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WORKING GROUP SUMMARY: SUPERCONDUCTING RF

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Abstract

16 talks were presented in Working Group 4, which are divided into four main themes. These themes along with their talks will be listed and summarized in the following.

ERL SRF SYSTEMS SPECIFICATIONS, DEVELOPMENT, FABRICATION, COMMISSIONING AND PERFORMANCE

This theme includes 5 talks [1-5] reporting on 2 different cryomodules and on tests with 2 dual-axis cavities for ERL applications.

The MESA ERL at KPH Mainz employs 2 cryomodules, which were ordered as turn-key modules from industry. The performance goal of 12.5 MV/m at a Q_0 of 1.25 x 10^{10} was readily achieved in vertical tests at DESY. The first assembled module was accepted after a cold module test at Mainz, while the second module did not achieve specifications and will be sent back to the manufacturer. This failure was most likely caused by the undefined state of a valve during transport, which may have produced particles that travelled into the cavity volume. Nevertheless, this experience shows that vendors have accumulated enough technical know-how to deliver complete turn-key cryomodules. As the MESA facility is still under construction a collaboration with bERLinPro was created to make beam test with the qualified MESA module at bERLinPro. There, the construction is more advanced but funds are currently lacking for the procurement of a cryomodule. Beam tests are foreseen in 2021 at bERLinPro. The module will then be shipped back to Mainz and MESA plans first operation in 2022.

A report on operational experience with 2 ERL cryomodules came from cERL at KEK. The required phase and amplitude stability (< 0.01% and < 0.01 deg) was achieved by damping microphonics from rotary pumps with simple rubber feet. The modules suffer from increasing field emission during operation, which is probably related to contamination, but also to a high ratio of peak surface fields to accelerating fields of the particular cavities used. An unexplained vacuum burst event in 2017 further degraded performance of one module, which could so far not be recovered by high power pulsed processing.

Dual-axis cavities where already discussed at ERL 2017 [6] where a recommendation for was given for more R&D on this type of cavity. The cold test results reported by ODU [4] of a twin-axis cavity showed that the expected gradient of 15 MV/m could be surpassed, however only for one of the 2 cavities. Due to a welding defect Cavity 2 only reached 5 MV/m. Nevertheless, the suppression of multipacting by design was successful as well as the chemical treatment and processing. Prototyping and warm tests of multi-cell dual axis cavities with bridge couplers were reported in [5] and showed good agreement between simulations and measurements.

HIGH LOADED Q CAVITY OPERATION (MICROPHONICS, LLRF, RF POWER SYSTEMS, TRANSIENT BEAM LOADING)

This theme comprised 6 talks [7-12] reporting on various types of RF control systems, encompassing both low-level and high-power technologies, as well as fundamental development of a HOM damped cavity solution.

Analysis of the microphonics characteristics of the two, cERL main linac cavities at KEK [7], has identified that the stability of the first cavity (ML1) has deteriorated over the past 5-years, whilst the second cavity (ML2) has remained stable. Further investigation has shown a cavity field-level dependency threshold of ~3MV/m for this limiting cavity, which is most likely related to a quench limit level. A transfer function characterisation has been developed for the cavity with its piezo tuner system, with future plans being made to optimise the cavity control more effectively utilising this analysis.

Three reports identified specific RF technology control processes employed for microphonics diagnostic and control for ERL operation. First single turn ERL operation was demonstrated at S-DALINAC in August 2017 with a new FPGA-based LLRF system [8], supporting a beam current of 1 µA to achieve up to 90% transmission efficiency for 6 out of 8 of the 20-cell S-band cavities. RF stability measurements showed a negligible phase control impact for beam currents <1 µA, however amplitude errors were much larger than expected and require further optimisation. A beam disturbance at 52 Hz was identified, which was assumed to originate from a gun-induced modulation, but this also requires further investigation to confirm. A new RF power measurement system has been developed and is ready for use with an optimization algorithm for improved RF Control.

Also at TU Darmstadt, system identification procedures for resonance frequency control of SRF cavities have been developed [9], driven by the primary motivation to overcome the impact of helium pressure transients and their effect on RF stability. By incorporating a 2-stage, least-square, close-loop transient analysis and integrating a suitable PID controller, optimised control parameters have been defined, which can effectively replicate the measured responses observed on the S-DALINAC accelerator. Reconfiguring the PID parameters with considerably increased differential gain has enabled the closed-loop re-

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sponse to be improved by approximately a factor of 3. Further investigations are planned in order to validate the control parameters against variable excitation errors.

As ERLs operate with low to zero beam loading, SRF linacs can operate with high loaded Q-factors (~10^8), which makes the cavities very sensitive to microphonics. Passive control of mechanical vibrations can include clamping and absorbing supports of mounting frames, waveguide components, vacuum and water pumps, cryogenic transfer lines and compressor systems. By analysing the mechanical eigenmodes of all components of the cryomodule, potential cryogenic instabilities can be identified which may become major microphonics drivers. Such drivers can be cryogenic pressure waves which induce thermoacoustic oscillations or otherwise turbulent cryogenic flow induced by transfer restrictions in distribution pipes and/or valves. Active control measures can complement passive processes, which invariably employ fast-tuner technologies and feedback techniques which can compensate for microphonic detuning. Utilisation of advanced Least Mean Square techniques, incorporating band-pass detection processes can considerably improve microphonics detection and correction. By using narrowband Active Noise Control (ANC), keeping the cavity phases in a stable region even when the cavity transfer function changes, resulted in impressive cavity isolation and reduced detuning levels by a factor of 2 for the CBETA main linac cavities [10].

Advances in ferroelectric ceramics has opened up possibilities for the development of fast reactive tuners for SRF cavity applications. Ceramic response times are now very fast, achieving < 10 ns capability. CERN has recently acquired and tested a Proof of Principle Ferro Electric Fast Reactive Tuner (FE-FRT), which was built by Euclid Techlabs with input from BNL [11] and which incorporates such materials. A 400 MHz cavity test has been successfully conducted at CERN at 4.5 K and 2 K, showing that the FE-FRT could react within 50 µs, considerably faster than the cavity filling time. Multi-application scenarios are envisaged utilising this technology i.e. for high beam loaded machines, the FE-FRT can directly be used to supress microphonics and for low beam-loaded machines (i.e. ERLs), the FE-FRT can be used to significantly reduce the RF power required. An 800 MHz estimate for PERLE, with a 3 x 10^8 Q_{ext}, can reduce the forward power requirement by a factor of 15!

For the High Energy Photon Source (HEPS) in Beijing, a 116 MHz main storage ring RF frequency is proposed by IHEP [12]. The SRF cavity design requires HOM damping (Q_{L} < 1000), so that the 5 x QWR structures are able to stably operate with 200 mA and 6 GeV electron beams. A first proof-of-principle cavity has been designed, fabricated and tested, exceeding the 12.5 MV/m and 1 x 10^9 target performance levels at 4 K. Further development of cavity ancillaries i.e. coupler, tuner and helium tank designs identified a field leakage issue with the cavity forward power coupler, requiring an elongation of the coupler tube and improved outer conductor cooling to reduce the dynamic losses, whilst also increasing the helium tank volume to improve 4 K operation stability. HOM power is extracted through large aperture beam-pipes which enables effective damping of dangerous monopole and dipole modes. A HOM coupler is also incorporated which extracts power through a C-shaped waveguide (see later session), which provides an effective high-pass filtering of the broadband power. The design optimisation is ongoing in order to achieve the required damping performance.

HOMS, HOM DAMPING AND HIGH-CURRENT OPERATION

Being able to extract HOM power efficiently from SRF cavities, without introducing potential breakdown weaknesses is a significant challenge for high current ERL linacs. Two talks in this session identified techniques for HOM management using i) waveguide HOM loads for high current operation [13] and ii) a C-shaped waveguide HOM coupler optimisation [14]. New broadband ceramic and ferrite absorbing materials are providing improved power handling capabilities. HOM load solutions at 1.3 GHz and 1.5 GHz [13], utilising a high thermal-conductivity AlN and SiC composite, have been developed by JLAb and HZB for BerlinPro and BESSY VSR respectively, each demonstrating good damping performance capabilities. Having overcome brazing challenges for this material, it is anticipated that such technology solutions can also be applicable for the JLEIC electron-ion collider in the future.

Efficient extraction of HOM power above the fundamental operating frequency, using a compact and easy to cool coupler has been innovatively developed at KEK [14]. The technique employs a C-shaped coaxial waveguide, which can be precisely tuned to maximise high-pass filtered RF power extraction from the SRF cavity. Due to its configuration, the central coax is much easier to cool and its conversion to a conventional coaxial transmission line is also much simpler than the standard coax-waveguide alternative. In addition, the physical size of the coupler can be reduced whilst providing excellent fundamental-mode isolation and effective damping of HOM impedances in the SRF cavity. Further developments are underway to be able to qualify its capability at high power levels.

At Mainz University, Beam Break-Up threshold estimations have been conducted [15], utilising comparative analysis of HOM measurements of single 1.3 GHz cavity tests performed at DESY and 2-cavity characterisation measurements performed at HIM for the integrated MESA cryomodule. Whilst the cavity HOM trends were similar, frequency deviations are observed because of fundamental mode tuning variations, the frequency spread differences between cavities is most likely due to fabrication tolerances and the larger Q-spread observed is most likely due to mechanical deviations from the cell elliptical shapes. A BBU threshold current limit of 13.4 mA is estimated, and whilst further MESA lattice optimisation is being performed, it is anticipated this threshold can be increased further.

HIGH Q0 CAVITY PERFORMANCE

The focus of this session was not on discussing the latest recipes or procedures to push the Q-value or the accelerating gradient. The purpose was rather to look at day-to-day operational issues or procedures, which may limit cavity performance. Both talks under this heading described real-life issues of i) cold testing SC cavities in a vertical test stand [16], and of ii) operating a SC CM in an ERL [17]. Both talks highlighted once more the importance of cleanliness during cavity testing, cryomodule assembly and also the effects of contamination during operation, which can yield performance degradation over time. Degrading operation was reported for the cERL main linac modules [1] as well as for the cERL injector module. Both modules also suffered from a certain performance degradation between vertical tests and tests of the assembled modules. In case of the cERL injector module, the performance can be recovered by applying plasma processing systematically before each run.

The fact that the performance degrades over time probably implies a slow contamination by the surrounding warm beam line elements. In case of the cERL injector module the situation is further complicated by the acceleration of field-emitted electrons hitting surrounding beam line elements (Faraday Cup or the photocathode gun) thereby producing X-rays. In large machines containing dozens or hundreds of cryomodules one usually has the luxury of having long distances in the order of several metres between cold and warm beam line elements. In small ERLs with 1 or 2 cryomodules this space cannot be afforded, which means that the cleanliness requirements for the warm machine parts should be as strict as for the cold parts and that cold traps should be employed to minimise cross-contamination once the cryomodules are cold.

REFERENCES FROM ERL 2019

[1] H. Sakai, “KEK ERL SRF Operational Experience“, TUCOYBS01, this conference.

[2] S. Thomas, “Integration of the MESA modules to bERLinPro for high power beam tests”, TUCOYBS04, this conference.

[3] F. Hug, “Cryomodules for the Mainz Energy-Recovering Superconducting Accelerator (MESA)”, TUCOZBS06, this conference.

[4] H. Park, “Superconducting Twin-Axis Cavity for ERL Applications”, TUCOYBS03, this conference.

[5] Y. Shashkov, “Asymmetric SRF Dual Axis Cavity for ERLs: Studies and Design for Ultimate Performance and Applications”, WECOYBS05, this conference.

[6] I. Ben-Zvi and F. Gerigk, „ERL 2017, Summary of WG4, Superconducting RF”, ERL 2017, CERN, Switzerland, `doi:10.18429/JACoW-ERL2017-FRIBCC004`

[7] F. Qiu, “Characterization of Microphonics in the cERL Main Linac Superconducting Cavities”, TUCOZBS04, this conference.

[8] M. Steinhorst, “LLRF ERL Experience at the S-DALINAC”,TUCOZBS05, this conference.

[9] S. Orth, “System Identification Procedures for Resonance Frequency Control of SC Cavities”, THCOWBS03, this conference.

[10] N. Banerjee, “Passive and Active Control of Microphonics at CBETA and elsewhere”, THCOWBS07, this conference.

[11] A. Macpherson, “A Ferroelectric Fast Reactive Tuner (FRT) to Combat Microphonics”, TUCOZBS02, this conference.

[12] P. Zhang, “The Development of HOM-Damped 166.6 MHz SRF Cavities for High Energy Photon Source in Beijing”, THCOWBS05, this conference.

[13] J. Guo, “Waveguide HOM Loads for High-Current Elliptical Cavities”, THCOXBS01, this conference.

[14] M. Sawamura, “Development of HOM Coupler with C-Shaped Waveguide for ERL operation”, THCOXBS02, this conference.

[15] C. Stoll, “Beam Breakup Limit Estimations and HOM Characterisation for MESA”, THCOWBS06, this conference.

[16] A. Macpherson, “High Q 704 MHz Cavity Tests at CERN”, THCOXBS05, this conference.

[17] E. Kako, “Degradation and Recovery of Cavity Performance in Compact ERL Injector Cryomodule at KEK”, THCOXBS06, this conference.