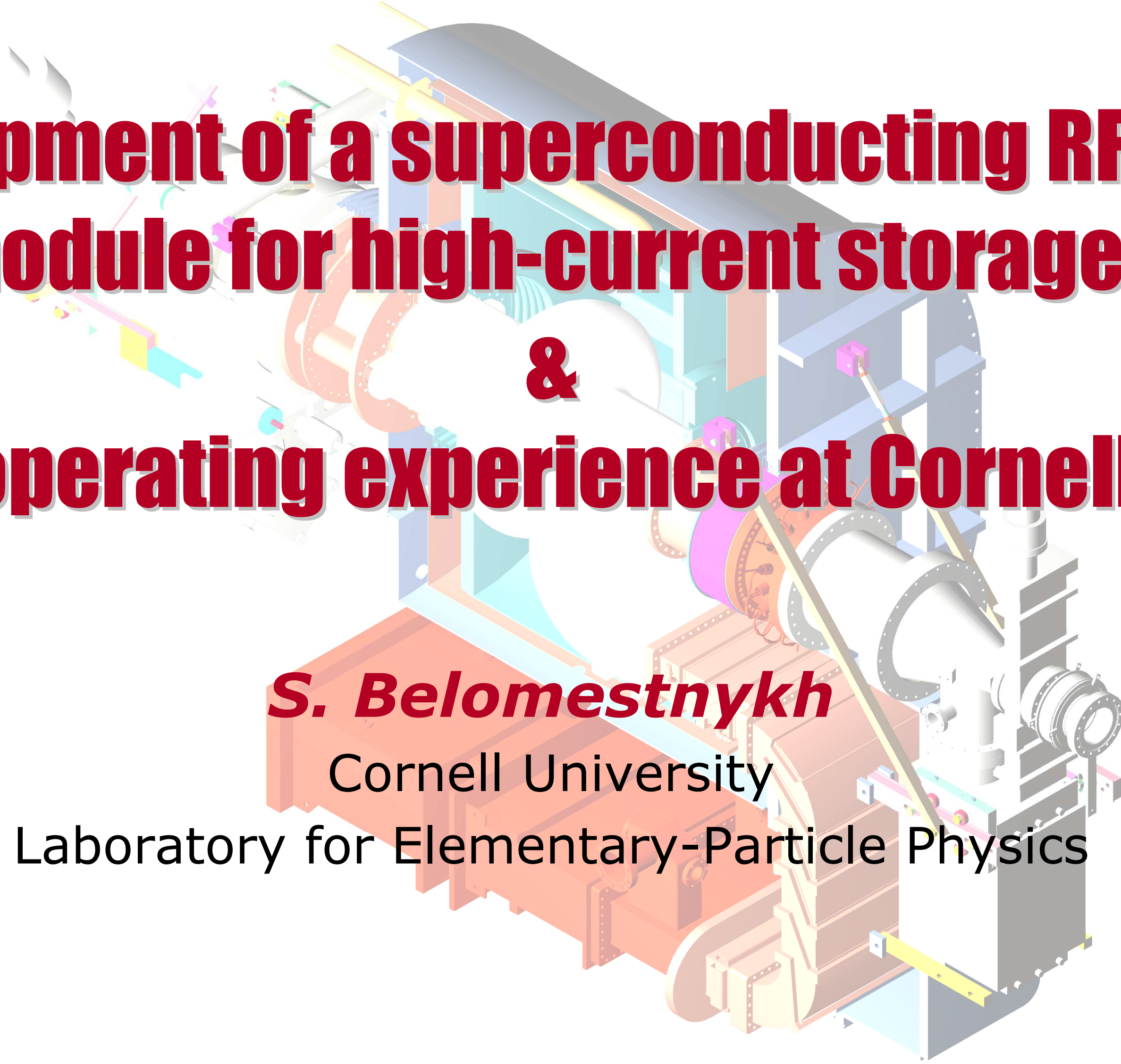
Development of a superconducting RF cavity cryomodule for high-current storage rings & operating experience at Cornell



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Abstract

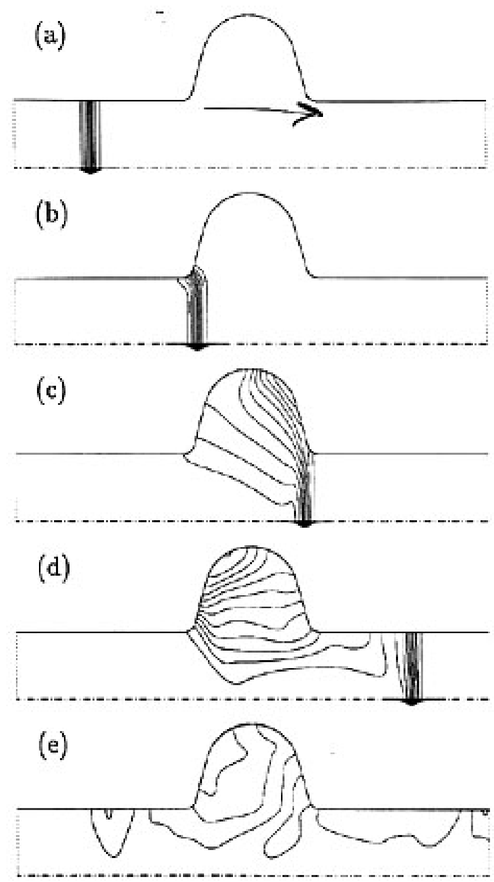
A single-mode 500 MHz superconducting cavity cryomodule has been developed at Cornell for the electron-positron collider/synchrotron light source CESR. The Cornell B-cell cavity belongs to the first generation of high-power, HOM-damped accelerating cavities designed to support high average beam currents in storage rings. The B-cell cryomodule is the key component of a four-cavity CESR RF system, which can support total beam current of several hundreds milliamperes. The Cornell design has been transferred to industry and the cryomodules are now available as turn-key systems. In this presentation we will describe main design features of the cryomodule and review operating experience and results obtained since the installation of the first cryomodule in CESR almost a decade ago.

Outline

- Why SRF?
- History of the Cornell cryomodule development
- Cryomodule description
- CESR RF system
- Operating experience: overcoming initial difficulties
- Operating experience: quest for high luminosity
- New challenges: satisfying two different sets of operating conditions (CESR-c and CHESS)
- Future: CESR-TF – ILC damping ring test facility
- Summary

Single-mode cavity concept

- In late 1980's – early 1990's, when physicists began pushing beam currents in storage rings toward 1 A, it became clear that a new type of accelerating cavity would have to be developed.
- Performance of such machines is limited by longitudinal multi-bunch instabilities caused by parasitic interaction of electron and positron beams with the fundamental and higher-order modes (HOMs).
- This interaction can be short-range and long-range. Short-range interaction can produce change of the bunch length with beam current (usually bunch lengthening due to an inductive wake potential) and single-bunch energy loss characterized by the loss factor.
- Long-range interaction can cause coupled-bunch instabilities and power loss due to resonant interaction with high-*Q* HOMs.
- A concept of so-called single-mode, HOM-free or HOM-damped cavity was proposed to deal with those problems.
- Both normal conducting and superconducting single-mode cavities have been developed in different laboratories, e.g. at Cornell, KEK, LBNL/SLAC, etc.



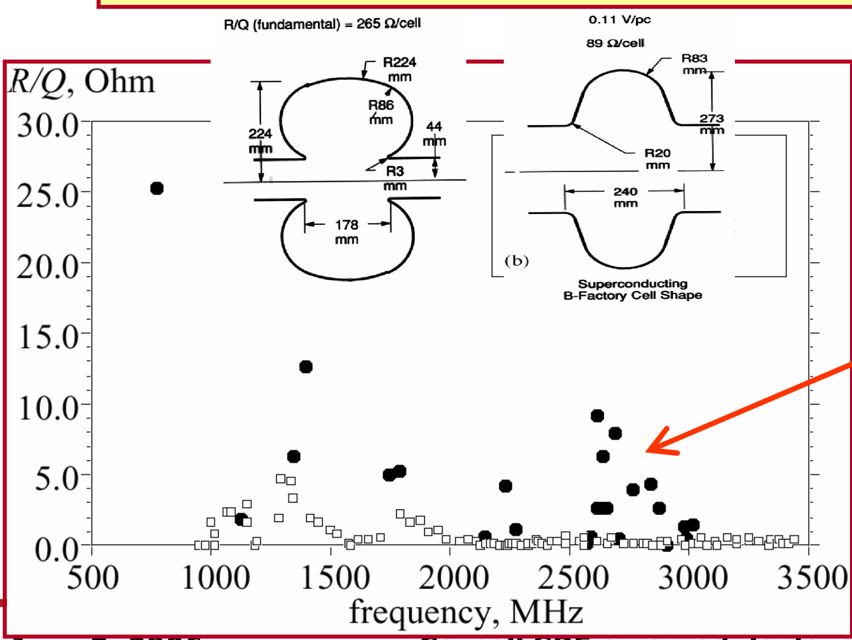
Why SC cavities are better?

1. Higher accelerating gradients

- accelerating gradient of n.c. cavities is limited by power dissipation in cavity walls and for 500 MHz cavities it corresponds to ≤ 1 MV/cell (SLAC B-factory single-cell cavity)
- higher accelerating voltage per cell (up to 3 MV) of s.c. cavities → fewer number of cells → less total impedance

2. Larger beam tubes

- due to the power dissipation limit in n.c. cavities they have to have high *R/Q* of fundamental mode → re-entrant shape and small beam tubes → high *R/Q*s of HOMs
- reduced the interaction of the beam with the s.c. cavity
- HOMs are removed easily → lower *Q* factors → better beam stability



Example: CESR

- **4 s.c. cells instead of 20 n.c. cells**
- **lower *R/Q* and *Q* of HOMs**
- **loss factor of only 1.22 V/pC for s.c. rf instead of 4.56 V/pC for n.c. rf (compare to 2.67 V/pC loss factor of the rest of CESR)**

Cornell Electron Storage Ring

- *e+e-* collider and first generation light source
- 1.55…5.6 GeV/beam
- detector CLEO
- SR facility CHESS

❖ CESR was built in late 70s for HEP.

❖ Both accelerator and detector were upgraded several times.

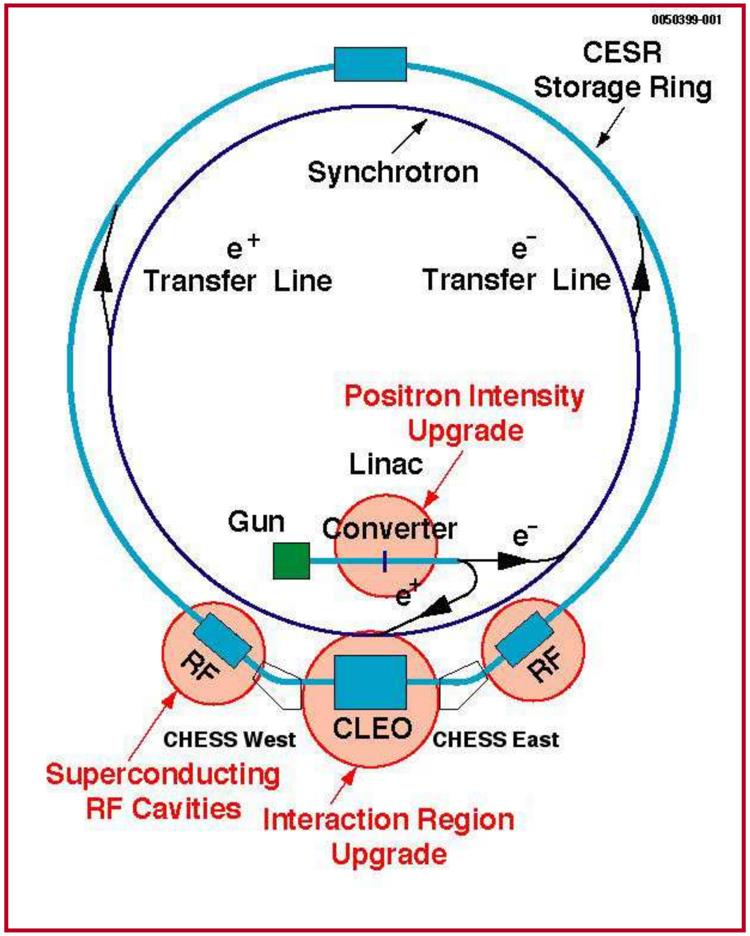
❖ Until 2003 CESR operated in collider mode at high energies (4.7 to 5.6 GeV) for B physics.

❖ CESR had highest luminosity in the world until ~2000, when B-factories surpassed it.

❖ SR experiments operated in parasitic mode.

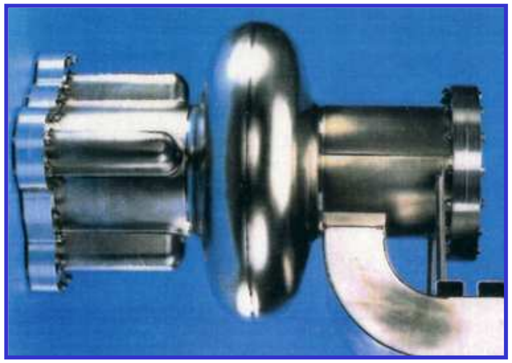
❖ Original RF system had two 14-cell copper cavities, later replaced with four 5-cell copper cavities.

❖ Single cell superconducting cavities were developed for a proposed Cornell B-factory CESR-B and then utilized in CESR-III upgrade (four cavities).

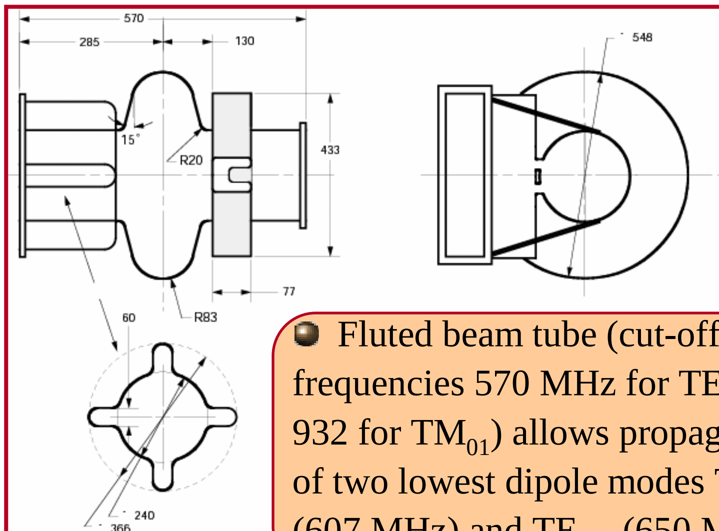


Cornell B-cell cavity

Originally developed for Cornell B-factory proposal in early 1990s



Resonant frequency	**499.765 MHz**
R/Q	**89 Ohm**
Q_0	**10^9**
Q_{ext}	**$2x10^5$**
Operating temperature	**4.5 K**
Accelerating field	**up to 10 MV/m**
Accelerating voltage	**up to 3 MV**
Effective cell length	**0.3 m**
Beam tube diameter	**0.24 m**
cut-off frequency (TE_{11})	**732 MHz**



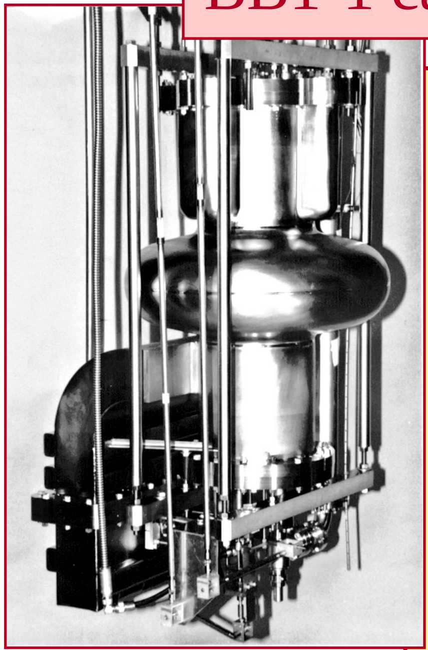
- Fluted beam tube (cut-off frequencies 570 MHz for TE_{11} and 932 for TM_{01}) allows propagation of two lowest dipole modes TM_{110} (607 MHz) and TE_{111} (650 MHz)

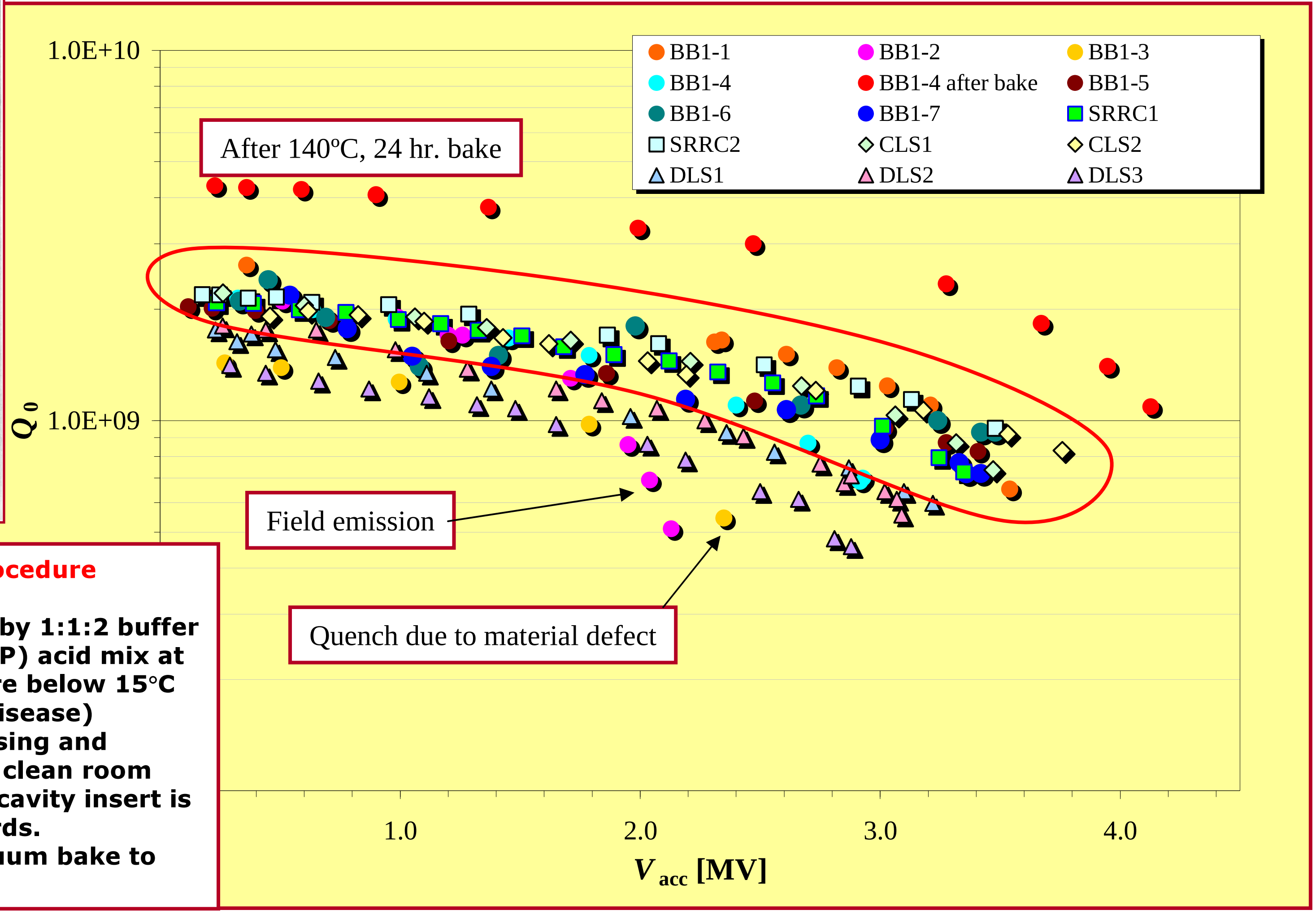
- Q_{ext} was chosen to provide the most efficient operation of RF system at maximum design beam power and cavity voltage (matched conditions, for proposed CESR-B):

$$Q_{ext} = Q_{beam} = \frac{V_c^2}{R/Q \cdot P_{beam}}$$

Vertical dewar test results

BB1-1 cavity was fabricated by Dornier, all others – by ACCEL



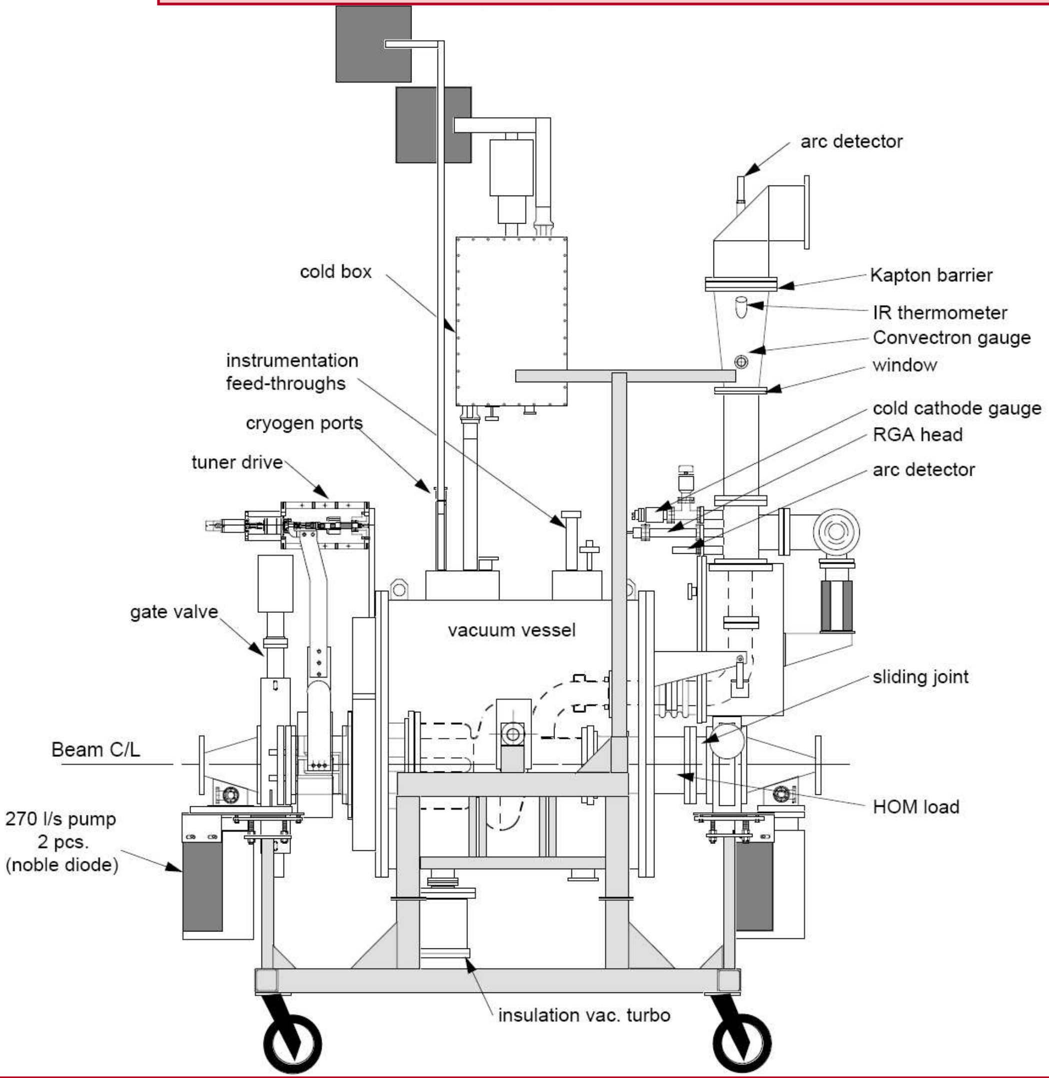


The cavity preparation procedure includes:

- ❖ chemical etching by 1:1:2 buffer chemical polish (BCP) acid mix at the acid temperature below 15°C (to avoid cavity *Q* disease)
- ❖ high pressure rinsing and drying in a class 10 clean room where the niobium cavity insert is assembled afterwards.
- ❖ 140ºC, 24 hr vacuum bake to improve *Q* factor

Mark I cryomodule & beam test

1994: Beam test, first demonstration of high current operation



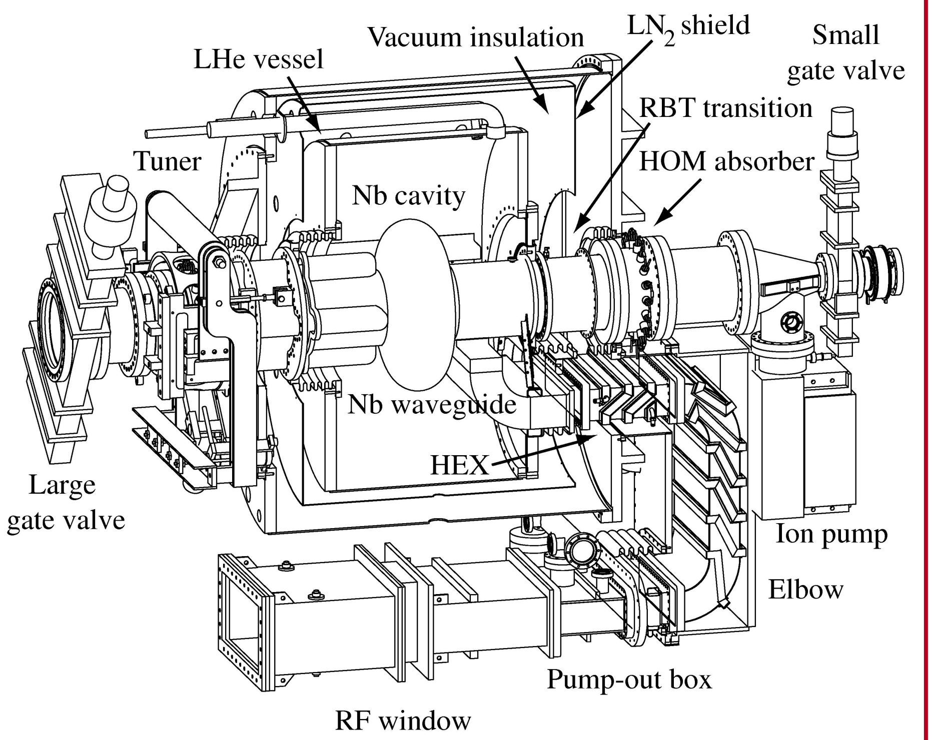
Several benchmarks for SRF cavities:

- ❖ **Stored beam currents up to 220 mA**
- ❖ **155 kW delivered to beam with 165 kW forward power**
- ❖ **2 kW of HOM power extracted by ferrite absorbers**
- ❖ **No resonant excitation of HOMs or beam instabilities were observed**
- ❖ **Performed critical cavity loss factor and impedance studies**

The test duration was one week

Mark II cryomodule

The cryostat was redesign to fit into the CESR tunnel



Cryostat liquid He volume	**520 liters**
Cryostat static heat leak	**30 W**
Cryomodule length	**2.86 m**

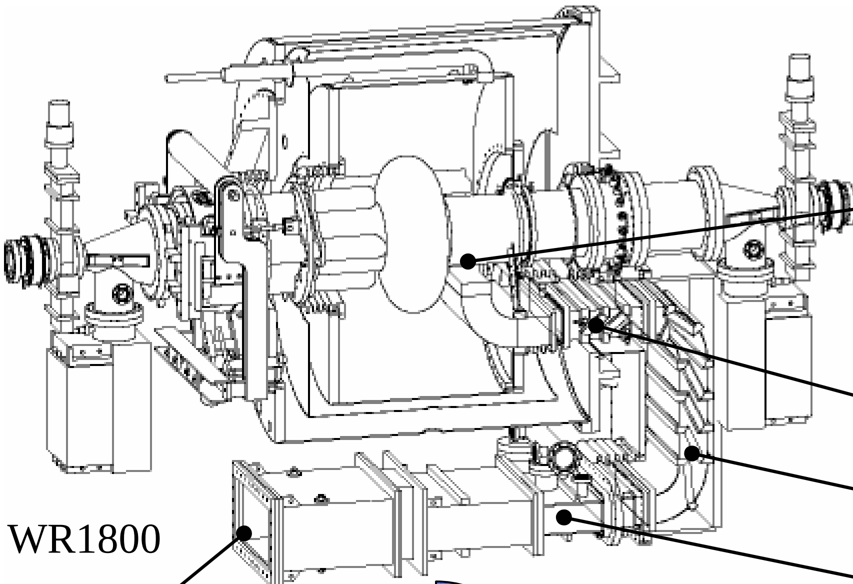
Main features:

- **Cryostat (fabricated by Meyer Tool & Mfg.)**
- **Waveguide input coupler with a disc ceramic RF window built by Thales**
- **Ferrite HOM load**
- **Folded, double-lever-arm mechanical tuner with stepping motor**
- **Large-aperture inter-cavity gate valve**
- **Taper and small gate valve**

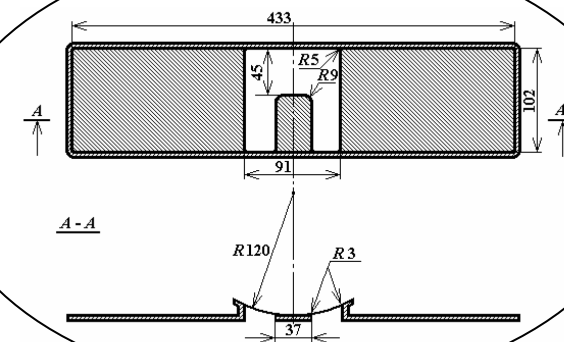
☑ **Prior to assembly all major components are subjected to acceptance tests**

☑ **All high vacuum components are baked prior to cryomodule assembly**

Waveguide input coupler



Coupling slot



Cold He gas cooled WG

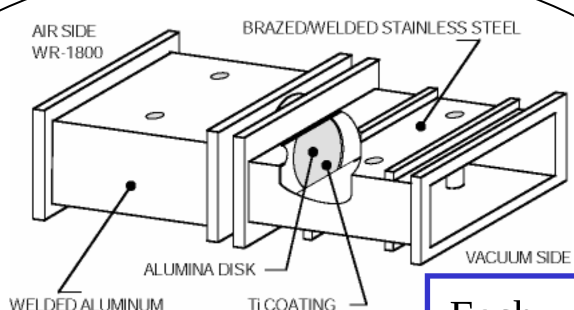
Liquid nitrogen cooled WG

Pumping section

WR1800

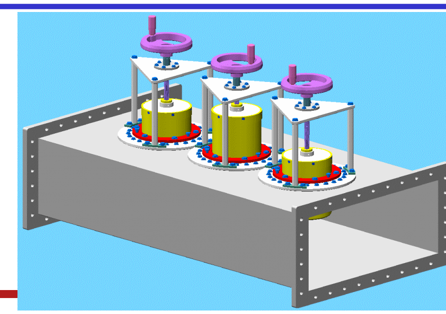
Kapton window

Warm RF window

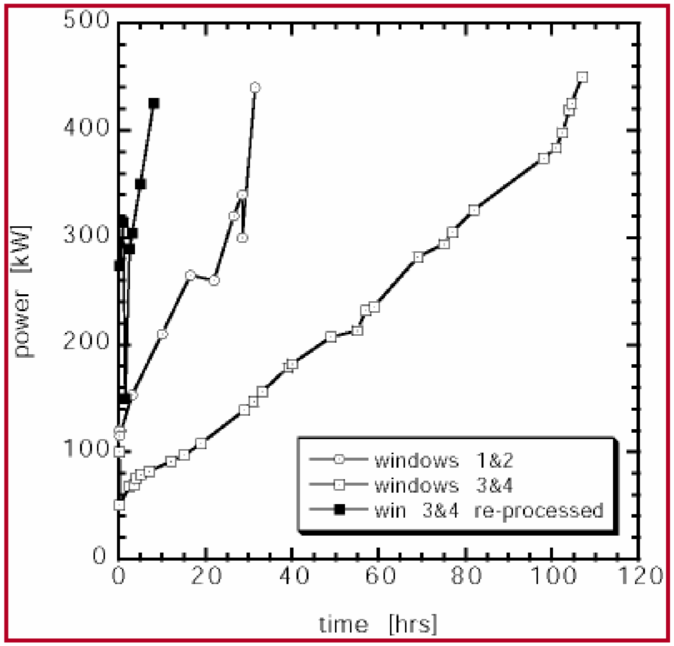


- **Fixed coupling @ Q_{ext}= 2×10^5**
- **Magnetic bias of the WG to suppress multipacting**
- **Adjustability is provided via a 3-stub WG transformer**

Each window is tested to 400 kW in TW and >125 kW in SW



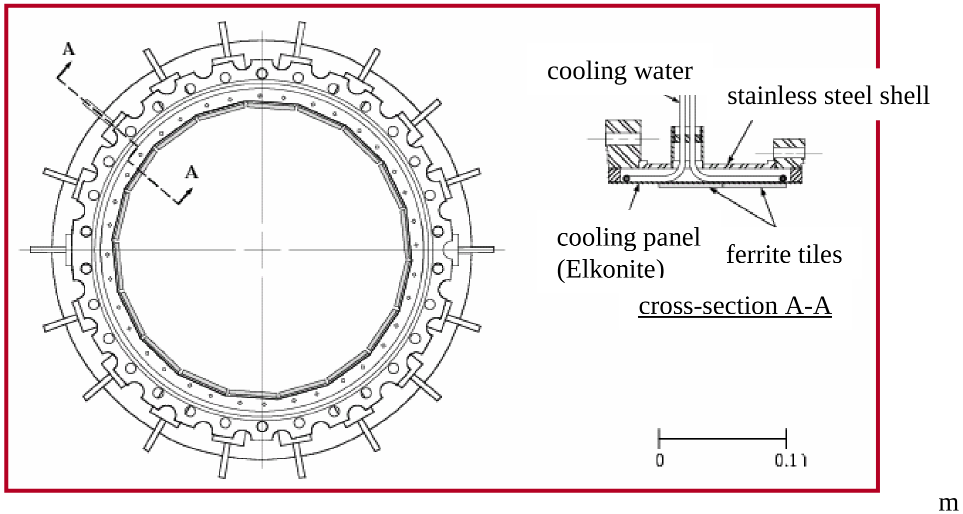
Windows processing



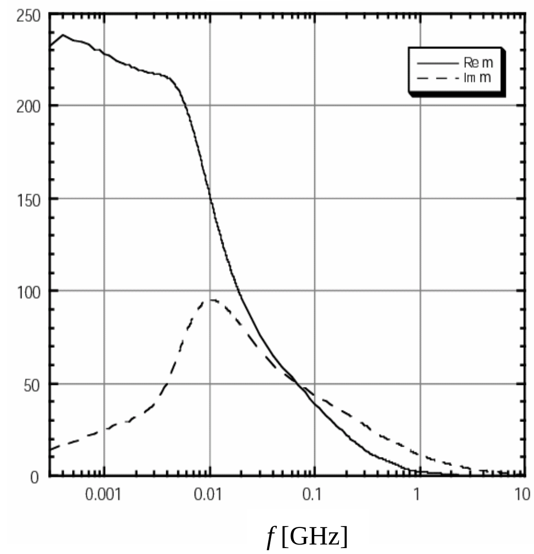
Processing:

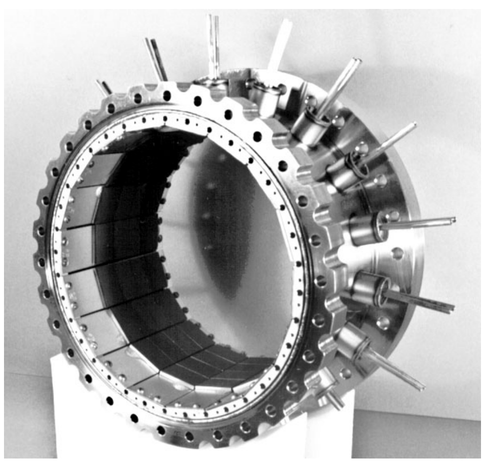
- **initial processing in TW mode**
- **then SW mode at different positions of reflection plane**
- **both CW and pulsed regime during power ramp**
- **tickle processing for hard multipacting barriers**
- **may take from several hours to several days to reach max P**
- **final processing after cryomodule assembly**
- ***in situ* processing**

Ferrite HOM load

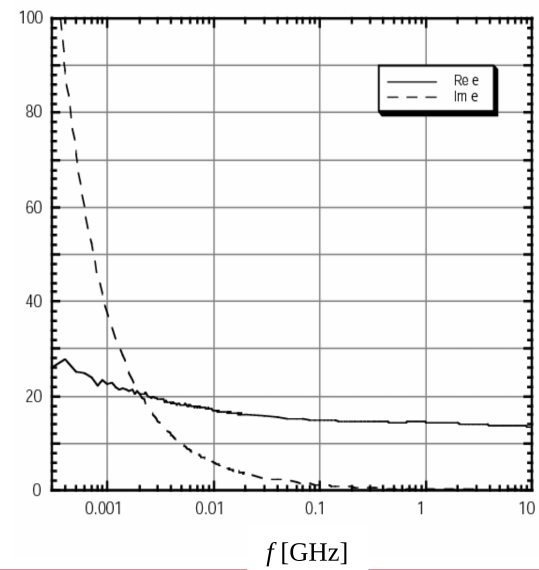


TT2-111



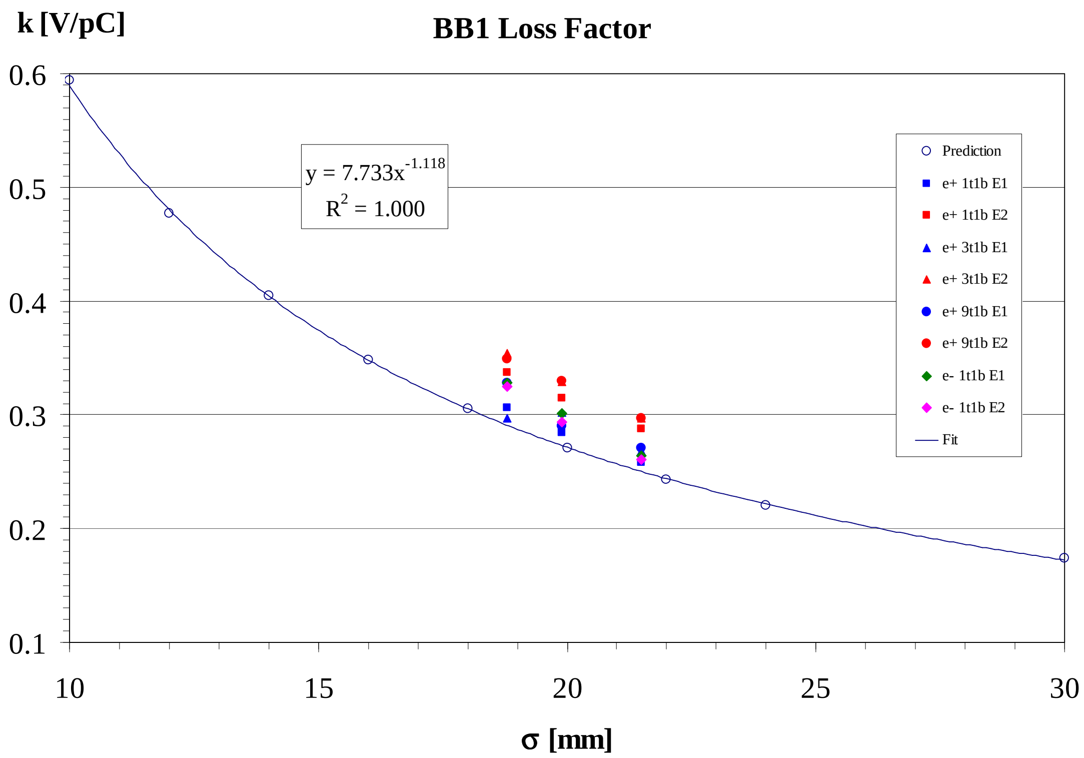


- modular design
- 18 water-cooled Elkonite (25% Cu + 75% W) panels
- two ferrite tiles (2″ × 1.5″ × 1/8″) soldered to each panel
- TT2-111 ferrite
- each panel is individually tested to power density of 15.5 W/cm^2

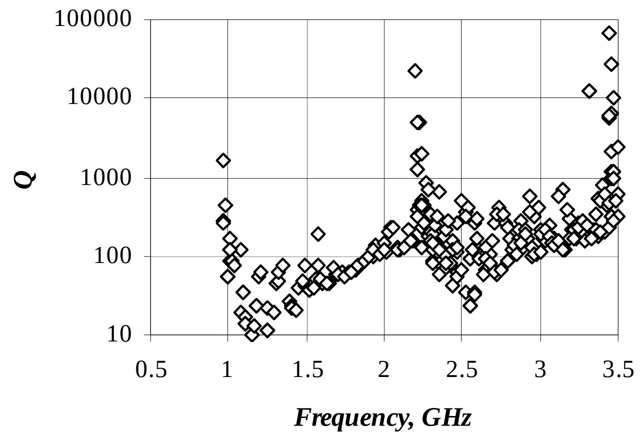


Loss factor and HOM spectra

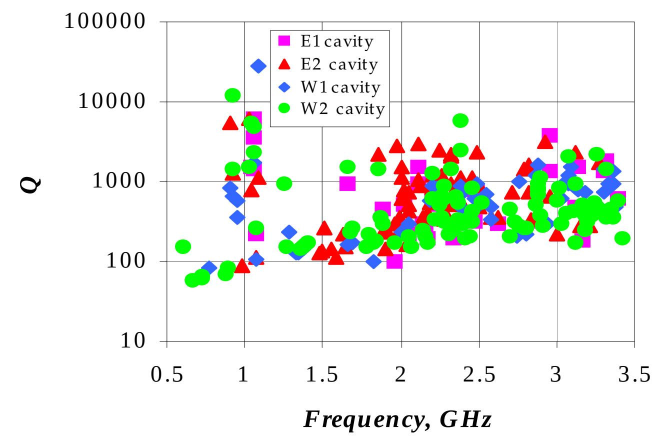
Comparison of prediction with measurements



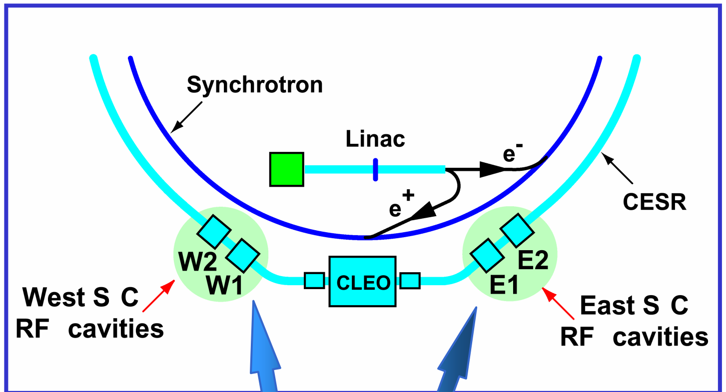
Calculated spectrum

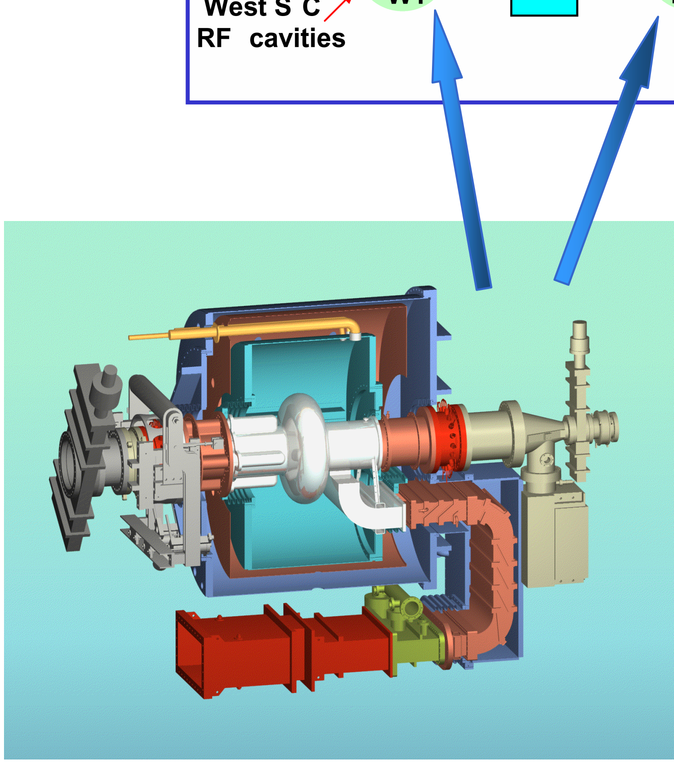


Measured spectrum



CESR superconducting RF system

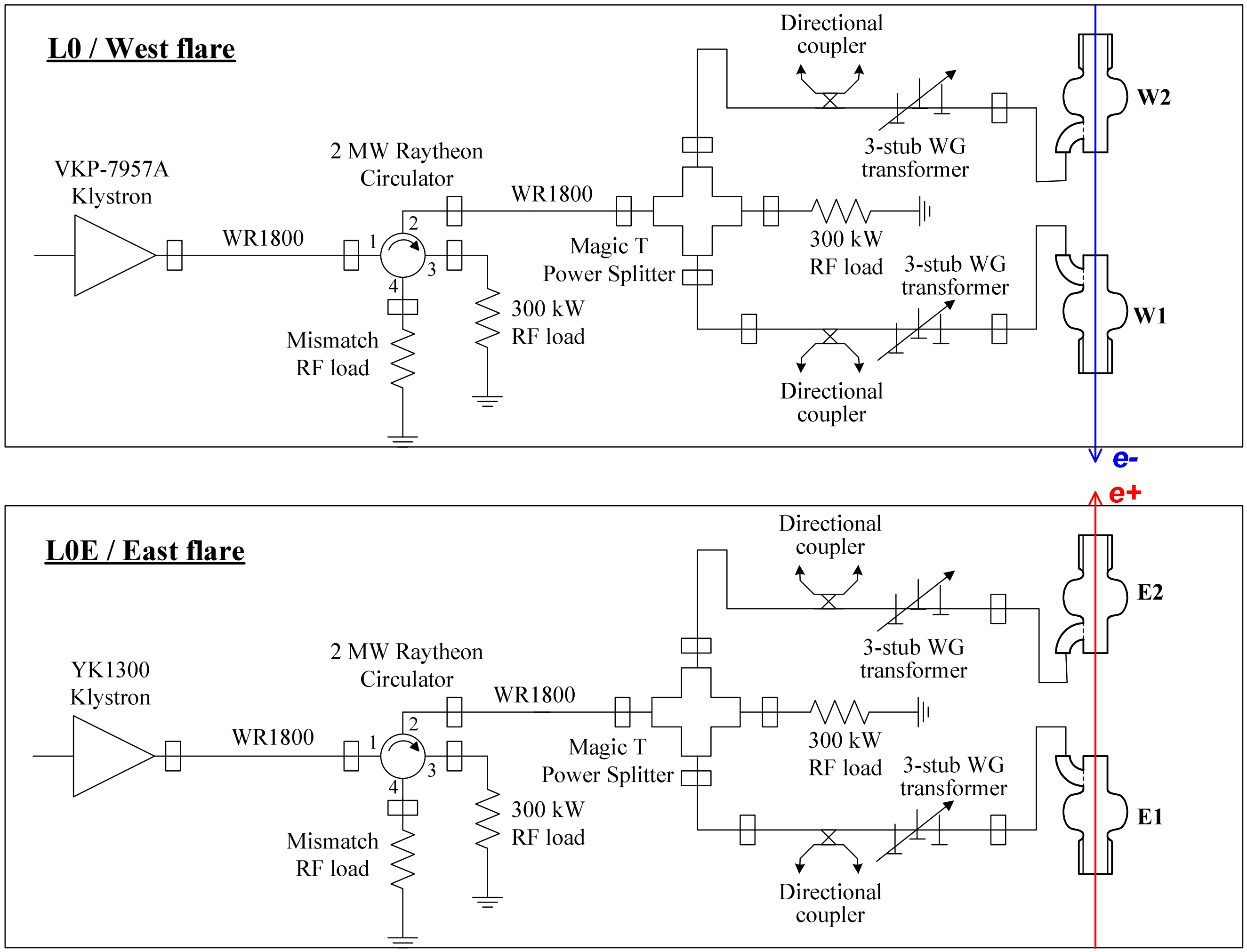




- CESR is a *e+e-* storage ring operating in two regimes: as a collider for HEP experiments and as a synchrotron light source
- Four superconducting single-cell RF cavities
- Two cavities are driven by one klystron in parallel
- High beam loading → low loaded *Q* factor

Beam energy	1.5 to 5.6 GeV
Beam current	0 to 500 mA
Frequency	500 MHz
Number of cavities	4
R/Q per single-cell cavity	89 Ohm
Q_{loaded}	2×10^5 to 4×10^5
Accelerating voltage per cavity	1.1 to 2.4 MV
Klystron power per cavity	up to 200 kW
Number of klystrons	2
Required ampl. stability	< 1%
Required phase stability	< 0.5°

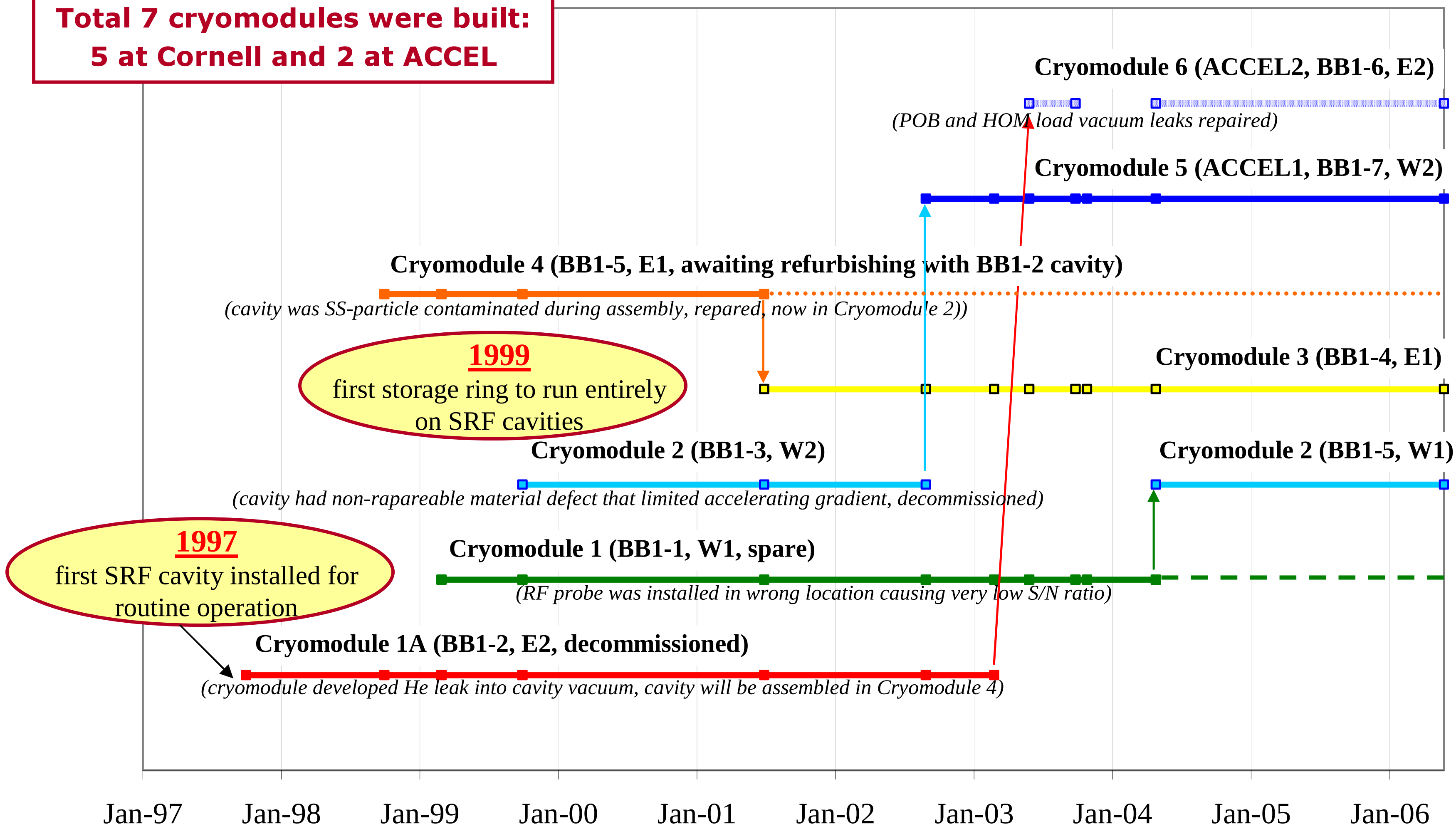
RF system diagram



CESR cryomodules history

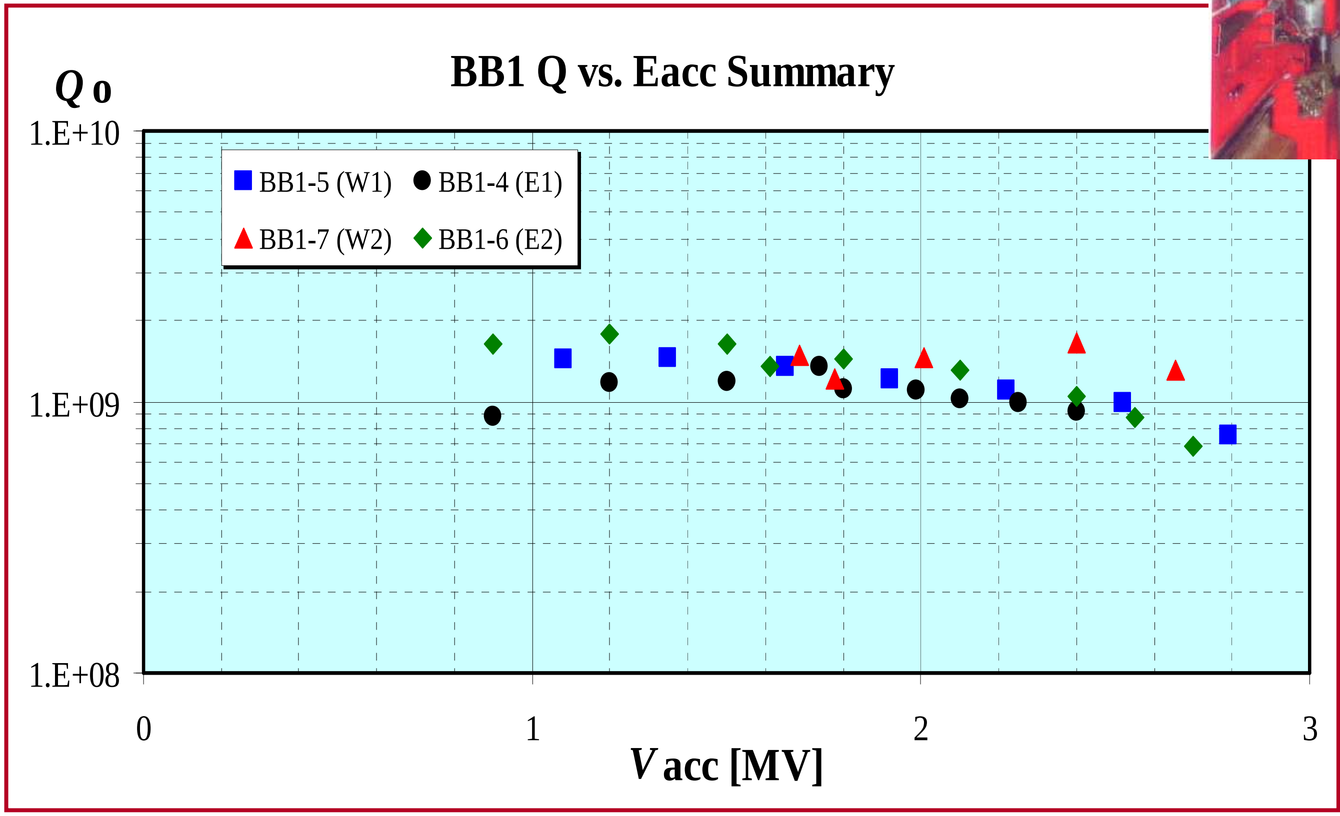
B-cell cryomodules in CESR

Total 7 cryomodules were built: 5 at Cornell and 2 at ACCEL



Cryomodule test results

4 cryomodules currently in service



Overcoming initial difficulties (1)

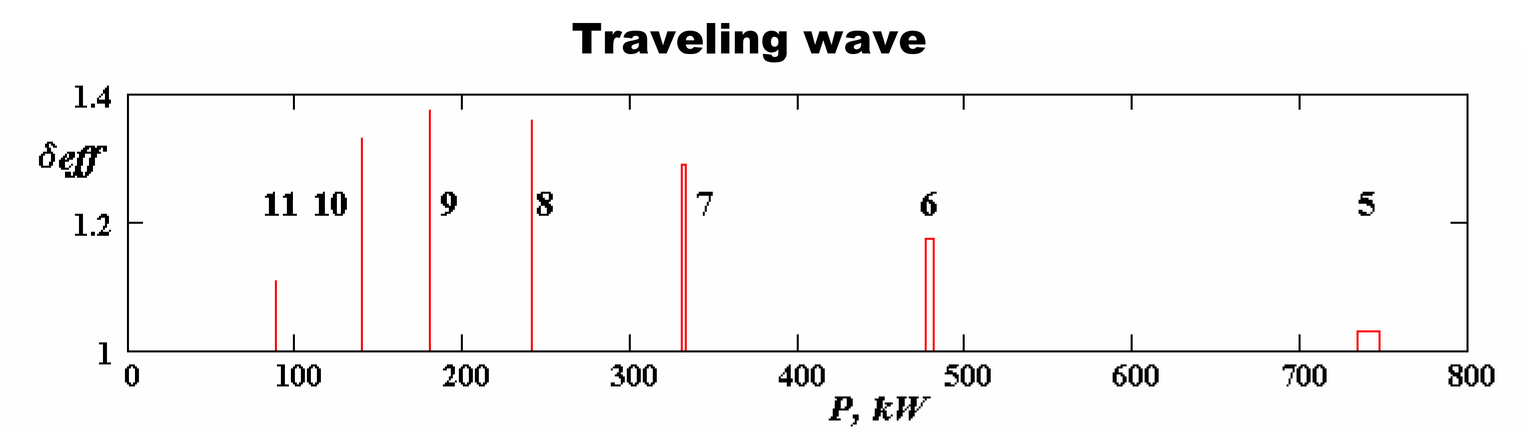
Multipacting in rectangular waveguide

The first SC cryomodule installed in CESR was assembled without baking its WG components.

The consequence of this was very strong multipacting at forward power levels of 90, 130, 180,… kW. We had to develop ways to process this multipacting *in situ*:

1. Processing with DC magnetic field bias (10 Gauss).
2. High power pulsed processing w/o beam. One can create TW in two ways: very high emitted power for a very short time after RF shut-off due to strongly over-coupled cavity, let cavity quench for ~10 ms at 10% duty cycle.
3. Beam processing by changing RF phase between two RF stations using a specially written software.

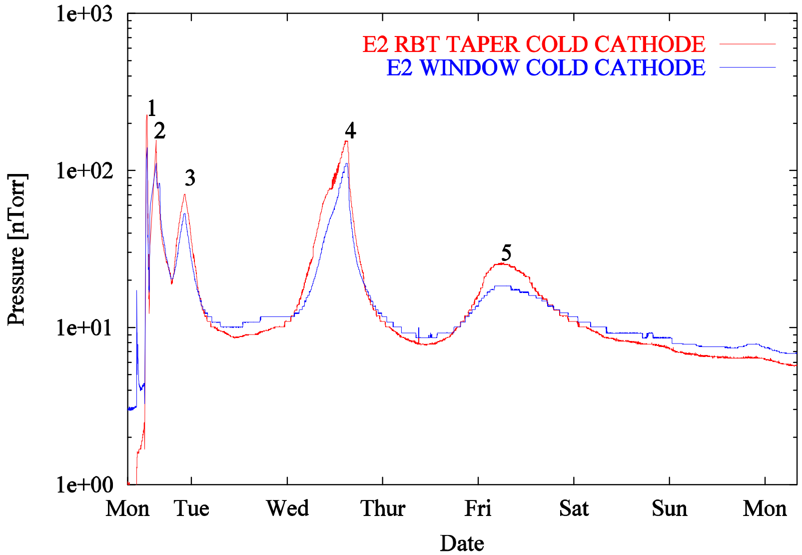
Further computer simulations confirmed our observations that TW and SW mixing ratio affects multipacting bands.



Overcoming initial difficulties (2)

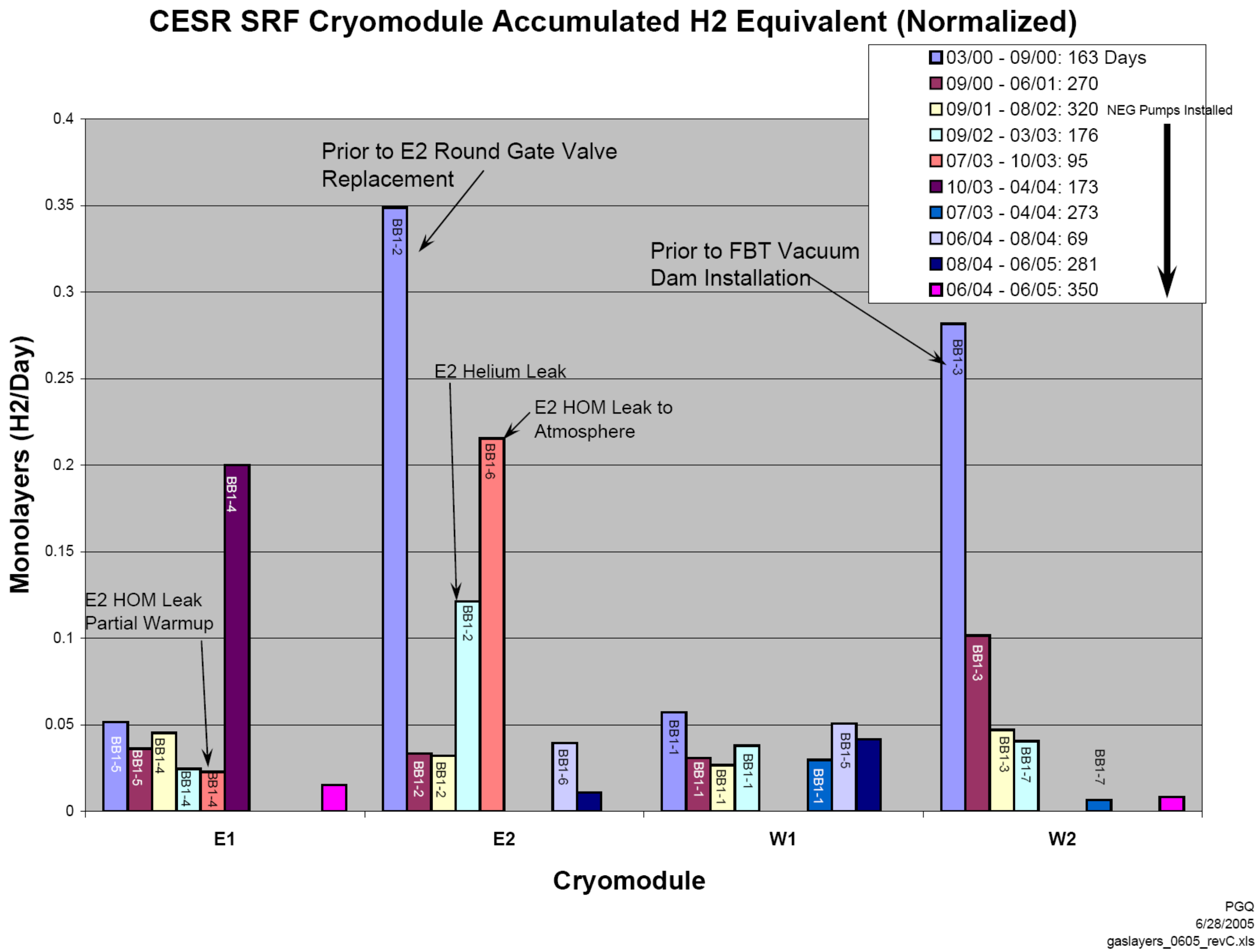
Residual gas evolution

After warming up the cryomodule we analyzed residual gas evolution and found that during first 3 months of operation cryomodule cold surfaces accumulated up to 7 equivalent monolayers of hydrogen. During CESR operation we had found that hydrogen plays very important role.



Peak #	Gas species	Cavity	HEX	Elbow
1	H_2, He	9 K	22 K	85 K
2	CO/N_2, H_2, O_2, Ne	27 K	35 K	92 K
3	CO_2, CO/N_2	83 K	92 K	130 K
4	H_2, H_2O, CO/N_2	163 K	165 K	190 K
5	H_2, H_2O	230 K	220 K	240 K

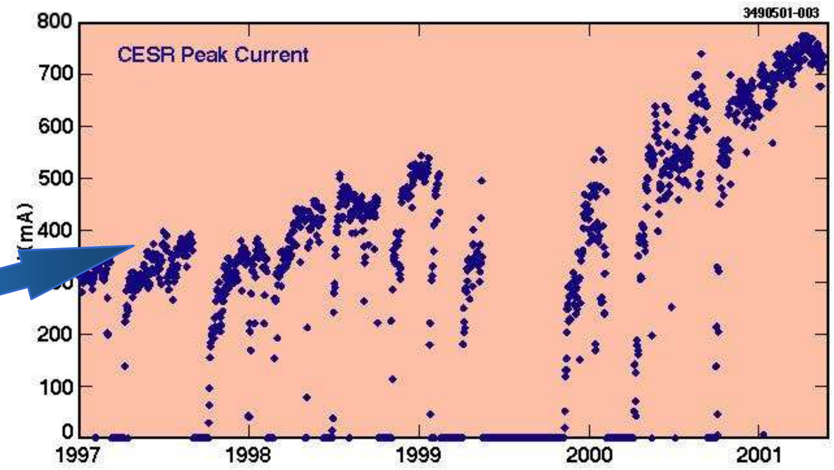
Overcoming initial difficulties (3)

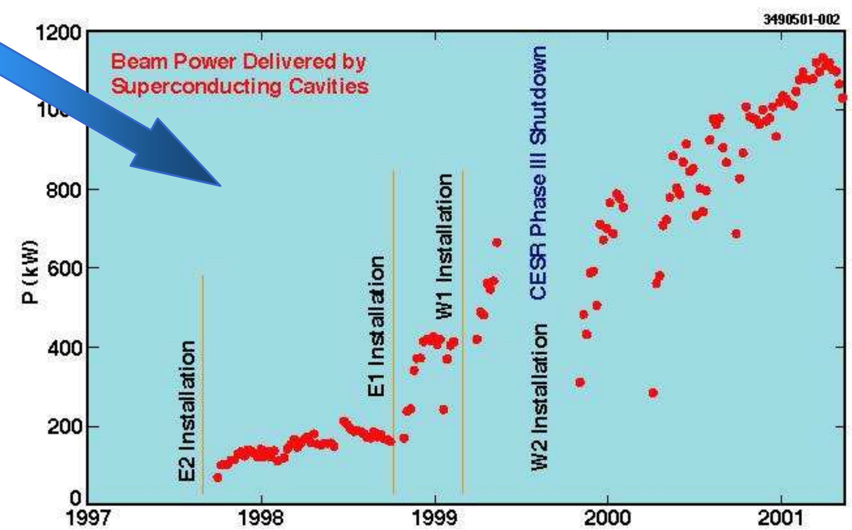


Quest for high luminosity

CESR was the highest-luminosity collider in pre-B-factory era

Peak luminosity	1.3×10^{33} cm^{-2}s^{-1}
Beam current	0.78 A
RF voltage with beam	1.85 MV/cavity (1.6 – 2)
Max. power transferred to beam	300 kW/cavity (360 kW forward power)
HOM power	5.7 kW/cavity at 0.75 A





Post B-physics: CESR-c & CHESS

Parameter	CHESS (until ~2012)	← CESR-c (until 2008, then – CESR-TF)		→
Energy [GeV]	**5.3**	1.55	**1.88**	2.5
No. of cavities	**4**	4	**4**	4
Gradient [MV/m]	**4**	6.25	**8.33**	10
Voltage [MV]	**4.8**	7.5	**10**	12
Beam power [MW]	**1.0**	0.04	**0.09**	0.16
Beam current [A]	**0.5**	0.26	**0.36**	0.46
Synch. frequency [kHz]	**18**	41	**43**	41
Bunch length [mm]	20	9.9	**10.2**	10.2

CESR-CHESS light source (E=5.3 GeV)

- relatively high RF power per cavity (160 kW per cavity)
- emphasis on long beam lifetime, short bunches are not required ⇒ low RF voltage (1.2 MV/cavity)

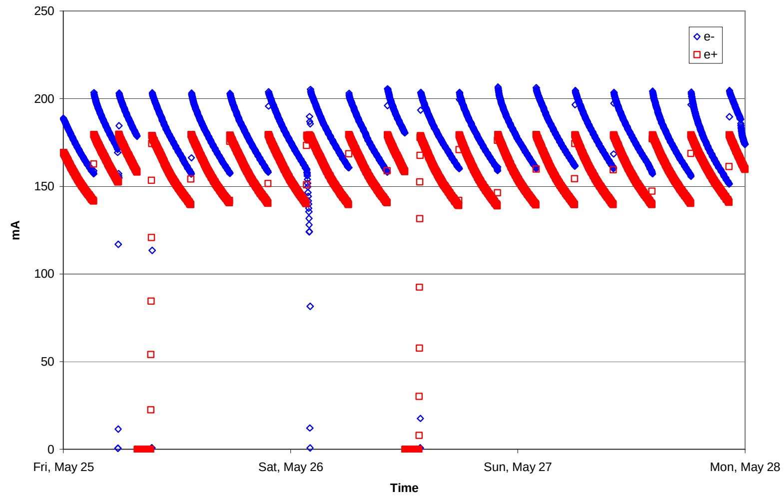
CESR-c tau/charm factory (E=1.55…2.5 GeV)

- high luminosity means strong IR focusing and short bunch length (1 cm) ⇒ high RF voltage (1.85…3 MV/cavity)
- low beam energy loss per turn & lower beam current ⇒ low RF power (10…40 kW per cavity)

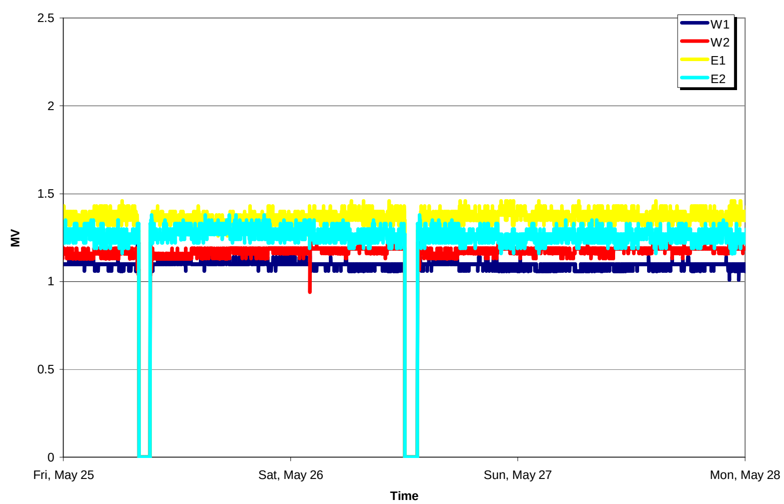
CESR-c & CHESS operation

CHESS

beam current

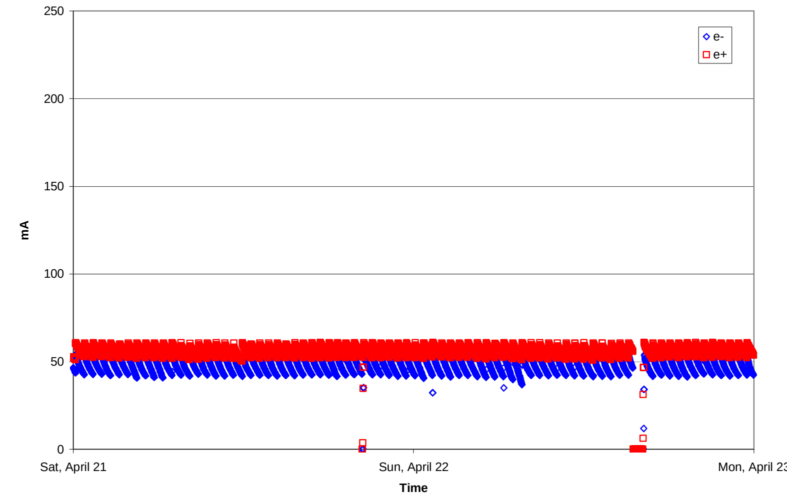


Cavity voltage

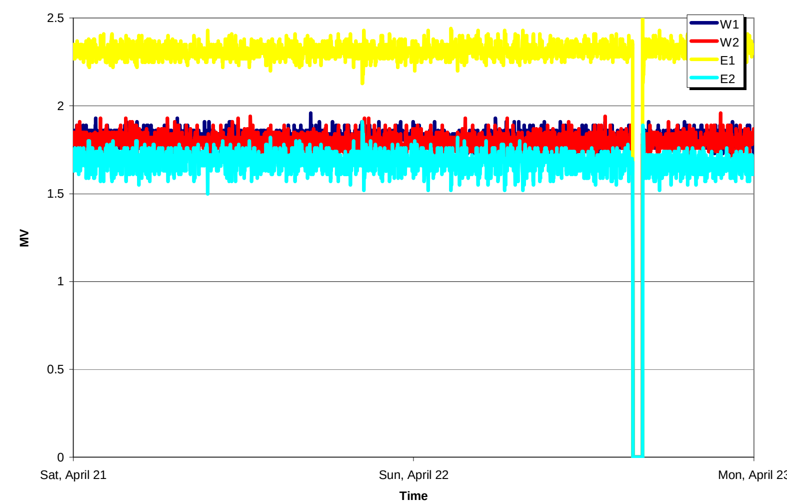


CESR-c

beam current

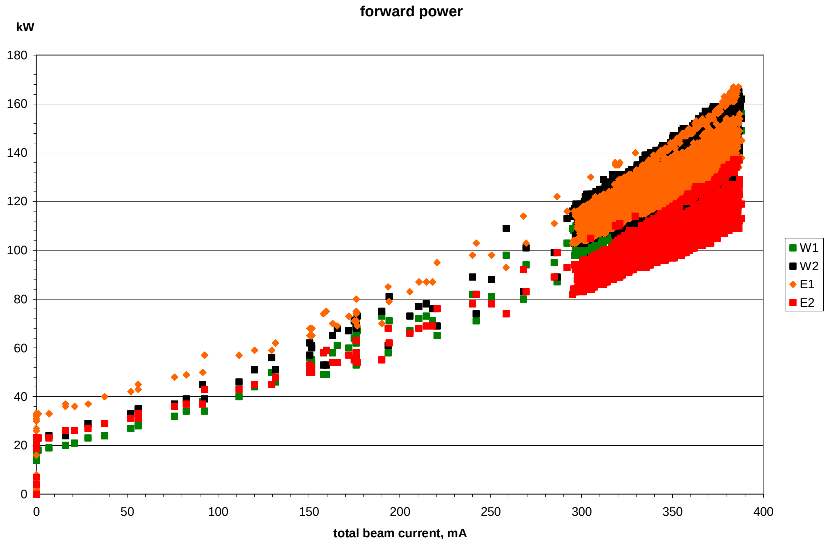


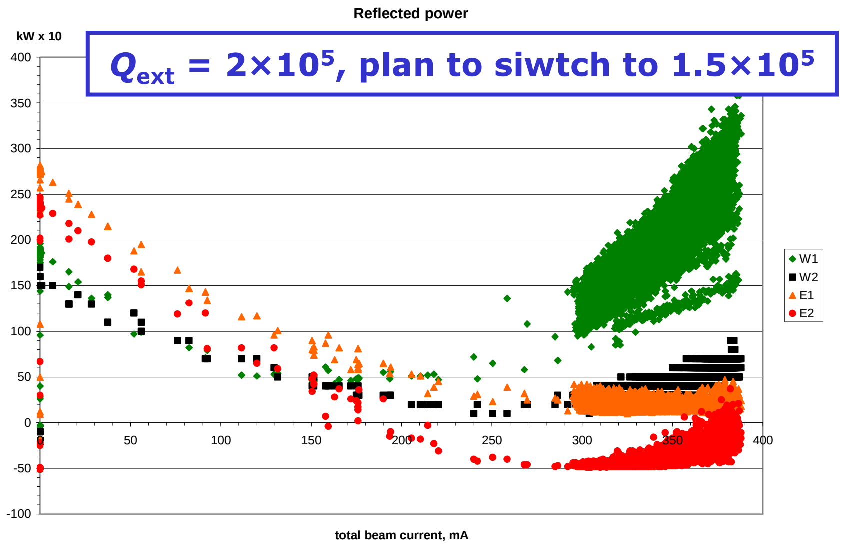
Cavity voltage



CESR-c & CHESS operation

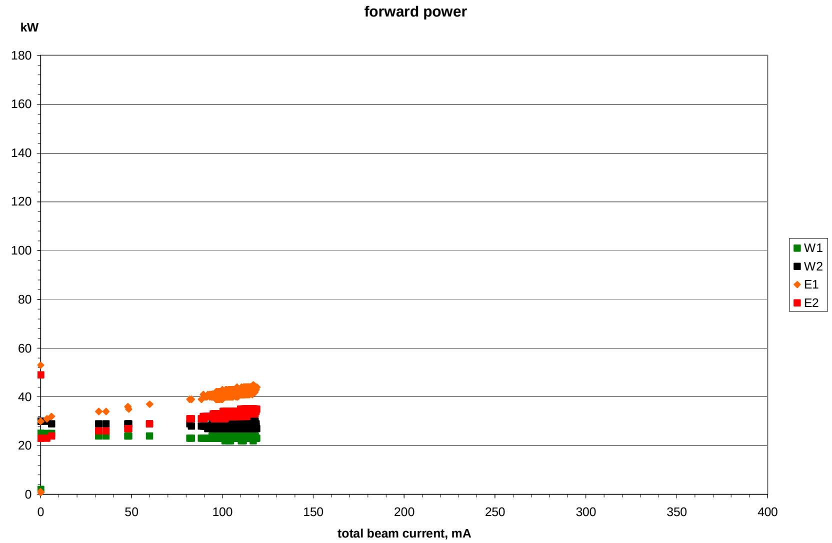
CHESS

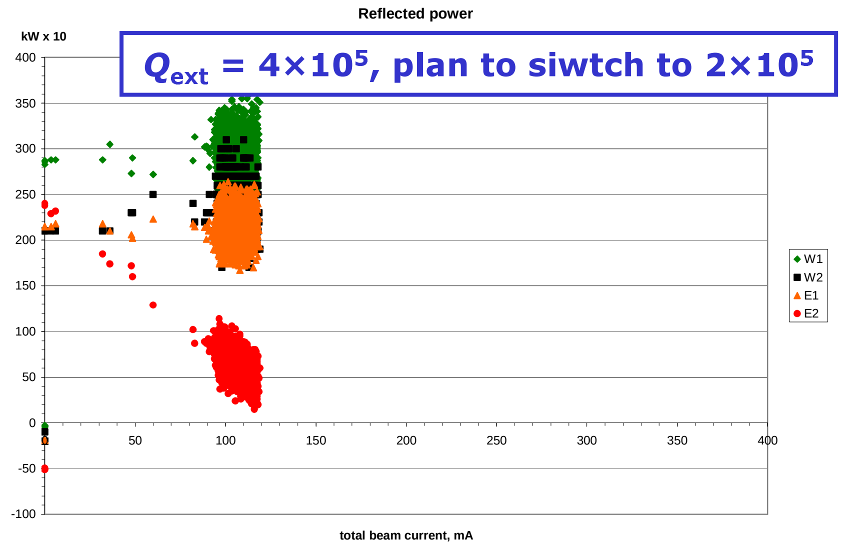




Q_{ext} = 2×10^5, plan to siwtch to 1.5×10^5

CESR-c





Q_{ext} = 4×10^5, plan to siwtch to 2×10^5

Toward ILC: CESR-TF

2008 – 2012: proposed operation of the CESR-TF

- **Goal: to perform crucial R&D in beam physics and instrumentation for ILC damping ring operability and reliability using a slightly redesigned CESR ring**

Beam energy	2.0 GeV
Total RF voltage	15 MV
(will need to add two more cryomodules in 2009)	
Total beam current	50 – 60 mA
Number of particles per bunch	2×10^{10}
Bunch length	6.9 mm

Summary

- Cornell has over-10-year experience of using SRF cavities in a high-current storage ring under different operating conditions
- Even though we had a beam test, its duration was short and the first several months after the first cryomodule installation were very tough, but provided us with invaluable learning experience
- After overcoming initial difficulties due to mostly multipacting in the rectangular waveguide input coupler/ceramic window region and residual gas evolution, we are able to provide stable and reliable RF system for CESR
- Successful operation of SRF cavities attracted interest from industry and laboratories and eventually the Cornell technology was transferred to ACCEL, which now provides CESR-type cryomodules to synchrotron light sources world-wide – NSSRC/Taiwan Light Source, Canadian Light Source, DIAMOND (UK), SSRF (China) – as turn-key systems
- In the near future we plan to add two more cryomodules to the CESR RF system as part of converting the machine to an ILC damping ring test facility
- There are many more RF system related developments at Cornell (cryogenic controls, digital RF controls, passive cavity operation, using piezo tuners, experimental and theoretical studies of multipacting, …) that are outside the scope of this presentation