# THE GROWTH OF SRF IN CHINA

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*Abstract*

The RF Superconductivity was first explored in China by Dr. Ding Yu of IHEP in early 1970's. Unfortunately the research was stopped for about 10 years after Dr. Ding passed away, until the first SRF laboratory was founded at Peking University by the end of 1980's. The early efforts of PKU SRF group on the design and fabrication of L-band high beta cavities using China-made niobium sheets as well as on developing Nb-Cu sputtering technology to construct SRF QWR as a post Tandem accelerator are described. The "SRF accelerator based FEL light source" project, which was proposed by PKU SRF group and joined by IHEP & SIAP, was formally approved by MOST in 2003 as a national key project of basic research. A series of work around the project carried out at PKU, including the construction and feasibility test of the DC-SC photo-injector, the R&D of multi-cell Nb cavities and cavities of large grain Nb are presented. Progresses of IHEP SRF group in developing SRF infrastructures and two 500Hz single-cell cavities for BEPCII as well as studies on 1.3 GHz & 700 MHz single cell cavities for proton acceleration are reported. Efforts made at CIAE on fabricating low beta Nb-Cu SRF QWR for heavy ion post acceleration and R&D activities in developing SRF technology for SSRF at SIAP are also presented. A growing phase of SRF in China is emerging.

## INTRODUCTION

The SRF was first explored in China by Dr. Ding Yu of IHEP in early 1970's on an X-band cavity. Unfortunately the research was stopped for about 10 years after Dr. Ding passed away, until the first SRF laboratory was founded at Peking University by the end of 1980's. At the early starting days, PKU SRF group was greatly benefited by a gift from DESY that is a 1.5 GHz Nb cavity made by Dornier, which enable the group to practice on the basic process of surface treatment, cryogenic tests of cavity performance under extremely clean and high vacuum conditions as well as to construct related components including cryostats, RF circuits & apparatus and high vacuum equipments etc. Eventually an accelerating field of 12.6 MV/m was obtained at 2.3K, with no Q-degradation after a number of cycling. Based on the preliminary experience, efforts were then concentrated in 1990's to the design and fabrication of L-band high beta cavities using China-made niobium sheets and to develop Nb-Cu sputtering technology for constructing SRF QWR as a post Tandem accelerator. Both types of cavities performed successfully in the respective beam test. While entering 21centry, inspired by the achievements of RF superconductivity and the prospects of superconducting accelerator based projects in the world such as TTF TESLA (FLASH) [1], X-FEL as well as ERL based high average power FEL [2], the PKU-IHEP Joint SRF Centre was established in 2001. After a careful preparation the PKU SRF group proposed a "SRF accelerator based FEL facility" project, so as to push on the development of photo-cathode high brightness superconducting injector, multi-cell Nb cavities as well as important applications of SRF accelerator. It was joined by IHEP and SIAP and was formally approved by MOST as a national key project of basic research in early 2003. A series of work around the project was then started at PKU and related components are being developed, including the design, construction and feasibility test of a DC-SC photo-injector, the upgrading of China-made Nb sheets, the design and development of multi-cell, particularly 9-cell cavities, as well as related cryomodules. Some progresses made by PKU group are presented in this paper; most of the work is still going on.

Encouraged by the Statement of ICFA on ILC in 2004, the Chinese science community attached more importance than ever on the development of SRF science and technology. Large grain SRF cavities are being developed in China since 2005. A TESLA type single-cell cavity of large grain Nb constructed by PKU group was tested at JLab which turned out that the $E_{acc}$ reached as high as 43 MV/m and $B_{peak}$ higher than 180 mT after processed with BCP only. Meanwhile infrastructures for developing SRF cavities were completed in recent years at IHEP. Collaborating with KEK, two 500 MHz single-cell cavities of IHEP were designed by joint efforts and fabricated in Japan. They are now running successfully on the ring of BEPCII. In addition, R&D activities on low and mid-beta 700 MHz and 1.3 GHz single cell cavities are carrying out at IHEP. Considerable progress has been made at CIAE on constructing low beta Nb-Cu SRF 150 MHz QWR for heavy ion post acceleration. In Shanghai, SIAP is also actively engaged in SRF technology. Three CESR type SRF cavities are being installed on the SSRF ring; meanwhile 1.3 GHz single cell cavities are being developed. A growing phase of SRF in China is emerging.

## THE STARTING PHASE OF SRF AT PKU

The early efforts made at PKU include the design and construction of L-band single cell cavity with China-made Nb sheets. One of the main difficulties encountered was that the RRR of these sheets were as low as ~50. With the help of Dr. Kneisel, the RRR of the sample sheet was raised to more than 400 after a heat treatment at 1400 $^0$C. Based on JLab's experience, the cavities were then treated in KEK in 1994. The RRR of the 1.5GHz cavities reached to higher than 270 and consequently the field gradient was raised to higher than 10MV/m @ $Q_0$ of $10^9$[3].

Meanwhile, a 1.3 GHz single cell cavity was processed by PKU for CAEP in the early days. It was tested with a pulsed beam at CAEP; the energy gain for a 0.1A peak, 10 ps beam was reported as 580 keV. With the above lesson in mind, PKU group determined to collaborate with Chinese enterprise like Ningxia OTIC in the later days, to improve substantially the quality of home made Nb materials from the origin of cavity fabrication.

By the end of 1995, Cu-Nb sputtering technology was explored for fabricating a SRF QWR to meet the needs of post acceleration after the Tandem. For this purpose, a 12.5 KW DC diode sputtering system was constructed. A series of experiments were carried out to study the effect of sputtering parameters including gas pressure, voltage, and current as well as biased voltage, on the quality of Nb film on Cu surface. A variety of samples was tested and was verified by the measurements at Cornell University. It turned out the $T_c$ of the film could be as high as 9.7K. By using a stainless steel QWR with glass probes distributed uniformly inside, the homogeneity of the film was studied under various combinations of sputtering parameters as well as geometry of electrodes. By the end 1990's, we managed to make a SRF QWR with sufficient high RRR and homogeneity of the film. The result of the beam test of the Nb-Cu QWR indicated that the accelerating field reached more then 3 MV/m. [4].

## PROGRESS ON SRF ACCELERATOR BASED FEL FACILITY

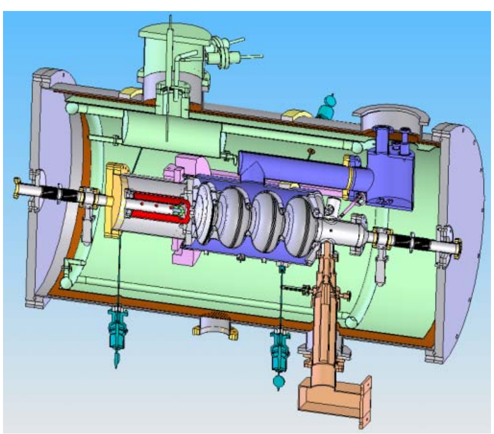

Figure 1: Layout of DC-SC Photo-injector.

As part of PKU SRF accelerator based FEL facility, the concept of DC-SC electron photo-injector was proposed, which was essentially an integration of Pierce gun and pre-accelerating 1+1/2 SRF cavity of 1.3 GHz [5]. For the feasibility test of the concept, a test facility was built. As limited by the capacity of cryogenic infrastructure, the injector had to be carried out with the long pulse mode (5% duty factor) under 4.4K in late 2004. The maximum energy gain obtained by the photo-electron beam was 1.1 MeV, while the rms beam emittance measured was about 5 m at 0.5MeV with an average current of 270 A. [6]. Efforts are being made to improve cryogenic system so as to enable the injector working under 2K. The L-140 Helium liquefier and related cryogenic facility was contracted with the Linde Company and will be installed by the end of 2008. Meanwhile a 3+1/2 cavity (Fig. 1) is under construction as a further step in developing DC-SC photo-injector [7]. The designed accelerating energy is about 5 MeV and the average current is 1 – 5 mA.

Researches on the main accelerating cryomodule have been carried out since 2006, which are based on the collaboration among Peking University, Ningxia OTIC and Harbin Institute of Technology. Now PKU group has finished the detailed design of the module (Fig. 2). Parameters for this module are listed in Table 1.

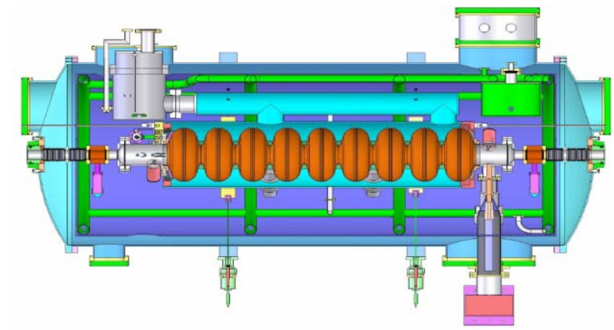

Figure 2: Layout of PKU Superconducting Accelerating Module.

Table 1: Designed Specifications

| | |
|---|---|
| RF frequency (cavity at 2.0 K) | 1.3 GHz |
| Accelerating voltage | 17 MV/m guaranteed, goal ≥ 20 MV/m |
| $Q_0$ @20 MV/m | $1\times10^{10}$ |
| Electron Beam Peak Current | 20~50 A |
| Bunch Charge | About 20~50 pC |
| Electron Beam Average Current | 1.6~4.0 mA |
| External Q of Power Coupler | $2\times10^6$~$1\times10^7$ |
| Cryogenic losses (stand-by) | 12W at 2K |

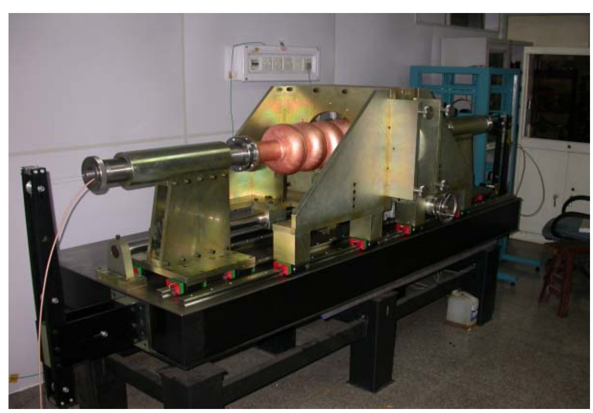

Figure 3: Tuning System for Multi-cell Cavities.

Before the fabrication of Nb cavity, a 9-cell copper cavity was first made for multi-purposes, including (1) qualification of dies of deep drawing, (2) cups trimming technology, (3) test of EBW tools and (4) cavity pre-tuning and field measurement. Every dumbbell of the cell is strictly measured and trimmed to ensure the non-uniformity of the resonant frequency and coupling constant within the tolerance. The turning system for multi-cell cavity has been set up too (Fig. 3). After the whole 9-cell Cu cavity was assembled, the field of mode was measured and is being tuned for better flatness.

The quality of Nb materials has been improved greatly through the collaboration between PKU and Ningxia OTIC. With the Ningxia materials (RRR>350), a 5-cell Nb cavity was fabricated (Fig. 4) to test the fabrication techniques of Nb cups, EBW technology and post processing (including BCP polishing, HPR, etc.) of multi-cell Nb cavity. The cavity tuning and performance tests of this 5-cell cavity will be carried out soon. Meanwhile the 1st 9-cell Nb cavity is under fabrication for further test on EBW and post processing technology.

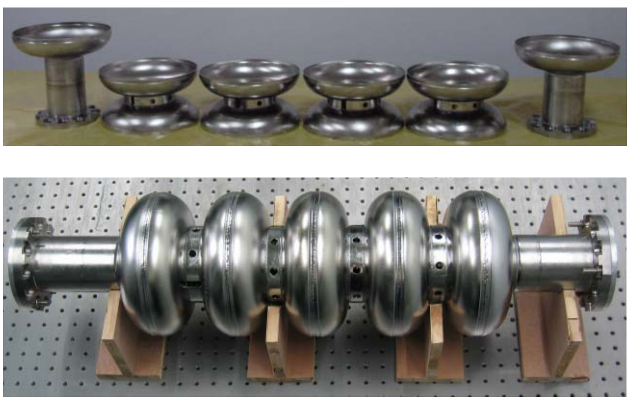

Figure 4: Dumbbells and 5-cell Nb cavity

## DEVELOPMENT OF CAVITIES WITH LARGE GRAIN NB SHEETS

With the collaboration of PKU and Ning Xia OTIC, large grain Nb sheets were developed and produced by OTIC Company since 2005. To examine the features of this kind of material as well as the SRF cavity fabrication technology in China, PKU group designed and manufactured a single-cell 1.3 GHz TESLA type cavity. After an 800oC heat treatment, the cavity was sent to JLab for performance test. With the help of Dr. P. Kneisel, the cavity was buffered chemically polished prior to carrying out the first cryogenic test. The first results show the material parameters for the niobium, compatible with parameters of "as processed" niobium: TC = 9.2K (fixed), London penetration depth lL = 36 nm (fixed), coherence length= 64 nm (fixed), energy gap/kTC =1.79 + 0.04 (fitted), mean free path l = (357 + 177) nm (fitted) and residual resistance Rres = (2.64 + 1.1n) (fitted). The cavity showed a rather flat Q versus Eacc dependence with a high Q-value and the typical Q-drop starting at ~ 25 MV/m; but no quench and no field emission at the highest gradient of ~ 29 MV/m. After several steps of heat & BCP treatments (Table 2) and "in-situ" baking at 1200C for 12 hrs the best performance of this cavity was obtained with Eacc ~ 43 MV/m, corresponding to a peak magnetic field of Hpeak ~ 183 mT, (see Fig. 5 ). Because of the very good performance of this cavity, an additional test was done after a disassembly and high pressure rinsing to re-confirm the performance. The result of additional test did confirm the previous measurement [8]. Based on the above experience, great efforts are being made on multi-cell cavity fabrication of large grain Nb.

Table 2 Summary of tests with PKU cavity

| Test No | BCP μm | HPR | Gas-ket | Eacc MV/m | $B_{peak}$ mT | Q@ $B_{peak}$ | Bak-Ing |
|---|---|---|---|---|---|---|---|
| 1 | | R&D | AlMg | 29 | 124 [QD] | $9x10^9$ | |
| 1a | | R&D | | 32.5 | 139 [Q] | $1.4x10^{10}$ | 12 Hrs |
| 2 | 57 | R&D | In | 8(MP) | | $9x10^9$ | |
| 3 | | R&D | In | ~15(FE) | | $6.4x10^9$ | |
| 4 | 41 | R&D | AlMg | ~11(FE) | | $6x10^9$ | |
| 5 | 24 | R&D | AlMg | 34 | 145 [QD] | $8.8x10^9$ | |
| 5a | | Prod | AlMg | 43.5 | 183 | $1.6x10^{10}$ | 12 Hrs |
| 6 | | Prod | AlMg | 42.2 | 180 | $1.4x10^{10}$ | |

(Q = quench, QD = Q-drop)

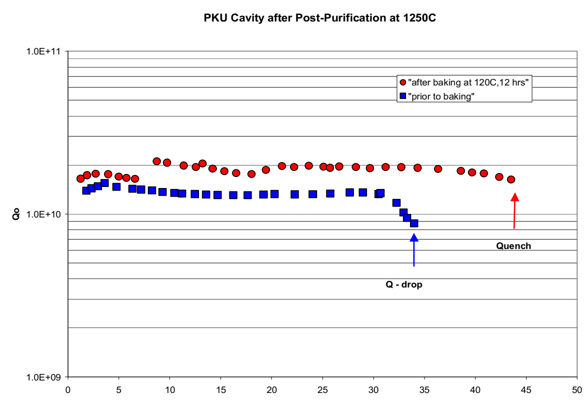


Figure 5: $Q_0$ vs. $E_{acc}$ of the single cell large grain cavity.

## SRF ACTIVITIES AND RECENT PROGRESS AT IHEP, CAS

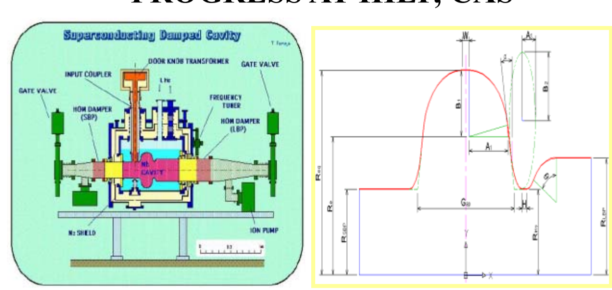


Figure 6: Structure of 500 MHz SRF cavities for IHEP

Collaborating with the KEK, IHEP started to the design of a 499.8MHz MHz SC cavity in 2001, on the base of KEKB's 508.887 MHz SC cavity. The resonant frequency was lowered by elongating the cell equator length w from 13 mm to 36.5 mm to meet the needs of BEPCII. The Nb cell, cryostat, coupler and the damper for two cavities were then fabricated by MELCO from 2003 to 2005 in Japan. (Fig. 6)

With the joint efforts of both sides, the cavities were assembled, processed in KEK so as to perform the first vertical test of cavities there. The result shows that at a gradient of 10 MV/m the $Q_0$ for two cavities are $1.59X10^9$ and $1.09X10^9$ respectively. After reassembled at IHEP, the horizontal test of two cavities was carried out successfully in 2006. It is shown that the $Q_0$ of two cavities for an energy gain of 2 MV are $0.99X10^9$ and $0.55X10^9$ respectively (Fig. 7), both cases exceed the design requirements of $0.5\ X10^9$. Nowadays, these two cavities run successfully on the ring of BEPCII [9].

Figure 7a: 500 MHz cavity assembled at KEK.

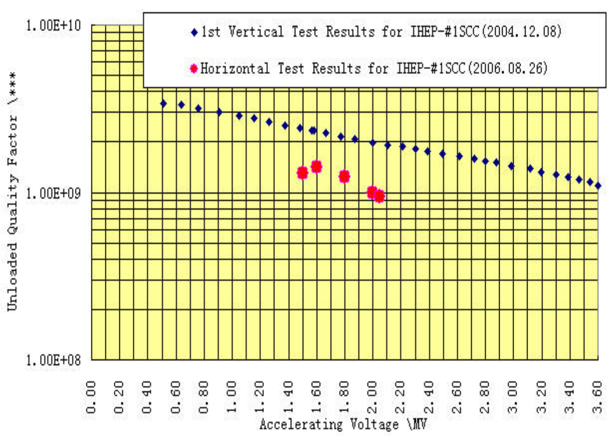


Figure 7b: Vertical and Horizontal test results at IHEP

In addition, infrastructures including Helium liquefier and related cryogenic system as well as the experimental laboratory building equipped with ultra clean rooms and facilities for cavity assembling and rinsing and also the trap for vertical test of SRF cavities have been installed in IHEP. On the basis of these efforts, R&D on low and mid-beta 700MHz and 1.3GHz SC cavities for proton acceleration are being carried out at IHEP to meet the future needs of China SNS.

## PROGRESS ON NB-CU QWR AT CIAE

A superconducting booster will be built after the existed HI-13 tandem accelerator to meet the needs of Beijing Radioactive Ion Beam Facility. [10] An illustration of a tandem linac system is given in fig. 8. At the first stage, only one cryogenic module, which consists 4 Nb-Cu QWR cavities, will be constructed and tested as a prototype. The design goal on the energy gain of one module is 2MeV/q for $\beta$=0.118 ions. The heat load of a cryostat is less than 10 W per module. The working frequency for each QWR is 150.4 MHz with a geometry factor of 26.17Ω. The Nb-Cu sputtering test facility was built up by the CIAE group for performing R&D on the sputtering technology in 2006, and a good technology on sputtering process is resulted and verified. The design and development of the key components of the SRF booster have been getting on smoothly last year. Besides, the clean assembling room, the sputtering platform, cryostats, and the RF-instruments are to be constructed this year. According to their schedule the fabrication of the superconducting booster will be finished by the 3rd quarter of 2009, and the first beam test for the booster is anticipated by the end of 2009.

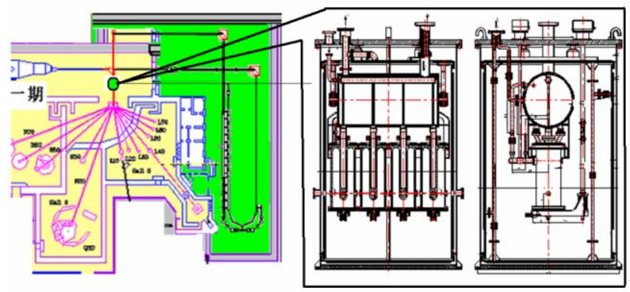

Figure 8: 150 MHz SRF QWR for post acceleration.

## PROGRESS ON SRF AT SIAP

Shanghai Synchrotron Radiation Facility (SSRF) is a 3.5GeV 3rd generation light source under construction. It is scheduled to start operation for users from April 2009. Three CESR type single cell SRF cavities of ACCEL are being installed on the SSRF storage ring for establishing 3-6MV accelerating voltage and providing up to 600kW to the stored beam. [11] Correspondingly, three 310 KW Klystron RF power amplifiers, a 650W Helium liquefier and related RF loads are to be installed.

Table 3 Parameters of the SRF Module of SSRF

| | |
|---|---|
| Frequency | 499.654 MHz |
| Operating temperature | 4.2K |
| $V_{acc}$ | >2.4MV |
| $Q_0$ @2MV | $1X10^9$ |
| Standby losses | <35W |
| Dynamic heat load at 2MV | <65W |
| $Q_{ext}$ of input coupler | $1.8 \times 10^5 \pm 0.2 \times 10^5$ |
| Power transferable to beam | >250 kW |

The parameters of cryomodules are in table3. The result of vertical tests at ACCEL is shown in Fig.9. So far the 1st module has been installed in the storage ring tunnel, while the 2nd module is to be tested in the test cave.

In order to manipulate the bunch length and to suppress beam instabilities, a CW passive SRF system with a frequency of ~ 1.5GHz is being developed at SIAP to provide 1.8-2.0 MV RF voltage. For this purpose, R&D efforts are being made on the construction of single and multi-cell SRF cavities. Meanwhile, infrastructures for cavity processing and performance tests are being built.

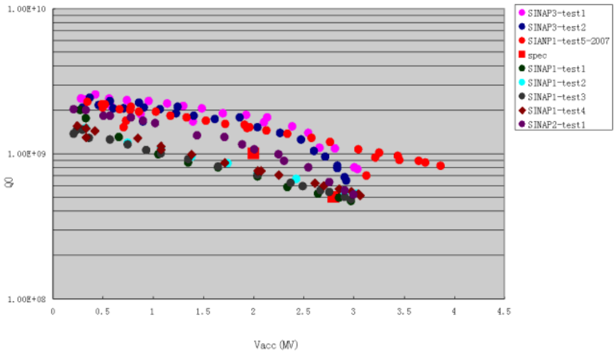


Fig.9 Vertical test results of SIAP single cell cavities

## CONCLUSIONS

SRF has been well developed in China in the last twenty years. PKU SRF group has made great efforts in the starting phase for developing capability on constructing low and high beta SRF cavities as well as cultivating peoples devoted to the SRF science and technology. Entering new century, a number of large scientific projects developed at national laboratories all round in the nation are being involved in the R&D of SRF. The inter-laboratory collaboration around the world promotes the progress of SRF in China. A growing phase of SRF is emerging in China.

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