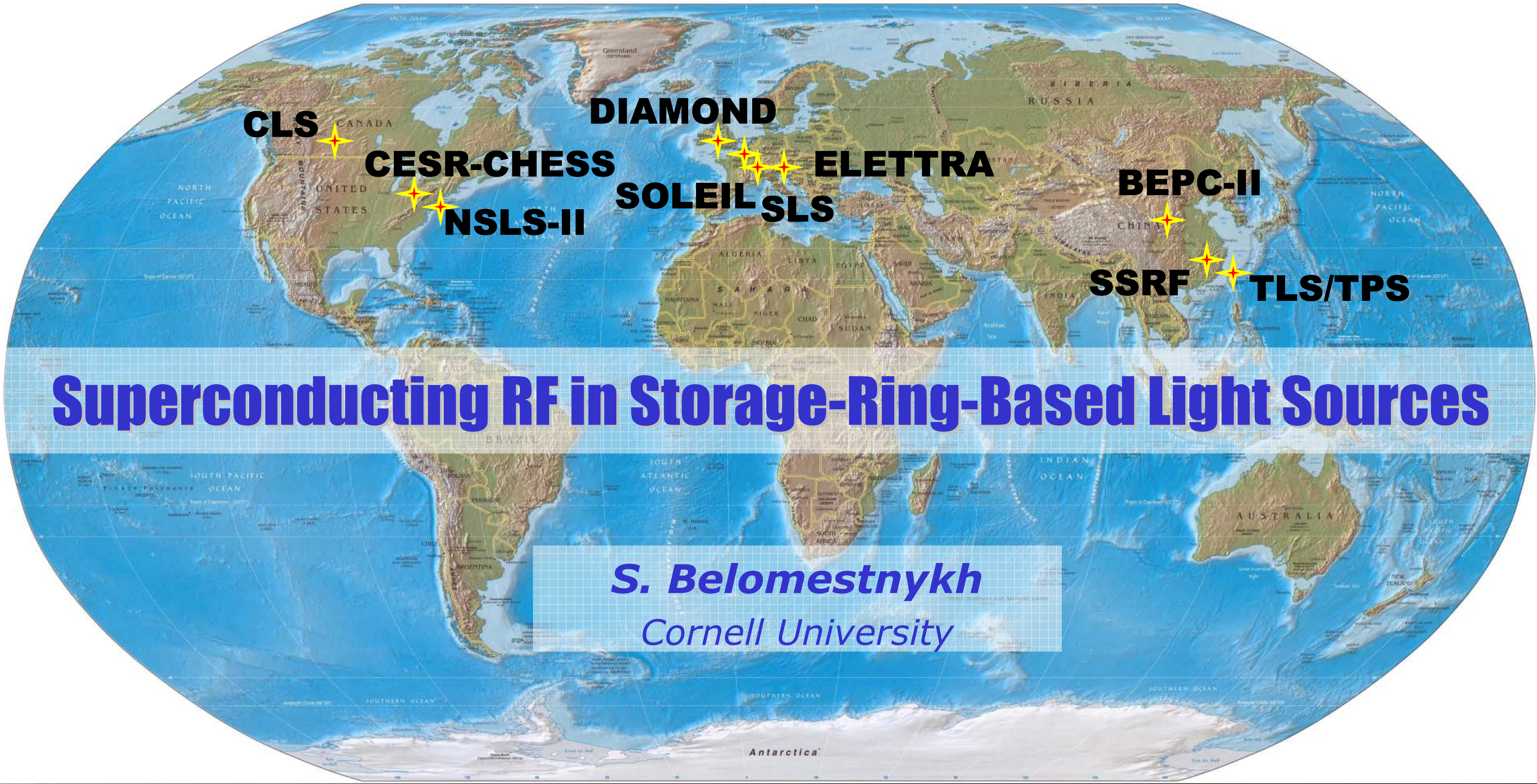
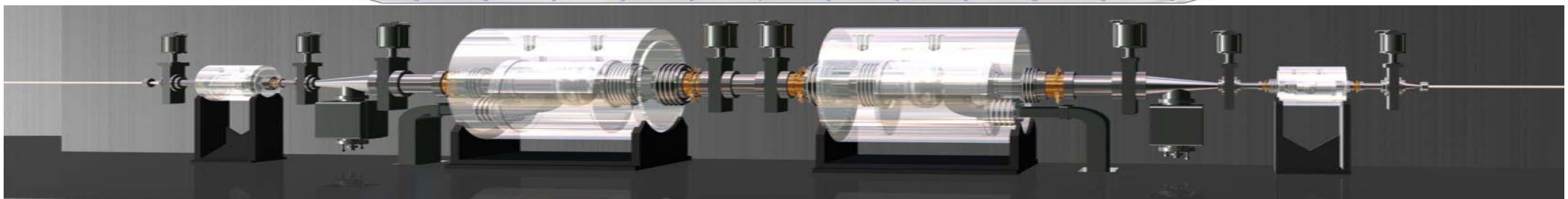
Cornell University
Laboratory for Elementary-Particle Physics



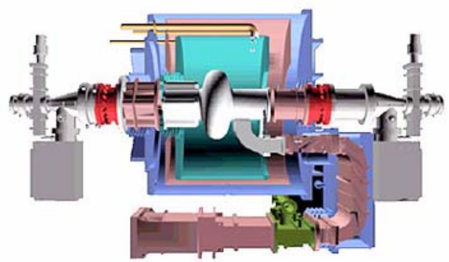
Superconducting RF in Storage-Ring-Based Light Sources

S. Belomestnykh
Cornell University

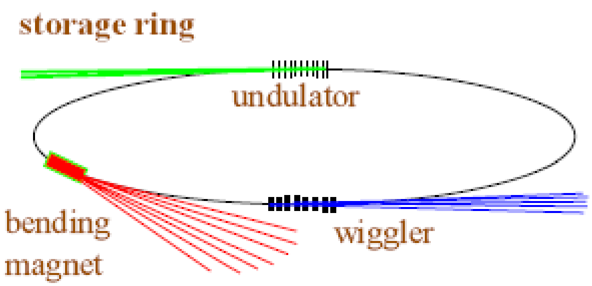


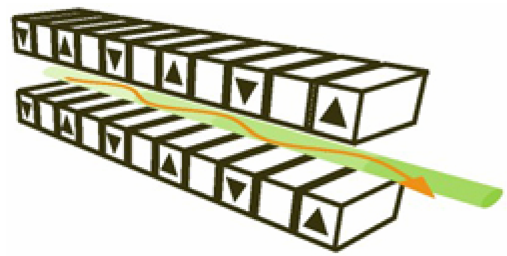
13th International Workshop on RF Superconductivity ● Peking University, October 15, 2007

Light sources

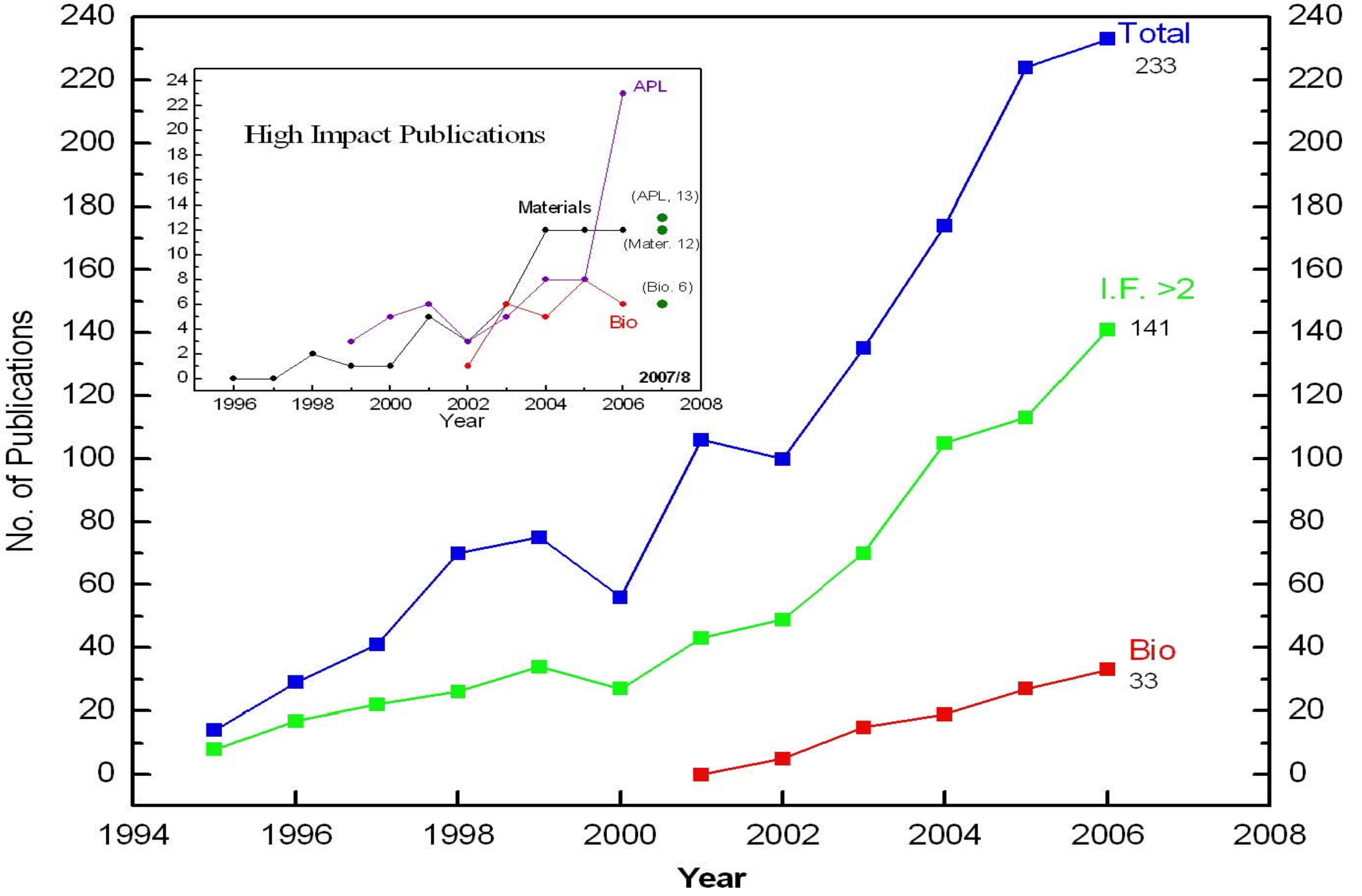


- Third generation synchrotron light sources are small specialized storage rings operating in the energy range of 1.5 to 3.5 GeV, where X-ray beams are generated in insertion devices (wigglers and undulators).
- They produce and will continue to produce the vast majority of research results in the field of X-ray science for years to come.
- Many of these sources are located at small specialized laboratories – user facilities that frequently have very limited resources available for accelerator R&D.





Scientific output: NSRRC example

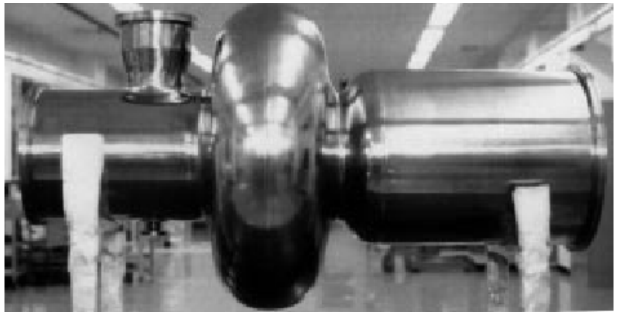


Advantages over normal-conducting technology

- CW operation at higher gradients (<≈10 MV/m) → fewer cavities → save space
- High wall-plug-to-beam power conversion efficiency
- Can transfer a lot of RF-power to the beam (up to 390 kW)
- Large beam aperture → low impedance for high-bunch-charge beams
- Easier HOM damping ($Q \sim 10^2$) → higher bunched beam instability thresholds
- Superconducting HOM-damped, single-cell cavities are ideal for storage rungs

SOLEIL cavity

CESR cavities

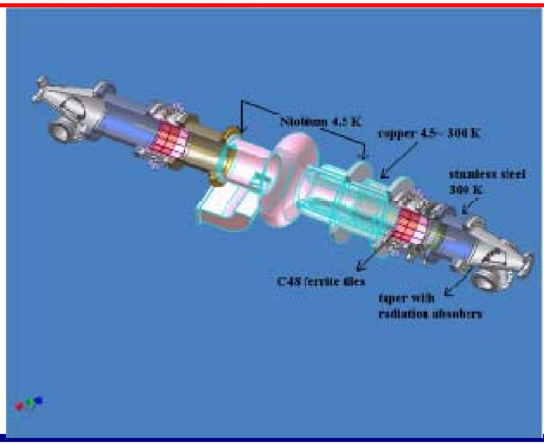


KEKB cavity

Introduction

Decision Making for the SRF Project at NSRRC (1997-2005)

- Guarantee the photon light stability at a higher beam current by using a HOM-free SRF cavity – SC cavity is better than conventional one;
  - Transverse feedback system is absolutely required to stabilize the photon beam;
- Doubling the photon intensity by operating at 500 mA in decay mode
  - Doubling of photon intensity has been achieved at a beam current less than 280 mA in top-up mode.
- Reduce the cavity occupied-length for installing one more insertion device – One cavity for SRF option but two for conventional cavity;
  - Superconduting wigger is installed in down-stream of the same straight section.
- Simplify the configuration of RF plant by using one cavity, one klystron, and one low level rf system;
  - Low-level rf system is challenged for operation with heavy beam loading.
- Increase the Touschek lifetime by enlarging the RF gap voltage (from currently 0.8 MV) to its optimal value, i.e. 1.6 MV
- Build-up the application of SRF technology to accelerators in Taiwan.
  - We are still in the learning stage…



- During the last decade a qualitative change has happened: with successful and reliable operation of HOM damped cavities at CESR and KEKB and the technology transfer to industry, SRF has become the readily available technology of choice for new and small labs with no prior SRF experience.
- Proliferation of superconducting insertion devices made having a cryogenic plant the necessity for every contemporary light source thus providing infrastructure for SRF as well.
- The light sources are user facilities – hence there is emphasis on reliable operation.
- Thus SRF has become a "workhorse" application.
- There are two modes of operation used in SR: active (fundamental RF systems) and passive (3rd harmonic cavities for bunch lengthening).

SR SRF systems

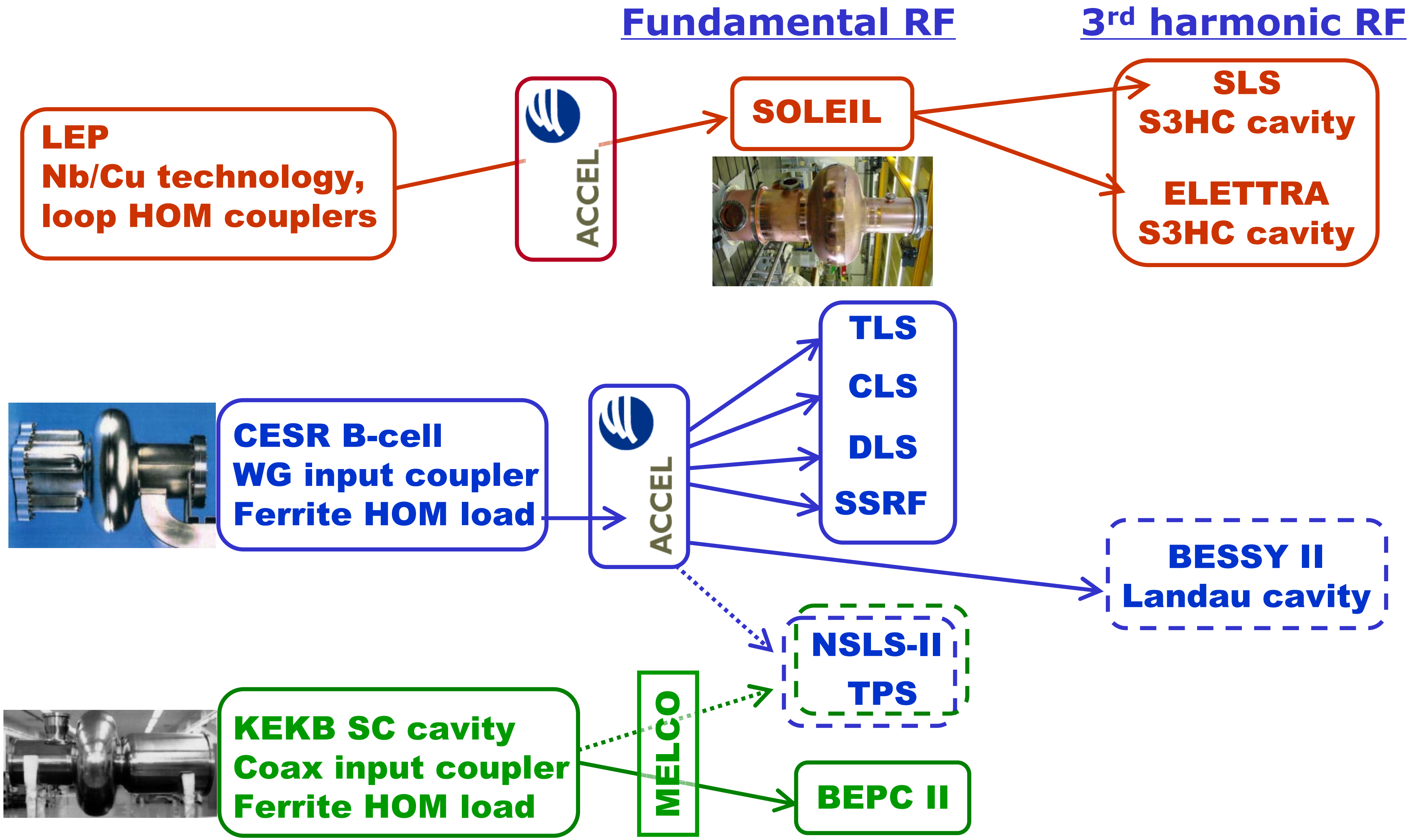
- To date there are **6 fundamental SRF systems** installed in storage-ring-based Light Sources (**CESR-CHESS, CLS, TLS, SOLEIL, Diamond, BEPC-II**) and **2 third harmonic** passive SRF systems (**SLS and ELETTRA**).
- **SSRF** is in early commissioning stage, **NSLS-II** is committed to use fundamental SRF systems, and **TPS** is considering it a base-line option.
- Several facilities are considering upgrades with 3rd harmonic systems.

Fundamental RF systems

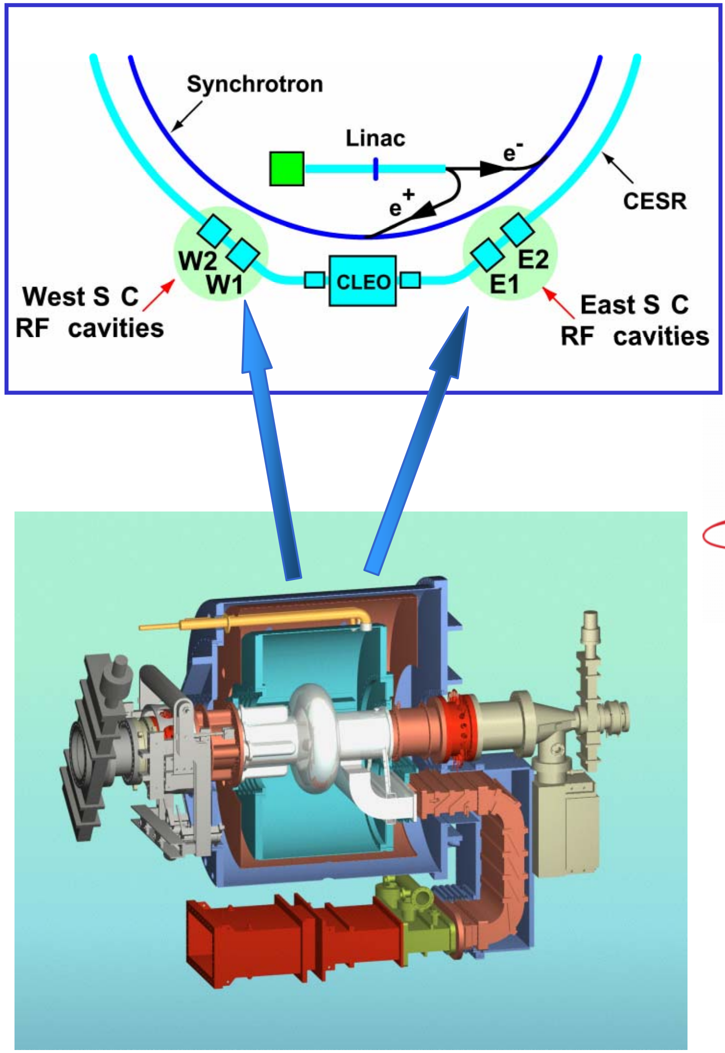
- **Moderate (by SRF standards) accelerating gradients of 4…8 MV/m**
- **Relatively low frequency 352…500 MHz, hence operation at ~4.5 K**
- $Q_0 \approx 10^9$
- **Single-cell cavities with strong HOM dampers ($Q_{HOM} = 10^2… 10^3$)**
- **High average RF power per coupler**

Parameter	units	CESR-CHESS	TLS	CLS	SOLEIL	Diamond	BEPC-II	SSRF	NSLS-II	TPS
Beam energy	GeV	5.3	1.5	2.5/2.9	2.75	3.0	2.5	3.5	3.0	3.0 – 3.3
Beam current	mA	500	500	250 (500)	500	300 (500)	250	200 (300)	500	400
Voltage	MV/ cavity	1.3	1.6	2.4	1.1	2.0 (1.3)	1.5	1.3 (2.0)	1.7 (2.5)	0.9 – 1.2
Number of cavities	–	4	1 (CESR-type)	1 (2) (CESR-type)	4	2 (3) (CESR-type)	2 (KEKB-type)	3 (CESR-type)	4 (2) (CESR- or KEKB-type)	4 (CESR- or KEKB-type)
Beam power	kW/ coupler	160	82	245	150	270 (300)	96	200	225 (500)	180
Status	–	← operating →						Early commissioning	R&D	R&D

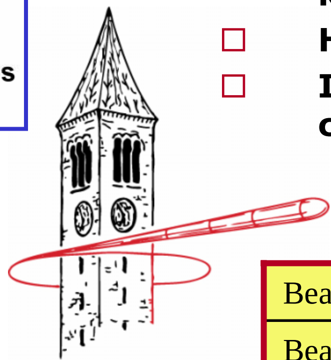
"Family trees"



CESR-CHESS superconducting RF system

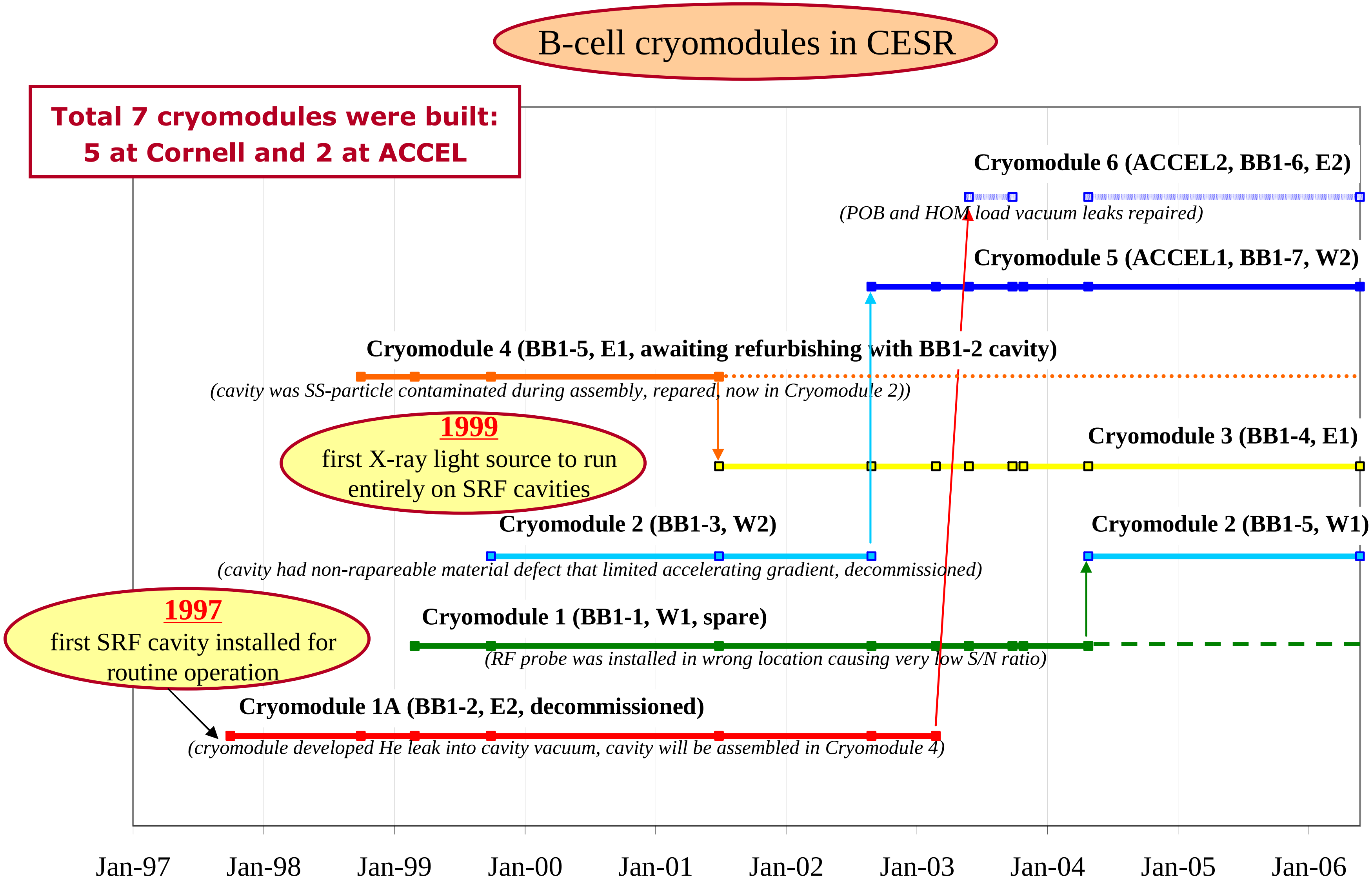


- CESR is a *e+e-* storage ring operating in two regimes: as a collider for HEP experiments and as a 2nd generation synchrotron light source (CESR-CHESS)
- Four superconducting single-cell RF cavities
- Two cavities are driven in parallel by one klystron
- High beam loading → low loaded *Q* factor
- Is scheduled to run until ~2012, when construction of ERL is anticipated to begin

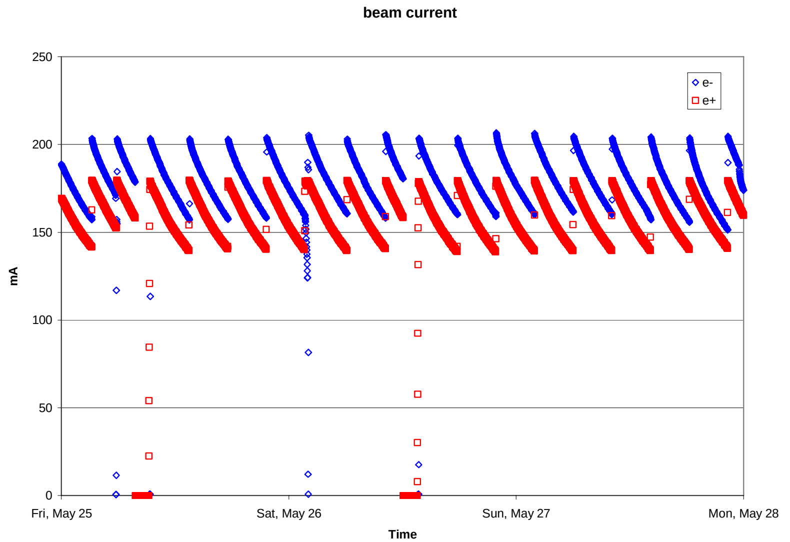


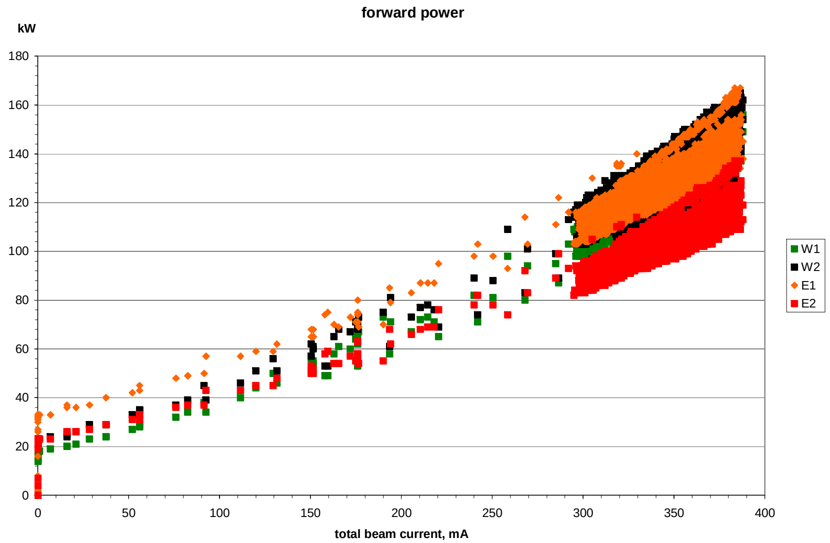
Beam energy	5.3 GeV
Beam current	500 mA
Frequency	500 MHz
Number of cavities	4
R/Q per single-cell cavity	89 Ohm
Q_{loaded} (tunable with WG xfmrs)	1.4×10^5 to 4×10^5
Accelerating voltage per cavity	1.3 MV
Beam power per cavity	160 kW
Number of klystrons	2

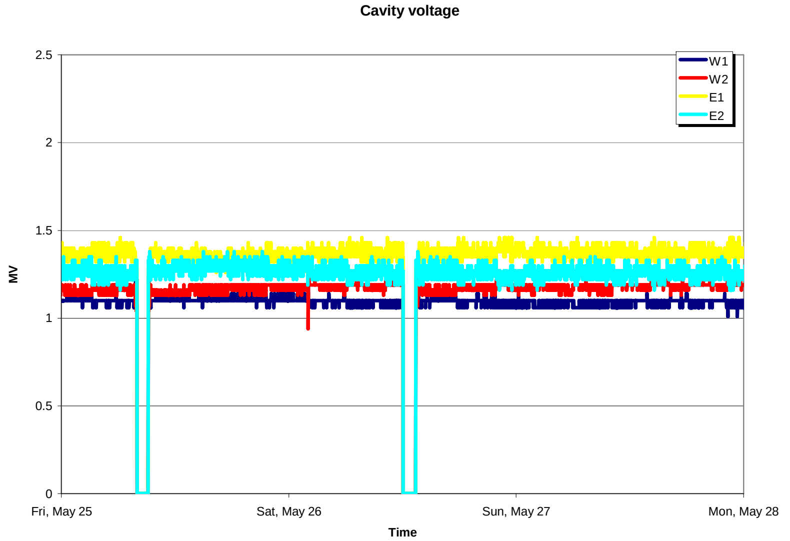
CESR cryomodules history

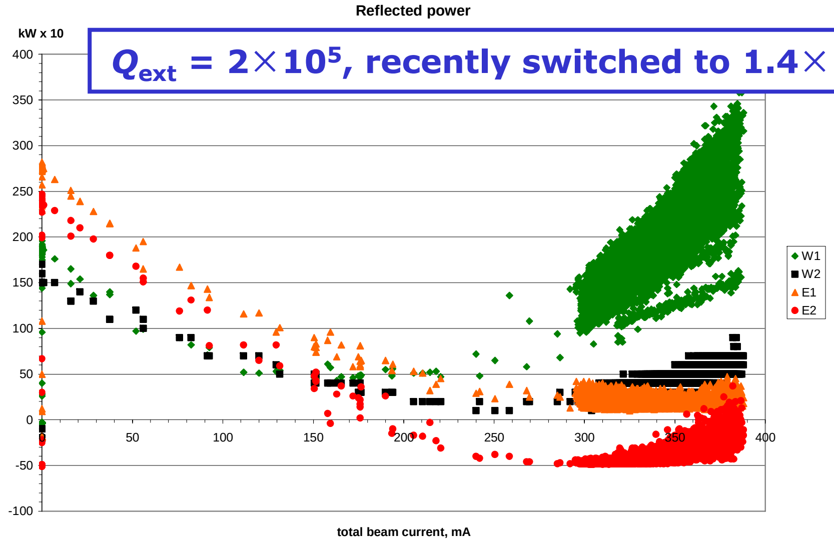


CESR-CHESS operation







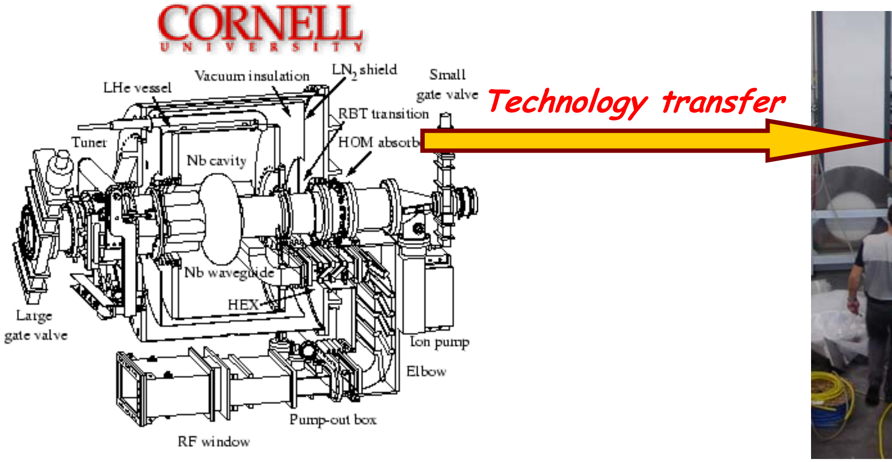


$Q_{ext} = 2\times10^5$, recently switched to 1.4×10^5

Technology transfer

Cornell modules (500 MHz): technology transfer to ACCEL

ACCEL



In **1999** **Cornell University and ACCEL agreed on a technology transfer of the 500 MHz SRF module**
Technology developed for CESR II.
NSRRC had decided to use the Cornell modules in their Light Source and were looking for an industrial supplier that could deliver the modules as a turn key system including valve boxes, transfer lines and SRF electronics.
The following contracts have been concluded meanwhile, making this technology transfer most successful:

2000: 2 SRF modules for NSRRC, Taiwan, delivered operational
2000: 2 SRF modules for CORNELL, USA, delivered operational
2000: 2 SRF modules for CLS, Canada, delivered, operational
2003: 3 SRF modules for DLS, Great Britain, delivered, operational
2005: 3 SRF modules for SSRF, China, 2 delivered and under commissioning, 1 under assembly

WEP52

Turn key system

Turn key Cornell style SRF modules

ACCEL

Scope can cover

- Cavity production
- Surface preparation
- Vertical test
- Coupler production
- Coupler conditioning
- HOM loads
- Module assembly
- Installation
- Commissioning
- Valve boxes
- transfer lines
- SRF Electronics
- Interlock and data acquisition system
- LLRF

Guaranteed module performance:
V_{acc} > 2 MV, Q_0 > 5 x 10^8

Cavity preparation

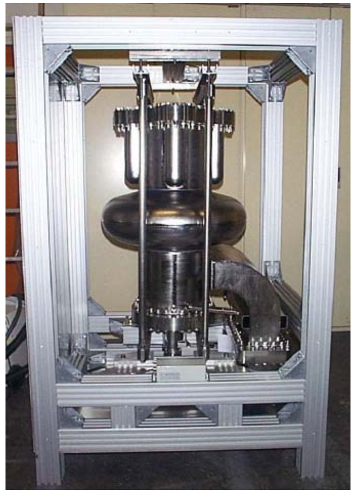
Cavity preparation for vertical test

ACCEL

Closed loop BCP

HPR

Assembly in clean room



Packing and shipping for vertical test

Cavity test results

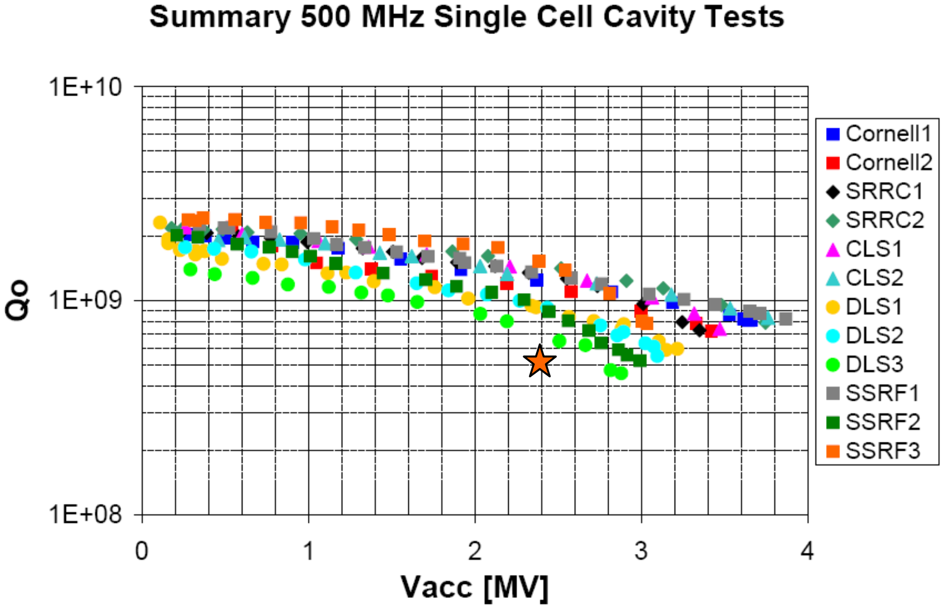
Bulk Nb Cavity preparation and test results

ACCEL

Preparation is done at ACCEL as follows:

- Degreasing
- Buffered chemical polishing (1:1:2), in closed loop chemistry, acid actively cooled to temperatures below 15 °C
- Water Rising > 17 MΩcm
- High pressure water rinsing (100 bar)
- Drying by pumping
- Assembly in class 100 clean room

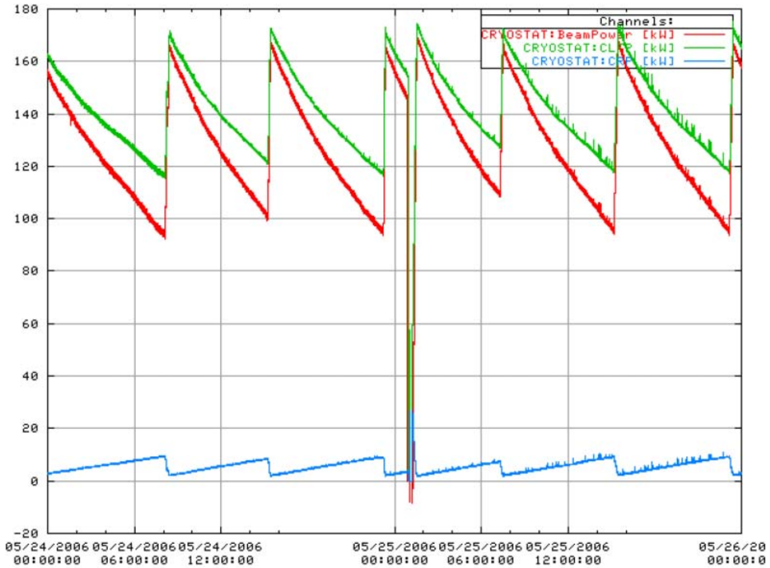
- All test results achieved in consecutive preparations / tests
- All field values limited by available RF power



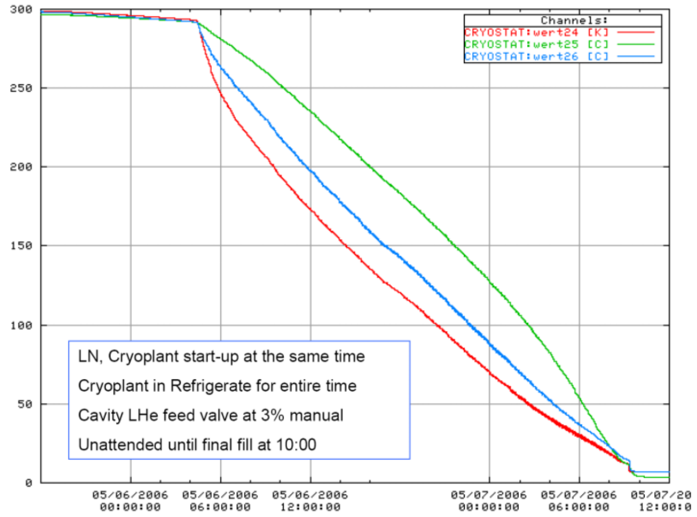
Canadian Light Source

- In 2003 CLS has become the first dedicated Light Source to use SC RF for normal operation
- One superconducting *ACCEL*-manufactured CESR-type cryomodule plus one spare, turn-key system included valve box, local controls and instrumentation
- Fully automated *Linde* TCF-50 cryo-plant with max. capacity of 284 W at 4 K, turn-key system including gas storage, 2000 L dewar, 35 m transfer line; no dedicated cryogenics staff
- 310 kW RF amplifier by *THALES*, turn-key system includes TH 2161B klystron, HVPS, circulator, two 300 kW loads, drive amplifier; spare klystron is stored in Paris, warranty does not start until it is delivered
- Siemens PLC (the same as used for cryo-plant) for xmtr control: $40k less than for EPICS controls if ordered from THALES; very reliable

Beam energy	2.5/2.9 GeV
Beam current	250 (500) mA
Frequency	500 MHz
Number of CESR-type cavities	1 (2)
Q_{loaded}	2×10^5
Accelerating voltage per cavity	2.4 MV
Beam power per cavity	245 kW
Number of klystrons	1 (2)

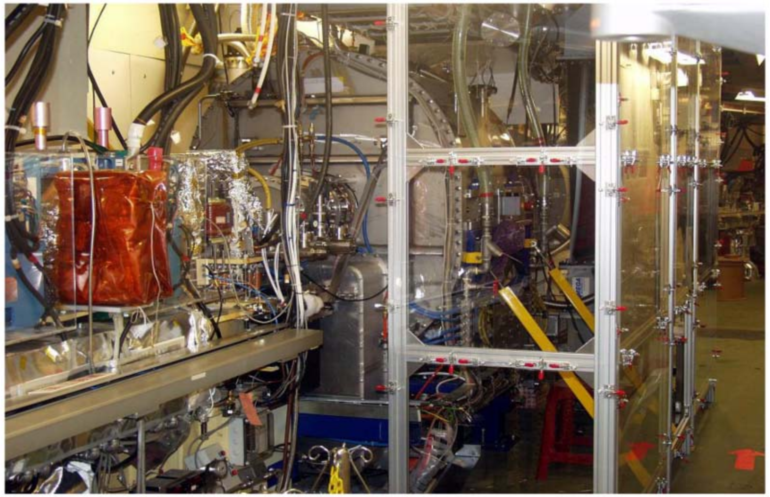


CLS experience



- ◆ Very satisfied with the system performance: it is robust and generally trouble-free
- ◆ RF related trip rate is low, but not yet quantified
- ◆ Rather slow cool-down rate: overnight in automatic mode
- ◆ Had two turbine failures on the cryo-plant
- ◆ ~3 warm-ups per year, during scheduled machine shutdowns (4 to 6 weeks each)
- ◆ Had gate valve failure on one of the cryomodules, replaced and recovered cavity performance
- ◆ WG input coupler required substantial beam conditioning at high power (cavity #1)
- ◆ After storage under dry nitrogen for 1 year, cavity #1 was operating at 2.2 MV in storage ring within 4 hours of cool-down
- ◆ LLRF: I/Q, PLC controls, slow RF ramp down for machine protection, fast for RF trips
- ◆ Routine operation at 2.3 to 2.4 MV with beam current up to 250 mA ⇒ 225 kW of RF power to beam
- ◆ During an early test achieved 300 mA, with 270 kW, presently limited by external coupling. Plan to begin routine operation at 300 mA soon
- ◆ Observe slow increase of the cavity vacuum from 0.1 to 1.5 nTorr over 3 – 4 months (mostly hydrogen) accompanied by increase of the cavity dissipation. The system warm-up and cool-down restores original low dissipation.
- ◆ Plan to replace *ACCEL*-supplied electronics with PLCs
- ◆ Long term plan: install second cavity with additional RF amplifier for 500 mA operation

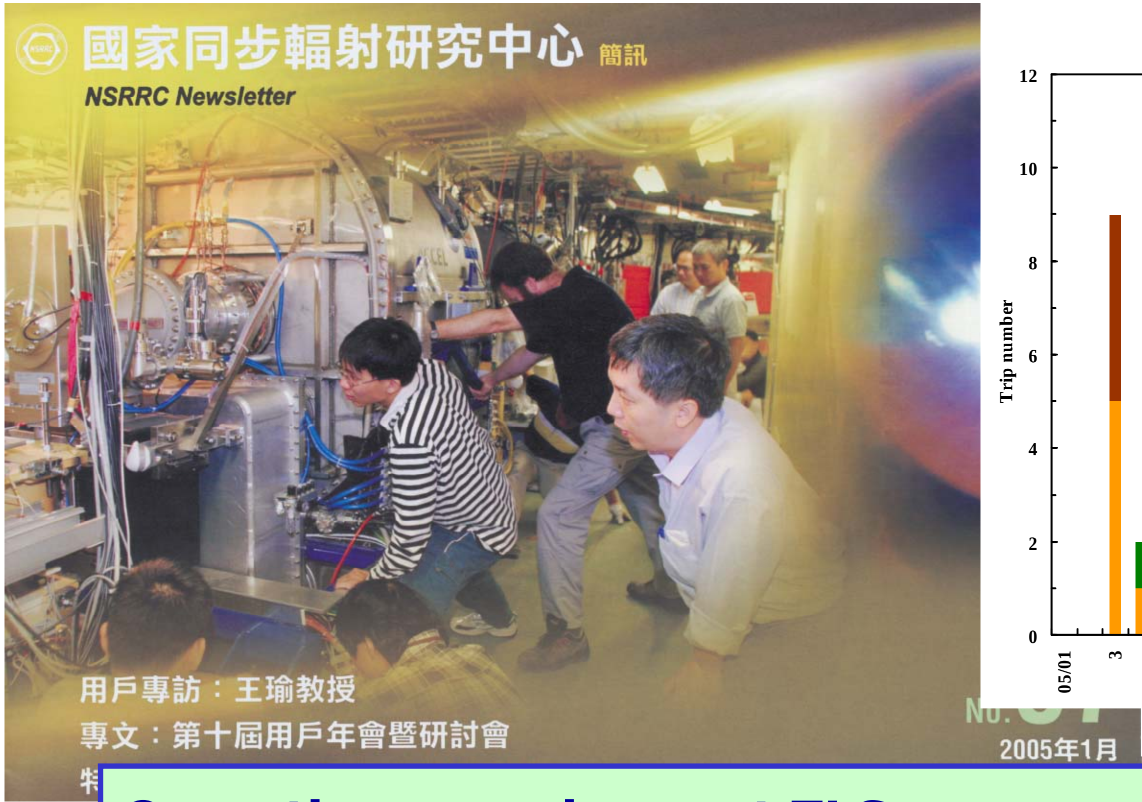
Taiwan Light Source

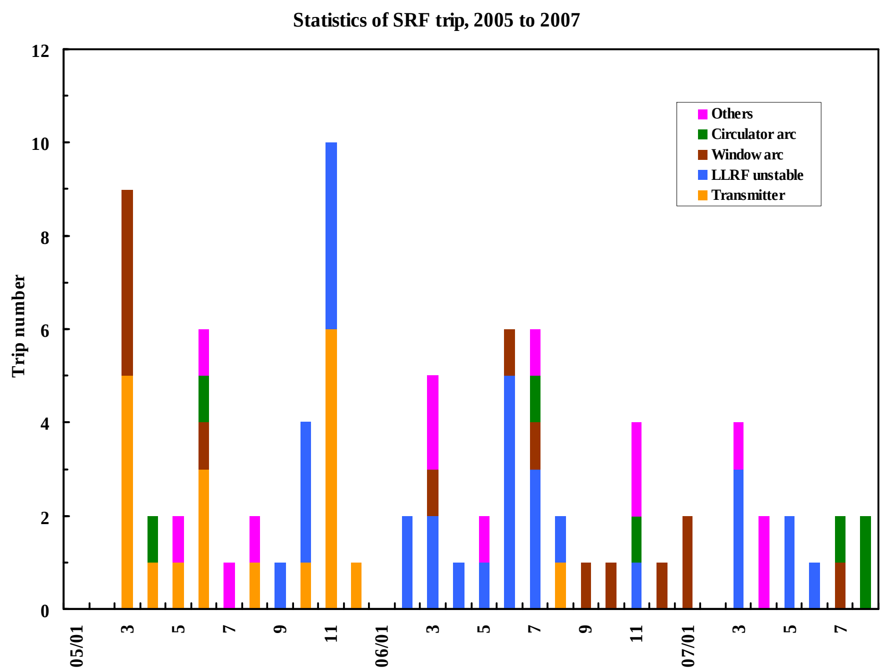


- TLS has begun its operation in 1992 with a normal conducting RF (DORIS cavities)
- SRF installation was part of an upgrade
- The first superconducting *ACCEL* CESR-type cryomodule has been in operation since 2004
- The second cryomodule is a spare (2005)
- Turn-key system included valve box, local controls and instrumentation
- 100 kW *CPI* klystron

Beam energy	1.5 GeV
Beam current	500 mA
Frequency	500 MHz
Number of CESR-type cavities	1
Q_{loaded}	2.2×10^{5}
Accelerating voltage per cavity	1.6 MV
Beam power per cavity	82 kW
Number of klystrons	1

TLS experience

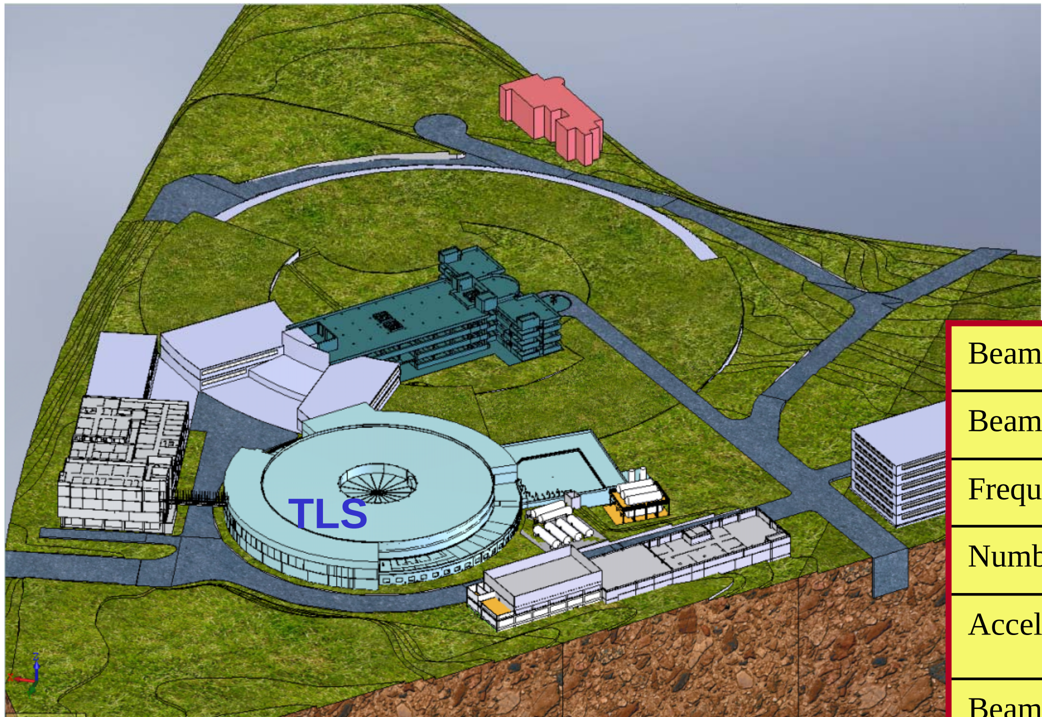




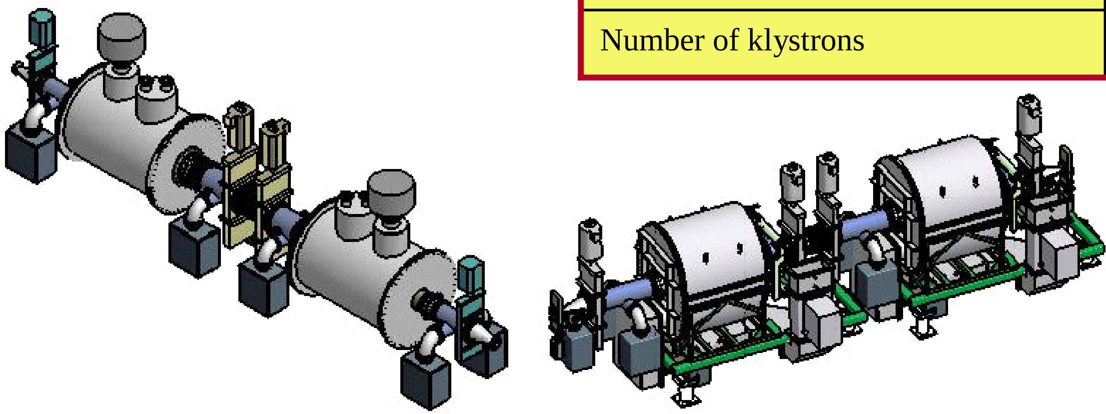
Operating experience at TLS:

- ◆ 300-mA top-up operation is routine; the machine is ready for 400 mA
- ◆ replacement of old cavities with the SRF cavity cured longitudinal coupled-bunch instabilities
- ◆ average 1 trip/wk during user shifts, recently improved to 0.5 trips/wk
- ◆ intensive manpower is required for SRF maintenance

TPS at NSRRC



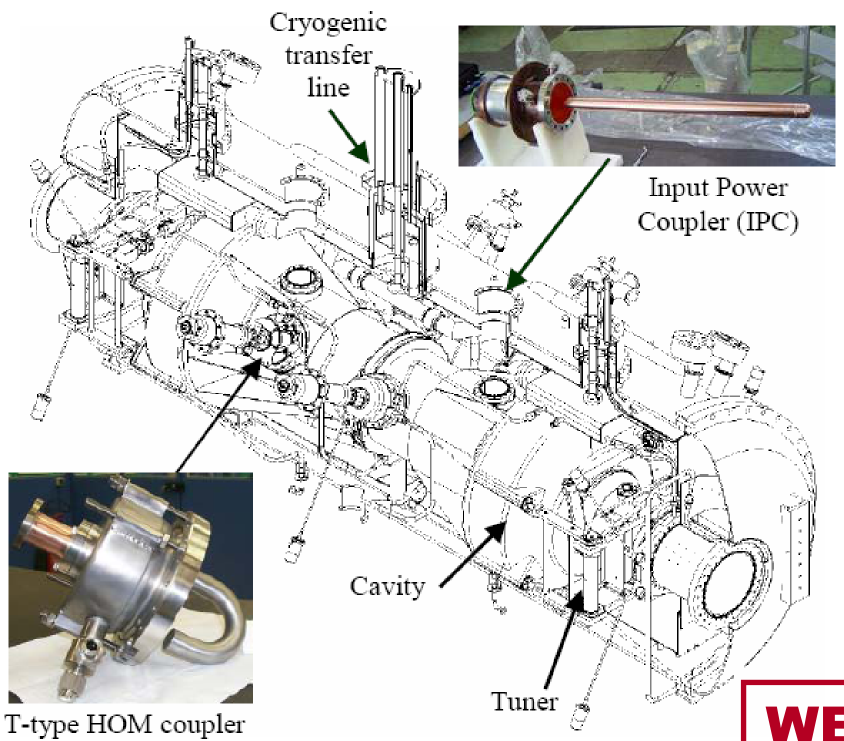
Beam energy	3.0 – 3.3 GeV
Beam current	400 mA
Frequency	500 MHz
Number of cavities	4
Accelerating voltage per cavity	0.9 – 1.2 MV
Beam power per cavity	180 kW
Number of klystrons	4

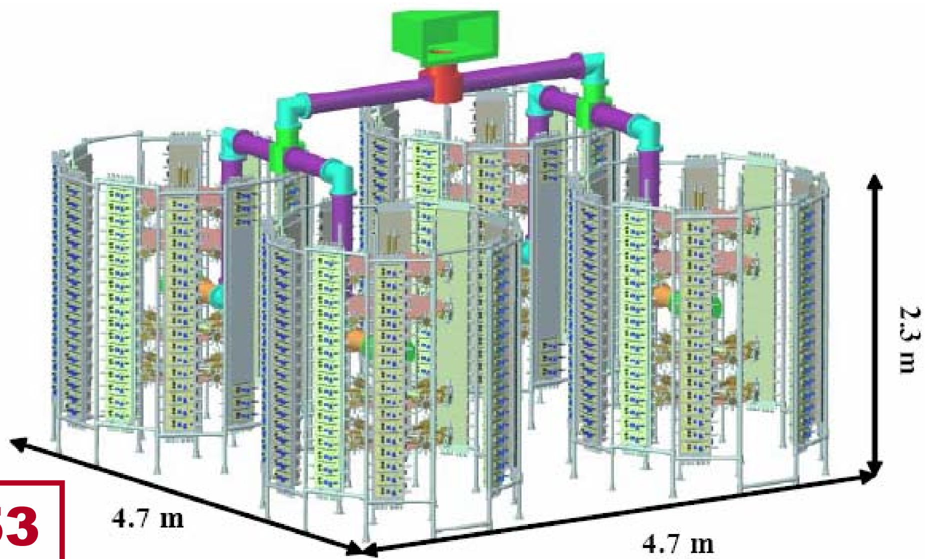


SOLEIL

- Nb/Cu single-cell HOM damped cavities
- 2 two-cavity cryomodules
- LEP input couplers, loop HOM couplers
- First cryomodule is designed and built by Saclay/CERN collaboration
- Second cryomodule is on order from *ACCEL*
- 180 kW solid state RF amplifier

Beam energy	2.75 GeV
Beam current	500 mA
Frequency	352 MHz
Number of cavities	4
Q_{loaded}	1×10^5
Accelerating voltage per cavity	1.5 MV
Beam power per cavity	150 kW
RF power plant	Solid state amplifier





WEP53

SOLEIL operational experience

CM1 had been RF conditioned with full reflection (I_{beam}= 0) up to 200 kW at CERN and up to 80 kW, once installed in the SOLEIL SR (always kept under HUV).

Re-conditioning with beam (2006) went quite smoothly: a few coupler vacuum trips, at first when reaching ~ 150 kW ; further conditioning likely would be required for operating at such power level ; however, with proper settings, P_i < 145 kW up to 300 mA with a single CM, which is more demanding than 500 mA with 2 CMs.

What the beam sees passing through the SOLEIL module

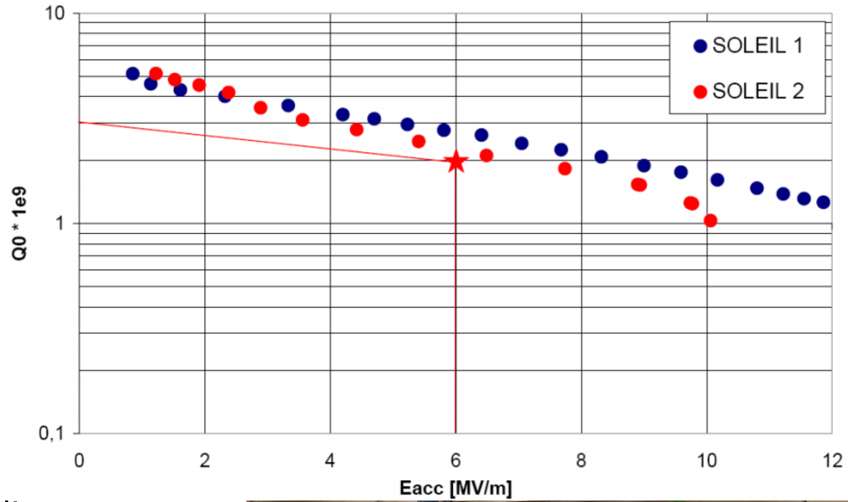
No evidence of HOM excitation: up to 300 mA, power dissipation in the HOM loads always negligible & residual beam phase oscillations < 0.1°

Taking care of using the cavity tuners sparingly → cst tuning operation as much as possible
+ additional diagnostic → rev counter for early detection of signs heralding a sticking

SOLEIL: status of the second cryomodule order from ACCEL

- **SOLEIL decided in October 2005 to order the second cryomodule from ACCEL**
- **All componects are produced; two cavities successfully tested in vertical cryostat at CERN (at first Nb sputtering for cavity 1and at second try for cavity 2) → CM2 is being assembled**
- **Complete CM2 (cryo + RF power) tests scheduled for beginning 2008 at CERN**
- **Installation and commissioning in SOLEIL SR → May 2008 shut-down**

After EB welding



After helium vessel welding

SOLEIL: operational experience with cryogenic plant

At the beginning of the commissioning, difficulties were encountered with pressure instabilities inside the cavity He tank, due to thermal oscillations.

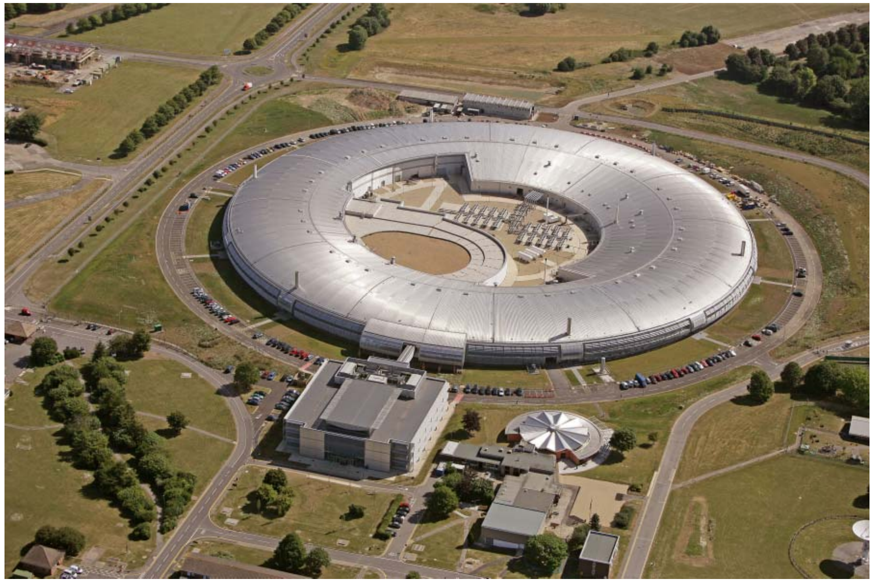
This was solved after bringing in slight modifications on the cryogenic valve box. The system has then become very reliable and the pressure variations could be kept below ± 1 mbar, namely ± 0.1° in phase.

A few shutdowns, triggered by utility losses (water or electrical), have demonstrated the ability of the system to restart automatically and recover within a short time.

SOLEIL: operational experience with RF power amplifiers

- The two 180 kW solid state amplifiers for CM1 have demonstrated a good reliability in operation : after 4 000 running hours, they are not yet liable for any loss of beam time
- Although not perturbing for the operation, 40 (out of 1450) modules have suffered a transistor failure; for 15 of them, it is the result of a circulator load failing
- The failure rate is decreasing with time
- **However, longer running periods are required in order to find out what comes from the *infant mortality* and what is the *actual MTBF***
- **100 available spare modules → turn over : 50 usable in house while 50 under repair**
- *Investigations of other suitable transistors are going on* **: 2 samples of the *BLF369*, newly developed by Philips, have been tested and the results are quite promising; a 2.5 kW unit (8 modules) is being constructed for long duration power tests**
- **Concerning the amplifiers 3 and 4 for the CM2, 6 of the 8 required 45 kW towers are already completed → Power tests of the 2 complete amplifiers by the end of 2007**

Diamond Light Source

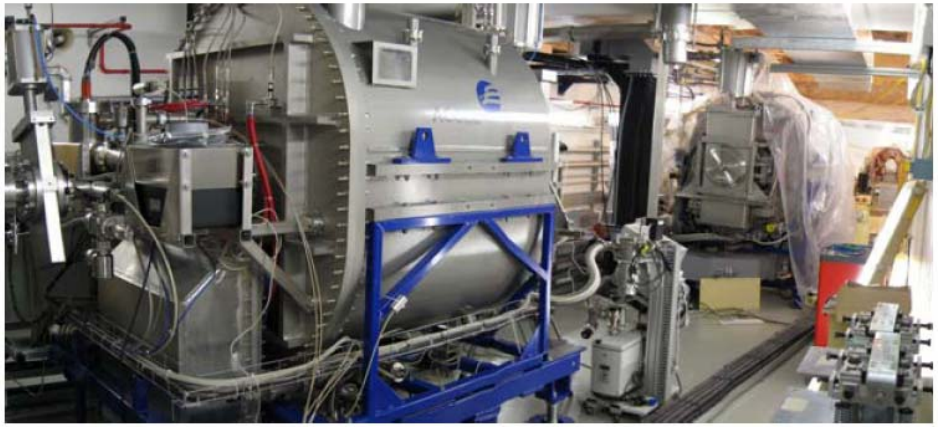


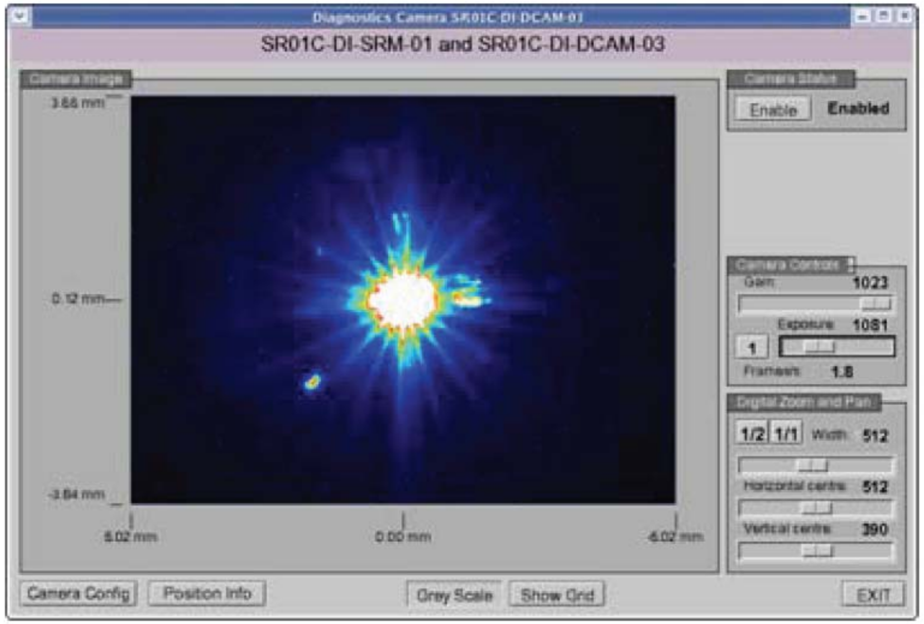
Beam energy	3 GeV
Beam current	300 (500) mA
Frequency	500 MHz
Number of CESR-type cavities	2 (3)
Q_{loaded}	2×10^5
Accelerating voltage per cavity	2.0 (1.3) MV
Beam power per cavity	270 (300) kW
Number of IOT RF stations	2 (3)

- **Three (initially two) superconducting *ACCEL* CESR-type cryomodules**
- **Cryostats are mechanically modified to fit into limited space and to accept multi-channel transfer lines**
- **300 kW four-tube IOT RF amplifiers from *Thomson Broadcast & Multimedia*, reached 61% efficiency**

WEP73

DLS experience





First synchrotron light from Diamond Storage Ring

Operational experience at Diamond:

◆ three cryomodules delivered, two installed, met specifications during commissioning w/o beam

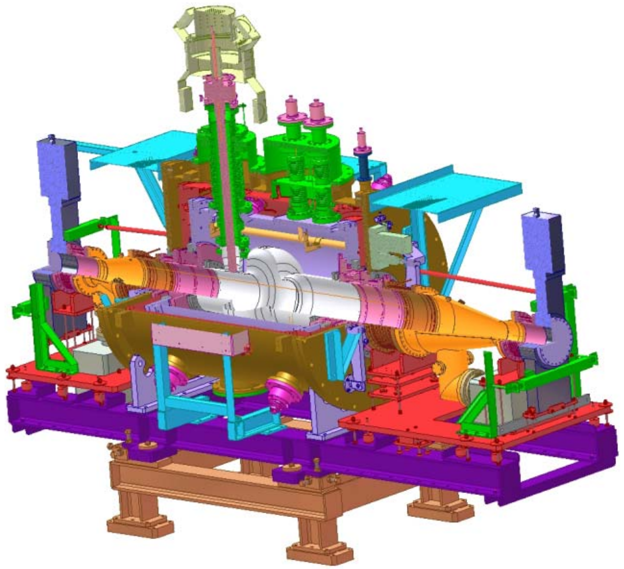
◆ during operation one of installed cryomodules developed a leak from He vessel to insulation vacuum, removed for repair

◆ started storage ring commissioning at 3 GeV with one cavity, the second was installed during the machine shutdown in March/April’07

◆ to date achieved 300 mA beam current although not yet with IDs operational

◆ a number of difficulties with processing cavities, cryogenics, tuner operation, still have quite high trip rate

BEPC-II



Beam energy	2.5 GeV
Beam current	250 mA
Frequency	500 MHz
Number of KEKB-type cavities	2
Q_{loaded}	1.7×10^{5}
Accelerating voltage per cavity	1.5 MV
Beam power per cavity	96 W
Number of klystrons	2

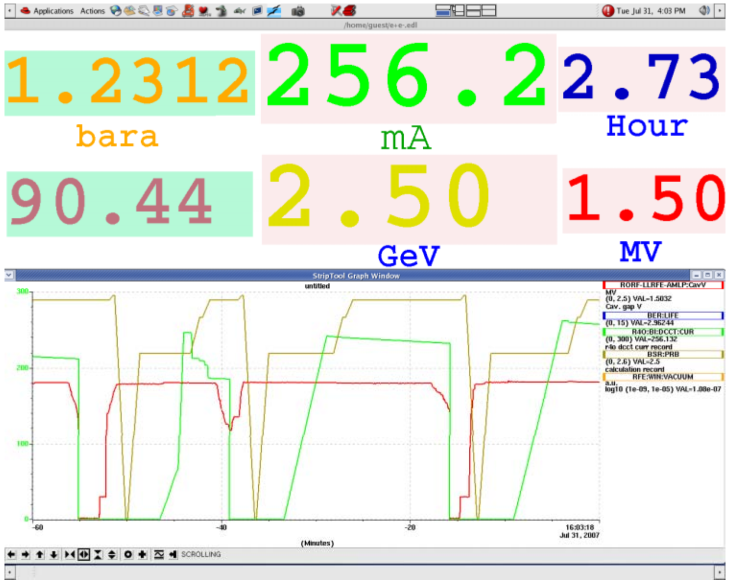
BEPC-II superconducting RF

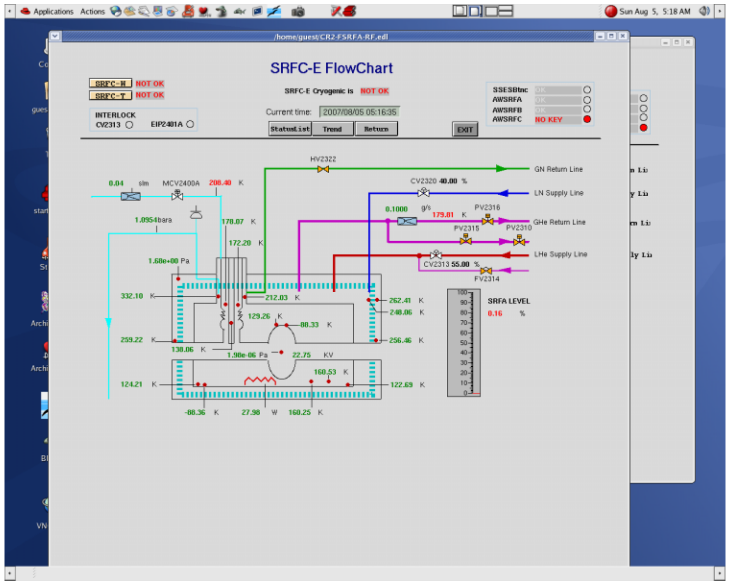
- Two superconducting KEKB-type cryomodules produced by KEK and MELCO, both reached 2 MV during horizontal tests
- Cavities redesigned from 509 MHz to 500 MHz
- Two modes of operation: light source and collider
- Last light source user run: 180 mA @ 2.5 GeV
- During a test run achieved 250 mA
- Major concerns: vacuum chambers temperature rise and the input coupler vacuum

**WEP16, WEP18
WEP19, WEP23
WEP44, WEP82
WEP51, TUP09**

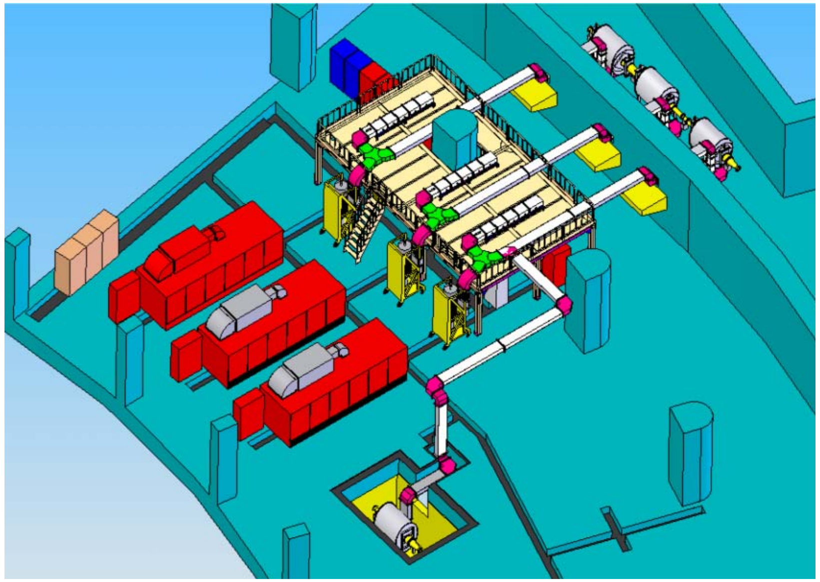
BEPC-II

KEKB cavity (blue) and IHEP cavity (white.)





SSRF



Beam energy	3.5 GeV
Beam current	300 mA
Frequency	500 MHz
Number of CESR-type cavities	3
Q_{loaded}	1.7×10^5
Accelerating voltage per cavity	2.0 MV
Beam power per cavity	250 kW
Number of RF stations	3

SRF system for SSRF:

- 3 *ACCEL* CESR-type cryomodules: 4 to 6 MV, 600 kW
- 650 W refrigerator (*Air Liquid*)
- three 310 kW klystron power amplifiers by (*THALES*)
- under consideration: 3rd harmonic passive cavity system to improve beam life time and SC crab cavities for short x-ray pulse generation

WEP38
WEP46

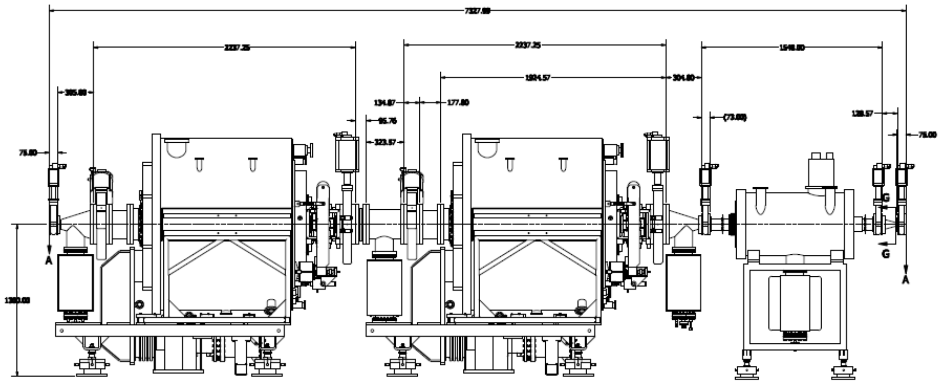
SSRF: commissioning progress

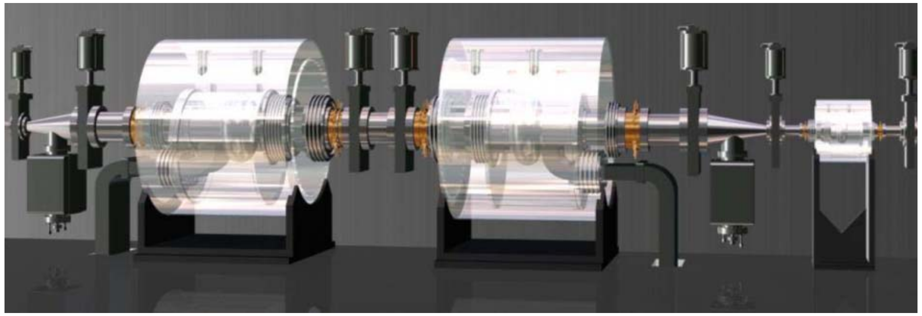
◆ The 1st module has been tested at 4.5 K temperature together with valve box and transfer lines at ACCEL, and it has been installed in the storage ring tunnel. The 2nd module has been tested in the same way and has arrived at SSRF. The 2nd module will be moved into the test cave and tested with digital LLRF control system.

◆ Transmitter is composed of TH2161B klystron and PSM power source, P_{max} = 300 kW. Up to now, the 1st set has been tested successfully running 50 hours continuously, all parameters met SSRF specifications. The other two sets are under test at SSRF.

◆ Digital LLRF control system adopts digital I/Q scheme based on FPGA to maintain the constant amplitude and phase of accelerating field in the superconducting cavity and to tune the cavity frequency resonant at 499.654MHz. The prototype set up has been developed and tested successfully.

NSLS-II





Beam energy	3 GeV
Beam current	500 mA
Frequency	500 MHz
Number of cavities	2+1 (4+2)
Q_{loaded}	1.2×10^{5} (6.7×10^{4})
Accelerating voltage per cavity	1.65 (1.25) MV
Beam power per cavity	270 kW
Number of RF stations	2 (4)

SRF in proposed NSLS-II:

◆ 3 GeV, 500 mA x-ray storage ring; full energy booster; 600 MeV linac

◆ will need over 5 MV and 1 MW of RF power in the x-ray ring: 4 CESR-type (KEKB-type is an option) cryomodules with 2 third harmonic cavities for bunch lengthening

◆ development of high power and/or dual antennae coupler would reduce number of cavities from 4 to 2

Third harmonic cavity for ELETTRA

The case for a Superconducting 3rd harmonic cavity

- Not having a full energy injector, a critical issue for Elettra was the Touschek dominated beam lifetime.
- In 1999 it was thus decided to use a **3rd harmonic RF cavity** to flatten the potential in the main RF bucket and increase the bunch length; a corresponding increase in the Touschek lifetime is foreseen.
- In addition, given the non-linearity of the RF waveform, a contribution in fighting the longitudinal coupled bunch instabilities (Landau Damping) was also foreseen.
- Following requirements were set for the 3rd harmonic cavity:
  - fit to the space constraints on the storage ring.
  - be passive (beam induced RF voltage) and require as minimum as possible extra RF power from the main, normal conducting, 500 MHz RF system.
  - be HOM free.
  - be easy to "park" in-between two revolution frequencies (make it invisible to the beam).
- A **SUPERCONDUCTING** cavity has been identified as the best solution to the above requirements.

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June 5-6, 2006 – NSRRC, Hsinchu
The ELETTRA SC 3rd HC - M.Svandrlik

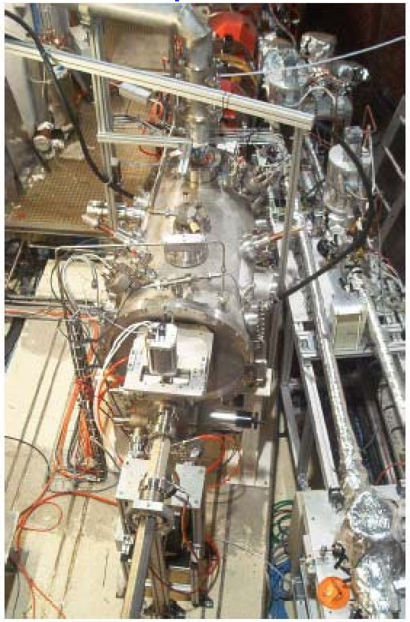
5

Super 3HC cryomodules for ELETTRA and SLS

The SUPER-3HC Project

In 1999 a collaboration was established to build 2 Superconducting Cavities based on a scaling to 1.5 GHz of the 350 MHz **SOLEIL cavity**.

- **CEA-DAPNIA Saclay:**
  - ✓ Cryomodule fabrication: tuning system working in vacuum and at cryogenic environment, thermal insulation, shield, HOM couplers, etc…
  - ✓ Structure optimization and HOM studies with ELETTRA.
  - ✓ Cryogenic system specification with PSI.
- **CERN :**
  - ✓ Cavity construction.
  - ✓ Final assembling in clean room (interfaces to Vacuum chambers).
- **Paul Scherrer Institute (PSI):** installation on the Swiss Light Sc
- **Sincrotrone Trieste:** installation on ELETTRA.



ELETTRA cryomodule

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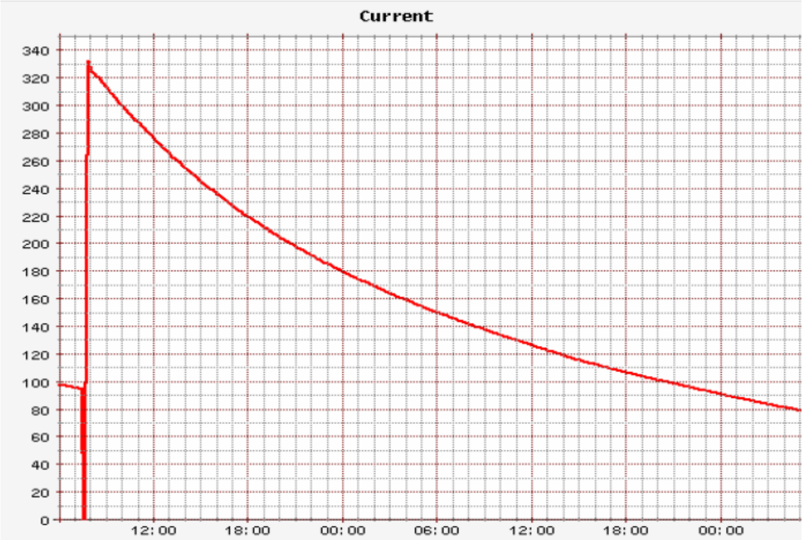
The ELETTRA SC 3rd HC - M.Svandrlik

ELETTRA experience



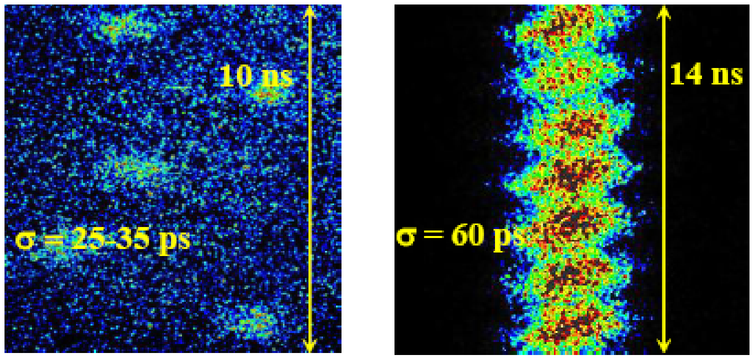


Figure 5: 250 mA, 2.0 GeV, streak camera images. On the left S3HC detuned, longitudinal oscillations present; on the right S3HC tuned, stable beam. Theoretical σ without S3HC is 18 ps.

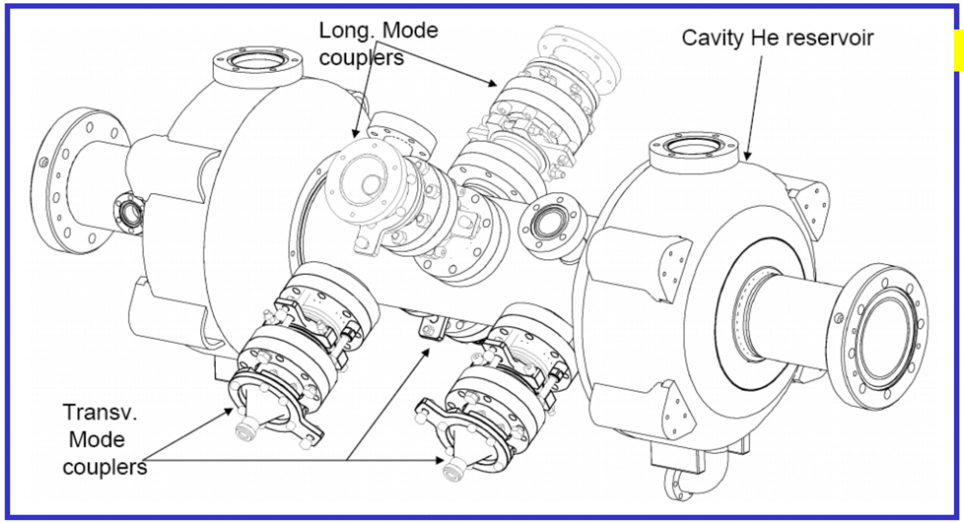
The ELETTRA SC third harmonic cavity:

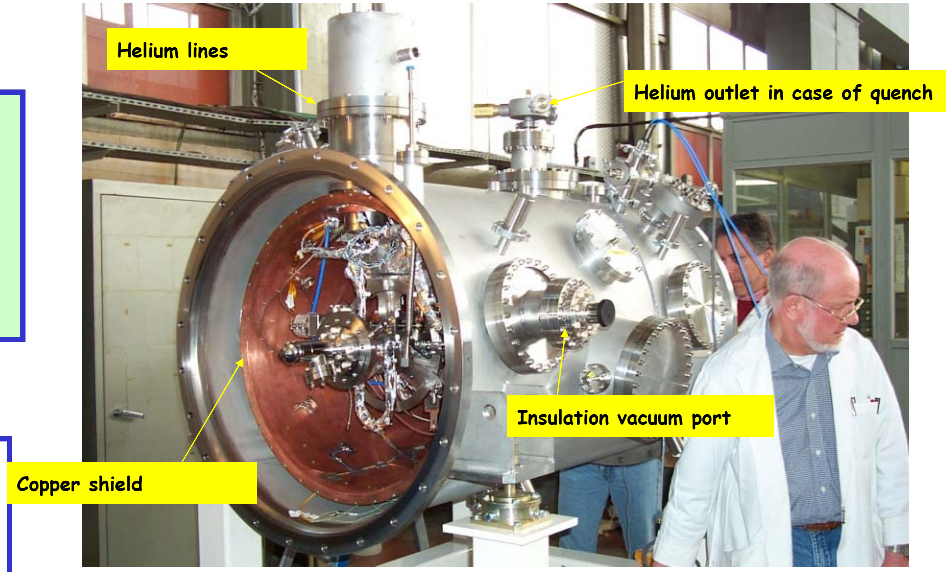
- ◆ 5,000 hrs/year for users, 6,000 hrs/year including m.s.
- ◆ beam current is 150 mA @ 2.4 GeV, 330 mA @ 2.0 GeV; injection energy is 0.9 GeV
- ◆ the 3HC is in operation since 2003: f_{3h}+64 kHz; 0.6 MV (1 MV_{max}) = 0.3 MV/cell ⇒ 3 MV/m (5 MV/m_{max}); dynamic RF power loss is 22 W; 1.1 m long cryomodule
- ◆ beam lifetime is increased by a factor 3 to 3.5 and is now 22 to 27 hrs; refill every 36 hrs
- ◆ longitudinal coupled bunch instabilities are suppressed
- ◆ reliability of the SC cavity and the cryo-plant (HELIAL 1000 refrigerator by *AIR LIQUID*) is very good
- ◆ bunch shortening experiment: detuned to -62 kHz from -140 kHz, observed bunch shortening by a factor of 1.6
- ◆ In the last years there were several problems with the cold gear boxes of the tuning system. Thermal heating due to operation of the motors can lead to damage the gear boxes covering and block the system. CEA team (P.Bosland et al.) is working on a new gear box design (planetary gear box), which is going to be installed and tested during the next long shut-down at the end of this year.

SLS experience

The S3HC at SLS:

◆ Stable operation at design beam current of 400 mA, lifetime is 8 hrs, factor of 2 higher than w/o S3HC





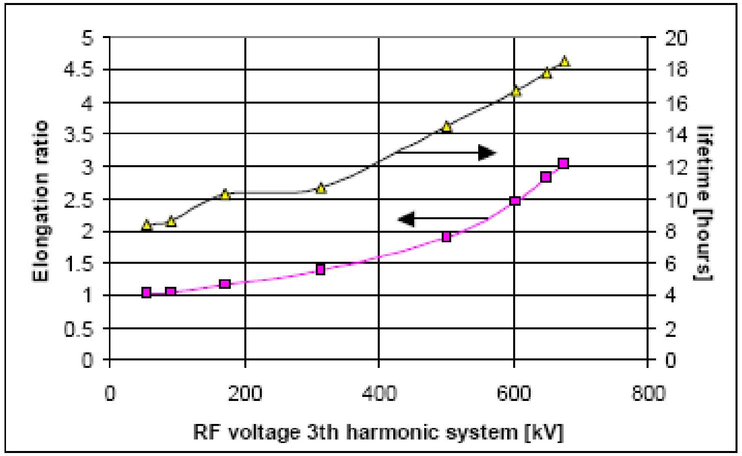


Figure 4:Average elongation ratio and lifetime versus S3HC voltage (180 mA – 2.08 MV operation).

Summary

- Three different reliable and proven superconducting RF cryomodule designs for storage-ring-based light sources exist and can be purchased from industry.
- Using passive cavities for bunch length manipulation to improve the beam lifetime and suppress longitudinal coupled bunch instabilities is very efficient. First successful applications are SLS and ELETTRA.
- Operating and commissioning experience with new SRF systems is in general very positive. The systems are robust, easy to operate and fulfill expectations.
- More new projects are coming (SSRF, NSLS-II, TPS…)

Acknowledgements

I would like to thank people who provided materials for this presentation:

Chaoen Wang (NSRRC)
Michael Pekeler (ACCEL)
Patrick Marchand (SOLEIL)
Morten Jensen (DLS)
Mark de Jong (CLS)
Guangwei Wang (IHEP)
Giuseppe Penco (ELETTRA)
Jianfei Liu (SSRF)
Jim Rose (BNL)
Alexander Anghel (PSI)