TESTS OF ELBE RF – COMPONENTS WITH INCREASED RF – POWER

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Abstract

The RF-system of the superconducting electron linac ELBE (40 MeV, 1 mA CW) is in permanent operation since 2001, but it is not completely free of RF-trips. Experience gained within eight years of operation shows that the better the RF-components were conditioned the better is their electrical stability during long time operation. To be prepared for the planned ELBE upgrade with 16 kW of RF-power per cavity several test benches have been built to study the performance of RF-couplers and waveguide windows. In cooperation with Bruker BioSpin / France and CPI / USA the prototype of a 30 kW RF-amplifier based on an IOT had been tested with beam at ELBE. This paper gives an overview about tests of RF-components with increased RF-power at ELBE.

THE ELBE RF COUPLER

The LINAC is designed for CW-operation at a maximum beam energy of 40 MeV and a maximum beam current of 1mA [1]. The LINAC has two cryomodules. Each module (Figure 1) contains two 9-cell TESLA cavities modified for CW operation.

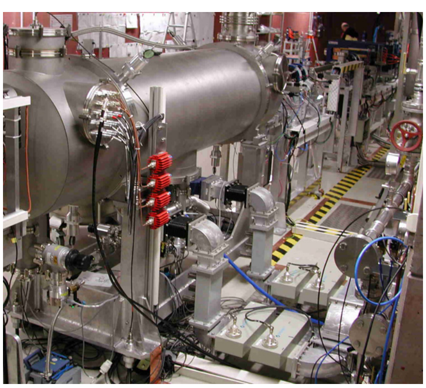
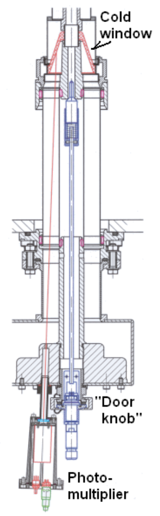


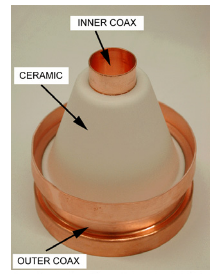
Figure 1: ELBE cryomodule equipped with two individually driven TESLA 9-cell cavities.

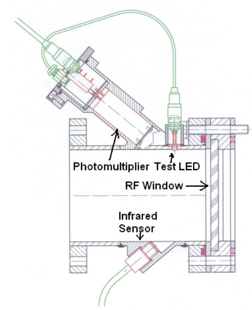
All cavities have identical couplers with a fixed antenna tip length. The loaded quality factor Q_L of 1.2 10^7 cavity bandwidth of 110 Hz. The cavity bandwidth can be tuned between 50 and 250 Hz with 3-stub waveguide tuners. Vacuum, temperature and light are monitored at all windows. Approved interlock set points at the ELBE waveguide windows are:

-vacuum: $1x10^{-6}$ mbar, -light: 0.5 lx, -temperature: 70C

Figures 2, 3 and 4 illustrate the RF-coupler with both windows and diagnosis [2].







Figures 2, 3, 4: The ELBE RF-coupler with cold (LN_2-cooled) ceramic window and warm waveguide window.

EXPERIENCE

The radiation source ELBE is operated as user facility in 3-shifts with interruptions only during planned shutdown periods. ELBE operation is characterized by many users running different experiments in separate caves with different setups. There is a need for high reliability, stable operation and fast beam changeover. The actual beam parameters are shown in table 1:

Table 1: ELBE beam parameters

	Thermionic Gun	SRF - Gun
Maximum Energy	40 MeV (CW)	>40 MeV (CW)
Bunch Charge	77 pC	77 pc / 2.5 nC
Beam Current	1 mA	1 mA
Bunch length (rms)	1 – 10 ps	4 / 20 ps
Transv.Emittance	2 mm mrad	1.5 / 3 mm mrad
Max. Rep.Rate	260 MHz@0.77pC 13 MHz@ 77pC	1 - 13 MHz
Energy Spread	35 keV /55 keV	40 keV

A thermionic gun is in permanent use since 2001, the new developed SRF gun has been commissioned. Activities to connect the SHF gun with the ELBE beam line are under way [4].

Because the maximum available RF-power per cavity by the klystron power (klystron VKL7811St, CPI) is limited at 8.5 kW at 1dB compression the LINAC could never be tested up to its limit. Full CW operation with a beam current up to 1 mA at lower gradients is used sometimes for high average power FEL operation.

As far as the achievable gradient is concerned, the main restriction is field emission causing Q-drop at gradients above 10 MV /m. Field emission at the first cavity downstream the thermionic injector triggers arcs in the thermionic gun. Comparable higher gradients at reduced field emission were obtained using high power processing with pulsed RF /5,6/.

RF-related problems during commissioning and eight years of continuously operation were:

- Damage of two "Rexolite" waveguide windows during commissioning, (one at first RF-ON with no sensors equipped, one during a self excitation of a klystron due to a defective coax cable).
- One waveguide window was exchanged just before it was damaged. The ELBE waveguide window is made from polystyrene (REXOLITE, part: OG9Y7-10073-702, WR650 Mega Industries). The "viton" (rubber) gaskets limit the achievable vacuum at the waveguide window.
- major repair of 3 klystrons (VKL7811St,CPI) due to leaky metal-ceramic welds,
- substitution of the 1 kW solid state driver PA because of a leaky alumina cooling block.

Activities to improve the RF-system for 16 kW RF operation focus on:

- Test of the RF-coupler components up to their limits,
- Test and improvement of different 16kW RF-power sources.

PREDICTIONS TO OPERATE ELBE AT 16 KW RF POWER

Fixed cavity bandwidth of 110 Hz:

At 110 Hz cavity bandwidth a beam current of 820 µA CW and 10 MV/m gradient is proper matched to the klystron with 8.5 kW RF forward power. Because of the good He-pressure stability (31mbar +/- 0.05 mbar) and low microphonics the RF-power reserve to compensate for microphonics is less than 1 dB [8]. Experience gained during FEL-operation has shown that stable operation at reduced accelerating gradients up to 7 MV / m at beam currents up to 1mA is possible without changing the cavity bandwidth. The following graphs are derived from "MathCad" using the following well known formulas:

$$P_G = P_{diss}\left(\frac{\left(1+\beta_{cavity}+\beta_{beam}\right)^2}{4\beta_{cavity}}\right)$$

$$P_{ref} = P_{diss}\left(\frac{\left(1+\beta_{cavity}+\beta_{beam}\right)^2}{4\beta_{cavity}}\right) - P_{beam} - P_{diss}$$

$$\beta_{cavity} = \frac{Q_0}{f_0}\cdot BW;\;\; \beta_{beam} = \frac{P_{beam}}{P_{diss}};\;\; P_{beam} = V_{acc}\cdot I_{beam}$$

$$P_{diss} = \frac{V_{acc}^2}{2r\cdot Q_0};\;\; r = R/Q = 518\Omega\ (ohmic\ def.)$$

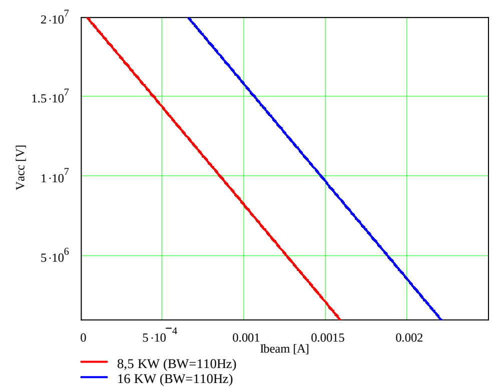


Figure 5: Acceleration voltage as a function of beam current at a cavity bandwidth of 110 Hz (ELBE setting).

Figure 5 shows a prediction for an 8.5 kW and a 16 kW RF power source at 110 Hz bandwidth.

Theoretically one can accelerate a 1.2 mA beam at 5 MV/m without changing the cavity bandwidth. Using a 16 kW power system a gradient of 12 MV/m is possible at 1.2 mA. One can also assume, that a 16 kW RF - amplifier offers the possibility to accelerate 1.5 mA at 10 MV/m at 110 Hz bandwidth.

Changing the bandwidth:

To adjust the coupling between klystron and cavity each RF system is equipped with a remote controlled 3-stub waveguide tuner to vary the bandwidth (loaded quality factor Q_L) between 50 Hz @ 2.6 10^7 and 250 Hz @ 5.2 10^6. Figure 6 shows the beam current as a function of the cavity bandwidth at different gradients and for 8.5 kW of RF- power. At 10 MV/m an ELBE cavity is best matched at 850 µA and 114.5 Hz bandwidth.

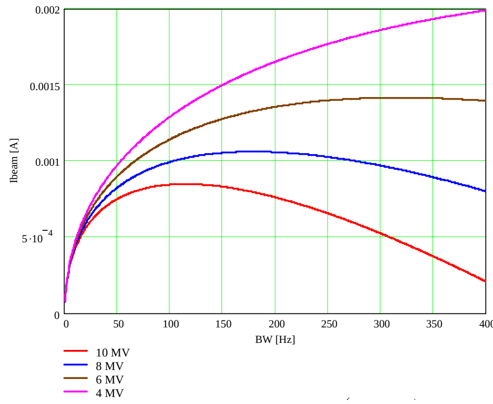


Figure 6: Beam current as a function of cavity bandwidth at different gradients at 8.5 kW RF power.

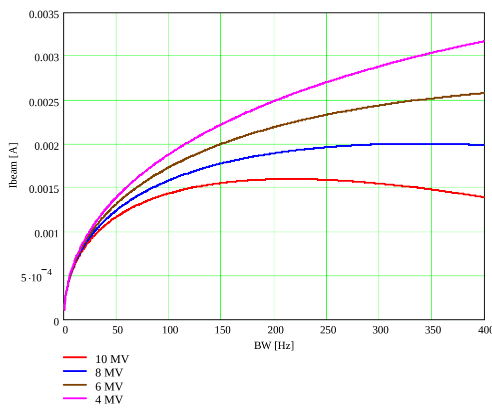


Figure 7: Beam current as a function of cavity bandwidth at different gradients at 16 kW RF power.

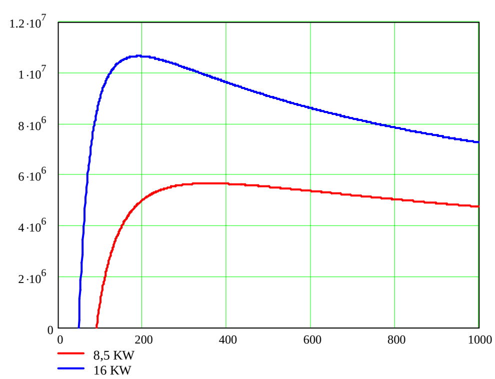


Figure 8: Gradient as a function of cavity bandwidth at 1.5 mA beam current and 8.5 kW as well as 16 kW RF-forward power. X-axis: Cavity Bandwidth in Hz, Y-axis: Gradient in V/m.

Figure 7 shows comparable curves for 16 kW. At 10 MV/m it seems to be possible to accelerate a beam current of 1.6 mA at a cavity bandwidth of 216 Hz or 2.7mA at 6 MV/m and 250 Hz. At a beam current of 1.5mA and the given limit of the cavity bandwidth of 250 Hz due to the tuning range of the 3-stub tuner a gradient of 5.5 MV at 8.5 kW of RF-power and 10 MV at 16 kW are possible (Figure 8).

TEST OF A 30 KW IOT-AMPLIFIER AT ELBE

In a close cooperation with Bruker BioSpin Wissembourg / France and CPI Palo-Alto / USA a prototype of an IOT-based 30 kW RF amplifier is installed in the ELBE RF-lab. A standard klystron amplifier was replaced by the IOT CHK5-1320W (CPI). The interlock requirements, the controls as well as the RF-levels of the IOT based transmitter were compatible to the klystron rack used normally, so that the operator could operate the system as a full substitute. Figure 9 shows the installation and Figure 10 the block diagram of the temporary replacement.

Figure 9: Test setup of the 30 kW IOT amplifier at ELBE.

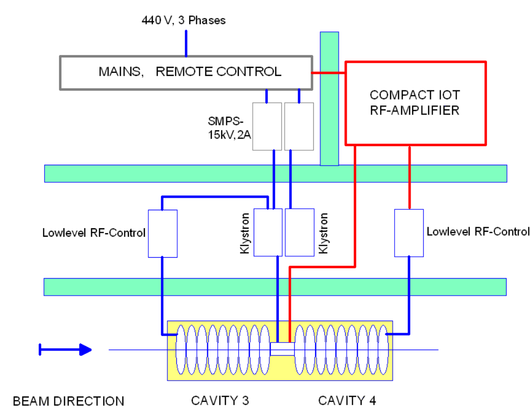


Figure 10: Replacement of a klystron by the IOT amplifier.

Using the setup of Figure 10 stable FEL operation was observed. Because the FEL is the most sensitive device on ELBE detuning curves of the FEL (undulator U27) had been measured for comparison using identical machine settings (Figure 11 and Figure 12).

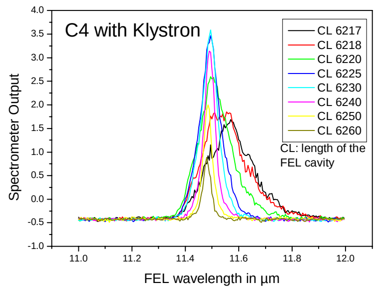


Figure 11: Detuning curve of the FEL (U27) with klystron operation.

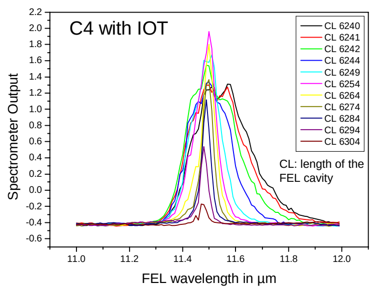


Figure 12: Detuning curve of the FEL (U27) with IOT.

Further tests of the prototype of a future "turn-key" 16 kW IOT amplifier are under way. A difficulty was the proper design of the switched mode IOT-power supply to react on fast changing loads. A klystron based power amplifier performs a stable load for a power supply independently of the cavity load or the beam load when operated in CW. ELBE uses the so-called "diagnostic mode". A macropulser as part of the injector is keying the time structure of the beam. This enables beam matching at full bunch charge but low average power to avoid damage of components. In "diagnostic mode" one can choose the "beam-on" time between 0.1 ms and 36 ms and the repetition rate between 40 ms and 1 s. In worst case the load of the klystron changes within the 0.1 ms from 10 % to 90 %. A critical point is the voltage stability during the 0.1 ms long pulses.

A NEW COUPLER TESTBENCH AT ELBE

The disadvantages of the first coupler test bench based on a waveguide sliding short to generate standing waves at all phases was, that the coupler environment was air, and the power was limited by the 8 kW klystron. This setup was successfully used to train several couplers /2, 9/. Within the EUROFEL framework a resonant ring has been built to study the behaviour of coupler as well as waveguide windows with RF power above 10 kW in CW operation Figure 13 shows the block diagram, Figure 14 the photograph of the ring with the connected coupler test box [10,11].

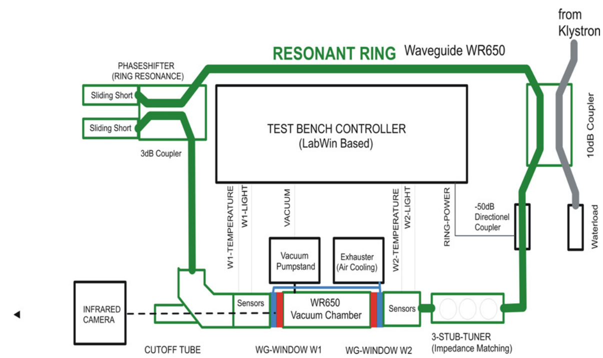


Figure 13: Block diagram of the Resonant Ring.

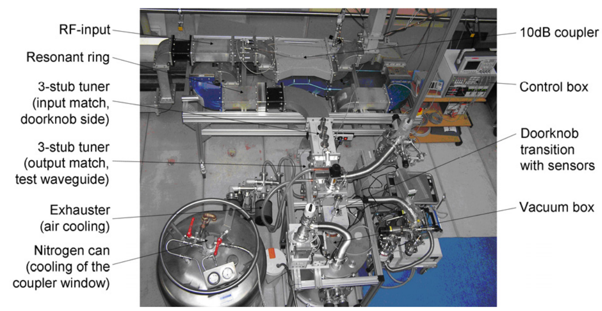


Figure 14: Resonant Ring at ELBE

The resonant ring is driven by a 10 kW klystron VKL7811St (CPI). The gain of the ring without insertions is 25. A waveguide phase shifter enables flexibility to bring the ring into resonance.

TEST PROCEDURES

A LabWindows based control and data acquisition software was written. The following 3 processing modes are foreseen:

Field processing implies low thermal load at the device under test and is done with pulses of 10ms pulse / 300ms repetition rate.

Thermal tests are done with constant CW-power. Any Interlock (light, vacuum or temperature) stops processing.

Mixed Mode with pulse trains from 1ms (10 times) to 1s (10times) is a combined test procedure to apply high gradients as well as significant thermal load. Interlocks reduce repetition rate as well as power.

Generally the output power of the klystron is stabilized with its own control loop. The gain was chosen that a power step of +50 W at the klystron is about +1 kW in the ring.

WAVEGUIDE WINDOW TESTS

The setup of two air-cooled waveguide windows before assembling (middle part: vacuum-waveguide, left and right: sensor boxes) is shown in Figure 12.

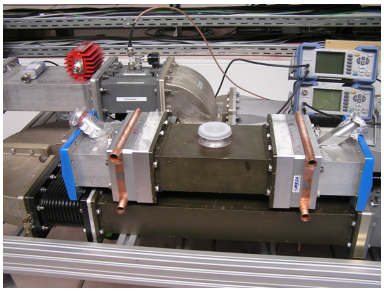


Figure 15: Waveguide window arrangement.

A cutoff tube (see Figure 14, left side),welded into a H-bend was used to enable infrared measurements at the windows during operation. The effect of air-cooling during operation (steady state after 20 min.) with 50 kW RF power in the ring was measured to be 15…20 deg.

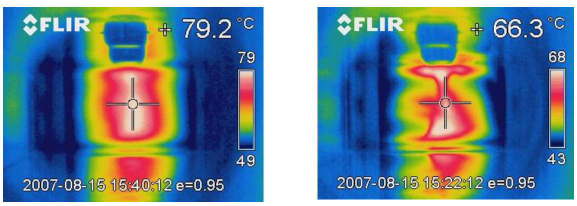


Figure 16 and 17: Thermograms of the waveguide window at 50 kW (CW) without (left), and with (right) air-cooling.

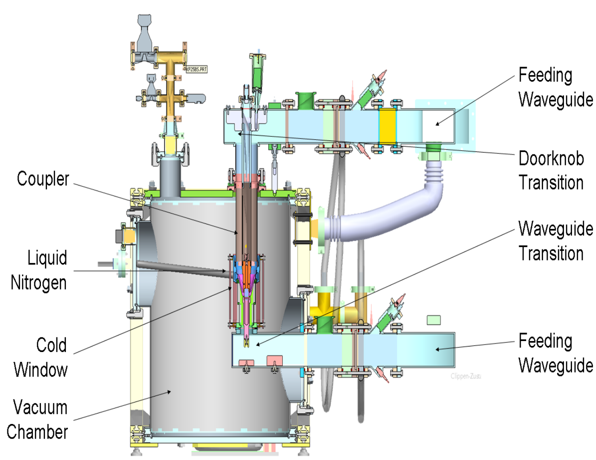


Figure 18: Vacuum box with ELBE RF-coupler and diagnostics used in the resonant ring.

An example of a typical training curve of a RF coupler is shown in Figure 19. The upper curve shows the power ramp versus time and the two lower curves show the detected light events on the ceramic window of the coupler (red) and the waveguide window at the lower coupler box.

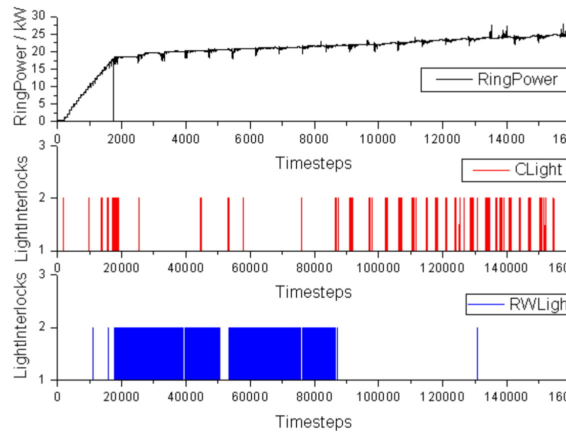


Figure 19: Typical RF-coupler training curve (80000 time steps are 1hour).

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