for instance to the 350 MHz LEP cavities) there are some difficulties to scale it down, particularly as concerns the coils located on the inside of the cathode used at CERN to stabilize the discharge, unless small permanent magnets are used that do not allow full control over all discharge parameters. A possible solution is to put the coils outside the cavity in a magnetic bottle configuration. A brief review on sputtering of cavities, the simulation of electrons trajectories in a magnetic bottle and the sputtering test setup are described.

I. INTRODUCTION

Sputtering is a well known and useful technique for coating RF copper cavities with superconducting thin film. In the sputtering process [1] one ejects source material from the cathode in vapor phase by bombarding the surface of the cathode with ions of sufficient energy (at least 30 eV), in our case Argon ions accelerated by an electric field; the ejected atoms condense on the wall in front of the cathode forming the thin film.

There are different sputtering configurations of which the simplest is the diode one. In this configuration the cathode is negatively polarized with respect to grounded copper substrate electrically connected to the anode. Some of the problems of this configuration are film contamination due to impurities coming from the pumping system, unavoidable at high working pressures and from the chamber wall degassing due to discharge heating, and mechanical complications in case of sputtering inside a cavity (first CERN approach [2], [3]).

Low pressure is therefore mandatory but to obtain reasonable sputtering rates at low pressure the ionization degree of sputtering gas has to be increased by increasing the ionization efficiency of electrons in the discharge. To accomplish this the electrons active path must be restrained to the vicinity of the cathode, for instance superposing a perpendicular magnetic field on the electric one so as to prevent electrons from losing their energy through collisions at the anode rather than through ionization.

This is the present sputtering system configuration used at CERN to coat 350 MHz copper cavities with Nb films [4]. The magnetic field necessary to confine electrons is produced by a coil placed inside the cathode; the coil is moved in steps along the cavity axis to achieve a uniform coating.

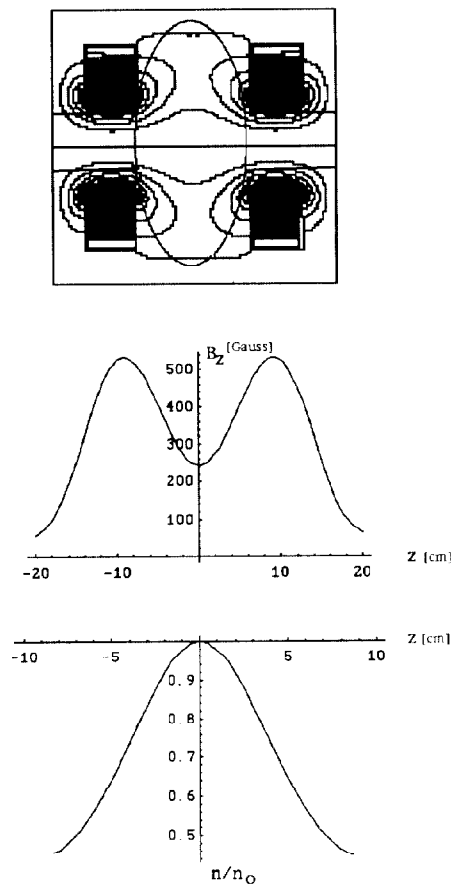


Figure 1. a) Magnetic mirror field lines
b) Longitudinal magnetic field intensity on cathode surface
c) Normalized longitudinal plasma density

The RF frequency selected for TESLA being 1.3 GHz, the cavities are 3 times smaller than those on which the CERN technique has been optimized. The CERN technique cannot therefore be scaled down straightforwardly, unless small permanent magnets (typically Samarium-Cobalt alloy) are used that fit comfortably inside the cathode. The latter however produce a fixed magnetic field configuration that limits the range of the discharge parameters variation. An alternative way of confining the discharge is to use a magnetic mirror field

configuration. The latter is well known from plasma physics and refers to the fact that charged particles spiraling around a static magnetic field line will be reflected by a region of stronger field due to the adiabatic constant of the motion $\mu = mv_{\perp}^2 / 2B$. A magnetic mirror can be obtained, as it is in our design (Fig.1a) by means of two coils placed on the outside of the cavity cut-off pipes. The field shape is obtained by suitable soft iron poles.

The field has a minimum (~ 200 Gauss) at the center of the cavity and a mirror ratio (that is a measure of the trapping efficiency) $B_{\max.}/B_{\min.} = 2$ (Fig.1b).

Doing so we expect to trap electrons and ions very close to the center of the cathode. In such a configuration in fact charges are subjected to an axial restoring force $F_z = -\mu(dU(z)/dz)$, where $U(z) = \mu B(z)$ is a potential well proportional to the magnetic field strength. Charges are confined if the condition $(v_{\perp} / v) \geq \sqrt{(B_{\min} / B_{\max})}$ holds. The charge density longitudinal distribution is given by

$$n(z) / n_{\min} = e^{-\frac{U(z)-U_{\min}}{KT}}$$

and is shown in Fig.1c for the worst case $(v_{\perp} / v) = 1/\sqrt{2}$.

II. ESTIMATE OF PLASMA PARAMETERS

Usual external discharge parameter ranges are: pressure of the working gas (10^{-4} - 10^{-2}) mbar corresponding to $n=2.65(10^{12}$ - $10^{14})\text{cm}^{-3}$, potential difference between electrodes $V \cong (500$ - $1000)$ Volt, magnetic field $B \cong (200$ - $1000)$ Gauss. To estimate the ionization fraction n_i/n , we neglect for the moment secondary electrons created by impinging ions and therefore assume that the cathode current is due to ions only.

The current is then given by $I = qn_i v_i S_c$ where q is the ion charge, n_i the ion density, v_i the ion velocity and S_c the active surface of the cathode.

The ion density is thus:

$$n_i = \frac{I}{qv_i S_c} = 9.5 \times 10^{10} I \times \text{cm}^{-3} = 9.5 \times 10^{10} \text{cm}^{-3}$$

with $S_c \cong 15\text{cm}^2$,

$v_i = 2.18 \times \sqrt{u} 10^5 \text{cm/s} = 4.366 \times 10^6 \text{cm/s}$ and $u = 400 \text{V}$.

The degree of ionization is

$$d_i = \frac{n_i}{n} \approx \frac{10^{11}}{2.65 \times 10^{13}} \approx 3.8 \times 10^{-3}$$

with $P=10^{-3}$ mbar $\Rightarrow n=2.65 \times 10^{13} \text{cm}^{-3}$.

Because the main part of the plasma is neutral, $n_e \cong n_i \cong 10^{11} \text{cm}^{-3}$. Assuming that the temperature (energy) of electrons is close to the ionization potential of Ar $V_i \cong 15.8\text{eV}$, the Debye length for the plasma becomes

$$\lambda_D = \sqrt{\frac{KT_e e^2}{n e^2}} = 7.43 \times 10^2 T^{1/2} n_e^{-1/2}$$

where λ_D in cm if T_e in volts and n_e in cm^{-3} .

For $T_e \cong 10 \text{eV}$ and $n_e \cong 10^{11} \Rightarrow \lambda_D \cong 0.743 \times 10^{-2} \text{cm}$.

The electrons Larmor radius is $r_{Le} = 3.37 \sqrt{u} / B \text{cm}$, for u in volts and B in Gauss: taking $u = KT_e \cong 10\text{eV}$ and $B=200$ Gauss one obtains $r_{Le} = 5.3 \times 10^{-2} \text{cm}$.

Finally, because the main potential drop in the plasma, in our case corresponding to the cathode drop, occurs over approximately one Debye length, one can assume that in this thin sheet no collisions occur; all ions created in the plasma and arriving to the cathode can thus be assumed to have at least an energy corresponding to the cathode voltage drop, i.e. about 0.75-0.80 of the total potential difference. On the other hand the secondary electrons, created at the cathode surface by impinging ions, also gain the same energy but, having Larmor radius much larger than Debye length, can enter the main plasma and thus become the primary source of ionization. Furthermore since the radial motion of electrons in the magnetic field is periodic, most of the electrons return to the cathode, unless they have experienced a collision with an atom or an ion.

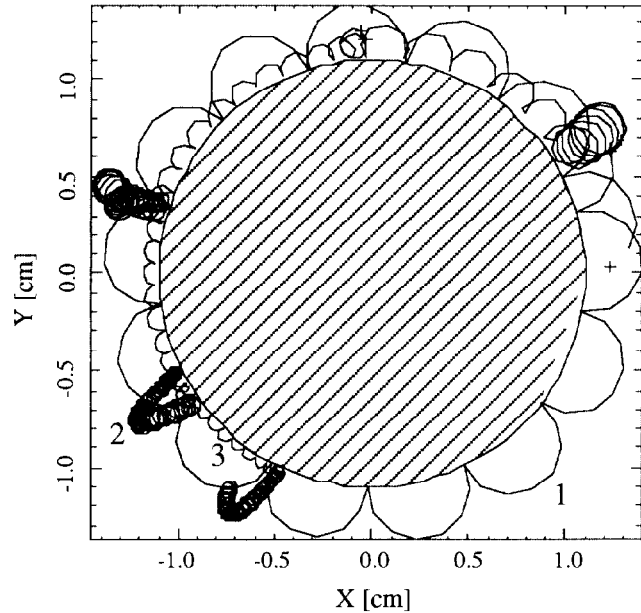


Figure 2. A simulated transverse electron trajectory with random collision (+)

Unless a collision occurs, the electron path in the transverse plane (X,Y) (Fig. 2) is always linked to the same magnetic field equipotential surface: an electron originating from the cathode experiences an intense electric field and starts to move in a cycloidal orbit around the cathode because of the drift effect $\mathbf{E} \times \mathbf{B}$ takes place (orbit 1). Usually collisions will occur in the main plasma body where the electric field is weak so that the orbit will be almost circular with a radius r_L depending on the perpendicular energy (orbit 2). At the same time electron with longitudinal component of the velocity, moves towards the stronger magnetic field end regions; its orbit is shifted closer to the cathode and if it moves back into the cathode drop region it restarts on a cycloidal path (orbit 3). In the longitudinal direction (Z) (Fig 3) the electron is reflected by the mirror (orbit 4) because $(v_{\perp} / v) > 1/\sqrt{2}$. Collisions will be another source of energy gain for low energy electrons created in the plasma and of radial and axial drift. We have estimated that on average electrons can have more than 100

collisions before arriving to the anode and can gain an energy of the order of 10 eV.

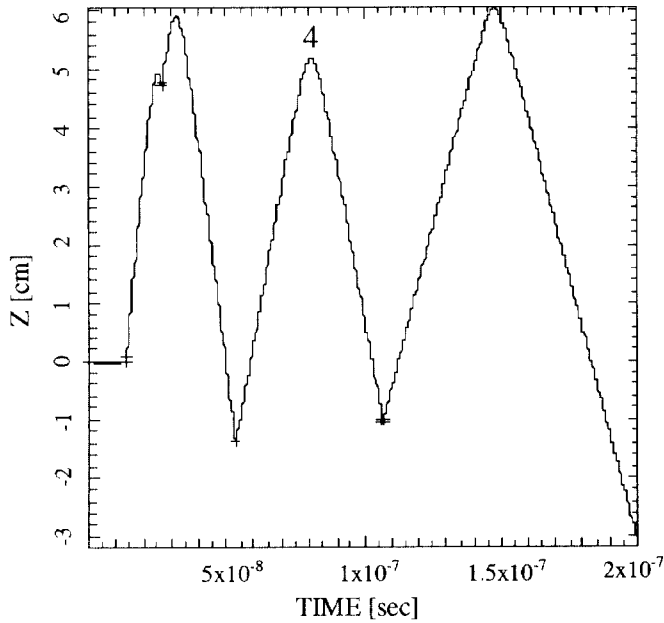


Figure 3. Longitudinal electron displacement with random collision (+)

III. SPUTTERING SYSTEM

The sputtering system that we are assembling is schematically shown in Fig.4.

It can accommodate different stainless steel TESLA type cavities on the inner walls of which, along the whole cavity profile, copper and sapphire samples can be fastened that allow studying the characteristics of the film over a wide portion of the surface. We plan to characterize the Nb film through RRR (Residual Resistivity Ratio) and T_c measurements, Auger, SEM (Scanning Electron Microscope) and X rays analysis. Plasma characteristics will be studied using Langmuir probes.

The system is evacuated by an ultraclean pumping group consisting of a 4 m³/h diaphragm pump for the primary vacuum and two cascaded turbo molecular pumps (pumping speed respectively 180 l/sec and 520 l/sec) one of which on magnetic bearings. A very good compression ratio for hydrogen, good ultimate pressure ($\sim 10^{-10}$ mbar) and total absence of hydrocarbons is obtained.

The system is equipped with a residual gas analyzer (RGA) to study the ultimate pressure gas composition, and to monitor the percentage of gas produced during sputtering, notably hydrogen, that damages the film structure if it exceeds a certain threshold. To use the RGA while sputtering, in a relatively high operating pressure ($\sim 10^{-3}$ mbar), we need differential pumping; the RGA therefore communicates with the cavity through a 0.6 mm diaphragm and it is equipped with another pumping system that produces a 3 order of magnitude pressure drop through the diaphragm.

The cathode consists of a vacuum tight stainless steel tube (17 mm inner diameter) surrounded by a niobium liner (20/24 mm inner/outer diameters). The liner is an high purity Nb tube (RRR value better than 100) without welds. The stainless steel tube is also equipped with an inner support to hold and center 7 SamCo permanent magnets (small cylinders 8 mm diameter 16 mm long) cooled by a liquid freon circuit sized to handle about 2 KW of power. Preliminary tests to optimize discharge parameters will be carried out both with permanent magnets and with the magnetic bottle field configuration.

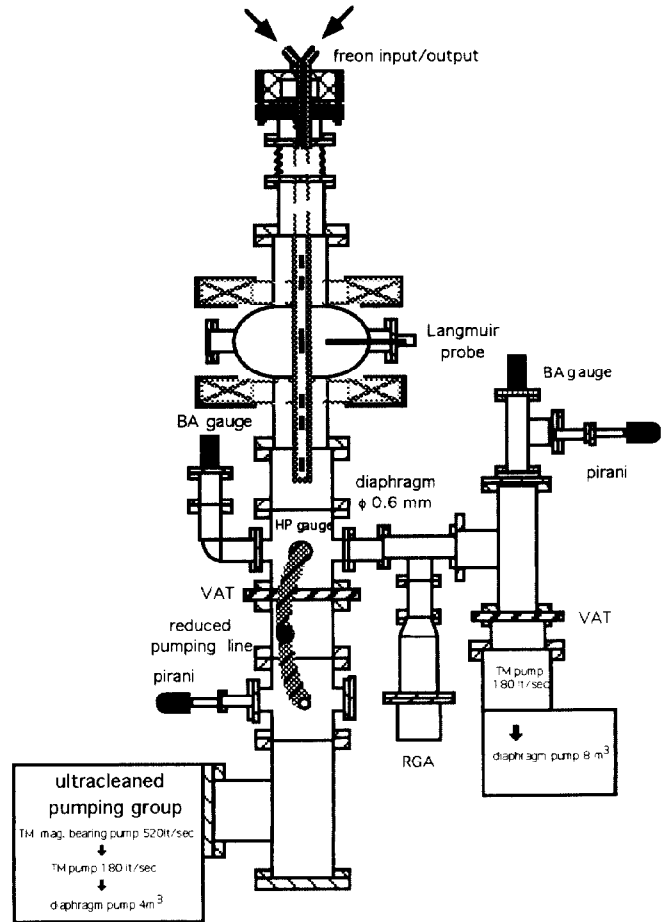


Figure 4. Sputtering system scheme

IV. REFERENCES

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