Comparison of Different Bunch Charge Monitors used at the ARES Accelerator at DESY

Remake from IBIC2023:
https://jacow.org/ibic2023/papers/tu3i04.pdf

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HELMHOLTZ

DESY.

Outline

00 Motivation

Motivation

Beam Charge Monitors at DESY

- Use in-house developed Charge Monitors
  - Transport Lines in other machines (from the 1980s, i.e. DESY ring)
  - Current installations: E-XFEL, FLASH = 60 monitors (Toroid type, some pC to 3nC)
    No absolute measurement with such a dynamic range needed so far
  - Important: Transport efficiency, Transmission Interlock (E-XFEL, FLASH)
- ARES R&D Accelerator
  - ARES is an R&D machine → install different types of charge monitors
  - eFLASH (medical) experiment needs an **absolute**, non-destructive charge measurement

01 ARES Overview

The ARES Linac

A dedicated accelerator R&D machine

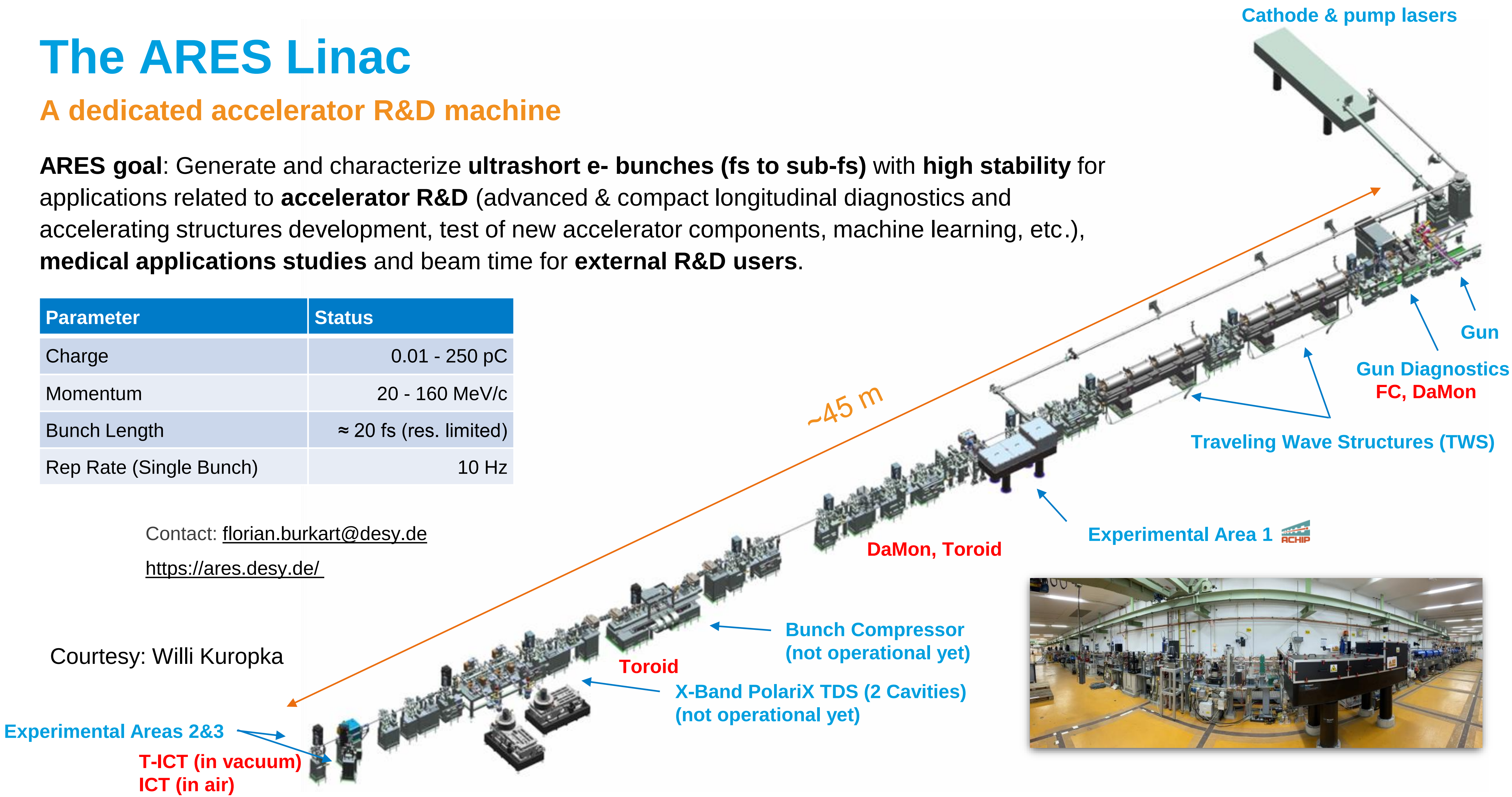
ARES goal: Generate and characterize **ultrashort e- bunches (fs to sub-fs)** with **high stability** for applications related to **accelerator R&D** (advanced & compact longitudinal diagnostics and accelerating structures development, test of new accelerator components, machine learning, etc.), **medical applications studies** and beam time for **external R&D users**.

Parameter	Status
Charge	0.01 - 250 pC
Momentum	20 - 160 MeV/c
Bunch Length	≈ 20 fs (res. limited)
Rep Rate (Single Bunch)	10 Hz

Contact: florian.burkart@desy.de

https://ares.desy.de/

Courtesy: Willi Kuropka

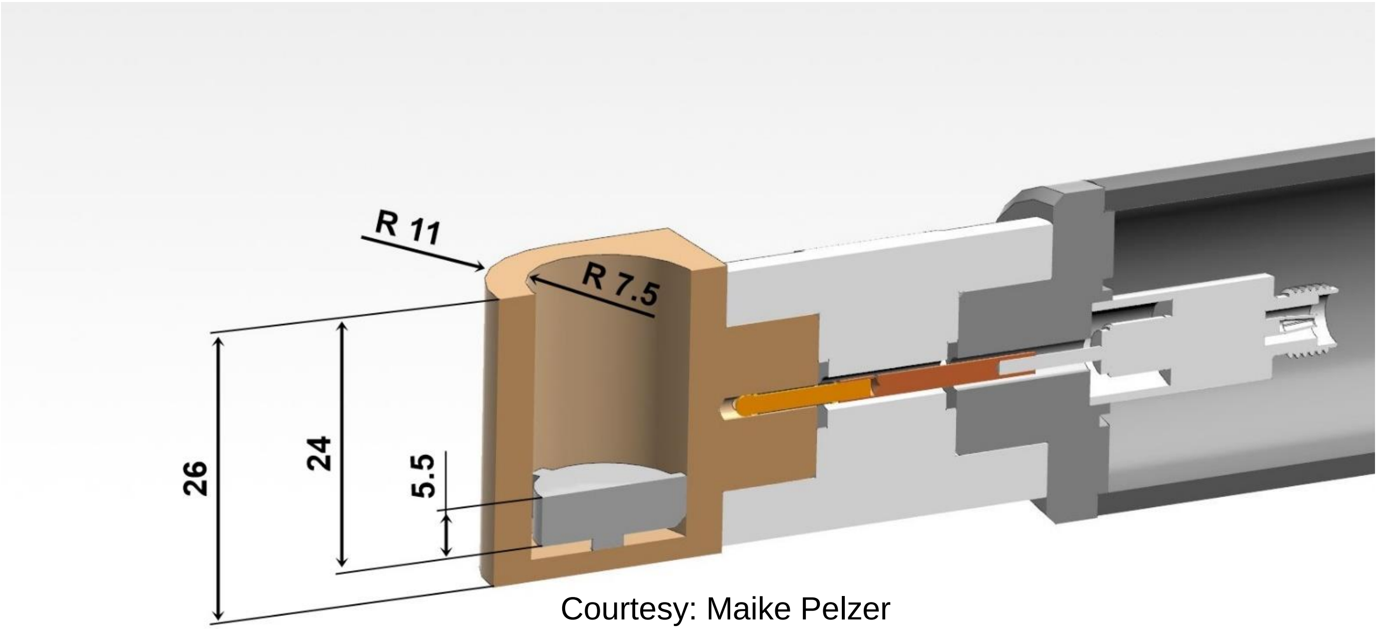


02 Faraday Cup (FC)

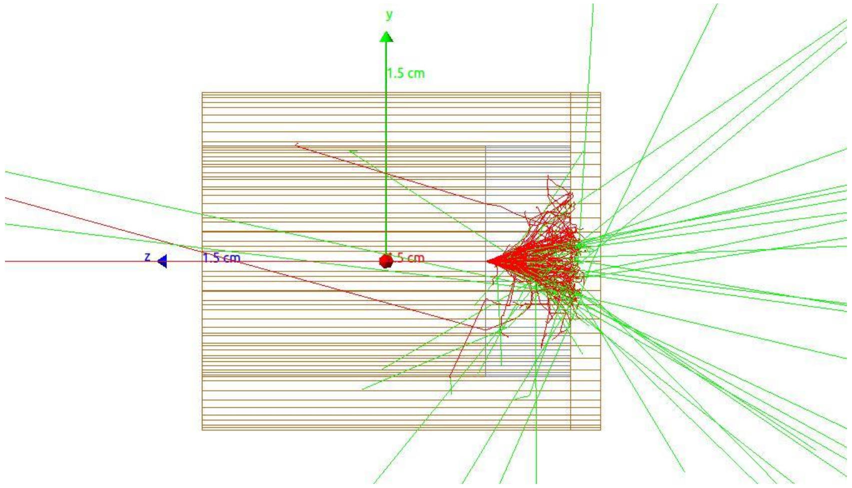
Faraday Cup

Simulation of new design for ARES

- Optimized design with Cu cup + Al Inlay, 15 mm diameter, 24 mm depth simulated
- Found <u>0.6%</u> of primary and secondary electrons escaping from the Faraday Cup at 5MeV
- Also different beam configurations and angles show very good results of <1% loss



Courtesy: Maike Pelzer



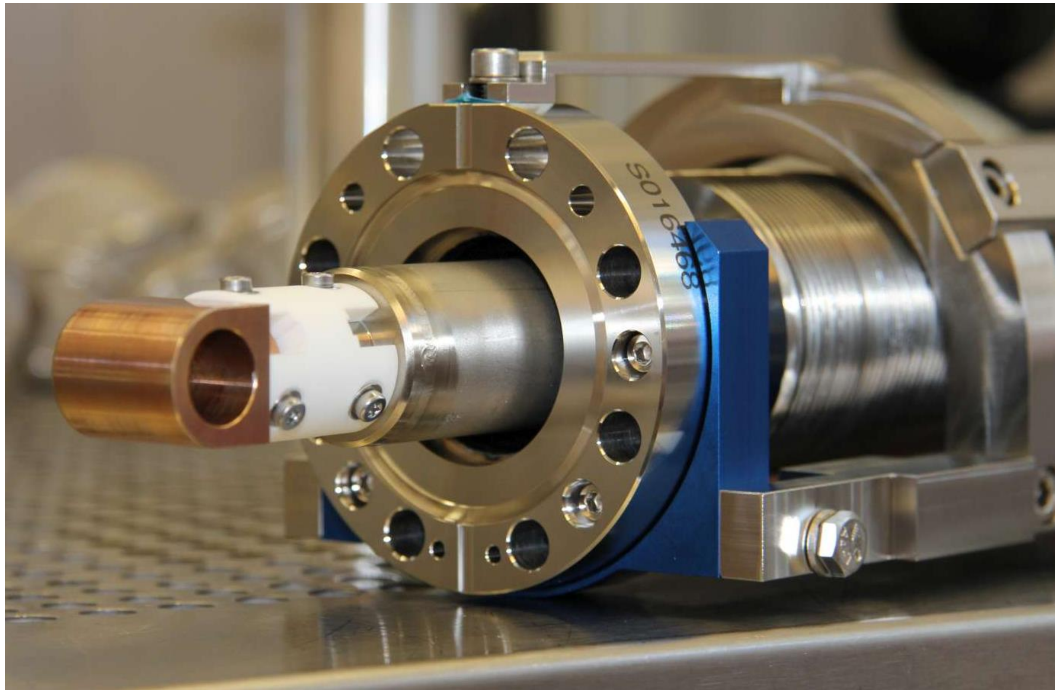
Green=Gammas, Red = Electrons

Courtesy: Sergey Strokov, Gero Kube

Faraday Cup

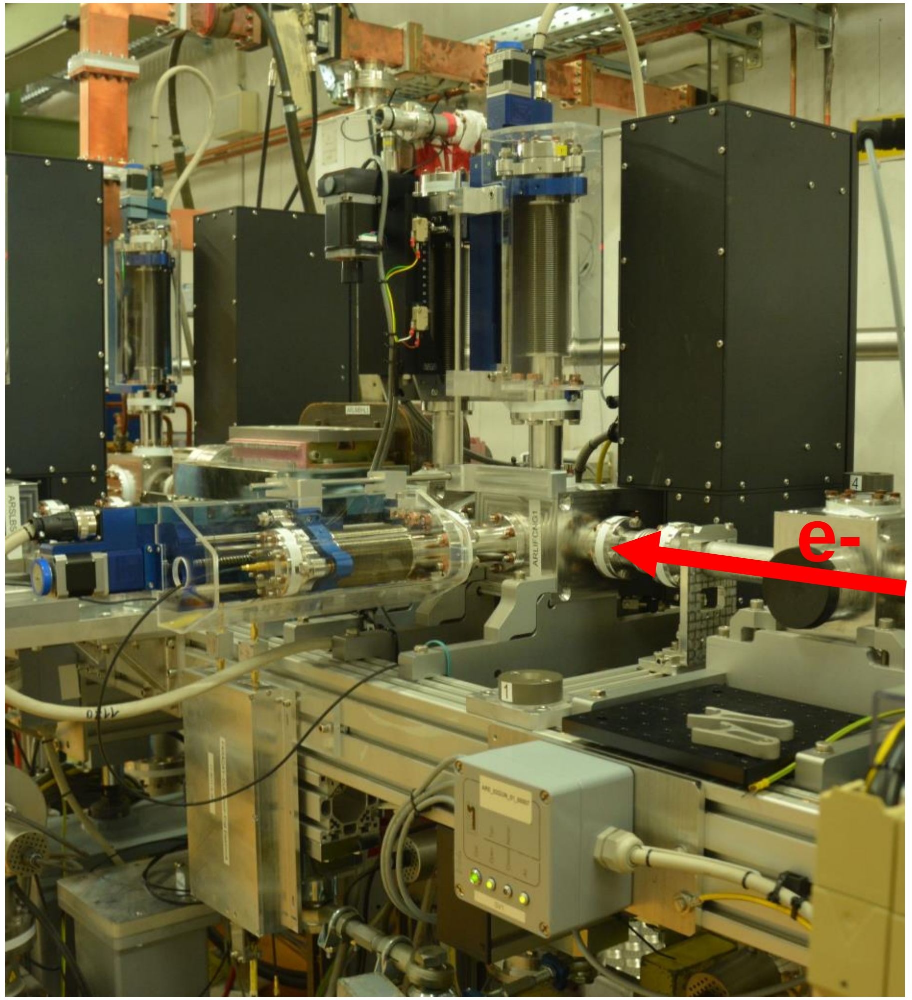
Final design

- Faraday Cup mounted on a Mover
- Without cooling due to low repetition rate (10 Hz)
- Screen at same position to check beam size + position



Courtesy: Maike Pelzer (FC), Christian Wiebers (Mover), Juergen Kruse (Support)

Tunnel installation with Faraday Cup horizontal, Screen vertical



03 Turbo-ICT (Bergoz)

Bergoz Turbo-ICT

Integrating Current Transformer + Front end Filter (Bergoz)

Turbo-ICT in vacuum

- BERGOZ Turbo-ICT and BCM-RF-E (outside tunnel, ~30m cable)
  - Use in Sample & Hold Mode
  - Range: 50 fC ... 300 pC
  - Noise: 10 fC rms or 1% of charge (whichever is higher)
- Connected to a KEITHLEY High Resolution DVM (DMM7510)
  - Resolution 1 µV (at range 10 V)
  - Ethernet for control system read out
- Triggering
  - 10 Hz trigger from timing system
- Apply Look-up-Table in Software with data from Bergoz’ calibration

10 Hz timing trigger

Trigger when conversion ready

Control system (DOOCS)

https://www.bergoz.com/products/turbo-ict/
https://www.tek.com/de/products/keithley/digital-multimeter/dmm7510#

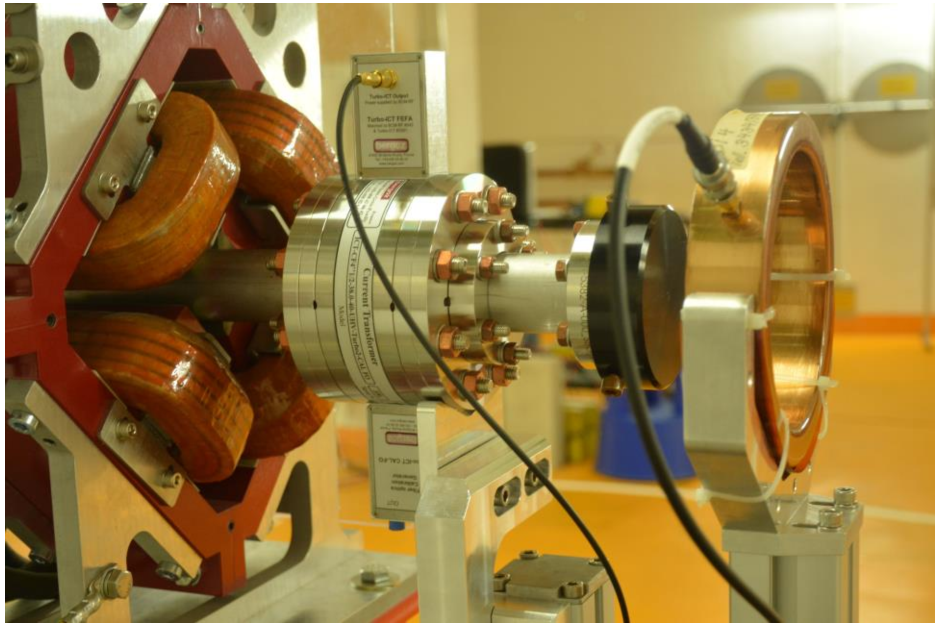
04 ICT (Bergoz)

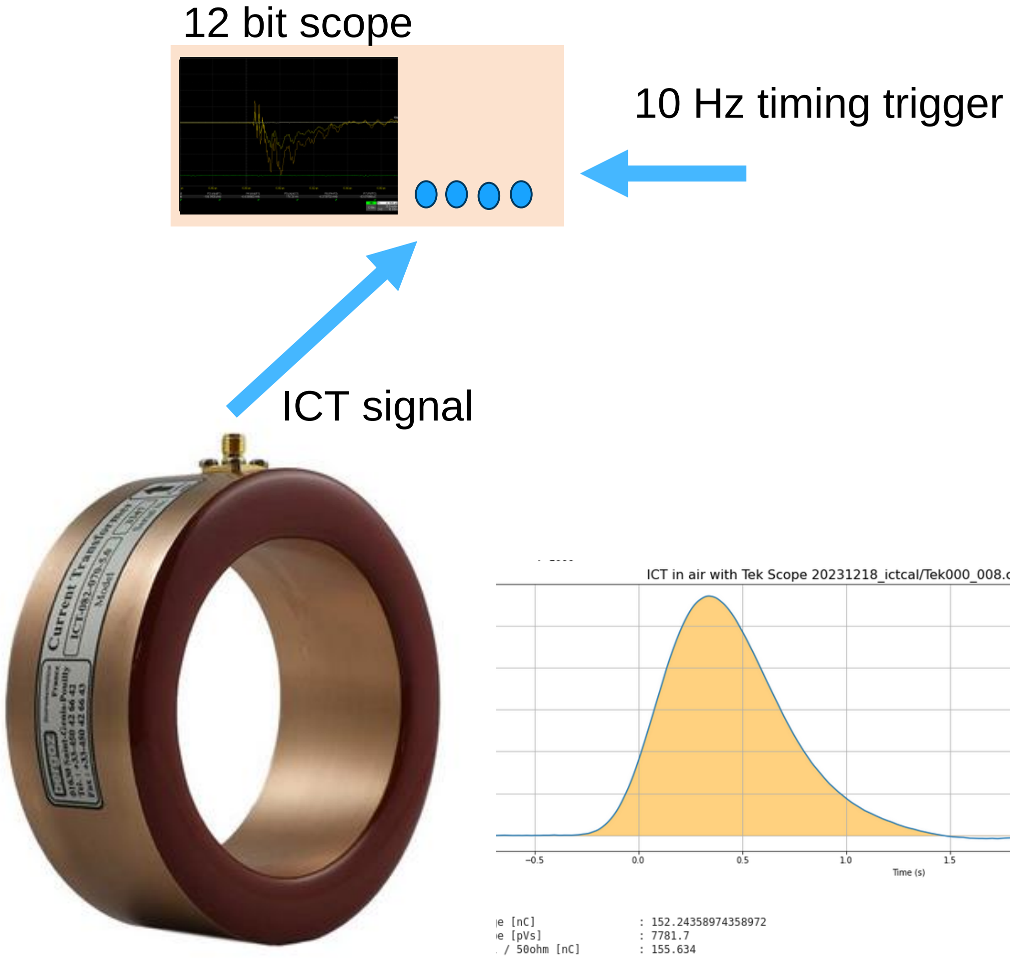
Bergoz ICT in air

Improvised installation for testing purposes

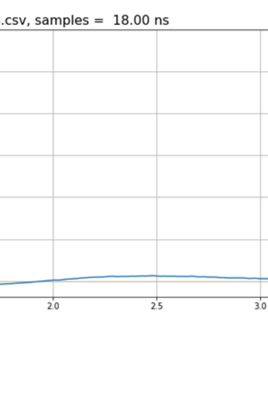
In-air ICT

- Placed after a window outside the end of beam pipe (~30 cm after T-ICT)
- Read-out, integration and scaling with 12 bit scope
- Can easily be moved to other DESY machines





https://www.bergoz.com/products/ict/

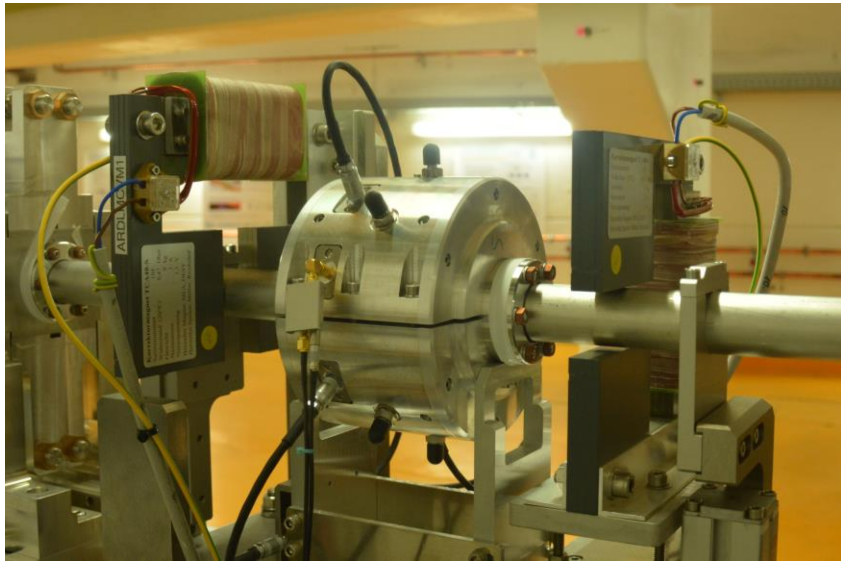


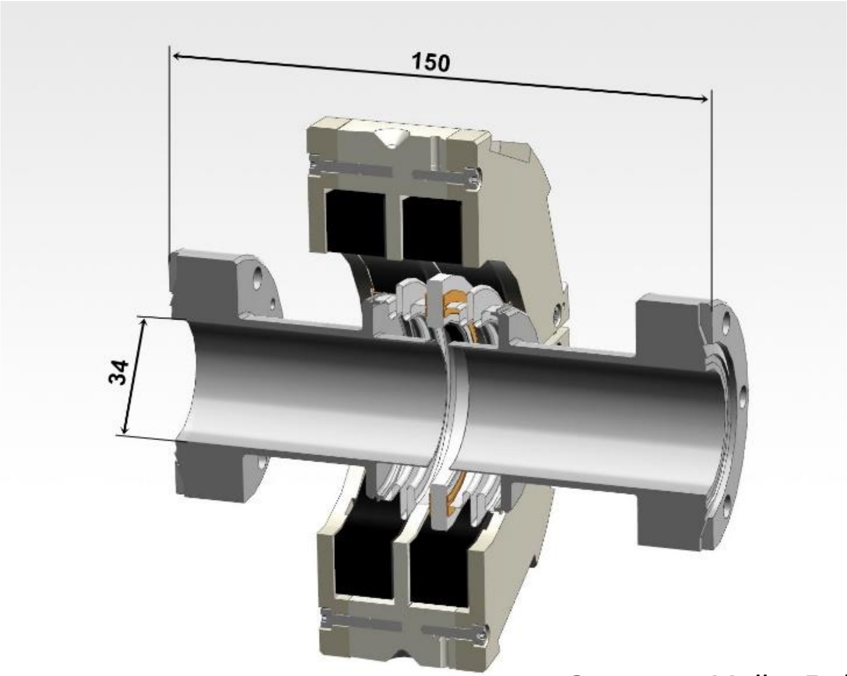
05 Beam Charge Transformator (Toroid)

Toroid

Optimization of existing Beam Charge Transfomators

- E-XFEL and FLASH design (4.5 MHz bunch frequency)
- Ceramic gap with one or dual core, easy half-shell installation (i.e. service w/o opening vacuum)
- Four separate coils, one winding each, concatenated outside monitor





Courtesy: Maike Pelzer

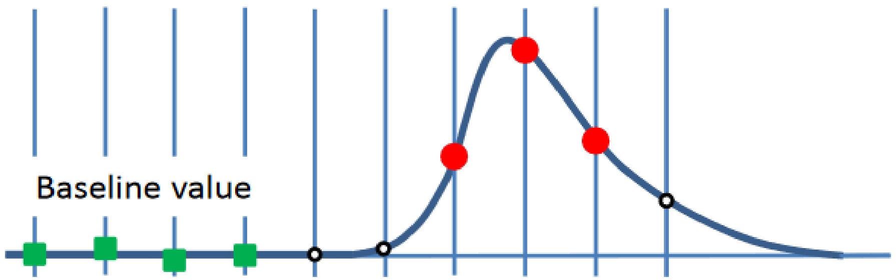
06 Calibration and read out (FC and Toroid)

Calibration and read-out Faraday Cup and Toroid

Electronics and Calibration

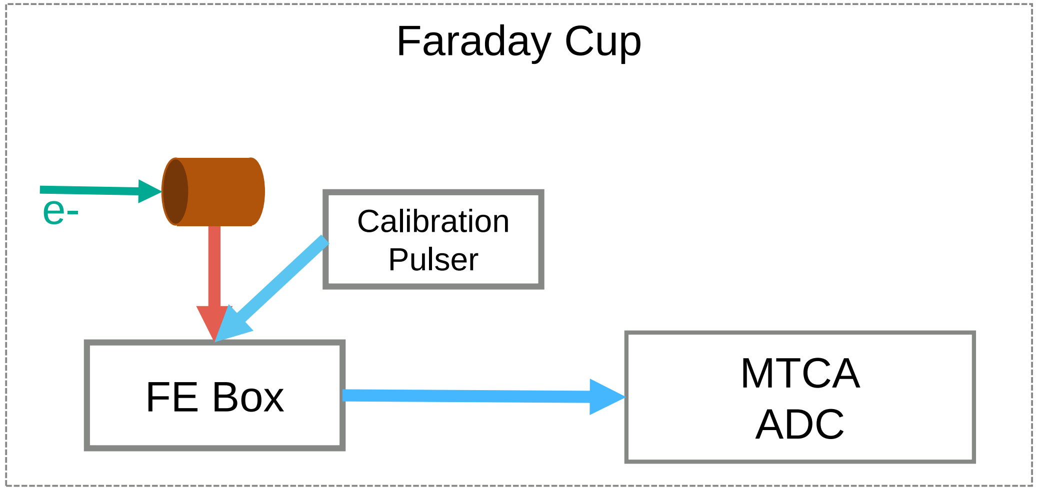
Read out

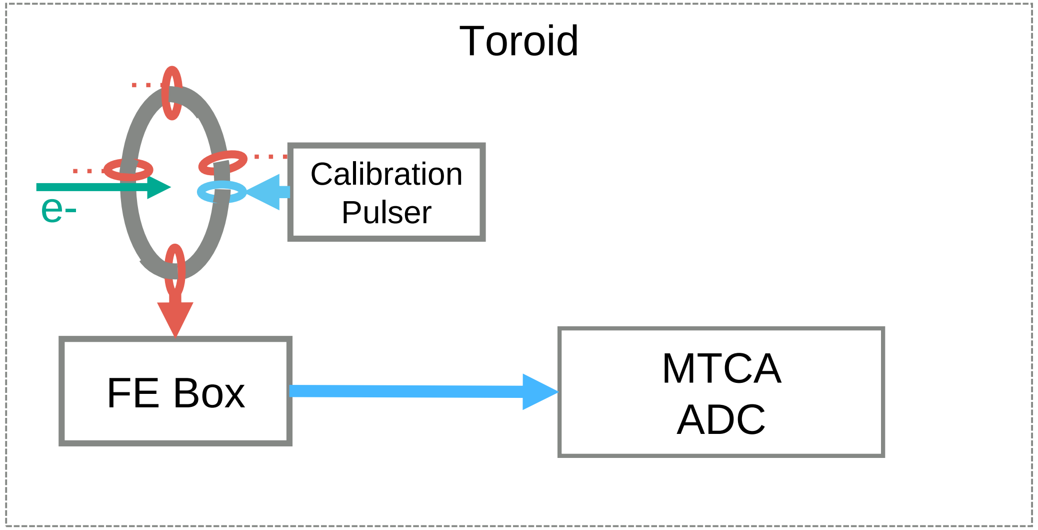
- Signal connected to front end with 15 MHz low pass filter and pre amp
- MTCA system with ADC: 16 bit, 125 MS/s
- *Pulse-form-fit with 3-point sampling*



Calibration with inhouse 1nC pulser

- Send electrical pulse to the FE electronic (FC) or
- Send electrical pulse to calibration coil (blue) (Toroid)
- Scaling the read out





07 Measurements

What has been measured?

- ARES at 10 Hz rep rate, single bunch
- ~100% Beam Transport (using Screens)
- Charge Sweep from 0.1 – 153 pC
- 500 values per charge from each monitor saved synchronously

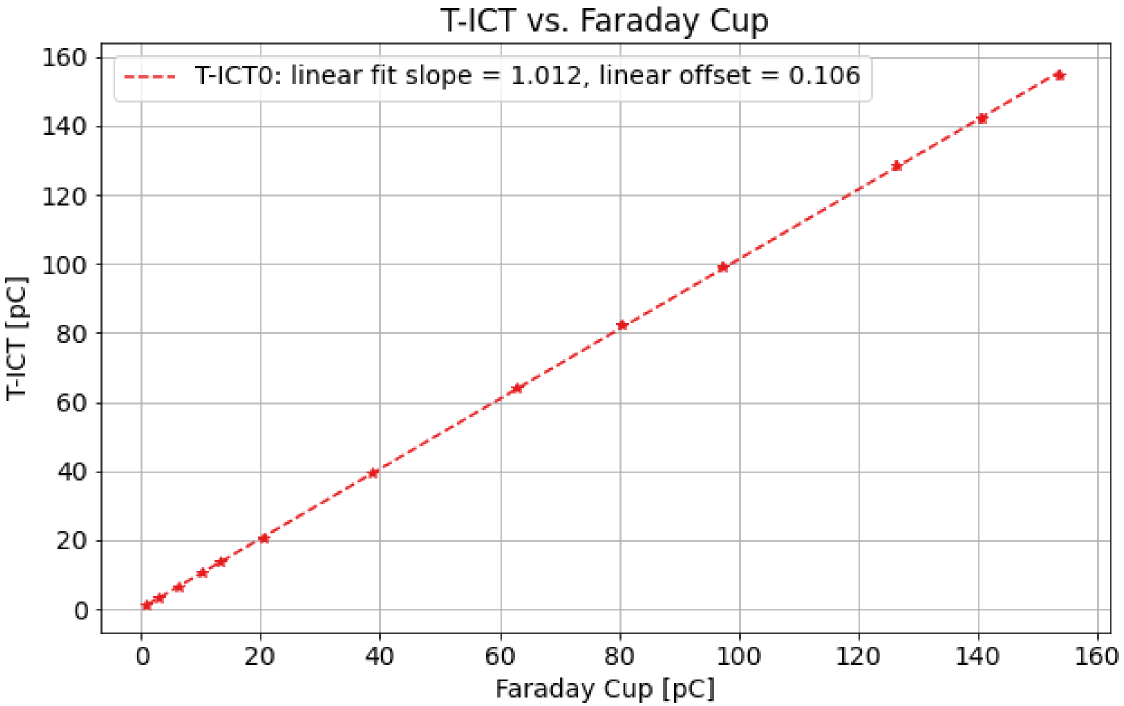
- Output will be plots of …
  - Linearity of each monitor compared to Faraday Cup (w/o uncompensated losses [0.6% simulation])
  - (Resolution of each monitor in the backup slides)

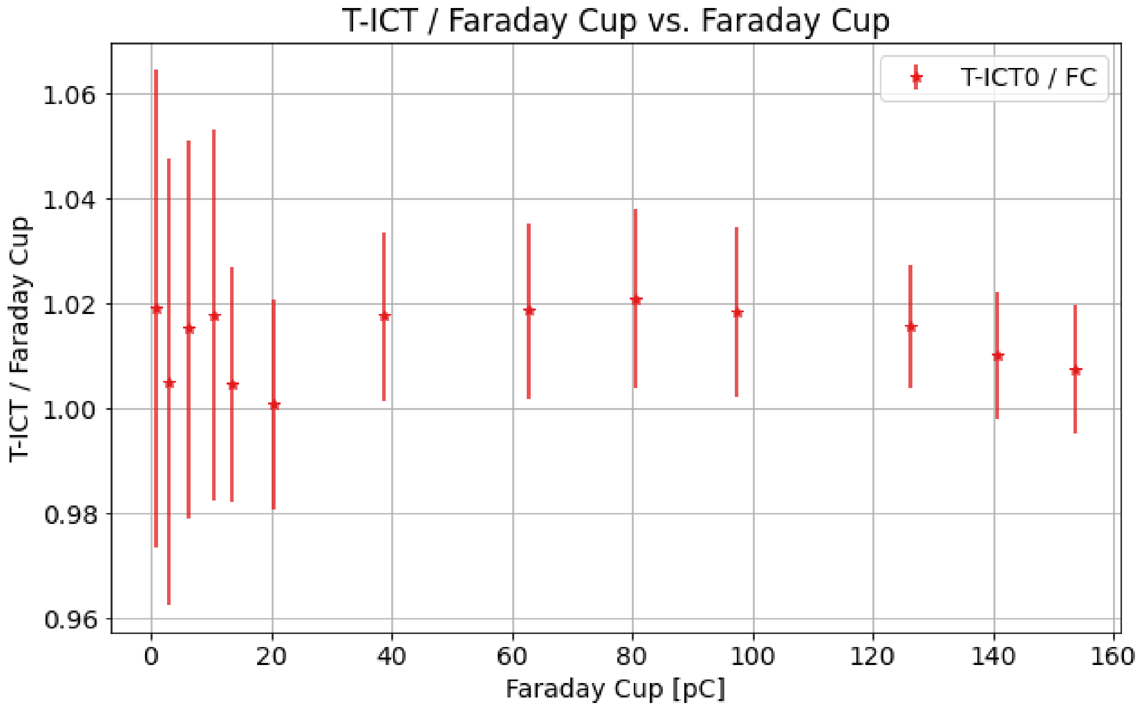
Bergoz Turbo ICT vs. Faraday Cup

Range 1 – 153 pC

	T-ICT
Linear fit slope	1.012
Linear fit offset	0.11 pC

- Calibrated at Bergoz





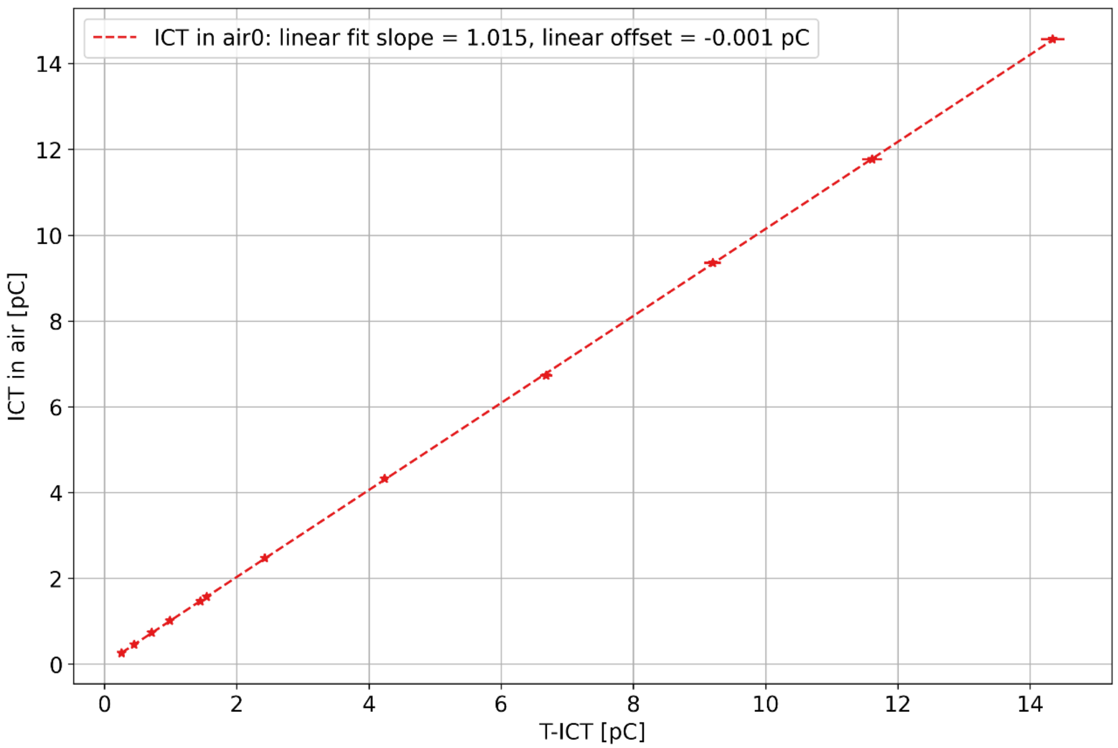
Error is standard deviation caused by beam charge jitter

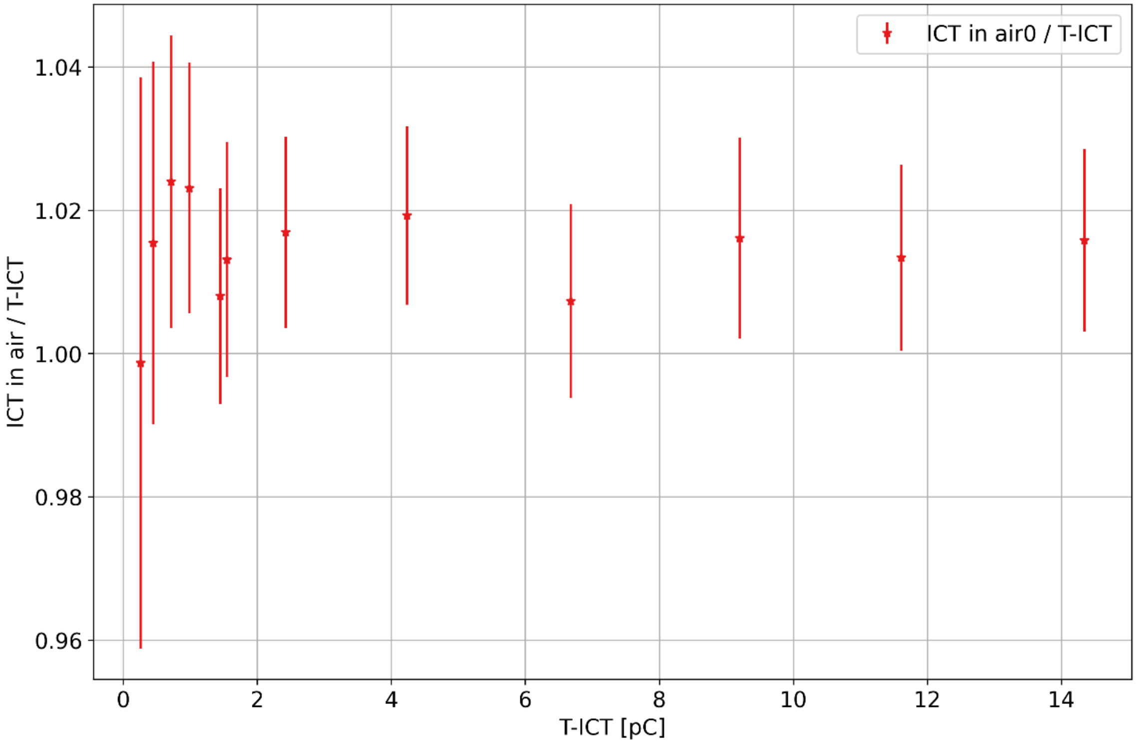
Bergoz ICT in Air vs. T-ICT

Range <1 – 14 pC

	ICT
Linear fit slope	1.015
Linear fit offset	-0.001 pC

- Calibrated with Bergoz and DESY Calibration pulser
- Read out with 12 bit scope and Python script
- Measurement had been taken independently from others





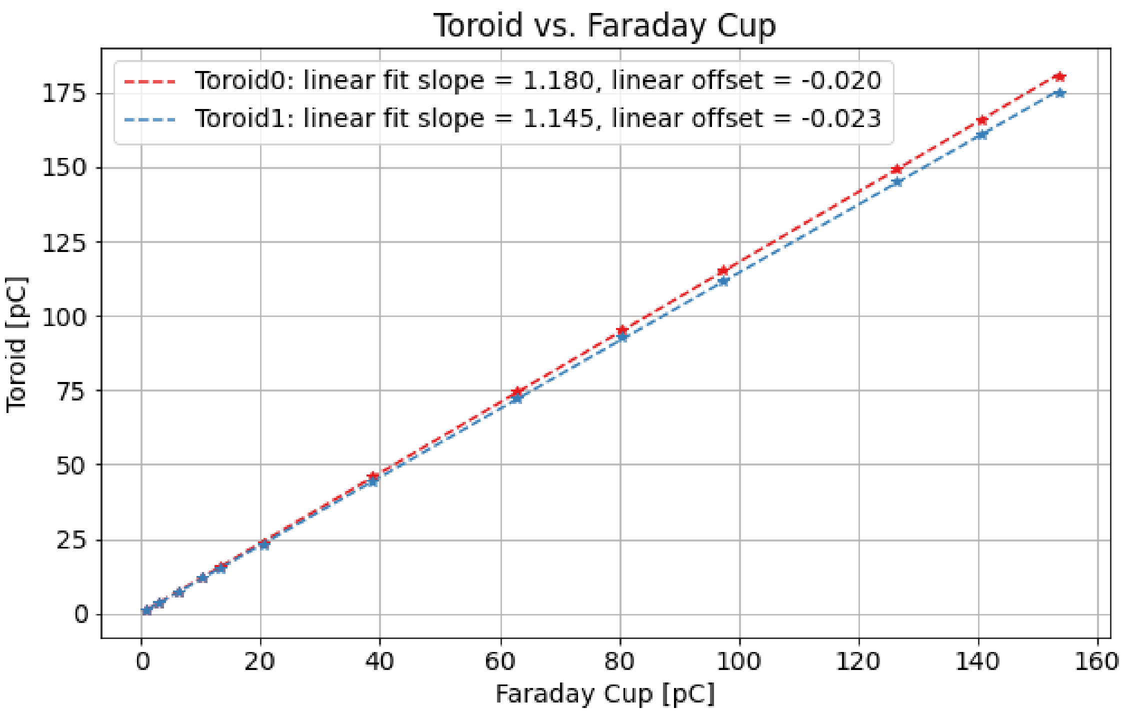
Error is standard deviation caused by beam charge jitter

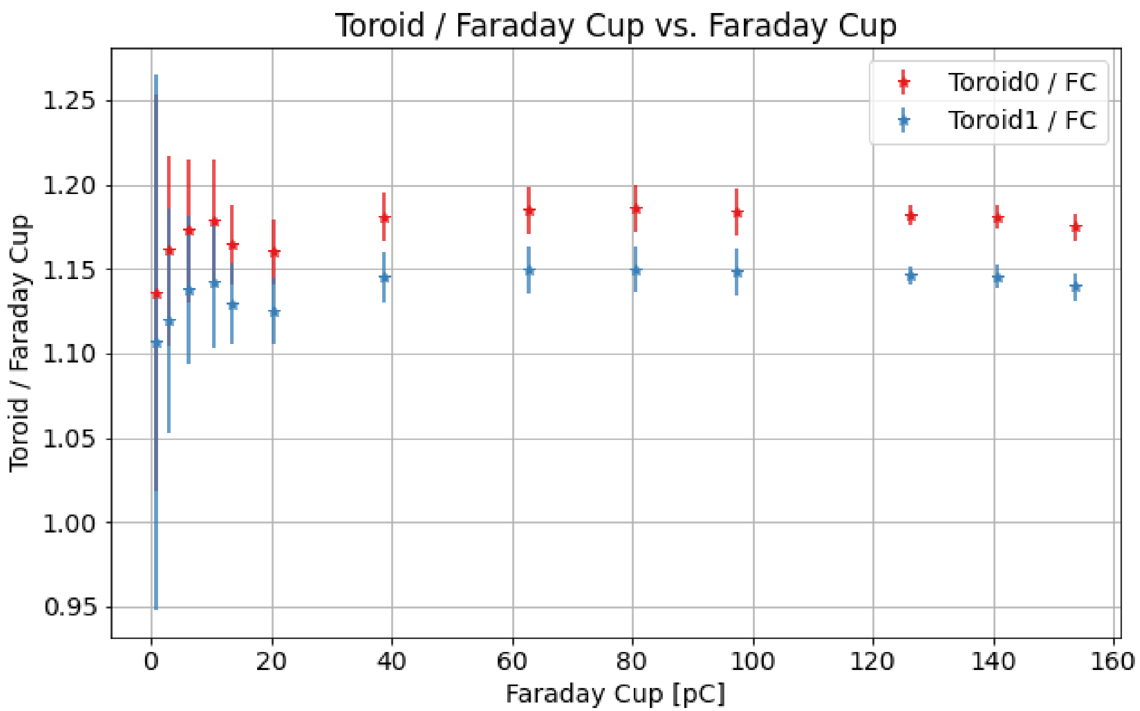
Toroid vs. Faraday Cup

Range 1 – 153 pC

- Calibrated with 1nC pulser
- Toroid shows ~15% more charge with electrons compared to calibration
- … but linear

	Toroid0	Toroid1
Linear fit slope	1.18	1.15
Linear fit offset	-0.02 pC	-0.02 pC





Error is standard deviation caused by beam charge jitter

08 Summary

Summary

Linearities and Resolutions of all non-destructive monitors @ARES compared to F-CUP

	DaMon DC*	DaMon Q*	Toroid	T-ICT	ICT
Measurement range [pC]	0.1 to 13	1 to 153	1 to 153	1 to 153	<1 to 14
Linear fit Slope	1.04 1.06	0.96 1.04	1.18 (Dual Core) 1.15 (Single Core)	1.01	1.015
Linear fit Offset [pC]	-0.002 -0.006	0.26 0.31	-0.02 -0.02	0.11	-0.001
Resolution rel. (min/max charge)	3.4% to 0.8% 3.3% to 0.6%	3.4% to 0.2% 3.7% to 0.3%	10.8% to 0.1% (Dual Core) 15.1% to 0.1% (Single Core)	3.1% to 1.1%	-
Use for	**Resolution ≤ 6 pC**	**Resolution 6 – 60 pC**	**Resolution >60 pC**	**Absolute measurement**	*take-away-ref*

*calibrated independent, very good aligned to Farday Cup as well (Dirk Lipka, DESY)

Summary

- New simulated Faraday Cup design, catches >99% of charged particles, proofed by …
- T-ICT shows very good agreement with Faraday Cup
- In-air ICT in line with T-ICT
- (and the DAMONs are calibrated independent as well and are inline)
- … but …
- **Toroids show 15-18% linear slope deviation**, but linear with good resolution at higher charges
  → Toroid shows ~15% more charge with beam compared to calibration

  - We do not need absolute Toroids yet, but would like to get better!

Thank you

Many people contributed to development, installation, commissioning and measurements

From the ARES team
Florian Burkhart, Willi Kuropka, Hannes Dinter, Frank Mayet, Max Kellermeier, Sonja Jaster-Merz

From Diagnostics Group (MDI)
Maike Pelzer, Gero Kube, Jürgen Kruse, Norbert Wentowski, Zlatan Pisarov, Klaus Knaack, Artem Novokshonov, Jörg Neugebauer, Sergey Strokov, Christian Wiebers, Bastian Lorbeer, Hans-Thomas Duhme, Igor Krouptchenkov, Jorgen Lund-Nielsen†

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Abstract

Comparison of Different Bunch Charge Monitors used at the ARES Accelerator at DESY

The 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. Different types of charge monitors are installed along the 45m long machine: A new Faraday Cup design had been simulated and realized. Two Beam Charge Transfomers (Toroids) are installed. Both, Faraday Cup and Toroids are calibrated independently with laboratory setups. At the end of the accelerator a Bergoz Turbo-ICT (in vaccum) and an in-air ICT are installed. This presentation will give an overview of the measured linearity and the deviations found at the Toroid measurement.

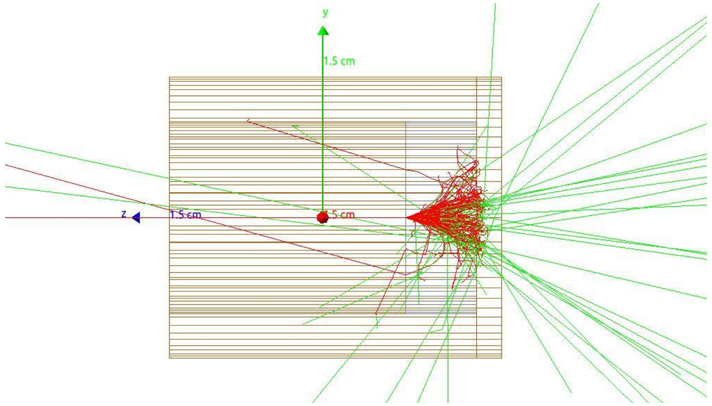
Toroids Thougts …

- Bunch Length ps to some 10 fs (E-XFEL)
- Pulse length calibration pulser ns
- Saturation of Core material?
- Calibration Coil only one winding = one position
- Does someone has a ps pulser?

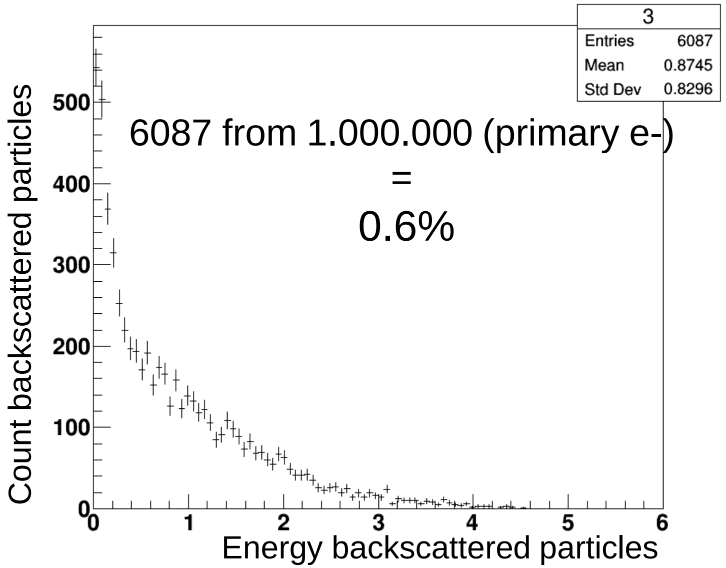
- Is it possible to achieve a better result with such setup

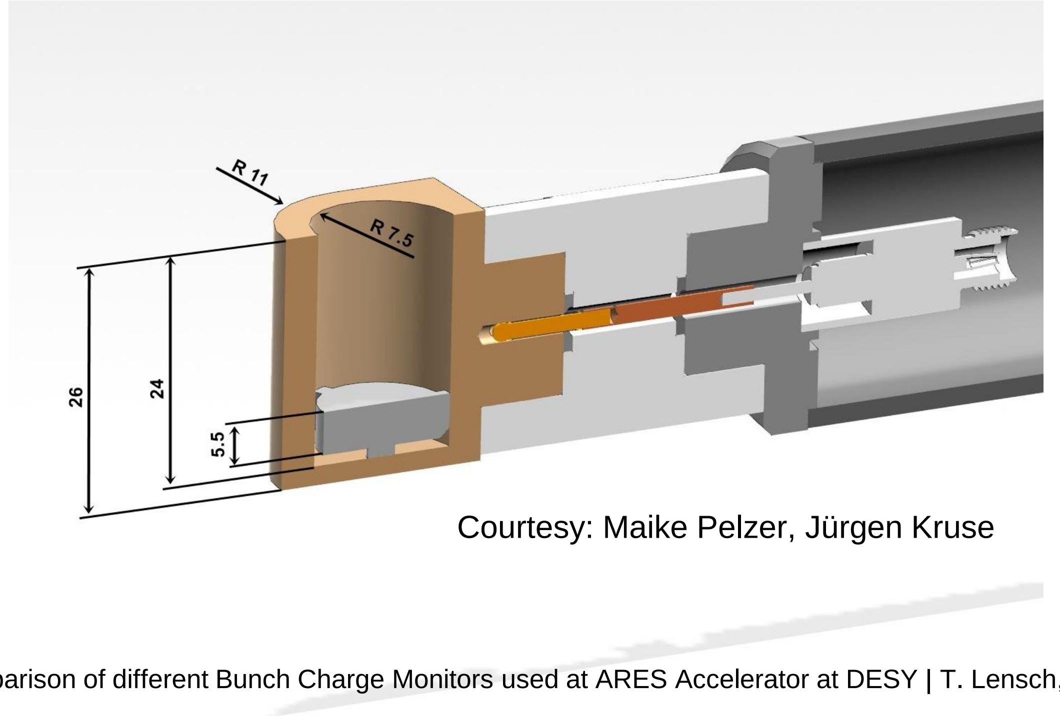
Backup: Faraday Cup

Simulation of new design



Green=Gammas, Red = Electrons



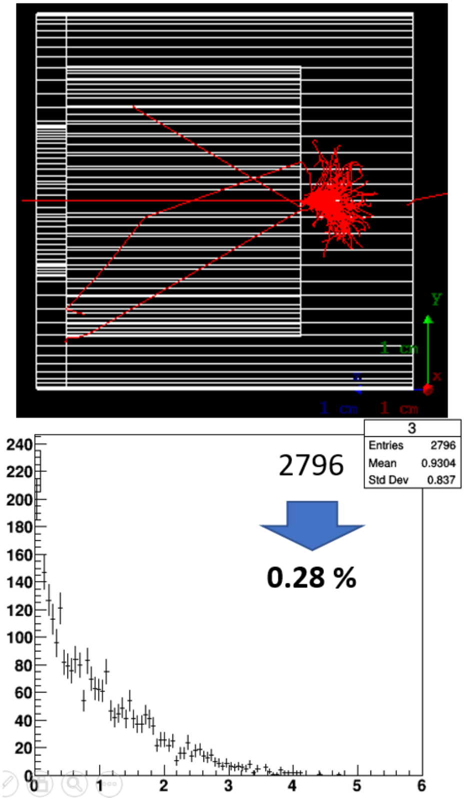


Courtesy: Maike Pelzer, Jürgen Kruse

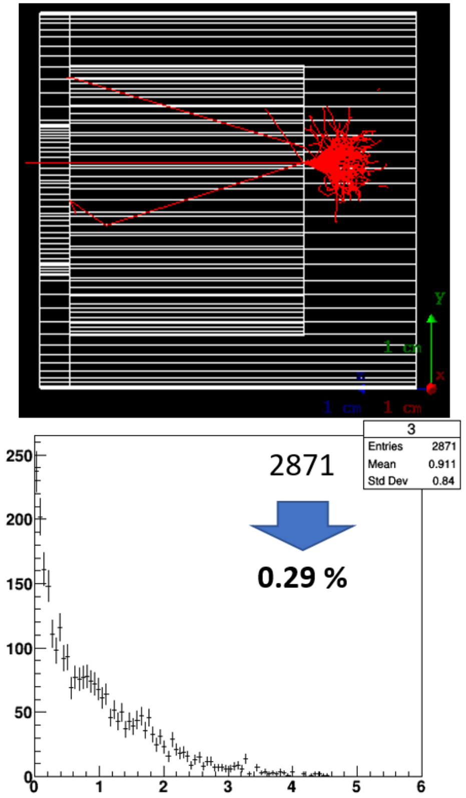
Courtesy: Sergey Strokov, Gero Kube

Backup

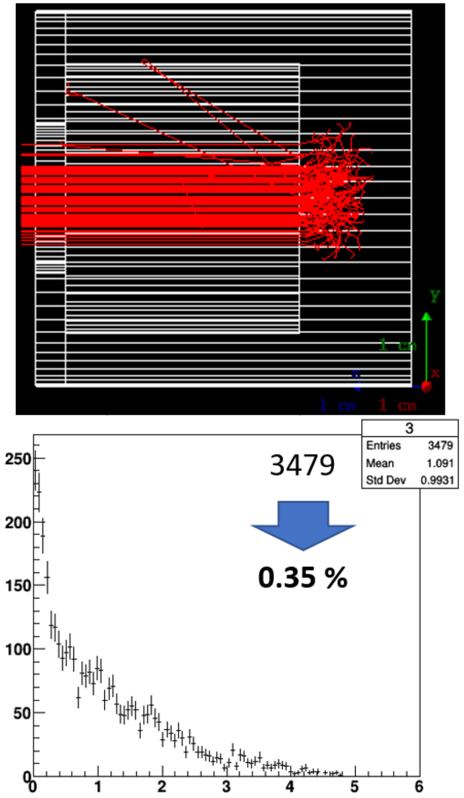
Pencil beam
at the center of FC



Pencil beam
5 mm off the center of FC



Beam with Gaussian distribution
over x,y plane. sigmax=sigmay = 2 mm



Resolution Measurement

Use standard deviation (rms) to calculate resolution

- Take all non-destructive charge monitors synchronously per charge step as reference value
- Compare monitor under test to the reference value
- Independent from machine optics

- We included Cavity BPM charge channel data to enhance the reference value

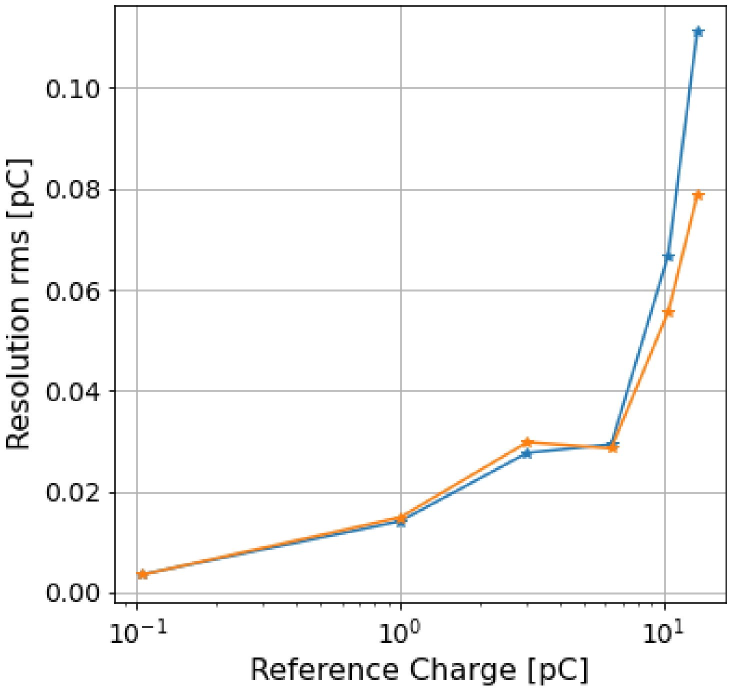
- Details of this procedure:
  - „Resolution Studies at Beam Position Monitors at the FLASH Facility at DESY“, N.Baboi, BIW2006

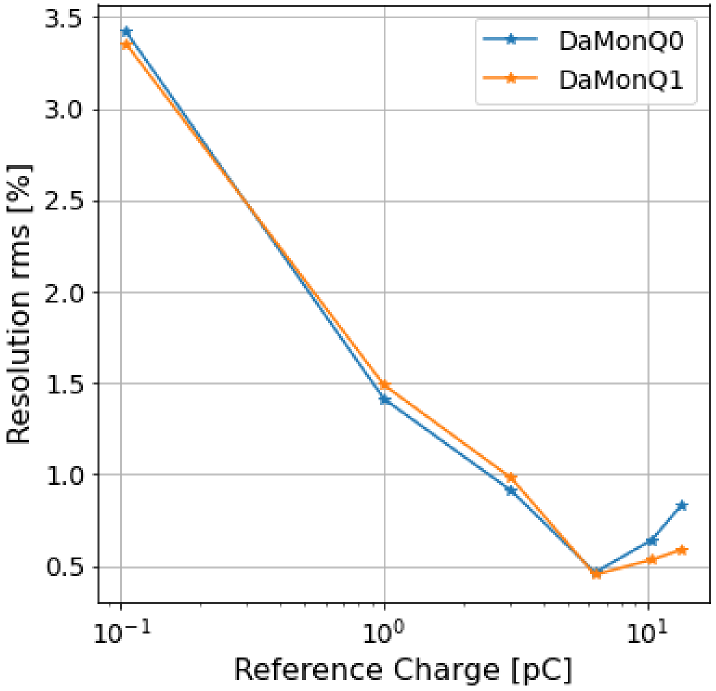
Resolution of DaMon DC Channel

Charge range from 0.1 – 13 pC

100 fC – 13 pC	DaMonDC0	DaMonDC1
Resolution [fC]	4 – 111	4 – 90
Resolution [%]	3.4 – 0.83	3.36 – 0.59

- DaMon DC Channels limited to <20 pC
- Very good at <10 pC



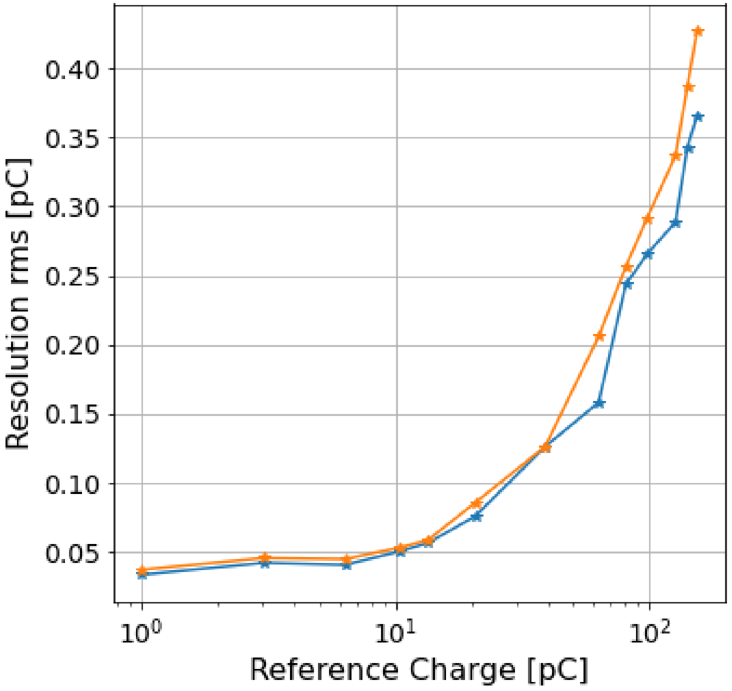


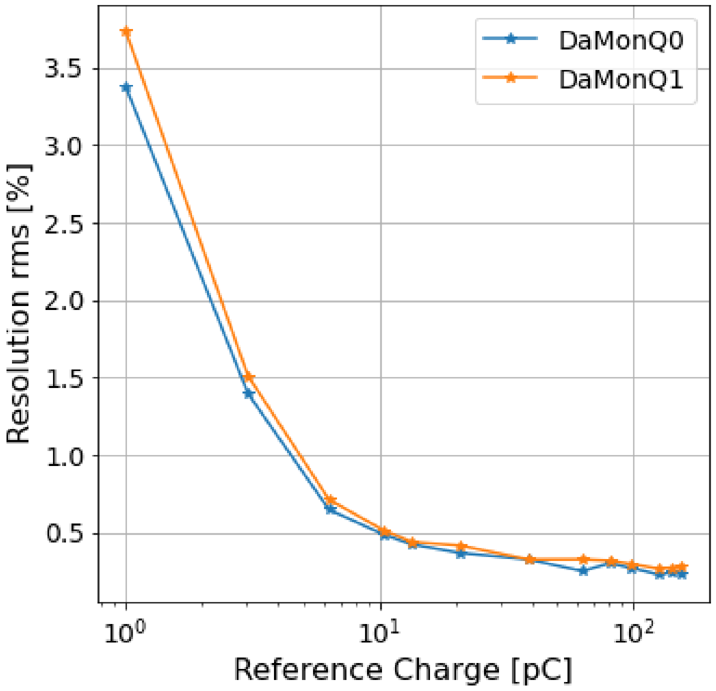
Resolution of DaMon Q Channel

Charge range from 1 – 153 pC

1 pC – 153 pC	DaMonQ0	DaMonQ1
Resolution [fC]	34 – 366	37 – 427
Resolution [%]	3.38 – 0.24	3.74 – 0.28

- For high charges resolution converges to <0.3%



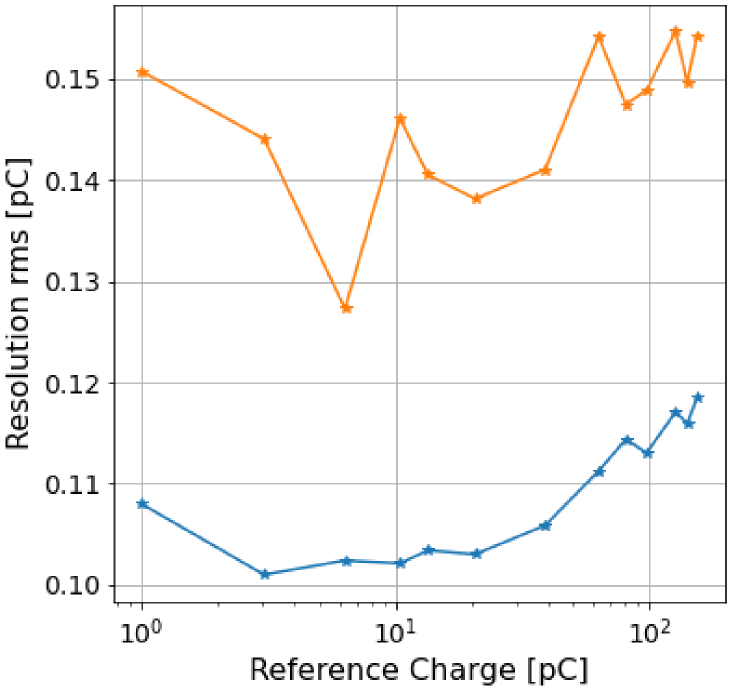


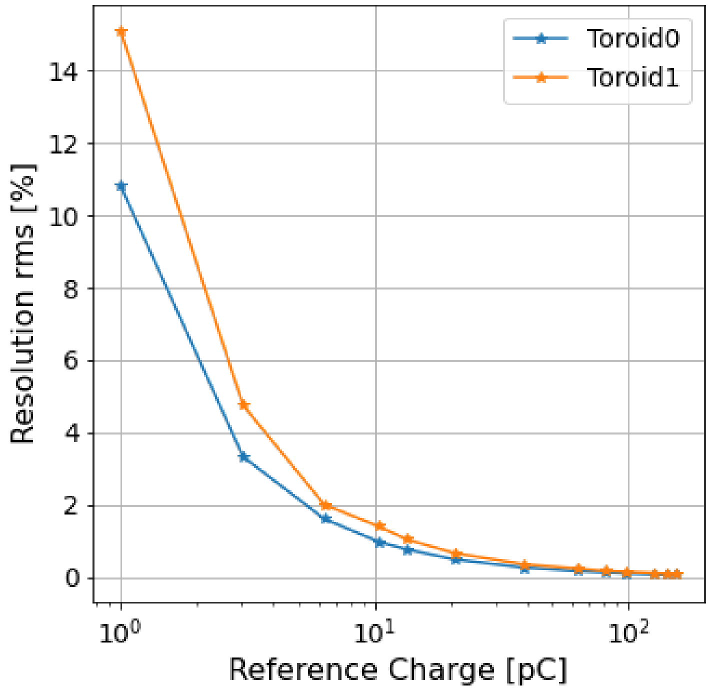
Resolution of Toroid

Charge range from 1 – 153 pC

1 pC – 153 pC	Toroid0 (dual core)	Toroid1 (single core)
Resolution [fC]	108 – 119	151 – 154
Resolution [%]	10.8 – 0.08	15.08 – 0.1

- For high charges resolution converges to 0.1%





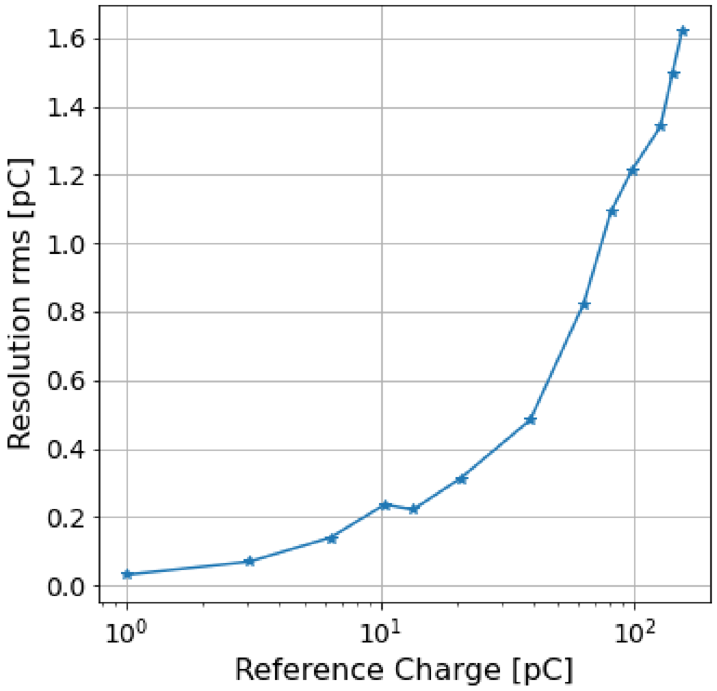
Resolution of T-ICT

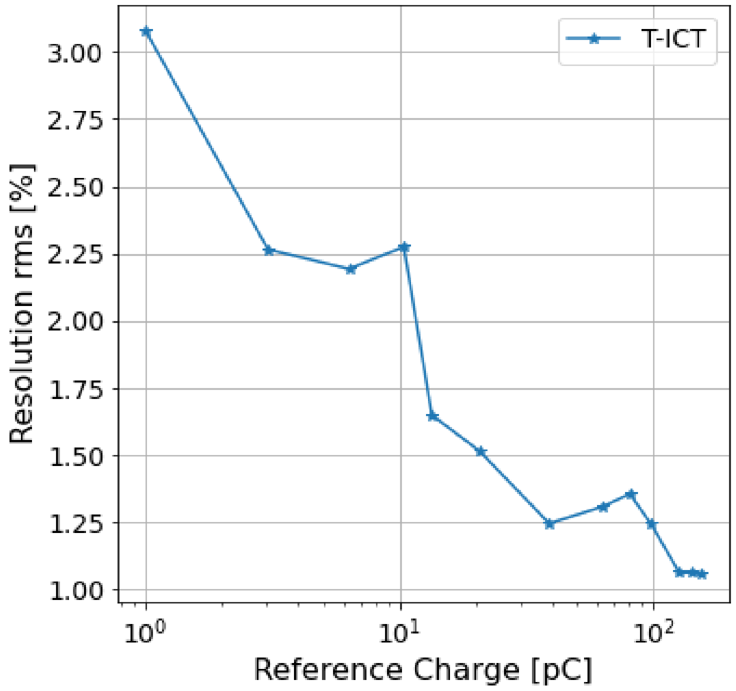
Charge range from 1 – 153 pC

- For high charges resolution converges to ~1%

- Resolution value larger due to extended cable (~30m) (expected 10 fC @5m cable)

1 pC – 153 pC	T-ICT
Resolution [fC]	31 – 1621
Resolution [%]	3.08 – 1.06



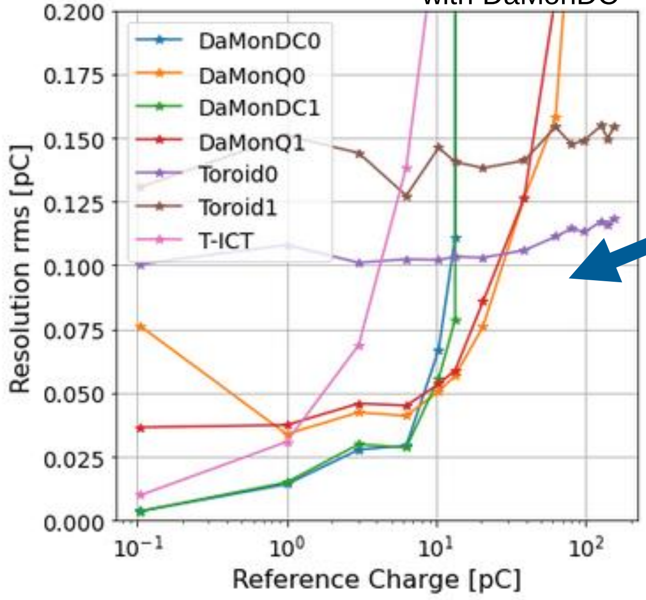


Compare Resolution

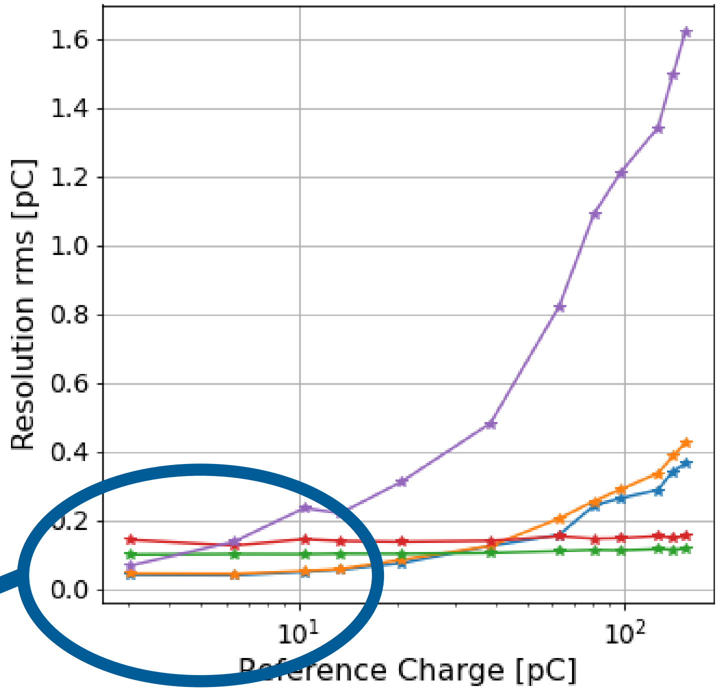
If we want to do a ranking …

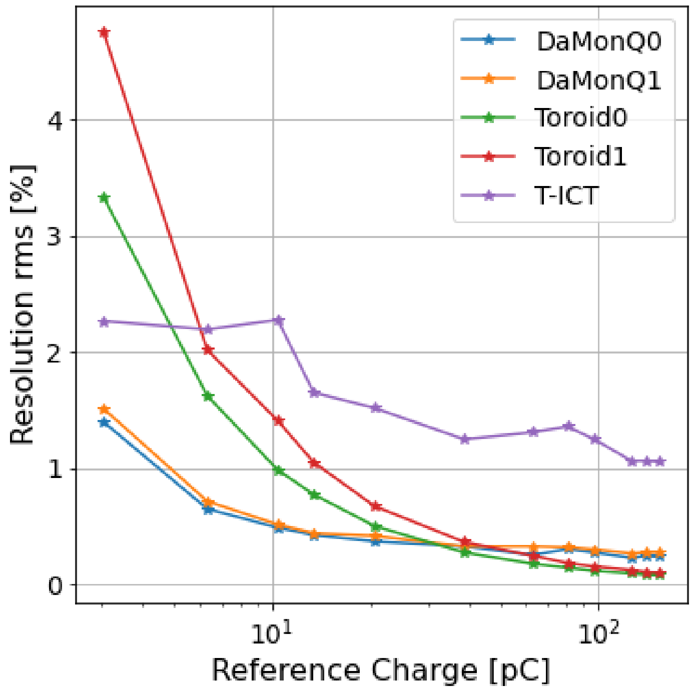
- DaMonDC: ≤ 6 pC
- DaMonQ: 6 – 60 pC
- Toroids: >60 pC Toroids best resolution
- T-ICT:
  - also good for <1 pC
  - used for absolute values

with DaMonDC



w/o DaMonDC

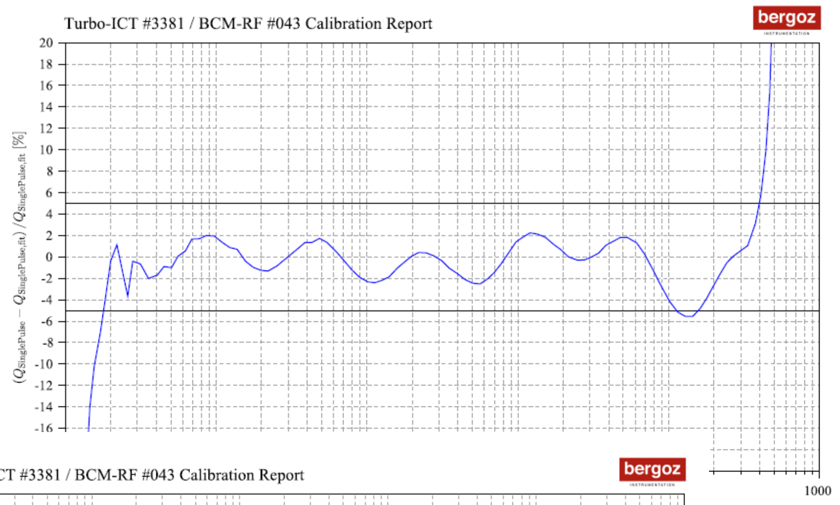




Legend colors differs!

Backup

T-ICT0 (red) : raw
T-ICT1 (blue) : Look up table



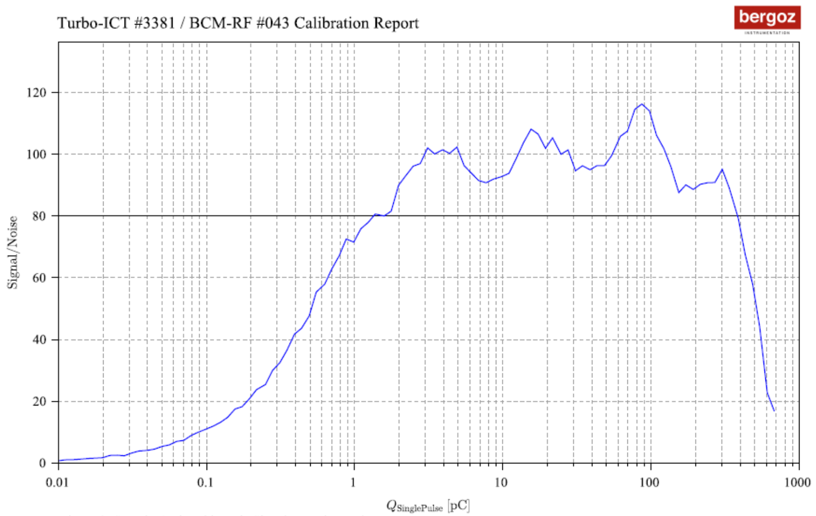
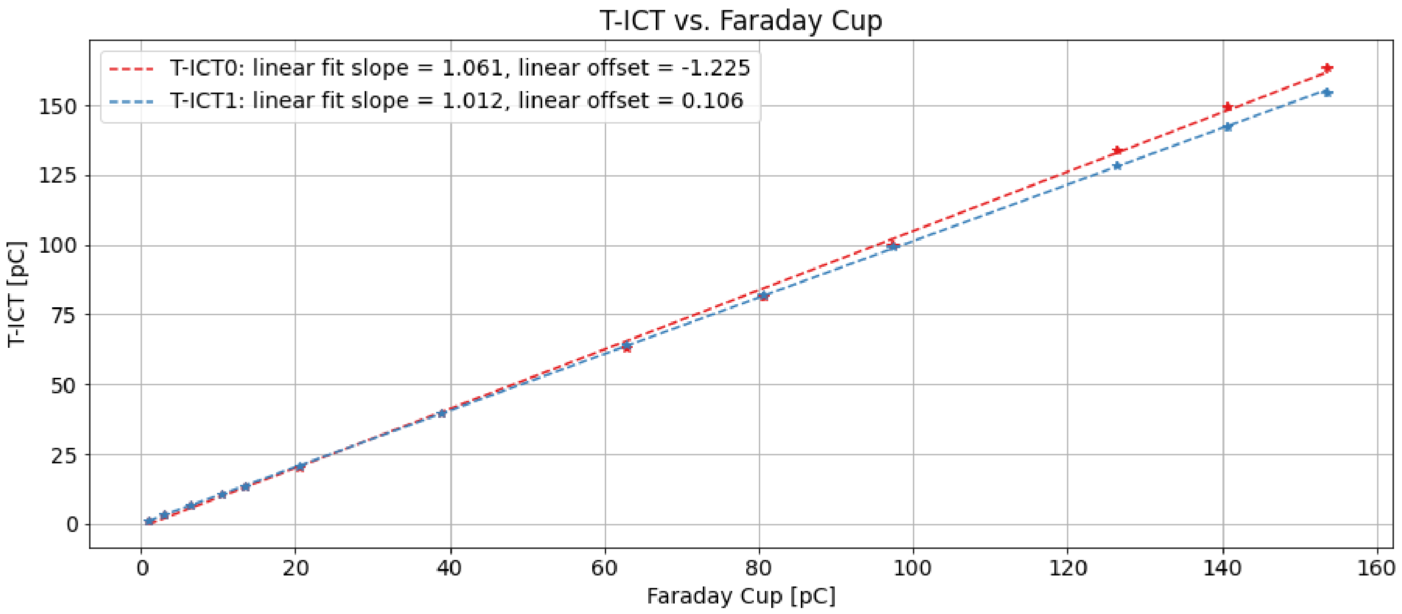


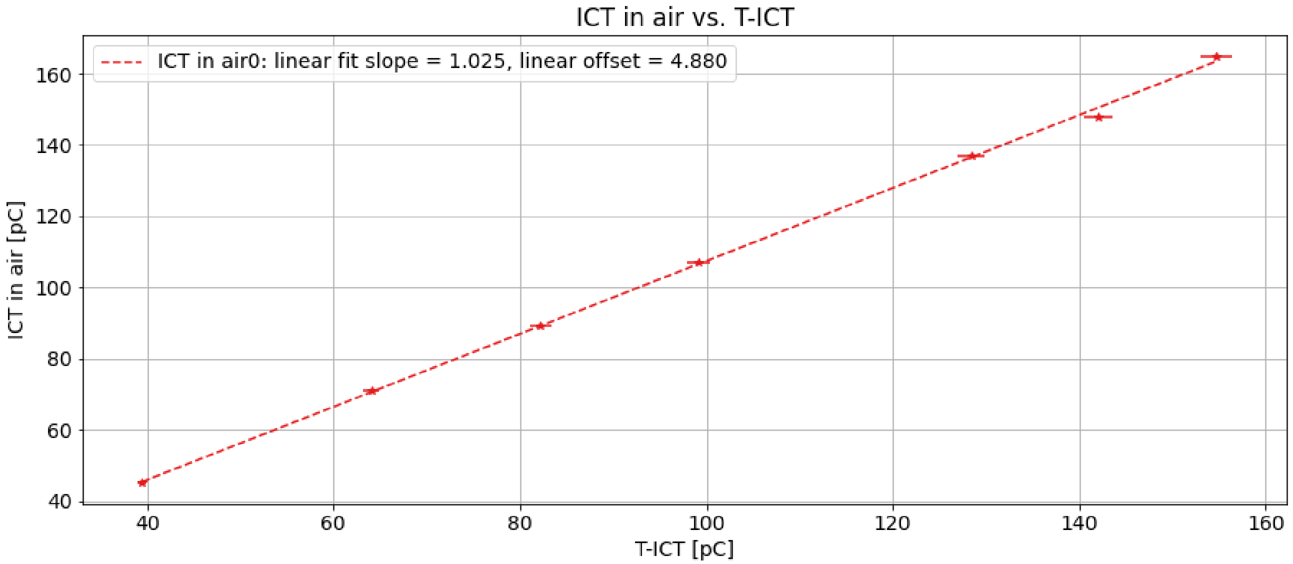
Figure 3: Sample-And-Hold Mode Signal-to-Noise Ratio.



Bergoz ICT in Air vs. T-ICT

Now compare ICT with <u>T-ICT</u>

- Located about 30 cm apart
- Calibrated at Bergoz
- Compared to **<u>T-ICT</u>**:
  - Linear slope factor: 1.025
  - Linear offset : 4.88 pC
- Read out with 12 bit scope
- Values <20 pC not measurable in the current scheme (catch noise by cable…)
- Fit not trustworthy due to improvised read out
- „Under Construction“
- Not to be taken at face value



Backup

- Sampling Faraday Cup and Toroid with 125 MS/s
- Approximation proved experimentally

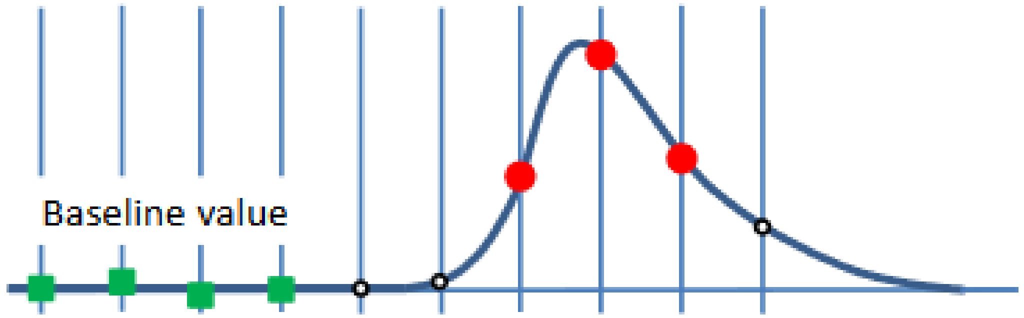


Figure 10: Basic charge calculation algorithm as currently implemented in software at the FLASH accelerator.

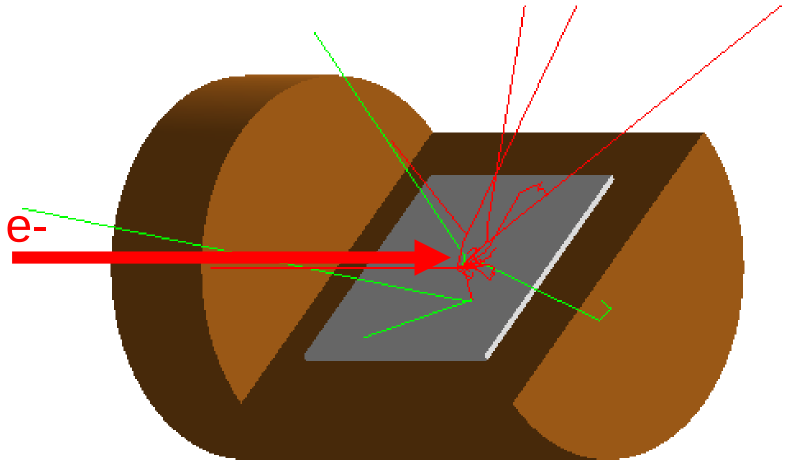
Faraday Cup

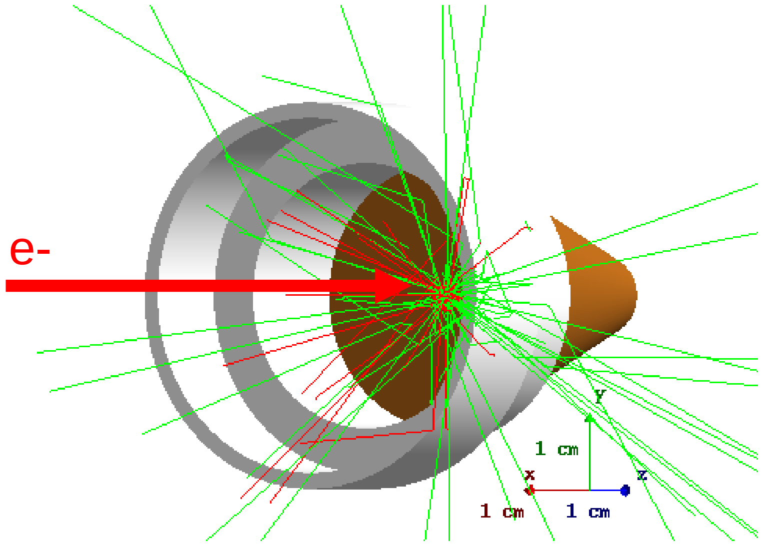
Simulations of former designs used at DESY

If you have other geometries…

- existing Faraday Cup variants at DESY
- Simulated for 5 MeV beam (ARES)
- Variants of materials (Copper - Aluminum combinations)
- Different geometries and angles of electron beam

- Between 4 - 22% of primary and secondary electrons escape from the Faraday Cup
- **→ not sufficient for ARES**





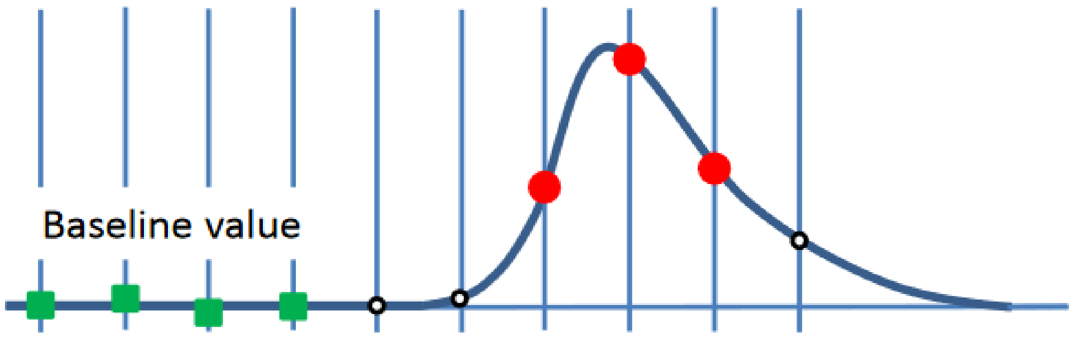
Courtesy: Sergey Strokov, Gero Kube

electrons
gammas

Faraday Cup

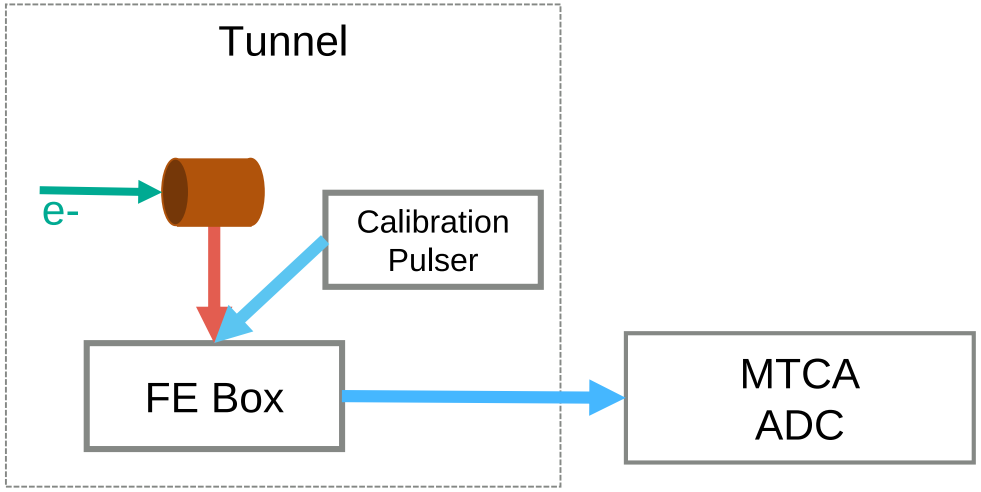
Electronics and Calibration

- FC signal connected to front end with 15 MHz low pass filter and pre amp (tunnel)
- Read out with MTCA system (outside tunnel)
  - Struck ADC SIS8300-L2D, 16 bit, 125 MS/s
  - *Pulse-form-fit with 3-point sampling*



Calibration

- Send electrical pulse to the FE electronic
- Corresponds to 1nC pulse
- Scaling the read out

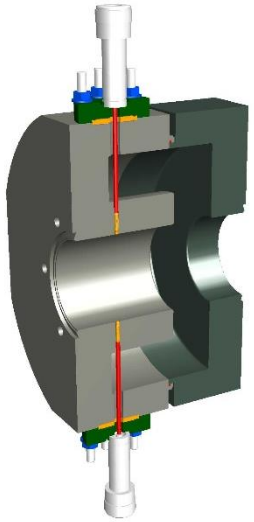


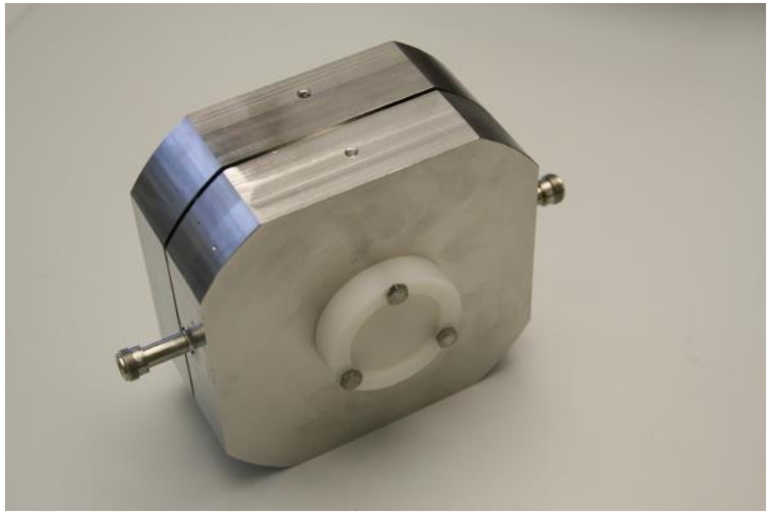
04 Dark Current Monitor (DaMon)

Dark Current Monitor (DaMon)

Invented to measure dark current of accelerators with 1.3 GHz acceleration frequency

- Consists of stainless steel resonator TM_{010} mode at 1.3 GHz, loaded quality factor about 200, results in bandwidth of about 6 MHz and decay time 50 ns
- RF Front End Electronic (RFFE) with two channels:
  - dark current (DC) with local oscillator, down conversion and logarithmic detector
  - Charge (Q) with logarithmic detector
- Send to MTCA system with 16 bit ADC (Struck 8300-L2D)



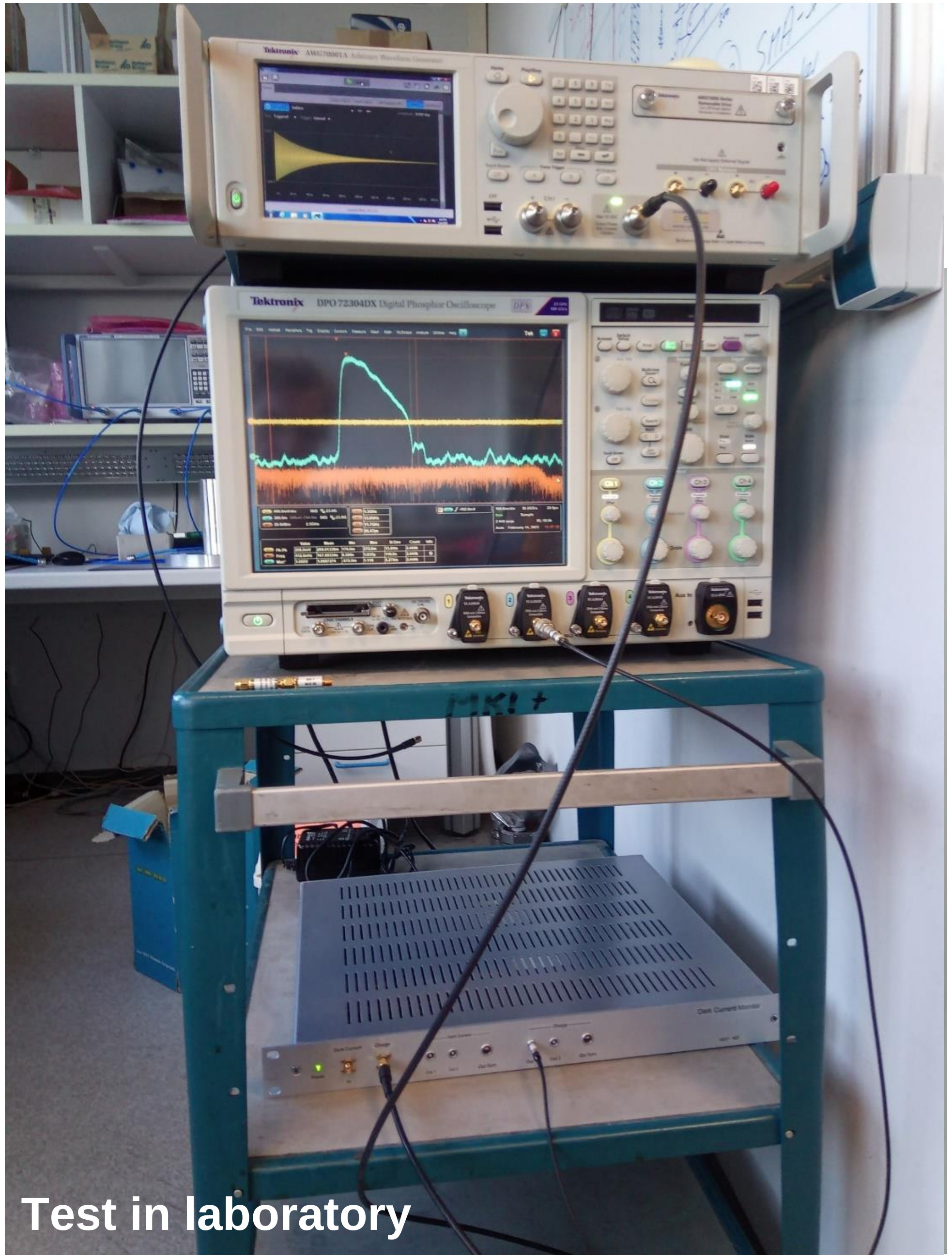


Refs: Lipka et al. DIPAC 2011 WEOC03 and IBIC 2013 WEPF25

Dark Current Monitor (DaMon)

Calibration

- For 3 GHz accelerator (ARES) both channels (DC and Q) are used for charge measurement: increase dynamic range
- Arbitrary Waveform generator (AWG) in laboratory simulates output of DaMon
- AWG as input for the RFFE at largest possible amplitude range
- Output of RFFE connected to ADC and monitors amplitude
- Results in an electronics response function look-up table
- Together with measured properties of each individual resonator (frequency, quality factors) and cable attenuation results in look-up table for each channel

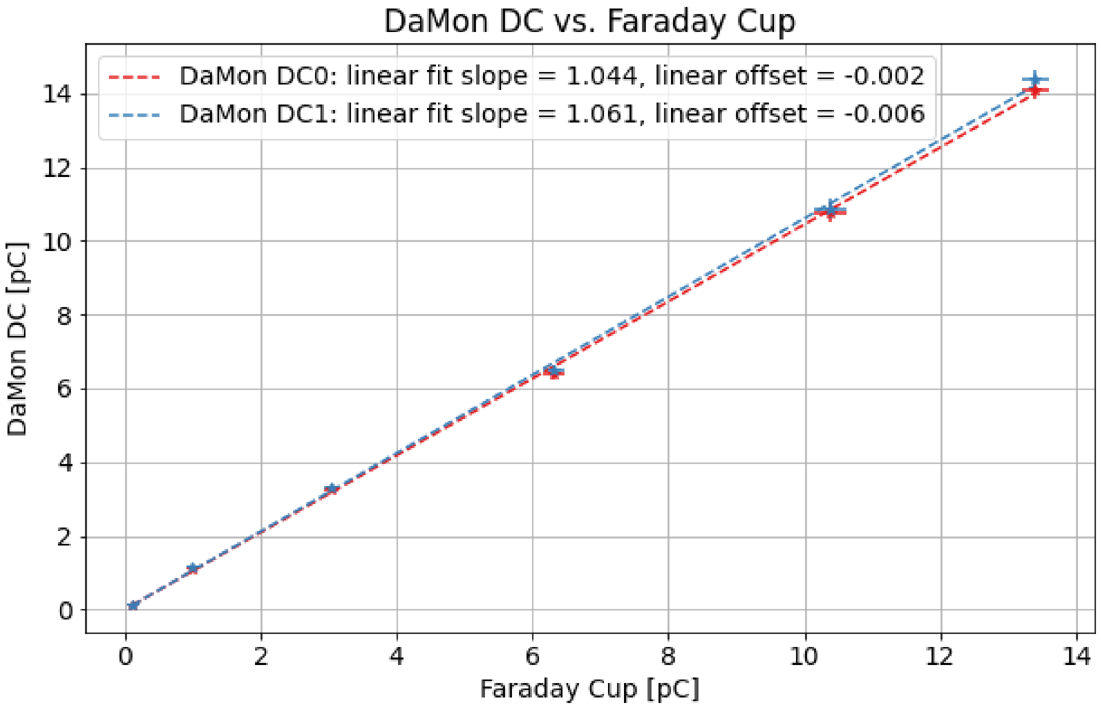


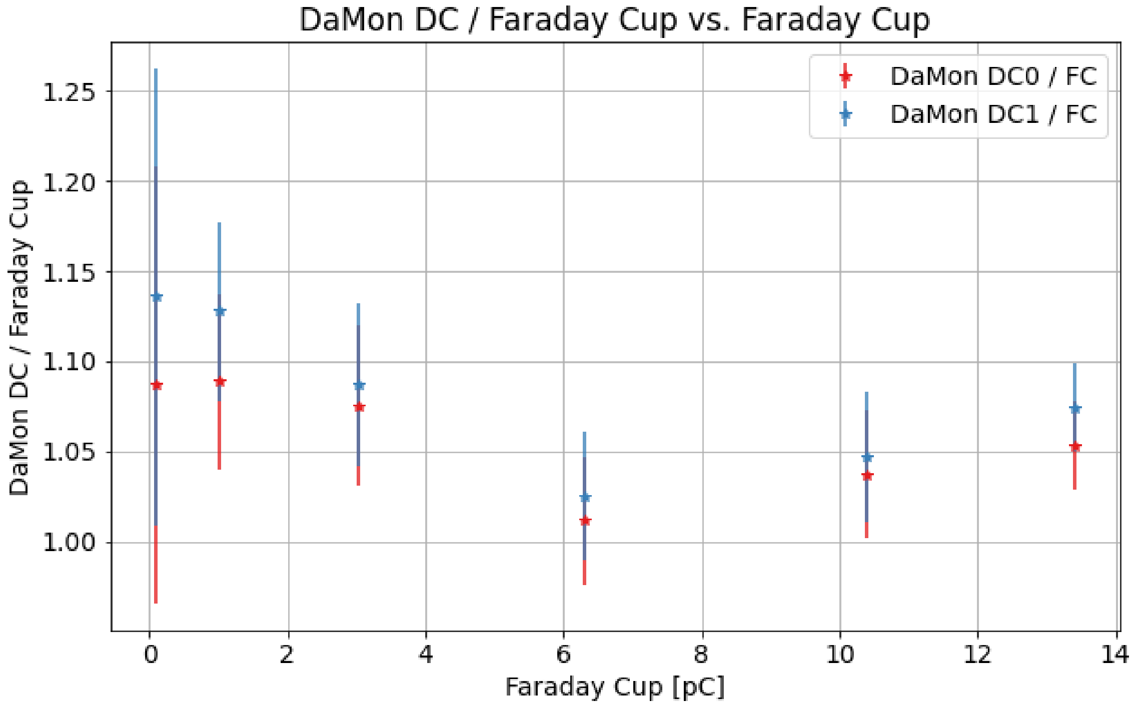
DaMon DC vs. Faraday Cup

Range 0.1 – 13 pC

	DaMon DC0	DaMon DC1
Linear fit slope	1.04	1.06
Linear fit offset	-0.002 pC	-0.006 pC

- Calibrated in the lab, not beam based
- Measure ~<20 pC only
- Error is standard deviation caused by beam charge jitter (relative plot)





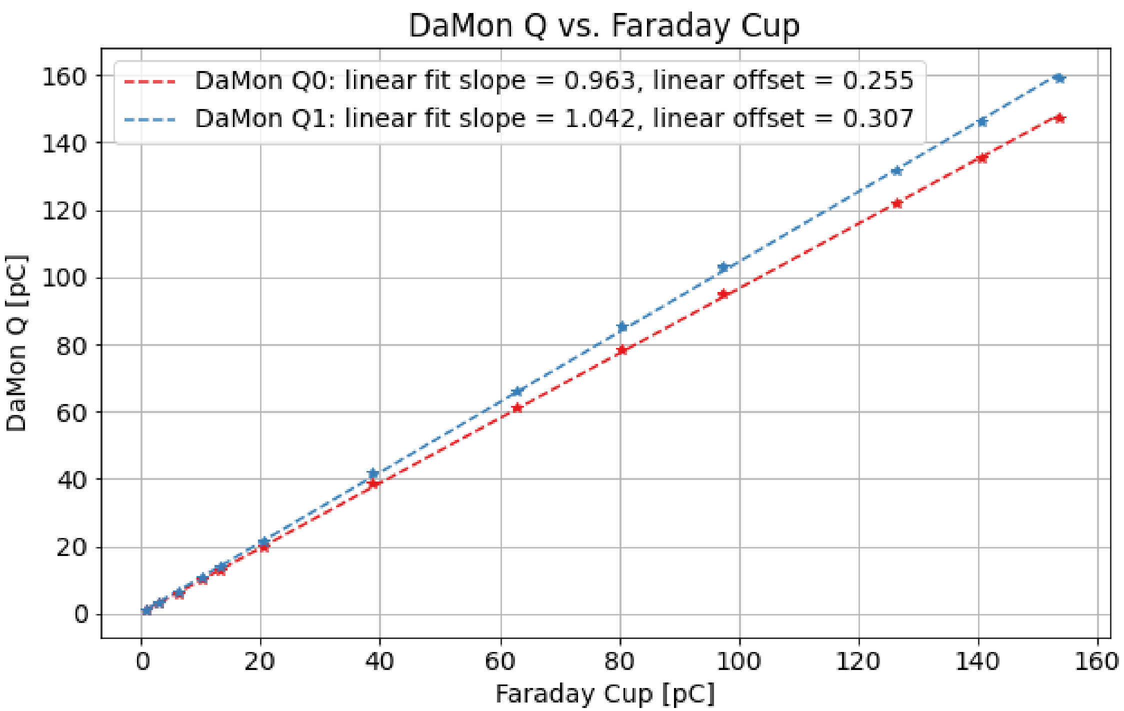
Error is standard deviation caused by beam charge jitter

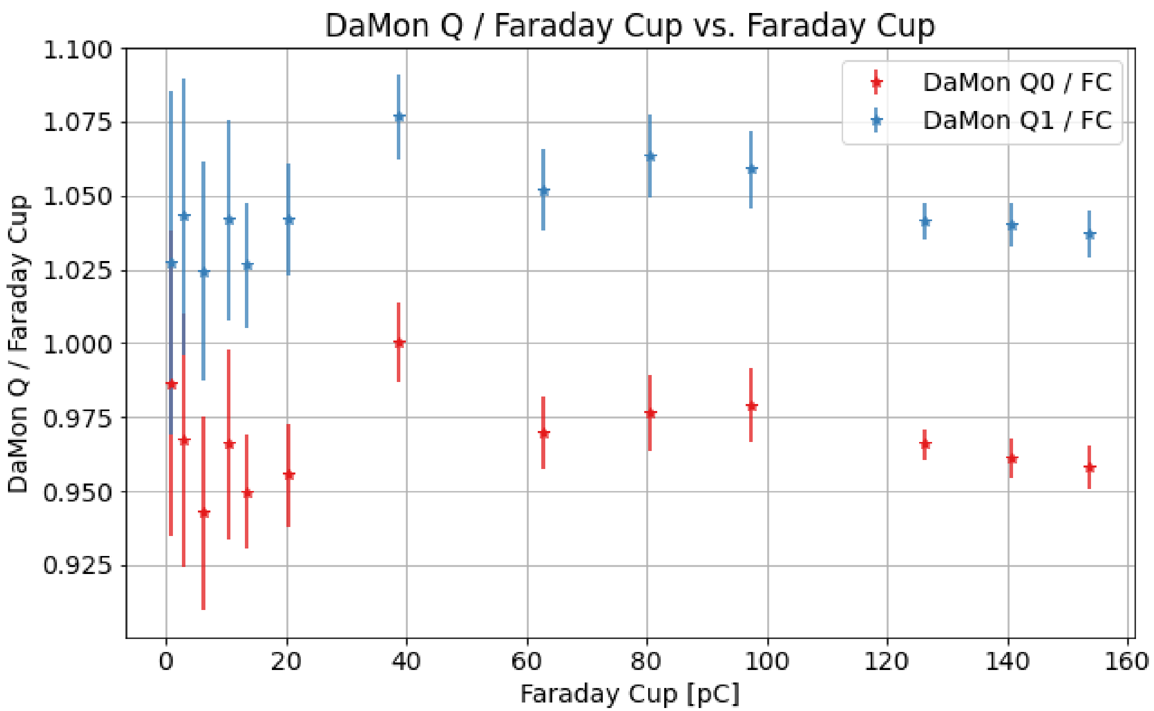
DaMon Q vs. Faraday Cup

Range 1 – 153 pC

	DaMon Q0	DaMon Q1
Linear fit slope	0.96	1.04
Linear fit offset	0.26 pC	0.31 pC

- Calibrated in the lab, not beam based





Error is standard deviation caused by beam charge jitter

Contact

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