SRF IN STORAGE RINGS

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Abstract

Superconducting cavities are used in storage rings worldwide as they allow to transfer almost all available RF power to the beam and to operate at high accelerating voltage thus minimizing the number of installed cavities. Further these cavities can be designed "HOM-free" allowing stable operation of high currents and providing better beam quality. Pioneering work was done by CERN for the LEP storage ring (352 MHz), by DESY for the HERA electron ring (500 MHz), by KEK for Tristan and the high energy ring of the KEK-B factory (508 MHz) and by Cornell for their B-factory proposal and later for the CESR upgrade program (500 MHz). Today such SRF technology can be delivered by industry and operation of SRF systems is done at institutions without an extended background in SRF technology. LEP technology will be used at the LHC (400 MHz) and at the Synchrotron SOLEIL (352 MHz) and KEK technology at the BEPC-II collider in Beijing. Cornell technology is used already at the Taiwan Light Source, the Canadian Light Source and will be used at the Diamond Light Source. In addition the Shanghai Light Source has decided to use SRF technology for their storage ring. Beside the main accelerating structures, higher harmonic superconducting cavities can be used to increase the bunch length and the beam lifetime. A collaboration of CEA, SLS, ELETTRA and CERN designed, installed and operated a 1.5 GHz system at the SLS and ELETTRA. A second approach with a Cornell CESR cavity scaled to 1.5 GHz was delivered from ACCEL to BESSY and the cryogenic test was done in this summer.

REVIEW OF FIRST INSTALLATIONS

For the application of superconducting cavities in storage rings with currents in the few mA regime pioneering work was done in Japan with the installation at TRISTAN [1] and in Europe at HERA [2] and LEP [3].

Table 1: Achievements of TRISTAN, HERA and LEP

	TRISTAN	HERA	LEP
Number of cavities	32 5-cell cavities	16 4-cell cavities	288 4-cell cavities
Frequency	509 MHz	500 MHz	352 MHz
Cavities per vacuum vessel	2	2	4
Time of installation	1988 and 1989	1991	1996-1999
Provided voltage	200 MV	30 MV	3600 MV
Technology	BulkNb	Bulk Nb	Nb/Cu

All those installations were very successful and impressive work was done at the respective laboratories. Figure 1 shows the installations and table 1 summarizes the achievements of TRISTAN, HERA and LEP.

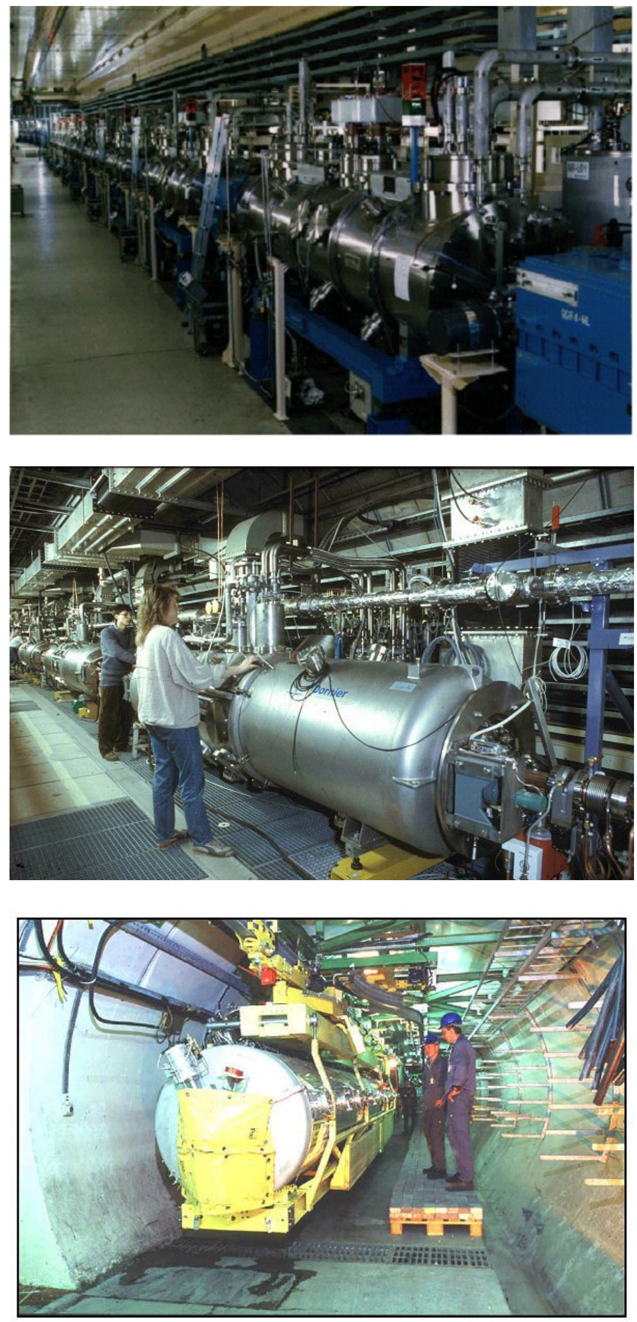

Figure 1: Installation of large scale SRF systems in TRISTAN (top), HERA (middle) and LEP (bottom).

B-FACTORIES, LHC AND THIRD GENERATION LIGHT SOURCES

With the quest for high current (up to one Ampere) B-factories, the development of a superconducting RF system was launched in Japan at KEK and the US at the Cornell University. Both designs are based on a single cell niobium cavity mounted to its own vacuum vessel building a superconducting RF module operating at 509 MHz (KEK-B [4]) or 500 MHz (CESR [5] at Cornell). Later on it was observed, that those cavities can be used in high current storage rings of third generation light sources and the technology was transferred through industry to different places all over the world. CESR technology is now used at the Taiwan Light Source at NSRRC [6], the Canadian Light Source (CLS [7]), the Diamond Light Source (DLS [8]) and the Shanghai Synchrotron Radiation Facility (SSRF [9]). The KEK technology will be used at the BEP-II e^+e^--collider at the IHEP in Beijing [10].

In parallel, the technology of coating copper cavities with a thin niobium layer developed at CERN for the LEP project was the basis for two new SRF module designs for high current storage ring usage. For the LHC [11], CERN developed a module housing 4 single cell cavities operating at 400 MHz. A second module operating at the LEP frequency of 352 MHz and housing two single cell cavities was build by a collaboration of CERN and CEA for the SOLEIL synchrotron [12]. This module has proven to work successfully; a second such module is currently built for SOLEIL in industry.

KEK-B achievements

The schematic of the KEK-B module is shown in Figure 2. Main design features of the KEK-B module are single cell niobium cavity operating at 509 MHz, ferrite based HOM dampers located at room temperature sections of the beam pipe and a coaxial input coupler.

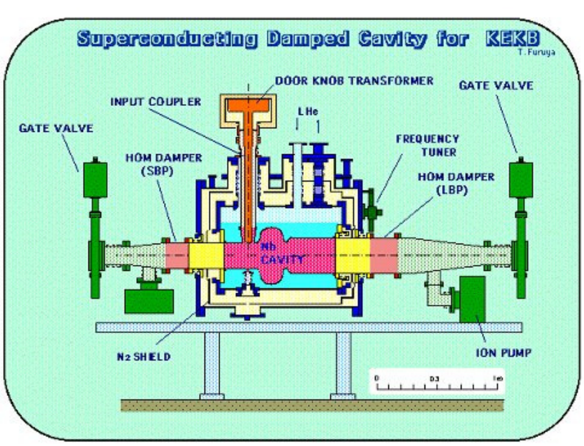

Figure 2: KEK-B cryomodule (Courtesy of T. Furuya, KEK)

Table 2 summarizes the achievements of the KEK-B module in detail. In routine operation the KEK-B superconducting RF system is transferring 2.4 MW of RF power to the beam by 8 superconducting RF modules.

The biggest achievement has been the stable operation of the SRF modules in the machine allowing luminosity records at KEK-B far beyond the design values. Those records strongly are demonstrating the general benefit of superconducting RF in high current storage rings. At present a luminosity of 15.8 /nb/s ($1.58{\cdot}10^{34}$ $cm^{-2}s^{-1}$) or 1178 /pb/day is reached at KEK-B.

Table 2: Achievement of SRF modules at KEK-B

	Design	**Achieved**
Number of cavities	8	8 (since 09/2000)
Beam intensity	1.1 A in 5000 bunches	1.34 A in 1389 bunches
Bunch length	4 mm	6-7 mm
Max RF voltage without beam		> 2.5 MV/cavity (2-2.8 MV/cavity)
RF voltage with beam	1.5MV per cavity	1.2-2.0 MV per cavity
Q-value	$1{\cdot}10^9$ at 2 MV	$0.5\text{-}2{\cdot}10^9$ at 2 MV
RF power transferred to the beam	> 250 kW per cavity	300-350 kW/cavity max 400 kW/cavity
HOM power	5 kW at 1.1 A	14-16 kW at 1.34 A

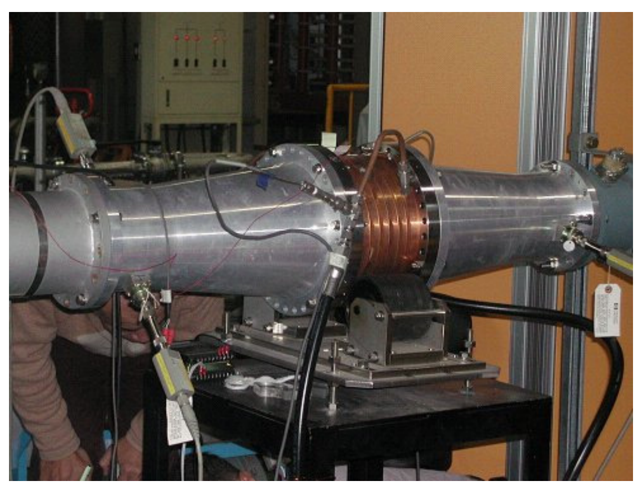

Figure 3: KEK-B HOM load test stand. The HOM power is absorbed by ferrite material placed onto the inside of a beam pipe section. The HOM power is cooled by water pipes from the outside (Courtesy of T. Furuya, KEK).

In order to achieve even higher luminosity, the beam current needs to be increased still. On a module test stand a spare module has already demonstrated to operate at 500 kW travelling wave power. Another limitation might be the damping of the HOM power. Currently on test stands the present HOM load design (see figure 3) allows absorption of up to 25 kW HOM power, enough for an operation with 2 A beam current. At this power level, the inner HOM load surface temperature however reaches already 200 °C and the out gassing behaviour needs further studies.

KEK-B technology cooperation with MELCO

KEK together with MELCO currently produces two SRF modules for the BEP-II e^+e^--collider τ-charm factory at the IHEP in Beijing. For this purpose a redesign of the cavity from 509 MHz to 500 MHz was necessary. The cavities have been tested already and safely achieve the required performance (see figure 4). The final installation and commissioning of the assembled modules at IHEP is planned for the first half of 2006.

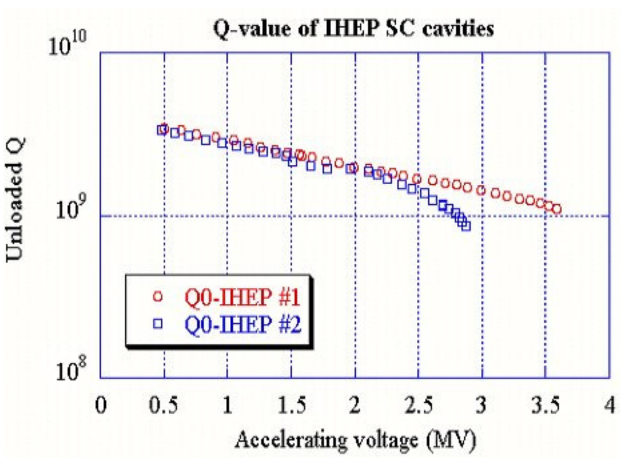

Figure 4: Vertical test results of the two cavities produced for IHEP (Courtesy of T. Furuya, KEK).

Cornell CESR technology

The Cornell CESR module design is shown in figure 5. Also here a single cell niobium cavity (500 MHz) and room temperature beam pipe HOM loads are used. In contradiction to the KEK-B module a waveguide input coupler is used to transfer the RF power to the beam.

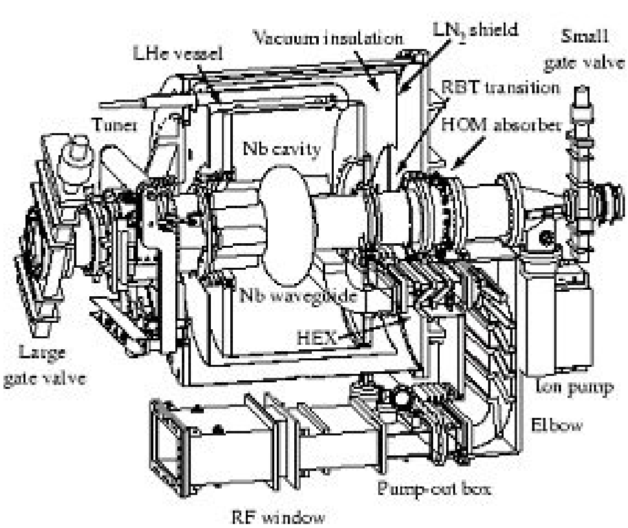

Figure 5: Cornell cryomodule (Courtesy of S. Belomestnykh, Cornell)

The achievements of SRF modules of the Cornell design installed in CESR are summarized in table 3. CESR has been the first storage ring to run in 1999 entirely on SRF cavities. Also CESR was operating on world record luminosity until the new B-factories at KEK and SLAC pushed to higher limits. CESR currently is operated in two modes: As a τ-charm factory and as a light source (CHESS). In the first mode high voltage and low beam power is needed, in the second, the requirements on voltage are relaxed, but high beam power is needed.

Performance of SRF modules installed in CESR

Peak luminosity	$1.3 \cdot 10^{33}$ cm^{-2}s^{-1}
Beam current	0.78 A
RF voltage with beam	1.85 (1.6-2) MV/cavity
Q-value	$1 \cdot 10^9$ at 2 MV $0.3\text{-}1 \cdot 10^9$ at 2.7 MV
RF power transferred to the beam beam	300 kW/cavity (360 kW forward power)
HOM power	5.7 kW/cavity at 0.75 A

CESR technology transfer to ACCEL

In 1999 a technology transfer agreement was signed between Cornell University and ACCEL allowing the industrial production of SRF modules for users that do not have intensive SRF infrastructure available. The Taiwan Light Source was looking for two SRF modules, followed by the Canadian Light Source requiring also two SRF modules. Two more modules were produced for Cornell University itself. Later the Diamond Light Source asked for three SRF modules and the Shanghai Light Source just currently ordered three more SRF modules. The vertical test results of cavities tested so far are summarized in figure 6. The typical specified voltage of 2 MV was safely reached in all cases.

In addition to the naked SRF module, ACCEL is able to deliver the complete SRF electronics, the cryogenic valve boxes and transfer lines and the LLRF system. The module installation, commissioning and demonstration of guaranteed performance is also part of the delivery.

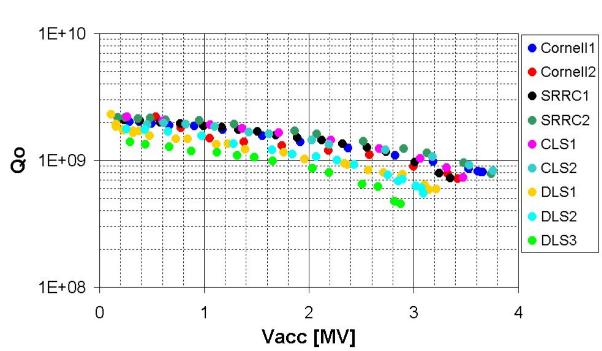

Figure 6: Vertical test results of cavities produced, prepared and tested from ACCEL

Performance of SRF modules produced at ACCEL

So far 6 SRF modules have been completely delivered and commissioned. The most important results are summarized below.

Two SRF modules for Cornell:

- Delivered in winter 2002 and summer 2003.
- Both modules are operating in CESR at up to 2.4 MV and up to 160 kW.

Two SRF modules for Canadian Light Source

- Delivered in summer 2003 and summer 2004.
- The CLS was the first light Source that was commissioned with superconducting RF.
- Both modules operated in the machine, the first one operated for more than one year and was then removed in order to install the second one. The first one now serves as hot spare.
- One module operated at up to 2.5 MV and above 200 kW, the other module operated at up to 2.4 MV and 160 kW.
- Maximum beam current achieved so far: 205 mA.

Figure 7: SRF module with valve box and SRF electronics after completion at ACCEL (top) and installation of that SRF module into the Taiwan Light Source at NSRRC (bottom).

Two SRF modules for Taiwan Light Source at NSSRC:

- Delivered in spring 2004 and winter 2004.
- One module is operating in the machine since fall 2004 at 1.6 MV (design value) and up to 85 kW.
- 400 mA beam current stored in the ring, upgrade goal of the machine achieved.
- Second module commissioned on test stand at NSSRC to 1.6 MV. This module now serves as a hot spare.

The production of modules produced for Diamond Light Source is well advanced. All cavities are tested and qualified and all RF windows processed on a separate test stand and qualified as well. The modules are currently under final assembly and installation into the DLS storage ring will start in August 2005.

SRF modules for LHC

CERN has chosen the LEP technology of sputtering niobium on a copper cavity for the RF system of LHC. Figure 8 shows one LHC SRF module housing 4 single cell cavities after assembly.

In total 4 such modules will be installed in the LHC (2 modules per beam). There will be in addition one spare module. The cavities (including niobium sputtering) were ordered in industry. After assembly done by CERN, two modules have already been tested on a high power test stand. Each cavity here reached more than 3 MV. Two more modules are currently under assembly and the installation of the modules into the LHC ring is scheduled for April 2006.

Figure 8: LHC module housing 4 single cell cavities operating at 400 MHz

SRF modules for SOLEIL

For the synchrotron SOLEIL, CERN and CEA developed a new SRF module containing two single cell cavities operating at 352 MHz (LEP frequency). In contradiction to the KEK-B and the CESR module, the damping of the HOMs is done here by several loop couplers situated on a large diameter beam pipe in between the two cavities. Figure 9 shows a view through the SOLEIL module, where the loops of the HOM couplers can be seen.

Figure 9: View through the SOLEIL module: what the beam sees from the SOLEIL module

The completed module was tested with high power at CERN on a separate test stand, where both cavities reached 2.5 MV and the input coupler was operated at 120 kW RF power at full reflection (standing wave operation). In 2001 a beam test at the ESRF took place during which the module provided in total 3 MV and each coupler transferred 190 kW RF power to the beam.

Some weak points observed at this test like high static cryogenic losses and HOM coupler design details were overcome in 2003 after introduction of a new thermal shield and an improved HOM coupler design. A new high power test at CERN took place in 2005 where each cavity reached 2.5 MV and each coupler was operated at 200 kW RF power at full reflection. The beam test of the module in the SOLEIL synchrotron is scheduled for spring 2006.

HIGHER HARMONIC CAVITIES

A scaled version (1.5 GHz, including HOM loop couplers) of the SOLEIL module was developed from a collaboration of CEA, PSI, Synchrotron Trieste and CERN for bunch lengthening and therefore increasing the Toushek lifetime in the SLS storage ring at PSI and the ELETTRA machine [13]. For the accelerating voltage a value of 0.5 MV per cavity was specified and achieved. The modules operate very well in the machines and they achieve a factor of three in bunch lengthening and a factor of two on beam lifetime. The module installed in ELLETRA is shown in figure 10.

A scaled version of the CESR module was developed by ACCEL for BESSY. The module is equipped with ferrite type HOM loads and shown in figure 11. It has been tested outside the storage ring where the specified voltage of 0.5 MV was demonstrated.

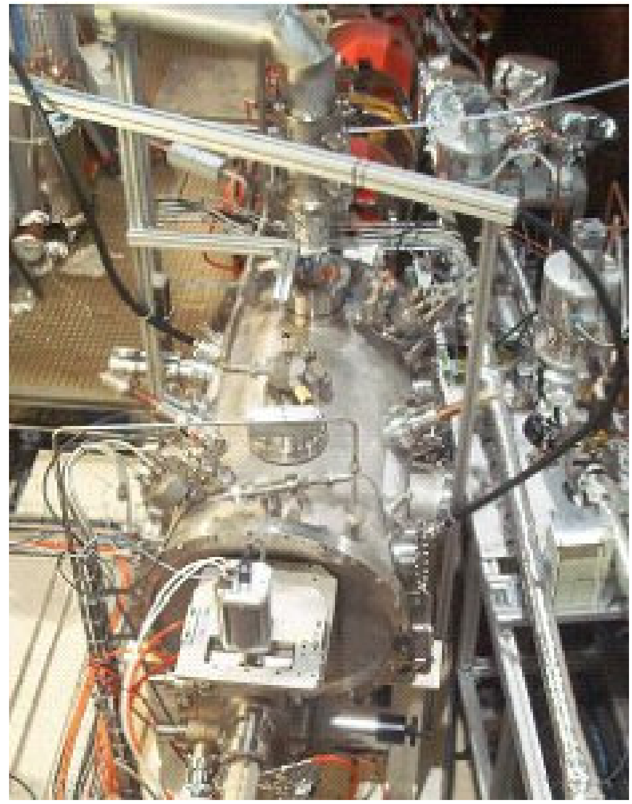

Figure 10: Higher harmonic cryomodule installed in the ELETTRA storage ring

Figure 11: Higher harmonic cryomodule for BESSY

SUMMARY

SRF technology is proven to operate reliable in storage rings all over the world and to provide in this applications a voltage of approximately 2 MV and about 250 kW RF power per cavity to the beam. The KEK-B module can be delivered with MELCO and the Cornell CESR module can be delivered by ACCEL to users worldwide. This gives also smaller laboratories and institutions the chance to use this technology without having the complete infrastructure for manufacturing and preparation of superconducting cavities in house.

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