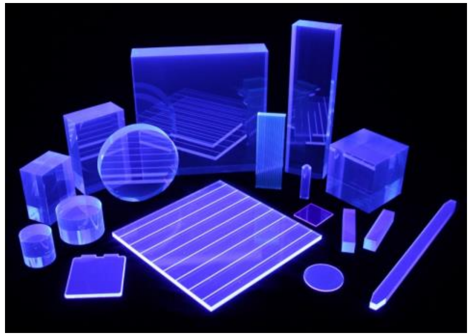
Optical photons

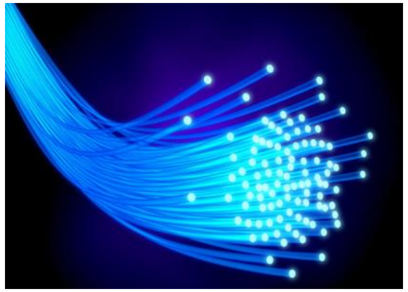
OPT-PROD, OPT-PROP, MAT-PROP, TCQUENCH

Simulating optical photons

Scintillators
(Eljen technology)

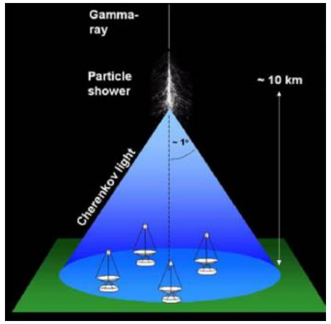


CT scanner
(Siemens corporation)

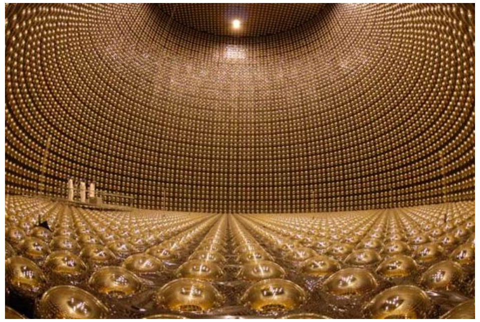


Optical/scintillating fibers

Gamma-ray astronomy
(Hess collaboration)



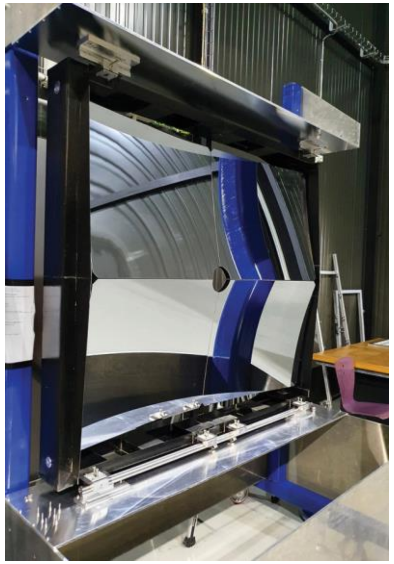
Neutrino observatories
(Super Kamiokande collaboration)



- 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

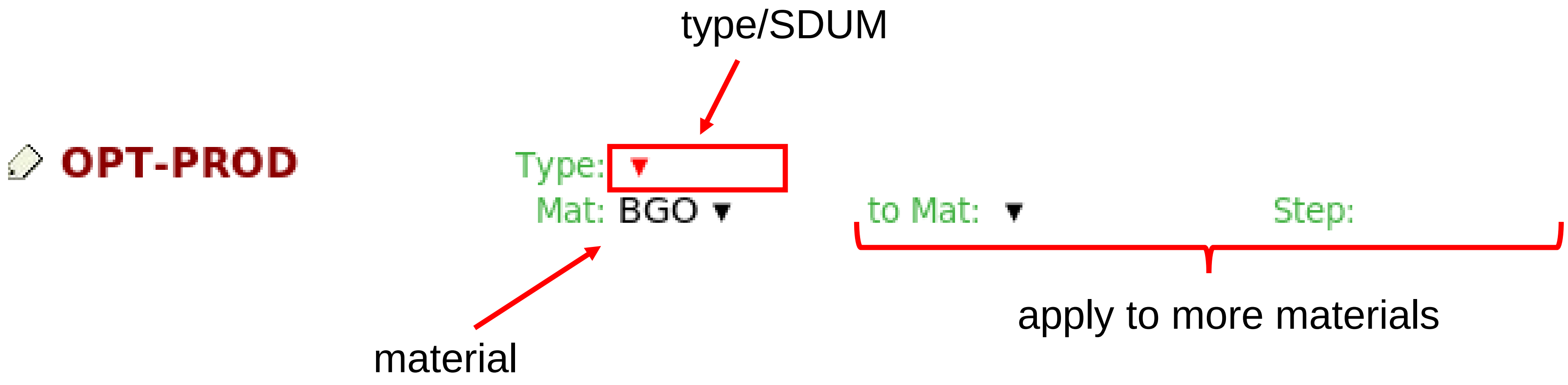
- Difference unrelated with the particle energy.
- Each associated to different physics processes but both:
  - transport and deposit energy,
  - can be used as primary particles,
  - have a defined energy range for transport and production,
  - have scattering and absorption cross-sections and,
  - 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 ($\omega_i = 2\pi f$)

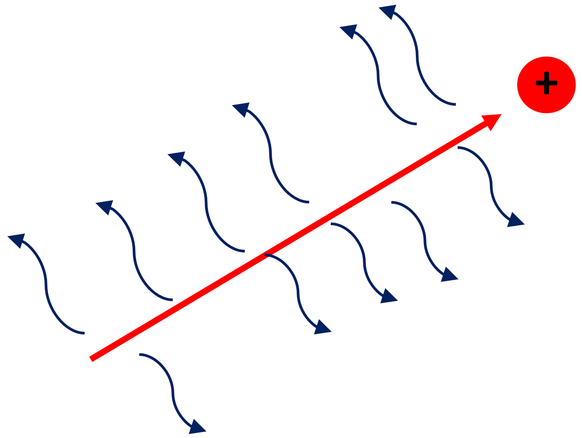
OPT-PROD Type: SCINTILL ▾ Ei: =2.76*eV fraction: 0.0276
Time: =300*ns Mat: BGO ▾ to Mat: ▾ Step:

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) × E_i (eV) × 10^{-6} or yield (photons/MeV) × 1.2398 × 10^{-3} / λ_i (nm)
- Scintillation photons are **monochromatic.**
  - Or up to 3 peaks can be defined combining 3 **OPT-PROD** cards.

Scintillation

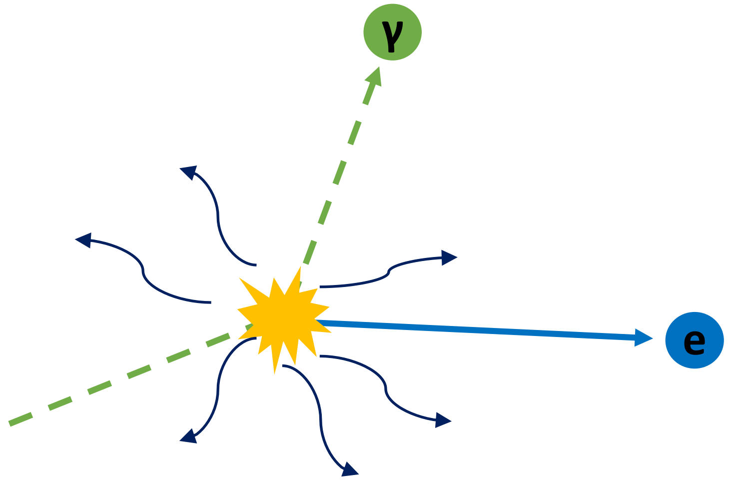
Continuous losses



- 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

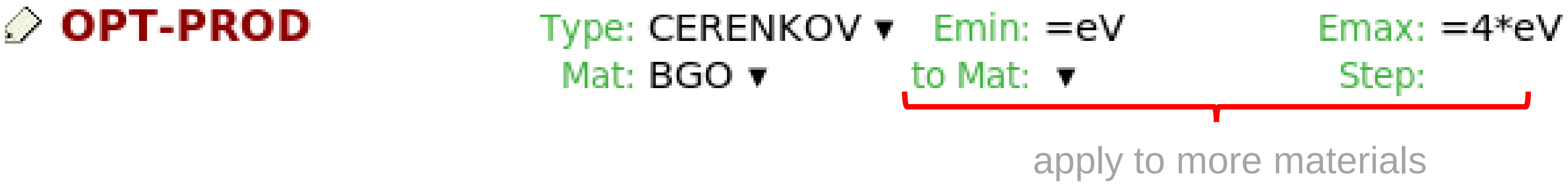
(electron below production cut-off)



- 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 ($\omega = 2\pi f$).



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

Conservation of energy

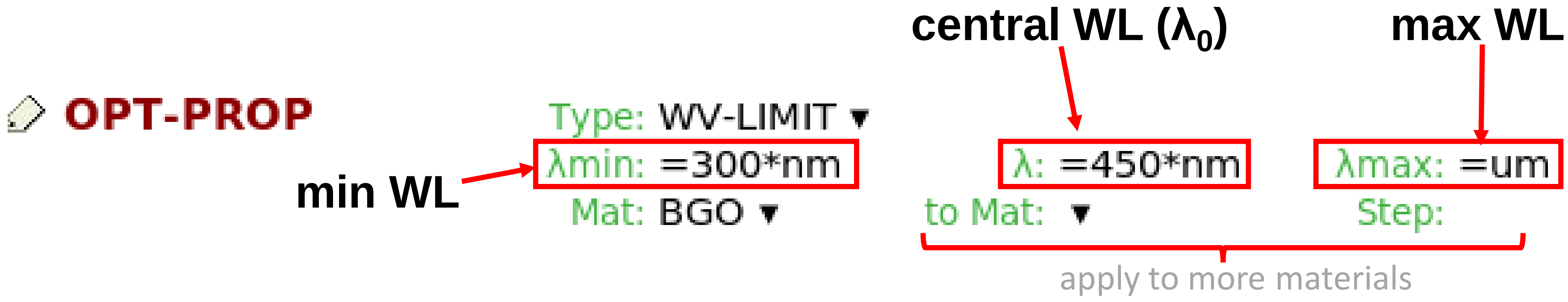
WARNING

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.
- Photons **transport** energy far from the interaction, therefore:
  - Scored local energy deposition or dose is lower!

Transport cuts (`OPT-PROP` card)

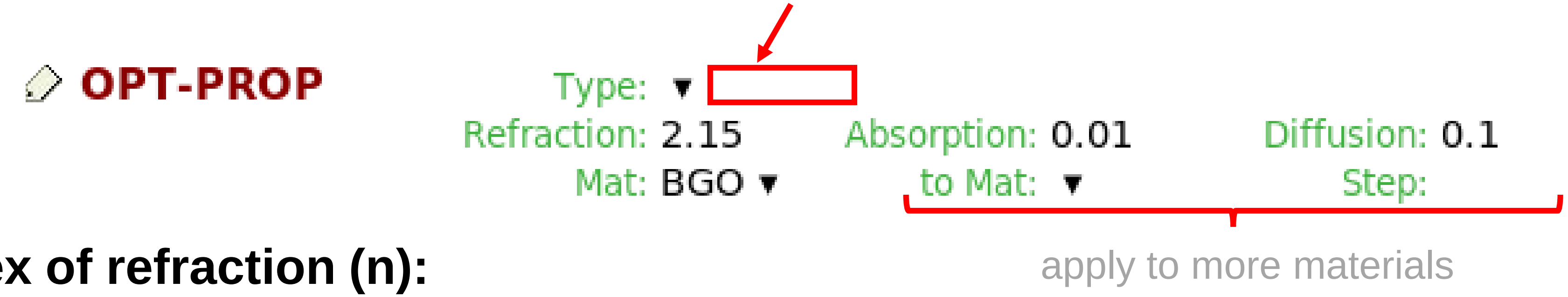
- Transport cuts defined using:
  - **`SDUM=WV-LIMIT`**: Wavelength cuts
  - **`SDUM=OM-LIMIT`**: Angular frequency cut



- The card defines the energy range. Central wavelength used for series expansions.
- **Note:** Transport cuts have no impact on the number of optical photon *produced* (for example when looking at the numbers found in the output file).
- **Warning:** The default cuts are 250 nm to 600 nm with central WL of 289 nm. To keep in mind when configuring **`OPT-PROD`** cards!
- **Tip:** More efficient to instead define narrow *production* cuts.

Transport properties – The `OPT-PROP` card

- For **`SDUM=BLANK`**:



- **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

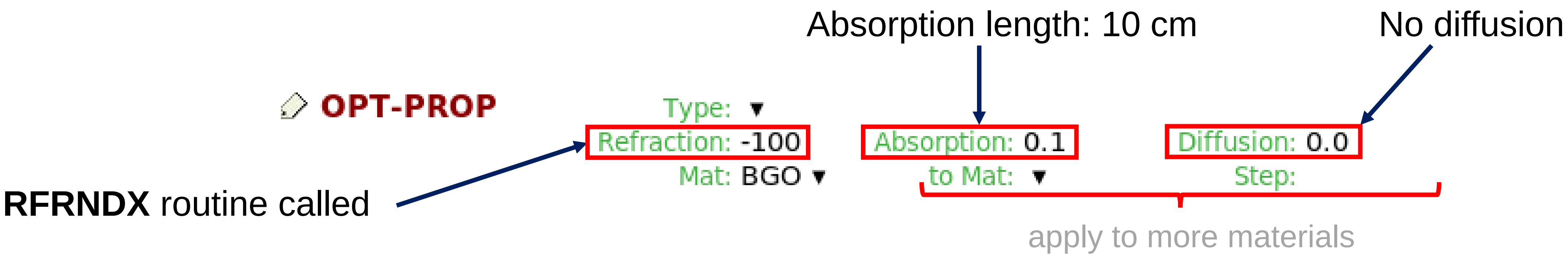
- Series expansion of the index of refraction, the absorption coefficient and the diffusion coefficient can be defined.
- Taylor series around central wavelength λ_0 (central angular frequency also available). Example for the index of refraction:

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

- 0^{th} 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
  - **ABSCFF**: Absorption coefficient
  - **DFFCFF**: 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.

- 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 ▾ 0th: 0.5 1st: 0.0
2nd: -5.0 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:

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

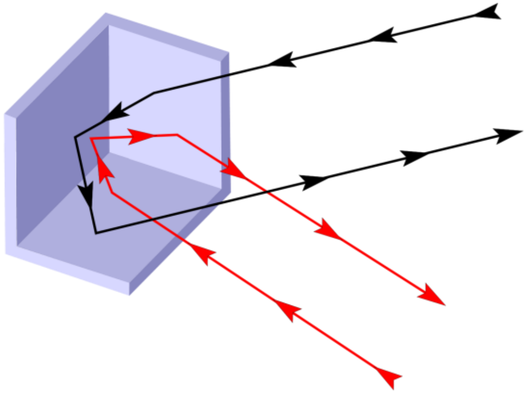
- Central wavelength (angular frequency) defined using **SDUM=WV-SENSI** (**SDUM=OM-SENSI**) along with the sensitivity curve domain.

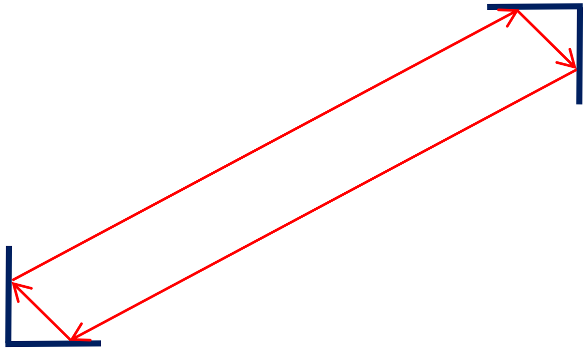
OPT-PROP Type: WV-SENSI ▾
λmin: =300*nm λ: =500*nm λmax: =1059*nm

- User routine **QUEFFC** for defining 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 incoming on a mirror corner made up of 3 perpendicular surfaces are reflected in the same but opposite direction. A region which contains 2 of such corners can trap photons indefinitely.





- **Solution:** Open paths for optical photons to exits the locked modes. Recommend setting a small absorption or a reflectivity which is not exactly 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.
- See the dedicated lecture on user routines for details on applying OPHBDX to all particle types.

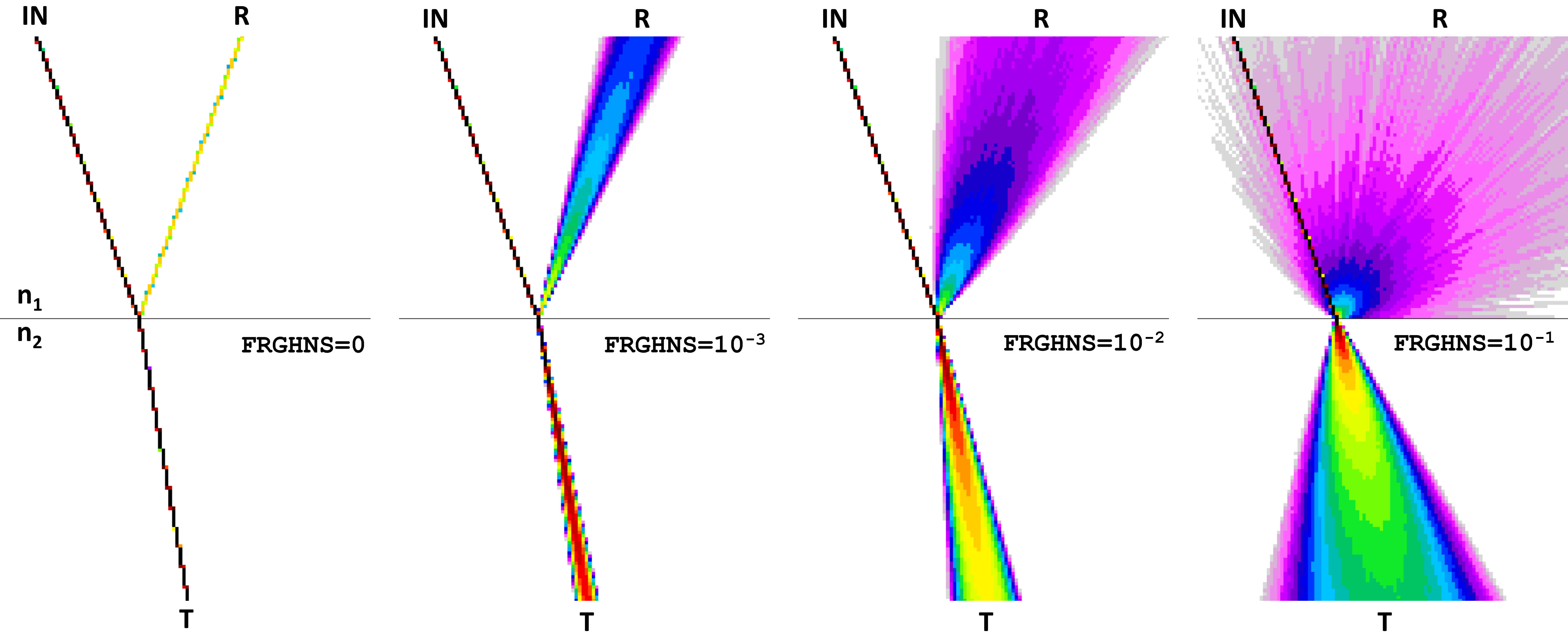
Wavelength shifting

- 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 (`TXX, TYY, TZZ`)
  - Particle direction normal to surface (`UXSRFC, UYSRFC, UZSRFC`)
  - 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).

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 simply kill the particle).

Polarization

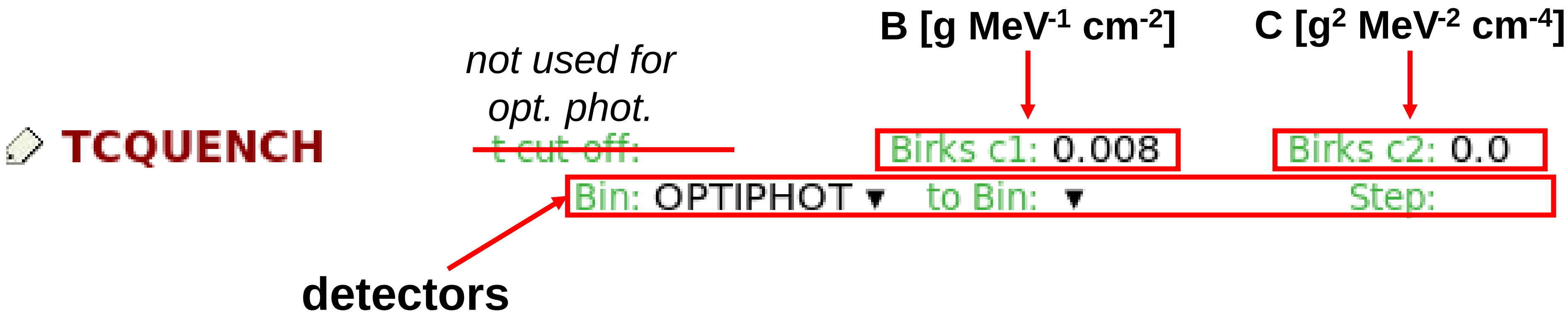
- All particles in FLUKA have a dynamic polarization state.
- The polarization vector is accessible for **ALL** simulated particles regardless if it makes sense or not. Only used for some physics processes in FLUKA, for example:
  - Fresnel transmission and reflection of optical photons.
  - Compton 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.



FLUKA