# EUROFEL-Report-2005-DS5-003

## *EUROPEAN FEL Design Study*

| | |
|---|---|
| Deliverable N°: | D5.19 |
| Deliverable Title: | PARAMETER SET FOR CW AND NEAR-CW OPERATION OF A XFEL DRIVING SUPER-CONDUCTING LINAC |
| Task: | DS-5 |
| Author: | Jacek Sekutowicz, DESY |
| Contract N°: | 011935 |

**Project funded by the European Community**
**under the "Structuring the European Research Area" Specific Programme**
**Research Infrastructures action**

# PARAMETER SET FOR CW AND NEAR-CW OPERATION OF A XFEL DRIVING SUPERCONDUCTING LINAC[1]

## *EUROFEL – DS5*

*Jacek Sekutowicz,*
*DESY- MPY, Notkestrasse 85, 22607 Hamburg, Germany*
*May 25, 2005*

## INTRODUCTION

This report is prepared in framework of the EUROFEL Design Study 5. The first stage, 3 months, of the study was devoted to the definition of continuous wave (cw) or near-cw generic operating parameters of a superconducting linac driving a coherent light source. While neither the final linac energy nor generated photons energy might be specified in these studies we proceed with a “modular approach”, presenting here an accelerating unit consisting of a cryomodule, housing eight 9-cell superconducting cavities, and an individual RF-source supplying the RF-power to all eight cavities. Having the operating parameters of the unit one can easily find for a particular project: number of units needed to reach energy spec, required capacity of a cryogenic plant, number of accelerated bunches/s, AC power consumption and other important data.

The study is intended to apply to future light sources and/or to an upgrade of the European XFEL linac. Its implementation should be seen as a long term process. This allows for exploring here not only the existing state-of-the-art technology but also those being under development and which preliminary experimental results are very promising.

In the next sections we will discuss relevant for the study results of the present superconducting technology and then the recent progress in the superconducting and RF-sources R&D program. The content of these sections should be seen as the justification for assumptions used to define the parameter set presented in the last section.

## CAVITIES AND CRYOMODULE

### *Intrinsic Qo of 1.3 GHz sc cavities*

Figure 1 shows measured data of fourteen 3-rd production TESLA Test Facility cavities. This production represents state-of-the-art superconducting technology with the buffered chemical polishing (BCP) surface cleaning.

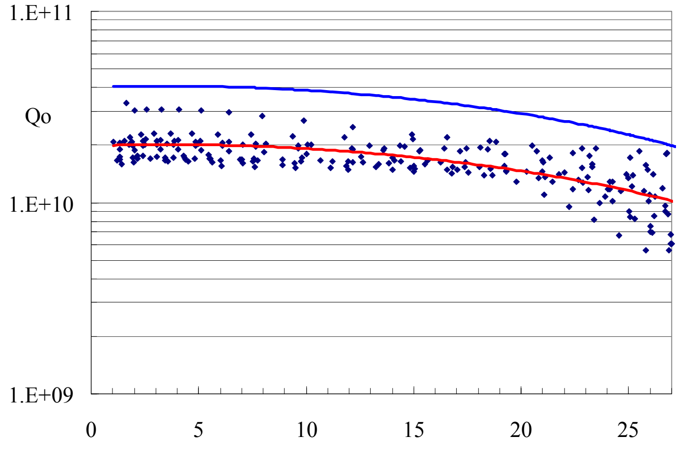

Figure 1. Measured intrinsic quality factor Qo vs. accelerating gradient Eacc for fourteen 1.3 GHz 9-cell TTF cavities at DESY.

---

[1] Work supported by EU under contract No. 011935 (EUROFEL)

The cavities were measured at 2K. The red solid curve is the mean value of the intrinsic Qo vs. Eacc for all data as measured at 2K. The blue upper curve shows its scaling to 1.8 K. Following the arguments presented in [1] a cryoplant can be more effectively operated at lower than 2K temperature as long as the cryogenic dynamic losses are due to the BCS part of the surface resistance.

A very promising R&D program leading to the significant cost reduction of sc cavities has been proposed by P. Kneisel at TJNAF in Newport News, USA [2]. The program is carried out to confirm very good performance of cavities made of big grains (single crystal) Nb sheets obtained directly from an ingot without expensive rolling process. Additionally to the new material a modified cell shape (so called Low Loss) with less magnetic field on the Nb wall [3] is also to be tested in the frame of this program. The performance of the first 2.3 GHz single cell single crystal LL cavity (diameter of available ingot was too small to make 1.3 GHz cell) at 2K is shown in Fig. 2. Priori to the test the cavity was treated with 1:1:1 BCP and baked at 120°C. The cavity had very small residual resistance, a fraction of nΩ, and its excellent performance is mainly due to the superior material purity. The upper curve illustrates the data scaled to 1.3 GHz by factor $(2.3\text{GHz}/1.3\text{GHz})^2$. The test confirms expectation that less grain boundaries, which usually are the locations of enhanced losses due to impurities and oxides, makes intrinsic Qo higher even at 2K with the BCP treatment. The surface of 0.2mm x 0.2mm samples of the big grain material was investigated after the 1:1:2 BCP treatment. The measured roughness was of the order of 30 nm only, much less than roughness after more expensive Electro Polishing treatment. A smooth and particulates free cavity wall shows no field emission phenomena. This additional loss mechanism was not observed during the test.

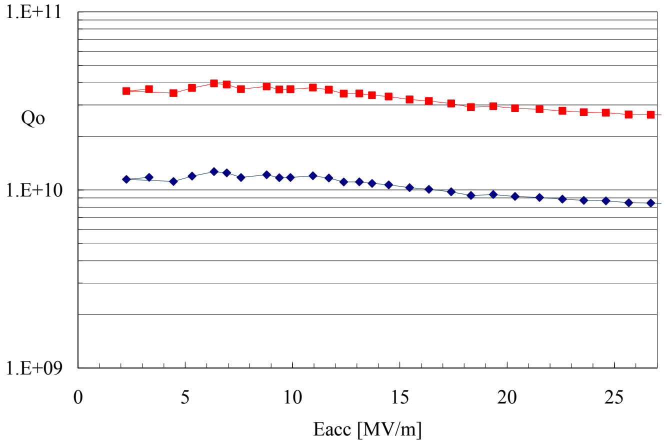

Figure 2. Measured at 2K intrinsic quality factor Qo vs. accelerating gradient Eacc for the single cell 2.3 GHz Low Loss single crystal cavity at TJNAF. The upper curve showed Qo scaled to 1.3 GHz.

The presented above data lead us to the assumption that for gradients up to 27 MV/m L-band 1.3 GHz accelerating structures when operated at 1.8 K or/and made of big grain Nb material can demonstrate intrinsic Qo higher than $2 \cdot 10^{10}$. We will accept this value defining the cw or near-cw operation parameter set for the accelerating unit.

## *Microphonics and cryogenic losses*

Suppression of frequency modulation caused by mechanical cavity vibration (microphonics) is of great importance for the cw or near-cw operation. Stabilization of the accelerating field (the amplitude and phase) i.e. compensation for this phenomena cost additional RF-power. Measurements at FZ Rossendorf on TTF cavities [4] showed that proper cryomodule construction may lead to an effective reduction of the frequency modulation. In the FZ Rossendorf cryomodule cavities demonstrate 10 Hz (2 Hz rms) frequency modulation, as compared to 24 Hz in the original TTF cryomodules [5]. Better suppression lowers effectively the capital and operation costs of an RF-system and also allows for higher energy reach as we will see in later presented diagrams.

The static cryogenic losses per cavity in the TTF type cryomodule is: 0.15, 1.0 and 7.5 W at 2, 5-8 and 40-80 K temperature levels respectively [6]. At cw or near-cw operations dynamic losses will be much higher than the static losses, so one has to adjust the length of a RF-pulse (duty factor) to keep the whole cryoplant at a reasonable size. Keeping in mind a possible upgrade of the European XFEL linac consisting of 116 cryomodules we assume that for the cw or near-cw operation the upper limit of the cryoplant capacity should not exceed 5 kW at 2K (similar capacity to one of the TESLA TDR cryo-unit or whole CEBAF cryoplant). This with 30 % safety margin limits cryogenic load per cryomodule at 2K to about 30 W. The limitation is to some extend arbitrary and for example for linacs which are shorter the limiting cryo load per cryomodule can be chosen higher.

## RF-SOURCE

Inductive Output Tubes (IOTs) are very compact and robust microwave power amplifiers used commonly in terrestrial TV broadcast industry. Their potential application to cw or near-cw operating accelerators is the motivation for R&D programs at companies like CPI and e2v which have many years experience with tubes for the telecommunication. The programs concentrate on a design of L-band 1.3 GHz tubes, their efficiency, gain and the life time. Recently, cw operating 30 kW tube was tested successfully at CPI in pulse mode up to 85 kW [7]. Its gain and efficiency are shown in Fig. 3.

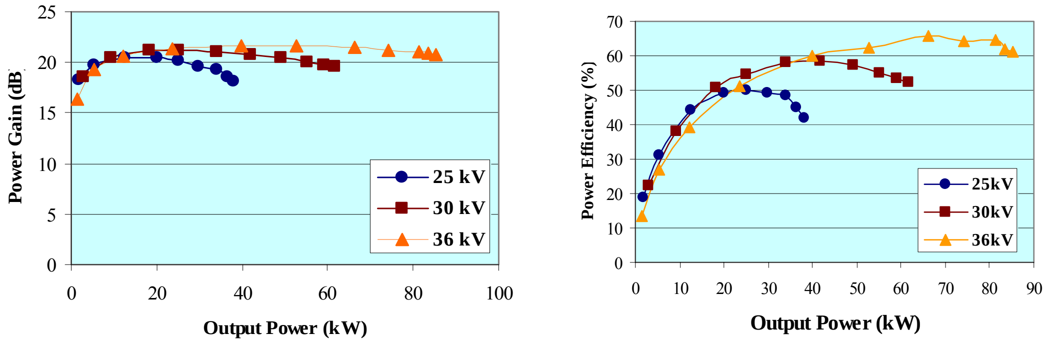

Figure 3. Test of 30 kW cw IOT in pulse mode. Pulse length ~ 1ms. *(Courtesy Y. Li CPI/Eimac).*

The CPI Company has offered to examine technical feasibility of a cw operating 1.3 GHz tube providing output power of 60 and 120 kW. The very preliminary modeling shows no fundamental technical difficulty to build such a tube [8]. The computed tube parameters are listed in Table 1. At the computed efficiency the tube will require a 165 kW power supply and a 760 W driving input amplifier at the gain of 22 dB.

Table 1. Preliminary parameters of 120 kW IOT.

| Parameter | Unit | $P_{out}$= 60 kW | $P_{out}$= 120 kW |
|---|---|---|---|
| Voltage | [kV] | 38 | 46 |
| Current | [A] | 2.5 | 3.7 |
| Gain | [dB] | 22 | 22 |
| Efficiency | [%] | 64 | 72.8 |

## ACCELERATING UNIT AND ITS PARAMETERS

The accelerating unit is shown schematically in Figure 4. It consists of: eight cavities housed in one cryomodule, the 120 kW IOT amplifier, a driving 760 W amplifier and the power distribution system. As it was mentioned we will limit 2 K losses to 30 W.

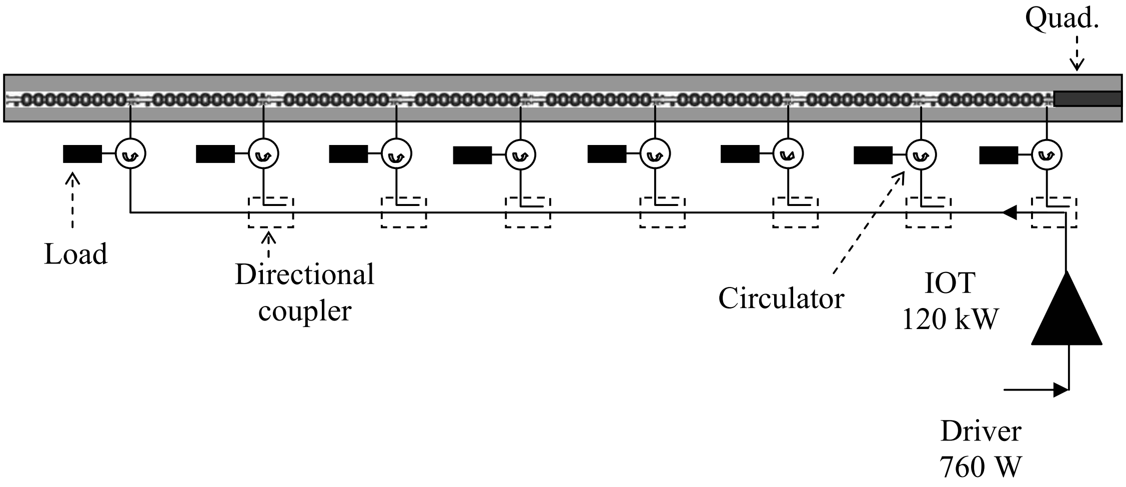

Figure 4. Accelerating unit consisting of: eight 9-cell cavities, 120 kW IOT, a driving amplifier and the power distribution system (eight circulators and loads, seven directional couplers).

We assume that distribution system dissipates ~3% of the transmitted power and that maximum available beam power is 77% of the total IOT power, reserving 20 % of it for the phase and amplitude stabilization. In addition, we will assume that an individual bunch charge is 1nC. In reality one can very flexibly change time separation and charge of bunches keeping constant an average current within the RF-pulse, which length depends only on the cryogenic load. The repetition frequency of RF-pulses is assumed to be 1 Hz.

Table 2 summarizes the parameter set for cw and near-cw operation resulting from the above discussed assumptions. The number of 1 nC bunches in the energy range 50-225 MeV (5.8 GeV to 26 GeV for 116 units of XFEL type linac, see last row in the table) is shown in Fig.5. The unit can accelerate up to 1.8 $\cdot 10^6$ bunches at 50 MeV down to 36000 at 225 MeV. The spacing of nominal 1 nC bunches varies from 0.54 to 2.42 µs. The RF-pulse length is 1000 ms (cw) at 50 MeV down to 96 ms at 225 MeV (near-cw regime). The potential upgrade of the XFEL linac based on the acceleration units will raise the average brilliance by the factor of 40 at ~6 GeV and by the factor of 3 at the nominal energy of 17 GeV.

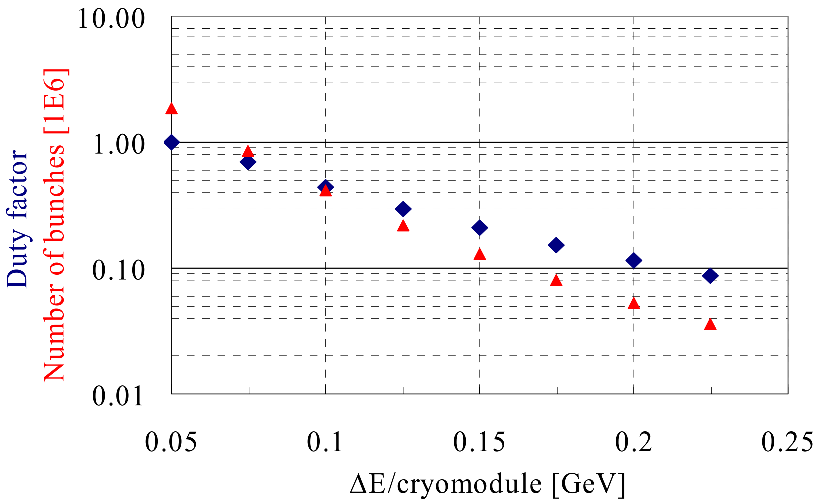

Figure 5. Duty factor (diamonds) and number of 1 nC bunches per second (triangles) for the parameters shown in Table 2.

Table 2. Parameter set for the cw and near-cw operation of acceleration unit.

| Parameter | Unit | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Energy gain /accelerating unit** | **[GeV]** | **0.05** | **0.075** | **0.1** | **0.125** | **0.15** | **0.175** | **0.2** | **0.225** |
| Eacc | [MV/m] | 6.01 | 9.01 | 12.02 | 15.02 | 18.03 | 21.03 | 24.04 | 27.04 |
| Qo | [$10^{10}$] | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| (R/Q) per subunit | [Ω] | 1020 | 1020 | 1020 | 1020 | 1020 | 1020 | 1020 | 1020 |
| Additional losses/cavity at 2K (HOM, static…) | [W] | 1.78 | 1.09 | 0.74 | 0.55 | 0.44 | 0.38 | 0.33 | 0.30 |
| Dynamic loss/cavity at 2K for DF = 100% | [W] | 1.91 | 4.31 | 7.66 | 11.97 | 17.23 | 23.46 | 30.64 | 38.78 |
| Total Loss at 2K/cavity for DF = 100% | [W] | 3.70 | 5.40 | 8.40 | 12.52 | 17.68 | 23.83 | 30.97 | 39.08 |
| Total Loss at 2K/cryomodule for DF = 100% | [W] | 29.6 | 43.2 | 67.2 | 100.2 | 141.4 | 190.7 | 247.7 | 312.6 |
| Max cryogenic load at 2K /cryomodule | [W] | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| Duty Factor; DF | [%] | 100.0 | 69.4 | 44.6 | 29.9 | 21.2 | 15.7 | 12.1 | 9.6 |
| **Beam time** | **[ms]** | **999** | **693** | **444** | **297** | **208** | **152** | **114** | **87** |
| Pulse length | [ms] | 1000 | 694 | 446 | 299 | 212 | 157 | 121 | 96 |
| Beam current | [mA] | 1.86 | 1.24 | 0.93 | 0.74 | 0.62 | 0.53 | 0.46 | 0.41 |
| Bunch spacing when charge/bunch = 1nC | [µs] | 0.54 | 0.81 | 1.08 | 1.35 | 1.62 | 1.89 | 2.16 | 2.42 |
| Number of 1 nC bunches/s | **[$10^6$]** | **1.855** | **0.857** | **0.412** | **0.220** | **0.129** | **0.081** | **0.053** | **0.036** |
| Optimum Qext to keep power ≤ 14.5 kW/cavity | [$10^6$] | 3.1 | 6.7 | 1.1 | 1.4 | 2.0 | 2.7 | 3.6 | 4.6 |
| 3 dB width for Qext minimizing power/cavity | [Hz] | 413 | 193 | 123 | 93 | 65 | 48 | 36 | 28 |
| Max. allowed microphonics peak-peak | [Hz] | 34 | 34 | 34 | 34 | 24 | 18 | 14 | 11 |
| Available power/cavity | [kW] | 14.5 | 14.5 | 14.5 | 14.5 | 14.5 | 14.5 | 14.5 | 14.5 |
| Beam power /cavity | [kW] | 11.6 | 11.6 | 11.6 | 11.6 | 11.6 | 11.6 | 11.6 | 11.6 |
| Total RF-peak power/cavity: beam + microphonics | [kW] | 12.1 | 12.4 | 13.2 | 14.5 | 14.5 | 14.5 | 14.5 | 14.5 |
| Total RF- mean power/cryomodule | [kW] | 97 | 69 | 47 | 35 | 25 | 18 | 14 | 11 |
| ***XFEL Energy for 116 acc. units*** | ***[GeV]*** | ***5.8*** | ***8.7*** | ***11.6*** | ***14.5*** | ***17.4*** | ***20.3*** | ***23.2*** | ***26.1*** |

The suppression of microphonics plays a crucial role for the accelerating unit performance, especially for the operation at the highest gradient. This is illustrated in Fig. 6. The left diagram shows required for the compensation additional power/cavity vs. peak-peak microphonics. The right one the optimum Qext values minimizing this additional power.

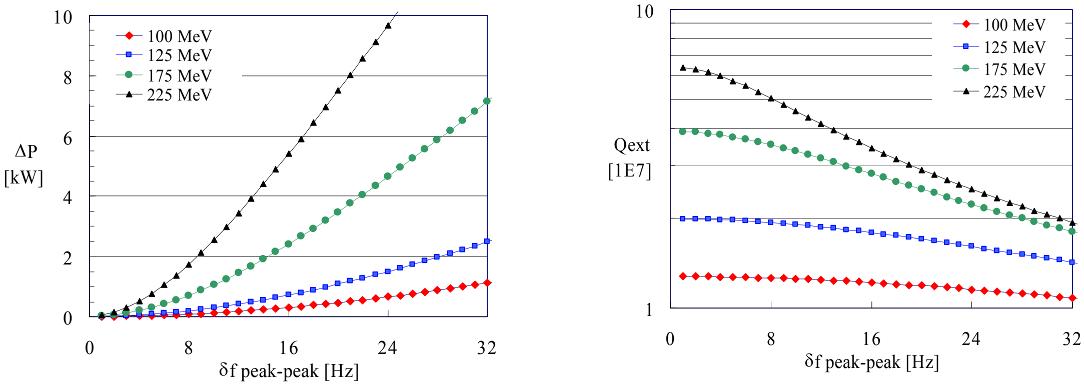

Figure 6. (Left) additional power/cavity vs. peak-peak microphonics. (Right) optimum Qext vs. peak-peak microphonics.

## FINAL REMARKS

R&D programs towards high intrinsic Q and 120 kW IOT amplifier will show what is a realistic time frame needed to build and test presented acceleration unit. Fortunately, at two laboratories (TJNAF and DESY) R&D programs on big grain material are continued, so one can expect relatively soon more experimental data to verify the assumed value of $2 \cdot 10^{10}$. The IOT amplifier needs still further modeling. In the next step we plan to carry out industry study to optimize the design. Finally, the IOT prototype should be built to demonstrate all computed parameter.

## REFERENCES

[1] B. Peterson, “SOME ASPECTS OF THE LAYOUT AND OPTIMIZATION FOR THE CRYOGENIC SUPPLY OF SUPERCONDUCTING LINACS”, Proceedings of ICFA ERL Workshop, March 2005, TJNAF Newport News, VA, USA.

[2] P. Kneisel et al., “PRELIMINARY RESULTS FROM SINGLE CRYSTAL AND VERY LARGE CRYSTAL NIOBIUM CAVITIES*, Proceed. of PAC2005, Knoxville, TN, USA, 2005.

[3] J. Sekutowicz et al., “LOW LOSS CAVITY FOR THE 12 GEV CEBAF UPGRADE“, JLAB TN-02-023, June 2002.

[4] A. Büchner et al., “NOISE MEASUREMENTS AT THE RF SYSTEM OF THE ELBE SUPERCONDUCTING ACCELERATOR”, PAC03, Portland 2003, USA.

[5] M. Liepe, “SUPERCONDUCTING MULTICELL CAVITIES FOR LINEAR COLLIDER”, DESY-Thesis-2001-045, October 2001, Hamburg, FRG.

[6] Editors: R. Brinkmann et al., “TESLA-TDR“, DESY, Hamburg, 2001.

[7] Y. Li et al., “DESIGNING AN L-BAND IOT FIR HIGH PEAK OUTPUT POWER” Proceedings of 6th International vacuum Electronics Conference IVEC2005, Huis ter Duin, Noordwijk, The Netherlands, 2005.

[8] Heinz Bohlen, CPI, private communication.