

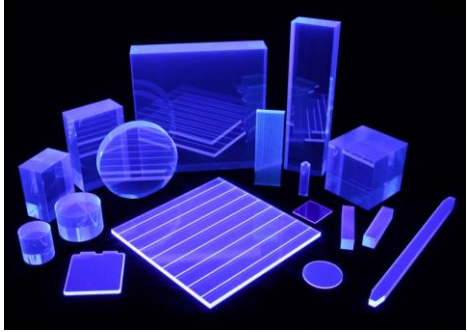


Optical photons

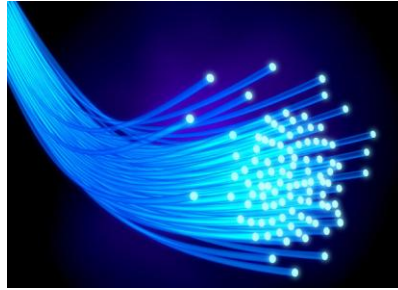
OPT-PROD, OPT-PROP, MAT-PROP, TCQUENCH

Simulating optical photons

Scintillators
(Eljen technology)

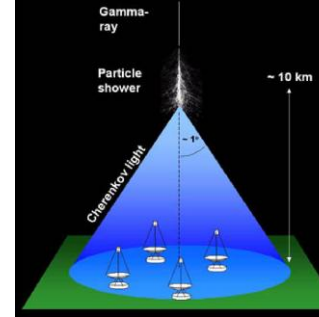


CT scanner
(Siemens corporation)

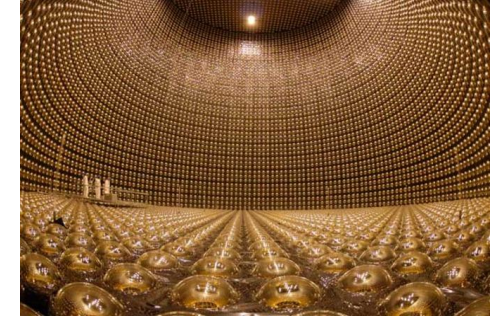


Optical/scintillating fibers

Gamma-ray astronomy
(Hess collaboration)



Neutrino observatories
(Super Kamiokande collaboration)



- Applications:

- Gamma-ray and neutrino observatories
- Dosimetry and area monitoring
- Medical imaging
- Hadron and electromagnetic calorimetry
- Geophysical probing

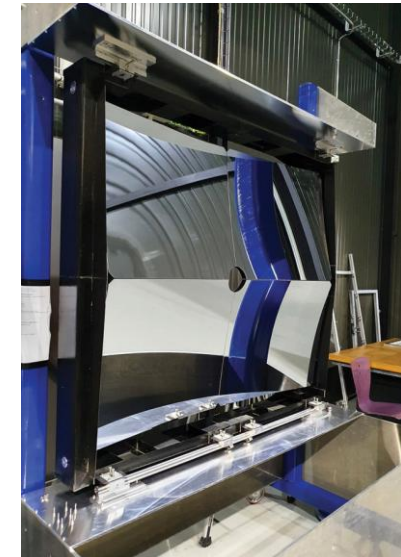
- Why simulate optical photons?

- Detection efficiency
- Energy and time resolution
- Material and geometry optimizations
- Background estimation and event reconstruction

Tile calorimeter
(CERN – ATLAS collaboration)



RICH detector
(CERN – LHCb collaboration)



Optical photons in FLUKA?

- In FLUKA, photons and optical photons are **NOT** the same particle!

Particle	FLUKA name	FLUKA particle ID
Photon	PHOTON	7
Optical photon	OPTIPHOT	-1

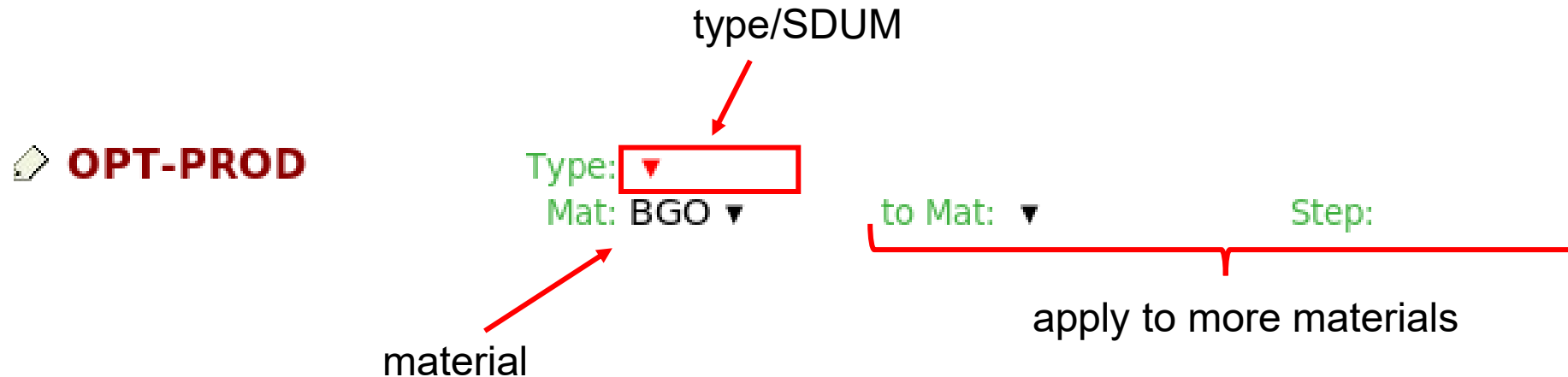
- Difference unrelated with the particle energy.
- Each associated to different physics processes but both:
 - transport and deposit energy,
 - can be used as primary particles,
 - have a defined energy range for transport and production,
 - have scattering and absorption cross-sections and,
 - have a polarization vector (which can be defined as "random").

Optical photons in FLUKA

- Optical photon production and transport **disabled by default**.
- Important mandatory cards:
 - **OPT-PROD**: Activates production (scintillation, Cherenkov)
 - **OPT-PROP**: Activates transport (energy cuts, reflections, boundary crossing, etc)
- Optional card:
 - **TCQUENCH**: Activates quenching (following Birk's law). Applies for scoring only.
- Plethora of user routines available for fine tuning of transport options.

Optical photon production (OPT-PROD card)

- Creation of secondary optical photons handled by the OPT-PROD card.
- Processes:
 - Scintillation
 - Cherenkov
- Production options applied to **materials**.



- **Note:** Transition radiation is **not supported** by FLUKA. Ignore the placeholder options.

Scintillation

- **SDUM=SCINTILL:**
 - Activate scintillation with defined peak photon energy (E_i).
- Other SDUM:
 - **SCINT-WV:** Define the peak wavelength (λ_i)
 - **SCINT-OM:** Define the peak angular frequency ($\omega_i=2\pi f$)

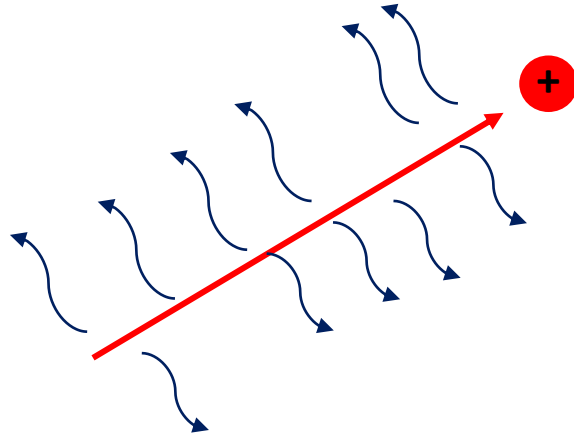
 **OPT-PROD** Type: SCINTILL ▼ $E_i = 2.76 \text{ eV}$ fraction: 0.0276
Time: =300*ns Mat: BGO ▼ to Mat: ▼ Step:

apply to more materials

- **Time:** Scintillation decay time in seconds.
- **Fraction:** Fraction of deposited energy converted in optical photons with energy E_i
 - fraction = yield (photons/MeV) $\times E_i$ (eV) $\times 10^{-6}$ or yield (photons/MeV) $\times 1.2398 \times 10^{-3} / \lambda_i$ (nm)
- Scintillation photons are **monochromatic**.
 - Or up to 3 peaks can be defined combining 3 **OPT-PROD** cards.

Scintillation

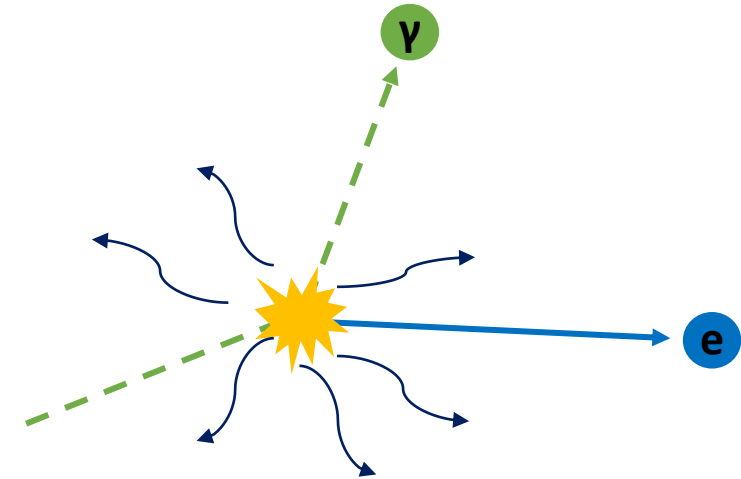
Continuous losses



- Optical photons generated randomly along tracks of charged particles.
- Photon momentum direction isotropic.
- Average number of photons proportional to the electronic stopping power (dE/dx).
- Exact number of photons Poisson distributed at each step.

Discrete losses

(electron below production cut-off)



- Optical photons created at the scattering vertex.
- Photon momentum direction isotropic.
- Number of photons proportional to the discrete energy loss.

Cherenkov radiation

- Produced with charged particles travelling faster than the speed of light in the material (i.e. $\beta > n^{-1}$).
- Activated with **SDUM=CERENKOV**. Must define the energy spectrum range for production.
- Other SDUM:
 - **CEREN-WV**: Define the wavelength range.
 - **CEREN-OM**: Define the angular frequency range ($\omega = 2\pi f$).

 **OPT-PROD**

Type: CERENKOV ▼
Mat: BGO ▼

Emin: =eV
to Mat: ▼

Emax: =4*eV
Step:

apply to more materials

- Optical photon produced along track in a characteristic cone with angle θ ($\cos(\theta) = 1/(n\beta)$).
- Uniform energy spectrum.

Conservation of energy

WARNING

Energy conservation applies for production of optical photons with FLUKA. Therefore, you should expect different results from **ENERGY** or **DOSE** scoring when using the **OPT-PROD** and **OPT-PROP** cards. Other MC codes (e.g. Geant4) may manage energy conservation laws differently.

- Total stopping power of particles, from electronic losses, elastic scattering and inelastic scattering **unchanged** with optical photons.
- But! Fraction of energy losses **converted** into optical photons.
- Optical photons **transport** energy far from the interaction, therefore:
 - Scored local energy deposition or dose is lower!

Transport properties – The OPT-PROP card

- For SDUM=BLANK:

Type/SDUM = "BLANK"

 **OPT-PROP**

Type: ▼ 
Refraction: 2.15 Absorption: 0.01 Diffusion: 0.1
Mat: BGO ▼ to Mat: ▼ Step: 

apply to more materials

- **Index of refraction (n):**
 - Related to Snell's law, total internal reflections and Fresnel reflections.
 - Changes the velocity of optical photons in the material ($v=c/n$).
 - **Must be defined for production and transport of optical photons in all materials!** (exception: vacuum)
- **Absorption:**
 - Equal to the inverse absorption length (in cm^{-1}) (follows the survival curve $\exp(-s/\lambda)$).
 - Energy of absorbed photons scored normally like for other particles.
 - Default: no absorption (=0.0)
- **Diffusion:**
 - Equal to inverse diffusion length (in cm^{-1}).
 - Random elastic scattering of photon with survival curve $\exp(-s/\lambda)$.
 - Photons scattered isotopically.
 - Default: no diffusion (=0.0)

Transport properties – Series expansion

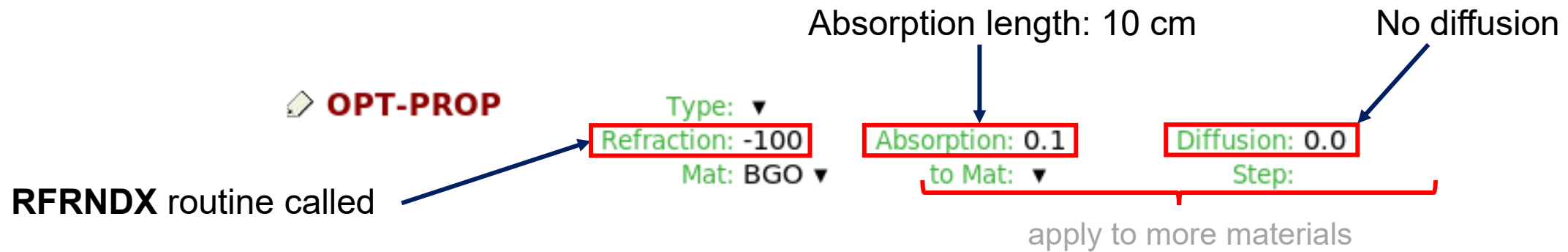
- Series expansion of the index of refraction, the absorption coefficient and the diffusion coefficient can be defined.
- Taylor series around central wavelength λ_0 (central angular frequency also available). Example for the index of refraction:

$$n(\lambda) = n(\lambda_0) + \frac{dn}{dx}x + \frac{1}{2}\frac{d^2n}{dx^2}x^2 + \frac{1}{6}\frac{d^3n}{dx^3}x^3 \quad \text{where} \quad x \equiv \frac{\lambda - \lambda_0}{\lambda_0}$$

- 0th order of the series defined with **SDUM=BLANK**.
- Derivatives defined with complementary **OPT-PROP** cards:
 - **SDUM=1**: First derivatives
 - **SDUM=2**: Second derivatives
 - **SDUM=3**: Third derivatives

Transport properties – User routines

- Arbitrary transport properties defined with user routines:
 - **RFRNDX**: Refraction index
 - **ABSCEF**: Absorption coefficient
 - **DFCFEF**: Diffusion coefficient
- Routine inputs:
 - Wavelength
 - Angular frequency
 - Material
- User routine called only if the property value is less than -99.



Reflections (OPT-PROP card)

- With **SDUM=METAL**, the material behaves like a reflector.

OPT-PROP

Type: METAL ▼
~~1st:~~ ~~2nd:~~ **3rd 1-r: 0.1**
Mat: ALUMINUM ▼ to Mat: ▼ Step:
apply to more materials

- Reflectivity (r) can be defined. In practice, the user sets the value of "3rd 1-r".
- Other card options (1st, 2nd) are not used.
- User routine **RFLCTV** for arbitrary reflectivities.
 - Inputs: wavelength, angular frequency, material
 - Return value: the material reflectivity

Sensitivity (OPT-PROP card)

- With **SDUM=SENSITIV**, the quantum efficiency of an optical sensor can be simulated.

 **OPT-PROP**

Type: SENSITIV ▼
2nd: -5.0

0th: 0.5
1st: 0.0
3rd: 0.0 Max sensitivity: 0.5

- For efficiency reasons, the option is applied at the production stage, **not** during scoring. The option is not material or region dependent.
- The n^{th} derivatives of the sensitivity curve at the central wavelength λ_0 (or angular frequency ω_0) are specified on the card. Similar series expansion as for transport properties:

$$\epsilon(\lambda) = \epsilon(\lambda_0) + \frac{d\epsilon}{dx}x + \frac{1}{2}\frac{d^2\epsilon}{dx^2}x^2 + \frac{1}{6}\frac{d^3\epsilon}{dx^3}x^3 \quad \text{where} \quad x \equiv \frac{\lambda - \lambda_0}{\lambda_0}$$

- Central wavelength (angular frequency) defined using **SDUM=WV-SENSI** (**SDUM=OM-SENSI**) along with the sensitivity curve domain.

 **OPT-PROP**

Type: WV-SENSI ▼

λ_{min} : =300*nm

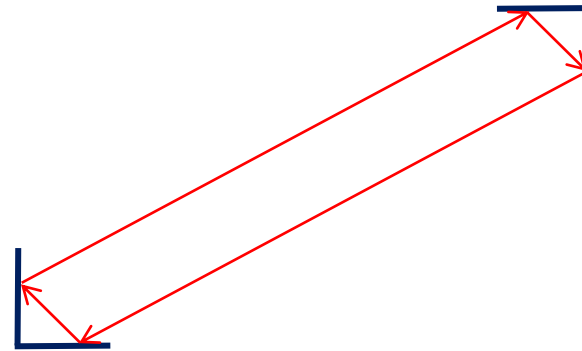
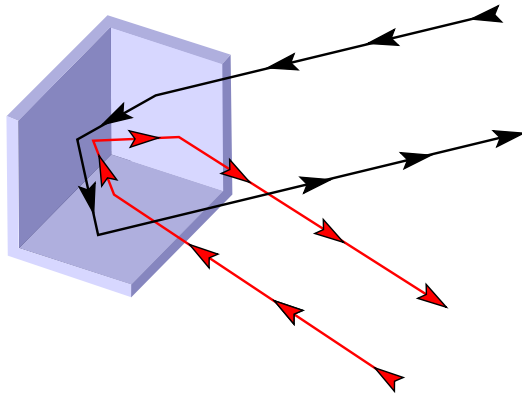
λ : =500*nm

λ_{max} : =1059*nm

- User routine **QUEFFC** to define arbitrary sensitivities.

Photons trapped in locked modes

- Optical photons produced in a box can be trapped in "locked modes", meaning they undergo an infinite number of reflections. Simulation appears stuck.
- **Reason:** Light rays incident on a corner mirror formed by three perpendicular surfaces are reflected back parallel to their incoming direction. A region which contains 2 of such corners can trap photons indefinitely.



- **Solution:** Open paths for optical photons to exit the locked modes. Recommend setting a small absorption (>0), or imperfect reflectivity ($r < 100\%$).

Boundary crossing routine (OPHBDX)

- Special boundary crossing treatment with the **OPHBDX** routine to override the treatment defined using the **OPT-PROP** card.
- Routine called each time an optical photon crosses boundaries predefined using the **OPT-PROP** card (**SDUM=SPEC-BDX**). Can define up to 40 boundaries using multiple **OPT-PROP** cards.



- Input variables of **OPHBDX**:
 - Wavelength / angular frequency
 - Current region and new region
- Output variables of **OPHBDX**:
 - Index of refraction, absorption coefficient and diffusion coefficient for the new region.
 - Group velocity in the new region.
 - Option to kill the photon.

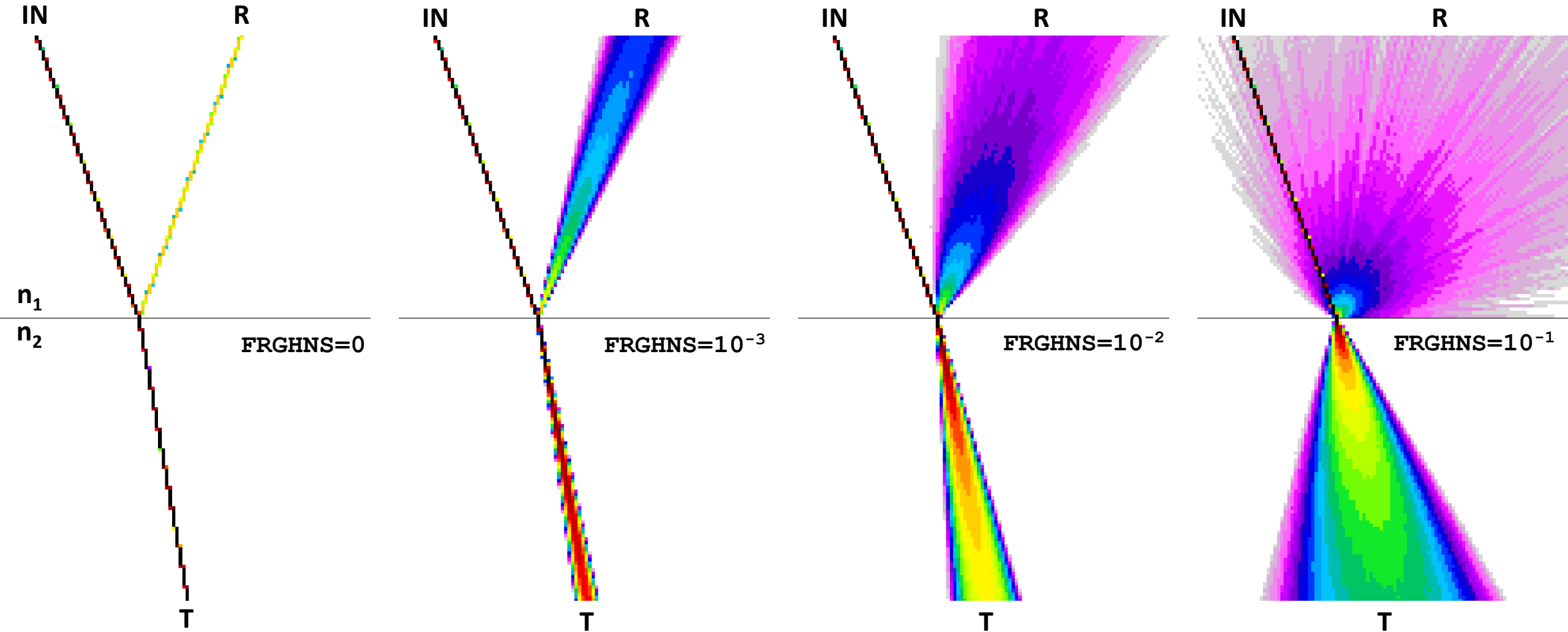
Wavelength shifting

- Option implemented as a user routine: **WVLNSH**
- Routine called every time an optical photon is absorbed.
 - Must set an absorption coefficient larger than 0 with the **OPT-PROP** card.
- Input variables:
 - Absorbed photon energy (wavelength)
 - Current material and region
- Output variables:
 - Number of secondary photons
 - Lists of energies (wavelengths) and production delays

Boundary roughness (FRGHNS routine)

- The roughness of a boundary can be simulated using the **FRGHNS** routine.
 - Routine called every time an optical photon is reflected or crosses between two regions.
 - Returns a roughness parameter, used to smear the direction of the outgoing photon.
 - New angle normally distributed. Gaussian width related to the roughness parameter.
- Input variables of **FRGHNS**:
 - Particle direction cosines (T_{XX} , T_{YY} , T_{ZZ})
 - Particle direction normal to surface (U_{XSRFC} , U_{YSRFC} , U_{ZSRFC})
 - Current material/region ($MMAT$, $MREG$) and new material/region ($MMATNW$, $NEWREG$)

Boundary roughness (FRGHNS routine)



Arbitrary transport properties: the USRMED routine

- **USRMED** routine can be used to take full control of the optical photon track in a material and at boundaries.
- Activated setting **SDUM=USERDIRE** in the **MAT-PROP** card.
 - Called for ANY particle travelling in the specified materials (not just for optical photons).

 **MAT-PROP**

Type: USERDIRE ▼
Mat: AIR ▼

Call: USRMED ▼
to Mat: ▼

Step:]

apply to more materials

- Input variables:
 - Particle ID (Note: =-1 for optical photons)
 - Kinetic energy and momentum
 - Current region
- Input/Output variables:
 - New region
 - Particle weight
 - Particle position at boundary
 - Momentum and polarization unit vectors
- Useful to define arbitrary interface physics for optical photons when a more complex model than generic options is required.
 - For reflection and transmission: Override the track direction.
 - For absorption: Override the particle weight (set $w=0$ to kill the particle).

Polarization


- All particles in FLUKA have a dynamic polarization state.
- The polarization vector is accessible for **ALL** simulated particles regardless if it makes sense or not. Only used for some physics processes in FLUKA, for example:
 - Fresnel transmission and reflection of optical photons.
 - Compton scattering of photons.
- **Note:** The **POLARIZATI** card sets the polarization of primary photons. This card does not work with optical photons.
 - To change the polarization of primary optical photons, you must use a source routine.

Quenching effects (Birk's saturation)

- Birk's law relates the stopping power in the material to the scintillation light production. Quenching or saturation of the light production occurs for high stopping powers.

$$\frac{dL}{dx} = S \frac{dE/dx}{1 + B \frac{dE}{dx} + C \left(\frac{dE}{dx}\right)^2}$$

- FLUKA does not apply Birk's law directly to the production of scintillation photons.
- However, the **TCQUENCH** card can be applied to an energy detector to reduce the scored energy or dose deposition according to Birk's quenching law.

 **TCQUENCH**

not used for opt. phot.
~~t cut off:~~

B [g MeV⁻¹ cm⁻²] **C [g² MeV⁻² cm⁻⁴]**

Birks c1: 0.008 Birks c2: 0.0

Bin: OPTIPHOT ▼ to Bin: ▼ Step:

detectors

