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EUROPEAN FEL Design Study

Deliverable N°:	D 5.28
Deliverable Title:	Activities at FZD to operate an ELBE cavity with a 16 kW IOT-based power amplifier and predictions to accelerate a beam current > 1 mA
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1. Introduction

The ELBE cryomodule, equipped with two Tesla cavities and designed for CW operation at gradients up to 10 MeV / m and a beam current of 1 mA is in permanent operation since 2001. A lot of experience has gained during the 6 years of operation and meanwhile the Dresden-Rossendorf module is produced by ACCEL Instruments under licence. Because the maximum available RF power per cavity is limited by the VKL7811St klystron (CPI) to 8.5 kW, the full performance of the ELBE cryomodule could never be checked.

ELBE is still discussing a possible upgrade to > 1mA beam current in 2008/2009. Studies of the performance of all critical components as well as the behaviour of the accelerator remain critical issues. Furthermore the results of high power operation of ELBE as well as the results gained through component tests will support the ERL activities.
Since a few years several companies offer 16 kW Inductive Output Tubes (IOT) for 1.3 GHz. In 2006 E2V-Chelmsford (UK) presented a compact 16 kW RF amplifier based on their IOT as a stand-alone system including the power supply. This unit allows simple replacement of one of the klystron amplifiers to double the available RF-power and to run performance tests. To meet the requirements fixed in the subtasks 5.36., 5.3.7, 5.8.8. Within a short time slot the activities at FZD were split into two parts. One part was to build a new test bench and to run waveguide window and coupler tests with very high power (at least 50 kW) to ensure proper operation of these critical components /1/. The test setup is based on a resonant ring with high gain and can be operated by a 10 kW klystron as well as an IOT. On this prosperous activity is reported in /2/.
The second part, with reference to subtasks 5.3.6 and 5.3.7 contains all activities to be prepared for IOT operation at an existing ELBE cavity. A cooperation agreement was signed by the directors of FZD and E2V and many activities described below were done at FZD as well as E2V. Last not least the IOT amplifier could not be delivered by E2V because of serious technical problems with the high voltage power supply.

2. Activities to install a 16 kW IOT – based RF-system at ELBE

- December 2006: Meeting E2V-FZD, IOT-presentation,
- 31st of Jan.2007: Workshop E2V-FZD (timetable fig.1)
- February 2007: Cooperation agreement between FZD and E2V,
- April 2007: Installation of a 40kW water cooling unit because the installed cooling capacity of the ELBE plant was overloaded,
- May 2007: Installation of a remote controllable main power plug,
- May 2007: Installation of a computer link at the test setup,
- June 2007: First tests with the resonant ring using the 10kW klystron amplifier of the SRF-Gun,
- August 2007: Decision to withdraw the cooperation agreement because of impossible delivery of the Compact IOT Amplifier system by E2V.

1	IOT at ELBE in 2007												
2	TASK	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec
3	SHUTDOWN (ELBE) (week)	1		xxxxxx 13	14,15,16xx			25-29 xx		xxxx38,39			xxxx51,52
4	**EUFEL 5.8.2 (selection/design for suitable components for cw-cpl.) and 5.8.3 (test and optimization of cpl. and windows for >10kw cw op)**												
5	**Improved RF-Source (IOT)**												
6	IOT-UNIT (Delivery)		delayed because of problems with hv-ps (third party)					28 latest					
7	IOT-Cooling, standby, tested	*		ready									
8	IOT-Cooling ,Interlock to ELBE												
9	Mains ,	xxxx3		ready									
10	IOT Istallation	**E2V-ASSISTANCE**						28/29					
11	IOT operation (stand alone checks)							29	REPORT 35				
12	Basic tests of the IOT using dummy load							29					
13	**Window Tests using resonant ring with klystron and new setup**												
14	warm-indow test using additional cooling												
15	new setup preparation (cleaning, vacuum test)						25						
16	implementation in resonant ring					18,19	26						
17	Running tests							27		REPORT37			
18	**Coupler Tests using the new test bench**												
19	Design (test bench)			9									
20	Delivery (test bench)							29					
21	clean room: coupler ,waveguide cleaning							30	31				
22	vacuum tests								32				
23	implementation in resonant ring								33,34				
24	Running tests								34,35	REPORT 38			
25	**OPERATING ELBE with IOT**												
26	LINK IOT-SIMATIC project								35				
27	LINK IOT-SIMATIC hardware,test								36				
28	Connection IOT,ELBE									xxxx38,39			
29	Operation										40,41,42,43		REPORT

Table 1: Timetable to coordinate IOT related activities in 2007

3. The Compact 16 kW IOT System of E2V

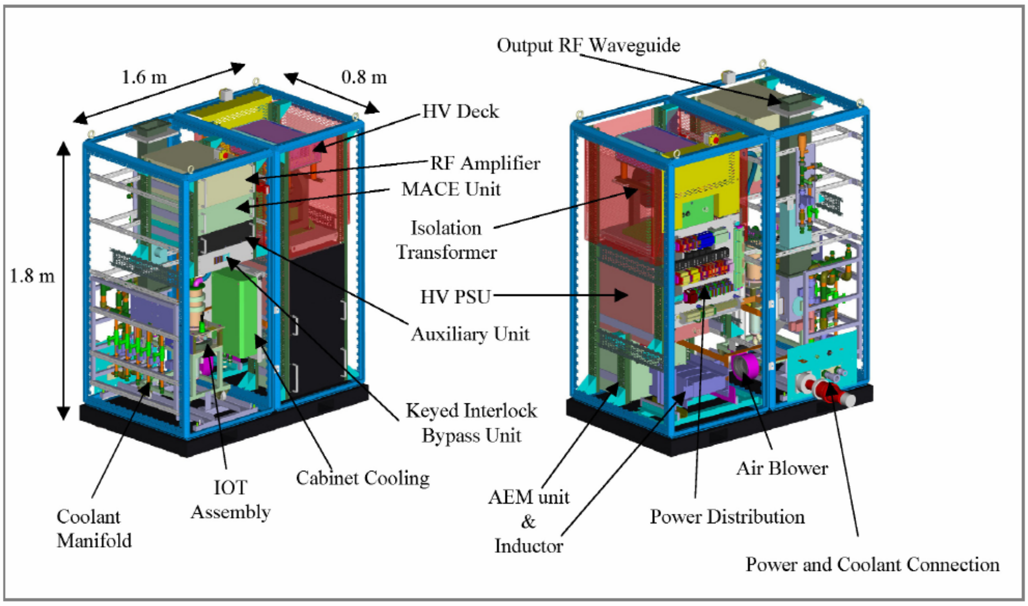

Figure 1: Drawing of the Compact 16 kW IOT RF power amplifier /2/

Technical Specification:

- Output Power at 1.3 GHz and +/- 5 MHz bandwidth 16 kW,
- IOT gain > 20 dB
- IOT efficiency > 60 %
- Power factor > 98 %,

The implementation of the compact E2V-RF-system based on a block of two19-inch racks into the ELBE RF-system is favourable because:

- the power supply is part of the unit and no external and normally not available power supply of 32 kV is necessary to operate the system,
- the input drive power of 0 dBm is exactly the same as for the ELBE klystrons,
- the E2V is self protected and allows to generate the same sum interlocks equal to ELBE,

To complete the system and to operate it at ELBE it was necessary to buy an extra 40 kW water cooling system with heat exchanger because of the overload of the ELBE cooling circuit and to install a power line (3-phases) with a remote controlled power switch. Because of the size of the unit we could not install the racks in the klystron room. A WR-650 waveguide transition from the klystron room to the IOT, placed on top of the accelerator cave has been built. It is now used to operate the resonant ring with the coupler test bench with power from the SRF-gun klystron. The implementation into the ELBE RF-system is shows in figure 2.

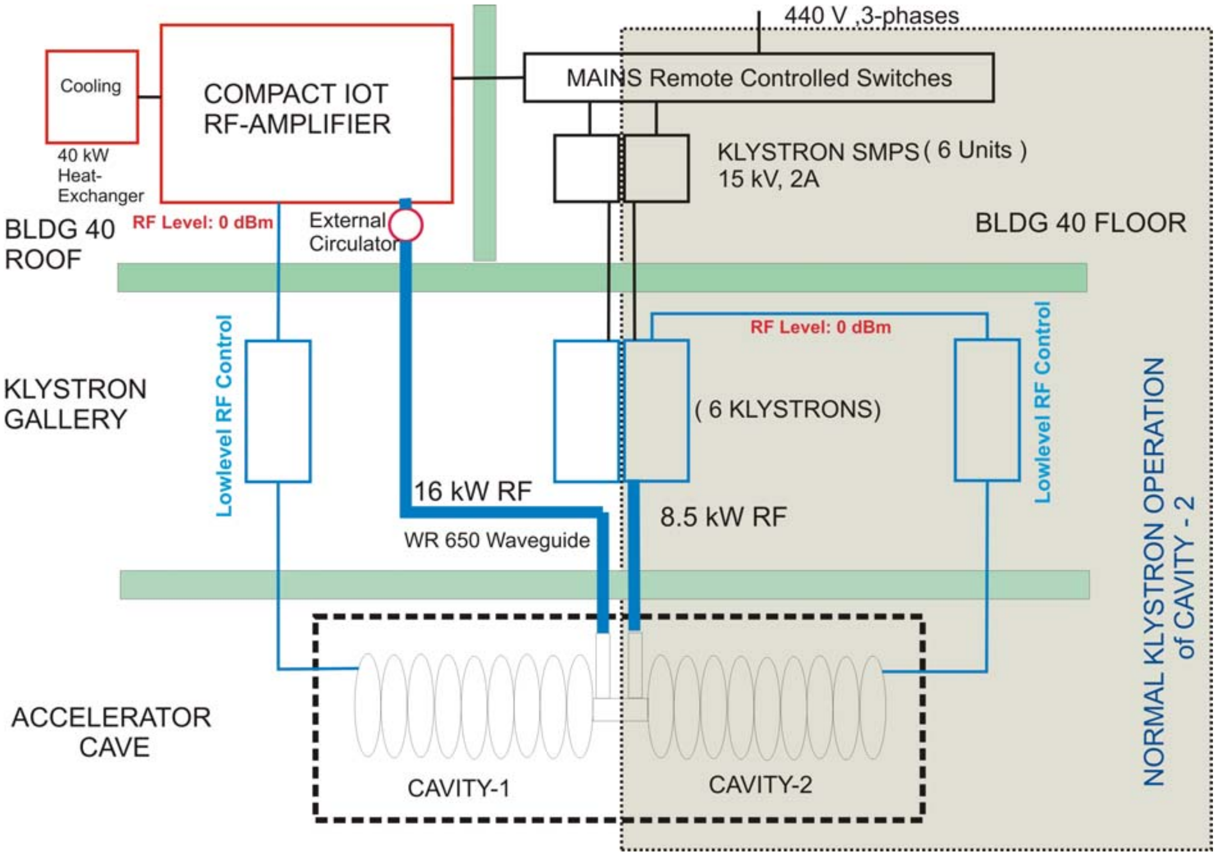

Fig.2: Replacement of klystron 1 by the IOT to operate cavity 1.

RED: new installations required. The waveguide between the roof and the klystron gallery is now used reverse to drive the resonant ring placed on the roof with a klystron; connection to the ELBE control system is arranged by a serial link

4. Theoretical predictions to accelerate a beam current > 1mA at ELBE

4.1. Standard operation of ELBE (cavity bandwidth 110 Hz)

The optimum coupling for the given RF forward power of 8.5 kW to the cavity is given at a bandwidth of 110 Hz, corresponding to a loaded quality factor Q_L=1.18 10^7. At this cavity bandwidth a beam current of 820 µA CW @ 10 MV/m gradient requires 8.5 kW RF forward power. For this application the antenna tip length of the ELBE couplers has been optimized. Experience gained during FEL-operation has shown that stable operation at reduced accelerating gradients (5 to 7 MV / m) with a beam current of 1 mA is possible without changing the cavity bandwidth. Routine FEL high power CW applications are usual with beam current between 500 µA and 800 µA.

The following graphs are based on a MathCAD tool using the formulas:

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

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

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

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

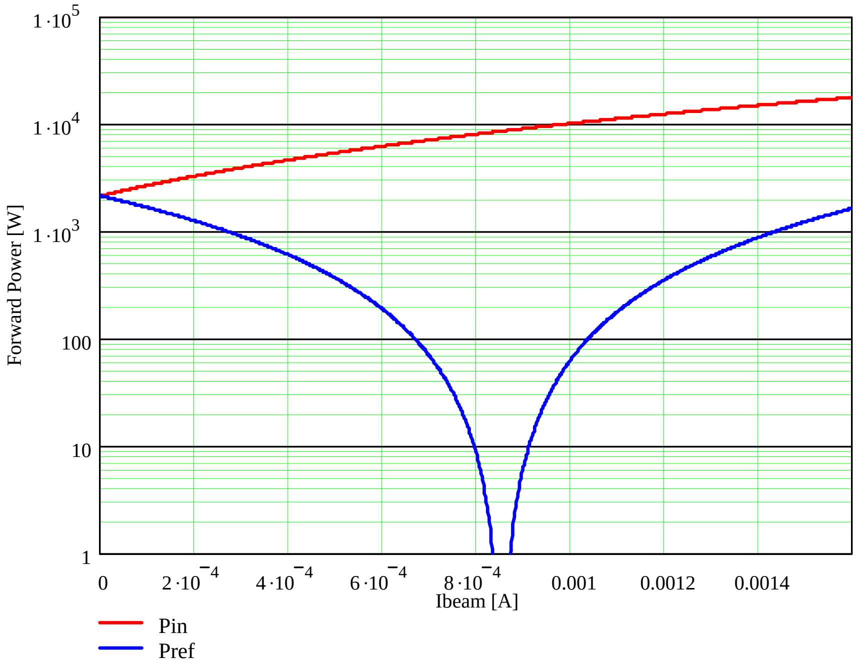

Figure 3: RF-forward power for a cavity bandwidth of 110 Hz and a gradient of 10 MV/m

4.2. Theoretical prediction for > 1 mA operation at 110 Hz cavity bandwidth

Fig 4 shows a prediction for an 8.5 kW and a 16 kW RF power source at 110 Hz bandwidth.

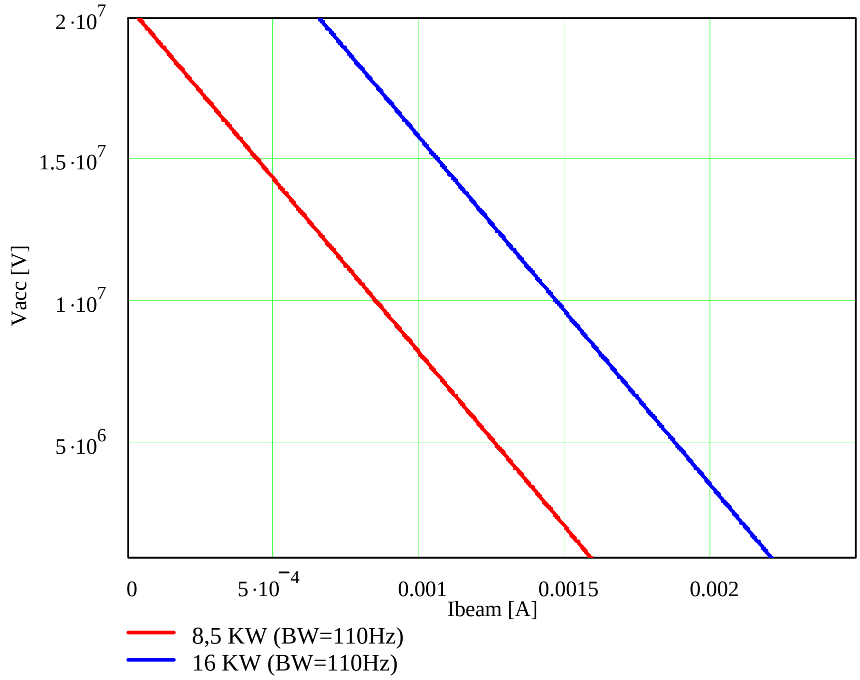

Figure 4: Acceleration voltage as a function of beam current at a cavity bandwidth of 110 Hz

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

Operation at > 1mA of beam current has never been tried because of several risks which can impact the stable 3-shift operation of the machine. That's why machine development tasks are focused on permanent improvements of the stability and reproducibility of ELBE parameters and on topics which can be carried out in parallel to user operation. Detuning and further retuning of all 3-stub tuners to increase the cavity bandwidth seems to be too risky without checking the reproducibility and without studying the performance of the RF system under different beam conditions before.

4.3. Predictions for different cavity bandwidths

To adjust the coupling between klystron and cavity each RF system is equipped with a remote controlled 3-stub tuner, which allows to vary the bandwidth (versus loaded quality factor Q_L) between 50 Hz @ 2.6 10^7 and 250 Hz @ 5.2 10^6. This option has been only used to adjust the bandwidth of all cavities to 110 Hz.

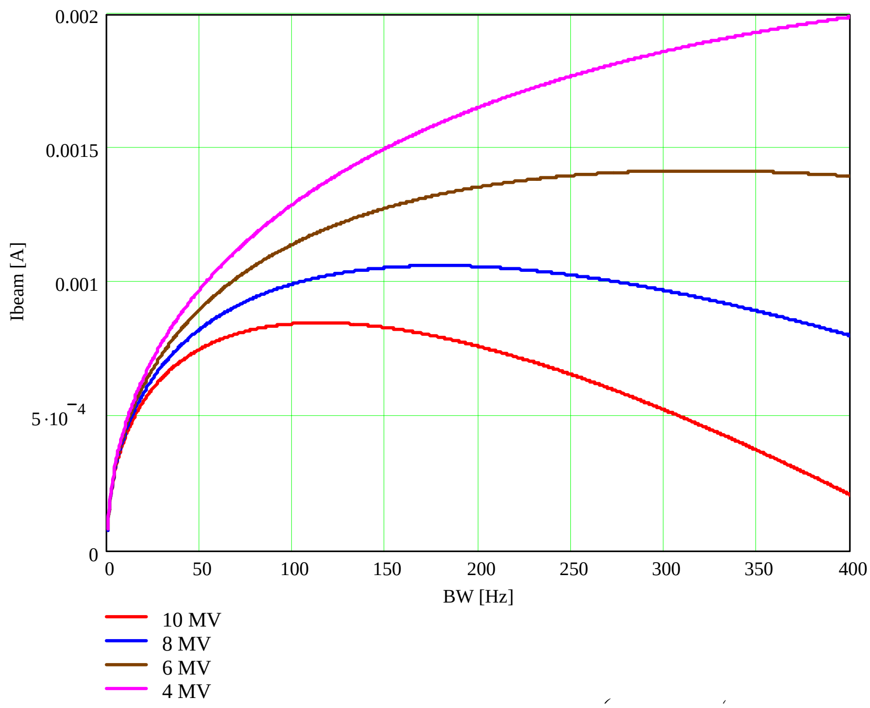

Fig.5: Beam current as a function of cavity bandwidth at different gradients and for a fixed RF- power of 8.5 kW. Best matching is given at 849 µA @ 10 MV/m and 114.5 Hz bandwidth.

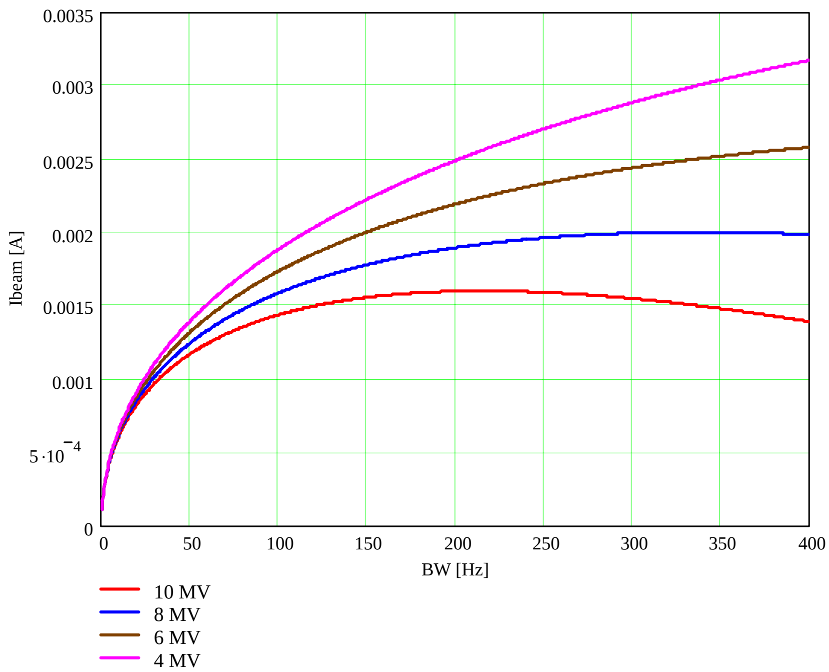

Fig.6: Beam current as a function of cavity bandwidth at different gradients and for a fixed RF- power of 16 kW. At 10 MV/m it seems to be possible to accelerate a beam current of 1.6 mA at a cavity bandwidth of 216 Hz or 2mA@ 8MV/m and 300 Hz.

Assuming a beam current of 1.5 mA one has to chose the best cavity bandwidth to get the highest gradient, or the best match.

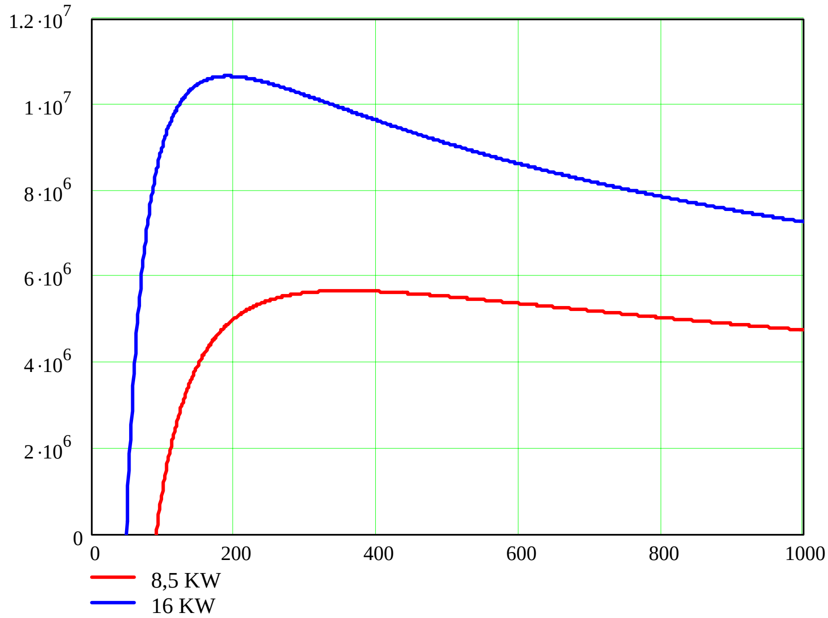

Figure 7: Achievable gradient as a function of cavity bandwidth for 1.5 mA beam current and 8.5 kW as well as 16 kW RF-forward power.
X-axis: Cavity Bandwidth in Hz, Y-axis: Gradient in V/m
Optimum at 8,5KW: BW=357Hz → 5.67MV ,Optimum at 16 KW: BW=190Hz → 10.07MV

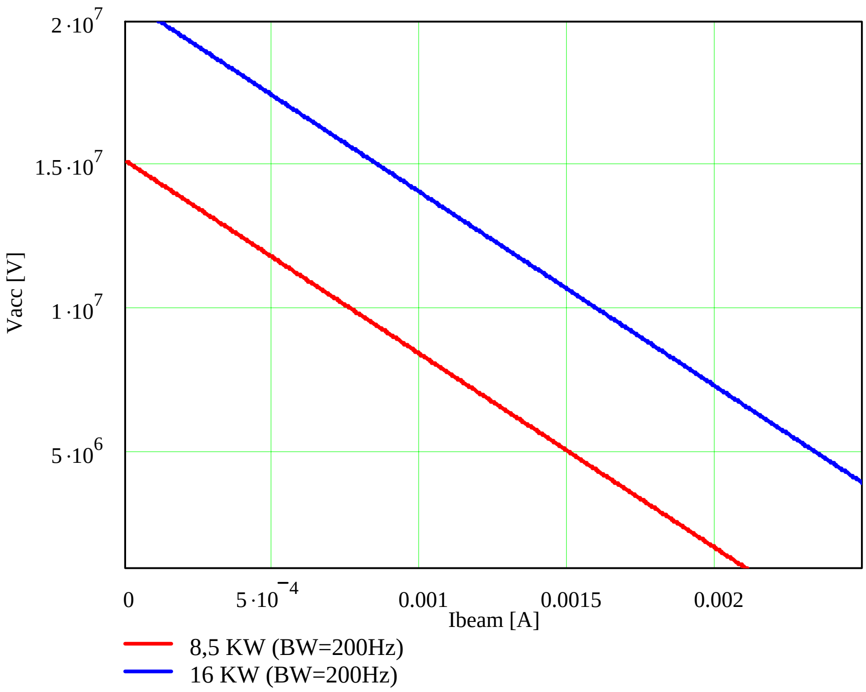

Figure 8: Energy gain versus beam current for a cavity bandwidth of 200 Hz

Using figure 5 the overall energy gain at 1.5 mA beam current with 3 cavities operated with 8.5 kW at 200 Hz cavity bandwidth and one system with 16 kW and 200 Hz is 3 x 5.05 MeV + 1 x 10.07 MeV = 25.16 MeV.

Using two ELBE cryomodules, each cavity equipped with a 16 kW RF-amplifier, it seems to be theoretically feasible to accelerate a beam current of 1.5 mA to 40 MeV. This theoretically prediction does not include any statement on the behaviour of the RF system, its interlocks triggered by light-, vacuum-, and temperature sensors or on beam load effects. To verify the prediction extensive studies of the accelerator are necessary.

5. Acknowledgement

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References:
/1/: Büttig, H. et.al.: Tests Of Air Cooled 1.3 GHz Waveguide Windows Using A RF-Coupler Test Bench Based On A Resonant Ring, Proceedings SRF 2007, Beijing

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/3/: Jan S. Przybyla et.al.: Development of a High Power RF Amplifier Using Industrial Power Electronics, Proceedings EPAC-2006.