Beam Instrumentation on CLEAR: proposed experiments and possible improvements

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and external collaborators

CLIC Workshop, CERN, 8th March 2017

Outline

- Beam instrumentation on CLEAR
  - Possible upgrades
  - Future needs ?

- Beam instrumentation tests on CLEAR
  - Planned tests for 2017
  - Wish list for the evolution of the facility

Beam Instrumentation on CLEAR:
'The Essentials'

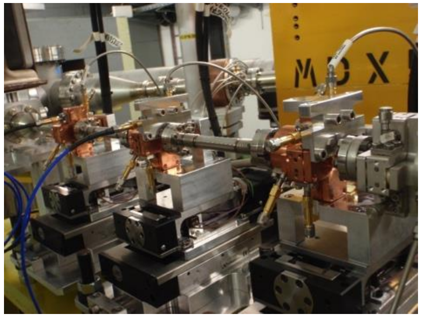
Beam parameter (end of linac)	Value range
Energy	130 - 220 MeV (60 MeV with upgrade)
Bunch charge	0.01 - 1.5 nC
Normalized emittances	3 um for 0.05 nC per bunch, 20 um for 0.4 nC per bunch (in both planes)
Bunch length	ca. 500 um - 1.2 mm
Relative energy spread	< 0.2 % rms (< 1 MeV FWHM)
Repetition rate	1 - 5 Hz (25 Hz with upgrade)
Number of micro-bunches in train	Selectable between 1 and > 100
Micro-bunch spacing	1.5 GHz

- **Beam intensity**: 1x ICT (Bergoz), 1x Faraday-cup in Vesper (low charge mode)
- **Beam position**: 6x Re-entrant BPM (Linac) – 5x Inductive PUs (TBTS)
- **Beam Size**: 4x OTR&YAG screens-Camera

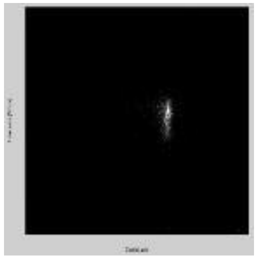
Beam Instrumentation on CLEAR
add. Equipment (1/4)

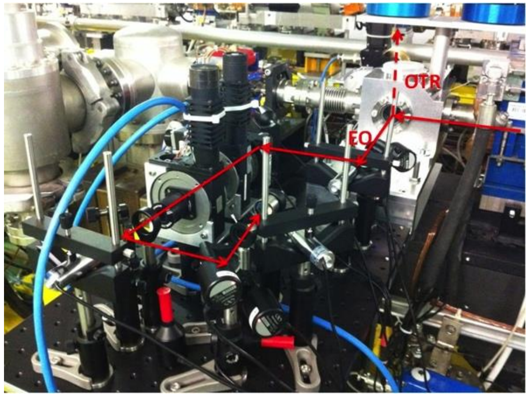
- Re-using CLIC BI development currently installed on CLEAR
  - High resolution (<1um) Cavity BPM for precise measurements

See talk by A. Lyapin on Tuesday morning



- Streak camera (shared with AWAKE) / Electro-optical spectral decoding for Bunch length measurement (sub-ps to ps)

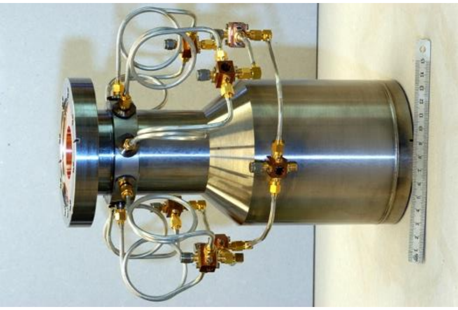
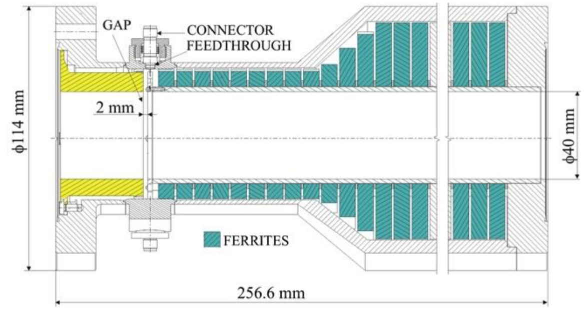




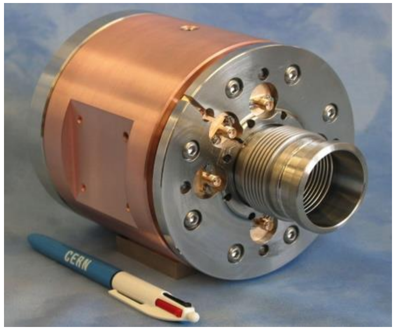
- Beam Loss monitors using Cherenkov fiber (TBTS)

Beam Instrumentation on CLEAR
Add. Equipment (2/4)

- Possible improvements for 2017-18 re-using CTF3 equipment
  - Beam intensity: 5x WCMs -High bandwidth (10kHz-7GHz) and High sensitivity (20dB att.)

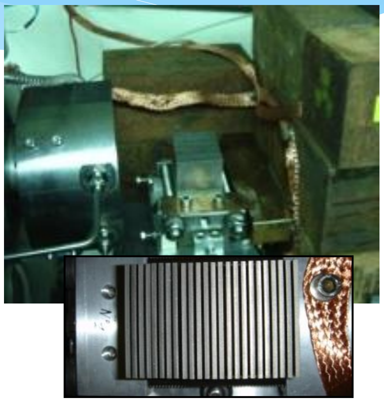



  - Beam position: 45x Inductive BPMs (with modified electronic for improved sensitivity)

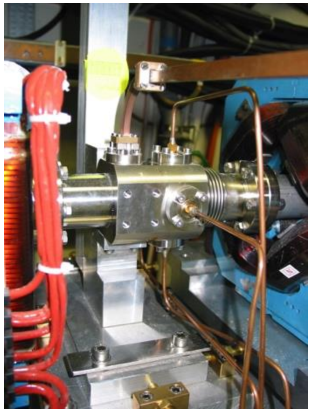


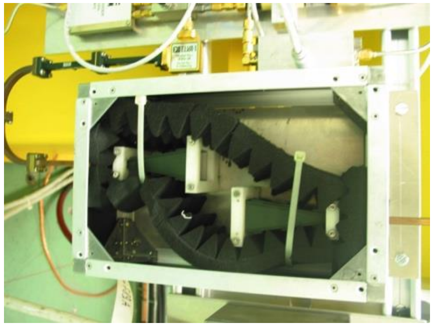
Beam Instrumentation on CLEAR
Add. Equipment (3/4)

- Possible improvement for 2017-18 re-using CTF3 equipment
  - Beam size using OTR screen system (x3) and Segmented dumps in spectrometer/dump lines (2x CTF3 Linac and 1x TBL)



  - Bunch length: 5x BPR's (Ka band power measurement) or 1x RF pick-up (down mixing stages in 4 frequency bands up 110GHz)





Beam Instrumentation on CLEAR
Add. Equipment (4/4)

- Large reserve of devices to cover some improvements of existing beam line and possibly to equip new beam lines
  - There are even more devices available on CTF3 – Contact us if you are interested in more details

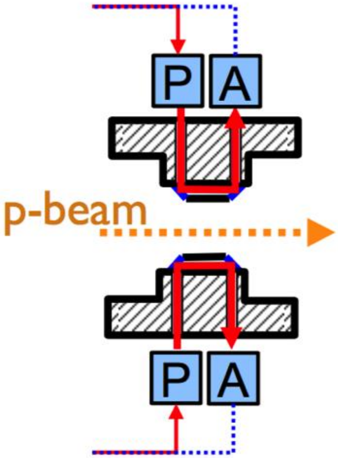
- All these changes would require
  - Proper integration study on the beam line
  - Small adaptation of the hardware configuration to cope with the smaller bunch intensity (i.e. removing attenuator, optimizing electronic, changing for high-sensitivity screens)
  - In some case pulling or re-routing (e.g. from TL2 or TBL) cables and moving front-end electronic and acquisition systems

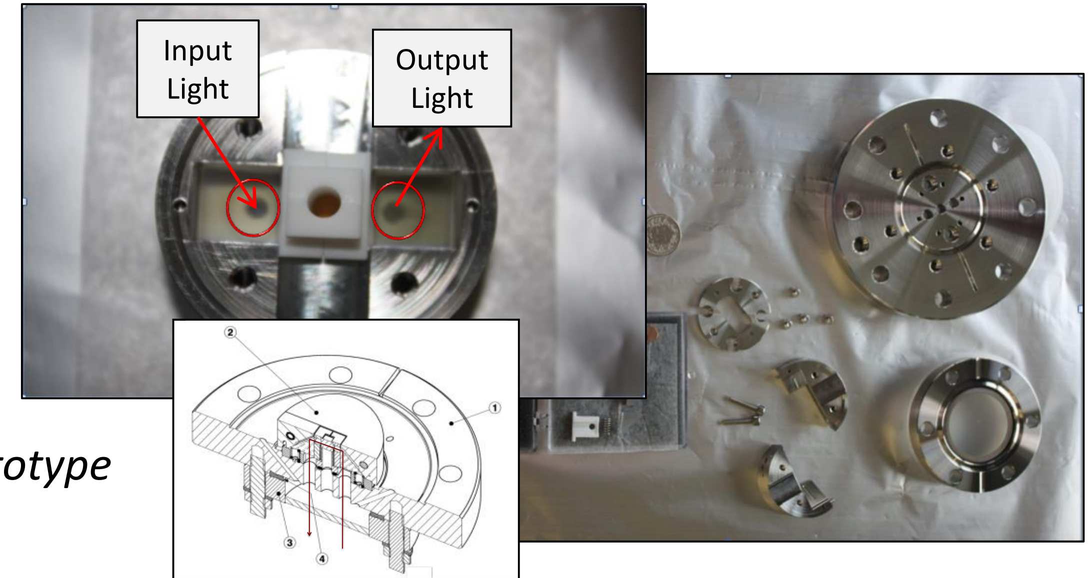
Instrumentation Test on CLEAR

Instrumentation Test on CLEAR

Electro-Optical Beam Position Monitor (1/2)

- Motivation – in the framework of HL-LHC
  - Providing an all-optical BPM using birefringent crystal and optical fiber
    - More compact, lower impedance, good time resolution, no expensive/big cable
- Concept and current development
  - Encoding the beam field onto a continuous laser beam using LiNbO3 crystal
  - Two configurations – either through **polarization change** or using interferences



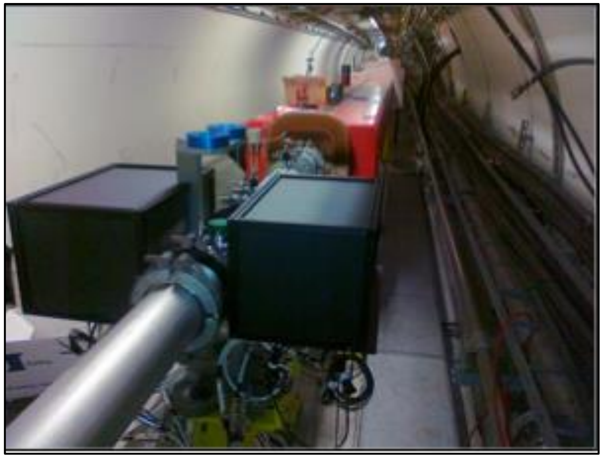


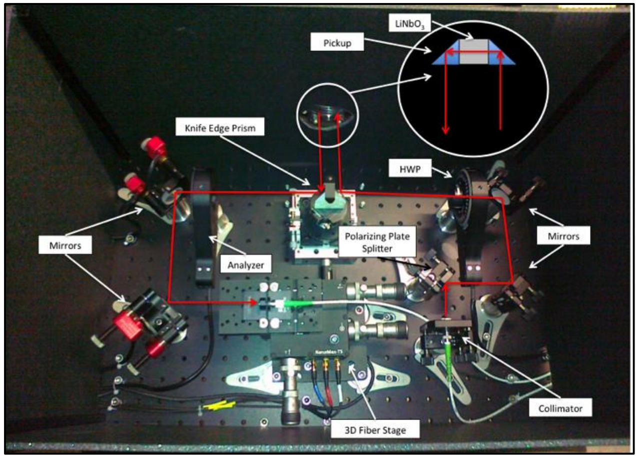
SPS prototype

Instrumentation Test on CLEAR

Electro-Optical Beam Position Monitor (2/2)

- Proposed test (*second part of the year*)
  - Install a spare SPS Pick-Up and optical set-up to perform detailed studies on CLEAR
    - Testing different crystal configurations: crystal with metal coating or not, special electrode,..
    - Perform beam position sensitivity curve
    - Develop the detection scheme: P/A method or interferometer





  - Re-using some of existing CLEAR infrastructure: motor controller, optical fiber, ..
  - Investigate the possibility to test in-air ?

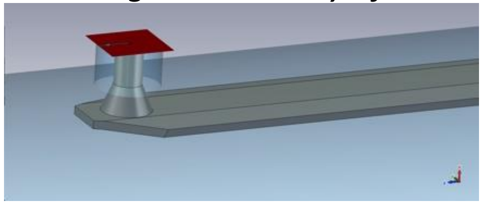
Instrumentation Test on CLEAR

HL-LHC Stripline BPM

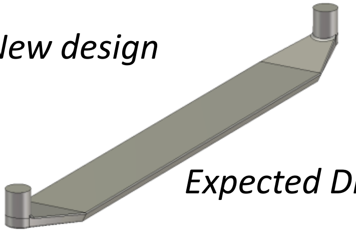
- Series of 40 BPMs being designed for upgraded interaction regions in LHC (IP1&5)
  - Cryogenic BPMs – in common beam pipe region (measuring counter-propagating beams)

- Testing the directivity of newly designed stripline using an existing LHC BPM in 2017

LHC design : Directivity of 20dB



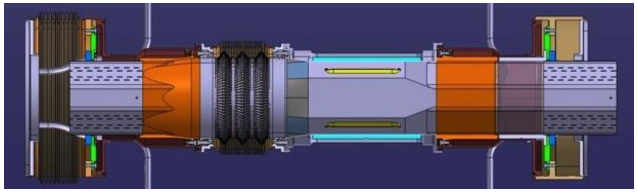
New design



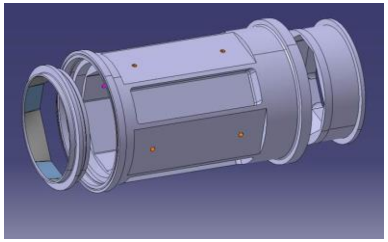
Expected Directivity of >30dB

- Validation of prototype in 2018 (in-air ?): Octagonal BPM with Inermet (W-alloy)

Interconnection between Quadrupoles



Beam screen *PIM (RF bellow)* *BPM* *Beam screen*

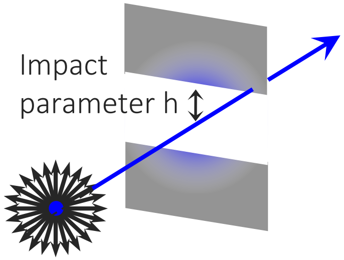


3D design of BPM under validation

Instrumentation Test on CLEAR
Diffraction Cherenkov Radiation studies

- Motivation and Concept
  - Similar radiation process (Coherent Diffraction Cherenkov radiation effect) as in **Dielectric loaded waveguides** proposed for high gradient acceleration, THz source and micro-bunching generation (Cherenkov FEL) and for short bunch length diagnostics
  - **Studying the properties of incoherent diffraction cherenkov radiation** (DChR) in dielectric materials for ultra relativistic beams
    - Radiation yield scales with $\gamma\lambda$ (i.e. large flux of photons for relativistic protons compared to Synchrotron radiation)
    - Radiation intensity proportional to the length of the dielectric
    - Radiation emitted in well defined Cherenkov angle (practical aspect)
    - Recent experiment on Cornell Electron Storage Ring demonstrated

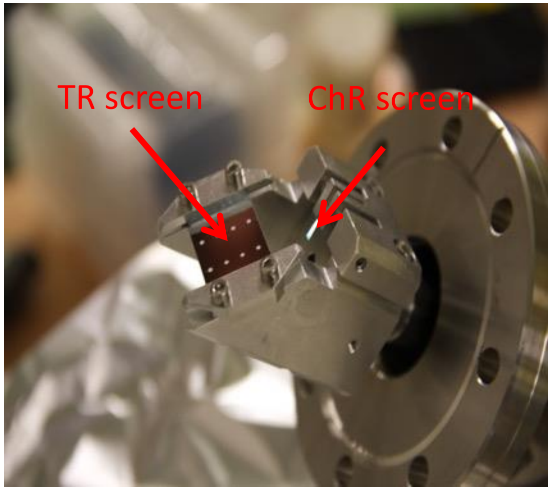
    large flux of photons in NIR emitted in 2cm long SiO2 radiator by 2.1GeV electrons

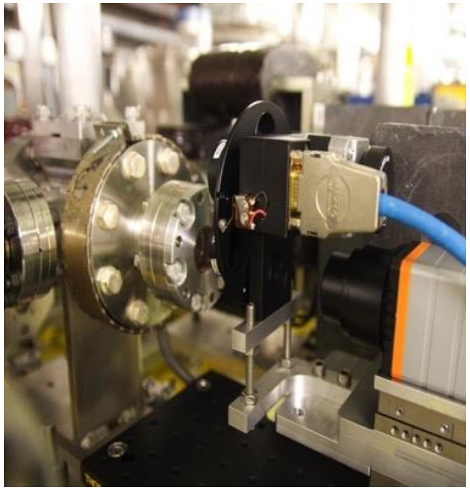


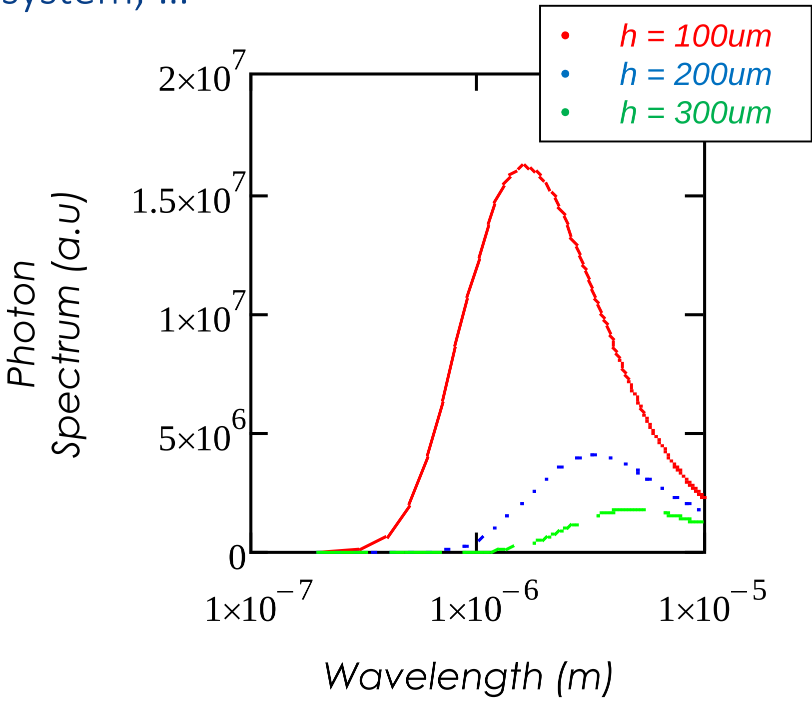
  - Possible use for future instrumentation projects (beam position and size)
    - Using diffraction cherenkov radiation for centering crystal collimator (LHC)
    - Developing a **very high directivity beam position monitor** for circular collider (Lepton, Hadron)

Instrumentation Test on CLEAR
Diffraction Cherenkov Radiation studies

- Testing with 200MeV electrons
  - Producing DChR in a 15x2x1.2mm Diamond crystal detected by IR Camera and photodiode
  - Comparing **Transition, Cherenkov and Diffraction Cherenkov** radiation:
    - Photons spectrum, Light yield, Light collection system, …



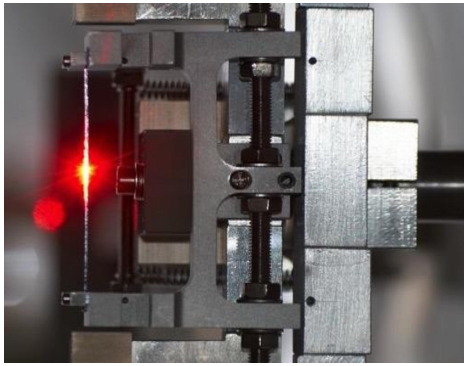


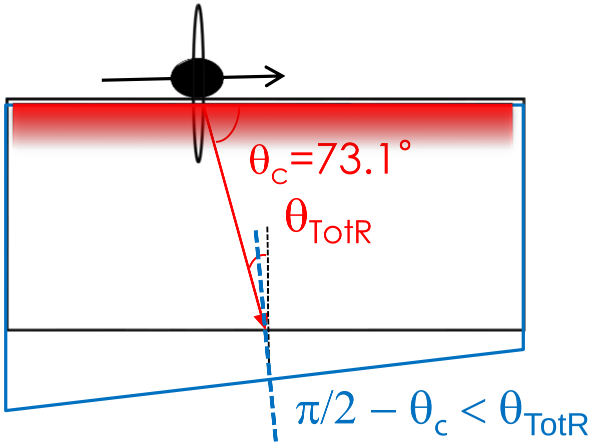


Instrumentation Test on CLEAR

Diffraction Cherenkov Radiation applications

- Bent Crystals (via channelling effect) are now seriously considered as primary collimators for LHC and FCC
  - Investigating the use of Cherenkov Diffraction Radiation as way to center the crystals around the beam
  - In a 3mm long Silicon Crystal and impact parameter of 1mm the LHC beam (7TeV p^+) would produce ≈5watts of radiation (1-10um wavelength)





- Crystal outer face built with different angle or with a high roughness to diffusive the light out
- Studying the detection system: e.g. coupling photons in an optical fiber
- Possible set-up in-Air to allow flexible developments

Beam instrumentation wish-list
Longer-term on CLEAR

- Possible beam line at low(er) energy after the RF gun
- Including radiation test stand for mm, infrared, visible, UV light generation/detection
- Including Electronic test stand for testing electronic devices using beam induced signals that cannot be easily obtained by standard pulse (voltage/current) generator
- Permanent installation for testing beam screens and EM devices (ceramic vacuum chamber: e.g. Inductive PU)
- Including an Under-Vacuum testing area for beam instruments– ex- BPM, Wire scanner, ..
- Including In-air testing area for particle detectors – low intensity option (VESPER)

Conclusions

- CLEAR will restart with a suite of beam instruments to guarantee its normal operation
  - Discussions on desired upgrades of CLEAR Beam instrumentation already started and we are looking for an implementation during 1st year of operation
  - Many (more) possibilities.. to be also discussed with CLEAR users
- Several tests of BI devices are planned for this year
  - Trying to perform in-air testing whenever possible
- Add. Beam lines and testing capabilities should be discussed and agreed in the near future for possible implementation in 2018

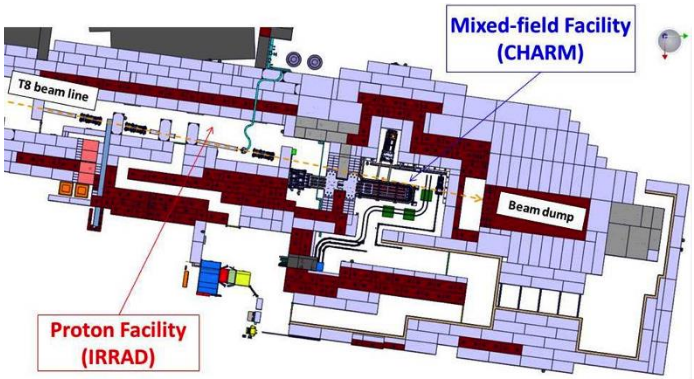
Thanks for your attention

Future Challenges in BI

- Unprecedented request for precision
  - Positioning down to well below the micron level
- Treatment of increasingly more data
  - Bunch by bunch measurements for all parameters:: Test of state of the art acquisition system (electric or optical domain)
- Dealing with high beam powers
  - Non-invasive techniques (Gas profile monitor, Quadrupolar PU, ..)
  - Robust and reliable machine protection and beam loss monitoring systems
- Dealing with the (ultra) fast
  - Sub-picosecond bunch lengths in AWAKE and CLIC
  - Longitudinal tomography in LHC (picosecond range)
  - Fast transverse beam position monitors (beam Instability diagnostics)

Developing Beam diagnostics at CERN

- Testing on **CERN PS Complex Area**
  - IRRAD – Proton irradiation (24GeV, max 5.10^{11} protons per spill, Up to 10^{18} protons)
    see https://irradiation.web.cern.ch/irradiation/
  - CHARM (CERN High-energy AcceleRator Mixed field facility) : mimic radiation environment found in the accelerator chain
    see https://charm.web.cern.ch/CHARM/

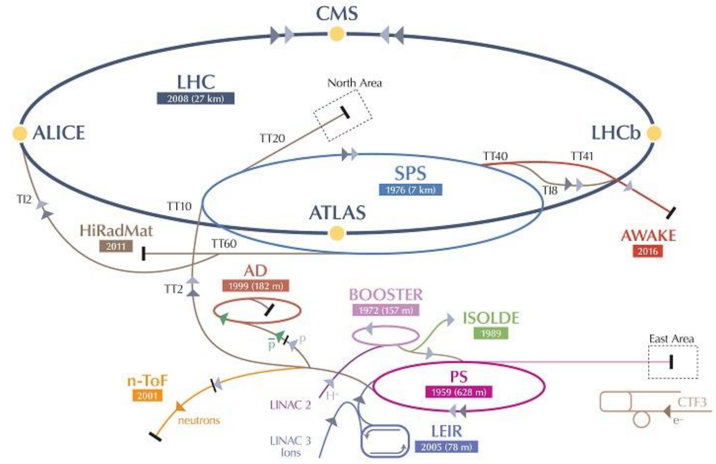


- Testing on **CERN SPS Area**
  - High Radiation to Material – 450GeV Protons with up to 288 Bunches with 25ns spacing (3 10^{13} protons per pulse)
    see https://espace.cern.ch/hiradmat-sps/Wiki%20Pages/Home.aspx
  - Gamma Irradiation Facility in NA with a 15 TBq ^{137}Cs source
    see https://gif-irrad.web.cern.ch/gif-irrad/

Developing Beam diagnostics at CERN

- Testing directly on the Operational Machines themselves
  - It works..but may lead to unpleasant surprises
    - *e.g. Beam position dependency of CERN Fast Beam Current Transformer on LHC*
  - Limited time for hardware installation/modification in the tunnel (i.e. Technical stops)
  - Limited beam time available for tests during MDs
  - R&D is not always compatible with the strict requirements for Operational Machines

e.g. Testing gas jet monitor and their performance as function of gas pressure would conflict with vacuum requirements

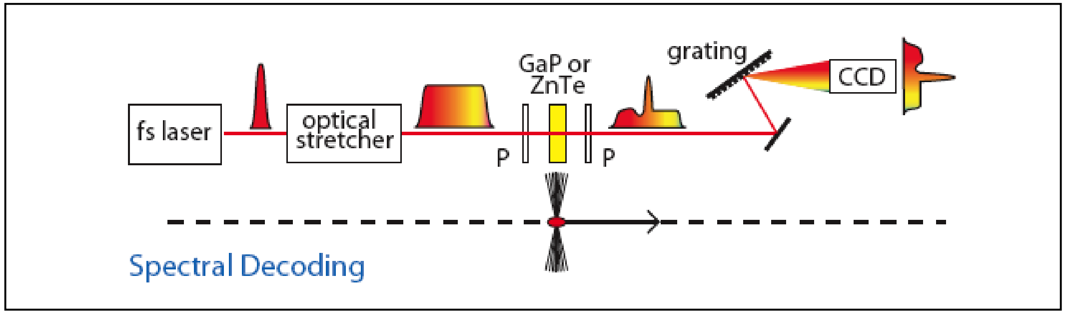


EO @ Califes

Single shot, non-destructive bunch length measurement

using

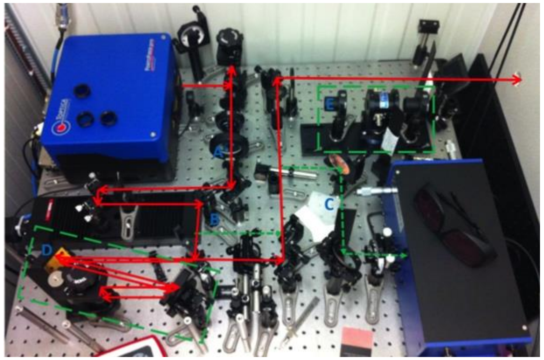
Electro- **O**ptical **S**pectral **D**ecoding Technique



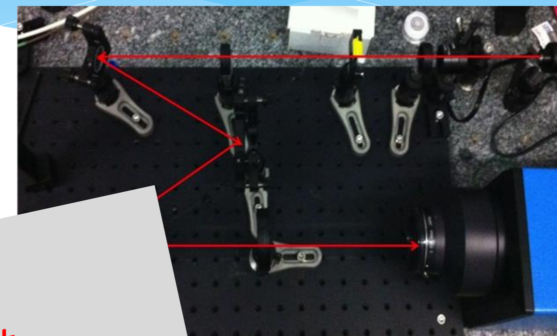
- Using beam induced bi-refringency in a non-linear crystal to encode the temporal profile of the beam field onto a chirped laser beam (time to frequency)

- Measuring the laser spectrum to decode the electron bunch length

EO @ Califes



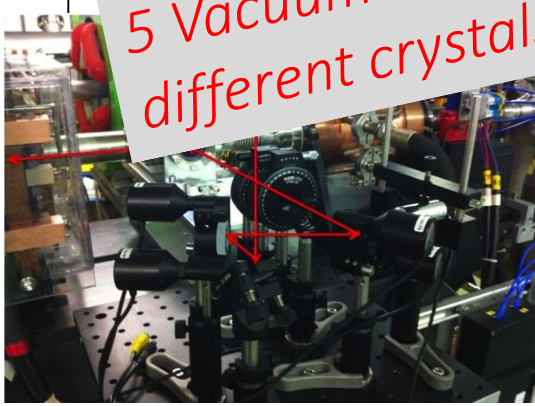
150fs Er (780nm) laser stretched to 12ps



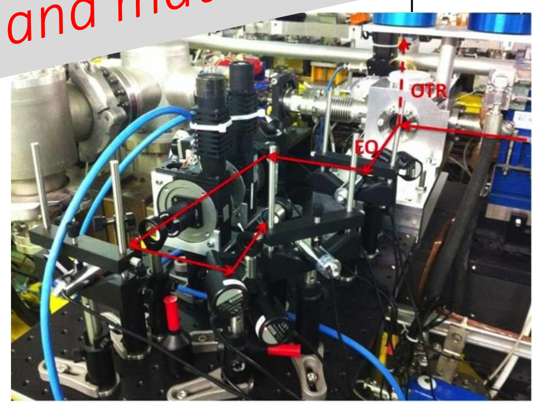
Spectrometer with grating and intensified gated CCD camera

It involves
Time consuming laser alignment

5 Vacuum interventions to test different crystals (sizes and materiel)



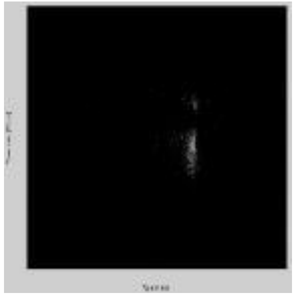
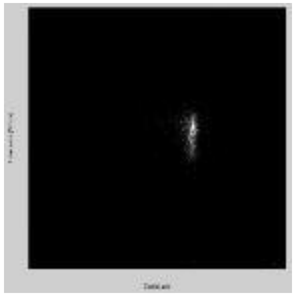
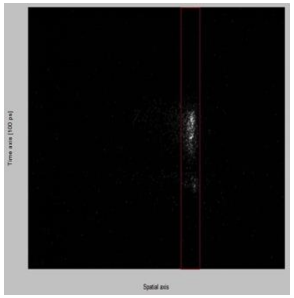
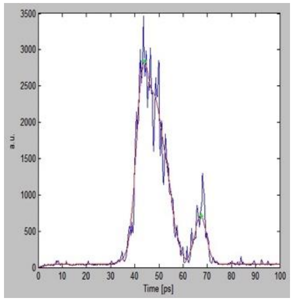
First polariser and
Laser injection Chamber



Crystal chamber (4mm ZnTe), crossed polariser and fiber coupling back to lab

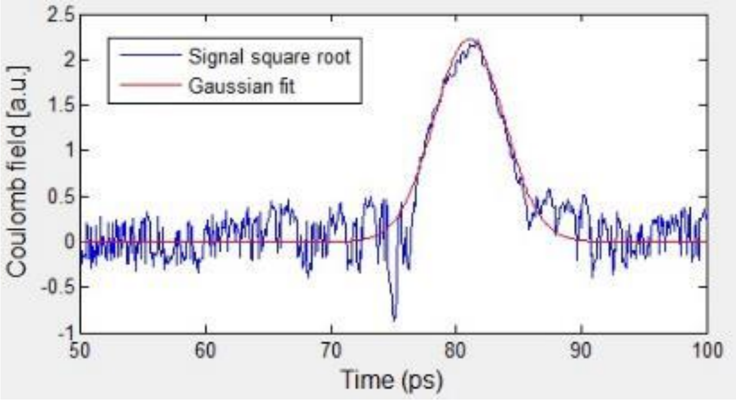
EO @ Califes

1 – Laser-electron beam synchronization

Done with Streak camera measurements with an accuracy of few ps

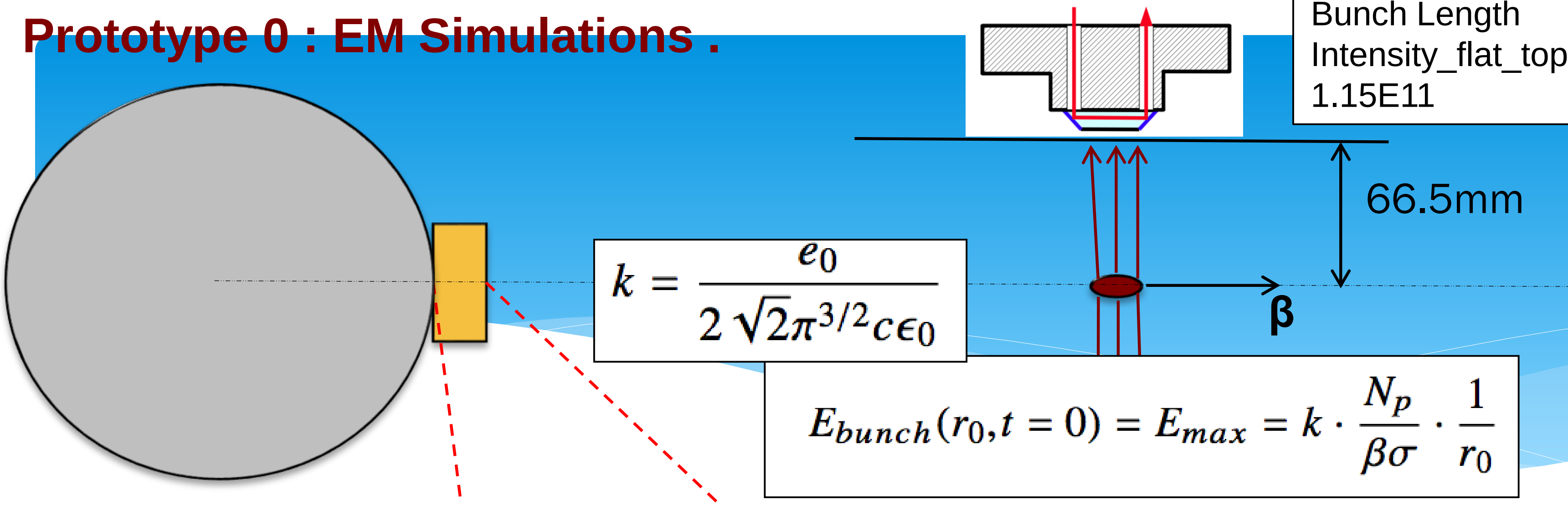
2 – EO measurements using spectrometer



- 6.6ps FWHM, 0.35nC bunch charge
- Measured down to 0.1nC per bunch
- S/N ratio was 2-3 times better than streak camera measurements

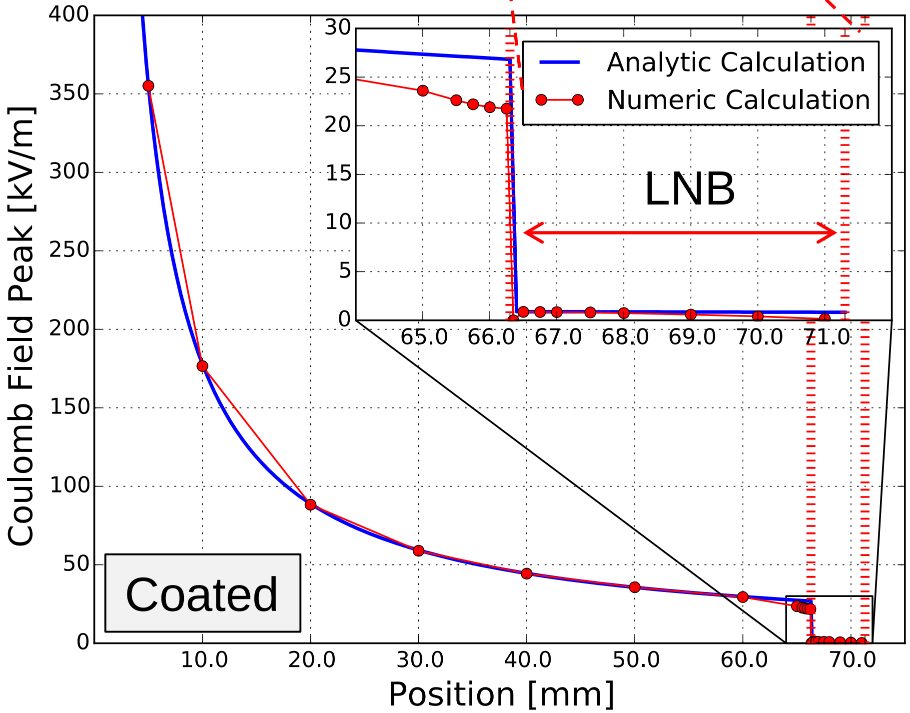
Prototype 0 : EM Simulations .

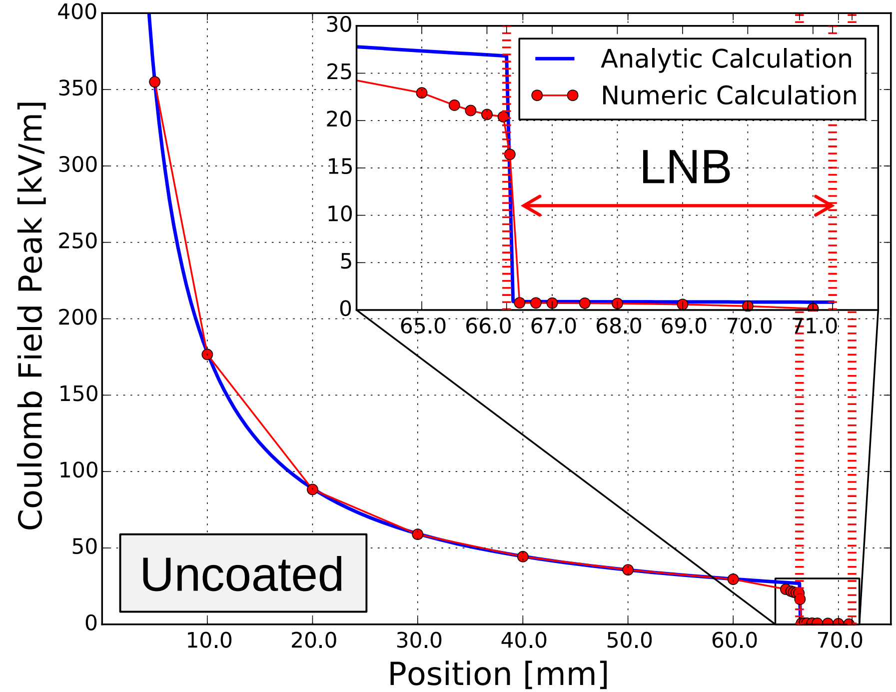
Bunch Length = 1.0ns
Intensity_flat_top = 1.15E11



$$k = \frac{e_0}{2\sqrt{2}\pi^{3/2} c \epsilon_0}$$

$$E_{bunch}(r_0, t = 0) = E_{max} = k \cdot \frac{N_p}{\beta\sigma} \cdot \frac{1}{r_0}$$

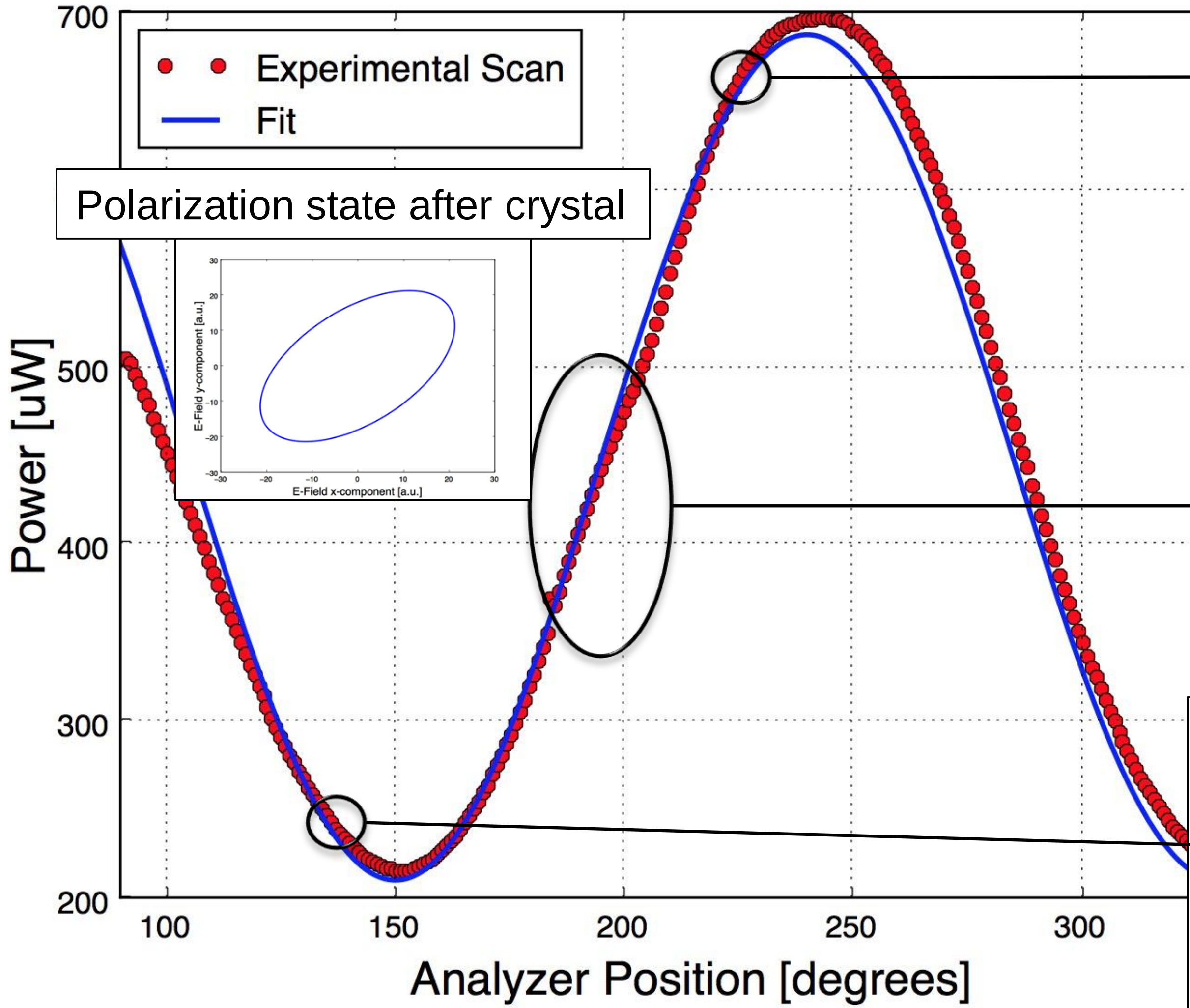


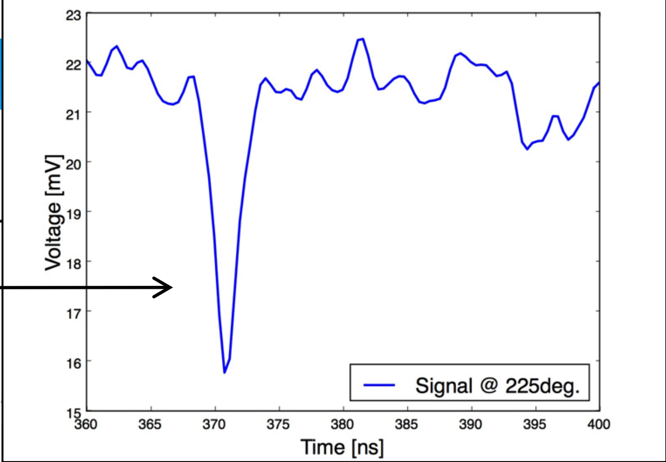


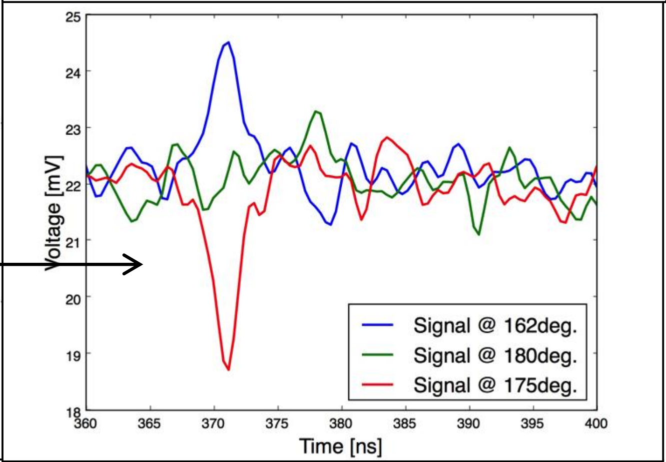
Electric Field inside the crystal ~ 0.6 kV/m ➔ per mil signal/background detection

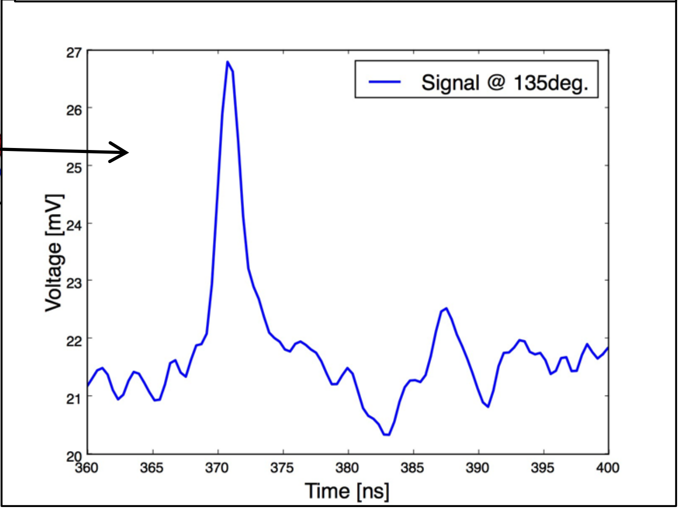
Prototype Zero: Measurements.

Beam conditions: AWAKE
Bunch Length = 1.8ns
Intensity_flat_top = 2.8E11

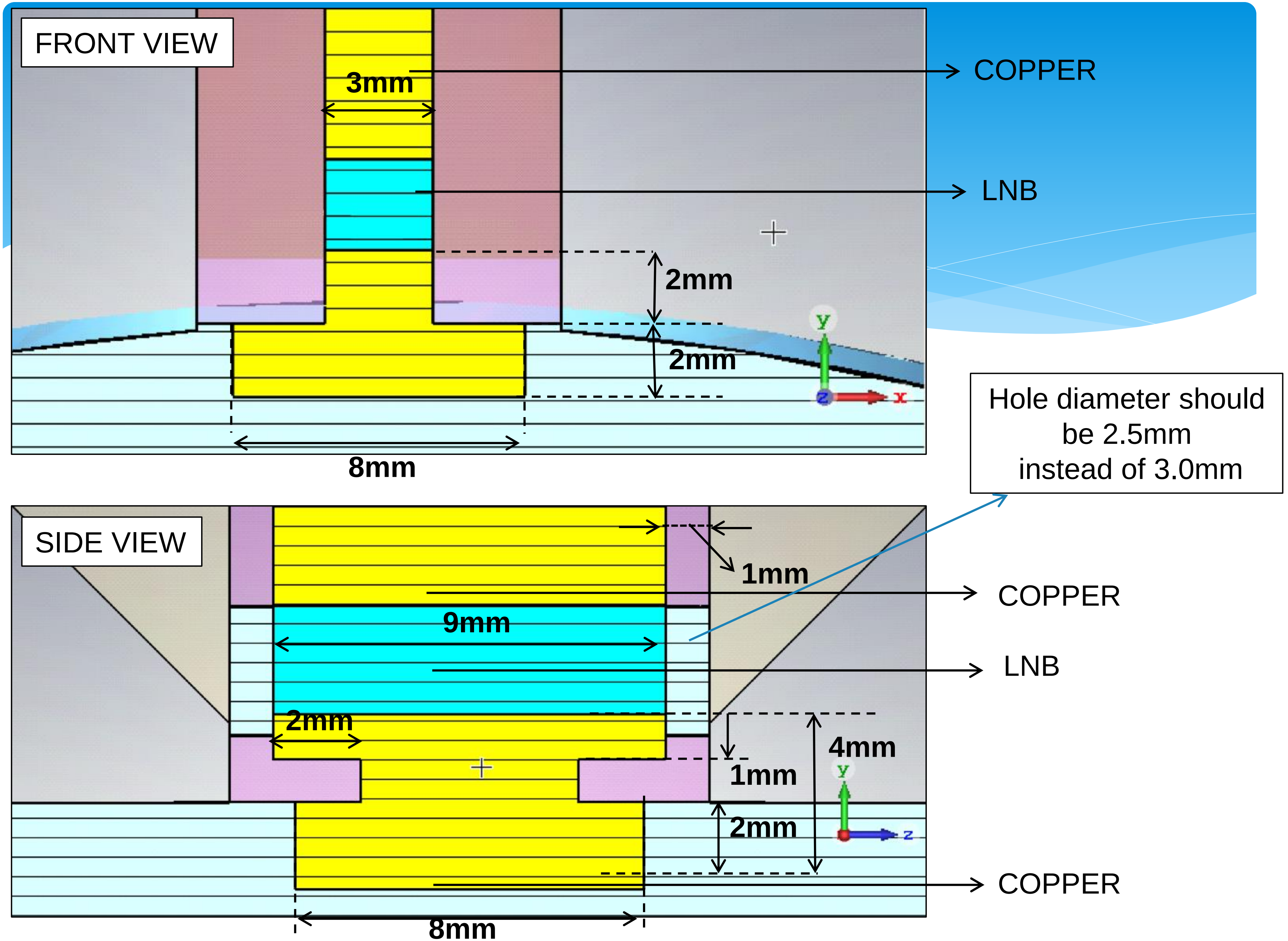








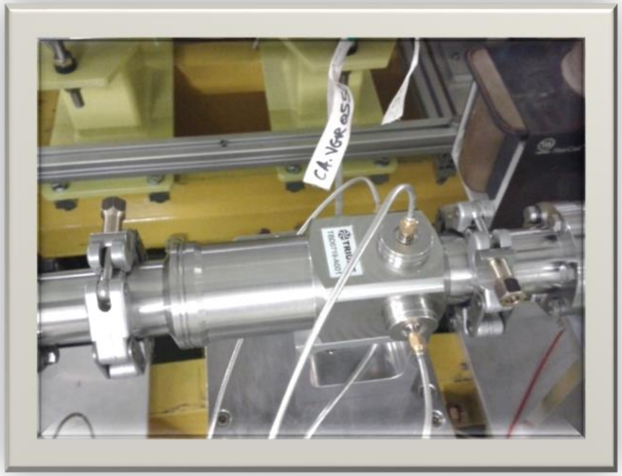
Correct optical behavior: Proof of concept achieved



FRONT VIEW
3mm
COPPER
LNB
2mm
2mm
8mm
Hole diameter should be 2.5mm instead of 3.0mm
SIDE VIEW
1mm
COPPER
9mm
LNB
2mm
4mm
1mm
2mm
COPPER
8mm

Examples of past developments BI for AWAKE

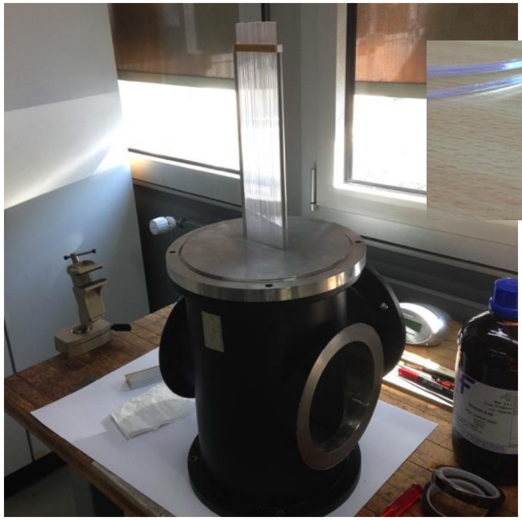
- AWAKE electron beam line is re-using BI devices for CTF3 (Streak camera, BTV)
- Test of the e- Beam Position Monitor developed by TRIUMF – June 2016

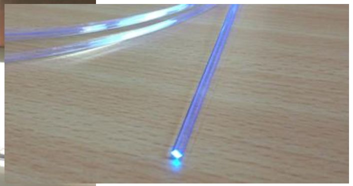


- Test of the pick-up, its electronics, software interfaces
- Single pulse data for different bunch charges to compare with simulations

Examples of possible future tests

- Test and calibration of Secondary beam line monitors (EA), Particle detectors, Beam Loss Monitors
  - **Possibility to reach low beam density down to 10^5 electrons/cm^2 per pulse**
  - Study of detector performance: i.e. MIP response, Time response, Saturation effects

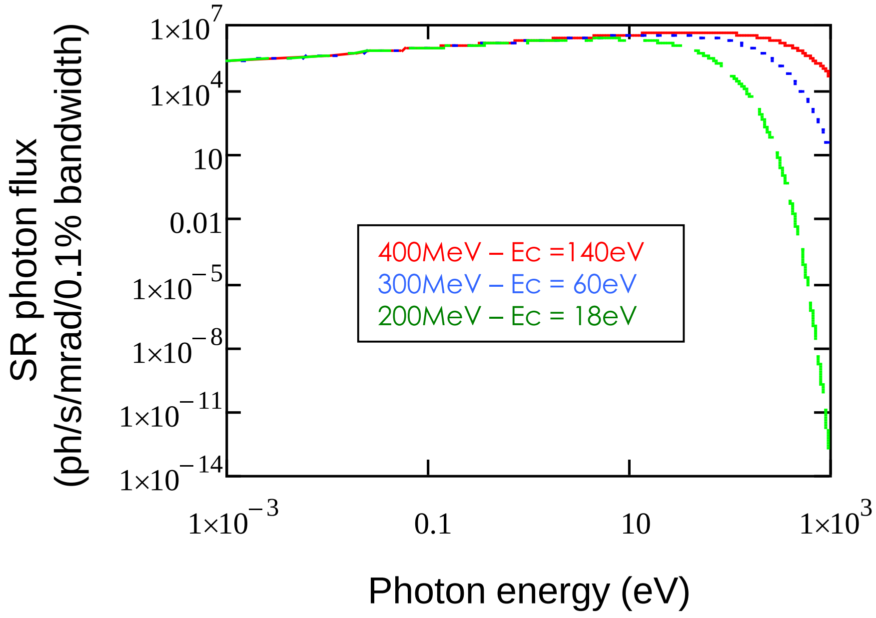




On-going development of high sensitivity Scintillating fiber for SPS NA and new EHN1 beam line

Examples of possible future tests

- Synchrotron light monitors
  - Imaging system for HL-LHC and FCC (visible, UV..)
  - Beam halo monitor, longitudinal density monitors, …

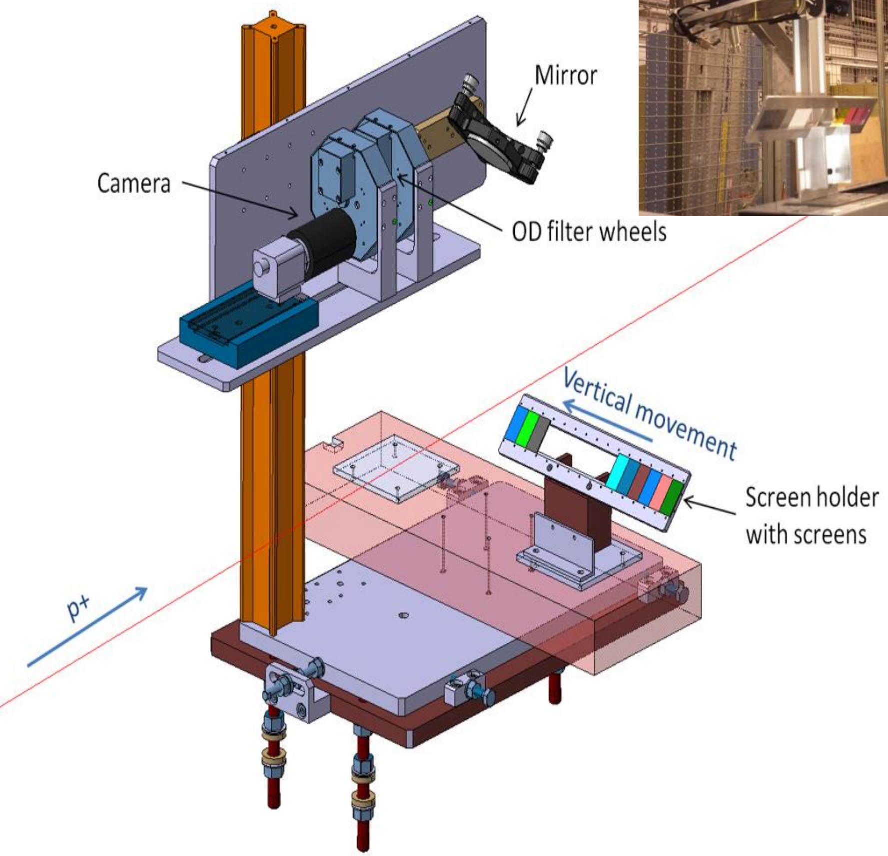


With 200MeV e^-, similar photon spectrum as in LHC

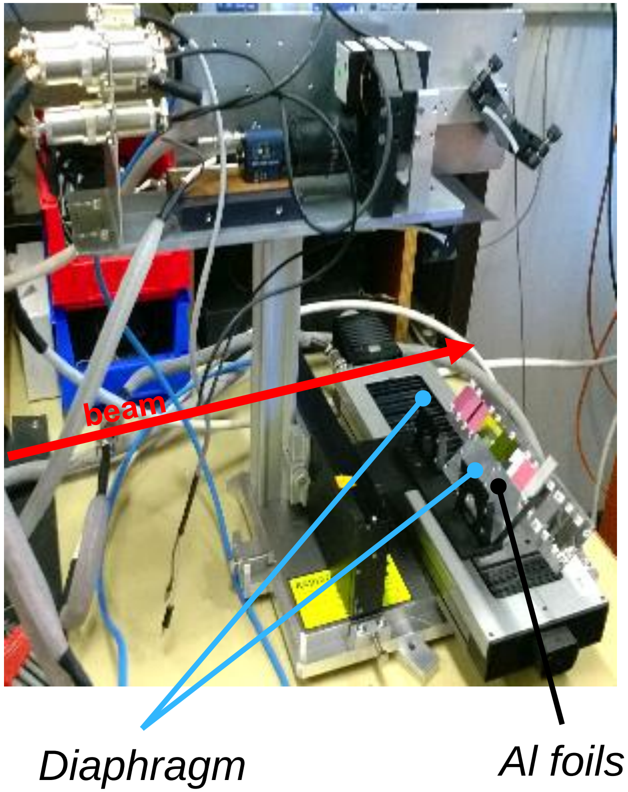
Possibly to go to EUV/low-energy X-ray if doubling the beam energy

Possible in-air BTV setup

<u>*Oct 2015 – HRMT30*</u>

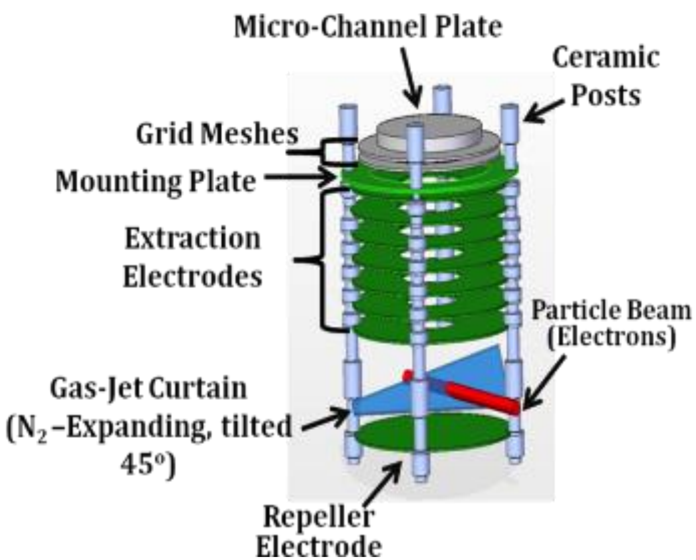


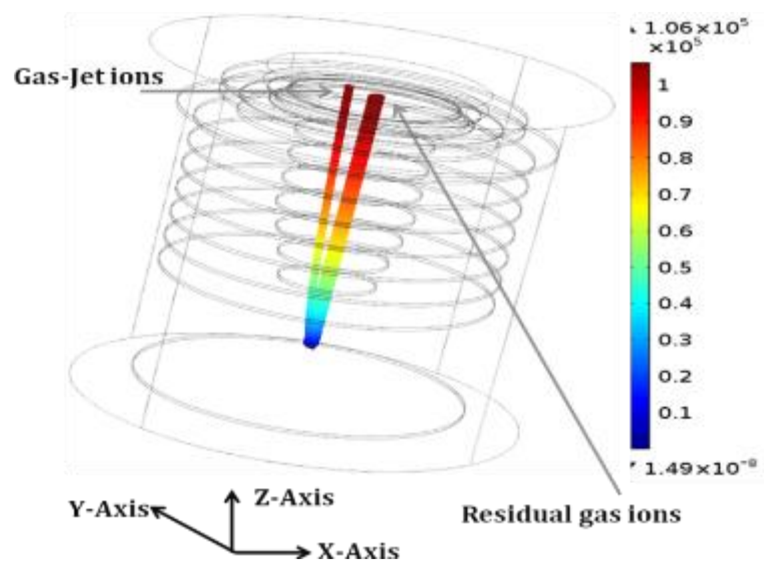
<u>*June 2016 – HRMT32*</u>



Gas-jet R&D with ULIV

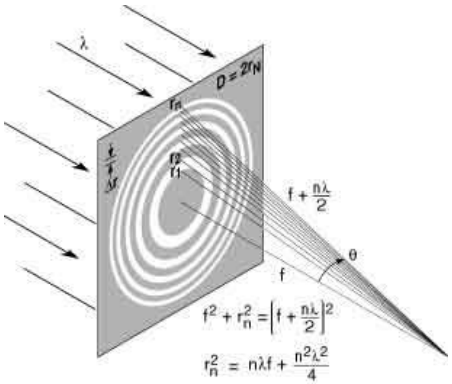
- Beam ionises gas molecules, ions are extracted by electric field
- Sufficiently thin gas jet would allow 2D image: if not used as a gas scanner
- Initial forwards momentum of gas jet separates gas jet ions from residual gas ions





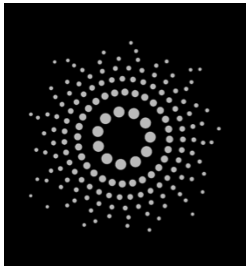
Gas-jet R&D with ULIV

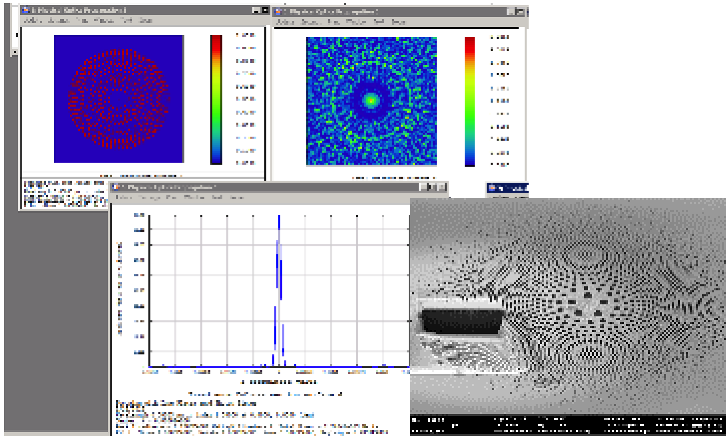
- Matter-wave focusing for a thin gas jet (down to Tens of micrometers) – Fresnel Zone plate principle



- The path difference between each successive light ring is equal to 1 wavelength (at the focal point) constructive interference.
- Each zone is equal in area
- Focal spot size is roughly the width of the narrowest (outer) zone
- Compared to traditional lens: no spherical aberration, large chromatic aberration

- Design (ZEMAX) and fabrication of **Apodised Photon Sieve** reduces higher order diffraction, increases central maximum





Beam instrumentation wish-list

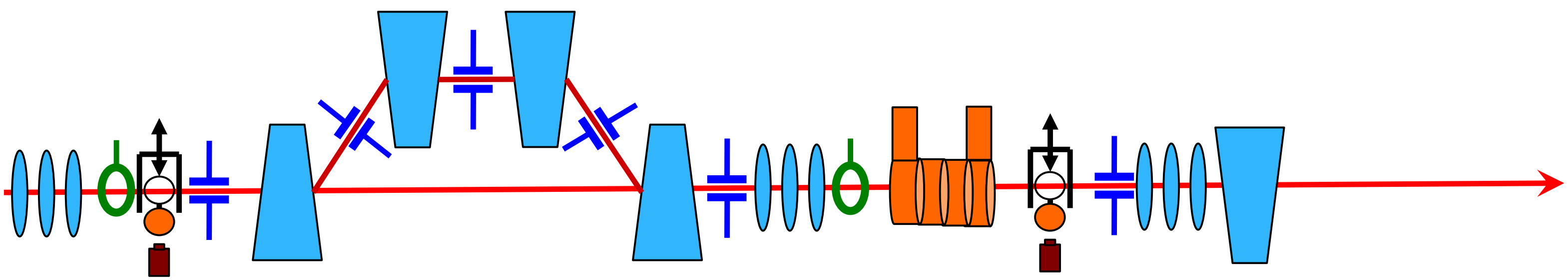
Longer-term on CLEAR

Short and long bunches
(100fs up to 200ps)

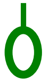
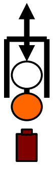
Magnetic chicane
Shorten or lenghthen

Time to position
correlation

RF deflector
for crabbing

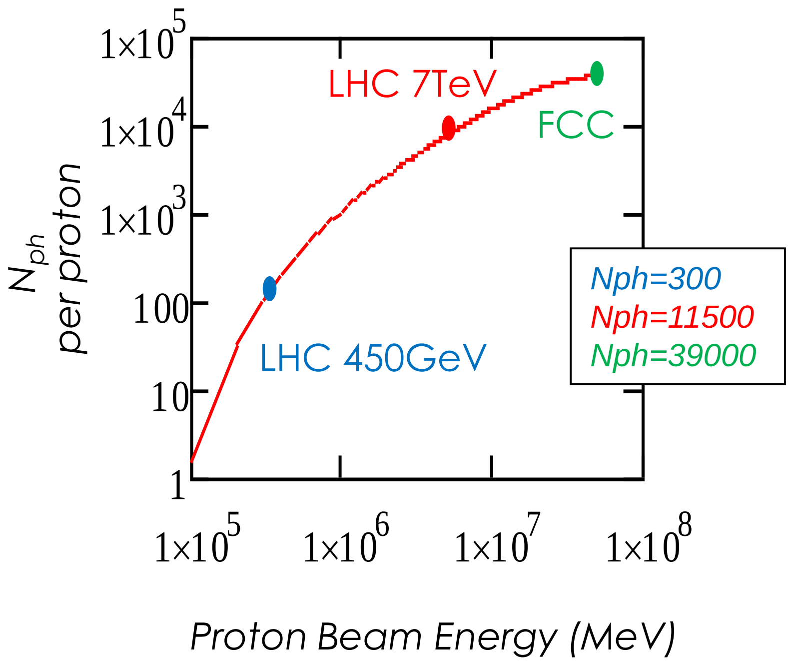


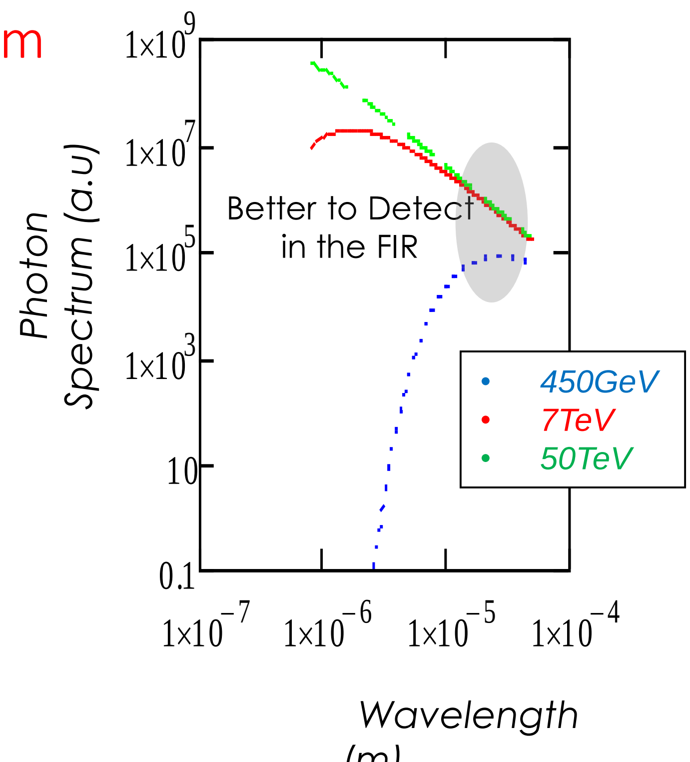
+ Adequate beam monitors for beam tuning and cross-calibration

Beam current monitor  Beam position monitor  Beam profile monitor 

e.g. Cherenkov Diffraction Radiation

- Number of DChR photons and photon spectrum as function of beam Energy (LHC-FCC)
  - 1m Si crystal and impact parameter h = 2mm

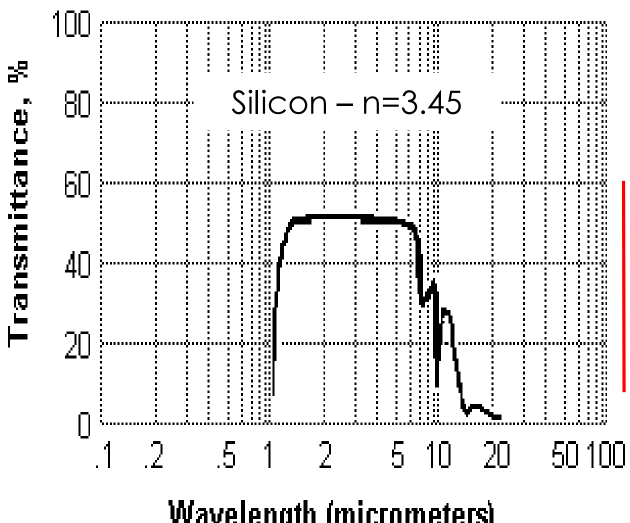




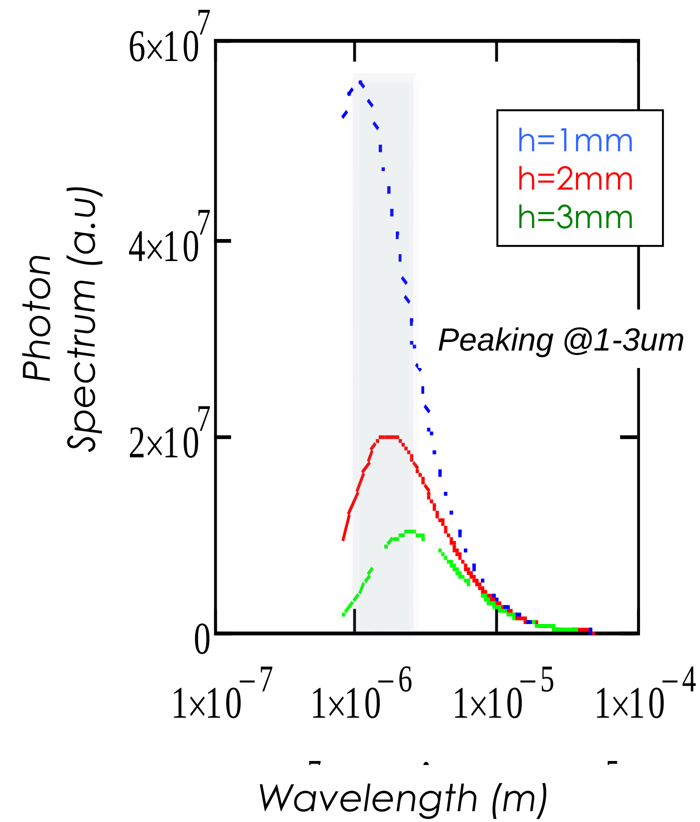
e.g. Cherenkov Diffraction Radiation

- DChR Photons spectrum in Silicon for LHC (7TeV protons) assuming different impact parameters

$$\frac{dP}{d\lambda} = \frac{2\pi\alpha \cdot L \cdot Tr(\lambda)}{\lambda^2} e^{\frac{-4\pi \cdot h}{\gamma\beta\lambda}} \left(1 - \frac{1}{(\beta n)^2}\right)$$

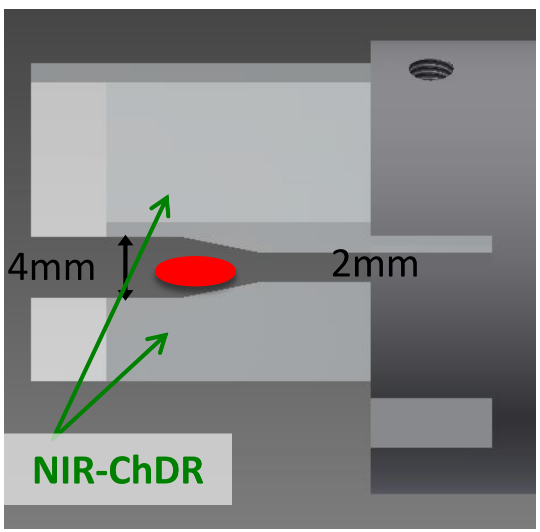


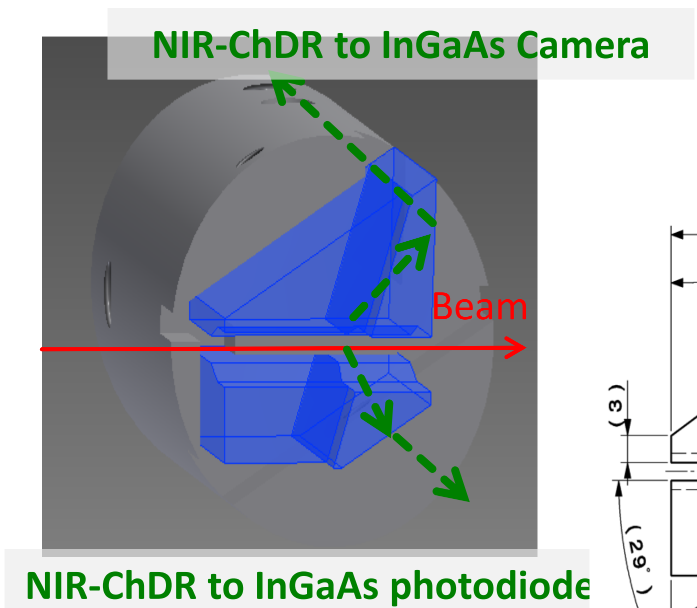
Photon spectrum only calculated over the transmission bandwidth of corresponding material

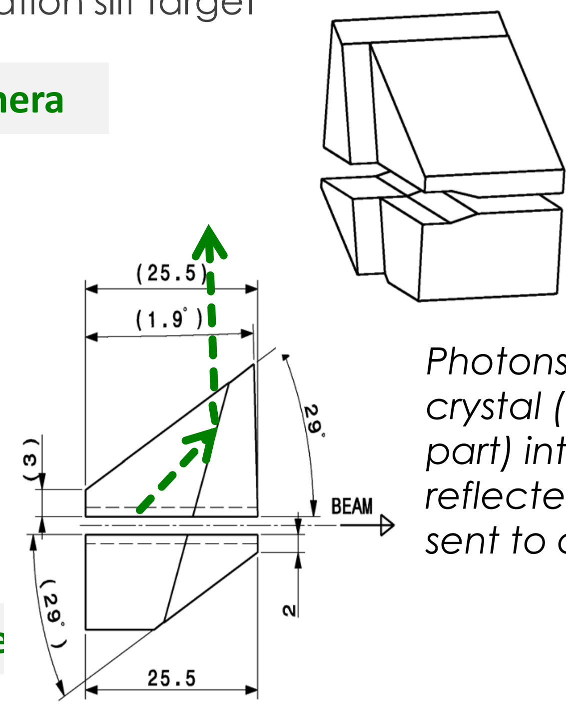


Test of Diff. Cherenkov Radiation on CESR

- Design a 2.5cm long SiO2 Diffraction and Cherenkov Diffraction target in IR (0.9-1.7um) built in two pieces
  - 4mm 20° angle tilted DR slit for imaging purpose to help centering the beam in the slit
  - 4mm and 2mm aperture Cherenkov diffraction radiation slit target



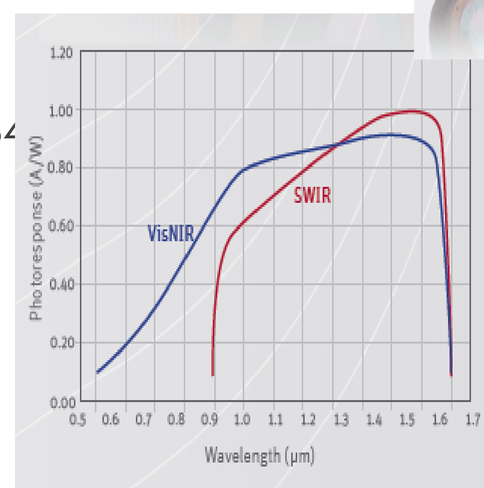




Photons from 1st crystal (top part) internally reflected – not sent to camera

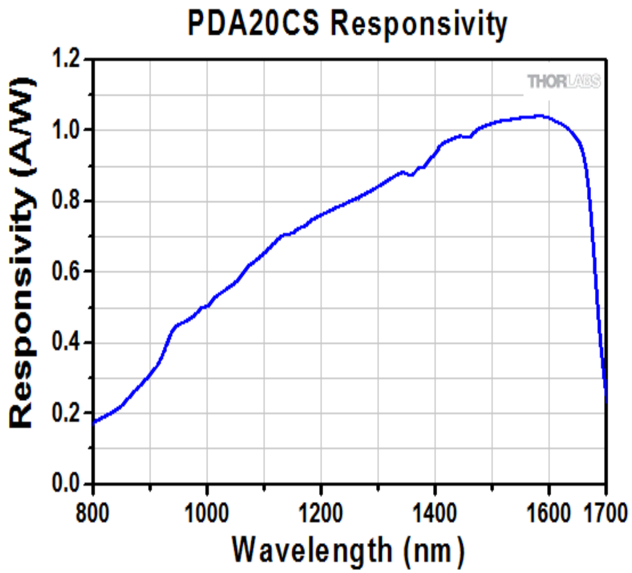
VIS/NIR detector

- **New NIR camera with a 35mm camera lens : Xenics Bobcat 640 GigE**
  - Cooled InGaAs 640x512 pixels : 20um pixel pitch
  - 0.9-1.7um wavelength sensitivity
  - QE up to 80% at 1.6um
  - 14bit ADC
  - 1us-40ms integration window
  - Size (WxHxL): 55x55x82 mm^3 : weight 334



VIS/NIR detector

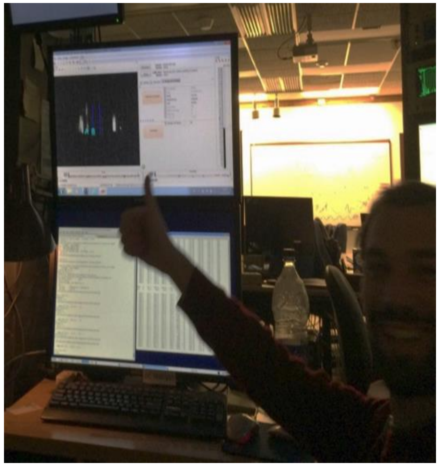
- **InGaAs amplified photodiode on the lower viewport**

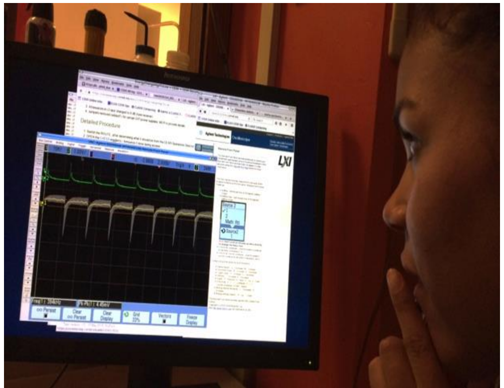


Performance Specifications			
0 dB Setting		**40 dB Setting**	
Gain[1] (Hi-Z)	1.51×10^3 V/A ±2%	Gain[1] (Hi-Z)	1.51×10^5 V/A ±2%
Gain[2] (50 Ω)	0.75×10^3 V/A ±2%	Gain[2] (50 Ω)	0.75×10^5 V/A ±2%
Bandwidth	10 MHz	Bandwidth	200 kHz
Noise (RMS)	365 µV	Noise (RMS)	590 µV
NEP	5.12×10^{-11} W/√Hz	NEP	1.14×10^{-12} W/√Hz
Offset	5 mV (10 mV max)	Offset	6 mV (10 mV max)
10 dB Setting		**50 dB Setting**	
Gain[1] (Hi-Z)	4.75×10^3 V/A ±2%	Gain[1] (Hi-Z)	4.75×10^5 V/A ±2%
Gain[2] (50 Ω)	2.38×10^3 V/A ±2%	Gain[2] (50 Ω)	2.38×10^5 V/A ±2%
Bandwidth	4 MHz	Bandwidth	67 kHz
Noise (RMS)	500 µV	Noise (RMS)	670 µV
NEP	3.11×10^{-11} W/√Hz	NEP	2.91×10^{-12} W/√Hz
Offset	6 mV (10 mV max)	Offset	6 mV (10 mV max)
20 dB Setting		**60 dB Setting**	
Gain[1] (Hi-Z)	1.5×10^4 V/A ±2%	Gain[1] (Hi-Z)	1.5×10^6 V/A ±5%
Gain[2] (5 0Ω)	0.75×10^4 V/A ±2%	Gain[2] (50 Ω)	0.75×10^6 V/A ±5%
Bandwidth	1.87 MHz	Bandwidth	25 kHz
Noise (RMS)	340 µV	Noise (RMS)	880 µV
NEP	6.54×10^{-12} W/√Hz	NEP	1.76×10^{-12} W/√Hz
Offset	6 mV (10 mV max)	Offset:	6 mV (10 mV max)
30 dB Setting		**70 dB Setting**	
Gain[1] (Hi-Z)	4.75×10^4 V/A ±2%	Gain[1] (Hi-Z)	4.75×10^6 V/A ±5%
Gain[2] (50 Ω)	2.38×10^4 V/A ±2%	Gain[2] (50 Ω)	2.38×10^6 V/A ±5%
Bandwidth	660 kHz	Bandwidth	4 kHz
Noise (RMS)	490 µV	Noise (RMS)	1.33 mV
NEP	3.04×10^{-12} W/√Hz	NEP	5.89×10^{-12} W/√Hz
Offset	6 mV (10 mV max)	Offset	8 mV (12 mV max)

Measurements at Cornell

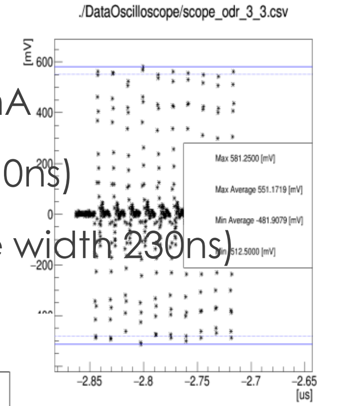
- **Identifying DChR light**
  - With camera:
    - SR present but not at the same position
    - DChR photons emitted in 1st crystal are internally reflected
    - Only see photons from 2nd crystal : Photons are observed at the expected position on the image
    - Do we see a larger image due to the surface roughness
  - With photodiode: only observing photons emitted from the 2nd crystal

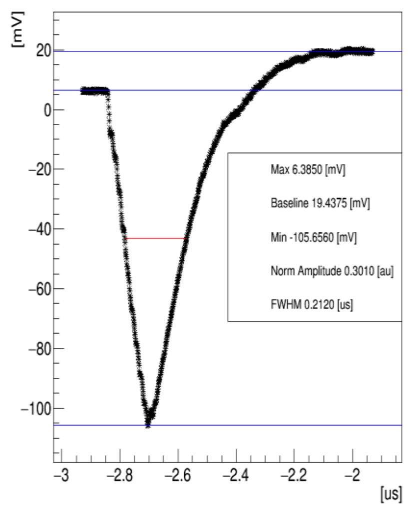


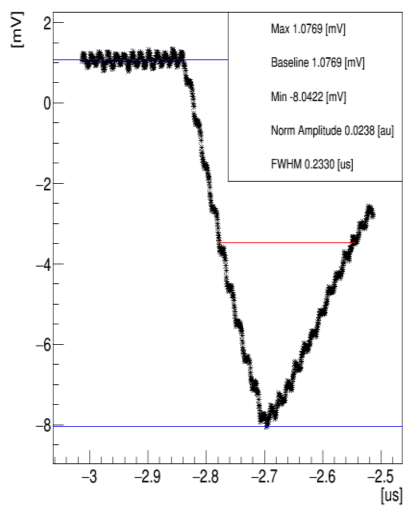


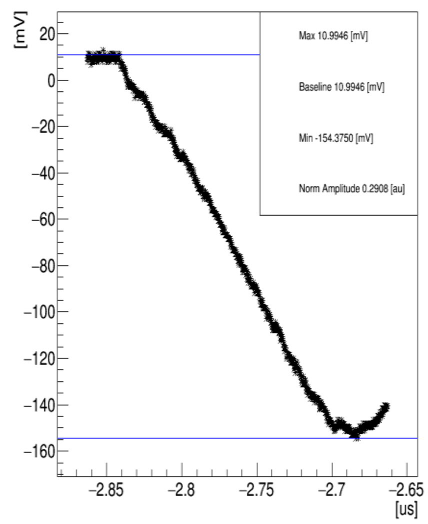
Measurements at Cornell

- **Measuring DCh Radiation light yield with the photodiode**
  - Most of the measurements performed with 10 bunches@14ns spacing – 10mA
  - Measurements with no filter – Gain at 40dB (measured FWHM pulse width 210ns)
  - Measurements with1300±10nm filter – Gain at 70dB (measured FWHM pulse width 230ns)







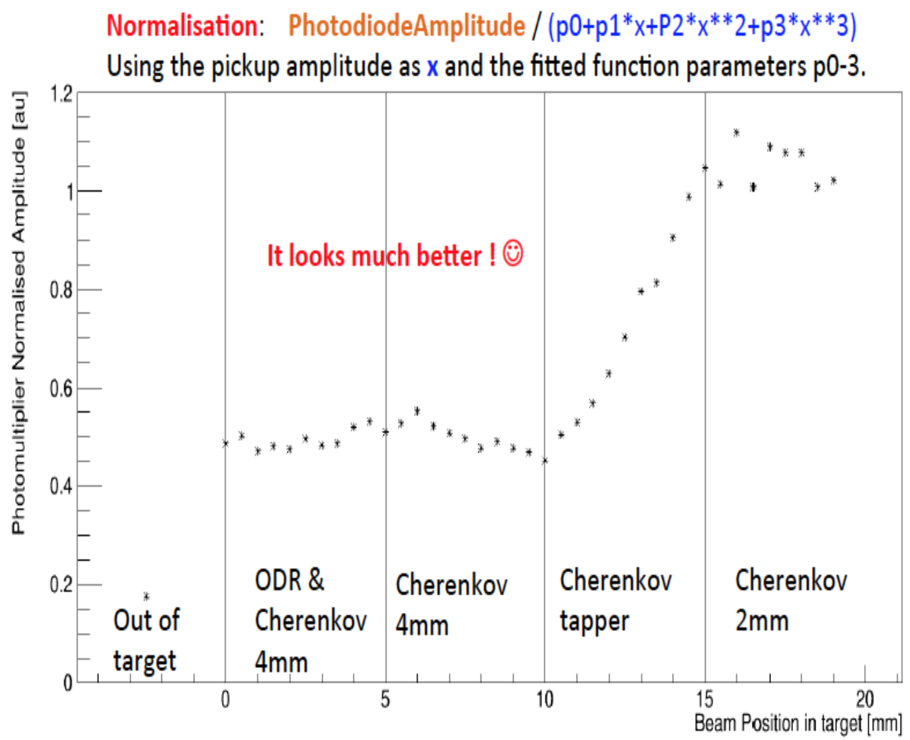


Measurements at Cornell

- **Measuring DCh Radiation light yield with the photodiode**
  - Most of the measurements performed with 10 bunches@14ns spacing – 10mA
  - Calculations take into account
    - the photodetector spectral sensitivity
    - the detector solid angle (20%)
    - Assumes 'zero' beam size / perfectly centered beam
  - Measurements with no filter – Gain at 40dB (measured FWHM pulse width 210ns)
    - Measuring 80 mV / calculating 30 mV for h=2mm
    - Measuring 280 mV / calculating 270mV for h=1mm
    - Possibly contribution of the diffusivity of the target and target metrology h=?
  - Measurements with1300±10nm filter – Gain at 70dB (measured FWHM pulse width 230ns)
    - Measuring 8-10 mV / Calculating 10mv for h=2mm
    - to be analyzed for h=1mm
  - Camera data to be analyzed

Measurements at Cornell

- **Measuring with DCh Light intensity as function of slit aperture**
  - around x5 increase from 4 to 2mm observed with photodiode (expecting a factor 9 from calculations)



- *Calculations gives a factor 6 increase for a change from 4mm to 2.6mm slit aperture*
  - *Should check the dimension of the SiO2 radiator*
- *Analysis to be confirmed once we have a linearity response curve of the photodetector measured in the lab*

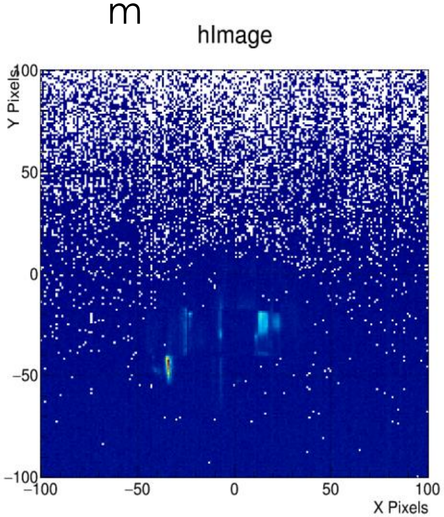
! Several videos performed with camera – to be analyzed !

Measurements at Cornell

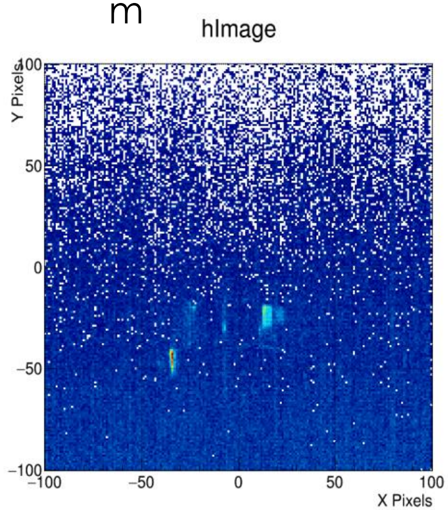
- **Measuring with DCh Light intensity as function of slit aperture**
  - Camera images to be analyzed – but normalization to beam current relatively tricky (due to SR and internal reflection of DChR)

Beam closer to the top crystal (camera)

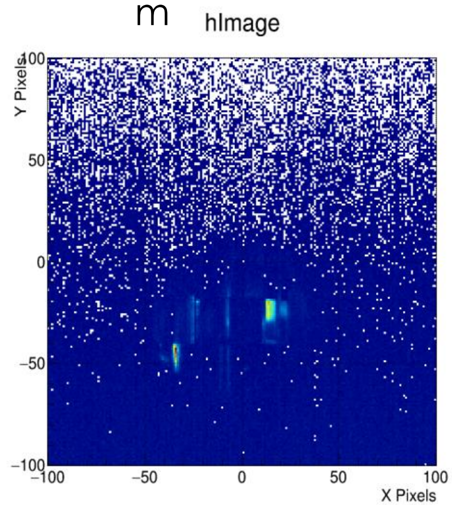
BPM@2640um



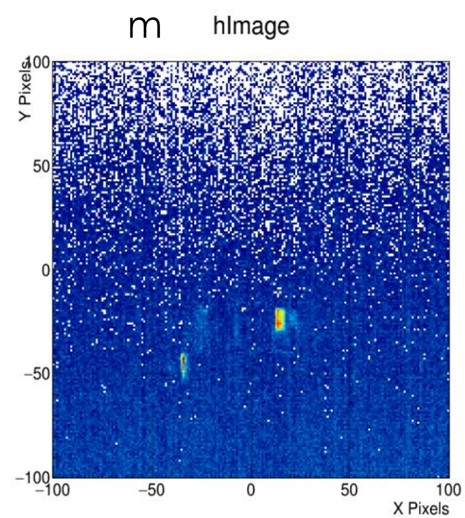
BPM@2878um



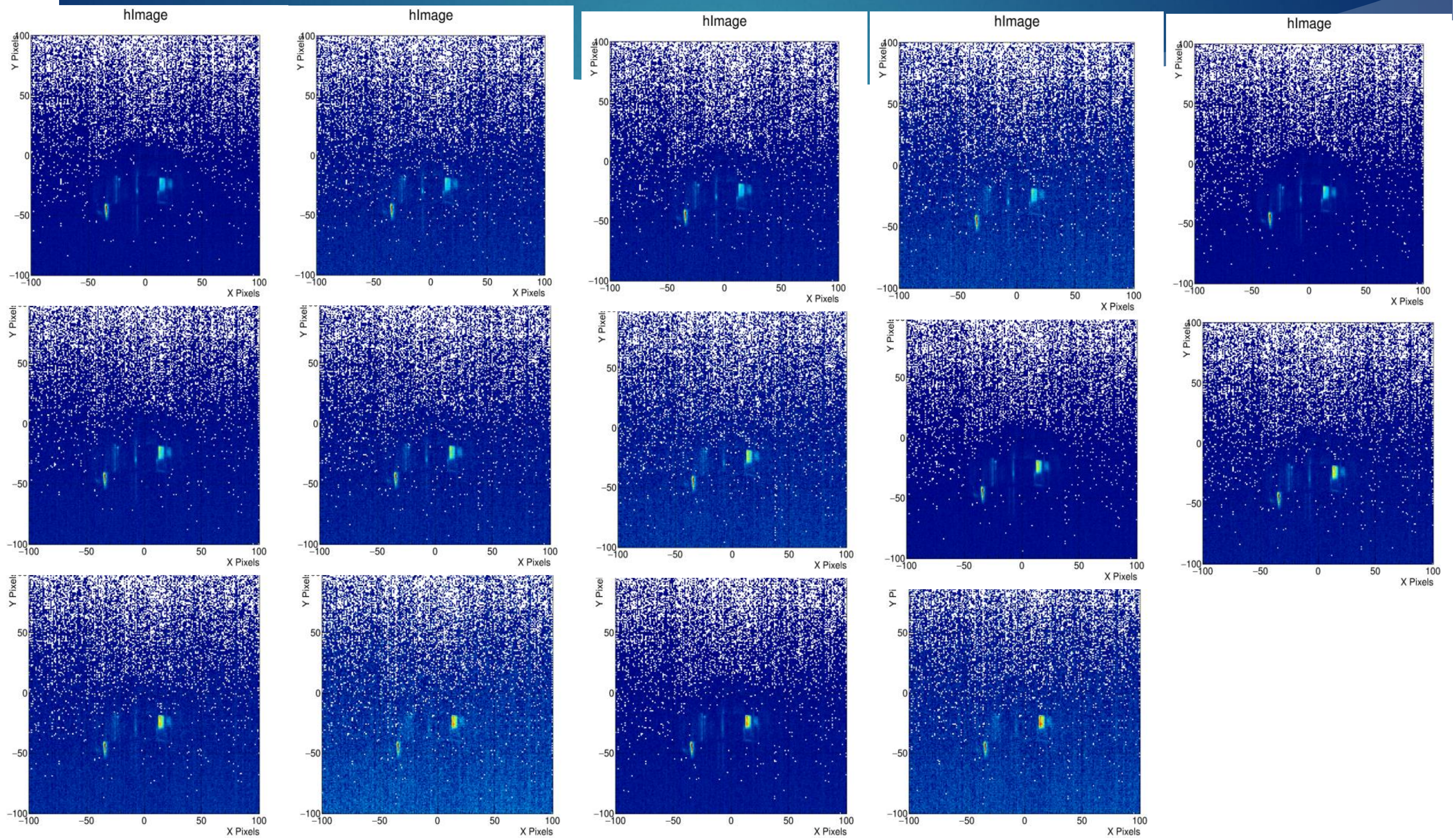
BPM@3157um



BPM@3455um



Full scan in position



Full scan in position

3x6 Integral