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European network
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I. 1st Phase: CREMLINplus

Development of collider technologies and fostering synergy between SCT, CLIC, and FCC-ee collider projects:

Initially, at the starting of CREMLINplus program, the effort was focused on the design of a sophisticated constant field dipole, the so-called B-COM magnet, a key element of the switchyards (the spreaders and the recombiners) of a multi-turn Energy Recovery Linac (ERL). In this type of accelerators configurated in a racetrack, the beams at different energies are accelerating (and decelerating) in the same Linac located in the straights, before being vertically separated (in the spreader) at different bending angles according to their beam rigidity and directed to the appropriate circulating arcs. The beams are thereafter recombined in a second switchyard (the recombiner) in a common trajectory via a second similar B-COM magnet before entering again in the accelerating sections (Cf. figure 1)

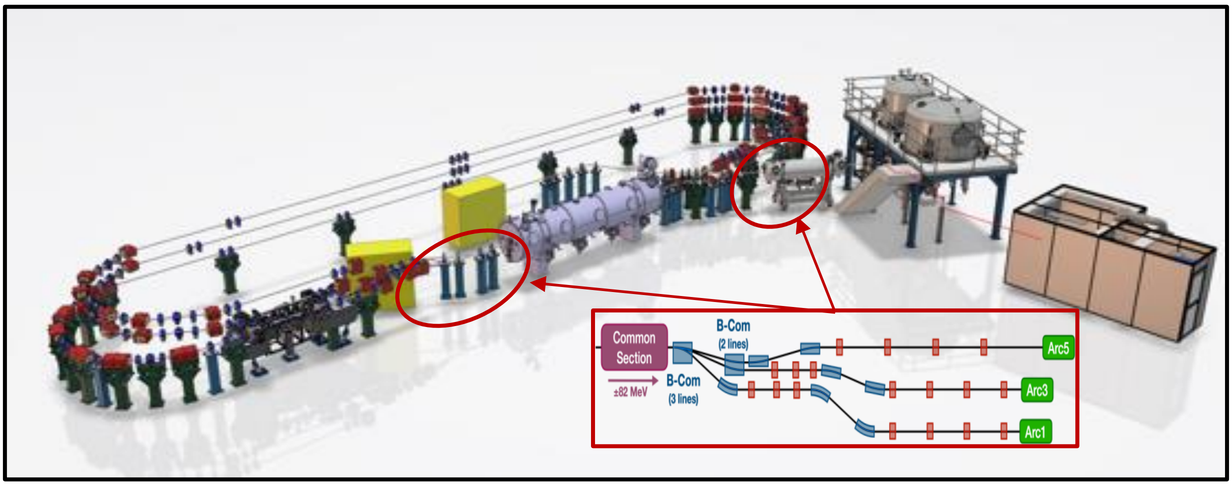

***Figure 1**: PERLE layout showing the different systems with the location of B-COM magnets highlighted*

From the beam dynamics study of PERLE lattice, it was shown that the beam size does not exceed 2 mm at 3σ. Taking into account the thickness of the vacuum chamber, an aperture of 4 cm was chosen for the B-COM. A H-magnet of 33 cm yoke length (along the z-axis) made of magnetic steal was considered for its design, in order to minimize the flux leakage and adapt to the available space in the ERL lattice. The coil is made of a hollow Copper conductor based on water cooling. A blend radius of 0.8 cm was introduced to the pole edges to reduce the harmonic content.

The dipole has to split vertically beams with energies: 171 MeV, 336 MeV, and 500 MeV. OPERA 3D simulations were performed to optimize the design (Yoke and Coil geometry, *Cf. Figure 2*), to define the field distribution and homogeneity in the dipole with required boundaries and to achieve the desired bend angles with acceptable harmonic content. Materials, cooling scheme, design completion with mechanical and thermal simulations were also studied and appropriate solutions were proposed. It was foreseen that the next steps (B-COM prototyping and measurements) would be pursued at BINP-Novosibirsk regarding their high expertise and skills in magnet fabrication and qualification field.

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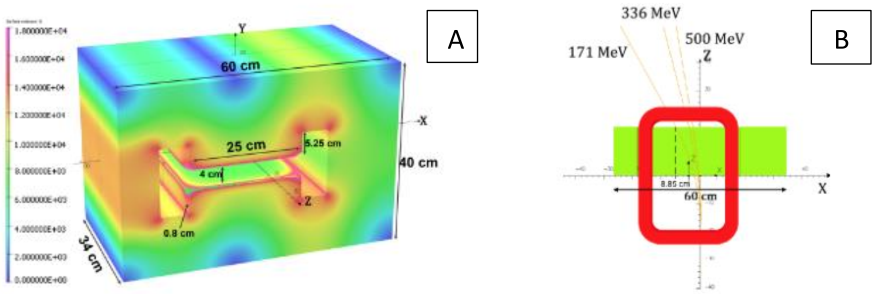

***Figure 2:** (**A**) B-com magnet design with Opera 3D. Magnetic field is in Gauss. Areas with $B > 1.8\ T$ are not shown. Asymmetrical geometry was chosen for enhanced mechanical stability. (**B**) Trajectory of the electron beam through the B-com magnet at three energies: 171 MeV, 336 MeV, and 500 MeV. Initial position of the beam is (4.4, 0, -60) cm.*

The decision to interrupt the CREMLINplus program, obliged us completely change the scope of the project, as a backup solution for the magnet prototyping and test within an industrial partnership in Europe induces an important delay regarding the program timeline and an over-cost regarding the allocated budget.

II. Second Phase: EURIZON:

Development of accelerator technologies for Energy Recovery Linacs (ERLs) and their use in colliders:

For the transition from CREMLINplus to EURIZON, we introduced new developments for high current ERLs. A complete study on High Order Modes (HOMs) was performed for a 5-cell 801.58 MHz Nb cavity specially designed and fabricated for a multi-turn, high power ERL. The study aims at identifying, minimizing the excitation and trapping of Radiofrequency HOMs, then facilitating their extraction and enabling their efficient damping outside of the cavity cells using the HOM couplers.

HOM couplers are devices attached to the accelerating cavities alongside the fundamental power coupler (FPC). The main role of the HOM couplers is to remove or dissipate unwanted HOM energy from a cavity. On the other hand, the primary function of the fundamental power coupler (or input coupler) is to supply power from the RF generator to the cavity at the fundamental mode (FM) frequency to accelerate the beam. Figure 3 shows a typical setup of a single-cell RF cavity with a HOM coupler and an FPC.

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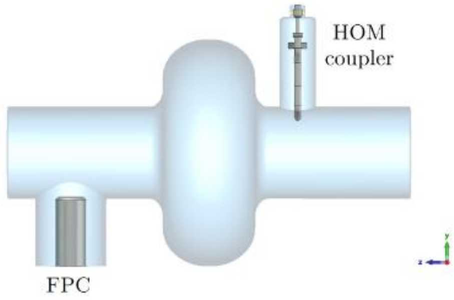

Figure 3: *Scheme of a single-cell cavity equipped with a fundamental power coupler (FPC) (left-side) and a HOM coupler (right-side).*

The HOM couplers are designed to efficiently transmit RF signals at frequencies where high beam-impedance HOMs exist while effectively rejecting the fundamental mode. This ensures that HOM couplers operate to attenuate cavity higher-order modes without absorbing the energy of the FM.

Prior to the design optimization of HOM couplers for the 5-Cell cavity, identification of the dangerous modes to be extracted is needed. Thus, a 3D-Eigenmode simulations (CST-Studio) focus on cavity monopole and dipole modes, which hold significant importance in high-current ERL due to their potential impact on its performance. Higher order modes with high (R/Q) values are of particular interest, as an elevated value of R/Q corresponds to a more amplified excitation induced by the circulating beam. If not adequately damped, monopole modes can lead to high HOM power loss in SRF cavities, while dipole modes can cause transverse beam instabilities. Modes with frequencies close to beam harmonics are also particularly relevant. When a HOM is near a beam harmonic, the induced voltage may become significant, leading to potential beam instabilities. Figure 4 illustrates the R/Q of the most relevant monopole and dipole passbands of the 5-cell 801.58 MHz cavity. The longitudinal geometric shunt impedance (R/Q)ǁ is calculated for the TM monopole modes, while the transversal geometric shunt impedance (R/Q)⊥ is computed for the TM and TE dipole modes. Additionally, it compares HOM resonant frequencies with respect to the PERLE beam current spectrum, corresponding to the filling pattern and bunch timing.

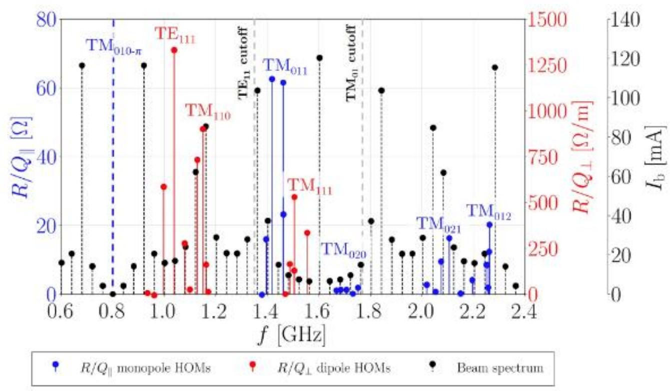

Figure 4: (*R/Q)ǁ (blue lollipops) and (R/Q)⊥ (red lollipops) of the most relevant monopole and dipole HOMs, respectively, of the 5-cell 801.58 MHz cavity until 2.4 GHz. Twenty-five monopole modes and fifteen dipole modes are shown. A blue-dashed line indicates the FM frequency. Gray-dashed lines represent the TM01 and TE11 beam pipe cutoff frequencies. Black-dashed lollipops depict the PERLE beam current spectrum.*

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The monopole passbands TM011 and TM020 and the dipole passbands TE111, TM110 and TM111 are confined within the cavity's cells. These trapped HOMs can limit the stable operation of the ERL. Consequently, they require strong damping to reduce their impedance (R/Q).QL below the beam instability limits and meet beam dynamics requirements.

The proposed damping approach involves using either a combination of redesigned and optimized versions of LHC coaxial HOM couplers: the probe (P) and the hook (H), or DQW couplers on the beam pipe tubes to damp beam-induced HOMs (Cf. Figure 5). These HOM couplers designs are selected as a starting point for optimizing their transmission characteristics based on the HOM spectrum of the 5-cell 801.58 MHz PERLE cavity.

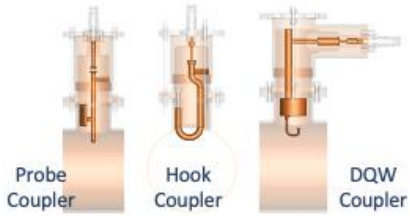

Figure 5: *HOM coupler designs to be geometrically optimized based on 5-Cell 801,58 MHz PERLE cavity HOM spectrum.*

They are optimized to obtain high transmission at frequencies where cavity HOMs with a high level of longitudinal and transversal impedance exist without compromising the FM efficiency. The primary objective is to achieve, for selected coupler designs, a transmission ideally higher than -15 dB for the high impedance TM011, TE111, TM110 modes to guarantee sufficient HOM-damping within these mode passbands. These HOMs usually reside below the corresponding beam tube cutoff frequencies and possess high R/Q values.

Figure 6 shows the longitudinal and transversal impedance of the single-cell, two-cell, and five-cell PERLE-type cavities

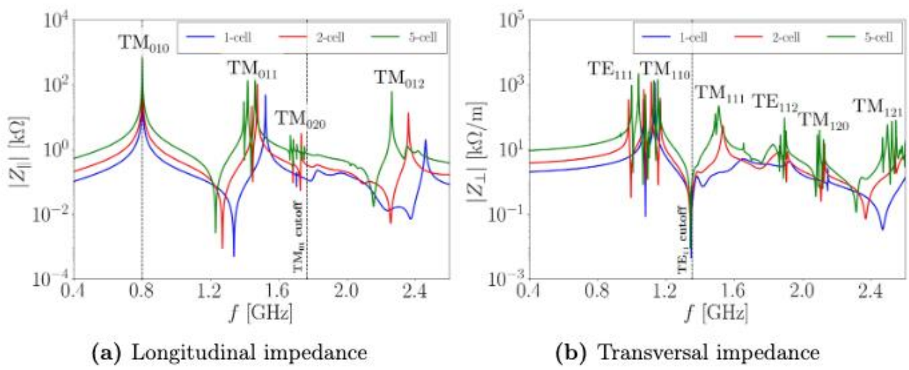

Figure 6: *Longitudinal (a) and transversal (b) impedance of the 1-cell (blue), 2-cell (red), and 5-cell (green) 801.58 MHz PERLE cavities. The dashed vertical lines in (a) and (b) represent the cutoff frequency of the TM01 and TE11 beam pipe modes.*

The peaks correspond to the HOM with high impedance values that must be damped using HOM couplers. The rather confined TM012-π mode at 2.26 GHz exhibits high-impedance, which cannot be

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reduced using coaxial HOM-coupler, as it resonates considerably above the TM01 beam tube cutoff. However, its impedance could be reduced by modifying the elliptical profile of the end-cells to improve the mode coupling to the beam pipe.

The S-parameters of the three investigated coupler designs have been optimized to provide high transmission at frequencies corresponding to the high-impedance HOMs of the 5-cell PERLE cavity while maintaining FM efficiency. Figures 7 (a) and (b) show the monopole and dipole transmissions of the optimized coupler designs respectively.

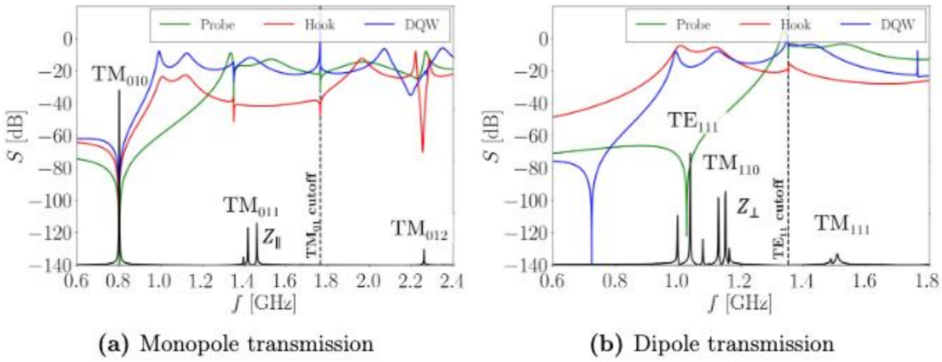

Figure 7: *Monopole (a) and dipole (b) transmissions of the optimized hook-type (red), probe-type (green), and DQW-type (blue) HOM couplers for the PERLE cavity. The longitudinal impedance Z∥ and transversal impedance Z⊥ of the 5-cell PERLE cavity are depicted as black curves in (a) and (b) for reference, respectively. The black vertical lines in (a) and (b) represent the cutoff frequency of the TM01 and TE11 beam pipe modes, respectively. The mode passband nomenclature is given.*

The DQW coupler provides higher transmission at the TM011 monopole passband than the probe-type coupler. Due to its design, the hook-type coupler is intrinsically unsuitable for damping the first monopole passband. Conversely, the hook-type coupler yields higher damping for the TE111 and TM110 dipole passbands than the DQW coupler. Due to its inherent design, the probe-type coupler remains inadequate for damping the first two dipole passbands. The DQW-type coupler emerges as the most advantageous solution for simultaneously damping both the first monopole and the first two dipole passbands, while a combination of the probe-type and hook-type couplers is required for efficiently damping them separately.

After the simulation work and the damping scheme numerical studies, the geometrically optimized HOM couplers of the studied designs were 3D-printed (polymer copper-coated couplers) to perform low level RF measurements in single and double copper-cell first, then on 5-Cell copper cavity.

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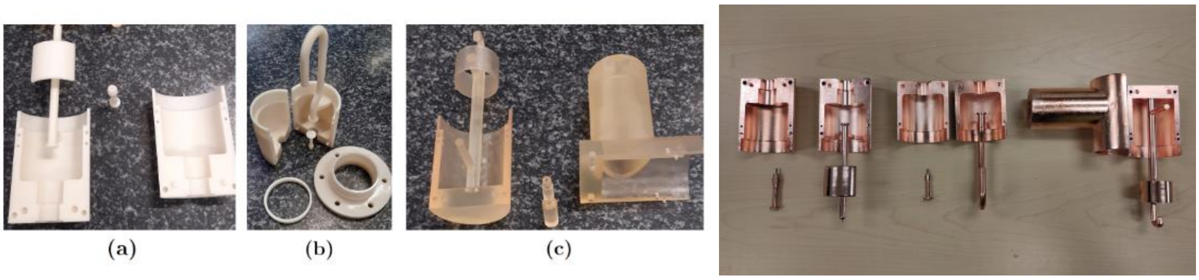
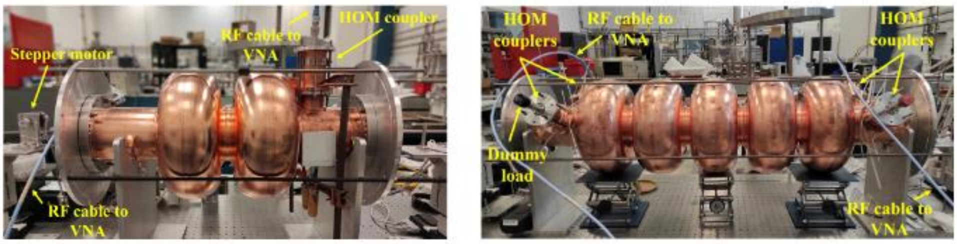


Figure 8: *HOM coupler prototypes fabricated using the stereolithography technique: Accura 25 probe (a) and hook couplers (b). Accura 48 HTR DQW coupler (c) then copper-coated. The figure falls under the Creative Commons Attribution 4.0 (CC BY 4.0) (license https://creativecommons.org/licenses/by/4.0/)*

The experimental setup used for low-power RF measurements on PERLE-type Cu cavities is depicted in Figure 9. The purpose of this setup is to enable the execution of multiple RF tests on the same test bench, including measurements of HOM frequency, bead-pull tests, and HOM-damping measurements.



(a) 2-cell Cu cavity with one HOM coupler (b) 5-cell Cu cavity with four HOM couplers

Figure 9: *Measurement setup for the 2-cell Cu cavity with one HOM coupler prototype installed on the right-hand beam pipe and a reference antenna (not visible in the picture) on the left-hand beam pipe (a). A similar setup is employed for the 5-cell Cu cavity with four HOM couplers (b). Two couplers are positioned on each side of the 5-cell cavity. Test cables are connected to a VNA. Figure (a) falls under the Creative Commons Attribution 4.0 (CC BY 4.0) license (https://creativecommons.org/licenses/by/4.0/).*

Low-power RF measurements on the 2-cell and 5-cell 801.58 MHz PERLE-type Cu cavities were performed. The frequency spectrum of both cavities was analyzed. The mode passbands reporting the largest average relative frequency deviations from the simulated frequency spectrum are the ones with longitudinal index p = 1. These modes are the most sensitive to errors due to the equator trimming. The fabricated HOM couplers were tested individually on the 2-cell PERLE-type cavity, and their optimal damping orientations were determined. The experimental findings demonstrate a reasonable agreement with the simulated eigenmode results. Measurements confirm that the DQW coupler is the most effective solution for damping both monopole and dipole HOMs. HOM-damping measurements were conducted on the 5-cell Cu cavity with the manufactured 2P2H and 4DQW HOM end-groups. Bead-pull measurements were conducted to identify HOMs based on their field profile. The measured Qext values of concerned resonant modes agree reasonably with the corresponding simulated values.

The experimental results show that the two analyzed HOM-damping options provide adequate mitigation of HOMs below the BBU instability Qext thresholds. Moreover, the 4DQW damping scheme

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performs better in damping confined cavity modes, confirming the validity of our simulation predictions.

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