Timepix detectors' arrays for Hadron Therapy

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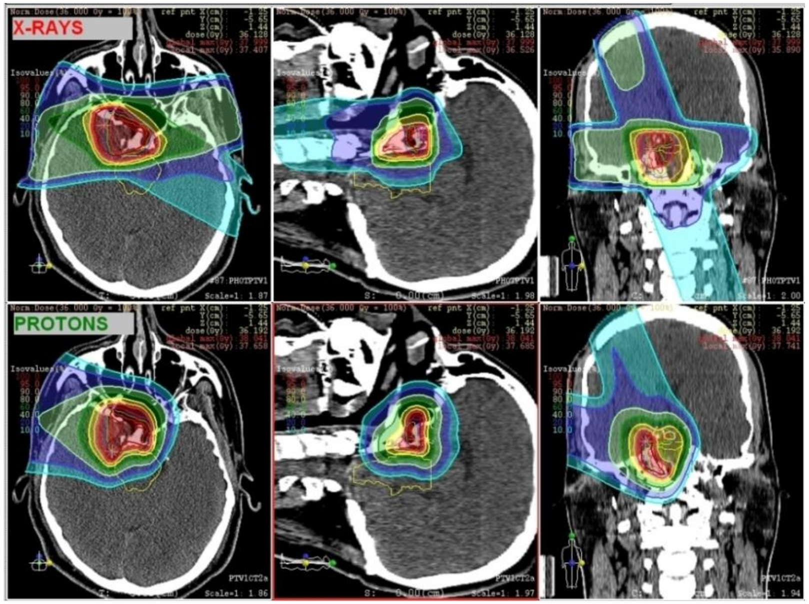
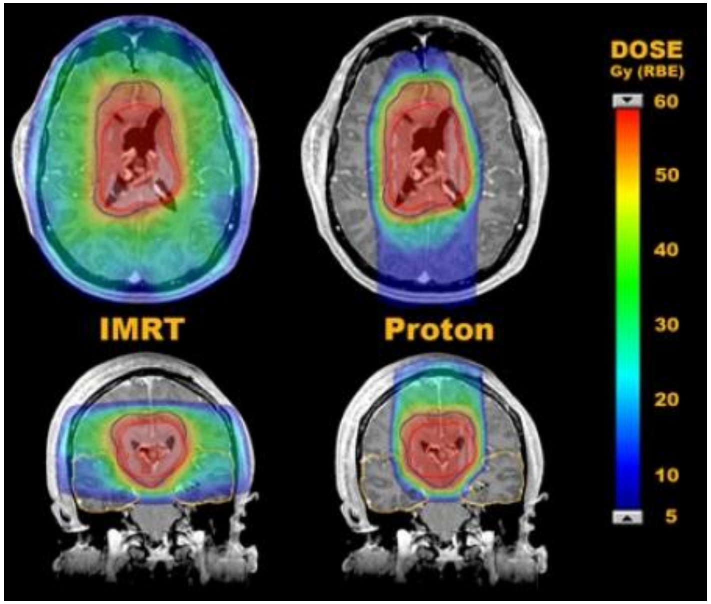
Terapia Hadrónica

En esta forma de radioterapia, En esta forma de radioterapia, haces de alta energía de partículas nucleares cargadas (Protones, iones pesados) son utilizados debido a sus propiedades de interacción con la materia (Curva de Bragg) para obtener una deposición de energía mucho mas específica en el tumor.



http://dev.rptc.de/fileadmin/user_upload/rptc/Bilder/Planvergleich/Planvergleich_3._MB_ENGL.JPG



http://iuhealth.org/images/sized/images/glo-body/Proton-Article-Image-400-450x0.jpg

Contextualización histórica

- 1905: Sir William Bragg Frenado de Alfas en aire → Curva de Bragg
- 1963: Robert Wilson "precision exposures of well-defined small volumes within the body will soon be feasible."
- 1948-1975: LBL Pruebas de propiedades de haces de protones e iones de 20Ne.
- 1975-1992: Bevalac at LBL Tratamiento de pacientes con "Passive Beam Scanning" con haces de neón.
- 1990: Lomalinda, USA Primer tratamiento con protones en un centro hospitalario
- 1994: HIMAC, Japón Primer centro de tratamiento con iones de 12C.
- 1993-1997: GSI (Alemania), PSI (Suiza) Desarrollo de "Active Beam Scanning"
- 2009: HIT, Alemania Primer centro hospitalario con protones e iones pesados.

Centros Actuales

Center	Country	Particle type	Maximum Energy	Operating since
Loma Linda	USA	Proton	250 MeV	1990
HIMAC, Chiba	JP	Carbon ion	800 MeV/u	1994
NCC, Kashiwa	JP	Proton	235 MeV	1998
HIBMC, Hyogo	JP	Proton	230 MeV	2001
PMRC, Tsukuba	JP	Proton	250 MeV	2001
NPTC, MGH, Boston	USA	Proton	235 MeV	2001
Shizuoka	JP	Proton	235 MeV	2003
MPRI, Bloomington	USA	Proton	200 MeV	2004
WPTC, Zibo	CN	Proton	230 MeV	2004
MD Anderson, Houston	USA	Proton (scanning)	250 MeV	2006
FPTI, Jacksonville	USA	Proton	230 MeV	2006
NCC, Ilsan	KR	Proton	230 MeV	2007
ProCure,	USA	Proton	230 MeV	2009
RPTC München	D	Proton (scanning)	250 MeV	2009
HIT, Heidelberg	D	Proton, Carbon ion	430 MeV/u	2009
Upenn, Philadelphia	USA	Proton	230 MeV	2010
CNAO, Pavia	IT	Proton, Carbon ion	430 MeV/u	2010
WPE, Essen	D	Proton	230 MeV	2010
CPO, Orsay	FR	Proton	230 MeV	2010
PTC, Marburg	D	Proton, Carbon ion	430 MeV/u	2010
Gunma, Maebashi	JP	Carbon ion	400 MeV/u	2010
HUPBTC, Hampton	USA	Proton	230 MeV	2010
SJFH, Peking	CN	Proton	230 MeV	2010

Curva de Bragg

La curva de Bragg es el resultado del comportamiento esperado de un ion al pasar a través de la materia. En el rango de energías de terapia hadrónica (~10^2 MeV/U), la deposición en el material es bien descrita por la versión relativista de la fórmula de Bethe-Bloch:

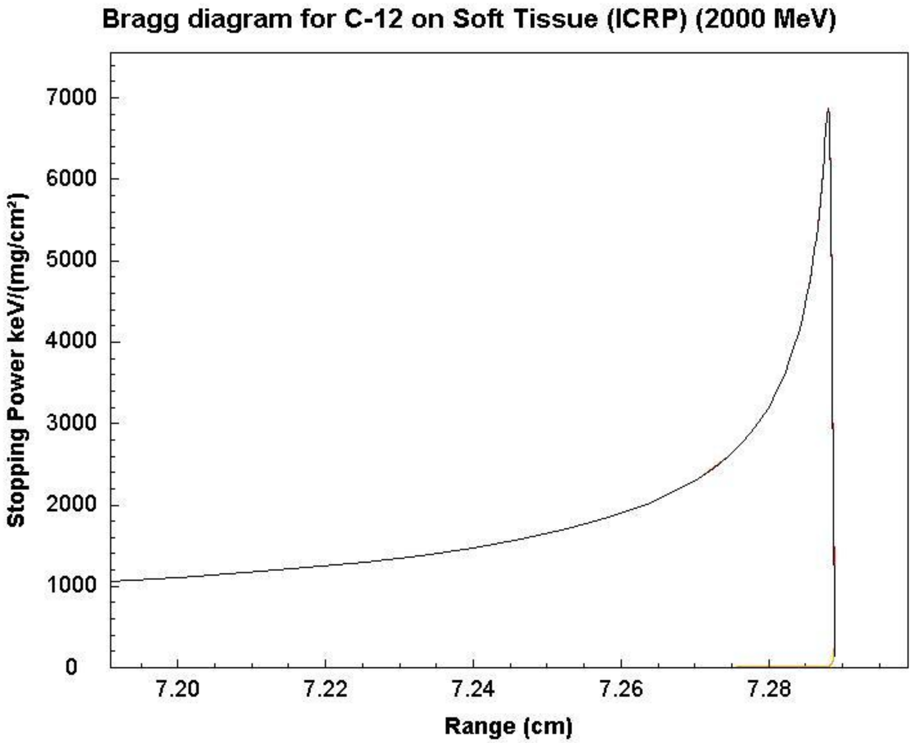
$$\frac{dE}{dx} = \frac{4\pi e^4 Z_t Z_p^2}{m_e v^2}\left(\ln[\frac{2m_e v^2}{< I >}] - \ln[1-\beta^2] - \beta^2 - \frac{C}{Z_t} - \frac{\delta}{2}\right) \qquad \beta = v/c$$

$< I >$: Potencial de excitación principal del material. (75-78 eV para iones pesados, 80 eV para protones, en agua)

δ : Polarización de los átomos del material debido a las partículas incidentes.

C : Corrección para velocidades equiparables a las de los electrones en los átomos del material.

Teniendo en cuenta lo anterior, la deposición crecerá pronunciadamente hacia el final y decaerá con fuerza luego de su máximo:

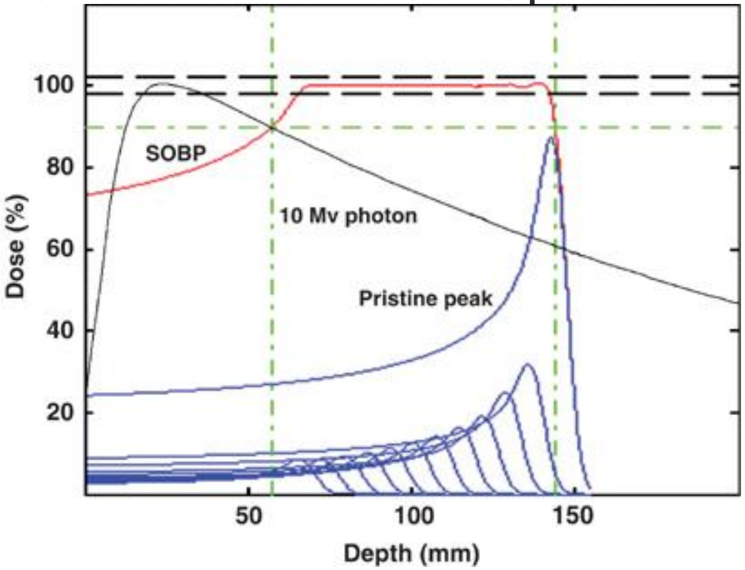


http://www.nucleonica.net/wiki/index.php?title=File%3ABragg_Peak.jpg

Terapia con protones

Protones de energías del orden de 70-250 MeV generados en un acelerador (ciclotrón o sincrotrón) inciden sobre el paciente. La energía de estas partículas está sujeta al alcance requerido para el tumor.

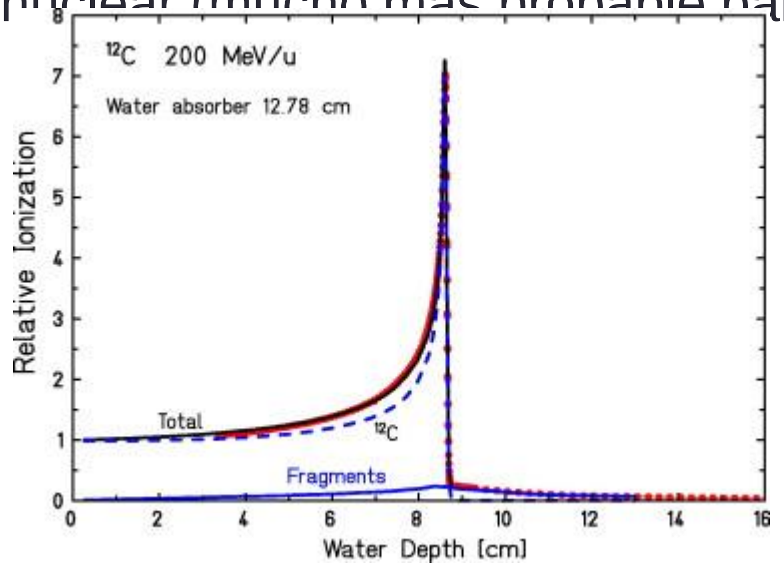
Debido a las estrechas dimensiones del pico de Bragg, para cubrir el tamaño deseado se aplican haces a distintas energías generando una distribución llamada "Spread Out Bragg Peak" (SOBP).



http://www.nature.com/bjc/journal/v93/n8/fig_tab/6602754f1.html

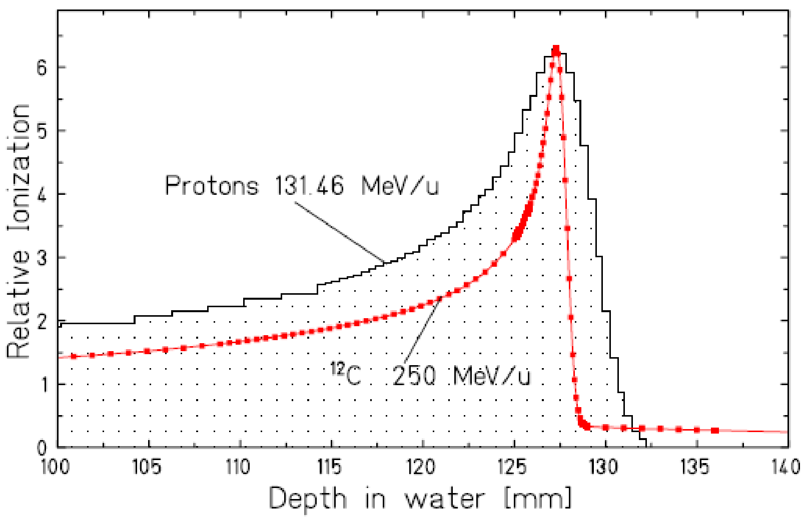
Terapia con iones pesados

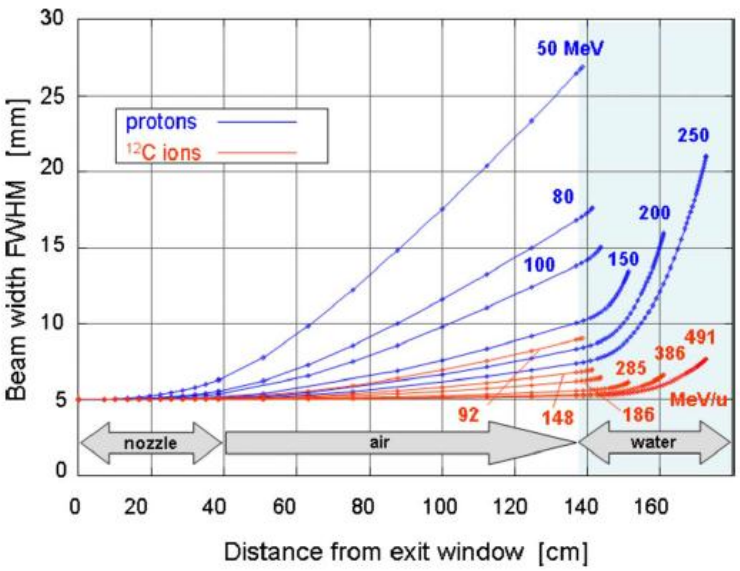
Iones “Pesados” (e.g. 4He, 20Ne, 16O, 28Si, 40Ar, pero en especial 12C) son acelerados a energías de 200 a 430 MeV por nucleón. Si bien el comportamiento en deposición de energía sigue regido por la curva de Bragg, los poderes de frenado son mayores, y la dosis presenta una “cola adicional” luego del pico debido a fragmentación nuclear (mucho mas probable para proyectiles mas grandes).



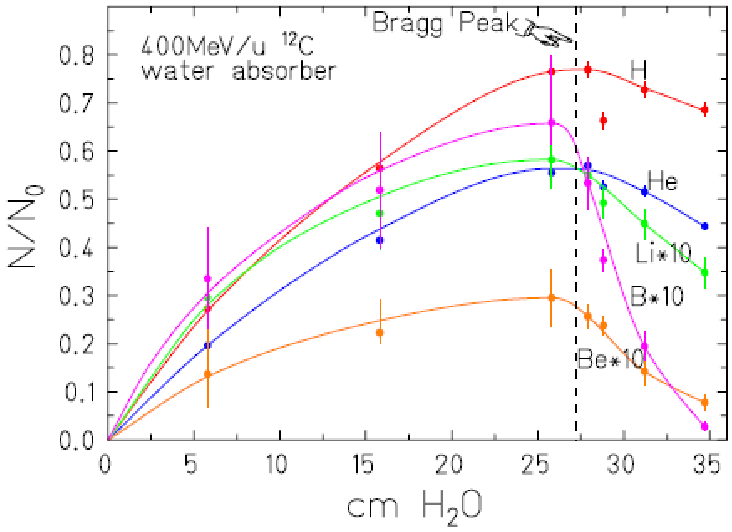
Protones vs. Iones Pesados

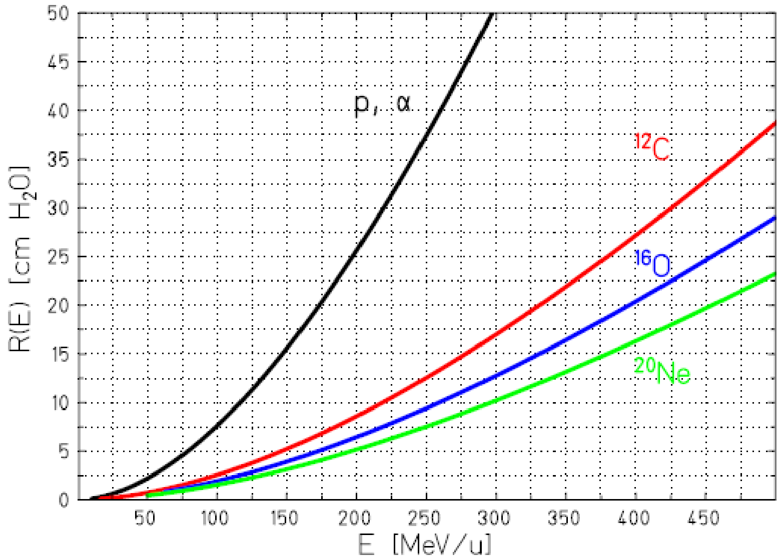
La dispersión lateral del haz es mayor para protones que para iones pesados, al igual que el grosor medio del pico de Bragg.





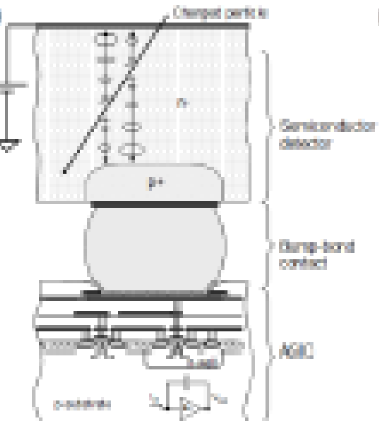
Por otro lado, la fragmentación nuclear es mayor en iones pesados, generando radiación secundaria, pero su alcance medio puede ser mayor que aquel posible con protones.





Timepix Detector

This hybrid semiconductor pixel detector of the Medipix type [18] consists of a radiation sensitive sensor bump bonded to an ASIC readout chip with integrated electronics per pixel (see Figure 2) . The chip is divided into an array of $256 * 256$ pixels of 55 μm pitch with full sensor size $14 * 14$ mm^2. Hybrid technology allows using sensors of different materials (Si, GaAs, CdTe) and thickness (300, 700, 1000 μm). Per-pixel pulse processing electronics provides fast and noise free images.



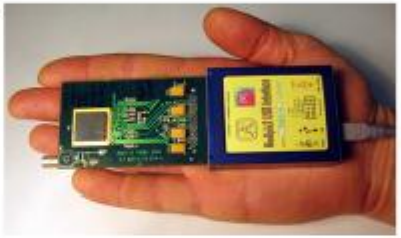


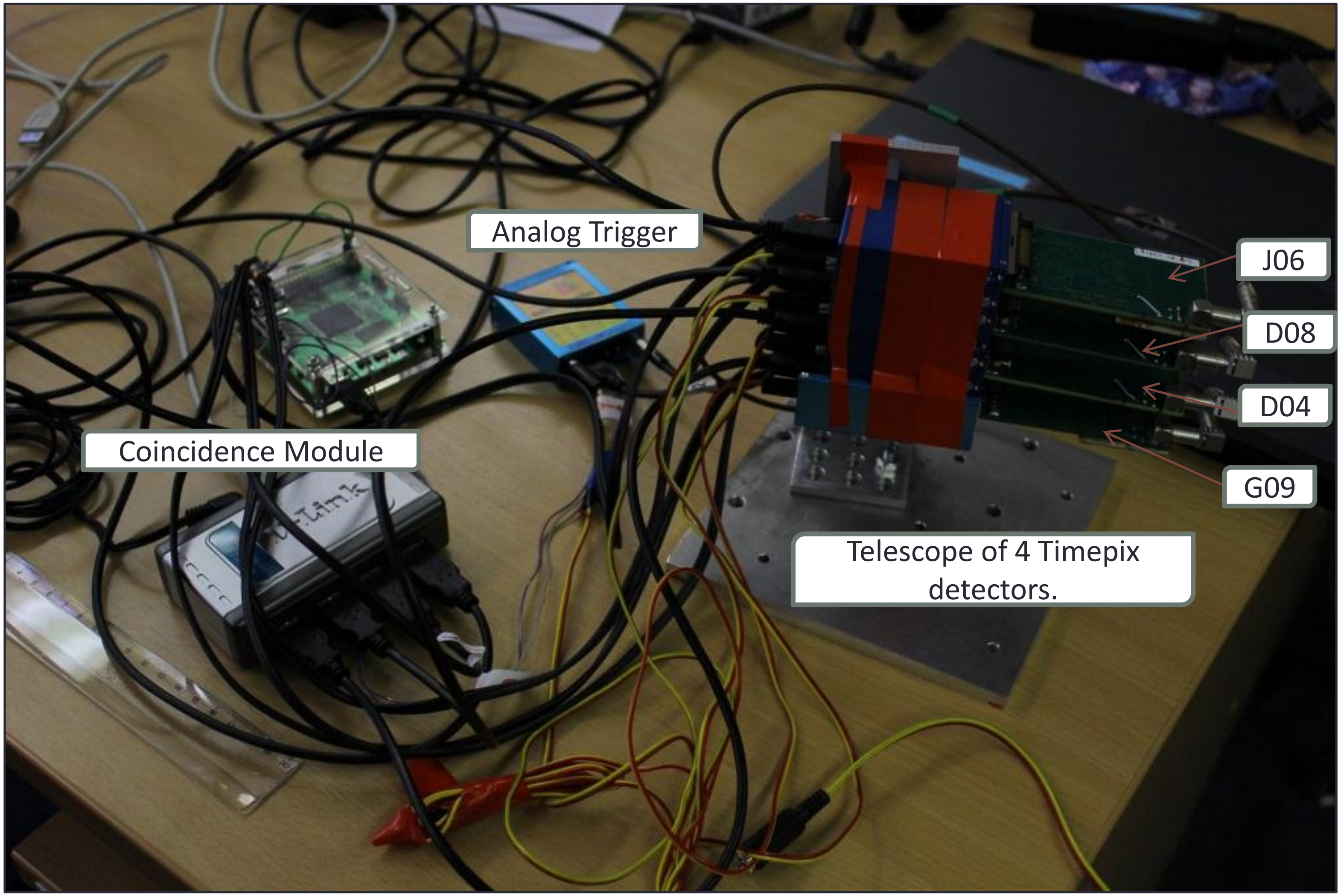
Figure 2: (Left) Principle of the hybrid pixel detector Medipix with the semiconductor sensor bump-bonded to the readout ASIC chip containing integrated signal electronics per pixel. (Right) Medipix/USB radiation camera assembled from the chipboard and USB-based readout interface. Data link to PC/notebook via USB port.

In addition to high granularity, wide dynamic range and per pixel threshold the Timepix device [19] provides energy and time sensitivity capability per pixel. The detector provides more complete information (position, energy, time, stopping power) for basically all types of ionizing particles. Per-pixel threshold is about 4 keV for a 300 μm silicon device. Interaction/arrival time can be determined with a step of 25 ns. For charged particles, the spatial resolution can reach, by event-by-event analysis and pattern recognition of the particle track, sub-pixel resolution down to few μm.

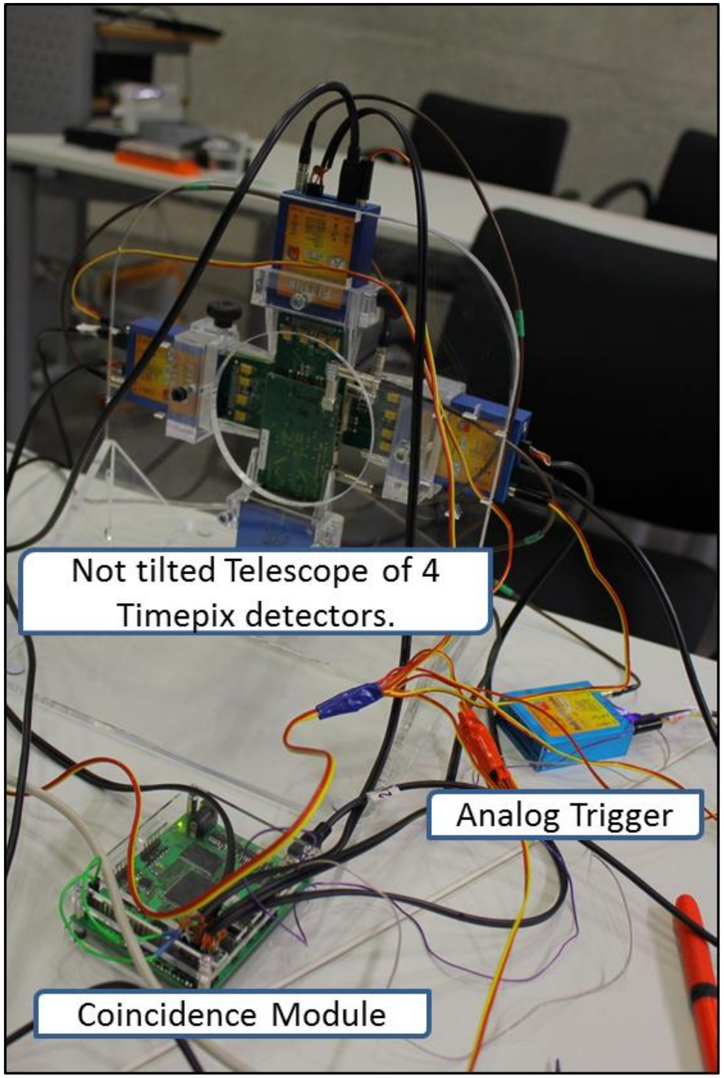
The pixel detector is operated with integrated USB-based readout interfaces such as the USB 1.0 [20] and FITPix [21] devices which provide control, power and DAQ. Operation and online visualization are enabled by the software package Pixelman [22] [23]. The assembled system serves as an online radiation camera [24] for table-top and vacuum operation, portability and configurability of different measurements and setups.

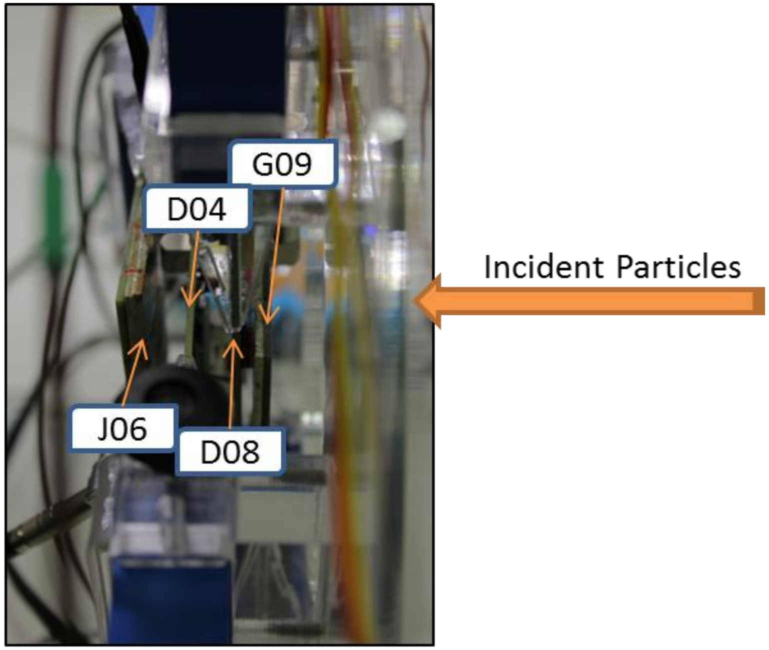
Timepix Detectors' Arrays

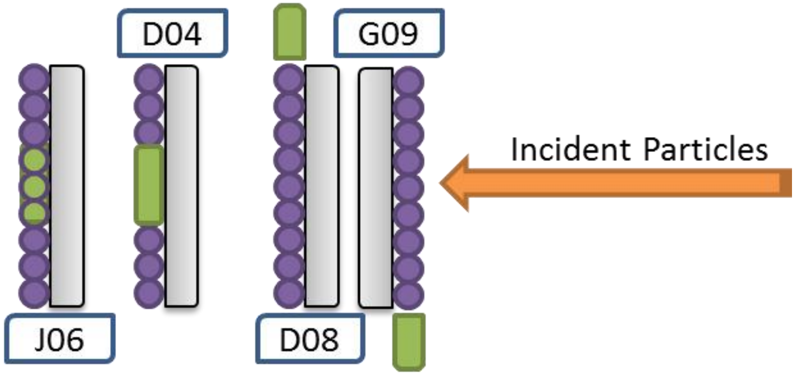
Basic Telescope Array of 4 Timepix Detectors



Telescope Array of 4 Timepix Detectors

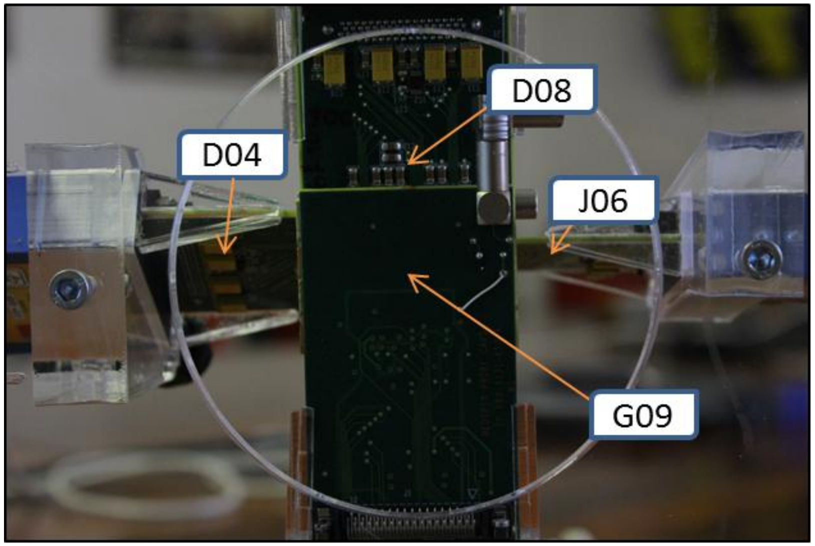




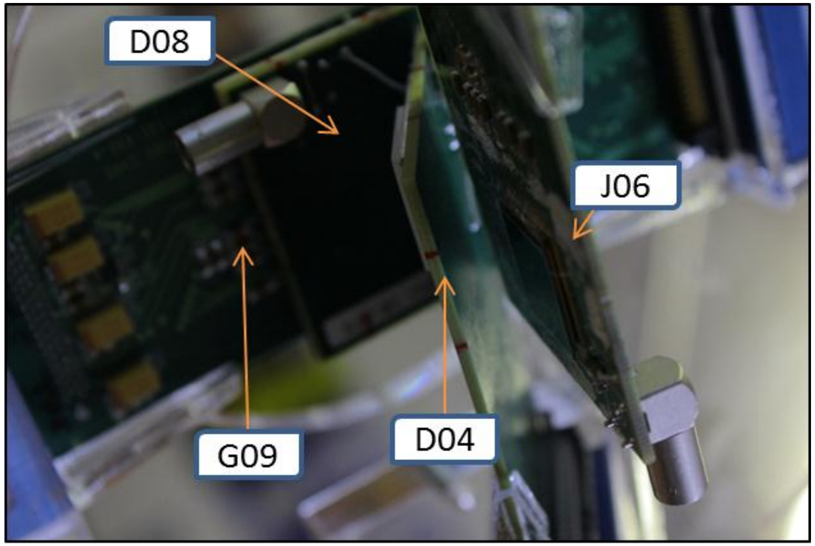


Side View

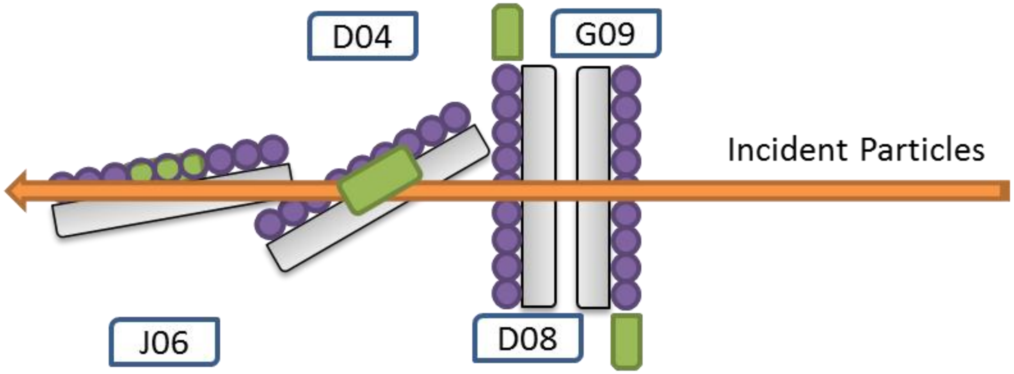
“Tilted” Telescope Array of 4 Timepix Detectors



View from the Incident Particles

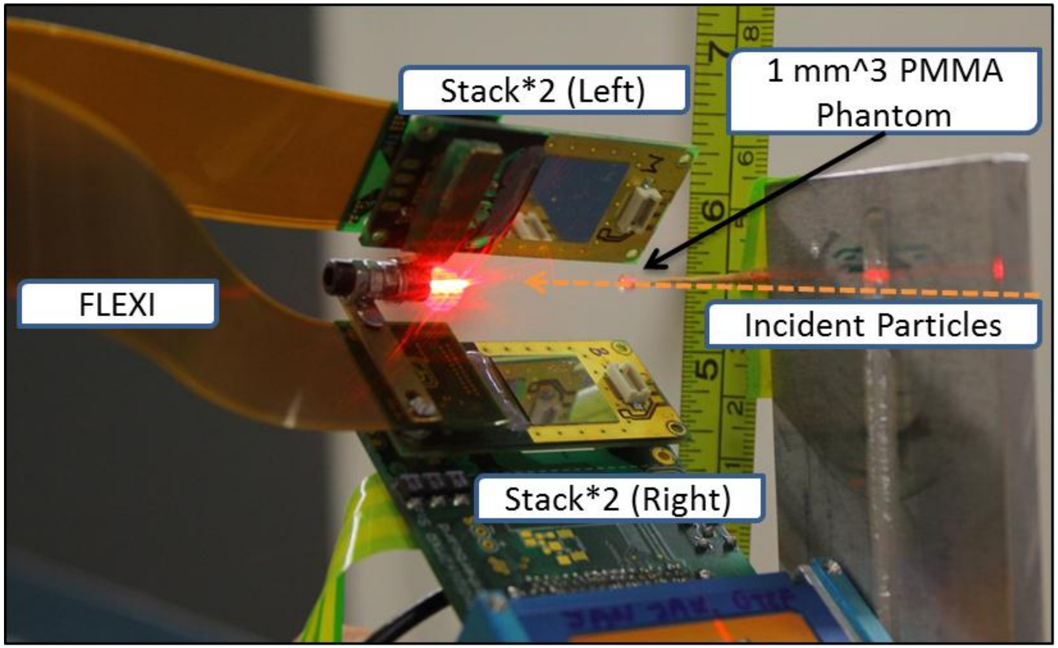


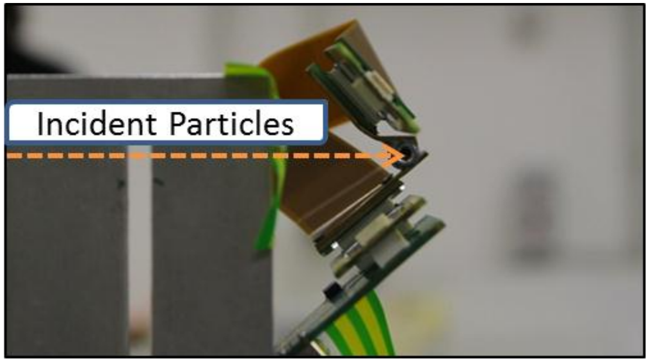
View from behind



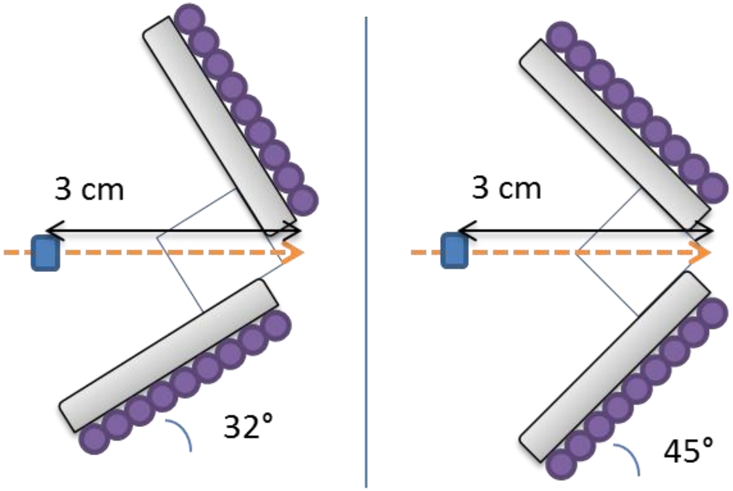
Side View

Variable Angle Array of 2 “Tiled” Timepix detectors + FLEXI





Side View



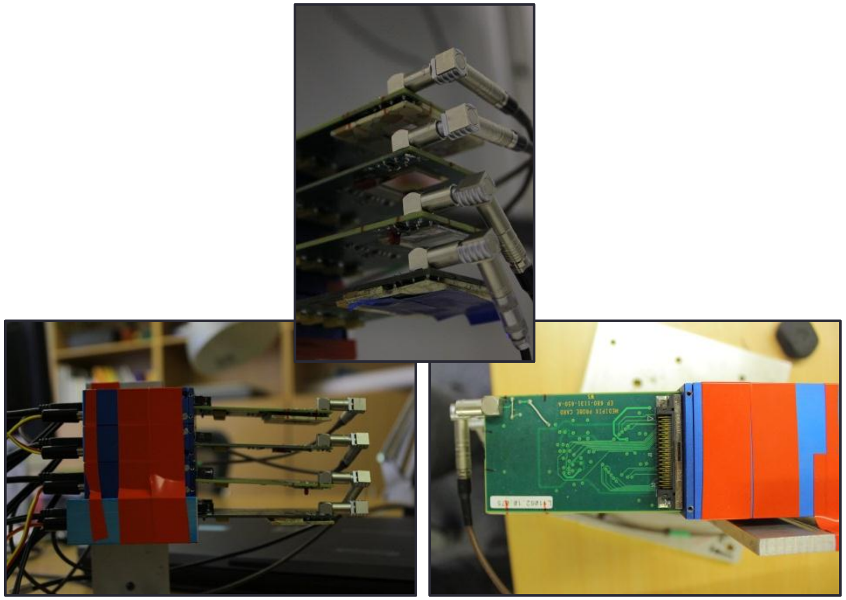
01/

02/

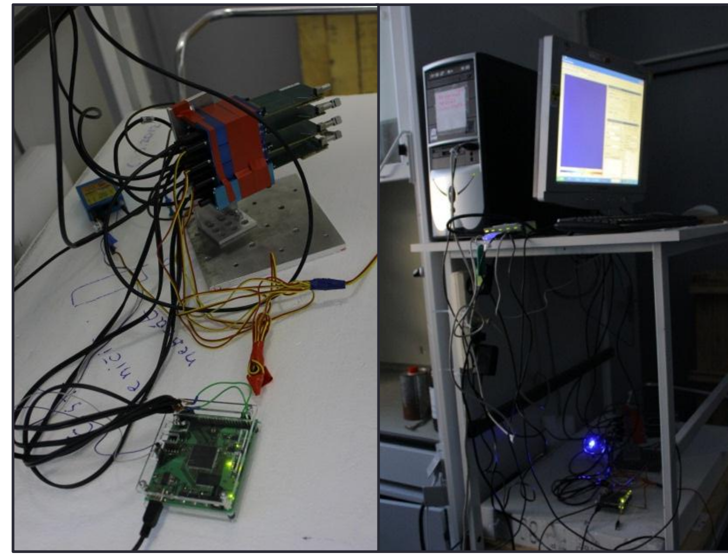
Testing of the Telescope Array and the software tool for analysis

(Cosmic Rays and VdG Accelerator)

Telescope Array: Test with Cosmic Rays

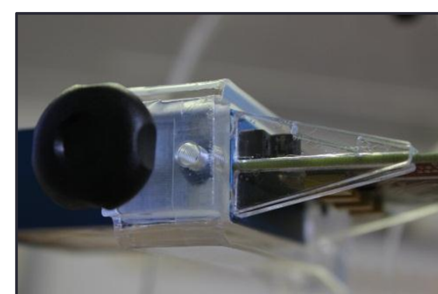


Basic Telescope Array
(The horizontal position was not the same for all Timepix devices, because the weight of the detectors tilted them small angles)

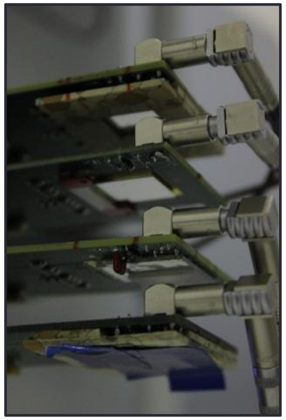


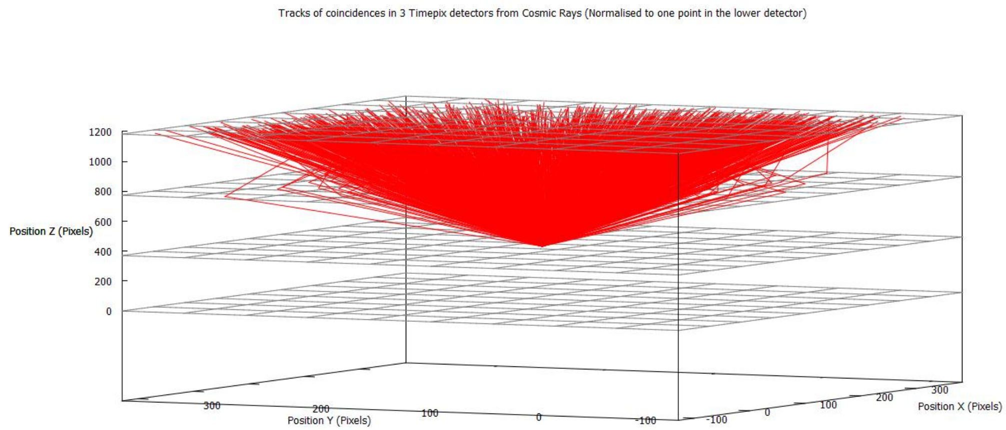
Telescope Array connected to the coincidence module, analog trigger and PC at the IEAP.

Plastic Holders adapted to Timepix and its USB interface.

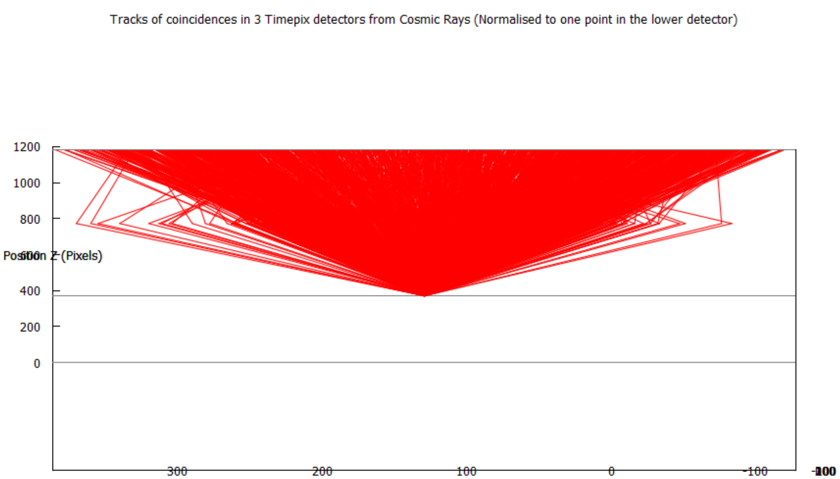


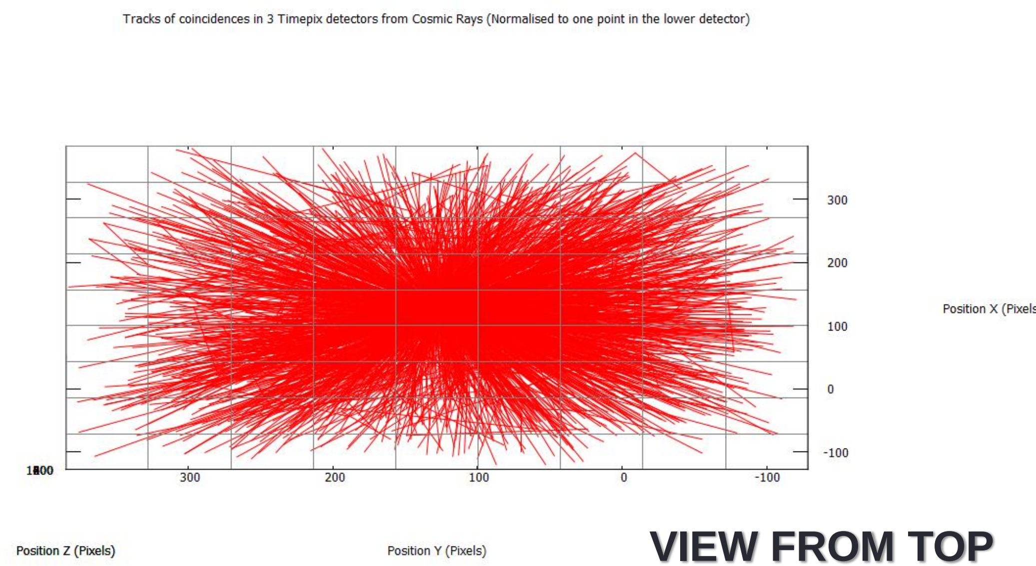
Coincidences for 3 detectors





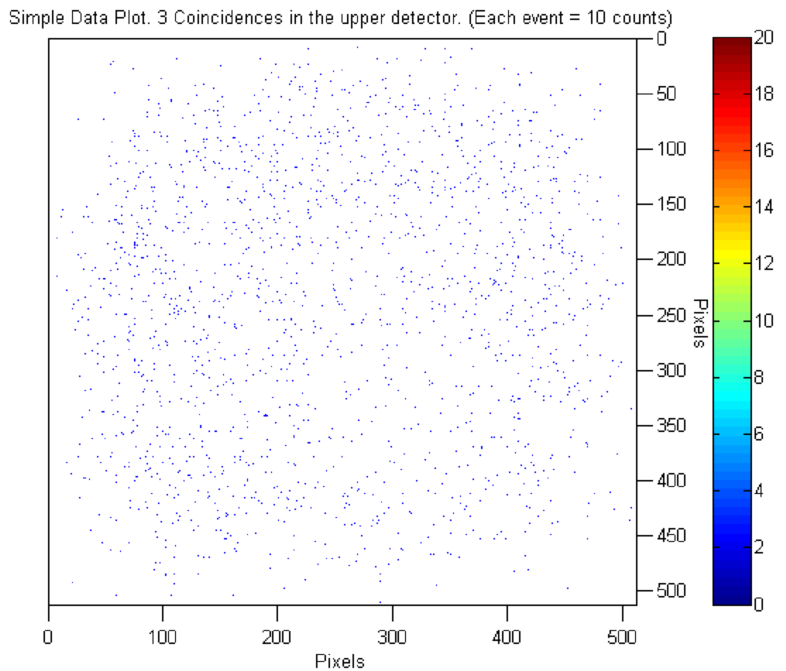
3D VIEW



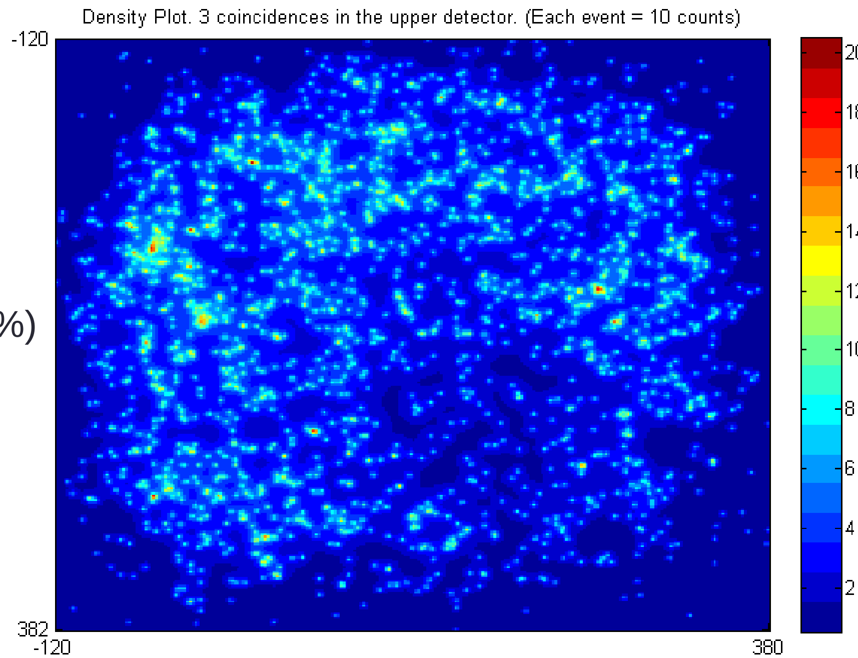


VIEW FROM Y-Z PLANE

VIEW FROM TOP



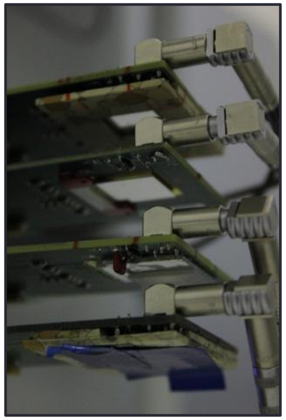
Coincidences for 3 detectors: Coordinates in the upper detector after normalization.

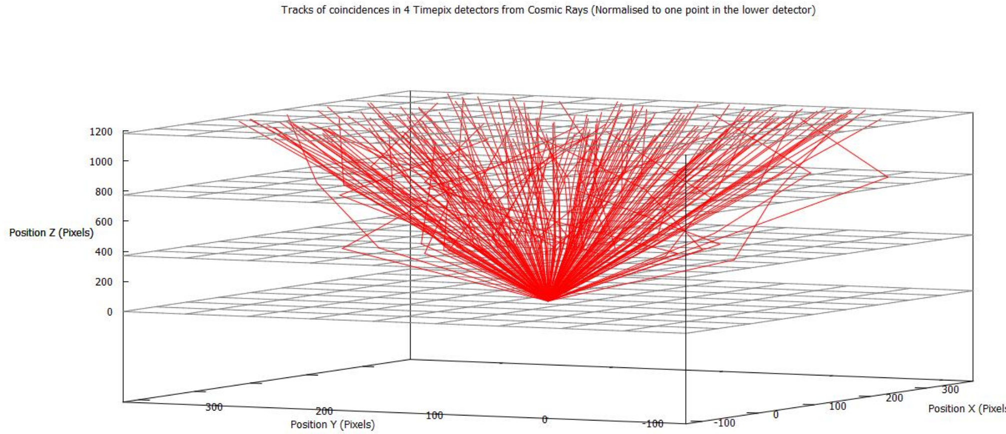


Total number of coincidences (2,3,4 det) : 23091
Total number of coincidences per hour (2,3,4 det) : 61.6
Total time: 15.6 days

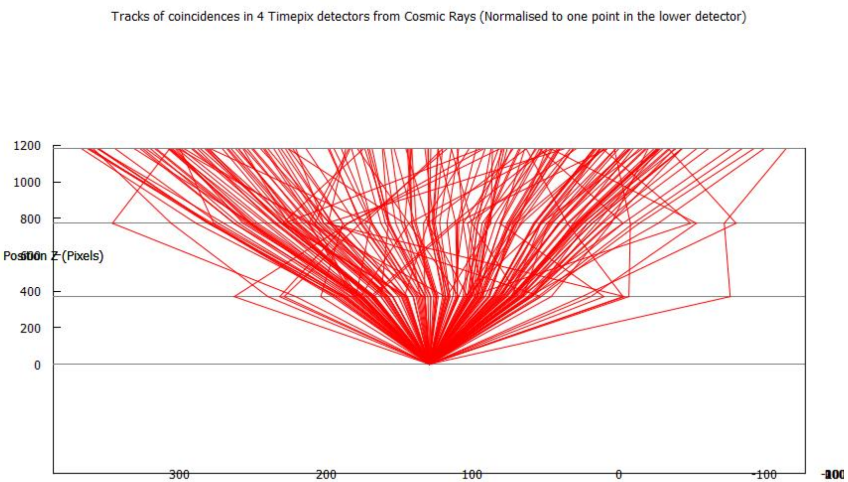
Total number of coincidences in 3 detectors: 1944 (8.43%)
Number of 3 coincidences per hour: 5.2

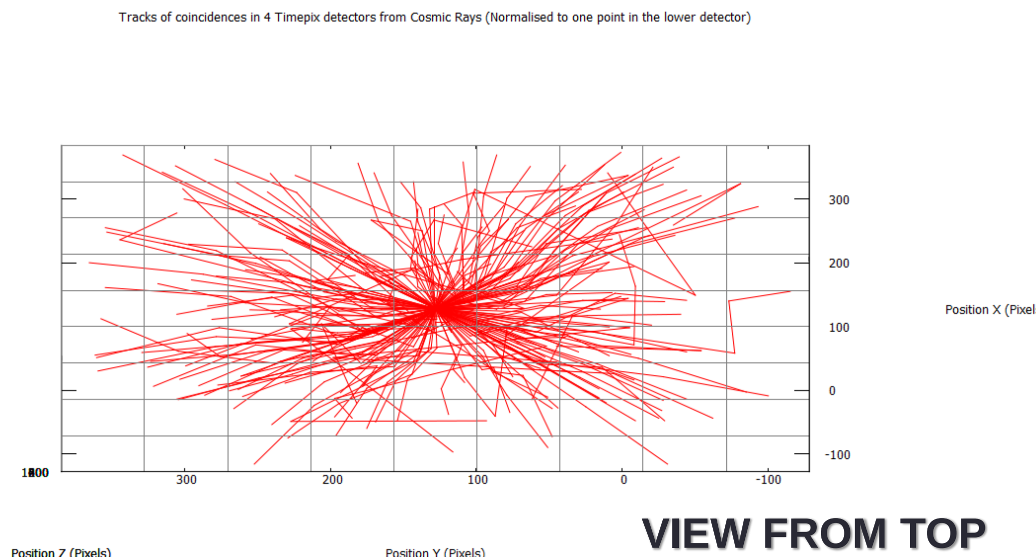
Coincidences for 4 detectors





3D VIEW

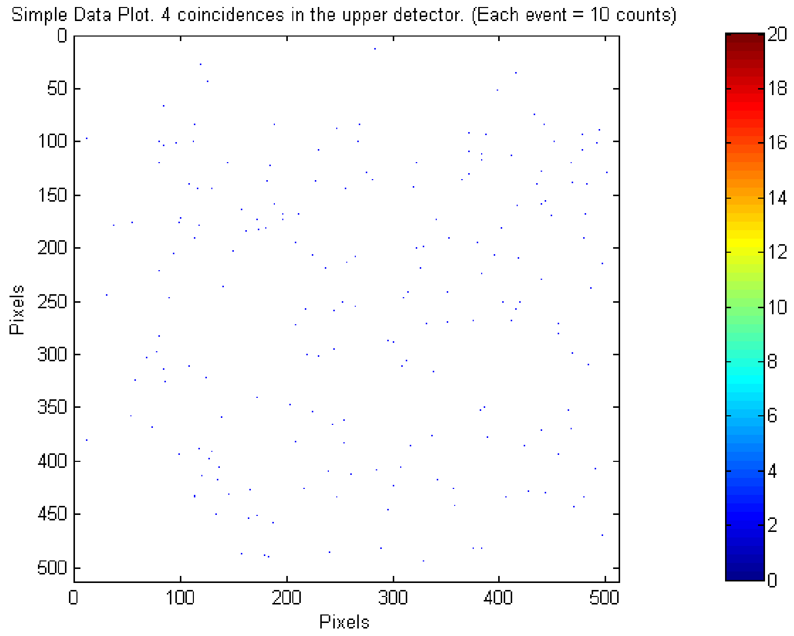




VIEW FROM Y-Z PLANE

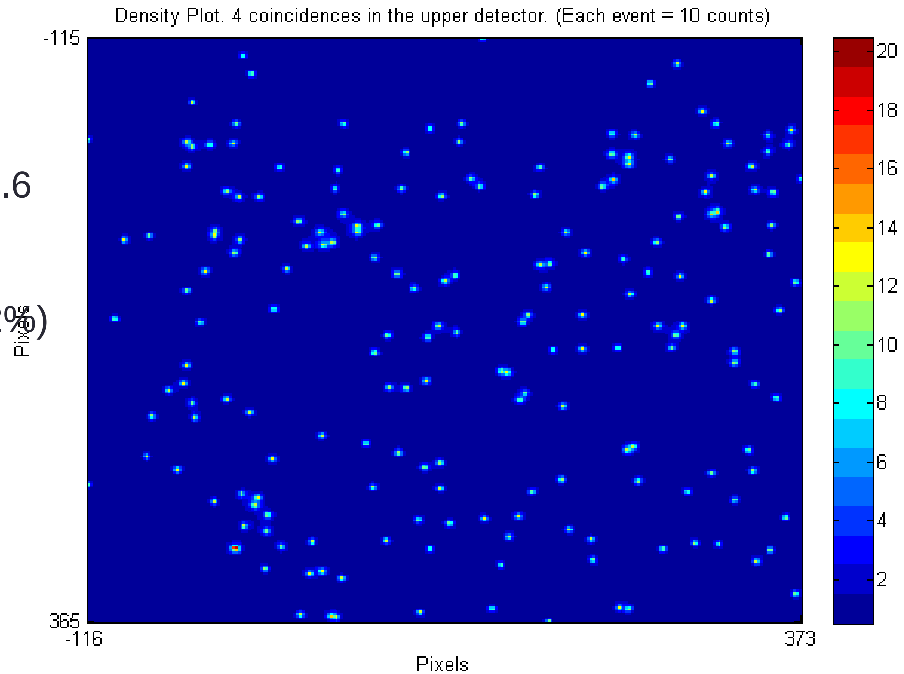
VIEW FROM TOP

Coincidences for 4 detectors: Coordinates in the upper detector after normalization.

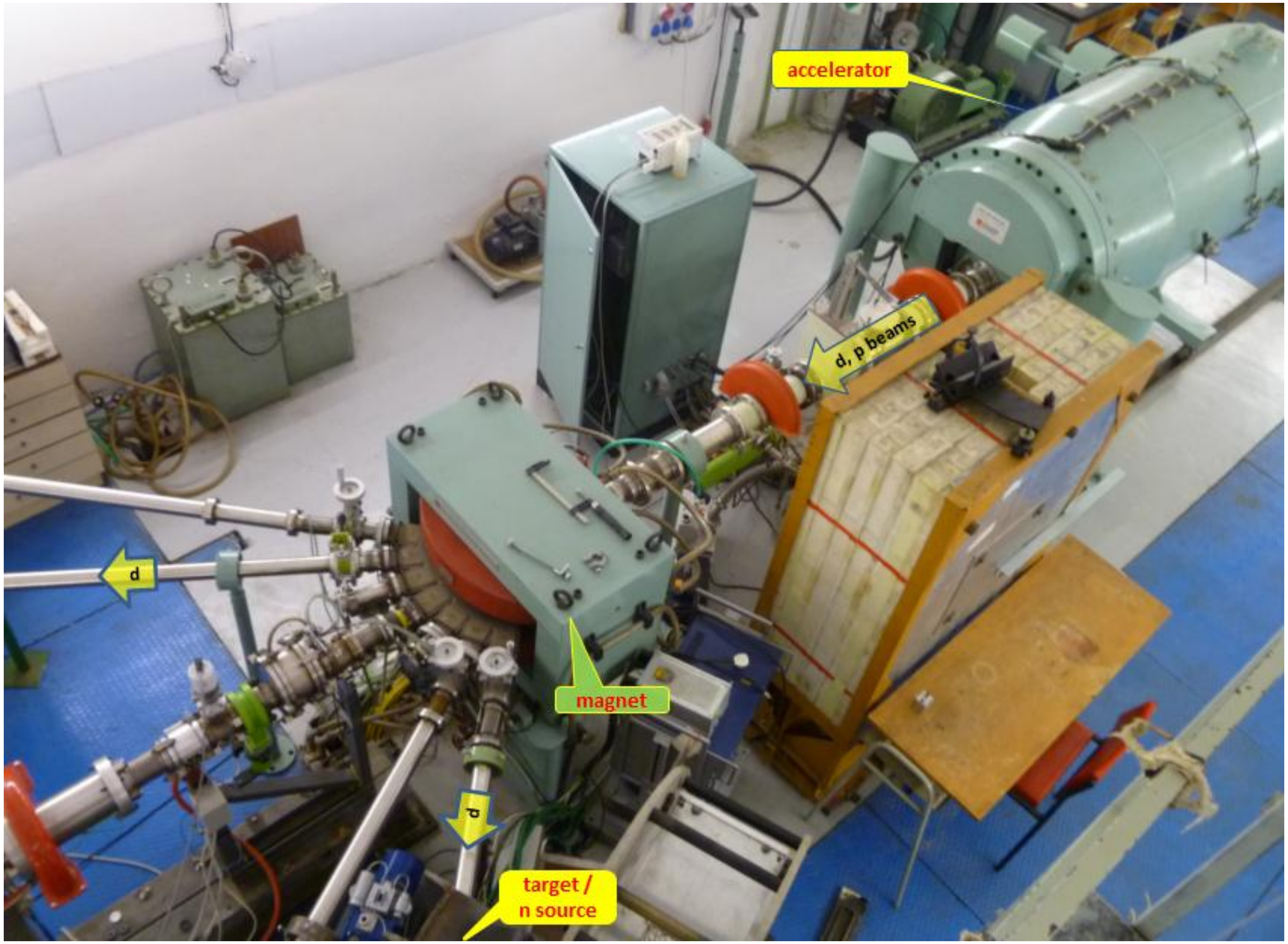


Total number of coincidences (2,3,4 det) : 23091
Total number of coincidences per hour (2,3,4 det) : 61.6
Total time: 15.6 days

Total number of coincidences in 4 detectors: 190 (0.82%)
Number of 4 coincidences per hour: 0.5

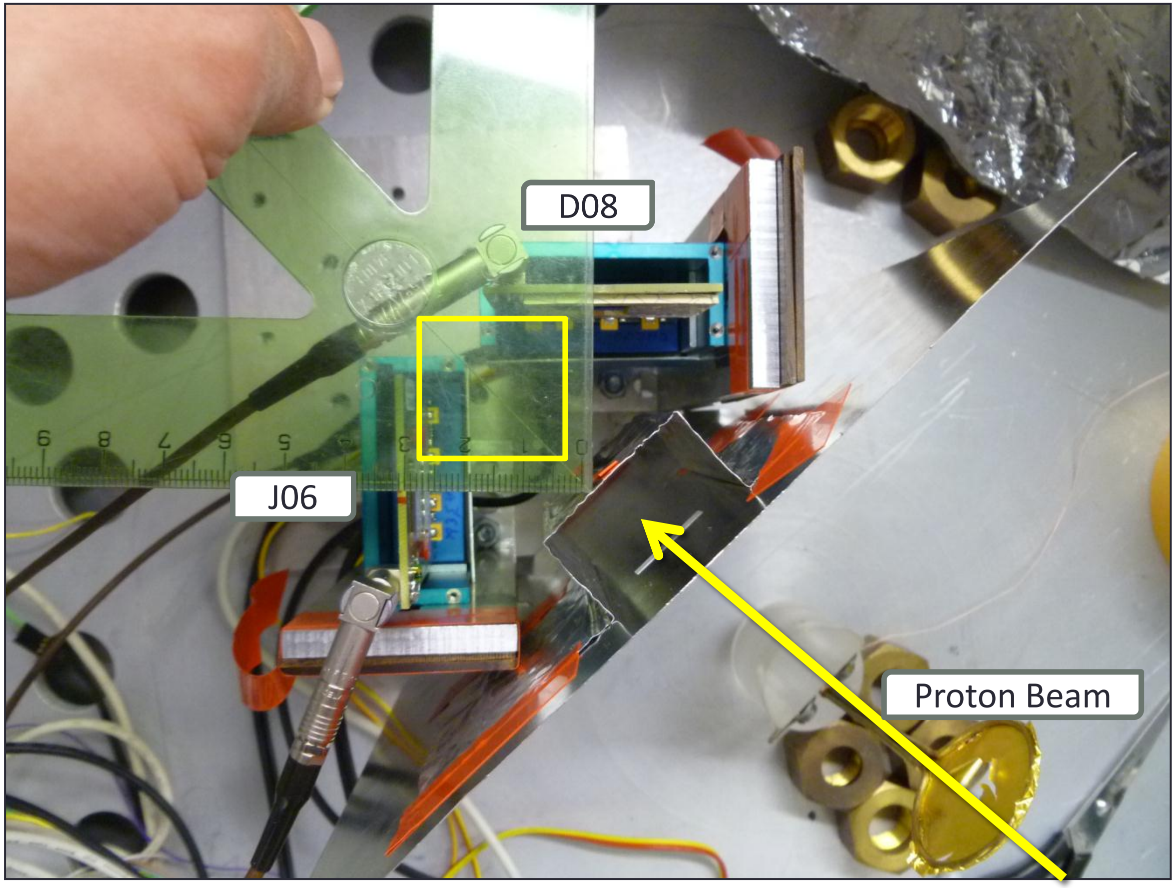


The IEAP VdG Accelerator



Energies (MeV): 0.3-2.5 MeV; **Current:** 0.5-50 µA
p,d,^{4}He; ^{3}He (future**)**
n (qm & monochromatic 40-60 keV, 4 MeV,15 MeV**)**

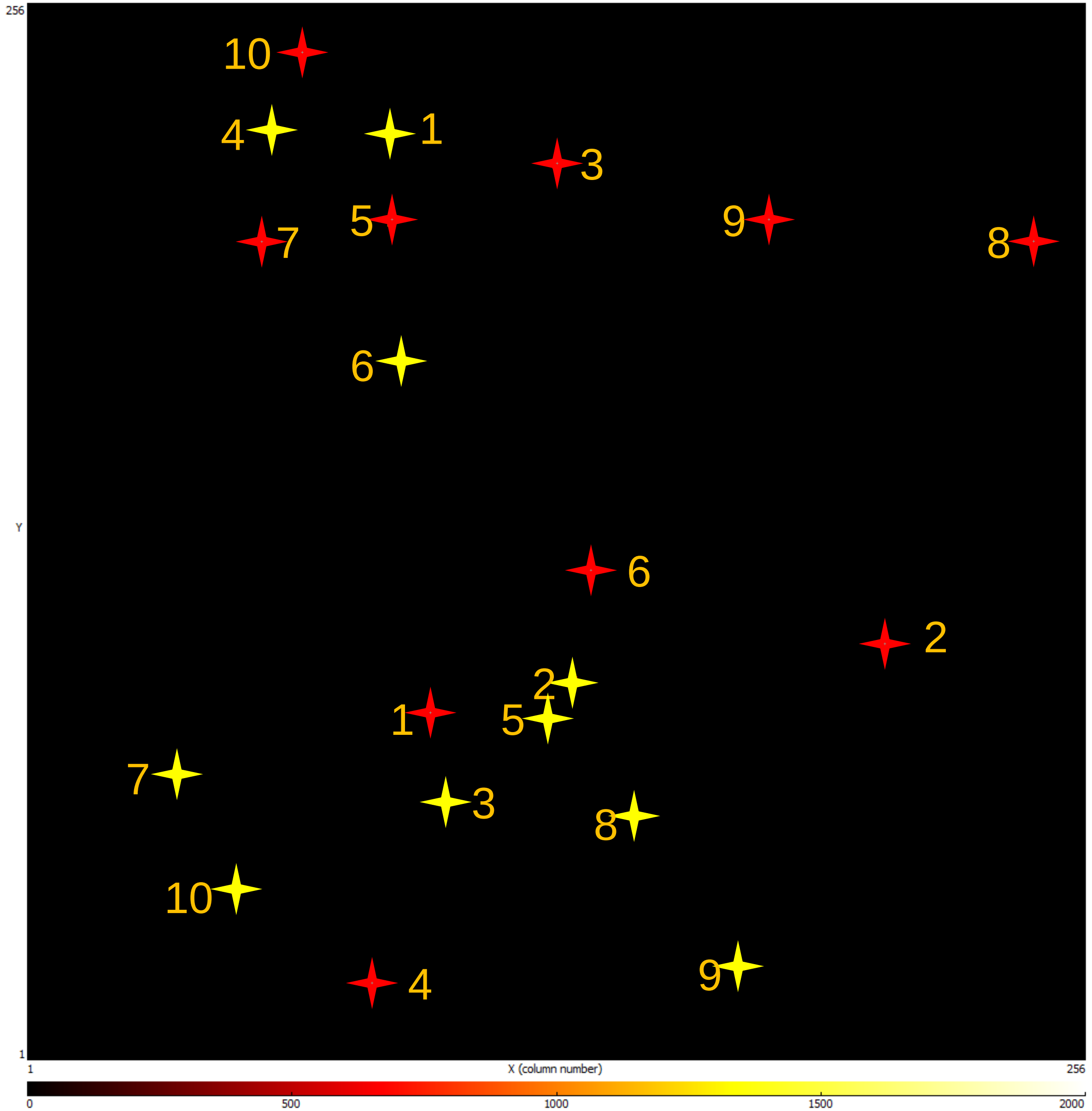
Analysis of measurements at the IEAP VdG Accelerator



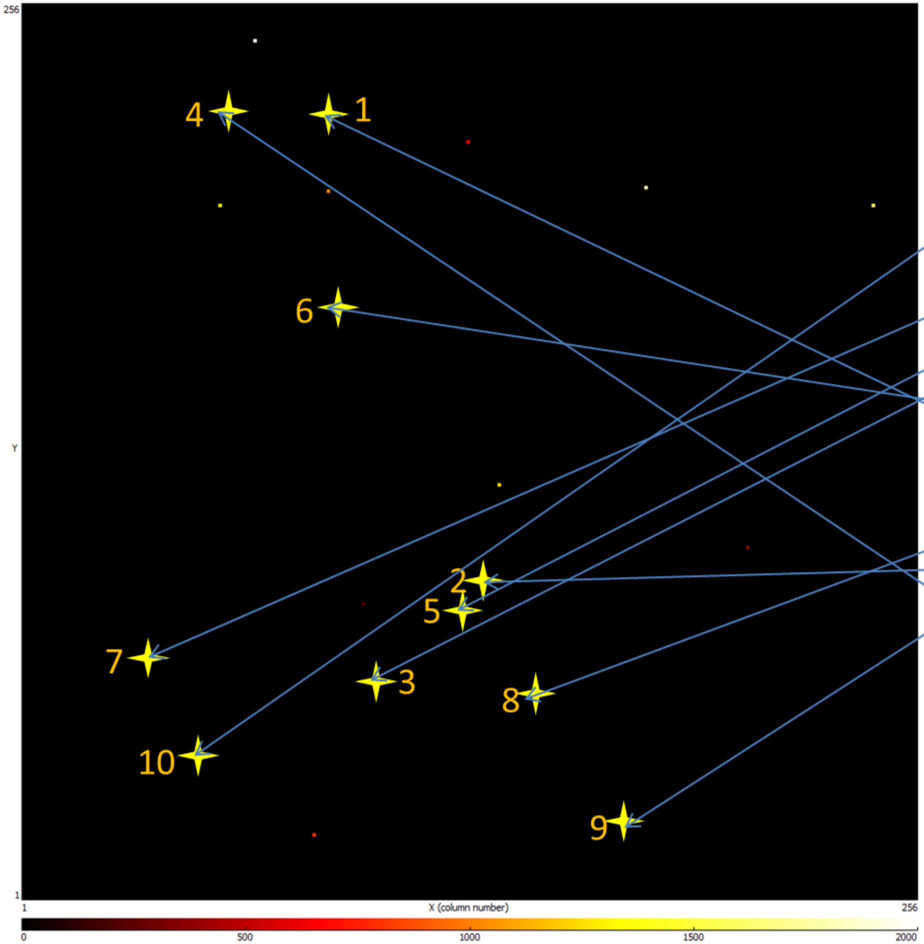
Proton-Proton Forward Scattering

Proton-Proton Forward Scattering: Time Mode Data Analysis

D08		J06	
x1	y1	x2	y2
98	85	88	224
208	101	133	93
128	217	102	63
84	19	59	226
126	83	88	203
137	119	92	170
57	199	37	70
244	199	148	60
179	204	173	23
67	246	52	42

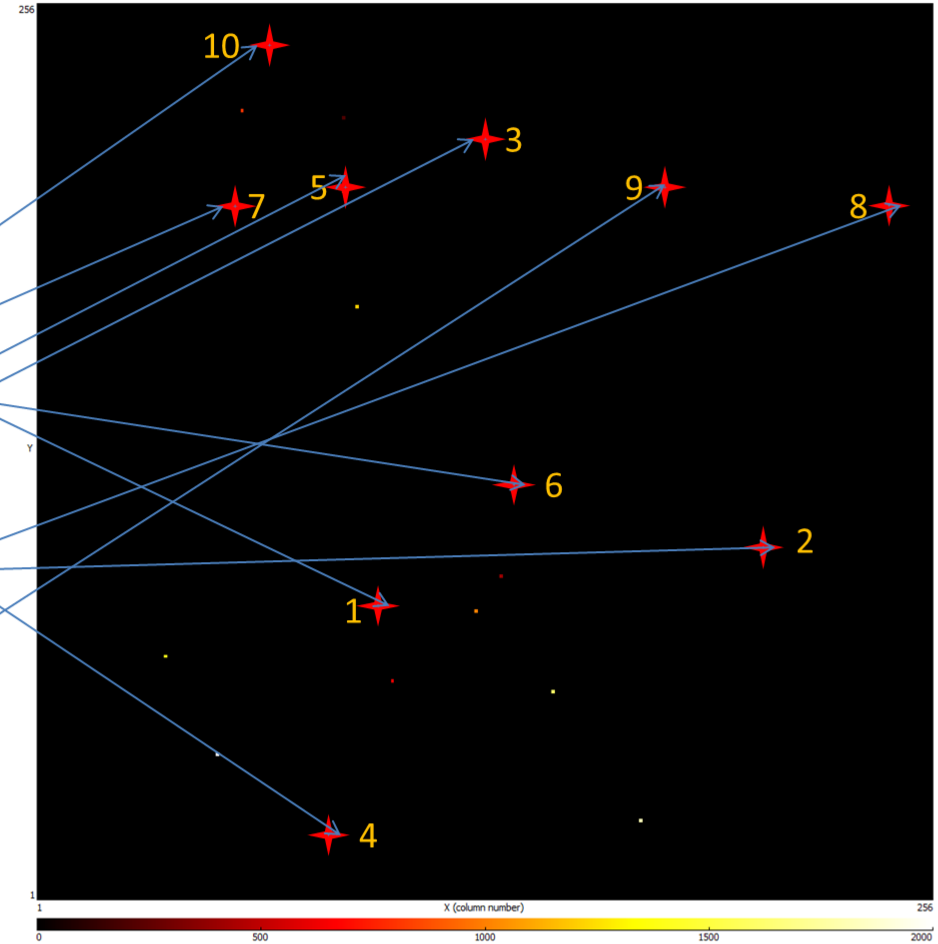


J06



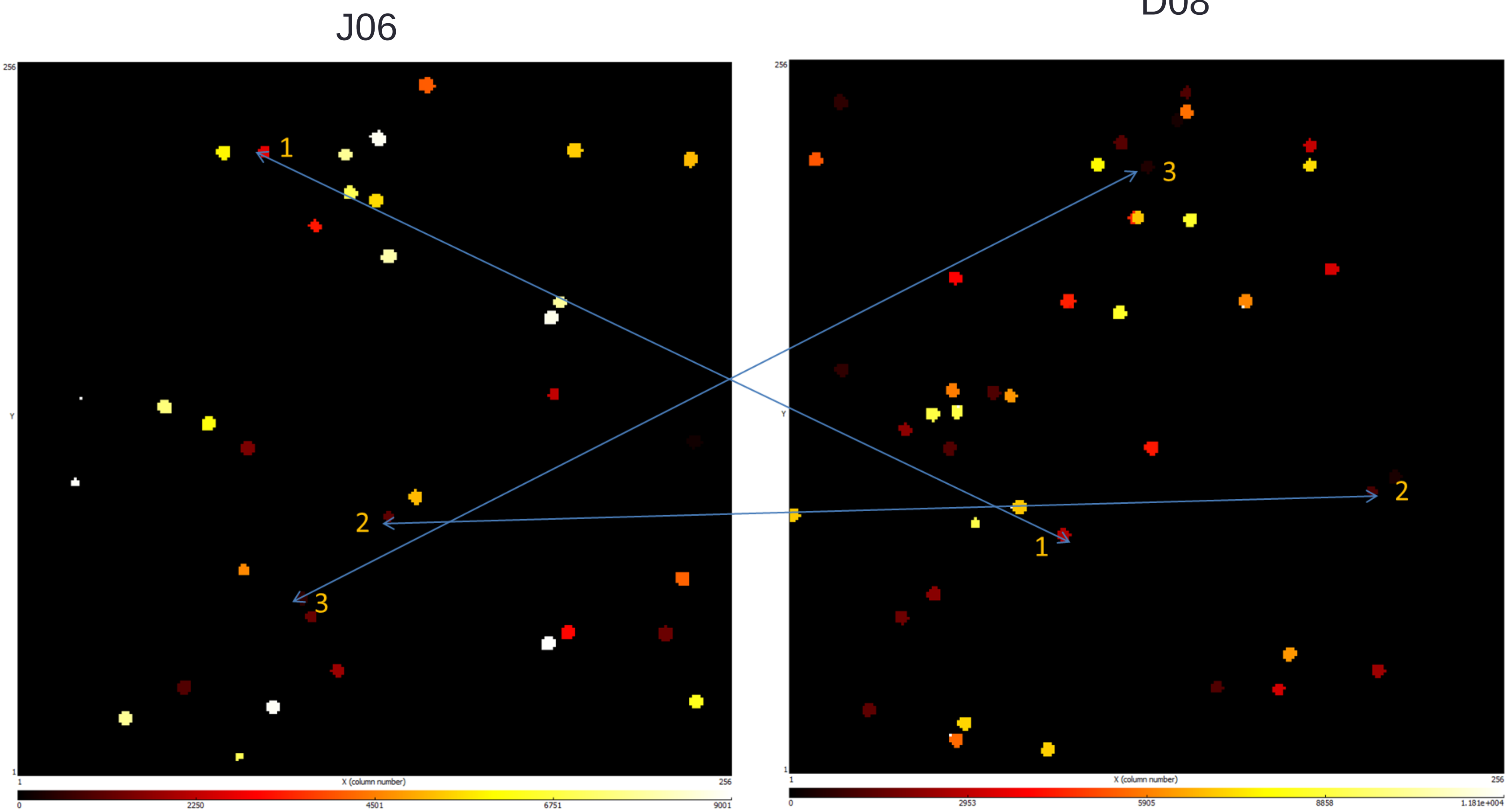
256
4
1
6
2
5
7
3
8
10
9
Y
1
X (column number)
256
0
500
1000
1500
2000

D08



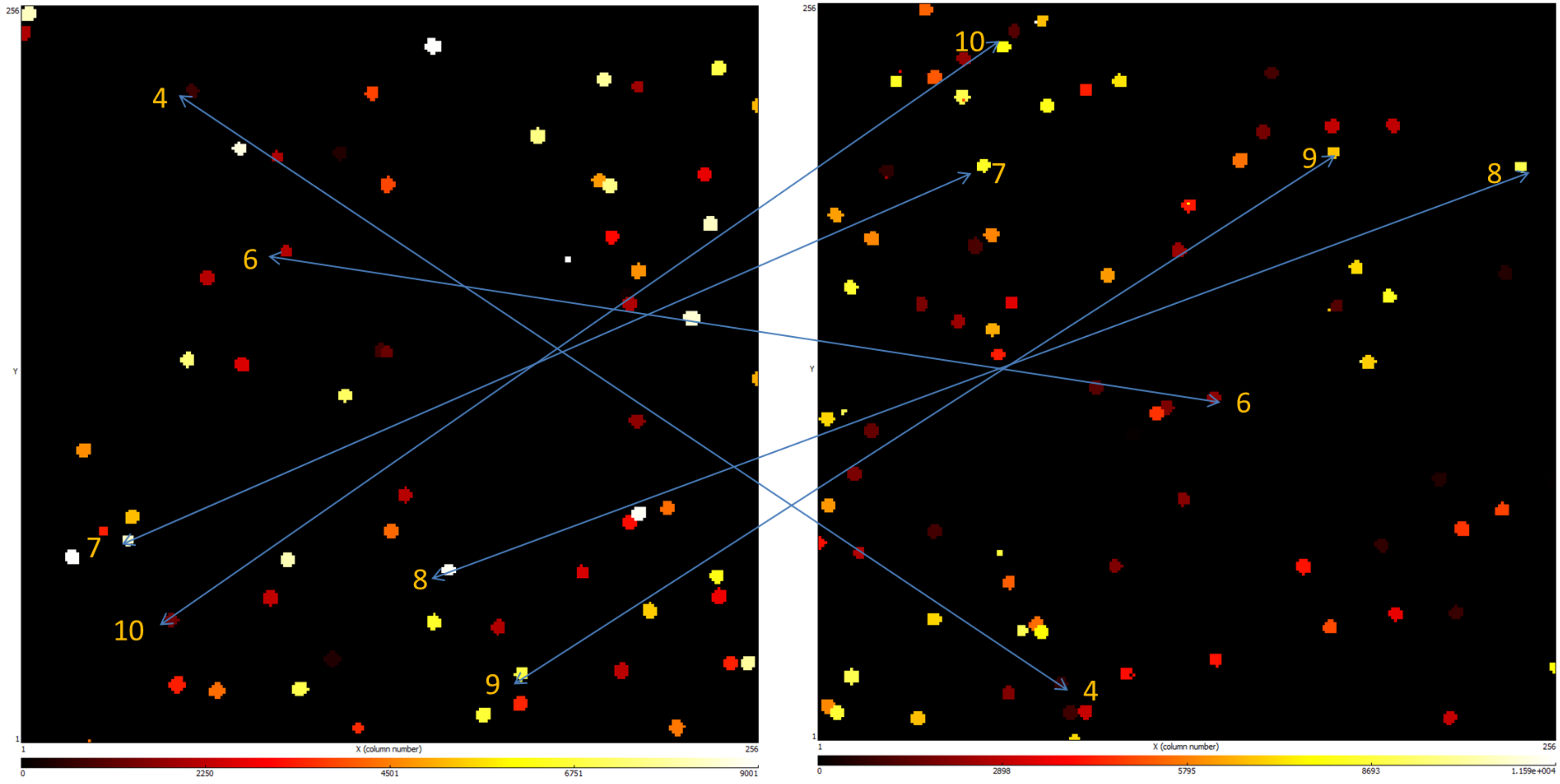
256
10
3
7
5
9
8
6
2
1
4
Y
1
X (column number)
256
0
500
1000
1500
2000

0000_TIM0000

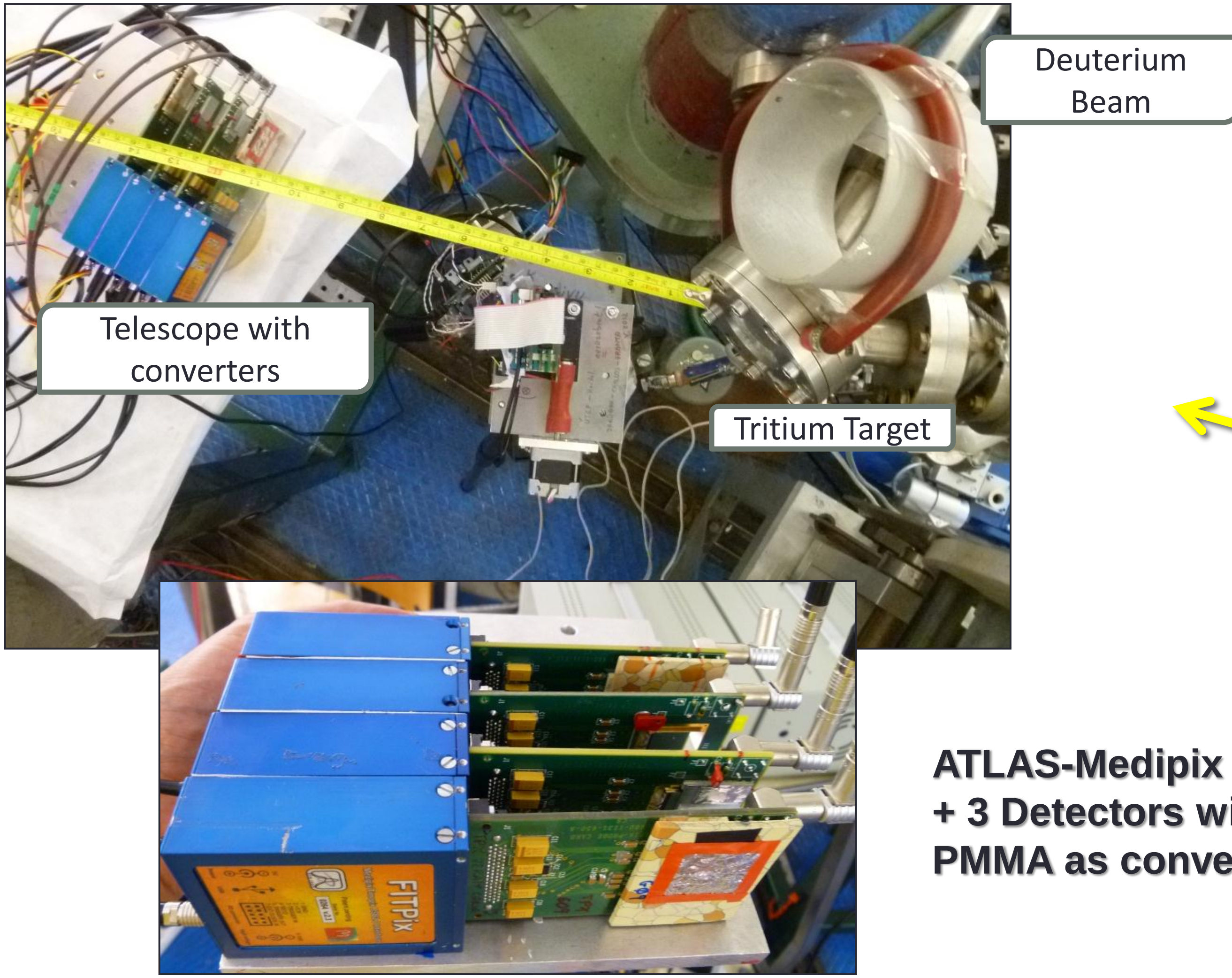


0000_TIM001

J06 D08



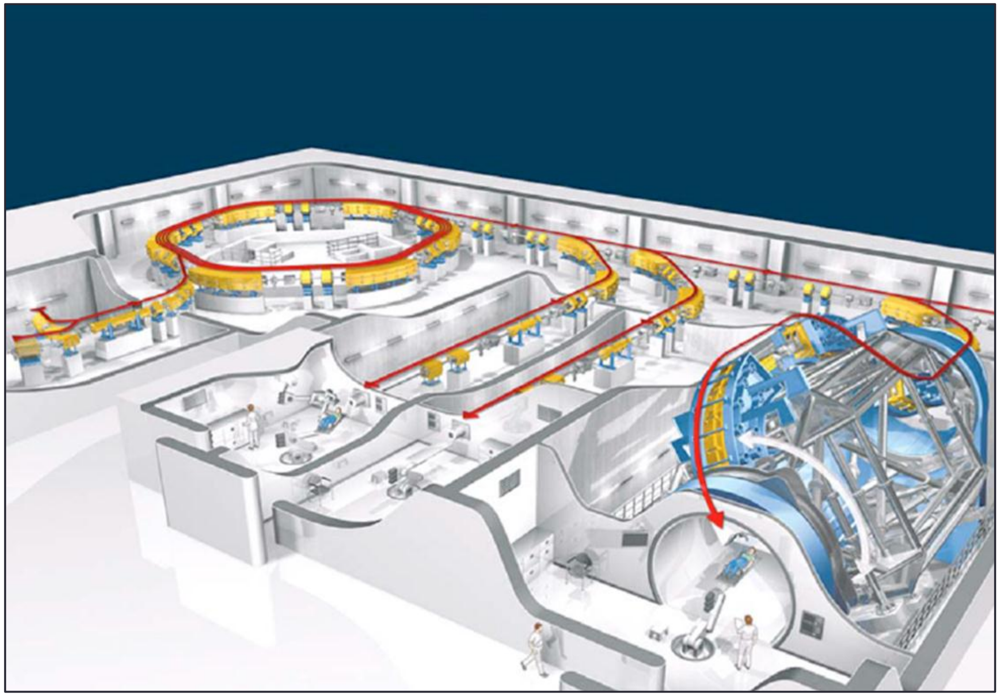
Deuterium (1 MeV) +Tritium ⟶ Neutrons (15 MeV)



ATLAS-Medipix Detector
+ 3 Detectors with a grid of PMMA as convertors

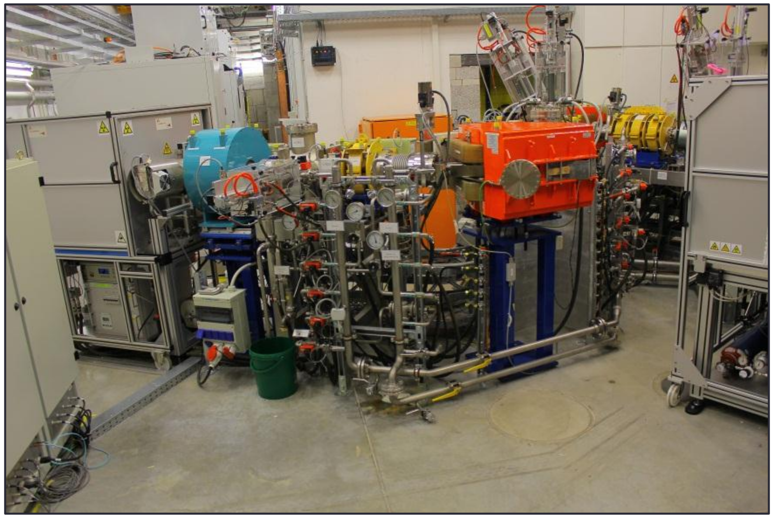
Acquisition of Hadron Therapy Data using arrays of Timepix Detectors

Heidelberg Ion Therapy Center

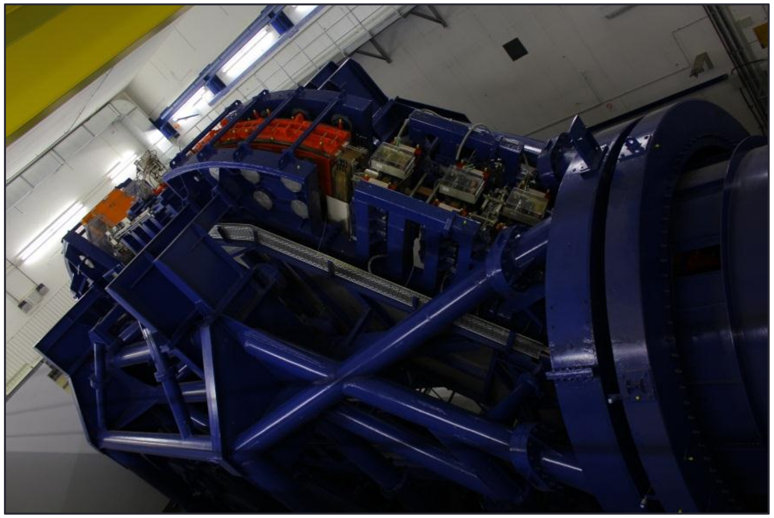


The Heidelberg Ion Therapy Center (HIT) is the world's first particle therapy facility for treatment with protons and carbon ions with a scanned beam delivery system, and the only one of its type in Europe. HIT uses a synchrotron to accelerate protons (up to 200 MeV), and carbon ions (or other ion species within research projects, up to 430 MeV/U).

Fully operational, patients are treated in two fixed beam treatment rooms and one carbon gantry room.

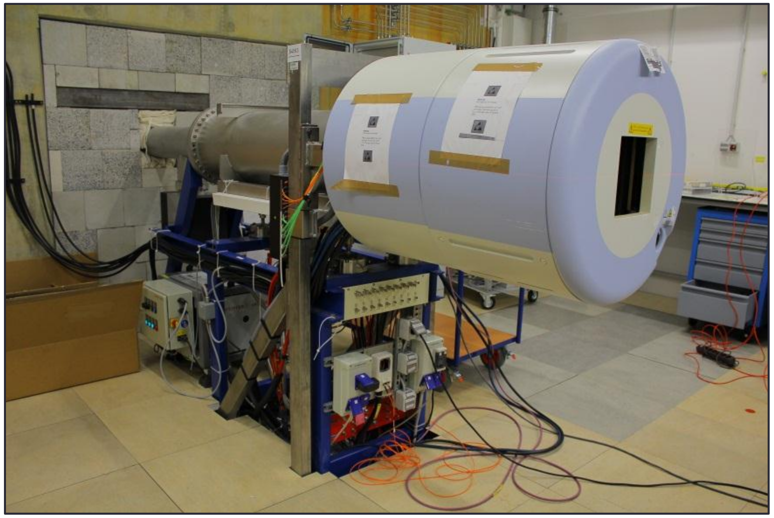


ECR PROTON / ION SOURCES



ION GANTRY

TREATMENT ROOM



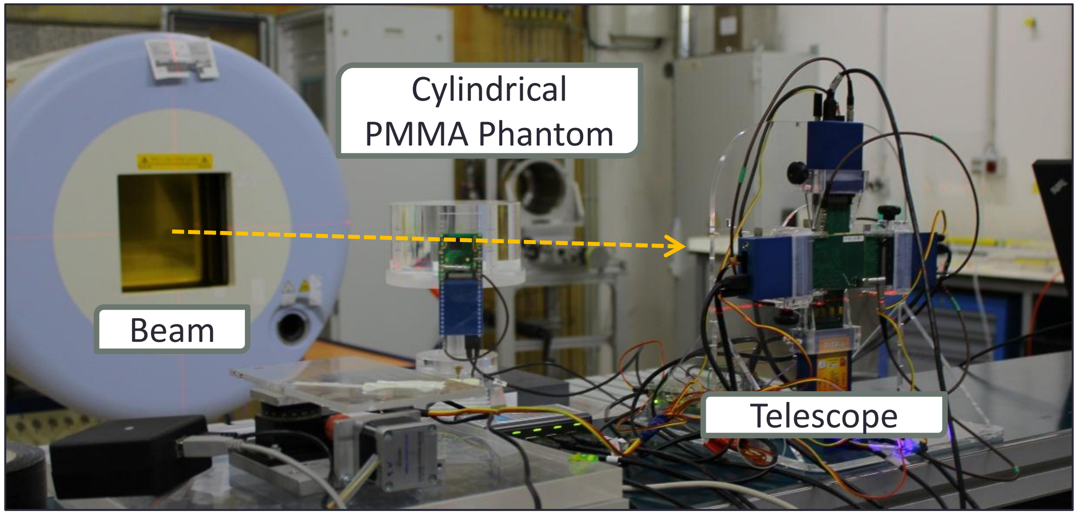
EXPERIMENTAL BEAM EXIT

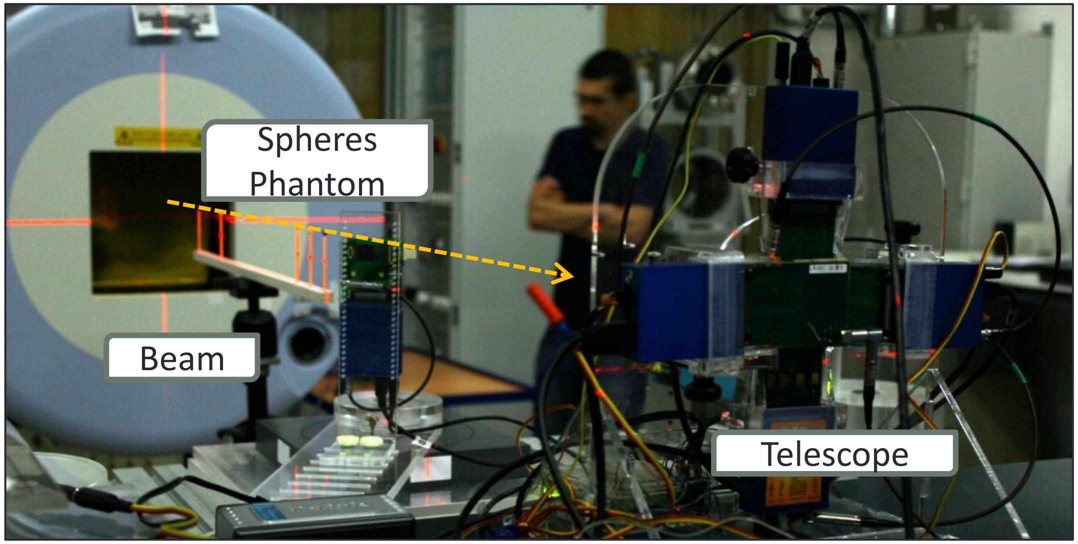
MAIN CONTROL ROOM

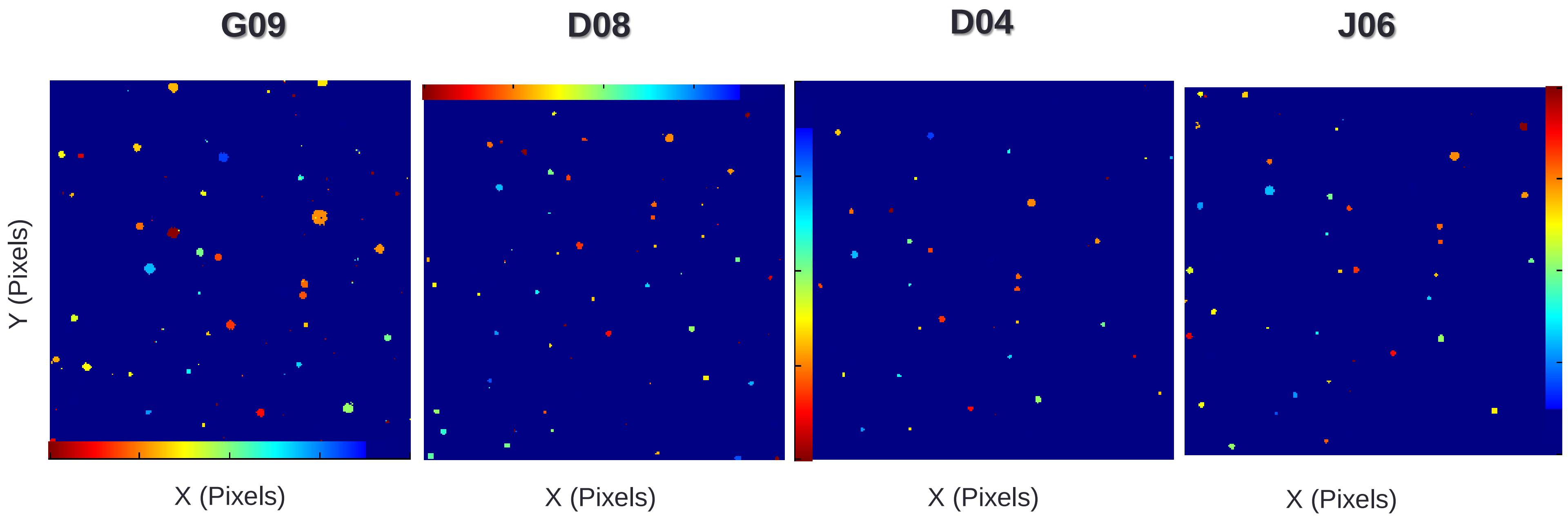
CONTROL ROOM FOR EXPERIMENTS

Shift 01: From Sunday 8th to Monday 9th. July 2012. HIT Heidelberg. (NOT tilted Telescope)

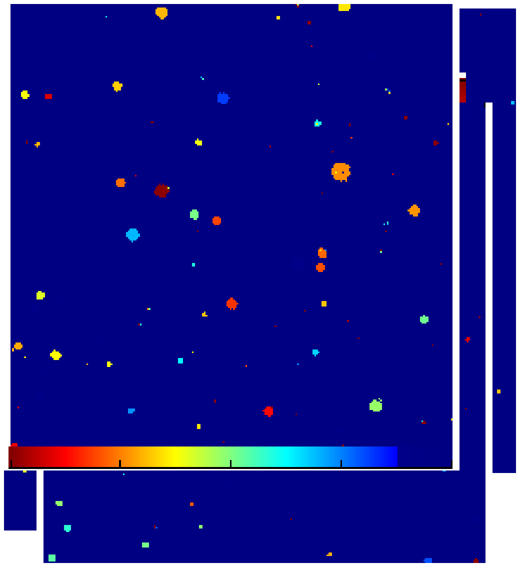
Setups.



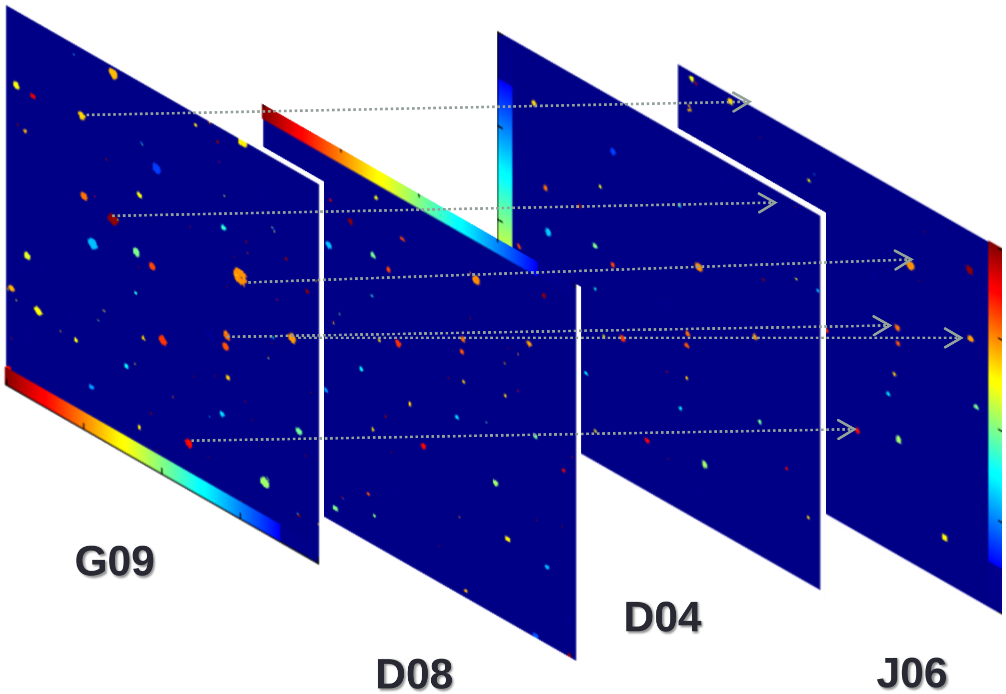




Example: 02/ 0001_Tim001.dat . Secondary products from a cylindrical phantom using a 225 MeV/U Carbon Beam



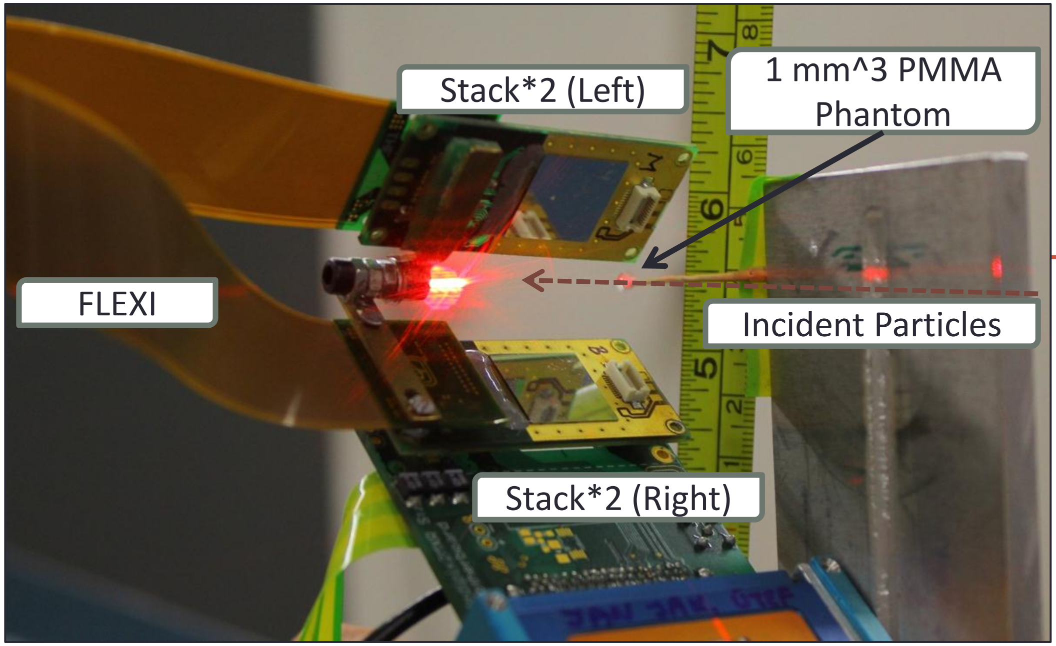
Example: 02/ 0001_Tim001.dat . Secondary products from a cylindrical phantom using a 225 MeV/U Carbon Beam

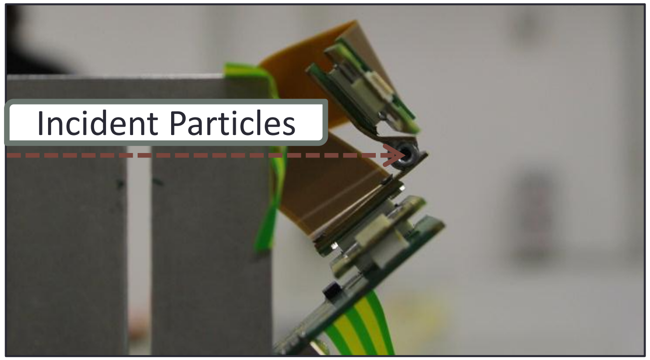


Example: 02/ 0001_Tim001.dat . Secondary products from a cylindrical phantom using a 225 MeV/U Carbon Beam

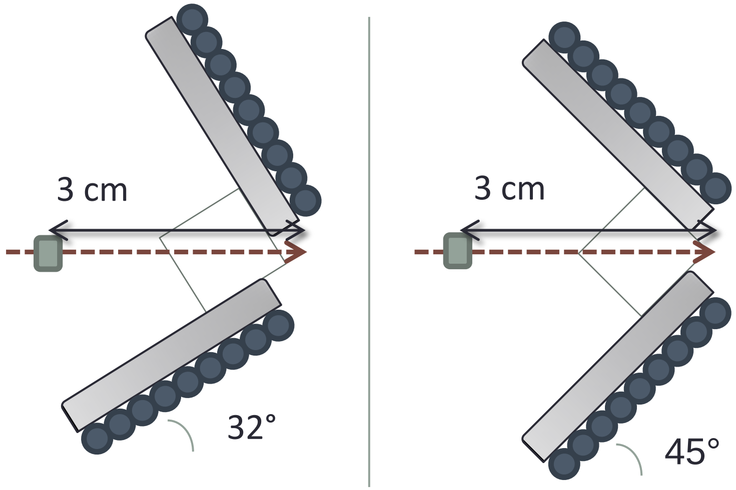
Shift 02: From Monday 9th to Tuesday 10th. July 2012. HIT Heidelberg. (Stack*2 + FLEXI)

Tiled*2 + FLEXI.

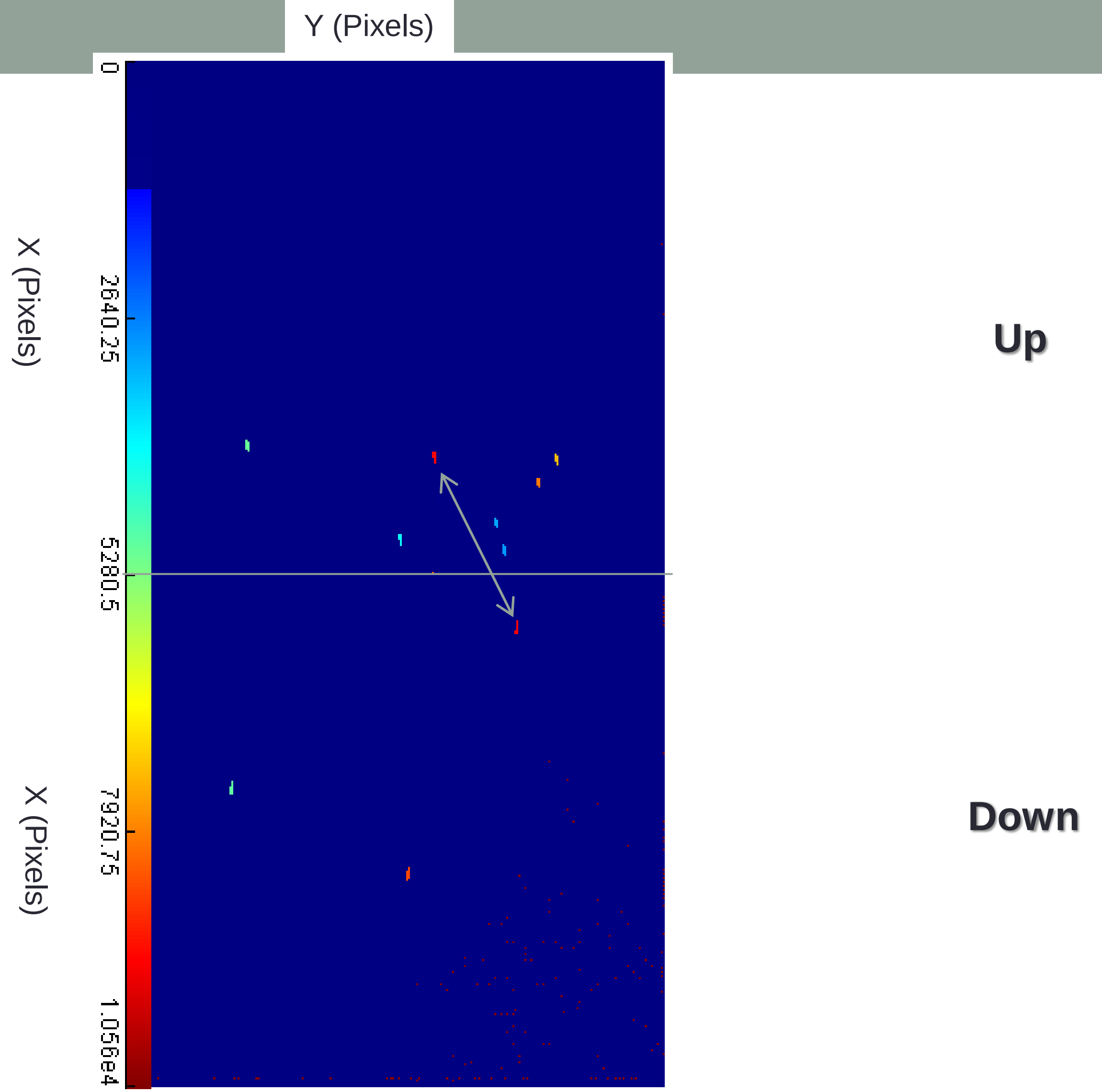




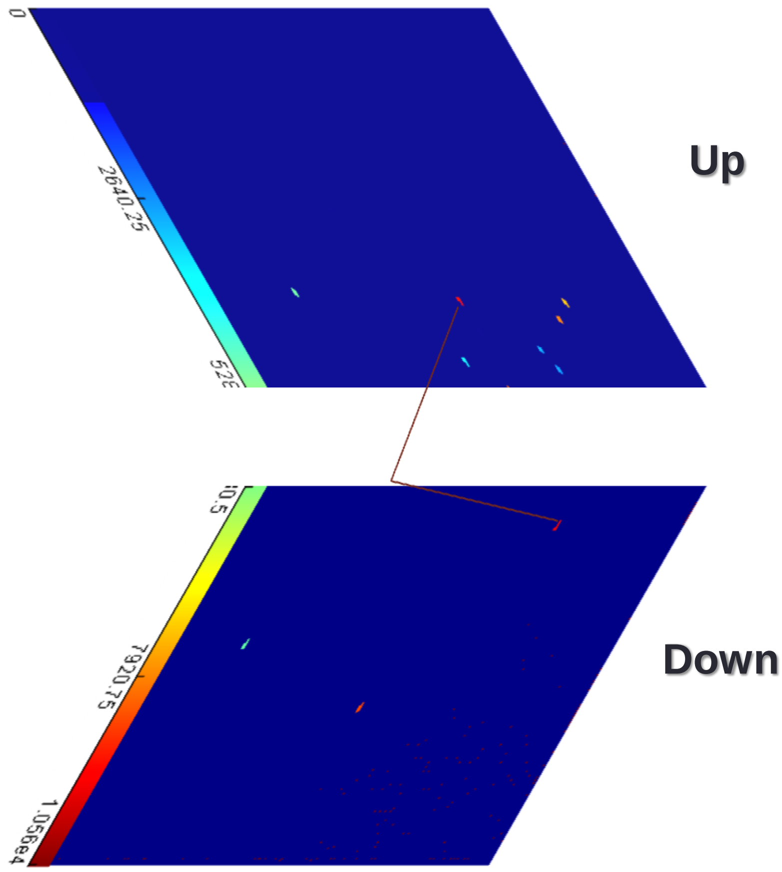
Side View



01/ 02/



Example: 02/ 0003_Tim004.dat . Secondary products from a 1 mm^3 PMMA Phantom using a 221 MeV Proton Beam

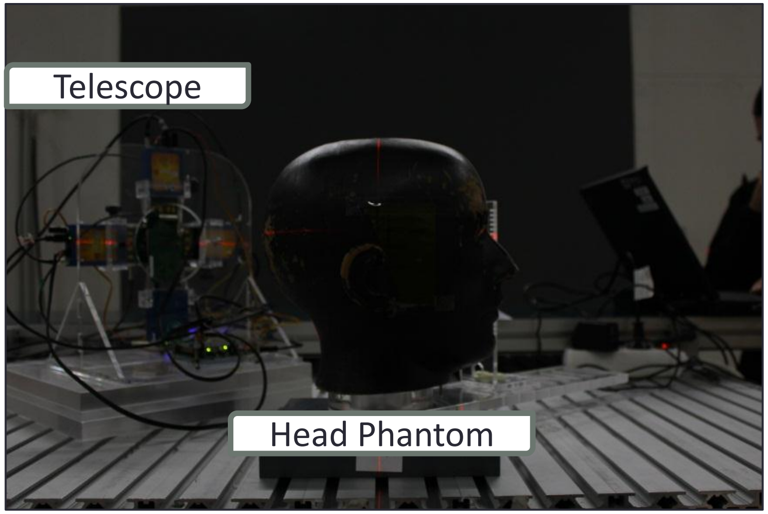


Example: 02/ 0003_Tim004.dat . Secondary products from a 1 mm^3 PMMA Phantom using a 221 MeV Proton Beam

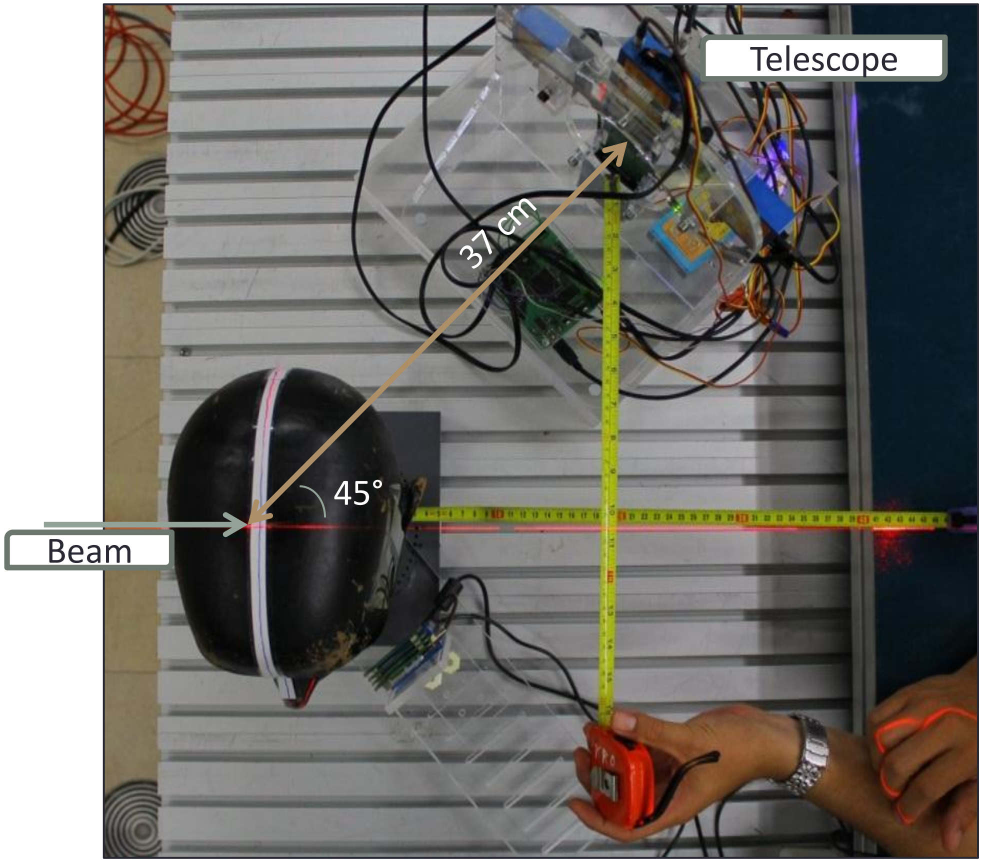
Shift 03: From Tuesday 10th to Wednesday 11th. July 2012. HIT Heidelberg. (NOT Tilted Telescope)

Setups.

View from the beam

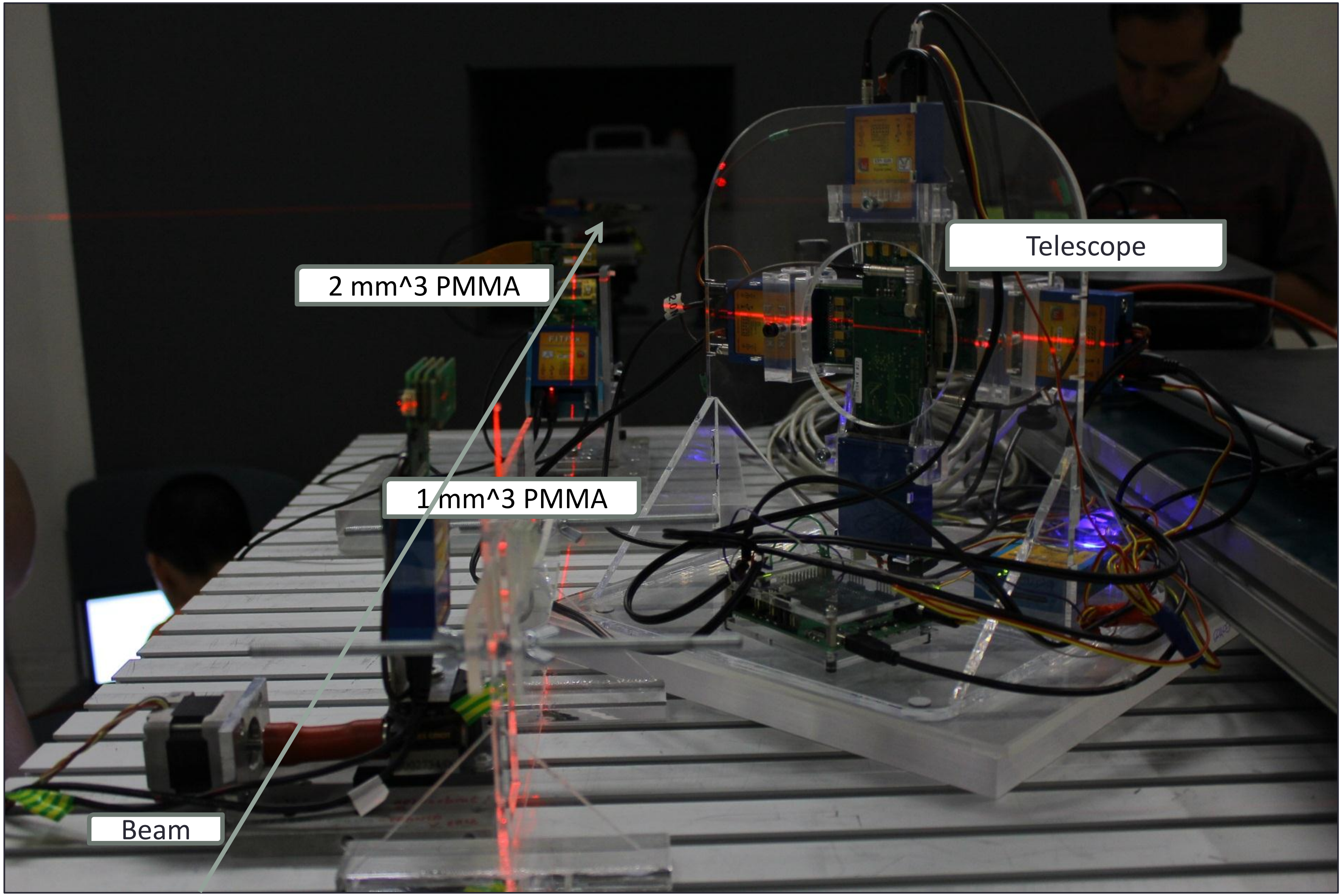


View from the top



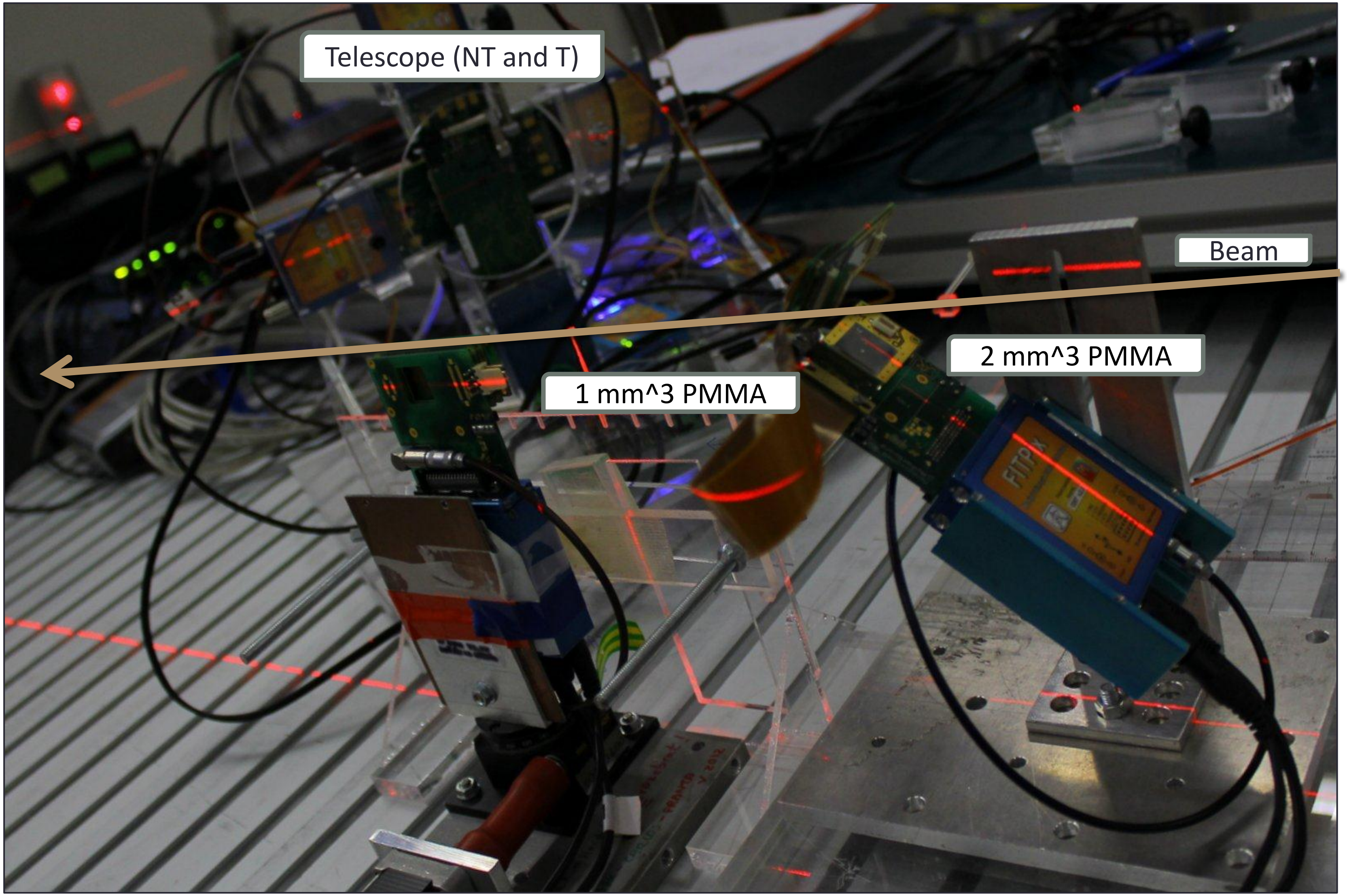
Shift 04: Wednesday Night 11th. July 2012. HIT Heidelberg.
(NOT Tilted Telescope, and Tilted Telescope)

Setups (01).



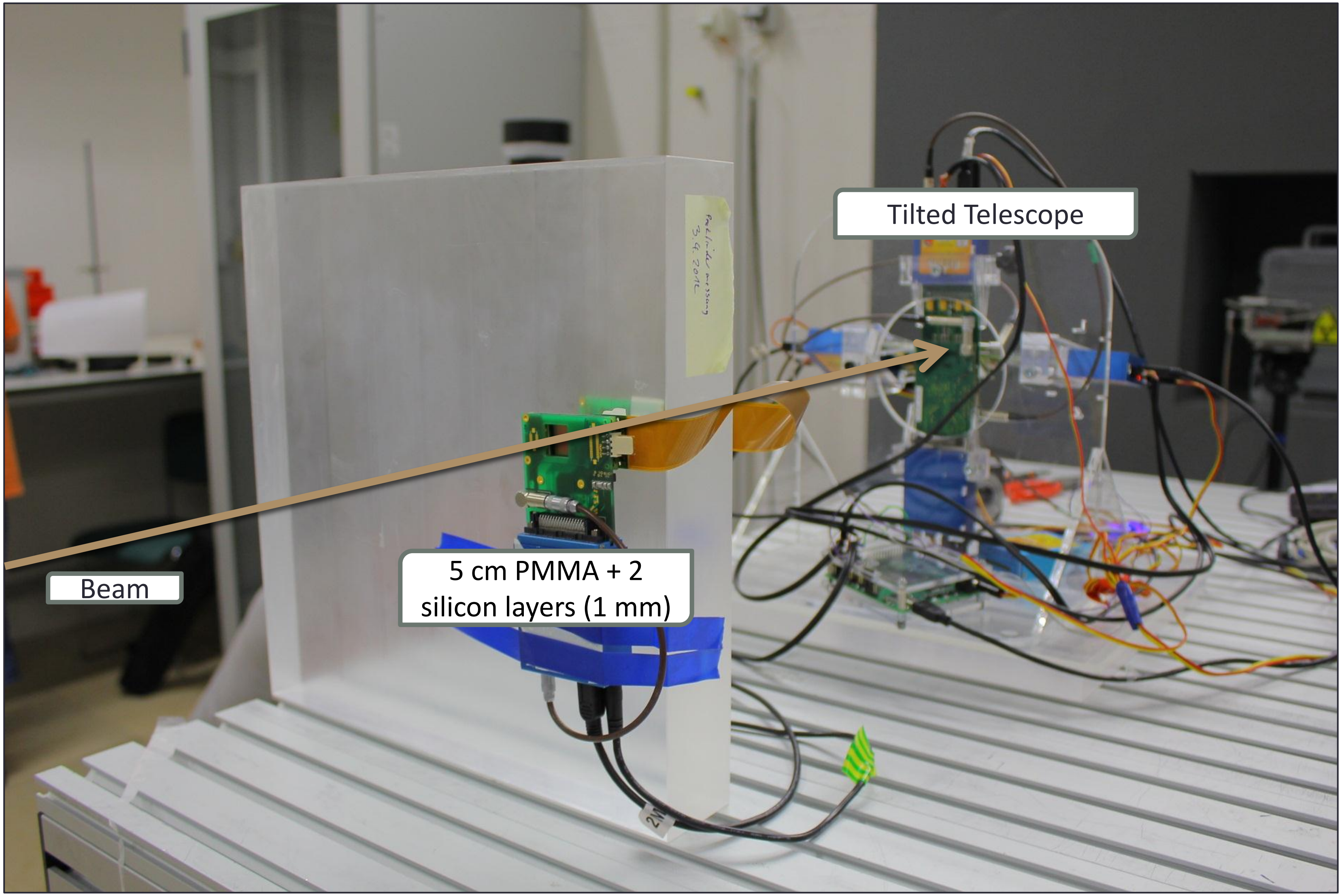
Shift 04: Wednesday Night 11th. July 2012. HIT Heidelberg.
(NOT Tilted Telescope, and Tilted Telescope)

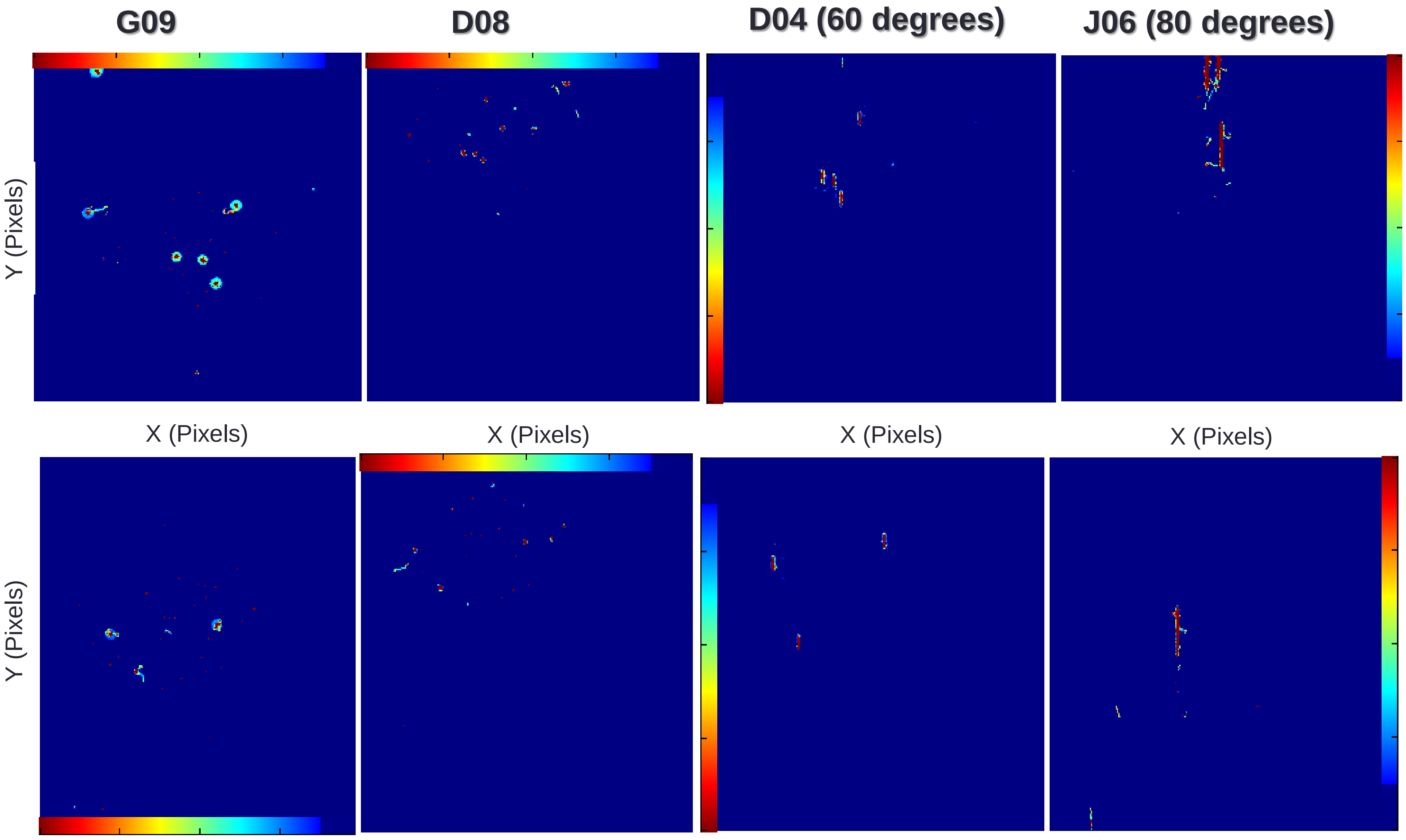
Setups (02-07).



Shift 04: Wednesday Night 11th. July 2012. HIT Heidelberg.
(NOT Tilted Telescope, and Tilted Telescope)

Setups (08-10).

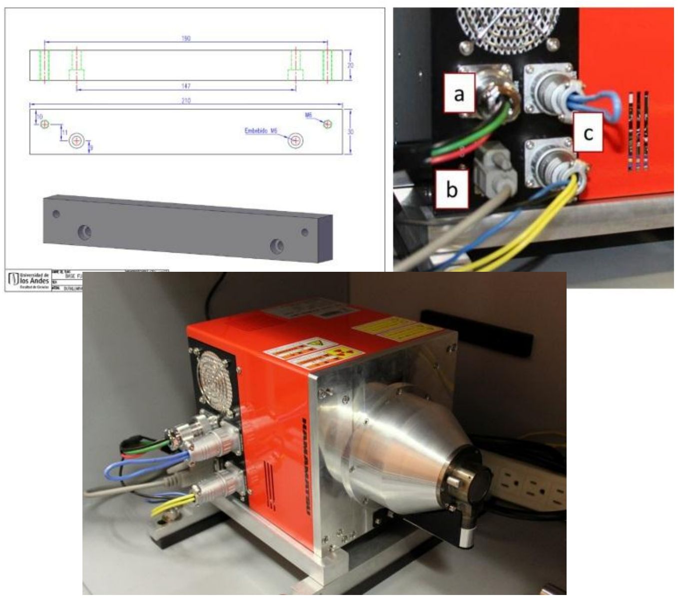




Example: 06/ 0001_Tim999.dat 0002_Tim001.dat . Secondary products from a two PMMA cubic phantoms using a 430 MeV/U Carbon Beam at low intensities

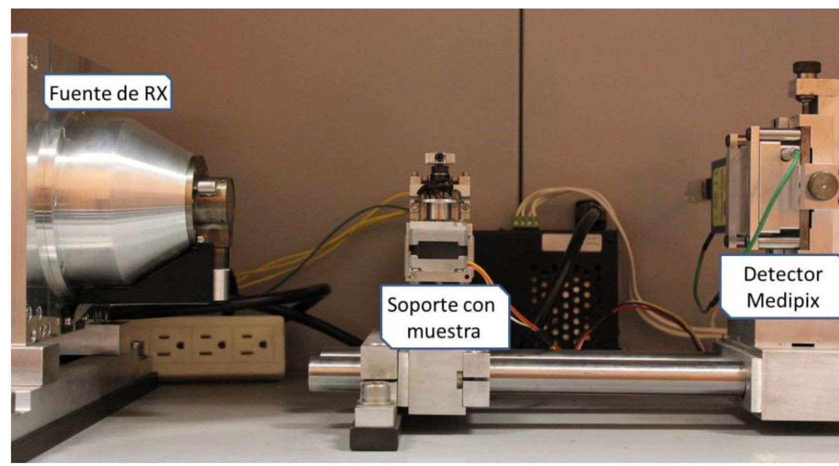
X-Ray Imaging / Micro-CT

Status of the setup at UniAndes

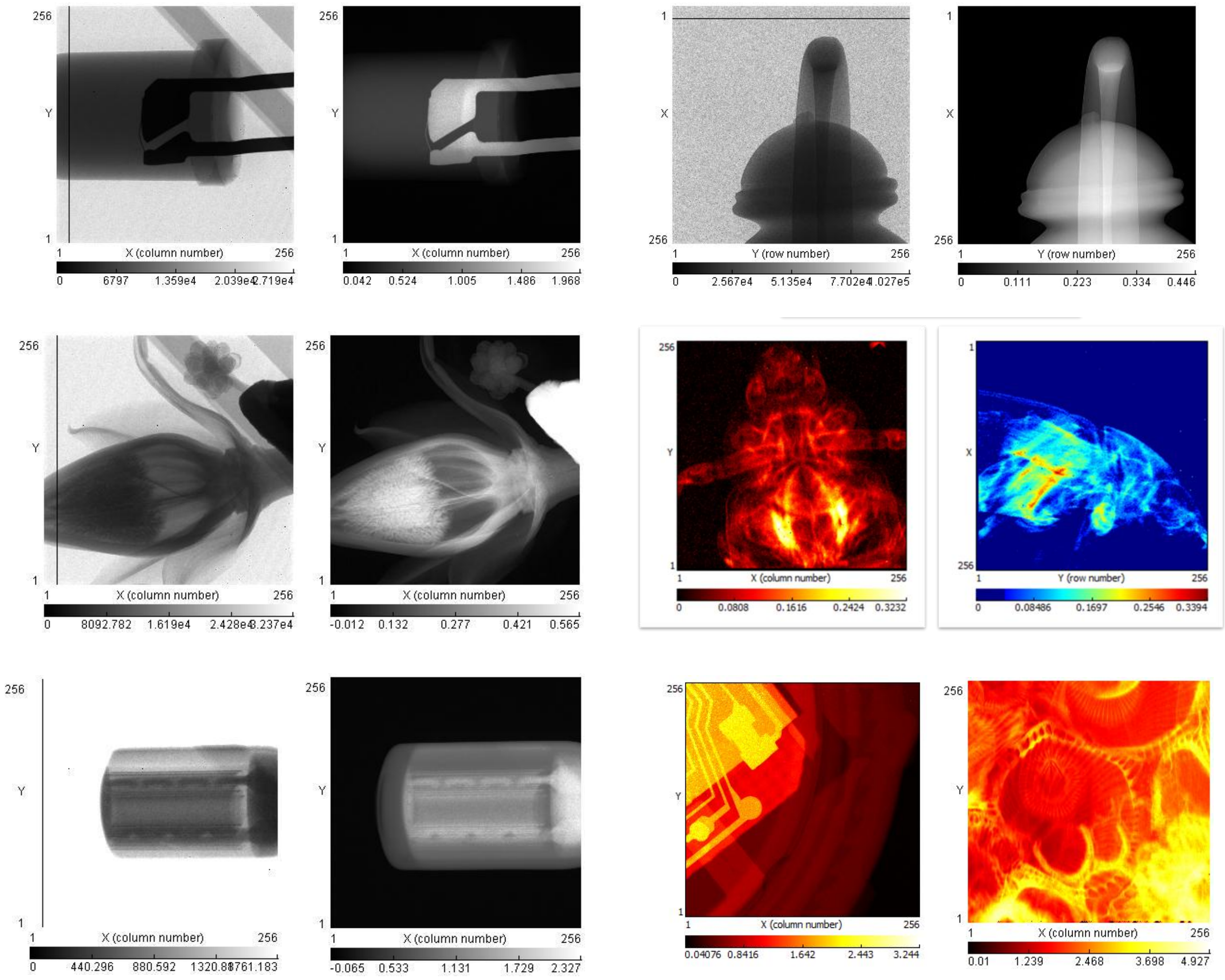


Microfocus X-Ray Source Installed

Functional setup at the laboratory

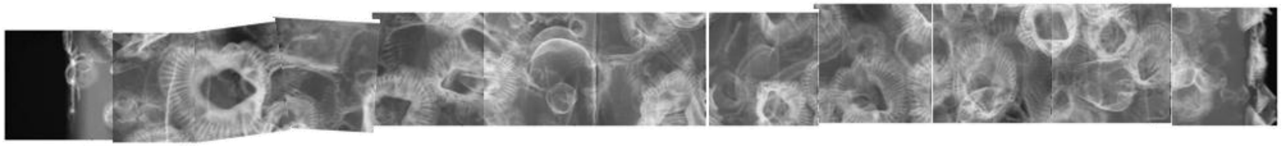


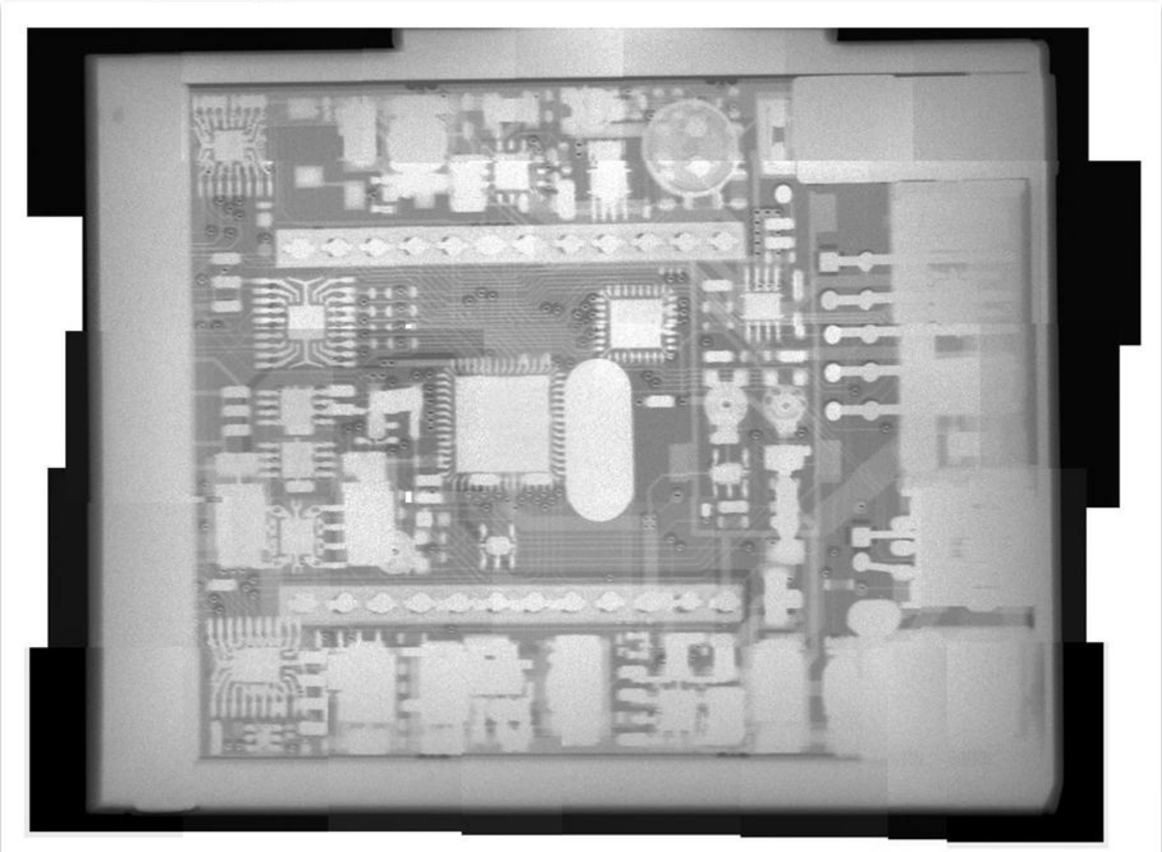
Corrected Images with BH

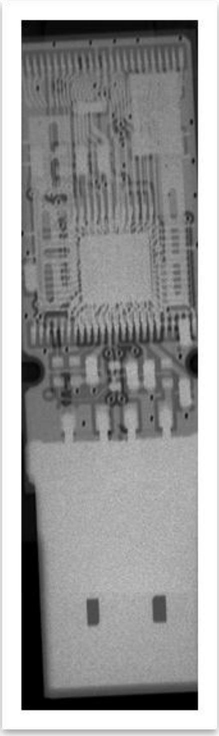


Corrected Images with BH

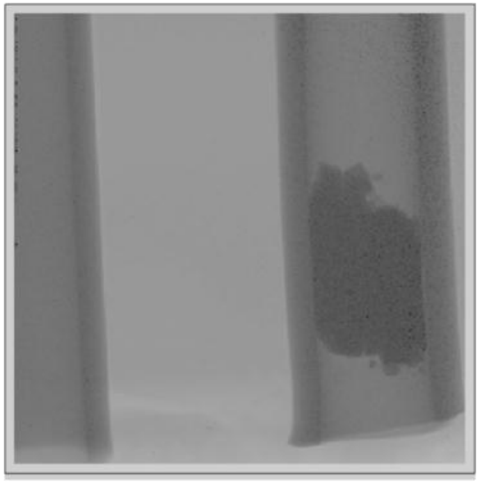
Obtención de imágenes corregidas con un área superior al tamaño del detector.

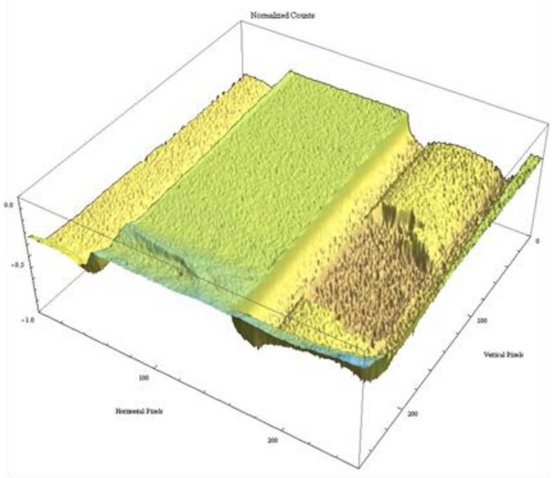


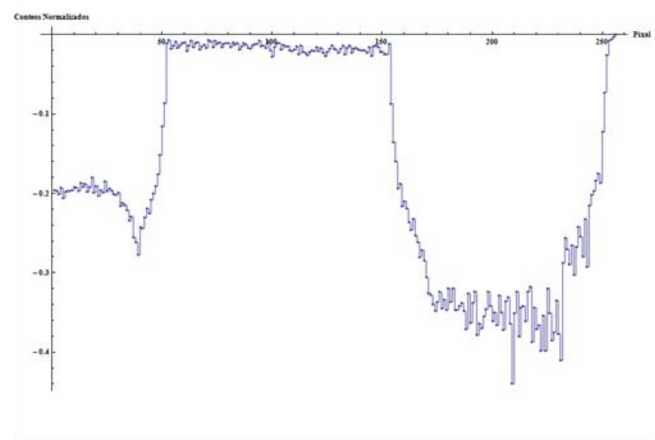




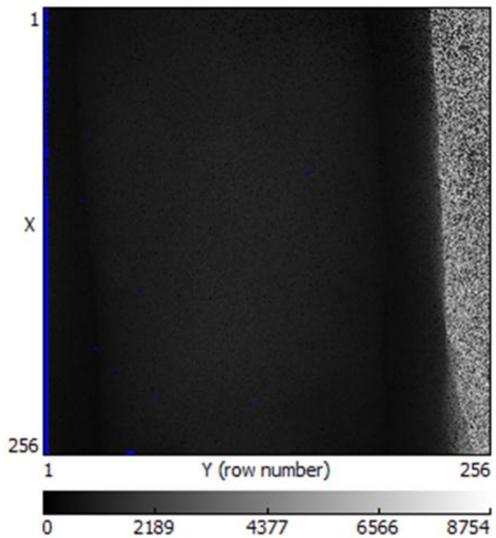
Imaging of nanoparticles as contrast agents (Col. With Ph.D. Manu Forero and Ch. Eng. Students):

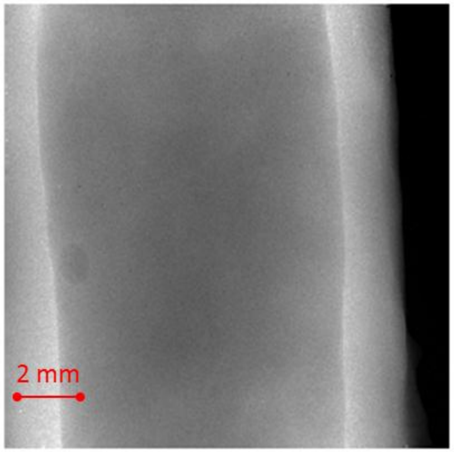


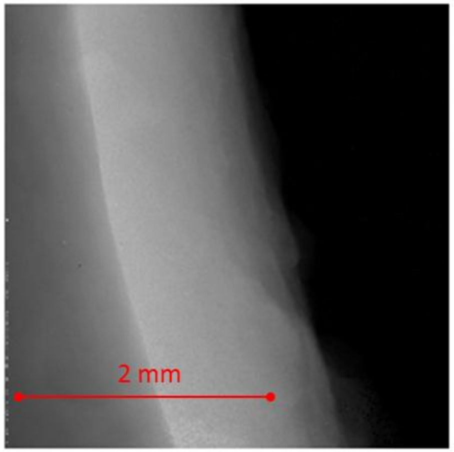




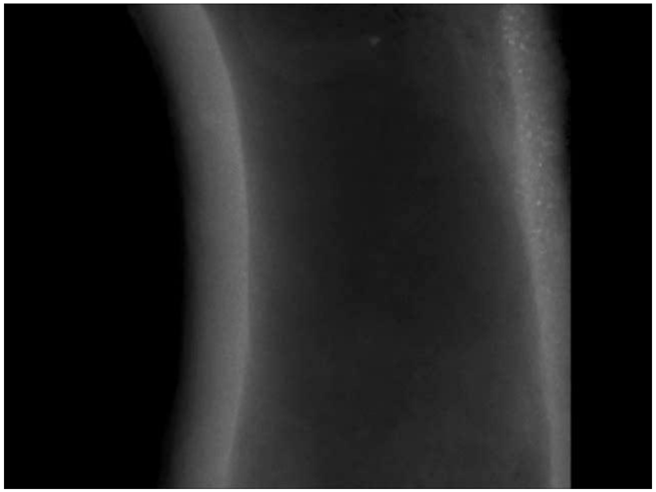
Micro-Imaging of carotids (Col. With Ph.D. Marcela Hernández, IMAGINE Group):



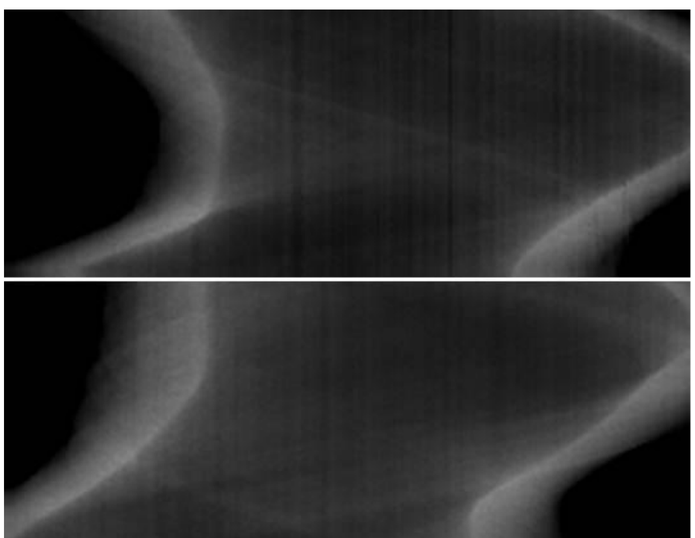


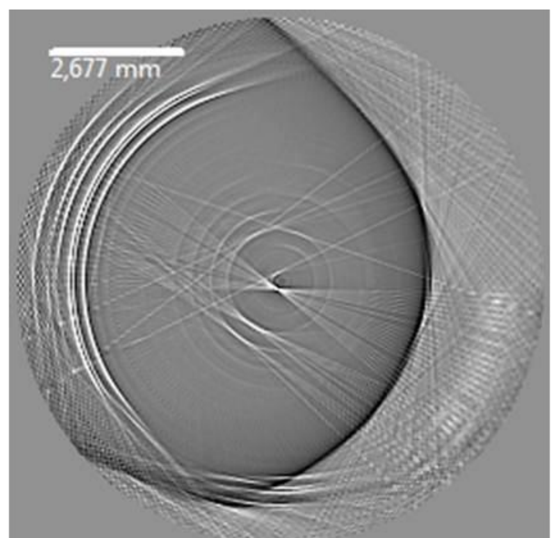


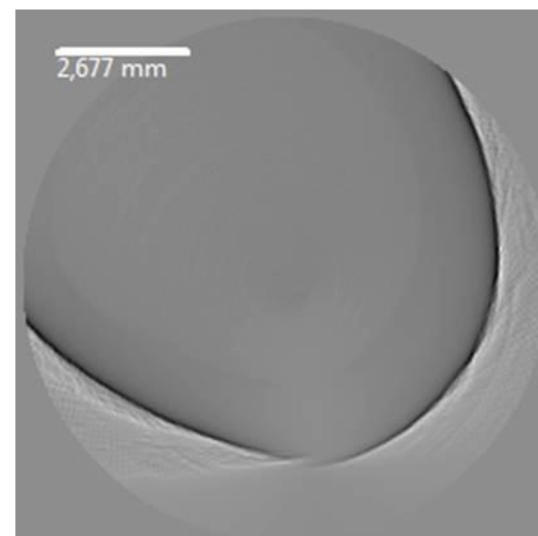
Computed Micro-Tomographies:



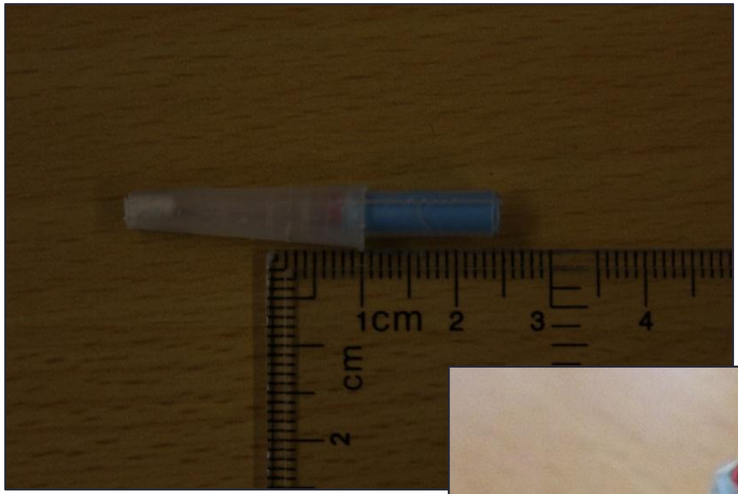
The software Octopus3D is installed and working at the laboratory, but there are issues with the alignment between the source, sample and detector, and the reconstruction might be also having fake artifacts due to pixels not working correctly.

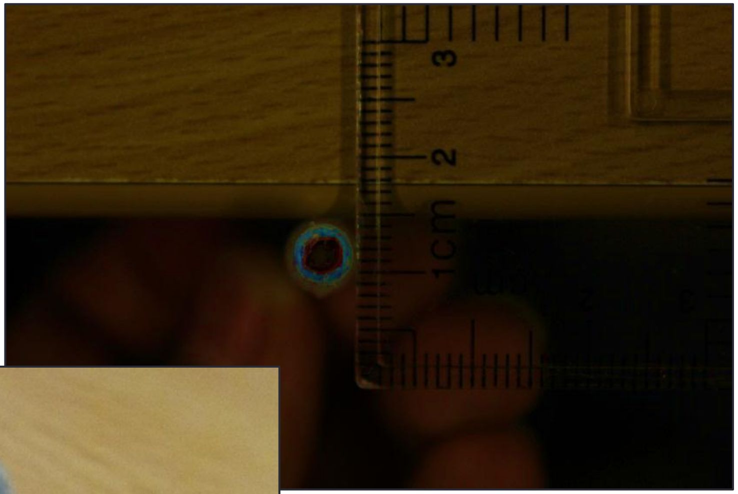


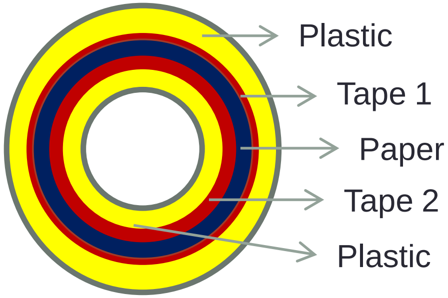




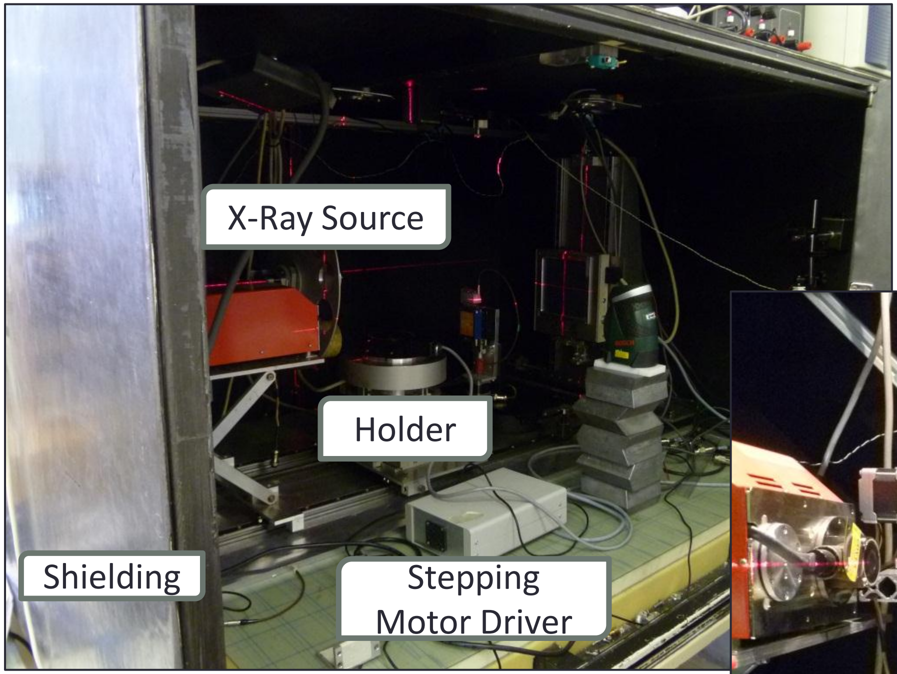
Reconstruction of bloodvessel-like phantom

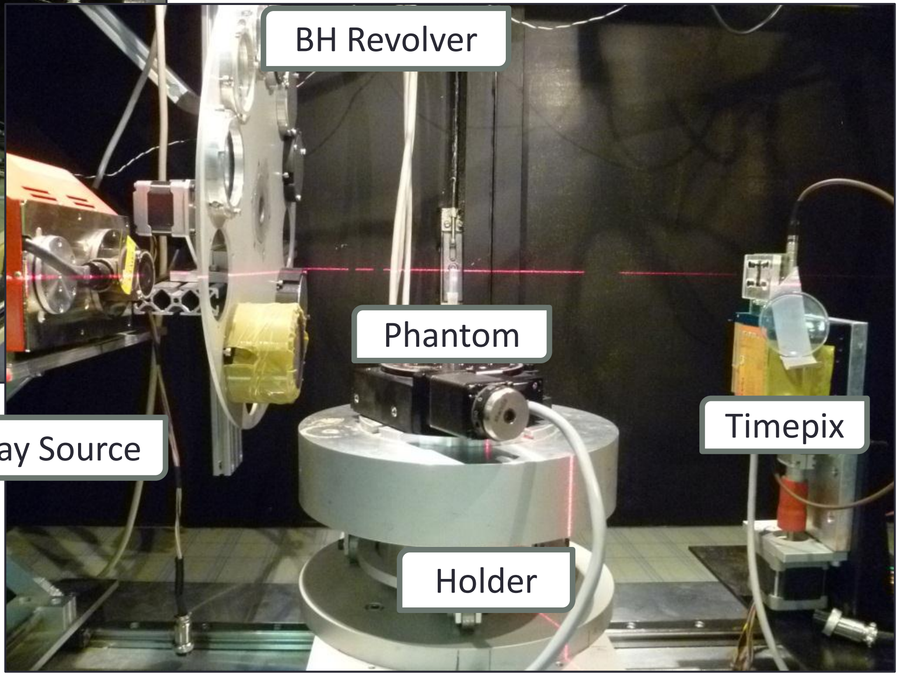




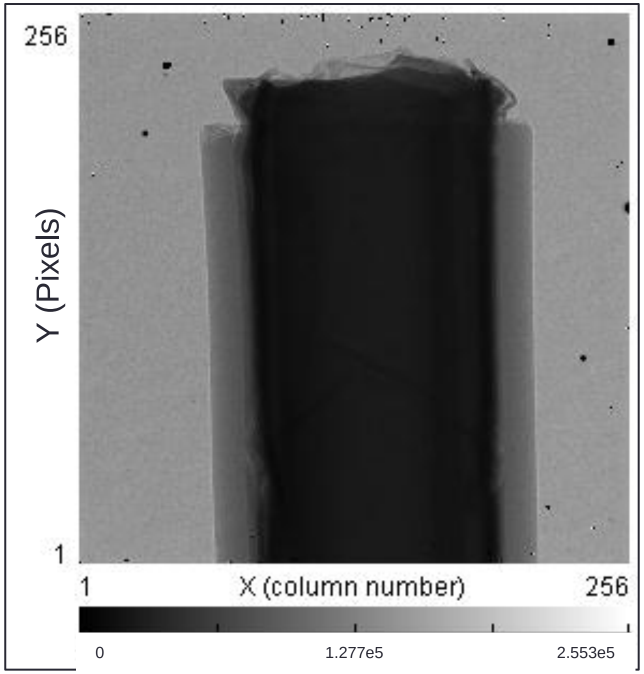


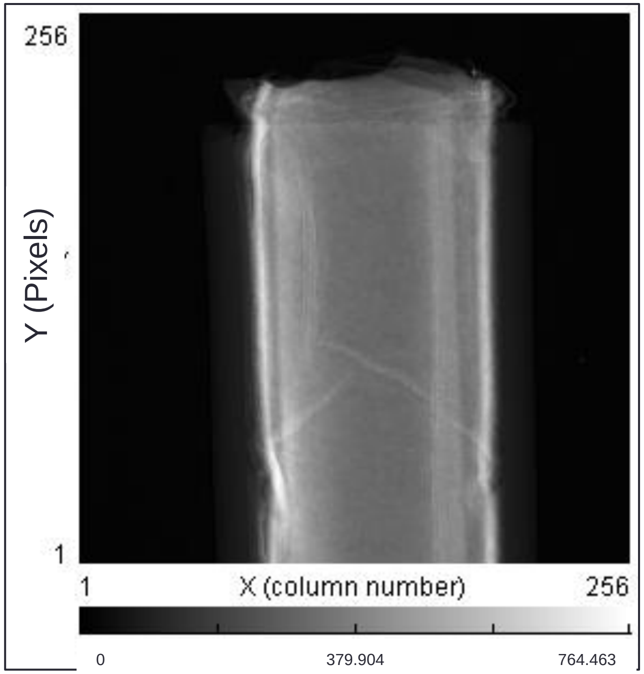
Phantom made of 5 different layers with similar attenuation coefficients, simulating the conditions of the wall of a blood vessel.





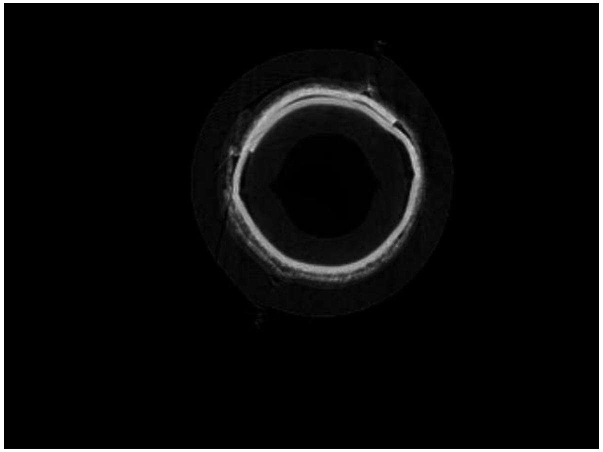
Acquisitions: 180 projections of 15 s. (0,5s.*30) using tungsten x-ray tube at 40 kV and 200 uA.
Detector: 1 Timepix device in Photon Counting Mode and 1 FITPIX.

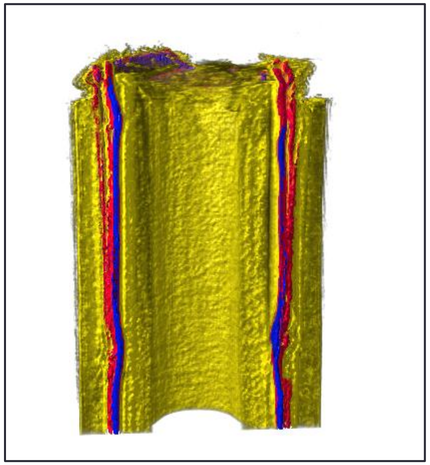


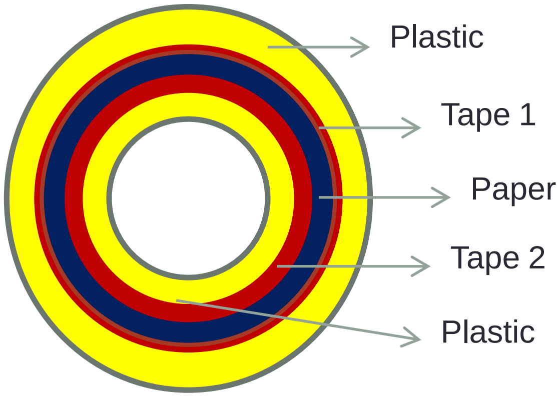


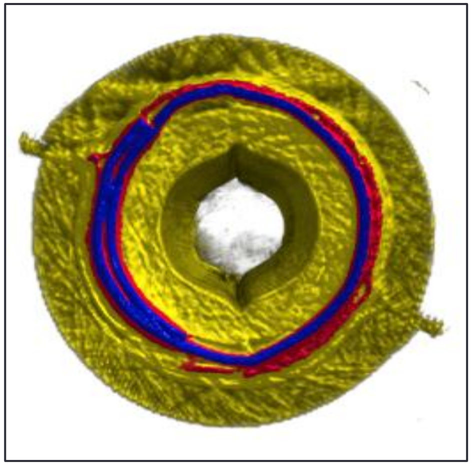
Two sample images before (left) and after (right) the BH correction.

The raw images show a higher definition than those from UniAndes and less noisy pixels (Maybe the problem is on the equalization of the Mpx2 at Bogotá?)









Tomographic reconstruction using ABCD to get the “slices” (3 iterations) and Voreen to do the volumetric render.

Conclusions

- Novel experiments with arrays of Timepix detectors were developed and tested, and a C++ tool to characterize signals and to operate with information from coincident detectors was developed.
- Regarding Cosmic Rays: 15 days of data were accumulated and tracks and yields for coincident events in 3 and 4 detectors calculated. There are still some directional filters to be implemented on the tracks, and double coincident signals to be analyzed (Compton effect?). These results motivated the idea to test some Timepix detectors in addition to the stations of the CZELTA Project.
- Regarding (p,p) collisions at the IEAP Van De Graff: The behavior of coincident protons agrees with the expected results of the technique used at the accelerator. It is still necessary to reproduce the geometry of the target using vertex reconstruction algorithms in order to completely validate the process.
- Regarding Hadron Therapy: Flexible new setups were assembled, and data considering variations from relevant parameters of the therapy and radiation dectecion was gathered (Energy, Intensity, Operation Mode, Bias Voltage) at the Heidelberg Ion Therapy Center for protons and carbon ions. This data will be processed during the next 6 months in order to obtain spectroscopic and directional information (Vertex reconstruction, characterization of secondary fragments production, etc.)

- Comparison between X-Ray/CT setups from UniAndes and the IEAP: Imaging of soft tissue with high contrast is possible at a micrometric scale using Medipix-type detectors, and it is possible to extract information from the CT’s. Similar techniques to those implemented at the IEAP are required to continue with the Carotid Imaging project between the IMAGINE Group and the HEP Group at UniAndes (Specially those related to the alignment of the sample).

Special Thanks

- **Medipix3 Collaboration.**
- **Institute of Experimental and Applied Physics CTU in Prague**: Carlos Granja, Jan Jakubek, Jan Zemlicka, Pavel Soukup, Stanislav Pospisil.
- **Heidelberg Ion Therapy Center**: Maria Martisikova.
- **Grupo de Altas Energías, Universidad de Los Andes:** Bernardo Gómez, Andrés Osorio, Proyectos Semilla de la Facultad de Ciencias.