Modelling radiation-effects in semiconductor lasers for use in SLHC experiments

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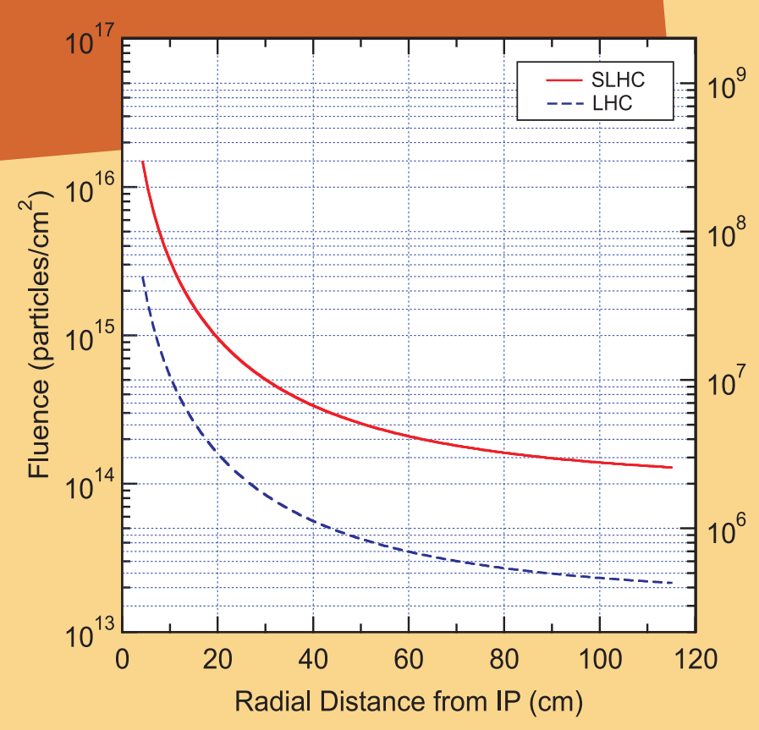
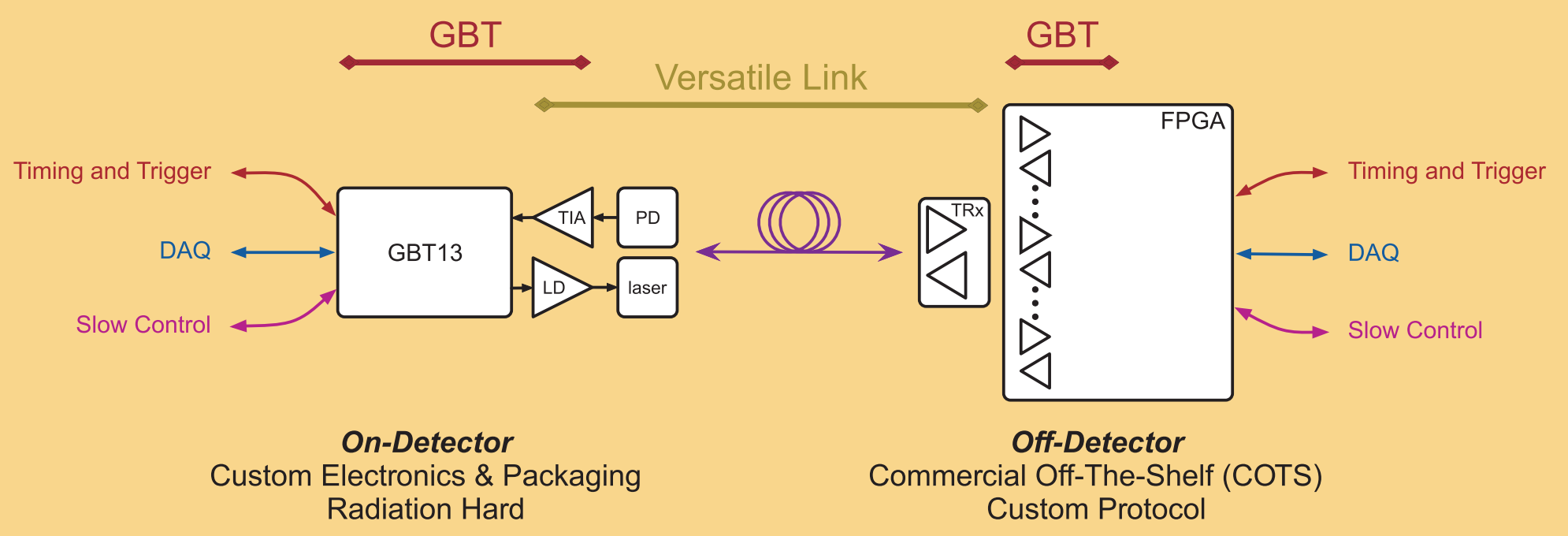
MOTIVATION

Optical link components will be exposed to intense radiation fields during operation in the SLHC inner detectors and their qualification in terms of radiation tolerance is thus required. We have created a model that describes a semiconductor laser undergoing irradiation to enable the extrapolation to full lifetime total fluences from lower fluence radiation tests. This model uses a rate-equation approach with modified gain calculation that takes thermal rollover into account. The model is used to fit experimental data obtained during high-fluence (in excess of 10^{15} p/cm^2) neutron and pion irradiation tests in 2009 and 2010, respectively and evaluate its prediction capability.



The expected CMS Si total flux and fluence for 500 fb^{-1} and 3000 fb^{-1} integrated luminosity.



Block diagram of a Versatile Link [1] for the SLHC detectors.

HIGH FLUENCE IRRADIATION TESTING

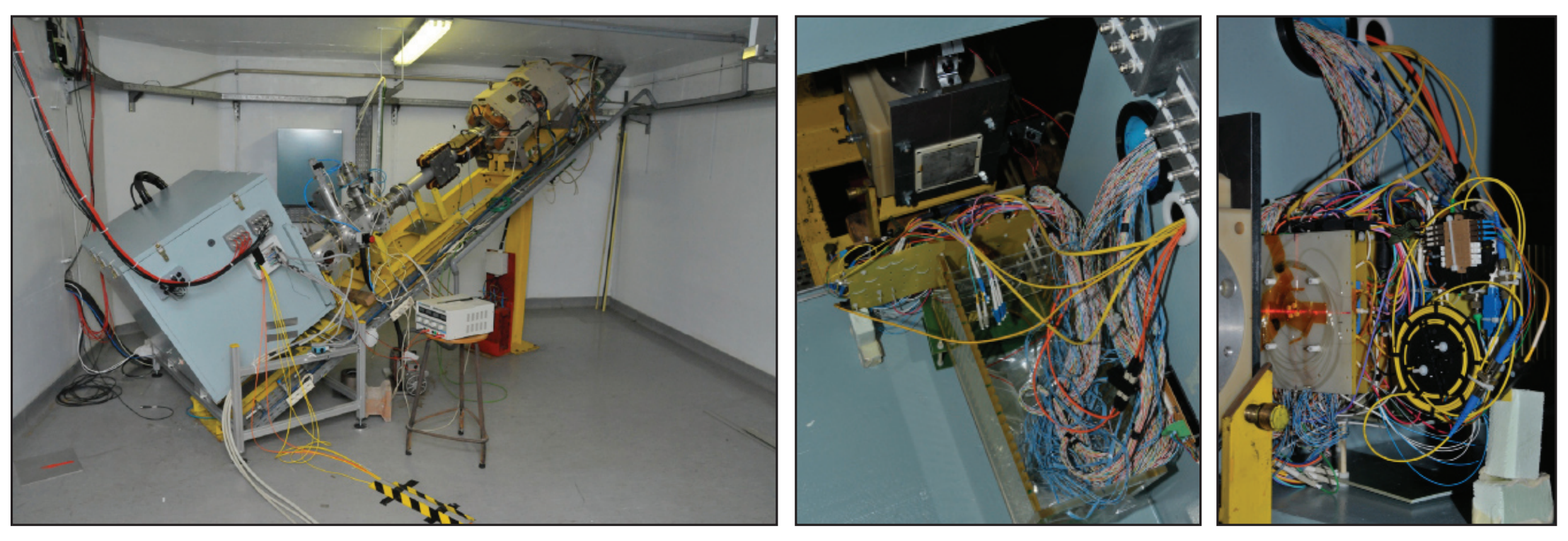
In order to evaluate new optoelectronic components in terms of their suitability for a Versatile Link for the SLHC, extensive exploratory high fluence neutron and pion irradiation tests took place. For reference, the qualification level for LHC silicon trackers was set to 4.0×10^{14} π/cm^2, which we initially set to 1.2×10^{15} π/cm^2 [1] by simple extrapolation.

- **Neutrons:**
  - Louvain-la-Neuve, Belgium, August 2009
  - Mean energy: 20 MeV
  - Irradiation time: 72 h
  - Annealing: 1 month
  - Lasers irradiated: 20
- **Pions:**
  - PSI in Villigen, Switzerland, August 2010
  - Mean energy: 300 MeV
  - Irradiation time: 17 days
  - Annealing: 2 weeks
  - Lasers irradiated: 13

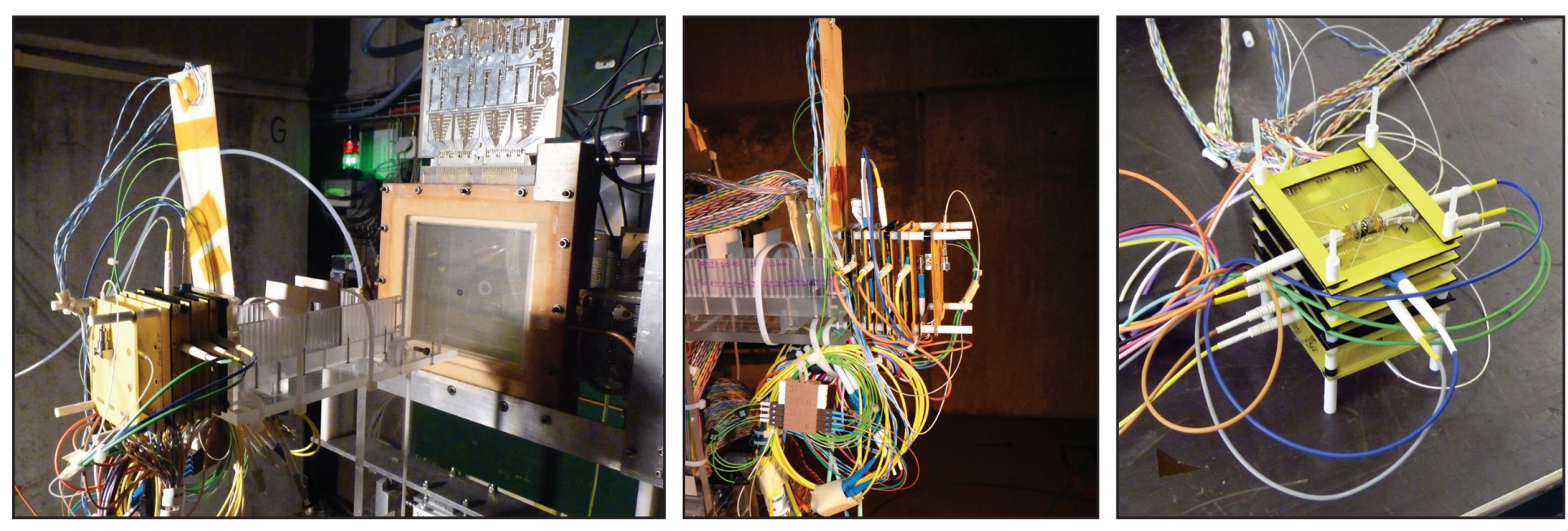
Device	Neutron fluence	Pion fluence
1310 nm 10 Gbps Fabry-Pérot laser	4.8×10^{15} n/cm^2	1.2×10^{15} π/cm^2
850 nm 10 Gbps VCSEL	4.7×10^{15} n/cm^2	1.5×10^{15} π/cm^2
1310 nm Mitsubishi CMS reference laser	6.3×10^{15} n/cm^2	1.7×10^{15} π/cm^2

IRRADIATION SETUP

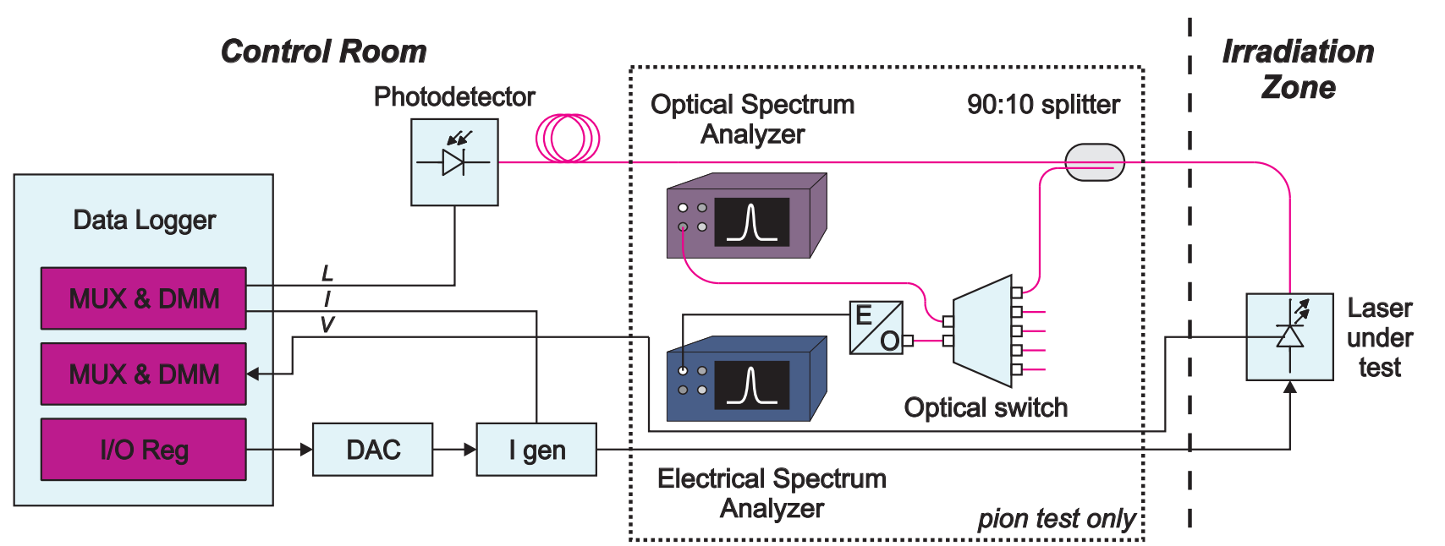
A similar setup was used for both neutron and pion irradiations. The *L-I-V* characteristics of all lasers were continuously measured at ~20 minute intervals. For the pion irradiation, the optical and electrical spectra were also recorded at 20 minute intervals.



Irradiation setup in Louvain-la-Neuve.



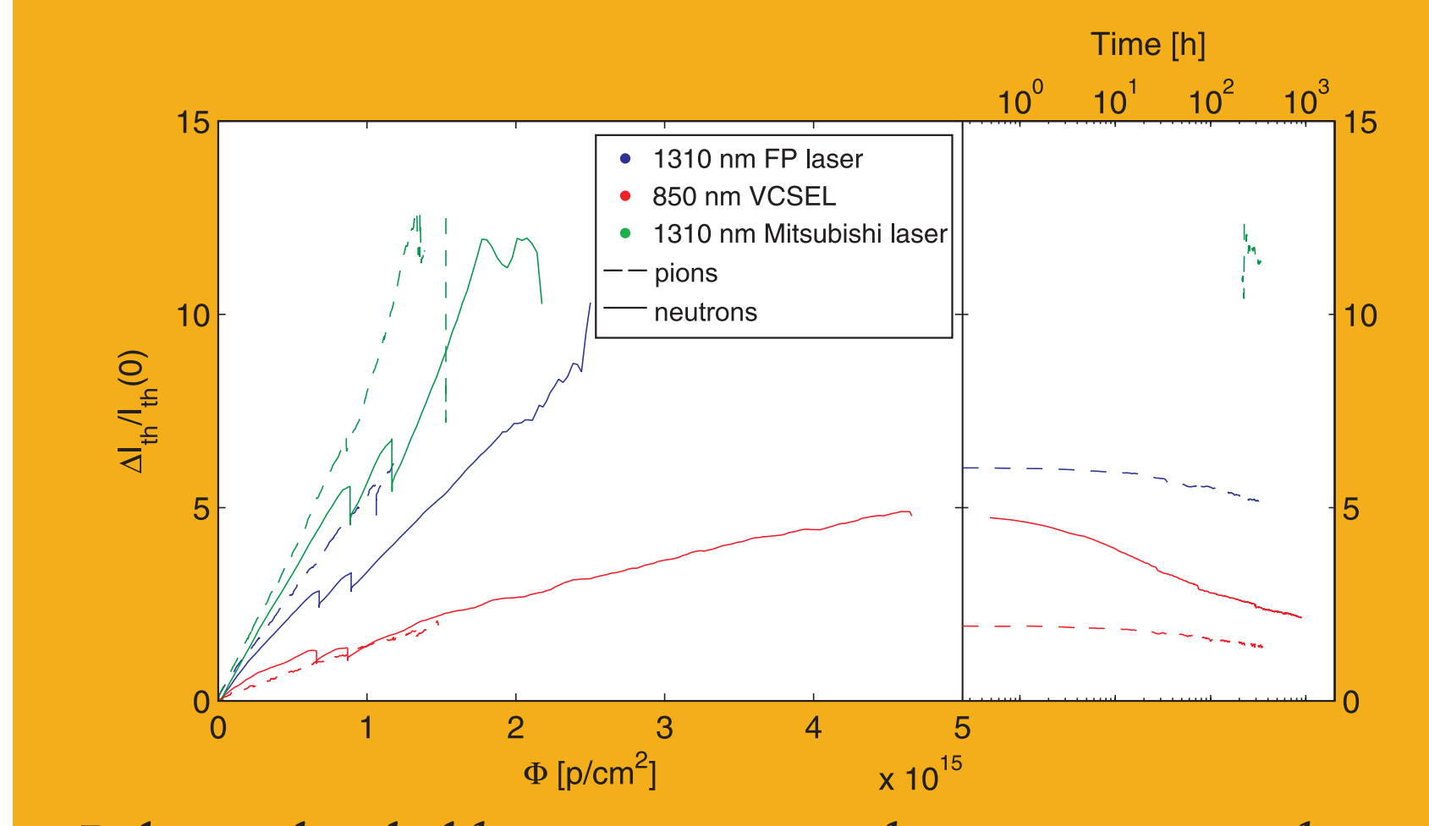
Irradiation setup in Villigen.



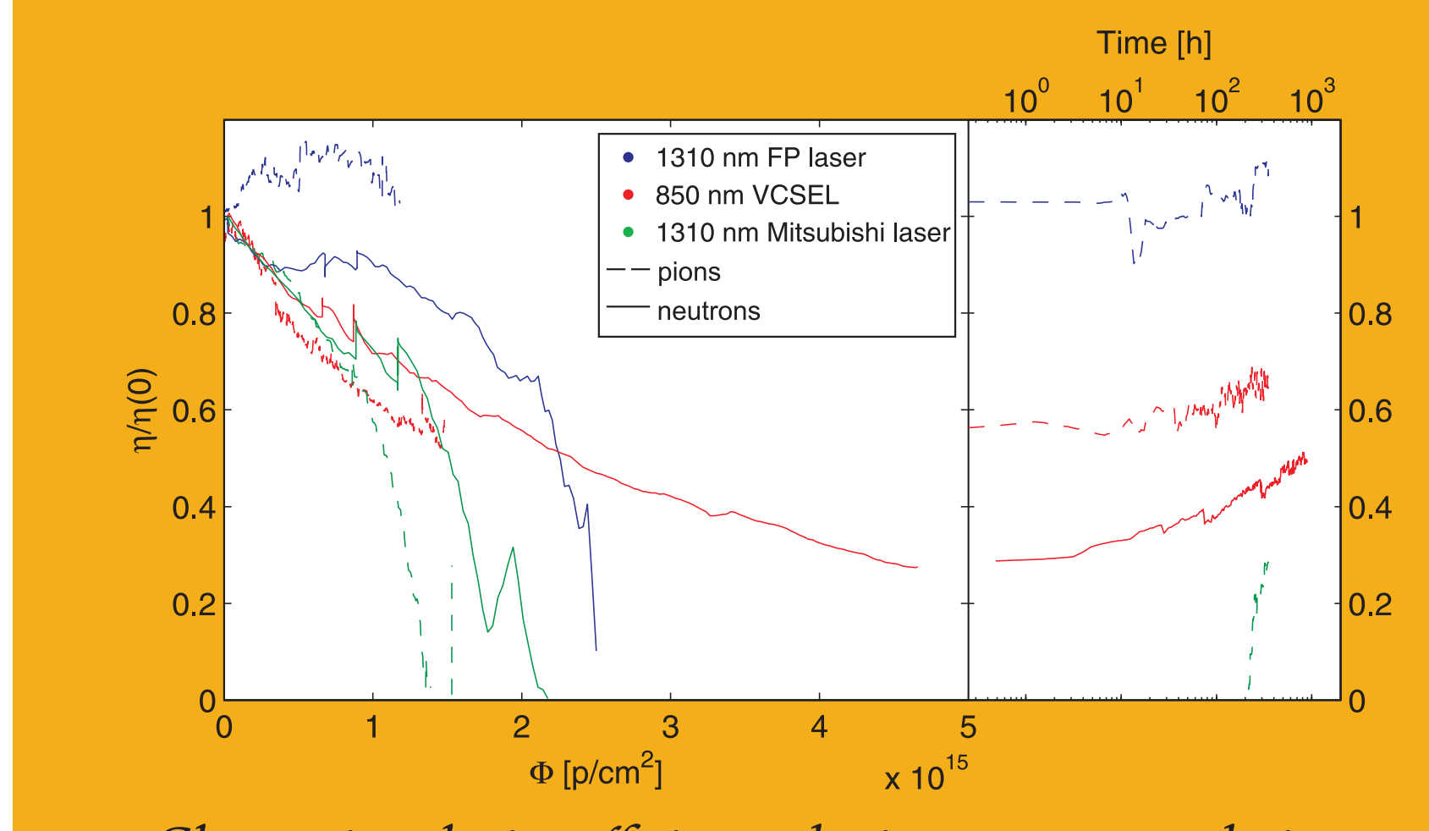
Measurement setup.

RADIATION DAMAGE IN LASERS

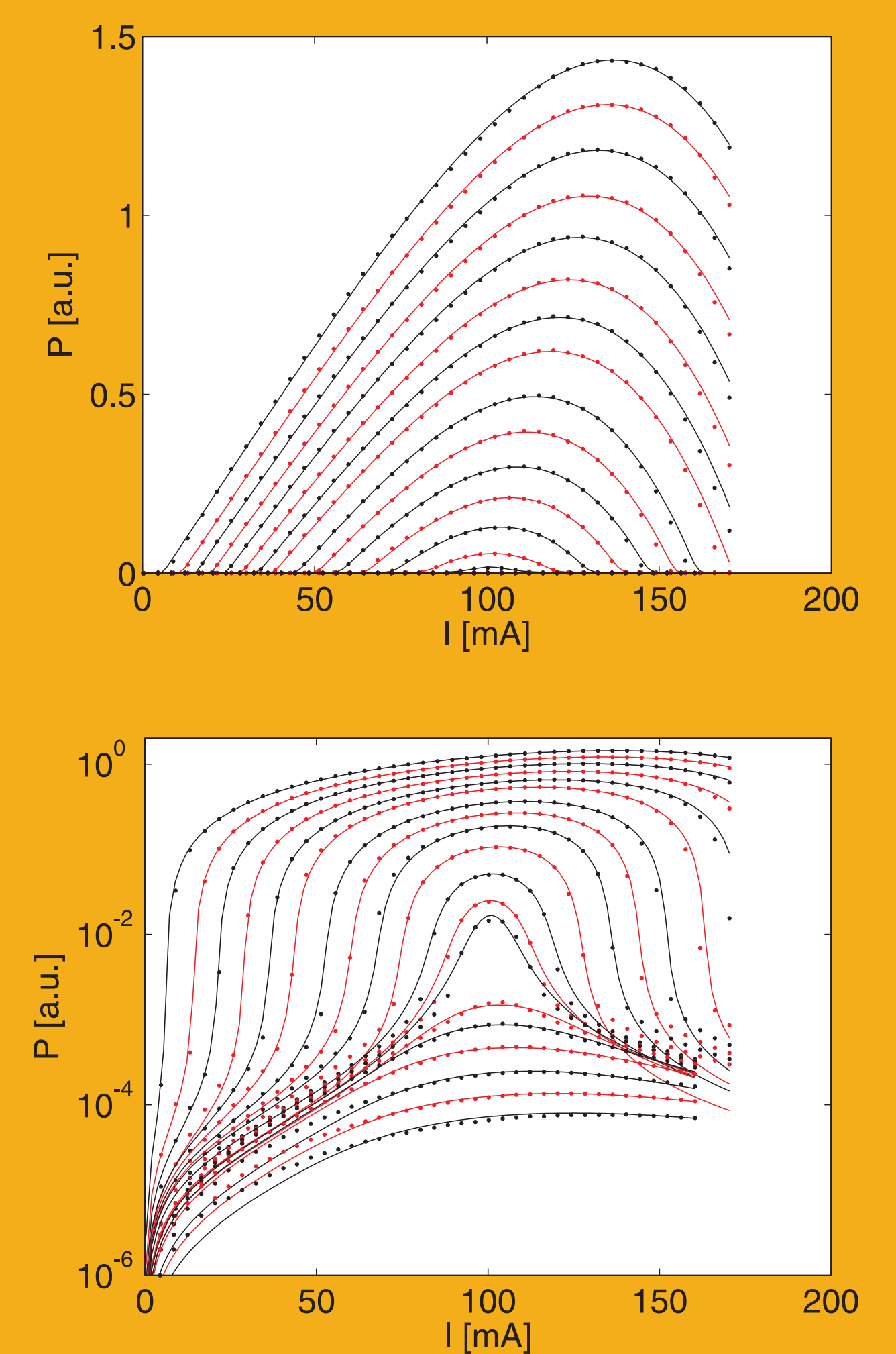
In lasers, recombination at defect states introduced via displacement damage during irradiation competes with radiative transitions, resulting in higher threshold current and lower light output efficiency. Lasers anneal after irradiation and can recover some part of the radiation-induced damage, a fact that leads to significant flux dependence of the observed damage.



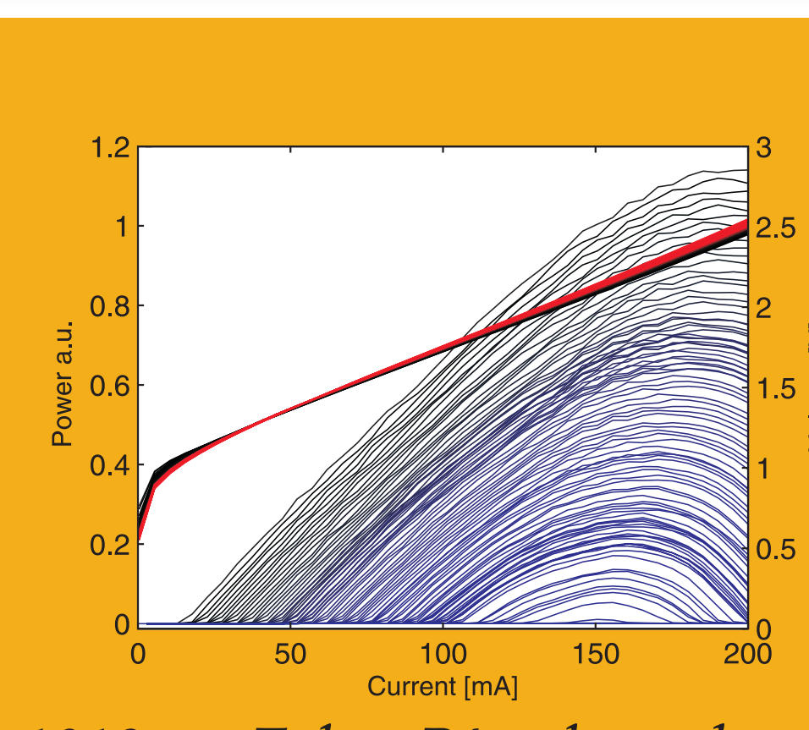
Relative threshold current increase during neutron and pion irradiation with annealing.



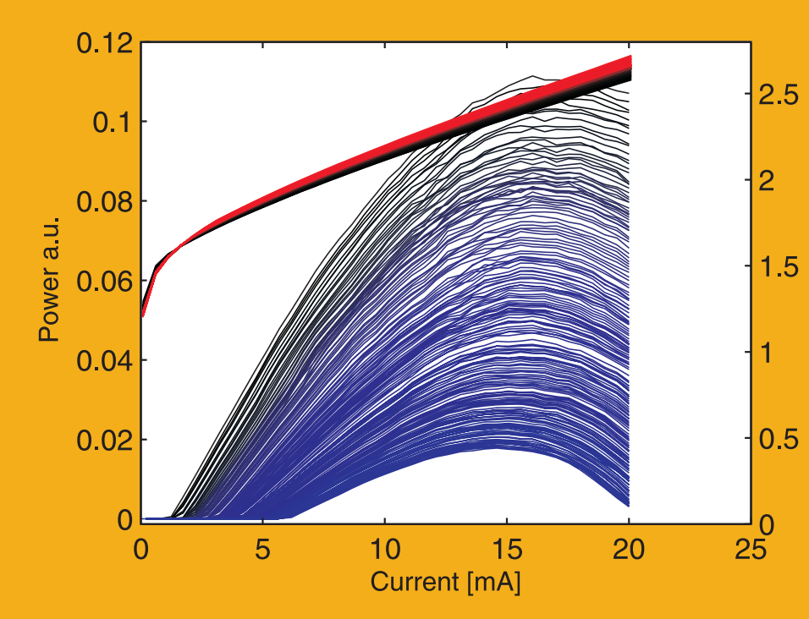
Change in relative efficiency during neutron and pion irradiation with annealing.



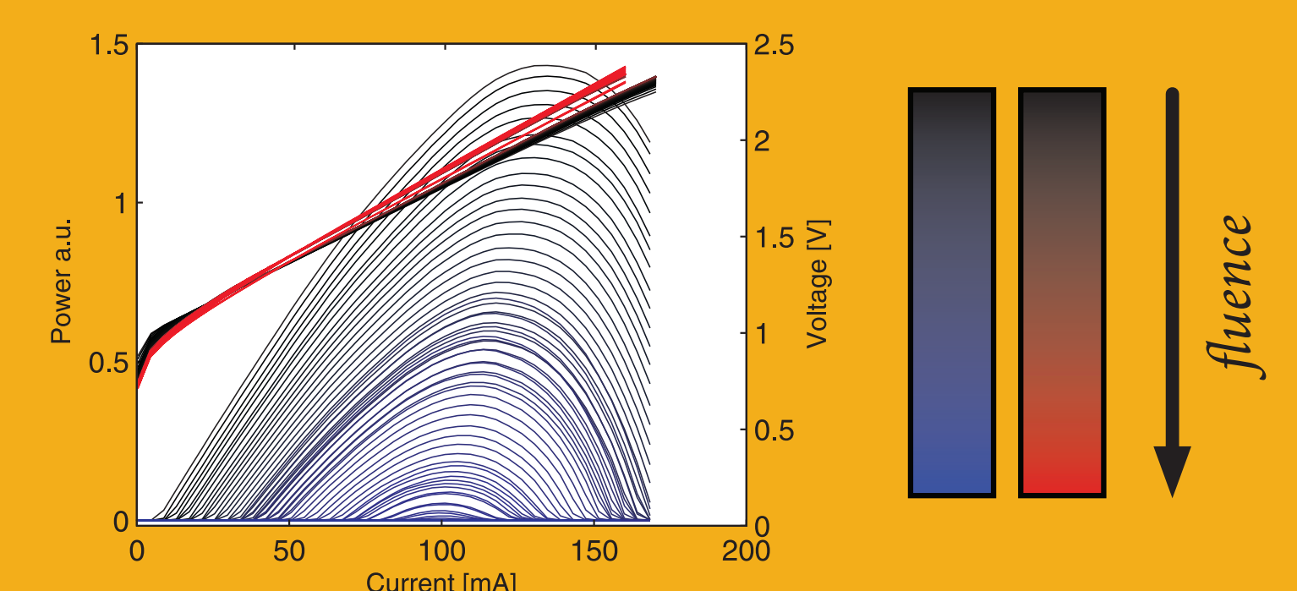
Fitted curves for 1310 nm Mitsubishi reference laser in linear and log scale. The fit works also for other devices.



1310 nm Fabry-Pérot laser during neutron irradiation.



850 nm VCSEL during neutron irradiation.



1310 nm Mitsubishi reference laser during neutron irradiation.

RATE-EQUATION MODEL

For a uniform electron density n in the conduction band of the active region of a semiconductor laser, the single-mode rate-equations can be written as:

$$\dot{n} = \frac{I}{qV} - \gamma_e n - GP$$
$$\dot{P} = VGP - \gamma P + R_{sp}$$

Denoting:

$$J = I/qV \qquad R_{sp} = \beta_{sp}\gamma_e V n$$

the rate-equations for the steady state become:

$$J - \gamma_e n - G(n)P = 0$$
$$P\left(G(n) - \gamma/V\right) + \beta_{sp}\gamma_e n = 0$$

In order to eliminate constant factors dimensionless quantities are denoted as follows:

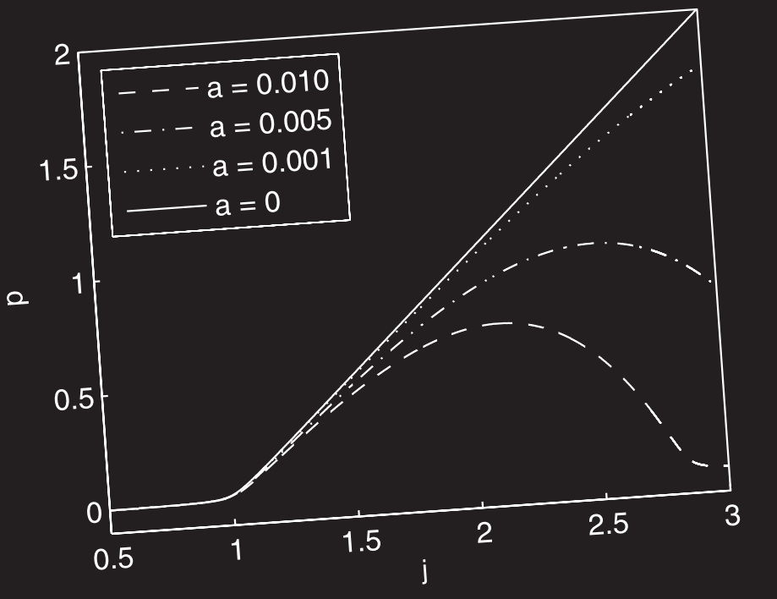
$$j = \frac{J}{J_{th}} \qquad N = n/n_{th} \qquad p = \frac{\gamma P}{J_{th}V}$$

Introducing the modified gain term:

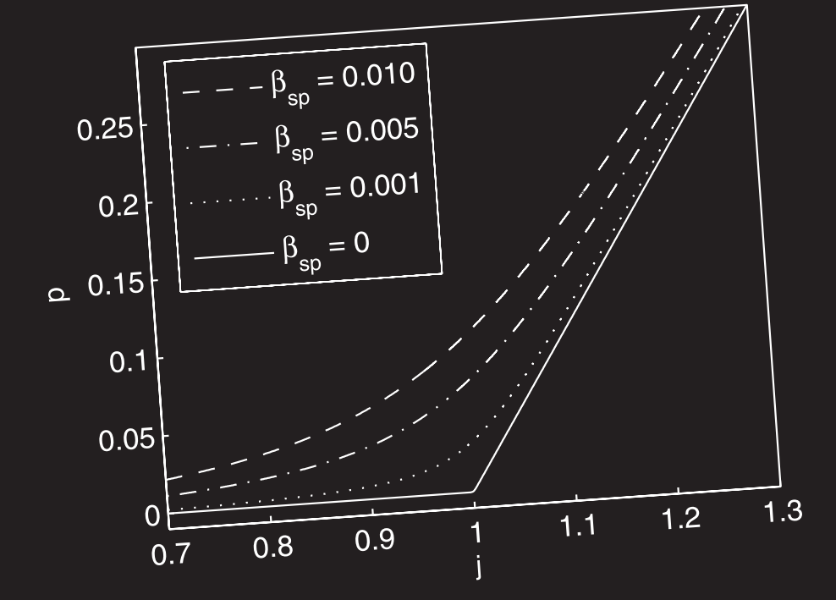
$$G(n,J) = G_0\left(n - n_0 J^l\right)$$

the normalized rate-equations can be written as:

$$j - N - p\left(\frac{N}{1-a} - \frac{aj^l}{1-a}\right) = 0 \qquad a = n_0\gamma_e J_{th}^{l-1}$$
$$p\left(\frac{N}{1-a} - \frac{aj^l}{1-a} - 1\right) + \beta_{sp}N = 0.$$



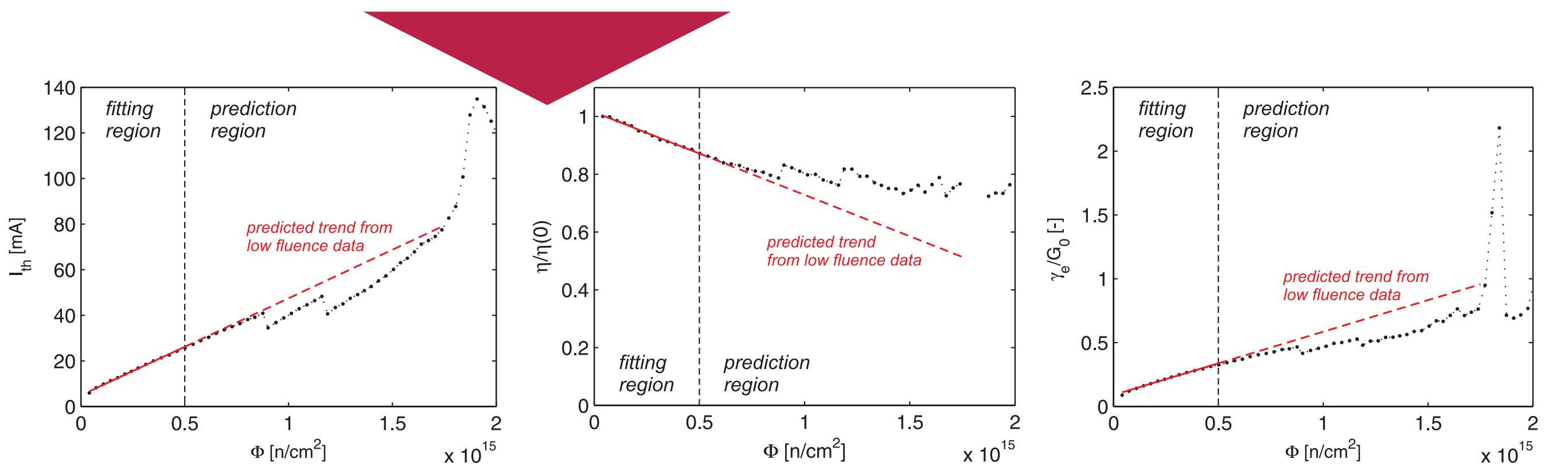
The normalized photon number p within the laser cavity as a function of normalized drive current j for different values of an arbitrary constant a with $\beta_{sp} = 1 \times 10^{-3}$ and $l = 5$.



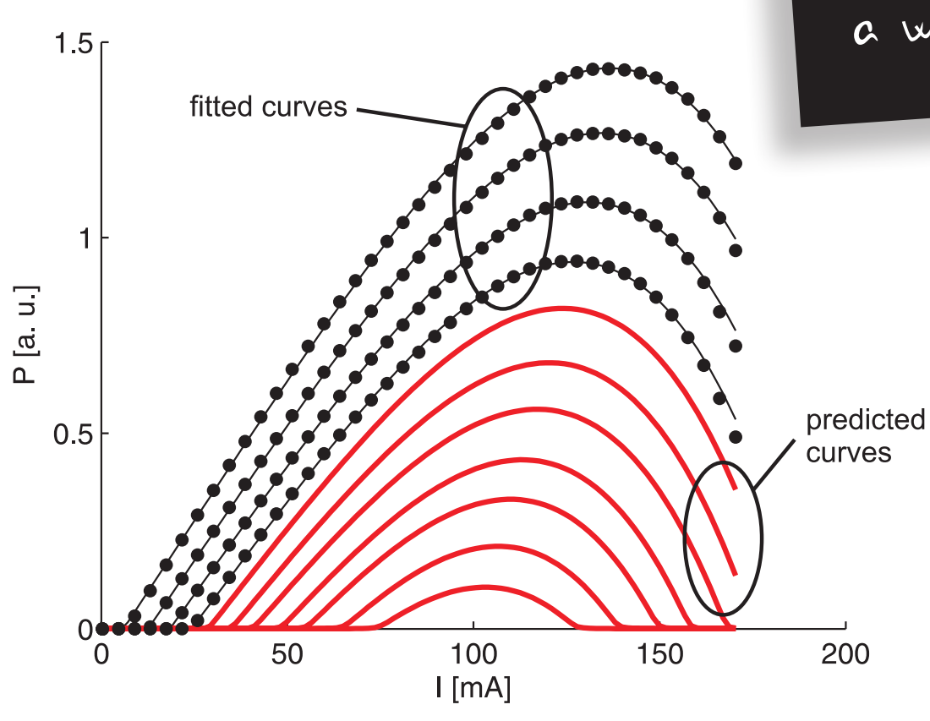
The normalized photon number p within the laser cavity as a function of normalized drive current j for different values of spontaneous emission factor β_{sp}.

FAILURE PREDICTION

Using the rate-equation model, it is possible to predict the device behaviour from low-fluence data. Data of the Mitsubishi reference laser from the neutron test are used for a demonstration. Fitted rate-equation model parameters from low fluence data (below 5.0×10^{14} n/cm^2) were linearly extrapolated and then used to predict laser *L-I* curves.



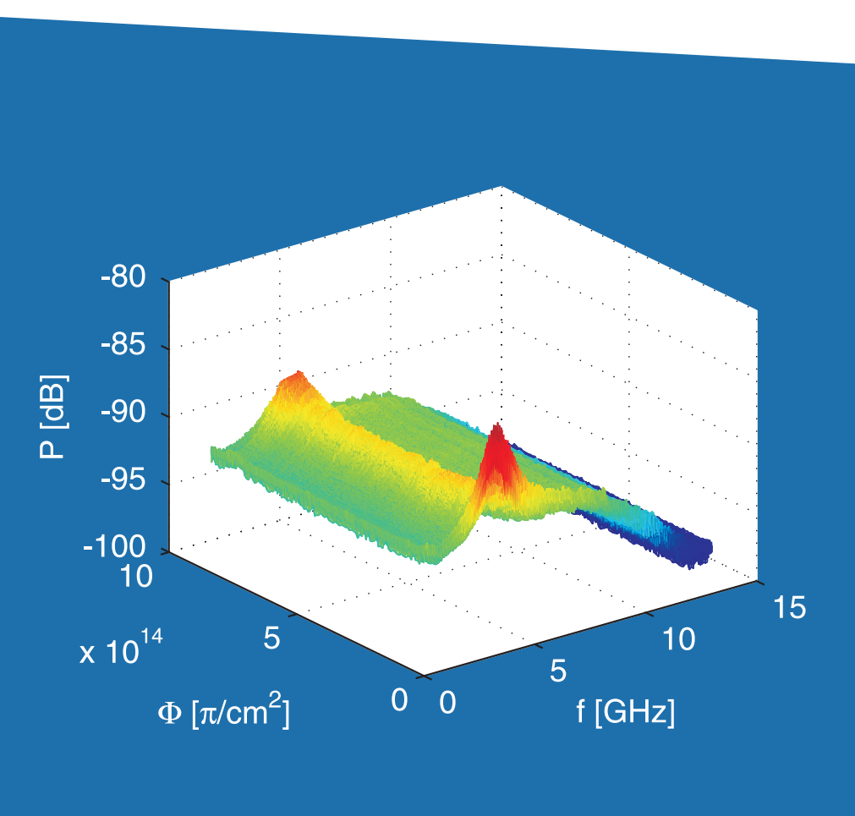
Fitting parameters of 1310 nm Mitsubishi reference laser from neutron irradiation test. The prediction doesn't work currently for 850 nm VCSELs.



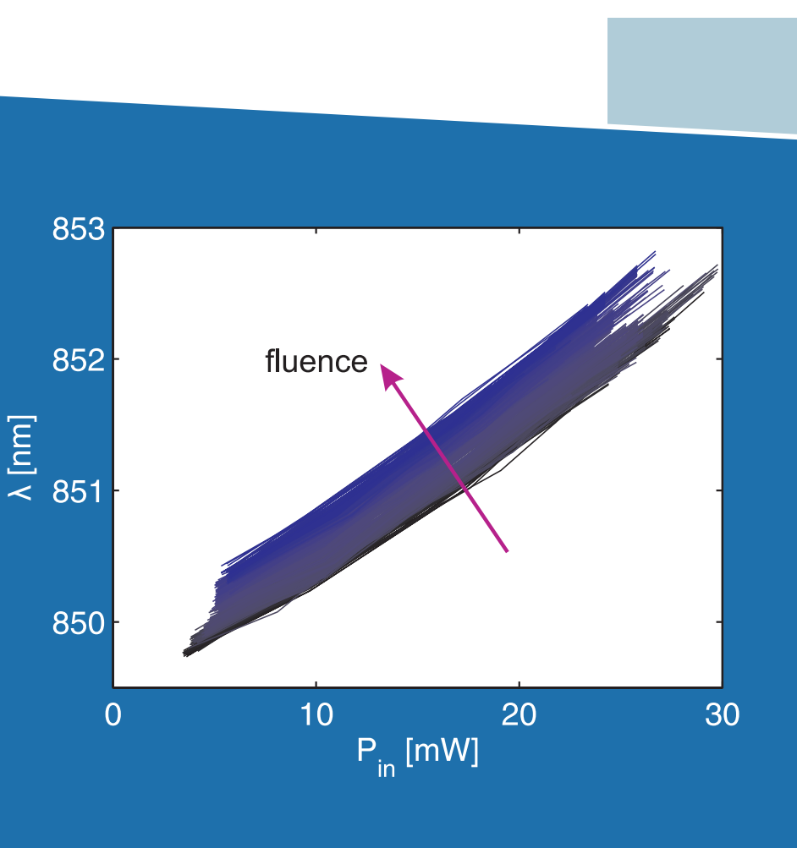
Fitted and predicted L-I curves of 1310 nm Mitsubishi reference laser from neutron irradiation test.

SPECTRA MEASUREMENT

In order to track temperature effects and high-speed performance of laser devices, the optical and electrical spectra were measured in-situ during the pion irradiation test. From the electrical spectrum measurement it can be concluded that the bandwidth of a laser does not decrease during irradiation as long as enough modulation current can be injected above threshold. The spectral data are currently being analysed.



Electrical spectra of a 1310 nm VCSEL for 3.7 mA bias.



Peak wavelength versus electrical input power for a 850 VCSEL.

CONCLUSION

The proposal of using rate-equation model for a description of semiconductor laser *L-I* curves was presented. Good agreement between the calculated and measured values was reached for all irradiated devices in both neutron and pion tests. Such a model is suitable for prediction of semiconductor laser operating characteristics during irradiation from low-fluence data. It might result in a refinement of future irradiation tests. The time spent in irradiation facilities, thus the cost as well, will be significantly reduced.

Concerning the neutron and pion irradiation tests, only minor deviations within device families were observed. In terms of degradation, VCSELs proved generally to be more radiation resistant than edge-emitting lasers. In terms of annealing, lasers are able to recover a substantial part of the induced damage. This will be significant in the final application where the irradiation to maximum fluence takes place over the system lifetime.

The scaling between neutrons and pions for different device materials still needs to be evaluated.

[1] Amaral, L., et al.: *The versatile link, a common project for super-LHC. J. Instrum.*, 2009, vol. 4, p. 12003