ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV008

VSR DEMO COLD STRING: RECENT DEVELOPMENTS AND MANUFACTURING STATUS

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Abstract

Bunch length manipulation is mandatory in modern storage ring light sources and CW SRF provides the required high voltage in a compact system to reach this goal [1]. One possible technique as proposed in [1] is to combine higher harmonic SRF cavities (3 and 3.5 harm.) with the fundamental frequency of the BESSY II storage ring. VSR DEMO seeks to develop and demonstrate the required SRF technology to achieve this by means of "off-line" testing at Helholtz-Zentrum Berlin (HZB) SupraLab facilities of a setup comprising two 1.5 GHz SRF cavities.

Due to the high level of higher order mode (HOM) power expected, caused by the beam-cavity interaction, these SRF cavities will be equipped with waveguide-connected HOM loads. On the cavity a blade tuner and piezos will be installed for frequency control and microphonics detuning. To demonstrate the feasibility of this complex system the VSR DEMO cold string consists of two cavities, each featuring five waveguides and a fundamental power coupler (FPC), plus all elements connected to the beam vacuum.

For most of these components the fundamental development work is complete and has been reported in the past. This paper summarizes recent enhancements, component design detailing and the manufacturing status.

COLD STRING COMPONENTS

The goal of the VSR DEMO project is a technology and feasibility demonstrator of the SRF setup. If successful, the two-cavity module would be ready for commissioning in a storage ring such as BESSY II. This will represent the final step towards validating the proposed technology and a subsequent module with four cavities as presented in [2] offering beam flexible dynamics could be built.

The VSR DEMO cold string comprises all components in direct contact with the beam vacuum (Fig. 1), although only some are operated at cryo temperatures, while others stay warm. Assembly of the cold string and integration into the VSR module (see [3] for a design report) is planned for 2024, after all components have passed individual tests.

Warm Endgroup with Scraper

The Warm Endgroups (WEGs), located at both ends of the cold string, feature a taper from the BESSY II profile to the circular beam-pipe cross section of 110 mm diameter, a water cooled HOM absorber and a junction for attaching vacuum pumps. Upstream, a tuneable scraper protects the cavity from synchrotron light incidence (cf. Fig. 1).

The design of the WEGs, as reported in [4], was finalized. The vacuum chambers and the scraper are currently being manufactured by PINK GmbH Vakuumtechnik.

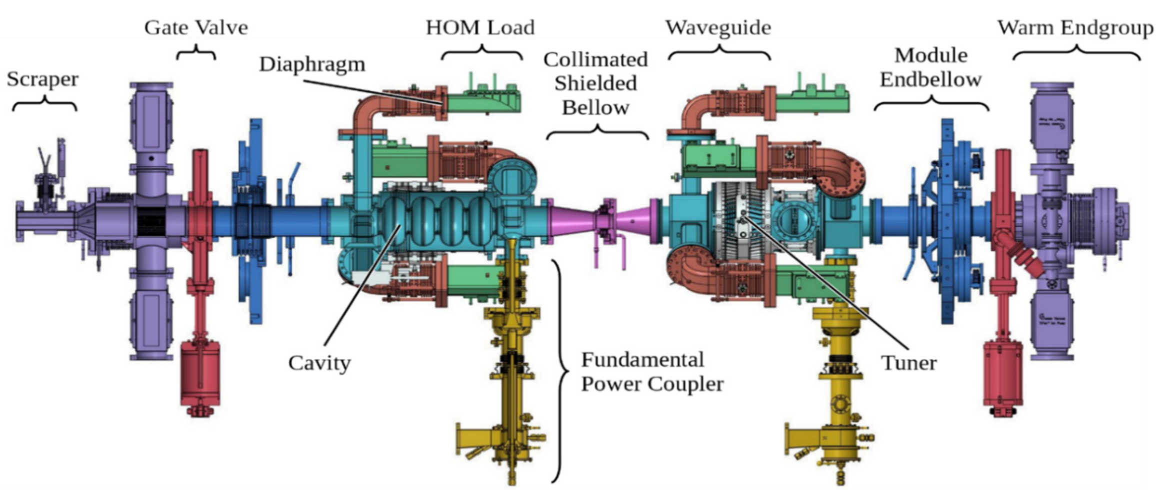

Figure 1: VSR DEMO cold string in top view.

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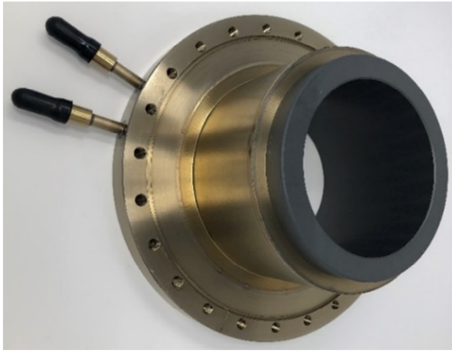

Figure 2: HOM absorber with cooling jacket (photo: courtesy of Xelera).

For the room-temperature operated HOM absorber a Ti cooling jacket was shrink fitted onto the SiC toroid (Fig. 2). This delicate manufacturing step was successfully performed for all absorbers by Xelera Research LLC.

PINK will deliver the two WEGs as complete clean assemblies in August 2021. Those will be in-situ tested in BESSY II storage ring in 2022, giving the possibility to assess the design and interactions with the beam.

Module Endbellow

The Module Endbellow (MEB), connecting gate valve and cavity, is composed of two bellows in the beam-pipe and an outer bellow connecting to the module door. The unshielded beam-pipe bellows are employed: to establish a thermal gradient from the warm gate valve and module door to the cold cavity; to achieve stable operation of the high current storage ring by providing the required RF properties; and to compensate for small length mismatches and thermal shrinkage of the entire cold string during cool down. The bellows must be designed to allow for very reliable cleaning to meet the UHV requirements of the neighbouring SRF cavities operated at high gradient CW regime.

To avoid trapped TM resonant modes close to the resonant line of the circulating beam, a series connection of two bellows with slightly different dimensions of convolutions and diameters (cf. Fig. 3) was preferred over a single bellow set-up, see [4] for a conceptual stage report. An active tuning mechanism touching the intermediate piece between the bellow pair was engineered to enable a tuning range of ±3 mm. This permits to shift the bellow resonant mode away from the beam resonant lines.

The electromagnetic (EM) geometry optimization of the bellow was done with CST studio software. To shift the trapped mode frequency and to reduce cross talk between the two bellows first the bellows geometry was optimized, followed by optimizing the intermediate cylinder size. The trapped mode resonant frequency was verified in frequency domain simulations by TM mode excitation at the beampipe port (resulting S_{11} parameter shown in Fig. 4). It results in a standing wave pattern at the same resonant frequency as simulated by the eigenmode solver (cf. Fig. 3).

A combined EM-mechanical simulation yields a frequency sensitivity of the bellow setup of 0.5 MHz/mm when actuating the intermediate cylinder axially. With a mechanical tuning range of up to ±3 mm a frequency shift

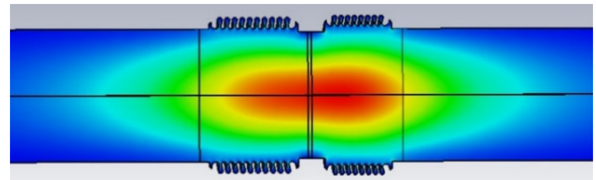

Figure 3: Electric field of the bellow's trapped resonant mode (f = 2010 MHz, R/Q = 0.74 Ω, Q = 1960).

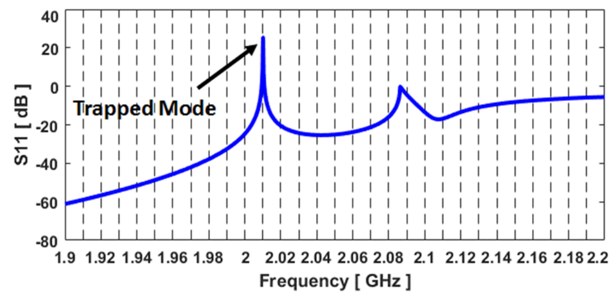

Figure 4: Reflection coefficient of the bellow for the TM mode excitation at the beampipe port.

of ±1.5 MHz of the trapped mode can be covered. Due to the ~1 MHz bandwidth of the trapped mode it is required to have the central resonant frequency at least 10 MHz off the beam resonant line.

The expected heat load during operation was estimated by application of a wakefield solver with active time-domain material losses. For the 300 mA multi-bunch filling pattern the heat load was evaluated by appropriate weighting of the single bunch loss in terms of bunch length and charge, resulting in about 16 W. This heat load must be considered in the cryo budget since the bellow intermediate piece is connected to the 80 K cooling circuit by a Cu braid and active cooling to 5 K is established at the beam-pipe towards the cavity. Note, if the frequency of the bellow trapped mode hits the beam resonance line the heat load can double and coupled bunch instabilities would restrict operation. Thus, for high current storage ring applications active detuning of the bellows away from the beam resonant frequencies is pivotal.

With this finalized design, tendering documents to purchase two MEBs are currently being prepared, such that delivery can be planned for mid-2022.

Cavity

The four-cell cavity with five waveguide (WG) extensions and the FPC port (cf. Fig. 5) is designed to provide damping of HOM power beyond 1 kW CW per cavity. For a summary of the RF design steps and challenges see [5].

RI Research Instruments GmbH was contracted in 2020 to manufacture two prototypes and – in a second stage – three clones of these 1.5 GHz cavities. The final design review was recently approved, and manufacturing is about to start, since the RF side of the Nb sheets has already been determined by eddy current scanning. First welding qualification steps and mechanical material testing is forthcoming. Cold RF tests at HZB's large vertical test stand are scheduled for the undressed cavity prototypes in Q4/2022 and for the dressed ones in Q1/2023.

20th Int. Conf. on RF Superconductivity SRF2021, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV008

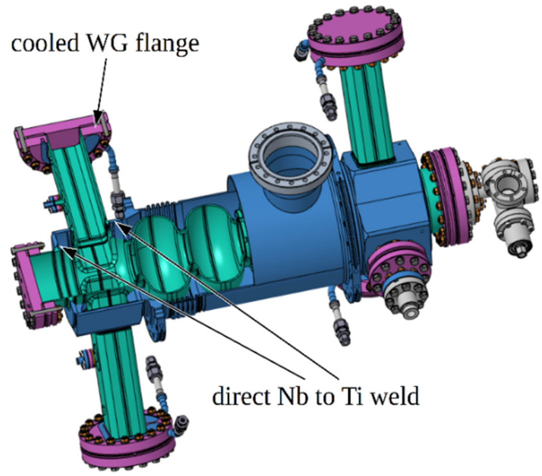

Figure 5: Cavity with ancillaries for cold test (Nb structure in green, NbTi flanges in pink and Ti parts in blue).

Three key challenges in the cavity design and manufacture are:

1. The cavity's endgroups, due to the complex shape of the Nb structure to be deep drawn, and due to the WG extensions intersecting with the He-vessel. To establish a reliable joint between these two parts a T-shaped intermediate Nb piece will be welded to the WGs and connected directly to the Ti vessel.
2. The 800°C annealing of the undressed cavity after the first two BCP treatments to degas free hydrogen implanted into the Nb. This heat treatment also affects the already installed Ti bellow on the He-vessel, and the WG flanges with cooling pipes featuring a Ti to stainless steel transition.
3. The safety valve of the 1.8 K He-cooling circuit with opening pressure defined as 3.5 bara. To avoid such high value (specified at a very early project stage), a cascade of controlled valves is implemented into this cooling circuit. However, very detailed quality control of material and manufacturing steps, especially welding is required and DEKRA GmbH is closely involved in the assessment.

To maintain superconductivity in the WG flanges a cooling channel is integrated to the NbTi flange and will be connected to the 5 K He circuit. Since these flanges need to be welded to the WGs before annealing, RI performed first tests to assess the reliability of the explosion bonded transition from Ti to stainless-steel in the cooling pipes after 800°C annealing. The tests confirmed both, pressure resistance (p = 23 bar for 30 min) and He-tightness after high temperature treatment and cold shocking with liquid Nitrogen of the transitioned pieces used for the pipes.

Tuner

A blade tuner is used for coarse tuning of the cavity supplemented by four piezos for fine and fast tuning. These piezos will be distributed evenly on the circumference and connect the blade tuner to the cavity tuner flange. The risk of damaging the piezos with shear forces or other parasitic influences is minimized by using encapsulated piezos as suggested by [6].

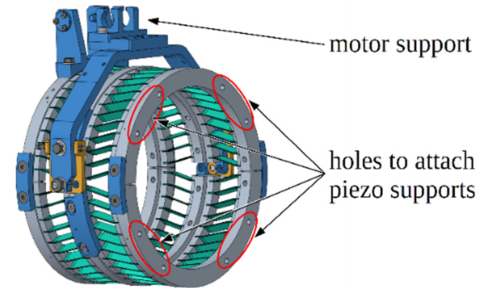

Figure 6: Blade tuner model with leverage.

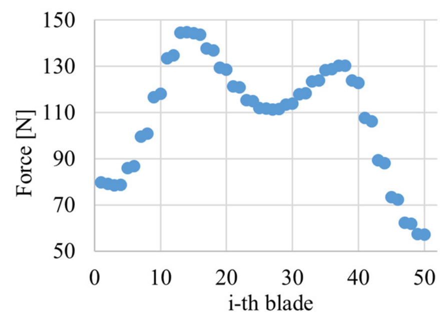

Figure 7: Force distribution on the 50 blades displayed for one tuner ring with 5 kN applied.

The blade tuner's basic design resembles that developed for TESLA cavities in the XFEL project [7]. However, due to the extended tuning range of 1.5 mm required to reach the operational states of the cavity and to park them, a thorough analysis and adaption of the design was performed by INFN-LASA starting from the experience of TESLA like coaxial tuner geometry (cf. Figs. 1 and 6).

The new blades were lengthened to reach the nominal stroke of 0.85 mm, i.e. allowing for some extra margin. Simulations of the single blade reveal buckling to be the critical failure condition, hence determining the max. load for the whole tuner. To study the uneven load distribution on the blades, caused by the four piezos on one side of the installation (cf. Fig. 6), the load on each blade was determined with $F_i = k{\cdot}\Delta x_i$ where Δx_i is the i-th blade displacement under a 5 kN loading force on each half-tuner and k denotes the blade's stiffness. It was found that the highest transmitted load per blade is up to 2.5 times higher than the lowest (Fig. 7). Because of torsion effects (caused by the central's ring rotation) affecting mostly the side blades the highest force transmission and the peak Von Mises stress do not occur in the same blade.

Simulations of the complex full tuner model reveal stress values in the blades at full stroke exceeding Titanium's yield strength. Thus, the tuner cannot be operated with max. stroke at room temperature but only at cold, due to considerable strength increase at cryogenic temperatures.

The overall tuner stiffness is calculated to be about 70 kN/mm, that is nearly 10-times higher than the cavity stiffness. The transmission ratio of the full tuner setup including the leverage is computed to be 1:38 requiring a max. motor force of only 340 N.

Three blade tuners and some test pieces for preliminary assessment are manufactured by Zanon Research & Innovation SRL and will be delivered in summer 2021.

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Coupler

The 1.5 GHz couplers for VSR are a scaled version of the Cornell couplers, with 2 cylindrical ceramic windows and bellows to allow for variable coupling. This design was modified to fit the constraints of VSR, reducing the cold coax dimension to suppress HOMs, increasing the warm coax dimensions to allow for compressed air cooling and modifying the tip to fit with the required coupling levels. The full design is reported in [8].

RI is manufacturing in collaboration with Thales two prototype couplers to be delivered this year. Conditioning is scheduled for early 2022. The four series couplers will be completed in Q2/2022. For an overview of the status of the couplers please see [9].

Waveguide

Stainless-steel-made WGs connect the cavity WG extensions with the room-temperature operated HOM loads (Fig. 8). These WGs comprise of a 90° bend, a slightly enlarging tapered cross section, two bellows and a cooling intercept with an RF pick-up. The WG entering cross section is such that the cut-off frequency of 1.65 GHz is met. The slightly tapered cross-section just before the first bellow avoids local trapped modes.

The entrance section up to the first bellow will be copper plated. The two rectangular bellows in the rear part are required to achieve the thermal gradient from the cold flange on the cavity side (5 K) to the HOM load operated at 300 K and to allow for mechanical misalignment and contraction during cool down. The bellows are interfaced by a thermal intercept connected with a copper braid to the 80 K cooling circuit. The tender for manufacturing 12 WGs, including two spares has just been opened.

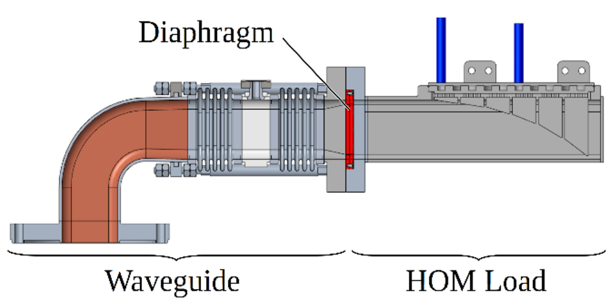

Figure 8: Waveguide with HOM load and diaphragm.

HOM Load with Diaphragm

Each WG will be terminated by a HOM load (cf. Fig. 8) with a generic design as reported in [4] and [10]. Following the experiences collected during manufacture of the three prototypes the manufacturing order was changed; the complete stainless-steel housing will be prepared separately to brazing the dielectric tiles at high temperature to the Cu backplate. These two main components are then mated in a final lower-temperature brazing step, thus strongly reducing particulate contaminations during production, and easing cleaning of the tile array after the first brazing step.

Systematic clean-room particulate testing experiments with purposely manufactured and processed dielectric tiles (STL-100 HTC by Sienna Technologies, Inc.), using a 4…6 bar N_2-gas blowing, and multiple counters revealed a moderate, but non-vanishing particulate release. Tests with tempered whilst otherwise identical samples showed that this is not enhanced by the heat exposure the tiles must withstand during the brazing processes. Against expectation no improvements were observed by employing so-called slow machining of the tiles, therefore standard process items were ordered and are currently manufactured.

In view of the risk that even single particulates, which reach in the SRF cavity regions of high field strengths, could act as quench-generating field emitters, a 20 µm thick Kapton© diaphragm was designed to separates the HOM loads from the WG-/cavity volume (cf. Figs. 8 and 9). A clamping frame can be integrated in the rectangular flange of the HOM loads. Dielectric losses in the foil (di-electric parameters taken as $\varepsilon_r = 3.4$ and $\tan\delta = 0.00294$) were simulated to amount ~0.6 W, whilst the stainless-steel support frame dissipates ~2.0 W mainly in a few resonances, which exist in the narrow gaps in between frame and flange (both normalized to 400 W incident HOM power with BESSY II standard fill pattern spectrum). Gas flow between the volumes of the HOM load and the WG is established by circular openings in each corner of the frame (Fig. 9), which are outside of any direct line of sight of the WG inner cross section. Thus, particulate propagation from the HOM loads towards the cavity is not fully excluded, but severely hindered, whilst pressure drops across the diaphragm are avoided.

Production drawings of the HOM loads have been completed recently by Jefferson Lab (JLab) in the framework of a JLab-HZB common research and development agreement. Production and testing of two pre-series HOM loads is planned for 2021 and of another 12 series loads for 2022.

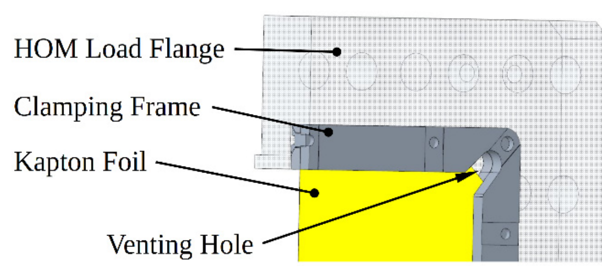

Figure 9: Detail of the diaphragm and its support frame. Venting holes in each corner also avoid creases in the foil.

Collimating Shielded Bellow

The Collimating Shielded Bellow (CsB) connects the two cavities and allows for slight displacement caused by cooling down or by active tuning of the cavities. It is actively cooled to 5 K by pipes twined around each end. The Cu labyrinth protects the cavity from synchrotron light and shields the bellow from RF and interactions with the beam.

A first CsB prototype was installed in the BESSY II storage ring (cf. [4]) and extensive experiences during more than 1.5 years of operation, covering any kind of machine fill pattern and experimental operational conditions (e.g. first time 200 mA low-alpha operation in BESSY II) was collected. These experiences validated the design, but also

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV008

demonstrated a long (~100 d) vacuum conditioning period and frequently appearing few-second spiking pressure bursts. Four main observations became apparent after cutting of the dismantled bellow:

- an areal discoloration inside the upstream taper as expected from synchrotron light radiation estimates (Fig. 10, green arrow),
- discolorations obviously corresponding to the 5 mm wide gaps in the RF lip of the modified Cu CF gasket, also to various extents distributed in the ring between RF lip and knife edge (Fig. 10, orange arrows),
- spot and track-like blackening distributed on the labyrinth's Cu surface (Fig. 11, orange resp. blue ellipses),
- widely distributed remainders of coating agent indicating insufficient cleaning during manufacturing before the closing weld (Fig. 11, e.g. green arrows).

Based on these operational experiences with the first CsB prototype an adapted design was developed to allow for improved cleaning. Thus, the new design features an additional flange next to labyrinth and bellow that permits to unbolt and open the component and access the enclosure. In addition, the gasket's RF lips were modified to smaller vacuum intermissions to dimmish RF interactions.

The new version of the CsB prototype was manufactured by VAb Vakuum-Anlagenbau GmbH and will be installed in the BESSY II during this year's shut down. This new operational experience will foster final design assessments and approval. Subsequently, the finalized version to be used in the cold string, featuring the required taper size and an outer flange for hexagon Al gasket, will be ordered.

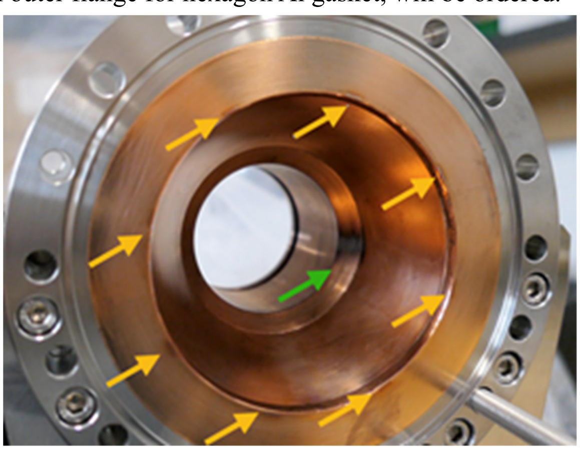

Figure 10: CsB upstream side and taper after operation.

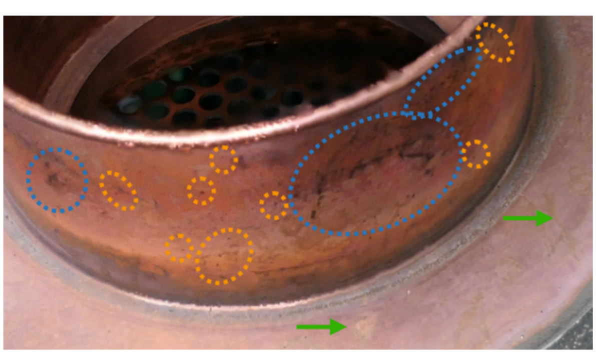

Figure 11: CsB inner labyrinth after cutting the bellow.

CONCLUSION

With all cold string components having passed the design phase, some awaiting further prototype qualification, the project goal of demonstrating operability of this complex and compact installation is coming closer. Single component acceptance tests are already running for some components, such as WEGs, gate valves and the new CsB prototype, and are under preparation for others, such as cavities, couplers, HOM loads and tuners. WGs and MEBs have just entered the purchasing phase. Once the cavity prototypes will be delivered in early 2023 particulate free assembly of the complex cavity system will be practiced, gradually integrating adjoining elements.

ACKNOWLEDGEMENT

VSR Demo combines several newly developed components which could not become real without the competences and dedication of industrial vendors. We especially appreciate the close and fruitful cooperation with –amongst others – PINK, RI, Sienna, Thales, VAb, Xelera, Zanon.

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