Imaging detectors

Zdeněk Doležal

Výjezdní seminář ÚČJF 2018

Particle Detector Applications in Medicine

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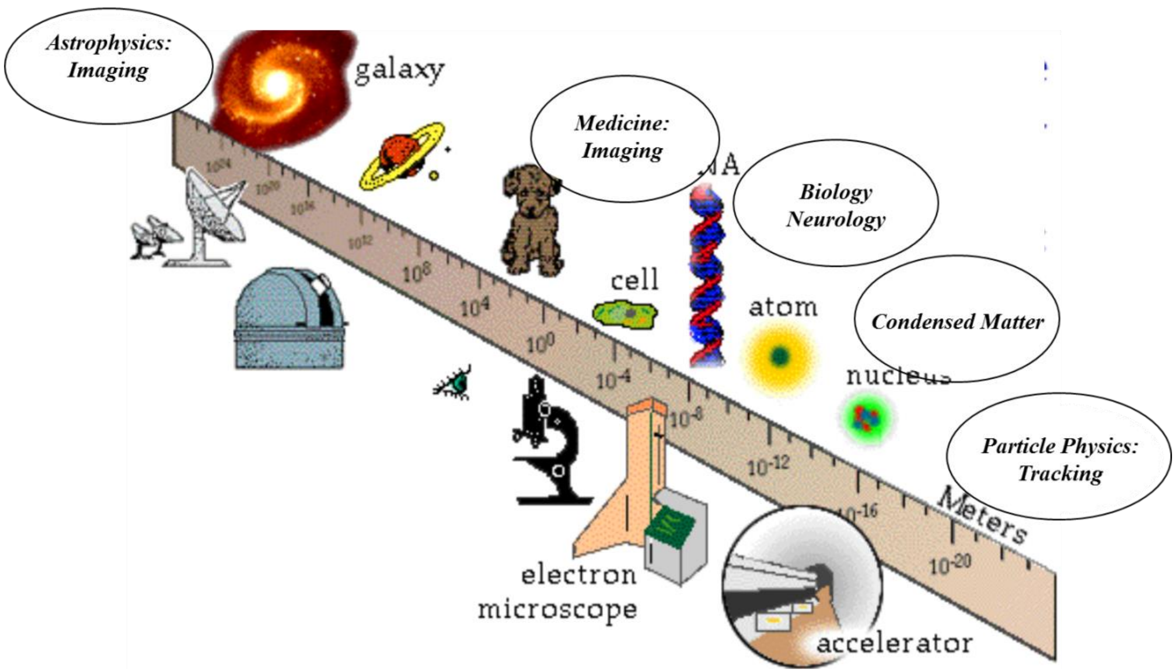

Review of X-ray Detectors for Medical Imaging

Martin Hoheisel

Siemens AG Medical Solutions
Angiography, Fluoroscopic- and Radiographic Systems
Innovations – Future Concepts
Forchheim, Germany

X-ray Detectors for Synchrotron Radiation Applications

5th EIROforum School on Instrumentation (ESI 2017)

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Detector & Electronics Group
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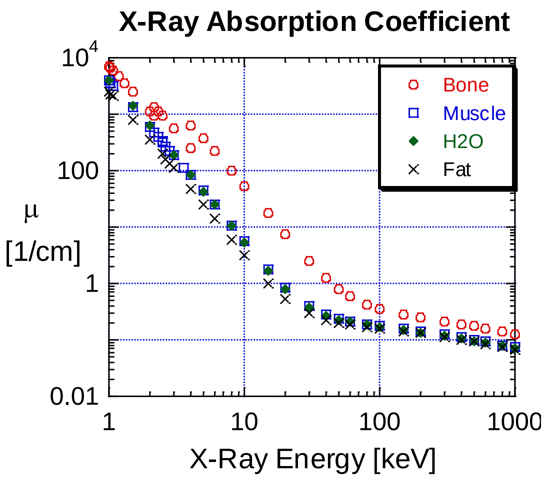
ESRF | The European Synchrotron

Medical Applications

Low-energy instrumentation,
small systems (until commercialization..) profiting from HEP and (even more so) from Astrophysics heritage
Scintillators & Semiconductors (for WCC heritage: Peskov, Nygren talks)

- Dosimetry, EH&S
- Imaging: Radiography, Tomography
  - Photons
  - X-ray CT
  - SPECT
  - PET & TOF-PET & PET/MRI & PET/CT
  - Hadrons (MedAustron)
  - Intercation Vertex Imaging IVI
  - Proton CT

Absorption of Photons $N(x) = N_o e^{-\mu x}$



Photons of Medical Interest, Energies & Resolution

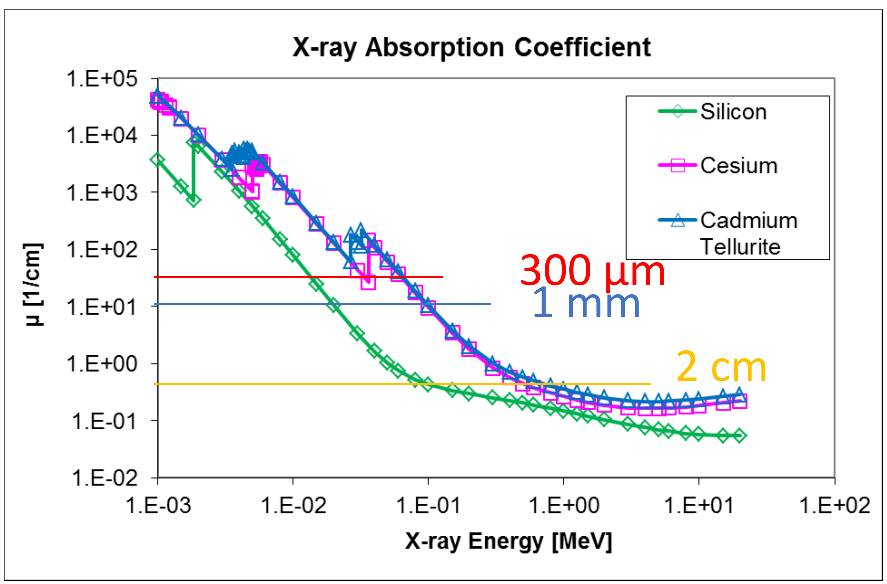
- μ-waves: MRI (10's μm)
- 10-100keV: X-ray radiography and CT (10's μm)
- 500 keV: PET and SPECT (mm)

No directional information with exception of Compton

High bone contrast 1-100 keV

Advantage of high-Z detectors:

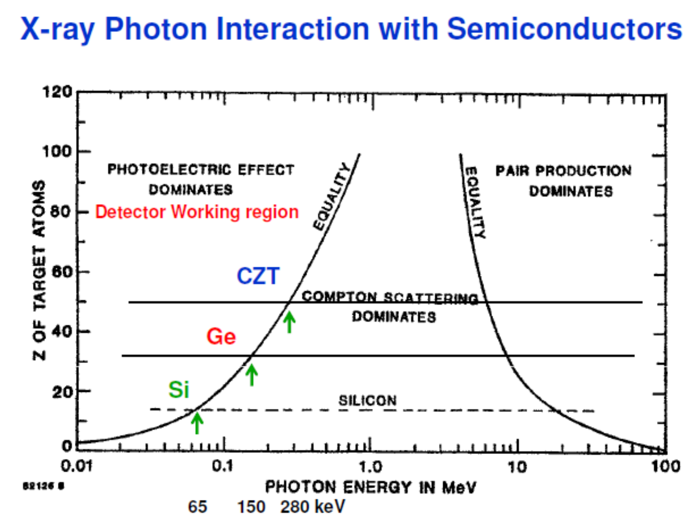
Larger energy reach (depends on thickness)



Shift of Compton region to higher E

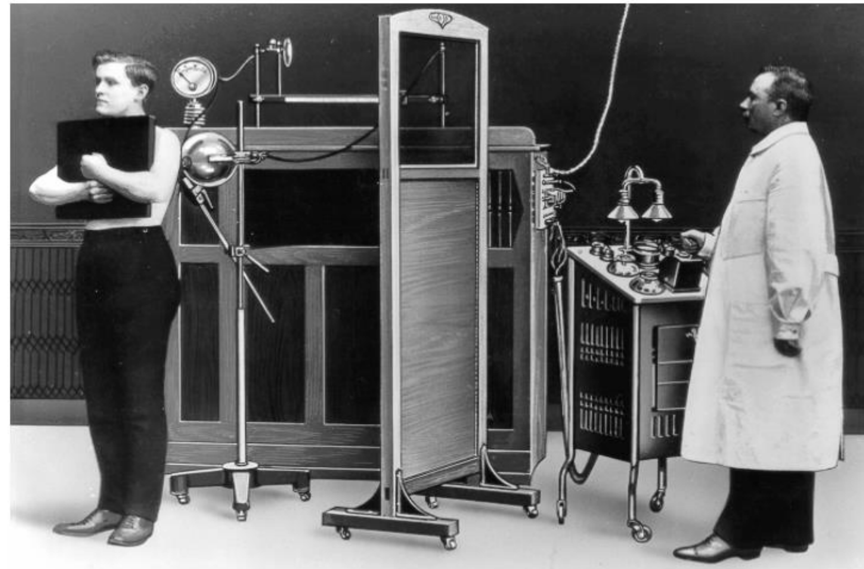
reduced range of Compton electrons

reduced range of positron in PET



History

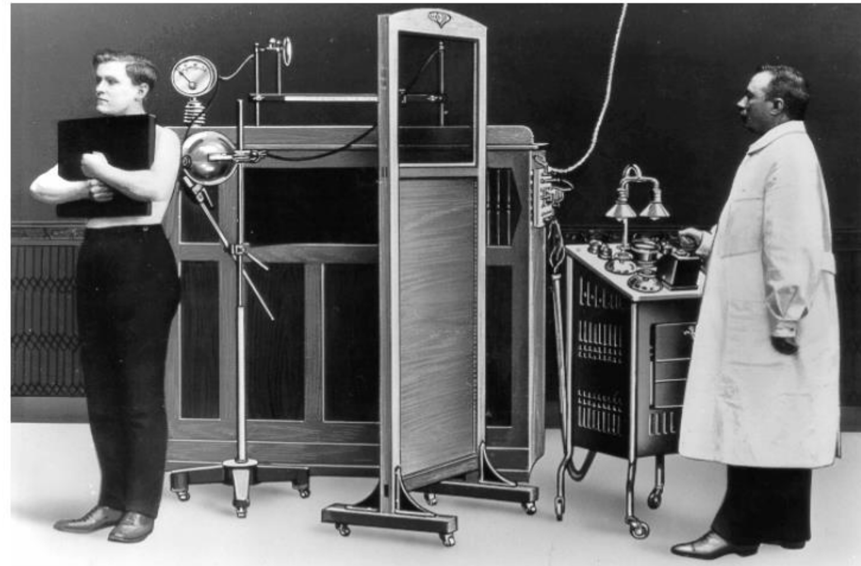
8 X-ray detectors started with film, screen, and film/screen systems (screen = scintillator)



Ms. Röntgen's hand with ring
(first image, Dec. 22, 1895)

Erlangen, Gynaecological Hospital
(1918)

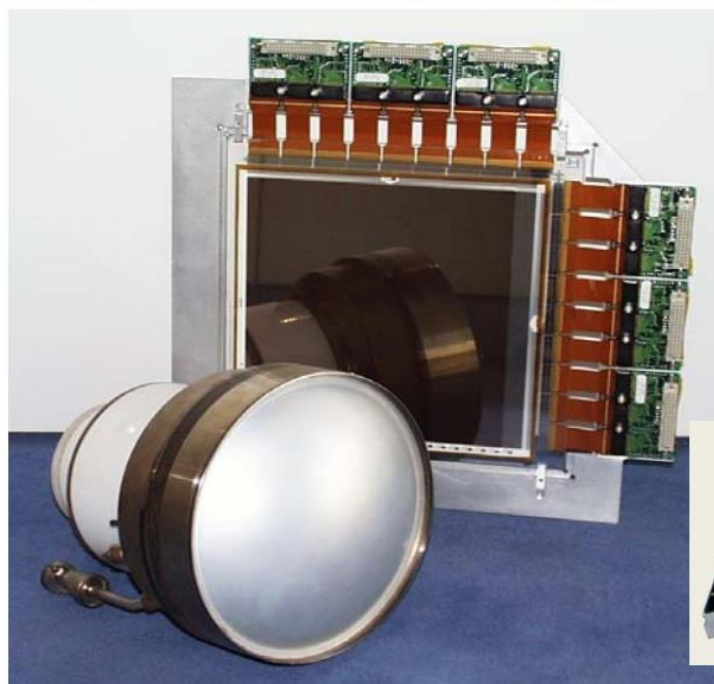
History



8 X-ray detectors started with film, screen, and film/screen systems (screen = scintillator)

8 X-ray radiography became digital with storage phosphor systems (“Computed Radiography”)

8 X-ray fluoroscopy is performed with X-ray image intensifier TV systems



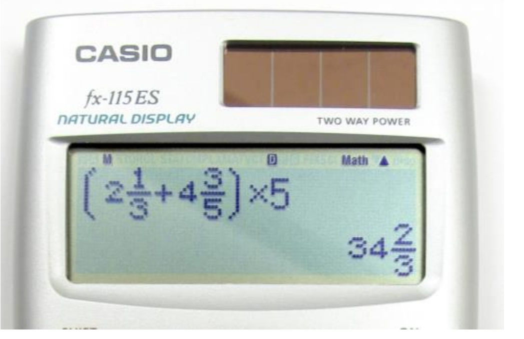
8 State-of-the-art X-ray imaging is done with flat-panel detectors

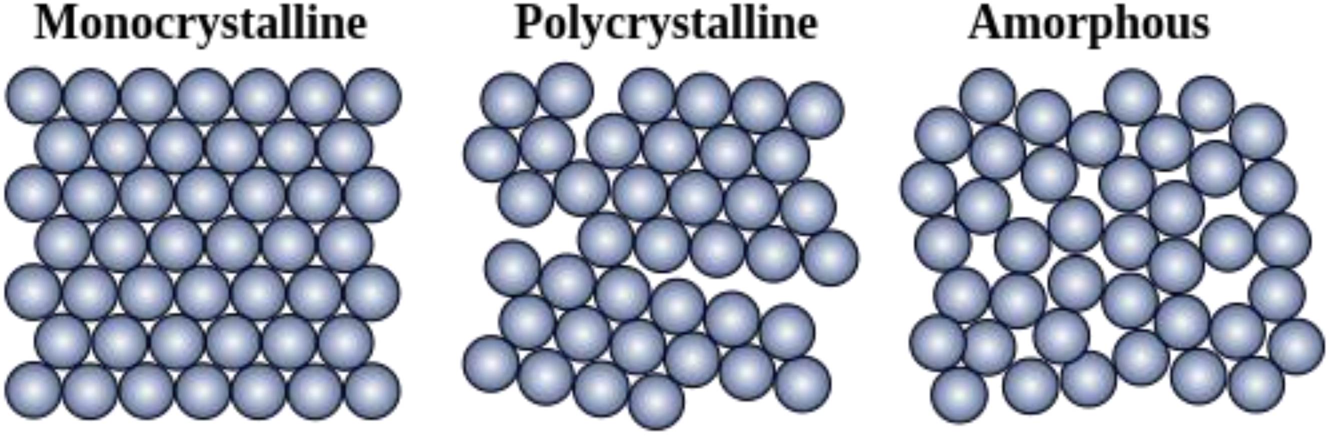
Flat panels

- Flat panel detector composed of:
  1. a-Si:H pixel detector: ≅ μm thin a-Si:H sensor coupled to array of thin film transistor (TFT) = high sensitivity to visible light, low sensitivity to X-rays
  2. Coating: 400÷500 μm thick layer of phosphor or scintillator = high sensitivity to X-rays
- Incident X-ray → converted into green light by the coating → green light converted into electric signal by the a-Si:H pixel detector
- Used in general radiography, mammography, fluoroscopy

Amorphous Silicon (aSi:H)

- Non-crystalline form of Silicon
- Worse electrical properties (leakage current, efficiency)
- Cheaper than crystalline
- Used at solar cells, etc.
- Dangling bonds passivated by Hydrogen





Analogue –vs– digital

Analogue imaging (films)	Digital imaging
Continuous range of possible optical densities up to some limiting value	Discrete and limited range of optical densities
Narrow exposure latitude → strict exposure requirements	Very wide exposure latitude
Little possibility of image processing	Image processing possible + needed to overcome limitations of manufacturing processes (bad pixels, spatial sensitivity variation)
Only one image display	Various image displays possible
Cheap but one use	Expensive but multiple use
High resolution	Low(er) resolution[1]

[1]Not clinically significant when choosing right matrix size and image receptor to match the application

Analogue → digital imaging (= more quantitative information available) thanks to:

1. Integrated electronics
2. Fast computers

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Specific requirements for medical imaging detectors

- Detector for medical application = special detector with its own specifications:

Detection range	– Low energies: 18 keV for mammograms for ex.
Read-out	– No trigger (no bunch crossing) → self-triggering electronics or free running – High acquisition rates > GHz – Manageable number of read-out channels
Event size	– Can be small 1 bit ÷ 10 bytes
Geometry	– Large area often required – Almost no dead space
Patient's requirements	– Meet stringent ethical requirements and regulation – Ensure patient's comfort
Market	– Can be large: $10^3 \div 10^6$ units

Different points of view

8 The medical point of view
- 7 **Application-driven**
- 7 Diagnosis or intervention ?
- 7 Morphological or functional imaging ?
- 7 Parameter requirements (size, speed, spatial and contrast resolution ...)
- 7 Workflow

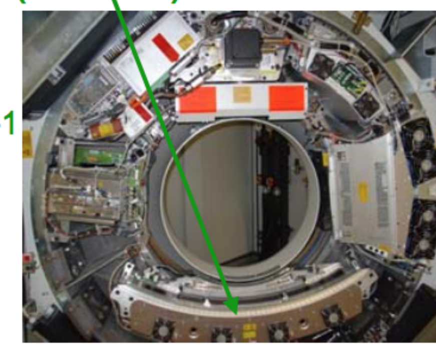
8 The physical point of view
- 7 **Technology-driven**
- 7 Wavelength (X-rays, gamma rays, visible light, NIR, Terahertz ...) ?
- 7 Feasibility determined by available sources, materials, electronics, computing power ...

8 And the economical point of view ...

Requirements for medical X-ray detectors

- Size
  - Radiography — 43 cm x 43 cm
  - Angiography — 30 cm x 40 cm
  - Full field mammography — 24 cm x 30 cm
  - Cardiology — 20 cm x 20 cm
  - Mammography biopsy — 5 cm x 9 cm
  - Computed tomography — 4 cm x 70 cm (curved)

- Frame rate
  - Computed tomography — 2000 – 6000 s^{-1}
  - Fluoroscopy, cardiology — 15 – 60 s^{-1}
  - Angiography — 2 – 30 s^{-1}
  - Radiography, mammography — 0.05 – 2 s^{-1}



- Spatial resolution (pixel size)
  - Computed tomography — 1 mm^{-1} (1 mm)
  - Soft tissue — 1 – 2 mm^{-1} (400 – 150 µm)
  - Bones — 3 – 4 mm^{-1} (165 – 125 µm)
  - Mammography, dental — 5 – 20 mm^{-1} (100 – 25 µm)

The physical point of view

8 Imaging needs ...

7 ... a radiation source,

- spectrum (monoenergetic, energy range)
- spatial extent, coherence

7 ... interaction with the object to be imaged,

- absorption (energy dependent)
- reflection, scattering, diffraction, refraction
- interaction differences of details of interest result in **contrast**

7 ... registration of the radiation carrying information about the object,

- interaction (e.g. absorption)
- conversion into an electrical signal
- **integrating** detection or **counting** detection

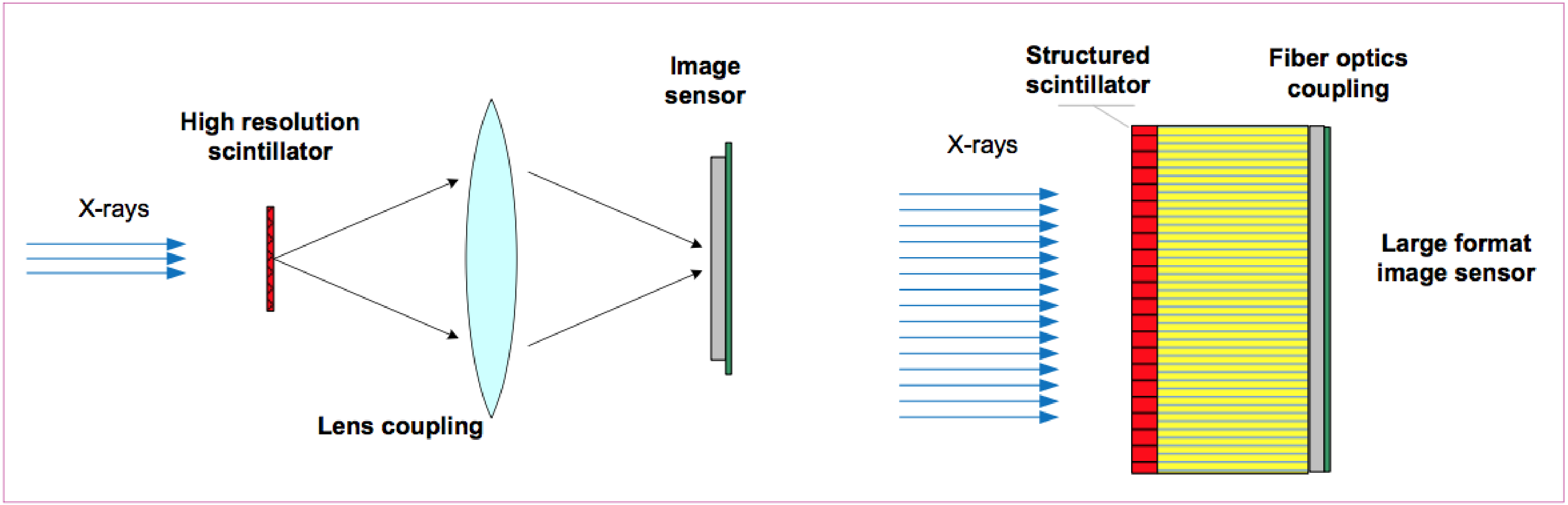
7 ... and signal processing

- corrections, enhancement, storage, display

Detection technologies used for photons

Photon energy range		Typical detection technologies
Soft X-rays	**200 eV – 2 keV**	***Drain current measurements*** *Si photodiodes* *MCPs* ***Direct detection CCDs*** *SDDs*
Hard X-rays	**2 – 20 keV** Low/medium energy	***PMTs***, ***APDs*** ***Hybrid pixel detectors*** ***Indirect detection****: CCDs and CMOS* *Gas filled detectors* ***Silicon drift diodes*** *(SDDs)*
	20 – 150 keV High energy	***a:Si flat panels (CsI, a:Se)*** ***CMOS flat panels*** ***Indirect detection****: CCDs and CMOS* *Image plates* *Image intensifiers* ***HPGe***

Scintillators: indirect detection



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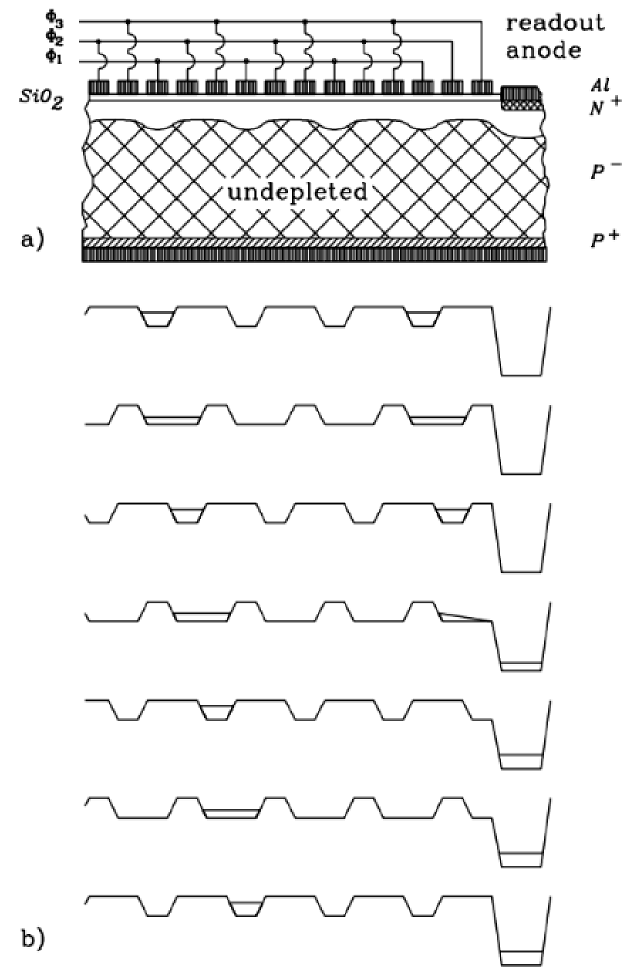
Scintillators

	Inorganic	Organic
Material	Mainly alkali halides with small activator impurity	Aromatic hydrocarbon compounds with benzene-ring structures
Density	High	Low
Atomic number	High	Low
Stopping power	High	Low
Light output	High	Low
Energy resolution	High	Low
N of photons generated	Linear[1]	Non linear[1]
Decay time	~500 ns	Few ns or less
Temperature dependence	Yes	No
Hygroscopic	Usually yes	No

[1]With energy of incident radiation

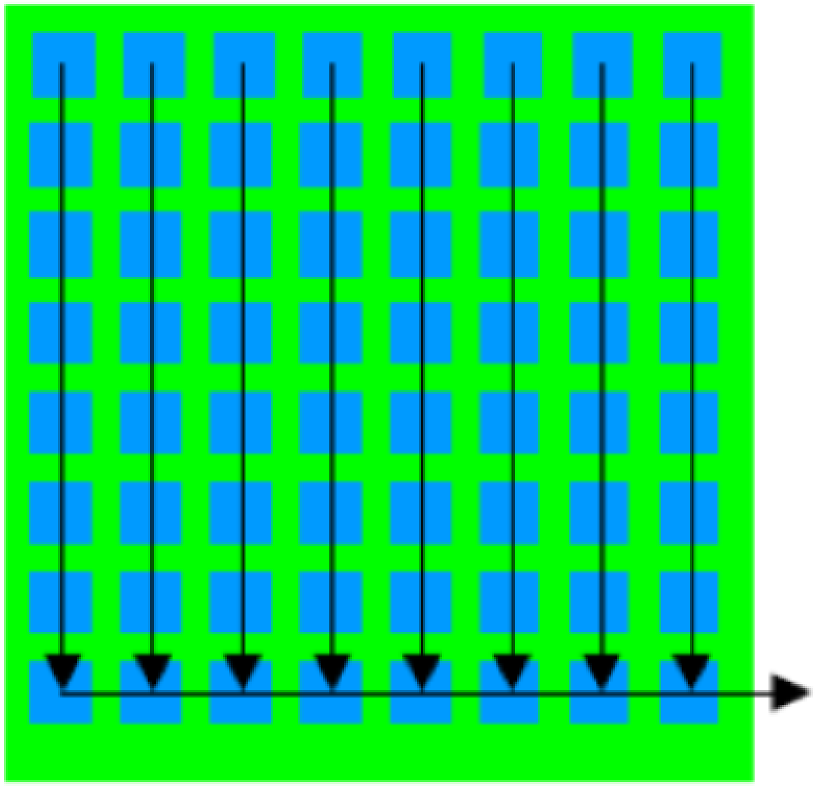
CCDs as detectors

Traditionally used for storing and transfer of charge and as optical sensors (cameras)
Also $p-n$ versions for particle detection
Used for vertexing at the Stanford Linear Detector (SLAC)
Periodic 3-phase potential
Shifting to next cell



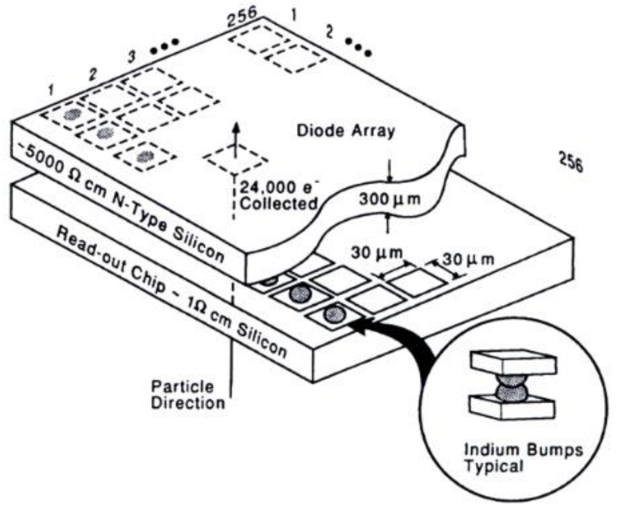
CCDs as detectors

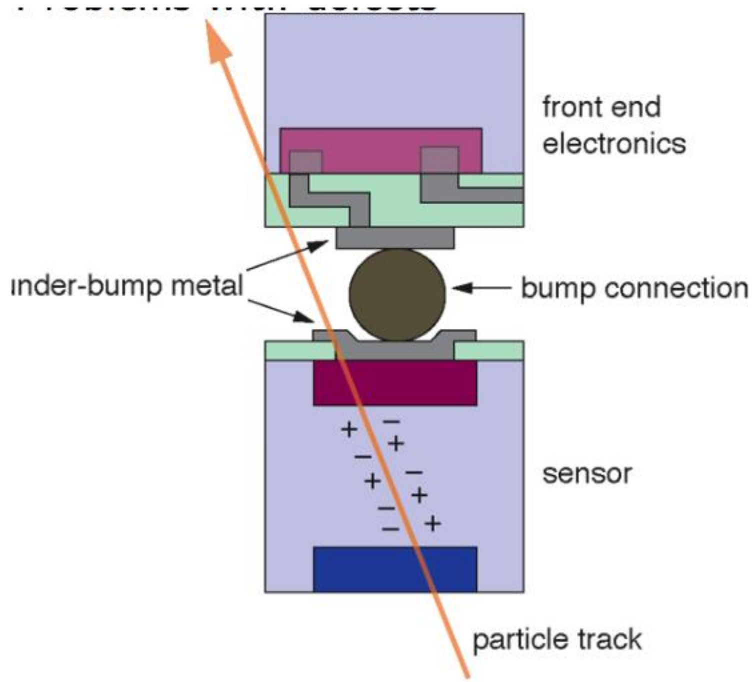
- 2D structure can be made
- Drawback: charge coming during R/O is misidentified



Hybrid Pixels

- Signal transferred to special readout chip attached to the pixel chip
- Typical pixel size is 50 µm ×50µm
- Often digital (binary) resolution
- Small pixel area
  Low detector capacitance
- Large S/N (e.g. 150:1)
- Small pixel volume: low leakage current
- Drawback: many R/O channels, data, large power consumption



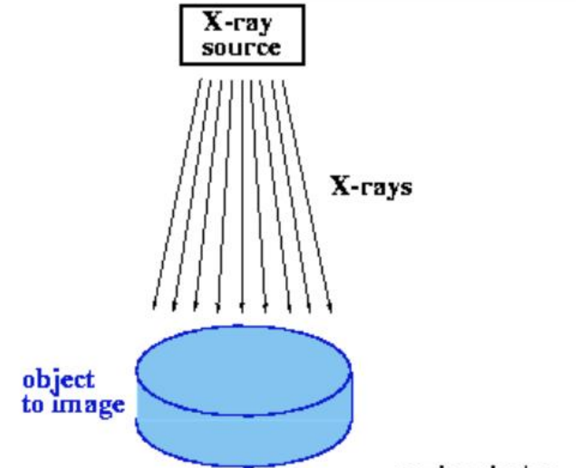


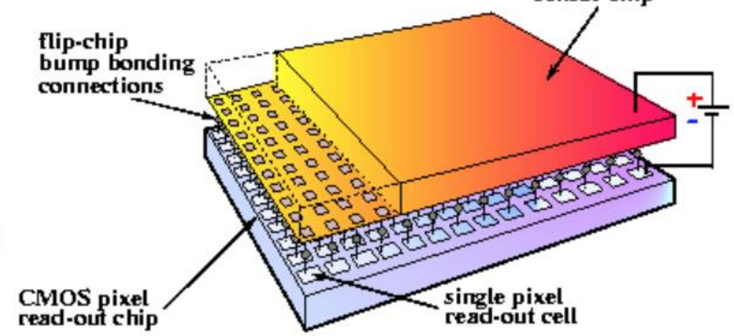
Monolithic Active pixels

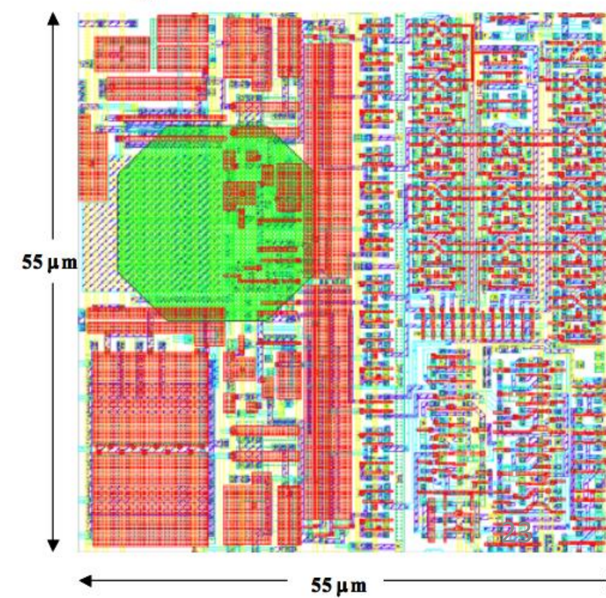
- Silicon used both in a detector and in processing electronics
- Why not integrated?
- Using the same wafer/substrate
- This is not so easy:
  - Electronics needs high conductivity Si
  - Detectors need high-resistivity Si (to achieve depletion) Several approaches to match these contradictions:
- Monolithic Active Pixels
- DEPFET Pixels

Quanta-counting detection

- 8 Advantages of counting
  - 7 Higher DQE possible (Swank factor = 1)
  - 7 No electronic noise, only zero effect and quantum statistics
  - 7 No digitization necessary
  - 7 Energy discrimination is feasible
- 8 Advantages of integrating
  - 7 High dose rates are easy to handle
  - 7 Simple and cheap
- 8 Medipix-2 chip 14 x 14 mm² with 256 x 256 pixels á 55 µm
- 8 Semiconductor layer (Si, GaAs, CdZnTe, CdTe, HgI_2, InSb, TlBr, PbI) with high-Z as an absorber for good DQE
- 8 Amplifier, discriminators and counters have to fit in pixel area



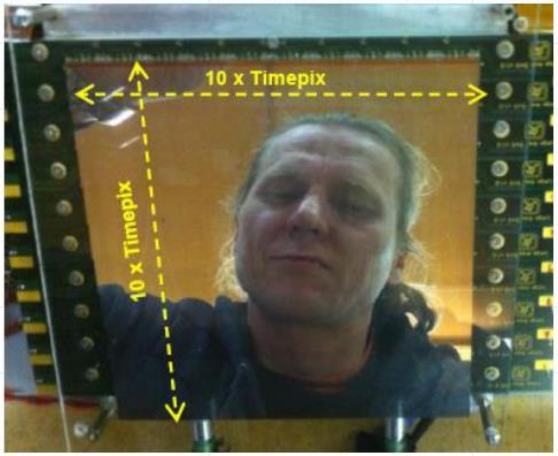




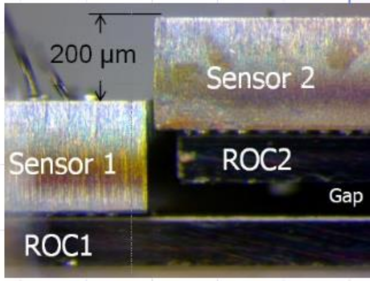
Large area photon-counting pixel detector based on Timepix chips

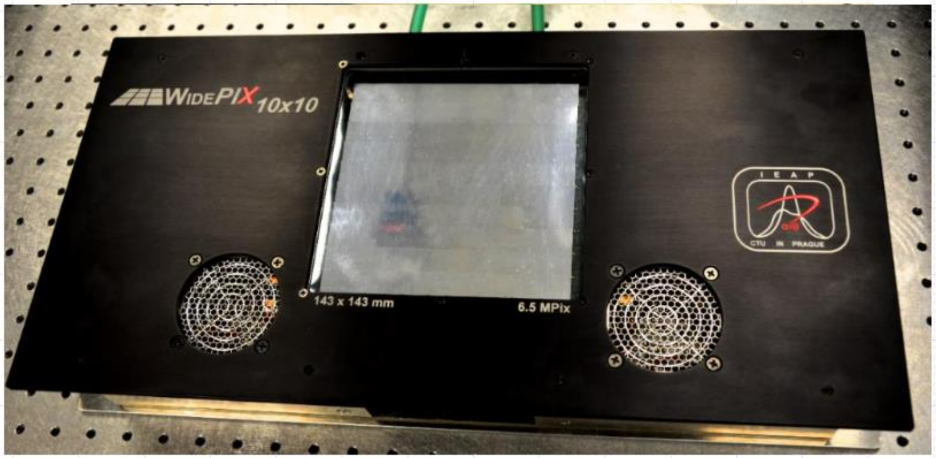
- **WidePIX 10x10 Timepix imager** consists of an array of 100 **edgeless** Timepix detectors (developed in VTT Finland and fabricated by ADVACAM Oy).
- The whole device was designed, developed and constructed at the IEAP CTU Prague
- Custom readout electronics + control software tool (Pixelman based)
- Versions: 10x10, 10x5, 5x4, 10x1, 5x1 chips

Features:
- Large (14 cm x 14 cm) **fully sensitive area** with **no gaps** between sensor chips
- Readout speed – depending on the matrix size (5 frame/s for the 100 chip device)
- Energy discrimination allowing “color” radiography
- Compact size and portability (1 x PC)
- Support for major operating systems: Windows, Mac OS, Linux



Detail of chip tiling

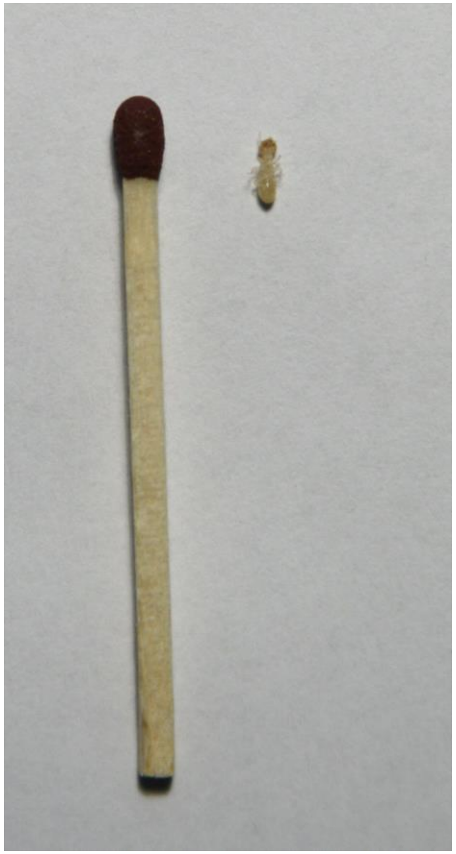




J. Jakůbek et al., "Large area pixel detector WIDEPIX with full area sensitivity composed of 100 Timepix assemblies with edgeless sensors", JINST 9 C04018 (2014)

High resolution X-ray radiography:

Imaging of Termites



The imaging of termites as a model **soft tissue organism** is particularly difficult due to their **poorly sclerotized** cuticle making difficult to observe the anatomic structures with an optimal contrast.

Moreover, they are vulnerable to damage when they are manipulated or treated during sample preparation.

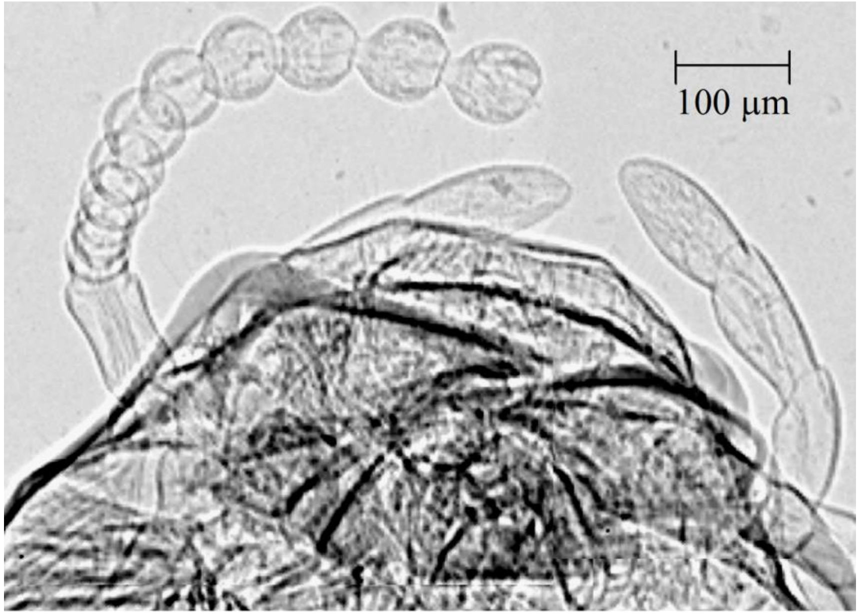
Thus, the termites represent an ideal model to optimize the accuracy and sensitivity of the developed method.

High resolution X-ray radiography:

Imaging of Termites

X-ray transmission image of termite worker body (left) and detail of its head (bottom). Even fine internal structure of the antennae is recognized.

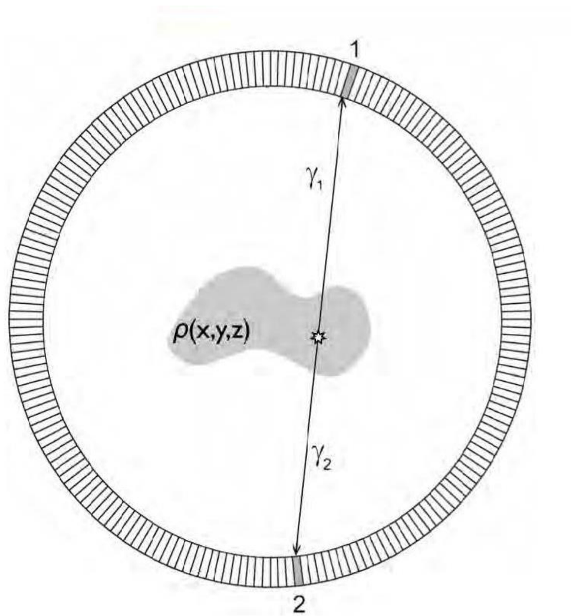
(Magnified 15x, time=30s, tube at 40kV and 70μA)



Positron Emission Tomography PET

Study accumulation of radioactive tracers in specific organs.
The tracer has radioactive positron decay, and the positron annihilates within a short Distance with emission of 511 keV γ pair, which are observed in coincidence.

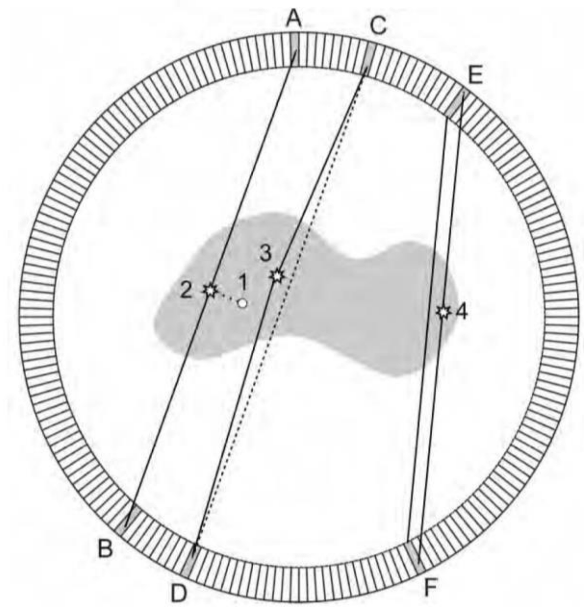
Perfect Picture:



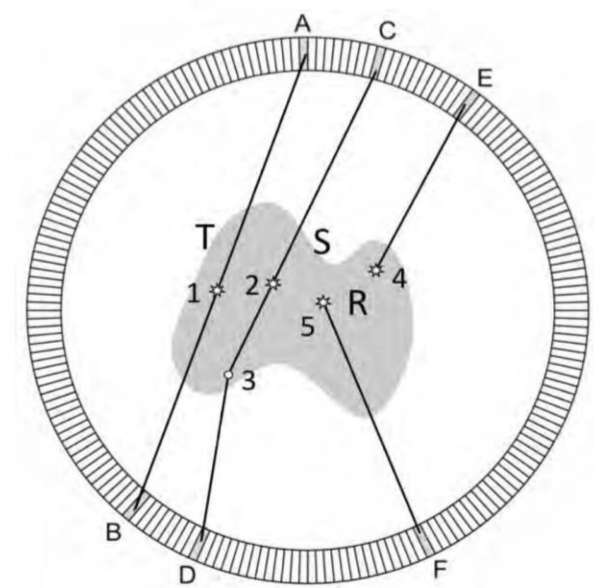
$$FWHM = 1.2\sqrt{\left(\frac{d}{2}\right)^2 + b^2 + (0.0022D)^2 + r^2 + p^2}$$

1.2	from analytical algorithm (FBP)
d/2	from the detector pitch
b	from the coding
0.0022D	from the 2 photon a-collinearity
r	from the positron range
p	from parallax

Resolution and S/N Effects:



Resolution of detector (pitch)
Positron range
A-collinearity
Parallax (depth)

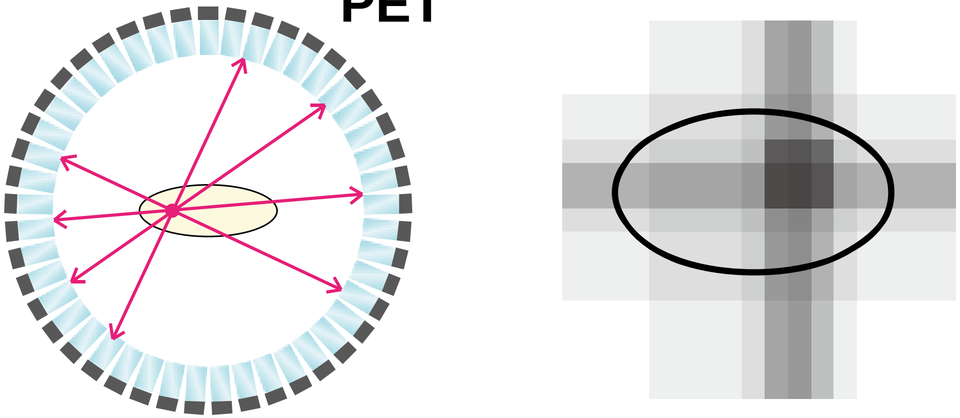


T: true event
S: Compton Scatter
R: Random Coincidence

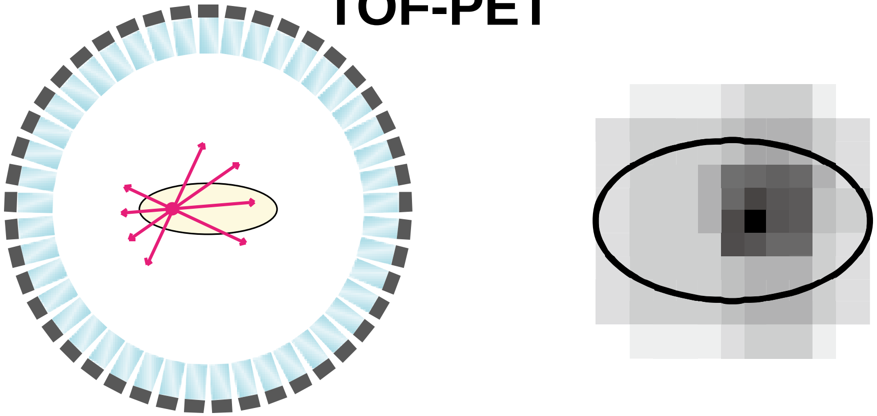
A. Del Guerra, RESMDD12

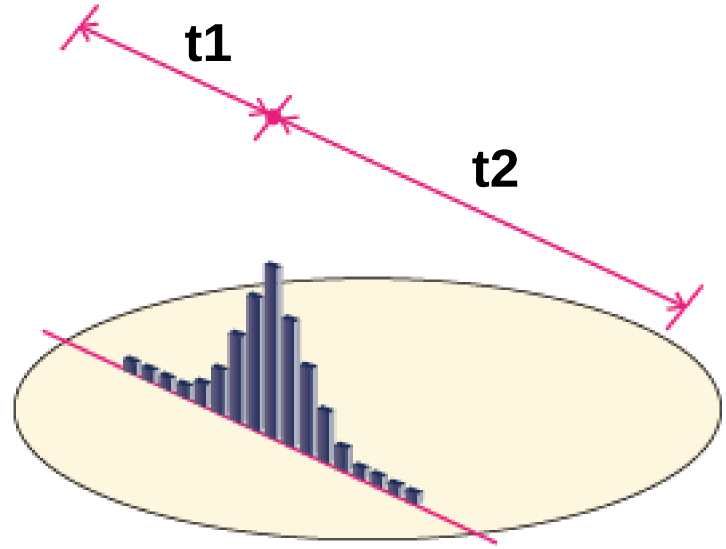
Reduce Accidentals & Improve Image: TOF-PET

PET



TOF-PET





Localization uncertainty:

$\Delta d = c \times \Delta t / 2$

When Δt = 200 ps

➔ Δd = 3 cm

@ VCI

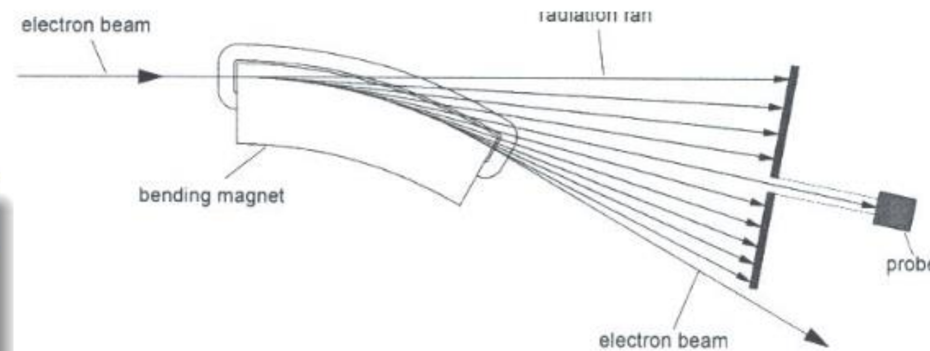
K. Yamamoto 2012 IEEE NSS-MIC

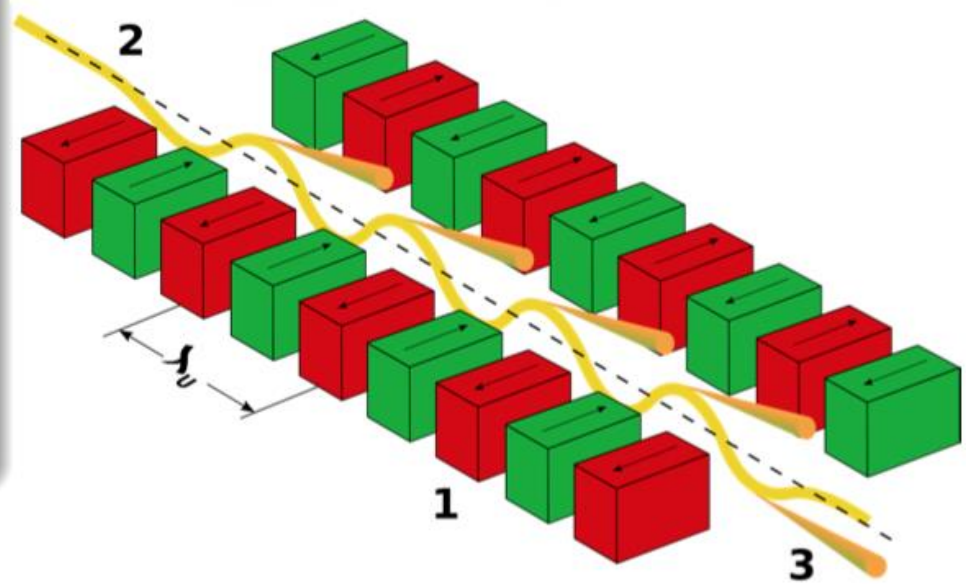
Synchrotronové záření

Produkce

Změna směru: emise záření
Do svazku jsou vkládána speciální zařízení (magnety) zvlňující svazek

- Wigglers: nekoherentní záření, $\alpha > 1/\gamma$
- Undulators: koherentní záření, $\alpha < 1/\gamma$

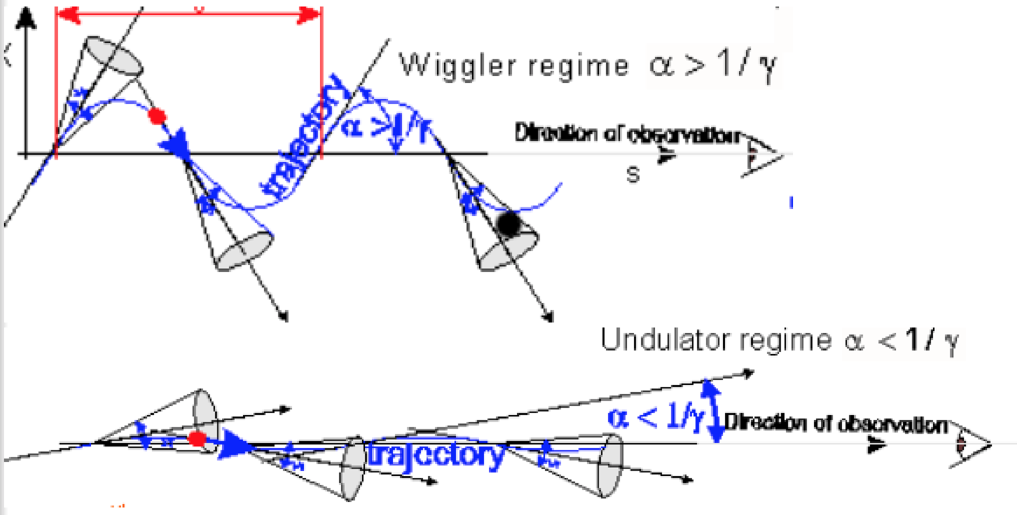




Synchrotronové záření

Parametr

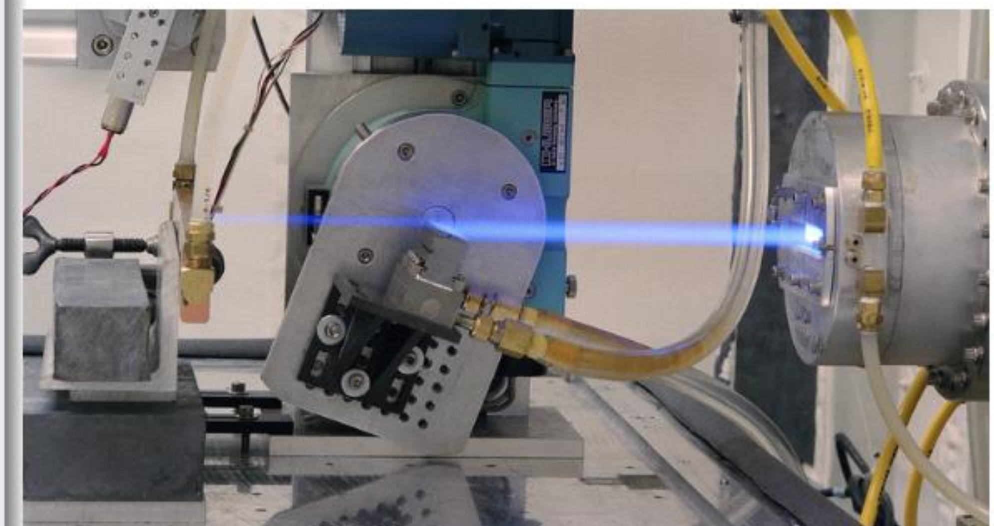
briliance: hustota celkového toku na počátku fázového prostoru
$B = \frac{\mathrm{d}^4 F}{\mathrm{d}x\mathrm{d}z\mathrm{d}\theta\mathrm{d}\phi}\big|_0$
Nejmodernější zdroje:
$B > 10^{18}\ \mathrm{s}^{-1}(\mathrm{mm\ mrad})^{-2}$
v intervalu frekvencí
$(\omega_0 - 10^{-3}\omega_0; \omega_0 + 10^{-3}\omega_0)$



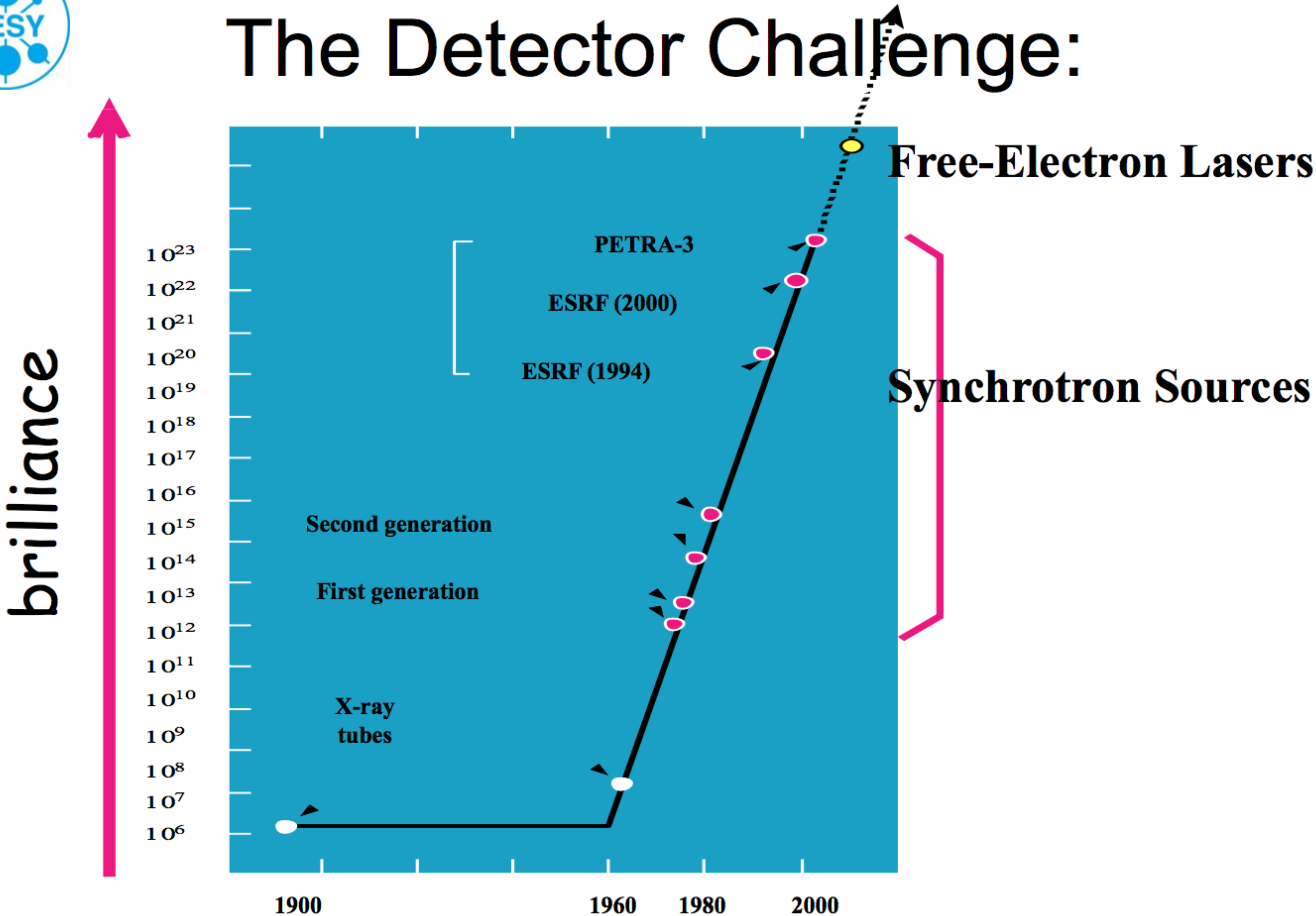
Synchrotronové záření

Zařízení

- 1. generace: urychlovače pro HEP využívané i jako zdroje SR
- 2. generace: urychlovače budované speciálně pro produkci SR
- 3. generace: urychlovače budované speciálně pro produkci vysoce kvalitního SR

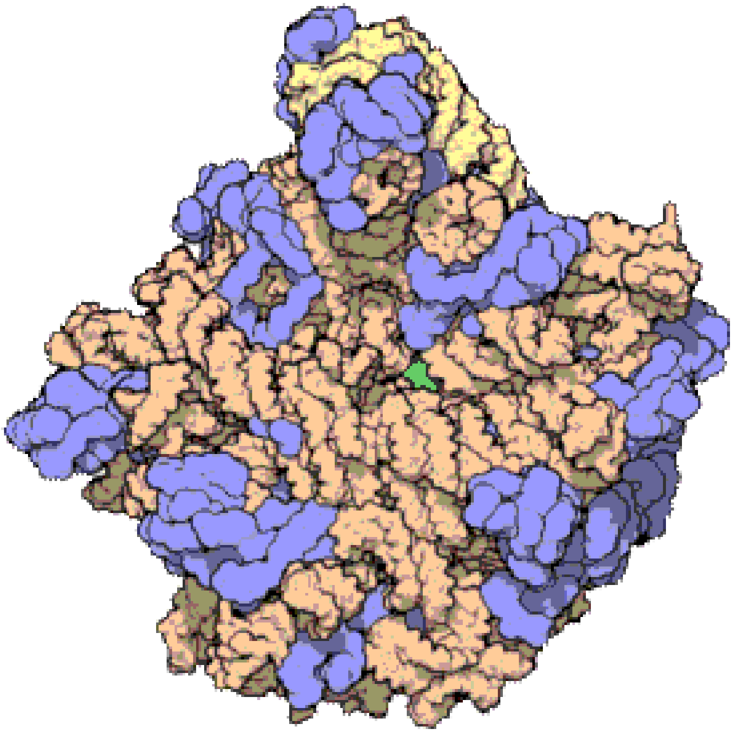


The Detector Challenge:

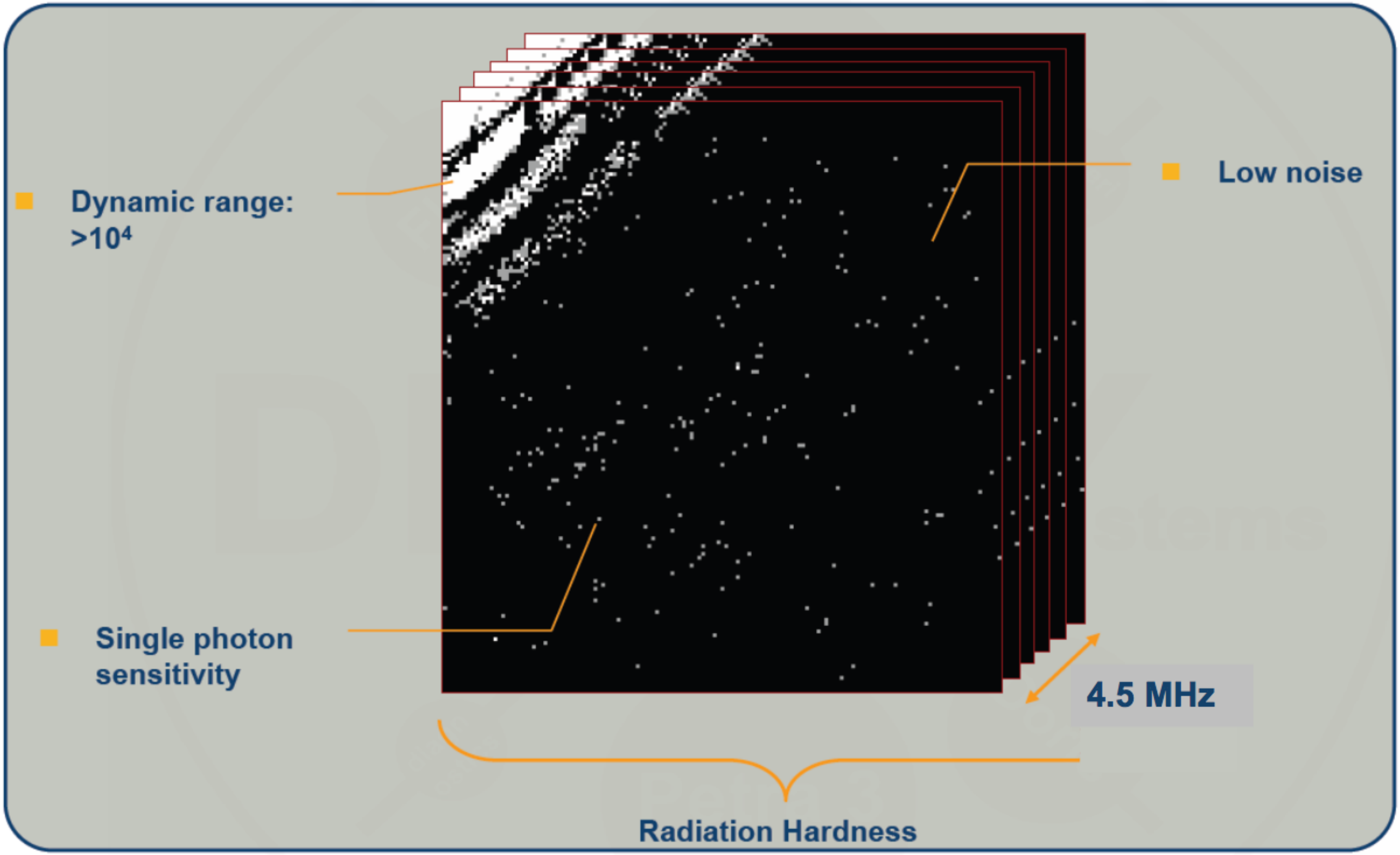


SR imaging

- Structural imaging
- Short beam time structure allows for dynamic imaging



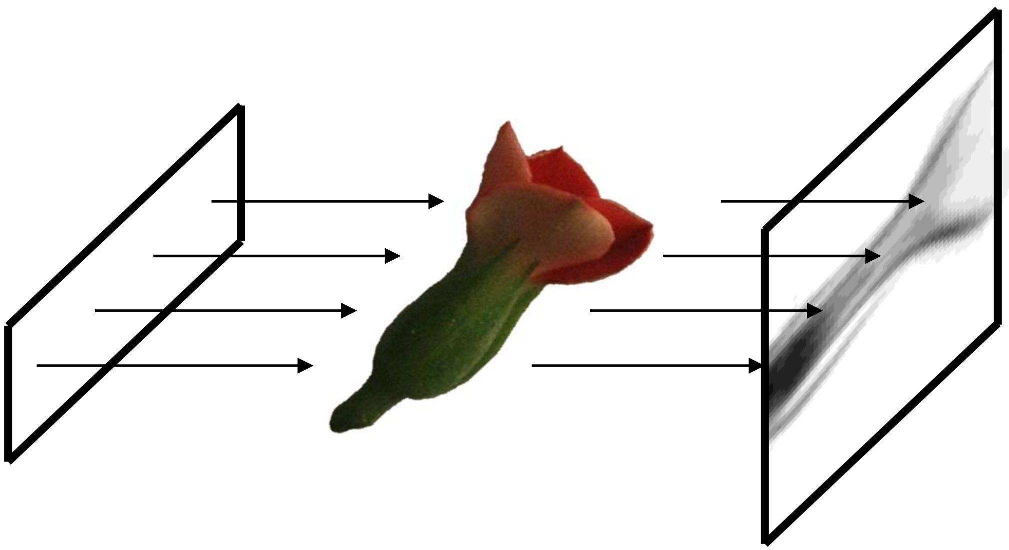
XFEL Detector requirements



Terahertz imaging

- 1 THz = 10^{12} Hz
  - Frequency range 0.1 THz … 30 THz (= FIR, far infrared)
  - Quantum energy range 0.4 meV … 120 meV
  - Wavelength range 3 mm … 10 µm
- Strong absorption in water
  - Only skin examination (≈ 1 mm)
- Sources are costly
  - Lasers, optical mixing
  - Photoconductive dipole antennas
- Applications
  - Dermatology, dentistry
  - Airport security (but THz waves will not penetrate a soaked coat)

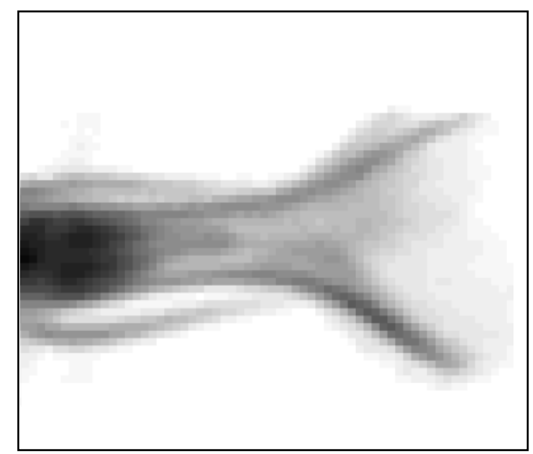
The Neutronography



Parallel beam of thermal neutrons

Specimen attenuating the beam

Shadow on detector plane



Neutronogram

Neutronography with Medipix

Conversion of thermal neutrons to heavy charged particles in **^{6}Li** or ^{10}**B** converter layer.

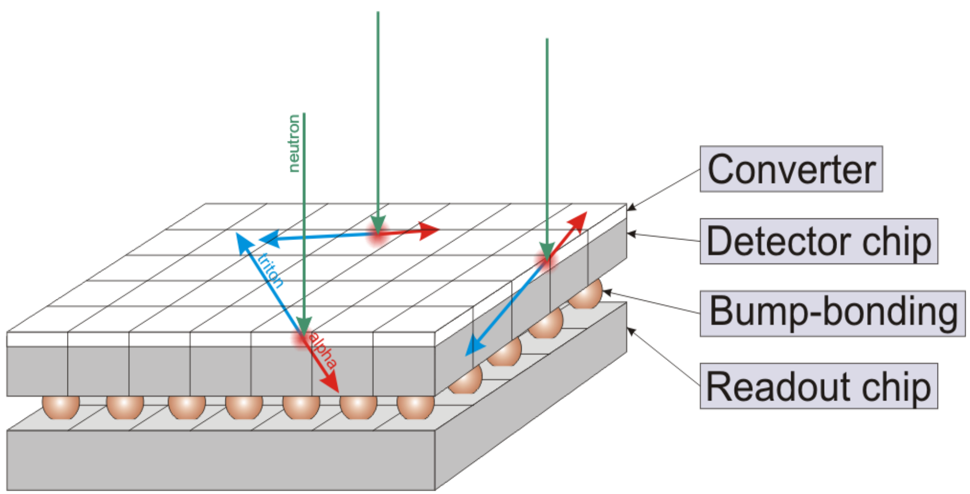
^{10}B reaction (Cross section 3840 barns at 0.0253 eV):

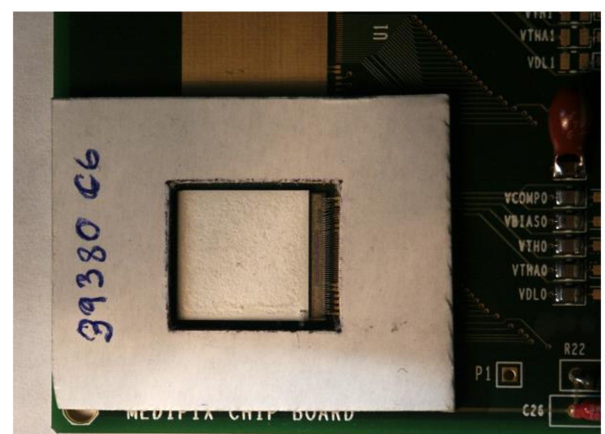
^{10}B+n $\rightarrow$ a (1.47 MeV) + ^{7}Li (0.84 MeV) + γ (0.48MeV) (93.7%)

^{10}B+n $\rightarrow$ a (1.78 MeV) + ^{7}Li (1.01 MeV) (6.3%)

^{6}Li reaction (cross section 940 barns at 0.0253 eV) :

^{6}Li + n $\rightarrow$ α (2.05 MeV) + ^{3}H (2.72 MeV)

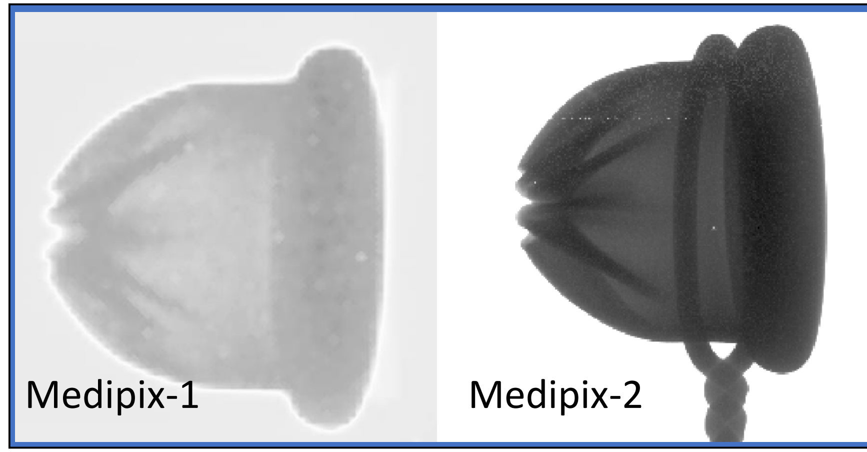




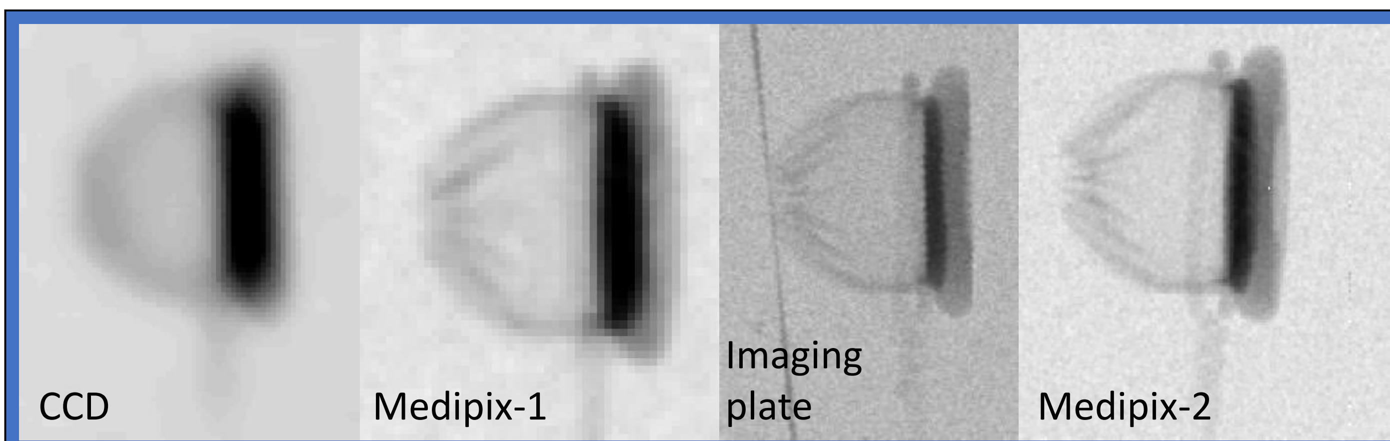
^{6}LiF layer: 3±1 mg/cm^{2}

Sample objects – blank cartridge

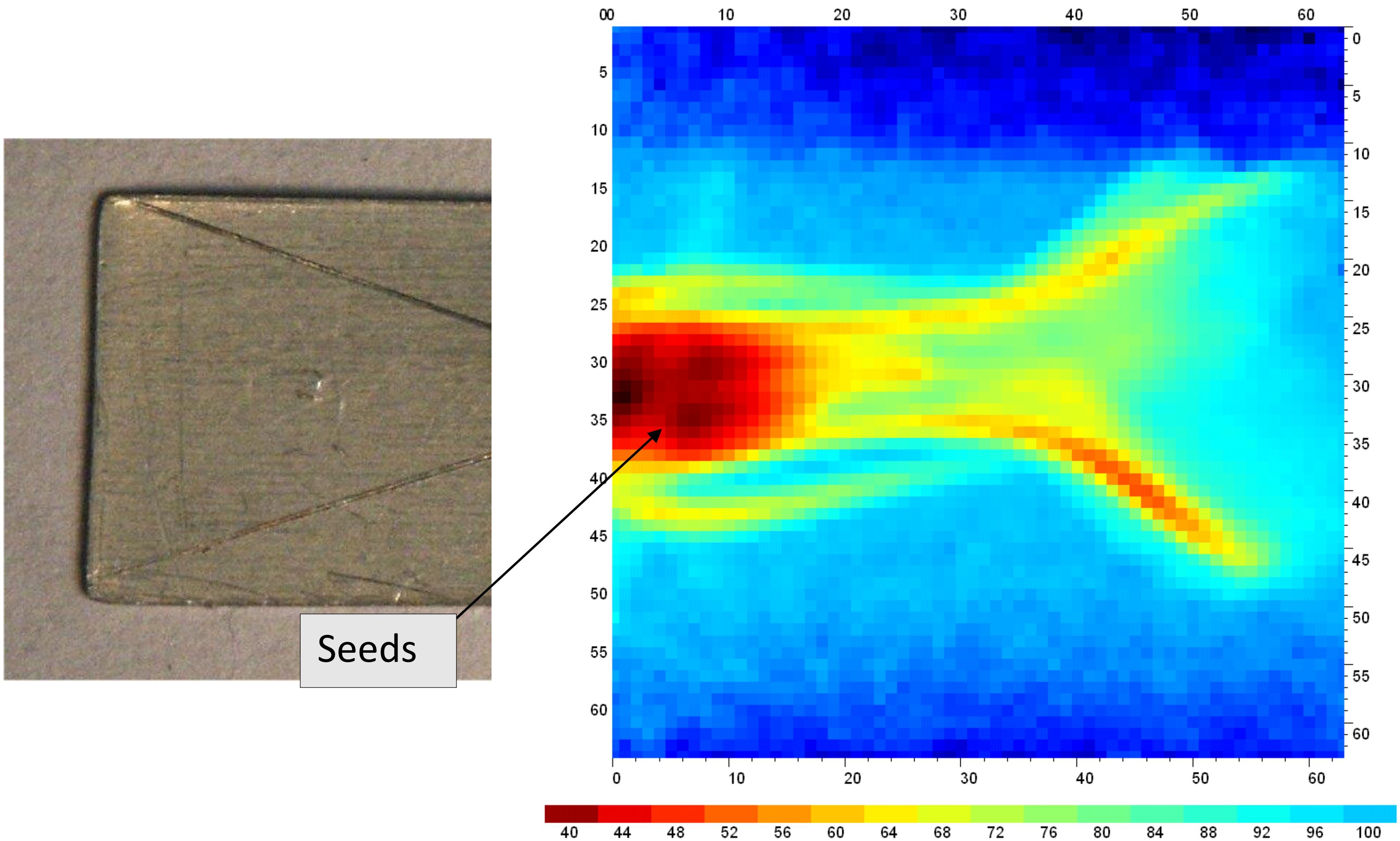
Roentgenography



Neutronography

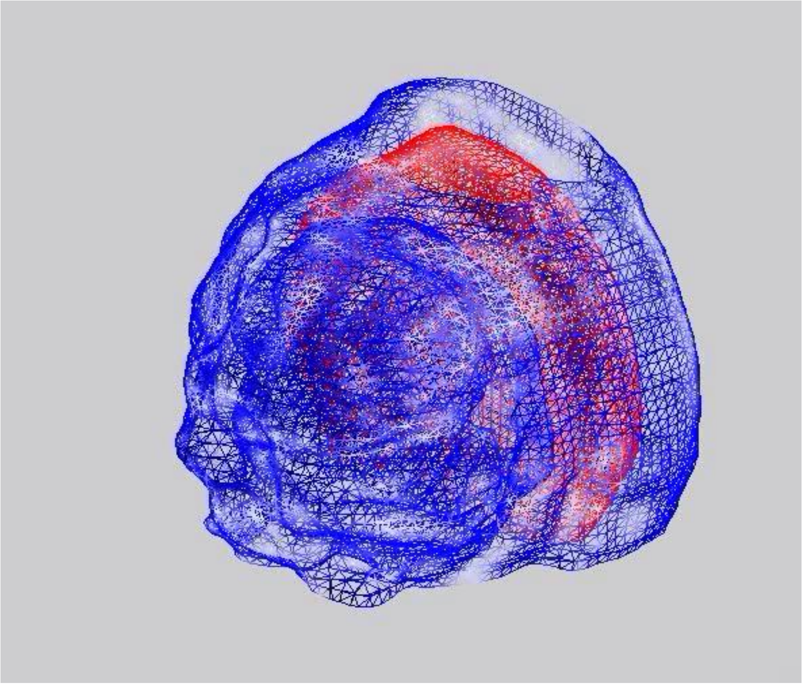


Flower behind Al plate

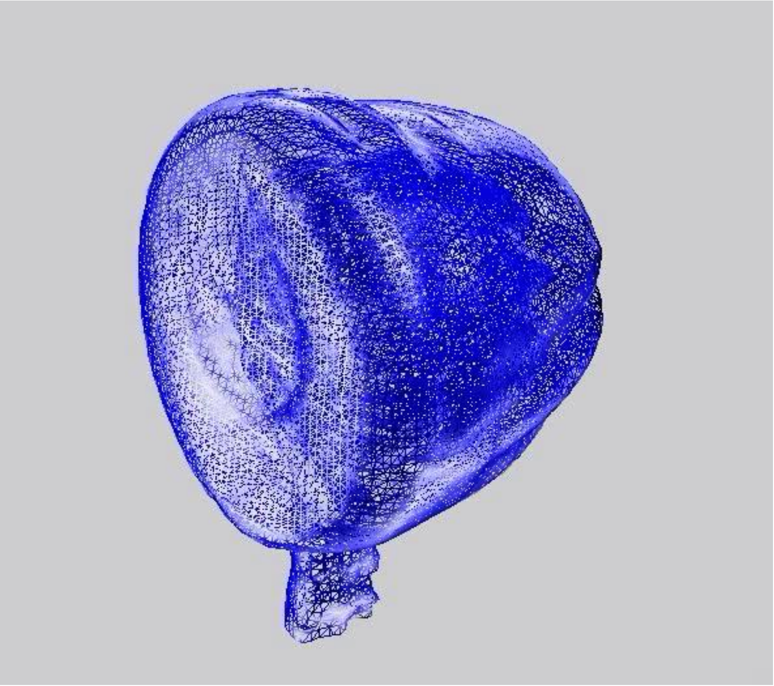


3D reconstructions

3D reconstruction - neutron



3D reconstruction – X-ray



Proton CT Basics

Proton therapy and treatment planning requires the knowledge of the stopping power in the patient, so that the Bragg peak can be located within the tumor.

X-ray CT has been shown to give insufficiently accurate stopping power (S.P.) maps in complicated phantoms or from uncertainty in converting Hounsfield values to S.P.

Range Uncertainties

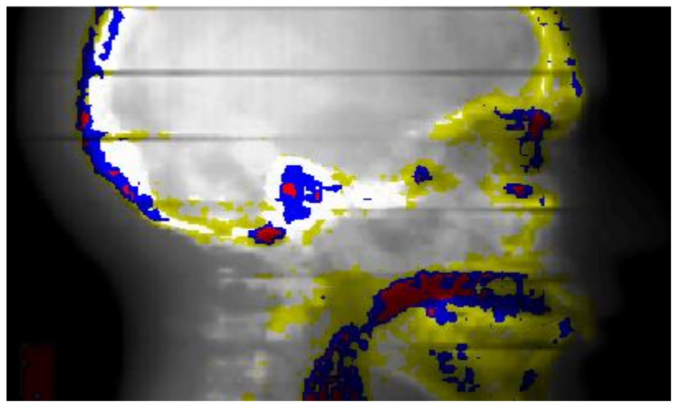
(measured with PTR)

> 5 mm

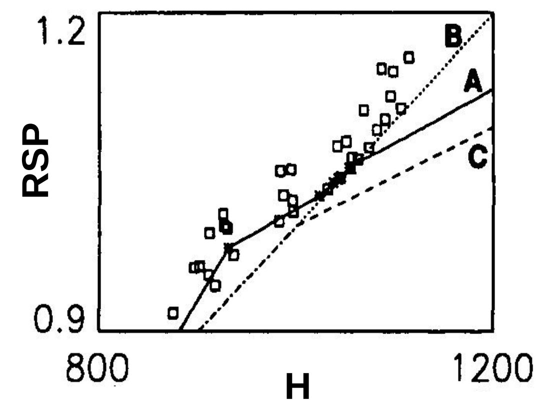
> 10 mm

> 15 mm

Schneider U. (1994), "Proton radiography as a tool for quality control in proton therapy," Med Phys. 22, 353.



Alderson Head Phantom



The goal of Proton CT is to reconstruct a 3D map of the stopping power within the patient with as fine a voxel size as practical at a minimum dose, using protons (instead of x-rays) in transmission.

In a rotational scan the integrated stopping power is determined for every view by a measurement of the energy loss.

Proton CT (pCT) Concept

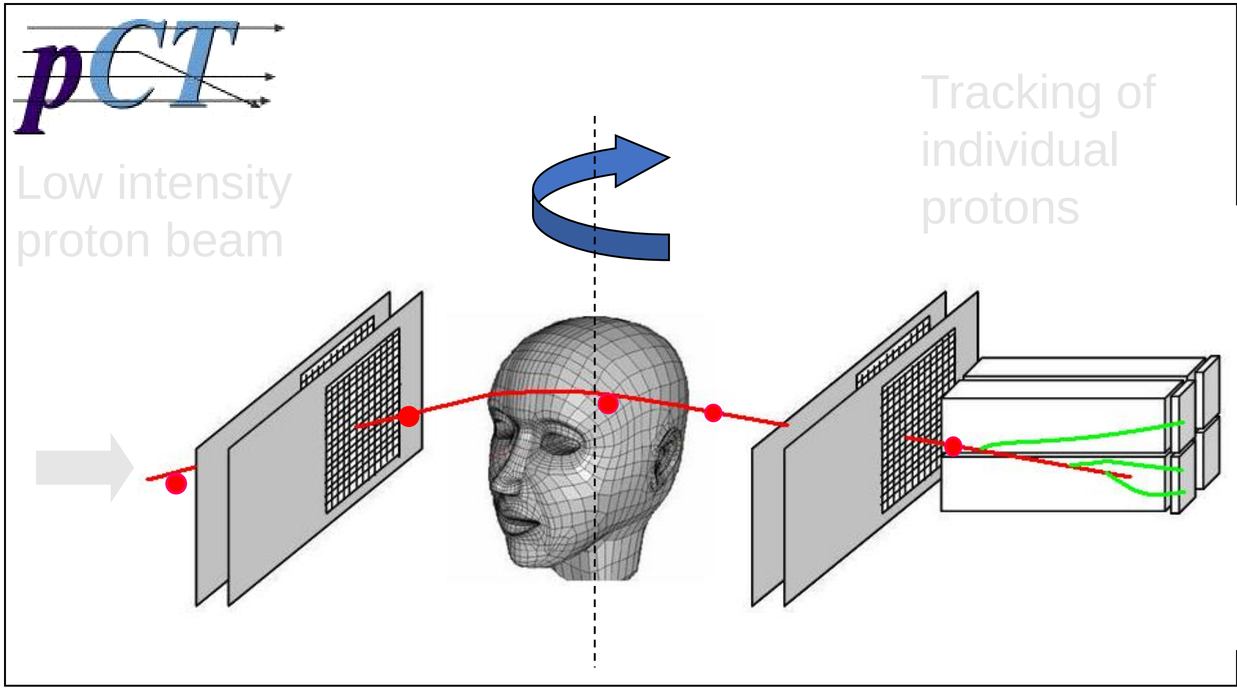
Measure Stopping power distribution directly (instead of converting X-ray CT scans

- An energetic low intensity cone beam of protons traverses the patient
- The position and direction (entry & exit) and energy loss of **each** proton is measured
- Proton histories are taken from multiple projection angles

  (angular “CT scan”)
- Minimal proton loss and high detection efficiency make this a low-dose imaging modality

Design of a Proton CT Scanner rotating with the proton gantry

(R Schulte et al. IEEE Trans. Nucl. Sci., 51(3), 866-872, 2004)



Low Contrast in Proton CT

High contrast in absorption of Photons

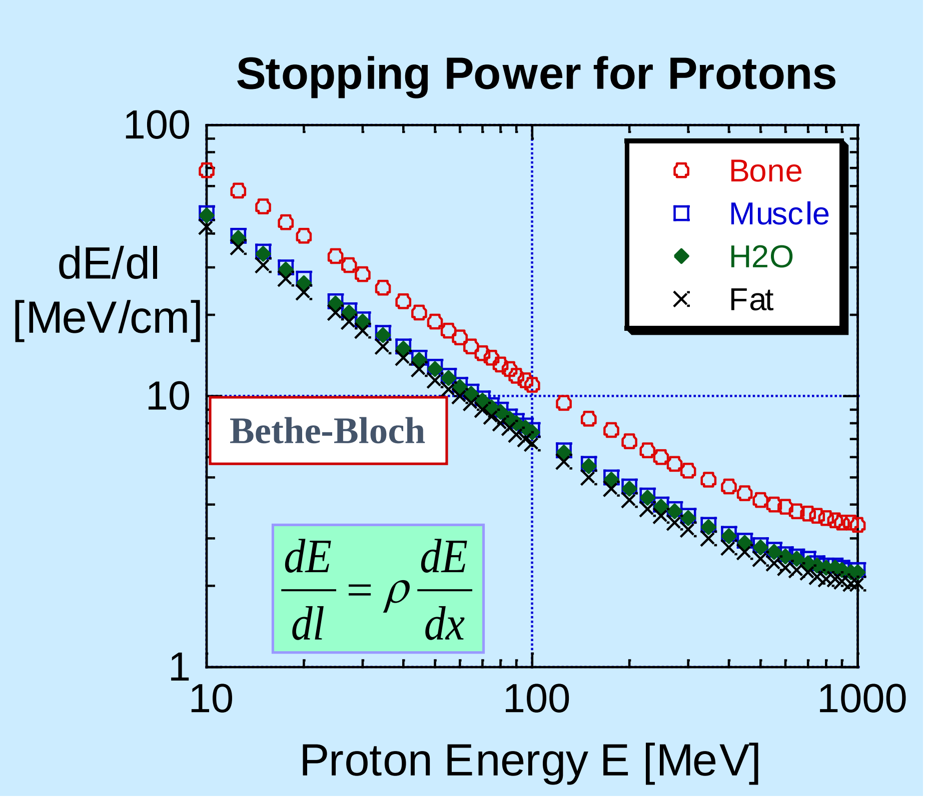
$N(x) = N_o e^{-\mu x}$

with the linear absorption coefficient μ differing by a factor 10 between bone and soft tissue.

Low contrast in energy loss of Protons

$$\Delta E = \int \frac{dE}{dx} dx \approx \sum \rho \frac{dE}{dx} \Delta l = \sum \frac{dE}{dl} \Delta l$$

with the stopping power dE/dl only 50% larger for bone than for soft tissue.

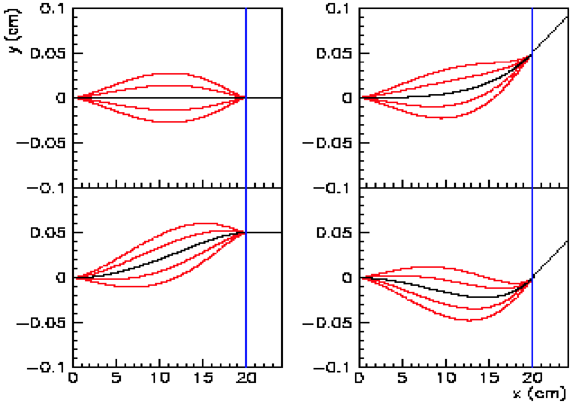


NIST Data

pCT Challenges

#1: Multiple Coulomb Scattering

The proton path inside the patient/phantom is not straight
→ the path of **every** proton before and after the phantom
has to be measured and its path inside
the patient reconstructed.



D C Williams Phys. Med. Biol. 49 (2004) 2899–2911

From deflection and displacement, calculate the "Most Likely Path MLP"

#2: Proton Data Rate

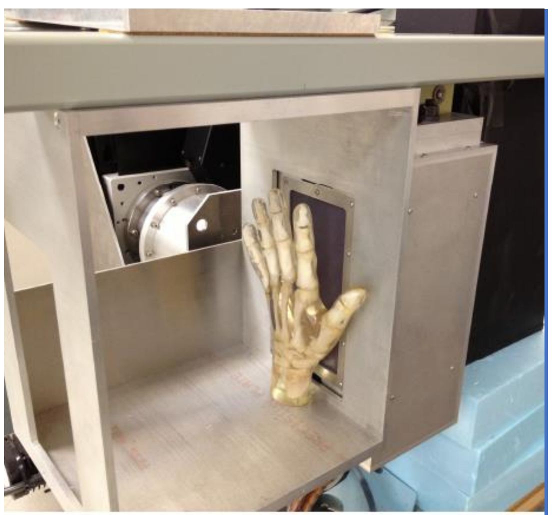
Data Flow math:

Assuming 100 protons / 1mm voxel and 180 views requires ~ $7*10^8$ protons.
A scan with a proton rate of **2 MHz** takes 6 min with a dose of 1.5 mGy.

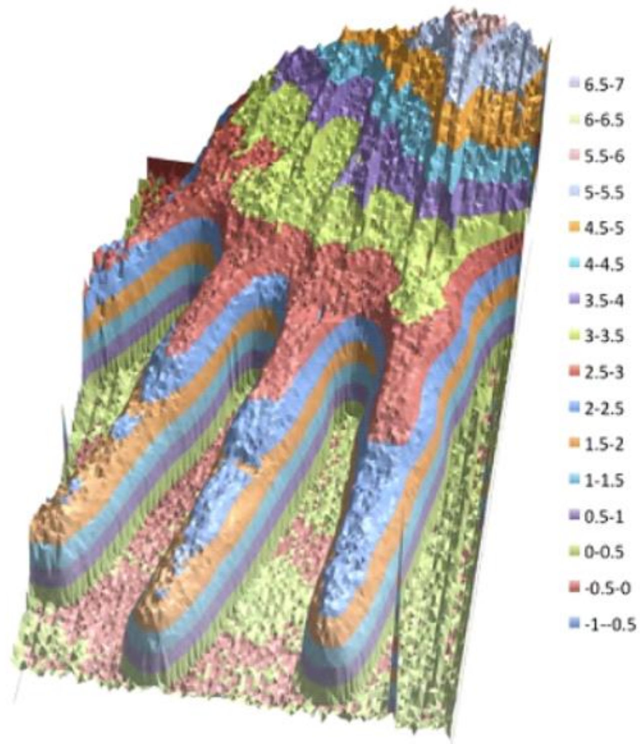
Image Reconstruction

To reconstruct images with > 10^7 voxels using ~10^9 protons is NOT trivial.
Our reconstruction code is already running on GPU's in anticipation of the much higher data rates of the future.

Hand Radiography: Something New (?)



Hand Phantom imaged with 200 MeV protons at the Loma Linda Synchrotron, using the existing pCT scanner.



Color-coded image of the summed-up stopping power in terms of water-equivalent thickness [in mm].

Note the varying thickness of the hand and clear structural details.

A step forward into Imaging History..

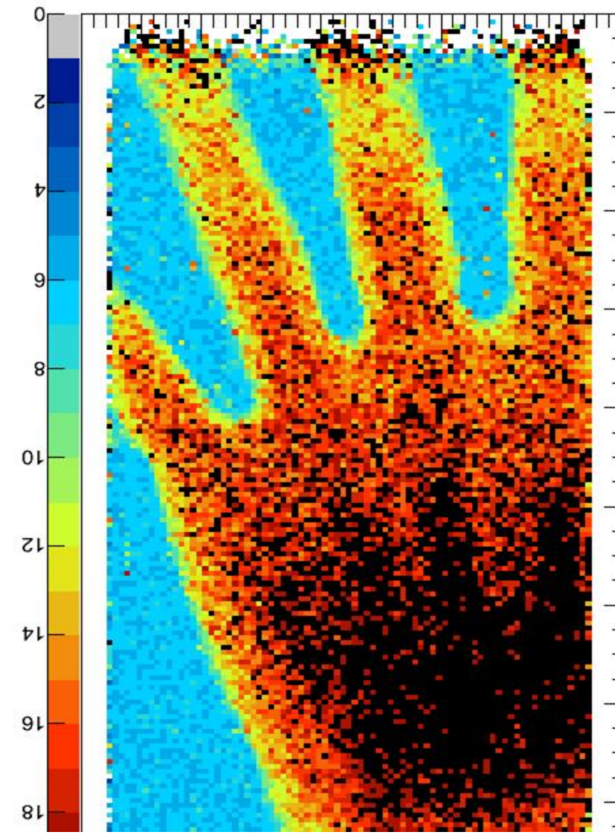
X-Rays

Wilhelm Roentgen,
Laboratory Radiology (1895)

200 MeV Protons

Stopping Power

Multiple Scattering



UCSC-LLU-CSUSB 2012, T. Plautz et al., 2012 IEEE NSS-MIC

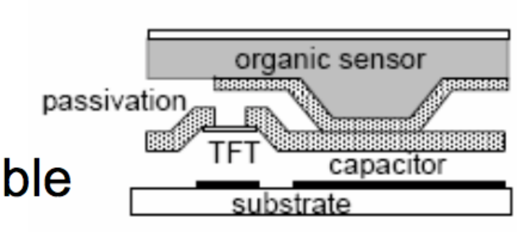
Summary

- Vivid field
- Broad range of applications
- Inspired by particle physics, but developing autonomously
- Particle physics experience still useful
- Companies exist also in the Czech Republic

Organic semiconductors

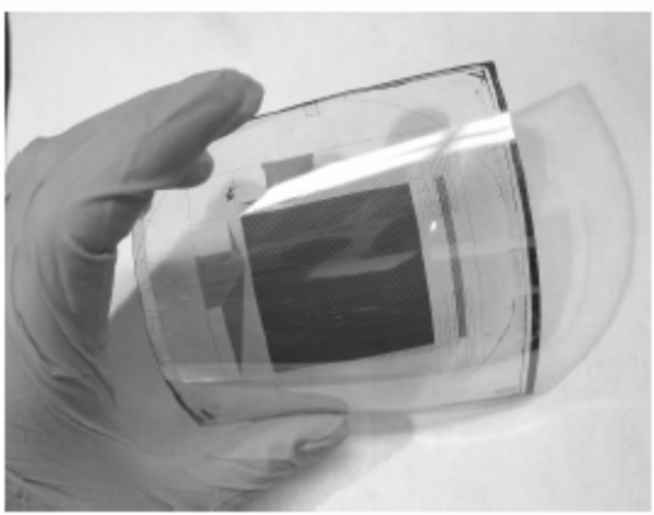
8 Motivation

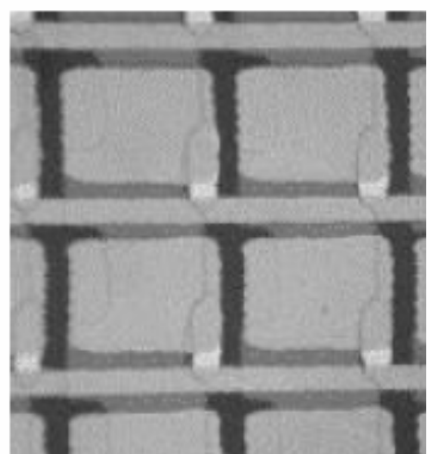
7 **Amorphous silicon**	**Organic semiconductors**
7 Glass substrates	Plastic substrates
rigid, heavy, fragile	flexible, light-weight, unbreakable
7 Structured by photolithography	Structured by jet printing
7 High-temperature processing	Low-temperature processing
7 Expensive	Cheap

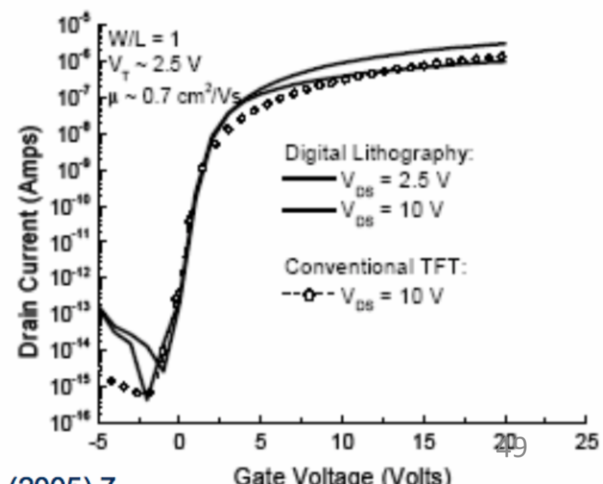


8 Result

7 Organic photodiodes and transistors are feasible







From Street et al., Proc. of SPIE 5745 (2005) 7

Energy-Resolved Methods (ERM)

- 8 Situation at the outset
  - 7 All conventional X-ray systems (film, storage phosphor, image intensifier, FD scintillator + photodiode, FD directly absorbing, CT) image the total absorption of an object
  - 7 Different combinations of objects can produce equal absorption
  - 7 ERM can differentiate between these different objects

- 8 Goal
  - 7 Improve detectability of details
  - 7 Improve signal difference-to-noise ratio (SDNR)
  - 7 Discriminate different materials / different types of tissue
  - 7 Enhance visibility of contrast media

- 8 Chance
  - 7 Allow for dose reduction, maintaining image quality / SDNR
  - 7 Save contrast media (patient stress, costs)

General trends in medical imaging

- All images become **digital**
- **3D** methods are gaining preference over 2D
- **Combination** of different modalities
- **Functional** imaging
  - Time-dependent, dynamic measurements
  - Aims at molecular methods
  - Quantitative methods
- Imaging for **therapy**
  - Image-guided interventions and operations
  - Individual treatments
  - Therapy planning and virtual reality
- **Connectivity**
  - Availability of images throughout the whole health care system
  - Tele-medicine
  - Electronic patient record
- **Computer-Assisted Diagnosis** (CAD)

Aims

- better diagnosis
- targeted therapy
- cost optimization
- prevention