ISBN: 978-3-95450-194-6 doi:10.18429/JACoW-LINAC2018-THPO083

TRANSVERSE DEFLECTING CAVITY FOR LONGITUDINAL BEAM DIAGNOSTICS AT bERLinPro

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Abstract

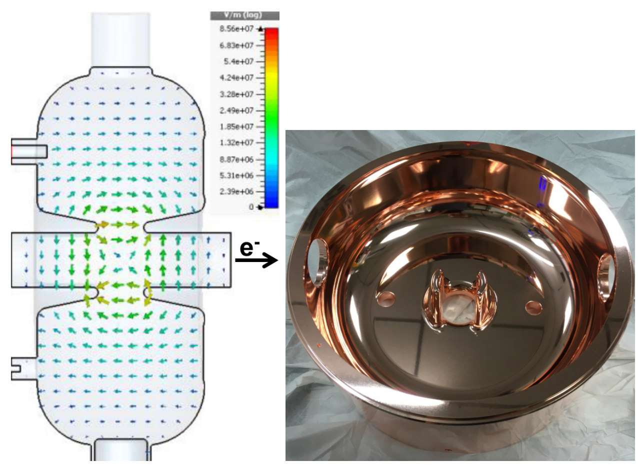
The Berlin Energy Recovery Linac Prototype (bERLinPro) at Helmholtz Zentrum Berlin (HZB) aims to deliver a continuous-wave electron beam of high average current (100 mA) and brilliance (normalized emittance below 1 mm·mrad). The achievement of these ambitious goals necessitates a thorough determination of the bunch parameters after the first acceleration stages, namely the photoinjector and the succeeding booster module. For the measurement of primarily the bunch duration and subsequently the longitudinal phase space and transverse slice emittance, a single-cell 1.3-GHz TM110-like mode vertically deflecting cavity was manufactured by RI Research Instruments GmbH, following the respective design developed for the Cornell ERL injector. This article summarizes the design parameters, manufacturing procedure and testing of this pulsed RF resonator, together with the expected temporal measurement resolution for the nominal beam energies at the initial acceleration stages of bERLinPro.

MOTIVATION AND DESIGN

A new Energy Recovery Linac (ERL) is being constructed at Helmholtz Zentrum Berlin (HZB) under the name Berlin Energy Recovery Linac Prototype (bERLinPro). The goal of this project is to develop the ERL operation principle towards user-oriented applications. The design of bERLinPro is that of a single-pass electron ERL which utilizes superconducting radiofrequency (SRF) technology to deliver a continuous-wave operation of high average current (100 mA) and brilliance (normalized emittance below 1 mm·mrad) [1]. The longitudinal beam properties at the initial acceleration stages (up to 6.5 MeV kinetic energy) will be diagnosed by a transverse deflecting cavity (TCAV).

A TCAV offers a straightforward way of measuring the electron bunch duration, or even the complete longitudinal phase space when combined with a spectrometer dipole, as well as the transverse slice emittance with the help of a quadrupole magnet [2]. It consists of an RF resonator operated in the TM_{110} mode (Fig. 1a), which when phased properly, transversely deflects the head and tail of the bunch in opposite directions. As a result, the longitudinal plane is projected into the transverse after some drift. Due to the damage threshold of the projection viewscreens, TCAV will be operated only in a special diagnostics mode of bERLinPro with reduced repetition rate which allows up to 0.5 μA average current. When passive, the cavity will not interfere with high beam currents as long as it is detuned from its resonant frequency (up to 75 mA demonstrated at Cornell ERL [3]).

The design of the cavity followed closely the one developed for the Cornell ERL injector, due to the resemblance of requirements for both applications [4]. In short, this design features a single-cell copper RF resonator with a transverse impedance of more than 5 MΩ and a resonance frequency of 1.3 GHz, tunable by a motorized plunger. Necessary adjustments were made to accommodate the available interfaces of HZB (Fig. 2): a) coaxial power feedthrough with 50 Ω matched impedance, 100 W average power rating and 2.7 kV_{rms} tolerance, b) coaxial 50 Ω RF pickup coupled at -51 dB to the input power, providing a mW signal level after cable attenuation (-13dB) at nominal operation, c) UHV-compatible linear stage for the adjustment of the plunger position up to ±25 mm, positioned at the bottom of the structure for improved particulate-free conditions, d) ion getter pump at the top of the structure.



(a) Electric field map. (b) Pot of TCAV after machining.

Figure 1: Inner contour of TCAV. Protrusion cones improve the vertical impedance and orientation of the dipole mode.

Two cavities were manufactured by RI Research Instruments GmbH according to these specifications. The manufacturing procedure, the results of the RF and vacuum testing and conditioning as well as the estimated resolution of the e-beam measurements at bERLinPro are described below.

CAVITY MANUFACTURING

The most significant adjustment from the original Cornell configuration was building the cavity out of two pieces, namely pot and lid, instead of two lids and a center ring. This increased the manufacturing precision, while minimizing the process time and risk. Each cavity part was milled from

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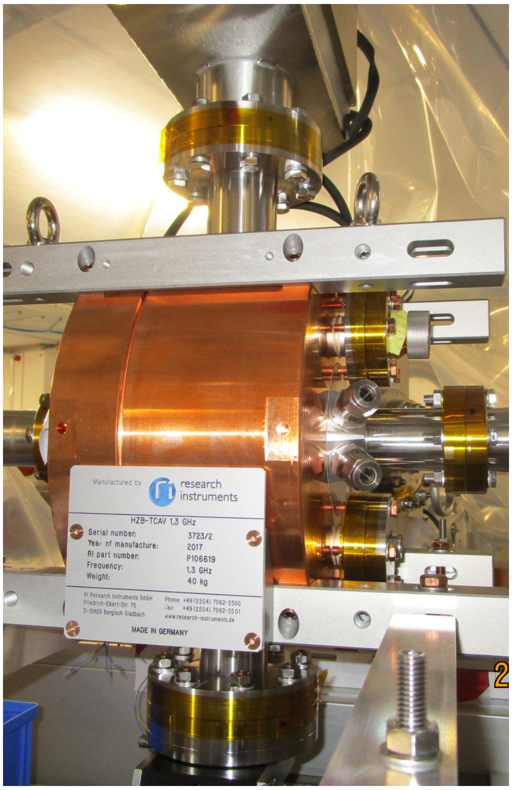

Figure 2: TCAV installed at bERLinPro. The ion getter pump can be seen on top, the ports of the input-power coupler, water cooling and RF pickup on the right side, and the frequency-tuning system on bottom.

OFHC copper on a 5-axis CNC milling machine. The surface roughness was better than R_a=0.2 µm, leaving a mirror like finish on the RF surfaces (Fig. 1b). Each individual part was equipped with the cooling channel lids, the CF ports for vacuum and RF equipment in a high temperature brazing step.

A new tuning concept was introduced to finally match the resonant frequency of the cavity before the last brazing step. A collar surrounding the noses was left on the lid of the cavity. The height of this collar was iteratively reduced by machining based on the results of clamped RF measurements until the resonance was matched. Then the final high temperature vacuum brazing was conducted. During the final RF testing also the field profile was recorded with an uncalibrated bead-pull measurement, showing a very symmetric distribution.

The cavity was assembled on a transport frame in a class ISO4 cleanroom together with the RF power coupler, the RF pickup, the ion getter pump and the motorized tuner. As part of the factory acceptance test (FAT), an integral leak test, a bake out at 130°C, a residual gas analysis (RGA) and pressure rise measurements have been performed (Table 1).

TESTING AND CONDITIONING

Before installing TCAV-2 in the bERLinPro beamline the following tests and procedures were performed at HZB:

Table 1: Resonance frequency f at 28°C, tuning range Δf for ±10 mm plunger movement, unloaded quality factor Q_0 and input coupling β_c from specification and FAT measurements

Parameter	Specs	TCAV-1	TCAV-2	Unit
f (28°C)	1300±0.2	1299.96	1300.02	MHz
Δf (±10mm)	~2	1.3	2.5	MHz
Q_0	>11000	12930	12460	-
β_c	1±0.1	0.9	0.97	-

- A leak test at a vacuum level of 10^{-9} mbar, measuring a leak rate in the order of 10^{-10} mbar·l/min.
- RGA showed low particulate concentrations, with peaks at H_2, H_2O, N_2 and CO_2.
- The resonant RF frequency, input coupling and quality factor were measured with respect to the plunger position at room temperature under vacuum. A 4 MHz tuning range has been demonstrated (Fig. 3), with the coupling ranging between 1.08-1.34 and the unloaded quality factor between 14200-12750 (6850-5550 loaded).
- RF conditioning was performed by feeding up to 12 kW peak power in the cavity with pulses of up to 40 μs at a repetition rate up to 200 Hz. Stable vacuum conditions were reached easily and no heating was observed with a 3.2 l/min flow of 28°C cooling water.

The results of the above tests met all specifications, while the design value of 5.3 MΩ for the transverse shunt impedance will be verified with beam measurements during operation.

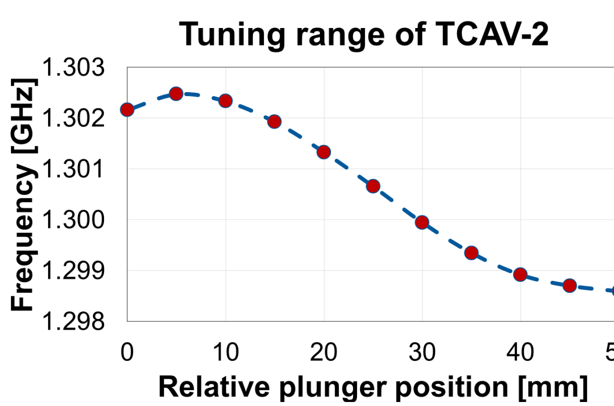

Figure 3: Measured range of the resonant frequency with respect to the relative position of its plunger. The nominal frequency is reached around 30 mm, which corresponds to a penetration of the plunger 10 mm inside the cavity.

TEMPORAL RESOLUTION

The vertical rms size of the deflected beam at the measurement screen downstream the TCAV is given by [5, 6]:

$$\sigma_s = \sqrt{\sigma_0^2 + \sigma_z S}, \tag{1}$$

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where σ_0 is the corresponding size at the screen in the absence of RF deflection, σ_z the rms bunch length and S the shear parameter, defined as $S = eV_T kl/pc$, where p is the longitudinal momentum, l the drift length between cavity and measurement screen, k is the wave number for 1.3 GHz and $V_T = \sqrt{2PR_T}$ the peak deflecting voltage, with P being the peak RF power and R_T the vertical shunt impedance.

The most widely-used definition for the temporal resolution, which is relevant for the longitudinal phase-space measurements and slice emittance measurements is mentioned here as *slice resolution*. This corresponds to the minimum longitudinal distance between adjacent slices (or alternatively the minimal slice length δ_z), so that their transverse distance after deflection ($\delta_z S$) is bigger than the non-deflected vertical beam size (regarded as $2\sigma_0$), namely $\delta_z \geq 2\sigma_0/S$.

On the other hand, the shortest bunch duration which can be measured is the one whose transverse deflected size is bigger than its non-deflected vertical size by the amount of the optical resolution ρ of the readout system. In terms of rms values, this criterion can be written as $\sigma_s - \sigma_0 \geq \rho/2$, so that 2 sigma of the beam's transverse size will occupy an additional pixel on the camera of the projection screen. In combination with Eq. 1, this results in: $\sigma_z \geq \frac{\sqrt{(\rho/2 + \sigma_0)^2 - \sigma_0^2}}{S}$, which is going to be referred as *bunch-length resolution* or *accuracy*.

For a given optical resolution, drift length, beam momentum, RF frequency and power, both definitions of the longitudinal resolution depend on the non-deflected vertical beam size at the projection screen σ_0. In order to reach the lower limit, a quadrupole magnet which is positioned 0.7 m upstream the TCAV can be used. The best focus (σ^*) which can be achieved in a drift section l can be calculated by the known beta-star optics relationship: $\beta(l) = \beta^* + l^2/\beta^*$, with $\beta^* = \sigma^*/\epsilon$ being the minimum achievable corresponding Courant-Snyder parameter for a geometrical emittance ϵ. After some calculations we get to $\sigma^* = \sqrt{\frac{\sigma^2 - \sqrt{\sigma^4 - 4l^2\epsilon^2}}{2}}$ under the condition that the beam size at the beginning of the drift is $\sigma \leq \sqrt{2l\epsilon}$. In this case the phase advance between quadrupole and projection screen approaches 90° and the measurement resolution is optimized [6].

Using all of the above, both resolution definitions are plotted in Fig. 4 versus RF peak power for the design kinetic energies of bERLinPro after the photoinjector (2.7 MeV) and the subsequent booster (6.5 MeV). For this calculation, the estimated optical resolution of 30 μm and a drift of 1.8 m were used, together with the expected beam parameters of 2 mm rms vertical beam size and 1 mm·mrad normalized emittance at the location of TCAV [7], assuming maximum focusing at the measurement screen. A 7.5 kW solid-state amplifier is planned to be used at bERLinPro, delivering 5 kW peak power into the cavity. This results to a bunch-length resolution of 70 fs and 100 fs for the photoinjector and booster regimes respectively and a 0.3 ps slice resolution, which will resolve more than 20 longitudinal slices according to the expected bunch parameters. When using realistic non-nominal beam parameters, a 35% variation of the bunch resolution and a 65% variation of the slice resolution in logarithmic terms is expected, according to a draft estimation. Simulations of the bunch-length measurement have been presented in [8].

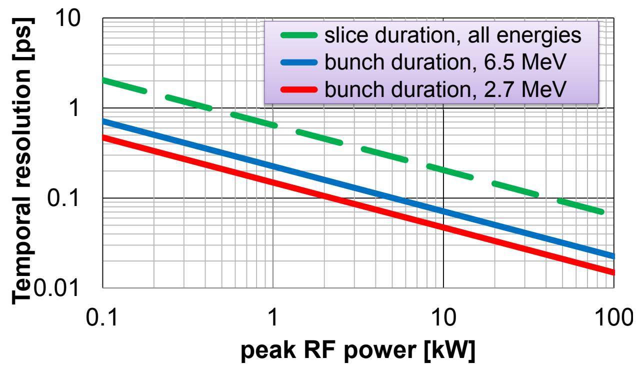

Figure 4: Temporal resolution of TCAV versus RF peak power for the nominal beam parameters at bERLinPro after the photoinjector (2.7 MeV) and the booster (6.5 MeV).

According to RF simulations, the cavity could receive up to 100 kW peak power without reaching the 2 Kilpatrick limit. However the existing feedthrough tolerance allows less than 40 kW when taking into account the doubling of the peak voltage due to the superposition of the incoming and reflected power during the filling time, plus a 30% safety margin. For this power level, the repetition rate should not exceed 200 Hz with RF pulses of 10 μs at minimum, according to the loaded quality factor and average power rating.

CONCLUSION

A transverse deflecting cavity for longitudinal electron beam diagnostics has been manufactured by RI Research Instruments GmbH by adapting a corresponding design developed at Cornell. The cavity has been installed at the straight diagnostics beamline of the bERLinPro facility at Helmholtz Zentrum Berlin after being tested and conditioned. The first beam measurements are expected to take place in 2019 and deliver a sub-ps temporal resolution.

ACKNOWLEDGEMENT

The authors would like to thank W. Anders, J. Hwang, F. Pfloksch, M. Schuster, H. Stein and J. Voelker from HZB for their technical support and useful discussions, as well as B. Dunham, F. Sannibale, V. Veshcherevich, D. Mallroy, T. Weis and M. Yan for sharing their work and experience on TCAV and the corresponding components.

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