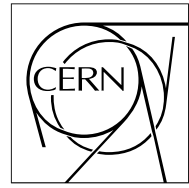


**The Compact Muon Solenoid Experiment**

# **CMS Note**

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## **In-system performance of MQW lasers exposed to high magnetic field**

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### **Abstract**

The effect of magnetic field has been investigated on 1310nm edge-emitting multi-quantum-well lasers. These lasers are candidate transmitters for the CMS tracker optical link, which will be operated in a 4T solenoidal magnetic field. In-situ measurements up to 2.4T of in-system laser analogue performance and laser spectral characteristics were carried out. No degradation of performance and spectral characteristics was observed

# 1 Introduction

The CMS Tracker optical data readout is based on semiconductor laser transmitters. These transmitters will be exposed to very high magnetic fields up to 4T in the CMS Tracker [1-5]. Extensive investigations have already been undertaken to ascertain that the semiconductor lasers intended for use in the tracker will survive the expected radiation environment [6, 7]. The effect of high magnetic fields on laser performance has not previously been reported within CMS. Research by other investigators have shown that wavelength (frequency) shifts, threshold current and/or output power shifts, and enhanced bandwidth may result from exposure to high B-fields [8-12]. A recent study [12] reports a relatively large threshold shift of  $\sim 2\text{mA}$  at 13T in room temperature for InGaAsP multi-quantum-well (MQW) lasers emitting at  $\sim 1300\text{nm}$ , of similar type as the Tracker link lasers. It is thus of interest to investigate if, and to what extent, the lasers intended for the CMS Tracker optical links, are susceptible to B-field effects.

This paper describes an experimental test of the effect of magnetic fields up to 2.4T on edge-emitting, semiconductor lasers emitting at 1310nm. Spectral and analogue performance characteristics were investigated with emphasis on threshold current, in-system linearity and in-system noise. The modulation bandwidth was not measured in this experiment as it is limited by the electronics, not the laser transmitter, in the current measurement setup.

The lasers under study were of the double-channel-planar buried- heterostructure (DCPBH), InGaAsP/InP, MQW-type emitting at  $\sim 1310\text{nm}$  [13]. The 4 tested lasers were encapsulated in a 4-way, non-magnetic, ceramic package, custom developed for the CMS tracker application [14].

Two types of experimental configurations were used for the spectral and performance evaluation respectively. In both tests the lasers were attached to a rotating support and inserted in a 2.4T test-magnet at CERN. The components were operated continuously with a laser driver delivering currents from 4.5 to 26mA [15]. The temperature was monitored using a Pt100 resistance placed near the device. Maximal differences of  $0.3^\circ\text{C}$  around  $25.5^\circ\text{C}$  were observed throughout the measurements.

## 2 Spectral dependence on magnetic field

The spectral measurement setup is shown in Fig. 1. Direct magnetic fields from -2.4 T to 2.4 T were applied while a series of spectra were recorded with a resolution of 0.1nm. The measuring platform was based on a spectrometer, an infrared camera and an oscilloscope. The calibration of the whole system was continuously performed with a Nd:YAG laser emitting at 1318.8 and 1338.2nm. The sensitivity of the camera to stray magnetic field, even when the camera was put far away from the field region (5m roughly), was a limiting factor to the resolution of the experiment. The laser peak wavelength was determined by referencing it to the 1318.8nm Nd:YAG peak for every captured spectrum.

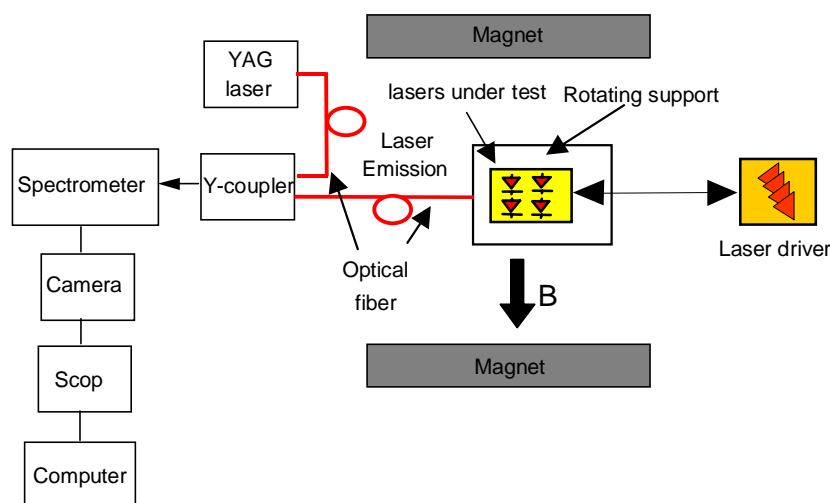


Fig. 1: Experimental setup for the spectroscopy of lasers in magnetic fields

The device was biased with the following currents: 12.5mA and 26mA for four hours before the measurements. Thus, the thermal stabilisation was achieved at that time. Seven intensities of B-field ranging from -2.4T to 2.4T were set. At each intensity, the wavelength measurement was repeated for six positions of the rotating support taking the reference 0° as the horizontal plane (B-field parallel to the laser QW plane). Fig. 2 shows the results obtained.

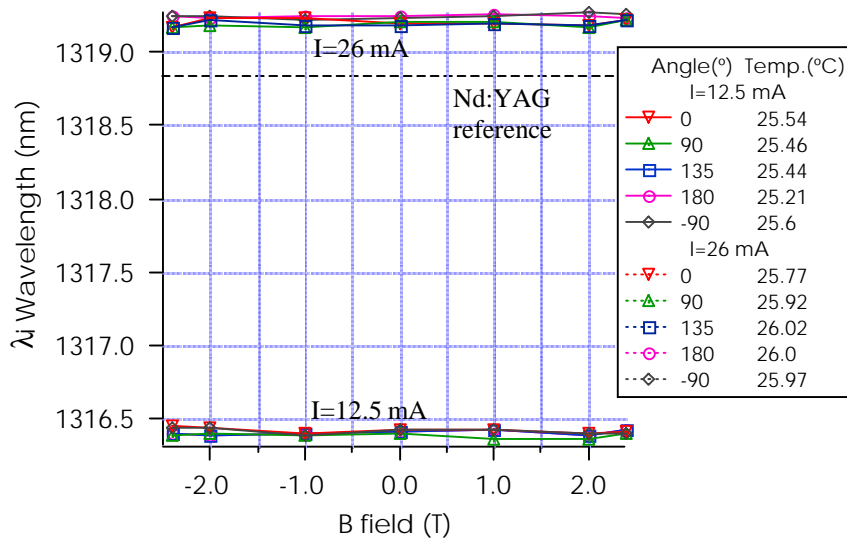


Fig. 2: Laser wavelength peak as a function of magnetic field. The temperature shown is the average of the instantaneous values measured when capturing the laser spectrum for 7 different B-field values

The laser peak wavelength remained independent of B-field for the two biasing currents. No effect of magnetic field intensity or angle was observed

### 3 Analogue performance in magnetic field

The in-system laser performance test arrangement is shown in Fig. 3. The laser evaluation was carried out with all other link components (laser driver, receiver, connector breakpoints, fibers) kept outside the magnetic field. The 4-way laser package was connected to the 4-way pin-diode receiver package via single-mode fiber and two breakpoints with MPO-connectors.

The performance evaluation of the lasers was based on the measurement of the system static transfer characteristic [16,17]. An arbitrary waveform generator (AWG) generated about 100 static voltage levels that were fed sequentially to the system input as a ramp, plus synchronization signals for the measuring instruments. For each static measurement point the average and standard deviation of the link output voltage was measured. A high-resolution (12bit) analogue to digital converter (ADC) was used to evaluate the static transfer characteristic and a large bandwidth (300MHz) oscilloscope was utilized to measure the noise into the system bandwidth. All system outputs were terminated with 50Ω resistors.

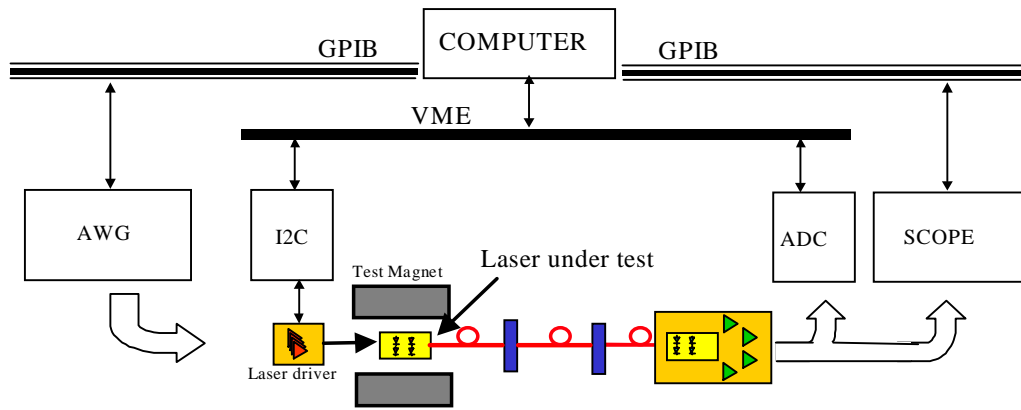


Fig. 3: Test setup for static and noise evaluation.

Measurements were performed sequentially at B-field values of +2.2T, +1.2T, 0T, -1.2T and -2.2T for angular positions 0°, 90° and 135° over four laser channels for a total of 60 measurements. For each measurement the laser driver input voltage,  $X$ , the receiver output voltage,  $Y(X)$ , and the output signal standard deviation,  $dY(X)$ , was registered. These parameters were then used to calculate the transfer characteristic, normalised RMS-noise and integral non-linearity as described in detail in [17].

### 3.1 Transfer characteristics

Fig. 4 shows typical measured transfer characteristics at 0T and 2.2T. No effect of increasing B-field (at 0°, 90° and 135°) on the transfer characteristic (or gain) was clearly visible. In Table 1 the average gains,  $G$ , over the measured four lasers for all angles and B-fields are shown. Only very small changes can be seen with changing magnetic field strengths. The slight decrease in gain going from 0°-90°-135° was probably due to a slight increase in temperature during the measurement, but the variation seen is clearly within an acceptable 2% measurement error.

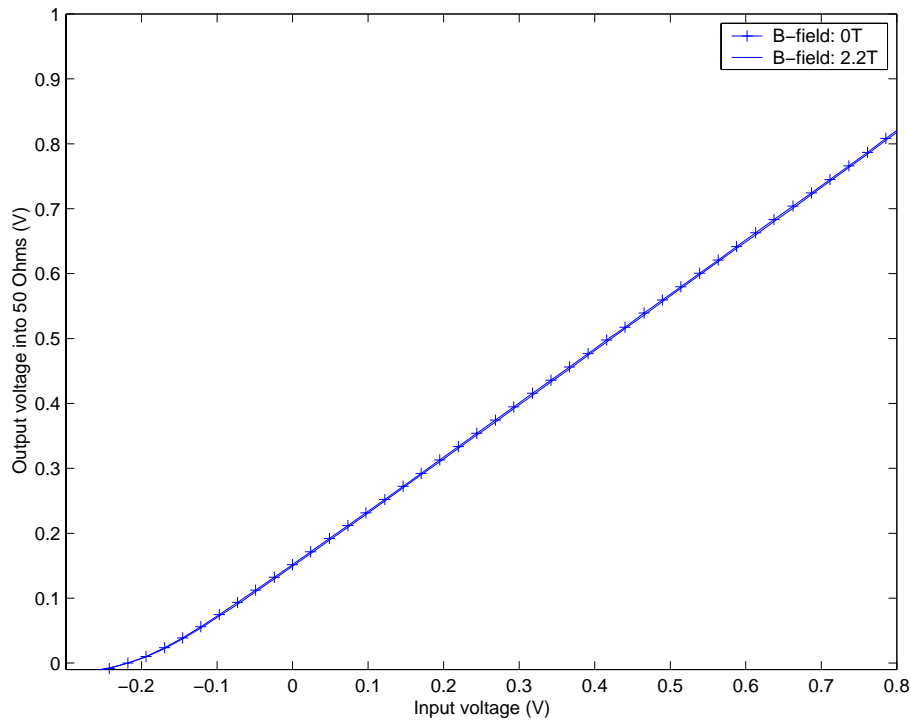


Fig. 4: Typical measured transfer characteristic at 0T and 2.2T (0°) for channel 2.

Table 1: Measured link gain (averages over 4 lasers)

Gain (V/V)					
	B-field				
angle	+2.2T	+1.2T	0T	-1.2T	-2.2T
0	0.87	0.87	0.87	0.87	0.87
90	0.87	0.86	0.86	0.87	0.86
135	0.87	0.86	0.86	0.86	0.86

The measured threshold currents are displayed in Fig. 5 and Table 2. Each point represent an average over the 4 laser channels measured. The angle dependence at 0T is probably due to small temperature shifts of the ambient temperature of the laser. Within the precision of the measurement no threshold current shift can be seen in the data obtained.

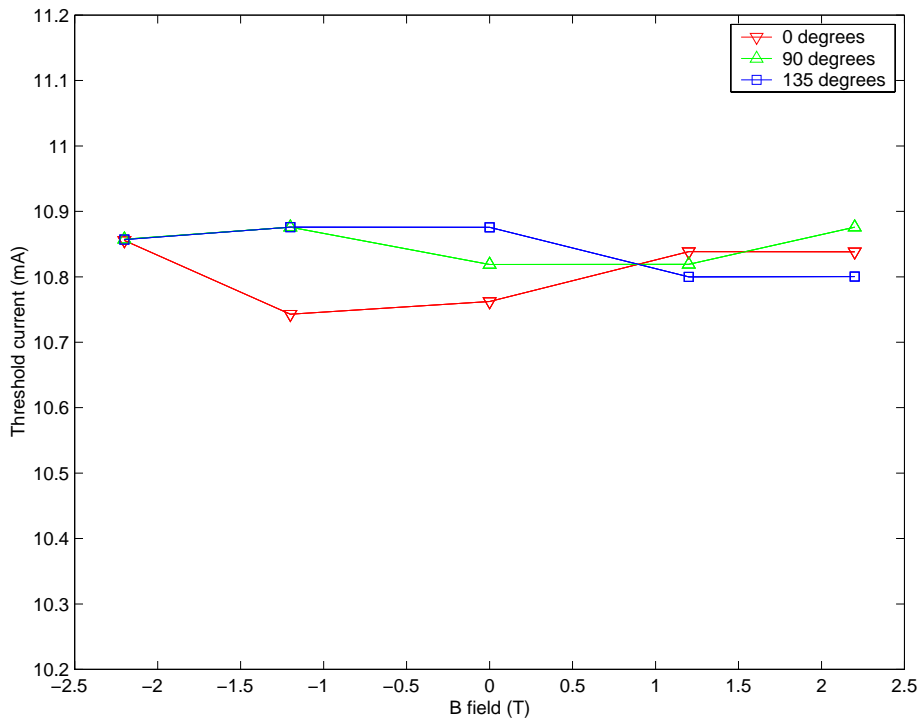


Fig. 5: Averaged laser threshold current of the 4 measured laser channels at B-fields -2.2T, -1.2T, 0T, +1.2T, +2.2T and angles 0, 90 and 135 degrees.

Table 2: Measured laser threshold current (averages over 4 lasers)

Averaged laser threshold current (mA)					
	B-field				
angle	+2.2T	+1.2T	0T	-1.2T	-2.2T
0	10.9	10.7	10.8	10.8	10.8
90	10.9	10.9	10.8	10.8	10.9
135	10.9	10.9	10.9	10.8	10.8

### 3.2 Normalised RMS-noise

Typical measured normalised RMS-noise data is shown in Fig. 6 at 0T and 2.2T. The normalisation is done in order to have a gain-independent measure of noise and is calculated (in percent) as:

$$dY_{norm}(X) = \frac{dY(X)}{G\Delta X} \times 100$$

where  $G$  is the link gain and  $\Delta X$  is the full input signal (0.8V) as described in [17]. The averages over the 4 measured lasers over the range 0-0.8V of the normalized RMS-noise are shown in Table 3. No clear effect on the measured noise could be seen with increasing magnetic field.

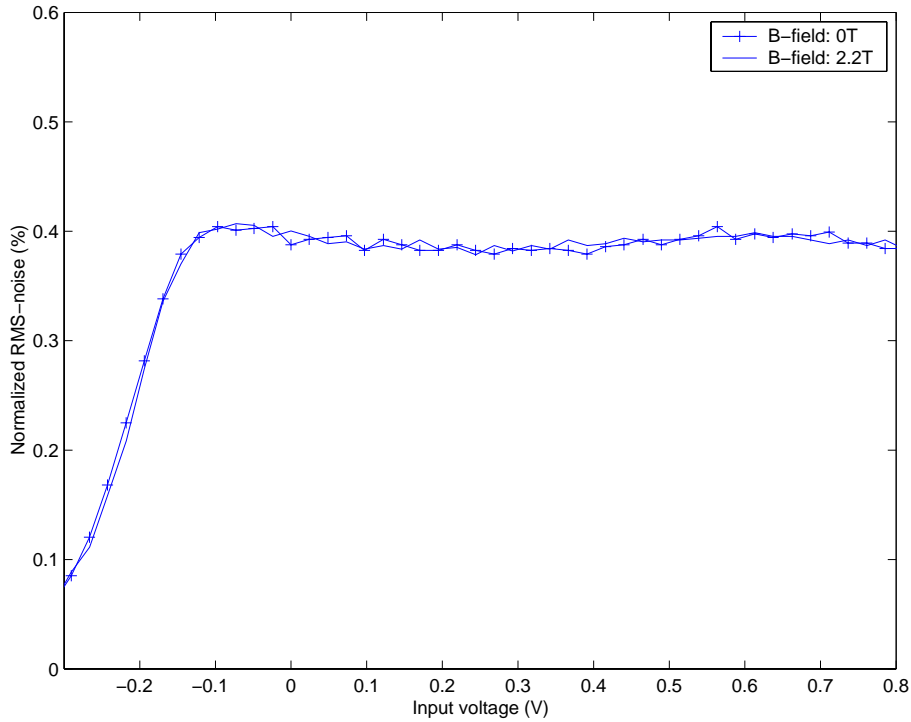


Fig. 6: Typical normalised RMS-noise at 0T and 2.2T (0°) for channel 2.

Table 3: Measured mean normalised RMS-noise (averages over 4 lasers)

Full range 0-0.8V average normalised RMS-noise (%)					
	B-field				
angle	+2.2T	+1.2T	0T	-1.2T	-2.2T
0	0.43	0.43	0.43	0.43	0.43
90	0.43	0.43	0.43	0.43	0.43
135	0.43	0.43	0.43	0.43	0.43

### 3.3 Integral nonlinearity

The parameter used to quantify deviation from linearity is integral nonlinearity,  $INL(X)$ , defined in percent as:

$$INL(X) = \frac{|Y(X) - GX|}{G\Delta X} \times 100$$

Typical measured *INL*-values are shown in Fig. 7 and 4-laser average values are shown in Table 4. Again it is not possible to clearly identify an effect of the increasing magnetic field. The measured nonlinearities were small and within a  $\sim 10\%$  measurement error.

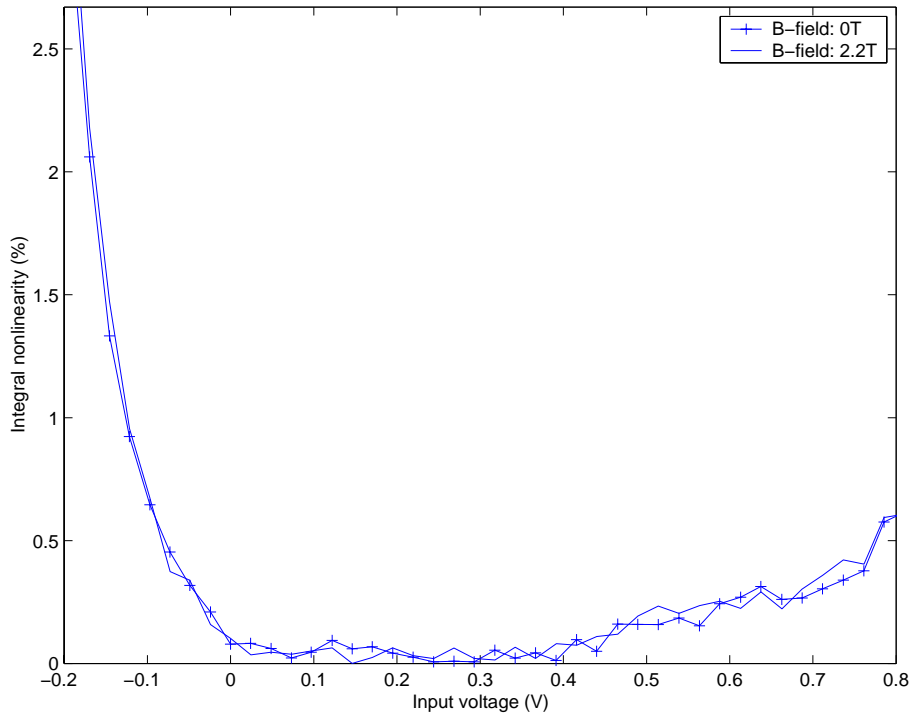


Fig. 7: Typical measured integral nonlinearity at 0T and 2.2T (0°) for channel 2.

Table 4: Measured mean integral nonlinearity (averages over 4 lasers)

Full range 0-0.8V average integral nonlinearity (%)					
angle	B-field				
	+2.2T	+1.2T	0T	-1.2T	-2.2T
0	0.24	0.25	0.25	0.24	0.27
90	0.24	0.28	0.24	0.22	0.26
135	0.23	0.21	0.24	0.25	0.25

## 4 Discussion and conclusions

Semiconductor lasers exposed to high magnetic fields have been investigated experimentally for wavelength shifts [8-11], threshold current shifts, [8-9,11-12], optical output power shifts [10] and enhancement of the modulation bandwidth [12]. Historically these investigations were carried out at very low temperatures ( $T < 100\text{K}$ ) and very high magnetic fields (4T-20T) as semiconductor lasers only could be brought to operate at very low temperatures. More recent work includes tests at room temperature [8,10,12] and lower B-fields [9,10].

In general the wavelength shifts found in the literature are very small ( $\ll 0.1\text{nm}$ ). If these results translate to the laser structures tested in this work they indicate that wavelength shifts will be of little importance for the performance of the lasers to be used in the CMS tracker. Further, the shifts measured are below the accuracy of our current measurement setup. Berendschot et.al. [8] investigated the effect of very high fields up to 20T on a high-power GaAs/AlGaAs graded-index separate-confinement heterostructure MQW laser. At 120K they found a shift of  $\ll 0.1\text{nm}$  ( $< 0.01\text{eV}$  at 805nm). Sato et.al [9] observed frequency shifts of 500MHz for an AlGaAs diode laser at a relatively low B-field of 1.4T at room temperature. In a later work (1998) Sato et.al [10] studied a high-power MQW laser oscillating at 780nm at room temperature. At 1.4T, frequency shifts of  $\sim 1\text{GHz}$  were

observed, at input currents of 48-95mA, once again too small to be observed in our measurements. In Sato's work the shift observed was a red-shift, contrary to most experimental results showing a blue-shift with increasing B-field, indicating device heating effects. It should be kept in mind that all the above work was conducted on AlGaAs-structures and not InGaAsP MQW lasers operating at ~1310nm, the type used in the present tests. We have not been able to find recent work on spectral properties of modern InGaAsP-lasers exposed to high B-fields.

Several authors have reported laser threshold current shifts, due to high magnetic fields. Berendschot et.al. [8] found a shift of 60K in the characteristic temperature,  $T_0$ , when the B-field was increased from 0T to 20T. This induces a threshold current shift which they approximated as  $I_{th}(T_2)/I_{th}(T_1) = \exp[(T_2 - T_1)/T_0]$ . For a threshold current of 10mA, at room temperature, this would give a threshold of 8.9mA at -10 °C at 20T as opposed to 8.6mA at 0T (a shift of +0.3mA). However the laser used was of a high-power type and the nominal threshold current on the order of several hundred milliAmperes. This result is therefore of limited or uncertain applicability for the MQW lasers we have investigated in the present work. Smetsers et.al. [11] observed a threshold current shift of 7% at 25T with the field lines parallel to the injection current direction. This result was again obtained using a GaAs/AlGaAs double heterostructure laser at very low temperatures (~20-46K). Sato and coworkers [10] did not report threshold shifts directly but instead showed output power shifts on the order of 0.1mW, close to threshold at 1.4T, 48-95mA injection current at room temperature. The power shifts were shown to be linear both with magnetic field and current. Sugawara [12] studied threshold currents of 1.3-1.6µm InGaAsP/InP strained quantum well lasers exposed to a magnetic field of 13T. At 318K Sugawara observed threshold current shifts of ~2mA when the 13T field was applied. It was also demonstrated in [12] that the threshold current shift increases with increasing temperature with a related increase in  $T_0$  of 9K.

To summarize, several researchers have showed that wavelength shift occurs under high B-fields, but the actual shifts observed are <<0.1nm (in AlGaAs). Such a small shift would have no measurable influence on the performance of the CMS tracker optical link lasers, and in fact, we did not measure any effect. Significant threshold and output power shifts have also been observed. The most relevant results for our application are those of Sugawara [12] and Sato [10]: Sugawara investigates InGaAsP/InP quantum well lasers of similar type as we have tested. At 13T he observed a threshold current shift of ~2mA for a nominal threshold current of ~10mA. Contrary to Sugawara's results we did not observe any threshold shift in our measurements on any of the 4 channels investigated. Sato [10] showed that the B-field induced power shift he measured, increased with increasing injection current. As the CMS-tracker lasers will be exposed to high levels of nuclear radiation, their threshold currents are expected to increase significantly, in some cases by as much as 10-20mA. Although basically no effects of the 2.2T B-field were observed in our tests, the results of Sugawara and Sato indicate that measurable effects possibly could be observed at higher operating currents. It may therefore be important to ascertain to what extent irradiated lasers, with correspondingly high injection currents, exhibit threshold current shifts when exposed to a B-field of 4T.

In this paper experimental results for MQW InGaAsP-lasers exposed to magnetic fields up to 2.4 T (spectral measurements) and 2.2T (performance measurements) have been presented. The results show that the magnetic field is not affecting the spectral characteristics of the device, within the measured B-field intensities and accuracy of the measurement. Furthermore, the 2.2T field did not influence the static and noise performance of the tested lasers. The variation seen with varying B-field intensities, and incident field angle, are certainly within the normal spread expected during repeated measurements. In particular considering the fact that the temperature was not controlled precisely, possibly inducing some gain, threshold, and noise variations.

It has to be seen in further measurements if the above conclusions (no effects) remain true when increasing the magnetic field to the CMS nominal intensity of 4T and exposing irradiated lasers, at high injection currents, to this field.

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