NEW CAVITY TECHNIQUES AND FUTURE PROSPECTS*

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Abstract

In the recent decades, Superconducting cavities have been widely used to accelerate electron, positron, and ions. Most SRF cavities are made from bulk niobium till now, which has developed fast in the past years and is hard to advance more. Take 1.3 GHz 9-cell cavity for example, the quality factor (*Q*) can keep above 1e10 when the accelerating field (E_{acc}) reach 40 MV/m, which nearly touch the theoretical limitation of *Q* and E_{acc} for bulk niobium. For large superconducting accelerators in future (FCC, CEPC, etc), *Q* and E_{acc} should be increased significantly compared to now, which can reduce the cryogenic power and use fewer cavities. So new cavity material and techniques are being studied at accelerator laboratories, while Nitrogen doping (N-doping) and Nb_3Sn have developed quickly and been paid attention to mostly [1]. N-doping can increase *Q* by one time for 1.3 GHz 9-cell cavity, which have been adopted by Linac Coherent Light Source II (LCLS-II) at SLAC [2].

INTRODUCTION

In recent years, N-doping technology has been proposed and proven to increase *Q* of superconducting cavity obviously, which lowers the BCS surface resistance. It was discovered in 2012 at FNAL, which has been promoted by FNAL, JLAB and Cornell together. Since 2013, there have been over 60 cavities nitrogen doped in USA laboratories. After N-doping, *Q* of 1.3 GHz 9-cell cavities increased to $3*10^{10}$ at E_{acc}*=16 MV/m*, while $1.5*10^{10}$ without N-doping [3].

Besides, thin film technologies have also developed very quickly, which include Nb_3Sn/Nb, Nb/Cu et al. There've been many good results of vertical tests. And superconducting cavities made of thin film would be more practical in future.

RESEARCH OF N-DOPING

Theory

N-doping of niobium can create a niobium nitride layer, which is about 2-micron deep and harmful to *Q* value. So this layer is removed by 5-micron electro polishing. Then, the diffraction pattern of transmitted electron microscope shows only clean niobium phase without nitride. It indicates that the interstitial nitrogen contributes to the increase of *Q* value.

N-doping has been proven to prevent Q-slope at medium accelerating fields for superconducting cavities, which is found to reduce the BCS surface resistance compared to ILC/XFEL standard by 50%. The non-trapped flux related residual resistance can also be reduced to 2 nΩ with N-doping [4]. But it also results to undesirable lower quench field. The levels of N-doping affect R_{BCS}, R_0, R_{MAG} and quench field, which is important and needs deeper research.

Achievements

The experiments of N-doping succeeded on the 1.3 GHz cavities firstly. And then it was applied to 650 MHz cavities.

Based on the research achievements above, the N-doping technique has been adopted by the LCLS-II project. To transfer it to industrial vendors, the protocol of N-doping has been optimized, as Table 1 [5].

Table 1: N-doping Parameters

Step	Temperature (℃), Pressure (Pa)	Duration (min)
Hydrogen degassing	800 ± 10, 0	180 ± 5
N-doping	800 ± 10, 3.5 ± 10	2 ± 0.1
Vacuum annealing	800 ± 10, 0	6 ± 0.1

Table 1 shows the latest recipe of N-doping adopted by LCLS-II, which is known as "2/6". It stands for 2-minute nitrogen injection and 6-minute annealing, both at 800C. Then, 5 microns of cavity inner surface are removed by electro polishing [6]. So it's different from the standard protocol of 1.3 GHz 9-cell cavities for XFEL. The 120C baking is cancelled, which may cause a decrease in Q and quench fields for cavities nitrogen doped.

Details of N-doping for LCLS-II are deeply analysed in [7]. Figure 1 shows the vertical test results of LCLS-II cavities adopted 2/6 recipe at FNAL and JLAB. All cavities meet the design target of 2.7e10@16MV/m at 2K. Average *Q* is 3.5e10@16MV/m at 2K, and average quench field reach 22 MV/m [2, 4].

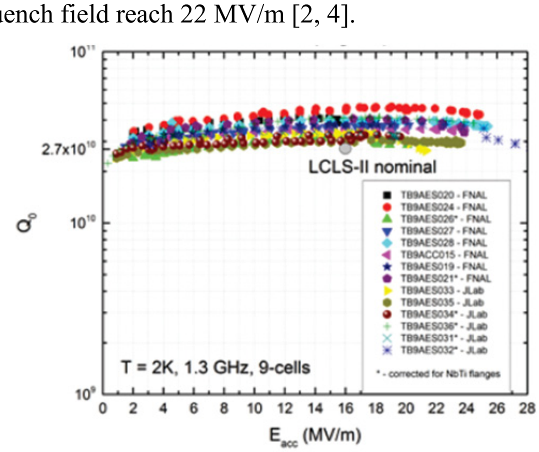

Figure 1: Performance of 1.3 GHz 9-cell cavities for LCLS-II.

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The same recipe is adopted by 650 MHz single-cell cavities for PIP-II, too. The vertical test results adopted 2/6 recipe and standard 120C baking are compared, as Figure 2 [8, 9]. The Q value increases by 100% and reaches 7e10@17MV/m at 2K, which is the world record at this frequency.

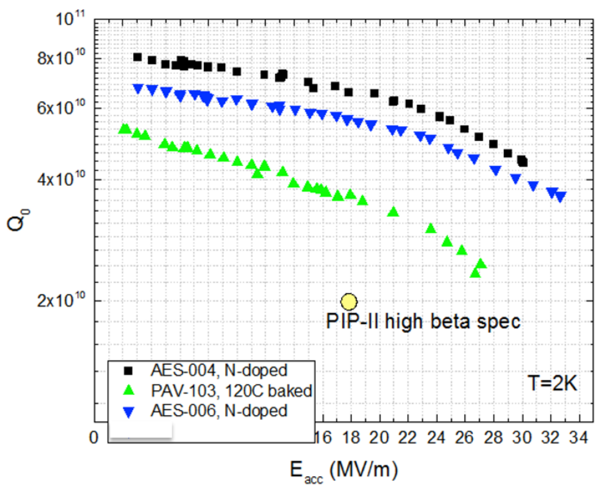

Figure 2: Performance of 650 MHz cavities for PIP-II.

N-doping at IHEP

Recently, the Circular Electron Positron Collider (CEPC) was proposed by Chinese high energy physicists, which contains more than 600 superconducting cavities (1.3 GHz and 650 MHz). So it's eager to increase Q value of cavities to minimize cryogenic capital and operating cost, as Table 2 [10].

Table 2: Target of Q Value for CEPC Cavities

Cavity	Qualification	Operation
650MHz 2-cell	4e10@22MV/m (VT), 2e10@20MV/m (HT)	2e10@16.5MV/m
1.3GHz 9-cell	3e10@25MV/m (VT)	2e10@20MV/m

It's hard to achieve such target with ILC/XFEL standard, while N-doping is a good choice. So research of N-doping was begun by IHEP in cooperation with Peking University in early 2015.

Firstly, niobium samples were nitrogen doped both at IHEP and Peking University, as Figure 3. Different methods were used to achieve that nitrogen enters into niobium surface and exists for long. To verify that, experiments of secondary ion mass spectrometry (SIMS) and auger electron spectroscopy (AES) were done, as Figure 4. Then, one method of N-doping was found to be useful.

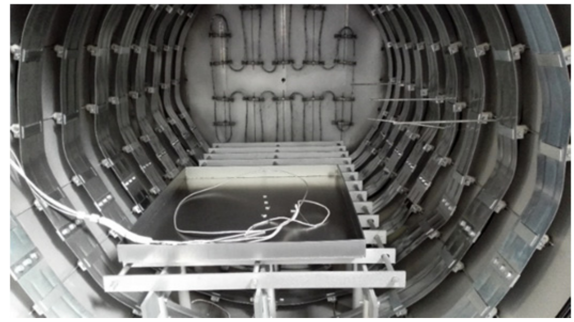

Figure 3: Niobium samples for N-doping in the furnace at IHEP.

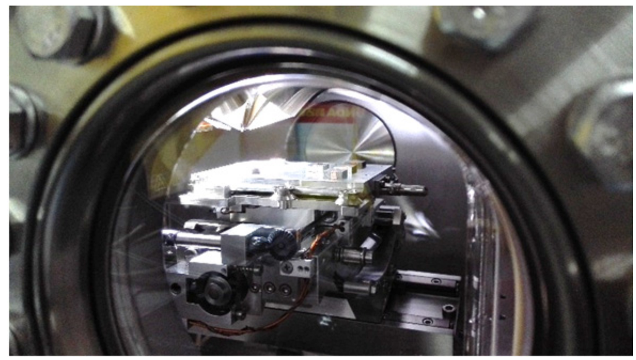

Figure 4: SIMS of niobium samples at Tsinghua University.

Secondly, a single-cell 1.3 GHz cavity was N-doped adopting the same technique. Afterwards, vertical test was held. But the performance of cavity N-doped was bad. The reasons are being investigated at present.

Low Temperature N-doping

Experiments show that N-doping can cause the decrease of quench field (23 MV/m for 1.3 GHz 9-cell cavities), which is unwelcome for superconducting cavity. In order to achieve both high Q and high field, low temperature (120C-160C) N-doping is being studied right now [11], which realizes very high Q at both medium and high accelerating filed. The quench field limitation increases to 45 MV/m for 1.3 GHz 9-cell cavities, as Figure 5.

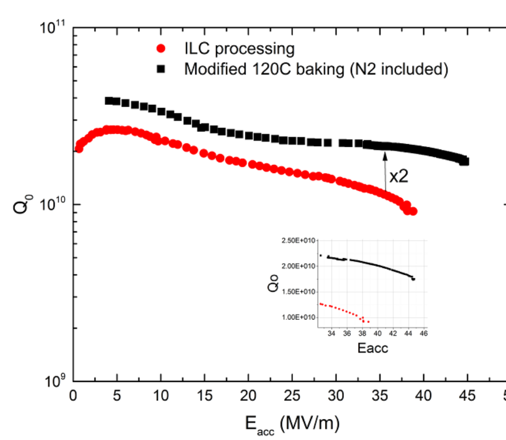

Figure 5: Vertical test result for low temperature N-doping (120C N_2 baking).

High temperature (800C) N-doping is proven to manipulate mean free path with several microns throughout. With contrast, low temperature N-doping manipulates mean free path at very near surface of bulk niobium. The actual regime of low temperature N-doping is still being studied.

RESEARCH OF THIN FILM

Figure 6 shows possible alternative materials for superconducting cavity [13].

Material	Critical Temp. T_c [K]	Normal-state resistivity $\rho_n(\mu\Omega cm)$	Critical Field $H_c(0)$ [T]	Lower Critical field $H_{c1}(0)$ [T]	Upper Critical field $H_{c2}(0)$ [T]	Penetration depth $\lambda(0)$ [nm]	Δ [meV]	Type
Nb	9.23	2	0.2	0.18	0.28	40	1.5	II
Pb	7.2		0.08	N/A	N/A	48		I
NbN	16.2	70	0.23	0.02	15	200-350	2.6	II, B1 comp.
NbTiN	17.3	35		0.03		150-200		II, B1 comp.
Nb_3Sn	18	20	0.54	0.05	30	80-100	3.1	II, A15
V_3Si	17				24.5	179		II, A15
Mo_3Re	15		0.43	0.03	3.5	140		II, A15
MgB_2	40	0.1-10	0.43	0.03	3.5-60	140	2.3/7.2	II- 2 gaps
YBCO	93		1.4	0.01	100	150	20	d-wave
Pnictides	30-55		0.5-0.9	30	>100	200	10-20	

Figure 6: Possible alternative materials for superconducting cavity.

Among these materials, Nb_3Sn has shown great potential for operation at medium gradients at 4.2 K. Cornell has completed several vertical tests of Nb_3Sn cavities (niobium cavities coating with Nb_3Sn), as Figure 7 [14]. Besides, MgB_2 may have even better performance, which is not as technologically ready yet.

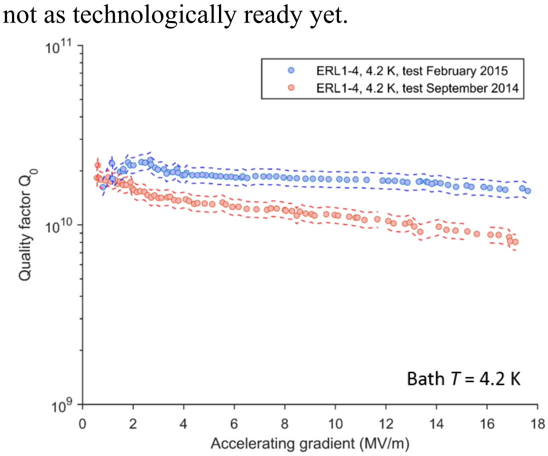

Figure 7: Vertical test results for Nb_3Sn cavities.

CONCLUSION

There've been many new superconducting cavity technologies for the large accelerators under planning, while N-doping technique is developing very fast. It has been applied in the LCLS-II project. Besides, cavity coating with Nb_3Sn is also very promising.

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