STATUS OF THE bERLinPro MAIN LINAC MODULE*

H.-W. Glock†, A. Frahm, J. Knobloch, A. Neumann,
Helmholtz-Zentrum Berlin für Materialien und Energie BESSY II, Berlin, Germany

Abstract

Beam operation of the bERLinPro energy recovery linac project, whose construction is under way, will initially start using the photoinjector and booster modules. In a second step the recirculation beam line and the main Linac module will be added. Here the current design status of the main linac module is described. Results of wake field simulations are compared for different set ups. We also report on the manufacturing aspects including the design of the waveguide groups needed for HOM damping and the choice of flange-gasket-pairings appropriate for rectangular waveguides. Also mechanical considerations are included.

INTRODUCTION

The Linac module (together with the recirculation arc) will complete the bERLinPro [1] construction after an initial commissioning with gun and booster module only. After a thorough cavity design ([2], [3]), studies were recently undertaken in order to analyse the interplay of wakefields in the entire module based on modal [4] and time-domain approaches, the latter being described in the following section. Spectral re-weighting of the single-bunch wake impedance with actual bERLinPro spectra (computed including charge and phase jitter as well as beam gaps for ion clearing purposes) resulted in ratings for beam-deposited power in all HOM absorber waveguides. Two set-ups were analysed, first the original approach with five waveguides directly attached to each of the three superconducting 1.3 GHz-, 7-cell-cavities (denoted as “3x5WG”, cf. Fig. 1), second with four groups of three normal conducting waveguides being separated from the superconducting cavities (“4x3WG”). The latter is considered as a back-up scenario since it would simplify some manufacturing aspects of waveguides, cavities and module, even though it performs slightly worse than the 3x5WG version. In the second main section of the paper the recent module design which is based on the 3x5WG set-up and its study status are described, pointing out some construction key issues.

TIME DOMAIN WAKE SIMULATIONS

Making use of the computing power of a recent multi-core workstation (2 x Xeon2643v2 6-core, 256 GB RAM) wake computations on a full string of three 7-cell 1.3 GHz cavities equipped with waveguides and fundamental power couplers were possible, using the time domain approach like it is implemented in the CST-ParticleStudio© wakefield solver [5]. Such a simulation numerically resembles a passage of a bunch of certain width through the device and propagates all electro-magnetic fields in time, making use of a discretised representation of Maxwell's equations. Obviously a shorter bunch excites shorter wavelengths, demanding for smaller mesh sizes (in three spatial directions) and shorter time steps; so shorter bunch lengths raise the computational cost in their forth order. The wakefield solver automatically performs single bunch wake potential, loss factor and wake impedance calculations, but especially also delivers by means of mode-decomposition the time-dependent field amplitudes of all selected modes of all waveguide / power coupler (FPC) / beam pipe ports of the structure. This feature makes that solver suitable to derive the spectra of outward propagating power excited by *any bunch pattern* (within the limited bandwidth). This is of extraordinary relevance when dealing with fully filled bunch trains of high bunch repetition rate like in the bERLinPro energy recovery linac (here 2 x 1.3 GHz) or, for instance, in storage rings. An external post-processing procedure dedicated to this purpose was written.

Single Bunch Simulations

The wake simulations were performed on two set-ups shown in Fig. 1. Both versions have straight cavity connections of 405 mm (total length of the beam pipe with 110 mm diameter, also covering all openings for the waveguides and FPCs); bellows or beam pipe absorber elements are not included. The waveguides have a common cross section of 105 mm x 50 mm with corner bends of 5 mm radius.

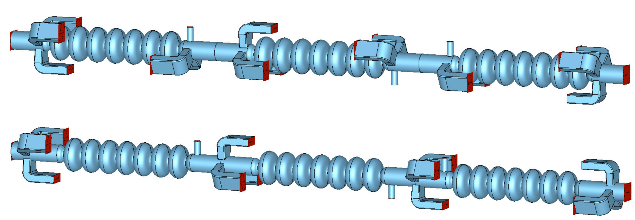

Fig. 1: Top: Baseline 3x5WG geometry, bottom: backup version 4x3WG with waveguide groups separated from the cavities. The fields at all waveguides, both beam pipe exits and the three coaxial FPCs (all marked in red) are evaluated in sets of the first 20 (50, 11 resp.) modes. This makes all the ports reflection-free terminated.

Within the given hardware limits ~ $1.1\cdot10^9$ mesh cells and a σ_s of 9 mm (4x3WG: 10 mm resp.) were feasible, corresponding to a highest evaluable frequency of ~ 11.3 GHz (~ 10.2 GHz resp.) within a structure of in total 3855 mm (4055 mm resp.) length. Computing took on the otherwise unloaded workstation 158 h (128 h resp.). The beam was given an offset of + 2.1 mm in both transversal directions (y/z) in order to excite dipole and higher multipole field patterns as well. (Computing times were prohibitively long for the study of other offsets.)

* Work supported by German Bundesministerium für Bildung und Forschung, Land Berlin, and grants of the Helmholtz Association
† email address: hans.glock@helmholtz-berlin.de

ISBN 978-3-95450-147-2

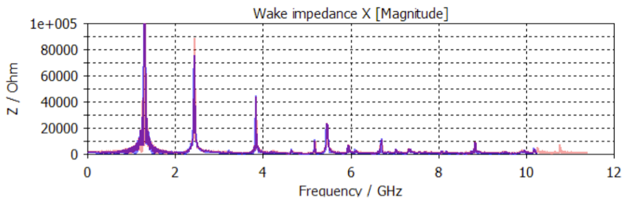

Fig. 2: Almost identical longitudinal beam impedance spectra (absolute value) of 3x5WG (light red) and 4x3WG (blue). The fundamental mode peak is clipped.

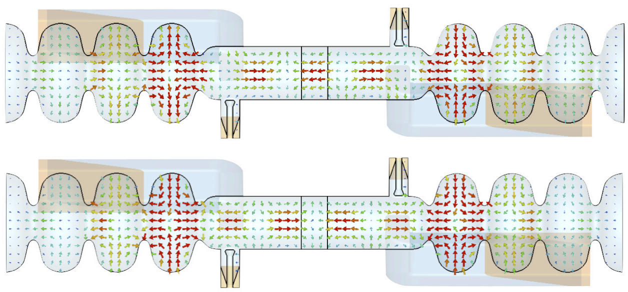

Fig. 3: Pair of beam-pipe-localised modes found in CSTMicrowaveStudio© [6] eigenmode simulations at (top) 2.4347 GHz with $R/Q = 79.3\,\Omega$, (bottom) 2.4364 GHz, $R/Q = 55.2\,\Omega$. The rotational symmetry of the TM_{01}-like field pattern in the beam pipe is distorted.

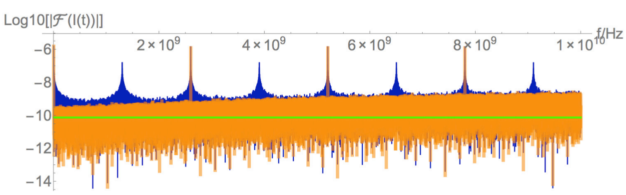

Figure 4: Lowest 10 GHz of the logarithmic-scaled current spectrum in relative units of the bERLinPro cw-beam. Orange: including jitter (cf. main text) and recirculation of the beam. Blue: also with 520 gaps after each 2080 bunches (96.25 pC bunch preserving total current of 100 mA). Green: Single bunch of 77 pC in 8 µs.

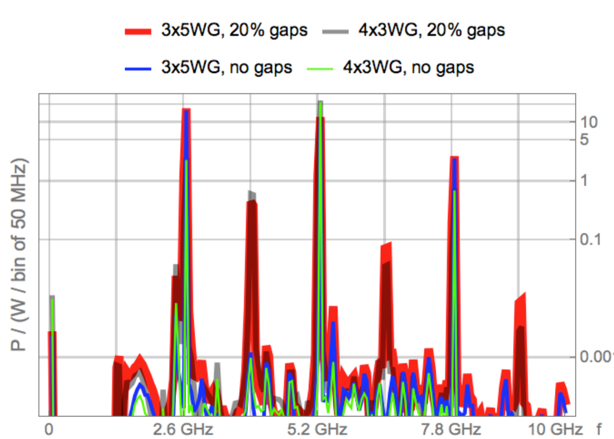

Fig. 5: Spectral resolved waveguide power, summed up over all waveguides. Relevant contributions only happen close to the beam harmonics (abscissa grid lines). The 2.6 GHz-line is more pronounced in the 3x5WG setup, whereas the 4x3WG setup has highest power levels at 5.2 GHz.

Figure 2 shows the computed longitudinal impedance which differs marginally between both set-ups. In either case there are only a few accentuated spikes, located at 1.30 GHz (fundamental), 2.44 GHz, 3.84 GHz, 5.18 GHz (minor, but very close to the 5.2 GHz beam harmonic), 5.45 GHz, 6.70 GHz and 8.85 GHz (and some smaller ones). The most relevant peak found at 2.44 GHz is attributed to two end-cell TM_{011}/beam-pipe TM_{01}-patterned modes found in an eigenmode search (Fig. 3) applied to a setup of two connected 3.5-cell cavity halves. Open ports were terminated with dissipative dielectrics.

Spectral Weighting

The spectra used for weighting the single-bunch port signals were generated using a Fourier transformation of an 8 µs long time-domain current sequence, sampled with 0.1 ps step width (i.e. a sequence of $8 \cdot 10^7$ values), which was populated with Gaussian-shaped bunches of $\sigma_t = 2$ ps having a nominal charge of 77 pC and a nominal spacing of $\Delta t = (1/1.3)\text{ ns} \approx 770$ ps. The bunch charges are modified in a worst-case-sense by a random factor $(1+x)$ with x evenly distributed in the range $-0.02 < x < 0.02$; also its phase according a 1.300 GHz oscillation jitters randomly with even distribution by ± 1°. This results in the beam current spectra shown in Fig. 4. The spectra were normalized so that the spectral energy norm was preserved.

Table 1: Power distribution

Power/W	3x5 WG	4x3 WG
beam pipe upstream	3.60	6.01
Upstream group 3 wgs.	4.51	4.71
FPC upstream cav.	1.40	12.19
2 wgs. @ FPC upstream	7.42	–
Second group 3 wgs.	6.18	11.89
FPC middle cav.	0.78	6.96
2 wgs. @ FPC middle	7.39	–
Third group 3. wgs.	–	10.15
FPC downstream cav.	0.52	5.67
2 wgs. @ FPC downstr.	5.26	–
Downstr. group 3 wgs.	5.60	3.60
beam pipe downstream	3.00	5.50
total	45.70	66.66

The current spectrum of the gap-free beam shows spikes at the harmonics of 2.6 GHz with amplitudes almost four orders above the noise level (in case of a jitter-free beam the spikes are elevated by 12 orders). The odd harmonics of 1.3 GHz do not appear since the beam is recirculated; here with a delay of 251.5 wavelengths, i.e. 57.998 m. Nevertheless those re-appear if the beam is gapped, as for certain times one of the accelerated and decelerated beams is solely present in the Linac module. In Fig. 5 the spike-dominated spectra of the total power in all waveguides is shown, whereas Table 1 illustrates how this power is distributed. It is remarkable that in the 4x3WG set-up the FPCs carry a significant HOM power.

CAVITY AND MODULE LAYOUT

In Fig. 6 the provisional module set-up is shown. The support of the cavities will be provided by the gas return pipe (GRP) on top of the module, which is split in three segments, each of them being individually adjustable from outside of the module (following the concept in [7]). Waveguide supporting structures and shielding details are not defined yet. Bending of the waveguides was chosen in order to avoid interference with the GRP, the 2-phase line and the blade tuners attached to the LHe-vessels. It also effectively reduces thermal radiation from the 300K loads to the cold parts. The waveguide loads will be water-cooled following a concept described e.g. in [8], whereas the two beam pipe absorber at the module ends will be cooled with 80K-He.

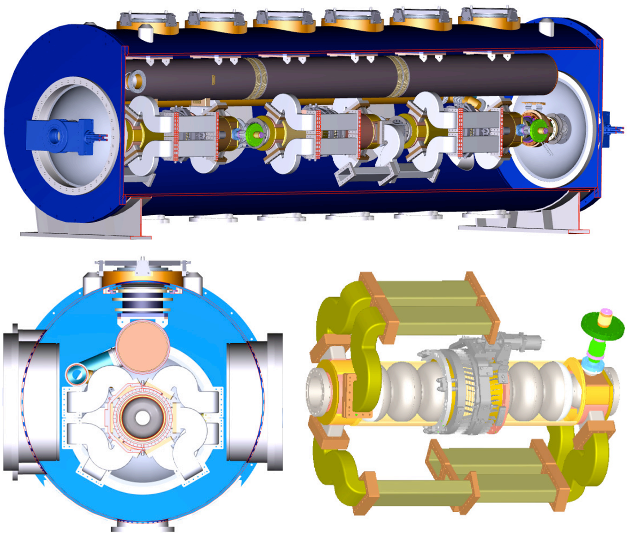

Fig. 6: Provisional layout of the bERLinPro Linac module seen from the side and the front together with the tank/waveguide arrangement of a single cavity. Straight waveguide sections will include the HOM absorbers.

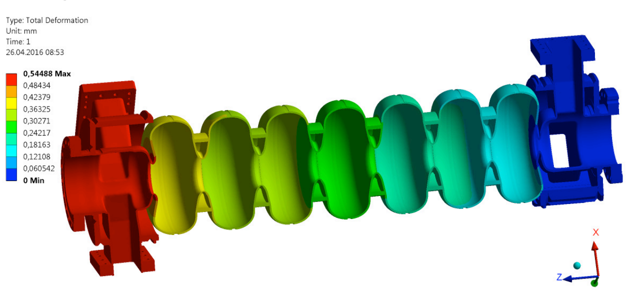

Fig. 7: Total deformation under 5 kN tuning force between the vessel flanges (right side fixed), computed with ANSYS [9] for 2 K Niobium of 3 mm wall thickness. Whereas the inner half cells are compressed by ~ 25 µm, both end half cells experience ~ 90 µm, the end-groups in total ~ 45 µm.

The waveguides will be attached with flanges both to the cavities and to the absorbers. The cavities will be cleaned after mounting the waveguides (but not with the absorbers attached) with high pressure rinsing in order to mitigate the risk of particles set free during the mounting procedure. That implies that they are tested in a vertical cryostat combined with the waveguides, which demands for rectangular gaskets, that withstand superfluid LHe. As a result of a technology survey it was decided to test VAT Series 35 plane copper gaskets [10] both in a silver coated and a plane copper version with respect to leak tightness in a 2 K LHe bath. For this purpose dedicated waveguide stubs and submersible pumping adapter are recently under production. This gasket technology is preferably used with similar materials on either side of the flange. For that reason the cavity flanges are foreseen to be of stainless steel like the waveguide flanges and to be brazed to the niobium components.

First mechanical simulations shown in Fig. 7 indicate a high susceptibility of the end half cells against deformations under tuning forces, which are likely to worsen the field flatness. This and appropriate means in order to stiffen this region will be subject to further investigations.

CONCLUSION

Detailed engineering of the bERLinPro Linac module is well underway: Wakefield computations of three-cavity-chains both based on time domain and eigenmode computations [4] demonstrated proper impedance characteristics; the former also gave access to waveguide and beam pipe HOM absorber power ratings. In view of the surprisingly low simulated values compared with experimental results reported about similar cavity shapes [11], a safety margin was applied in the specification of the HOM absorber elements. Each absorber now is demanded to be capable of 25 W, using the calculated spectral distribution with a scale factor of ≈ 3. An alternative set-up with waveguide groups centered between the cavities, thus easing several engineering aspects but showing higher HOM power levels than the baseline design, was also investigated.

The baseline design was further developed: Mutual distances and orientations of the cavities now are fixed. Engineering studies demonstrated the feasibility of the integration of waveguide end-groups into a LHe-vessel, providing a four-sided waveguide cooling. A gasket technology for the rectangular waveguide flanges is being evaluated experimentally in the near future. A provisional module layout was designed. Its mechanical eigenmodes together with Lorentz force and pressure sensitivity will be subject of upcoming mechanical computations, which also will allow to define particular positions of stiffening rings, the cavity wall thickness, the waveguide gantry and the shielding design.

ACKNOWLEDGEMENT

The authors are indebted to colleagues from JLAB, esp. G. Cheng, J. Guo, F. Marhauser, B. Rimmer and H. Wang, from Cornell, esp. R. Eichhorn, from DESY, esp. A. Matheisen, and E. Zapatlin, FZ Jülich, for many discussions, contributions and hints. We also wish to acknowledge the fruitful collaborative efforts together with the team of Research Instruments. We further would like to thank M. Dirsat, HZB, for providing thermal and mechanical computation results.

ISBN 978-3-95450-147-2

REFERENCES

[1] M. Abo-Bakr et al., "Status Report of the Berlin Energy Recovery Project bERLinPro", presented at IPAC'16, Busan, Korea, May 2016, paper TUPOW034, this conference.

[2] A. Neumann et al., "Update on SRF Cavity Design, Production and Testing for bERLinPro, in *Proc. SRF2015*, Whistler, BC, Canada, September 2015, paper THPB026, pp. 1127-1131.

[3] A. Neumann et al., "Final Design for the bERLinPro Main Linac Cavity", in *Proc. LINAC2014*, Geneva, Switzerland, September 2014, paper MOPP070, pp. 217-220.

[4] T. Galek et al., "Report on SSC Calculations for bERLinPro Module Containing Three SRF Cavities", Universität Rostock, 2016, unpublished.

[5] CST AG, ParticleStudio© v. 2015, Darmstadt, Germany.

[6] CST AG, MicrowaveStudio© v. 2015, Darmstadt, Germany.

[7] M. Liepe et al., "Latest Results and Test Plans from the 100 mA Cornell ERL Injector SCRF Cryomodule" in *Proc. IPAC2010*, Kyoto, Japan, May 2010, paper WEPEC066, pp. 3043-3045.

[8] F. Marhauser et al., "Status and Test Results of High Current 5-Cell SRF Cavities Developed at JLAB", in *Proc. EPAC2008*, Genoa, Italy, June 2008, paper MOPP140, pp. 886-888.

[9] ANSYS Inc., ANSYS© v.17, Canonsburg, PA, USA.

[10] VAT Vakuumventile AG, VATSEAL Serie 35, Haag, Switzerland `http://www.vatvalve.com/de/business/valves/catalog/H/350_1_A`

[11] D. Hall, "Measuring HOM parameters with beam for Cornell's ERL cavities", talk, given at ICFA Mini Workshop on Higher order Modes in Superconducting Cavities, Fermilab, 14.7.2014. `https://indico.fnal.gov/getFile.py/access?contribId=8&sessionId=5&resId=0&materialId=slides&confId=7942`