AXIOMA Project

Laser-based coherent scintillator

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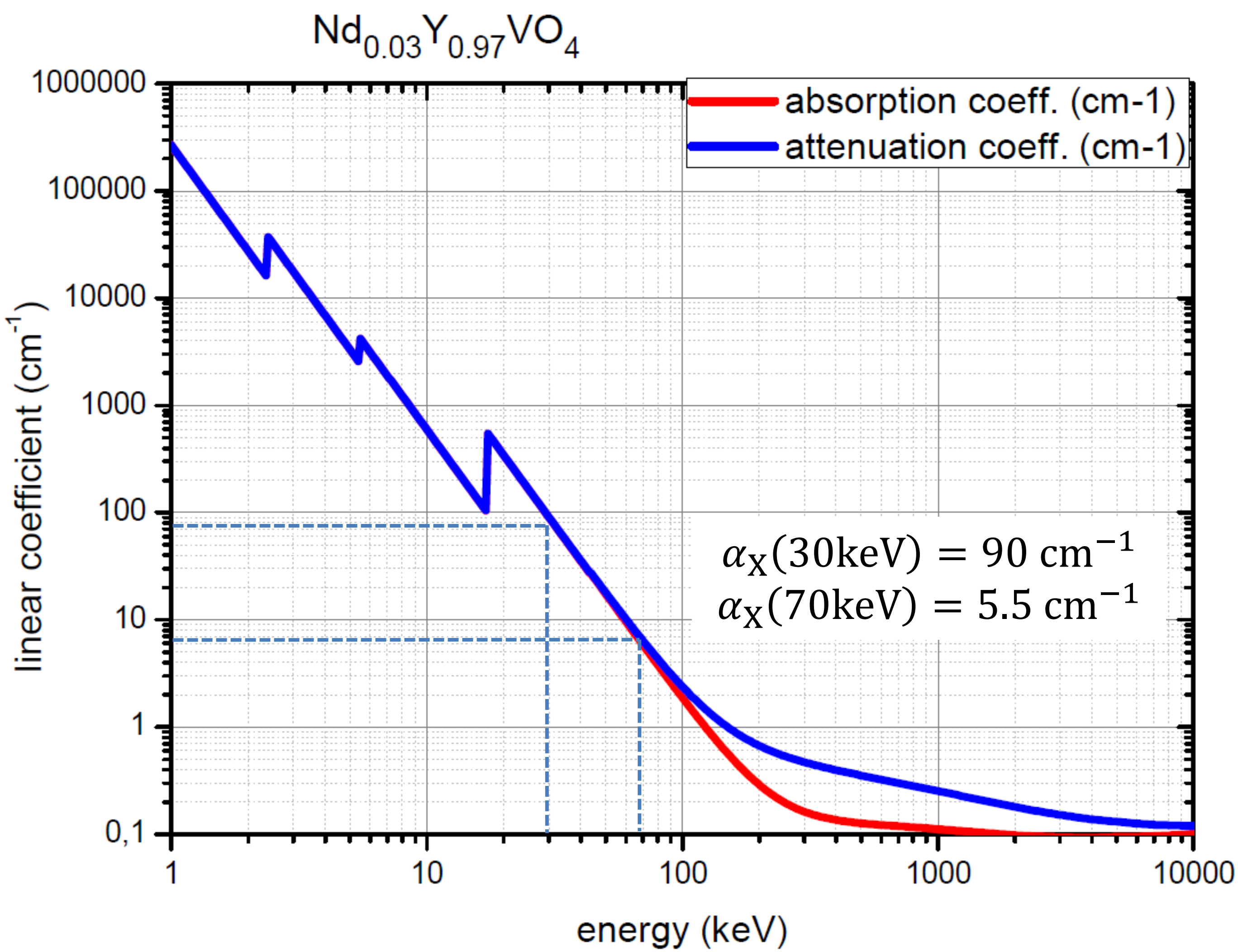
X-ray absorption in Nd:YVO$_4$ laser medium



Laser design

Nd:YVO$_4$ (a-cut):

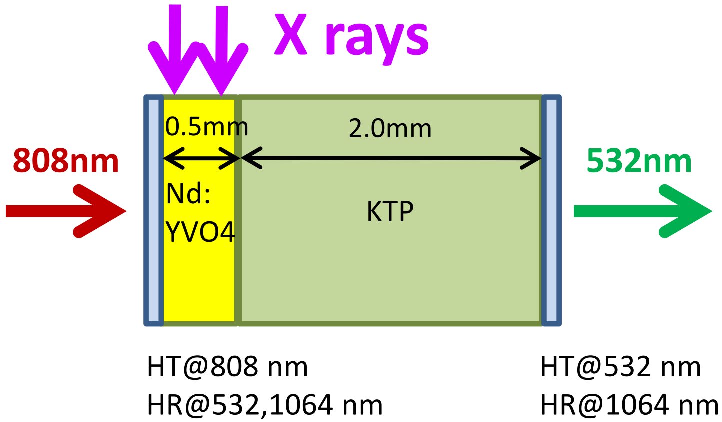
$$1\ \%\ \text{at.} \equiv 1.26 \times 10^{20}\ \text{cm}^{-3}$$

$$\sigma_A = 2.8 \times 10^{-19}\ \text{cm}^2$$

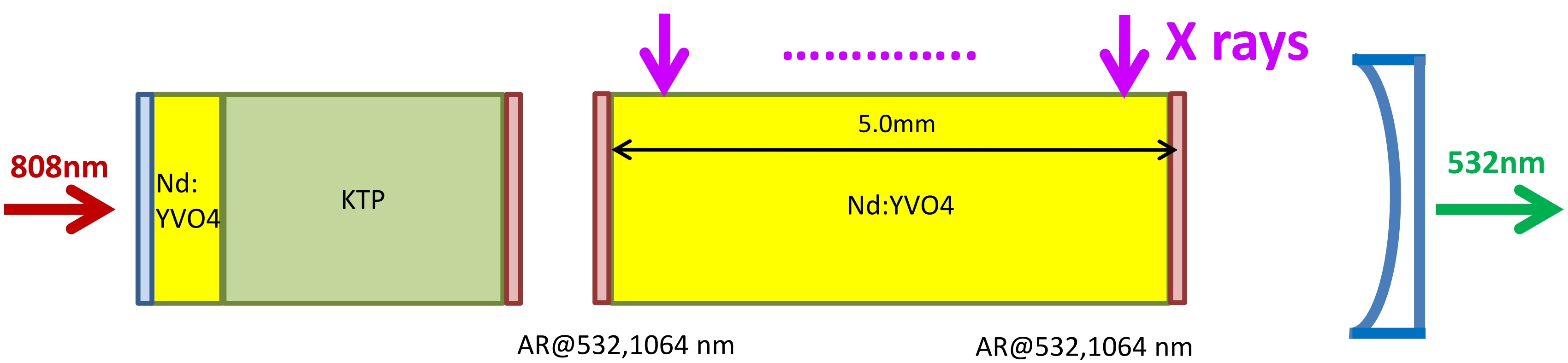
$$\sigma_E = 25 \times 10^{-19}\ \text{cm}^2$$

$$\tau_{sp}(3\%\ \text{at.}) \approx 30 \times 10^{-6}\ \text{s}$$

1)



2)



X-ray detection limits

Pump/laser beam parameters: $w_0\,(808\text{ nm}) = w_0\,(1064\text{ nm}) = 100\ \mu\text{m}$

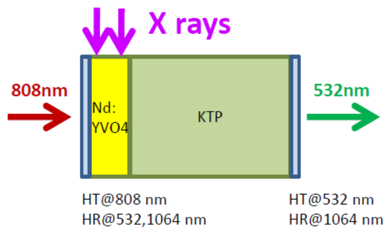
$M^2(808\text{ nm}) = 20 \quad M^2(1064\text{ nm}) = 1.5$

Cavity parameters: $L = 0.5\text{ mm}, L_c = 2.5\text{ mm}\ (+5\text{ mm} + \cdots), \text{Loss} = 3\%$

Nd sensitization efficiency: $\eta_{X-Nd}(30\text{ keV}, 3\%\text{ at.}) \approx 4500$

Pump noise: $\sigma_{noise}(808\text{ nm}) = 0.5\%\text{ rms}$

1)

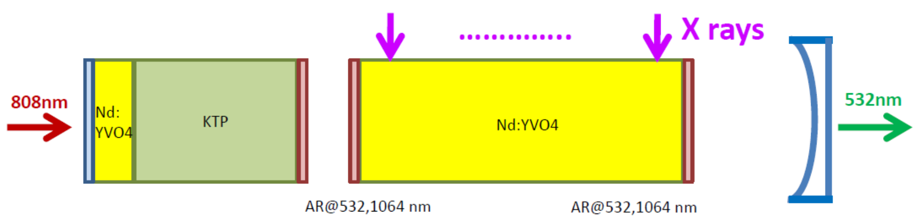


$P_{th} = 32\text{ mW}$

$\phi_{X,min} = 2.7 \times 10^{14}\text{ ph s}^{-1}\text{cm}^{-2}\ (1.3\text{ W cm}^{-2})$ cw

$F_{X,min} = 8.2 \times 10^{9}\text{ ph cm}^{-2}\ (39\ \mu\text{J cm}^{-2})$ short pulse

2)



$P_{th} = 32\text{ mW}$

$\phi_{X,min} = 2.7 \times 10^{13}\text{ ph s}^{-1}\text{cm}^{-2}\ (0.13\text{ W cm}^{-2})$ cw

$F_{X,min} = 8.2 \times 10^{8}\text{ ph cm}^{-2}\ (3.9\ \mu\text{J cm}^{-2})$ short pulse

1) Model for coherent scintillator based on green laser pointer (Nd:YVO4+KTP)

$f := 1.6 \cdot 10^{-19}$ eV/J

$c := 3 \cdot 10^{8}$ speed of light (m/s)

$\lambda p := 808 \cdot 10^{-9}$ $\quad \lambda l := 1064 \cdot 10^{-9}$ pump (laser) wavelength (m)

$hvp := \frac{1240}{\lambda p \cdot 10^{9}} \cdot f$ $\quad hvl := \frac{1240}{\lambda l \cdot 10^{9}} \cdot f$ pump (laser) photon energy (J)

laser crystal parameters

$Nion := 3 \cdot 1.26 \cdot 10^{26}$ Nd-ion density : (% at.) x (ion density at 1% at., m-3)

$L := 0.5 \cdot 10^{-3}$ $\quad s := 2 \cdot 10^{-3}$ $\quad d := 0.2 \cdot 10^{-3}$ Nd-doped YVO4 crystal length, size and laser beam distance from irradiated edge (m

$\sigma A := 2.8 \cdot 10^{-23}$ a-cut absorption cross-section at pump wavelength (m2)

$\sigma E := 25 \cdot 10^{-23}$ a-cut stimulated-emission cross-section al laser wavelength (m2)

$\tau sp := 30 \cdot 10^{-6}$ fluorescence lifetime (s)

$\eta := 0.49$ optical pump quantum efficiency

$vg := 1.5 \cdot 10^{8}$ YVO4 group velocity at laser wavelength (m/s)

laser cavity parameters

$Lc := 2.5 \cdot 10^{-3}$ cavity length (m)

$Loss\_L := 0.03$ linear round-trip loss (OC transmittivity included)

$\alpha m := -\frac{1}{2Lc} \cdot \ln(1 - Loss\_L)$ $\quad \alpha m = 6.0918$ linear modal loss coefficient (m-1)

pump (laser) beam characteristics

$np := 1.9721$ $\quad nl := 1.9573$ refractive index of Nd-doped crystal at pump (laser) wavelength

$M2p := 20$ $\quad M2l := 1.5$ pump (laser) M2 factor

$w0p := 100 \cdot 10^{-6}$ $\quad w0l := 100 \cdot 10^{-6}$ pump (laser) beam minimum waist (radius, m)

$zp := \frac{\pi \cdot np \cdot w0p^2}{\lambda p \cdot M2p}$ $\quad zl := \frac{\pi \cdot nl \cdot w0l^2}{\lambda l \cdot M2l}$ pump (laser) Rayleigh range in Nd-doped crystal (m)

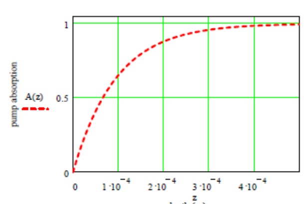
$wp(z) := w0p \cdot \sqrt{1 + \left(\frac{z}{zp}\right)^2}$ $\quad wl(z) := w0l \cdot \sqrt{1 + \left(\frac{z}{zl}\right)^2}$ pump (laser) beam waist in Nd-doped crystal (m)

$Gp(x,y,z) := \frac{2}{\pi\, wp(z)^2} \cdot e^{\frac{-2(x^2+y^2)}{wp(z)^2}}$ $\quad Gl(x,y,z) := \frac{2}{\pi\, wl(z)^2 \cdot Lc} \cdot e^{\frac{-2(x^2+y^2)}{wl(z)^2}}$ pump flux (laser photon density) distribution function

pump photon flux, Φp (ph m-2 W-1)

$\Phi p\_P(x,y,z) := \frac{1}{hvp} \cdot e^{-\sigma A\, Nion\, z} \cdot Gp(x,y,z)$

$A(z) := 1 - e^{-\sigma A\, Nion\, z}$



local inversion density, ΔN (m-3 W-1), and gain coefficient, g (m-1 W-1)

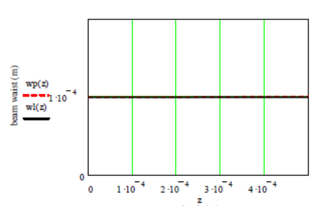
$\Delta N\_P(x,y,z) := \sigma A \cdot \Phi p\_P(x,y,z) \cdot \eta \cdot Nion \cdot \tau sp$

$g\_P(x,y,z) := \sigma E \cdot \Delta N\_P(x,y,z)$

modal inversion density, ΔNm (m-3 W-1), and modal gain coefficient, gm (m

$\Delta Nm\_P := \int_0^L \int_{-0.5s}^{0.5s} \int_{-d}^{s-d} \Delta N\_P(x,y,z) \cdot Gl(x,y,z)\, dx\, dy\, dz$

$gm\_P := \sigma E \cdot \Delta Nm\_P$



threshold pump power, Pth (W), density, Dth (W m-2) and photon flux, Φth (ph s-1 m-2)

$Pth := \frac{\alpha m}{gm\_P}$ $\quad Pth = 0.0321$

$Dth := \frac{2}{\ln(2)} \cdot \frac{Pth}{\pi \cdot w0p^2}$ $\quad Dth = 2.9525 \times 10^{6}$

$\Phi th := \frac{Dth}{hvp}$ $\quad \Phi th = 1.2024 \times 10^{25}$

modal inversion (m-3) and peak inversion fraction at threshold

$\Delta Nm\_th := \Delta Nm\_P \cdot Pth$ $\quad \Delta Nm\_th = 2.4367 \times 10^{22}$

$fract\Delta Nth := \frac{\Delta N\_P(0,0,0) \cdot Pth}{Nion}$ $\quad fract\Delta Nth = 3.4306 \times 10^{-3}$

minimum X-ray flux (CW mode) and fluence (short pulse mode), ΦXth (ph/s/m2) and FXth (ph/pulse/m2)

$hvX := 30 \cdot 10^{3} \cdot f$ X-ray photon energy (J)

$\alpha X := 9 \cdot 10^{3}$ X-ray absorption coefficient (m-1)

$\eta XtoNd := 4.5 \cdot 10^{3}$ X-ray-pump quantum efficiency

$LX := 0$ X-ray detecting crystal length (m)

$\sigma noise := 5 \cdot 10^{-3}$ pump laser RMS noise

$\Delta NX\_\Phi(x) := \alpha X \cdot e^{-\alpha X (x+d)} \cdot \eta XtoNd \cdot \tau sp$ X-ray induced local inversion density (m-3 ph-1 s m2)

$\Delta NmX\_\Phi := \int_0^L \int_{-0.5s}^{0.5s} \int_{-d}^{s-d} \Delta NX\_\Phi(x) \cdot Gl(x,y,z)\, dx\, dy\, dz$ X-ray induced modal inversion density (m-3 ph-1 s m2)

$\Phi Xmin := \frac{\sigma noise \cdot \Delta Nm\_th}{\Delta NmX\_\Phi}$ $\quad DXmin := hvX \cdot \Phi Xmin$ $\quad \Phi Xmin = 2.7416 \times 10^{18}$ $\quad DXmin = 1.316 \times 10^{4}$

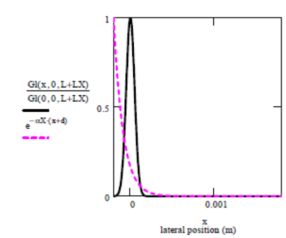
$FXmin := \Phi Xmin \cdot \tau sp$ $\quad EXmin := hvX \cdot FXmin$ $\quad FXmin = 8.2249 \times 10^{13}$ $\quad EXmin = 0.3948$

pulsed X-ray source peak flux, ΦXs (ph/s/m2), and fluence, FXs (ph/pulse/m2)

$NX := 1 \cdot 10^{8}$ X-ray photons per pulse

$SX := 1 \cdot 10^{-5}$ X-ray emission surface (m2)

$FXs := \frac{NX}{SX}$ $\quad FXs = 1 \times 10^{13}$



2) Model for coherent scintillator based on green laser (Nd:YVO4+KTP+Nd:YVO4)

$f := 1.6 \cdot 10^{-19}$ eV/J

$c := 3 \cdot 10^{8}$ speed of light (m/s)

$\lambda p := 808 \cdot 10^{-9}$ $\quad \lambda l := 1064 \cdot 10^{-9}$ pump (laser) wavelength (m)

$h\nu p := \frac{1240}{\lambda p \cdot 10^{9}} \cdot f$ $\quad h\nu l := \frac{1240}{\lambda l \cdot 10^{9}} \cdot f$ pump (laser) photon energy (J)

laser crystal parameters

$Nion := 3 \cdot 1.26 \cdot 10^{26}$ Nd-ion density : (% at.) x (ion density at 1% at., m-3)

$L := 0.5 \cdot 10^{-3}$ $\quad s := 2 \cdot 10^{-3}$ $\quad d := 0.2 \cdot 10^{-3}$ Nd-doped YVO4 crystal length, size and laser beam distance from irradiated edge (m)

$\sigma A := 2.8 \cdot 10^{-23}$ a-cut absorption cross-section at pump wavelength (m2)

$\sigma E := 25 \cdot 10^{-23}$ a-cut stimulated-emission cross-section al laser wavelength (m2)

$\tau sp := 30 \cdot 10^{-6}$ fluorescence lifetime (s)

$\eta := 0.49$ optical pump quantum efficiency

$vg := 1.5 \cdot 10^{8}$ YVO4 group velocity at laser wavelength (m/s)

laser cavity parameters

$Lc := 0.2$ cavity length (m)

$Loss\_L := 0.03$ linear round-trip loss (OC transmittivity included)

$\alpha m := -\frac{1}{2Lc} \cdot \ln(1 - Loss\_L)$ $\quad \alpha m = 0.0761$ linear modal loss coefficient (m-1)

pump (laser) beam characteristics

$np := 1.9721$ $\quad nl := 1.9573$ refractive index of Nd-doped crystal at pump (laser) wavelength

$M2p := 20$ $\quad M2l := 1.5$ pump (laser) M2 factor

$w0p := 100 \cdot 10^{-6}$ $\quad w0l := 100 \cdot 10^{-6}$ pump (laser) beam minimum waist (radius, m)

$zp := \frac{\pi \cdot np \cdot w0p^2}{\lambda p \cdot M2p}$ $\quad zl := \frac{\pi \cdot nl \cdot w0l^2}{\lambda l \cdot M2l}$ pump (laser) Rayleigh range in Nd-doped crystal (m)

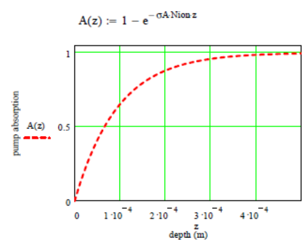
$wp(z) := w0p \cdot \sqrt{1 + \left(\frac{z}{zp}\right)^2}$ $\quad wl(z) := w0l \cdot \sqrt{1 + \left(\frac{z}{zl}\right)^2}$ pump (laser) beam waist in Nd-doped crystal (m)

$Gp(x,y,z) := \frac{2}{\pi\, wp(z)^2} \cdot e^{\frac{-2(x^2+y^2)}{wp(z)^2}}$ $\quad Gl(x,y,z) := \frac{2}{\pi\, wl(z)^2 \cdot Lc} \cdot e^{\frac{-2(x^2+y^2)}{wl(z)^2}}$ pump flux (laser photon density) distribution function

pump photon flux, Φp (ph m-2 W-1)

$\Phi p\_P(x,y,z) := \frac{1}{h\nu p} \cdot e^{-\sigma A\, Nion\, z} \cdot Gp(x,y,z)$

$A(z) := 1 - e^{-\sigma A\, Nion\, z}$



local inversion density, ΔN (m-3 W-1), and gain coefficient, g (m-1 W-1)

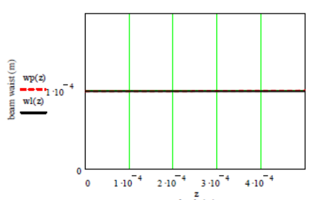
$\Delta N\_P(x,y,z) := \sigma A \cdot \Phi p\_P(x,y,z) \cdot \eta \cdot Nion \cdot \tau sp$

$g\_P(x,y,z) := \sigma E \cdot \Delta N\_P(x,y,z)$

modal inversion density, ΔNm (m-3 W-1), and modal gain coefficient, gm (m

$\Delta Nm\_P := \int_0^L \int_{-0.5s}^{0.5s} \int_{-d}^{s-d} \Delta N\_P(x,y,z) \cdot Gl(x,y,z)\, dx\, dy\, dz$

$gm\_P := \sigma E \cdot \Delta Nm\_P$



threshold pump power, Pth (W), density, Dth (W m-2) and photon flux, Φth (ph s-1 m-2)

$Pth := \frac{\alpha m}{gm\_P}$ $\quad Pth = 0.0321$

$Dth := \frac{2}{\ln(2)} \cdot \frac{Pth}{\pi \cdot w0p^2}$ $\quad Dth = 2.9525 \times 10^{6}$

$\Phi th := \frac{Dth}{h\nu p}$ $\quad \Phi th = 1.2024 \times 10^{25}$

modal inversion (m-3) and peak inversion fraction at threshold

$\Delta Nm\_th := \Delta Nm\_P \cdot Pth$ $\quad \Delta Nm\_th = 3.0459 \times 10^{20}$

$fract\Delta Nth := \frac{\Delta N\_P(0,0,0) \cdot Pth}{Nion}$ $\quad fract\Delta Nth = 3.4306 \times 10^{-3}$

minimum X-ray flux (CW mode) and fluence (short pulse mode), ΦXth (ph/s/m2) and FXth (ph/pulse/m2)

$h\nu X := 30 \cdot 10^{3} \cdot f$ X-ray photon energy (J)

$\alpha X := 9 \cdot 10^{3}$ X-ray absorption coefficient (m-1)

$\eta XtoNd := 4.5 \cdot 10^{3}$ X-ray-pump quantum efficiency

$LX := 5 \cdot 10^{-3}$ X-ray detecting crystal length (m)

$\sigma noise := 5 \cdot 10^{-3}$ pump laser RMS noise

$\Delta NX\_\Phi(x) := \alpha X \cdot e^{-\alpha X (x+d)} \cdot \eta XtoNd \cdot \tau sp$ X-ray induced local inversion density (m-3 ph-1 s m2)

$\Delta NmX\_\Phi := \int_L^{L+LX} \int_{-0.5s}^{0.5s} \int_{-d}^{s-d} \Delta NX\_\Phi(x) \cdot Gl(x,y,z)\, dx\, dy\, dz$ X-ray induced modal inversion density (m-3 ph-1 s m2)

$\Phi Xmin := \frac{\sigma noise \cdot \Delta Nm\_th}{\Delta NmX\_\Phi}$ $\quad DXmin := h\nu X \cdot \Phi Xmin$ $\quad \Phi Xmin = 2.7396 \times 10^{17}$ $\quad DXmin = 1.315 \times 10^{3}$

$FXmin := \Phi Xmin \cdot \tau sp$ $\quad EXmin := h\nu X \cdot FXmin$ $\quad FXmin = 8.2189 \times 10^{12}$ $\quad EXmin = 0.0395$

pulsed X-ray source peak flux, ΦXs (ph/s/m2), and fluence, FXs (ph/pulse/m2)

$NX := 1 \cdot 10^{8}$ X-ray photons per pulse

$SX := 1 \cdot 10^{-5}$ X-ray emission surface (m2)

$FXs := \frac{NX}{SX}$ $\quad FXs = 1 \times 10^{13}$