SRF WORKING GROUP SUMMARY *

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Abstract

This working group focussed on the status and challenges of superconducting Radio Frequency (SRF) cavities and systems for present and future high luminosity lepton colliders, the so-called “factories”. Submissions covered the state of the art of SRF cavity designs, HOM damping, high power couplers, operational experiences and the needs of future colliders. Active work on similar SRF systems for the electron complex of a future electron ion collider (EIC) was presented. Much of this technology is also useful for next generation high brightness light sources and other applications.

OVERVIEW

The session contained nine talks covering:

- SRF cavities
- High level parameter optimization
- LLRF controls
- Power couplers
- HOM damping
- New materials and processes

The talks were all of a high standard and packed with useful information but all speakers managed to stay on schedule.

SRF CAVITIES

The success of existing high current SRF cavity designs at CESR and KEK-B, figures 1, 2, which continue to operate reliably after many years of service, prove that the technology is mature and can be relied upon for future applications. However the increasing demands for higher voltage, higher currents, better HOM damping, higher efficiency, lower cost and more compact installations is driving the development of new and more specialized designs. These designs expand upon this experience but are increasingly specialized and optimized for different operating scenarios [1]. Table 1 shows the main parameters of the operating scenarios of FCC-ee.

Looking forward to the highest energy future circular colliders such as FCC and CEPC it is clear that:

- One solution doesn’t fit all needs.
- Operating at the Z and W (high current, lower energy) needs 1 or 2 cell cavities, probably 400 MHz).
- Operating at the Higgs or Top energy (lower current, higher energy), could probably benefit from multi-cell cavities, higher frequency.

NEW DESIGNS

New design concepts were shown that are under consideration for the JLab EIC collider rings and cooler ERL [2] and the FCC-ee rings, figures 3-5. In these designs the cavity shape should be optimized to avoid harmful HOMs being resonant with harmonics of the RF frequency, to minimize the HOM power. The number of cells is determined by the maximum power per coupler and the HOM damping requirements. The higher-current machines favour one or two-cell low frequency cavities, while the higher energy lower current machines may use more cells per cavity and higher frequency. Total RF power is capped and therefore the higher energy machines must run at lower current due to synchrotron radiation.

Table 1: Main arameters of the FCC perating Modes

	V_tot	n_bunch	I_beam	σ	E_turnloss
FCC-hh	0.032		500		
Z	0.4 / 0.2	30180 / 91500	1450	0.9/1.6	0.03
W	0.8	5260	152	2	0.33
H	3	780	30	2	1.67
t	10	81	6.6	2.1	7.55

Figure 1: CESR-B type 500 MHz cavity cryomodule produced by Industry.

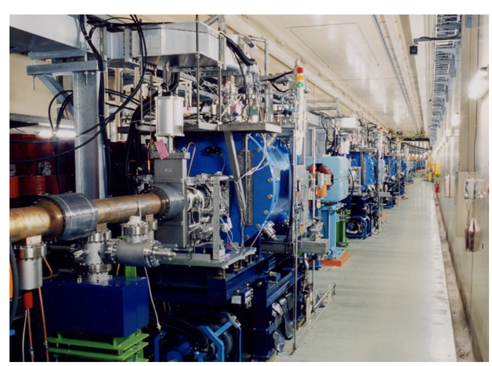

Figure 2: KEK-B type 508 MHz cavity cryostat produced by Industry.

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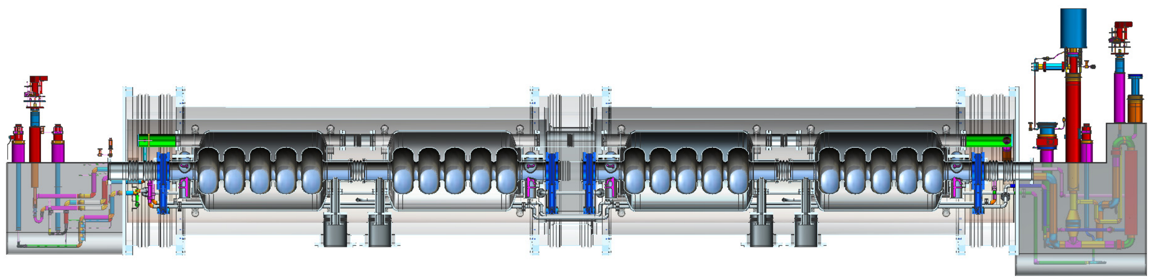

Figure 3: JLab modular cryostat concept. Supply and return end cans and bridging sections are standardised and join together cryounits that can be optimized to hold a variety of cavity types (5-cell ERL cavities illustrated).

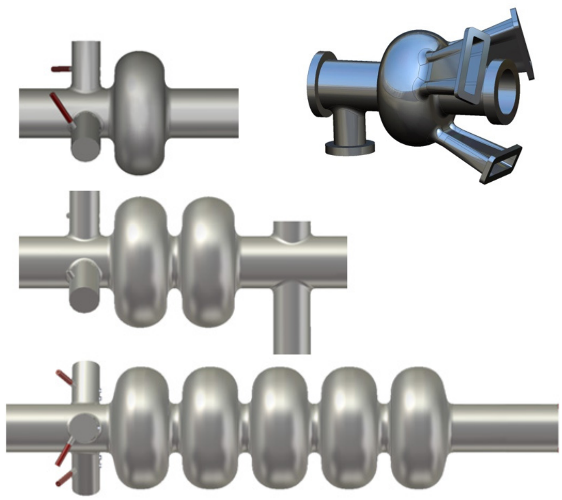

Figure 4: JLab EIC 952.6 MHz concept cavities in single cell, two-cell and five-cell variants, plus single-cell cavity with on-cell damping waveguides.

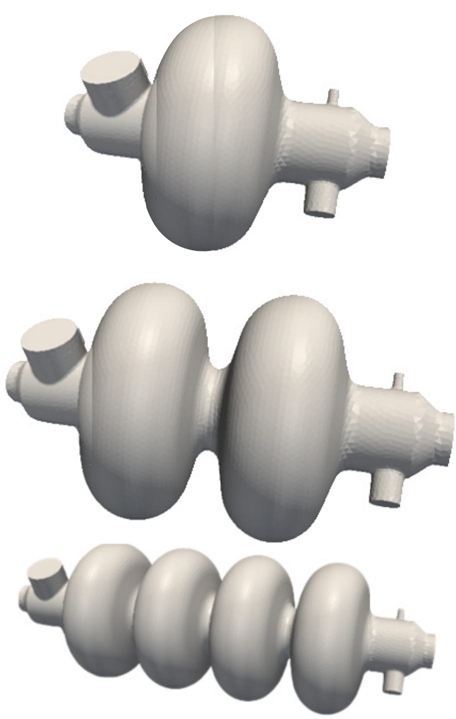

Figure 5: CERN FCC concept cavities in 400 MHz 1-cell, 400 MHz 2-cell and 800 MHz 4-cell varieties.

Modular Cryostat

For the JLab EIC a number of different cavity varieties will be needed including the ion storage ring single-cell cavities (and possibly electron ring cavities) figure 6, crab cavities, figure 7, five-cell cavities for the cooler ERL and single cell cavities for the cooler injector. To avoid having multiple different cryomodule designs it is planned to use a modular concept that can easily accommodate different cavity types with minimal changes. Such a concept could also be useful for other machines. Figure 3 shows the concept.

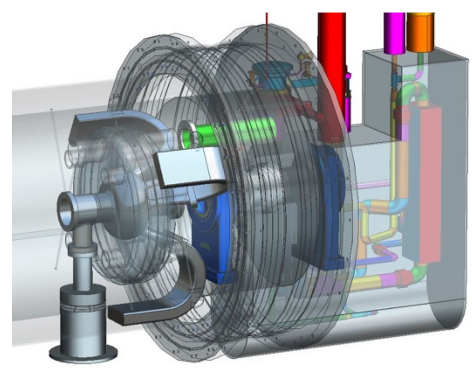

Figure 6: JLab modular cryostat concept with 952.6 MHz “on-cell-damped” cavity. Note the folded waveguides bringing HOM power out to room temperature loads.

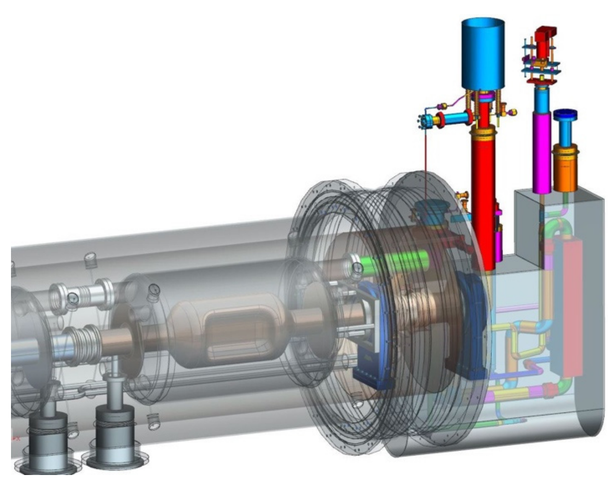

Figure 7: JLab modular cryostat concept with 400 MHz “RF Dipole” crab cavity (HOM dampers not shown).

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TECHNOLOGY OPTIMIZATION

The technology choice for each operating scenario is a complex optimization involving many factors as illustrated in figure 8, including as input the beam physics requirements, cost models, expected component performance, efficiencies and experience [3]. Constraints can then be applied including total available wall-plug power or tunnel length, performance limitations such as cavity gradient or coupler power etc. Doing this in a systematic way can quickly eliminate unfavourable technology choices and highlight possible configurations that have either a local optimum or a broader range of applicability. The model can also be quickly updated if any constraint is relaxed as a result of technology development and can highlight which constraints are most limiting and therefore worthy of R&D investment. Applying this methodology to the four FCC-ee scenarios quickly confirms the preference for low frequency and low number of cells per coupler at the Z and W, and the advantage of multi-cells and higher frequencies at the Higgs and Top. The FCC-hh is quite relaxed in comparison and may use the same technology as the Z but with less power required.

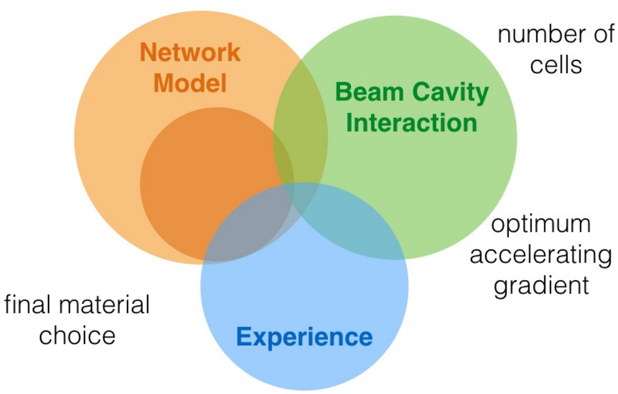

Figure 8: Interplay of factors in determining optimum technology choice.

ENERGY CONSUMPTION

Energy consumption of future large accelerators (FCC, CLIC, ILC, ESS) is in the range relevant for society and public discussion [1]. Figure 9 shows the expected energy consumption for FCC and the expected efficiencies at each stage of conversion. Clearly the biggest loss is in the DC to RF generation stage, where even the best existing high power klystrons have only about 70% efficiency. However recent exciting developments in non-traditional klystron design offer the prospect of raising this above 80 or even 90%. High power magnetrons may also approach these efficiencies and work is under way to test their suitability for SRF accelerator applications.

Cryogenics are another major source of power consumption, however again major steps forward in SRF cavity efficiency have been recently demonstrated with quality factors twice or more higher than the assumed best case for bulk Nb [4]. Figure 10 shows a set of cavity results for the LCLS-II prototype cryomodule in which final N_2 doping was applied directly after H_2 degassing. Other developments such as Nb_3Sn coated cavities or other new materials may eclipse even these impressive achievements. CEPC is counting on similarly high Q's at both 1.3 GHz and 650 MHz. Table 2 gives the high level operating parameters [4].

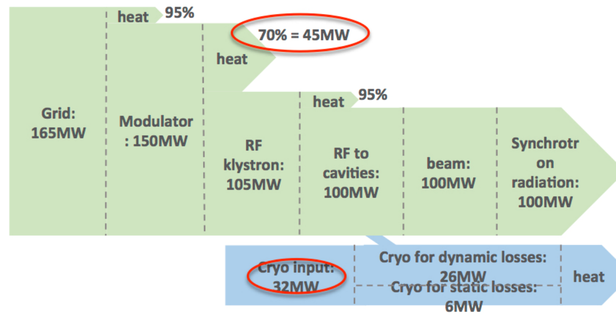

Figure 9: Energy consumption model for FCC-ee.

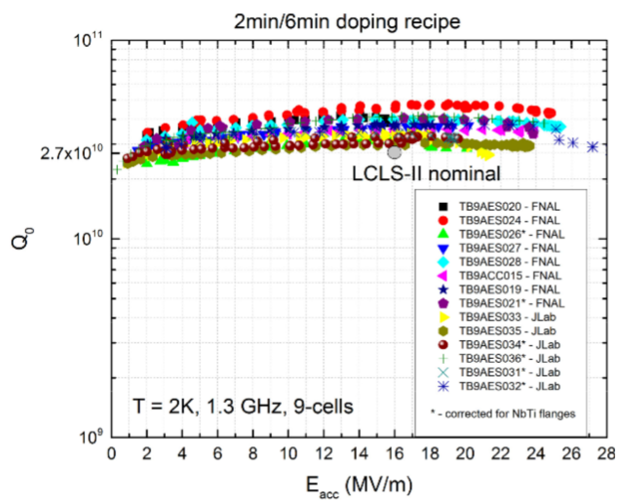

Figure 10: Cavity results after nitrogen doping for high Qo, adopted by LCLS-II.

Table 2: CEPC Cavity Requirements

Cavity	Qualification	Normal Operation	Max. Operation
650 MHz 2-cell Cavity	VT 4E10 @ 22 MV/m HT 2E10 @ 20 MV/m	2E10 @16.5 MV/m	2E10 @ 20 MV/m
1.3 GHz 9-cell Cavity	VT 3E10 @ 25 MV/m	2E10 @ 20 MV/m	2E10 @ 23 MV/m

VT=Vertical Test, HT= Horizontal Test

BEAM STABILITY

Coupled Bunch Instabilities (CBI)

High current storage rings with many bunches are susceptible to collective instabilities driven by the ring impedance, and in particular the narrow band resonances from the RF cavities. Preliminary estimates of the thresholds for the four FCC-ee cases and CEPC were presented. As expected the lowest energy, highest current case has

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the lowest threshold, figures 11, 12. However preliminary studies suggest that strongly HOM damped 1-cell cavities such as the JLab on-cell damped design can meet this requirement, figure 13, 14. For the higher energy, lower current cases two- or multi-cell cavities may be acceptable, but strong HOM damping will still be needed and the HOM power will be significant. A very preliminary look at CEPC requirements suggests that a HOM-damped 650 MHz 5-cell scaled from the JLab ERL cavity might be acceptable, figure 15 [2].

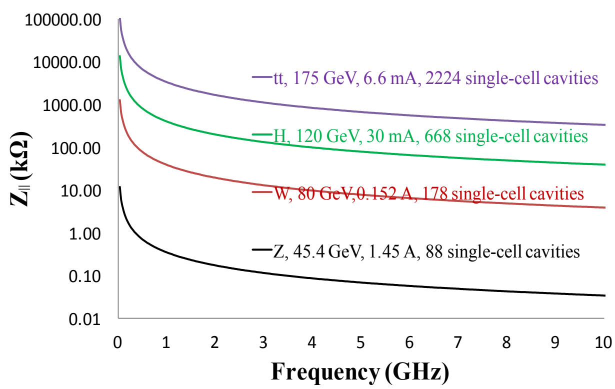

Figure 11: Estimated FCC longitudinal CBI thresholds. Note that the worst case is the lowest energy, highest current Z configuration.

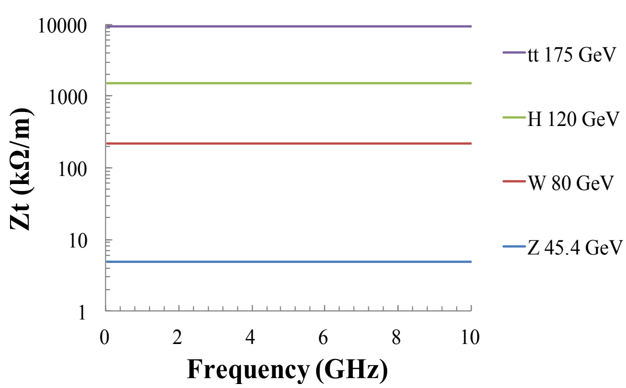

Figure 12: Estimated FCC transverse CBI thresholds.

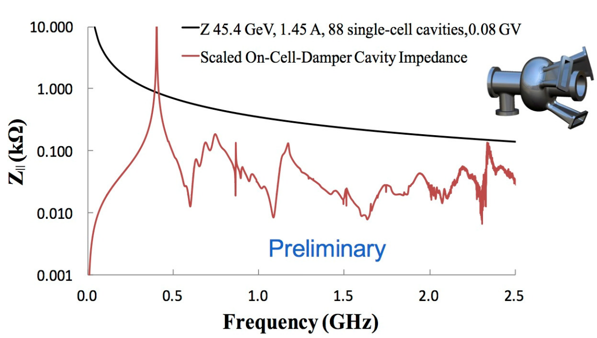

Figure 13: Estimated FCC-Z longitudinal threshold and impedance of the JLab heavily damped 1-cell cavity.

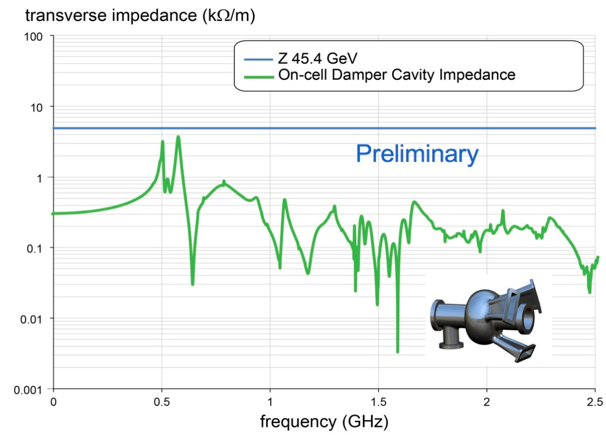

Figure 14: Estimated FCC-Z transverse CBI threshold and cavity impedance.

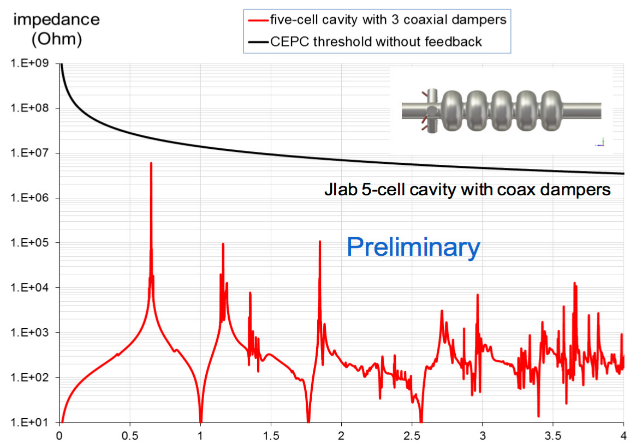

Figure 15: Estimated CEPC longitudinal threshold and impedance of a scaled 650 MHz 5-cell cavity.

With such high beam currents detuning of the fundamental mode will cross multiple revolution frequencies so sophisticated feedback systems such as those used in the B-factories will be needed. This may also have implications for klystron bandwidth and RF power overhead needed.

Robinson Stability and Transient Effects

Such heavily beam loaded RF systems rely on direct feedback to remain Robinson stable, but as the power approaches the klystron limit the stability margin decreases and the systems are less robust against disturbances. Since the rings must run with gaps for abort kickers and ion or perhaps e-cloud clearing, there will be significant amplitude and phase transients in the cavities. The B-factories mitigated this by using the shortest possible gaps (or multiple mini-gaps) and by trying to maintain even fill patterns. RF systems were programmed to learn and adapt to the transients to avoid saturating the klystrons. Transients were matched between the colliding rings to keep the collision point within the acceptable range of the detectors. Figure 14 shows the gap transient in the super KEK-B high-energy ring (HER) [5]. The response is complicated by the mixture of NCRF and SRF cavities. The ringing

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during the gap results from the three-coupled-cavity ARES NCRF system. By shaping the current fill in the gap region and offsetting the gaps in the two rings it is possible to match the transients in the two rings to less than one degree of phase, figure 15 [5].

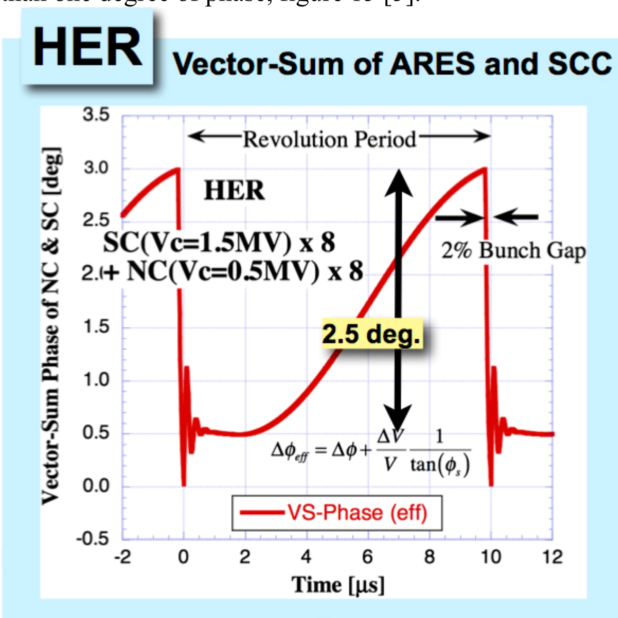

Figure 16: Phase transient in Super KEK-B HER due to beam gap. The ringing directly after the gap is from the ARES 3-cavity system.

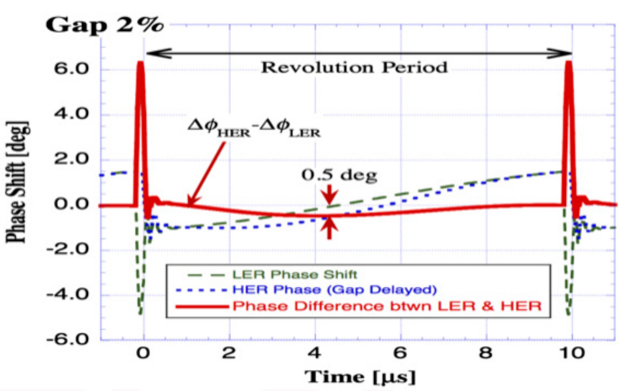

Figure 17: Residual Phase error between the HER and LER after shaping and offsetting the gaps in the two rings.

The new KEK digital LLRF system, figures 15, 16, has been fully commissioned, and features dedicated m=-1, -2 and -3 mode dampers to accommodate the large detuning needed in Super KEK-B, figure 17 [5].

The Newly developed digital LLRF control systems were applied to 9 stations in the HER, and successfully operated in phase I commissioning, in which the Super KEK-B rings were scrubbed before installation of the detector.

The m=-1 mode damper was tested in the HER, and the coupled bunch instability due to detuned cavities was suppressed successfully. The m=-2 and -3 mode damper systems will be implemented in Phase 2.

The CEPC single ring and partial-double rings also have a challenge with beam transients, because they cannot operate with a uniform or near uniform filling pattern. Because of the pretzel scheme intense bunch trains are needed with large gaps in between. Novel cavity detuning schemes such as detuning some cavities by one revolution frequency may be able to compensate the transient along the train providing the phase can recover during the gap. A higher fraction or complete double ring, although more costly, would mitigate this effect and allow higher luminosity.

All these effects will need careful study in the proposed future machines.

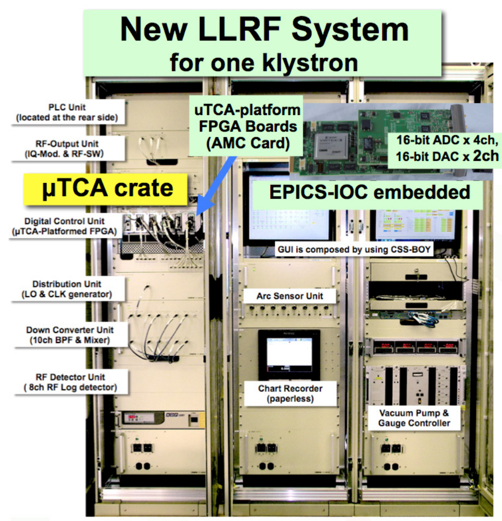

Figure 18: New KEK digital LLRF system.

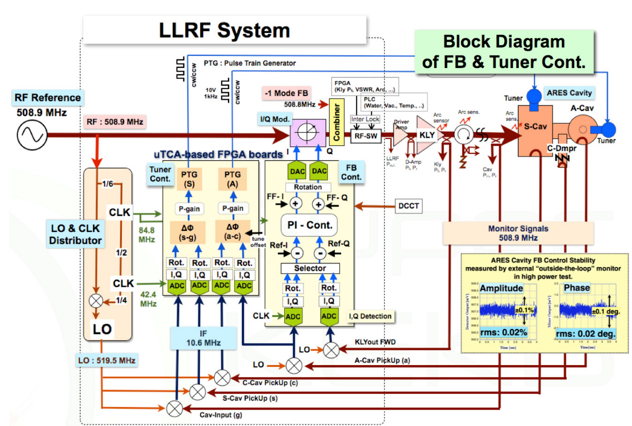

Figure 19: New KEK digital LLRF system schematic.

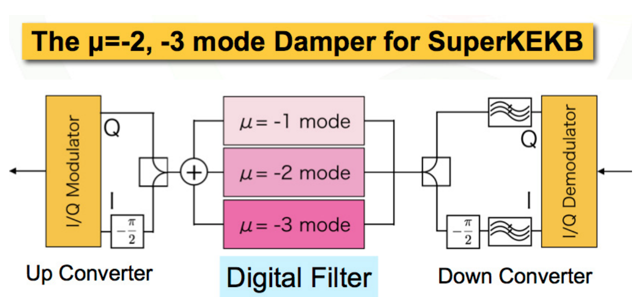

Figure 20: New mode -1, -2, -3 filters for super KEK-B.

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POWER COUPLERS

The fundamental power coupler (FPC) is one of the most critical parts of any SCRF system [6]. They have high geometric complexity and need many different materials, joining technics, coating technics etc. In the end the cost is comparable to that of a cavity and power coupler failure can lead to serious contamination of the very delicate SC cavity surface. Recovery is time consuming and expensive and may severely impact machine operations. In light of this the couplers must be handled and assembled as cleanly as the cavity and should be qualified and conditioned separately before installation on the cavity.

Power couplers typically are either waveguide type or coaxial and may have planar or cylindrical ceramic windows, figure 21. Increasingly double-window configurations are being used on SRF cavities for additional security. CW power of 500-600 kW has been successfully transmitted into operating accelerators through a single coupler, although MW-class windows have been designed and tested.

Figure 22 shows the result of an arcing event in a high power coaxial coupler. Multiple interlocks monitoring vacuum, light, electronic activity, reflected power etc. should be installed to prevent such failures.

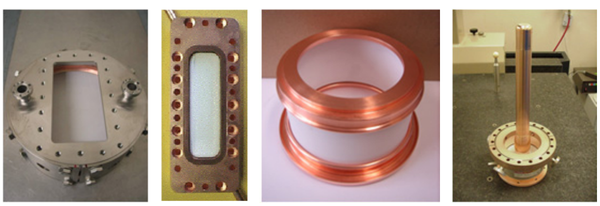

Figure 21: Examples of planar and cylindrical waveguide and coaxial windows.

Figure 22: Example of coaxial power window failure due to arcing.

HOM DAMPERS AND ABSORBERS

Just as critical as the fundamental power coupler, and not far behind in terms of cost and complexity, are the HOM couplers and absorbers. These must damp the dangerous HOMs to Q values that will ensure beam stability and extract or absorb the HOM power safely. They typically must operate close to the cavity and must therefore avoid particulate contamination or outgassing and must reject the evanescent fundamental mode fields. Again these fall into two main types, coaxial antennas and waveguide types. Beam line absorbers that can absorb HOM power propagating away from the cavity above cut-off are a special case of circular waveguide damper. They have excellent power handling capability and are broadband but they must be spaced sufficiently far from the cavity to allow the fundamental mode to decay.

A number of highly HOM-damped cavities have been developed in the past for high-current storage rings, ERLs and future colliders [7]. The best HOM damping solution depends on beam requirements and practical constraints, and the HOM damping scheme should be developed as part of the cavity system optimization.

Important questions when selecting the HOM damper type include:

- Use single cell storage ring cavities or multi-cell ERL-type cavities?
- Do same order modes (SOMs) present a problem?
- Is damping through the FPC sufficient?
- How to deal with HOM power propagating through the beam pipes (short bunch length – high frequency part of the spectrum)?
- Which RF absorbing material to use?

Examples of existing or proposed HOM damper and absorber designs are shown in figures 23 - 26.

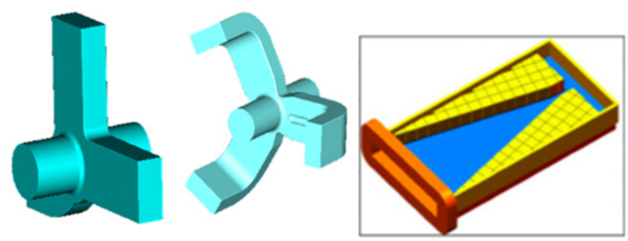

Figure 23: JLab original CEBAF and FEL waveguide HOM dampers and high power load.

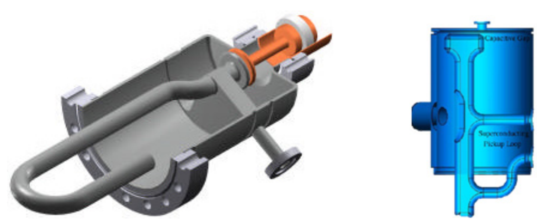

Figure 24: Original and later, modified hook type coaxial HOM couples.

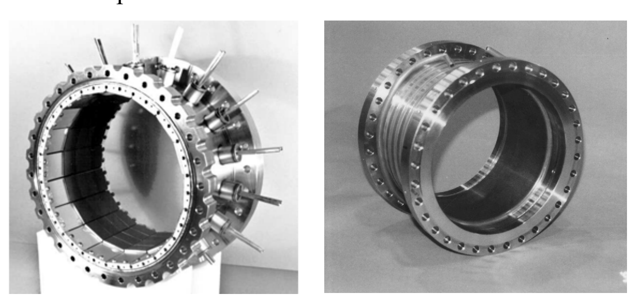

Figure 25: CESR and KEK-B type warm high power beam line HOM absorbers.

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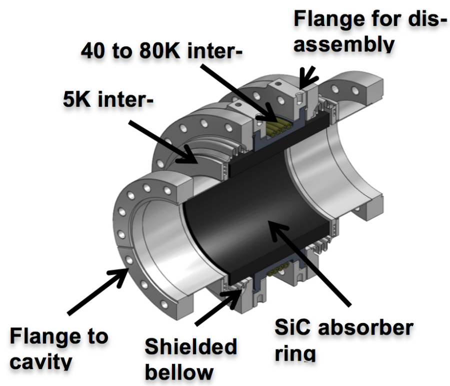

Figure 26: Cornell type cold beam line HOM absorber.

ALTERNATIVE MATERIALS

Recently interest has returned to niobium-tin (Nb_3Sn) as a promising material for higher efficiency and possibly also higher gradients. Recent work at Cornell [7] has shown that the previous Q-slope seen in earlier studies is not a fundamental property of Nb_3Sn, but a result of the forming process. New and exciting results, figure 27, show improved consistency and greatly reduced Q slope up to 16-17 MV/m. Ongoing work at Cornell and also Fermilab and JLab aims to exploit and extend this performance. Figure 28 shows the temperature dependent losses for Nb_3Sn compared to N_2 doped Nb cavities. If these residual resistances can be achieved in real cavities clearly 4K operation is not only viable but preferable.

Advantages of Nb_3Sn include:

- SRF operation at ~4K instead of 2K
- Greatly simplified cryo-system
- Greatly reduced cryo AC power

CERN's general strategy strategy for SRF development is as follows [8]:

- Maintain Nb on Cu technology & infrastructure used for operational machines such as LHC.
- Establish state of the art infrastructure and performance of bulk Nb elliptical and crab cavities using existing recipes.
- R&D: Explore full potential of Nb on Cu, new materials, etc.

At CERN research is also underway into alternative materials, including A15 compounds (Nb_3Sn or V_3Si), on copper. This would add the advantage of a high conductivity substrate to the low losses of the SRF material. To avoid the very high temperature reaction of the "Wuppertal" process CERN is experimenting with sputtering from A15 material targets directly onto copper. Process parameters include:

- $5x10^{-4}$ mbar < p < $5x10^{-2}$ mbar
- Sputtering gas: Kr or Ar
- 150 mm alloy targets of Nb_3Sn or V_3Si
- Magnetron sputtering
- Flat samples + *in situ* substrate heating

Two approaches are being pursued, coating followed by annealing to obtain the A15 phase, and high temperature coating to obtain the A15 phase directly. Figure 30 shows the CERN experimental set up for sample studies.

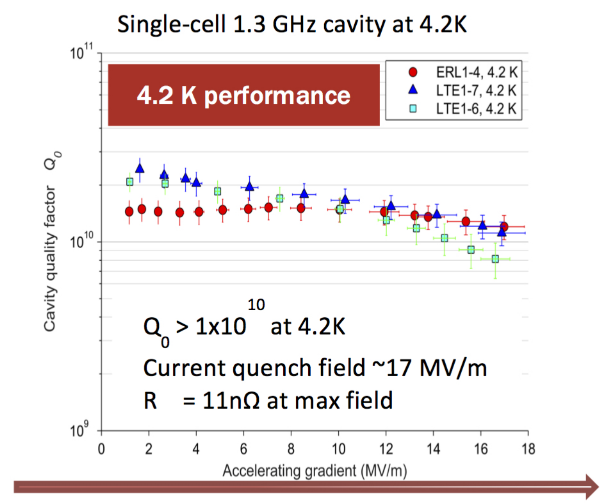

Figure 27: State of the Art and Repeatability of Nb_3Sn in cavity tests at Cornell.

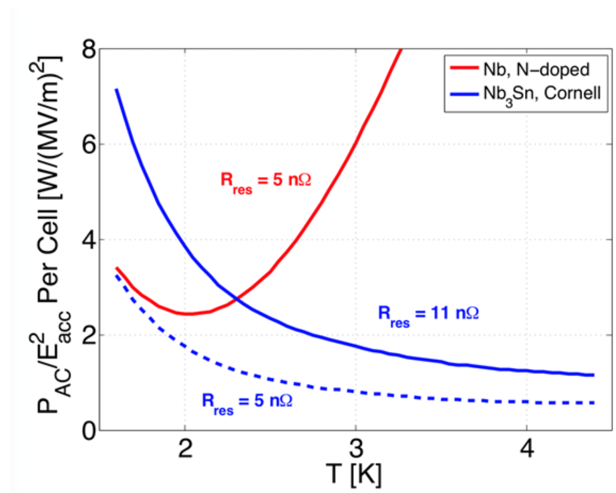

Figure 28: Temperature dependence of cavity losses for Nb_3Sn and N_2 doped Nb (Cornell).

As a first priority coating of spare LHC cavities is proceeding. Figure 29 shows an LHC cavity being prepared for coating. Process parameters are as follows:

- Intended $Q_0 \geq 2x10^9$ @ 5 MV/m
- Cavity as UHV chamber
- Cavity = anode, grounded
- Nb cylindrical cathodes tubes
- Movable electromagnet inside, liquid cooled.
- DC-magnetron sputtering, 6.4 kW, 6.10^{-4} mbar Kr
- 1h 20' coating in 7 steps at low temp. (150°C)
- Layer thickness about 2 mm
- Production cycle = 1.5 month/cavity

Improved Nb on copper coating procedures are also being developed at JLab and CERN using energetic condensation methods such as biased ECR and HIPIMS [9],

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figure 31. These methods supply additional energy to the incoming ions to enable high quality fully dense films to be grown without heating the substrate to excessive temperatures. Sample films have been tested in the CERN quadrupole resonator (QPR) and show greatly reduced Q-slope compared to traditional sputtered films, figure 30.

Figure 29: LHC spare cavity assembly for Nb coating.

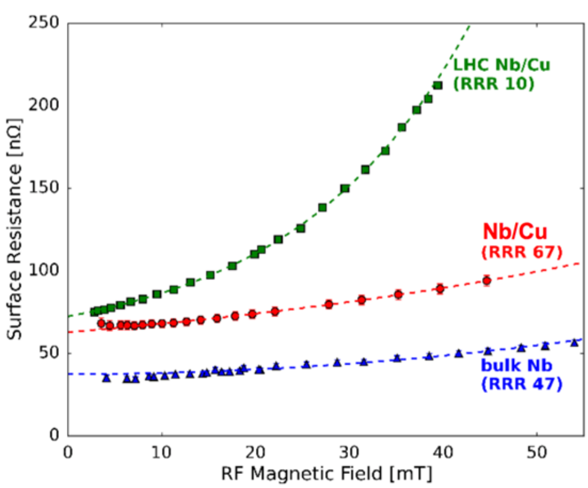

Figure 30: Surface resistance as a function of field for JLAB ECR films, showing greatly reduced non-linear losses (Q-slope). CERN HIPIMS films show very similar characteristics.

CERN is pursuing several FCC-ee prototypes cavities that will be fabricated by advanced spinning technology pioneered by INFN, Frascati. These include "H-machine" 800MHz 1- and 2-cell seamless cavities, and Z-machine" 400MHz 1 cell (+ 2-cells option). These will be fabricated as per the LHC cavities, but seamless. The copper cavities will then be coated with the best available thin film SRF technique.

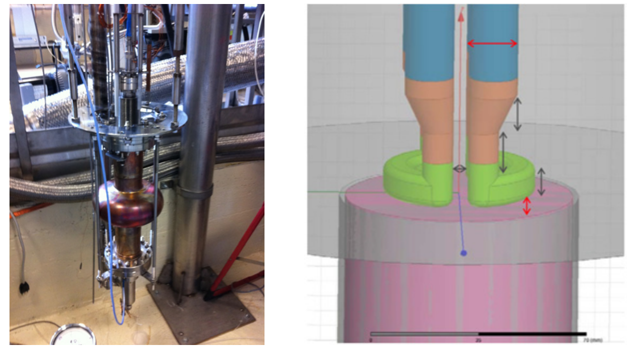

Figure 31: CERN HIPIMS cavity coating system and QPR sample test cavity concept.

CONCLUSIONS

- Good progress in all areas
- Much evidence of productive collaboration
- Valuable lessons and experience still coming from operating machines and new projects
- Much R&D still to be done on:
    - Cavity optimization
    - HOM dampers and loads
    - Power couplers
    - RF controls and gap transients
    - Prototypes and Proof-of-Principle tests

Many thanks to all the participants in this session.

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