

# A BEAM ARRIVAL TIME CAVITY FOR REGAE AT DESY \*

Matthias Hansli<sup>†</sup>, Aleksandar Angelovski, Andreas Penirschke,

Rolf Jakoby, TU Darmstadt, Darmstadt, Germany

Benno Zeitler, Florian Josef Gruener, CFEL, Hamburg

Klaus Floettmann, Dirk Lipka, Holger Schlarb, Silke Vilcins, DESY, Hamburg

## Abstract

REGAE (Relativistic Electron Gun for Atomic Exploration) at DESY in Hamburg is a linear accelerator for electron diffraction experiments. It is upgraded to allow for laser driven wake field accelerator experiments. The bunch length is around 10 fs and the wakefield structure is about 100 fs and the synchronization of the laser and the electron bunch needs to be in order of the bunch length. To achieve this, a RF-based scheme will be used, comparing the phase of a beam induced signal with the reference clock. To improve the performance for the operation with charges well below 1 pC a beam arrival time cavity (BAC) at 3.025 GHz is foreseen as a highly sensitive pickup. To provide the maximum energy to the measurement electronics, the cavity needs a high  $R/Q$ -value and an optimized coupling. An over-coupled setting might be beneficial as it provides a higher signal-to-noise ratio for the first samples. In this paper the concept of the beam arrival time cavity, the influence of the dark current on the measurement and parameter studies and optimization of the cavity itself are presented.

## INTRODUCTION

REGAE, the Relativistic Electron Gun for Atomic Explorations at DESY was designed for time resolved electron diffraction experiments. It utilizes a photo cathode RF gun operated at 3 GHz with a  $1\frac{1}{2}$  cell gun cavity, accelerating electrons to energies of up to 5 MeV. The ability to generate high quality pC-charge bunches with a length of a few femtoseconds makes it possible to conduct external injection experiments into laser induced plasma in order to study the fundamental beam dynamics for these scenarios. Multiple well defined beam parameters will be used to investigate the structure of the wakefield to compare the measurements with simulations. Therefore the synchronization between laser and electron bunch needs to be in the order of around 10 fs for charges well below 1 pC. This requires measurement of the arrival time of the electron beam with a few fs precision. A comparison between a resonant and a broadband arrival time detection scheme was presented in [1]. It was concluded that a resonant detection scheme with a pillbox cavity at a frequency of around 3 GHz has the potential to fulfill the sub-10 fs arrival time resolution. The strong accelerating field in the gun cavity causes the emission of electrons, called dark current, which distributes over nearly every RF bucket [2, 3]. The dark current will influence the measured data if it has

a significant power level at the detection frequency. This paper presents the design and the optimization of a pillbox cavity as a part of a resonant arrival time detection scheme. The influence of the dark current on the measured cavity signal is investigated and recommendations are given.

## CONCEPT OF THE BEAM ARRIVAL TIME CAVITY

The aim of the Beam Arrival Time Cavity (BAC) is to utilize the high sensitivity of a cavity to allow for the extraction of precise timing information for the very low charge operation below 1 pC. While cavities for acceleration are well studied and optimized, the use case presented here has different limitations and demands coming from beam parameters like the very low charge and the bunch repetition rate of about 50 Hz. The main concept is to extract the phase of the  $TM_{010}$ -mode induced by the passing bunch using a fitting algorithm and compare the extracted phase to a reference. The energy transferred to an empty cavity by a passing particle is proportional to the  $R/Q$ -value [4]. It is used as figure of merit for the optimization because it is solely dependent on the geometry. A magnetic loop coupling will be used to extract the signal from the cavity. The maximum total energy can be coupled out if a critical coupling is achieved. However, because a fitting algorithm is used this might not be the optimum case here. The quality of the fit will scale with the average signal-to-noise ratio (SNR) of the used digitized samples. Given the low charge of the bunch and the exponential decay of the cavity signal, the SNR will be much higher for the first samples compared to the latter ones. The normalized average SNR as a function of the used samples shown in Fig. 1 indicates a drop after the optimum value is achieved. With over-coupling the amplitude of these first sampling points will be higher at the expense of a faster decay and therefore less sample points. The determination of the optimum coupling strength is currently ongoing.

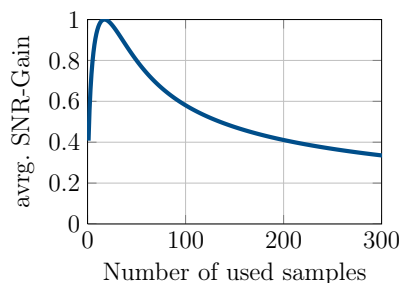


Figure 1: Normalized average signal-to-noise ratio as function of number of used samples.

\* Work supported by the Federal Ministry of Education and Research (BMBF) within FSP 302 under the contract number 05K13RDC

<sup>†</sup> hansli@imp.tu-darmstadt.de

## THE DARK CURRENT

As addressed earlier, the strong accelerating field in the gun cavity causes dark current. Especially for the low charge operation the influence of the dark current should be minimized for an optimal performance of the BAC. To allow for the use of S-band components and cables the operation frequency should be kept close to 3 GHz. A numerical calculation was done to investigate the behavior at the given parameters. At REGAE the RF is fed into the accelerating cavities for a period of 4  $\mu$ s which corresponds to around 12000 periods. It is assumed that within each period there will be one dark current bunch and an overall dark current of 0.15 fC is distributed equally over these bunches. Furthermore the bunch shape shall be Gaussian with a 6- $\sigma$  length of half a RF period resulting in a length of 27.78 ps. A cavity mode is excited proportional to the Fourier component of the excitation signal at its resonance frequency. Using the principle of superposition, at each passing of a bunch  $nT_{DC}$ , the voltage currently present inside the cavity and the newly induced one  $V_{DC,n}$  are added, taking phases into account. The resulting voltage inside the cavity after the  $n$ th-bunch has passed can be written as

$$V_{cavity,n} = V_{cavity,(n-1)} \cdot e^{j\omega_c T_{DC}} \cdot e^{-\frac{t}{\tau}} + V_{DC,n}, \quad (1)$$

with respective bunch charges and shapes taken into account. The dependency of the maximum accumulated cavity voltage caused by the dark current and the cavity operational frequency was calculated with equation 1 and the result is shown in Fig.2. After a rapid drop the further decrease is regressive. It can be concluded that a shift up in operational frequency is advantageous and tolerances and design should prevent a shift towards 3 GHz due to tolerances.

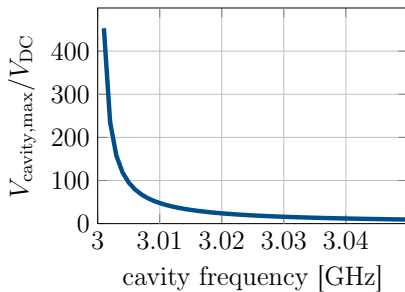


Figure 2: Maximum accumulated amplitude of dark current normalized to the single pass voltage in dependency of cavity frequency.

## DESIGN AND OPTIMIZATION OF THE CAVITY

The  $R/Q$  value is used as figure of merit for the optimization. For the ideal pillbox (without beam pipe) it can be shown analytically that the optimum length is achieved if length and radius are nearly equal. Using Eigenmode simulations with CST STUDIO SUITE the influence of the beam pipe opening was investigated for a 3.025 GHz pillbox cavity

with a beam pipe of 15 mm diameter (this value was later changed to 21 mm). The result is shown in Fig.3. Since by introducing the beam pipe opening the monopole mode frequency is not independent of the cavity length anymore, the cavity radius was adapted for each length to keep the same resonance frequency. To concentrate the field along

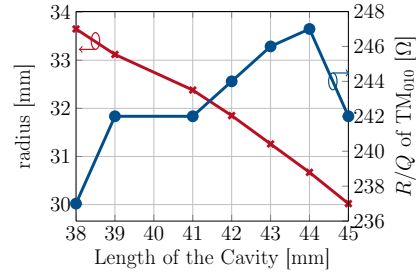


Figure 3:  $R/Q$  (right scale) and  $Q$  (left scale) for a pillbox cavity at 3.025 GHz with a 15 mm beam pipe as a function of the cavity length.

the middle of the beam pipe to increase the coupling to the beam, a tapering is introduced, leaving a gap (see Fig.5a). To determine the influence of the gap length, a second parameter sweep was conducted. The results are depicted in Fig. 4. It shows the highest  $R/Q$ -value for a gap length of 25 mm indicating that there is an optimum solution. The gap length has a strong influence on the needed cavity radius to keep the desired resonance frequency. As the design seems

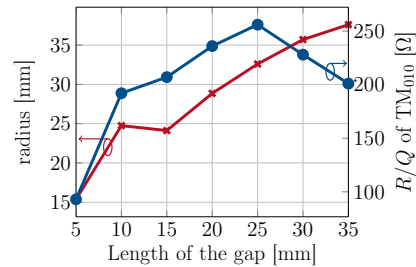


Figure 4:  $R/Q$  (right scale) and cavity radius (left scale) for the pillbox-like cavity at 3.025 GHz with a 15 mm beam pipe for different gap length.

very simple, a comparison to a more sophisticated design was drawn. Figure 5 shows the described pillbox-like design with a gap (Fig.5a) and a design used at the KEK Photon Factory ring [5] depicted in Fig.5b. The latter design was scaled to the wanted frequency, the beam pipe radius was set to 21 mm and a parameter sweep was conducted to check for potential improvements. The result is an  $R/Q$ -value of 220  $\Omega$  and a quality factor of around 12000. Both values are in the range of the pillbox-like design, with a slightly lower  $R/Q$  and higher  $Q$ . The KEK-like cavity has a length of 54.41 mm in this case, around 10 mm more than the pillbox-like design. Summing up the results of the comparison the pillbox-like design is preferred. The optimized values for this design are shown in table 1.

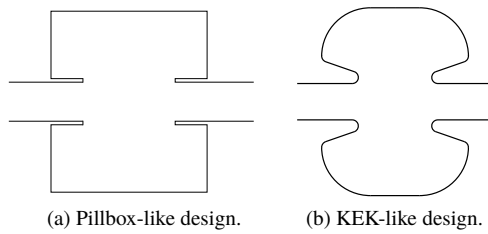


Figure 5: Schematic cross sections of the investigated cavity designs.

Table 1: Optimized Parameters for the BAC

Cavity length	44 mm
Cavity radius	$\approx 30.78$ mm
Gap length	25 mm
Gap height	1 mm
$R/Q$	236 $\Omega$
$Q_0$	11167

### Tolerance Analysis

To determine the required fabrication tolerances and temperature stability, a tolerance analysis was conducted. Hereby the change in resonance frequency due to deviations of the cavity length and radius, as well as gap length and height were simulated. To determine the change in geometrical dimensions with temperature, it was assumed, that the cavity cannot extend in longitudinal direction because of its mounting. Therefore the noses will extend into the cavity and thereby decrease the gap length. The extending transversal cavity walls, set to two times 10 mm will decrease the cavity length by the same assumption. On the other hand, gap height and cavity radius will increase with temperature. The resulting numbers, including the temperature caused frequency shift, are given in Tab.2, calculated for copper with a temperature coefficient of  $16.5 \times 10^{-6} \text{ K}^{-1}$ . Considering a worst case scenario, where all deviations cause a shift towards lower frequencies, a precision of 2/100 would be needed to keep the operating frequency between 3.02 GHz and 3.05 GHz. To ease the restriction going up in operating frequency about 20 MHz will be advantageous.

Table 2: Tolerance Analysis for the BAC Design

	Geo. $\Delta f$ [GHz mm $^{-1}$ ]	Expansion [nm K $^{-1}$ ]	Temp. $\Delta f$ [kHz K $^{-1}$ ]
Gap $l$	0.0595	-313.5	-18.5
Gap $h$	-0.05	16.5	-0.825
Cavity $l$	-0.0465	-330	15.3
Cavity $r$	-0.075	330	-24.98

### CONCLUSION

To address the demanding requirements for the resolution of the arrival time measurements at the low charge a resonant approach was favored over a broadband solution after comparing both. For resonant approach, two cavity shapes were compared, the influence of the dark current was investigated regarding the operating frequency of the cavity and a tolerance analysis was conducted. The result is a pillbox-like cavity with an  $R/Q$ -value of 236  $\Omega$  at 3.025 GHz + (0-20 MHz). The investigations imply that an over-coupling will give a better average SNR for the fitting algorithm and therefore a lower measurement jitter in the arrival time. As these investigations are ongoing, the following example shall give a rough estimate. One configuration calculated with the Wakefield Solver of CST STUDIO SUITE gave a start amplitude for the cavity ringing of around 930  $\mu\text{V}$  at a loaded quality factor of around 7800 for a 1 pC bunch with  $\sigma = 5$  mm. The optimum sample number was found to be 128 and give a gain in effective SNR of 16 dB resulting in an effective SNR of 83 dB and a theoretical measurement jitter in the order of 1-3 fs. How close the real system can get to this very promising value will be shown by further investigations.

### ACKNOWLEDGMENT

The authors would like to thank CST for providing the CST STUDIO SUITE Software.

### REFERENCES

- [1] A. Angelovski et al., "Pickup design for arrival-time measurements at REGAE", EAAC 2013, Elba, Italy, 2013.
- [2] J.-H. Han, "Dynamics of Electron Beam and Dark Current in Photocathode RF Guns", Thesis, Universität Hamburg, 2005.
- [3] D. Lipka et al., "Dark Current Monitor for the European XFEL", Proceedings of DIPAC2011, Hamburg, Germany, 2011.
- [4] P. B. Wilson, "Transient Beam Loading in Electron-Positron Storage Rings", CERN-ISR-TH-78-23-Rev., 1978.
- [5] Koji. Takata, "Fundamental Concepts of Particle Accelerators IV: RF Technology", Accelerator Course, Sokendai, October 2013, <http://accl.kek.jp/sokendai/corecurriculum/corecurri13/Takata/acf131024-4-web.pdf>