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COMPARISON OF DIFFERENT BUNCH CHARGE MONITORS USED AT THE ARES ACCELERATOR AT DESY

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Abstract

The SINBAD (Short and INnovative Bunches and Accelerators at DESY) facility, also called ARES (Accelerator Research Experiment at SINBAD), is a conventional S-band linear RF accelerator allowing the production of low charge ultra-short electron bunches within a range of currently 0.01 pC to 250 pC. The R&D accelerator also hosts various experiments. Especially for the medical eFLASH experiment an absolute, non-destructive charge measurement is needed. Therefore different types of monitors are installed along the 45 m long machine: A new Faraday Cup design had been simulated and realized. Further two resonant cavities (Dark Current monitors) and two Beam Charge Transfomers (Toroids) are installed. Both, Dark Current Monitors and Toroids are calibrated independently with laboratory setups. At the end of the accelerator a Bergoz Turbo-ICT is installed. This paper will give an overview of the current installations of charge monitors at ARES and compare their measured linearity and resolution.

INTRODUCTION

The SINBAD facility (Short and INnovative Bunches and Accelerators at DESY) hosts various experiments in the field of production of ultra-short electron bunches and novel high gradient acceleration techniques. ARES (Accelerator Research Experiment at SINBAD), is a conventional, 45 m long S-band linear RF accelerator allowing the production ultra-short electron bunches (fs to sub-fs) with high stability. The machine is operated with a repetition rate of 10 Hz with a charge range of 0.01 pC up to 250 pC. ARES is used for applications related to accelerator R&D in the field of advanced and compact longitudinal diagnostics and accelerating structures development, test of new accelerator components, machine learning and others. In the field of medical application studies an experiment has been set up to perform studies on cancer irradiation techniques with electron beams. For this experiment an absolute, non-destructive charge measurement is essential [1] .

As ARES is also related to Accelerator R&D several dedicated charge monitors had been installed: one Faraday Cup and a Dark Current Monitor (DaMon) at the gun section, one DaMon and two Beam Charge Transformers (Toroid) along the machine and one Bergoz Turbo-ICT [2] in-vacuum at the end of the beam line. An additional Bergoz in-air ICT [3] is installed 30 cm next to the T-ICT outside the beamline.

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CHARGE MONITORS AT ARES

Faraday Cup

Simulations of at DESY existing Faraday Cup geometries showed 4 % to 22 % of primary and secondary charged particles escaping from the cup. This does not fulfill the ARES demand for an absolute charge measurement at the Gun. Due to this, a new Faraday Cup geometry had been simulated for an energy of 5 MeV. This geometry of a copper cup with an inner diameter of 15 mm, inner depth of 24 mm and an Aluminum plate inlay shows only 0.6 % of charged particles escaping from the Faraday Cup in the simulation. Also different beam configurations (pencil beam, out of center, angled beam) had been taken into account. None of them showed more than 1 % loss of charged particles [4]. Figure 1 shows the final design of the simulated Faraday Cup for ARES prior vacuum installation.

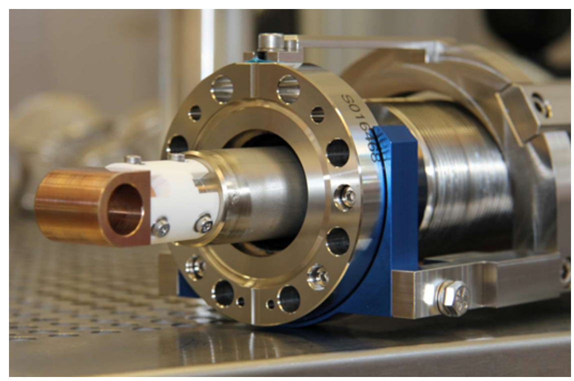

Figure 1: New Faraday Cup mounted with ceramic spacer on a mover rod.

The signal from the Faraday Cup is connected to an MicroTCA system [5] via a 15 MHz low pass and a pre amplifier. A Struck SIS8300-L2D [6] ADC board samples the pulse with 125 MS/s. The charge is reconstructed using a *pulse form fit* with three samples as described in Ref. [7]. For calibration of the electronics and cables an electrical pulse which corresponds to 1 nC is fed into the front end box input. An appropriate scaling factor is set in the software.

Beam Charge Transformers (Toroids)

Different types of in-house developed charge monitors based on transformers (Toroids) had been used at DESY machines since the 1980s. Beginning in 2010 an optimization of existing Toroids for the E-XFEL and FLASH accelerator had been started. These new monitors are based on one or two ferrite cores with four pickup coils, each consisting of a single winding. These four coils are combined outside the Toroid housing. The read out procedure is the same as with the Faraday Cup. Details of the optimization details can be found in Ref. [8]. An additional calibration coil is used to fed an electrical pulse which corresponds to 1 nC to the Toroid core(s). An appropriate scaling factor is configured in software to match the calibration pulse. Figure 2 shows a Toroid Beam Charge Monitor installed in ARES.

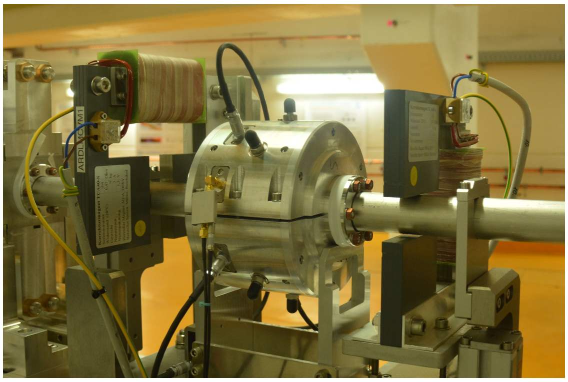

Figure 2: Toroid installed in the ARES accelerator. The diameter of the beam pipe is 34 mm, the length of the Toroid (flange to flange) is 150 mm.

Dark Current Monitors

The Dark Current Monitor (DaMon) was invented to measure dark current of accelerators with 1.3 GHz acceleration freqeuncy. The monitor consists of a stainless steel resonator with TM010 mode at 1.3 GHz with a loaded quality factor about 200. This results in a bandwidth of about 6 MHz and a decay time of 50 ns. The cavity is connected to a RF front end electronic (RFFE) which implements two channels. One is a dark current channel *DC* with a local oscillator, down conversion and a logarithmic detector. The second channel is for measuring charge, Q with a logarithmic detector only. For a 3 GHz accelerator like ARES, both channels, *DC* and Q, are used for charge measurement to increase the dynamic range. For calibration an Arbitrary Waveform Generator (AWG), which feeds a signal to the DaMon RFFE, is used. Details of the system and the calibration can be found in Ref. [9].

Bergoz Turbo ICT

At the very end of the beam line a Bergoz Turbo-ICT (T-ICT) is installed in vacuum. Together with the BCM-RF-E electronic the T-ICT is operated with a 10 Hz timing trigger in the Sample&Hold mode. After the T-ICT conversion has finished a trigger is given to a Keithley DMM7510 High Resolution Digital Volt Meter (DVM) which is read out over Ethernet [10]. A look up table, implemented in software with data from Bergoz' calibration to further improve the result. The measurement range given by Bergoz is 50 fC to 300 pC, the noise is 10 fCrms or 1% of bunch charge.

Bergoz ICT

For test purposes a Bergoz in-air ICT is installed direct after the end of the beamline, 30 cm after the T-ICT. A detailed description of the ICT principle can be found in Ref. [11]. The in-air ICT is read with an 12 bit oscilloscope, which is also doing averaging, integrating and scaling the 70 ns long pulse to get a value in pC. Figure 3 shows both, T-ICT in vacuum and the neighboured in-air ICT.

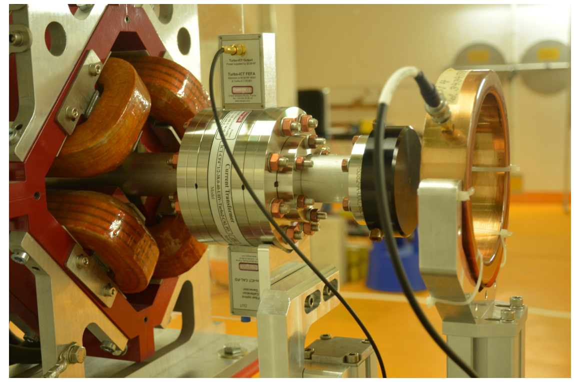

Figure 3: T-ICT (left) installed in vacuum, output window of the beam line (black cover in the middle) and the in-air ICT (copper colored toroidial shape on the right). The electrons are used for in-air experiments direct downstream the in-air ICT.

The ICT installation is improvised yet. Later the setup might be moved easily to other DESY machines which allows the installation in-air (*take-away-charge-reference*).

MEASUREMENTS

For the linearity and resolution measurements the ARES accelerator was setup with 100 % beam transport down to the T-ICT and the in-air ICT at (45 m). In total 14 different charges in the range from 0.1 pC to 153 pC at a bunch repetition rate of 10 Hz had been carried out. For each charge 500 values of each monitor had been taken synchronously. As the Faraday Cup measures destructive, its data had been taken independently (move FC in, take 500 values, move FC out, take 500 values for the other monitors, move FC in, change charge, ...). The DaMon *DC* channels are limited to less than 20 pC. Therefore a sweep from 0.1 pC to 13 pC had been carried out. The DaMon Q channels, the Toroids and the T-ICT had been measured with a sweep of 1 pC to 153 pC.

Linearity

The upper plots of the Figs. 4 to 8 show the monitor charge as a function of the Faraday Cup, the lower plots show the ratio of the monitor to Faraday Cup as a function of the Faraday Cup charge. The error bars shown are the standard deviation caused by beam charge variation.

Figure 8 shows the linearity fit slope, fit offset and the in-air ICT charges relative to the Faraday Cup. As this setup is improvised yet, this measurement should not be taken as a face value yet.

Resolution using Standard Deviation (rms)

A reference charge was defined by using all existing charge information (except the device under test), including also the

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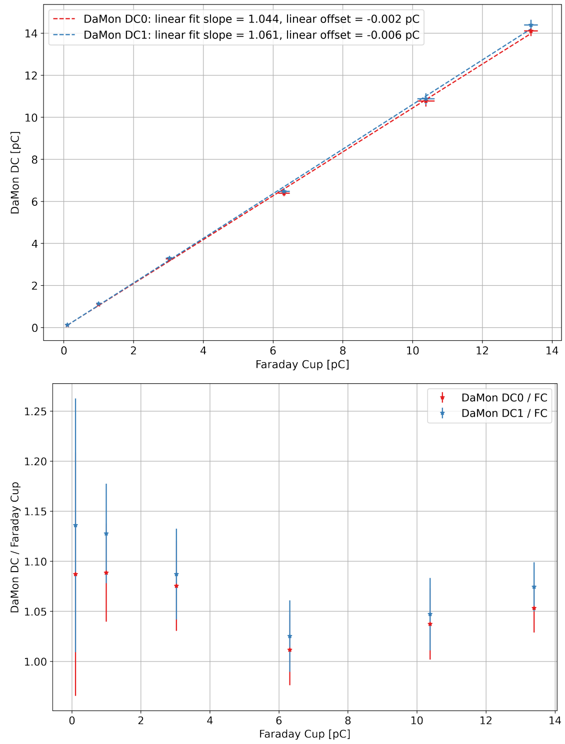

Figure 4: Linearity of the DaMon *DC* channel.

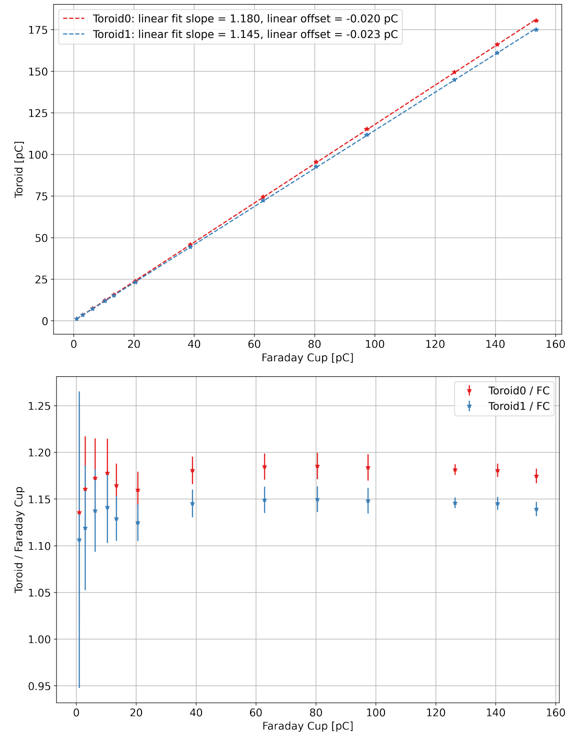

Figure 6: Linearity of the Toroids.

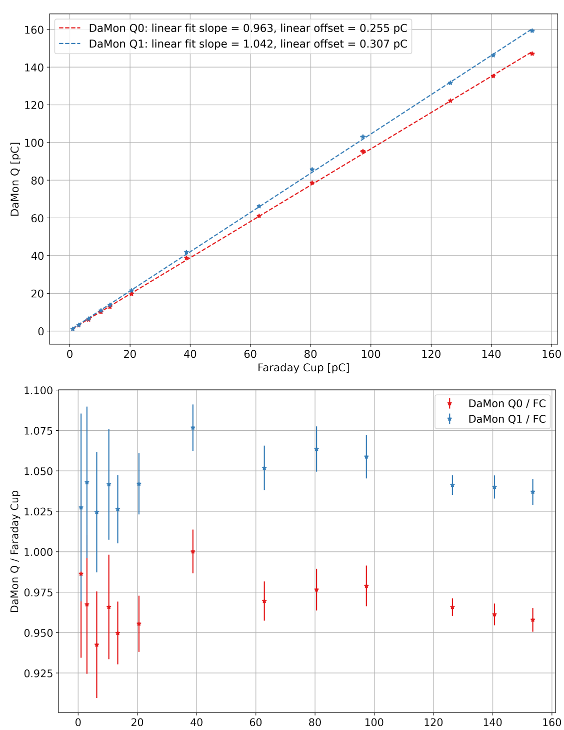

Figure 5: Linearity of the DaMon *Q* channel.

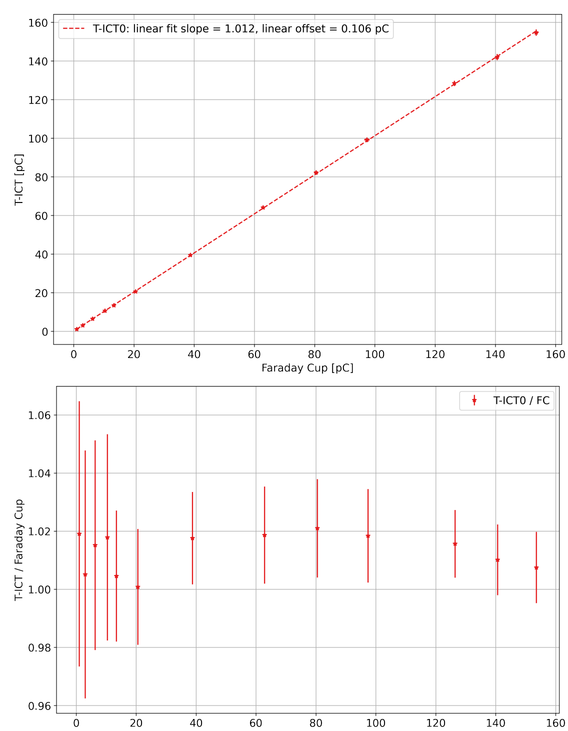

Figure 7: Linearity of the T-ICT.

existing Cavity BPMs. This reduced the statistical variation of the charge determination and it was used to determine the resolution of the monitor under test. This procedure is machine optics independent. A detailed description of this calculation can be found in Ref. [12]. To get better results, also charges measured by seven Cavity BPMs had been included. These devices can measure charge as well, but are not calibrated independent [13]. The resolution had been calculated for the DaMon channels *DC* and *Q*, the Toroids and the T-ICT. Figures 9 and 10 show the resolutions.

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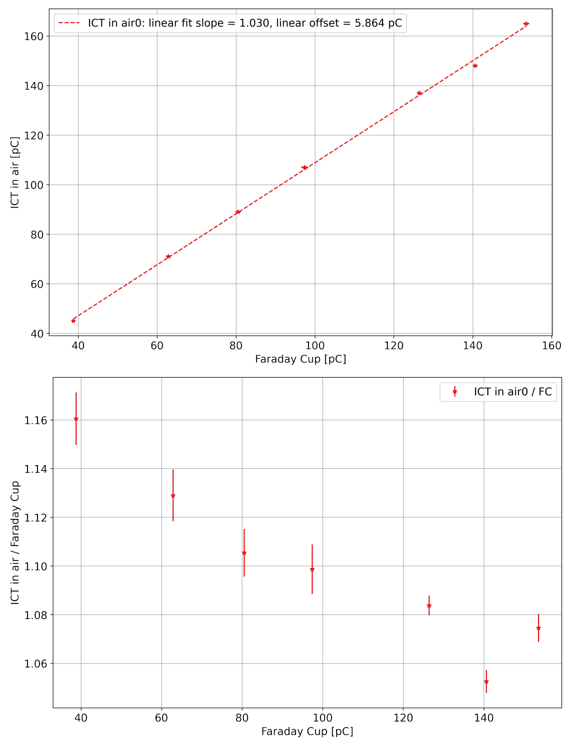

Figure 8: Top: measured charge of the in air ICT as a function of Faraday Cup charge; below the ratio of the in-air ICT to Faraday Cup charge as a function of Faraday Cup charge. Both in the range of 30 pC to 153 pC.

As the in-air ICT could not be measured synchronous to the other monitors, the resolution could not be determined.

Results

Table 1 shows the linearity and resolution measured at ARES.

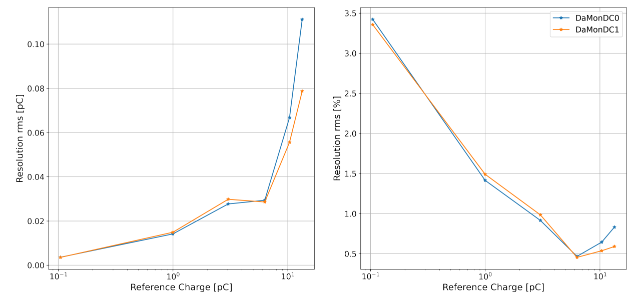

Figure 9: Absolute and relative resolution of the DaMon *DC* channels in the range of 0.1 pC to 13 pC.

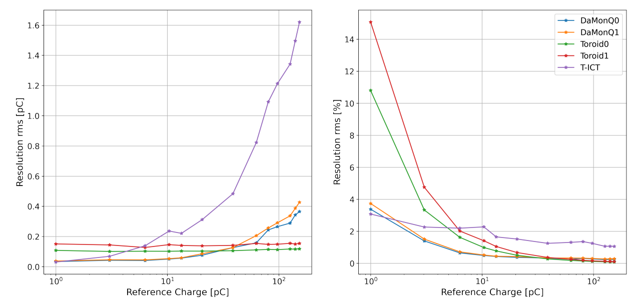

Figure 10: Absolute and relative resolution of DaMon *Q* channels, Toroids and T-ICT, each in the range of 1 pC to 153 pC.

The DaMon *DC* channels are limited to a maximum charge of about 20 pC. For a range from 0.1 pC to 13 pC the DaMon *DC* channels show reasonable linearity results. The resolution measured up to about 6 pC is the best of all charge monitors compared during this measurements.

For the charge range from 1 pC to 153 pC both, the DaMon *Q* channels and the T-ICT show reasonable results of linearity with a linear fit slope of almost 1 and an offset of close to 0 pC.

Table 1: Resolution results for all monitors. Upper values are the upstream monitor.

	DaMon DC	**DaMon Q**	**Toroid**	**T-ICT**
Charge Range	0.1 pC - 13 pC	1 pC - 153 pC	0.1 pC - 13 pC	0.1 pC - 13 pC
Linear fit Slope				
Monitor 1	1.04	0.96	1.18	1.01
Monitor 2	1.06	1.04	1.15	—
Linear fit Offset				
Monitor 1	-0.002 pC	0.26 pC	-0.02 pC	0.11 pC
Monitor 2	-0.006 pC	0.31 pC	-0.02 pC	—
Resolution	(@0.1 pC - @13 pC)	(@1 pC - @153 pC)	(@1 pC - @153 pC)	(@1 pC - @153 pC)
Monitor 1	4 fC - 111 fC 3.4% - 0.83%	34 fC - 366 fC 3.4% - 0.2%	108 fC - 119 fC 10.8% - 0.1%	31 fC - 1621 fC 3.1% - 1.1%
Monitor 2	3.7 fC - 90 fC 3.36% - 0.59%	37 fC -427 fC 3.7% - 0.23%	151 fC - 154 fC 15.1% - 0.1%	— —
Use for	Resolution <6 pC	Resolution >6 pC – 60 pC	Resolution >60 pC	Absolute charge

The Toroids show a linear fit slope of 18 respectively 15% higher compared to the Faraday Cup but also an offset of nearly 0 pC. Nevertheless, the relative plot in Fig. 2 shows good linear accordance to the Faraday Cup, so that a correction can easily be applied. Depending on the charge range, different areas of resolution could be determined in our setup. The DaMon Q channels show the best resolution between 6 pC – 60 pC, the Toroids for charges greater than 60 pC. As the upstream Toroid in ARES has a dual core installation the resolution is better (10.8%) than the downstream Toroid (15.8%), which only has a single core installed. For higher charges both Toroids converge to a resolution of 100 fC. The T-ICT's resolution might suffer from the installation in ARES: the cable between the T-ICT in the beamline and the Bergoz electronics outside had to be extended by about 30 m. The cable damping had been compensated, but environmental noise is captured anyway. However, the monitor is suitable for absolute measurements out of the box.

CONCLUSION AND OUTLOOK

Three DESY in-house developed monitors had been presented briefly. These monitors had been compared to each other and to two commercial available monitors (ICT and T-ICT) from Bergoz. Taking the new Faraday Cup as a (destructive) reference at the Gun Section it could be shown that the in-house developed (non destructive) Toroids and the DaMons are very linear compared to the Faraday Cup. Additionally the Bergoz T-ICT at the end of the beam line shows a very good linearity as well. Also the resolution of all (non destructive) monitors could be calculated. All this monitors can be read out with the required repetition rate of 10 Hz. In the future we would like to improve the calibration scheme of the Toroids. The in-air ICT can be moved and be used as a kind of *take-away-charge-reference* to easy cross-check charge measurements in other DESY accelerators.

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