Instrumentation for Neutron Imaging

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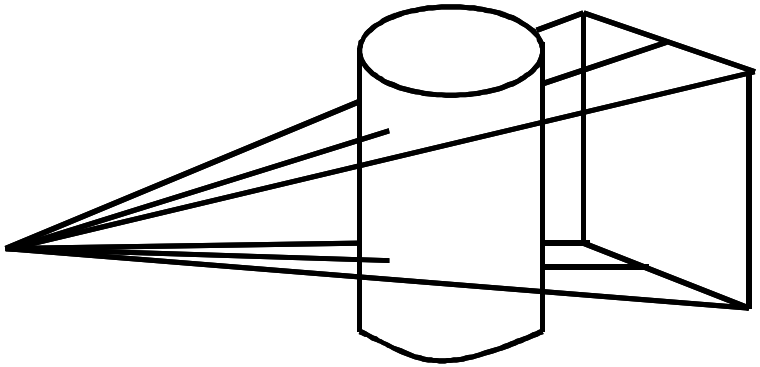
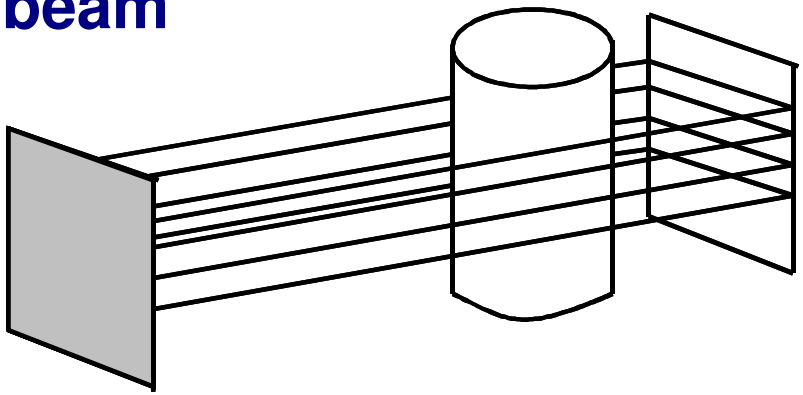
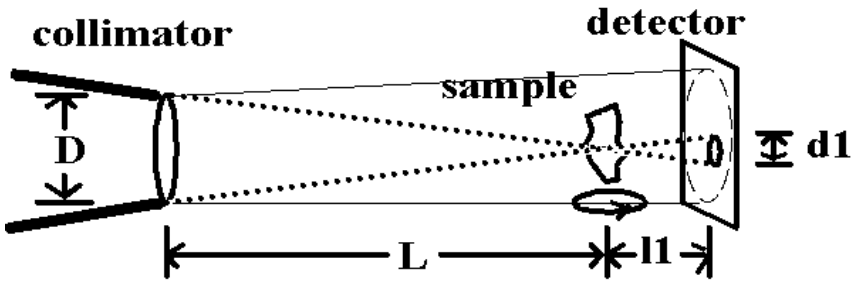
- **Radiography principle:**
  Cone beam vs. parallel beam: Resolution and L/D
- **What happens at a Neutron guide?**
- **Reactor sources: Radial vs. Tangential beam tubes**
- **Direct flight tube, neutron guide or neutron guide plus flight tube?**
- **Massive shielding required**
- **The components of the imaging setup:**
  Flight tube, Scintillation screen, mirror and cooled CCD camera.
- **The signal chain: How many neutrons are needed?**
- **The new ANTARES Upgrade facility**

Radiography principle: Cone beam vs. parallel beam





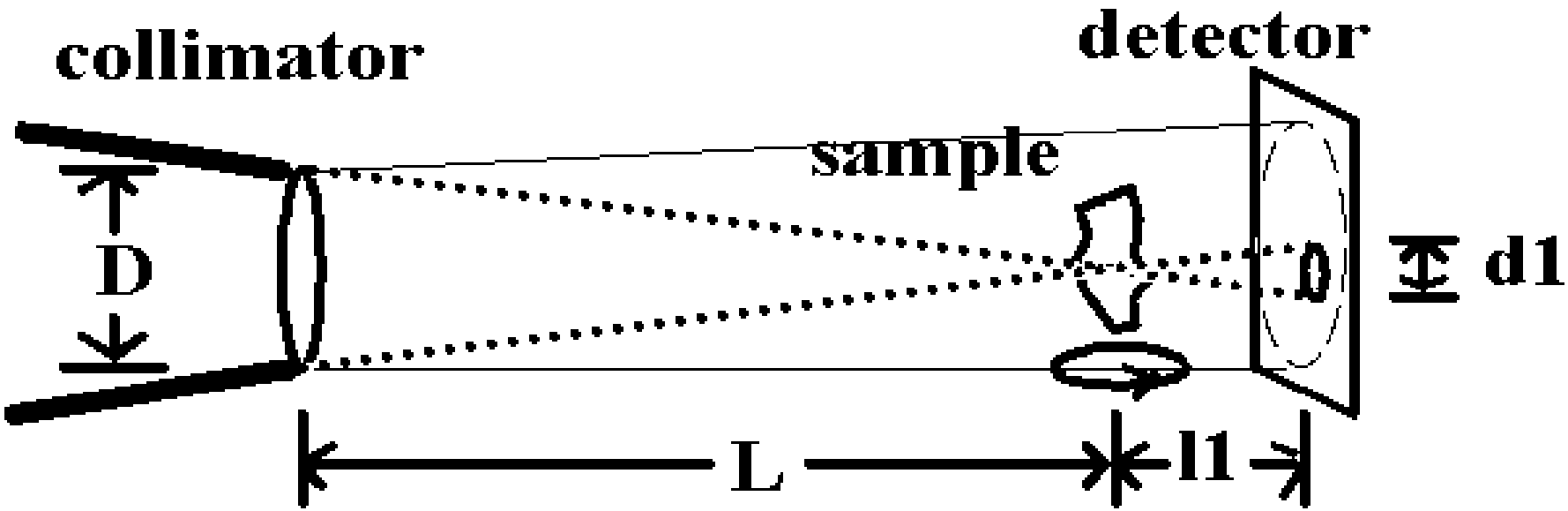


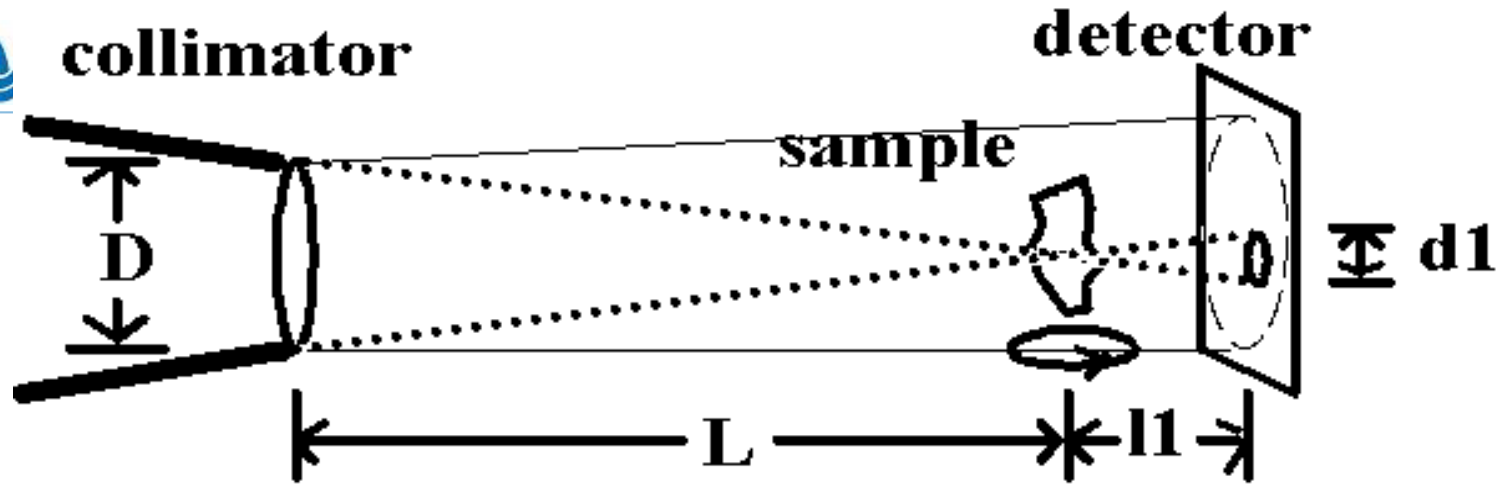
X-rays:Cone beam geometry
Inherent magnification by projection
High resolution image with
medium resolution detector

Neutrons: quasi-parallel beam geometry
No inherent magnification
Detector resolution equals
image resolution

The neutron case - flight tube vs. beam guide

For all cases, the angle of the source seen from the sample position determines the achievable resolution of a projection, assuming an ideal detector of infinite resolution.





The parameter to characterize a radiography setup is the inverse tangential of the opening angle, given as the ratio *L/D* of the source-to-sample-distance *L* vs. the source diameter *D*.

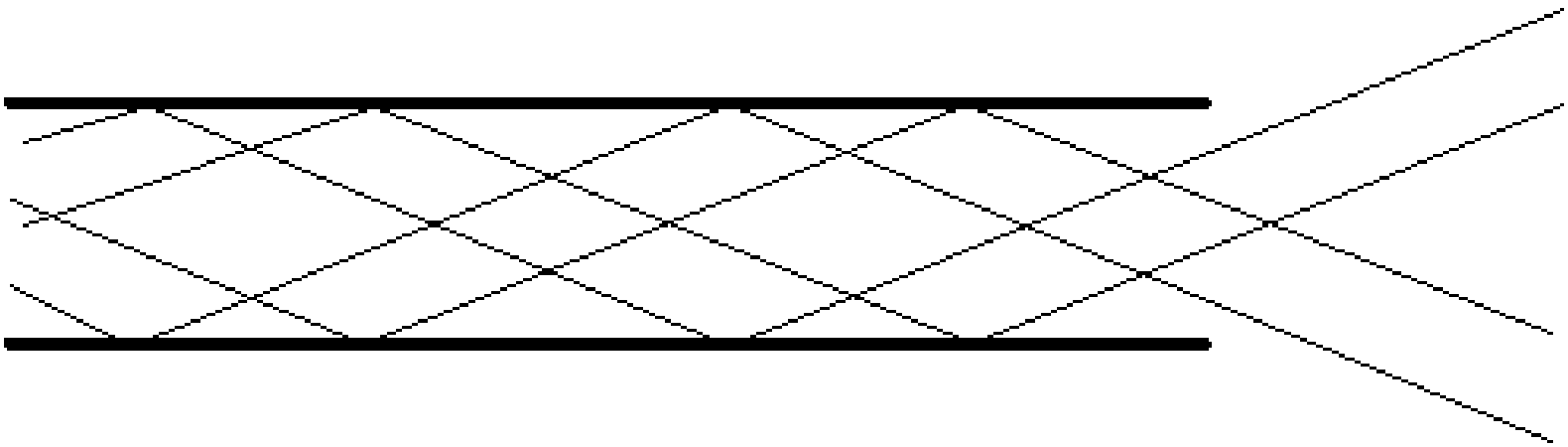
For a classical radiography setup, *D* is the diameter of a diaphragm in the beam path.

An infinitesimal volume element of the sample is projected onto a circle on the detector.

This image blur can be expressed as $d1=l1/(L/D)$, the magnification can be expressed as $M=L/(L-l1)$.

If radiography is performed at the end of a neutron guide, the divergence of the beam is given by the critical angle of reflection γ_c of the neutron guide.

The divergence is constant within the cross section of a straight neutron guide, it acts like a divergent area source.



Beam geometry at a neutron guide

Slow neutrons can be totally reflected from surfaces up to a critical angle of

$$\gamma_c = \sqrt{2(1-n)} = \lambda \sqrt{\frac{Na}{\pi}} \qquad \approx 10^{-3} \ldots 10^{-2}$$

N is the atomic density of the wall material, a the coherent scattering length, and λ the neutron wavelength .

For a guide coated with natural nickel, we get
$\gamma_c = 1.73 \cdot 10^{-3}$ rad /Å, or 0.1°/ Å .

For a supermirror guide, the angle is multiplied
by the parameter m of the supermirror.

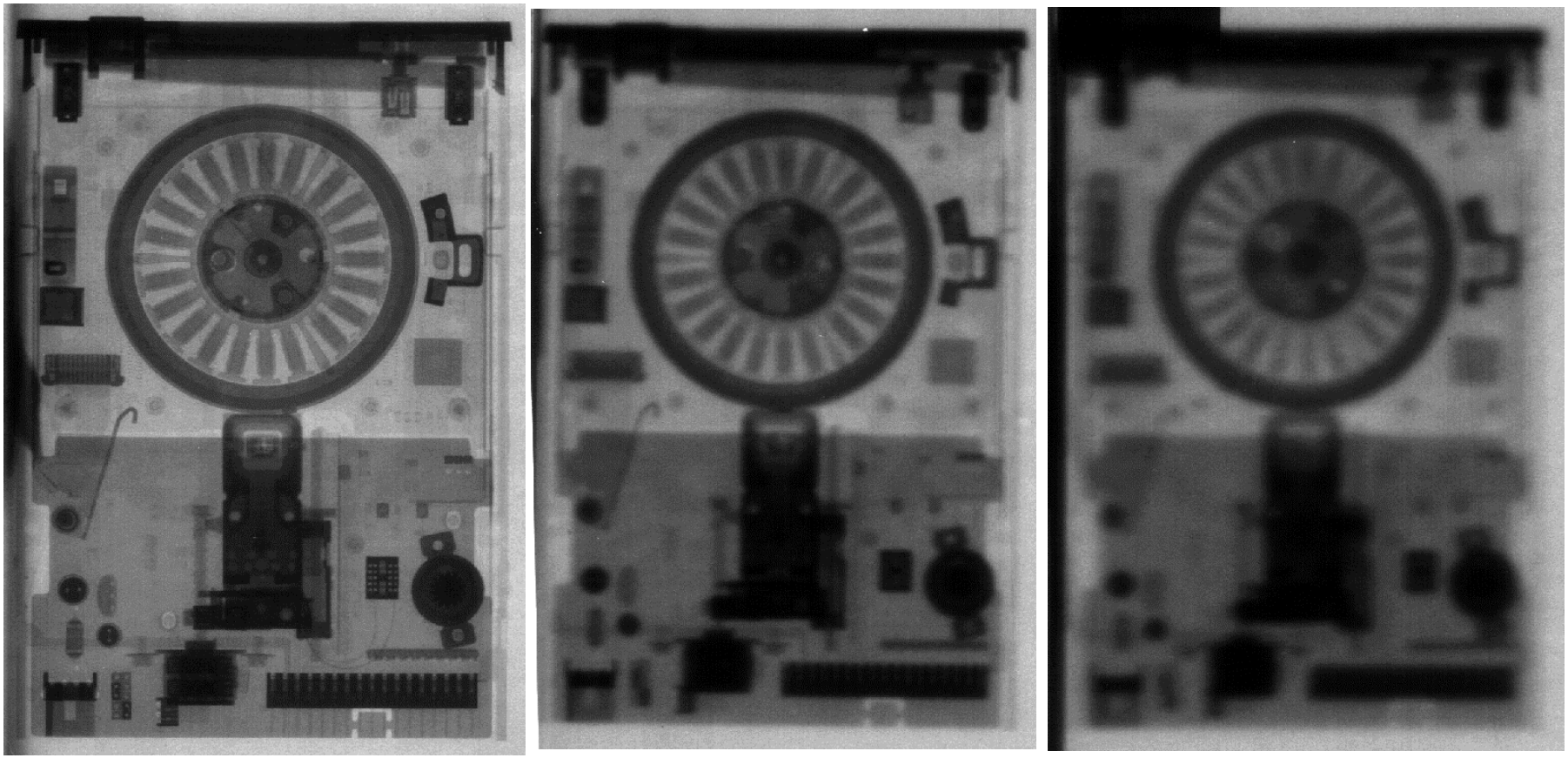
The beam divergence becomes dependent on the wavelength, and we need to calculate an ”effective” *L/D*-ratio which determines the quality of a projection.

If the spectrum is known, we can estimate *L/D* by calculating the arithmetic mean value of all wavelengths as λ_{av} and by substituting λ_{av}, we can calculate

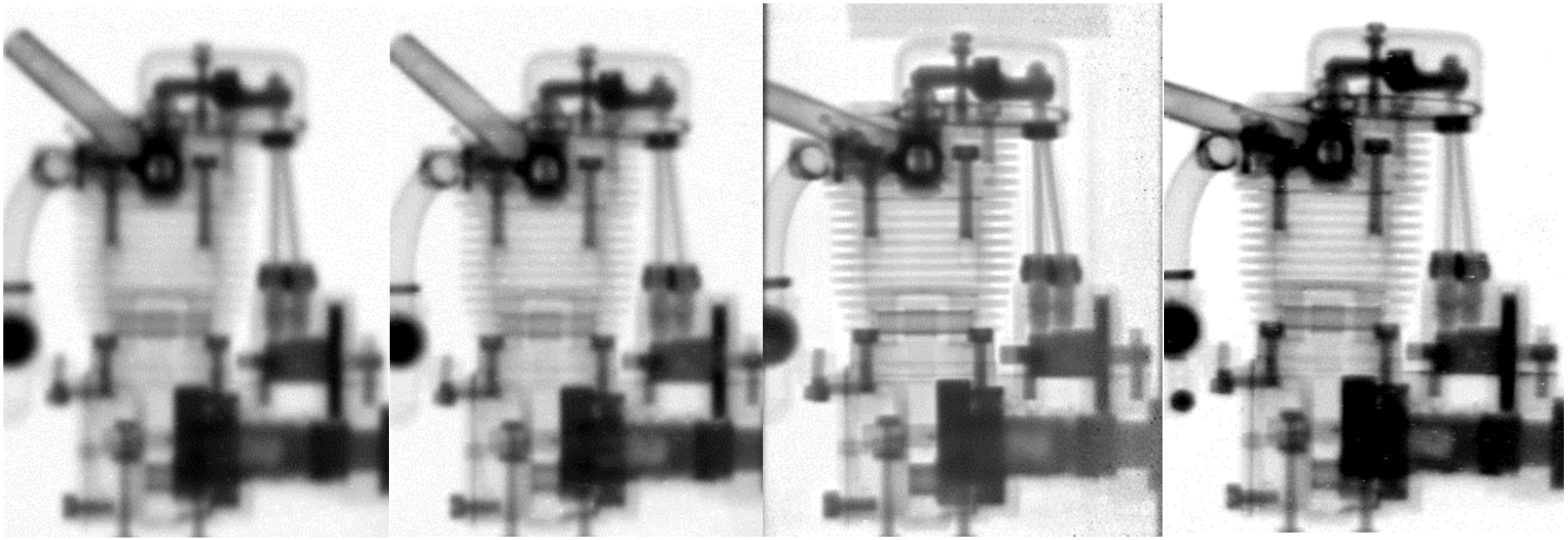
$$L/D = 1/\tan(2\gamma_c).$$

Still, a more accurate calculation has to take into account the angular distribution for each wavelength, integrated over all wavelengths.

A Neutron guide alone is not a good choice for a neutron radiography facility, as can be shown by the measurements below.



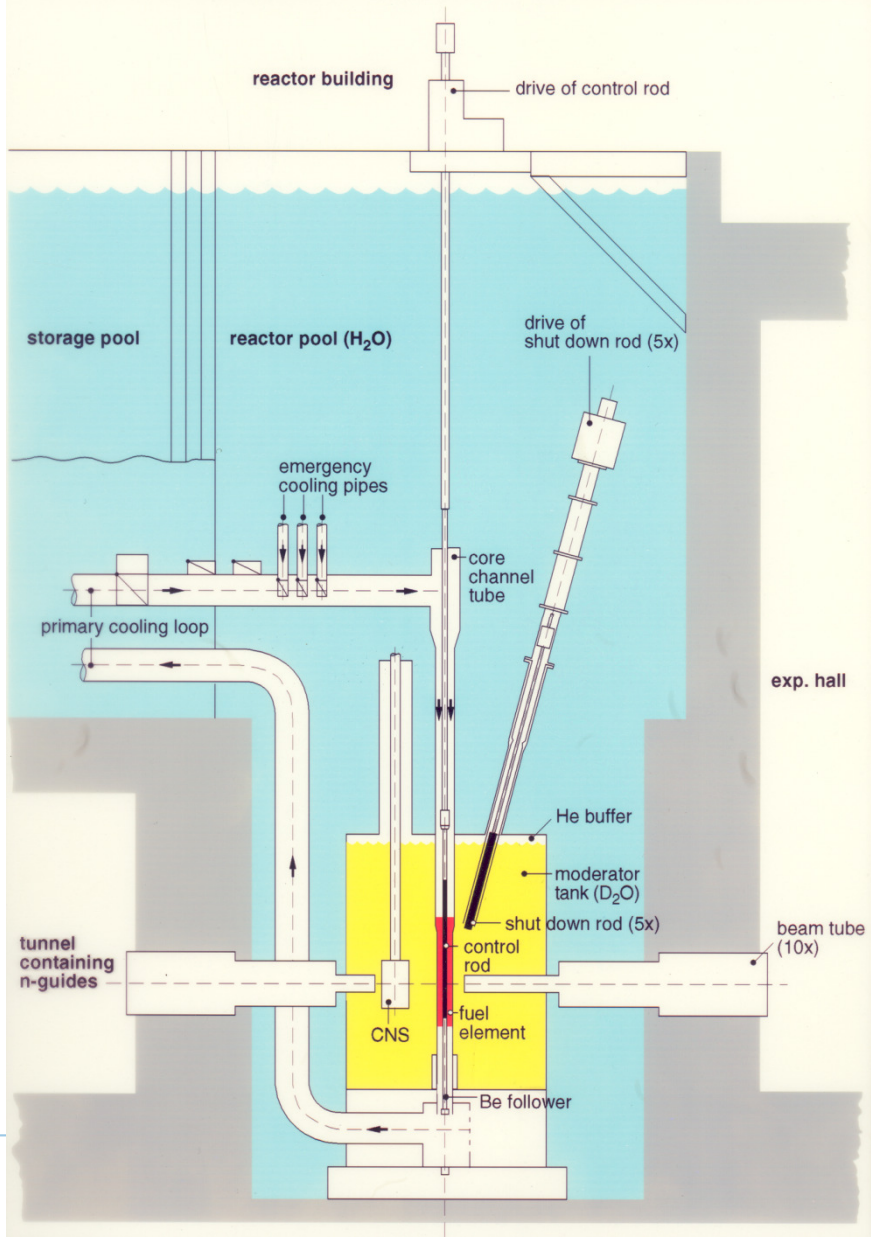
Radiographs of a 3,5" floppy drive in 0 cm , 10 cm and 20 cm distance from a film + Gd sandwich taken at a cold neutron guide with *L/D*=71.



L/D=71 L/D=115 L/D=320 L/D>500.

Radiographs of a small motor taken at different beam positions with different L/D ratios.

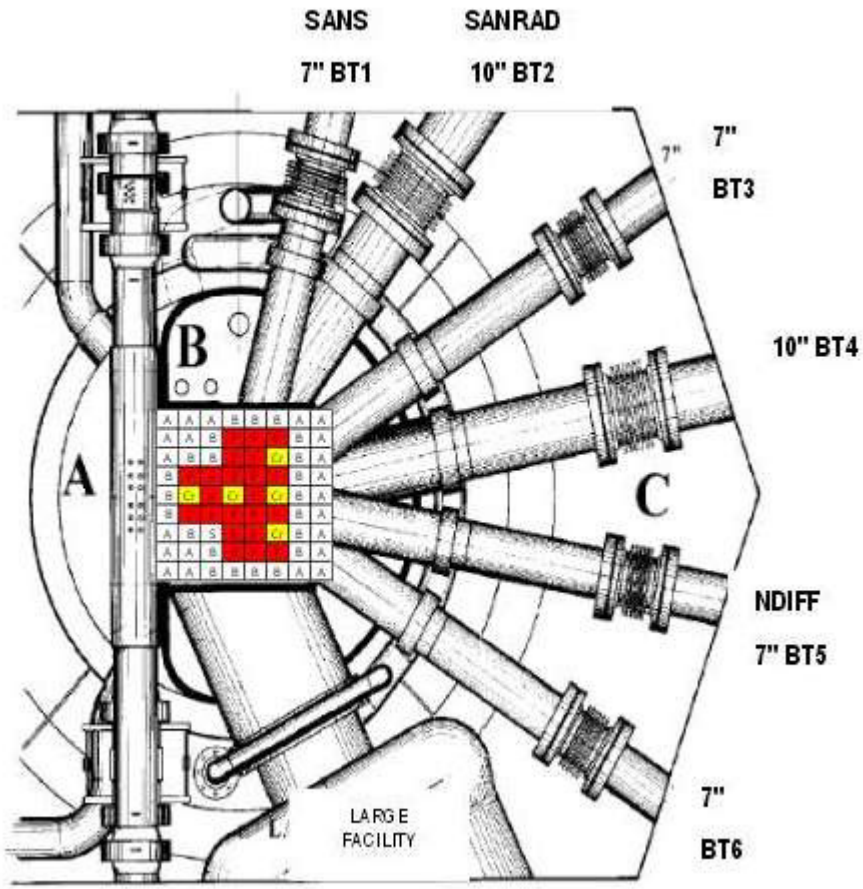
The radiographs were taken at a cold guide, a thermal guide, a cold guide with a consecutive 15 mm pinhole and 4.8 m flight tube and at a classical 20 mm pinhole and 10 m flight tube arrangement.



Schematic construction of the neutron source FRM II

- Compact fuel element with Uranium silicide
  (~ 8kg Uranium, 93% enrichment)
- Heavy water moderator
- Thermal power 20 MW
- Primary cooling cycle with light water
- Two independent shutoff systems
- Biological shielding by 1.25m water and 1.5m heavy concrete sideways, and 10m water upwards

Traditional reactor design:
Radial beam tubes at the SAFARI reactor

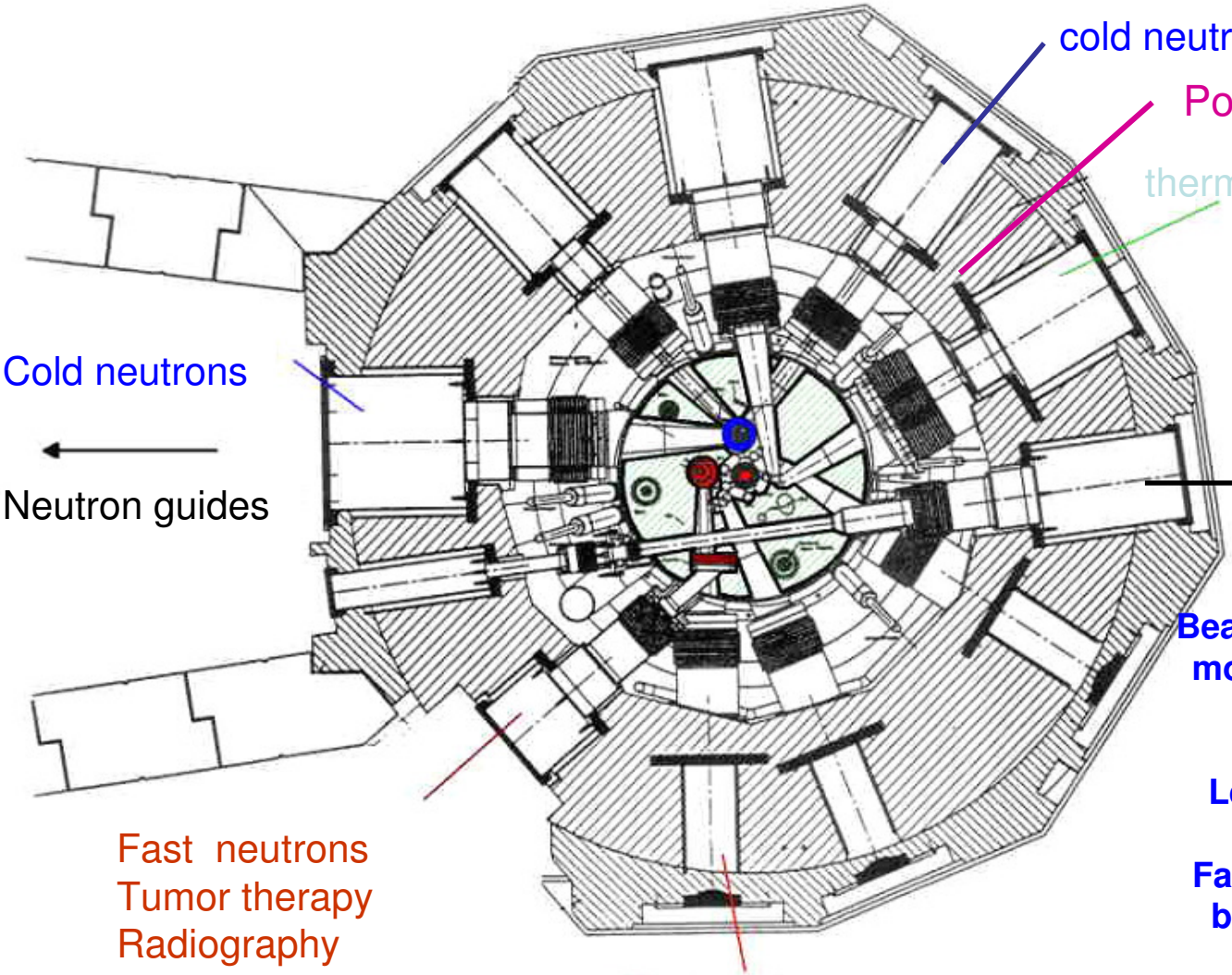


Direct view to the core

Problem:
Direct view to fission-generated gamma Radiation and fast neutrons –

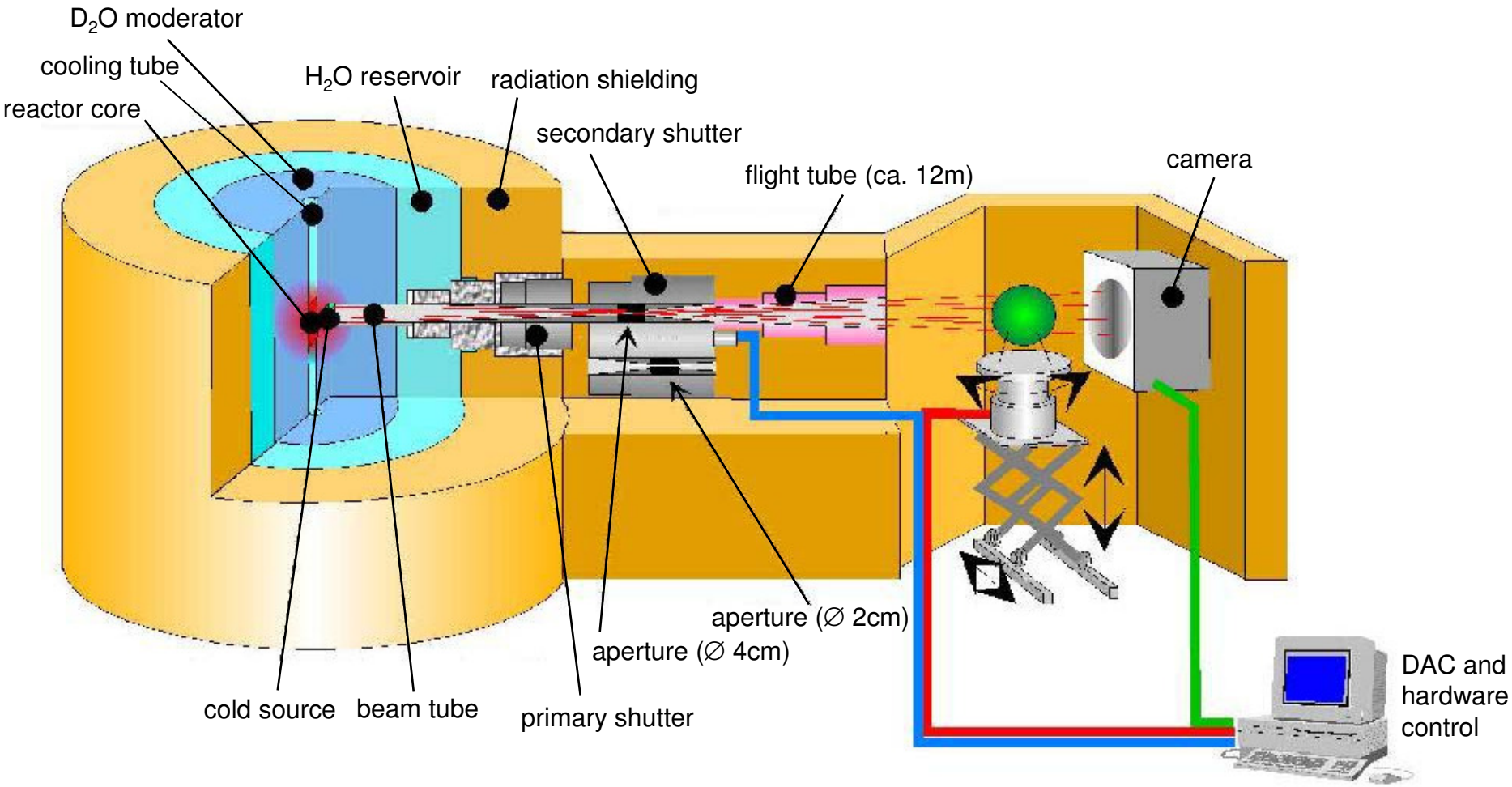
requires massive shielding at experiment.

Modern reactor design:
Tangential beam tubes at the FRM II reactor (First introduced 1967 at the ILL Reactor)



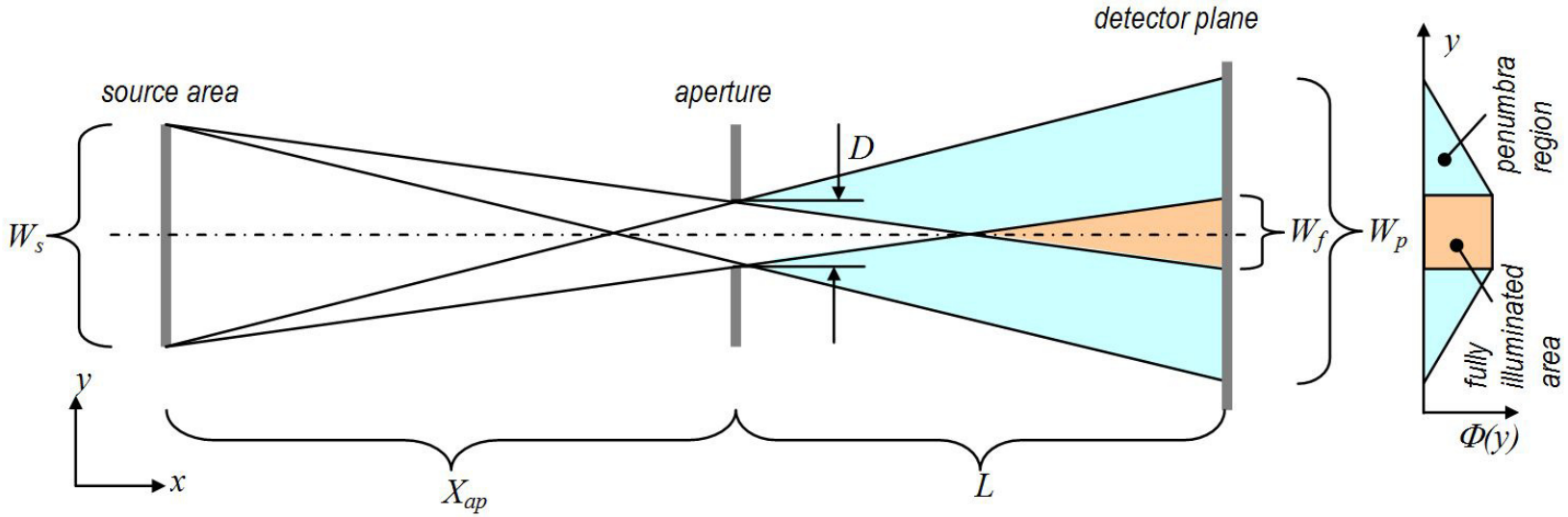
Beam tubes look into cloud of moderated neutrons around the core-
no direct view to core,
Less shielding required at experiment.
Fast neutrons can still enter beam tubes by one single scatter process.

Principle setup with flight tube for imaging with thermal neutrons



The source is projected onto the sample position.

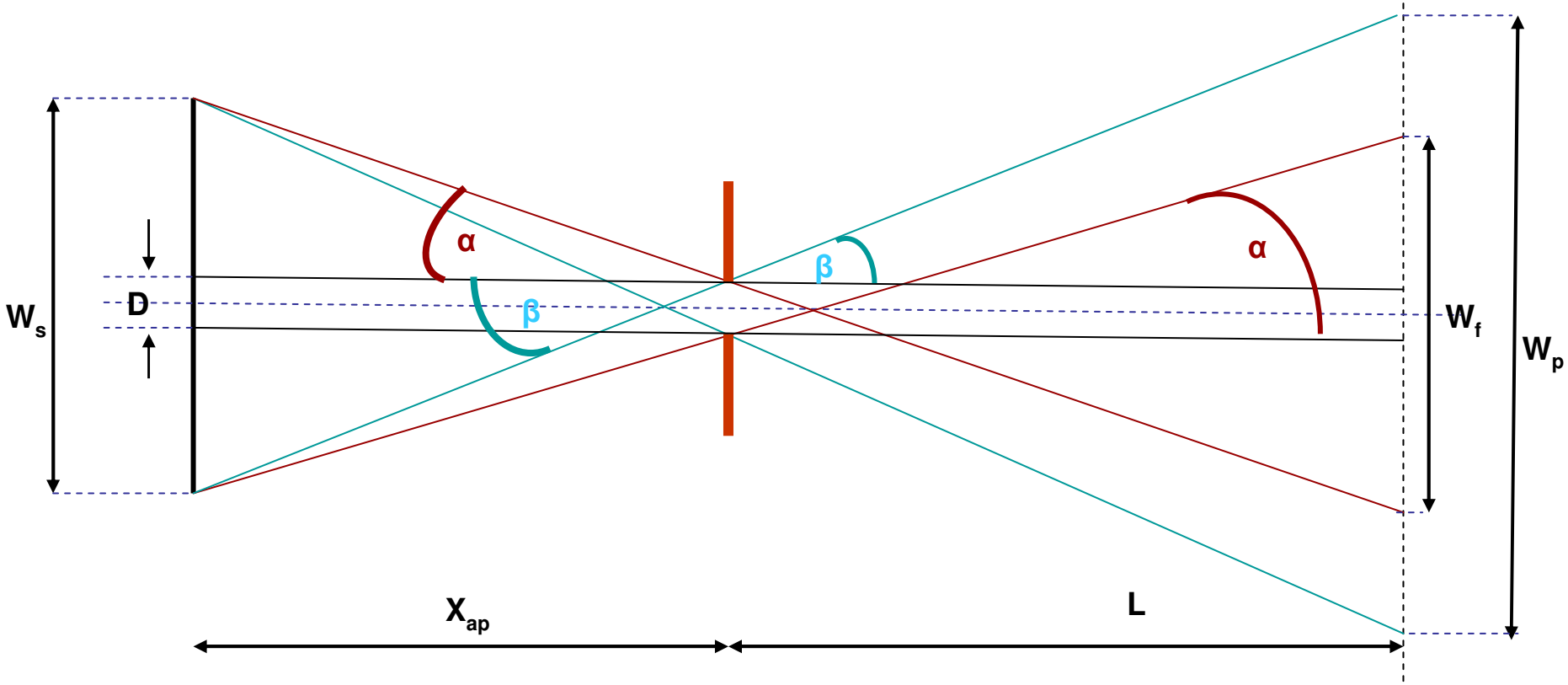
From the fully illuminated area in the center, intensity decays in a penumbra region.



$$W_f = \frac{-D + W_s}{X_{ap}}\left(X_{ap} + L\right) - W_s$$

Ph.D. thesis F. Grünauer, 2005

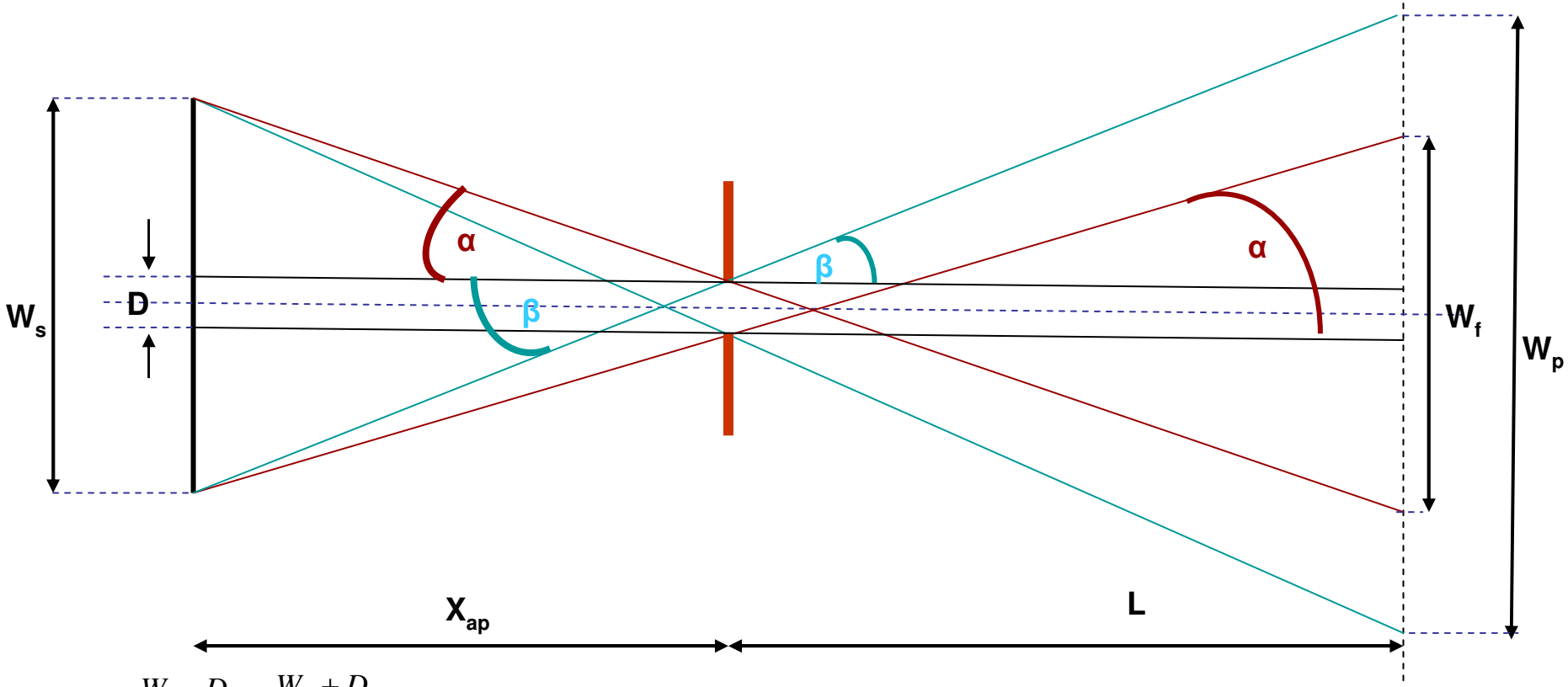
W_s : width of source
D : diameter of aperture
W_f : width of fully illuminated area
X_{ap} : distance source-aperture
W_p : width of penumbra
L : distance aperture-detector



$$\tan\alpha = \frac{\frac{W_s}{2} - \frac{D}{2}}{X_{ap}} = \frac{W_s - D}{2X_{ap}} = \frac{\frac{W_f}{2} + \frac{D}{2}}{L} = \frac{W_f + D}{2L}$$

$$\tan\beta = \frac{\frac{W_p}{2} - \frac{D}{2}}{L} = \frac{W_p - D}{2L} = \frac{\frac{W_s}{2} + \frac{D}{2}}{X_{ap}} = \frac{W_s + D}{2X_{ap}}$$

W_s : width of source
D : diameter of aperture
W_f : width of fully illuminated area
X_{ap} : distance source-aperture
W_p : width of penumbra
L : distance aperture-detector



$$\frac{W_s - D}{2X_{ap}} = \frac{W_f + D}{2L}$$

$$\frac{L(W_s - D)}{X_{ap}} = W_f + D$$

$$\boxed{W_f = \frac{L(W_s - D)}{X_{ap}} - D}$$

$$\frac{W_p - D}{2L} = \frac{W_s + D}{2X_{ap}}$$

$$W_p - D = \frac{L(W_s + D)}{X_{ap}}$$

$$\boxed{W_p = \frac{L(W_s + D)}{X_{ap}} + D}$$

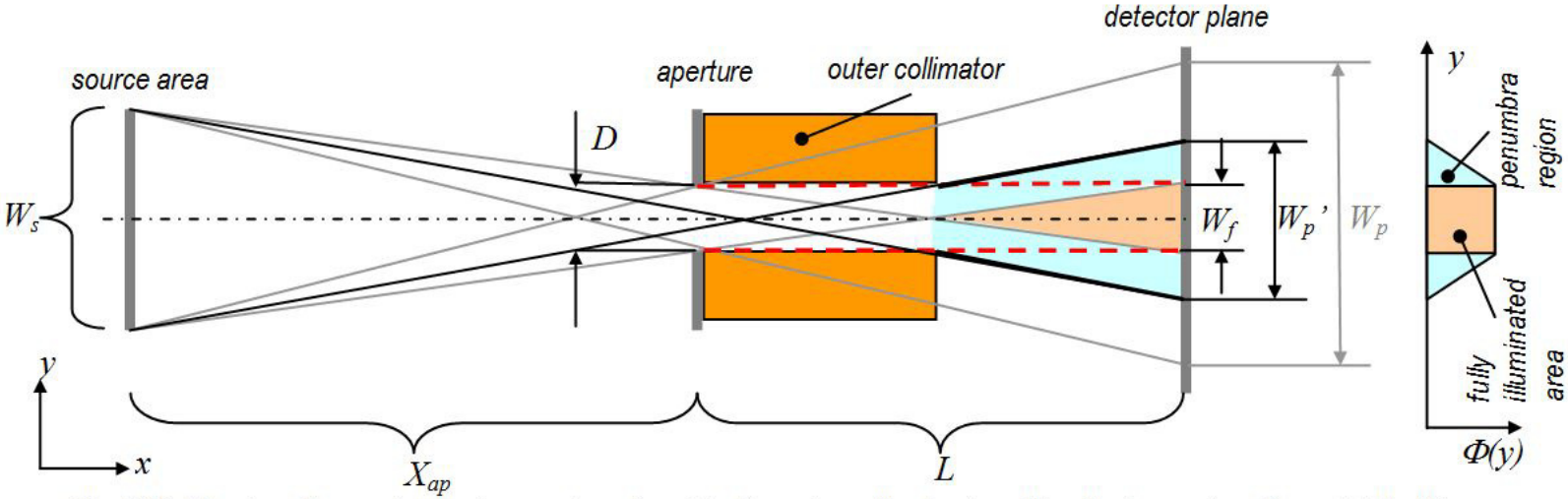
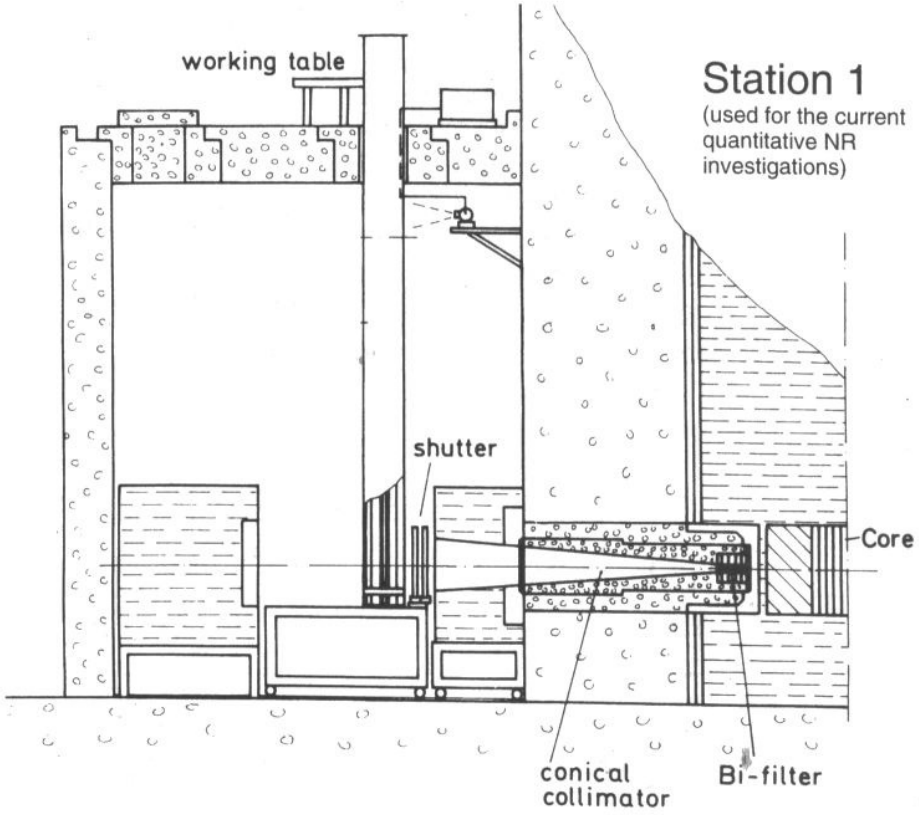
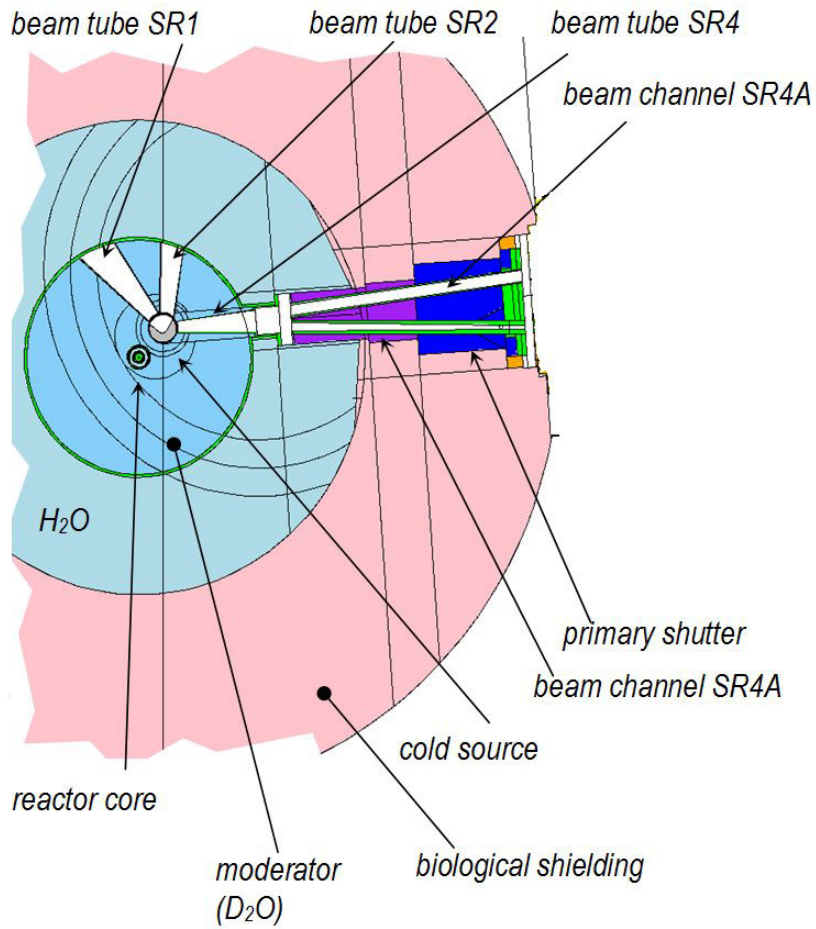


Fig. 2.29: The size of penumbra region can be reduced by the outer collimator by cutting the beam along the red dotted line

$$W_p = \frac{D + W_s}{X_{ap}} \left(X_{ap} + L \right) - W_s$$

Ph.D. thesis F. Grünauer, 2005





250 kw TRIGA @ Atominstitut Wien (1964)

Radiography facility with single aperture close to thermal column and conical beam tube

L/D=50

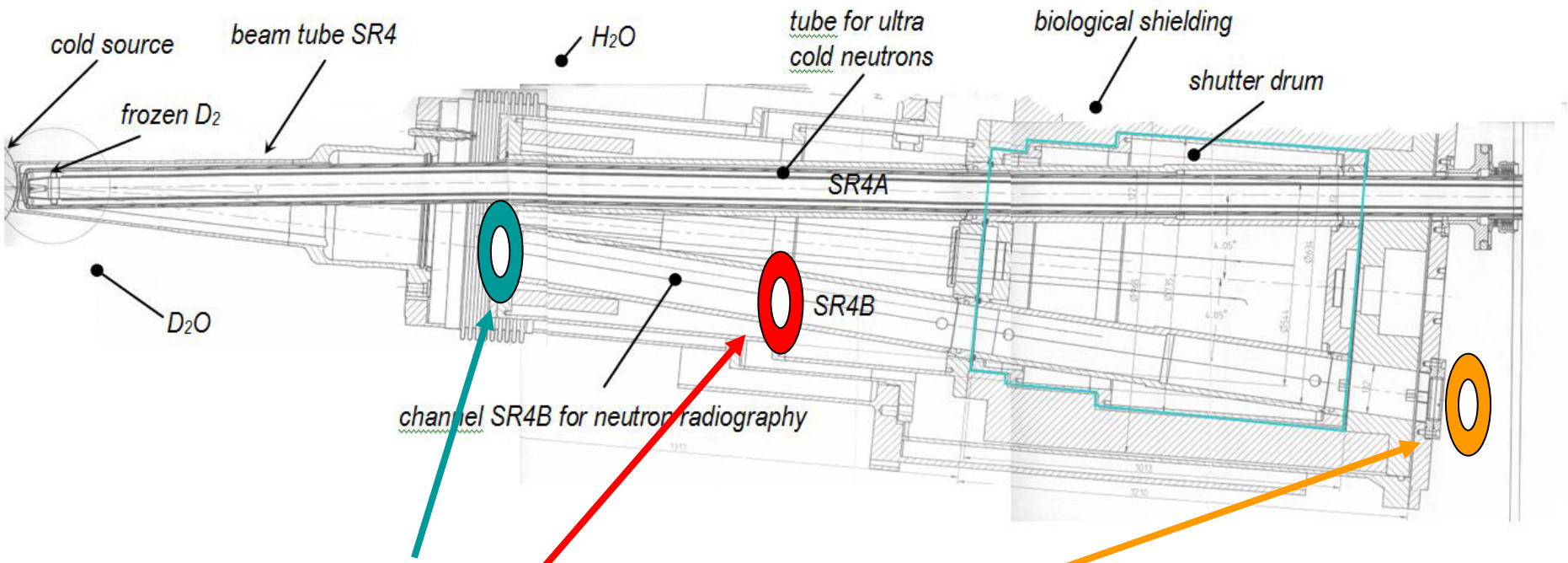
S. Körner, 1996

Beam tube concept on FRM II reactor

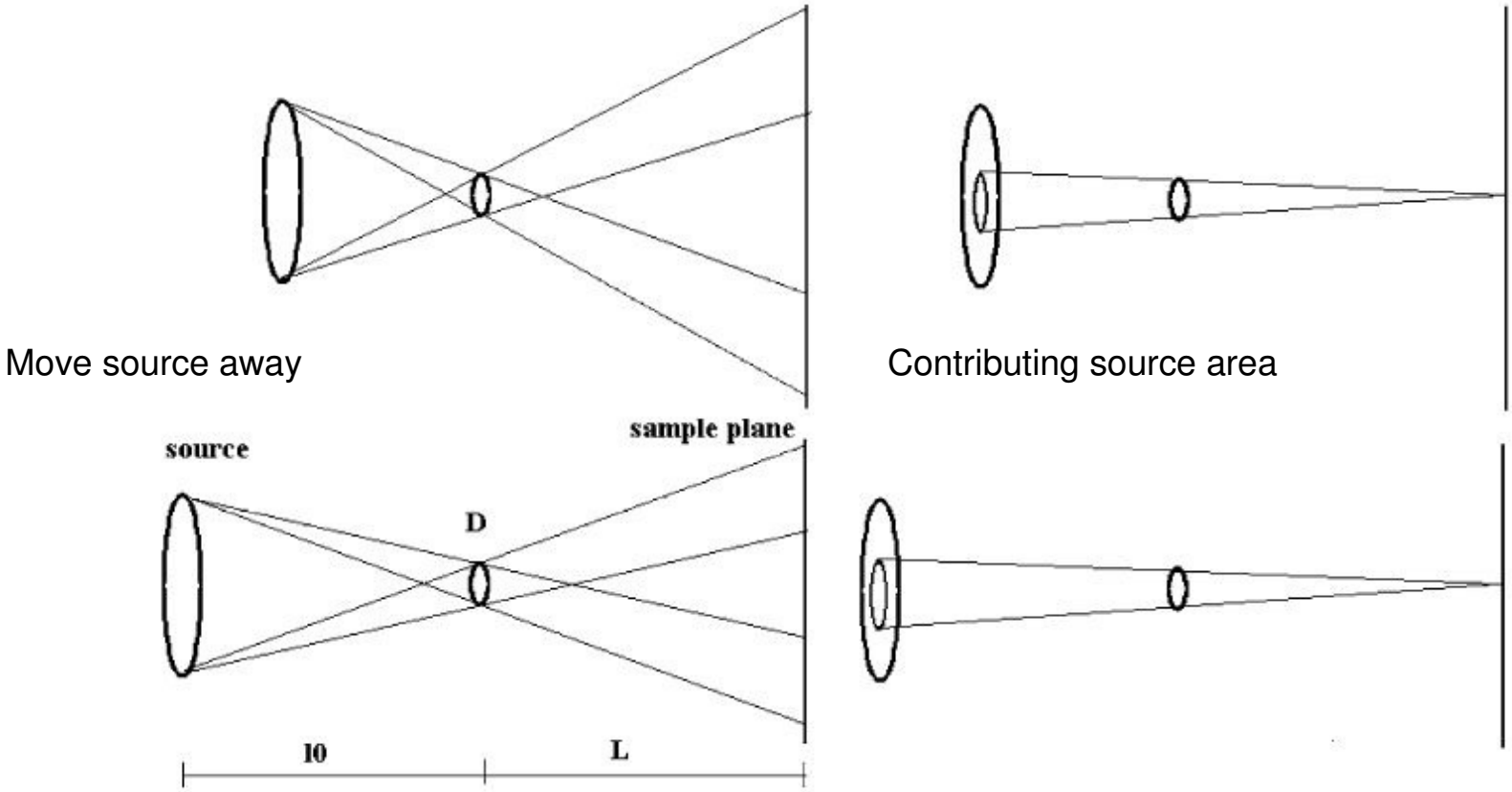
Channels of fixed width – Where to put the aperture?

Ph.D. thesis F. Grünauer, 2005

SR4 Beam tube on FRM II, with originally planned UCN source in SR4a



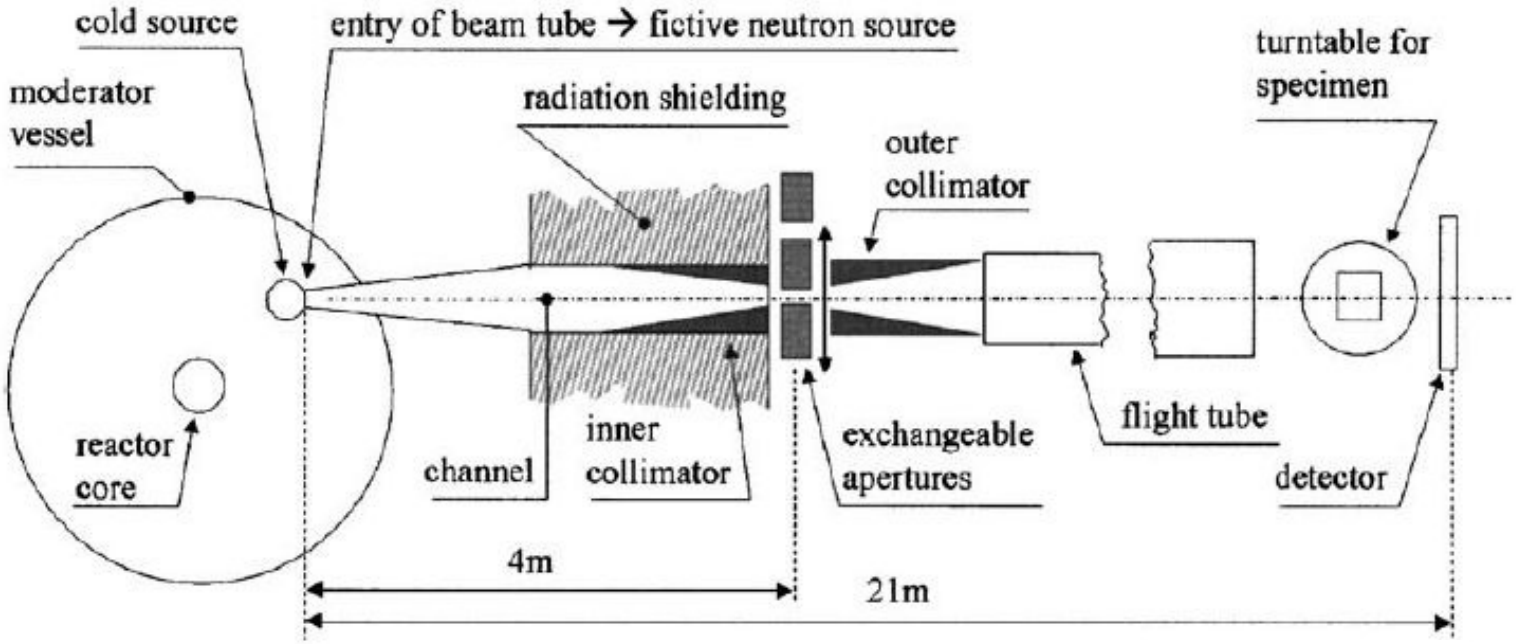
- **Place the aperture here, close to the source? Biggest projected field after the aperture, but – cut off by limited channel width.**
- **Place the aperture here, in the middle between source and channel exit? Maximum use of channel width, biggest transmitted beam, but – cannot be changed here.**
- **Place the aperture here, after the channel exit? Beam size limited, BUT: Aperture can be exchanged here, and the beam can be optimized for high intensity or high resolution!**



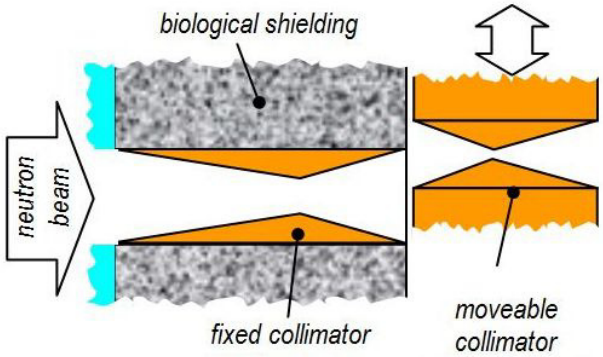
- **Moving the aperture away from the source (while keeping the distance to sample + detector constant) decreases the fully illuminated area.**
- **But the source area contributing to the intensity in one point increases!**
- **The effects cancel each other out, the intensity in the center of the detector remains the same – but always smaller than the 1/R² intensity value without an aperture.**

B. Schillinger et al. / Applied Radiation and Isotopes 61 (2004) 653–657

SR4 Beam line concept for radiography



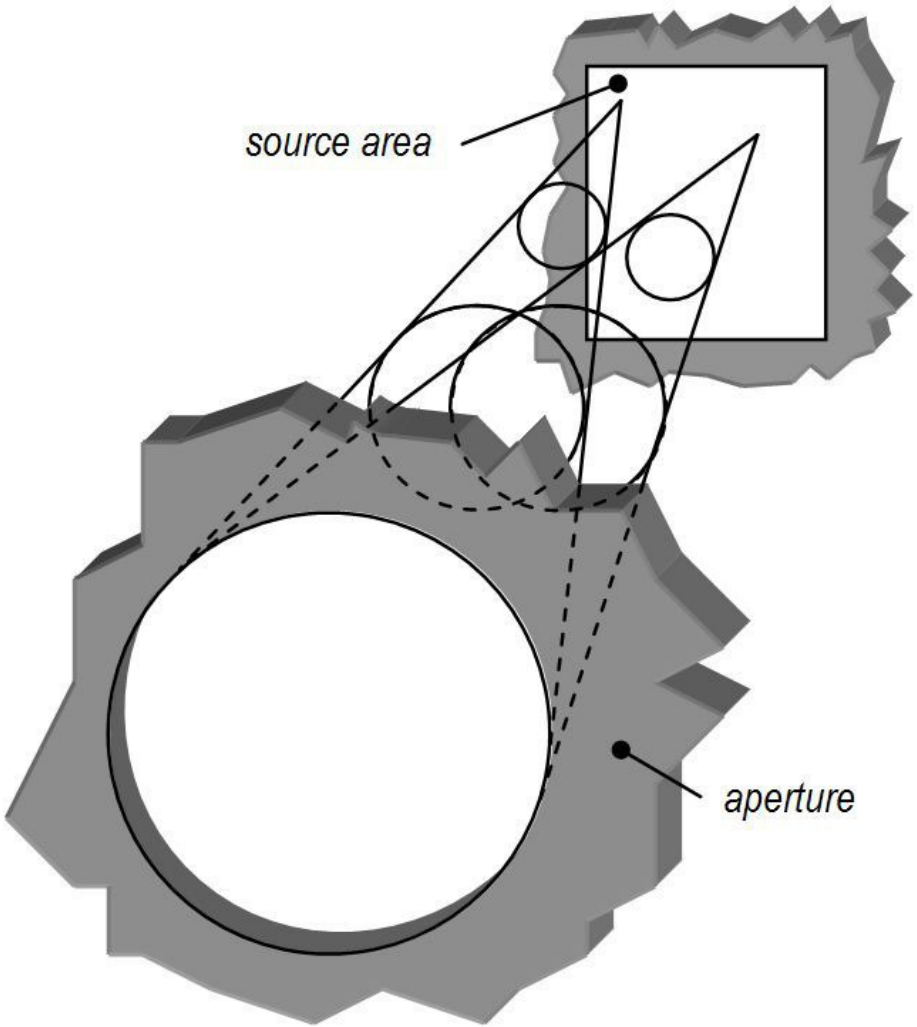
- **Inner collimator in channel with large aperture – to keep as much radiation as posssible inside the biological shielding.**
- **Exchangeable apertures outside the channel**
- **Large distance to sample position for high collimation and large beam spread**



F. Grünauer et al. / Applied Radiation and Isotopes 61 (2004) 479–485

Flight paths emerging from one point on the source area and passing through the transmitting area of the desired aperture are confined by elliptical cones.

View from the aperture to the source area.



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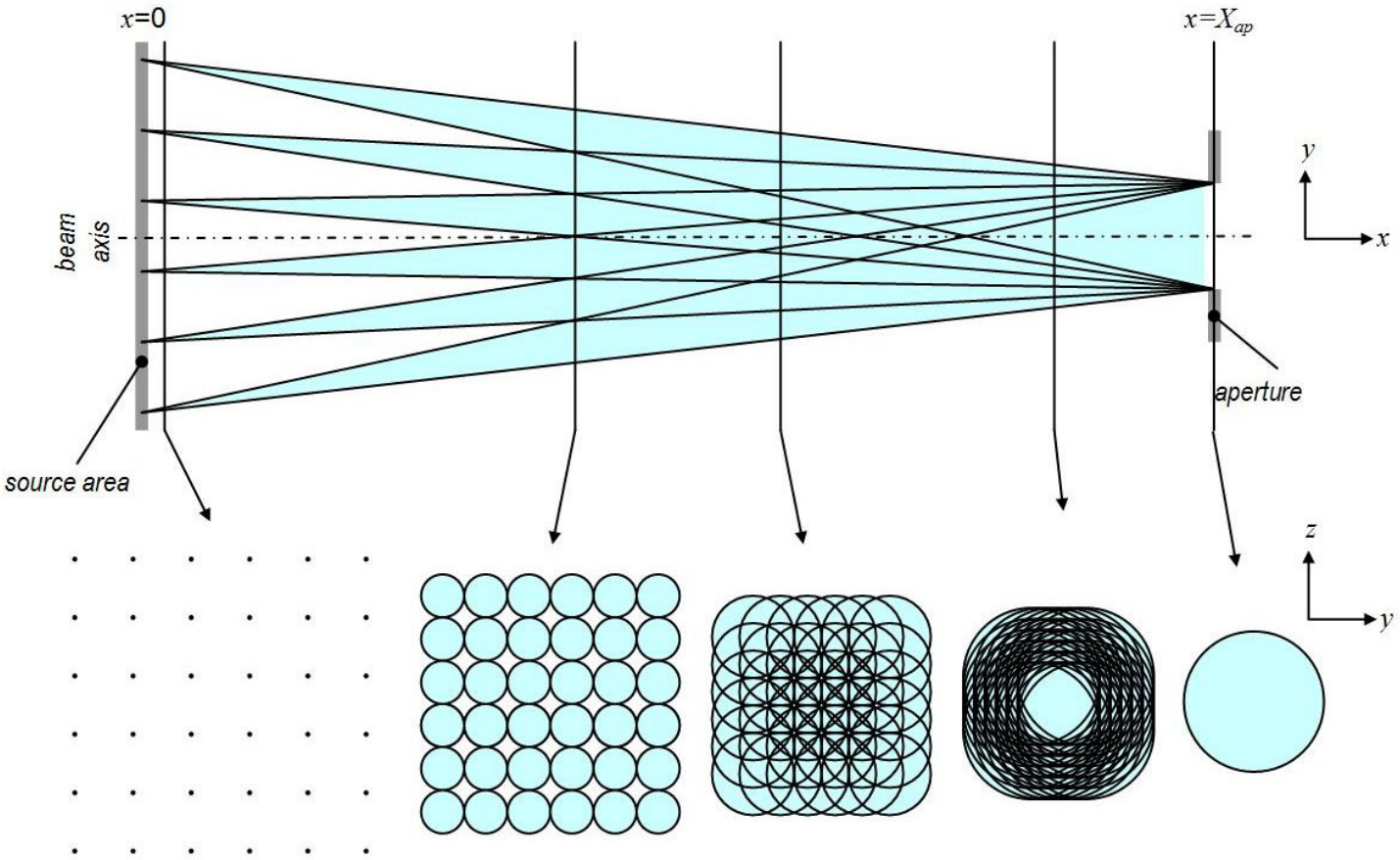

Top: Horizontal cross section through the ones emerging from 6 source points between source and aperture.

Bottom: Vertical cross section through the cones emerging from all 36 points at different distances from the source area.

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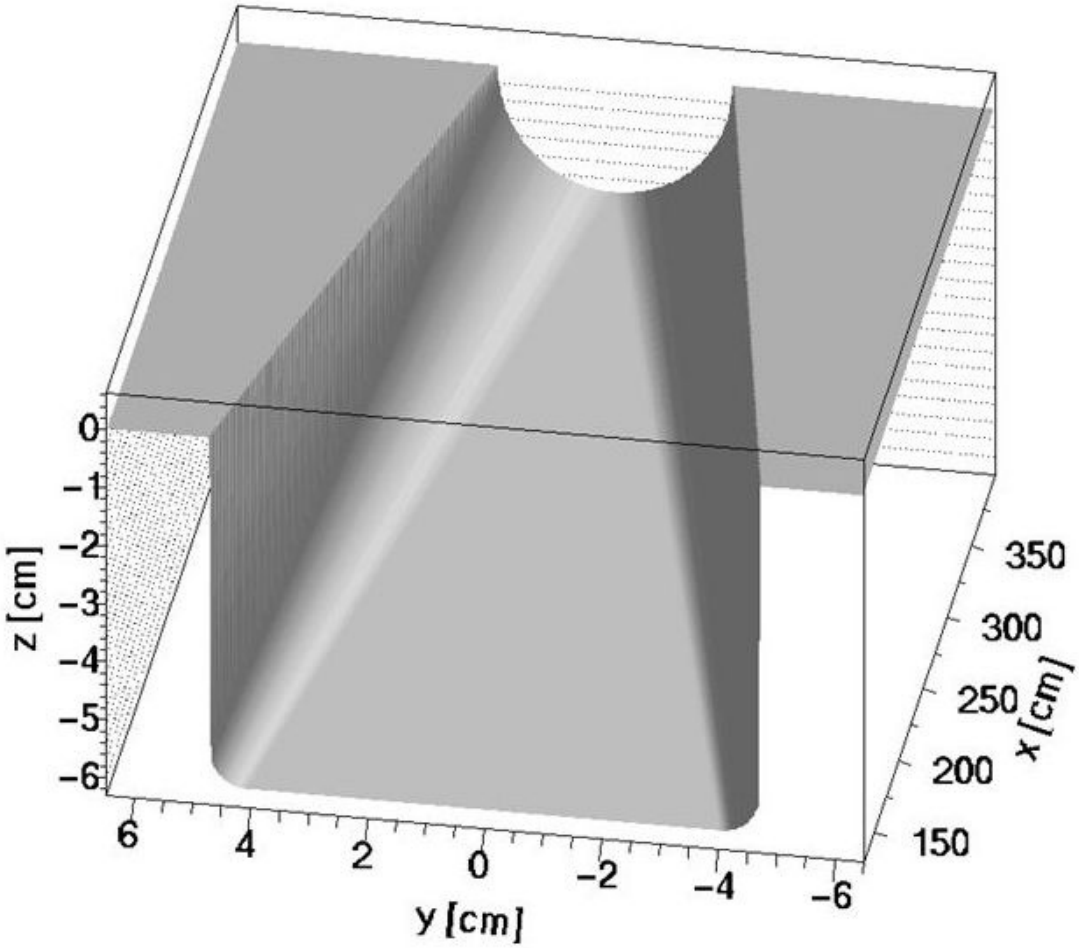
The ideal beam adapted collimator: Projects a square source area onto a square detector, suppressing everything else

Lower half of the surface that confines all deswired neutron paths between source area and aperture. The volume inside the surface corresponds to the to the transmitting volume of an ‘optimal beam adjusted‘ collimator.



F. Grünauer et al. / Applied Radiation and Isotopes 61 (2004) 479–485

The ideal beam adapted collimator: Projects a square source area onto a square detector, suppressing everything else

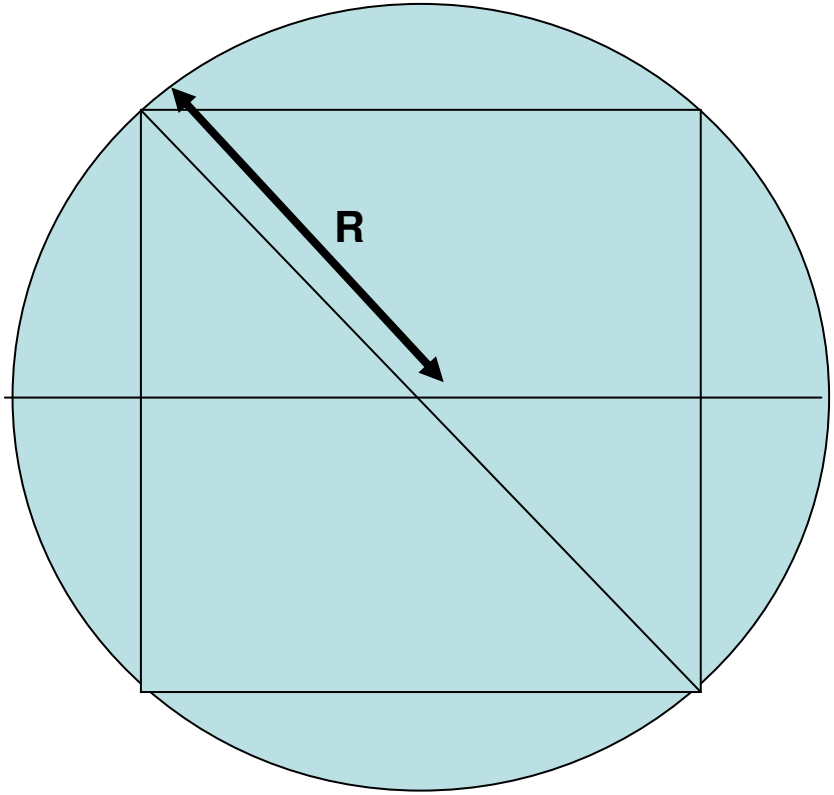
Area of square: 2 * R^2

Area of circle: Pi * R^2

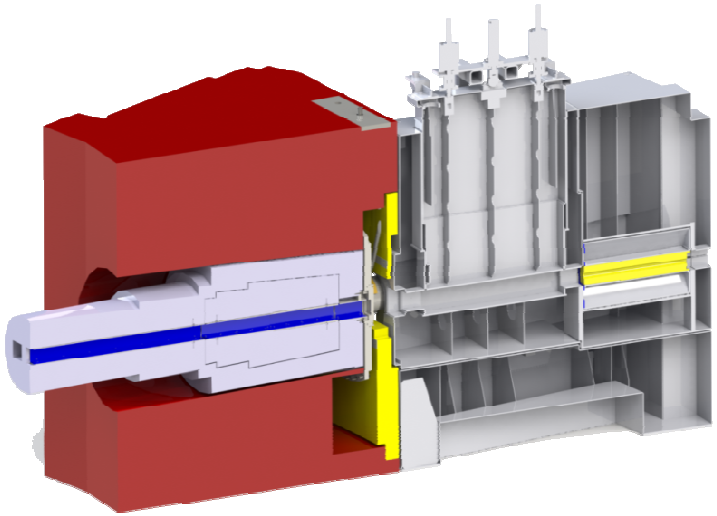
Ratio: Pi/2 =1,57

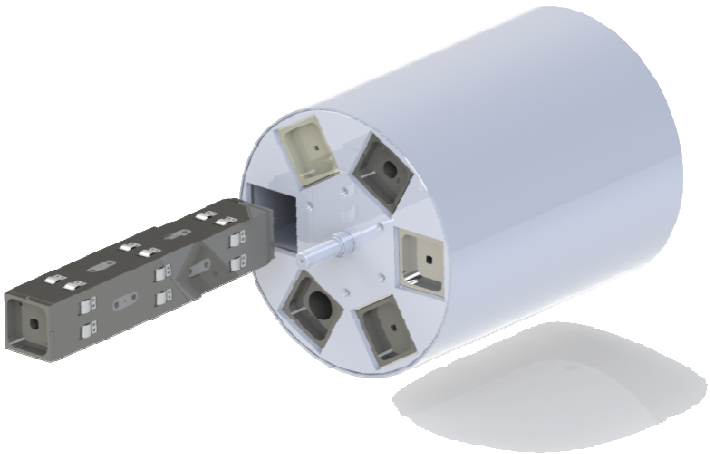
For beam adjusted collimator (square detector):

More than one third of the original round beam suppressed as unnecessary background!



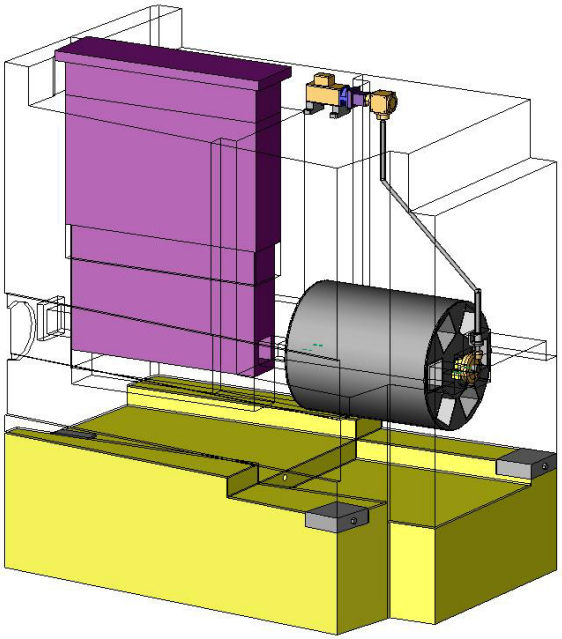
New ANTARES Upgrade: Separate shutter and collimator changer



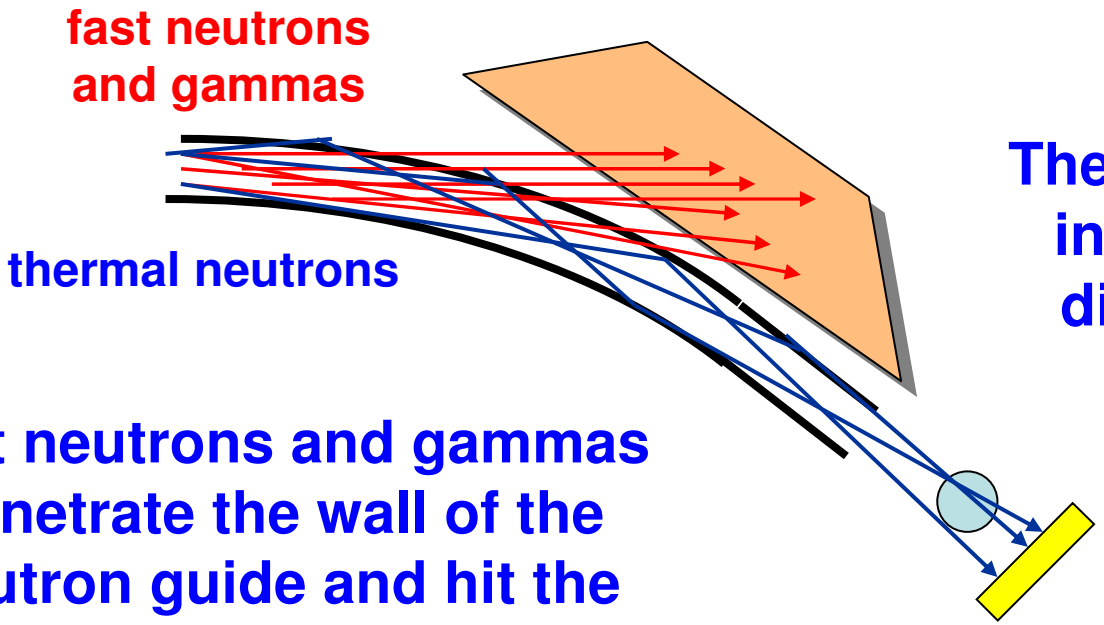


Collimator drum with 6 different collimators

- Pinholes: 2mm … 70mm
- L/D = 200 … 7100
- Flux: 10^8 n/cm²s @ L/D = 400
- Machined from stack of borated steel plates
- Length: 800mm



Principle setup with single neutron guide for imaging with thermal neutrons (e.g. SACLAY)

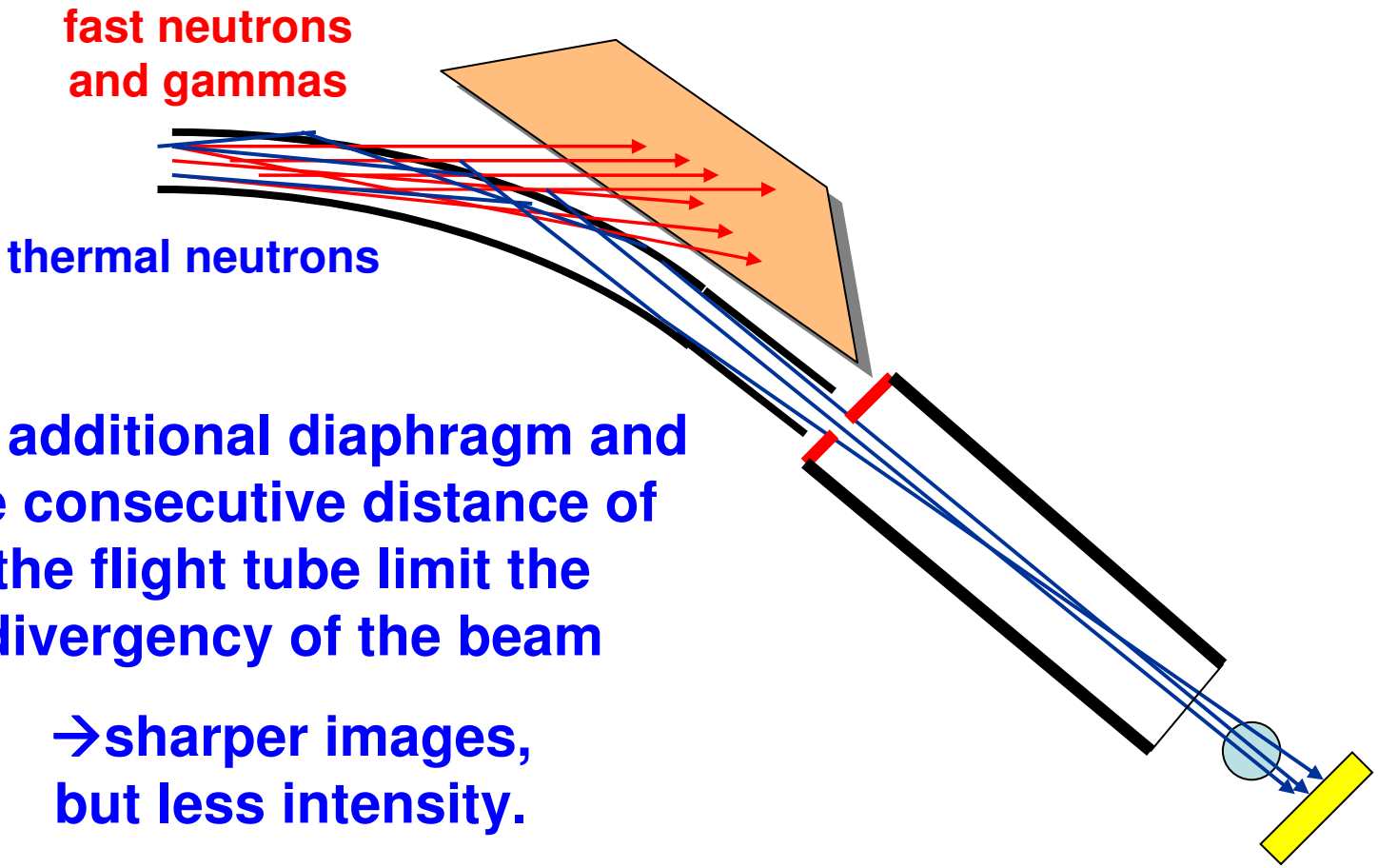


Problem:
The multiple reflections in the guide create a divergent beam and unsharp images.

Fast neutrons and gammas penetrate the wall of the neutron guide and hit the shielding outside.

Only thermal neutrons are reflected in the neutron guide and guided to sample and detector.

Principle setup with neutron guide plus diaphragm and flight tube for imaging with thermal neutrons (e.g. CONRAD)



The additional diaphragm and the consecutive distance of the flight tube limit the divergency of the beam

→sharper images, but less intensity.

Some words about shielding:

- **Gamma rays must be attenuated by high-Z elements**
- **Fast neutrons must be moderated to low energies**
- **Low-energy neutrons (thermal) must be absorbed**

Some words about shielding:

- **Gamma rays must be attenuated by high-Z elements**
- **Fast neutrons must be moderated to low energies**
- **Low-energy neutrons (thermal) must be absorbed**
  - **Lead absorbs Gammas, but is completely transparent for neutrons.**
  - **Polyethylen scatters and moderates neutrons, but is completely transparent for gammas.**
  - **Boron as B_4C or borated PE absorbs low-energy neutrons while emitting the lowest possible gamma energies (487 keV).**
  - **Iron attenuates gammas well, and shows resonance absorption of high-energy neutrons, emitting them again at much lower energies. Problem: Activation of Cobalt traces in the iron.**

Some words about shielding:

- **Traditional shielding:**
  Sandwich of Borated PE and Lead.
- **Modern shielding:**
  Heave concrete containing steel chips and Colemanite, a mineral with lots of crystal water and Boron
- **Best possible shielding:**
  Iron granulate plus Boron powder and H-containing liquid (20% more efficient than heavy concrete, patented by TUM)

Some words about shielding THICKNESS:

For the full fast and thermal beam:

- **Traditional shielding:**
  Sandwich of Borated PE and Lead or B-PE and Iron.

Typically 1-2 m for a collimator – not applicable for walls (too expensive and inefficient)

- **Modern shielding:**
  Heave concrete containing steel chips and Colemanite, a mineral with lots of crystal water and Boron

Typically 80-120 cm for walls, more at the reactor interface

- **Best possible shielding:**
  Iron granulate plus Boron powder and H-containing liquid (20% more efficient than heavy concrete, patented by TUM)

Typically 60-80 cm for walls, more at the reactor interface

Some words about shielding THICKNESS:

Rough estimate for stopping length for THERMAL neutrons:

- **Borated PE and Lead**

Typically 1-2 cm B-PE
plus 5-10 cm of Lead to stop the 487 keV gamma radiation

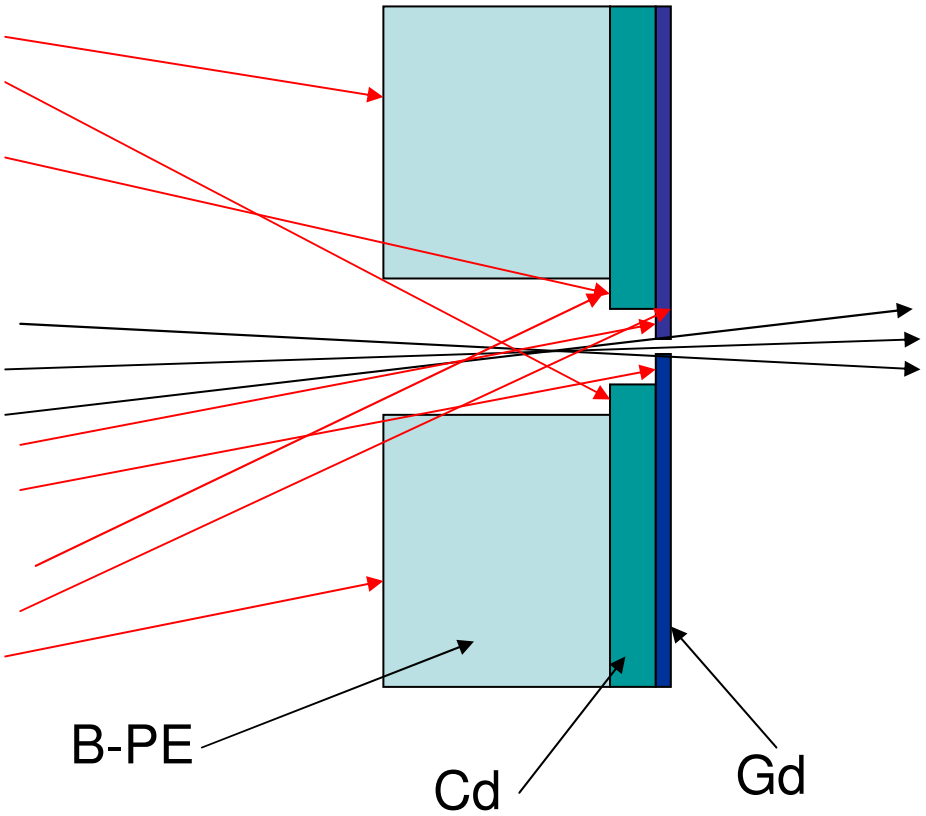
- **Cadmium, good for diaphragms**

Typically 2 mm,
BUT generates 1.2 MeV gamma radiation which is hard to shield

- **Gadolinium**

Typically 0.01 to 0.1 mm,
BUT generates a cascade of several 10 keV up to 8 MeV gamma radiation which is VERY hard to shield

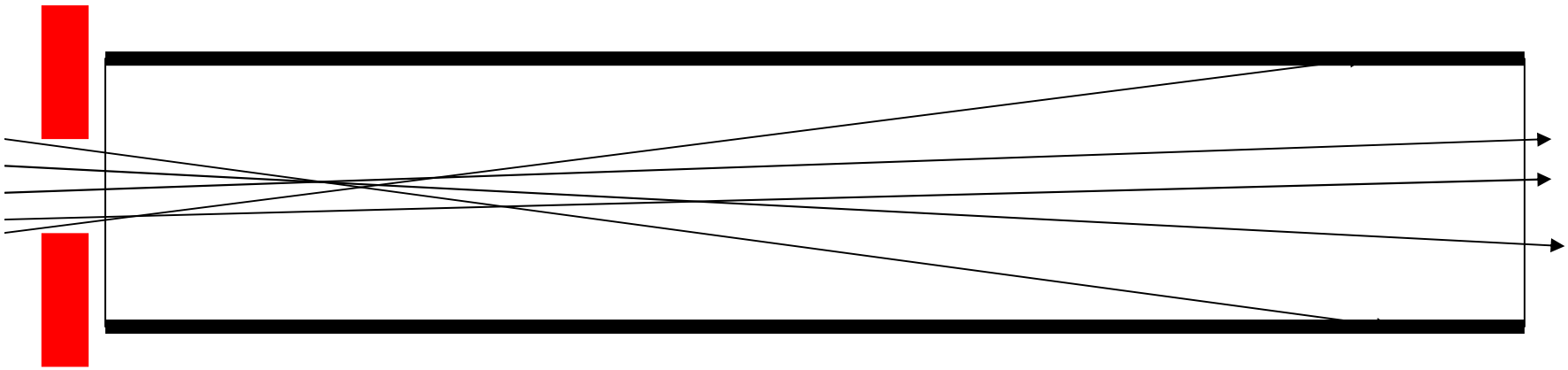
Diaphragm for thermal neutrons, optimized for low gamma emission :



Gd produces a very sharp edge for thermal neutrons.
The exposed area is minimized by the Cd and B-PE.

The exposed area of Cd is minimized by the B-PE.

Some words about the flight tube:

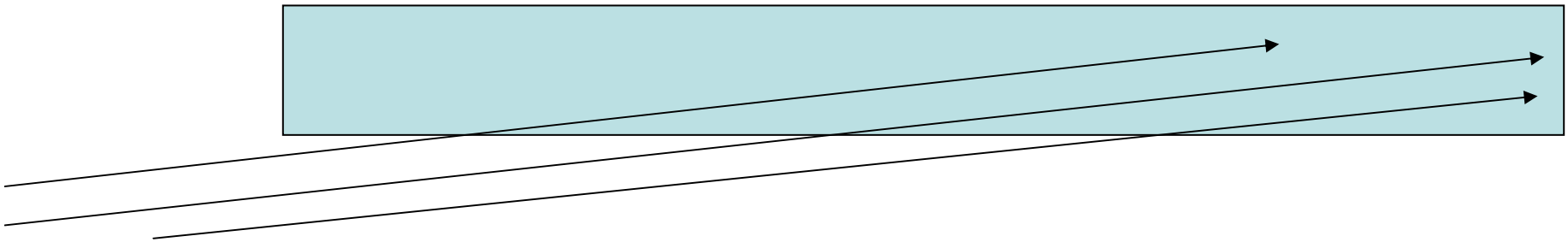


A neutron beam suffers several % loss in air – and activates N, O and Ar in the air.

The beam must thus be encased in a flight tube which is either evacuated or filled with He.

Aluminium is the material of choice for tube and windows – high transparency and short activation time (2.5 mins half-life).

Some words about the flight tube:

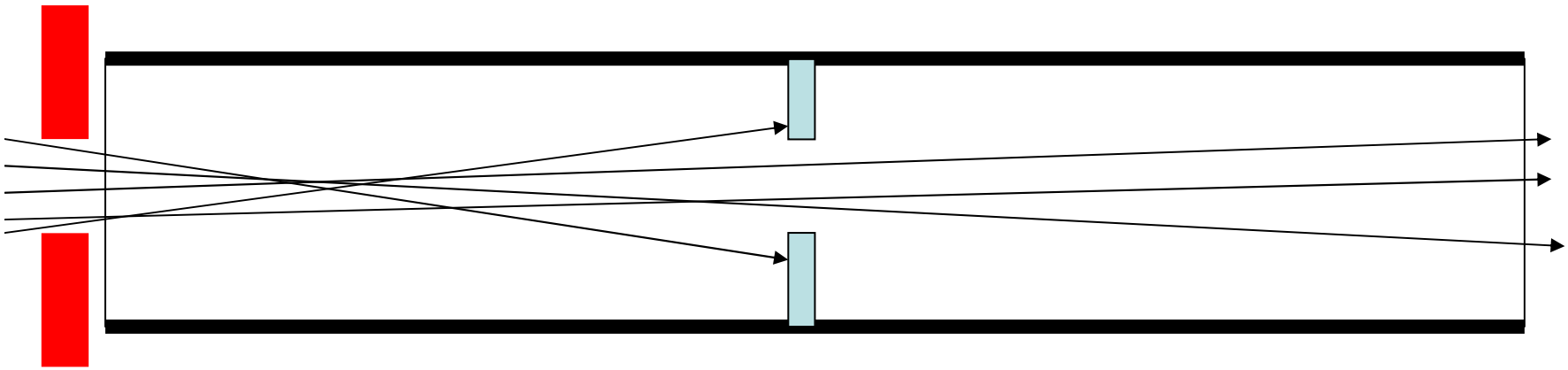


BUT even though the absorption probability is low, absorption creates a hard 8 MeV gamma.

IF the beam runs into the tube wall tangentially, it sees a meter of Aluminium, is fully absorbed –

and generates so much hard gamma radiation that a meter of heavy concrete will not be sufficient!

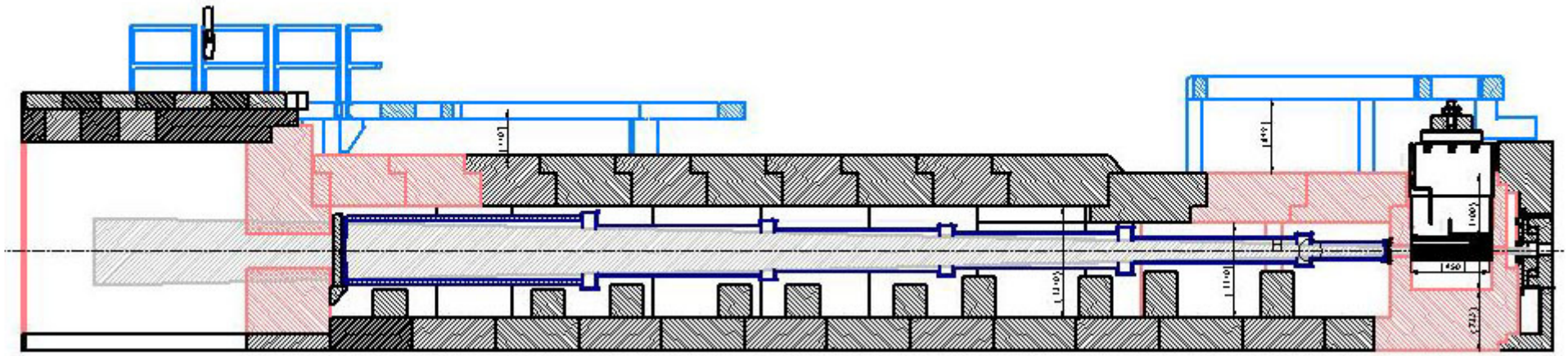
Some words about the flight tube:



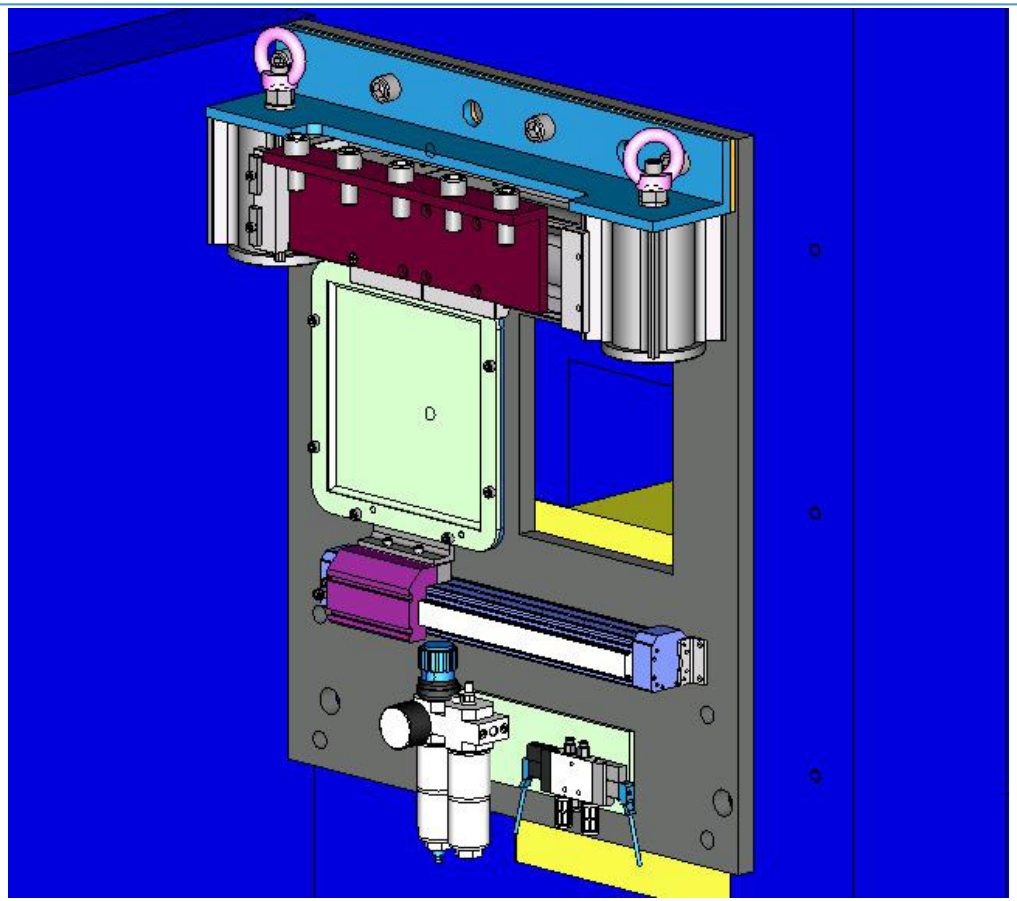
This can be remedied by introducing beam strippers of Borated PE inside the flight tube – which produces comparatively low gamma energies of only 487 keV.

The old ANTARES facility (dismantled in 2010) had a long flight tube with increasing diameter that was never touched by the beam.

The shutter was hydraulically driven, was 1.2 m long and contained two different collimators.



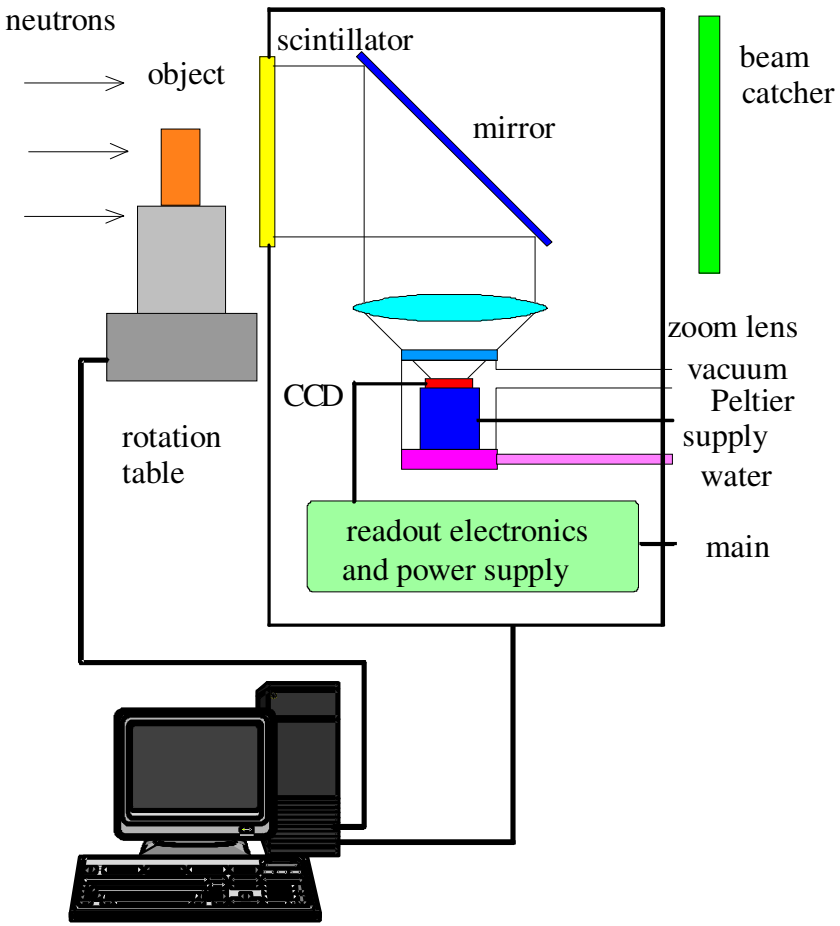
Cross section of the ANTARES facility.



Since only thermal neutrons cause activation, a pneumatic fast shutter at the beginning of the flight tube was used to shut off the thermal beam between exposures in order to minimize activation of the sample.

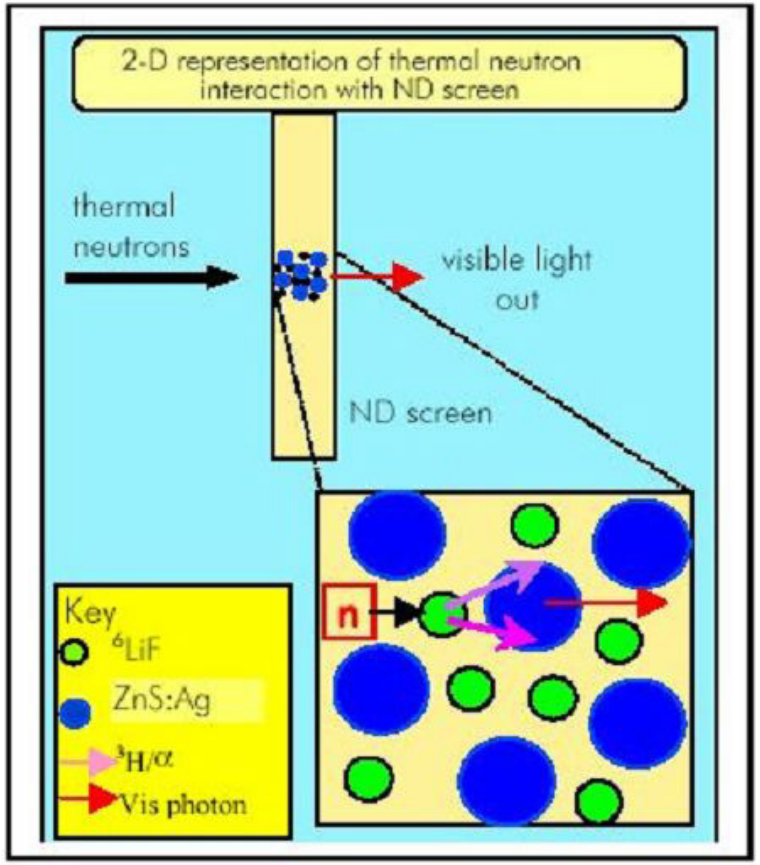
The principle detector setup for neutron imaging is very simple:

- A sample rotation stage
- a scintillation screen
- a mirror to keep the camera out of the beam
- a sensitive camera and
- a beam catcher



Let us look at the details!

The ZnS+^{6}LiF scintillation screen is the limit of resolution.



The reaction products of

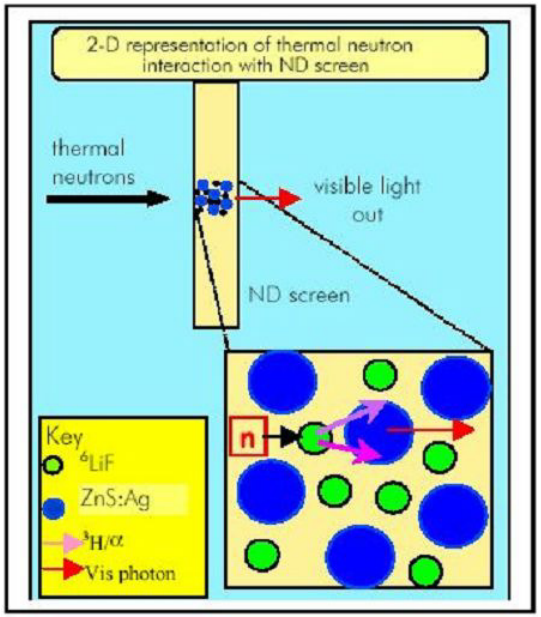
$^6Li(n,\alpha)^3H + 4.7$ MeV

have to be stopped in the ZnS scintillation screen.
Their average range is in the order of 50-80 µm.

About 177,000 photons are generated per detected neutron.

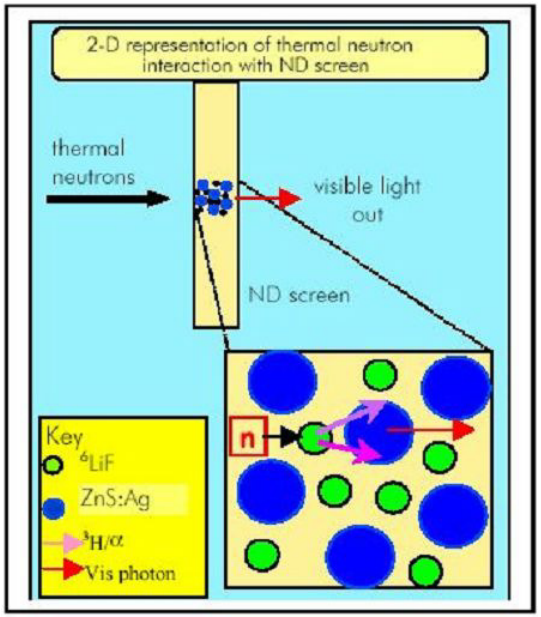
With thinned scintillation screens, we can achieve resolution in the order of 20-30 µm.

The ZnS+^{6}LiF scintillation screen

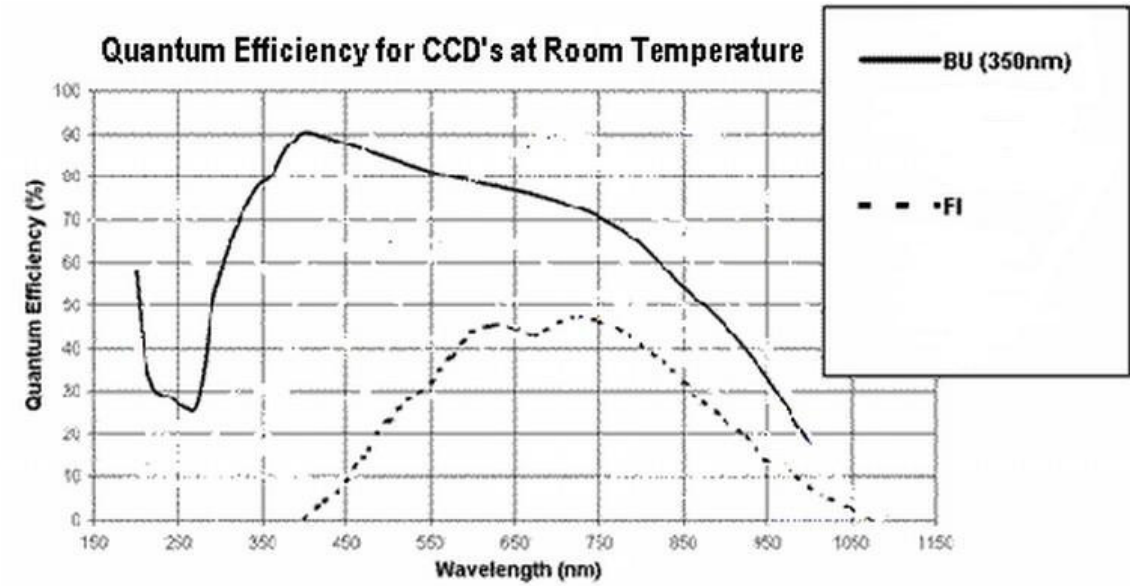


- One detected neutron produces about 177,000 photons, roughly into 4 Pi space
- The material is opaque for its own light
  - →thickness beyond 0.3 mm makes no sense, produces less light
  - →Due to exponential attenuation, more neutrons are absorbed in the beginning of the screen
    - →less light output to the back
  - →No fixed amount of light per neutron emitted towards the back
  - →Absolute counting is not possible
- Best thickness: 0.1 mm
  Resolution about 0.08 mm
- 0.2 mm thickness producs only 1.5 times as much light

The ZnS+^{6}LiF scintillation screen



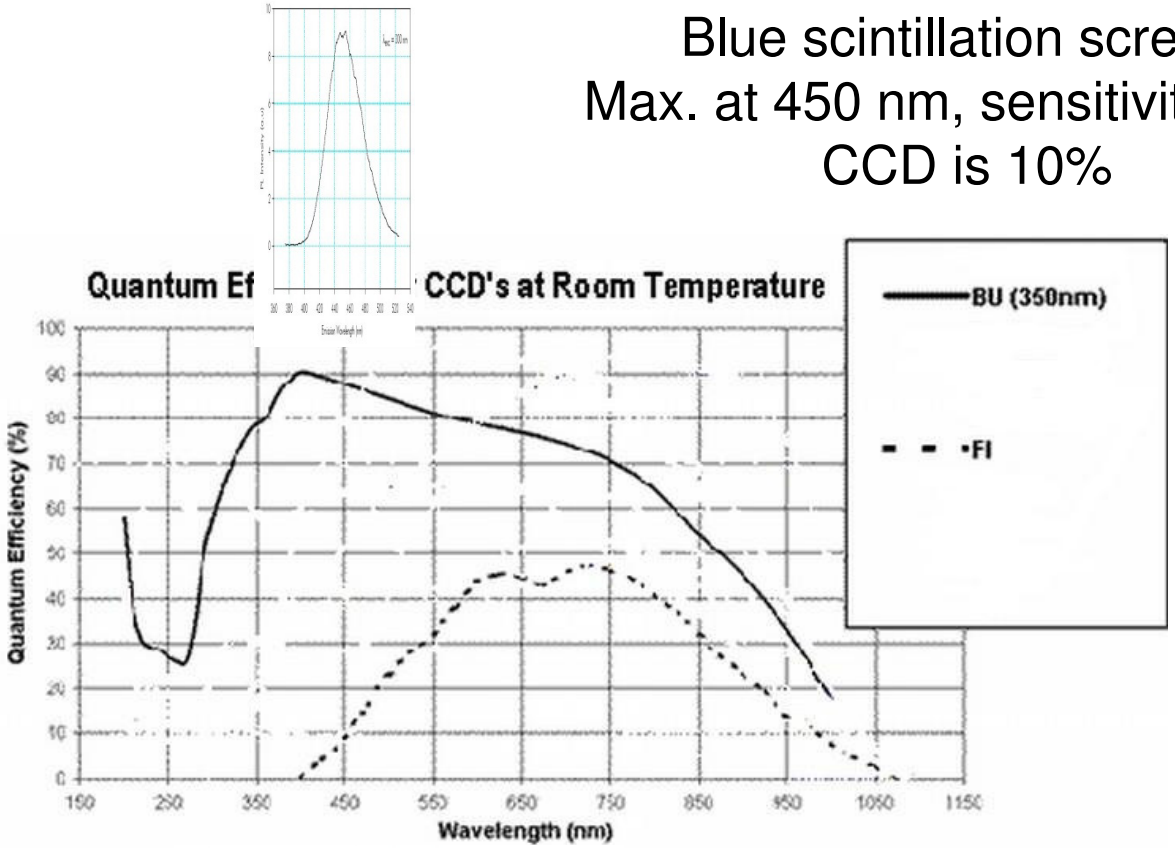
- The original ZnS+6LiF screens were doped with Ag and emitted blue to UV light (400-450 nm) – optimised for photo cathodes of photo multipliers – but NOT for CCDs!

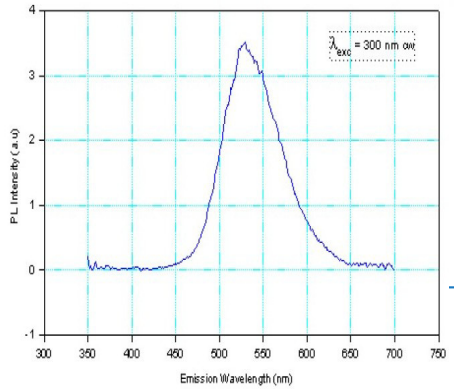


Quantum efficiency for back side illuminated CCDs and front side illuminated CCDs

For neutron imaging, screens are doped with Cu and Au to produce green light emission.

Blue scintillation screen:
Max. at 450 nm, sensitivity for FI CCD is 10%





Green scintillation screen:
Max. at 540 nm, sensitivity for F CCD is 30% !

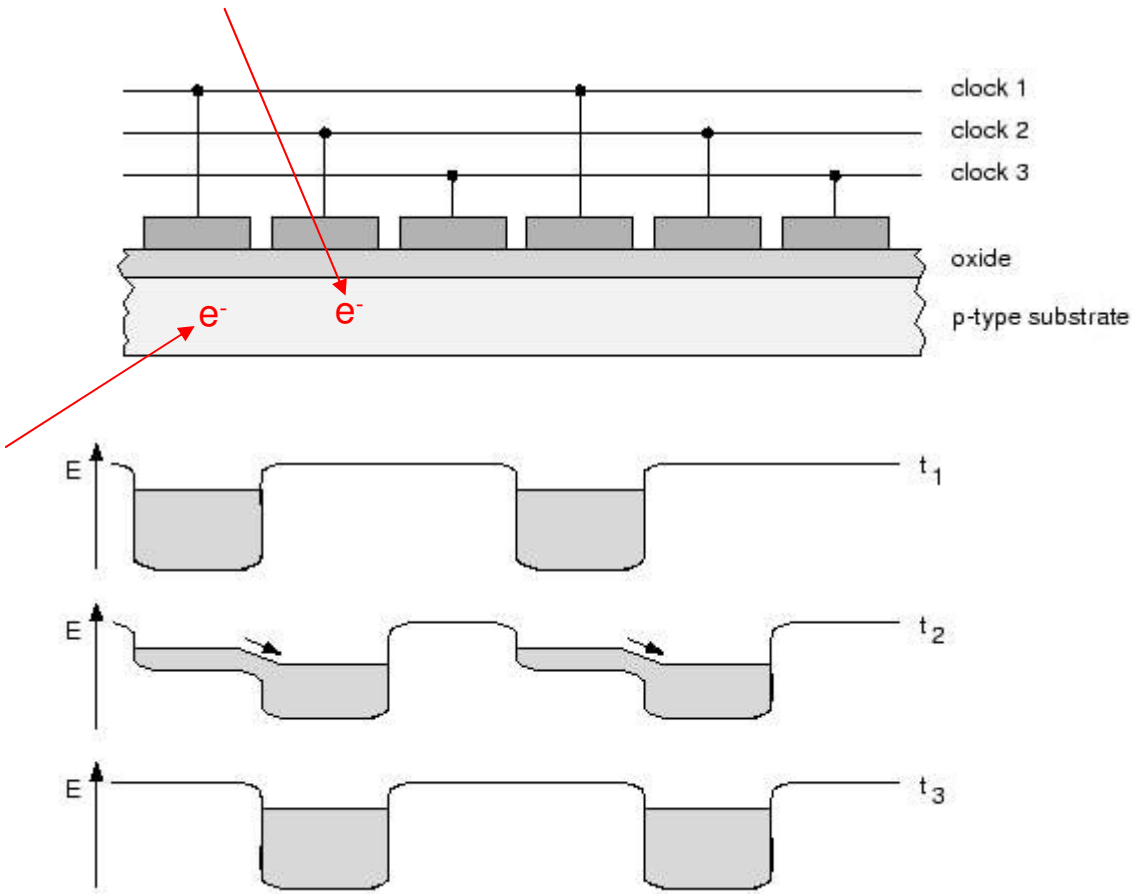
Also for the surface mirror (do not take a bathroom mirror!), the choice of reflecting material is important:

Reflectivity of metal coatings

MICRONS	ALUMINUM	SILVER	GOLD	COPPER	RHODIUM	PLATINUM
0.38	92.5	92.8	37.8	44.5	78.1	64.9
0.4	92.4	94.8	38.7	47.5	77.4	66.3
0.45	92.2	96.6	38.7	55.2	76	69.1
0.5	91.8	97.7	47.7	60	76.6	71.4
0.55	91.5	97.9	81.7	66.9	78.2	73.4
0.6	91.1	98.1	91.9	93.3	79.7	75.2
0.65	90.3	98.3	95.5	96.6	81.1	76.4
0.7	89.9	98.5	97	97.5	82	77.2
0.75	88	98.6	97.4	97.9	82.6	77.9
0.8	86.3	98.6	97.7	98.1	83.1	78.5

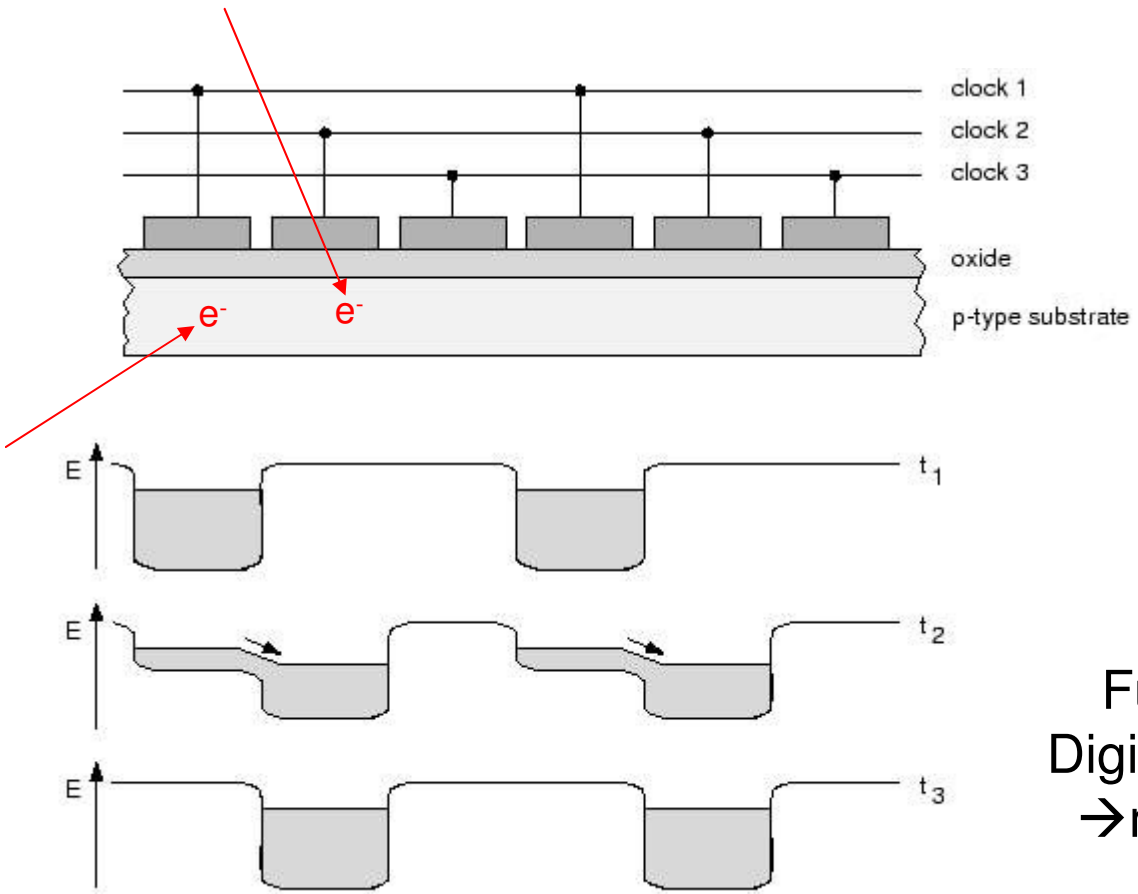
Space Optics Research Labs

The reflectivity of Silver is best in the blue and green region, but Silver becomes activated and oxidised, so Aluminium is the choice!



A CCD consists of a Si slab, an insulating oxide layer, and electrodes.
A positive electrode potential creates a potential well in the Si that can store photo generated electrons.

In a front side illuminated CCD, the photons must first penetrate the gate electrodes, in a backside illuminated CCD, the photons reach the potential well directly (→more sensitivity).

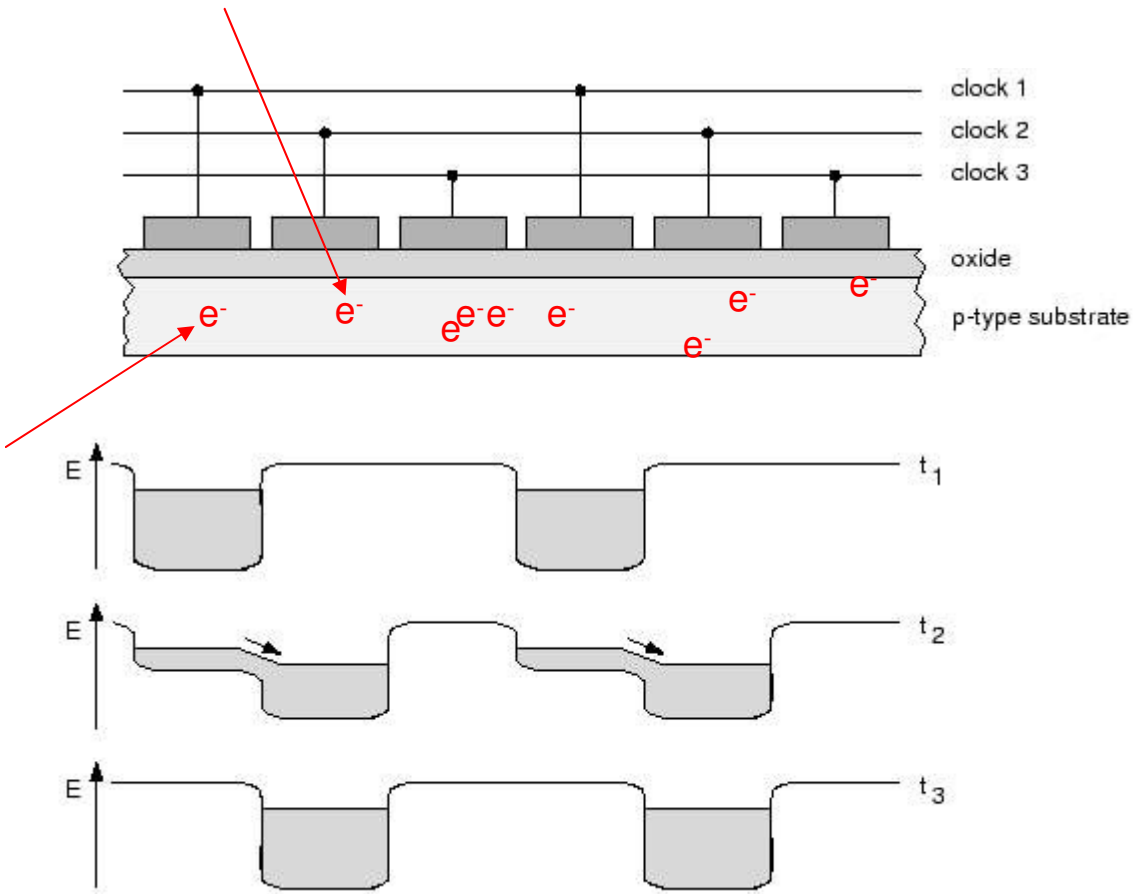


The pixel size determines the *full well capacity*, the maximum number of electrons that can be collected in one pixel.

The full well capacity limits the *dynamic range* of the camera – along with the digitization depth (how many bits).

Example 1:
Full well capacity = 42,000 e-
Digitization depth =16 bit (65,535)
→max. 42,000 true gray values

Example 2:
Full well capacity = 17,000 e-
Digitization depth =12 bit (4,096)
→max. 4,096 true gray values



In the silicon, electrons are also generated as thermal charges.

Typically, a normal video camera delivers a white image in one second if not continuously read out.

→Cooling required!

(Typical required exposure times are a few minutes.)
The thermal charge generation is cut in half for every 6 degrees of cooling.

Cooling to -30 °C is sufficient,
high-end cameras reach -60°C to -100°C by Peltier and water cooling,
cameras in astronomy use liquid nitrogen.

The signal chain

Now let's do it backwards:

- We have a sample that attenuates the neutron beam by 50%.
- We want to detect a 2% variation in the sample.
  (Say, a crack or bubble within the sample.)
- This means 1% of the full neutron fluence (without sample) on one pixel.
- The Poisson noise in any particle distribution is sqrt(N), and our signal must be above the noise.
- sqrt(100) =10, sqrt(1,000)= 31.6 , sqrt(10,000)=100
- so we must DETECT at least 10,000 neutrons per pixel to be equal to noise level !
- The detection efficiency of the screen is in the order of 20-30%, say 25%.
- This means we need 40,000 incoming neutrons on one pixel !

The signal chain

Now let's do it backwards:

- Let's say the lens system projects an area of 0.1 mm x 0.1 mm of the screen onto one pixel of 12 um x 12 um size, we detect several photons per neutron (remember: 177,000 photons are generated in the screen per detected neutron), so the photon statistics does not influence the detected neutron statistics, and the amplification of the camera is set so that it can detect more than 10,000 gray levels – without overflowing, e.g. 4 electrons per gray level.

- So we need 40,000 neutrons per 0.1 mm x 0.1 mm, which is 40,000 x 10,000 neutrons per 1 cm^2, a total fluence of $4x\ 10^8 n/\ cm^2$.

- In a beam with a neutron flux of $1 \times 10^6/\ cm^2 s$, we need 400 seconds or 6 minutes 40 seconds exposure time.

The signal chain

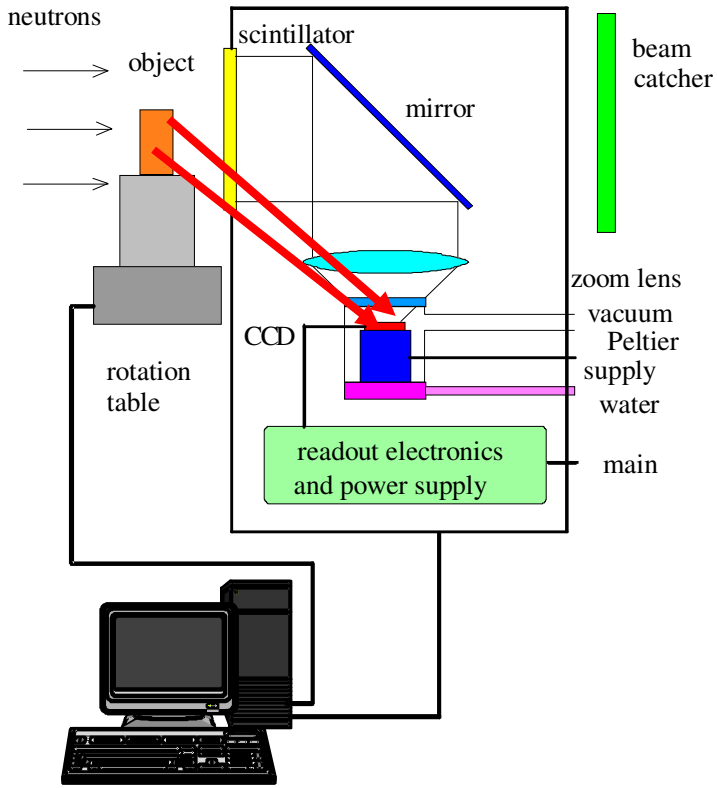
Now let's do it backwards:

- This means the dynamic resolution of neutron imaging depends on the NEUTRON statistics, and NOT on the PHOTON statistics!

- It makes no sense to employ a super light collecting lens that transmits dozens of photons per neutron – and makes the camera overflow before the required neutron statistics is reached!

- BUT the lens should collect several photons per detected neutron so that the photon statistics does not influence the neutron statistics.

Shielding the camera



- The camera chip may be hit directly by gammas generated in the sample, and by scattered neutrons.

- gamma rays appear as white spots in the image, but neutrons can generate defects in the silicon that produce white or dark pixels.

- Therefore, the camera must be shielded both with lead and with Borated rubber or PE.

- For the same reason, the beam catcher should be as far away as possible, and as little material as possible in the beam (mirror thickness, back wall of the detector box).

ANTRES Beam Line Concept: 3 Chambers

- 3 chambers
- Beam accessible along flight path
- Same possibilities as old ANTARES
- Higher flexibility
- New & lighter shielding material
- Abundant space available for experiments & sample environment
  - Cooling Water & Pressurized Air Supply
  - Electric Supply up to 400V@400A