SRF Performance Requirements and Challenges for ERL Light Sources

A. Nassiri

Advanced Photon Source

Argonne National Laboratory

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Outline

- Operation Requirements
- Key Performance Parameters
- Challenges
- Summary

Operation Requirements

- CW Mode
  - High dynamic head loads
- High-current (100’s mA, ampere-class operation)
  - Mitigating large HOM power
    - Cryogenic load issue
    - Beam stability
- Managing dynamics losses from accelerating cavity mode
  - Important for GeV-class machine
- Small net beam loading
  - Small bandwidth
    - More prone to microphonic detuning
- Stable RF fields

Key Performance Parameters (KPP)

- Frequency
  - Chosen to limit excited HOM power
    - Lower frequency is favored
      - $K_{longitudinal} \propto 1/(\text{iris radius, ir})^2$, ir $\propto 1/f$
    - Preferred choice for ampere class machine
      - BNL electron cooler , 704 MHz
      - TJNAF, 750 MHz
  - At lower frequency, BCS losses decrease at given operating temperature
      - Power dissipation per meter acceleration is decreased
      - Total losses eventually are dominated by temperature independent residual losses
        - » Sets a lower bound on frequency
  - For multi-GeV, high-current machines, higher frequency is desirable
    - 1.3 – 1.5 GHz (smaller dynamic cavity losses at optimized temperature)
    - In addition, cavity surface area is proportional to (frequency)$^{-2}$
      - Higher frequency : minimizing risk of compromising cavity performance due to surface defects, electron field emission

KPP (2)- Accelerating Gradient &Q

- Maintain high-Q in the range of 15-20 MV/m

$$Q_0 = \frac{G}{R_s}$$

$$R_{BCS}(T,f) = \frac{A}{T} f^2 e^{-\Delta/k_B T} \qquad T < T_c/2 \qquad A = f(\lambda_L, \xi, \iota)$$

$$R_s = R_{BCS} + R_{res}$$

At low field (peak surface field magnetic flux density, B_p, of ~10-20 mT)

$$R_{res} = \alpha H_{dc} \sqrt{f/GHz} \qquad \alpha = 0.2 - 0.3\, n\Omega/mG$$

Goal: Reducing the power dissipated by the cavity into He bath by developing processes to limit its contribution.

- Lowering the cost of CW SRF accelerators

The lowest values of R_{res} which have been measured in Nb are ~0.5 -2 nΩ*

	805 MHz	1300 MHz	1497 MHz
Mean	6.6 ± 2.0 nΩ	8.0 ± 2.6 nΩ	10.3 ± 4.2 nΩ
Standard deviation	2.8 nΩ	2.8 nΩ	4.6 nΩ
Median	6.1 nΩ	7.9 nΩ	10.2 nΩ
No. of cavities	83	24	83
No. of tests	86	57	127

G. Ciovani, et al., IEEE Trans. Appl. Supercond. Vol. 21, No. 3, 2011

* A. Septier, et al., J. Phys. E: Sci Insrum., vol 10, no. 12

KPP (3)- Cavity

- High current operation
  - Limited by higher-order-modes in the cavity excited and cause beam loss.
- High repetition rate (700 – 1500 MHz)
- Large value of $R/Q \times G$ for fundamental mode
  - Minimizing dynamic cryogenic load
  - Limiting E_{pk}/E_{acc} (electron field emission)

KPP 4- Damping of HOMs

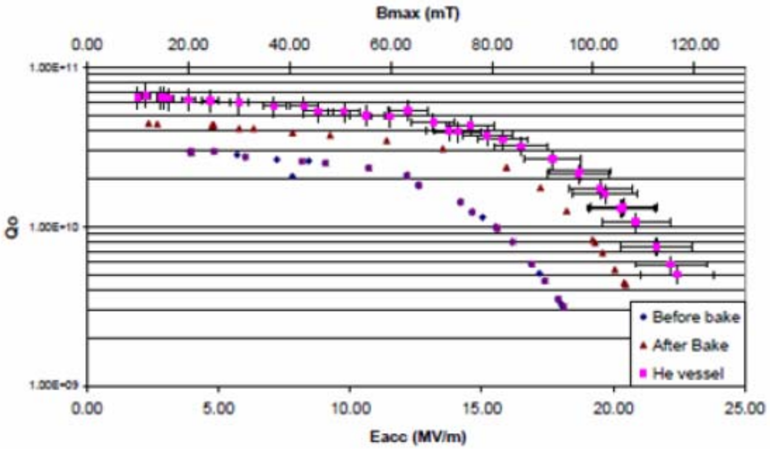
- High current (100's mA)
- Higher bunch charges
  - 10's of nC
- Short bunches
  - ~ 20 μm
- High beam current requires high power handling capabilities of HOM damping
- Avoid resonant mode excitation and beam instability
- Short bunches in ERLs require broadband HOM damping scheme
  - Up to 100 GHz

ERL	Beam Current [mA]	Average HOM power per cavity [W]	Required monopole Q	Required dipole Q
Cornell	100	200	5×10^3	1×10^4
KEK-c	100	185	1×10^6	1×10^4
BERLinPro	100	150	1×10^4	1×10^4
eRHIC	300	7,500	1×10^4	4×10^4

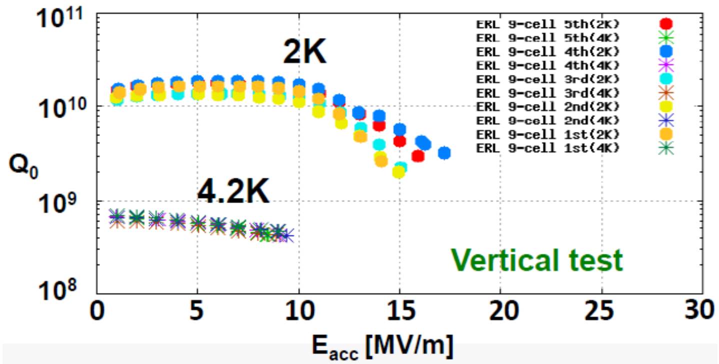
Challenge 1

- Gradient (cavity and real-estate)
  - Optimizing for high R/Q and strong HOM damping
  - Optimum gradient depends of the choice of Q_0
    - Consistently achieving 2×10^{10} @ 20 MV/m
    - Pushing for 5×10^{10} @ 15 MV/m
  - Reliability is a key to users facility
    - Lower gradient results in lower field emission and less x-rays
    - More uptime and less beam trip

BNL 5-cell, 703 MHz



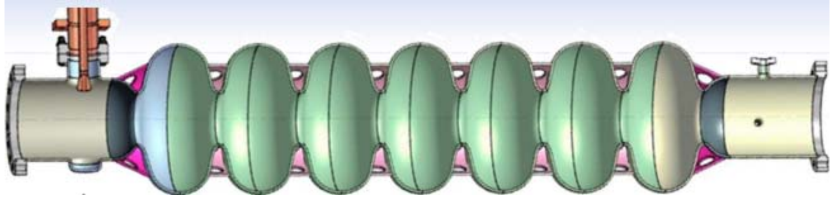
KEK 9-cell, 1.3 GHz
(Model 2)



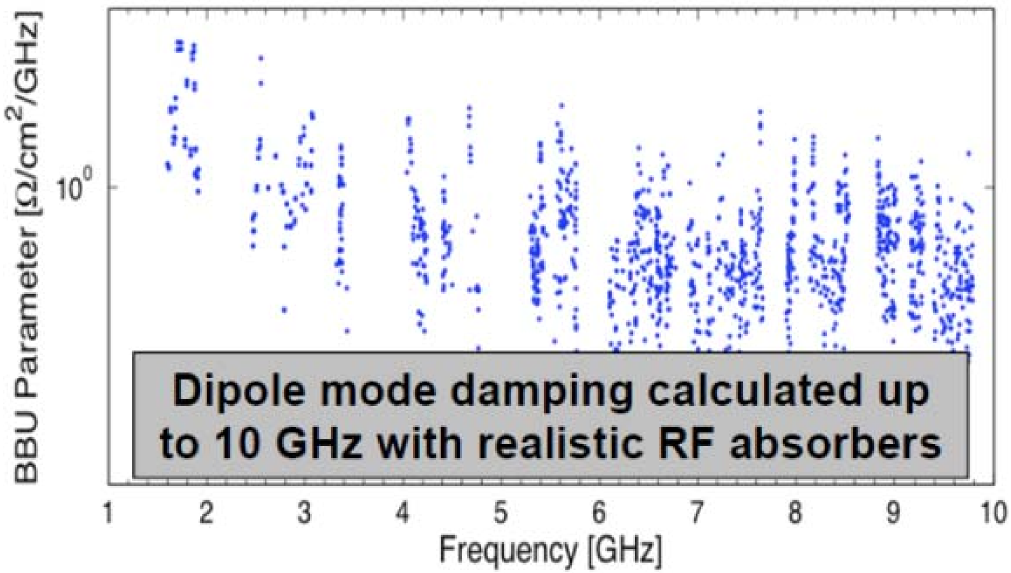
Accel. Grad. is limited by F.E.

Challenge 1 - cont.

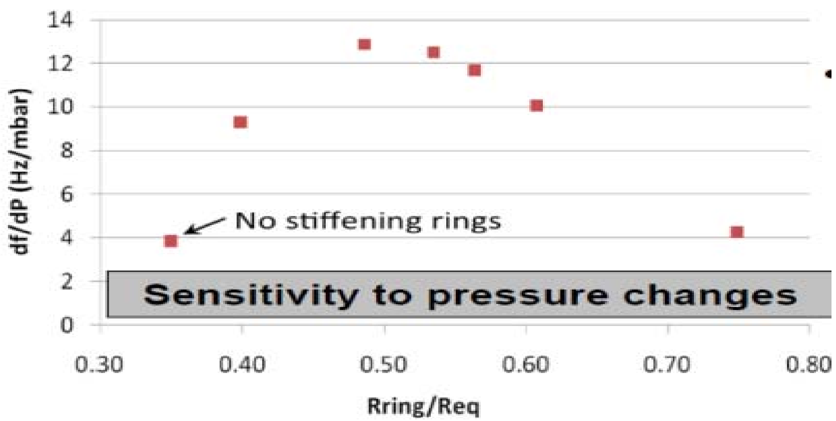
Cornell 7-cell



Cell shape optimized for high R/Q of fundamental mode and strong HOM damping

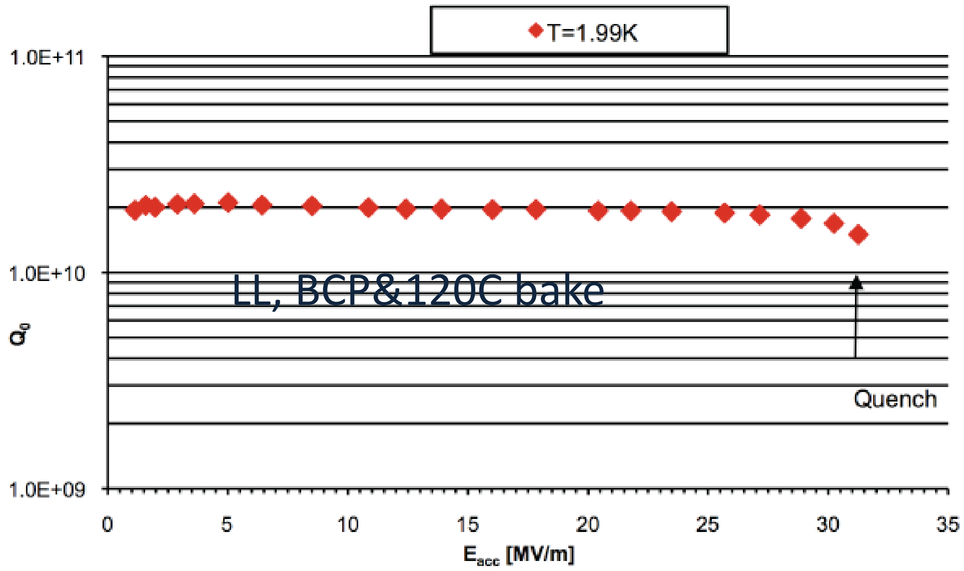


- ❑ Cavity shape tolerances relaxed:
  - Increase HOM freq. Spread
  - increase risk of trapped HOMs
- ❑ Use several classes of cavities, small, controlled variation of baseline cavity:
  - I_{th} > 4 times design value
- ❑ Optimized for low microphonics
- ❑ Stiffening rings between the cells. Cavity under fabrication

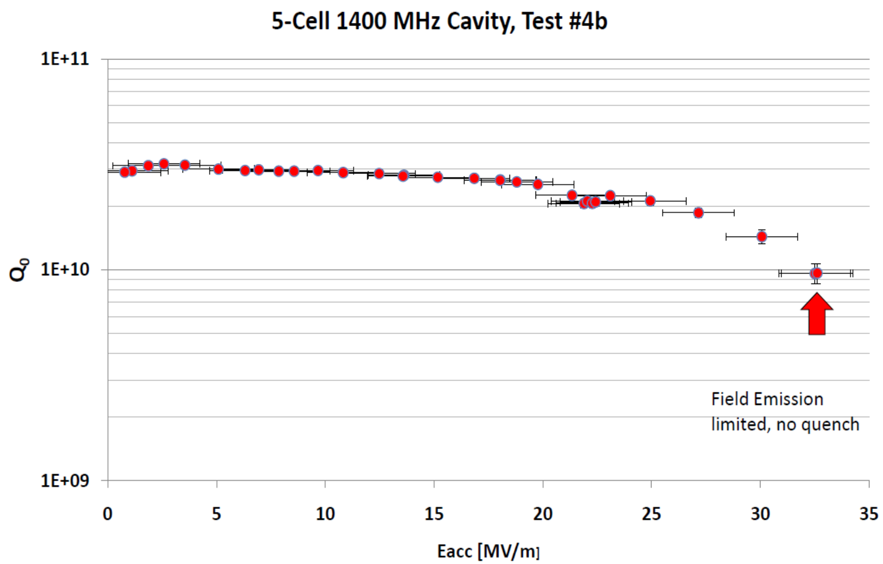


Challenge 1- cont.

JLab 1.3 GHz, 7-cell



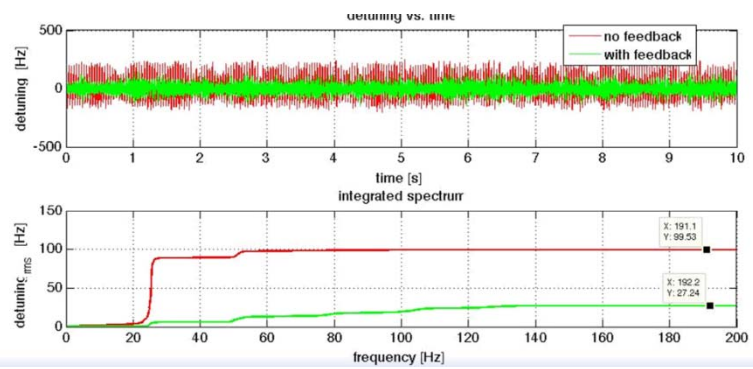
Final Test after Baking

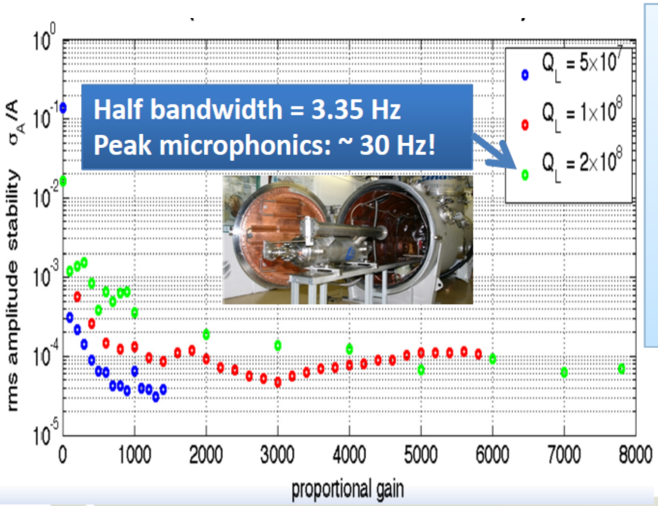


ANL 5-cell, 1.4 GHz

Challenge 2

- Stable RF fields operation
  - $\sigma_A / A < 1\times10^{-4}$, $\sigma_\phi \sim 0.01^\circ$
  - Also, cavities need to be operated with high Q_L ($10^7 - 10^8$)
  - Lorentz-force detuning during cavity turn-on
    - Cavity BW few 10s of Hz, LFD detune cavities by 100's Hz during cavity filling
  - Small cavity BW also makes the RF field in the cavity very sensitive to perturbation due to microphonics
  - Unstable FB loop caused by LFD and field amplitude fluctuations (generator-driven LLLRF systems)
    - Smaller cavity BW, results in higher risk of this instabili
      - Need high field stability to suppress this type of instabilit
  - Residual beam loading due to small phase and beam current
    - It needs to be compensated by field control system
      - Availability of RF drive power





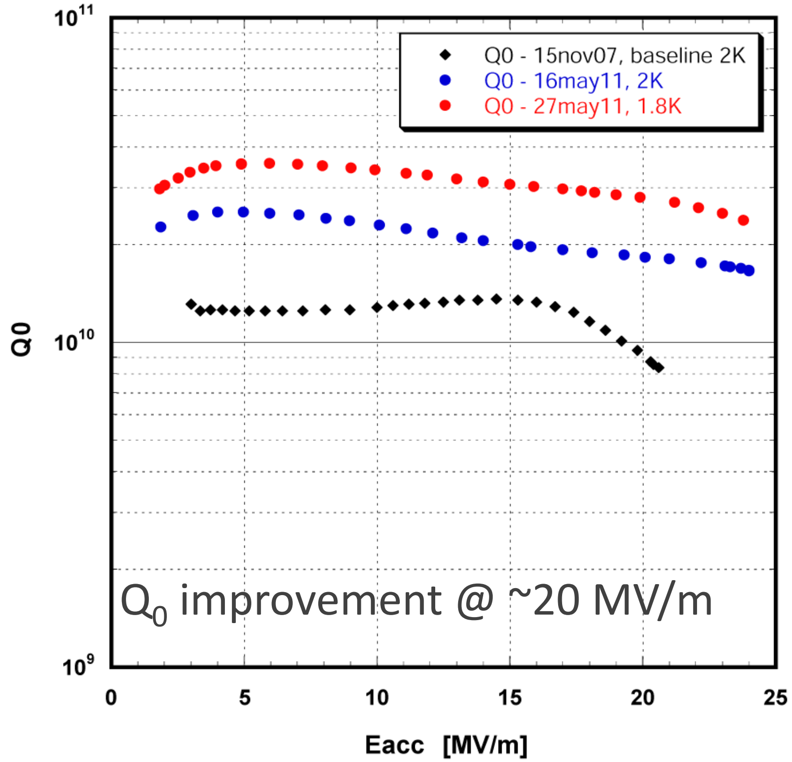
- 9-cell cavity at very high loaded Q (test of Cornell's LLRF system @HoBiCaT at HZB)
- Fast RF field ramp up to 0.5 s to high fields with piezo tuner

- Active microphonics compensation
- Piezo FB on cavity freq. (Inj. Cavity)
  - o Reduced rms microphonics by up to 70%
- Very essential for main linac with high loaded Q
- RF power $\propto \cdot f$ $\Delta P_g = \frac{V_c^2}{R/Q}\frac{f_{1/2}}{f_0}\times\left(\frac{\Delta f}{f_{1/2}}\right)^2$

Challenge 3

- CW operation
  - Focus should be on reducing dynamics losses and not highest field
  - Roust cryostat design
    - Improve magnetic shielding (reduce residual losses)
  - Cryogenics
    - CW loads, Q
    - Temperature (BCS: $R_s \propto e^{-1/T}$)
    - LHe distribution and pressure stability
  - Strong damping of HOM
  - FPC
    - High average power (injector)
    - Adjustability
  - Cavity tuning
    - Minimizing microphonics
    - Active microphonics compensation
  - RF sources
    - Reliable 10's of kW CW
    - Cost

9-cell Cavities



R. Geng et al., SRF11, Chicago, 2011

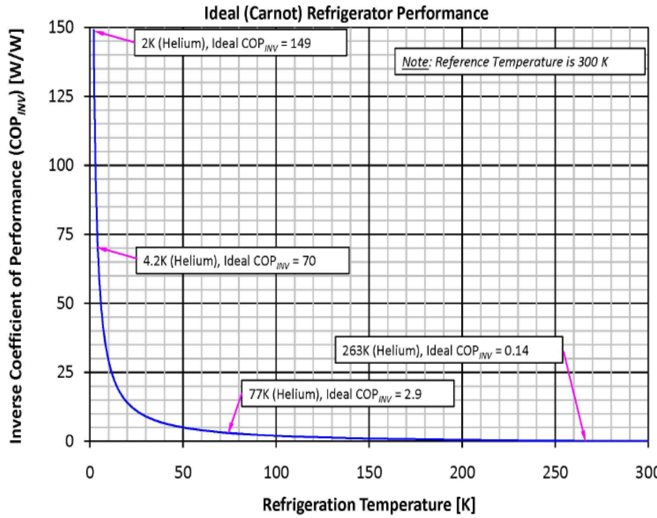
- Reduce dynamic losses
  - Cavity shape, frequency, and proper magnetic shielding
  - Improve clean room processes and cavities handling to eliminate/minimize anomalous losses
    - Electron field emission!
  - Proper choice of operating field and bath temperature

Challenge 4

- Cryogenics – System optimization
- An “optimal” system should result in:
  - Minimizing
    - Operating cost
    - Capital cost
    - Maintenance cost
  - Maximizing
    - System capacity
    - Availability
- Wall-plug power
  - Coefficient of Performance (COP) is the power required from Wall-plug to absorb power at a given low temperature

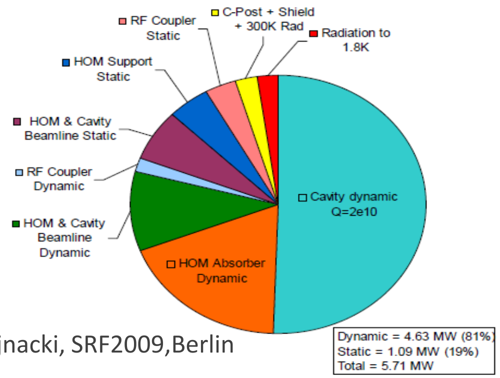
$$COP(T) = \frac{P(293K)}{P(T)} = \frac{1}{\eta_c(T) \bullet \eta_p}$$

$$\eta_c(T) = \frac{T}{293K - T}$$



Efficiency and COP’ of modern cryoplant

Temperature [K]	η_C	η_p	COP
1.8	0.006	0.230	720.3
5	0.017	0.300	196.7
60	0.250	0.168	23.9
70	0.304	0.168	19.6
80	0.364	0.168	16.4
90	0.429	0.168	13.9
100	0.500	0.168	11.9
110	0.579	0.168	10.3
120	0.667	0.168	8.9
130	0.765	0.168	7.8
140	0.875	0.168	6.8
150	1	0.168	6.0
160	1	0.168	6.0



E. Chojnacki, SRF2009,Berlin

CERL – Main Linac SRF Cavities

R/Q=804 Ω, $Q_0=2\times10^{10}$, $R=1.61\times10^{13}$ Ω, E=16.2 MV/m
Voltage gain, V=13 MV per cavity
P_{dissp} (1.8 He bath) = 10.4 W
COP (1.8K)=720.3 , $P_{wall\text{-}plug}$ =7.3 kW/cavity
#of cavities: 64 modules × 6 cavities= 384 cavities
$P_{wall\text{-}plug}$ = 2.8 MW (~1/2 the total cryoplant load)
Any decrease in the average cavity Q will result in an increase in wall-plug power and could easily eat up the typical 50% over-capacity budget.

Per module		Wall Plug
1.8K Static [W]	5.68	4091
1.8K Dynamic [W]	68.99	49692
1.8K Total [W]	74.67	53782
5K Static [W]	64.27	12640
5K Dynamic [W]	25.65	5045
5K Total [W]	89.92	17685
100K Static [W]	32.58	389
100K Dynamic [W]	1455.49	17369
100K Total [W]	1488.07	17757
Module wall plug [W]		89225
# modules	64	
Linac Total [W]		5.71E+6
Safety Factor	1.5	
Linac Total · Safety Factor [W]		8.57E+6

Cryoplant Examples (1)

- ELBE (Dresden-Rossendorf)
  - Electron Linac
  - Linde custom refrigerator operating since 1999
  - 220 W at 1.8 K
- TRIUMF (Vancouver)
  - RIB Linac (ISAC-I, II)
  - Dual Linde *TCF50* refrigerators commissioned 2006 and 2008
  - Total 1200 W at 4.5 K
- BESSYII (Berlin)
  - Light Source, ERL R&D
  - Linde *L70*0 liquefier: 710 L/hr
  - Linde *TCF50* refrigerator: 150 W at 4.5 K + 55 L/hr liquefaction
  - *HoBiCaT*: 80 W at 1.8 K via warm vacuum pump (+/- 0.04 torr)

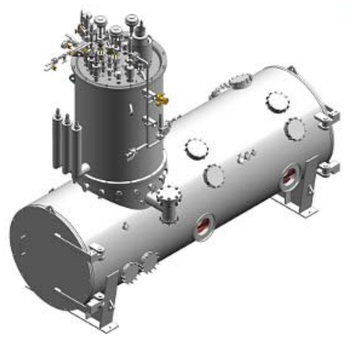
ELBE compressors, coldbox

ELBE compressors, coldbox

TRIUMF coldboxes & dewar

TRIUMF compressor

BESSY II coldboxes



HoBiCaT test cryostat

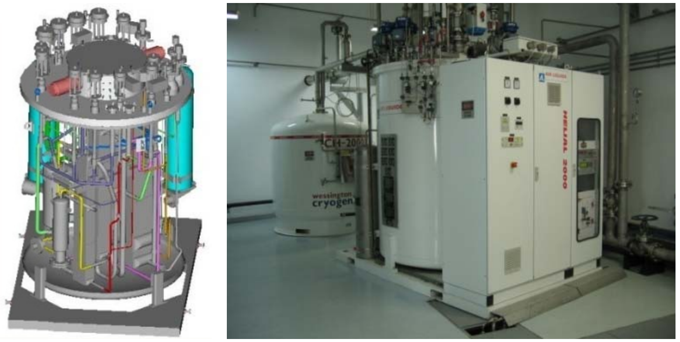
Slide courtesy of J. Fuerst, ANL

Cryoplant Examples (2)

- SSRF (Shanghai)
  - Light Source w/CESR-type srf cavities
  - Air Liquide *HELIAL 2000* commissioned 2008
  - 650 W at 4.5 K
  - +/- 0.3 mbar stability (=0.22 torr)

- ALICE (Daresbury)
  - Light Source Development ERL
  - Modified Linde *TCF50* commissioned 2006
  - 220 L/hr liquefier supporting 180 W maximum at 2.0 K via warm vacuum pump
  - +/- 0.06 mbar stability (= 0.045 torr)

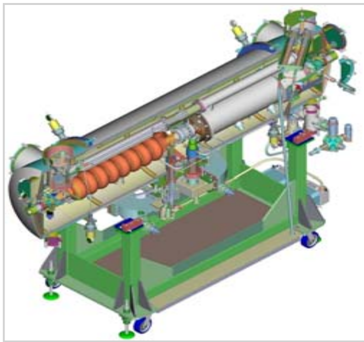
SRF cavity



Cold box model (L) and installed (R)

SSRF storage tanks

SSRF helium compressor



ALICE 2-cavity cryomodule

ALICE compressor & coldbox

Slide courtesy of J. Fuerst, ANL

Summary

- Many groups are actively working on ERL designs.
- Active R&D and advanced developments are currently underway at Cornell University, KEK/JAEA and BNL.
- It is important to reduced microphonics to a peak detuning of ~20Hz or so to take advantage of smaller, more reliable rf sources. Solid-state amplifiers should be considered as an attractive option.
- Dedicated test facilities such as HoBiCaT and planned BERLinPro are essential to conduct extensive long-term CW studies of cavities systems and training students.
- Make full use of existing facilities as test beds for ERL physics and technology R&D.
  - USA (Cornell, BNL, JLab)
  - Europe (HoBiCaT, BERlinPro, ALICE)
  - Asia (KEK, PKU)