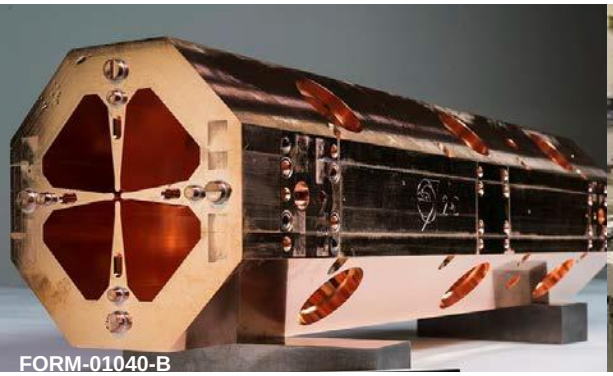
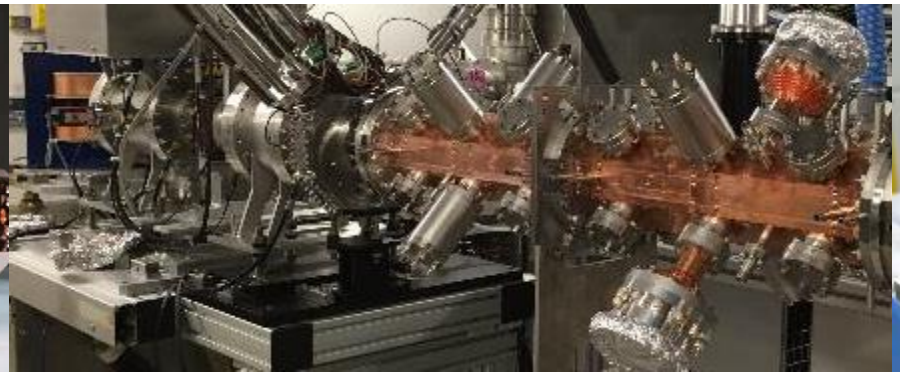
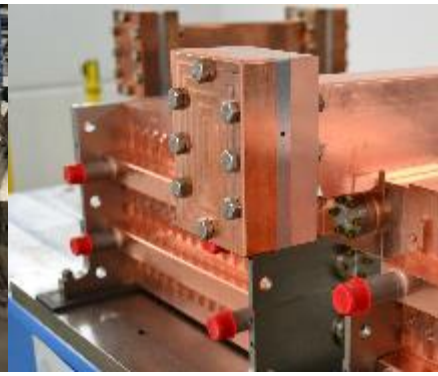
04.09.2019
Michele Caldara

an ADVANCED ONCOTHERAPY company

CERN spin-off

Beam Diagnostics

OMA International Conference on Medical Accelerators and Particle Therapy

CERTIFIED ISO 13485 UKAS

Introduction

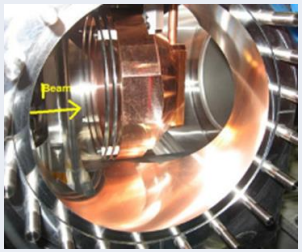
Beam Diagnostics for medical accelerators

BD Instrument

Physics	
Control System	**Electronics**
Mechanics	**Vacuum**
Not interceptive (Treatments>10hrs/day)	Compact in z (Space costs money)
Fast commissioning and debugging	Easy-to-use (operators deserve that)
Robust (>10yrs lifetime)	Trustworthy (Calibration!)

~10% of accelerator production costs

BD Instrumentation overview (a selection)

Physical Effect	Instrument	Measured Quantity	Derived Quantity	Destructive
EM field 	**Beam Current Transformer**	In combination with Slit, Dipole, Quadrupoles, kicker: • Transverse and longitudinal emittance • Energy • Energy spread • Tune		
	BPM			
	Phase Probe			
Coulomb interaction, E deposition, charge collection	**MWPC**			
	Luminescent screen			
	**Wire Scanner**			
	Si/Dia Detector			
	Faraday Cup			

[1-2-3]

Beam Current:
Beam current transformers and Faraday Cup

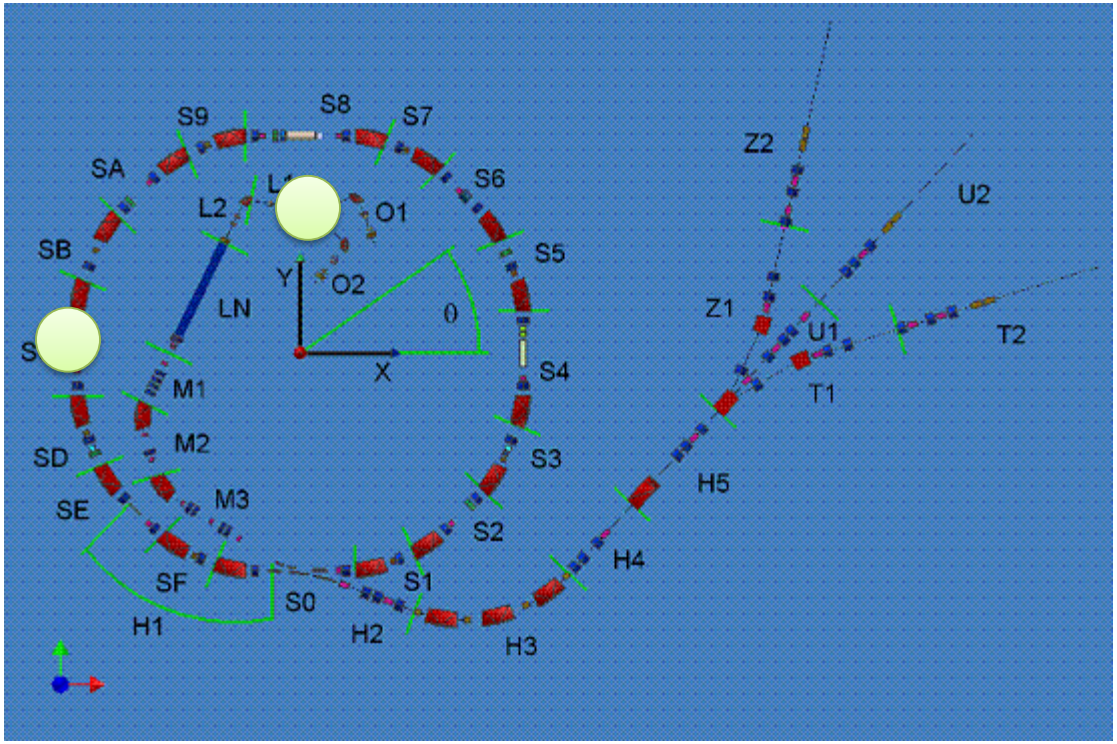
Beam Current Transformers: DCCT or ACCT?

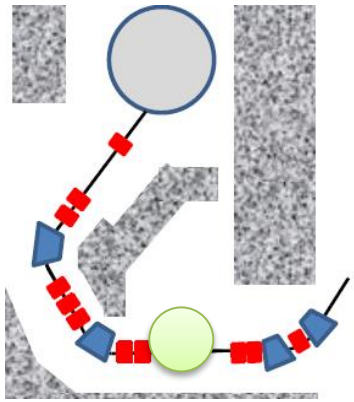
DCCT: 0.5 μArms/sqrt(Hz), DC-8kHz BW → **45 μArms**

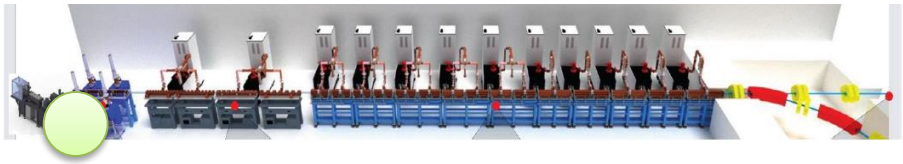
- Ok where current is in **mA** range
- In a synch ring Ibeam changes with Tr
- More interesting to monitor **charge**! Need **beta** normalizer

[1]

$$Q_b = I_{dc}\, T_r = I_{dc}\, \frac{L_m}{\beta c}$$



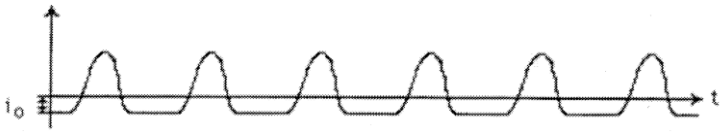


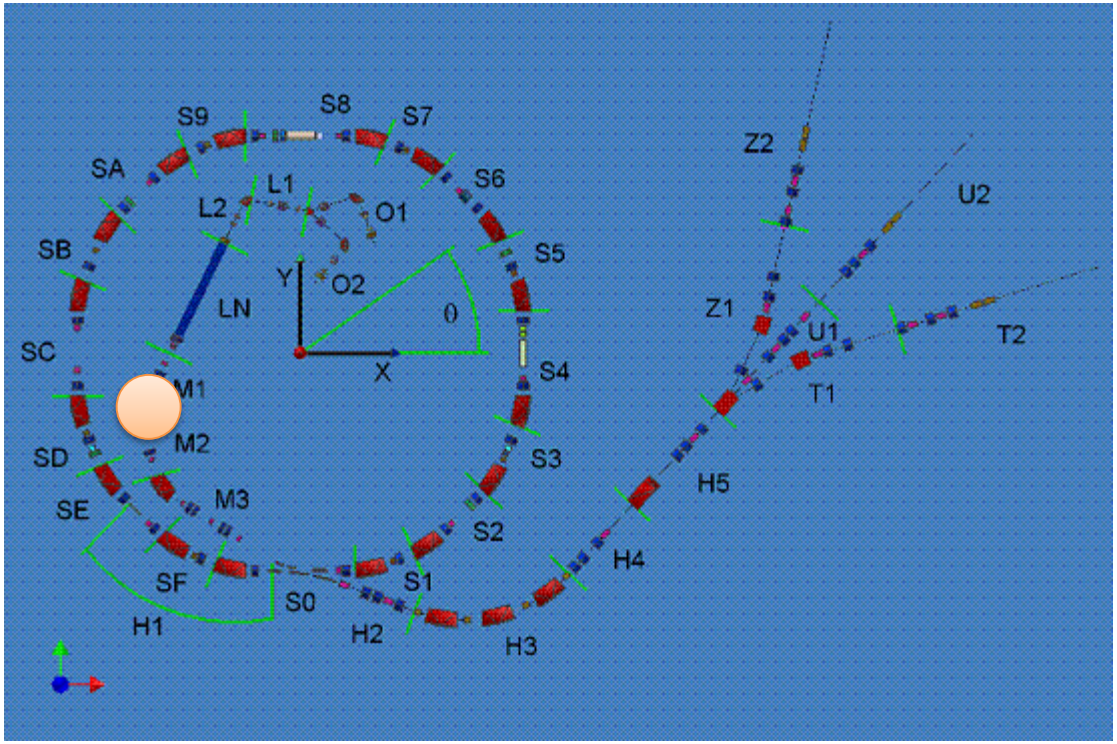


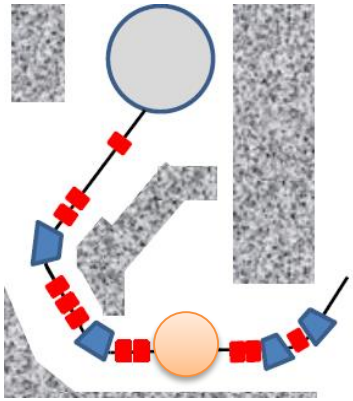
Beam Current Transformers: DCCT or ACCT?

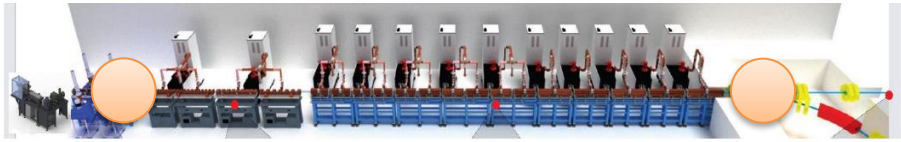
ACCT: 1.5 μArms noise, 3Hz-1MHz BW

- Ok for **beam pulses**
- Droop <2%/ms
- **Ok** for **charge estimation** if signal is in the BW, but needs <u>baseline correction</u>!



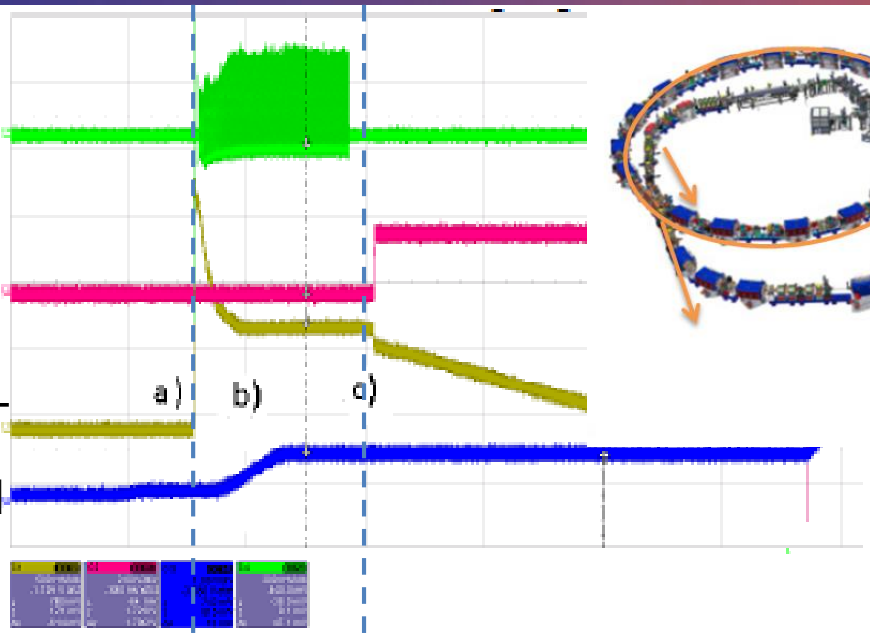






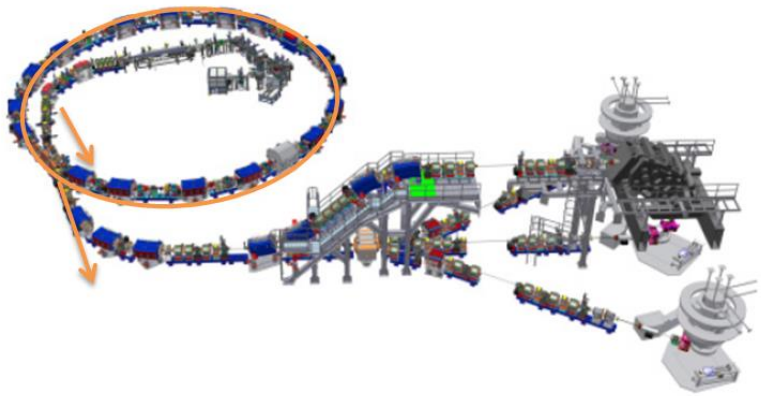
After chopper

Normalized DCCT signal is displayed in CNAO Page1

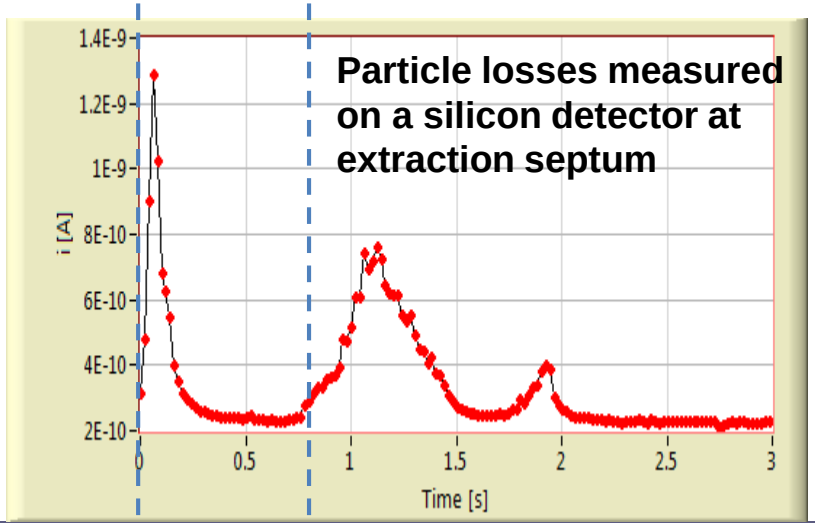


N charges from DCCT

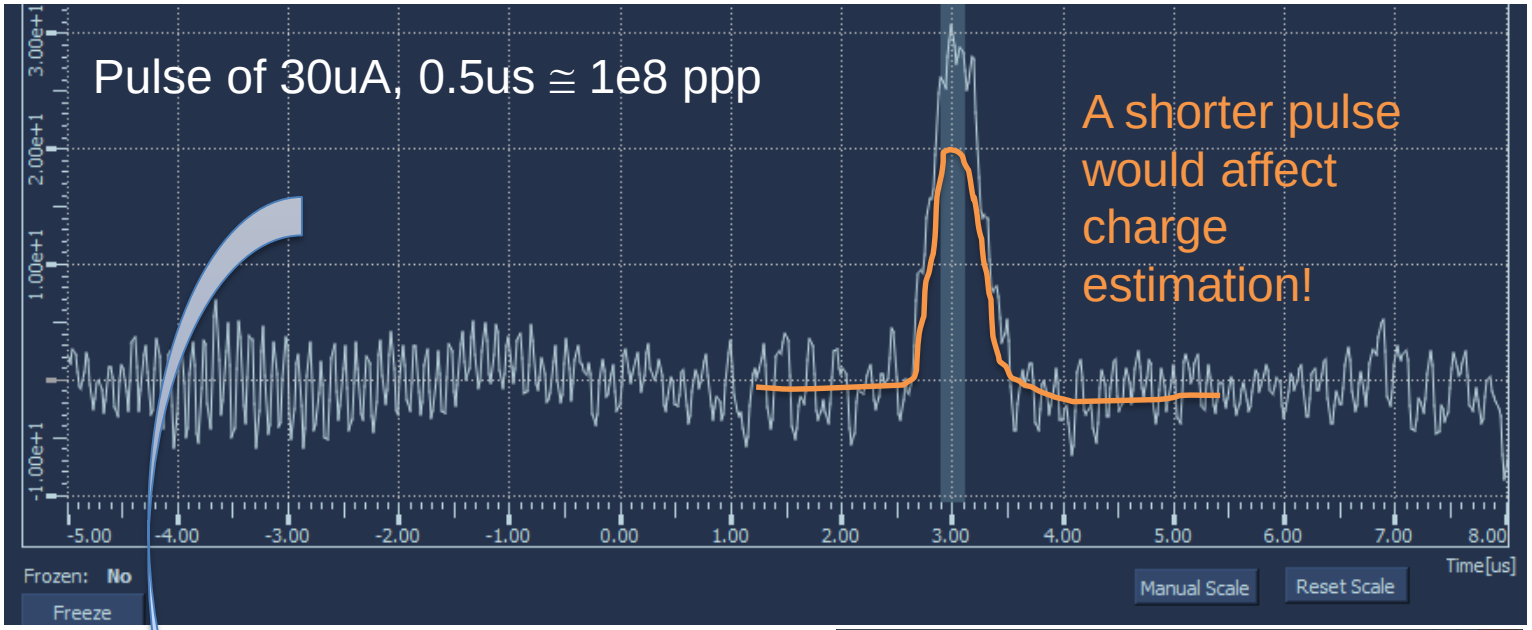
Dipole B field

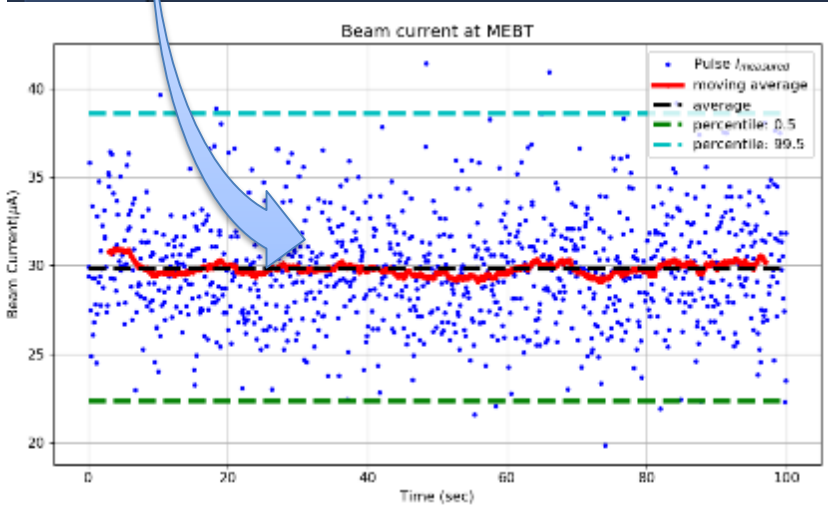


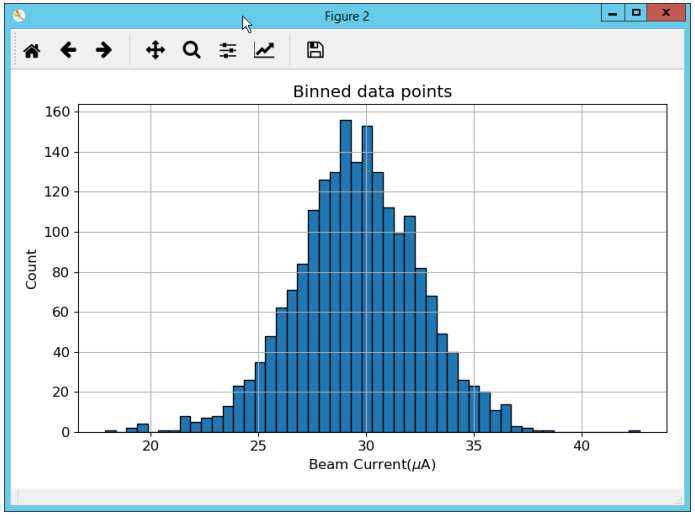
a) Synch Injection
b) Acceleration
c) Start extraction



ACCT in LIGHT MEBT1

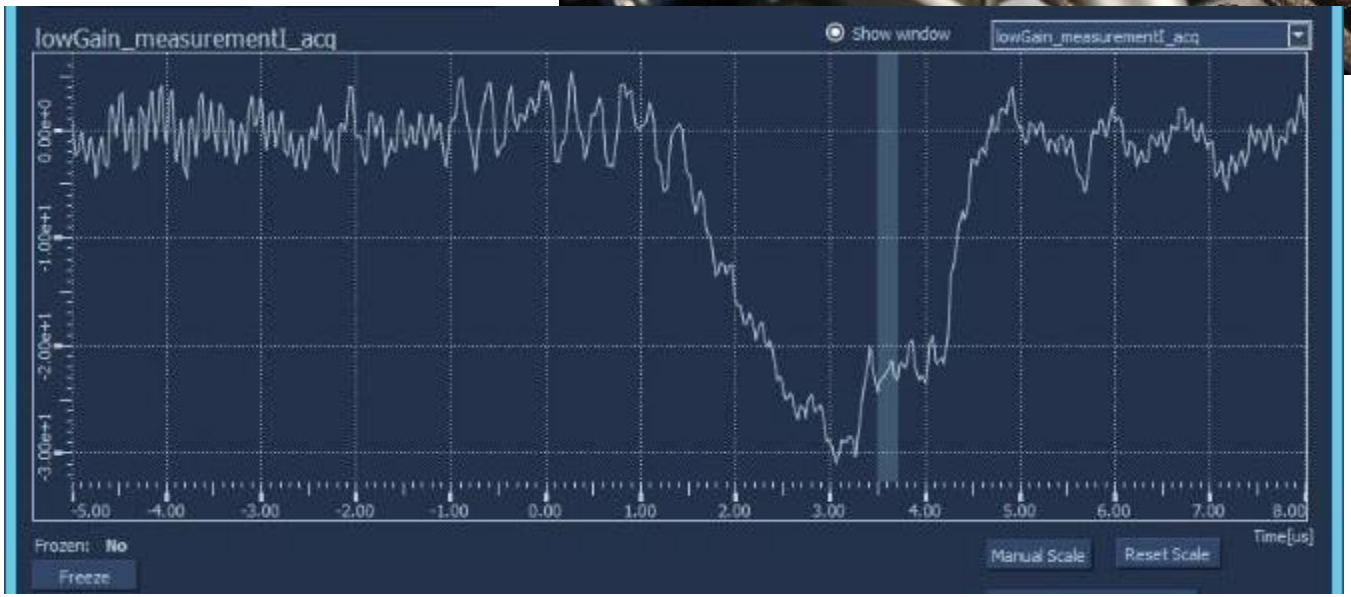






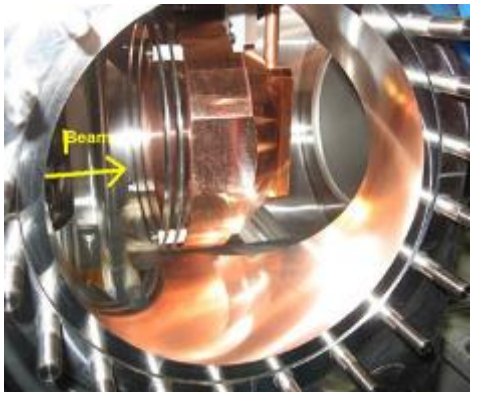
ACCT limitation

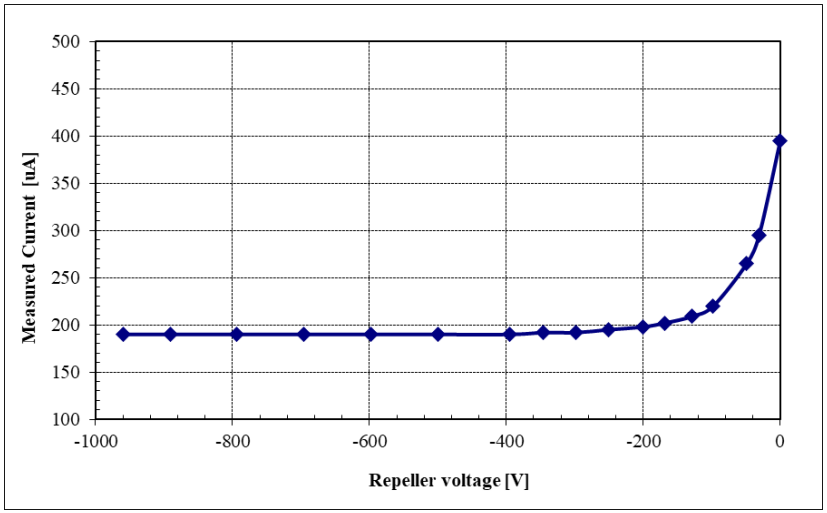
- **Electron field emission** from an accelerating cavity is a **signal** for the ACCT!
- ACCT sensor should not be close to a cavity

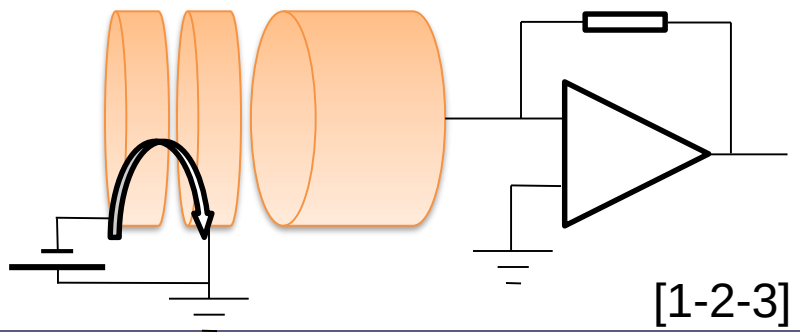


Destructive beam current: Faraday Cup

- Insertable or fixed (end cup)
- The best option for DC beam *(but might need **cooling**…)*
- Typically up to 10MHz BW
- **Secondary electrons** (emitted at cosθ), need to measure at least once the curve **below**
- If need to measure weak currents a **guard ring** is probably needed



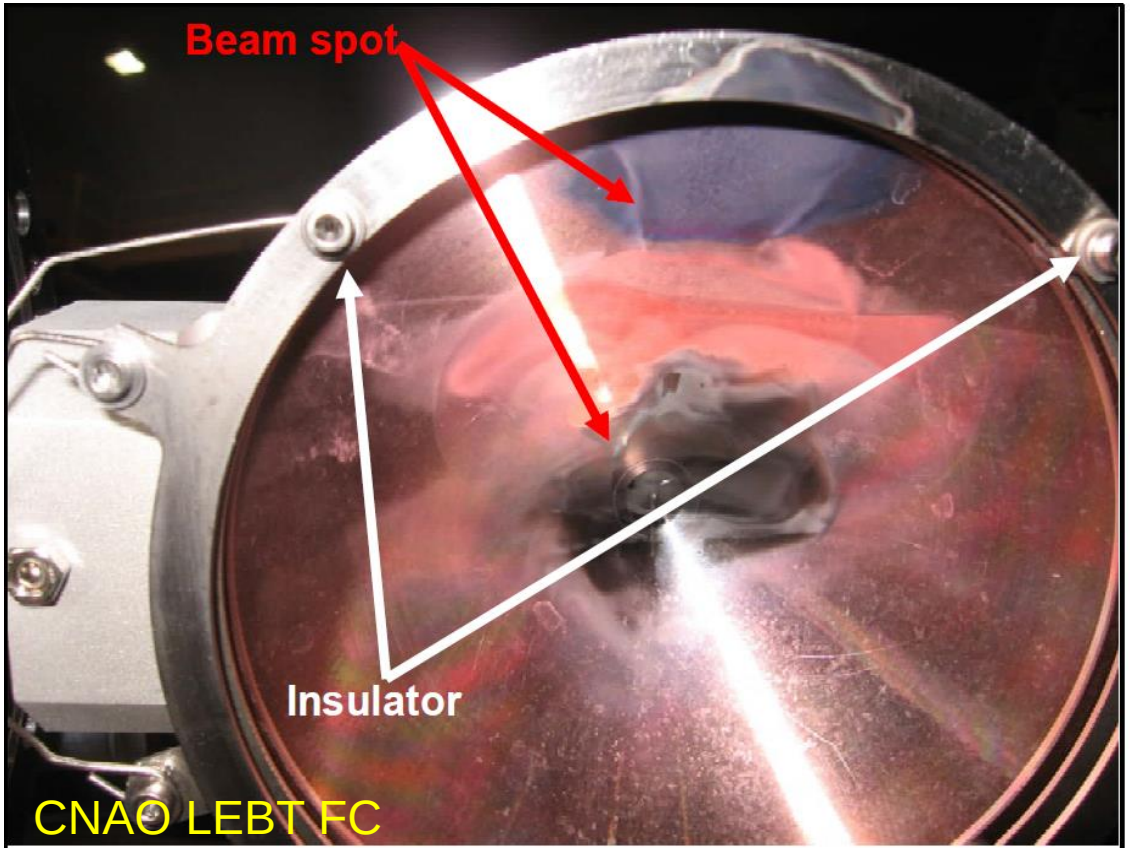




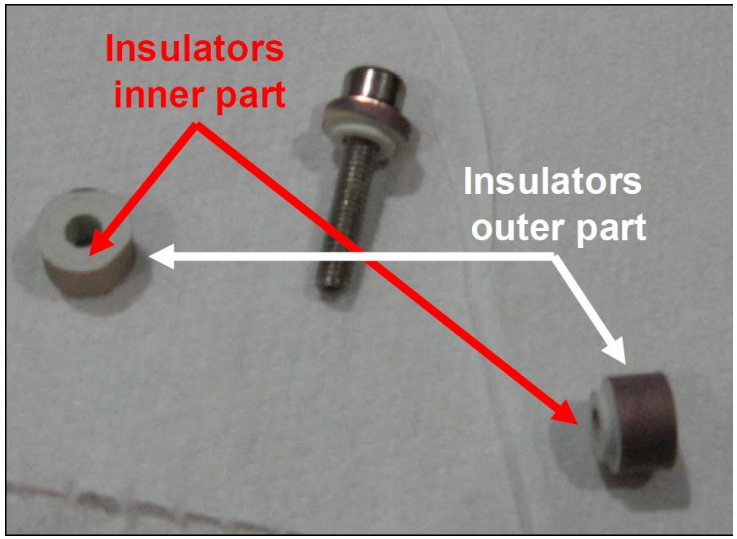
[1-2-3]

Faraday Cup: What can go wrong…

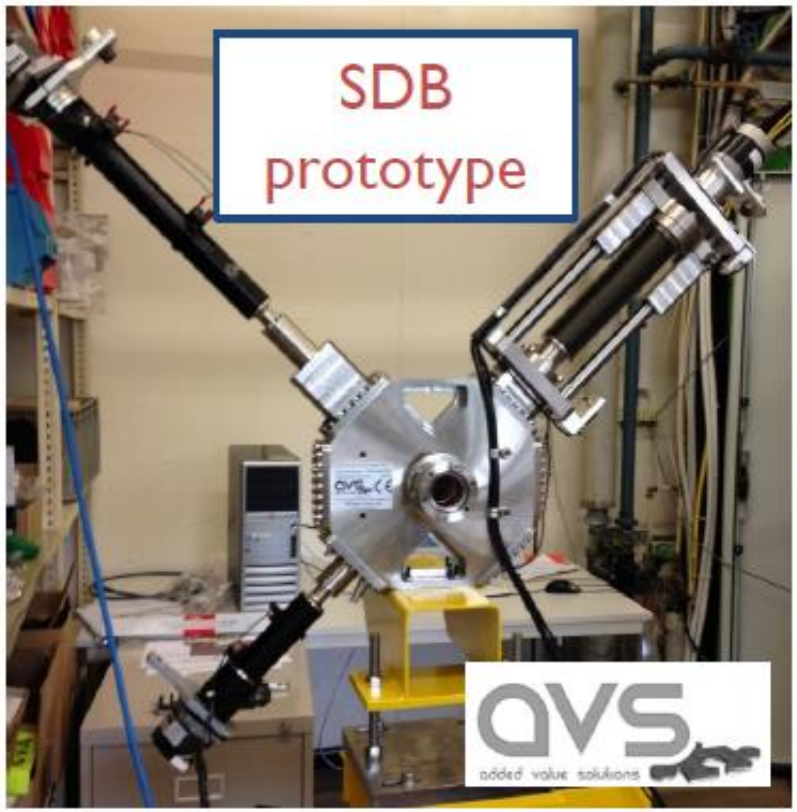
- **Sputtering effect due to carbon ion beam**
- **Insulators became nice small value resistors…**
- **How could you detect this from the ctrl room?**

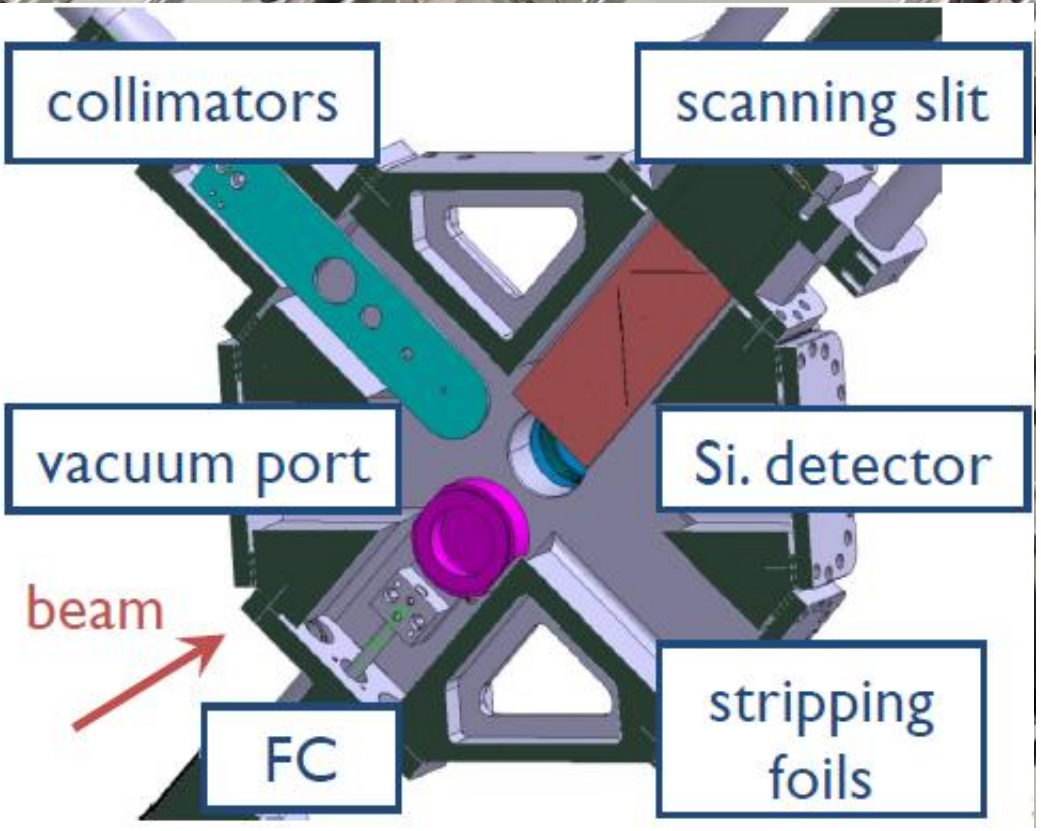


- A discharge to the cup -> spikes
- Cup shorted to the guard ring → perfectly flat signal to 0V
- Repeller shorted with the guard ring → cup reads more than usual and HV power supply is in current compliance or alarm



If longitudinal space is narrow… Compact Faraday Cup



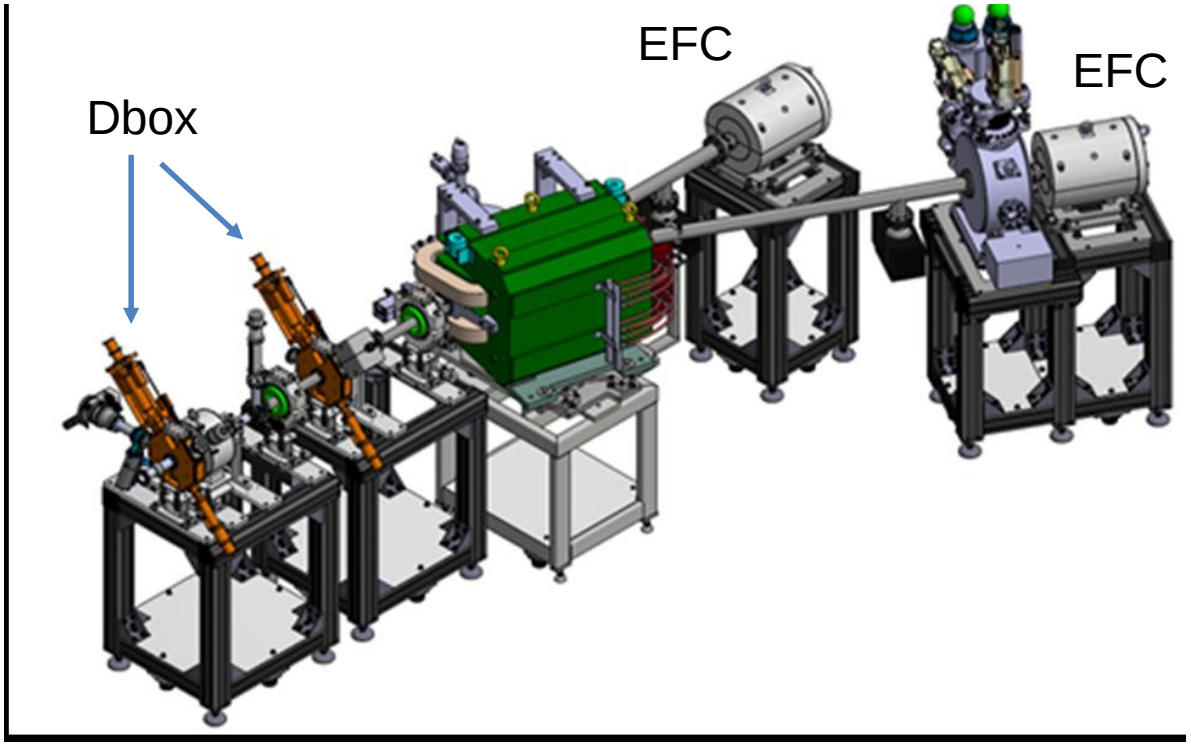


Cantero et al, THE STATUS OF BEAM DIAGNOSTICS FOR THE HIE-ISOLDE LINAC AT CERN, Proceedings of IPAC 2014, WEPF13

https://www.a-v-s.es/areas/accelerators

Faraday Cup

- **2 Dboxes used in a BD Test Bench**
  - 6cm flange to flange length!
  - Suitable for proton beam up to 40MeV
  - 1FC + 1 H+V Slit Blade



- **Transverse beam emittances (Slit+Slit+FC)**

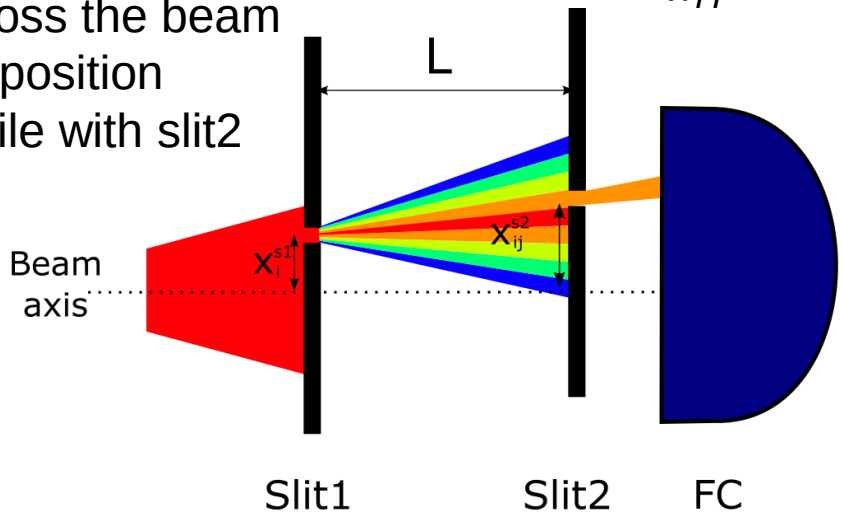
A.Jeff et al, A DIAGNOSTIC TEST BENCH FOR THE LIGHT ACCELERATOR, Proceedings of IPAC 2018, doi:10.18429/JACoW-IPAC2018-WEPAF001
A.Degiovanni et al., STATUS OF THE COMMISSIONING OF THE LIGHT PROTOTYPE, Proceedings of IPAC 2018, doi:10.18429/JACoW-IPAC2018-MOPML014
V.Dimov et al., BEAM COMMISSIONING OF THE 750 MHz PROTON RFQ FOR THE LIGHT PROTOTYPE, Proceedings of IPAC 2018, doi:10.18429/JACoW-IPAC2018-TUPAF002

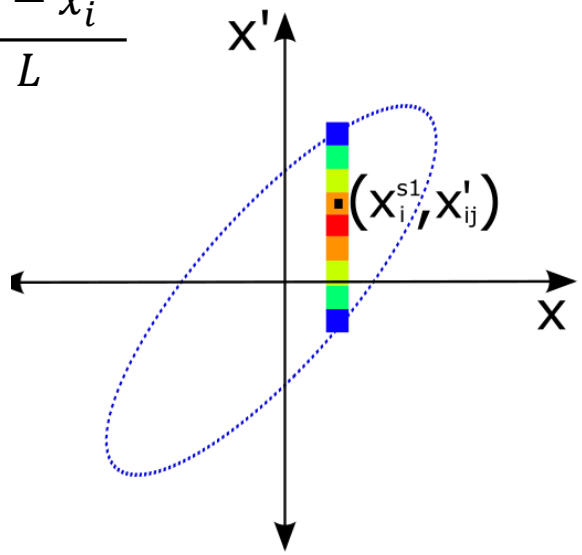
Direct transverse emittance measurement: phase space

Procedure for the Slit+Slit+FC method:

1. Move slit1 across the beam
2. For each slit1 position
   - beam profile with slit2

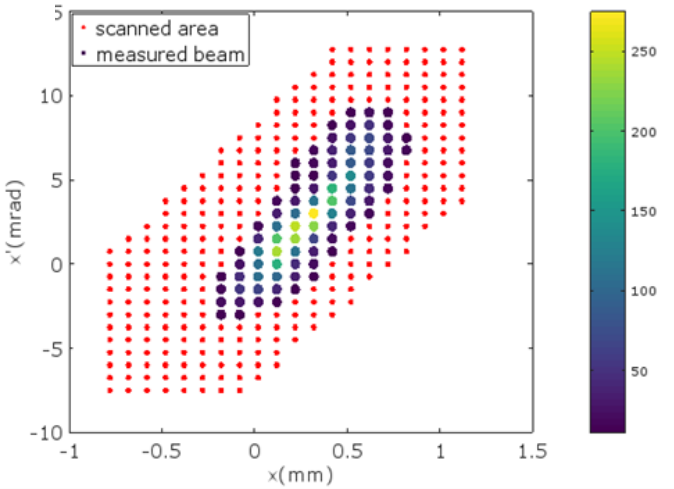
$$x'_{ij} = \frac{x_{ij}^{s2} - x_i^{s1}}{L}$$





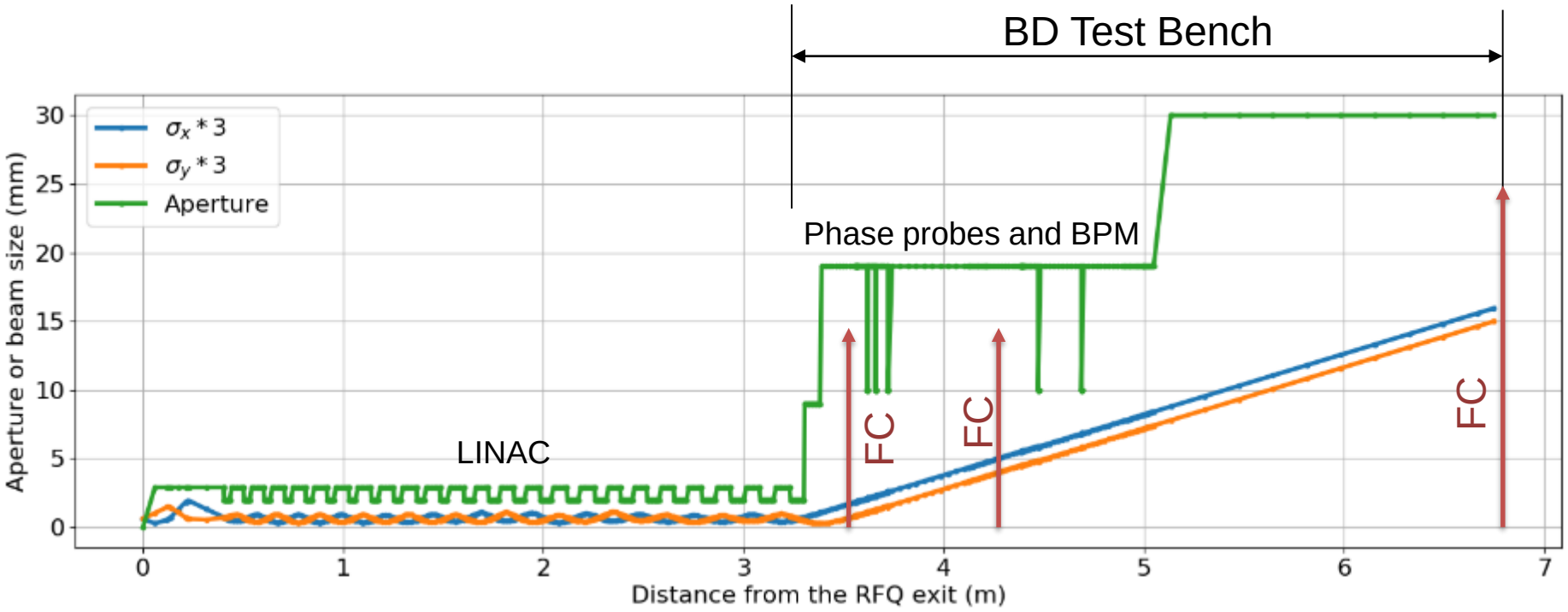
Considerations:

- **Time consuming** → phase space area to measure can be **minimized**
- Resolution (**Slit aperture**) has to deal with FC electronics resolution
- If the emittance is **small** need precise mechanics, actuators and sensitive electronics



Courtesy of V.Dimov

Sizing correctly the apertures in a BD Test Bench



- Simulation of beam size 3sigma compared with apertures
- A margin should be added to take into account beam errors in x-x' y-y'

If particles fall onto BPM electrodes → wrong position reading
If 3σ>FC radius →wrong ibeam reading → wrong transmission and charge

Capacitive pickups:
Beam Position Monitor and Phase Probe

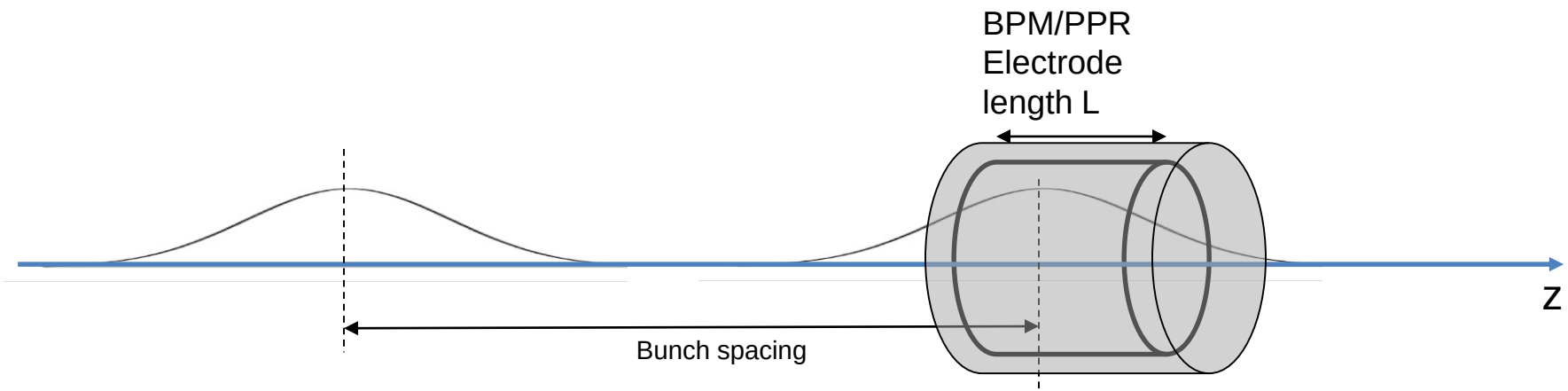
Capacitive Pickup: BPM or Phase Probe (PPR)

Image Current on the electrode

$$I_{im}(t) = \frac{dQ_{im}(t)}{dt} = -\frac{dQ_{beam}(t)}{dt} = -\frac{l}{\beta c}\frac{dI_{beam}(t)}{dt}$$

- Proportional to the **derivative** of **instantaneous beam current (bunch)**
- **Independent** on electrode **aperture** (up to a certain extent)
- Signal **higher** for **slow** beam and/or **long** detector (**l=length**)
- *L* Cannot be too long for machine compactness and also because:

$$l < Bunch\ spacing = \frac{\beta c}{f_{rf}}$$

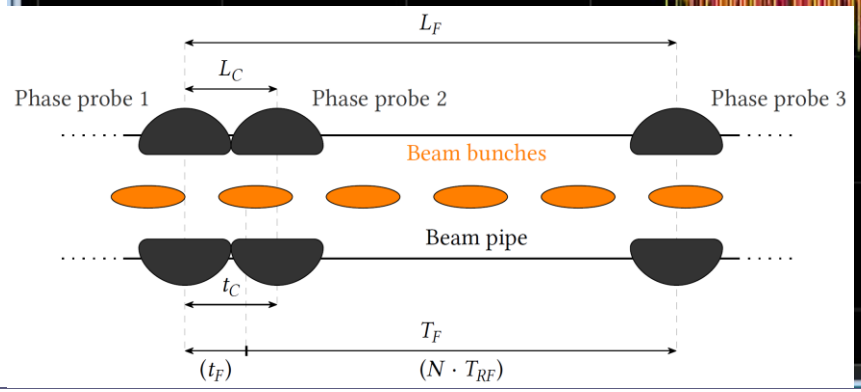


Beam Energy Measurement: Time of flight with Phase Probes

$\beta c = L_F / T_F = 1.2\text{m}/40\text{ns} \rightarrow \beta = 0.1 \rightarrow E = 5\text{MeV}$

The uncertainty on where to place the cursors introduce a considerable error

40ns?

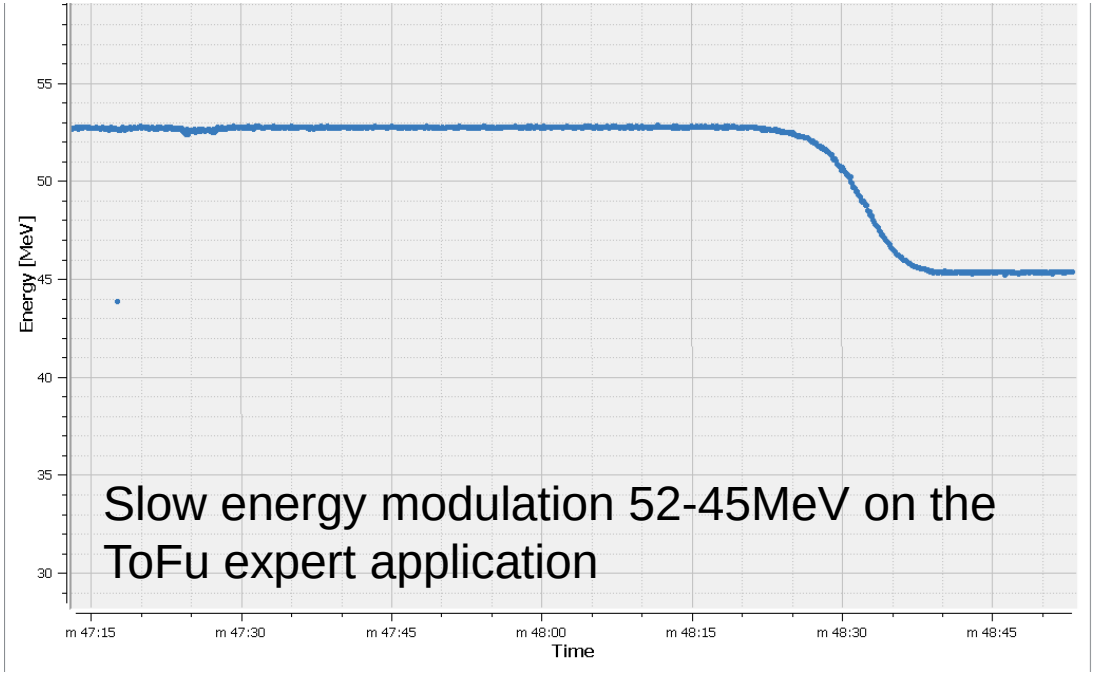


ToF should be measured here!
That is why a 3rd probe is needed, to give a rough estimation of E

▪ 50ns/div

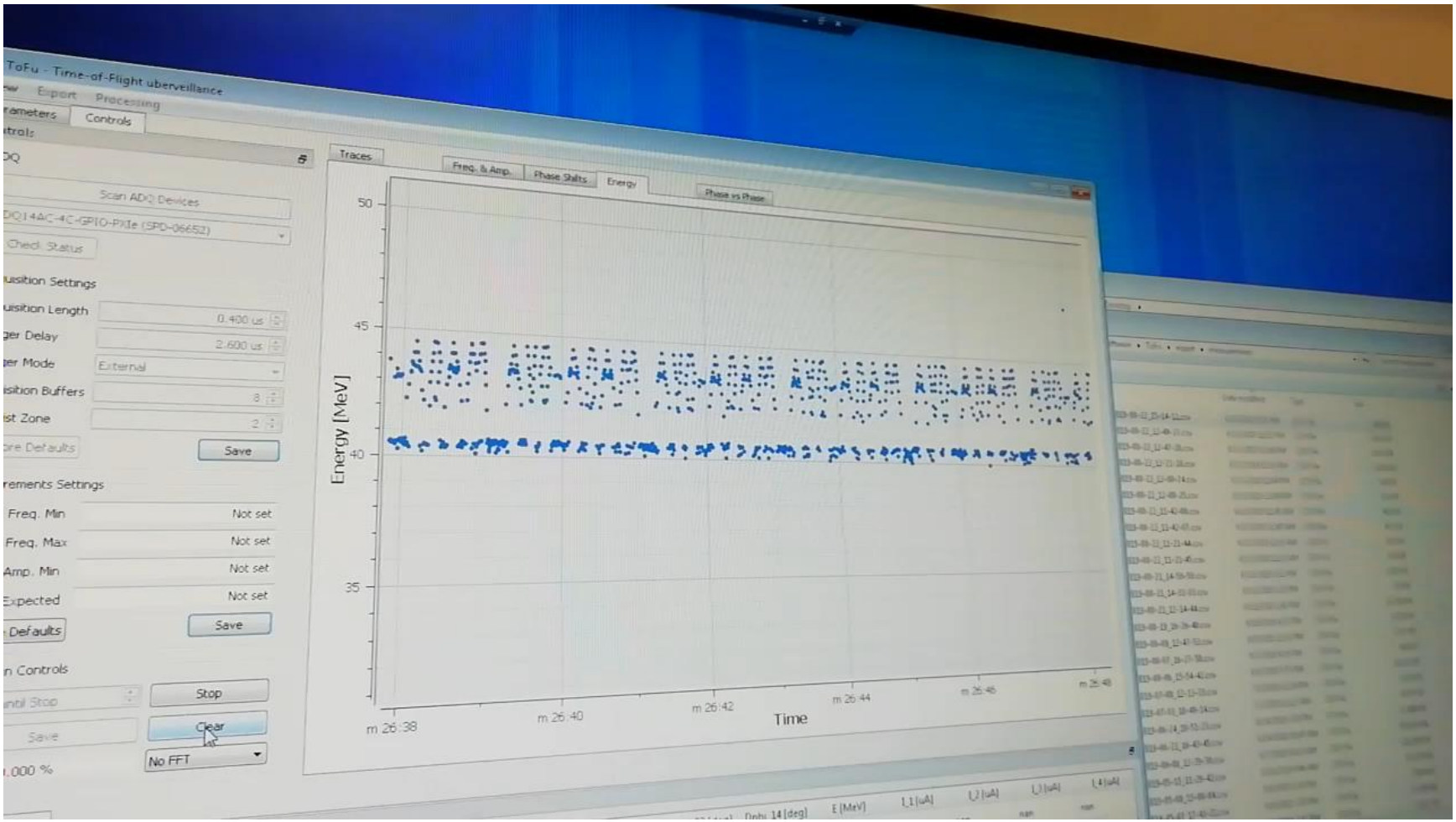
Beam Energy Measurement: Time of flight

- **Three** PPR configuration, **calibration** feature, ADC+FPGA
- Energy range **5-230MeV**
- Energy resolution of **0.03%** (0.2mm at 230MeV in water)
- Energy result available in **1-2ms**
- IQ down-conversion in FPGA to obtain phase differences



F.Galizzi, M.Caldara, and A.Jeff, A TIME-OF-FLIGHT BASED ENERGY MEASUREMENT SYSTEM FOR THE LIGHT MEDICAL ACCELERATOR, Proceedings of IPAC 2018, doi:10.18429/JACoW-IPAC2018-THPML119

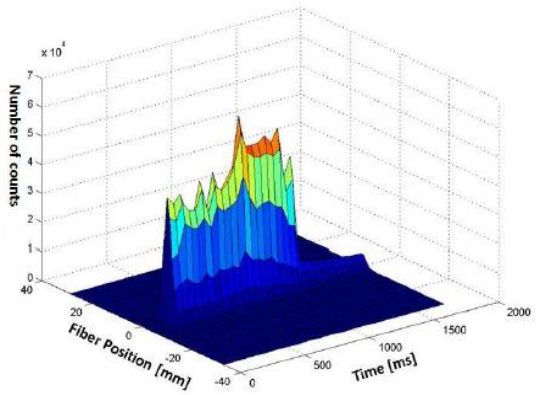
Beam Energy Modulation with LLRF amplitude at 100Hz!



HEBT Profiler based on scintillating fibres: CNAO experience

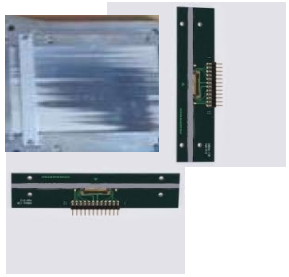
- CNAO is currently using **SFH** along the HEBT as profile monitors
- Both based on **128x0.5mm** square adjacent fibres with cladding per plane
- **SFP** is a more compact, higher performance, cheaper profiler

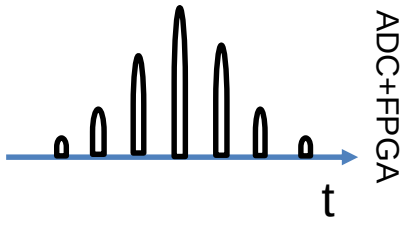
SFH or SFX (MedAustron)

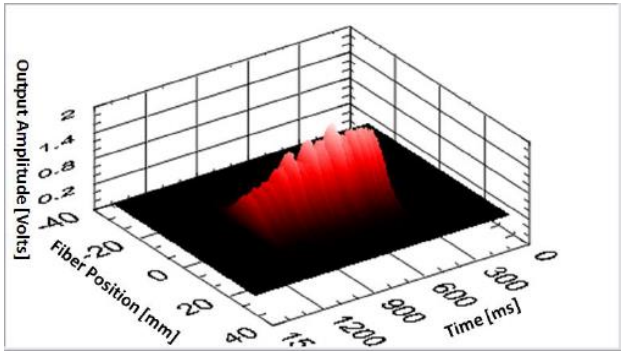


Spill of 1e8 p 65MeV
20Hz H profiles

SFP





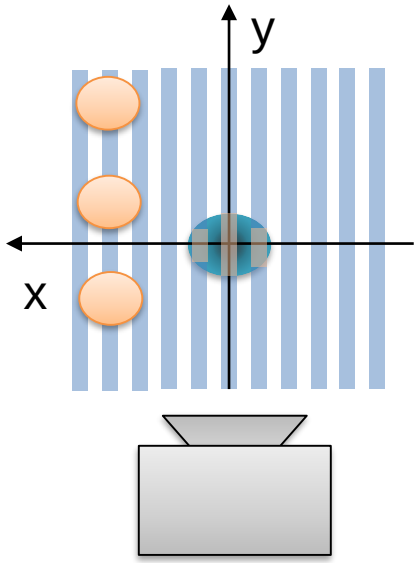


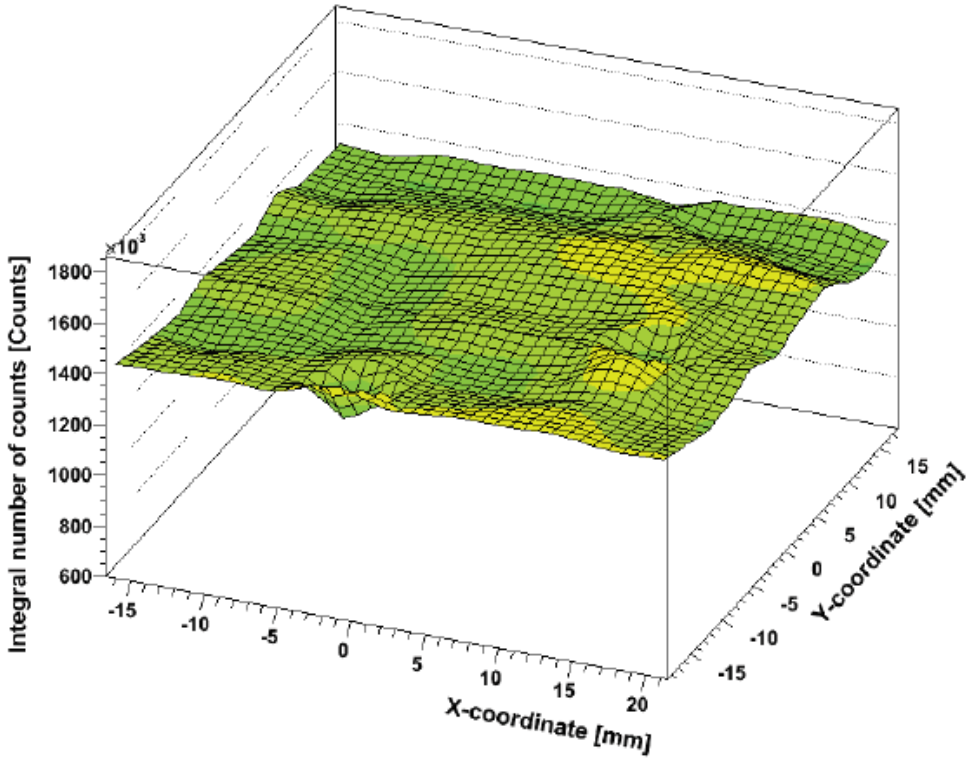
Spill of 1e8 p 111MeV
300Hz H profiles

E. Rojatti, SCINTILLATING FIBERS USED AS PROFILE MONITORS FOR THE CNAO HEBT LINES, Proceedings of IPAC 2015, doi:10.18429/JACoW-IPAC2015-MOPHA051

Ionizing radiation effect on SFH

- After few years operation **decrease** in performance of **most irradiated** fibres was observed (**less light yield** and **transparency**)
- Need to **recalibrate** the detector
- Technique: scanning active area with **beam + scanning magnets at isocentre**



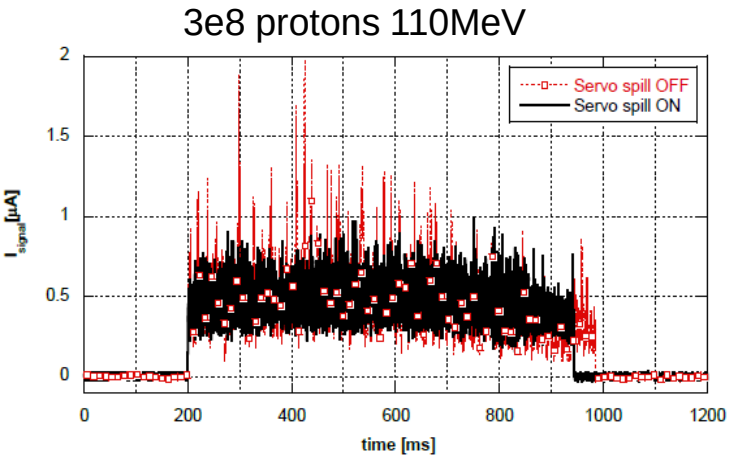


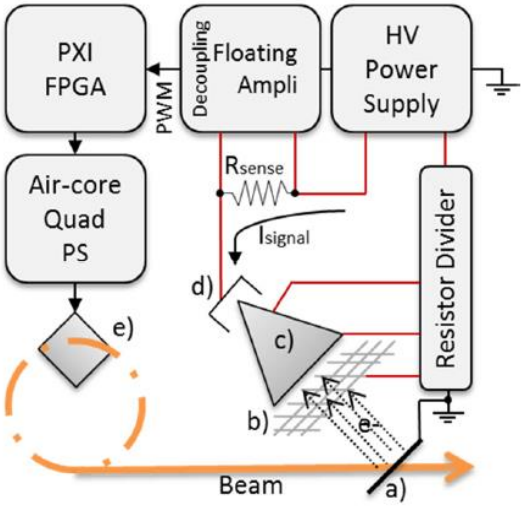
E.Rojatti et al., STUDY OF THE RADIATION DAMAGE ON A SCINTILLATING FIBERS BASED BEAM PROFILE MONITOR, Proceedings of IBIC2016, TUPG68

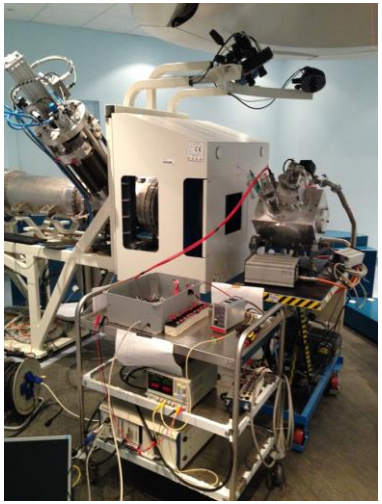
Ultra thin Fast Intensity Monitor at CNAO

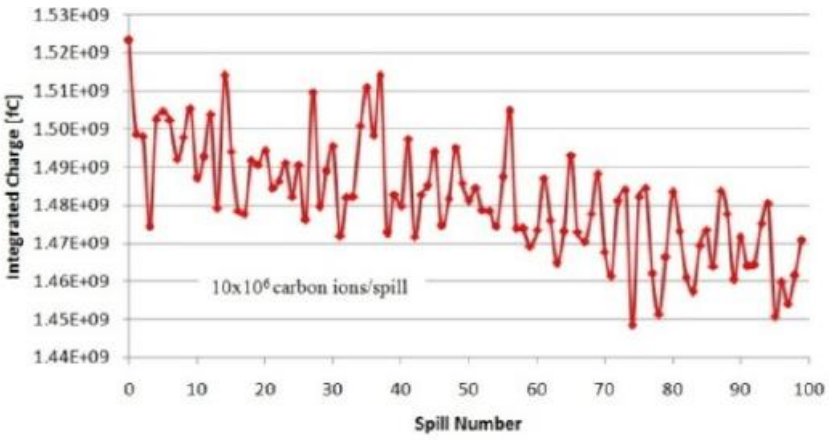
Aim: to measure the spill intensity ripple and mitigate it with air-core quads in the ring

- **Uniform** beam extraction **minimize** beam aborts from Nozzle → faster treatments
- **0.8um** metallic foil → ~OK during treatment
- Secondary **e** attracted and amplified
- **Real-time** processing and **feedback** to Quad PS
- Issue: slight decrease of the integrated charge over the spills





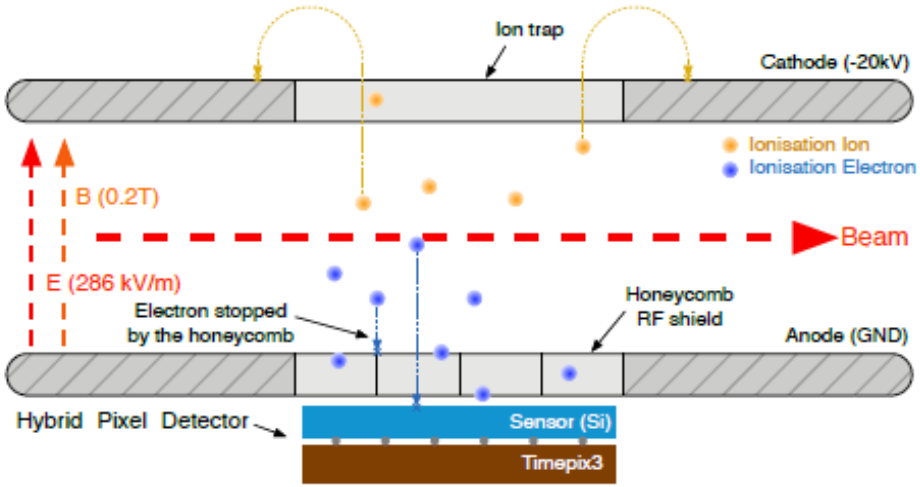


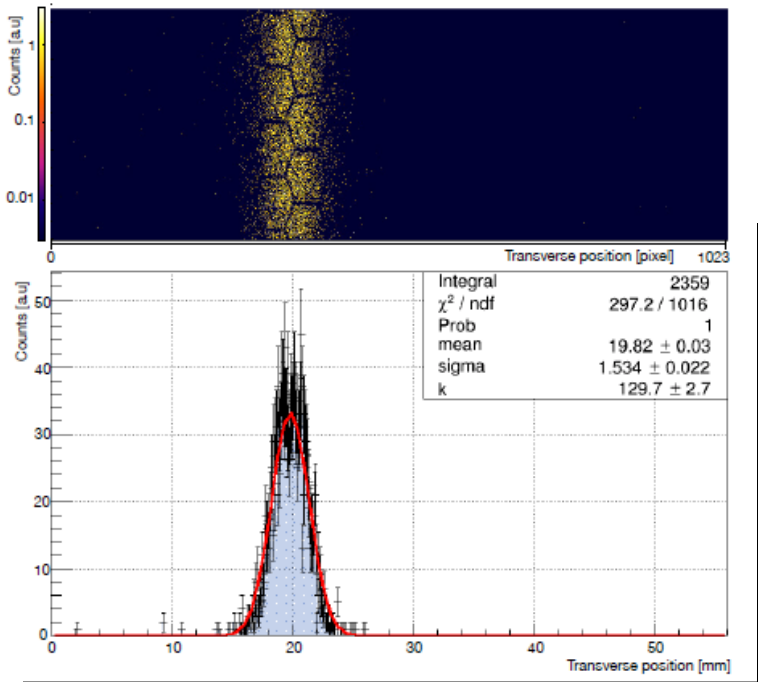


doi:10.18429/JACoW-IPAC2018-WEPAF025

Not-interceptive Profiler: RGM with Timepix3

- **Operated in a vacuum of 2e-10mbar!**
- **The beam ionizes rest gas and electrons are directed to the detector**
- **Silicon pixel detector bonded to Timepix3**
  - If the charge overpasses a threshold an event is created:
    - Pixel location
    - Timestamp
    - Time over threshold

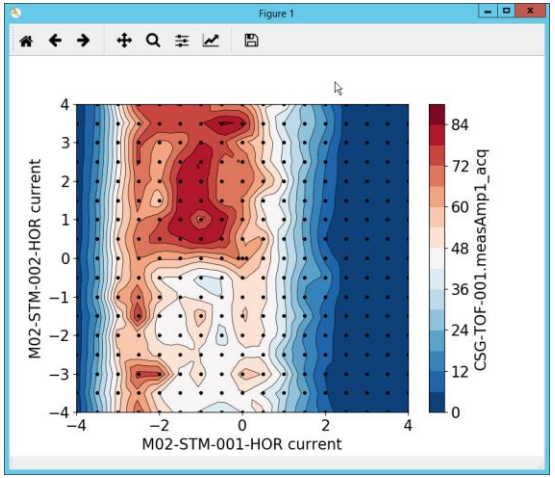




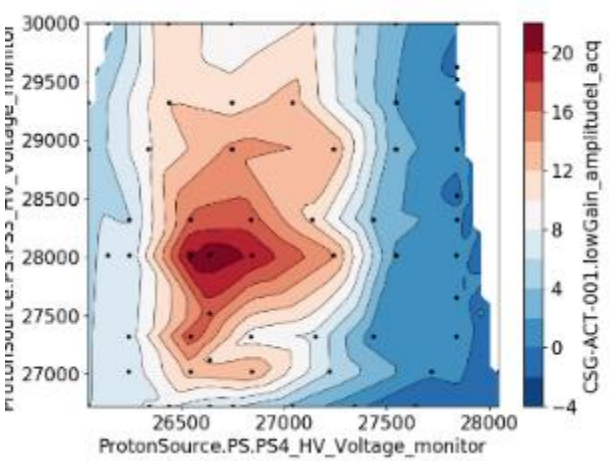
S. Levasseur, TIME-RESOLVED TRANSVERSE BEAM PROFILE MEASUREMENTSWITH A REST GAS IONISATION PROFILE MONITOR BASED ONHYBRID PIXEL DETECTORS, Proceedings of IPAC2018, doi:10.18429/JACoW-IPAC2018-WEPAL075

The beauty of colour plots: BD instrument is the observable

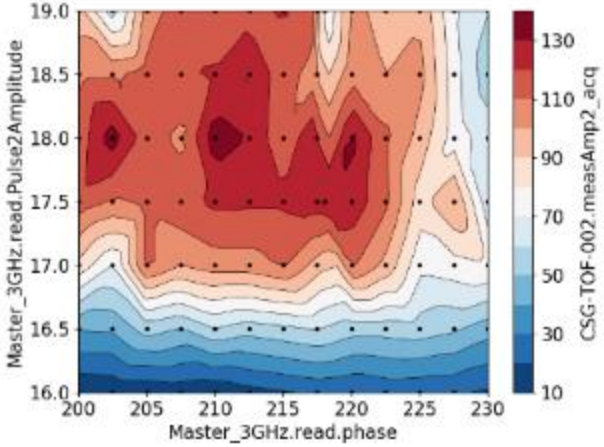
- During commissioning and operation BD integrated in sw procedure is a **must**



Knobs: 2 hor steerers
Observable: Phase Probe amplitude mV



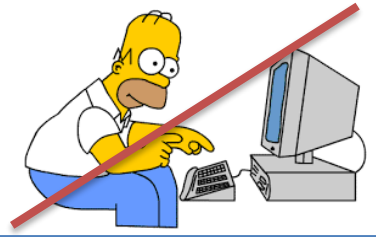
Knobs: 2 source power supplies
Observable: ibeam [uA] from ACCT



Knobs: LLRF amplitude and phase
Observable: Phase Probe amplitude mV

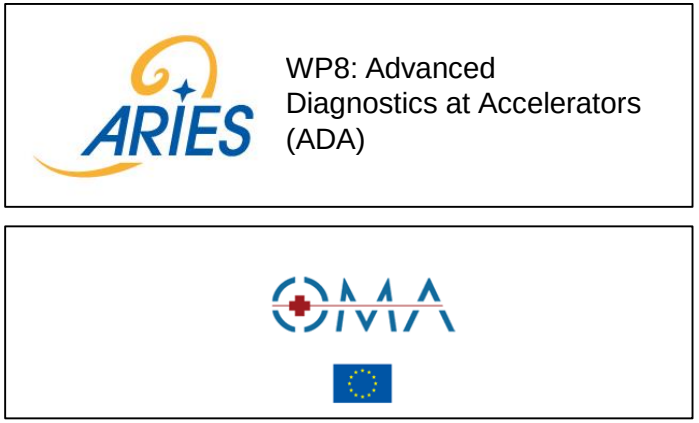
Should we profit of the machine learning – AI trend?

The proton source for ESS has been commissioned with automatic procedure and a genetic algorithm optimization code able to automatic tune the source towards a precise current value and stability.

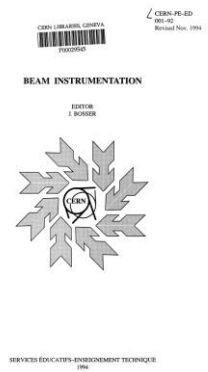


L. Neri, et al., “High level control system code with automatic parametric characterization capabilities”, Proc. ICALEPS2017, Barcelona, Spain, paper THPHA035

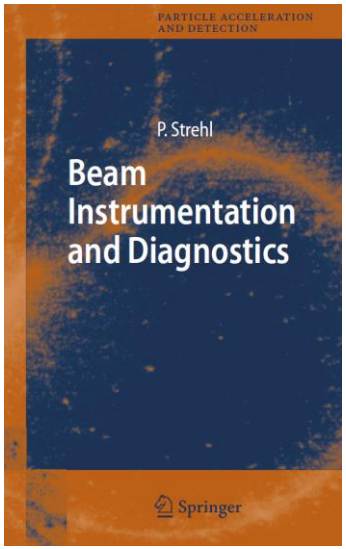
References



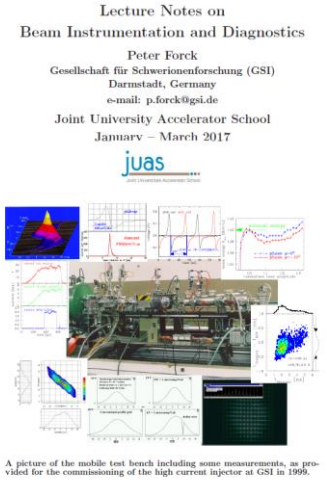
- **[1]** J.Bosser, Beam Instrumentation



- **[2]**



- **[3]**



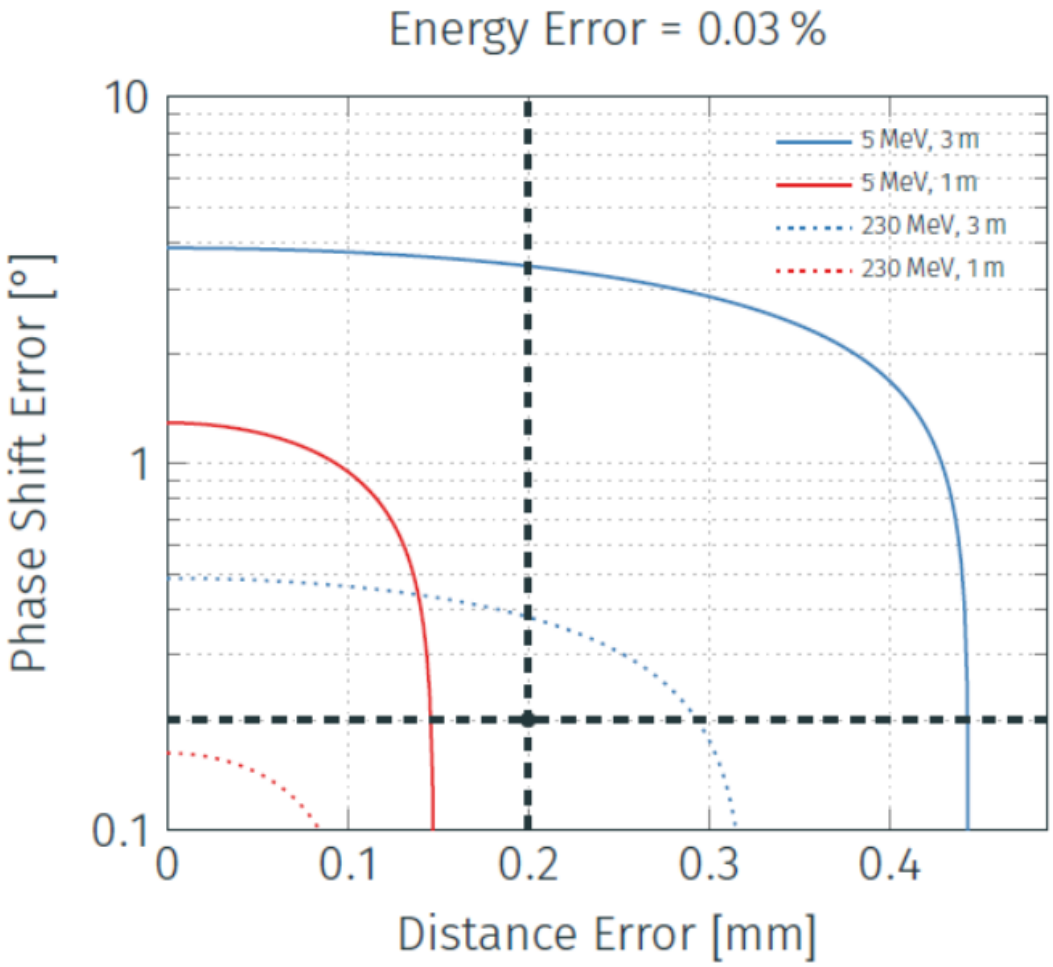
Final remarks

- **Hadron therapy machines should have >95% uptime (during treatment)**
  - **Not interceptive** BD instrumentation running during treatment can predict a fault?
  - In case of a problem, have **procedures, BD instruments and SW** ready for fast debugging
- **BD is not just taking measurements → Data analysis!**
  - Prepare scripts in advance
  - Reserve time for analysis (better just after data taking)

Thanks for the attention!

Backup slides

Backup ToF



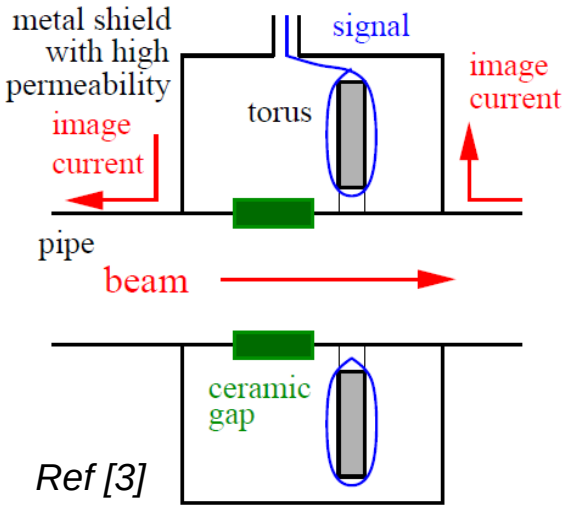
2m distant probes are sufficient to achieve the Energy resolution!

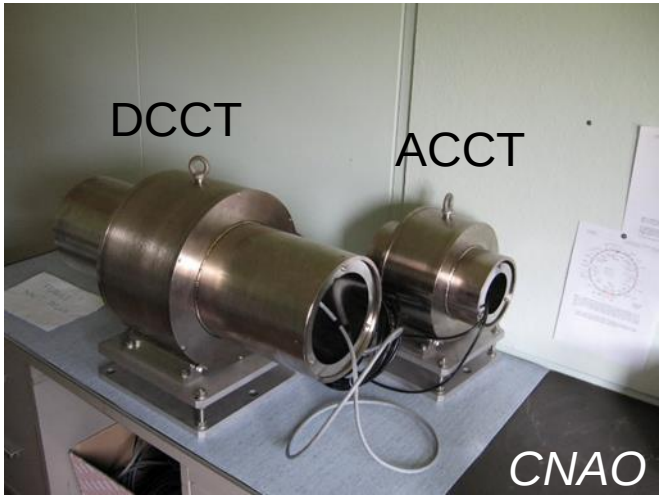
Backup SNR

- $N_i \left[\frac{dBm}{Hz}\right] = N_o \left[\frac{dBm}{Hz}\right] - NF - G_{dB}$

Beam Current Transformers optimization

- **If some longitudinal space is available a magnetic shielding is the optimal solution**
  - Sources of unwanted B field: **magnets fringe field or EMI**
  - Needs **in-air** sensors
  - Needs vacuum chamber with **ceramic break** and **external path for beam pipe image current**





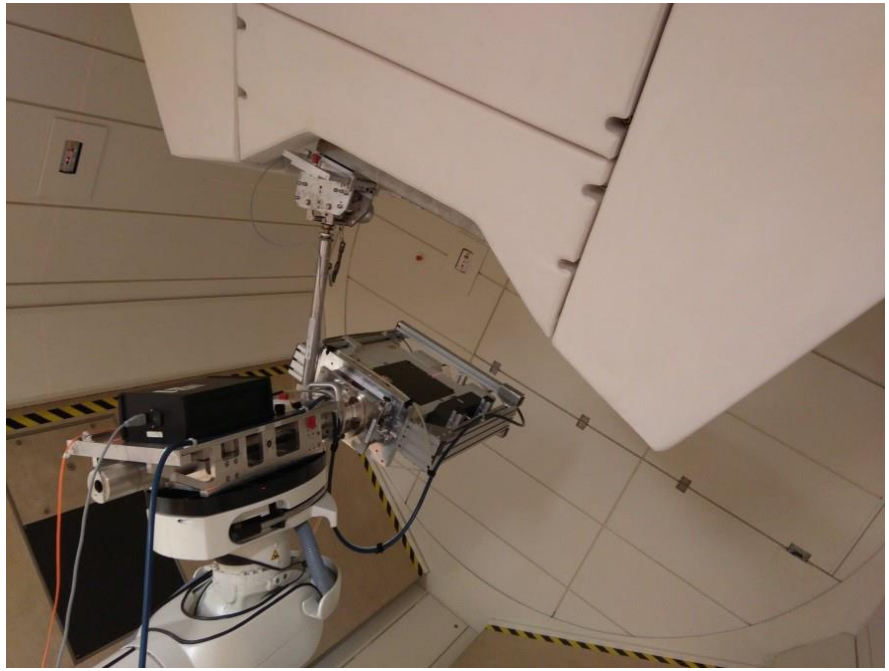
Scintillators based instruments: QA monitor at HIT

Determine beam properties at isocentre in gantry room is complex (=time consuming)

- **Beam Position (allowed abs. deviation < 1 mm)**
- **Beam Width (allowed deviation < +25%, > -15%)**

A different approach is under study:

- Conical scintillator screen + camera
- Axial symmetry (cone axis parallel to gantry axis)



HIT
Heidelberger Ionenstrahl-Therapiezentrum

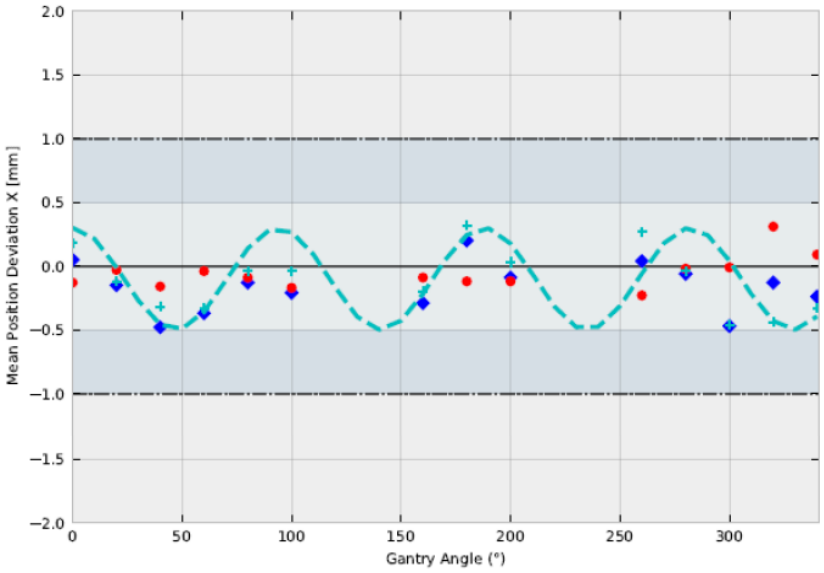
Andreas.Peters@med.uni-heidelberg.de

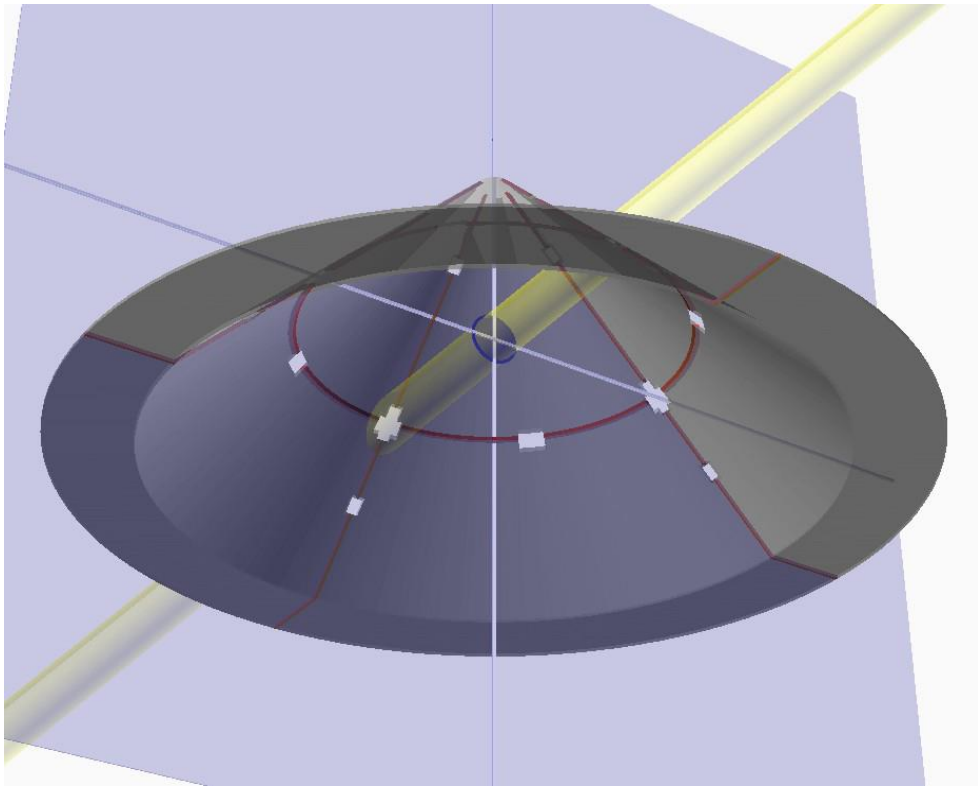
https://indico.cern.ch/event/765975/contributions/3370885/attachments/1821630/2979755/UsageOfScintillationScreensAtMedicalFacilityHIT_final_pdf-version.pdf

Updates from HIT

Aim:

1. to deduce a beam profile, center of gravity and direction from entrance and exit images;
2. reconstruct the isocenter of the gantry with beam images from different angles
3. characterize the beam much faster than today





HIT
Heidelberger Ionenstrahl-Therapiezentrum

https://indico.cern.ch/event/765975/contributions/3370885/attachments/1821630/2979755/UsageOfScintillationScreensAtMedicalFacilityHIT_final_pdf-version.pdf

BPM Upgrade study at CNAO

- **CNAO (and MA) use a CERN-like orbit measurement system**
  - Head amplifier providing Δ and Σ
  - Normalizer (Analog Δ/Σ) at 1kHz
  - i-tech Libera tested to perform **turn by turn** orbit measurements

$$500kHz < f_{rev} < 3MHz$$

Normalizer and distribution amplifier installation

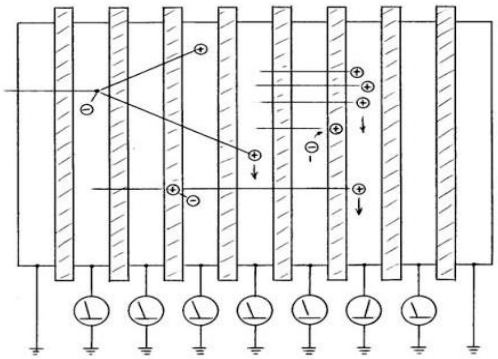
`Libera Spark typically installed close to BPM

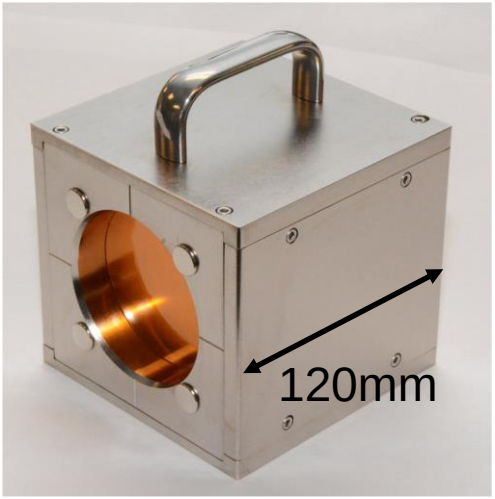
- ADC+processing
- Ethernet interface

M. Znidarcic et al.,TURN-BY-TURN POSITION MEASUREMENTS AT CNAOWITH THE LIBERA SPARK HR PROTOTYPE, Proceedings of IPAC 2018, doi:10.18429/JACoW-IPAC2018-WEPAF024

Multilayer Faraday Cup (MLFC) or Range Verifier or Multi-leaf FC

- Used in QA or as a Beam Dump
- In-air, needs a vacuum window and rad shielding
- Beam current and energy (+ approx. energy spread)
- Resolution is a compromise between N channels and foils thickness
  - 128 layers (0.508 mm thick=65mm) enable meas in range 50-250MeV
  - 0.5mm Cu ≅ 2.5mm H_2O
- Electronics has 128 ch integrators
  - For ibeam avg need to integrate for 1s
  - For pulsed beam integrate for bit more than pulse, but then need to know Dt



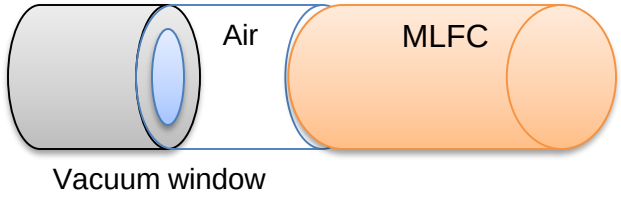


C. Kunert et al, A MULTI-LEAF FARADAY CUP ESPECIALLY FOR PROTON THERAPY OF OCULAR TUMORS, Proceedings of Cyclotrons2013, TH2PB04

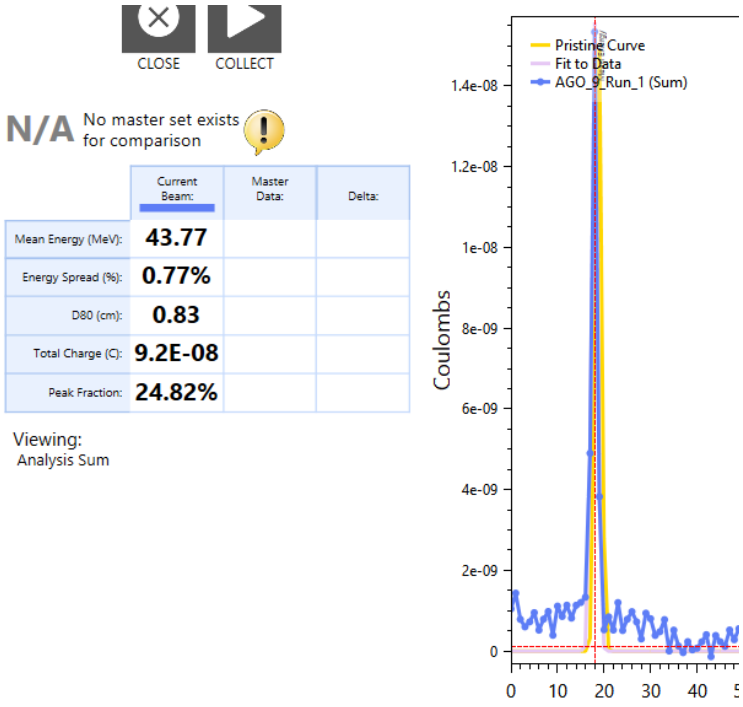
http://www.ptcusa.com/files/datasheet/MLFC-128-250_DS_150316.pdf

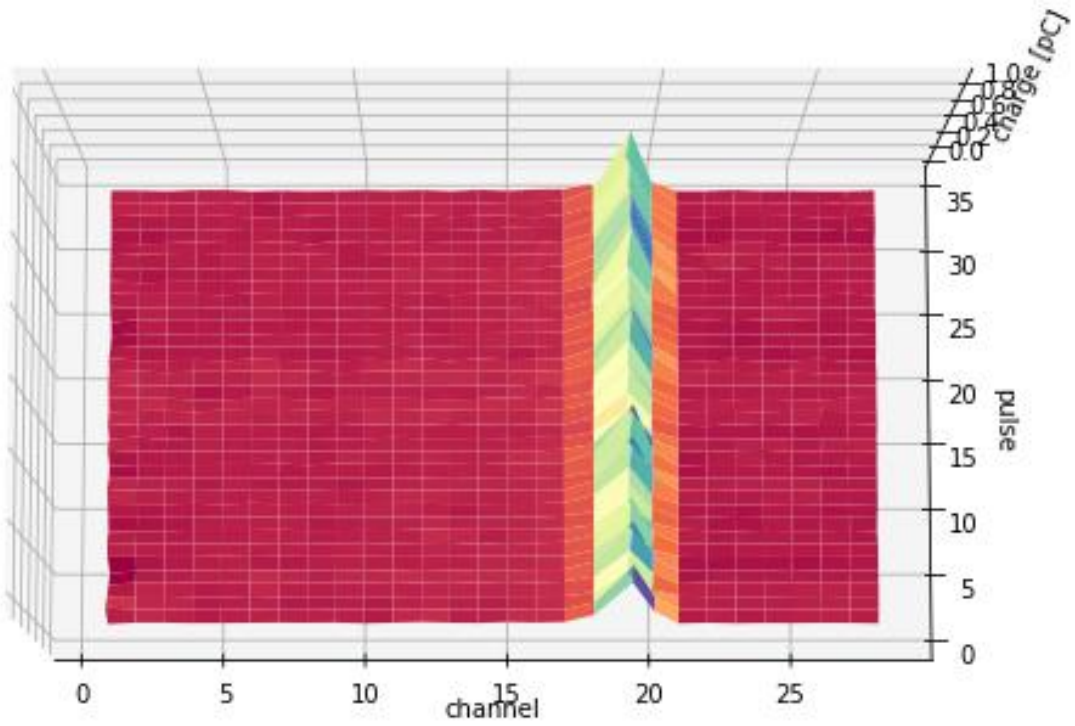
MLFC optimization

- **Need to evaluate contribution of upstream material**
  - Specs of the window and length of air sector
  - http://www.srim.org/

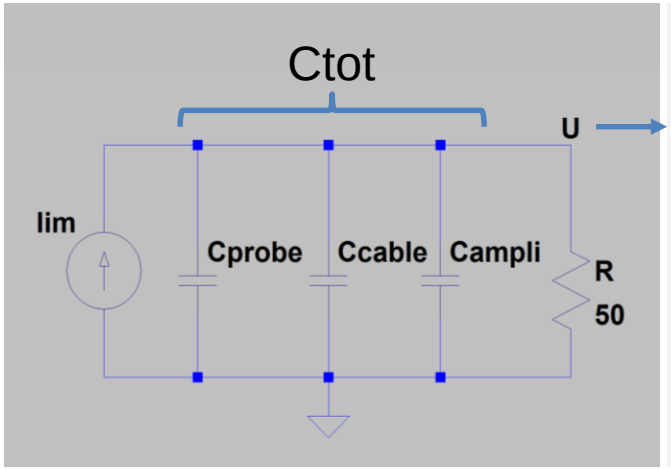


- **Use interpolation or weighted average to get the energy**





Signal formation into a BPM or PPR



$$U(s) = Z(s) \cdot I_{im}(s) = \underbrace{\frac{A}{2\pi a}\frac{1}{\beta c}}_{\text{L for a PPR}}\frac{1}{C_{tot}}\frac{sRC_{tot}}{1+sRC_{tot}} \cdot I_{beam}(s)$$

- U = voltage signal at amplifier input, can be computed once **Ibeam is known**
- **U/Vin_noise >> 1 for all energies and intensities in order to use BPMs and PPRs**
- Good practice to **maximize** SNR: minimize **Ctot** (**short cables**!) and choosing **low noise amplifiers (low noise figure NF)**