Pulse Energy Detector

Digital Twin Specification

Twin Code:	`DF-PENG01`
Twin Name:	Pulse Energy Detector
Category:	Detector
Type:	Function-Based
Version:	1.0
Package:	Platform
Last Updated:	`2026-03-20`

Description

The Pulse Energy Detector is a specialized detector twin that measures the total energy content of optical pulses. It evaluates electromagnetic fields over a defined rectangular region and calculates the pulse energy by first reconstructing the time-domain fields, then computing the instantaneous flux, and finally integrating over time. This detector provides the single quantity of most practical importance for pulsed systems: the total energy carried by the pulse through the detection area.

Measured Quantity

The detector outputs a single scalar value:

- **Pulse Energy $E_{\mathbf{pulse}}$**: The total electromagnetic energy passing through the detector area, obtained by time-integrating the instantaneous flux $\Phi(t)$:

$$E_{\text{pulse}} = \int_{-\infty}^{\infty} \Phi(t)\ \mathrm{d}t \tag{1}$$

  where the instantaneous flux $\Phi(t)$ is the integral of the Poynting vector component normal to the detector surface over the detector area.

Model Parameters

The Pulse Energy 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 pulse energy 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 pulse's spatial profile.
- **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 integration of the instantaneous flux over time.

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:

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

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

Instantaneous Flux Calculation

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

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

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):

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

Pulse Energy Integration

The pulse energy is the time integral of the instantaneous flux:

$$E_{\text{pulse}} = \int_{-\infty}^{\infty} \Phi(t) \; \mathrm{d}t = \int_{-\infty}^{\infty} \iint_{\text{detector}} \boldsymbol{S}(\boldsymbol{\rho}, t) \cdot \hat{\boldsymbol{z}} \; \mathrm{d}^2\rho \; \mathrm{d}t \tag{6}$$

This double integral (spatial over the detector area, temporal over the pulse duration) yields the total energy in Joules (J) that passes through the detector.

Relationship to Other Quantities

While the detector only outputs pulse energy, the calculation internally involves:

- **Electric Field $\boldsymbol{E}(t)$ and Magnetic Field $\boldsymbol{H}(t)$**: The fundamental field quantities from which all others derive
- **Poynting Vector $\boldsymbol{S}(t)$**: Represents the instantaneous energy flow direction and magnitude
- **Flux $\Phi(t)$**: Instantaneous power through the detector (in Watts)

The pulse energy is the time integral of flux, representing the total energy (in Joules) contained in the pulse.

Typical Application Scenarios

1. **Ultrafast Laser Characterization**: Measure the pulse energy of femtosecond and picosecond laser systems to verify output stability and compare with specified values from manufacturer datasheets.

2. **Laser Material Processing**: Determine the energy per pulse delivered to a workpiece in cutting, drilling, or ablation applications, where pulse energy directly influences processing quality and material removal rates.

3. **Pulse Energy Transmission Studies**: Analyze how much pulse energy is lost through optical systems containing absorptive components, apertures, or imperfect coatings.

4. **Laser Safety Assessment**: Verify that pulse energies in optical systems remain below damage thresholds for components and within safe exposure limits for potential human access points.

Software Usage

After adding the Pulse Energy 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 Pulse Energy Detector or the Pulse Evaluation (Point) add-on with increasing oversampling factors until the calculated pulse energy converges. This ensures accurate temporal integration.

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 pulse cross-section at all times during its 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. Values typically range from 1-4, with higher values for pulses containing steep temporal features or broad spectral content.

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

7. **View Result**: After simulation, examine the output:
   - The Pulse Energy value (in Joules) displayed in the detector's result window
   - Optionally, view the temporal flux evolution to understand how energy is distributed over time

8. **Parameter Studies**: For investigating how system parameters affect pulse energy, use Parameter Run features to sweep parameters (e.g., aperture size, propagation distance, input pulse energy) while monitoring the detector output.

Important notes:

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

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Keywords: pulse energy, instantaneous flux, ultrafast, time-domain, flux, Poynting vector, energy measurement, femtosecond, picosecond, pulse characterization, laser energy, energy integration, pulsed laser
Related Twins: DF-PDTE01, DF-PDUR01, DF-IFLX01, DF-PDFR01, DF-POWM01