Performance study of a fan beam collimator for a multi- modality small animal imaging device

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Study Objectives

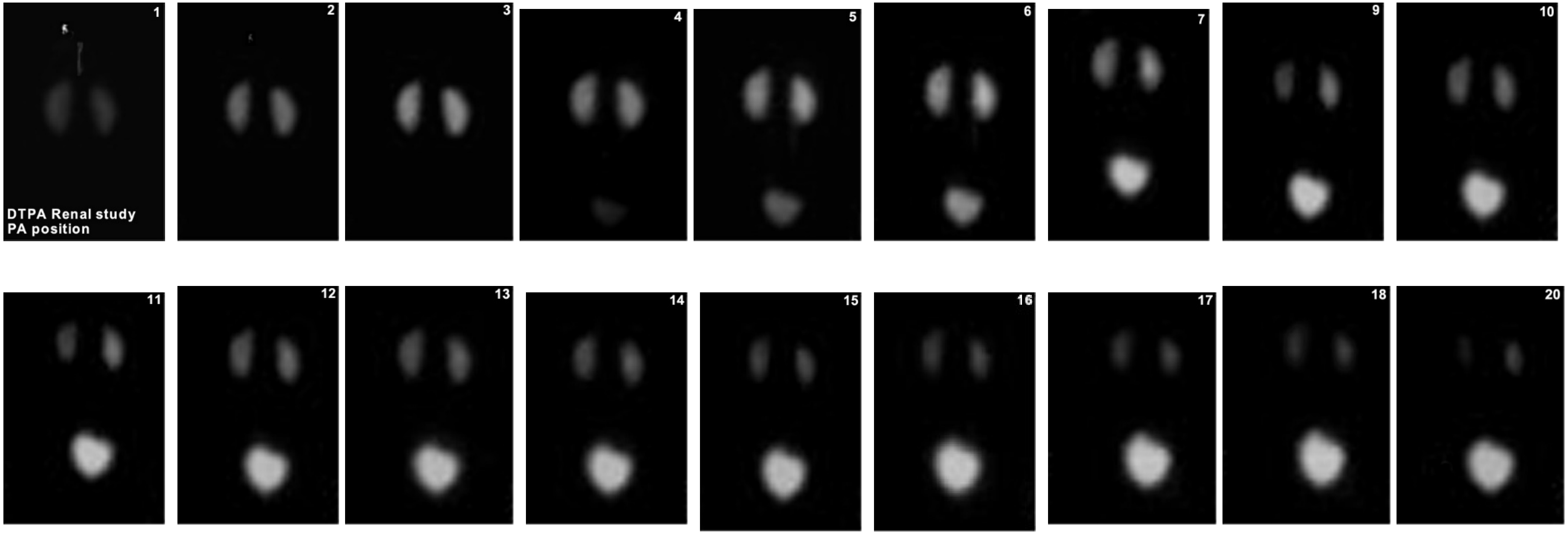
Design of a fan beam collimator for a small animal imaging device to perform rapid dynamic study with improved efficiency and spatial resolution.

A Monte Carlo model to optimize the collimator's parameters, to conduct a performance study by analyzing the scattering and noise indexes for a 3D geometry.

Canada

Study Importance

Pharmacokinetic data distribution revels important functional information of the living bodies.

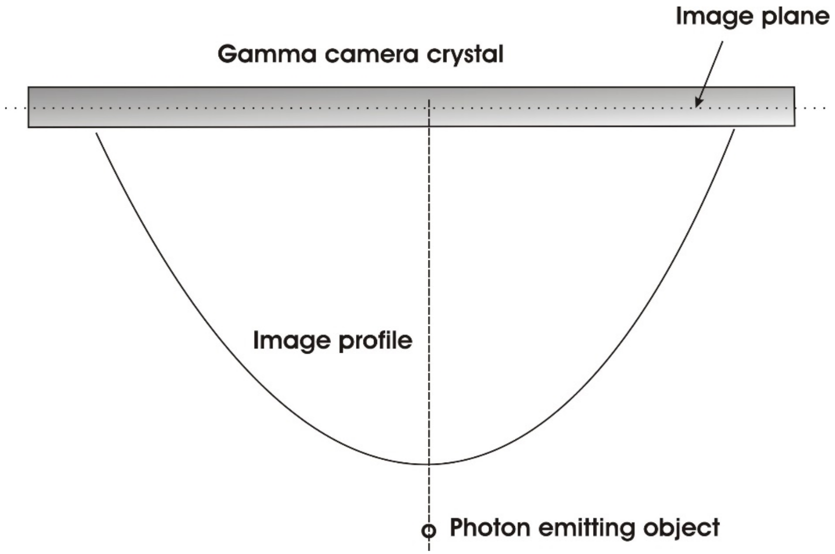


High sensitive collimator is essentially required for rapid dynamic acquisition where higher count rates are to be recorded in short time frame.

Canada

Introduction

Collimator's role in scintillation imaging



Scintillation imaging without proper collimation spoils the ultimate objective

*) The desired collimator material has high linear attenuation coefficient; e.g. tungsten, lead, tantalum etc.

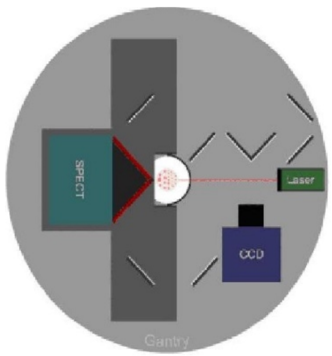
*) **Most desirable**, geometrically collimated rays pass the collimator without interacting the septal wall

*) **Undesirable**, penetrating gamma rays pass through one or more septal walls and scattered photons deflected by scattering.

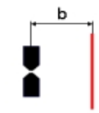
*) Penetrating and scattered photons produce noises and substantially degrade image quality

Introduction

The small animal imaging device

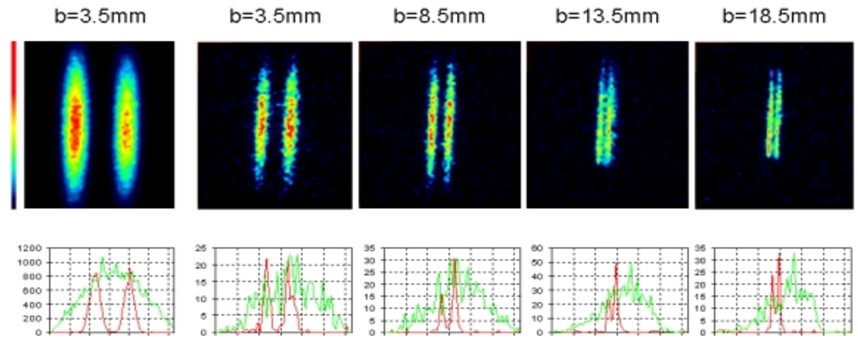


Projection of capillary tubes (hot/cold/hot)

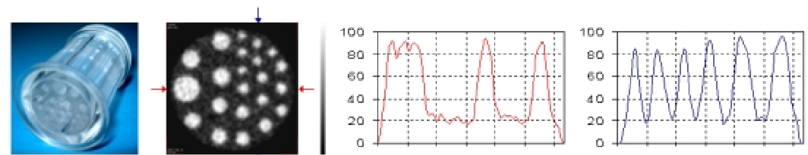


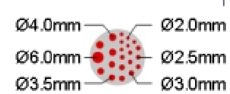
1mm PH
1.5mm OD

0.5mm PH
0.9mm OD



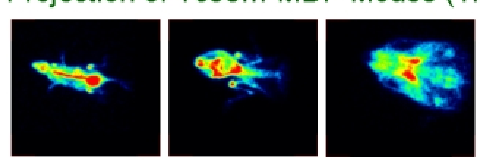
Reconstructed acquisition of the Derenzo-like phantom





3.5mCi Tc^{99m}, 60 sec/proj, 120 projections
1mmPH∅, ROR = 23mm, OSEM 5/10, A-C, COR-C

Projection of Tc99m-MDP Mouse (1.2mCi, 1mm PH∅)

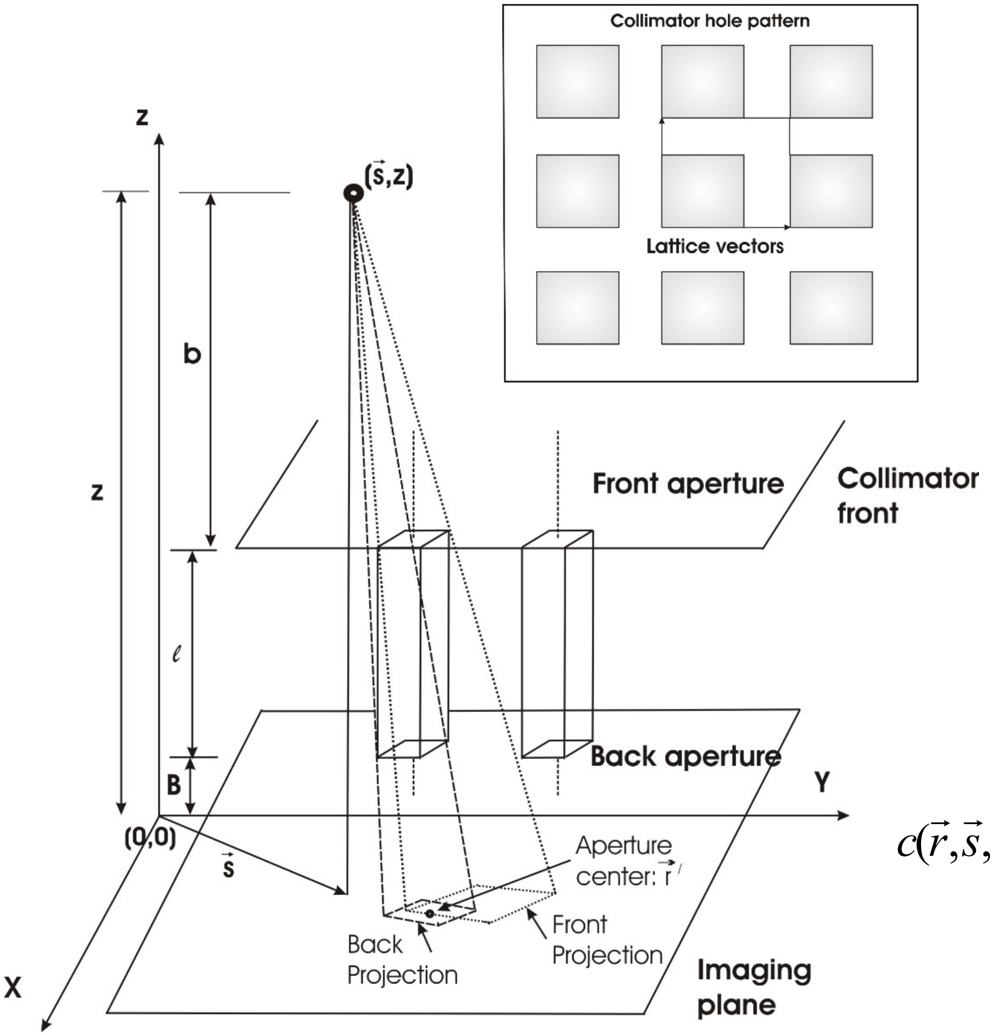


b=53mm t=19.4min 104k cnts.
b=23mm t=13.8min 65k cnts.
b=0.4mm t=10.6min 86k cnts.

Patent: EP2006/122804.5; J. Peter et.al., IEEE, 2005

Introduction

Theoretical formulation for modeling



efficiency and resolution
[Scattering/attenuation/penetration=0]

A photon from source s $(\vec{s}$, z) will pass through the collimator if the photon passes within front and back projections of the hole on image plane.

As a collimator is composed of repeated lattice structure with respect to a source, so the ***collimator response function*** is periodic with respect to source position and it depends on front and back aperture function: i.e.

$$c(\vec{r},\vec{s},z)=\sum_{j,k}^{\infty} h\left[\vec{s}+\left(\frac{z-B-l}{z}\right)\vec{r}-\vec{r}'_{jk}\right] h\left[\vec{s}+\left(\frac{z-B}{z}\right)\vec{r}-\vec{r}'_{jk}\right]$$

Introduction

Theory: efficiency and resolution

If the collimator response function is decomposed in a Fourier series, the above equation becomes,

$$c(\vec{r},\vec{s},z) = \sum_{M,N=-\infty}^{\infty} c_{MN}(\vec{r},z)\exp[2\pi i(\vec{s}.\vec{m}_{MN})]$$

where M and N are referred to as the hole-pattern harmonics.

For a parallel hole collimator, the point source response function is independent of the source position s; In that case, all the harmonics except c_{00} vanish.

Collimator geometric **transfer function** can be written in terms of the photon fluence **at the collimator face** and the two collimator-aperture functions,

$$g(\vec{s},z) = \phi(\vec{r},z)c(\vec{r},\vec{s},z) \cong \frac{1}{4\pi z^2}\sum_{M,N=-\infty}^{\infty} c_{MN}(0,z)\exp[2\pi i(\vec{s}.\vec{m}_{MN})]$$

Taking the Fourier transform

$$\frac{1}{4\pi l_e^2\Delta}\sum_{M,N=-\infty}^{\infty} H\left[-(\frac{z-B-l}{l})\vec{m}_{MN}\right] H\left[(\frac{z-B}{l})\vec{m}_{MN}\right]\exp[2\pi i(\vec{s}.\vec{m}_{MN})]$$

where $l_e = 1 - 2\mu^{-1}$ is the effective length of the collimator, □*=(d+t)*^{2} is the area of a lattice. Hence hole pattern harmonics except *M=N=0 can be neglected.*

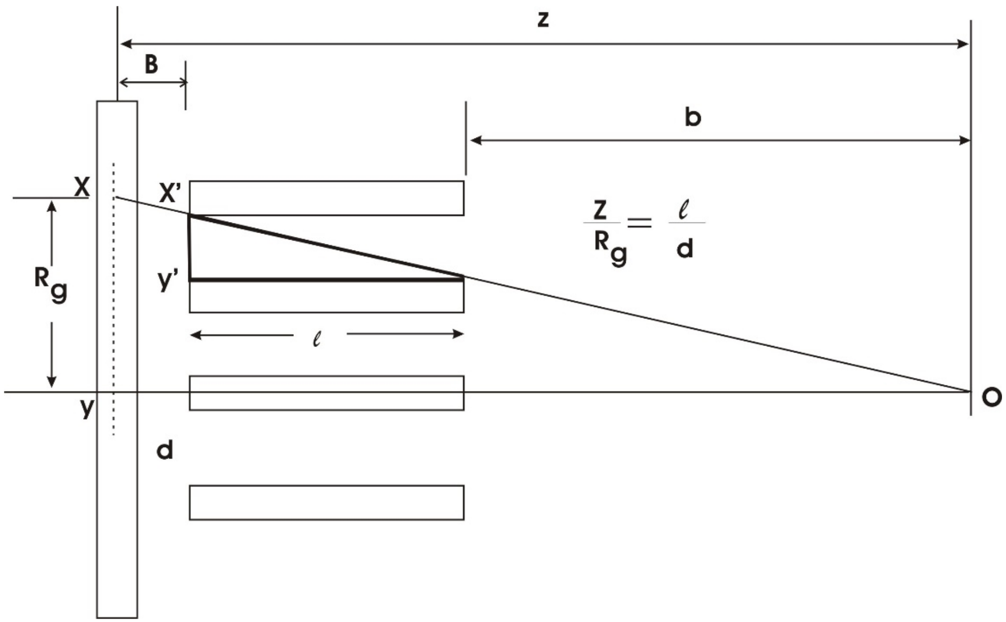
Introduction

Theory: efficiency and resolution

The **Average efficiency** for the parallel-hole collimator g_p can be written as,

$$g_p^0 = \frac{H(0)H(0)}{4\pi l_e^2 \Delta} = \frac{(Hole\_area)}{4\pi l_e^2 (Lattice\_area)}$$

Total lattice area >FWHM



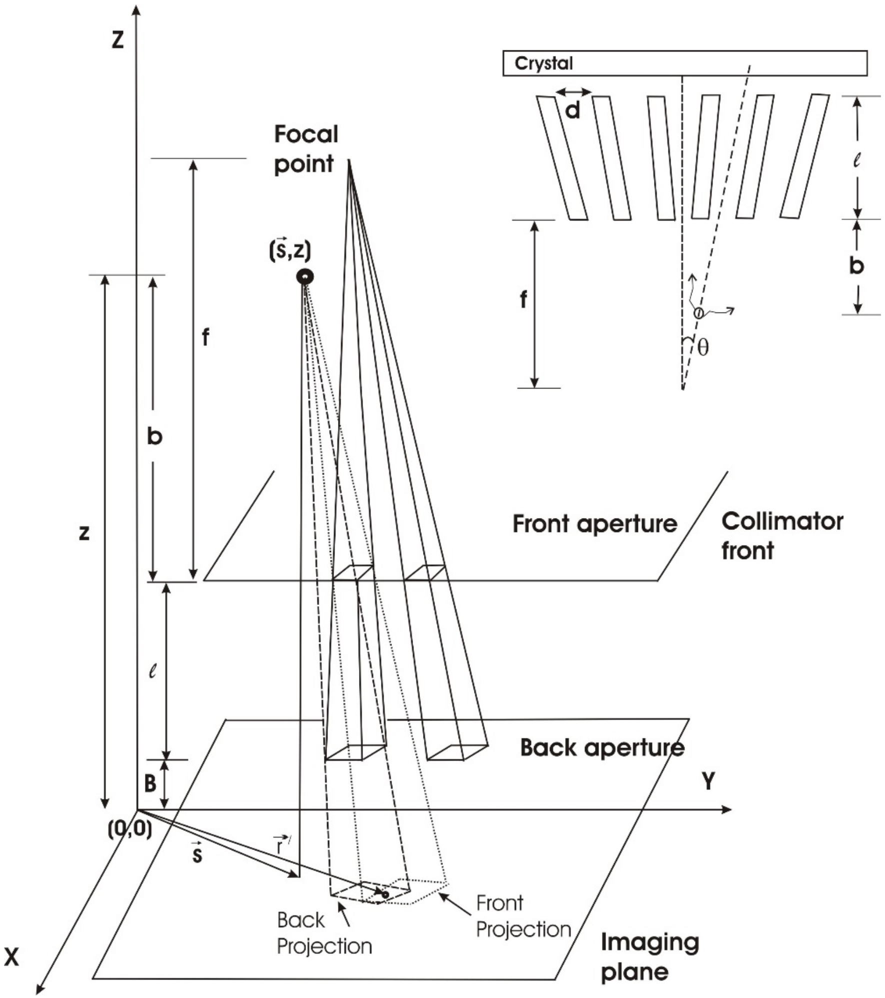
The resolution of a parallel-hole collimator measures the width of the point source response function (PSRF) as a function of $\vec{r}$. The width of the PSRF is strongly dependent on the source position in front of the collimator. The geometric resolution of the parallel-hole collimator (R_p^0) is defined as the FWHM of the PSRF by the relation

$$R_p^0 = \frac{zd}{l_e} = \frac{d}{l_e}(B + l + b)$$

Henkin RE et.al., *Nucl Med*, Mosby Ins (1996)

Introduction

Theory: : Fan beam efficiency and resolution



For fan beam geometry, individual hole-axis aligns differently at every position on the collimator face and hence the efficiency of the fan beam collimator depends strongly on source position.

The geometric efficiency for the fan beam collimator is given as,

$$g_f^0(b) = g_p^0[\cos^2\theta]\left(\frac{f}{f-b}\right)^2$$

where $(z - B - l) = b$ is object distance, g_p^0 is efficiency of the parallel collimator, θ is the angle between collimator axis and the object position. The distance *b* varies from 0 to *f*; i.e., *0<b<f.*

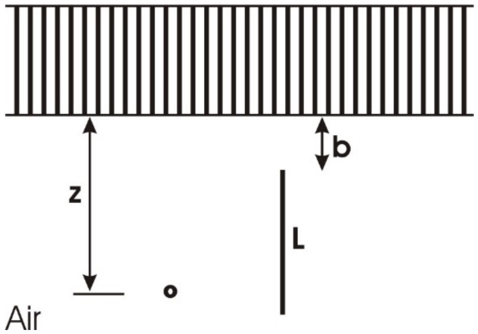
The resolution of the fan beam collimator

$$R_f^0 = \frac{R_p^0}{\cos\theta}\left(1 - \frac{l_e/2 + b}{f - b}\right)$$

[**Tsui BMW**, *IEEE* (1996)]

Introduction

Theory: : Equation derivation for line and point source



If a line source of length *L* is placed in air, the geometric efficiencies for a parallel hole and a fan beam collimator are :

No scattering or attenuation included

$$g_p^{0l} = g_p^0$$

$$g_f^{0l}(L,b) = \frac{1}{L}\int_b^{b+L} g_f^0 dz \quad = g_p^{0l}(L,f)\left[\cos^2\theta\right]\left[\frac{f^2}{(f-b)(f-b-L)}\right]$$

<u>For attenuating medium:</u>

No scattering included

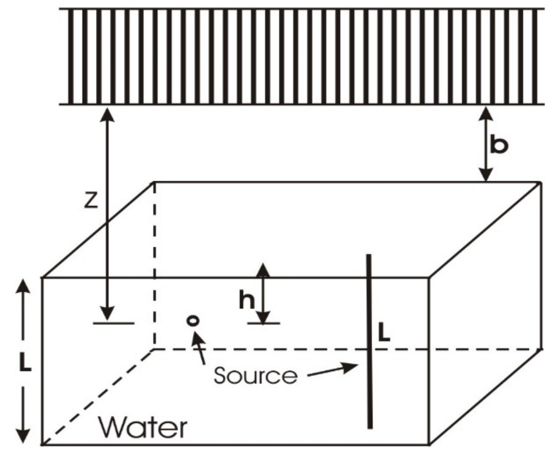
[Point source]

$$g_p^a(\mu,h) = g_p^0 \exp(-\mu h), \qquad g_f^a(\mu,b,h) = g_f^0(b)\exp(-\mu h),$$

[Line source]

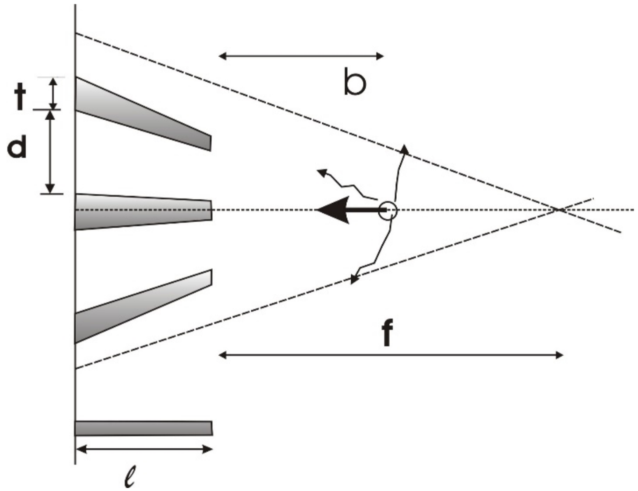
$$g_p^{al}(\mu,L) = \frac{1}{L}\int_b^{b+L} g_p^0 \exp[-\mu(z-b)dz] = \frac{g_p^0}{\mu L}\left[-e^{-\mu L}\right]$$

$$g_f^{al}(\mu,L,h) == \frac{g_p^0\left[\cos^2\theta\right]}{L} f^2 e^{-\mu A}\left[\frac{\mu A E_i(\mu A) - e^{\mu A}}{A} - \frac{\mu B E_i(\mu B) - e^{\mu B}}{B}\right]$$



Methodology

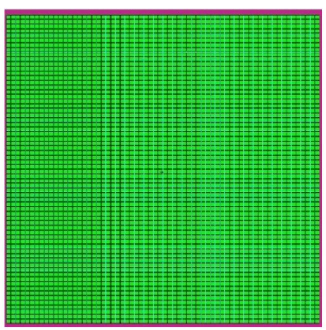
The small animal imaging device: Collimator's Specifications

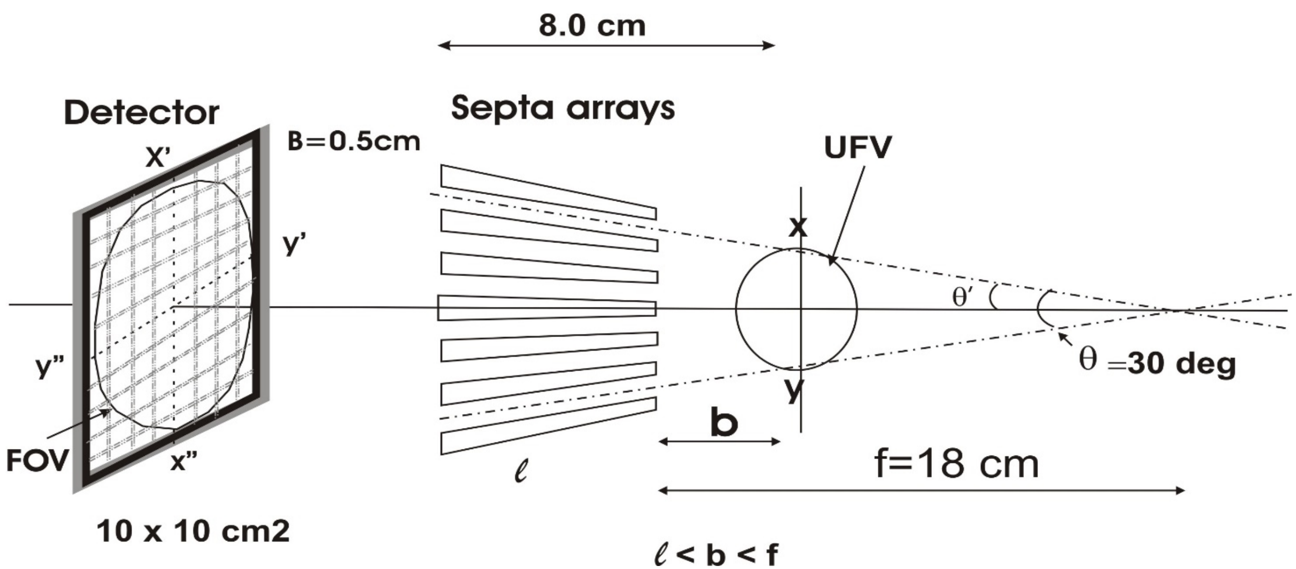


The scintillation crystal consists of 66x66 array (0.02 cm separation) of square shaped individual NaI(Tl) crystal elements (0.13 x 0.13 x 0.6 cm^3).

The proposed collimator is designed to match with the crystal dimension. Tungsten material (attenuation coefficient μ=36.34 cm^{-1}) is proposed for this collimator.

Thickness (t)=0.02 cm, Hole size (d)=0.13 cm, focal length (f)=18 cm.



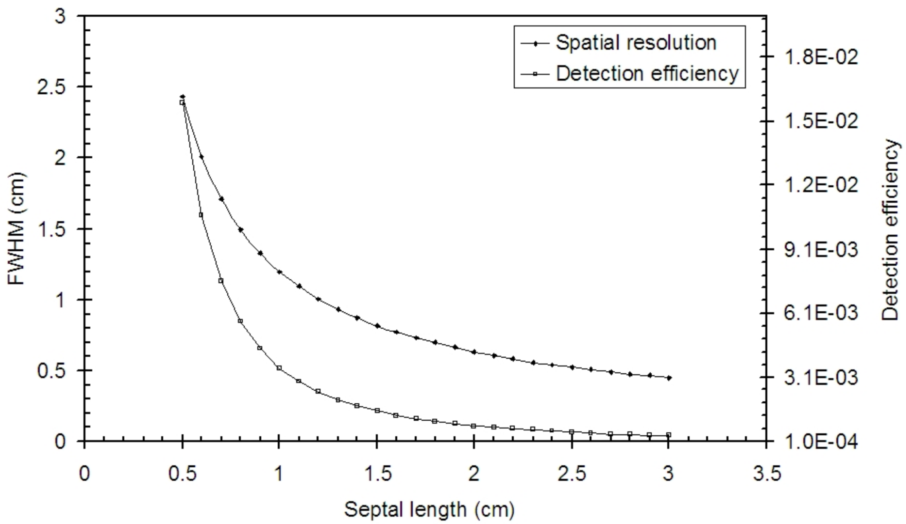


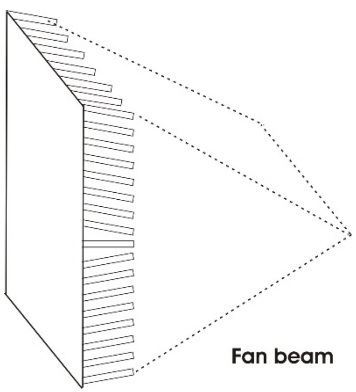
Methodology

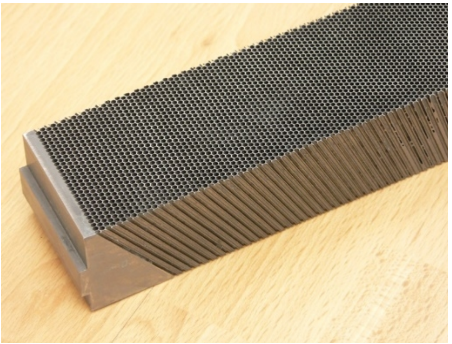
Collimator Design consideration

The proposed fan beam collimator was designed to study the whole body dynamic study. The focal length (f) was calculated as 18 cm .

A hole length ℓ =1.8 cm was calculated for the new converging collimator.





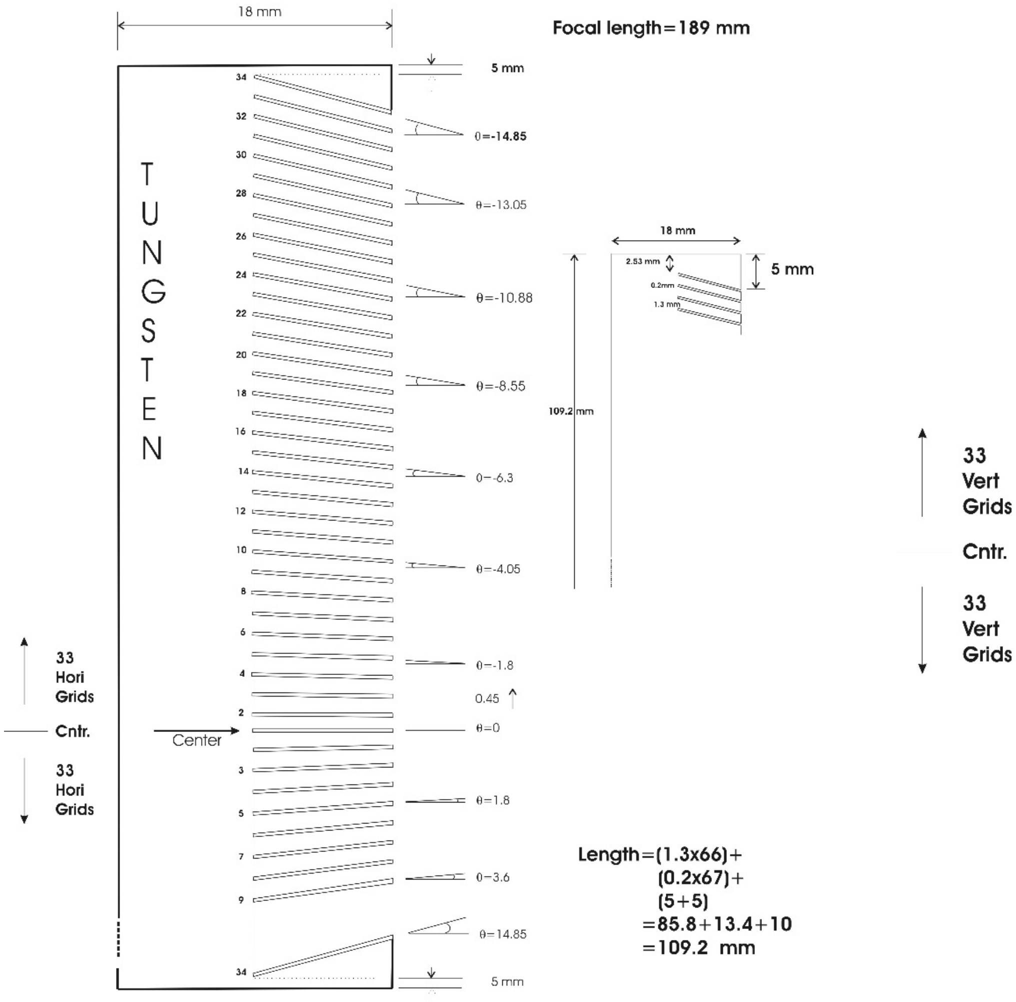


A fan beam is a combination of parallel and converging collimator. Collimator’s hole axis‘s are converged toward the object short axis and parallel to object long axis.

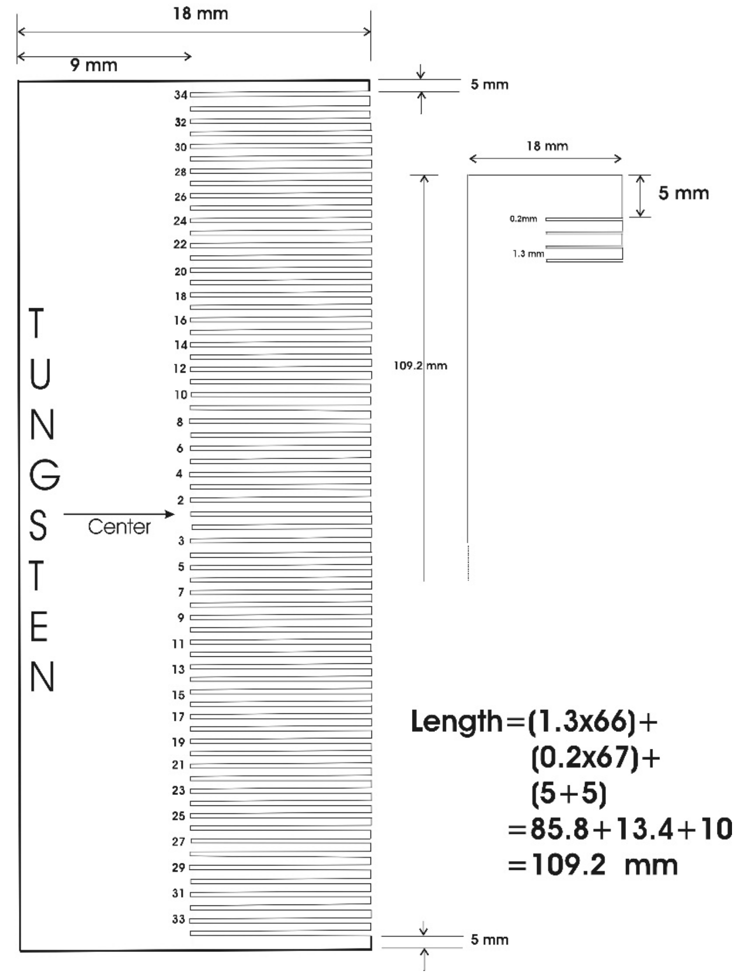
Methodology

Collimator Design

VERTICAL GRIDS [Total 67 same size]



Central Horizontal GRIDS

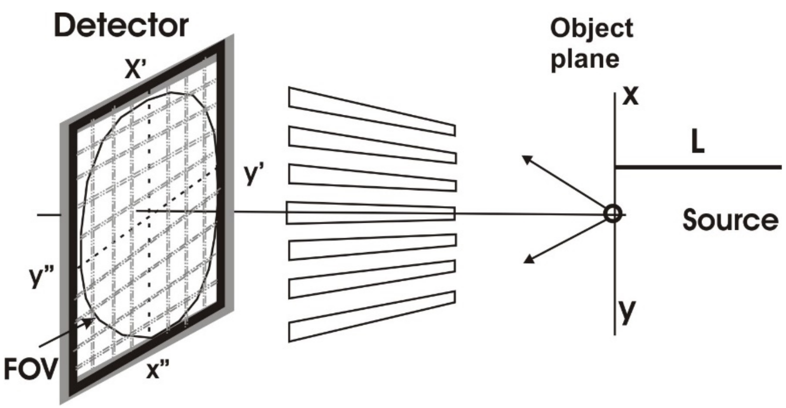


Methodology

Calculation of Scattering index (SI)

Monte Carlo method (MCNP) was used to calculate the fluence for individual detector-element for point and line sources.

This fluence included scattered and unscattered photons emitted from the source.



Same number of particles were tallied for all cases.

F4 tally calculated the number of photons over a cell that was normalized per incident particle.

F4 tally $\Phi(r,E,t) = vN(r,E,t)$

$$\int_V \int_E \int_T \Phi(r,E,t)\,dE\,dt\,\frac{dV}{V} \cong \frac{wvt}{V} \cong \frac{w}{V} T_L$$

Scattering index (SI)=
Total fluence – unscattered fluence

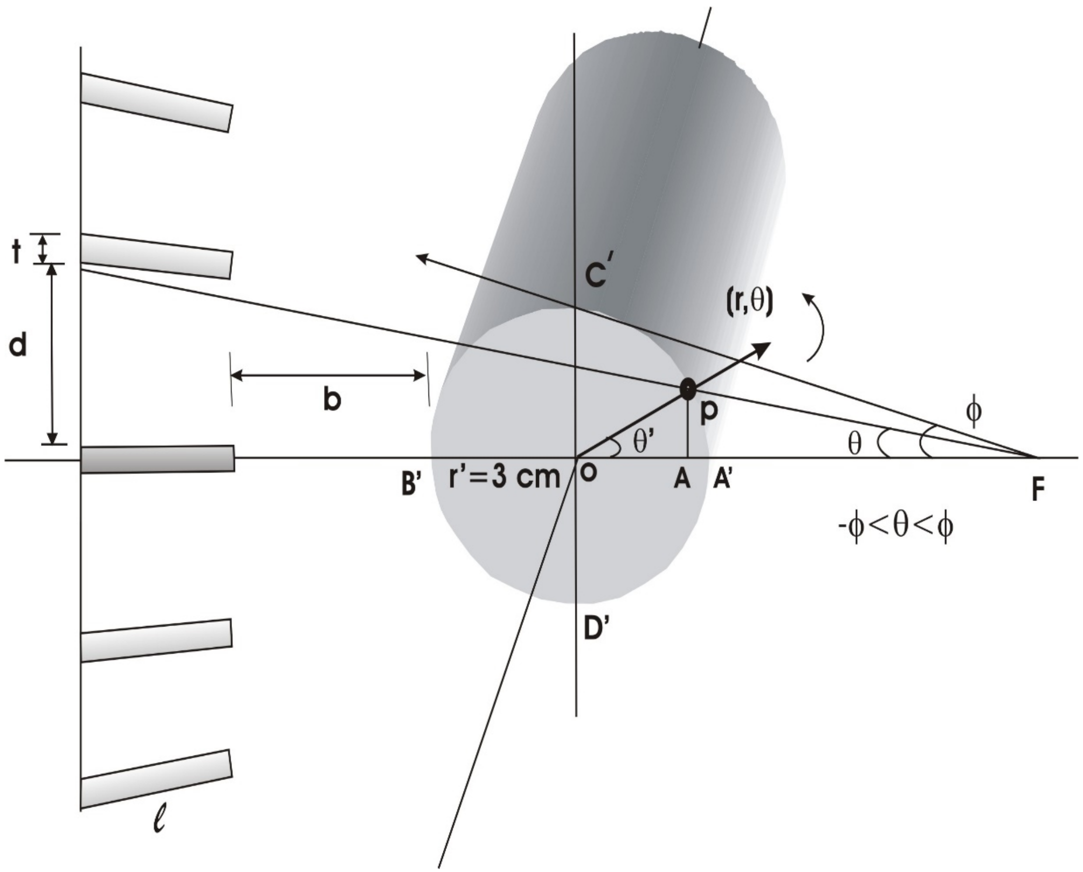
Particle density (N) = Particle weight/Volume □ w/V

T_L = vt = Track length in the medium

17x17 detector blocks were included in the model study. The sources were biased within the solid angle.

Methodology

Angular dependency of 3D object



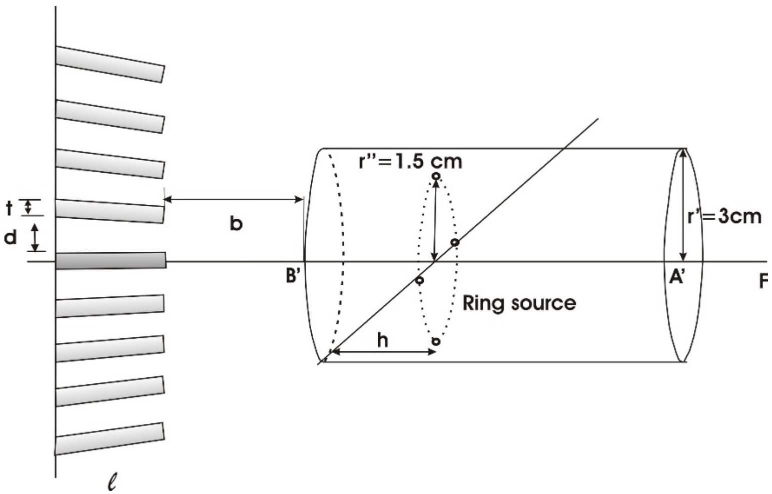
A water filled cylindrical object (r=3 cm), that compares to standard mouse, was placed at a distance b from collimator face.

Because of symmetry, the upper half (A'B'C') was only considered where A' and B' exist in the most and the least depth points inside attenuating medium, C' in the middle.

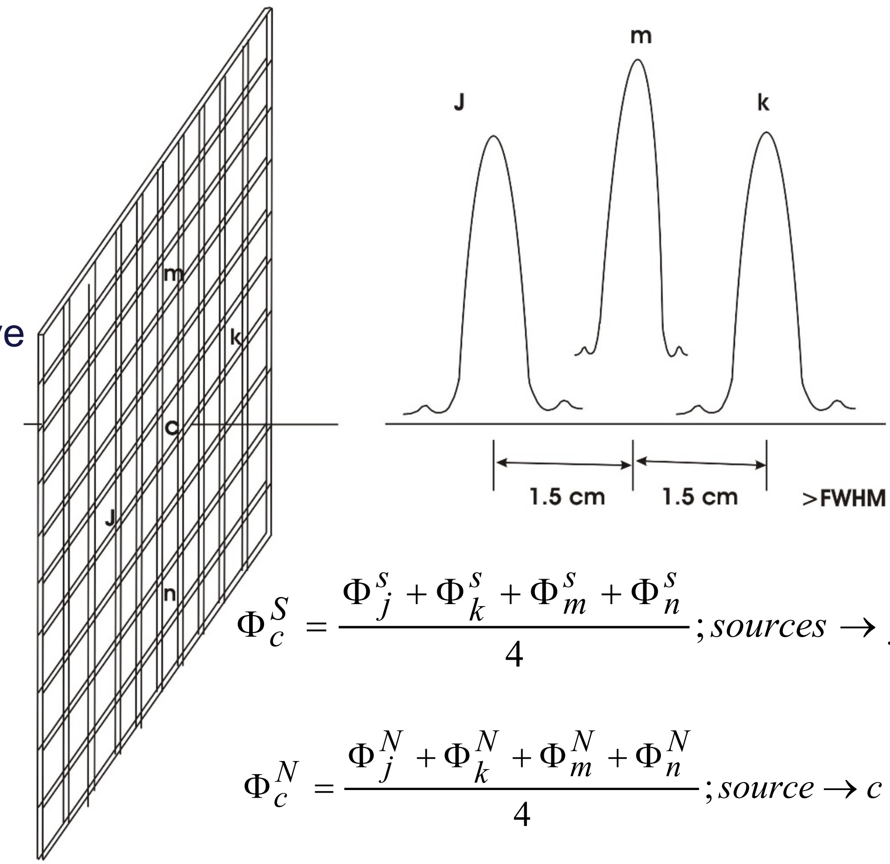
For every θ' angle at the object center, a corresponding θ angle was calculated at the focal point. θ varied from –ϕ to +ϕ ($-\phi<\theta<\phi$)

Methodology

Calculation of Signal noise index (SNI)



A ring source (radius 1.5 cm) consists of four point sources were placed inside water filled cylinder at different depths. All sources make same magnitude of angle with the collimator axis.



The shortest distance between two consecutive peaks was long enough not to interrupt each other.

$$\Phi_c^S = \frac{\Phi_j^s + \Phi_k^s + \Phi_m^s + \Phi_n^s}{4}; sources \rightarrow j, k.m.n$$

The signal at the ring-center can be taken as the average of the signals at j, k, m, n with four sources at these locations. The noise at the center is calculated as the noise calculated at j, k, m, n with a point source at the center c.

$$\Phi_c^N = \frac{\Phi_j^N + \Phi_k^N + \Phi_m^N + \Phi_n^N}{4}; source \rightarrow c$$

$$\text{SNI} = \frac{\Phi_c^S}{\Phi_c^N}$$

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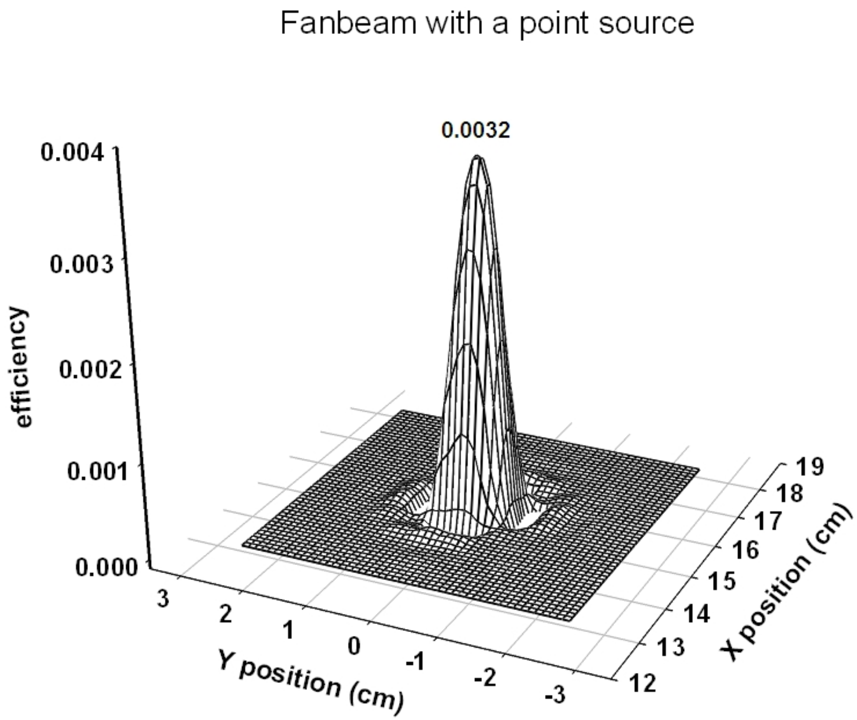
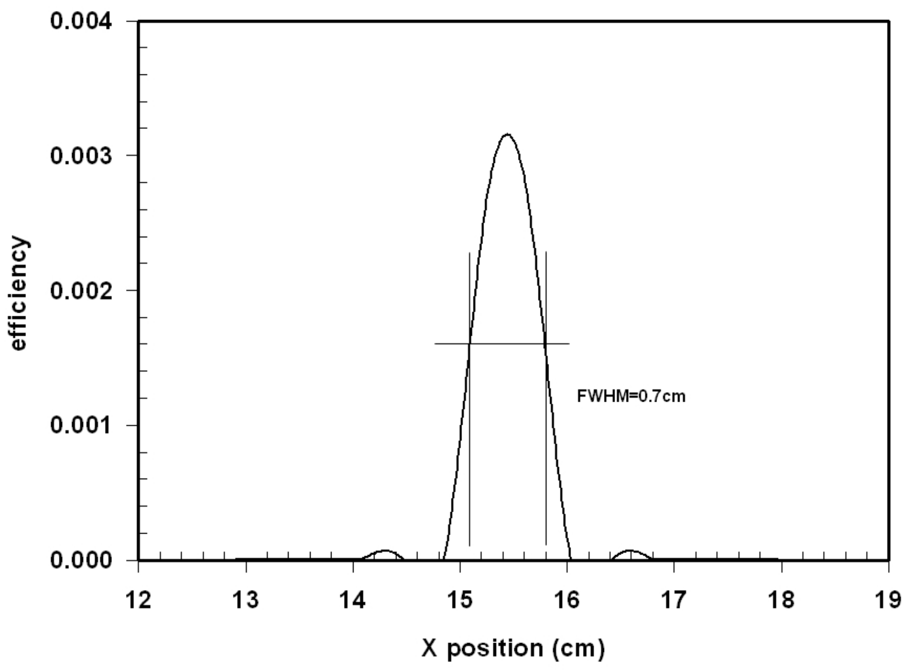
Results & Discussion

Point source profile for the collimator

A point source in air at 10 cm away from the collimator face.





Focal length f=18 cm, b=10 cm

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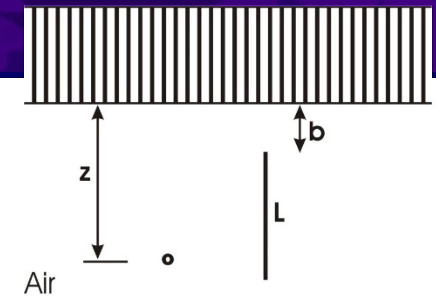
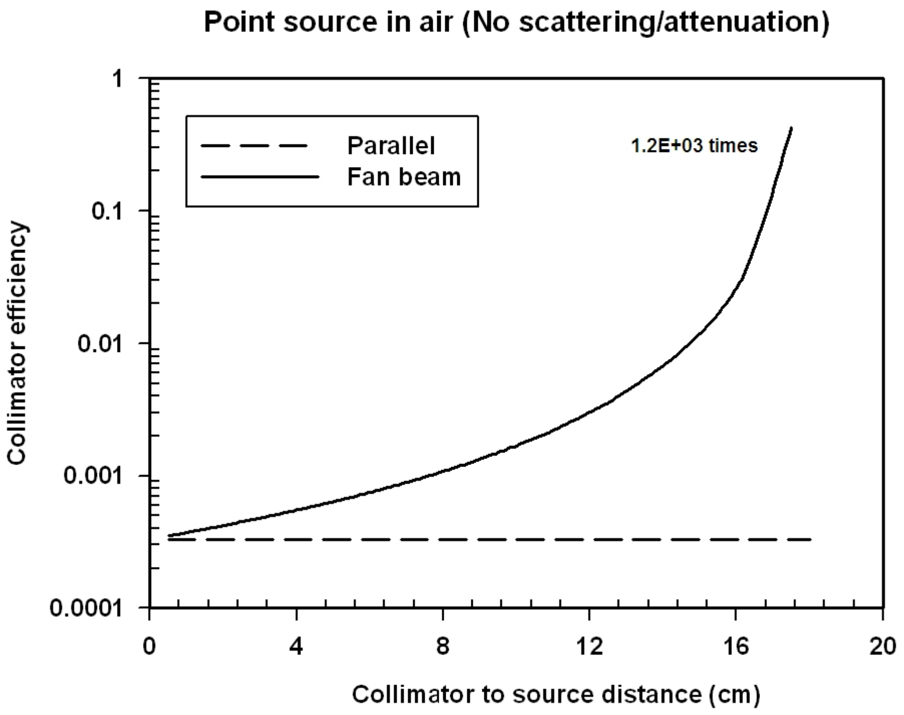
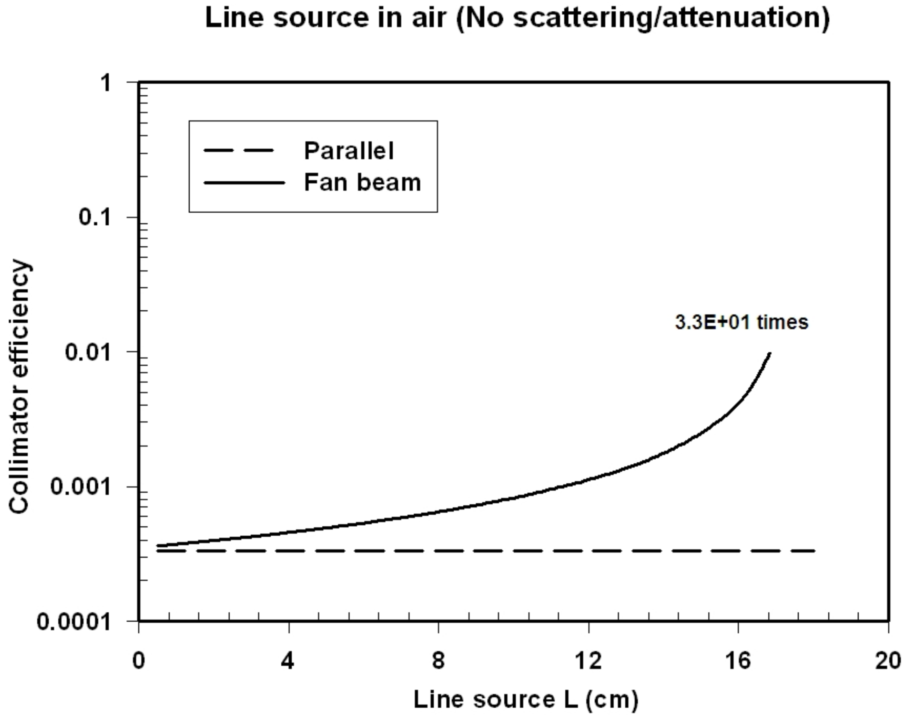
Results & Discussion

Point and line source in air





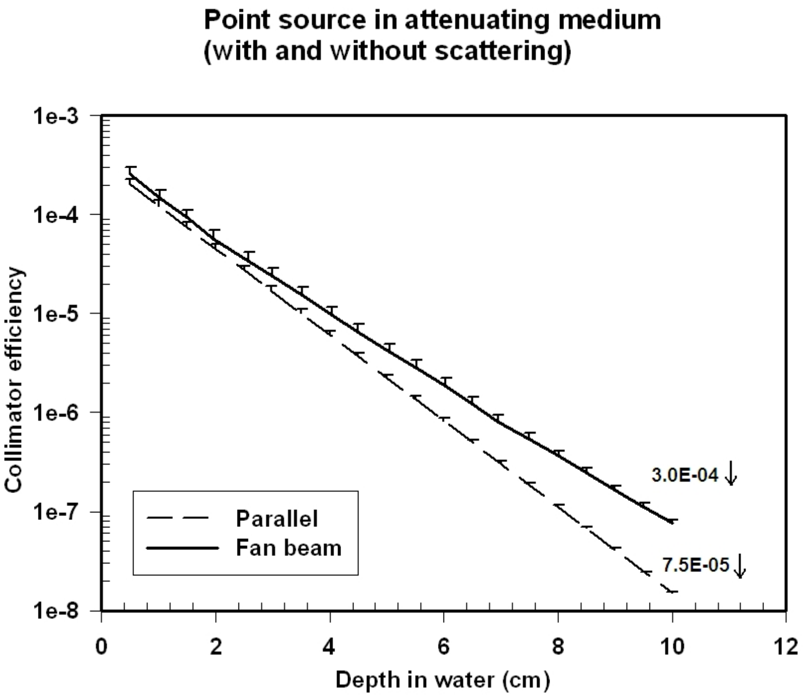


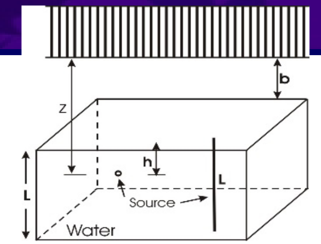
For point source, the detector efficiency increases 1.2E+03 times near the focal point.

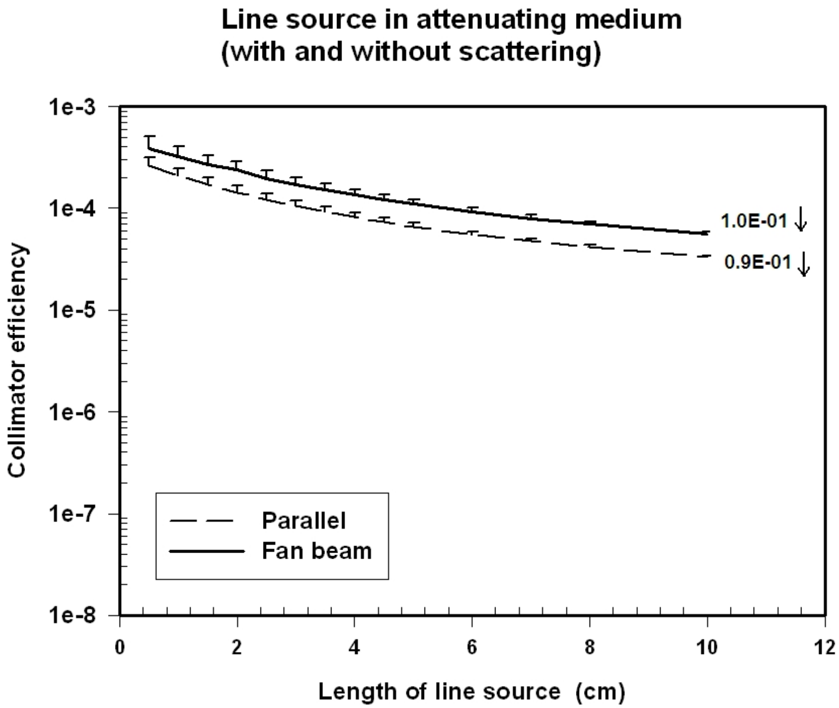
For line source it's increases 3.3E+01 times

Results & Discussion

Point and line source in water







At 0.5 cm depth, scattering □ 14 % for parallel

19 % for fan beam

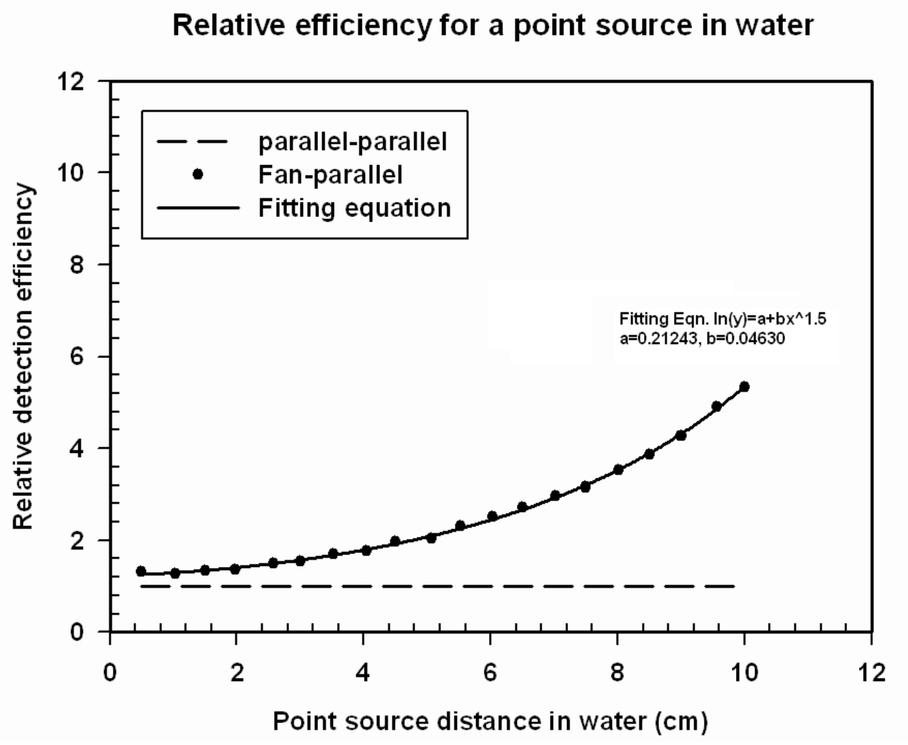
At 0.5 cm depth, scattering □ 19 % for parallel

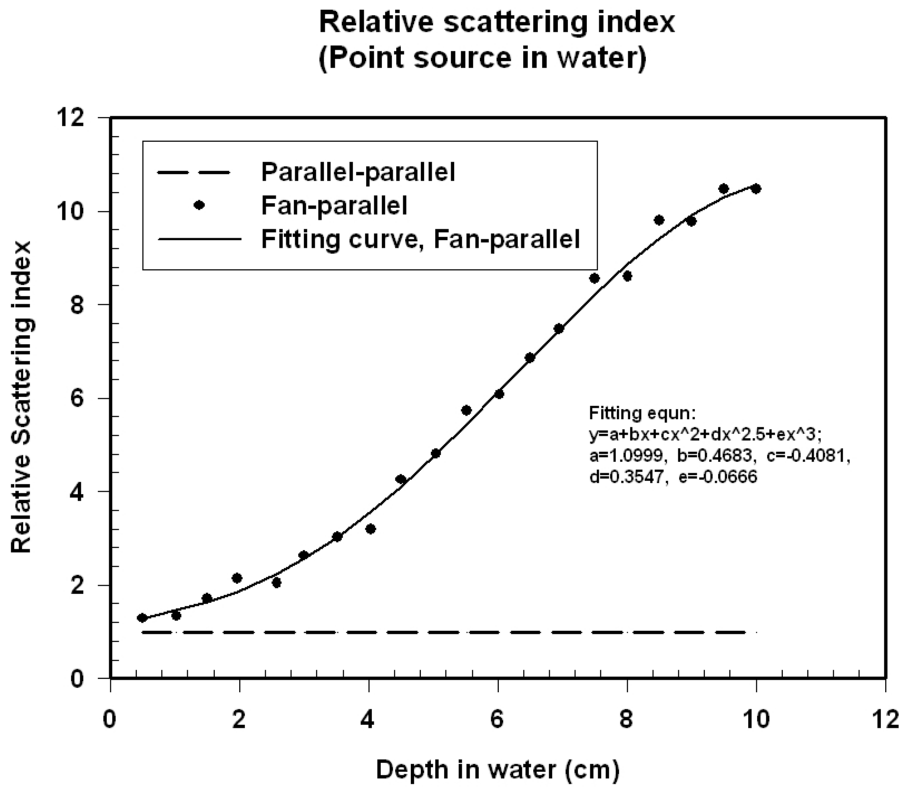
30 % for fan beam

Results & Discussion

Relative efficiency and Scattering index for point source in water

The attenuating medium was fixed at 3 cm away from the collimator face.



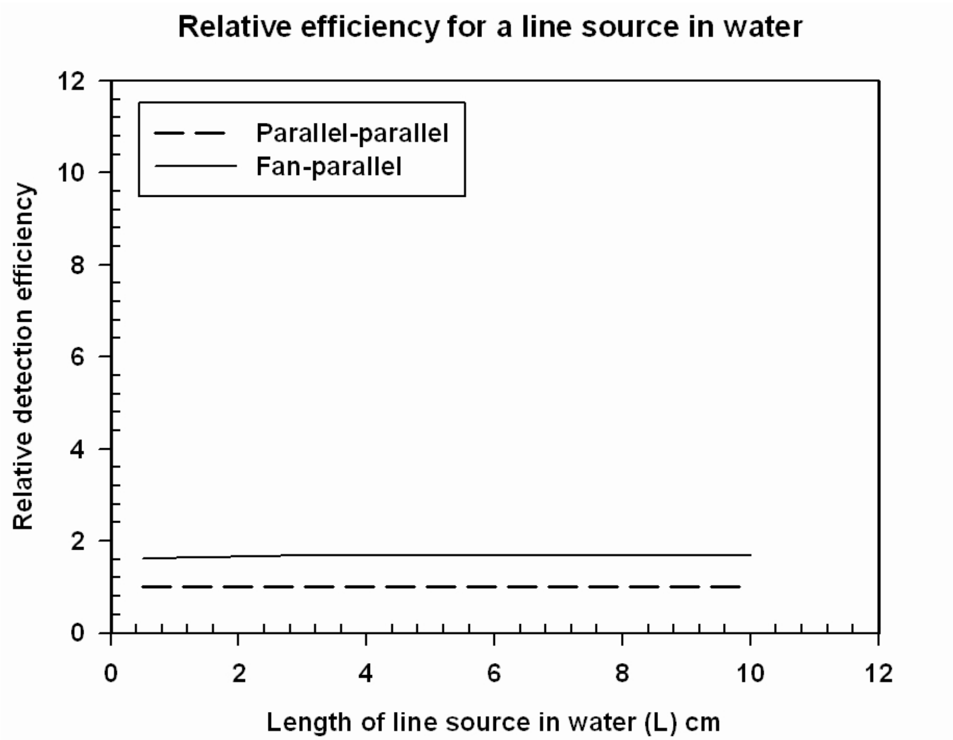


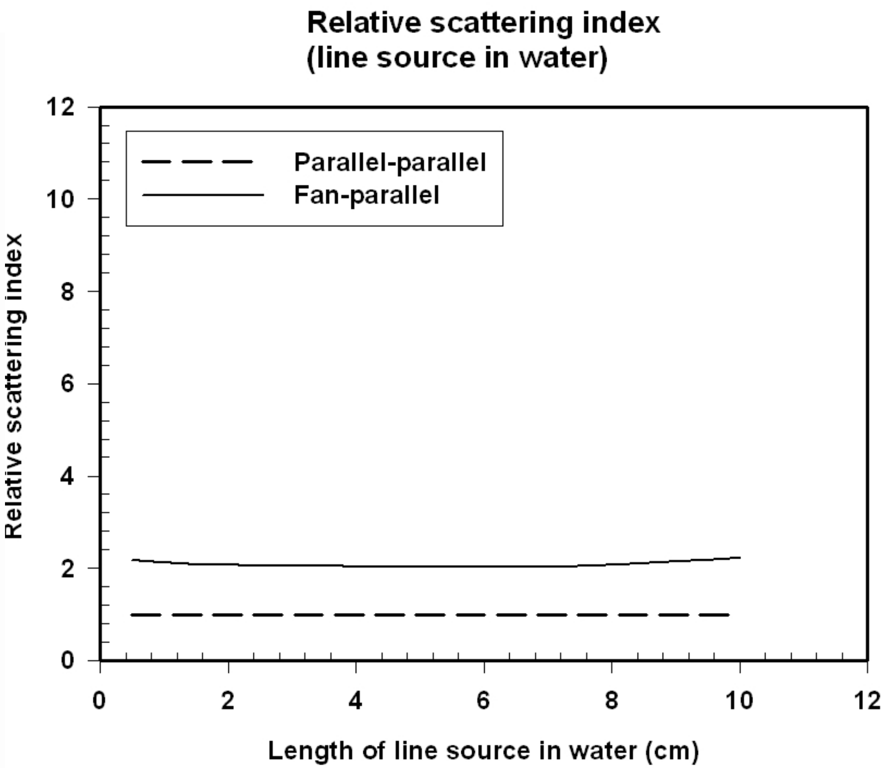
For point source, relative efficiency increases about 6 times than that of Parallel

The fan beam scattering index increases about 11 times than that of parallel collimator

Results & Discussion

Relative efficiency and Scattering index for line source in water



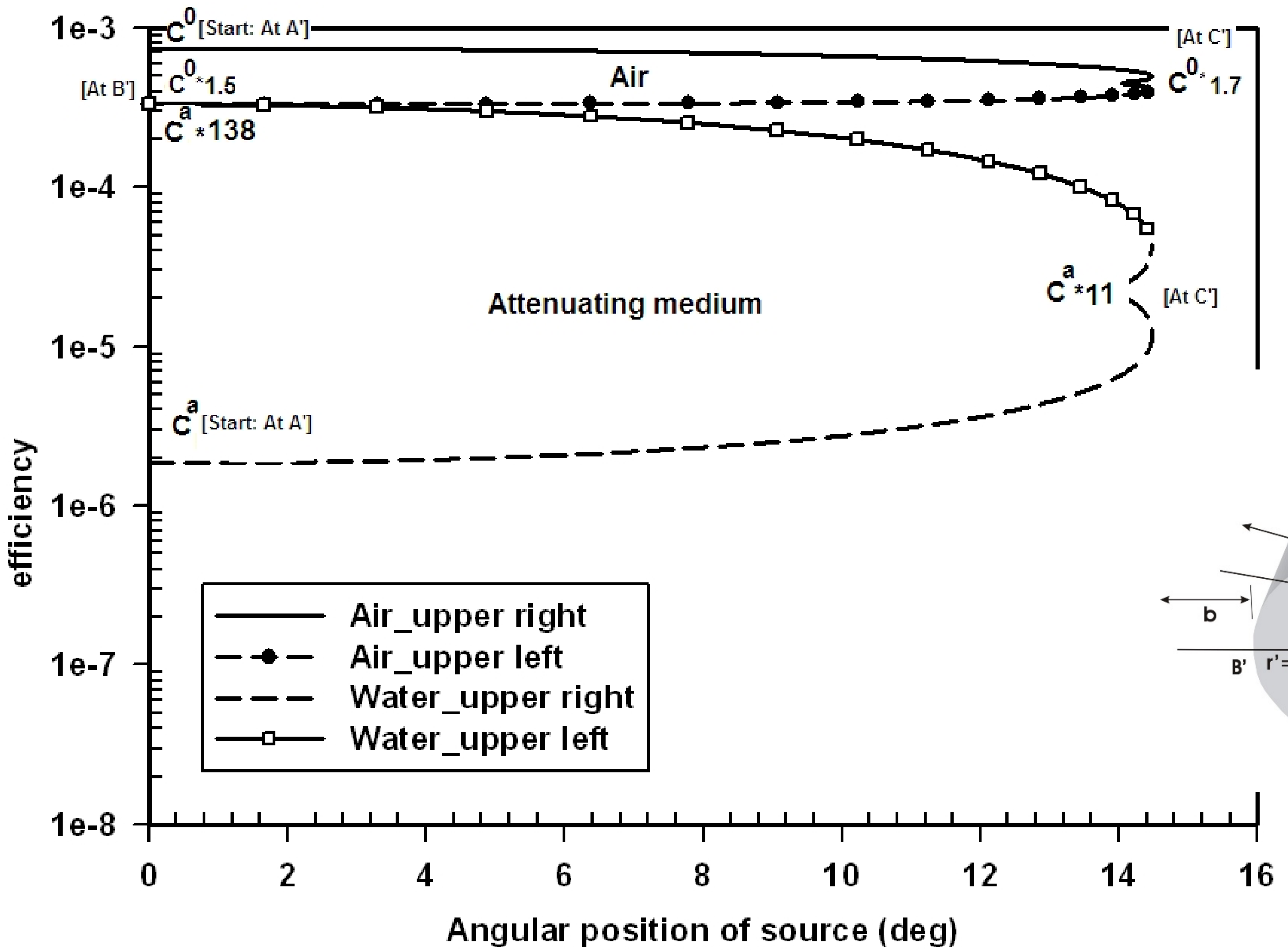


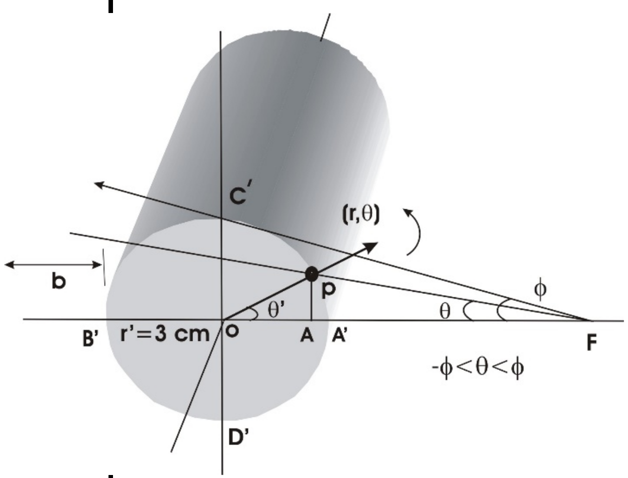
The relative efficiency is linear for line source

The scattering index is linear for line source

Results & Discussion

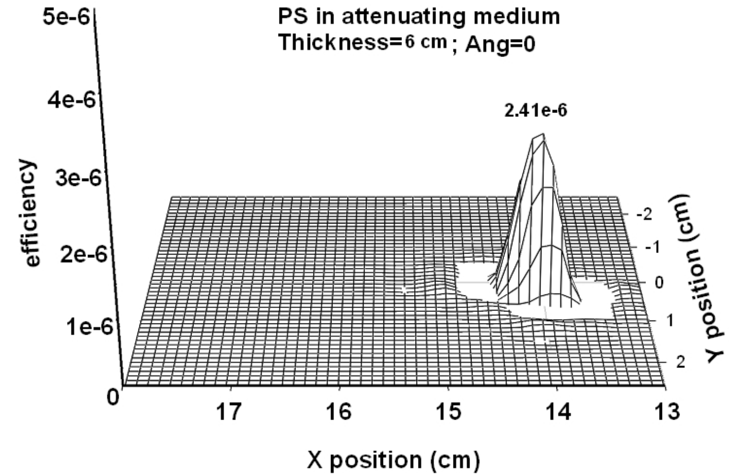
Angular dependency of a 3D object

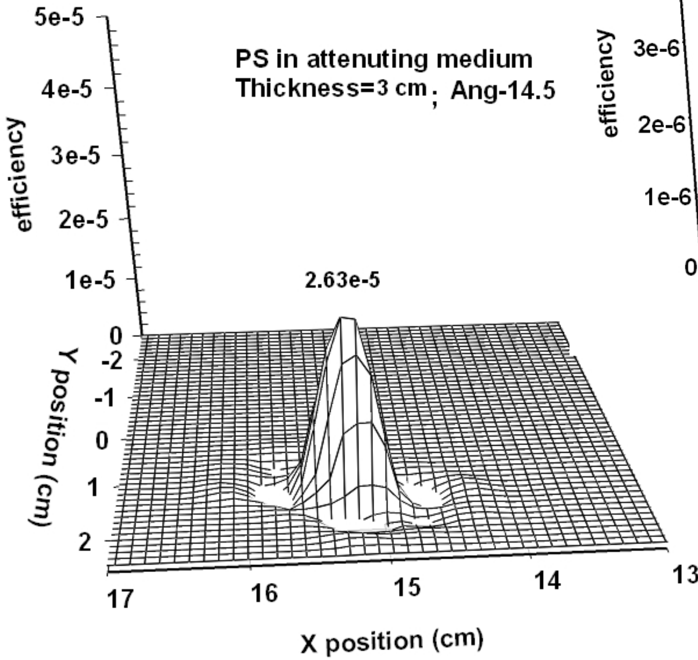


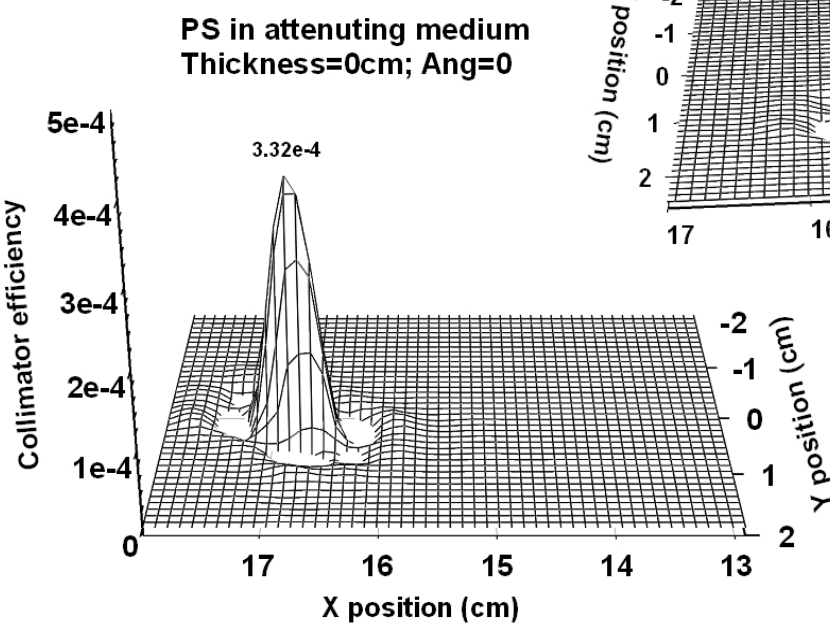


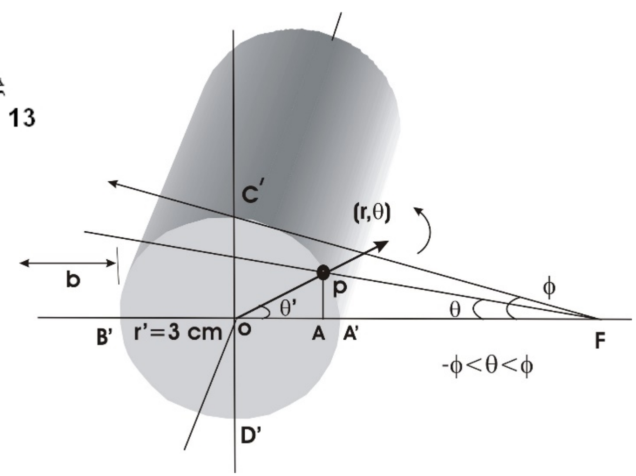
Results & Discussion

Angular dependency of a 3D object









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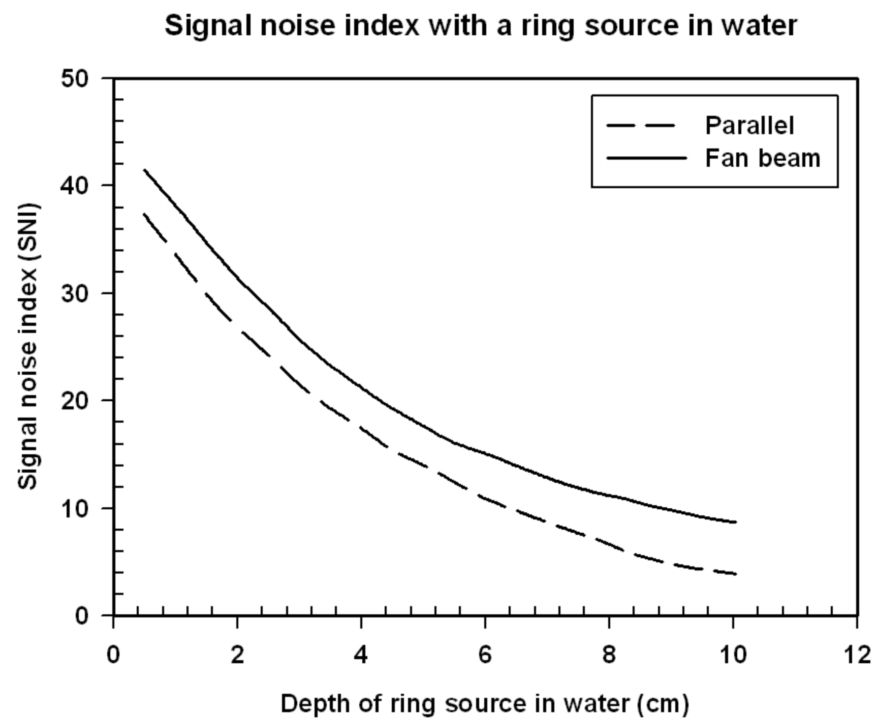
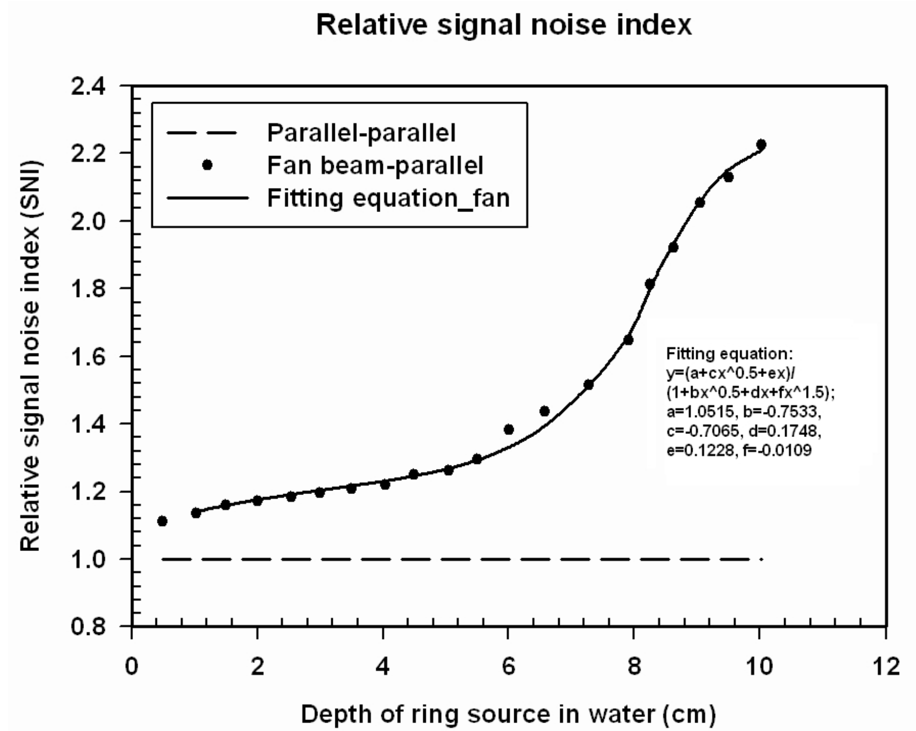
Results & Discussion

Signal noise index (SNI)





With fan beam, the SNI increases about 2.3 times than the that of the parallel collimator

Canada

Conclusion

*) The performance characteristic of the proposed fan beam collimator has been studied for different source configurations based on analytic formulation and Monte Carlo simulation studies.

*) The results shown in this study revealed that, a fan beam collimator is useful for scintillation imaging. But the advantage of fan beam is not predictable from mathematical derivation with a point source in air alone. Details particle transport calculation is essential.

*) Its performance strongly dependent on the source distribution and differs significantly for different source configuration.

*) Inside attenuating medium, the increased attenuating effect **outweighs** the fan beam increased geometric efficiency when a line source moves toward the focal point (Supported by: Tsui BMW, IEEE 1996; brain imaging).

*) The performance of a fan beam collimator should be evaluated for specific application and purpose.

QUESTIONS ?