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LARGE SCALE SUPERCONDUCTING RF PRODUCTION

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Abstract

The efficient plug to beam power conversion promised by the use of Superconducting RF to accelerate particle beams is still the driving force to pursue the development of this technology. Once the effective gain reached the level to pay for cryogenics, big physics laboratories started to believe on SRF, investing resources and proposing large challenging projects. Since then the cooperation with industry has been crucial to transform a few lab results into reliable SRF cavities and related ancillaries. This process started in the eighties and reached the actual paradigm with the realization of the European XFEL. All the new large scale projects in construction or proposed should start from the analysis of this experience and move forward from there.

INTRODUCTION

Superconducting radiofrequency (SRF) cavities have been in routine operation over the past 30 and more years in a variety of settings, from pushing frontier accelerators for particle physics to applications in nuclear physics and materials science. Used in a number of accelerator based projects, with different frequencies and shapes, they were instrumental in pushing CERN's LEP collider to new energy regimes, in getting high energy and in driving the newly inaugurated European X-ray Free Electron Laser. Nowadays, being the basic technology well understood, almost any type of accelerating structure can be successfully built taking advantage of the technological level that has been reached thanks to the investments done by the big projects in 1980s and 1990s.

At first, it was not clear that superconductivity had much value for RF technology. But it was soon realized that in the practical frequency range of RF accelerators, from hundred MHz to a few GHz, the use of SRF cavities would produce in any case a significant breakthrough due to the increase in the conversion efficiency from plug-to beam-power, cryogenics included. It was simply a question of developing the technology, and that required investment and big projects.

The High-Energy Physics Lab at Stanford University in the US was a pioneer in applying SRF to accelerators, demonstrating the first acceleration of electrons with a lead-plated single-cell resonator in 1965. Also in Europe, in the late 1960s, SRF was considered for the design of proton and ion linacs at KFK in Karlsruhe, but to really compete with the well-established normal conducting technology the path was still long and tortuous. Following these forerunners since the early 1970s SRF has been introduced in the design of particle accelerators, but results were modest and a number of limiting factors had to be understood and handled. As usual for any new technology a lot of science supported industrial development was needed to reach the current status of the art. In particular lead and niobium used as superconductor were originally too dirty for SRF. In practice, the different orders of magnitude obtained theoretically with superconductivity in terms of surface resistance were strongly reduced by the normal conductive impurities coming from both the superconductors themselves and the TIG welding electrodes.

However, the pioneering results while not astonishing have been sufficient to convince scientists that was just a question of technology and, once the effective gain reached the level to pay for cryogenics, big physics laboratories started to believe on SRF investing resources and proposing challenging projects. Since then the cooperation with industry has been crucial to transform lab results into reliable items.

SRF TECHNOLOGY AND BIG PROJECTS

The first successful test of a complete SRF cavity at high gradient and with beam was performed at Cornell's CESR facility at the end of 1984, involving a pair of 1.5 GHz, five-cell bulk niobium cavities with a gradient of 4.5 MV/m. This cavity design was then used as the basis for the CEBAF facility to be built at Jefferson Lab in US and convinced KEK in Japan to ask industry to produce a large number of SRF cavities to upgrade the energy of their TRISTAN electron-positron collider.

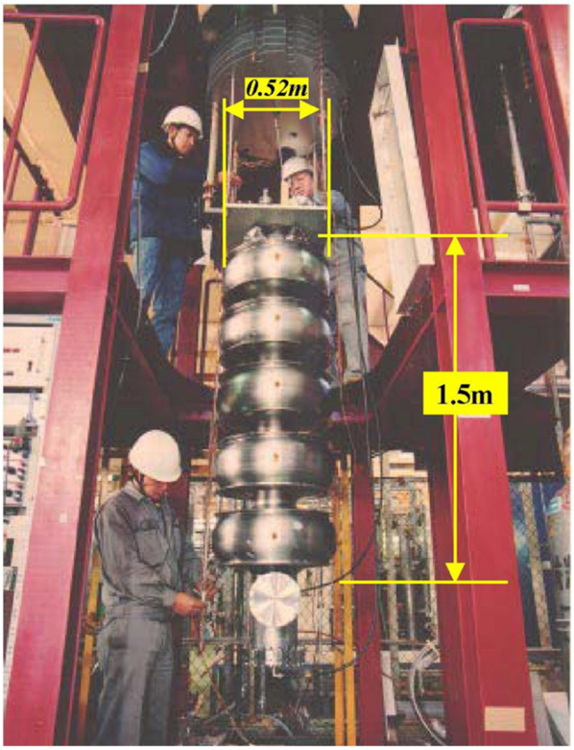

Figure 1: TRISTAN cavity prepared for test at KEK.

In 1989 TRISTAN reached a centre of mass energy of 32 GeV thanks to the installation of 32 large superconducting cavities, 5-cell, 508 MHz, made from bulk niobium sheets [1]. It's important to stress that these cavities were fully produced by industry with the external support of KEK. The consequence has been a fast production of very good cavities for that time (Eacc up to 7-8 MV/m), but the technological know-how was just marginally maintained inside the scientific community and then was rapidly lost by the industry itself because of the marginal expected market. One of the TRISTAN cavity equipped for vertical test at KEK is shown in Fig. 1.

A small number of cavities for other projects were meanwhile designed and built in Europe (HERA at DESY, ALPI at LNL, etc.) and US (ATLAS at ANL, etc.), but their number was too small to really impact technology. All considered it turns out that the biggest contribution to the creation of a reliable and reproducible SRF technology has been mainly given, starting from the end of the eighties, by the only two very large projects based on SRF: LEP2 at CERN and CEFAF in US. The two projects chose quite different ways to successfully develop the SRF technology but the combination of them created the basis for all the steps forward of such a complex system that together with the accelerating cavities includes all the needed ancillaries, like couplers, tuners, cryostats and cryogenic infrastructures.

Because of the size and the novelty, both projects had to locally set up a group of dedicated scientist and a very large infrastructure to completely design and test all the SRF items that were required. CEBAF took care also of the cryogenic plant because the cavity operation at 2 K, i.e. in superfluid Helium, was asking for something new for the global cryogenic industry.

Both projects had to produce and qualify roughly the same number of cavities, about 300, with the respective cryomodules and ancillaries, but the size of these objects was very different. Considering that all the sizes are more or less scaling in a similar way, it's enough to compare the respective cavity active lengths: 0.50 m for CEBAF and 1.70 m for LEP2. For both projects the accelerating gradient and the quality factor were crucial and the quality of the superconducting material was poor at that time. Lead plating was out and the bulk niobium was reasonable just for the smaller sheet sizes requested by the production of the CEBAF cavities. First bulk niobium prototypes of the big 352 MHz cavities for LEP2, asking for sheets close to 1 square meter, turned out to be not sufficiently good to reliably obtain the accelerating field that was justifying the effort. Hopefully, in the middle of the crisis, a scientist of CERN, Cris Benvenuti, developed just in time the magnetron sputtering technique that was depositing on the inner surface of a copper cavity a thin layer of niobium that was good enough to sustain an accelerating field higher than the 5 MV/m originally dreamed [2].

Once reached the goal on house made prototypes, both projects had to face the problem of the series production and the industrialization process had to start.

Because of the small size of the cavities, the large number of people involved in the SRF development and the size of the in house infrastructure, in the case of CEBAF the industrialization process was practically limited to the cavity mechanical fabrication, which was finally performed by an European company. Discussing the pros and cons of this decision are not in the scope of this note, but surely the production of more than 300 bulk niobium cavities for an important National Project in US pushed the Niobium producer to invest on material quality. This effect turned out to be crucial for all the following projects. From then on the niobium available on the marked started to be better and RRR=150 became an available standard.

On the other hand the human and infrastructural resources at CERN, while adequate for the R&D program performed so far, were not consistent with the production in a limited time of a few hundreds of large cavities, with ancillaries and cryostats. Anticipating the industrialization process as much as possible, all the steps of the fabrication of SRF cavities, ancillaries and cryostats was specified in detailed notes and controlled in house. On the basis of this material and with the support of all the CERN SRF group the complete technology was transferred to brother institutions, like INFN and CEA, and finally to three European companies to share the production of 256 + spares, 2.4 m long, accelerating cavities, completed with ancillaries and cryostated in a 4-cavity cryomodule (Fig. 2).

Figure 2: LEP2 cavities in industries during cryostating in large clean rooms of class 100/10.000.

All the process was finally done in industry, from the forming of the half cells to the final ultra-pure water rinsing and module assembly, going through electron beam welding, copper chemistry and magnetron sputtering. Electron beam welding, class 100 clean room assembly and ultra-pure water rinsing became the standard for SRF cavity fabrication and scientific and technical

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personnel from CERN, with the support of INFN and CEA, spent an important fraction of their time in the three industries to control the process and make experience of the industrial world with its limits and potentialities. A standard for QC, quality control, and QA, quality assurance has been so implemented at that time and used thereafter for this kind of productions. A qualification RF test in a vertical cryostat of each of the naked cavities was performed at CERN before the module assembly, to control the quality of the niobium coating.

At the end of the 1980s a number of labs were playing with SRF, performing fundamental research but with limited capability to sensibly impact on the SRF technology. The status of the art for the accelerating field reliably obtainable with multi-cell elliptical cavities was 5 to 8 MV/m, and this value was consistent with the production technologies developed both at CERN and Jefferson Lab. While using two different approaches, magnetron sputtering and bulk niobium, these two laboratories were indeed the places where all the production infrastructures and the human expertise were present. Concerning the four industries engaged in the large scale production for LEP-2 and TRISTAN they had to rescale or dismantle infrastructures and human resources according to the lack of large projects asking for SRF, but the process for the SRF industrialization was set and ready to be implemented and eventually improved.

THE TESLA COLLABORATION IMPACT

Was in this context that the TESLA collaboration was set up with the challenging goal of developing the SRF technology at the level needed to be globally accepted as the most promising technology for the future electron-positron collider to be built after LEP2. To understand how hard was the game it is worth remembering that three large collaborations were already competing for the linear collider working hard on three projects, CLIC, JLC and NLC, with somehow different approaches but all working at room temperature. Additionally, to be competitive in term of cost and performances, it was mandatory to improve the established SRF technology by at least a total factor of about 20; namely a factor 5 on the cavity accelerating gradient, from 5 to 25 MV/m, and a factor 4 in the total SRF cost, with ancillaries, cryogenics and power supplies, once expressed in cost per MV installed.

Ten years later, when the TESLA TDR was presented (March 2001), the objective was widely reached and the game with the other competitors was ended in the August 2004 when the ITRP (International Technology Recommendation Panel) chose the TESLA cold technology as the one to be globally adopted for the ILC (International Linear Collider).

INDUSTRY AND THE TESLA SUCCESS

The great success of the TESLA collaboration in opening a new era for the SRF technology had a number of concomitant causes, in addition to the great enthusiasm, friendship and some ingenuity of the those involved. The fresh experiences from LEP2 and CEBAF was the basis, for instance, plus cryogenic experience from DESY and Fermilab. The bounding MoU helped to inspire a pure scientific research style, with no secrets among the partner institutes and constructive competition to produce the best technology possible. Once the cavity frequency (1.3 GHz) and the number of cells per cavity (nine) had been agreed, we designed the TESLA Test Facility. This central infrastructure at DESY was to treat the active/internal surface of cavities, control and verify each step of the material and cavity production, and finally test the cavities and ancillaries in all conditions, naked and fully dressed, with and without beam. In contrast to the construction of LEP2 and CEBAF, the fabrication of the cavities themselves was handed over to industry. This turned out to be a crucial decision, forcing researchers to a strict collaboration with competing firms and taking advantage of all their expertise and ingenuity.

Niobium material was the first suspected for the modest cavity performances. We started improving its thermal conductivity (identified indirectly through the RRR) heat treating the cavities up to 1400 °C. The process was expensive and detrimental to mechanical robustness but excellent to produce soon two 9-cell prototypes reaching the goal of 25 MV/m. The cavity production was performed in a big company that produces aircrafts and the surface treatment in the new infrastructure set up at DESY collecting all the experience from CERN and CEBAF, but also adding the experience of electronic companies for clean polishing, handling and assembling. Starting from a cavity design challenging for the number of cell but with the simplest possible geometry and at one of the frequency available on the RF market, we put our effort identifying for each step of the production the best available and accessible in industry, avoiding to spend a single minute to “find a better way to warm up the water”. The international enthusiasm and the perspective of a very big project simplified our work. As a typical example, the success with heat treated prototypes together with the availability of a Eddy-current instrument, developed by DESY with industry and able to detect big (100 µm) foreign inclusion on the surface of the niobium sheets to eventually reject them before the cavity fabrication, pushed the niobium producer to do some effort to improve their production and to make cleaner all the steps of the process from the ingot to the sheets delivered. The high temperature heat treatment was then abandoned and the cavity performances remained as good as before. The well-known Fig. 3 shows the status of the stable cavity production at the end of nineties. All the production steps were well defined and documented. A few companies were qualified to deliver niobium according to the specs and a few other companies were able to produce good cavities able to reach the TESLA specs once surface treated at DESY in a well-defined, quasi-industrial way [3].

Two main results from the ongoing R&D in the TESLA collaboration laboratories improved the cavity per-

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formances just before the presentation of the TESLA TDR. The first came from KEK and consisted in the application of a final Electro Polishing (EP) on the active surface that turned out to improve the gradient by a few MV/m. The second improvement was discovered at CEA-Saclay and consisted in the final application of the so called low temperature backing (120 °C under vacuum at the end of the process) that turned out to cure the Q drop at high field that was still present also in the EP treated cavities [4]. The typical performance of a TESLA cavity after the application of EP and 120 °C backing is presented in Fig. 4. The significant gain in term of achievable accelerating gradient is clearly visible.

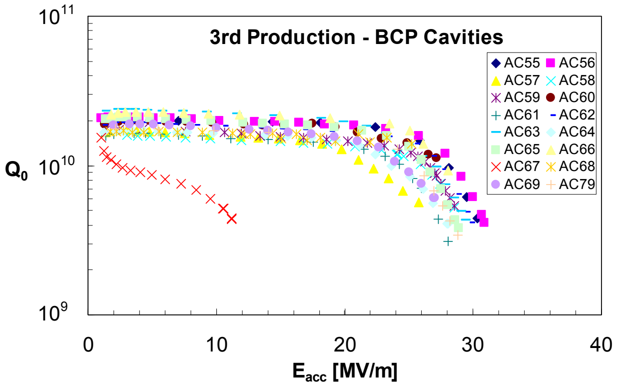

Figure 3: Excitation curves at 2 K of the TESLA cavities of the third production, before the adoption of EP and 120 °C backing. All cavities but one fulfilled the TESLA objective: E_{acc}=23.6 MV/m at $Q_0=1\text{x}10^{10}$.

Both the new ideas were rapidly implemented in the standard process of the TESLA cavity production and became ready for a complete industrialization that soon took place thanks to the European XFEL Project. Most of the labs worldwide were members of the TESLA Collaboration, TC, and so this SRF cavity technology, together with the others technologies developed for cryomodules and cavity ancillaries, were shared worldwide. After the choice of the TESLA technology for the ILC, the Collaboration modified its name including the word Technology after TESLA, TTC, and a few important labs like SLAC became new members.

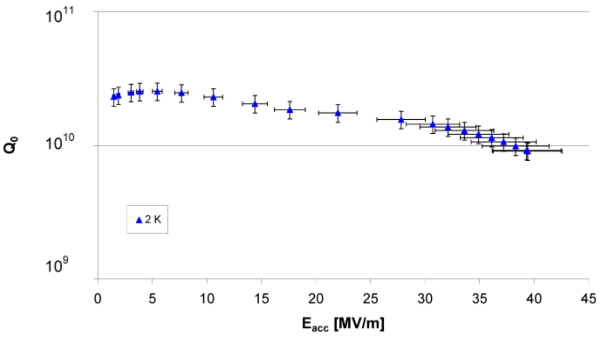

Figure 4: Excitation curve of a standard TESLA cavity after the application of EP and 120 °C backing. Data taken in 2004, at the time of the ITRP (International Technology Recommendation Panel).

It's worthwhile to point out that in parallel with the SRF cavity development, which was obviously mandatory to be competitive in the game for the linear collider, also cavity ancillaries, RF power sources, control electronics and cryomodule design were developed to a level never reached before. Skipping all the others it's important to point out the importance of the success on the cryomodule design, because what counts for a linear collider is the real estate gradient of the entire linac that includes all the dead interconnection lengths. As a reference example the TESLA design is twice more efficient than the one developed for CEBAF, and with a substantially lower cost per meter.

It is important to point out that the global effort of TESLA to qualify the SRF technology for the future lepton collider was done having in mind the large scale production that would have been necessary in case of approval. As a natural consequence all the ingredients already available on the market were selected and possibly improved through the most qualified industries possibly sustaining competition whenever possible. The perspective of the realization of a very large project like TESLA was an effective stimulus and produced good results. As a consequence, most of the RF and cryogenic equipment, adapted to the TESLA specs became available on the market.

Concerning the most specific components of the SRF technology, the realisation of the TESLA Test Facility, TTF, at DESY set up the reference infrastructure to develop SRF cavity treatments, RF tests, module assembly and beam operation, with LLRF (Low Level RF) and diagnostic. For the TESLA cost estimate presented in the TESLA TDR, on March 2001, several industrial studies have been commended and payed to trained companies.

THE EUROPEAN XFEL CONTRIBUTION

With the TESLA collider as objective, the SRF technology development was done from the beginning in the context of a strong collaboration with industry in order to be prepared to move toward the complete industrialization required by the envisaged large scale production. This was the favourable framework in which the European XFEL was successfully built. In particular, while the more conventional parts of the SRF technology were then available on the market, the two main efforts were to complete the technology transfer to industry of the complete SRF cavity production, including surface processing, and to transfer in a new bigger site, outside DESY, the module assembling process. The latter was finally hosted by CEA-Saclay in a dedicated building where copies of the INFN design infrastructure operational at DESY were duplicated and enlarged for E-XFEL mass production. Concerning the critical cavity processing, it was transferred to the two more qualified companies already trained in the mechanical production of the high quality cavities that up to then were surface treated in the DESY dedicated infrastructure.

Because of the quite big number of dressed cavities that was required by the E-XFEL project, 800 + 24 for

ILC R&D, the project management decided to implement both the technologies applied so far on the TTF cavity production, respectively based on Buffer Chemical Polishing, BCP, and Electro-Polishing, EP. This was done in spite of the fact that the latter had already demonstrated a better performance in term of maximum accelerating field. The reason was that both process should in principle safely generate cavities with performances higher than the project specifications, namely: E_{acc}>23.4 MV/m at $Q_0>1x10^{10}$. Based on the experience done through the past production of about 100 cavities in the TTF/ILC framework, the bulk chemical process that removes the damaged surface layer after all the mechanical processes, was decided to be done by EP in both cases. This decision was also important to have both companies up to date and maintain a competition on the SRF cavity market.

All the details of the technology transfer process and the SRF cavity production for the European XFEL are described in an exhaustive paper published on PRST-AB [5] that, together with the references thereafter, gives a complete picture of the largest and successful SRF cavity production globally done so far. In the same paper also cavity performances and statistics are widely described.

For the scope of this note few concepts that can be taken as useful references follow, meant for future projects that will need large scale cavity production:

- Once a receipt is fully defined and reproducible, with all the steps perfectly documented, a few industries (>1) should be selected, on the basis of the past experience, and helped to set up the required infrastructure. For the E_XFEL this took nearly 2 years, with some defined steps of pre-qualification before the start of the large scale cavity production .
- The use in industry of generic infrastructures and mixing production with an uncomplete R&D preparation phase should be avoided in large projects.
- In qualified industries QA and QC procedures are usually well established and, as a consequence, the results obtained are more stable.
- Industry is reproducing at the best level what the leading lab has transferred.
- In the field of SRF cavities, qualified industries can guarantee the respect of all the specified steps of QA and QC, not the final performances that remain under the responsibility of the project.

As properly shown in ref [6] the usable gradient is typically a few MeV/m lower than the maximum obtained in the vertical test. Field emission and high field Q drop are the principal causes. Looking at the average value on the production of 800 SRF 9-cell cavities an usable gradient of 29.0 MeV/m and 26.3 MV/m was measured respectively for EP and BCP treated cavities. Concerning the cavity quality factor Q_0 an average value of $1.5x10^{10}$ was obtained for E_{acc} < 20 MV/m, slightly higher with BCP. These results widely exceed the E-XFEL goals of E_{acc}=23.6 MV/m at $Q_0=1x10^{10}$, but it's important to note that an additional HPR (High Pressure Rinsing) was needed on ca. 40% of the cavities.

THE LESSON LEARNED

The application of SRF in particle accelerator is nowadays well established and a few companies worldwide can deliver reliable SRF cavities, while others can produce niobium material, or build related ancillaries and equipment, all more or less based on what has been developed in the framework of the TESLA Technology Collaboration. The large scale superconducting RF production for the realization, on budget and on time, of the European XFEL set the standard that can be expected by industry on the basis of what was the results of a global R&D effort standing for more than two decades.

The past history teaches that in practice only two choices are viable: either ordering cavities to already qualified industries basing requests on what has been already established, or starting from a lab that has developed in house all the technology and has the time, the personnel and the wish of setting up or promoting a new company.

To conclude it is worthwhile to note that the SRF global market is small with respect to the required technologies and infrastructures, and because it's also very irregular, it cannot sustain many actors. The possible case of a positive decision for the construction in Japan of the 250 GeV ILC could modify this statement but the result would be the same because in this case also global market companies, momentarily in standby, could decide to enter in the market. In reference [7] the excellent results of a batch of cavities produced in Japan a few years ago by the same company that produced in the eighties the SRF cavities for TRISTAN are presented.

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