ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV009

A NEW PROCESS FOR NITROGEN DOPING OF NIOBIUM CAVITIES

M. Cavellier†, Omega Physics, St Gildas De Rhuys, France

Abstract

The author presents a process for Nitrogen doping of Niobium cavities based on ion beam implantation, with a description of equipment needed and beam parameters.

EXISTING DOPING PROCESSES

Nitrogen doping to improve quality factor of Niobium SRF cavities has been widely investigated over the past years [1-10]. Several doping processes based on thermal diffusion has been defined experimentally and their results were confirmed by different research teams.

Although some of the mechanisms explaining how Nitrogen improves quality factor are understood, like the reduction of mean free path in Niobium [7], many questions remain open.

The multiple experimental attempts with the aim to obtain the best cavity (changing infusion temperature from 90 °C to 800 °C from 20 hours to 300 hours [8-10]) reveal that the current empiric approach is more likely a cooking recipe [2, 10] than a mastered process.

The existing Nitrogen doping processes for Niobium cavities have several drawbacks, either regarding the processing point of view, or regarding the accuracy to control key parameters.

First, we can wonder how efficient it is to bake cavities during tens or hundreds of hours in a Nitrogen gaseous solution, to finally remove by electro-polishing 50 to 100 µm of material of the inner cavity surface to remove unwanted intermetallic compound (Niobium Nitride and Oxide). Besides the necessity for a furnace large enough to welcome multiple-cell cavities, the process is clearly far from being environment-friendly.

Then, the thermal diffusion process can be simulated, but by removing some of the inner cavity surface where Nitrogen diffused, we complicate the prediction of Nitrogen depth and stoichiometry.

As previous studies showed, the quality factor improvement may be linked to the presence of Nitrogen as interstitial sites, hence the necessity to know and master the Nitrogen stoichiometry in Niobium.

A more precise Nitrogen doping process is obviously needed to master and tune each parameter. This will allow to understand fully the role of each parameter (such as Nitrogen doped stoichiometry, penetration depth, created phases, ...) on the Niobium cavity quality factor improvement.

This work proposes such doping process, with the possibility to answer all issues highlighted previously.

† matthieu@omega-physics.com

PROPOSED PROCESS

Ion beam implantation is a well-known process used in semiconductor industry and metals modification for decades, and this process coupled with a custom-made cavity implanter allows to achieve an accurate Nitrogen doping of Niobium cavities.

This custom-made implanter, shown in Fig. 1, will include an ion source, preferably ECR type to have multi-charged Nitrogen ions, a small electrostatic acceleration system, a spectrometer such as Wien filter or dipole magnet, and a support where the cavity to be doped will be installed. This mechanical support allows the rotation of the cavity. It is important to highlight that no large vacuum furnace is needed as flanges of the cavity are used for vacuum sealing.

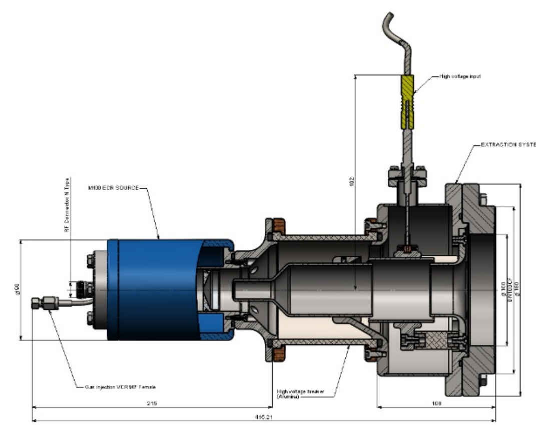

Figure 1: Possible ECR ion source and acceleration system for Nitrogen ion implantation (courtesy of Pantechnik).

Skin depth in superconducting cavities is known to be less than 50 nm [10, 11], therefore a SRIM calculation (see Fig. 2) allows to estimate the maximum energy that Nitrogen ions must have to implant on all this thickness: 25 keV.

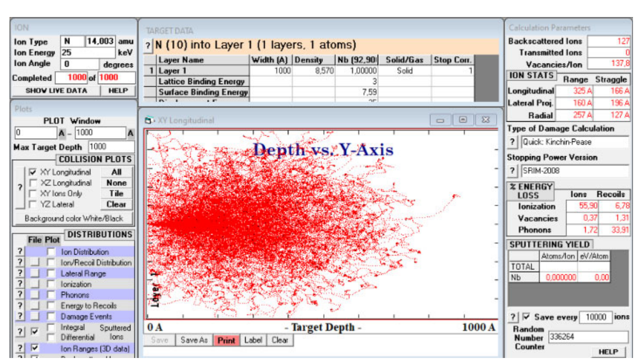

Figure 2: SRIM simulation of Nitrogen implanted into Niobium at 25 keV.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV009

The most difficult part is to bend the Nitrogen beam once it entered the cavity to implant all inner surface. A system using a pair of coils creating a vertical magnetic field would allow such bending and guarantee a small volume allowing this deviation system to enter through the cavity flanges. Multicharged Nitrogen ions must be preferred for their lower magnetic rigidity (N^{4+} at 25 keV has a rigidity of approx. 42 T.mm), allowing the coils to be as compact as possible.

First magnetic calculations show that 2000 ampere-turns per coil are sufficient to bend the 25 keV N^{4+} beam by 90°. Then, the treatment of the complete inner surface is made by a combination of coil current variation and mechanical rotation of the cavity.

Multiple-cell cavities could be implanted using the same magnetic device repeated several times, or displaced in each cell, as shown in Fig. 3.

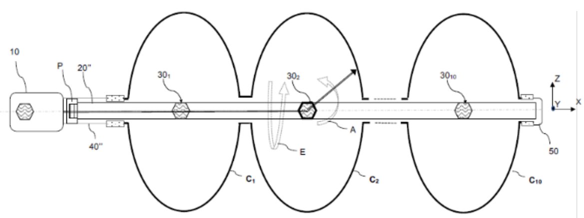

Figure 3: Principle of multi-cell cavity implantation with the proposed system.

Finally, an interesting feature of ion implantation is the sputtering effect: cavity surface roughness will be decreased by this phenomenon, making the electro-polishing process completely unnecessary.

The proposed process and associated system have many advantages compared to the existing nitrogen doping processes and equipment, they are listed below:

- No need for special vacuum furnace,
- No need to heat during hours: economy of energy and reduction of carbon footprint,
- Each atom of Nitrogen ends up in the Niobium cavity: economy of gas,
- No need to remove tens of micrometers of Nitrogen-doped Niobium : economy of material and energy,
- Low temperature kept by scanning the beam on the inner surface of the cavity,
- Control of doped thickness by the energy of Nitrogen ions,
- Control of Nitrogen stoichiometry by ion beam current and implantation time,
- Possibility of in-situ monitoring,
- Possibility to use the same device to implant other ions (Carbon, Oxygen, ...).

CONCLUSION

An European patent request (PCT/EP2021/053014) is under review for this process and equipment, and applications for patents in other countries are ongoing.

Omega Physics is currently fundraising to build a prototype system and is looking for academic partners to collaborate on the scientific aspects. Industrial partners willing to implement this breakthrough process in their factory are welcome to collaborate too.

REFERENCES

[1] A. Grassellino *et al.*, "Nitrogen and argon doping of niobium for superconducting radio frequency cavities: a pathway to highly efficient accelerating structures", *Supercond. Sci. Technol.*, vol. 26, p. 102001, 2013. doi:10.1088/0953-2048/26/10/102001

[2] A. Vostrikov, M. Checchin, A. Grassellino, A. Romanenko, and Y. K. Kim, "Modifications of Superconducting Properties of Niobium Caused by Nitrogen Doping Recipes for High Q Cavities", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 3312-3314. doi:10.18429/JACoW-IPAC2015-WEPTY022

[3] M. Checchin, A. Grassellino, M. Martinello, S. Posen, A. Romanenko, and J. Zasadzinski, "Enhancement of the Accelerating Gradient in Superconducting Microwave Resonators", in *Proc. North American Particle Accelerator Conf. (NAPAC'16)*, Chicago, IL, USA, Oct. 2016, pp. 113-116. doi:10.18429/JACoW-NAPAC2016-MOPOB20

[4] M. Checchin, A. Grassellino, M. Martinello, S. Posen, A. Romanenko, and J. Zasadzinski, "Ultimate Gradient Limitation in Niobium Superconducting Accelerating Cavities", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 2254-2257. doi:10.18429/JACoW-IPAC2016-WEPMR002

[5] M. Martinello *et al.*, "Advancement in the Understanding of the Field and Frequency Dependent Microwave Surface Resistance of Niobium", in *Proc. 18th Int. Conf. RF Superconductivity (SRF'17)*, Lanzhou, China, Jul. 2017, pp. 364-367. doi:10.18429/JACoW-SRF2017-TUYAA02

[6] M. Martinello *et al.*, "Tailoring Surface Impurity Content to Maximize Q-factors of Superconducting Resonators", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 2258-2261. doi:10.18429/JACoW-IPAC2016-WEPMR003

[7] D. Gonnella, "The Fundamental Science of Nitrogen Doping of Niobium Superconducting Cavities", PhD Thesis, Cornell University, 2016.

[8] D. Gonnella *et al.*, "Update on Nitrogen-doped 9-cell Cavity Performance in the Cornell Horizontal Test Cryomodule", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 3446-3449. doi:10.18429/JACoW-IPAC2015-WEPTY072

[9] D. Gonnella *et al.*, "RF Performance of Nitrogen-Doped Production SRF Cavities for LCLS-II", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 1156-1159. doi:10.18429/JACoW-IPAC2017-MOPVA128

[10] P. N. Koufalis, M. Liepe, and J. T. Maniscalco, "Low Temperature Doping of Niobium Cavities: What is Really Going on?", in *Proc. 18th Int. Conf. RF Superconductivity (SRF'17)*, Lanzhou, China, Jul. 2017, pp. 353-358. doi:10.18429/JACoW-SRF2017-TUXBA01

[11] K. Saito, "State-of-the-Art and Future Prospects in RF Superconductivity", in *Proc. 3rd Int. Particle Accelerator Conf. (IPAC'12)*, New Orleans, LA, USA, May 2012, paper MOYBP01, pp. 11-15.