Instantaneous Flux Detector

Digital Twin Specification

Twin Code:	`DF-IFLX01`
Twin Name:	Instantaneous Flux Detector
Category:	Detector
Type:	Function-Based
Version:	1.0
Package:	Platform
Last Updated:	`2026-03-19`

Description

The Instantaneous Flux Detector is a specialized detector twin that measures the time-dependent optical power passing through a defined rectangular region. It evaluates electromagnetic fields over the detector area and calculates the instantaneous flux by reconstructing the time-domain fields and integrating the normal component of the Poynting vector. This detector provides the temporal evolution of optical power, which is essential for understanding pulse shapes, peak power, and dynamic behavior of pulsed optical systems.

Measured Quantity

The detector outputs a time-dependent scalar quantity:

- **Instantaneous Flux** $\Phi(t)$: The optical power (in Watts) passing through the detector area as a function of time, obtained by integrating the normal component of the Poynting vector over the detector surface:

$$\Phi(t) = \iint_{\text{detector}} \boldsymbol{S}(\boldsymbol{\rho}, t) \cdot \hat{\boldsymbol{z}} \; \mathrm{d}^2\rho \tag{1}$$

  where $\boldsymbol{S}(\boldsymbol{\rho}, t) = \boldsymbol{E}(\boldsymbol{\rho}, t) \times \boldsymbol{H}(\boldsymbol{\rho}, t)$ is the instantaneous Poynting vector.

Model Parameters

The Instantaneous Flux Detector itself has no configurable parameters. Its spatial and temporal sampling is controlled through the associated **Pulse Evaluation (Rectangle)** add-on:

- **Start Point / End Point**: Define the rectangular region in the x-y plane over which the instantaneous flux is evaluated. These points determine the spatial extent of the detector.
- **Number of Evaluations**: Specifies the sampling grid resolution in the x and y directions. Higher values provide better spatial resolution for accurately capturing the spatial profile of the field.
- **Oversampling Factor**: Controls the sampling density for the Fourier transform into the time domain. Higher oversampling factors improve temporal resolution and reduce aliasing artifacts, ensuring accurate representation of the flux temporal evolution.

Simulation Model

Time-Domain Field Reconstruction

The detector operates on electromagnetic fields provided by the Field Tracing Engine. For pulsed sources, fields are represented in the frequency domain as a superposition of monochromatic components. The detector performs an inverse Fourier transform to reconstruct the time-domain fields:

$$\boldsymbol{E}(\boldsymbol{\rho}, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{\boldsymbol{E}}(\boldsymbol{\rho}, \omega) e^{-\mathrm{i}\omega t} \, \mathrm{d}\omega \tag{2}$$

$$\boldsymbol{H}(\boldsymbol{\rho}, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{\boldsymbol{H}}(\boldsymbol{\rho}, \omega) e^{-\mathrm{i}\omega t} \, \mathrm{d}\omega \tag{3}$$

Poynting Vector Calculation

From the reconstructed time-domain fields, the detector computes the instantaneous Poynting vector at each spatial point and each time step:

$$\boldsymbol{S}(\boldsymbol{\rho}, t) = \boldsymbol{E}(\boldsymbol{\rho}, t) \times \boldsymbol{H}(\boldsymbol{\rho}, t) \tag{4}$$

The Poynting vector represents the direction and magnitude of electromagnetic energy flow at each point in space and time, with units of W/m^2.

Flux Integration

The instantaneous flux through the detector area is obtained by integrating the component of the Poynting vector normal to the detector surface (typically the z-component for a detector perpendicular to the optical axis):

$$\Phi(t) = \iint_{\text{detector}} \boldsymbol{S}(\boldsymbol{\rho}, t) \cdot \hat{\boldsymbol{z}} \; \mathrm{d}^2\rho \tag{5}$$

This spatial integral yields the total instantaneous power (in Watts) passing through the detector as a function of time.

Relationship to Other Quantities

The Instantaneous Flux Detector provides the time-dependent power, which is related to other pulse quantities:

- **Pulse Energy**: The time integral of instantaneous flux gives the total pulse energy:

$$E_{\text{pulse}} = \int_{-\infty}^{\infty} \Phi(t) \; \mathrm{d}t \tag{6}$$

- **Peak Power**: The maximum value of $\Phi(t)$ over time represents the peak instantaneous power of the pulse.
- **Pulse Duration**: The temporal width of $\Phi(t)$ (e.g., full width at half maximum) characterizes the pulse length.

Typical Application Scenarios

1. **Ultrafast Pulse Shape Analysis**: Measure the temporal profile of femtosecond and picosecond pulses to determine pulse duration, shape, and presence of pre- or post-pulses.

2. **Peak Power Determination**: Determine the maximum instantaneous power in a pulsed laser system, critical for nonlinear optics experiments and laser-material interaction studies.

3. **Temporal Pulse Quality Assessment**: Evaluate pulse symmetry, rise/fall times, and modulation effects in shaped pulses or pulses affected by dispersion.

Software Usage

After adding the Instantaneous Flux Detector to your system, follow these steps:

1. **Initial Oversampling Assessment**: Before final simulations, perform a preliminary test to determine the required oversampling factor. Use the Instantaneous Flux Detector or the Pulse Evaluation (Point) add-on with increasing oversampling factors until the temporal flux profile converges. This ensures accurate temporal representation.

2. **Configure Detector Settings**: Open the detector properties and navigate to **Detector Add-ons**. Edit the **Pulse Evaluation (Rectangle)** add-on to configure spatial and temporal sampling.

3. **Set Spatial Parameters**: Define the rectangular evaluation region by specifying Start Point and End Point coordinates. The region should be large enough to capture the entire beam cross-section at all times during pulse passage.

4. **Set Spatial Resolution**: Choose the Number of Evaluations in x and y to adequately sample the spatial profile. For Gaussian pulses, ensure the grid extends to at least $3\times$ the beam radius and provides sufficient points across the beam.

5. **Adjust Oversampling Factor**: Enter the Oversampling Factor determined from convergence tests. Higher values (2-4) are typically needed for accurate temporal resolution of steep pulse edges or complex temporal structures.

6. **Run Simulation**: Execute the field tracing simulation. The detector calculates the instantaneous flux during propagation.

7. **View Results**: After simulation, examine the output:
   - The instantaneous flux $\Phi(t)$ as a function of time, displayed in the detector's result window
   - Key metrics derived from the flux: peak power, pulse duration (FWHM), rise/fall times
   - Optionally export the time-series data for further analysis in external tools

8. **Parameter Studies**: For investigating how system parameters affect pulse dynamics, use Parameter Run features to sweep parameters (e.g., dispersion, nonlinear coefficient, aperture size) while monitoring the flux temporal profile.

Important notes:

- The detector area must be sufficiently large to capture the entire beam cross-section; truncating the beam spatially will lead to underestimation of instantaneous flux.

- Temporal resolution is determined by both the spectral content of the pulse and the Oversampling Factor. Ensure the simulation includes enough frequency samples to accurately represent the pulse spectrum.
- Computational time scales with both spatial sampling (Number of Evaluations) and temporal sampling (Oversampling Factor). Find the minimum acceptable values through convergence testing.
- The detector automatically handles polarization information; the Poynting vector is correctly calculated from the full vector electromagnetic fields.
- For highly divergent or focused pulses, ensure the detector plane is perpendicular to the local propagation direction, or use the appropriate component of the Poynting vector for flux calculation.
- The instantaneous flux output can be integrated numerically after simulation to obtain pulse energy, providing a consistency check with dedicated Pulse Energy Detector results.

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Keywords: instantaneous flux, optical power, time-domain, Poynting vector, pulse shape, peak power, pulse duration, femtosecond, picosecond, temporal profile, detector, time-dependent, flux
Related Twins: DF-IIRR01, DF-PDTE01, DF-PDUR01, DF-PENG01, DF-PDFR01