STATUS of Nb-Pb SUPERCONDUCTING RF-GUN CAVITIES

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Abstract

We report on the progress and status of an electron RF-gun[*] made of two superconductors: niobium and lead [1]. The presented design combines the advantages of the RF performance of bulk niobium superconducting cavities and the reasonably high quantum efficiency of lead. The design of RF-gun and performance of 3 test cavities without and with the emitting lead spot are reported in this contribution. Measured quantum efficiency for lead at 2K is presented briefly. More details are reported in [9].

INTRODUCTION

Motivation

Improvement in RF performance of superconducting (sc) cavities over the past decade has made feasible continuous wave (cw) and near-cw operations of superconducting electron linacs at high accelerating gradients. Both operation modes require injectors operating at cw or near-cw, providing low emittance electron beams. An example of such an injector (so called split injector) is discussed in [2]. The most demanding component of a cw injector is the RF-gun, operating in a cw mode and delivering highly populated (~1 nC) low emittance bunches. When generating highly populated low emittance bunches, both room temperature and superconducting RF-guns have to be operated at high accelerating gradients to suppress space charge effects that dilute the emittance. Normal conducting RF-guns face difficulties in meeting this requirement in the cw or near-cw mode. Their copper walls dissipate many kilowatts of power in fulfilling high gradient conditions even when they operate at low pulse repetition rate. Superconducting RF-guns (SRF-guns) dissipate orders of magnitude less power than the normal conducting devices. They can be operated at high duty factor. The challenge here is integration of a non superconducting photo-cathode into a sc cavity [3] in a way that preserves its original high intrinsic quality factor Q_o (small cryogenic losses). One possible solution to this problem, based on a choke filter design, is investigated at Forschungszentrum Rossendorf [4, 5]. Another approach, very attractive and technically feasible for miliampere-class SRF-guns, is to use a superconducting material as the photo-cathode. In this case, difficulties arise from the moderate quantum efficiency (*QE*) of the superconducting materials, which must be compensated with shorter wave-length and higher pulse energy of the illuminating laser. The niobium cathode proposed and tested at BNL [6] demonstrates rather poor *QE*. A complementary approach with lead [7] is discussed in the following section.

LEAD *QE* AND RF-DESIGN

QE of lead

Lead has superior *QE* to niobium. Test results of lead *QE* at room temperature were reported by us in [8]. Fig. 1 shows the summary of the tests at 300 K vs. photon energy E_p for niobium, bulk lead and lead samples deposited with various techniques. The highest *QE* of 0.55% has been measured for the arc-deposited sample illuminated with 6.5 eV photons. For 5.8 eV photons (5th harmonics of 1064 nm infrared laser) the *QE* of that sample was still 0.25%. *QE* of the electroplated and magnetron deposited samples at this photon energy is ~0.17%. Generation of 1 nC bunch with this *QE* will require 3.4 µJ energy per pulse on the cathode. The cold *QE* test was done very recently and is reported elsewhere in these proceedings [9].
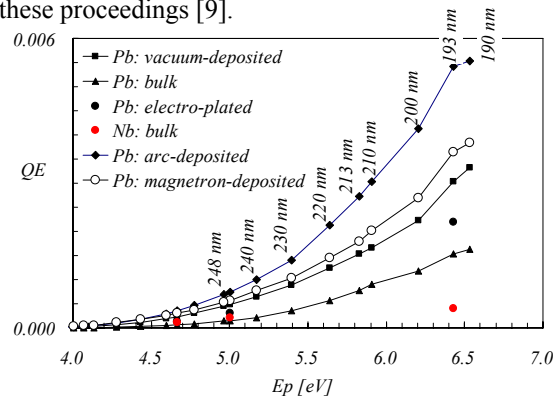

Figure 1: Measured *QE* of lead deposited with various coating methods. Bulk Pb and Nb data are displayed for comparison.

RF-design

In the hybrid Pb-Nb gun, a small emitting spot of lead (Ø<3 mm) will be located in the center of the back wall of the 0.6-cell of a 1.6-cell[†] cavity (Fig. 2), which will be

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[†] The first cell is 0.6· λ/2 long. This length provides the lowest emittance growth.

made of high purity niobium. The cavity, equipped with two HOM couplers, input coupler and pickup probe will be assembled for operation in a dedicated cryostat. The gun is designed to be implemented in the split injector. A solenoid, installed directly after the cavity, will be used for emittance growth compensation. Tables 1 and 2 and Figure 3 show RF-parameters and the Higher Order Mode (HOM) suppression (Q_{ext}) for the present design. The damping of HOMs in a SRF-gun is crucial for the beam quality, which can be diluted by the interaction between non-relativistic electrons (in the first 0.6-cell) with deflecting dipole modes. The operating electric field on the lead cathode E_{peak} will not exceed 60 MV/m. At this field, the emitting spot will be exposed to $B = 4$ mT, which is much smaller than the lead critical magnetic flux $B_c = 70$ mT.
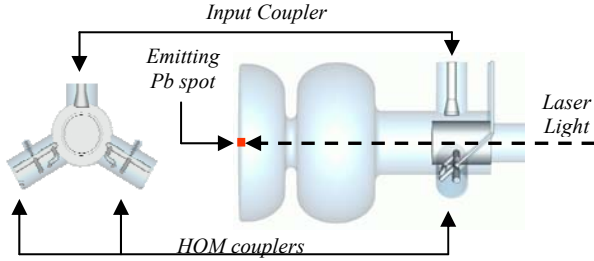

Figure 2: 1.6-cell SRF-gun cavity with 2 HOM couplers and the input coupler.

Table 1: RF-parameters of the 1.6-cell SRF gun

Parameter	Unit	Value
π-mode frequency	[MHz]	1300
0-mode frequency	[MHz]	1286.5
Cell-to-cell coupling	-	0.015
Active length 1.6·λ/2	[m]	0.185
Nominal E_{cath} at cathode	[MV/m]	60
Energy stored at nominal E_{cath}	[J]	20
Nominal beam energy	[MeV]	6

Table 2: HOMs of 1.6-cells

Mode	f [MHz]	(R/Q)
Dipole: TE111-1a	1641.8	1.85 [Ω/cm^2]
Dipole: TE111-1b	1644.9	1.30 [Ω/cm^2]
Dipole: TM110-1a	1883.5	10.1 [Ω/cm^2]
Dipole: TM110-1b	1884.0	9.99 [Ω/cm^2]
Dipole: TM110-2a	1957.0	3.90 [Ω/cm^2]
Dipole: TM110-2b	1957.1	3.85 [Ω/cm^2]
Monopole: TM011	2176.5	43.2 [Ω]

Two types of half-cell resonators have been built to measure the QE of lead at 2 K and to test the RF performance of Nb-Pb cavities. Both types are shown in Fig. 4. The left one was built at TJNAF. It has an opening in the center of the back wall, which is vacuum sealed with a niobium plug and an indium gasket. The advantage of this cavity type is that plugs can be easily coated with emitting materials to test various deposition methods and various superconductors for photoemission.
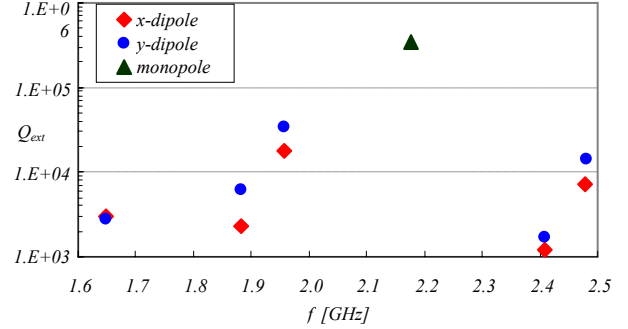

Figure 3: 3D modelling of the HOM suppression for the 1.6-cell SRF-gun.

It can be an alternative solution to the second cavity type, built at DESY (Fig. 4, right), in which, the technically difficult coating is done directly on the back wall. An additional difficulty in this version is that the emitting spot must withstand cleaning procedures applied to the cavity. Two of the cleaning steps could degrade QE: chemical treatment and high pressure water rinsing. Both procedures are essential for good performance of sc cavities. On the other hand, two features make this version very attractive: the smooth back wall does not enhance locally the electric field near the cathode and there is no RF electric contact needed in the high field region, which may reduce the intrinsic Q_o of the cavity. The plug cavity and the first DESY cavity were tested several times without and with lead coating. The baseline test without the coating, of the second DESY cavity fabricated in 2006, was recently carried out at TJNAF.
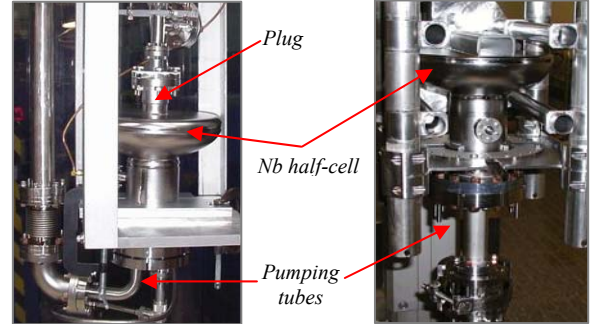

Figure 4: Test half-cell cavities built at TJNAF (left) and at DESY (right) assembled on inserts for the RF-cold test.

RF-PERFORMANCE TEST

Cold test without coating

Figure 5 displays the best results for the half-cell cavities without lead coating on the back wall and on the plug. The tests showed that chemical treatment and high pressure water rinsing are challenging for the half-cells and need to be improved in the future. We observed, testing DESY type cavities, few multipacting levels between 30 and 40 MV/m, which could be processed for cavities without lead. It took some time to overcome these levels by RF-processing. In the plug cavity, we observed heating of the first plug version, which was due to insufficient cooling by LHe. The cooling was improved for the tests shown.
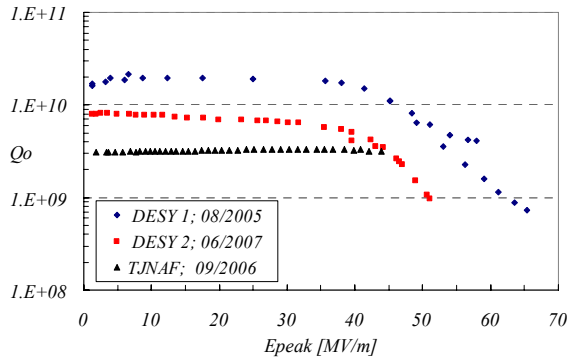
Figure 5: Cold (2K) RF-test results without lead coating.

Cold test with lead coating

The emitting 4 mm diameter lead spot at the center of the back wall of the DESY cavity was deposited by the arc-discharge method at A. Soltan INS. The 7 mm diameter plug of the TJNAF cavity was electroplated with lead at Stony Brook University. As mentioned before, the final cleaning of the cavities is challenging, especially for the DESY type when coated. That cavity reached 40 MV/m peak field (Fig. 6), but a lot of processing events and heavy radiation was observed during the cold test. The second DESY cavity will be coated and tested soon. The TJNAF cavity is somewhat easier to clean because of the absence of the coated plug during surface treatment. It demonstrated almost the same performance as without lead, which confirms our expectation that the emitting spot located on axis should not limit the performance.

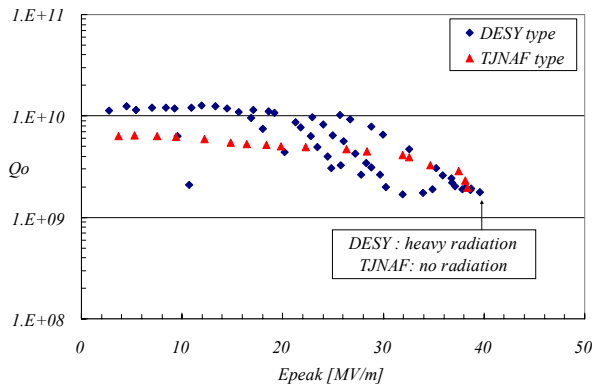Figure 6: Cold (2K) RF-test results with lead coating.

Irradiation with laser

One of our concerns from the very beginning of this project was the recombination time of broken Cooper pairs in the emitting spot by the irradiating laser. The theoretical investigation presented in [1] led to the conclusion that the recombination time strongly depends on temperature. Fortunately, the time is shorter for higher temperature. The 248 nm excimer laser used for the cold tests generated 5.3 ns long pulses (FWHM) at up to 250 Hz repetition frequency. The maximum energy per pulse was 5.5 mJ. Half of it could be transferred to the cavity for the QE and relaxation time experiments. The maximum available peak power of 0.518 MW at the

cathode was two times higher than the power needed for the nominal operation of the gun, when 1 nC bunches are generated within 20 ps. The preliminary relaxation time experiment was performed with the TJNAF cavity, operating at 1.42 GHz. For that experiment the cavity had to be attached to a straight vacuum tube oriented vertically upward, to enable direct irradiation with the laser light via the sapphire window installed at the top-plate of the vertical cryostat. The 3 m long vacuum tube contaminated the cavity with particulates and degraded its performance. At 3 MV/m Q_o was only $2.25 \cdot 10^9$, almost 3 times lower than Q_o measured at this gradient in the RF-performance test. When the Nb wall was irradiated with the maximum available laser power, Q_o dropped to $\sim 1.6 \cdot 10^9$, but the cavity did not quench and behaved still very stable. The additional dissipation, due to the locally broken Cooper pairs in the irradiated area, was 5.2 mW. The surface resistance, r_s, of the irradiated area increased during the laser pulse by a factor of 630. The ratio of r_s after and before the irradiation indicates that the concentration of quasi-particles rose to their equilibrium concentration at 8 K. According to the theoretical model, their relaxation time is shorter than 100 ps at this temperature.

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