International Workshop on Future Linear Colliders 2014 (LCWS14)

Status of Beam Loss Monitoring system for the CLIC Two-Beam Module and Damping Rings

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Motivation

- Compact Linear Collider (CLIC): Large nominal power (Drive Beam 70 MW, Main Beam 14 MW)
- Loss of a small fraction of the beam → severe impact on accelerator components

Beam Loss Monitors:

→ Machine Protection

- Detect potentially dangerous instabilities → destruction of the surrounding materials, activation of the accelerator components
- Prevent subsequent injections into the Main Beam Linac and the Drive Beam decelerators

→ Beam Diagnostics

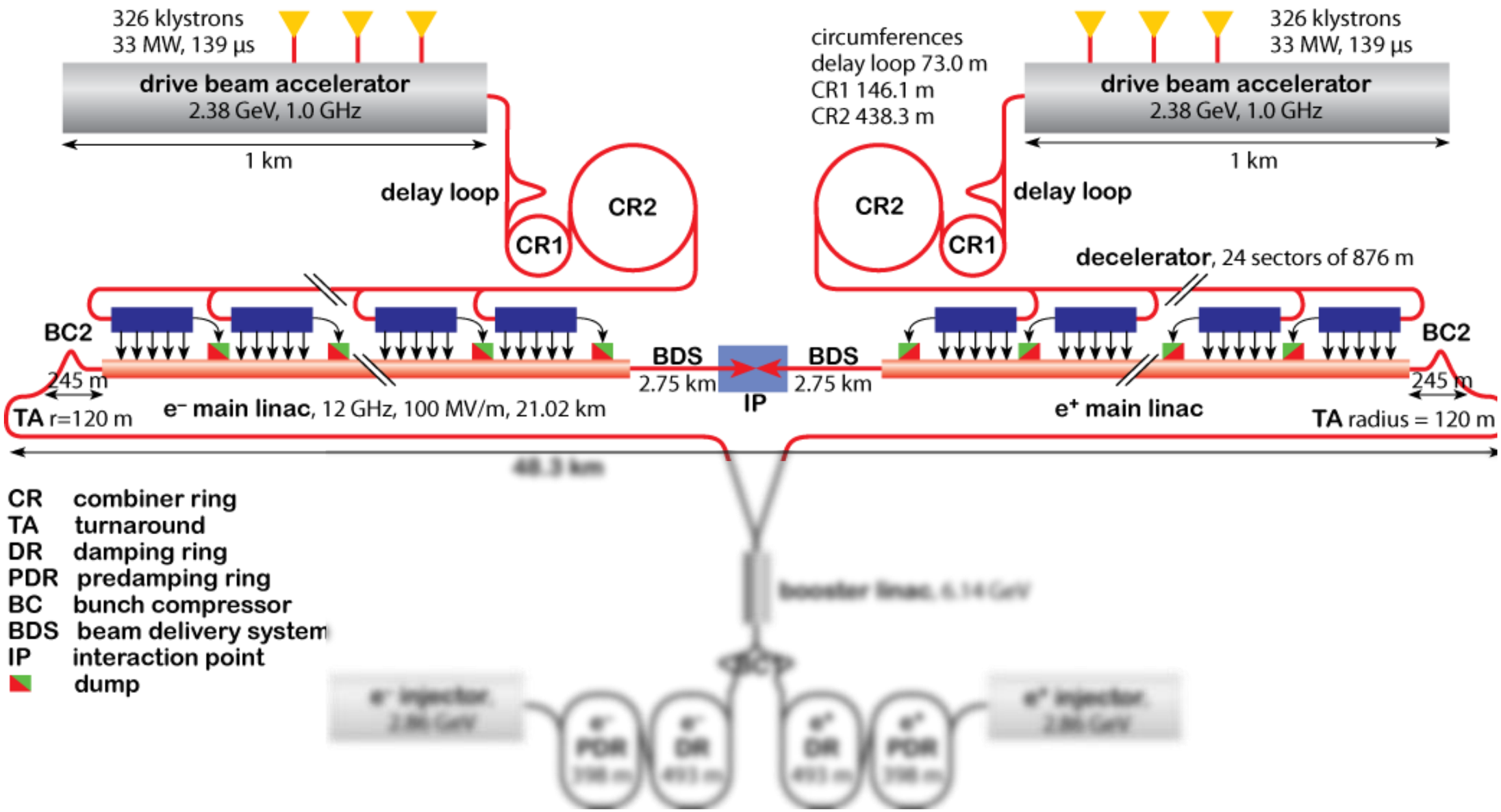
- The fraction of beam particles lost has to be carefully controlled to achieve good beam transmission
- Localise and characterise the Beam Loss distribution

Outlook

- BLM system for the Two-Beam Module (TBM):
  - Requirements
  - Detector Technology choice: Ionisation Chambers (IC), Diamonds and Quartz Crystals
  - Optical fibre based BLM (OBLM) system: Challenges
    - Radiation Hardness
    - Choice of photon sensors
  - BLMs at the Test Beam Line (TBL): Measurements and Monte Carlo model
  - Installation at the dogleg experiment and first measurements
  - Installation at the TBM and BLM program

- First look at Damping Rings
  - Considerations for detector technology choice
  - Measurements at Australian Synchrotron
  - Sensitivity studies
  - OBLM single shot calibration
  - User fill measurements (Topup injections)
  - Dynamics (CLIC-like fill scans)

- Summary and conclusions


326 klystrons
33 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
1 km
delay loop
CR1
CR2
circumferences
delay loop 73.0 m
CR1 146.1 m
CR2 438.3 m
326 klystrons
33 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
1 km
CR2
CR1
delay loop
decelerator, 24 sectors of 876 m
BC2
245 m
TA r=120 m
e⁻ main linac, 12 GHz, 100 MV/m, 21.02 km
BDS
2.75 km
IP
BDS
2.75 km
e⁺ main linac
BC2
245 m
TA radius = 120 m
48.3 km
CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump

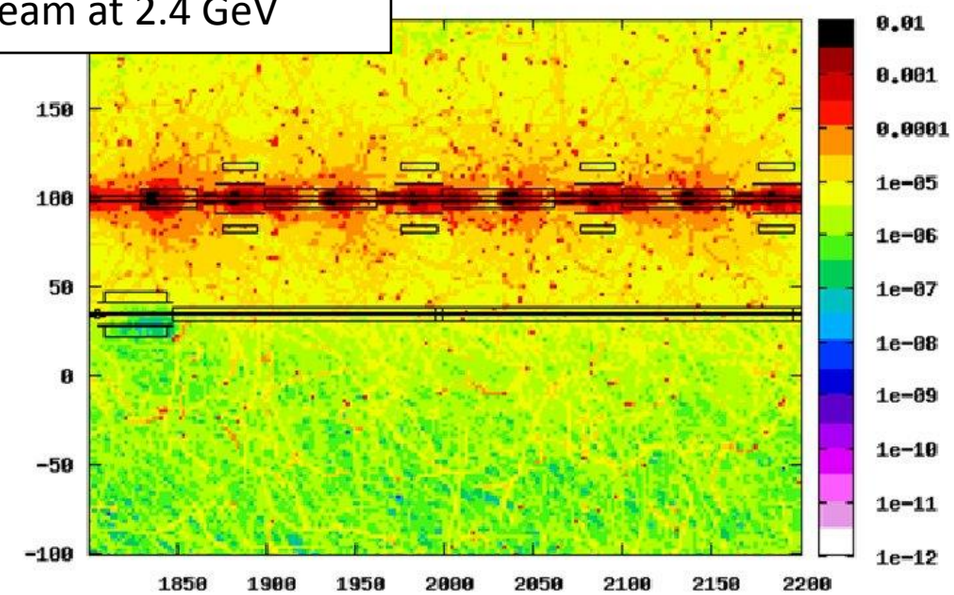
Requirements: A recall

A MULTI-TEV LINEAR COLLIDER BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

- Sensitivity
  - Losses should be controlled to 0.1% to avoid luminosity losses due to beam loading variations
- Dynamic range
  - Detect onset (10%) of dangerous losses
  - 0.1% of DB
  - 0.001% of MB
- FLUKA simulations

Dose in Gray per pulse due to maximal operational losses of the Drive Beam at 2.4 GeV

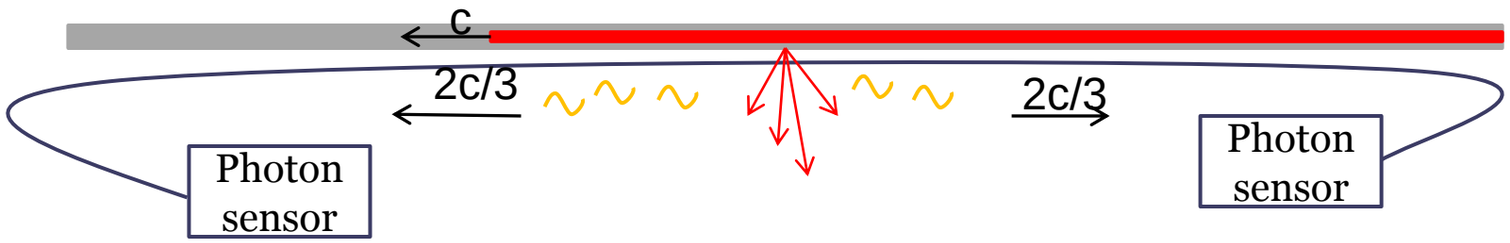


	Sensitivity [Gy]	Dynamic Range
DB 2.4 GeV	10^{-7}	5×10^{5}
DB 0.24 GeV	5×10^{-8}	2×10^{5}
MB 9 GeV (Type 1)	10^{-9}	10^{6}
MB 1.5 TeV (Type 4)	10^{-8}	10^{5}

Detector technology

- A system based on Ionization Chambers **satisfies** the requirements of Machine Protection –(CLIC Conceptual Design Report)
  - LHC (1.5 l N_2): Sensitivity 5.4 x10^{-9} C/Gy (1 pA). DR > 10^{+7}
  - But requires a large number of BLMs (> 40000)

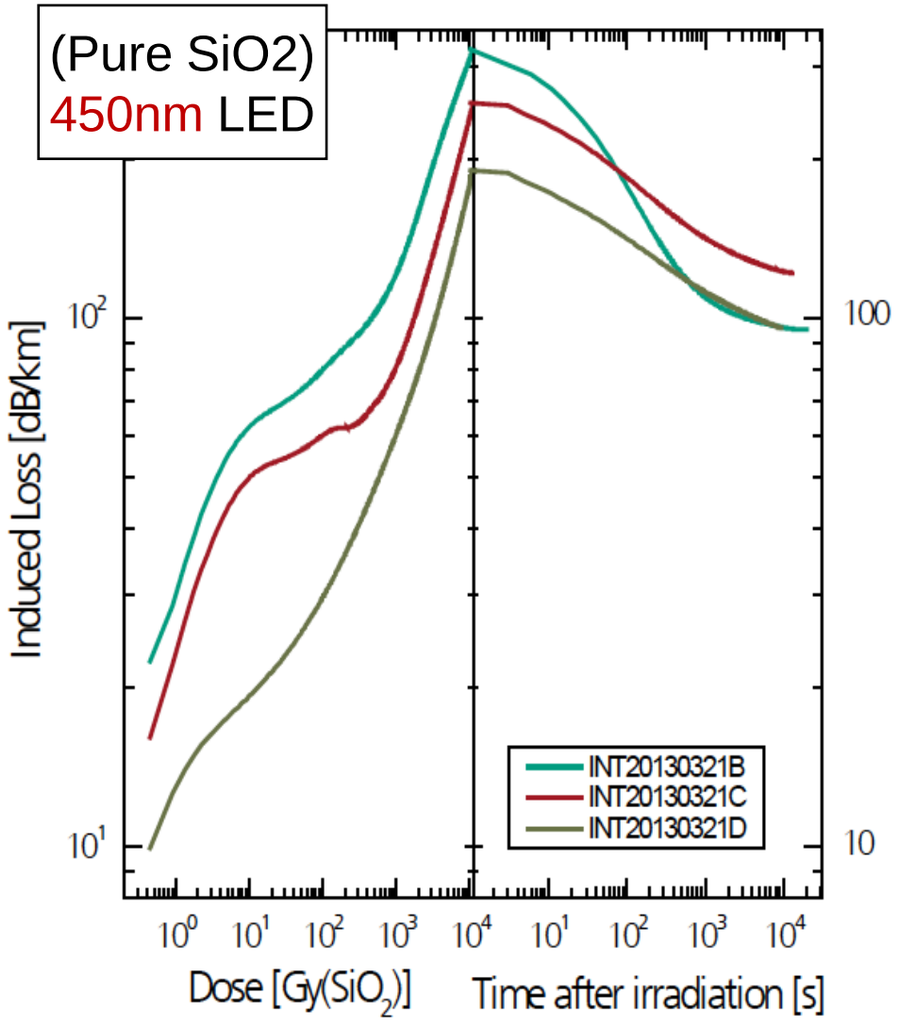
- Optical fibre based BLMs (OBLMs)
  - Pure Silica core multimode fibres as Cherenkov radiators. Both ends of fiber couples to photon-sensors
  - Potential of covering full beam line in a cost-effective way. Position resolution within 30 cm of beam loss has been demonstrated

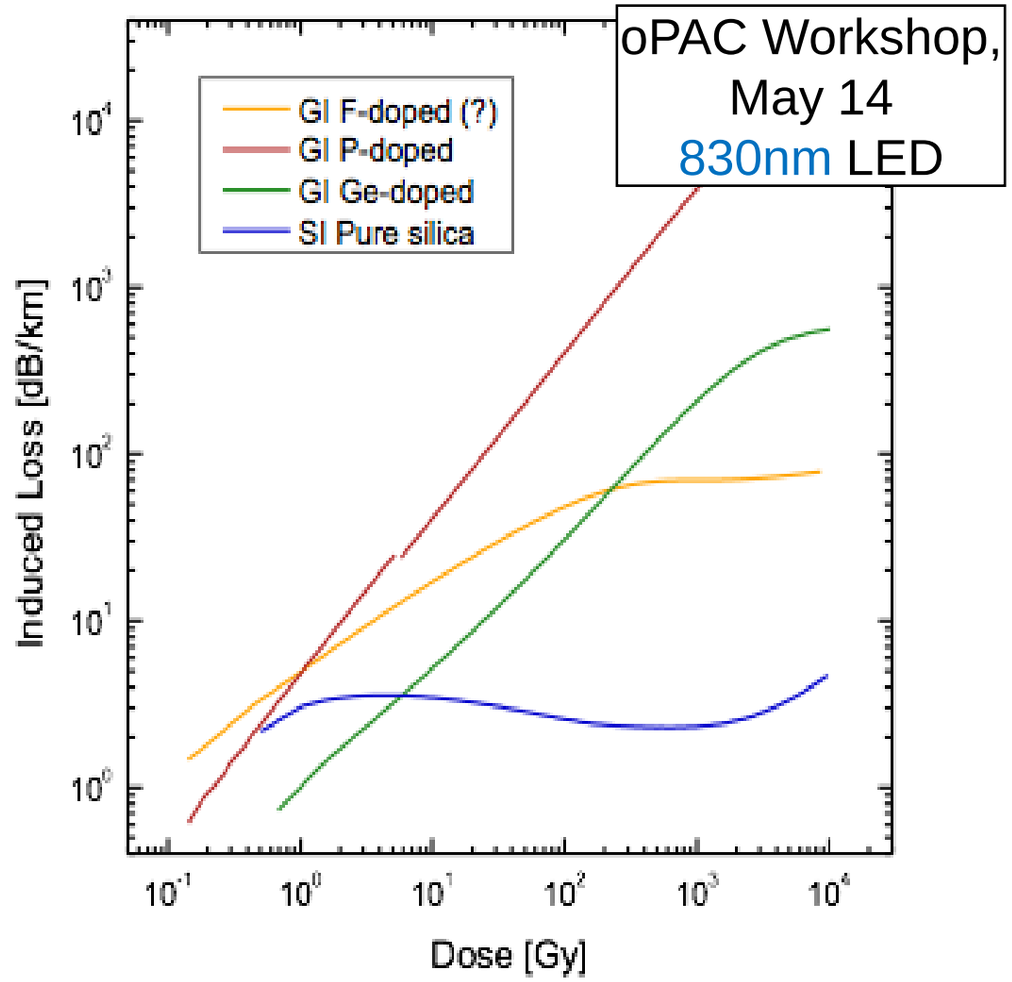


- Fast BLMs (diagnostics oriented): Diamond and Quartz:
  - Diamonds (1 ns): LHC for bunch by bunch beam loss monitoring
  - Quarzt crystals + photon sensor: time response depends on volume of crystal (~50ps/cm^3) and photon sensor. Potential for ultra-fast Beam Loss Monitoring

Cherenkov fibers: Challenges I

- Radiation hardness
  - Material, manufacturer, type of radiation
  - Pure Si core with high OH recommended
  - Radiation Induced Attenuation strongly dependent on λ
  - SiO_2 fibers rather insensitive for 800 nm and above.



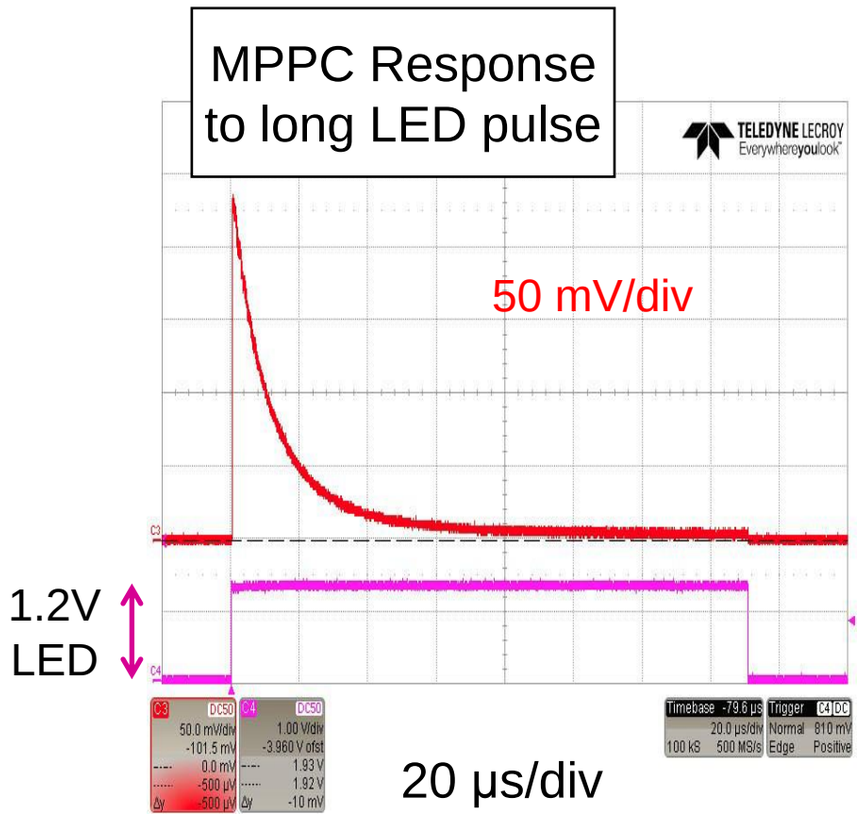


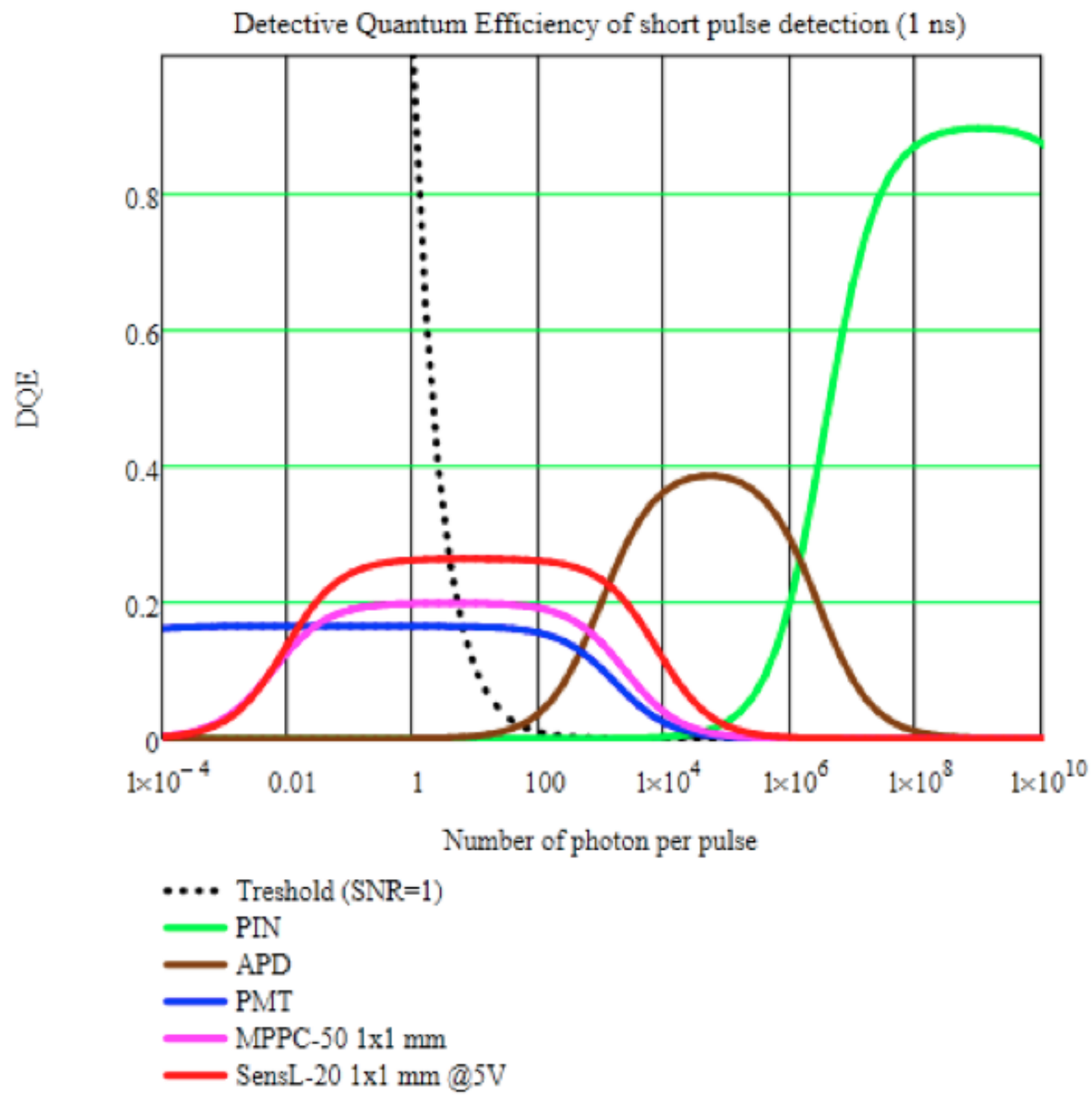
J. Kuhnhenn

Fiber irradiation test at Fraunhofer institute 10kGy@0.22Gy/s

Cherenkov fibers: Challenges II

- Choosing a photon sensor
  - Quantum Efficiency
  - Saturation Effects
  - Time Response
  - Achievable Bandwidth

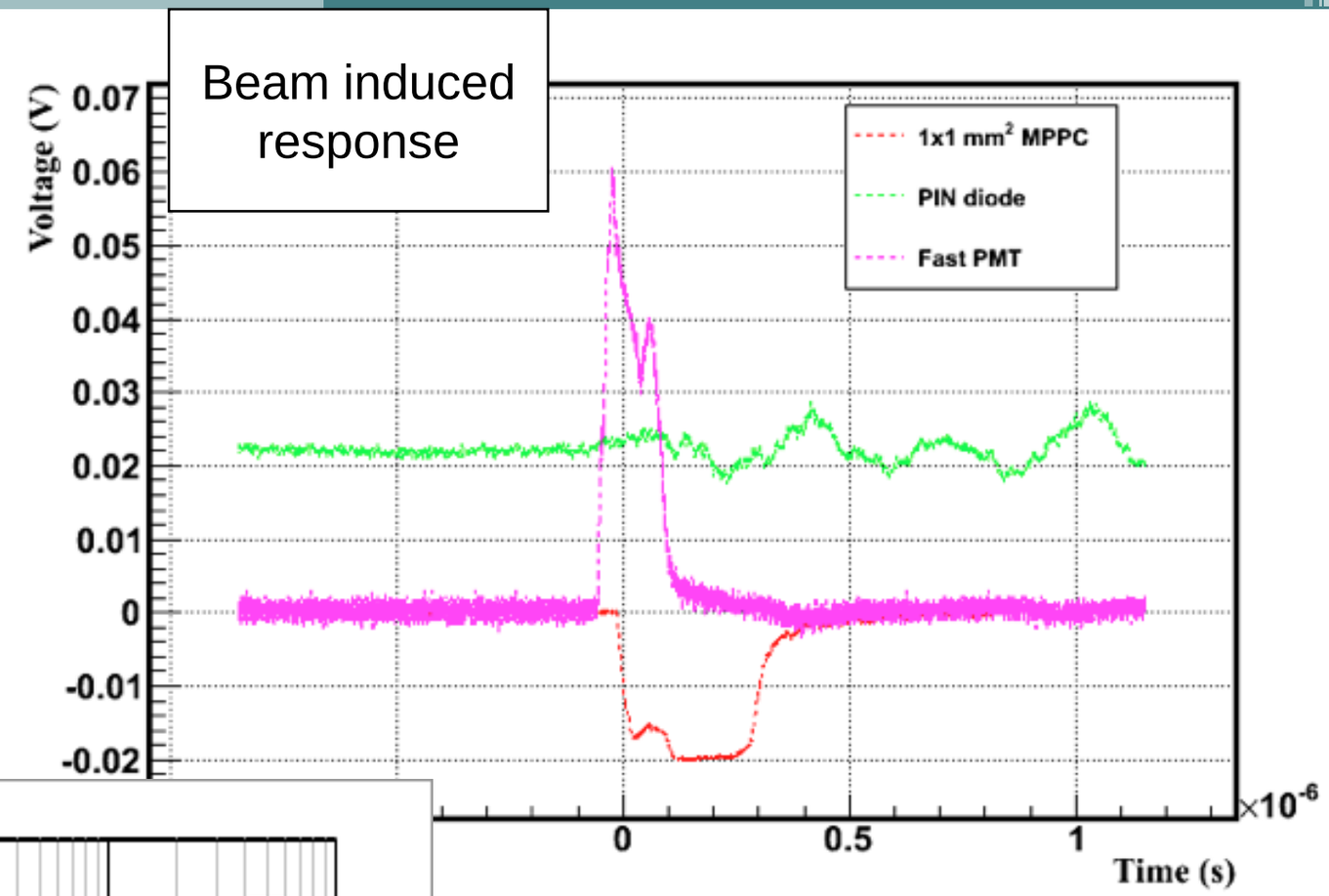


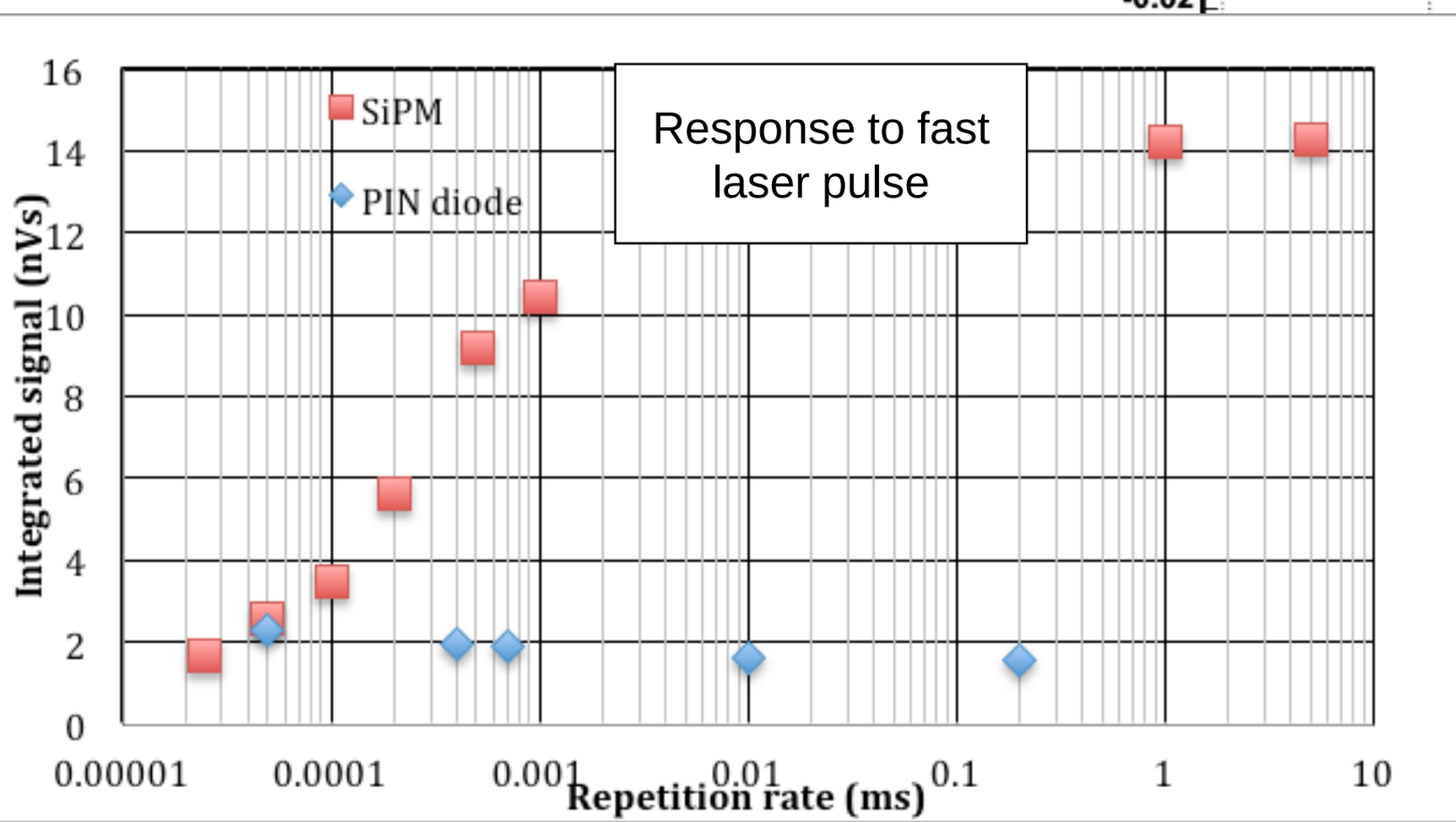


Avalance Photo Diode (APD)
Photon Multiplying tube (PMT)
Multi Pixel Photon Counter (MPPC)

Cherenkov fibers: Challenges II

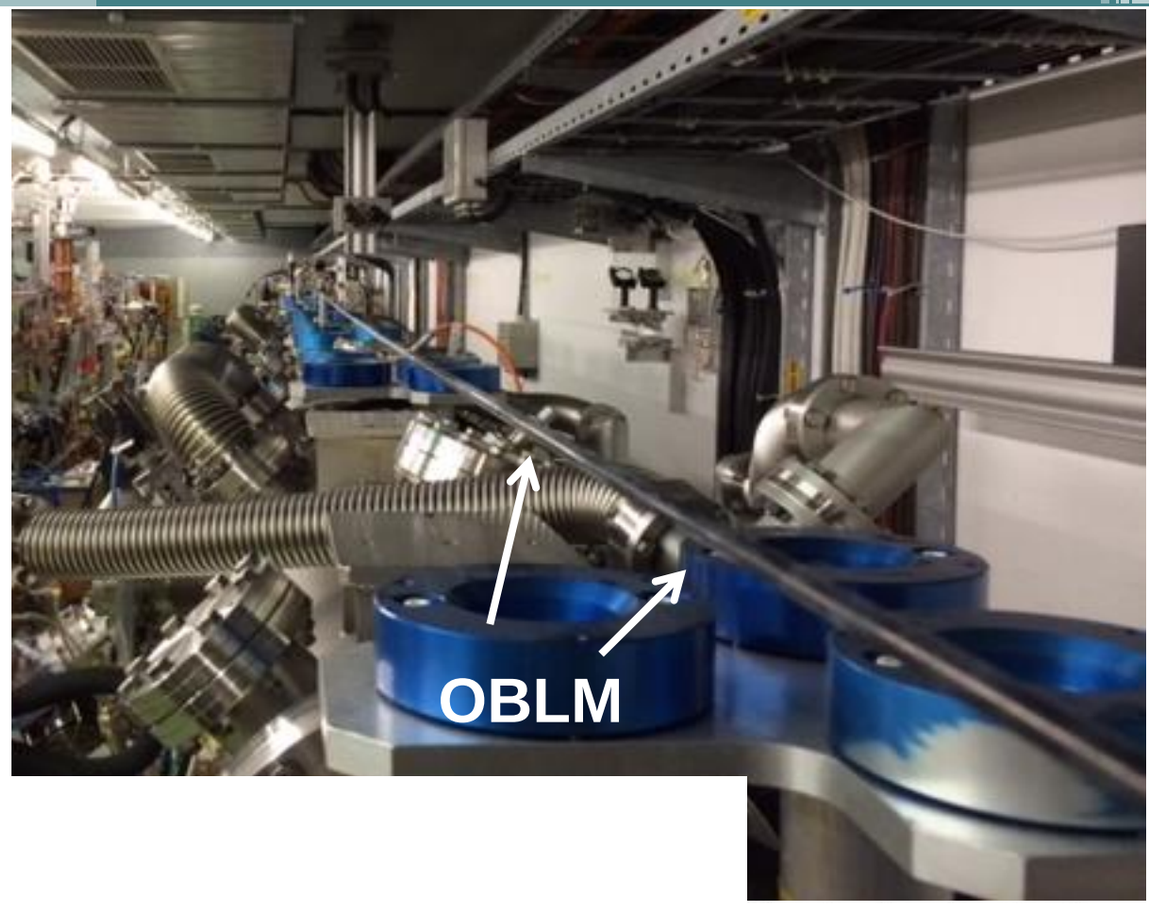
- Choosing a photon sensor
  - Quantum Efficiency
  - Saturation Effects
  - Time Response
  - Achievable Bandwidth

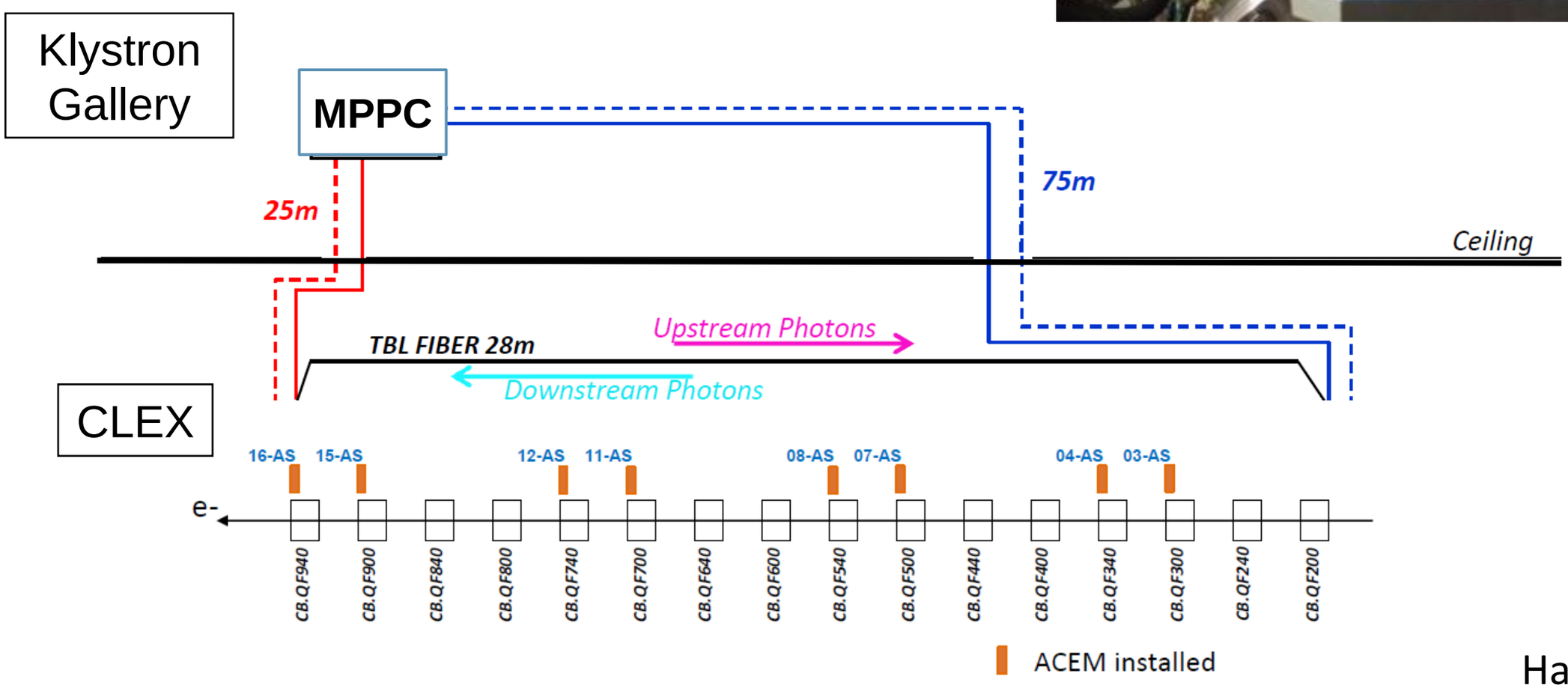


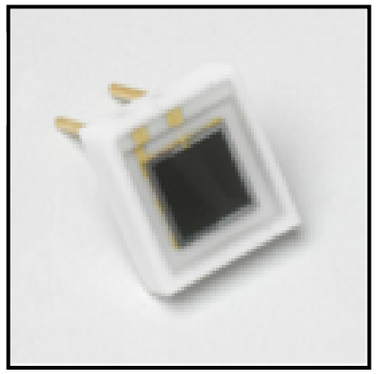


BLMs at the Test Beam Line: Cherenkov fibre

- Pure Silica 200μm core multimode optical fibre located 28cm on top of the beam line
- 25 (75) meters of read-out fibre in the downstream (upstream) direction
- 14400 pixel (25um) 3x3mm^2 Hamamatsu MPPCs
- Trans-impedance amplifier (opAmp THS3601 GBW 300 MHz) with Rf = 500 Ω





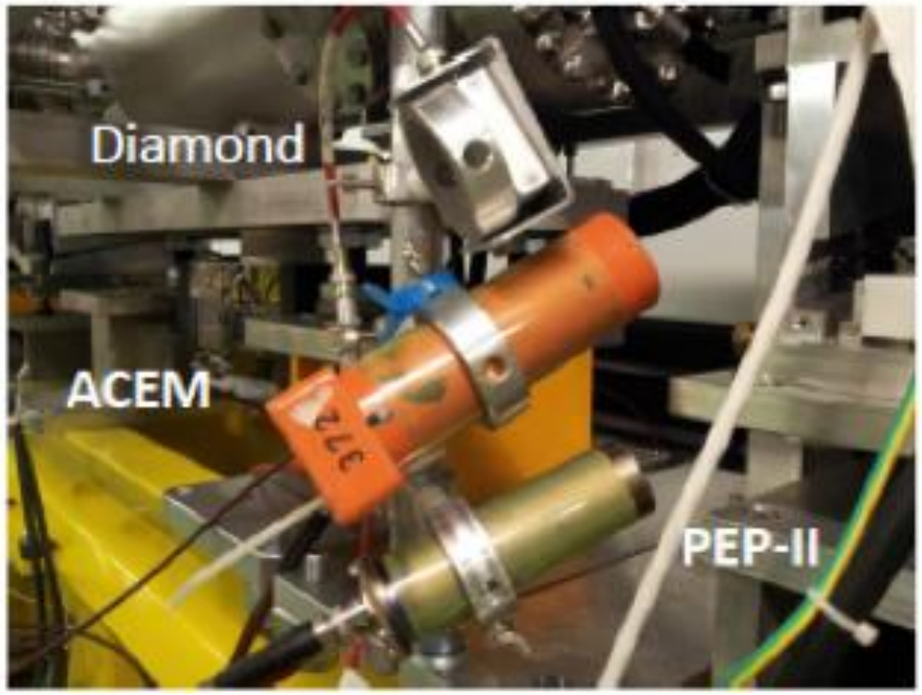


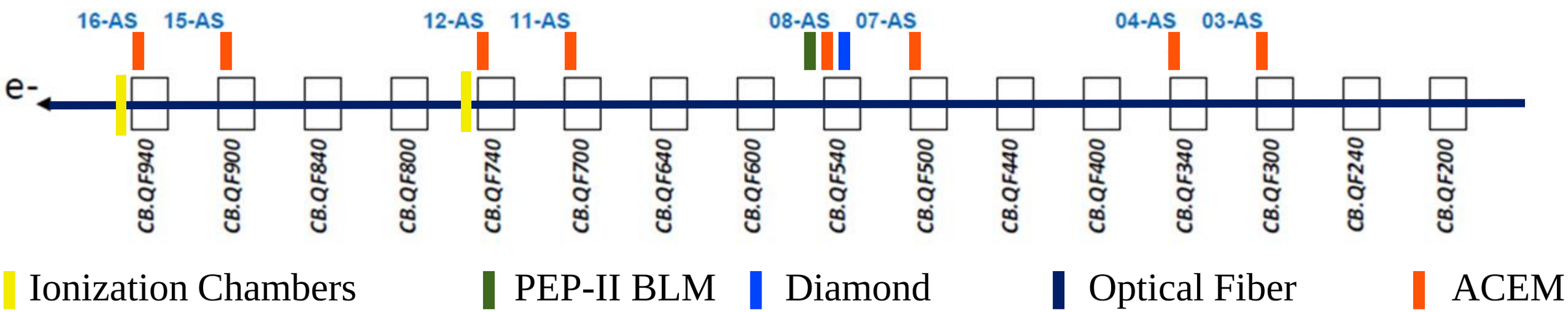
Hamamatsu MPPC

Localised BLMs at TBL

Installation during 2013

- Four detector technologies
  - Ionisation chamber x2
  - Aluminium Cathode EMission (ACEM) + PMT x8
  - pCVD diamond x1
  - PEP-II (Cherenkov crystal + Fast PMT) x 1
- Read via 250 MHz 8 Bit ADC (OASIS)
  - Occasionally 5GHz/10Gs/s for timing investigations

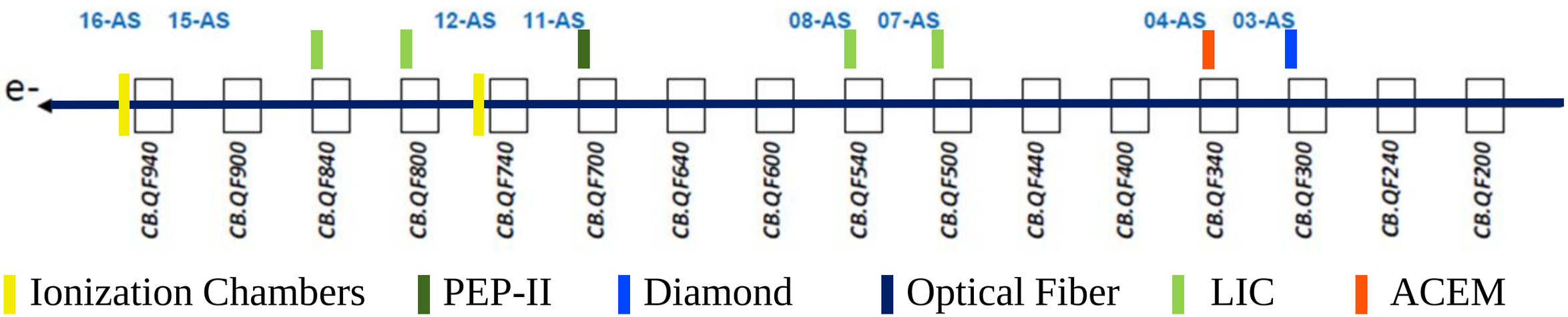




Localised BLMs at TBL

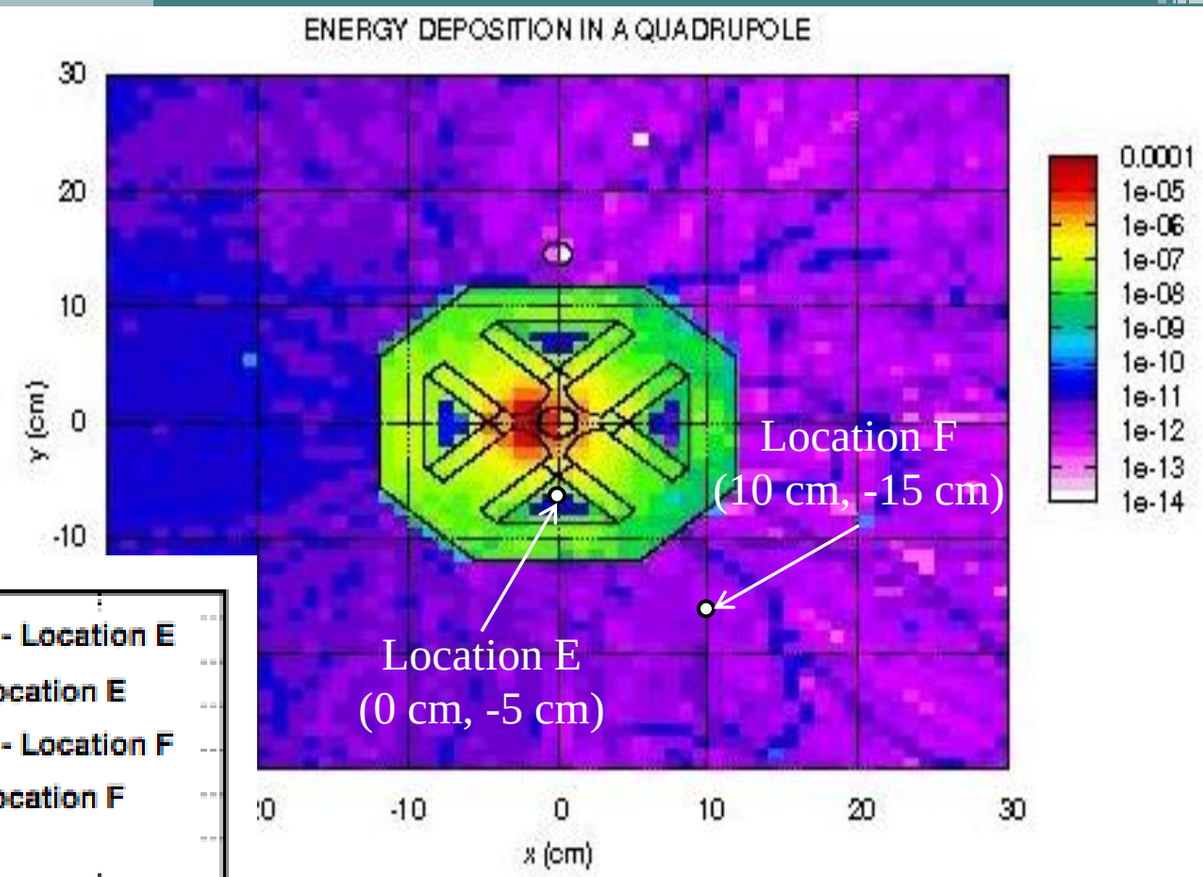
Installation during 2014

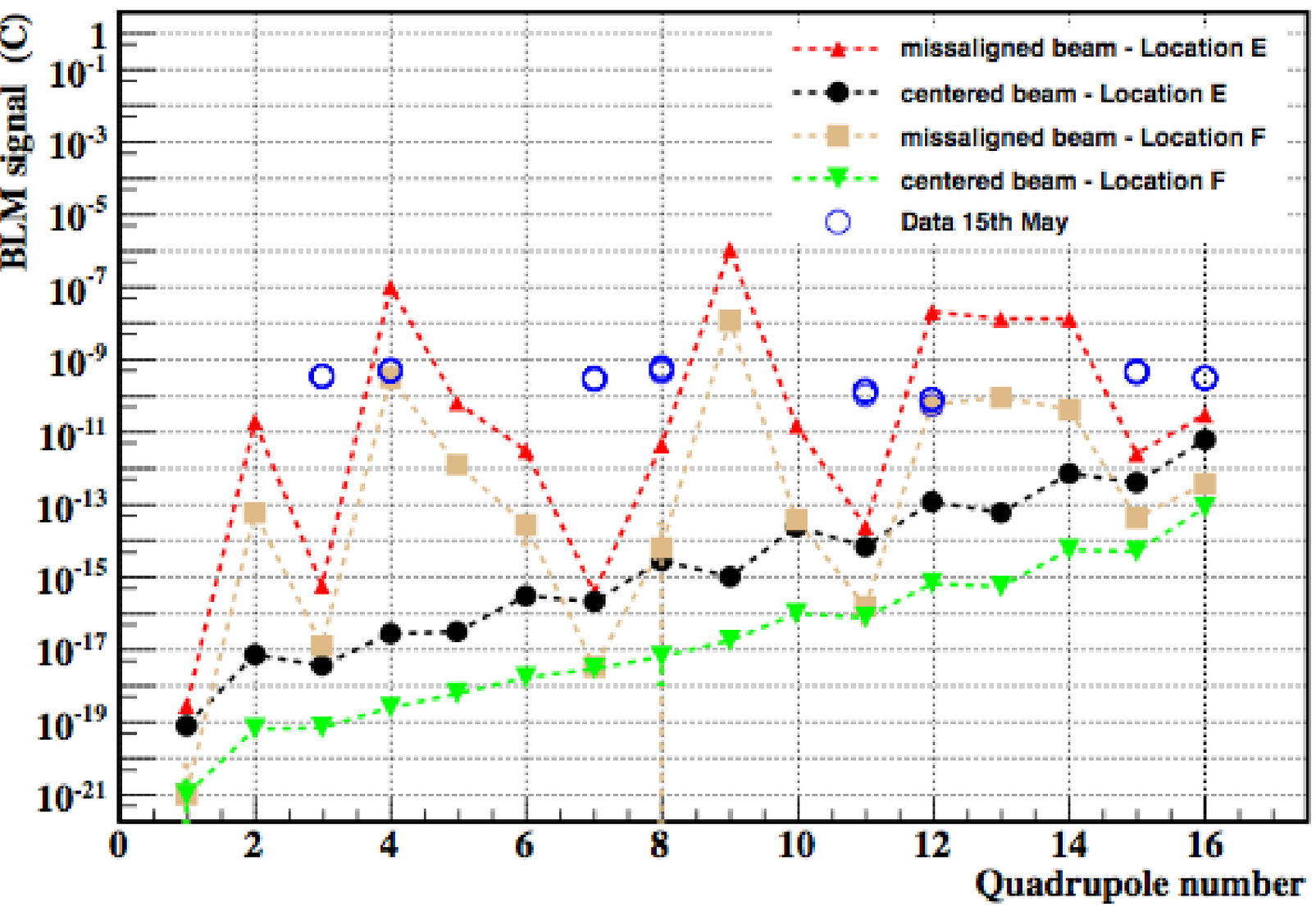
- Four detector technologies
  - Ionisation chamber x 2
  - Little Ionisation Chamber (LIC) x 4
  - pCVD diamond
  - PEP-II (Cherenkov crystal + Fast PMT) x 1
  - ACEM (Al foil + PMT) x 1
- Read via 250 MHz 8 Bit ADC (OASIS)
  - Occasionally 5GHz/10Gs/s for timing investigations



Monte Carlo Model losses at the TBL

- FLUKA-MAD-X simulation for estimation of losses at TBL
- Comparison to ACEMs measurements





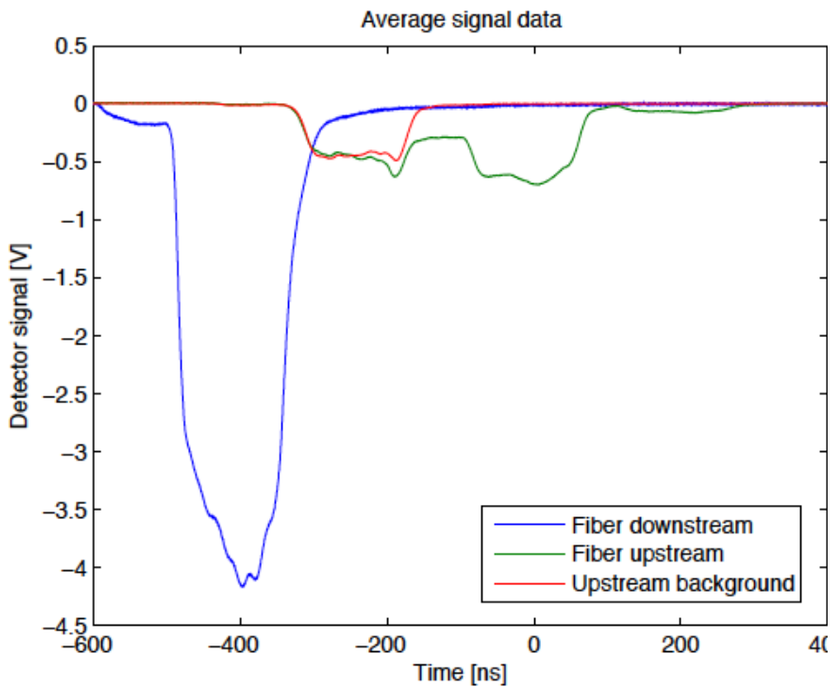
Flat behaviour of data

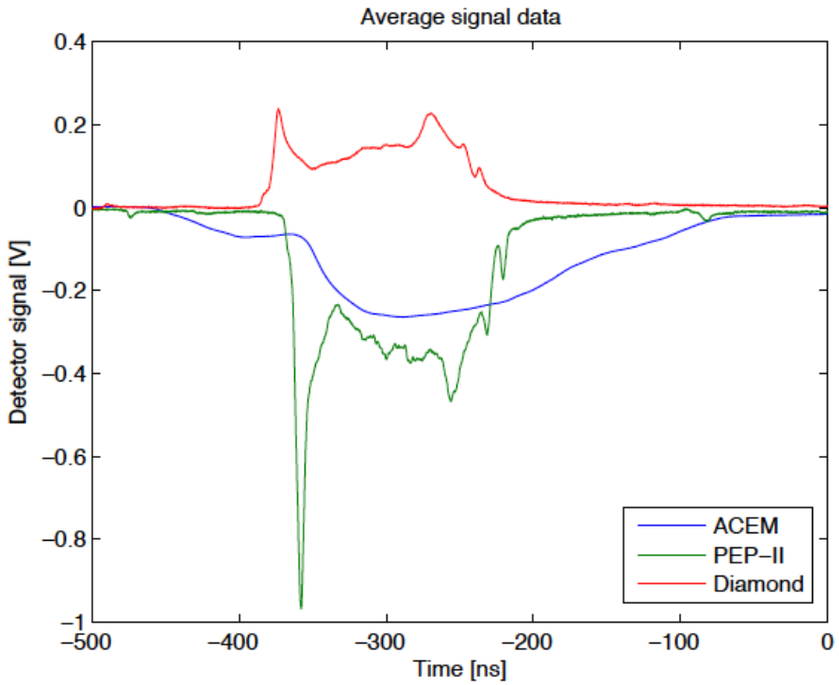
→ Beam Halo

→ Non Gaussian Beam profiles after full recombination

Beam loss measurements at the TBL

- Measurements with 16A, 150ns pulse:
  - ~100% beam transport
  - losses < 0.5 A (sensitivity of BPMs)
  - Agreement of BLM and BPM data





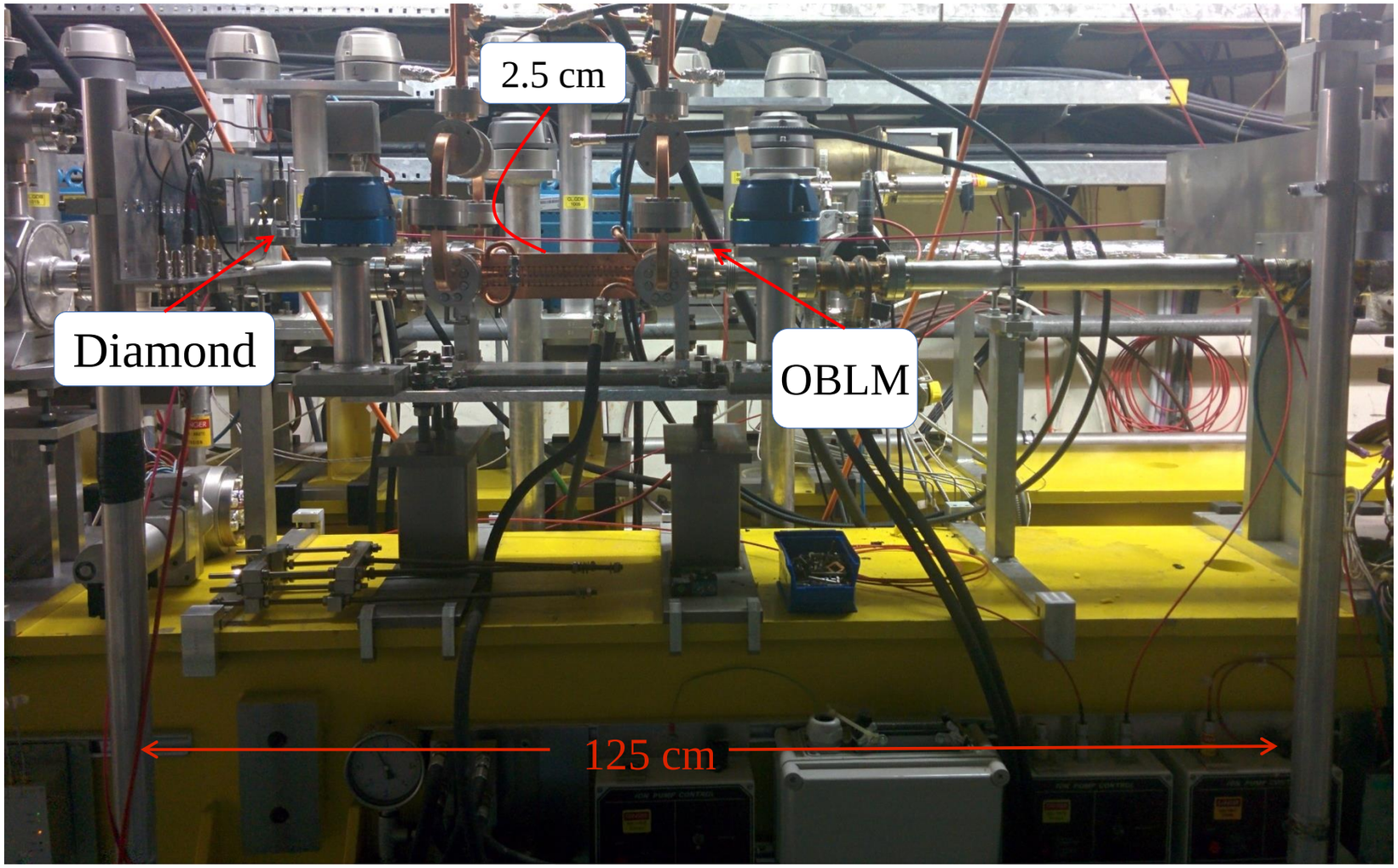
	Detector	FLUKA Simulation (pC/e)		Measurement 15th May 2013 (nC)	Combined Beam Loss estimation (mA)
		Systematic variation	Most realistic value		
fiber	Downstream fiber	(2.5 - 19.0) x 10^{-6}	9.0 x 10^{-6}	2.36	**260**
fiber	Upstream fiber	(0.037 - 4.4) x 10^{-6}	1.4 x 10^{-6}	0.15	**370**
Localised BLM	ACEM	(0.93 - 5.0) x 10^{-20}	2.3 x 10^{-20}	1.21	**34**
Localised BLM	PEP-II	(1.1 - 11.0) x 10^{-20}	4.2 x 10^{-20}	1.25	**13**
Localised BLM	pCVD	(0.97 - 4.0) x 10^{-20}	2.1 x 10^{-20}	0.42	**19**

✓ The BLMs detect losses lower than the BPM sensitivity!

Installation at the dogleg experiment

- Measurements of the RF Breakdown and dark current in the accelerating structure
- Comparison of the signals without and with beam loading

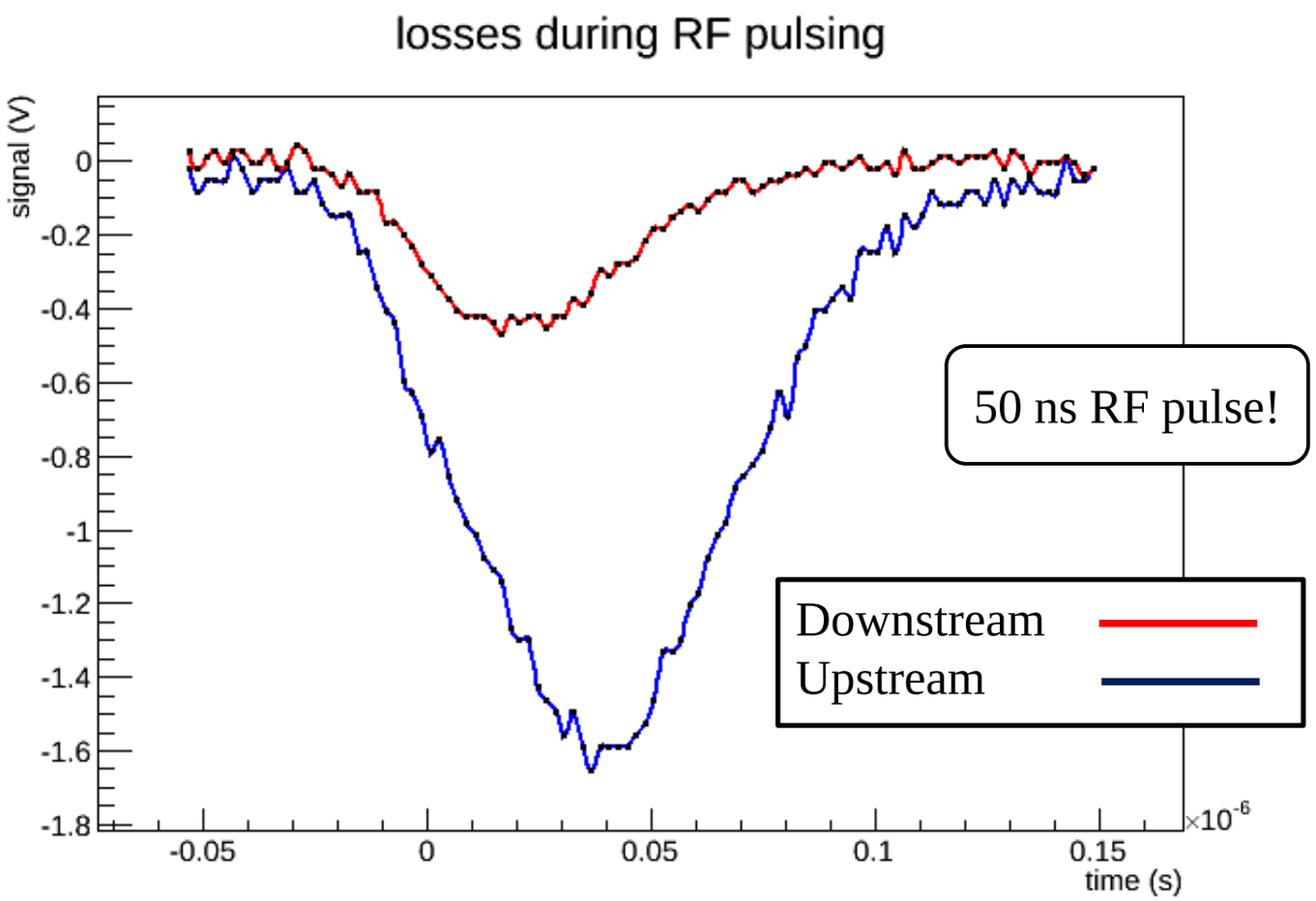
- Localised
  - pCVD diamond
  - 40 dB Broadband Current Amplifier
- OBLM
  - Ø 900 μm fibre + SiPM
  - Custom-made low-pass voltage filter and crate modules

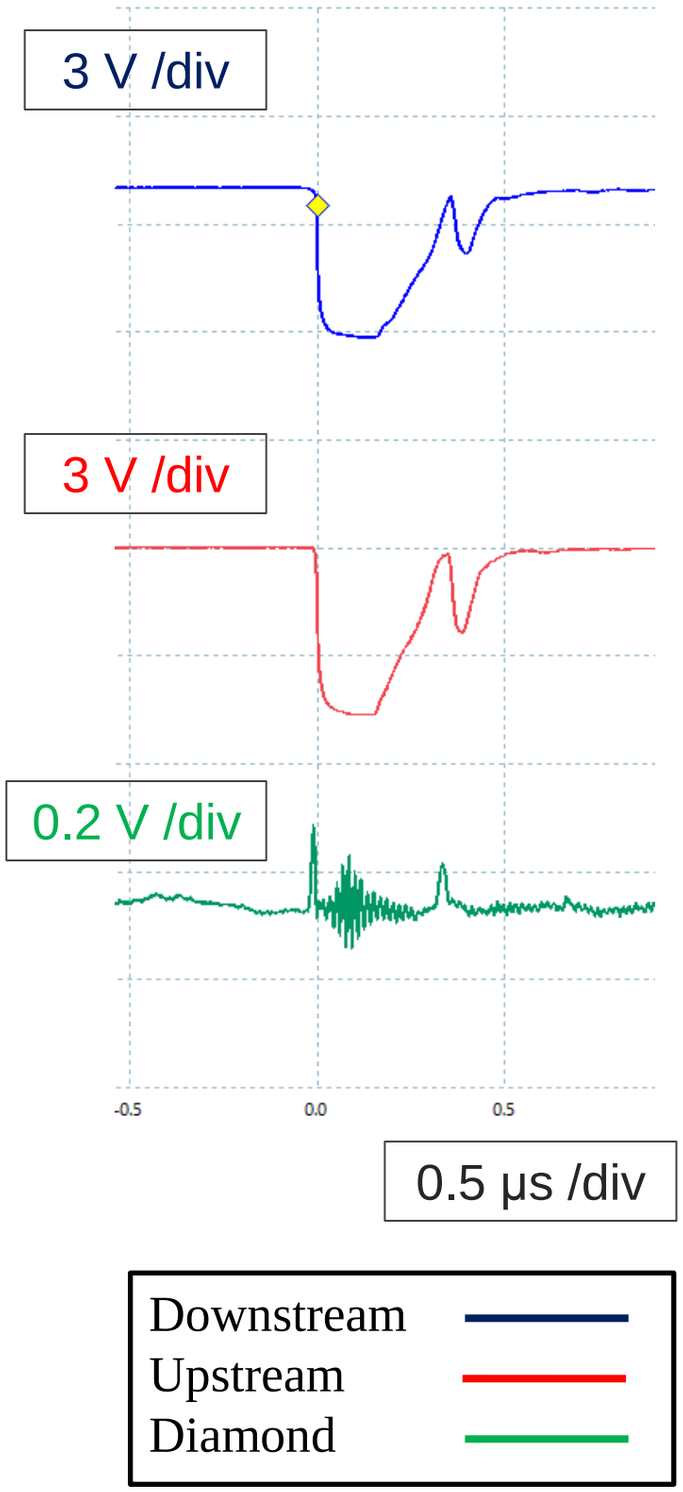


Preliminary data without beam

- ✔ System optimised for dark current measurements
- ✔ RF pulse length and shape

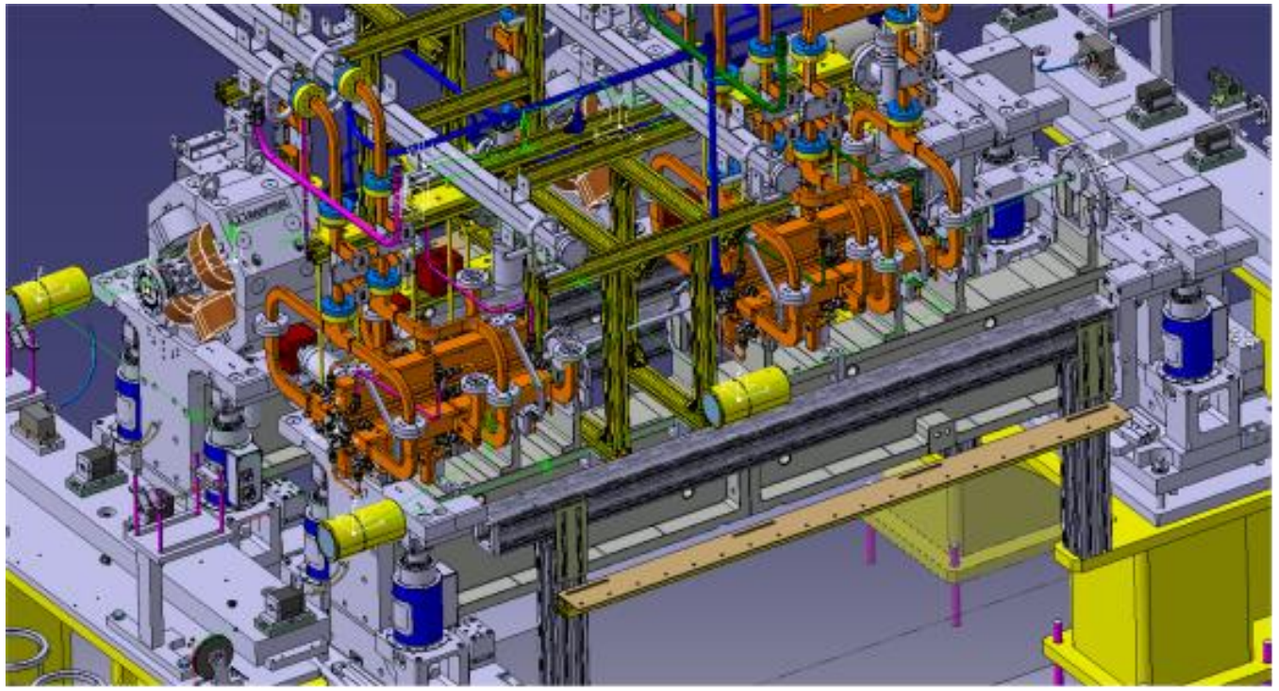
→ Under improvement for RF Breakdown diagnostics.





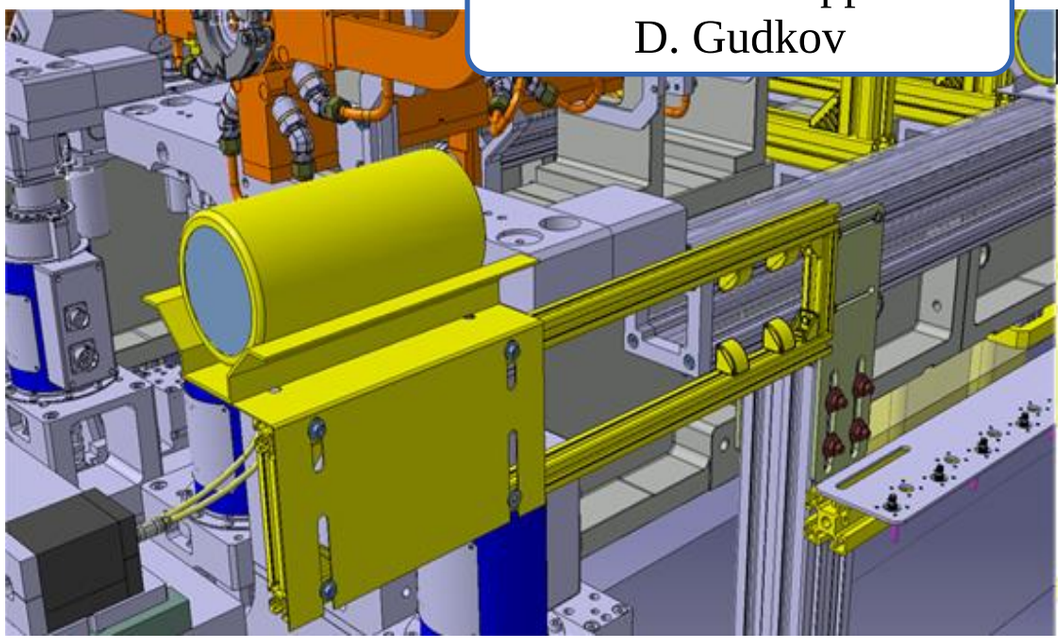
Installation at the Two-Beam Module (TBM)

- 4 Little Ionisation Chambers
  - Downstream of quads at the Drive Beam
  - Downstream of accelerating structures at the Main Beam
- OBLMs along the Drive Beam and the Main Beam
- Supports for the integration on the TBM.

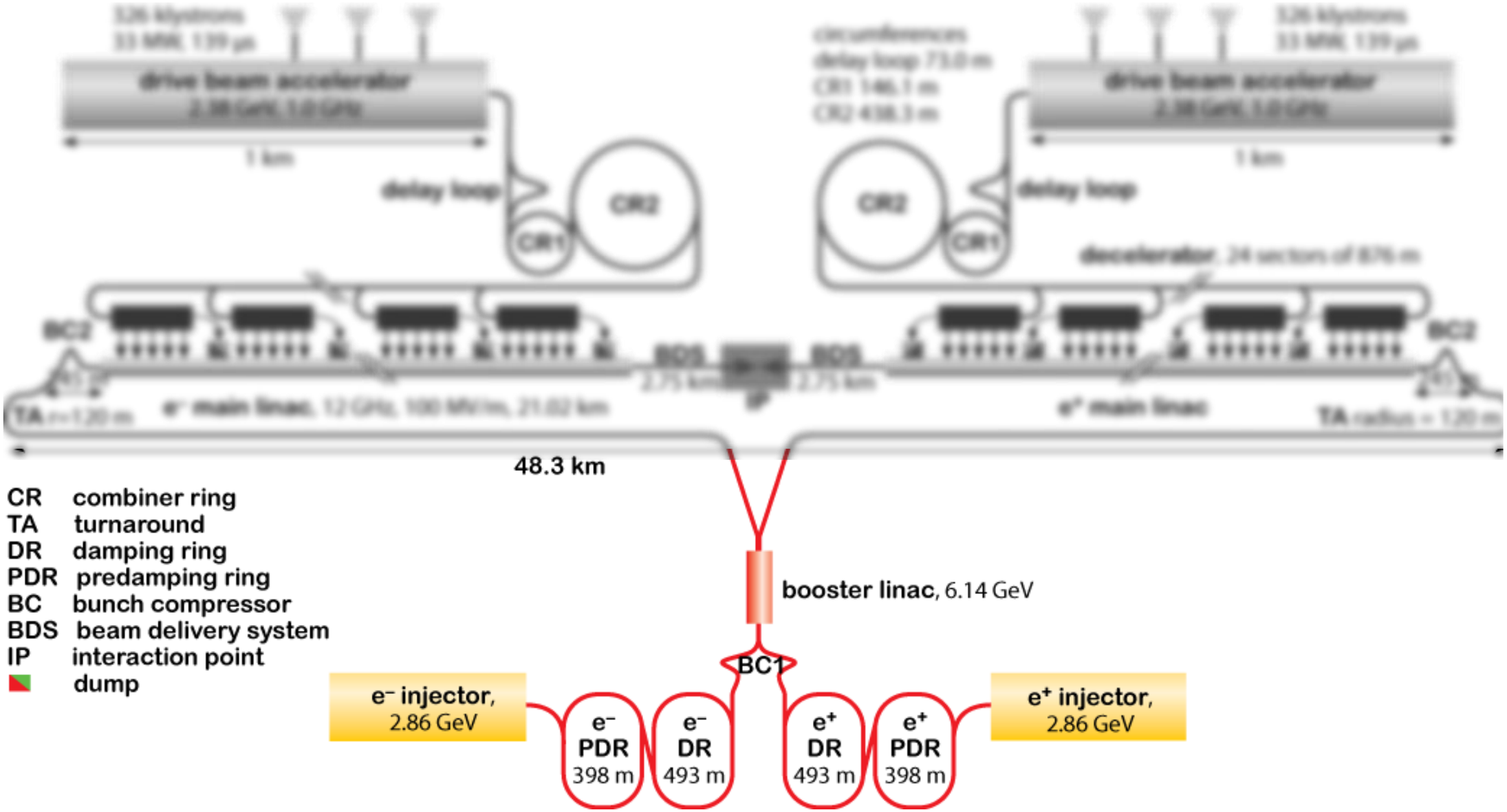


TBM BLM aim of studies

- Nominal beam losses at the TBM
- Comparison with simulations
- Extrapolations to high energy
- X-talk of losses



3D model & supports:
D. Gudkov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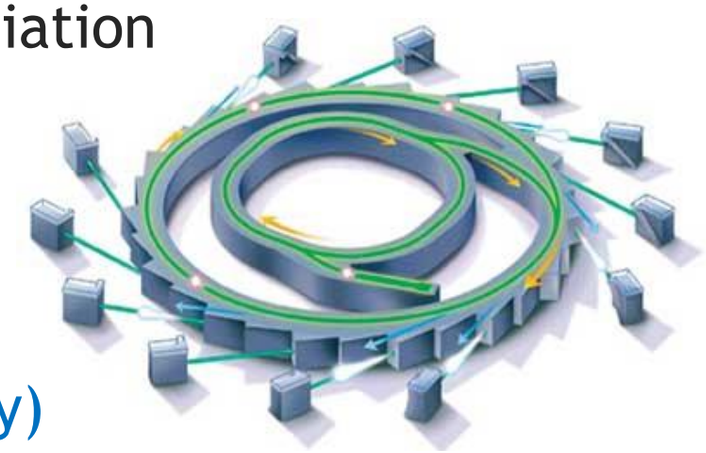
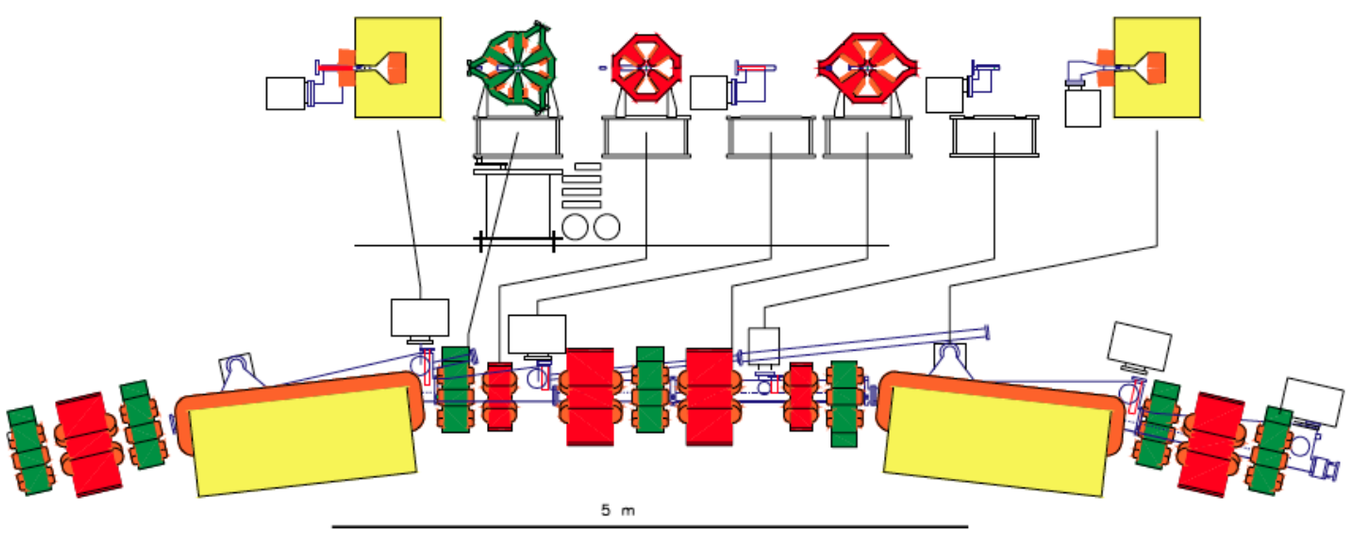
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump
booster linac, 6.14 GeV
BC1
e− injector, 2.86 GeV
e+ injector, 2.86 GeV
e− PDR 398 m
e− DR 493 m
e+ DR 493 m
e+ PDR 398 m

CLIC damping rings

- Considerations
  - Synchrotron light production as a means of beam cooling ⇒ insensitivity of BLM system
  - Sensitive to potential "quench inducing" beam losses
- OBLM system
  - The full ring can be covered with ~4 BLMs
  - Cherenkov-based fibre BLMs are insensitive to synchrotron radiation



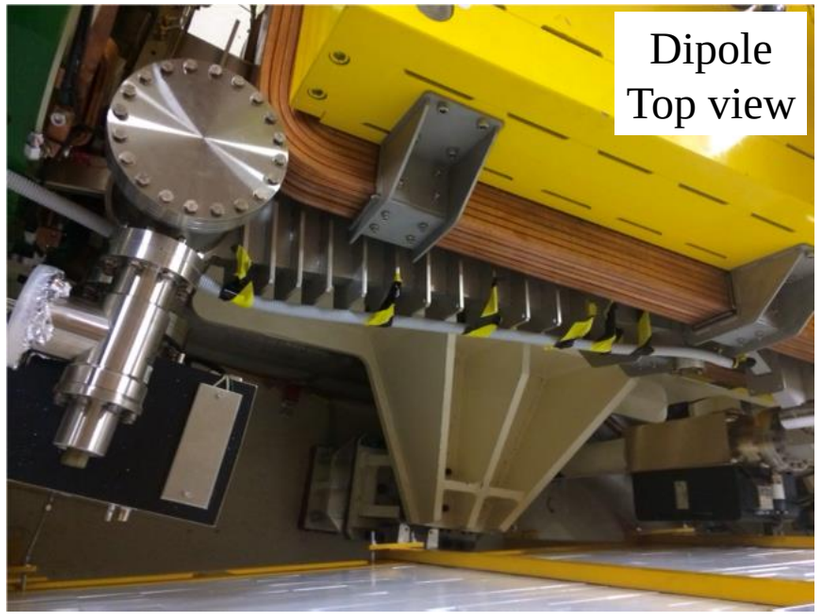
- Tested in the Australian Synchrotron (AS)
  - LINAC (10 m): 90 keV to 100 MeV
  - Booster (130 m): 100MeV to 3 GeV
  - Storage Ring (216 m): 3 GeV (Similar parameters and flexibility)

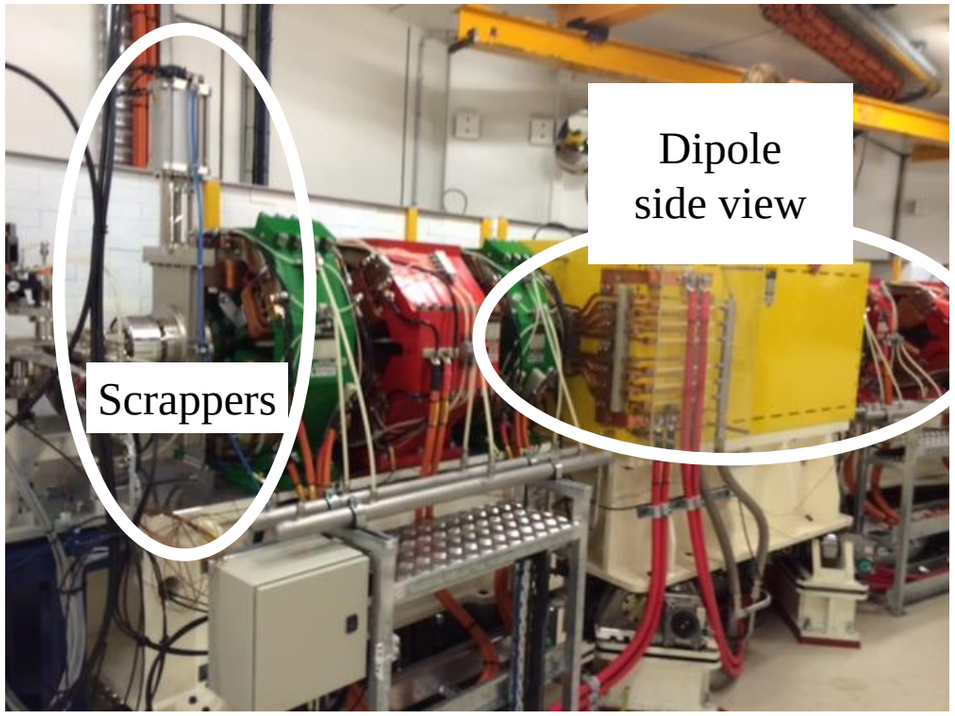


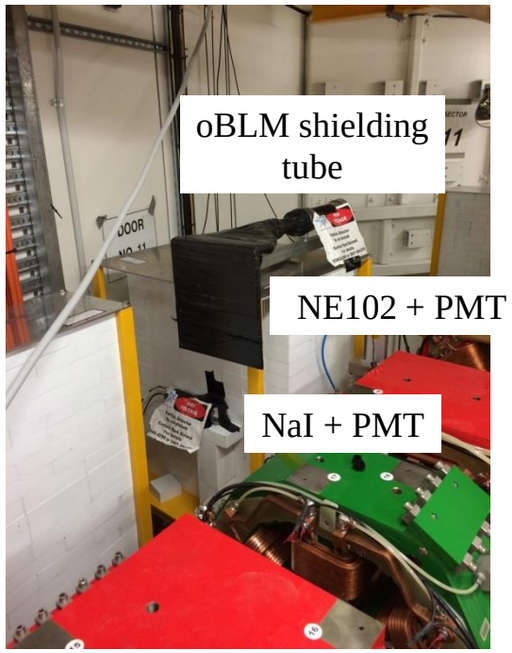
Parameter	AS	CLIC DR
Energy (GeV)	3.0	2.86
Intensity (elec)	$9.0 \cdot 10^{+11}$	$1.28 \cdot 10^{+12}$
Number of bunches	300	312
Pulse lenght (ns)	600	156
Circ. lenght (m)	216	427.5
f_{rev} (MHz)	1.38	0.73
Bunch spacing (ns)	2	0.5
$\gamma\epsilon_x$ (nm rad)	58708	472
$\gamma\epsilon_y$ (nm rad)	< 5	4.8

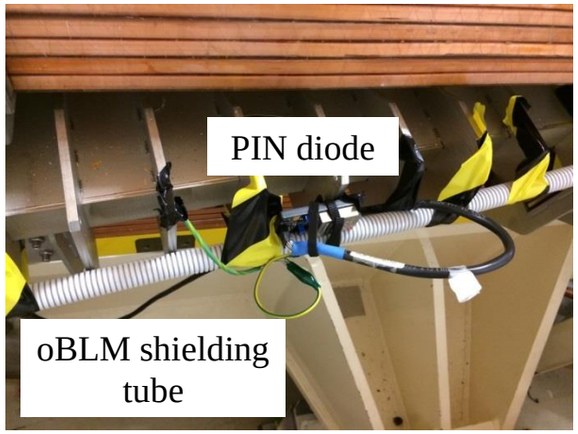
Australian Synchrotron measurements

- Installation of several prototypes in the AS
- Two (one) 7 m (5 m) optical fibres with 365 μm (200 μm) SiO2 core:
  - Multi Pixel Photon Counter (MPPC)
  - Photon Multiplier Tube (PMT)
  - Avalanche Photon Diode (APD)
- Pin diode, NaI and NE102 scintillators in neighboring locations for comparison



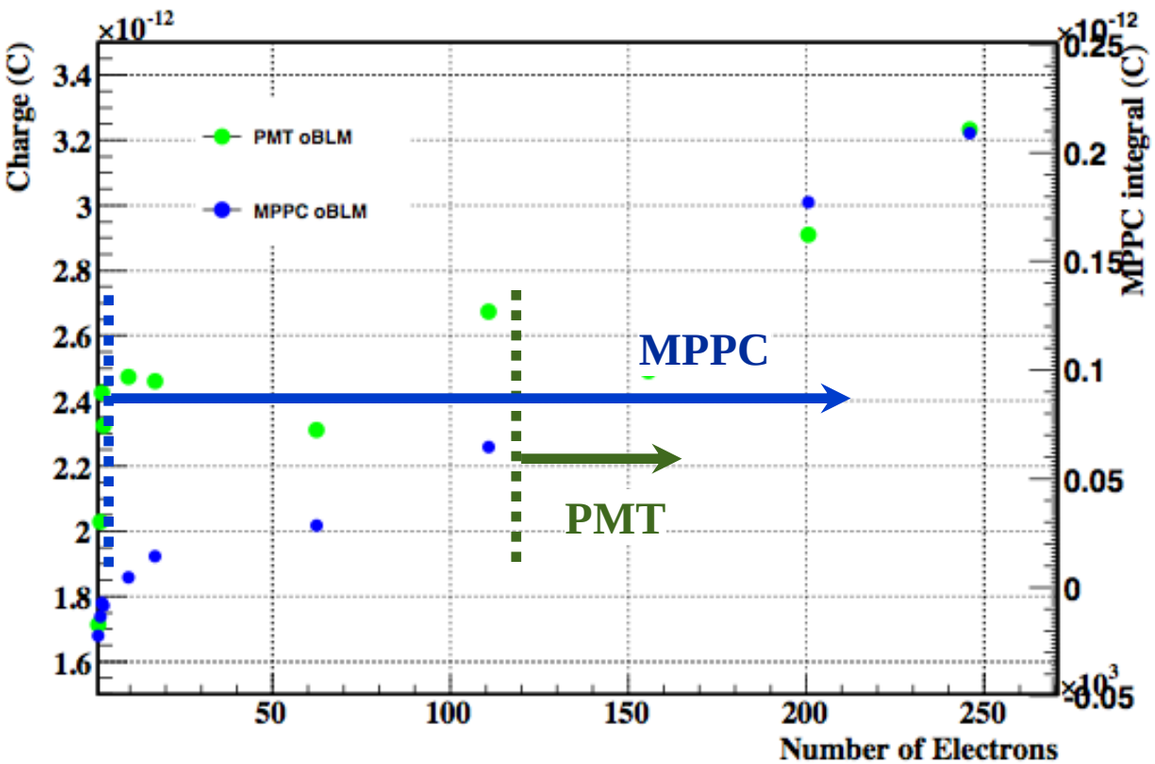


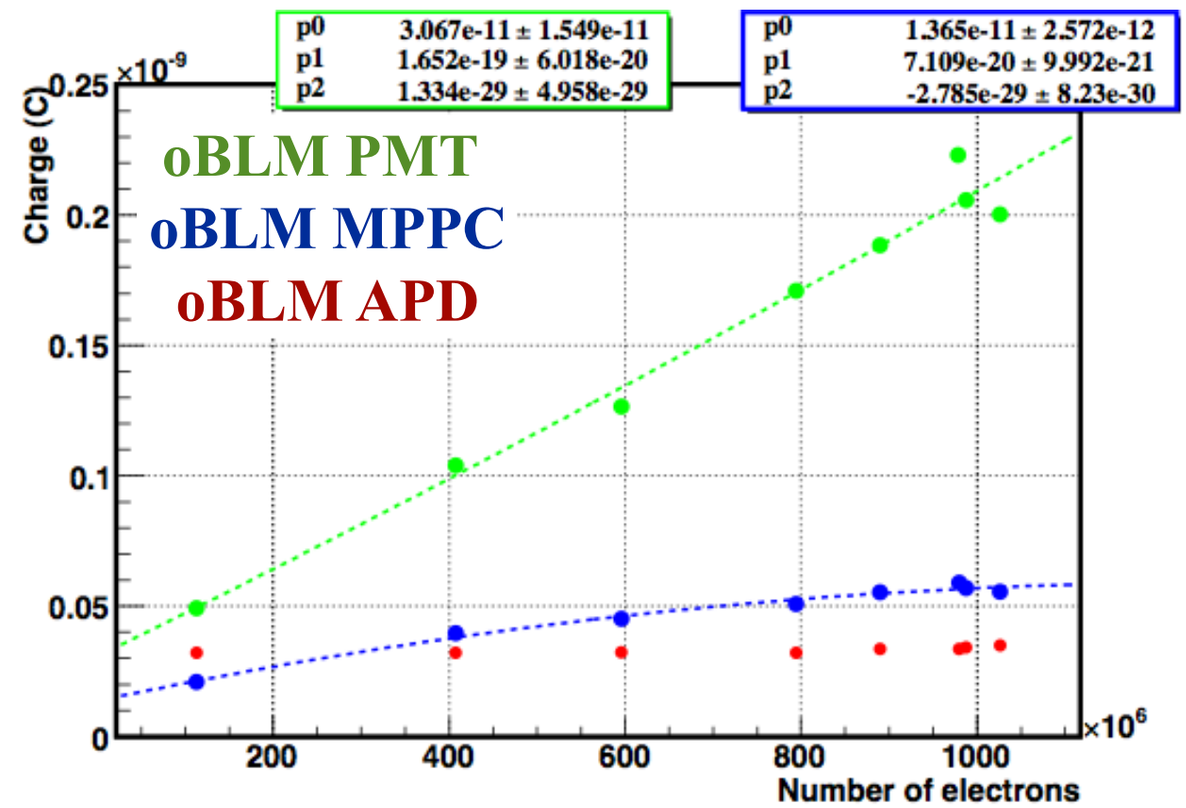




OBLM calibration

- Intensity variation
  - 10^3-10^9 charges
- Single bunch directed onto closed scraper

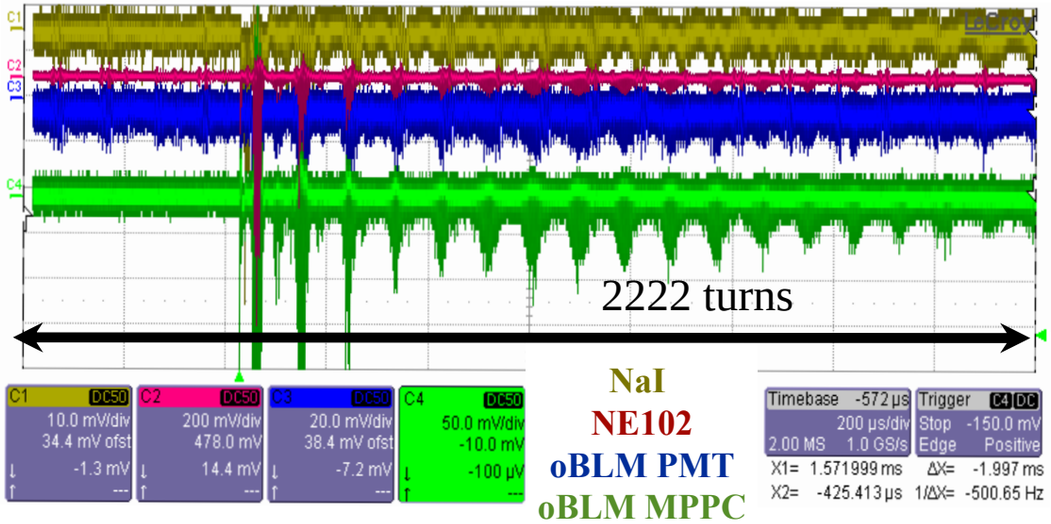


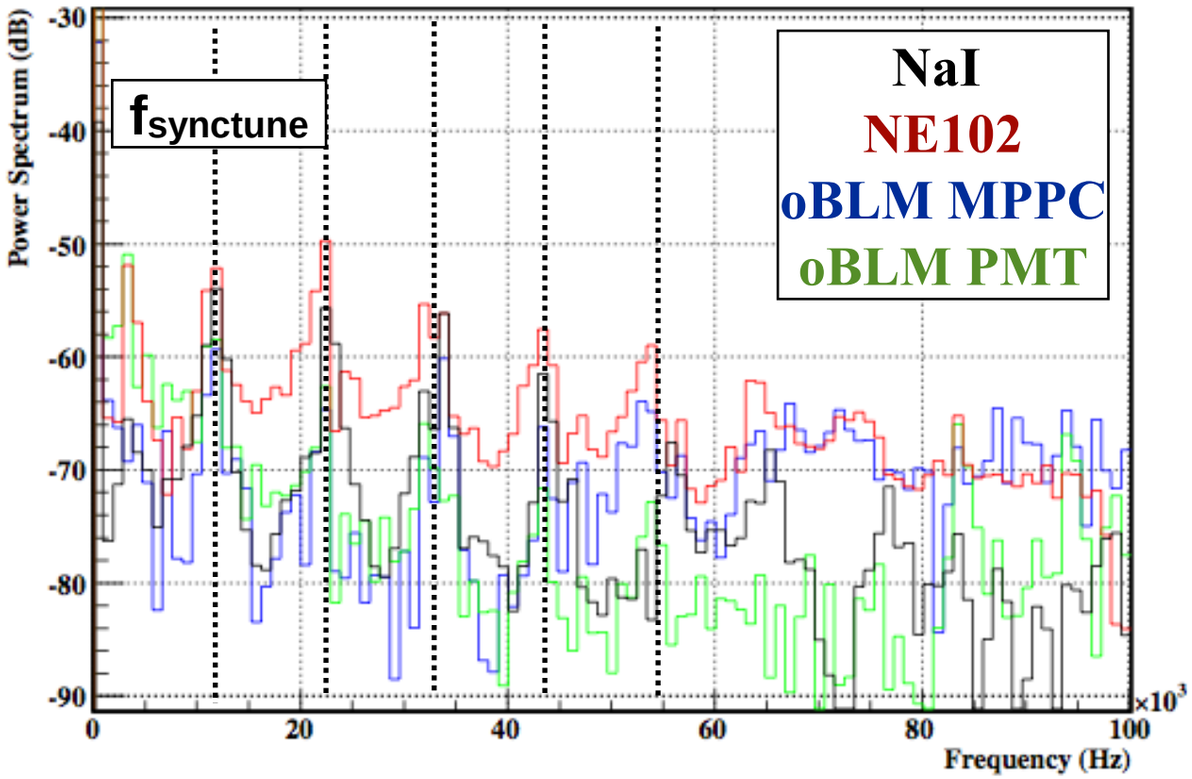


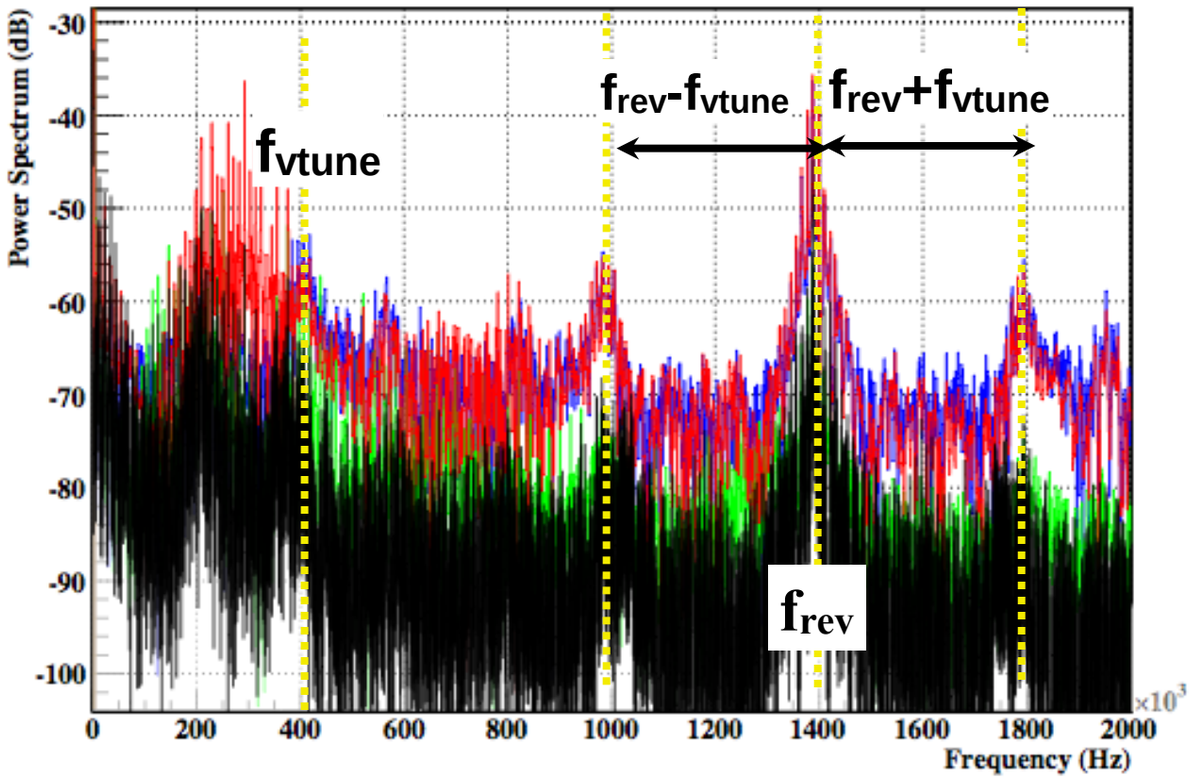
- OBLM system sensitive to localized losses down to ~10^{-9} and linear up to 0.001 of the full CLIC pulse.
  - Saturation effect observed for MPPC due to small spot illumination

BLM measurements during topup injections

- AS works on topup mode to keep a constant 200 mA for > 24 hours
- Frequency Analysis
  - SR ~ 0.5 mA / Booster ~ 1.1mA / Injection efficiency ~80%
  - harmonic number Booster/SR = 216/360
  - $1.25 \times 10^{+9}$ electrons lost within the first several turns
- Frequency Analysis
  - 11 kHz band (synchrotron tune)
  - 1.38 MHz (rev frequency)
  - 400 kHz band (vertical tune)



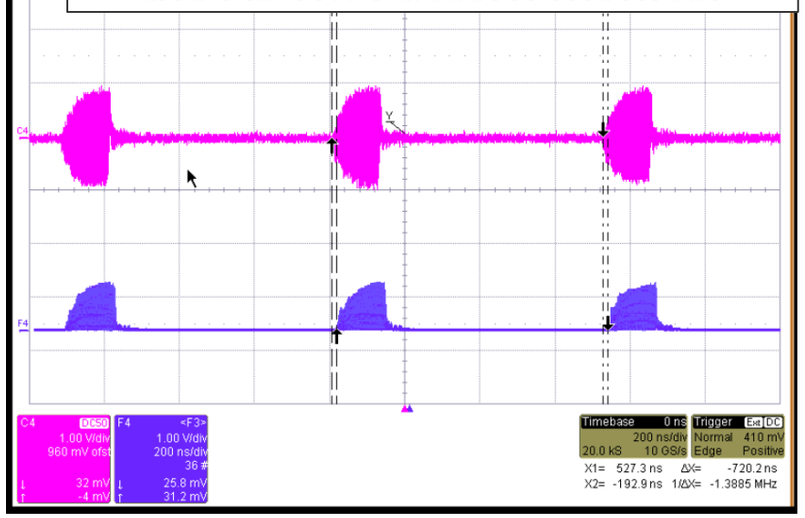


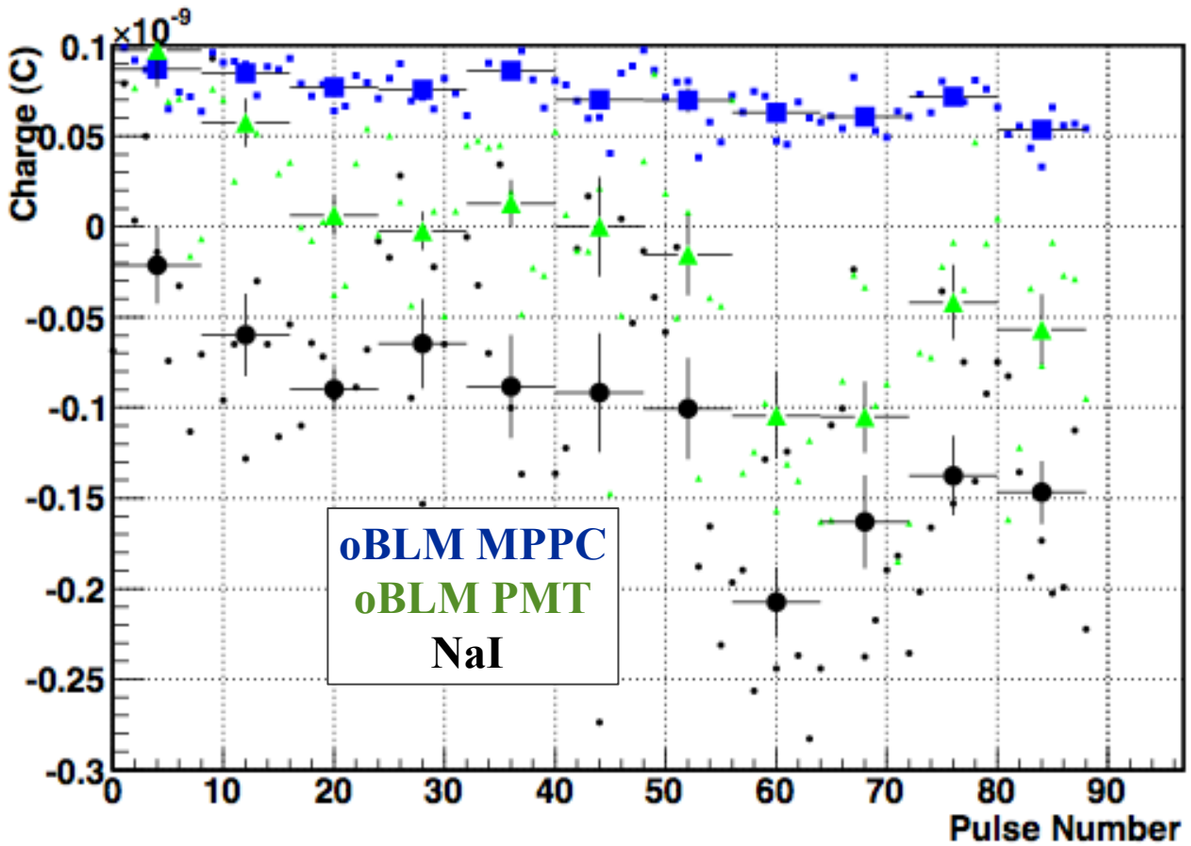


CLIC-like beam

- CLIC-like bunch length, 150 ns
- 11 independent skew quadrupole settings to change the coupling and vertical emittance
  - 8 pulses per setting
- Measurement of beam losses during betatron coupling scan

CLIC-like beam measured with the AS fill Pattern monitor





- ✓ Amount of losses seems to increase steadily with the emittance

measurement	1	2	3	4	5	6	7	8	9	10	11
Vert. emitt (pm)	1	2	5	10	20	50	100	200	500	1000	2000

Summary & Conclusions

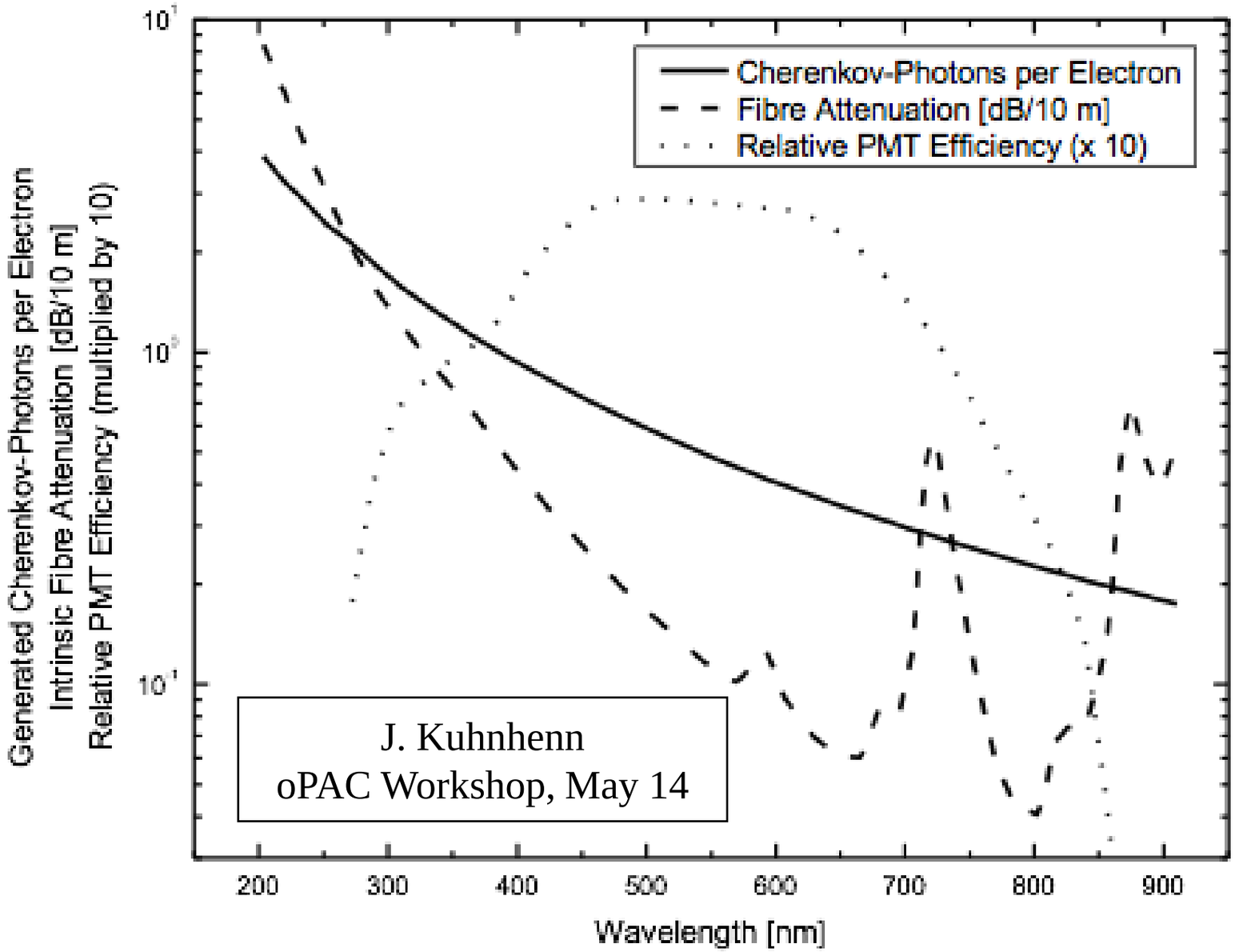
- Different detector technologies examined for the CLIC Two-Beam Module BLMs
- Optical fibre BLM development: ongoing tests at CTF3
- The ideal BLM system will combine OBLMs and localised detectors for beam diagnostics

- OBLM system tested on damping ring – like conditions
  - ✓ Measure Beam losses 10^3- 10^9 electrons
  - ✓ Indications of insensitivity to SR
  - ✓ Measurement of losses for a CLIC bunch train

Thank you!!!

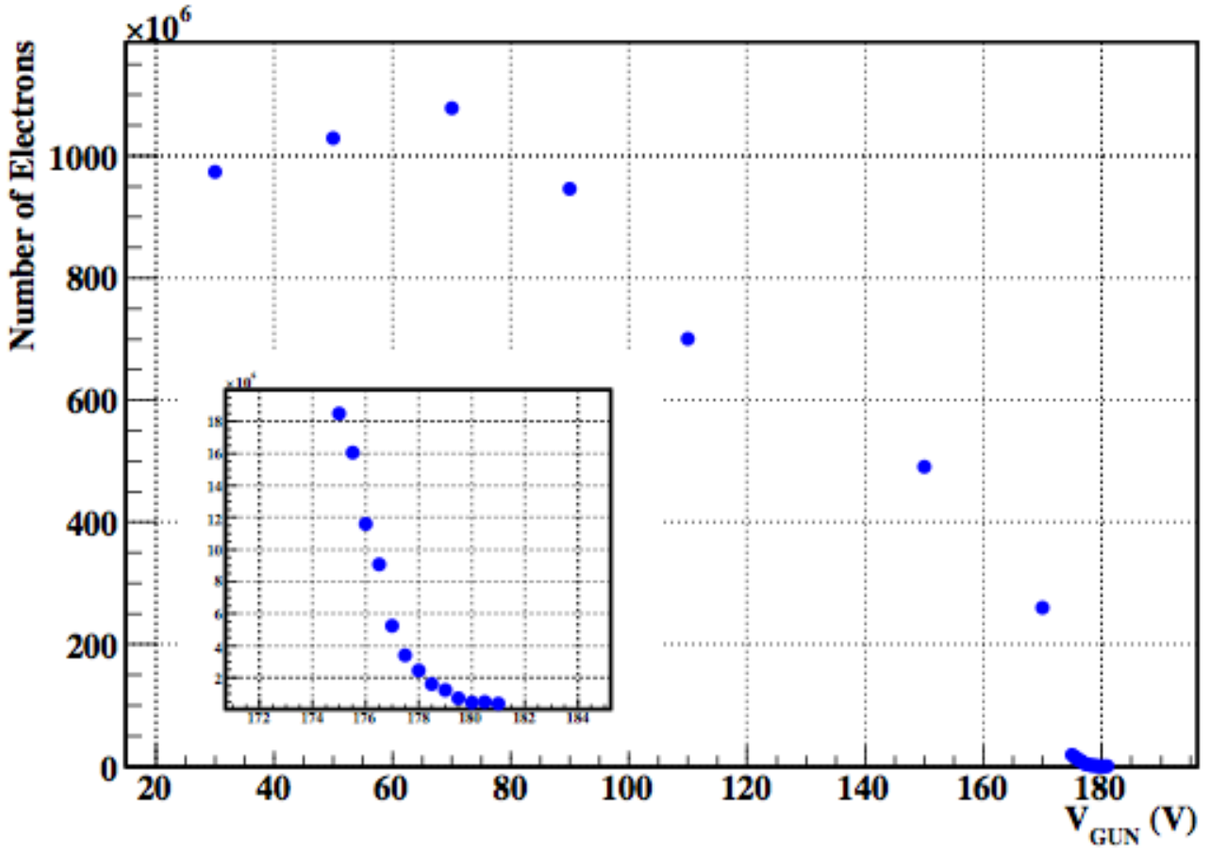
Cherenkov fibers: light spectrum

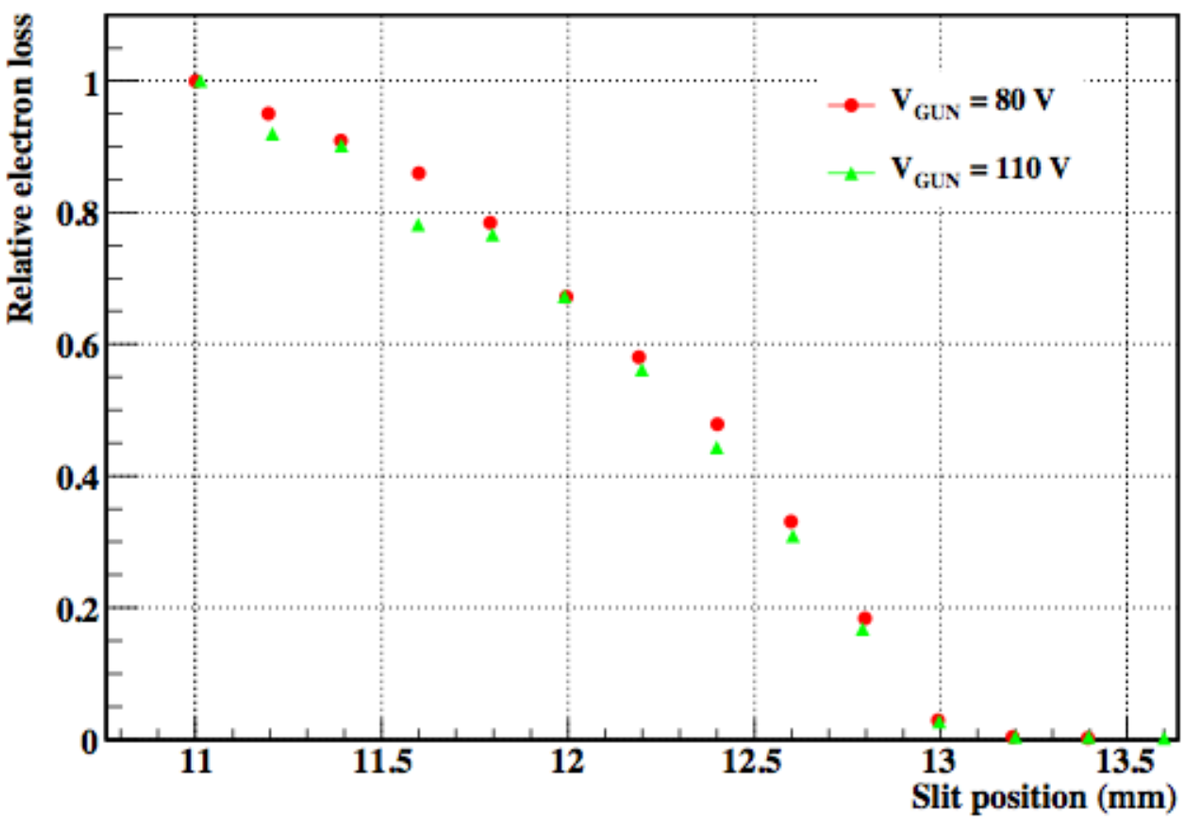
- For a quantitative estimation of beam losses we need to consider:
  - Cherenkov light spectrum (λ^{-2})
  - Length and λ dependence of light attenuation
  - Quantum efficiency of selected photosensor (~400-900 nm)



OBLM calibration

- Intensity variation
  - Vgun increase to reduce the bunch charge down to ~10^{+5} charges
  - Closings slits in Booster to SR to further reduce down to ~10^{+3} charges

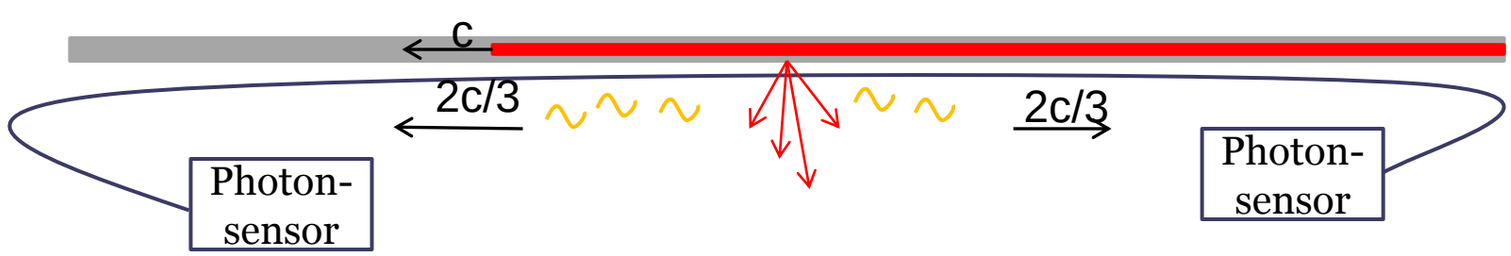




Detector technology

- A system based on Ionization Chambers **satisfies** the requirements of Machine Protection –(CLIC Conceptual Design Report)
  - LHC (1.5 l N_2): Sensitivity 10^{-9} Gy (1 pA). DR > 10^{+7}
  - LIC (0.5 l N_2): Sensitivity 10^{-8} Gy (4 pA)
  - LHC-like Current to Frequency Converter: DR=10^{+5}
  - But requires a large number of BLMs (> 40000)
  - Electron (ion) total collection/rise time is ~500 ns/10 ns (400 µs/10 µs). No time information of origin of beam loss

- Optical fibre based BLMs (OBLMs)
  - Pure Silica core multimode fibres as Cherenkov radiators. Both ends of fiber couples to photon-sensors
  - Potential of covering full beam line in a cost-effective way. Better time resolution (position resolution within 30 cm of beam loss has been demonstrated)



- Fast BLMs (diagnostics oriented): Diamond and Quartz:
  - Diamonds (1 ns): LHC for bunch by bunch beam loss monitoring
  - Quarzt crystals + photon sensor: time response depends on volume of crystal (~50ps/cm^3) and photo sensor. Potential for ultra-fast Beam Loss Monitoring