Scintillation Screens and Optical Technology for transverse Profile Measurements

ARIES-ADA Topical Workshop, Krakow, Poland, April 1 to 3, 2019

Irradiation Test of Commercial Digital Cameras at the CERN CHARM facility

S.Burger – CERN
Thanks to BI colleagues !

Screen characterization with a 440GeV/c proton beam in air at the CERN HiRadMat facility

HiRadMat
High-Radiation to Materials

CHARM

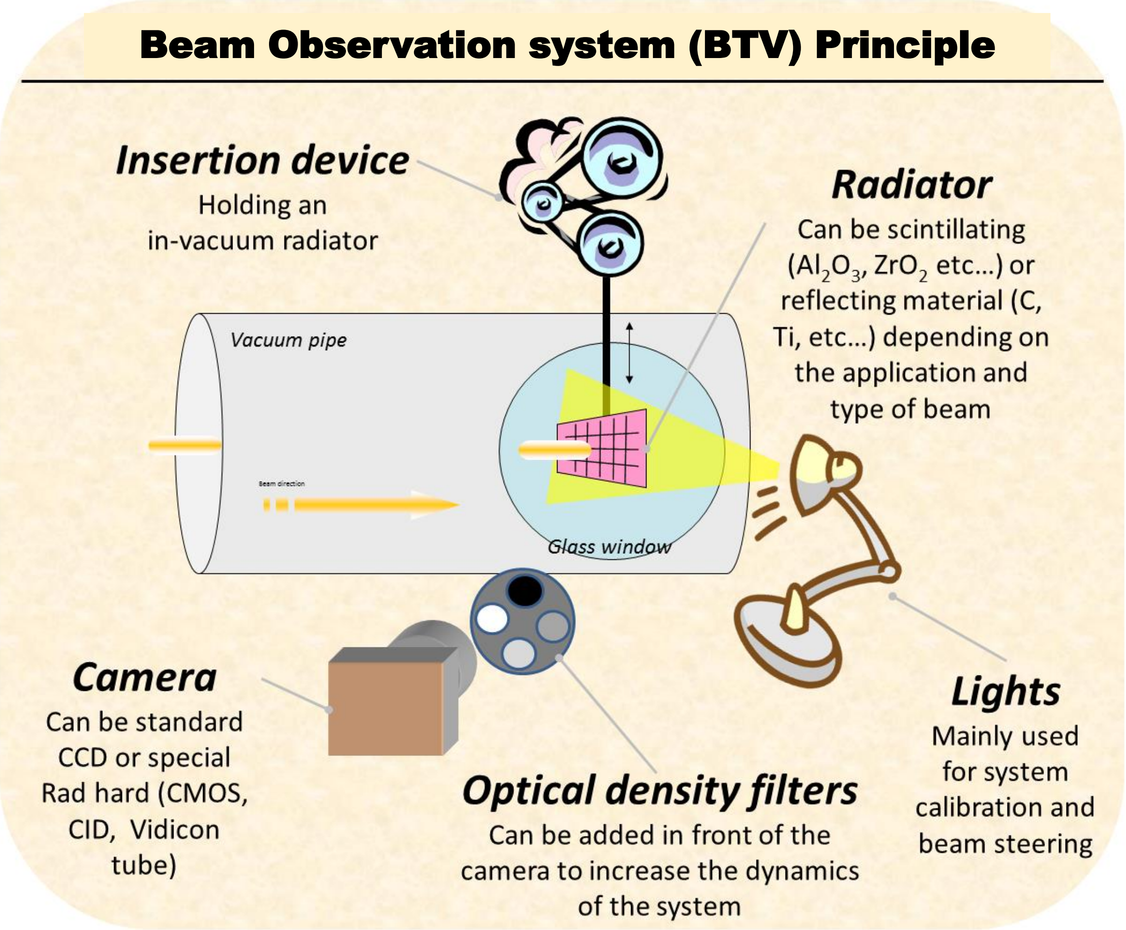
Irradiation Test of Commercial Digital Cameras at the CERN CHARM facility

CONTENT

- *Introduction / Motivation*
- *Cameras*
- *CHARM Setup / Installation*
- *Results*
- *Conclusion*

Introduction / Motivation

BI group has ~200 instruments mainly based on **analogue** cameras (standard CCD, "rad hard" like tube based or commercial rad tolerant cameras, etc…)



- Analogue cameras are getting to an end in the market
- Digital cameras are obvious candidates to replace analogue ones
  - It is 'known' that they don't work in radioactive environment
  - so far **no values available**

→ Decision is to **characterize the performance under radiation of commercial products, define some radiation limits**

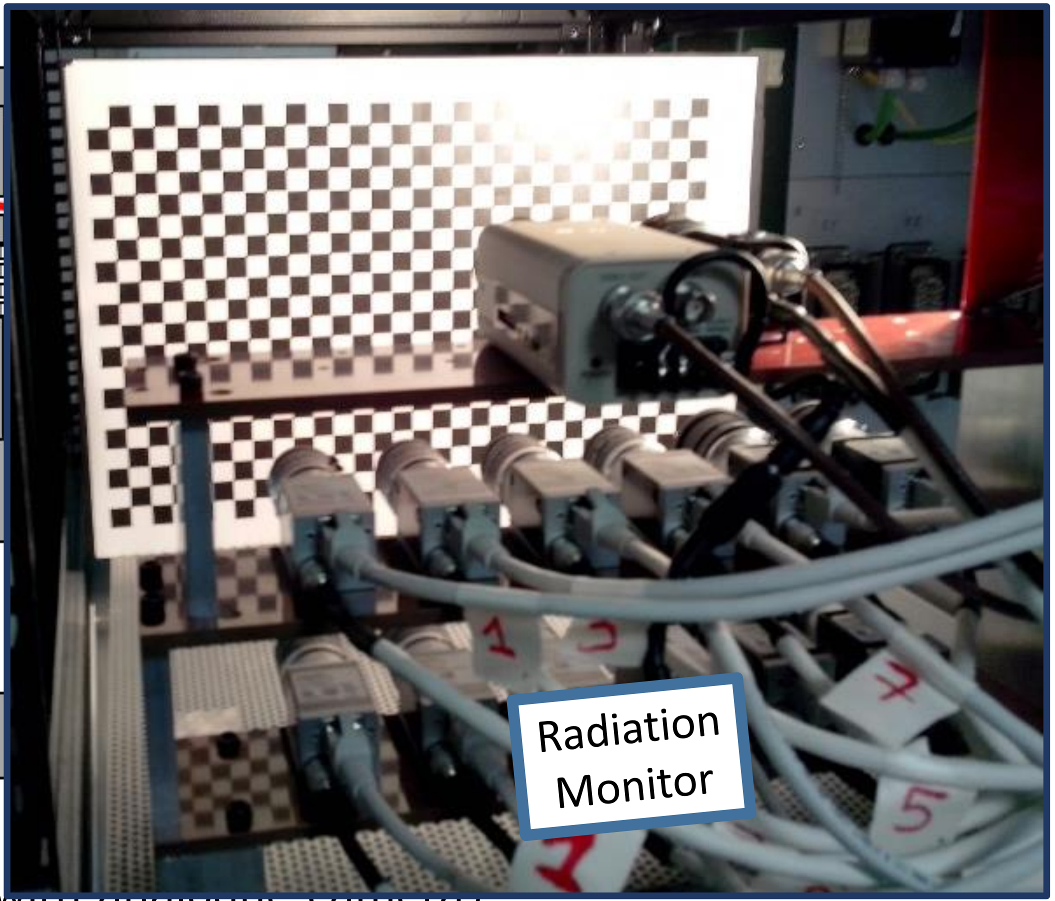
Cameras

BASLER was chosen as it is one of the biggest digital camera producer:
- Easy procurement (from many different vendors)
- Many different chips available…

	acA1300-60gm	acA1920-50gm	acA1920-40gm	acA640-300gm	acA800-200gm	acA2000-50gm
Sensor type	CMOS	CMOS	CMOS	CMOS	CMOS	CMOS
Sensor	E2V EV76C560	SONY IMX174	SONY IMX249	ONSemi PYTHON 300	ONSemi PYTHON 500	ONSemi PYTHON 500
Exposure Method	Global / rolling shutter	Global shutter	Global shutter	Global shutter	Global shutter	Global shutter
Resolution H	1280	1920	1920	640	800	2048
Resolution V	1024	1200	1200	480	600	1088
Pixel size H [um]	5.3	5.86	5.86	4.8	4.8	5.5
Pixel size V [um]	5.3	5.86	5.86	4.8	4.8	5.5
H [mm]	6.784	11.2512	11.2512	3.072	3.84	11.264
V [mm]	5.4272	7.032	7.032	2.304	2.88	5.984
Optical size	1/1.8"	1/1.2"	1/1.2"	1/4"	1/3.6"	2/3"
Frame Rate	60 fps	50 fps	42 fps	376 fps	240 fps	50 fps
Interface	GigE	GigE	GigE	GigE	GigE	GigE
Synchronisation	Y	Y	Y	Y	Y	Y
Dark Noise	24.7e-	6.7 e-	6.7 e-		10.7 e-	13.9 e-
Dynamic Range [dB] (lin.)	51.7 (385)	73.5 (4500)	73.6 (4500)	57.2 (724)	57.3 (732)	56.5 (668)
S/N ratio [dB]	39.8	45	45	38.8	38.9	39.7
Saturation capacity	9.5Ke-	31.9 ke-	31.8 ke-		7.8ke-	9.3Ke-
Power supply	+12V	+12V	+12V	+12V	+12V	+12V

- 2 of each type have been tested
- Analogue cameras also tested in parallel for reference – SANYO VCB3380P & WATEC ULT 902H3

CHARM Setup / Installation

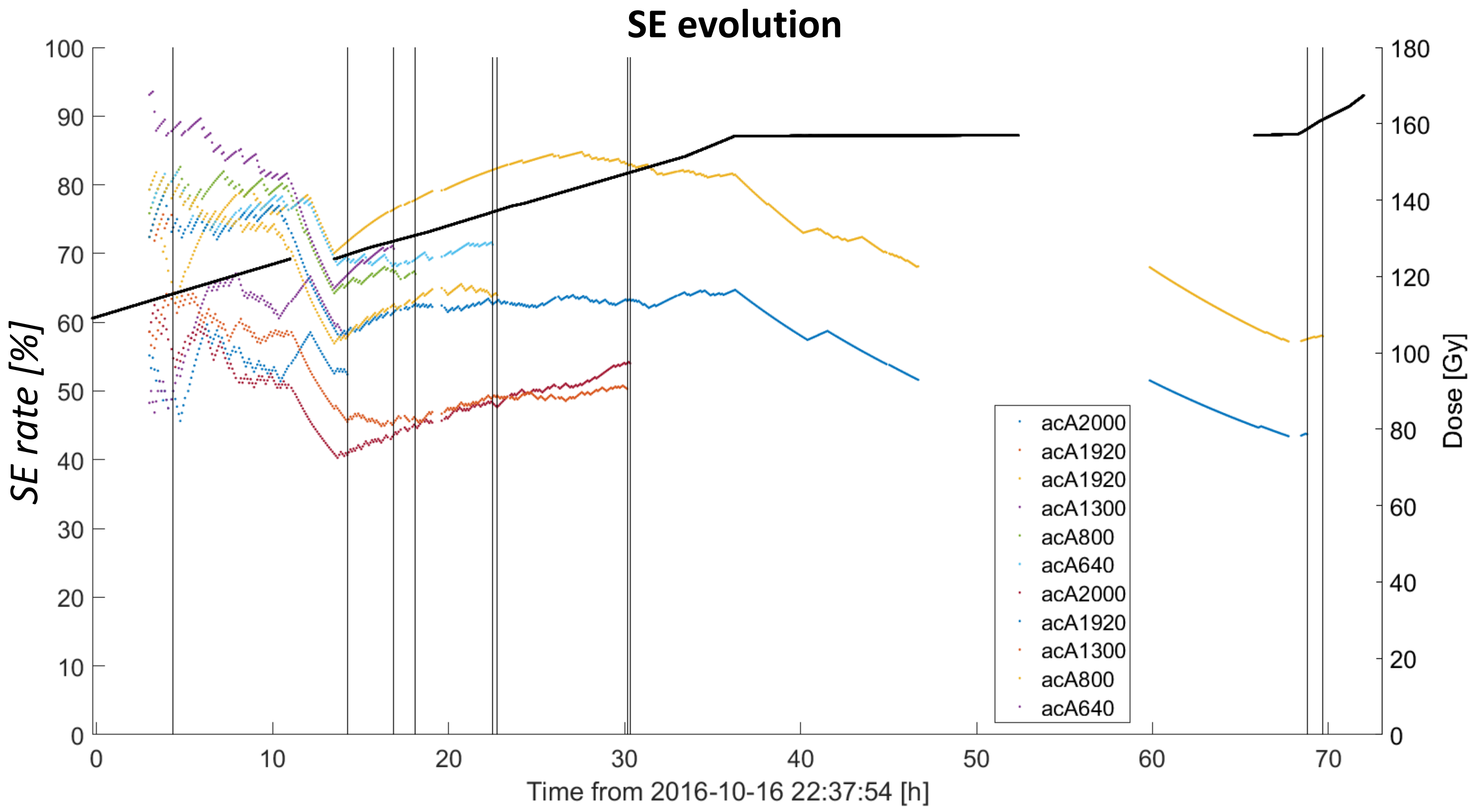


- Request to reach **300 Gy** (= max value observed with analogue camera)
  - 1st week → **150Gy**
  - 2nd week → **350Gy**

Observations

- **Camera failures appeared few minutes after the beam arrived**
- **Power cycle** was put in place from the second day (hours of acquisitions lost)
- **Logging of the cameras status** to evaluate the failure rate
    - Check if camera is alive
    - If not → apply power cycle
    - Re-check if camera is alive
    - Image acquisition

Results (2)



Probability of having a SE measured every 5 minutes

Mean value of failure after 10 shots is 70%.

Psurv = (1-P$_{SEU}$)^N

P$_{SEU}$ = 1-Psurv^(1/N)

→ SE probability per shot is 11%

Results (2)

Run 1 (→ 150Gy)	
Dose [Gy]	4.8E-3
POT	4.1E11
1 MeV Neutron eq. Fluence/cm2	5.4E7
HEH eq. Fluence / cm2	1.68E7

Radiation measurements for a single beam extraction

SE Sensitivity

Cross section

→ $\sigma SEE = \frac{N}{\Phi_{\mathrm{HEH}}}$

6.5e-10 cm2

Fluences

→ Φ_{HEH} during 5 min

1.68e8/cm2

→ $\Phi_{\mathrm{failure}} = \frac{1}{\sigma SEE}$

1.5e9 HEH/cm2

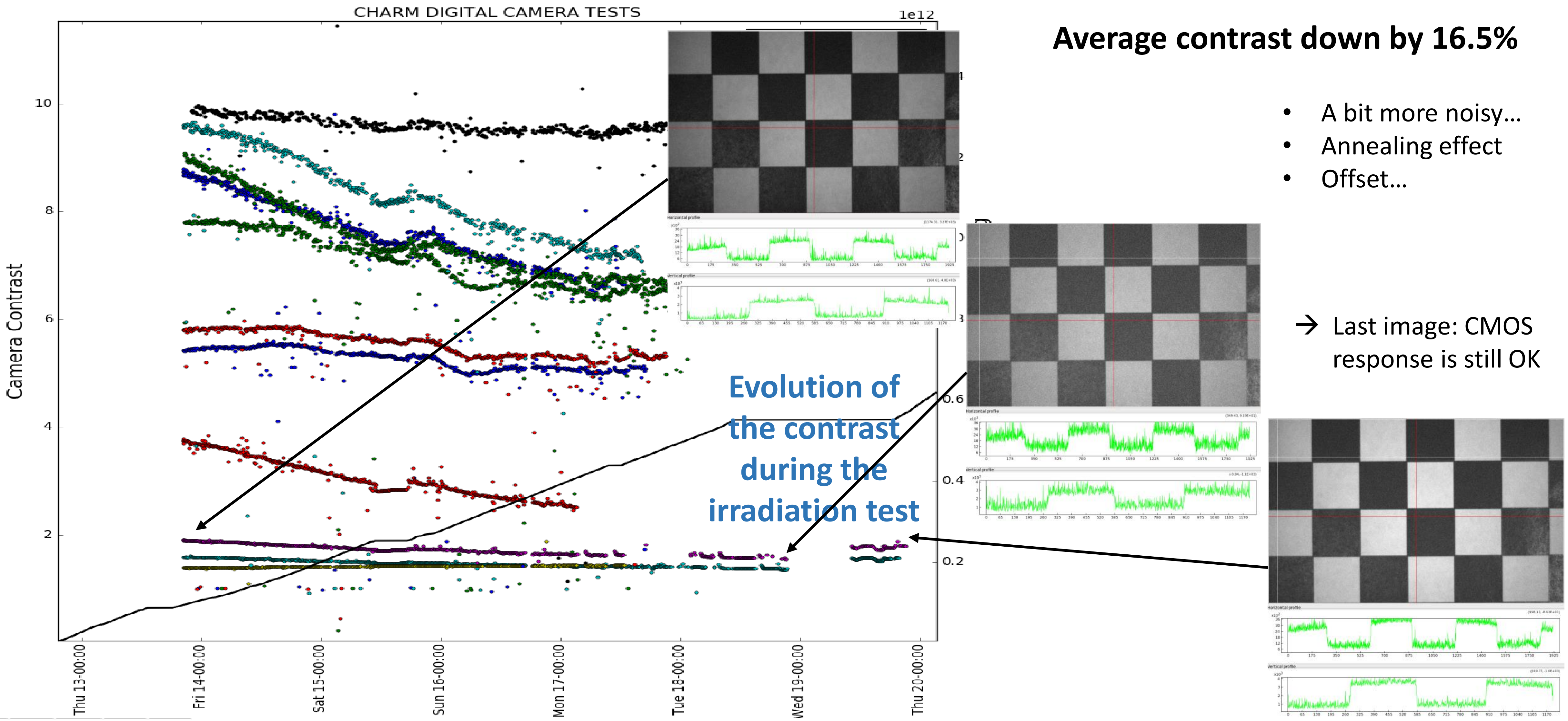
Max irradiation

	Mean	Median	Min	Max
TID [Gy]	137.3	131.1	116	161
Fluence [HEH/cm2]	4.84E11	4.80E11	4.07E11	5.56E11

Measured TID and Fluence @ camera end of life

Results (4)

Digital image evolution



Average contrast down by 16.5%

- A bit more noisy…
- Annealing effect
- Offset…

→ Last image: CMOS response is still OK

Results (4)

Analogue image evolution

Analogue camera WATEC
0 Gy

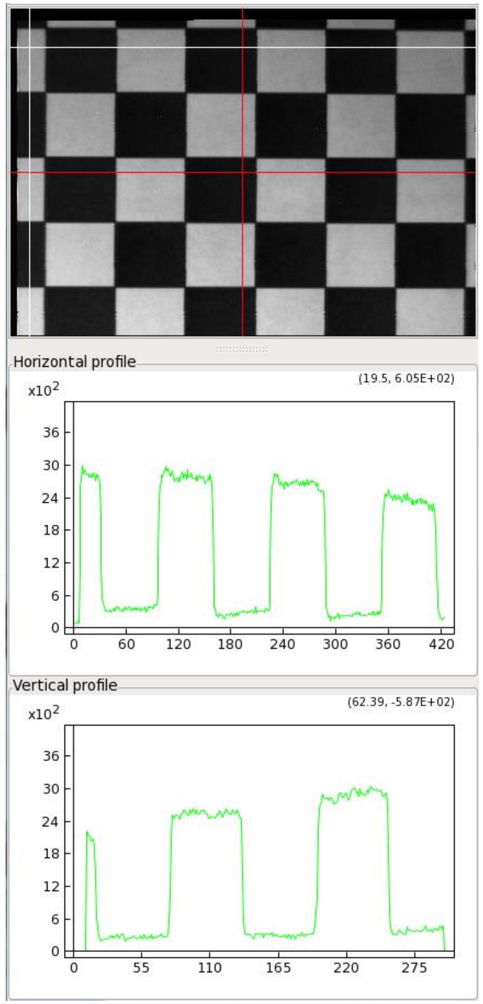


Image after 125.6 Gy

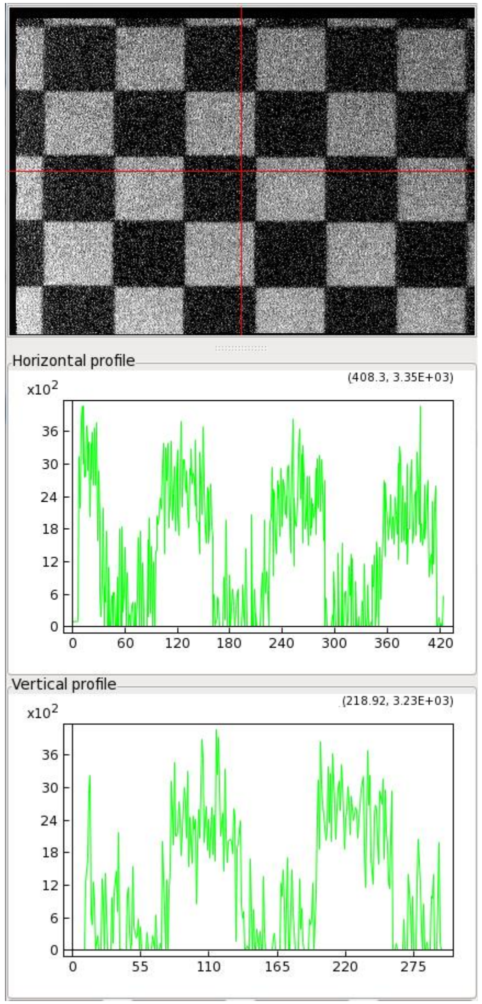
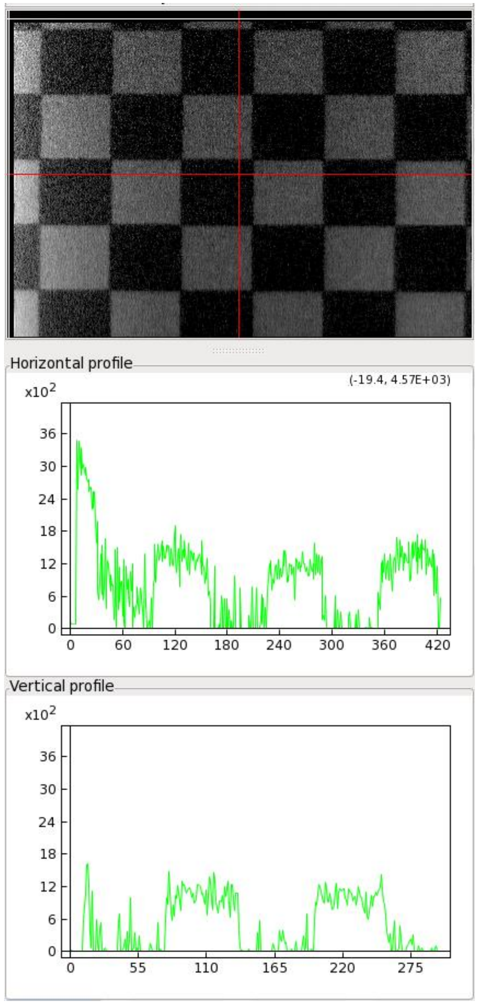


Image after 500 Gy



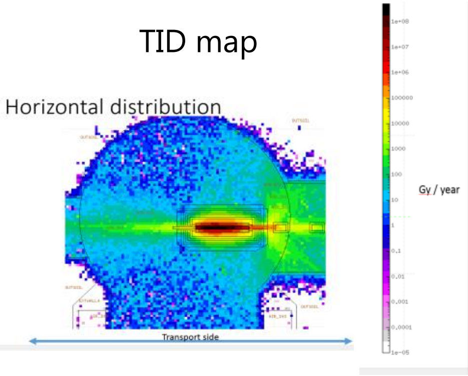
→ Degradation is clearly visible
→ (CCD) Analogue much noisier than (CMOS) digital one
→ **Camera still alive after 500Gy**

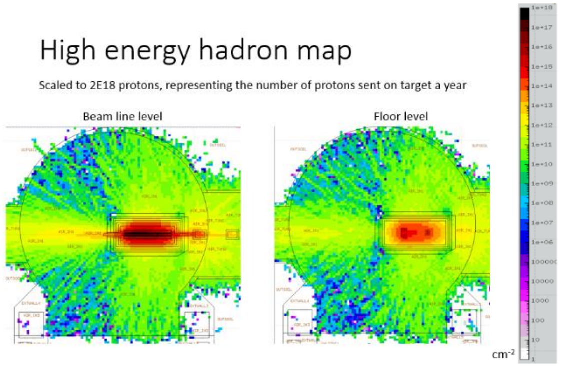
Conclusion

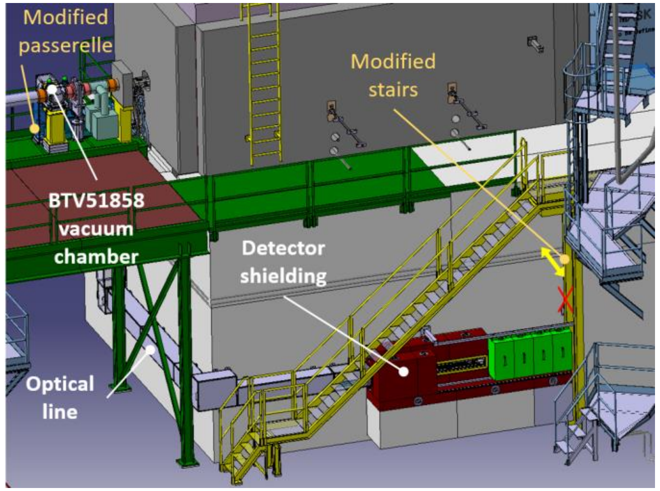
- As expected commercial digital cameras are delicate to use under radiation.
- The irradiation is not affecting dramatically **the image quality** of the CMOS types sensor (vs 'analogue' CCD).
  → *It seems it is either the power supply, ADC or data transfer that suffers from radiation up to death of camera.*
- With this test we can now refer to some values to estimate the operation of diagnostics with digital cameras
  - → **Threshold for a SE** **σSEE**: **6.5e-10 cm2 - Φfailure: 1.5e9 HEH/cm2**
  - → **Limit to 'kill' the cameras**, with few hundreds on power cycles:

TID	**116 - 161 Gy**
HEH/cm2	**4.68 - 4.68e11**

Many projects are already taking into account these numbers to benefit and optimize the use of digital cameras.
Example: SBDS Beam observation system







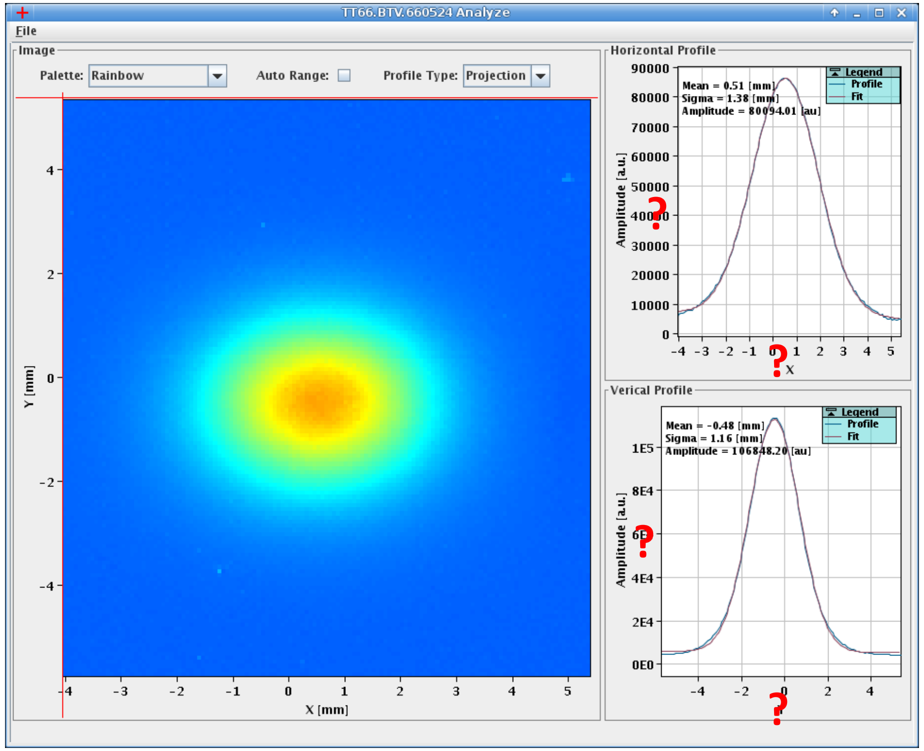
Screen characterization with a 440GeV/c proton beam in air at the CERN HiRadMat facility

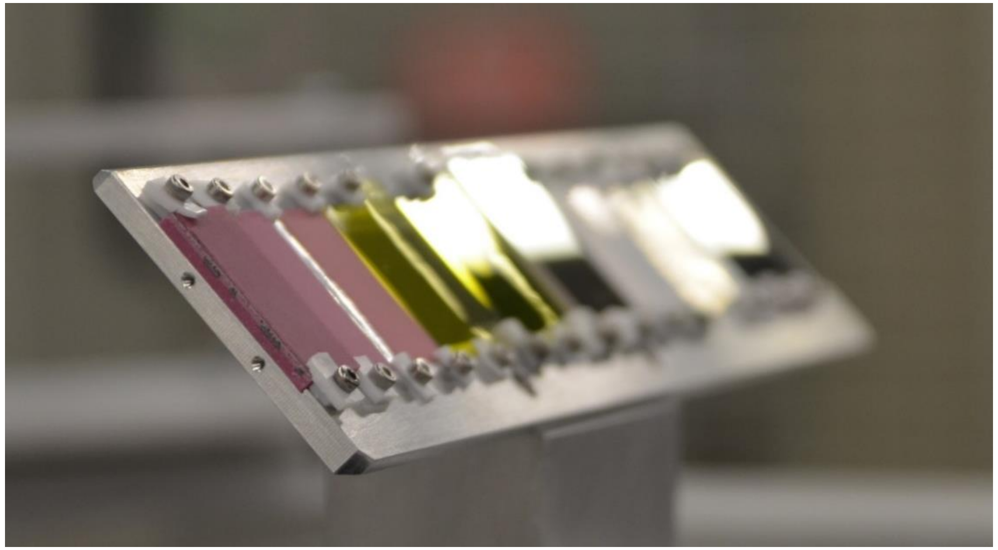
CONTENT

- *Introduction / Motivation*
- *Screens*
- *HiRadMat Setup / Installation*
- *Light Emission in air*
- *Results*
- *Conclusion*

Introduction / Motivation

- The AWAKE experiment, at that time under construction at CERN, required a **detailed understanding of screen sensitivity** and the associated **accuracy of the beam size measurement** (→ Self-Modulation Instability process validation).
- Even though the emission of scintillation and OTR light is very well understood, comparative measurements of commonly used screen types are hard to find.





Screens

Screen Nr	Material	Thick. [mm]	Supplier
1	Chromox (Al_2O_3:CrO_2)	3.0	CeraQUest
2	Chromox (Al_2O_3:CrO_2)	1.0	CeraQuest
3	Chromox (Al_2O_3:CrO_2)	0.5	CERN stock
4	YAG (YAG:Ce)	0.5	Crytur
5	YAG (YAG:Ce)	0.1	Crytur
6	YAG back-coated (YAG:Ce+Al)	0.5	Crytur
7	YAG back-coated (YAG:Ce + Al)	0.1	Crytur
8	Alumina (99% purity)	1.0	GoodFellow
9	Chromox-old type (Al_2O_3:CrO_2)	1.0	CERN stock
10	Aluminium	1.0	CERN stock
11	Titanium	0.1	GoodFellow
12	Aluminium coated Silicon	0.25	MicroFabSolutions
13	Silver coated Silicon	0.3	Sil'Tronix

List of screen material for the test @ HiRadMat

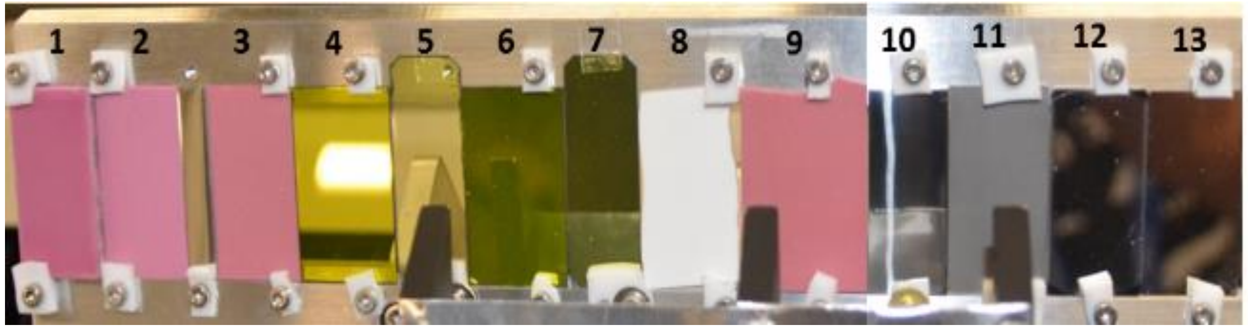
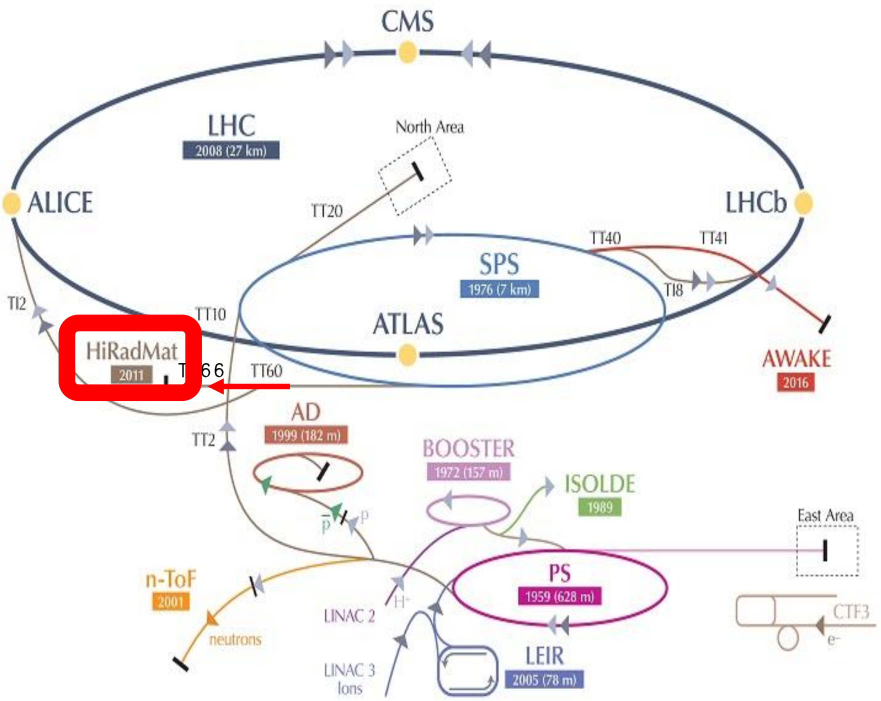
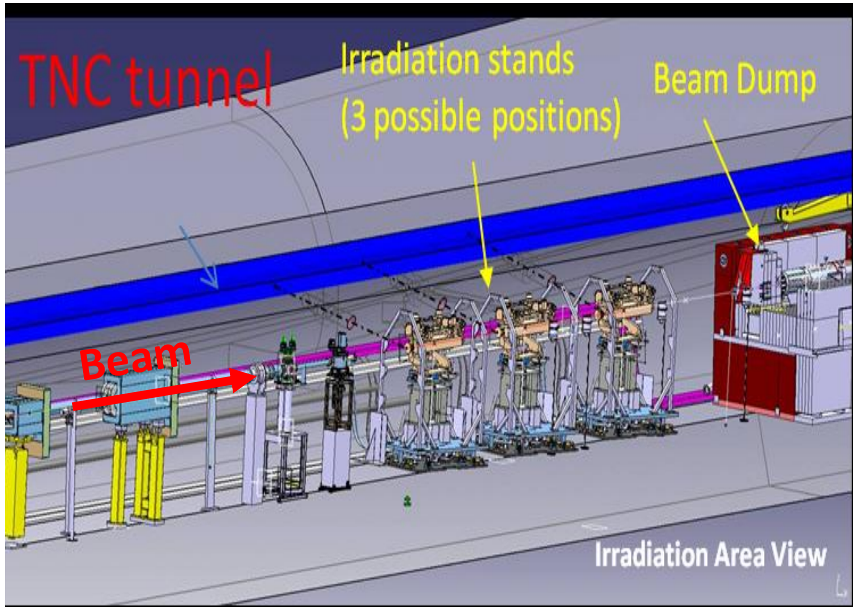


Image of the screen material samples mounted on the screen holder.

HiRadMat

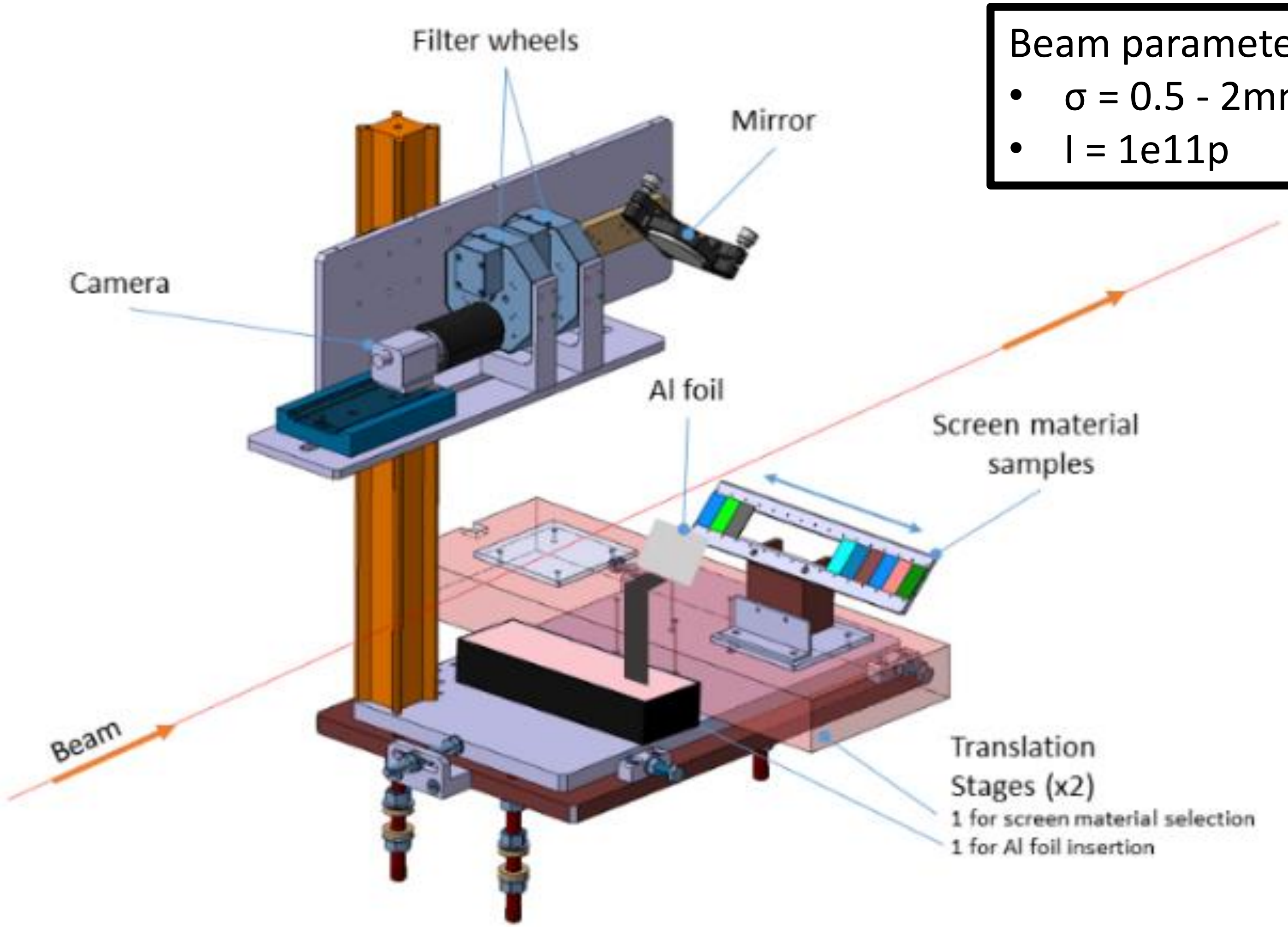
The High Radiation to Materials facility - hereafter HiRadMat - was designed for testing accelerator components, in particular those of the LHC and its injectors, with the impact of high-intensity pulsed beams.





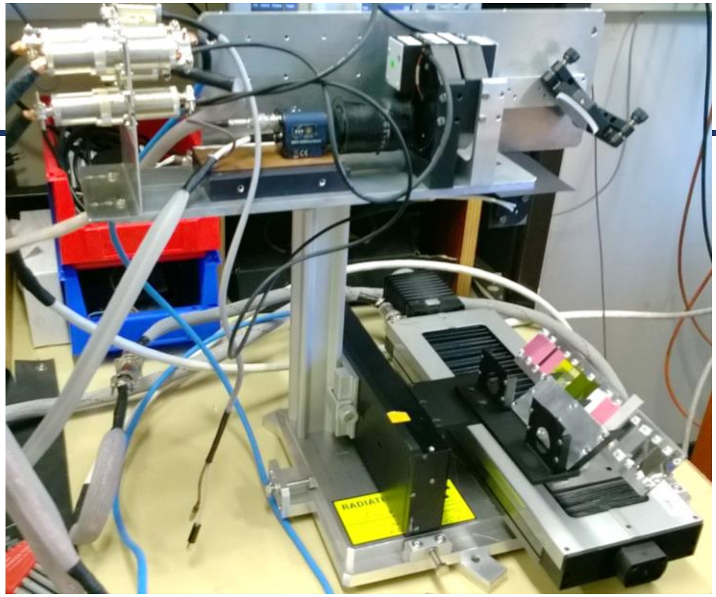
HiRadMat beam specs	
Beam Energy	440 GeV
Pulse Energy	up to 3.4 MJ
Bunch intensity	3E9 to 1.7E11 p
Number of bunches	1 to 288
Maximum pulse intensity	4.9E13 p
Bunch length	11.24 cm
Bunch spacing	25, 50, 75 or 150 ns
Pulse length	7.2 µs
Minimum cycle length	18 s
Beam size at target	0.1 to 1.5mm (σ)

HiRadMat Setup / Installation



3D image of the in air screen test setup

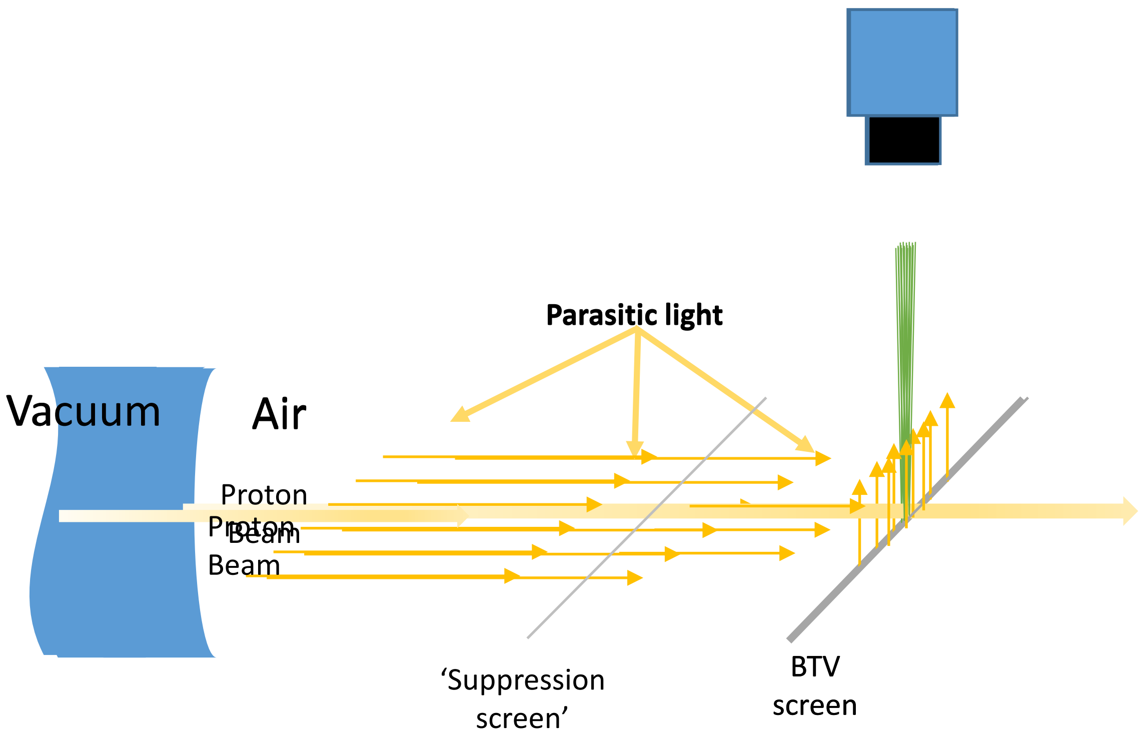
Beam parameters
- σ = 0.5 - 2mm
- I = 1e11p



Picture of the setup ready to be installed

Picture of the setup installation ready for beam

Light emission in air (1)



	Without Foil	With Foil
Number of photons	**N**	**N_f**
N_{OTR} (protons on screen)	2.98E-2	2.98E-2
NCherenkof (protons in air)	**4.266**	**1.132**
N_{Lu} (protons in air)	6.60E-2	1.23E-04
Total	$N_{OTR}+N_{Ch}+N_{Lu}$	$2xN_{OTR}+Nf_{Ch}+Nf_{Lu}$
Ntotal	4.36E+00	1.19E+00
N/Nf	3.66E+00	

Expected light yields from OTR screens and expected contributions from parasitic light for no blocking foil and with blocking foil inserted

Parasitic light from:

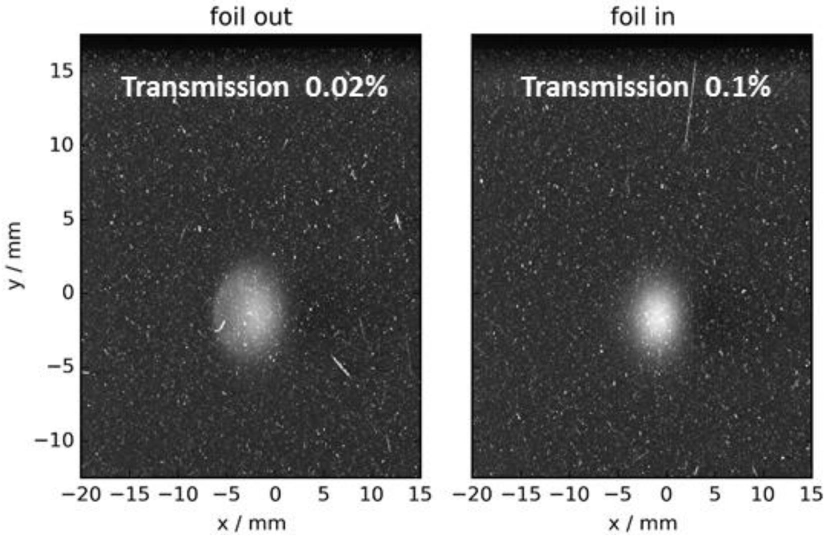
- *Cherenkov*
- *Luminescence*
- *OTR*

→ **Cherenkov is the main contributor** in both (with and without foil)

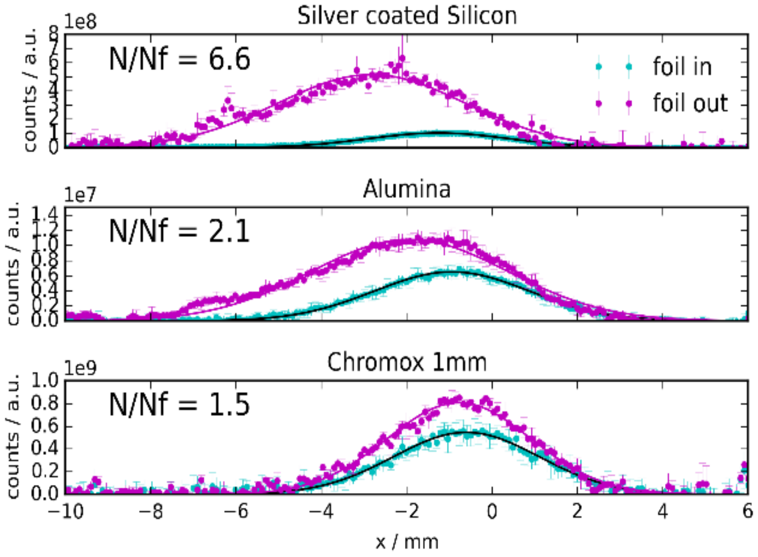
→ Insertion of the foil **reduces by a factor 4** this contribution

→ Effect expected less important using scintillation due to higher light yield and lower reflectivity.

Light emission in air (2)



Example of raw images of the proton beam in air on a Silver coated Si OTR screen without (left) and with (right) blocking foil in place.



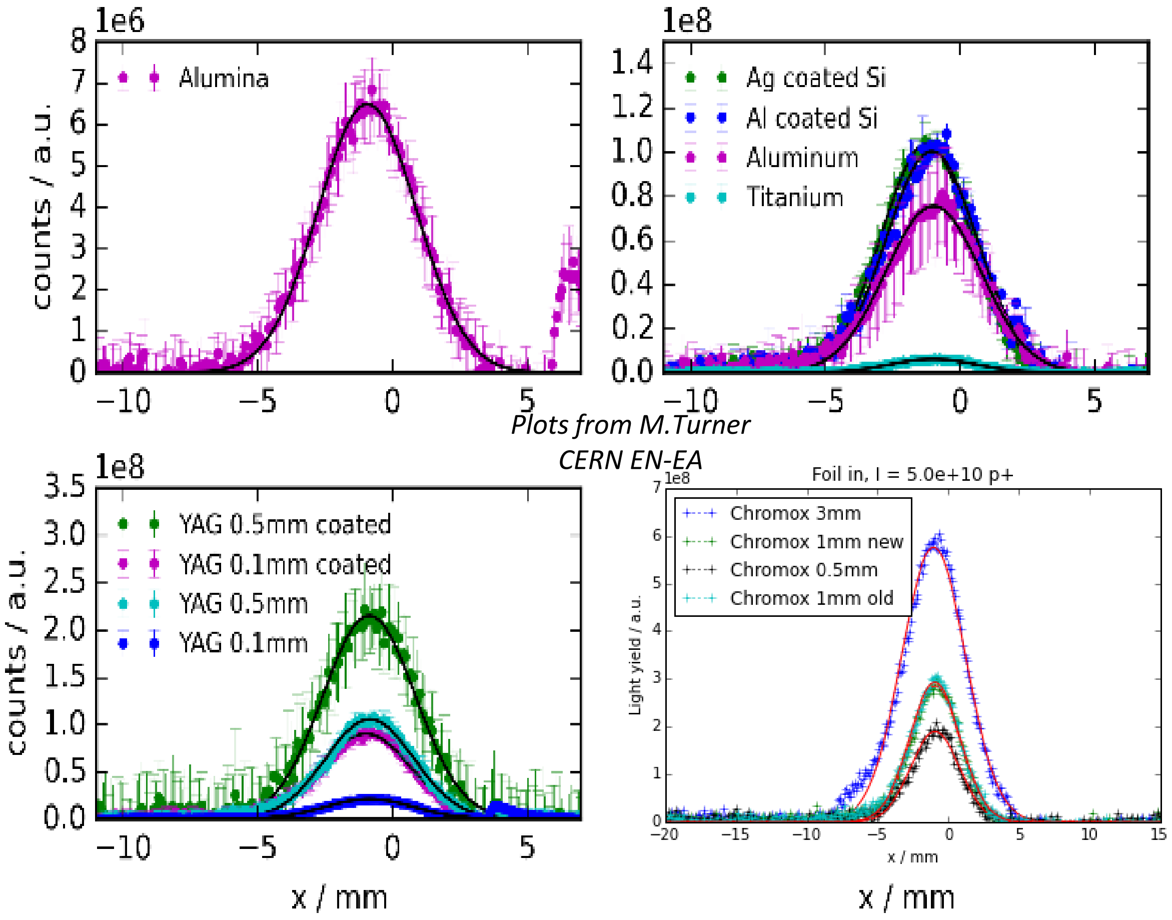
Results of the beam profile measurement showing the response of the silver coated silicon, Alumina and Chromox screens with and without blocking foil.

→ **Change of intensity and beam size is clearly visible**

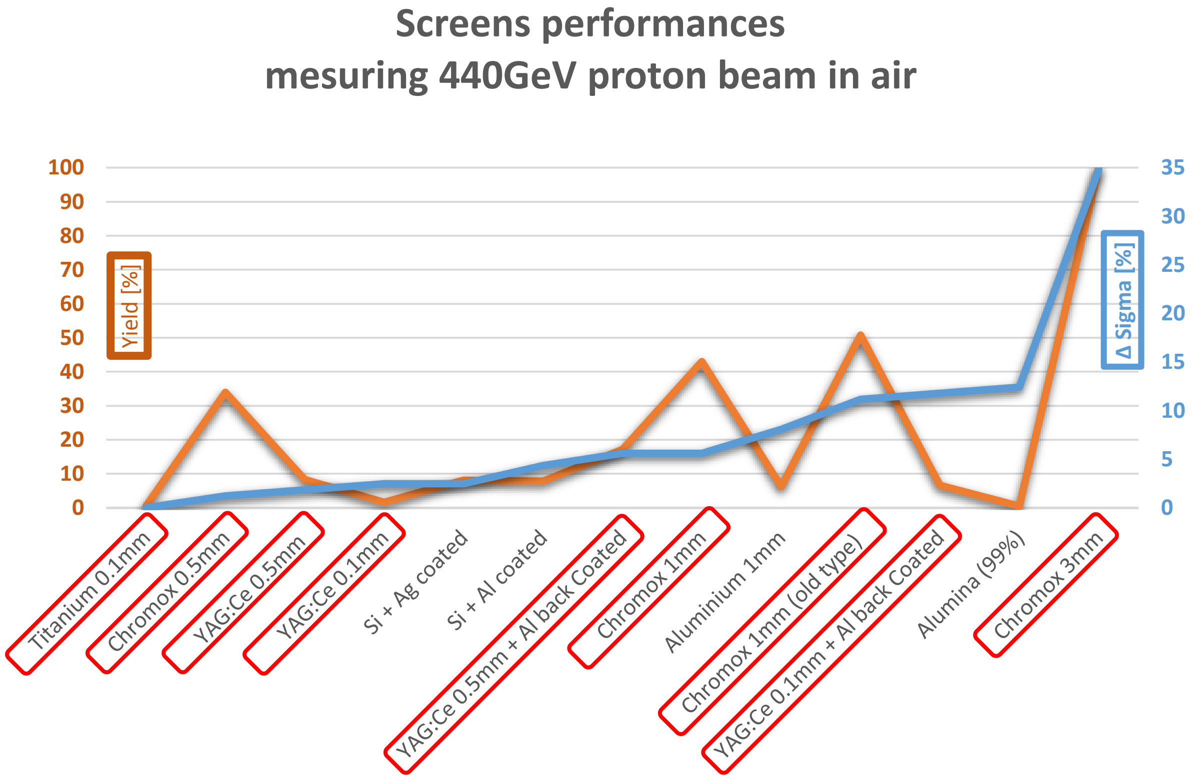
→ **Shift of the centre of the Gaussian:**

- reflectivity and/or the diffusivity of the material
- errors in the alignment of the optical line.

Results (1)



Results of beam profile measurements showing the response of all screens listed in table 1 with a foil blocking the parasitic light installed 43mm upstream.



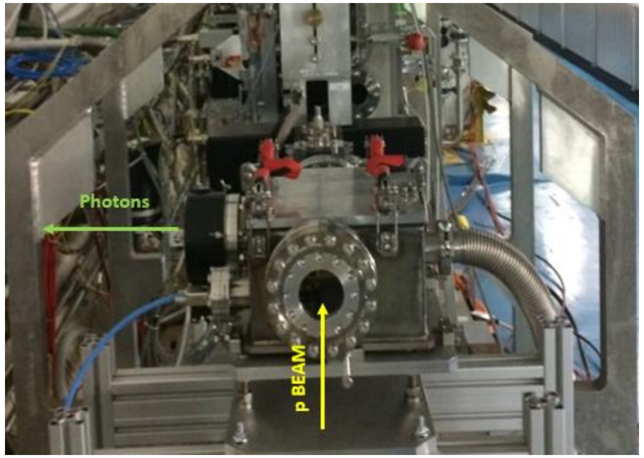
Light yield and sigma measured on each screen with a foil positioned 43mm upstream to block part of the parasitic light.

Conclusion

- Measurement of light emission screens from a 440GeV proton beam **in air** was performed
- **3 scintillators** of different thicknesses and **4 OTR** screens
- A light **blocking foil** was inserted to reduce parasitic light contribution
- **We have data to be used as reference for setting up a beam imaging system in air**
- However, as the Cherenkov light contribution is very important in the OTR case and not very well know in the scintillation case, **no precise OTR and scintillator light yield and subsequent resolution studies can be performed with this data**. Future studies under vacuum are thus foreseen to better asses these questions

→ **HiRadMat instrumentation request**

- **In vacuum screen** setup to get rid of parasitic lights *(still need blocking foil to suppress forward OTR)*
- **Long optical line** to avoid backscattered particles on the camera
- **New OTR material resisting high intensity/small beam size…**



New HRM in vacuum Beam observation station

Thank you for your attention !

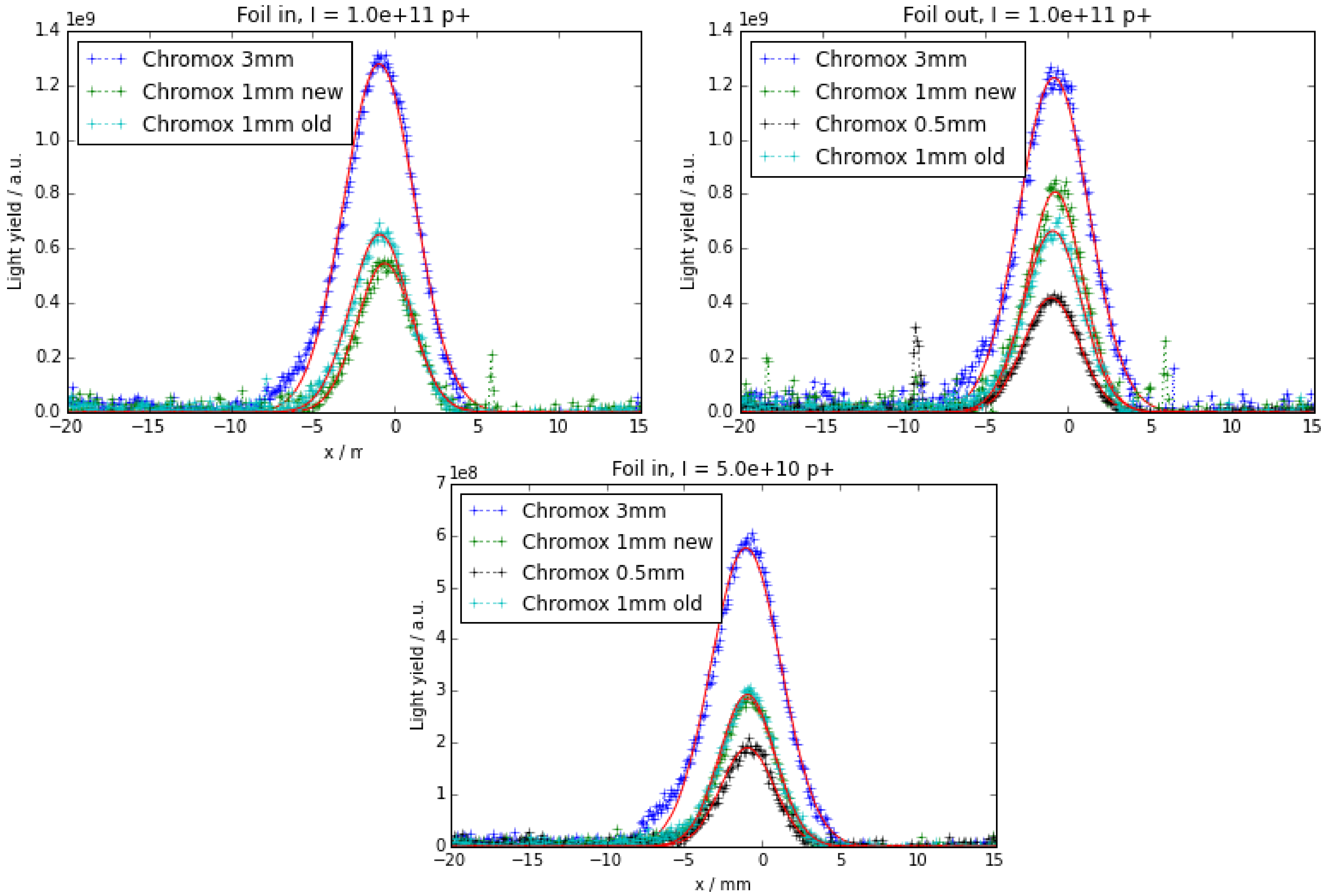
BACKUP SLIDES

	Type	Yield [%]	Error [%]
$Al_2O_3:CrO_2$ 3mm	Scint.	232.73	±5
Chromox 1mm (old type)	Scint.	118.18	±4
$Al_2O_3:CrO_2$ 1mm	Scint.	100	±4
$Al_2O_3:CrO_2$ 0.5mm	Scint.	79.1	±2
YAG:Ce 0.5mm + Al back Coated	Scint.	40	±2
YAG:Ce 0.5mm	Scint.	19.27	±1
Si + Ag coated	OTR	18.91	±4
Si + Al coated	OTR	18.18	±4
YAG:Ce 0.1mm + Al back Coated	Scint.	15.45	±5
Aluminium 1mm	OTR	14.55	±25
YAG:Ce 0.1mm	Scint.	3.87	±0.1
Alumina (99%) 1mm	Scint.	1.2	±0.1
Titanum 0.1mm	OTR	1.13	±10

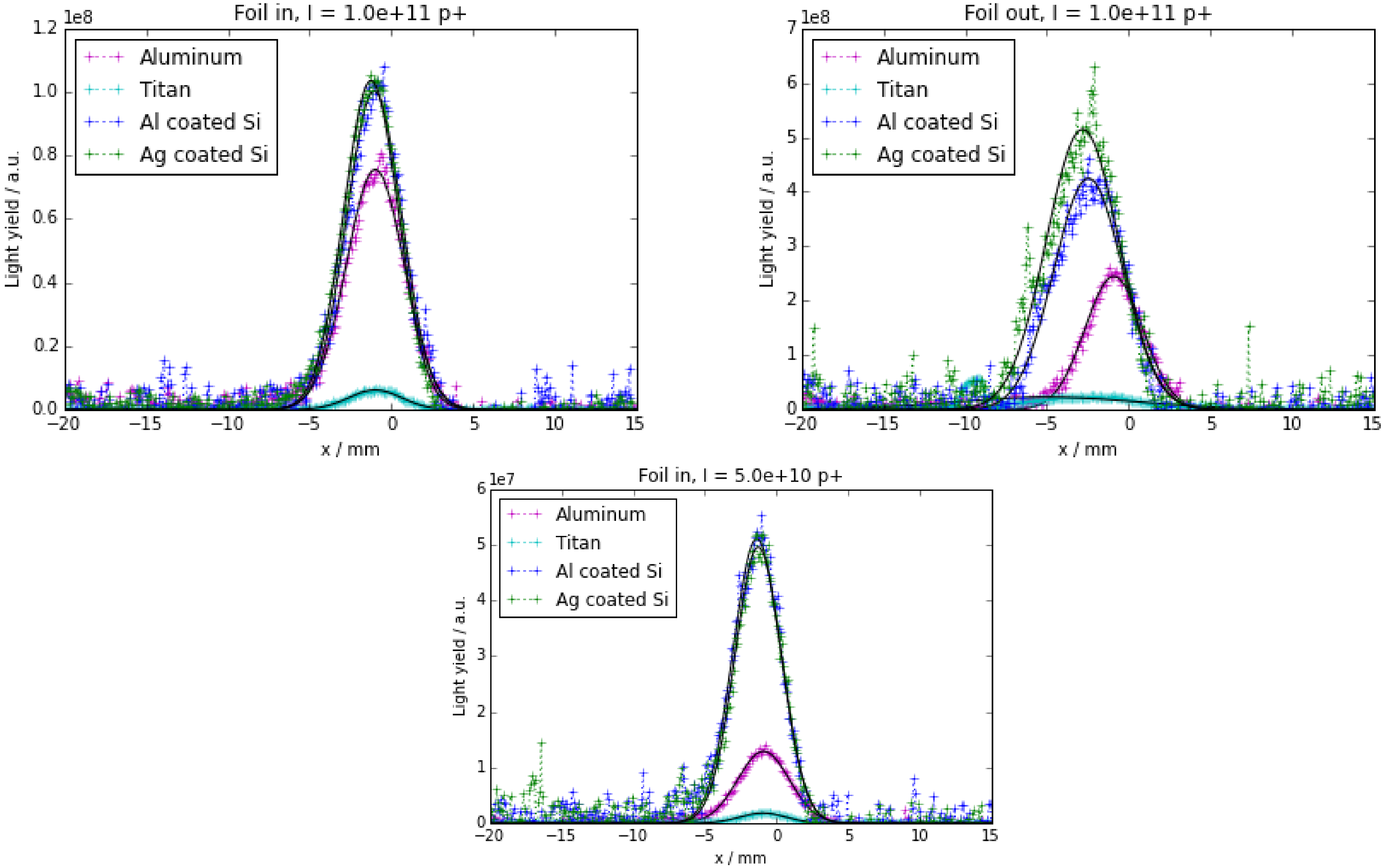
Light yield *measured on each screen with a foil positioned 43mm upstream to block part of the parasitic light. The values are referenced to a 1mm thick Chromox screen as it is commonly used in many of the CERN beam observation systems*

	Type	Sigma diff. with ref. Ti screen [%]	Sigma [mm]	Error [mm]
Titanium 0.1mm	OTR	0	1.61	±0.016
Chromox 0.5mm	Scint	1.24	1.63	±0.05
YAG:Ce 0.5mm	Scint.	1.86	1.64	±0.06
YAG:Ce 0.1mm	Scint.	2.48	1.65	±0.05
Si + Ag coated	OTR	2.48	1.65	±0.03
Si + Al coated	OTR	4.35	1.68	±0.03
YAG:Ce 0.5mm + Al back Coated	Scint	5.59	1.7	±0.1
Chromox 1mm	Scint	5.59	1.7	±0.1
Aluminium 1mm	OTR	8.07	1.74	±0.06
Chromox 1mm (old type)	Scint	11.18	1.79	±0.06
YAG:Ce 0.1mm + Al back Coated	Scint.	11.8	1.8	±0.5
Alumina (99%)	Scint.	12.42	1.81	±0.1
Chromox 3mm	Scint	34.78	2.17	±0.06

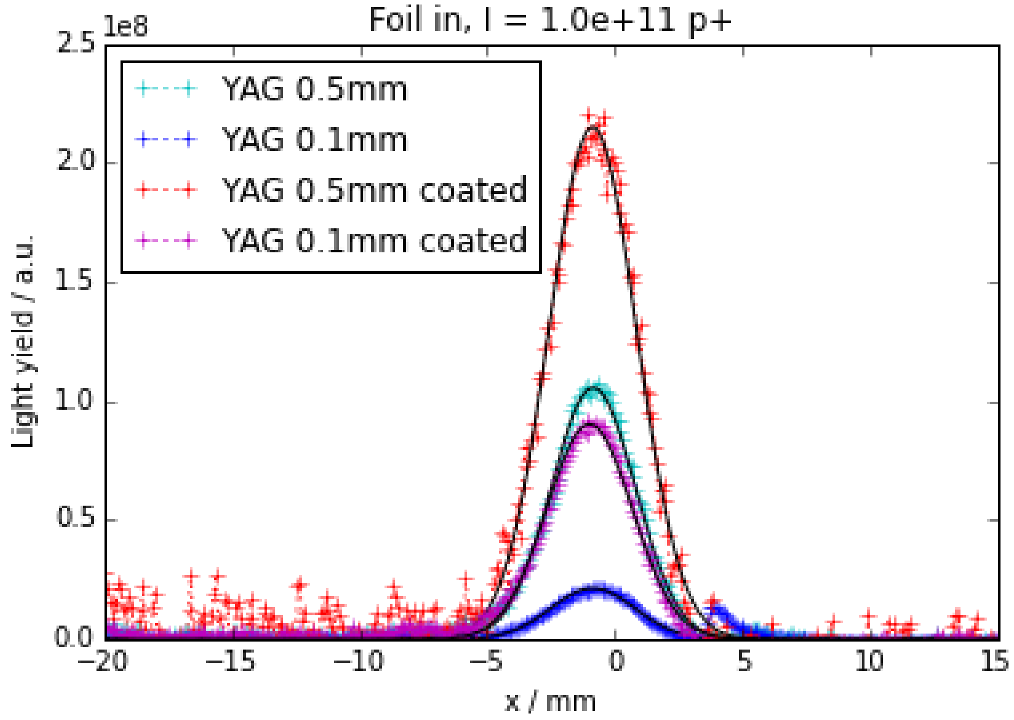
Sigma *measured on each screen with a foil positioned at 43mm upstream to block part of the parasitic light. The values are referenced to the Titanium screen as it gives the smallest sigma value of 1.61mm*

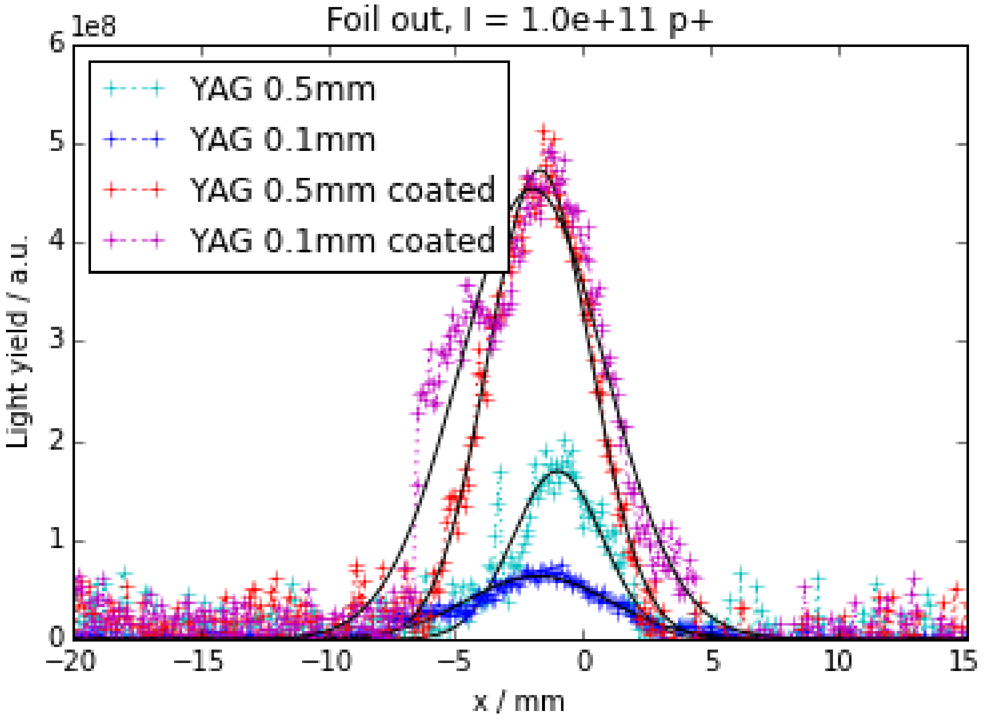


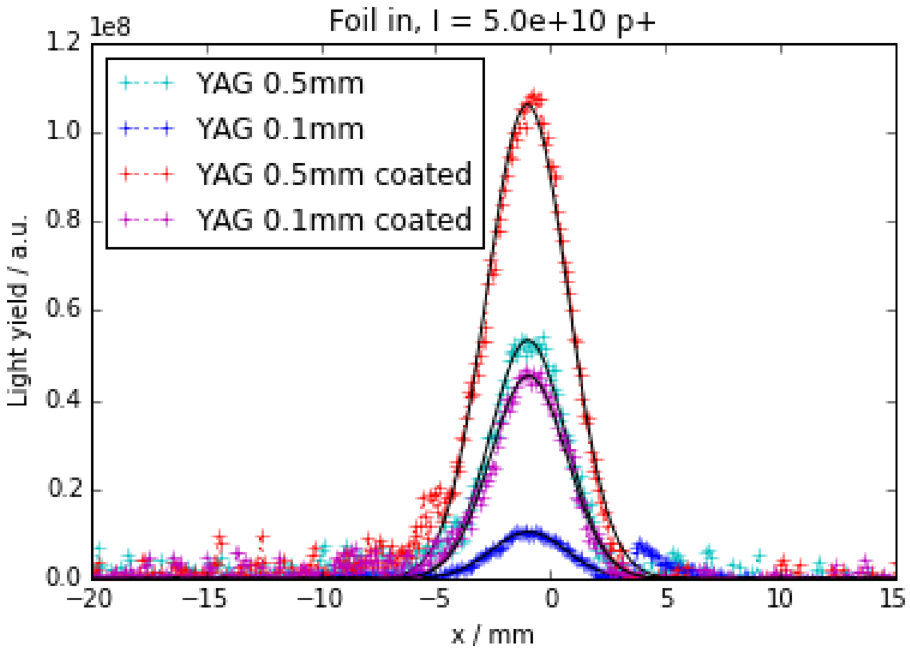
Foil in, I = 1.0e+11 p+
Chromox 3mm
Chromox 1mm new
Chromox 1mm old
Light yield / a.u.
1e9
Foil out, I = 1.0e+11 p+
Chromox 3mm
Chromox 1mm new
Chromox 0.5mm
Chromox 1mm old
Light yield / a.u.
1e9
Foil in, I = 5.0e+10 p+
Chromox 3mm
Chromox 1mm new
Chromox 0.5mm
Chromox 1mm old
Light yield / a.u.
1e8
x / mm



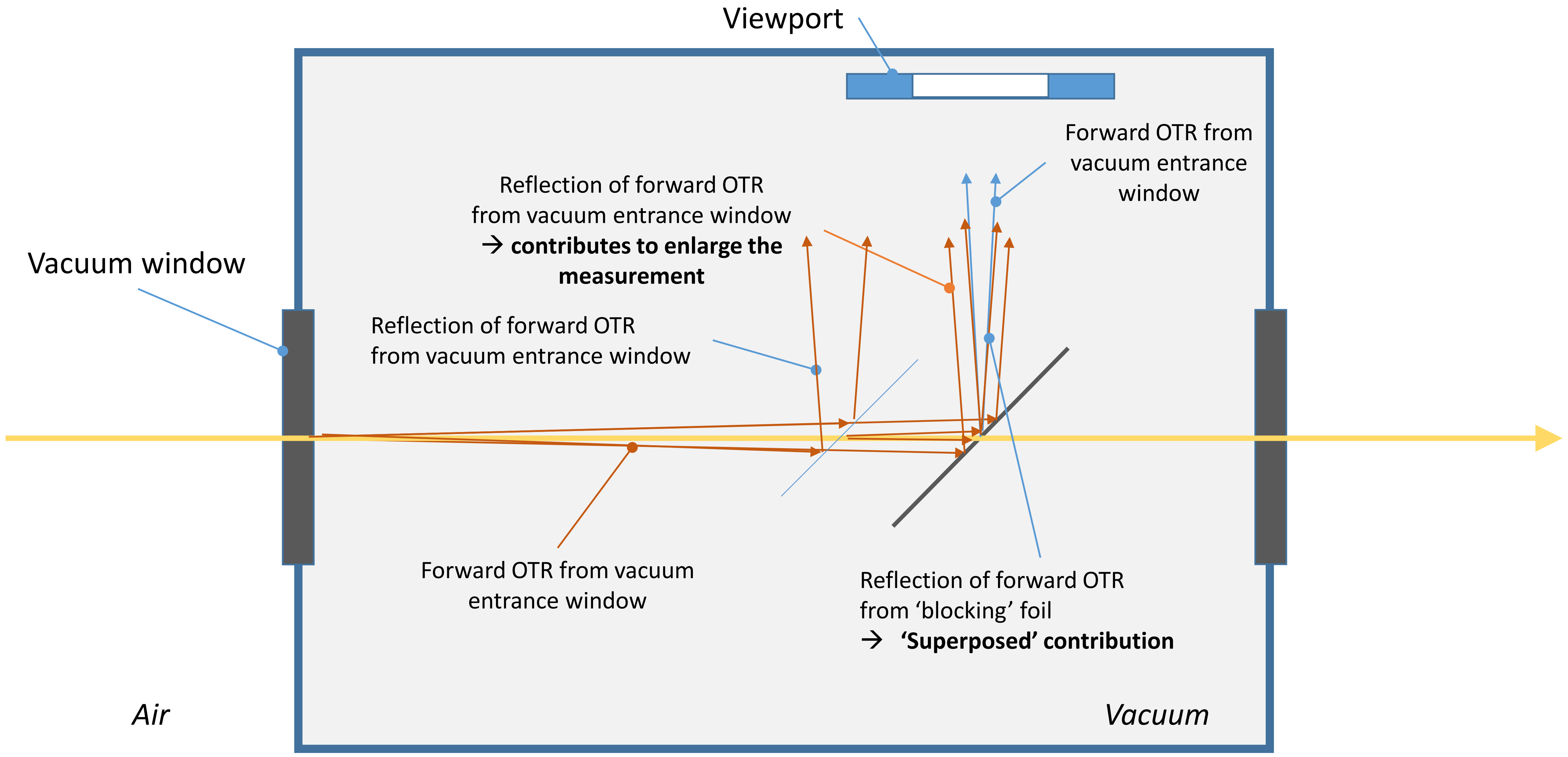
Foil in, I = 1.0e+11 p+
1e8
Aluminum
Titan
Al coated Si
Ag coated Si
Light yield / a.u.
x / mm
Foil out, I = 1.0e+11 p+
1e8
Aluminum
Titan
Al coated Si
Ag coated Si
Light yield / a.u.
x / mm
Foil in, I = 5.0e+10 p+
1e7
Aluminum
Titan
Al coated Si
Ag coated Si
Light yield / a.u.
x / mm


Foil in, I = 1.0e+11 p+
1e8
Light yield / a.u.
x / mm
YAG 0.5mm
YAG 0.1mm
YAG 0.5mm coated
YAG 0.1mm coated
0.0
0.5
1.0
1.5
2.0
2.5
−20
−15
−10
−5
0
5
10
15


Foil out, I = 1.0e+11 p+
1e8
Light yield / a.u.
x / mm
YAG 0.5mm
YAG 0.1mm
YAG 0.5mm coated
YAG 0.1mm coated
0
1
2
3
4
5
6
−20
−15
−10
−5
0
5
10
15


Foil in, I = 5.0e+10 p+
1e8
Light yield / a.u.
x / mm
YAG 0.5mm
YAG 0.1mm
YAG 0.5mm coated
YAG 0.1mm coated
0.0
0.2
0.4
0.6
0.8
1.0
1.2
−20
−15
−10
−5
0
5
10
15

Blocking parasitic forward OTR – In vacuum setup (no Cherenkov emission light)



Energy threshold for Cherenkov emission in air: 37.4GeV
Vacuum < 7.07mbar to eliminate Cherenkov light

OTR measurements

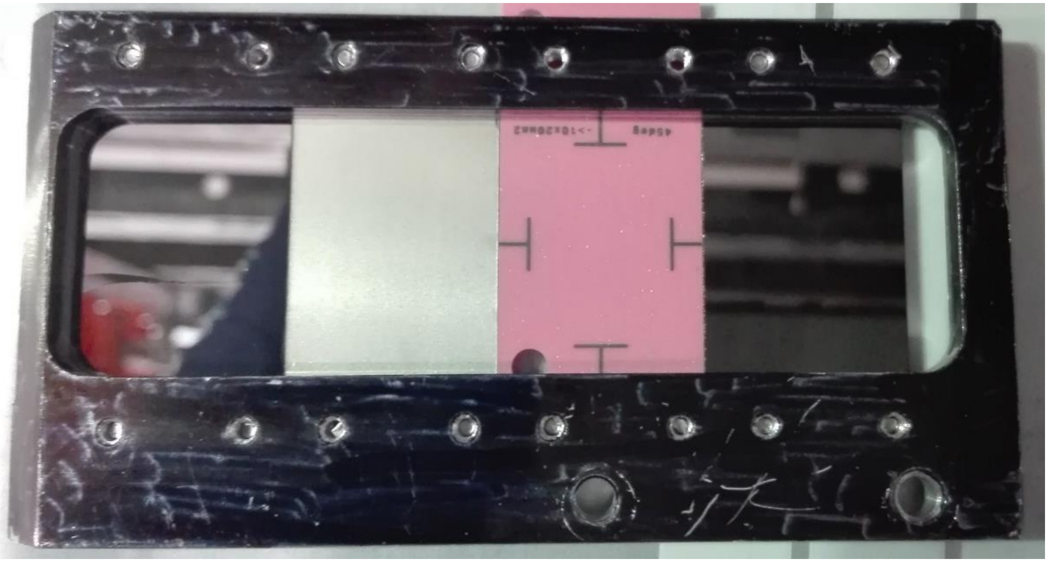
2017_08_22 (FH)

Comparison of different screen materials: SiC, Ti and GlassyC

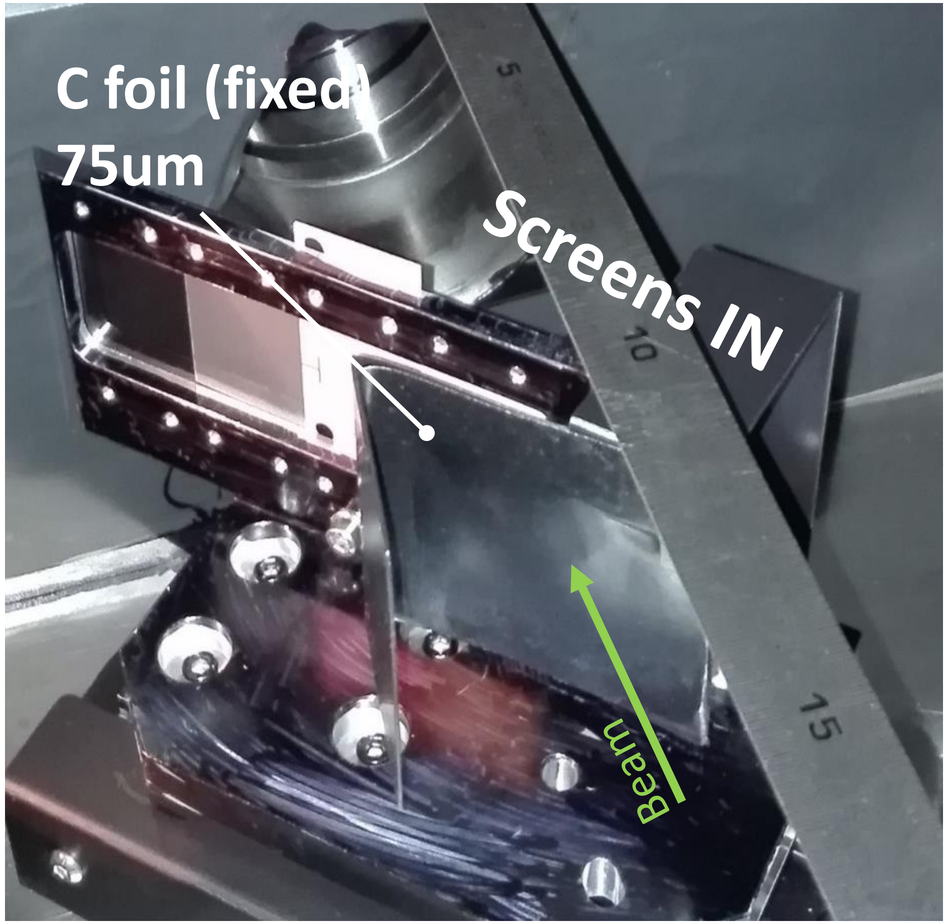
Beam parameters
- FP_2 0.3mm sigma
- 1E11ppb
- Single bunch

BTV setup
- Fixed red filter in front of the camera
- No OD filter needed for single bunch here

New screen setup

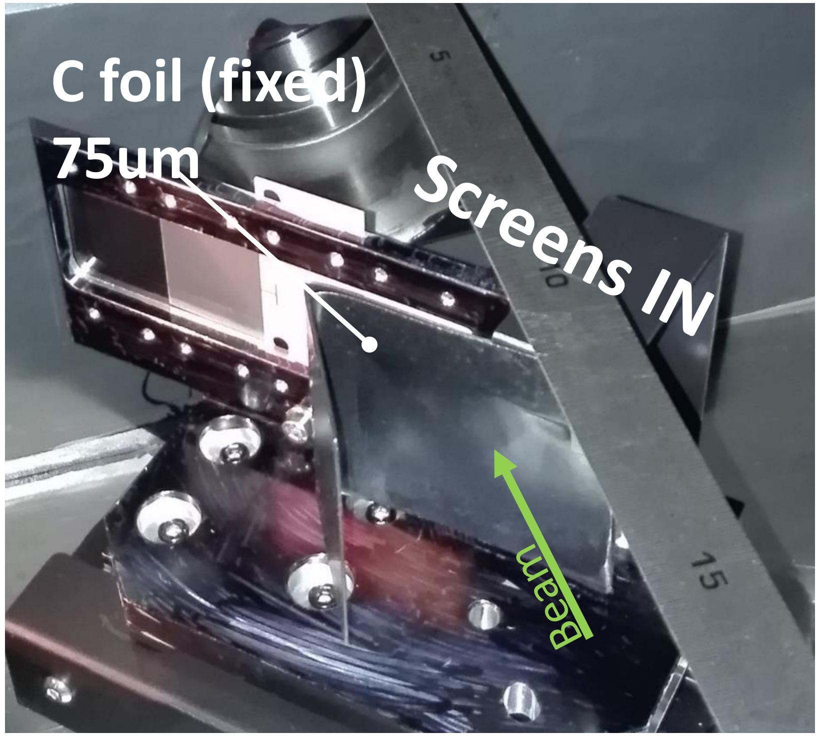


SiC 0.5mm	Ti 0.1mm	Chromox 0.5mm	Sigradur G Glassy C 0.5mm



Screen setup installation in its vacuum tank with the C foil to block the forward OTR from the entrance vacuum window

2017_08_03

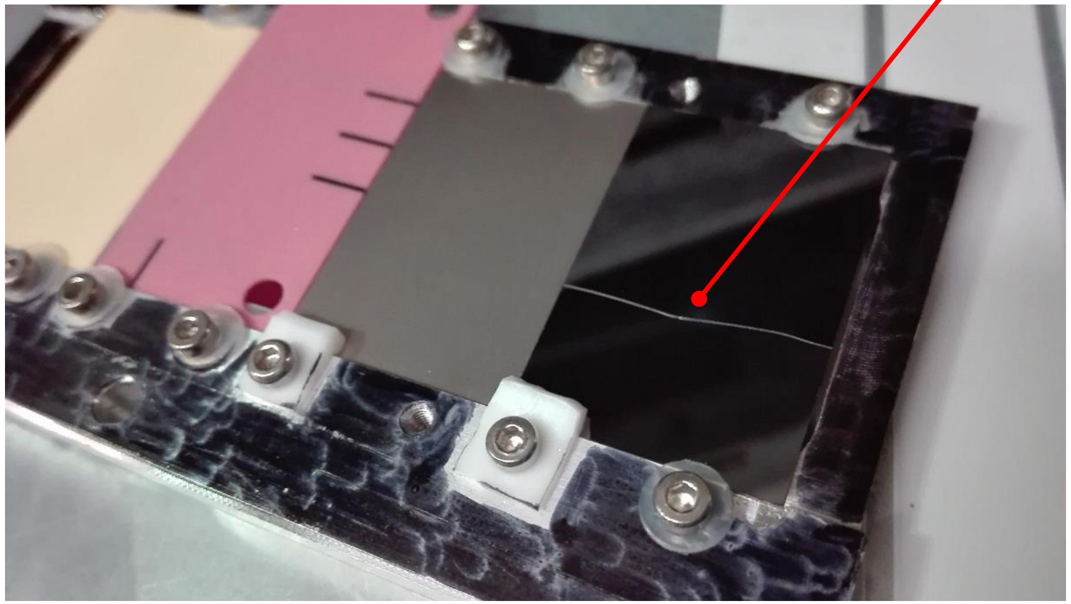


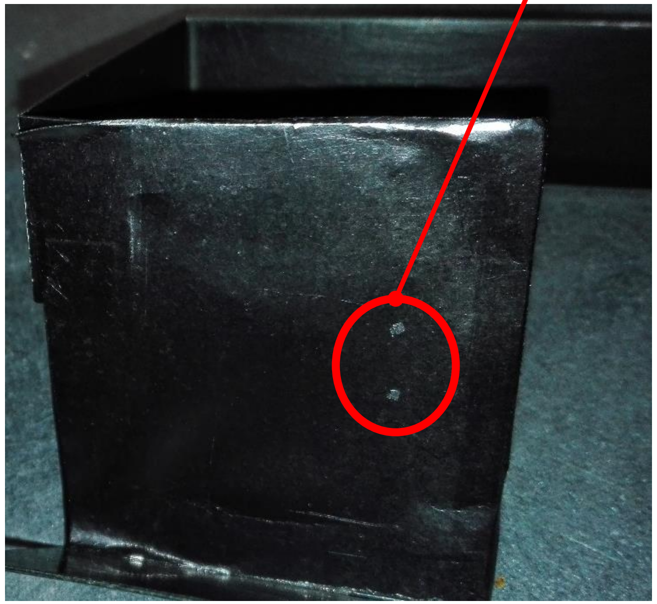
Screen change in HRM BTV

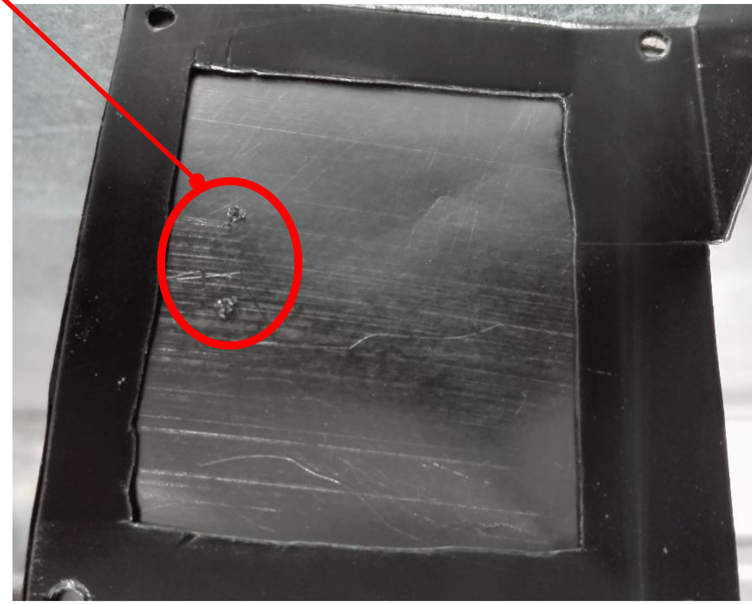
- Al2O3 replaced by new Glassy C Sigradur G
- Keep amorphous SiC even if broken to compare quality/sensitivity

SiC broken…

288 bunches 0.25mm sigma traces on the C foil.
Not holes yet but not far…



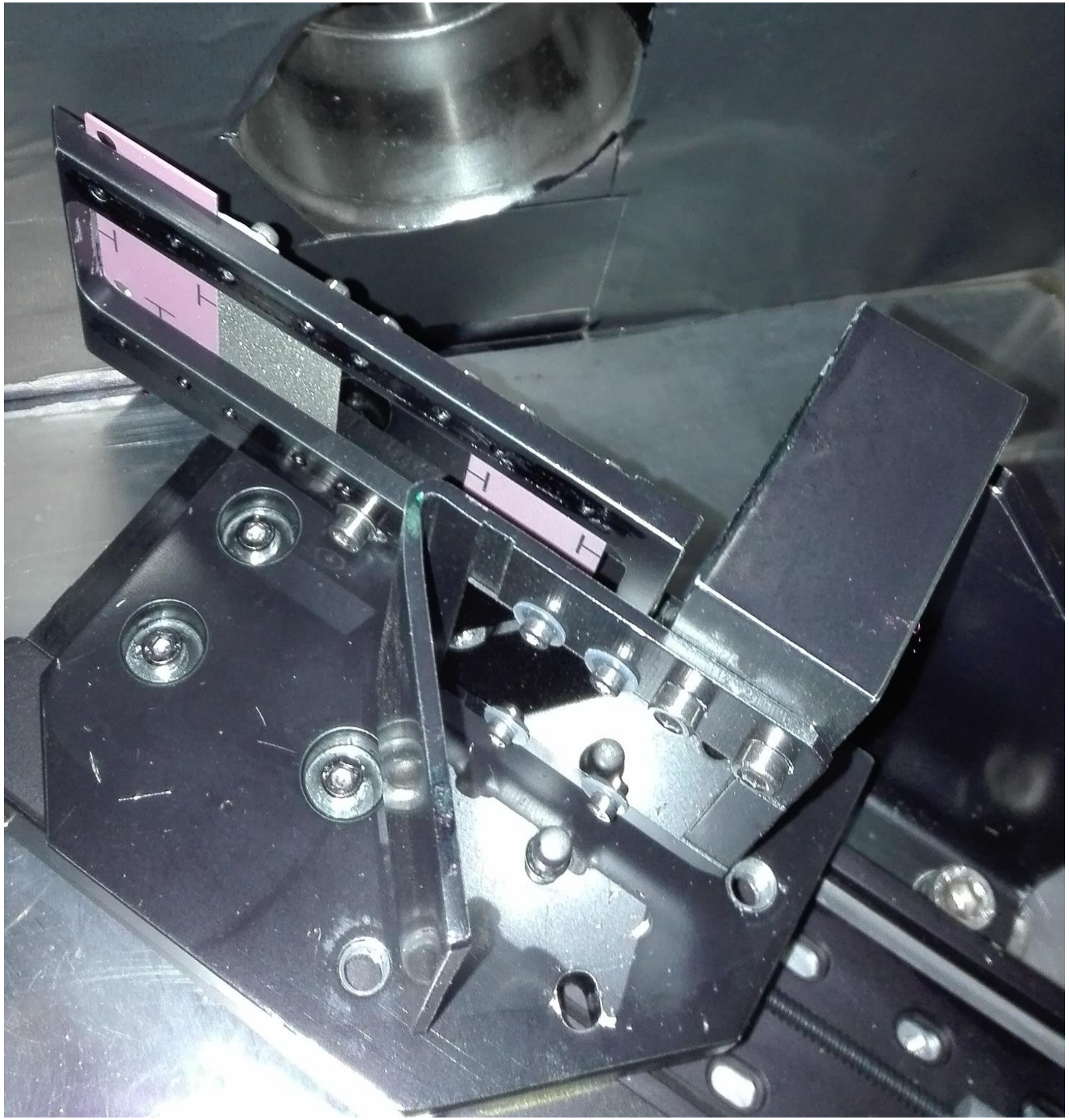




Latest screen setup

Chromox 250um
GlassyC from Sigradur
Ti substrat with diamond powder (test)
Chromox 400um

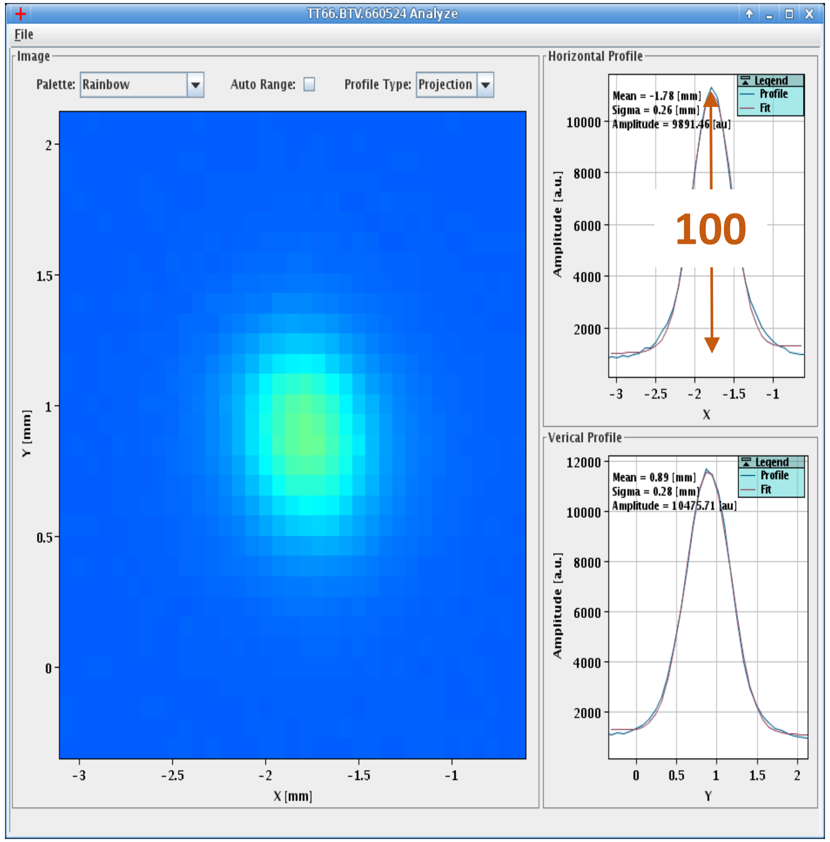
Blocking 'foil' GlassyC from Sigradur



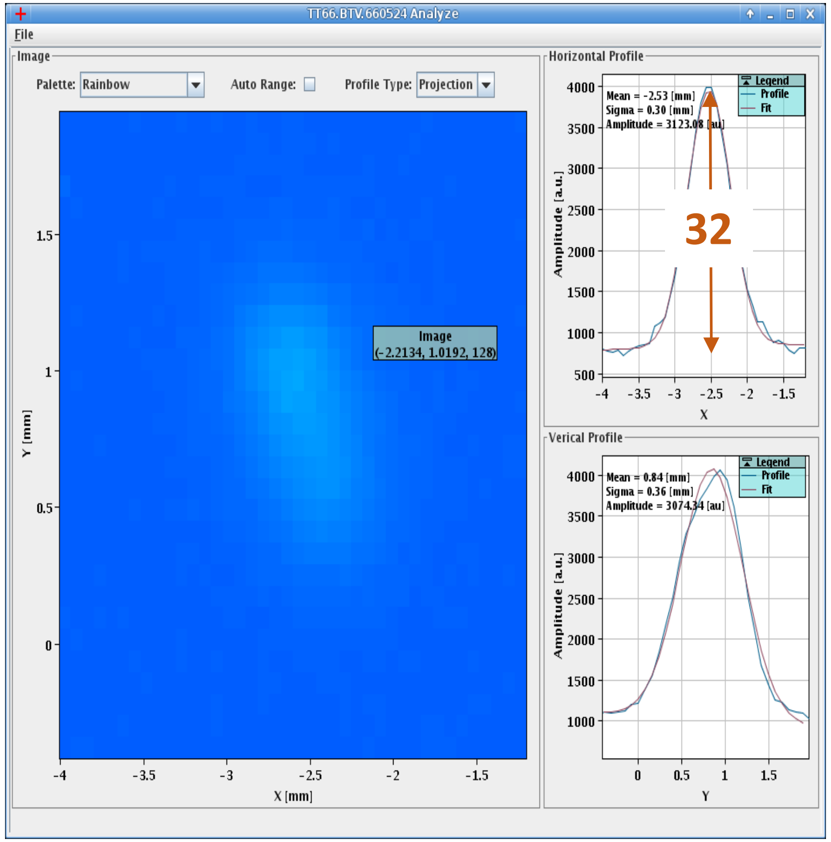
Measurements

>50 measurements/screen

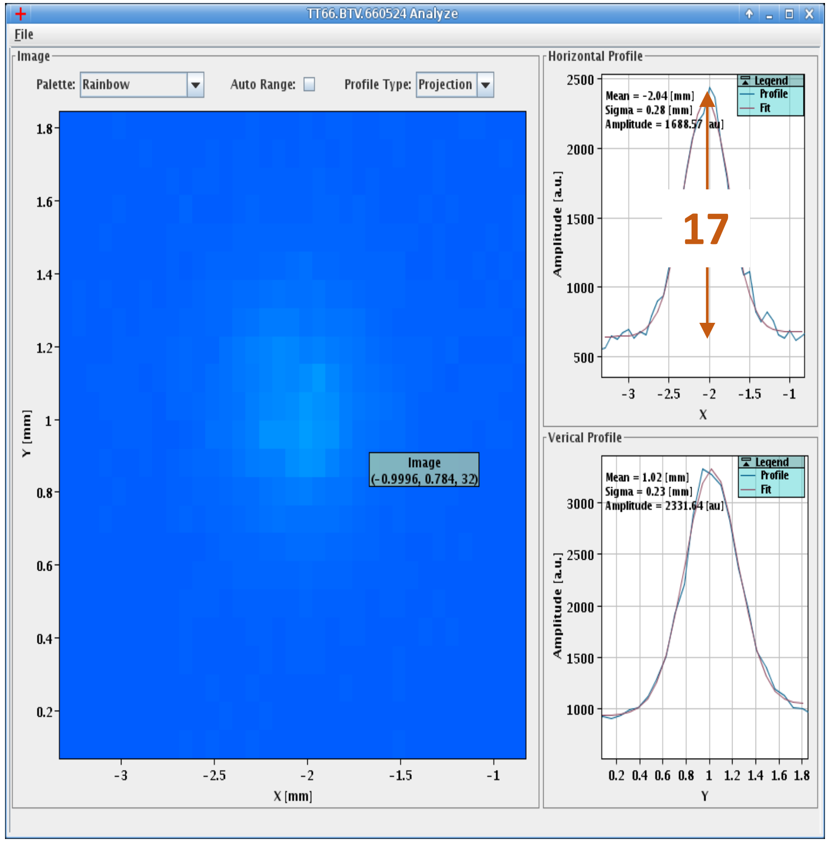
SiC



GlassyC - Sigradur G



Ti



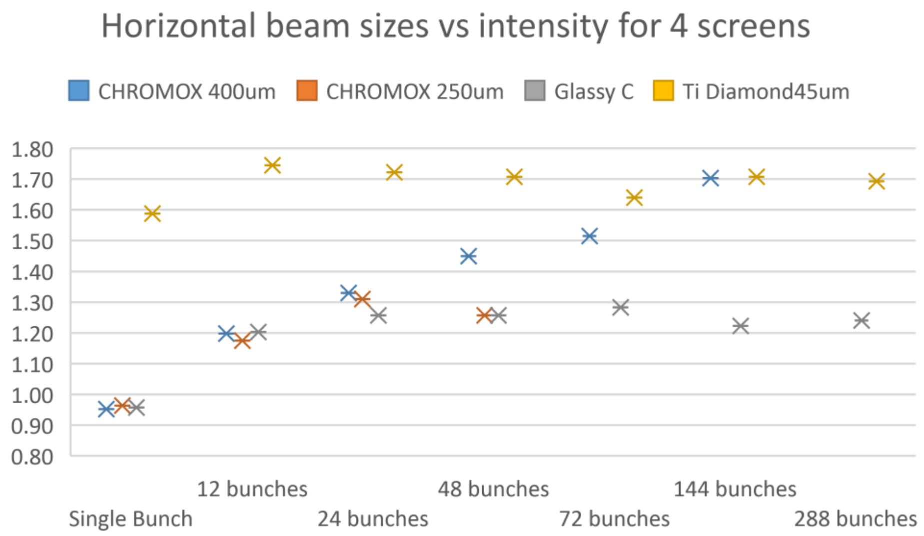
HRM New in vacuum BTV - MD 2018_06_03

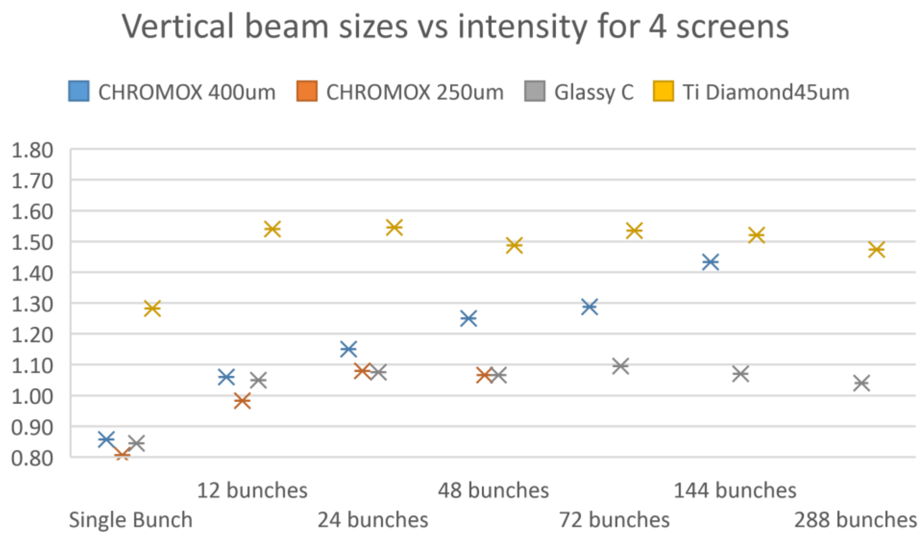
OPTICS FP_2 1mm

(size to be confirmed on BTV screen (~50cm upstream FP_2 → +20%?)

Intensity per bunch 1.05E+12 [p]

	Single Bunch	12 bunches	24 bunches	48 bunches	72 bunches	144 bunches	288 bunches
				H [mm]			
CHROMOX 400um	0.95	1.20	1.33	1.45	1.52	1.70	
CHROMOX 250um	0.96	1.175	1.31	1.26			
Glassy C	0.96	1.2025	1.2575	1.256667	1.28	1.2225	1.24
Ti Diamond45um	1.59	1.745	1.7225	1.7075	1.64	1.7075	1.69
	Single Bunch	**12 bunches**	**24 bunches**	**48 bunches**	**72 bunches**	**144 bunches**	**288 bunches**
				V [mm]			
CHROMOX 400um	0.86	1.06	1.15	1.25	1.29	1.43	
CHROMOX 250um	0.81	0.9825	1.08	1.07			
Glassy C	0.85	1.05	1.075	1.066667	1.10	1.07	1.04
Ti Diamond45um	1.28	1.54	1.545	1.4875	1.54	1.52	1.47

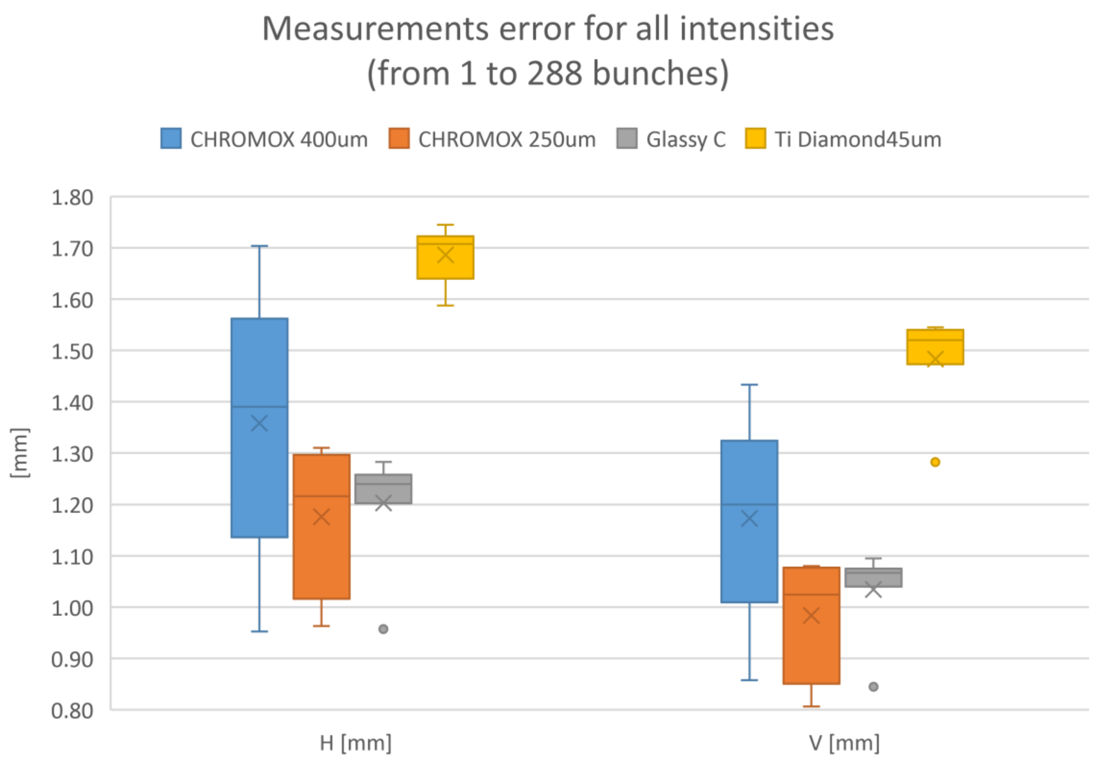


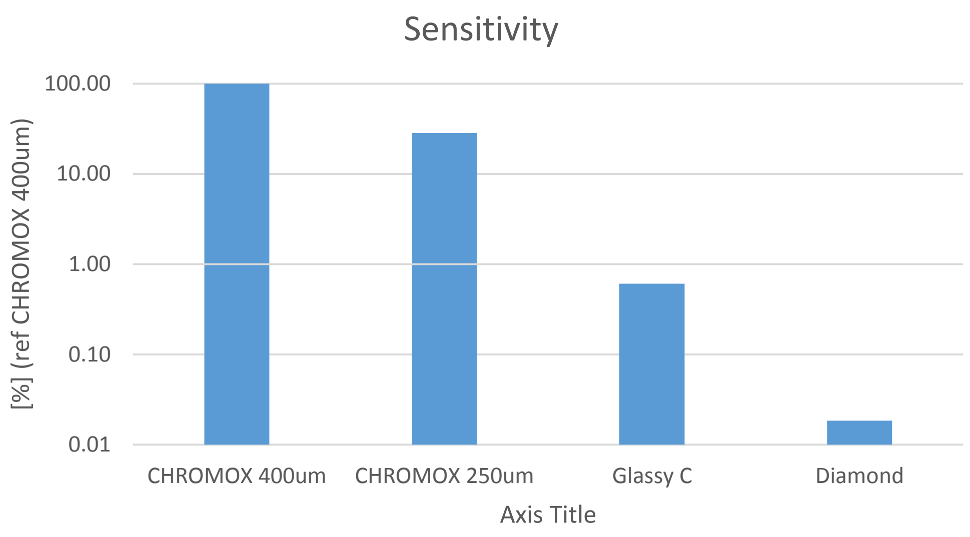


OPTICS FP_2 1mm

(size to be confirmed on BTV screen (~50cm upstream FP_2 → +20%?)

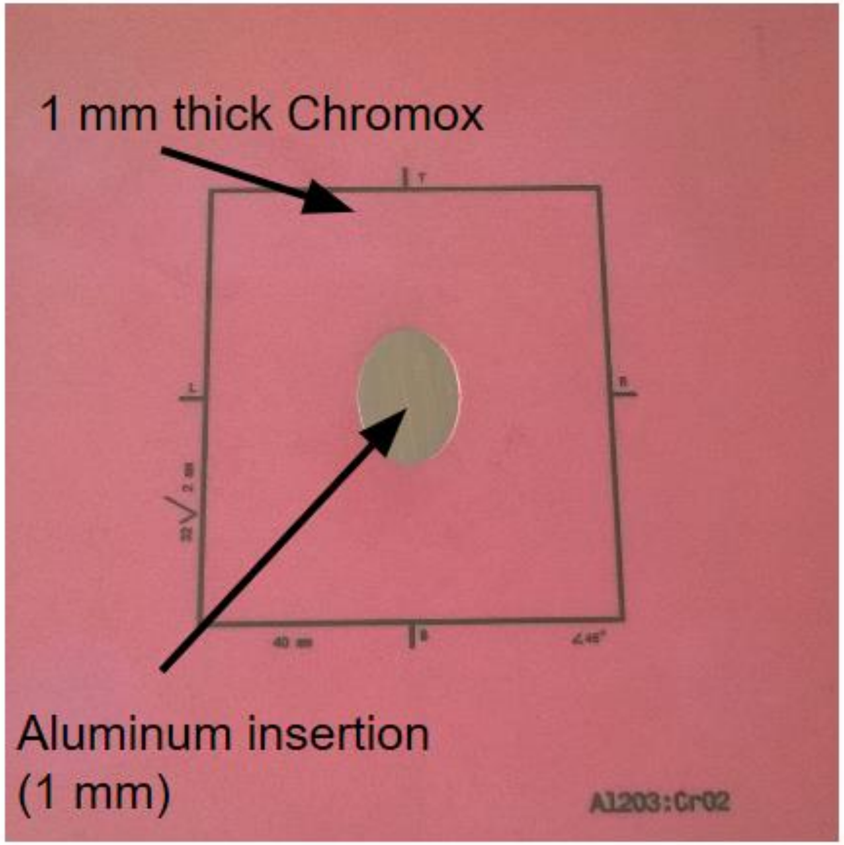
Intensity per bunch 1.05E+12 [p]



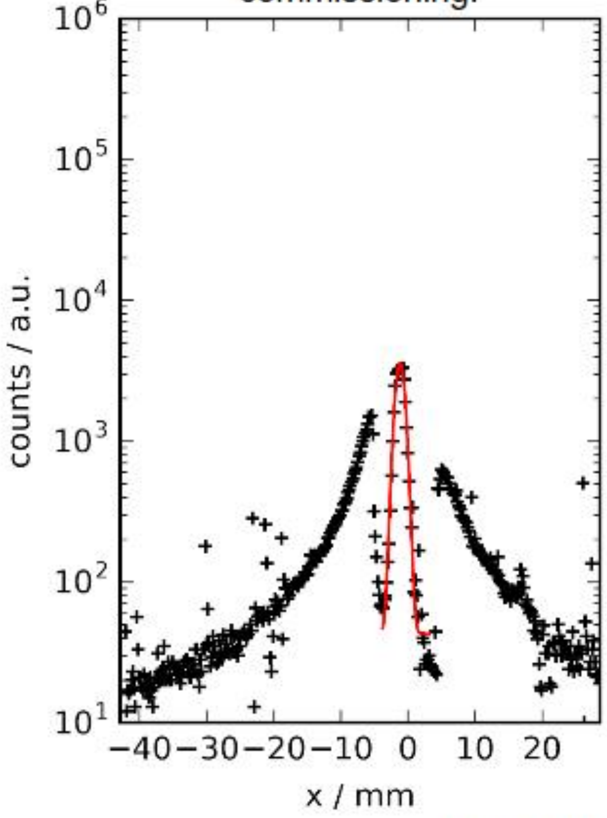


Final screen choice for AWAKE

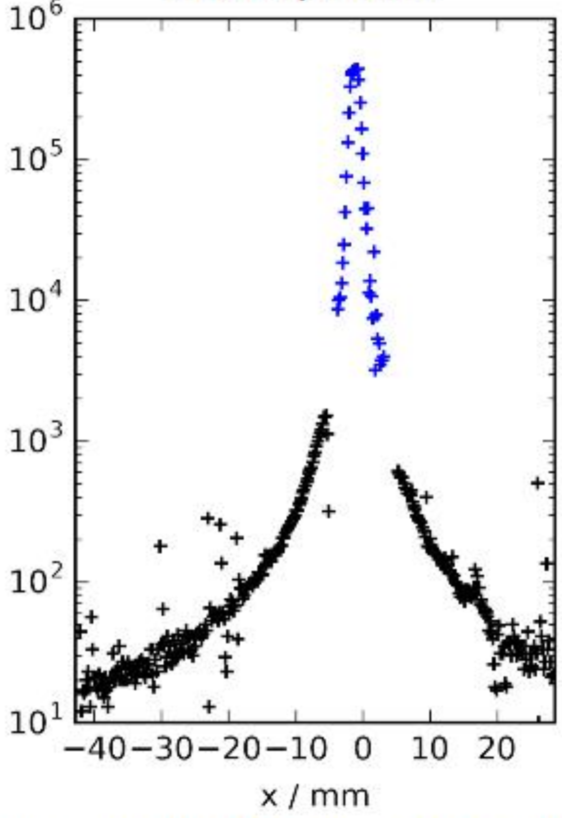
Final screen design:



Measurement of a Gaussian (unmodulated) 400 GeV/c proton beam during the AWAKE commissioning.



Reconstructed proton beam profile.



https://dx.doi.org/10.1016/j.nima.2017.02.064

- Combination of these two screen materials can image proton beam distributions over **4-5 orders** of magnitude with a standard CCD (10 bit) camera.

M. Turner et al.