Analysis of the Imperfections Associated with Current Sensing System Based on Polarization Optical Time Domain Reflectometry

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Abstract

Accurate current measurement is mandatory for the safe operation of the ITER. In practice, the accuracy of the current sensors based on Polarization-OTDR (Optical Time Domain Reflectometry) may suffer from imperfect coil shape, fiber bending and noise on the POTDR photodetector. In this project, the effects of D-shape coil, fiber bending and POTDR noise is modeled and implemented as add-ons to the already-present POTDR simulator in MATLAB which is created by Research Assist. Şamil Şirin. Effects of the D-shape coil is investigated and current measurement is done by using least square method with 10kA resolution. An error anaysis is made on current measurement accuracy in the expected ITER operating current range for both low range (0-1MA) and high range (1-17MA). The effect of fiber bending on current measurement accuracy in the expected ITER operating current range (0-17MA) is analysed for D-shape. It is observed that a proper choice of beat length can improve the current measurement accuracy and spun fibers can be used to alleviate the bending effect.

Introduction

State of Polarisation (SOP)

State of Polarization is the pattern drawn by the tip of the electric field vector as a function of time. A monochromatic light is described as fully polarized. However, it is not the case for most of the time and when it is not possible to define a polarization state for a light wave it is defined as unpolarized. SOP can be characterised by the shape of the pattern and it can be linear, circular and elliptical.

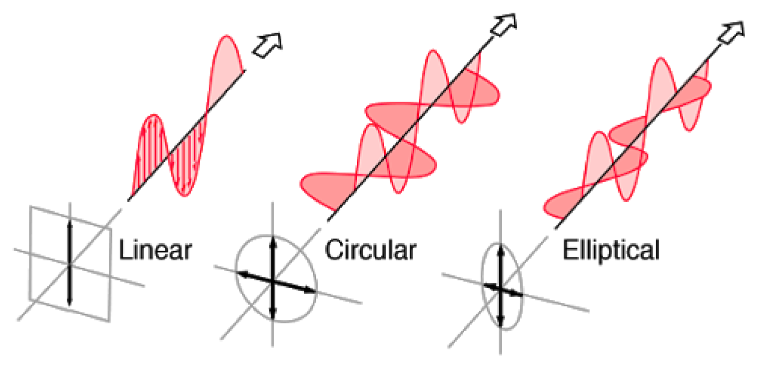


Figure 1: Different State of Polarization patterns.

Birefringence

An ideal single-mode optical fiber with circular symmetry allows the propagation of two degenerate orthogonal polarization modes which is called eigenmodes. In practice, effective refractive index of the fiber is different due to the non-symmetrical structure of the fiber. This causes two different group velocities of the modes that changes the state of polarization of the propagating light wave. This type of mediums that changes the state of polarization of the propagating light wave is defined as birefringent medium [1]. The birefringence can be defined as;

$$\Delta\beta = |\beta_x - \beta_y| = \frac{2\pi}{\lambda}|n_x - n_y|$$

If the eigenmodes of the fiber are linear it is called linear birefringent, if the eigenmodes are circular it is called circular birefringence. When both are present it is called elliptical birefringence. When a light wave propagating through a uniform birefringent medium the phase delay will reach 2π after some length and in such case the SOP of the incident light wave is identical to that of the input. This length is defined as beat length [1].

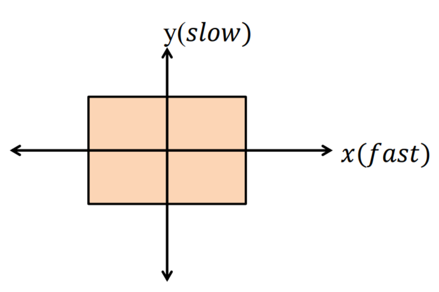


Figure 2: Eigenmodes of a material.

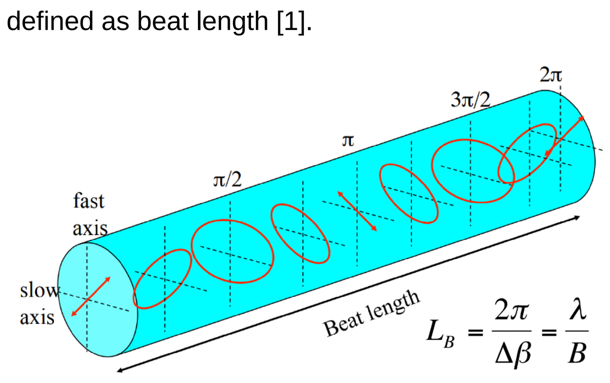
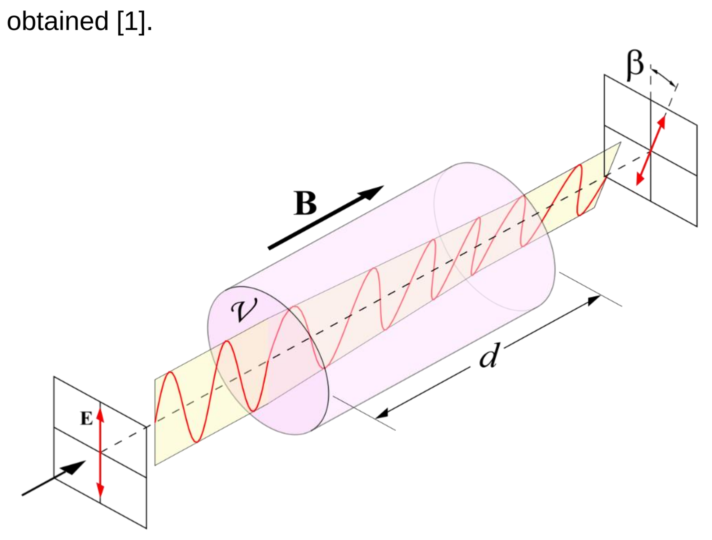


Figure 3: Linearly Birefringent fiber Beat Length.

Faraday Magneto-Optic Effect

When a linearly polarized light propagates in a magneto optic material that is subjected to a magnetic field, state of polarization of the light rotates [3]. This phenomenon is called magneto-optic effect. Verdet constant (V) is the magneto optic property of the material and the rotation angle can be obtained by integration of the Verdet constant multiplied with the magnetic field along the material. By using the Ampere's Law, rotation angle can be related with the current and the circular birefringence, which is defined as the rotation angle per distance, can be obtained [1].



Rotation Angle

$$\beta = \int_L V\mathbf{B}(l)\mathbf{dl}$$

Circular Birefringence

$$\rho_B = \frac{V\,\mathrm{I}\,\mu_0}{2\pi\mathrm{R}}$$

Figure 4: SOP rotation due to Faraday Magneto Optic Effect.

Polarization Optical Time Domain Reflectometry (POTDR)

POTDR is a polarization sensitive system which is widely used to measure the polarization properties of optical fibers [1]. An optical pulse is sent into the fiber by using a coupler and state of polarization of the pulse is fixed by a linear polarizer before entering the fiber under test. The propagating light inside the fiber attenuates and backscatters continuously via the Rayleigh scattering process. The backscattered light propagates through the polarizer and obtained by the receiver. If the state of polarization of the light varies along the fiber, SOP of the backscattered light varies as well. The changes of the SOP can be obtained as power fluctuations. When the fiber under test is subject to magnetic field, the SOP of the light rotates. This rotation can be obtained at the reciever and it can be used to measure current [1].

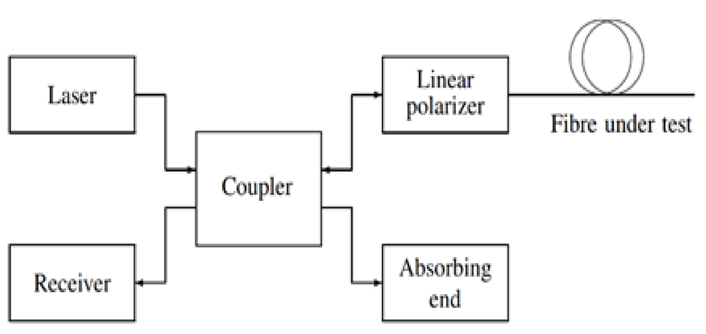


Figure 5: POTDR measurement setup.

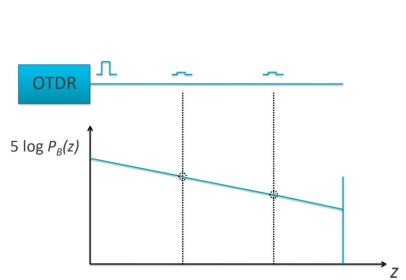


Figure 6: POTDR Trace.

ITER Tokamak

ITER is a project to build the world's largest Tokamak in South France, a magnetic fusion device to maintain fusion for long periods of time. Project has several purposes like producing net energy, testing tritium breeding. The fusion energy is absorbed in the walls of the doughnut-shaped vacuum vessel and the plasma current inside vessel needs to be measured. Classically, plasma current is measured by using inductive sensors like Rogowski coils. But these methods have some problems. Rogowski coils are depend on the derivative of the magnetic flux through the coil. However, it is foreseen that in ITER, plasma shots may last long time with a relatively constant current. Also, the presence of strong radiations may severely affect the useful signal. An alternative method is using POTDR based current sensors and they have some advantages like linearity over a wide current range, good radiation resistance, direct measurement of the current without the need for the integration operation.

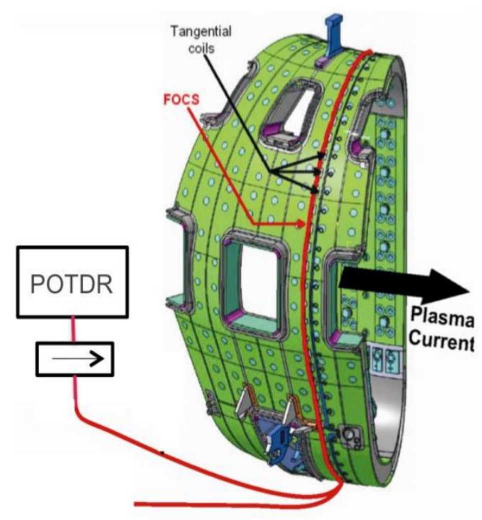


Figure 7 : A section of ITER Tokamak.

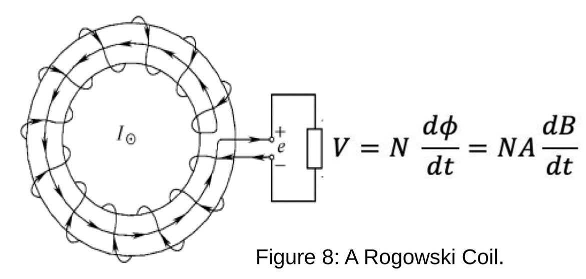


Figure 8: A Rogowski Coil.

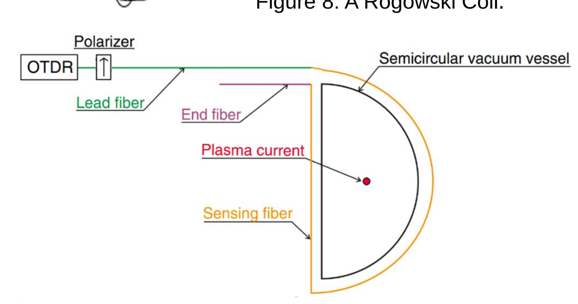


Figure 9: POTDR Setup with a sensing fiber along a semicircular shape.

Imperfections

Current sensing systems based on POTDR has some imperfections that needs to be overcome to be used in the ITER.

- If the shape of the sensing fiber is not a circle, magnetic field along the sensing fiber is not uniform. The distance between the fiber and the current is changing along the D-shape and also the magnetic field is not parallel to fiber.
- When a fiber is subjected to bending an additional linear birefringence is introduced to the fiber.
- There is noise at the POTDR photodetector and it is important to take the noise into account because the backscattered power is close to zero.

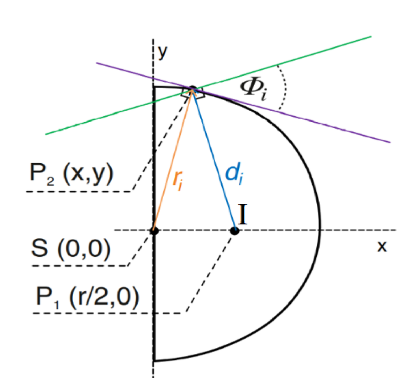


Figure 10: Geometry of the D-shape and analysis of the curved part.

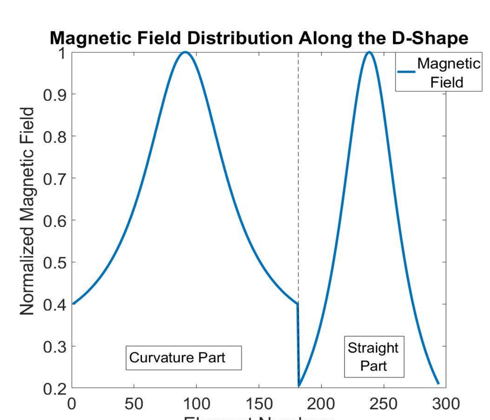


Figure 11: Magnetic Field Induced Circular Birefringence Distribution along the D-shape.

Simulation Process

Single-mode optical fiber has modeled as a concatenation of uniform fiber elements characterized by uniform polarization properties [1].

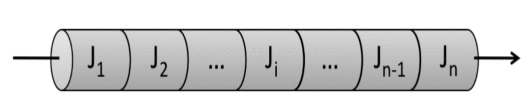


Figure 12: Fiber Modeling.

The D-shape has modelled on MATLAB. Since the magnetic field is not parallel to fiber, the angle between the magnetic field and the fiber has calculated and circular birefringence is calculated for all points along the sensing fiber. Then, this code is implemented to the simulation.

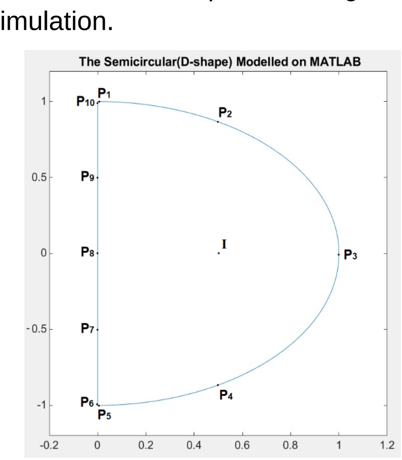


Figure 13: Modeled D-shape on MATLAB.

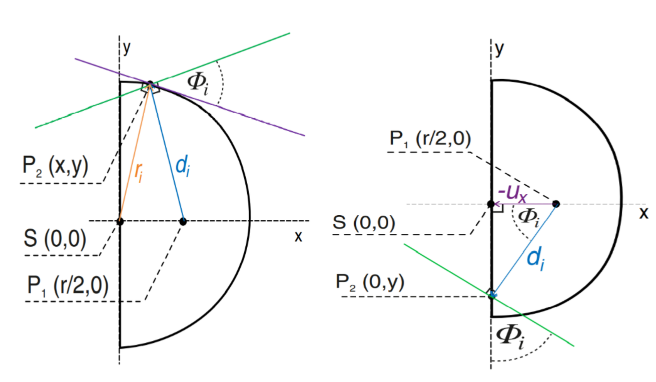


Figure 14: Geometry of the D-shape and analysis of the di and ϕ i.

Simulation Results

Simulations is done with the given parameters below the POTDR traces. The fiber has intrinsic linear birefringence and it can be adjusted by the beat length parameter. The current sensing is made on sensing fiber which is subjected to magnetic field. Lead fiber is the part between sensing fiber and polarizer. End fiber is the part after the sensing fiber. Due to the non uniform distribution at the sensing fiber, power trace has a cosine like behavior. When the plasma current increases the circular birefringence increases aswell, so SOP rotates faster and more oscillations can be observed at the sensing fiber.

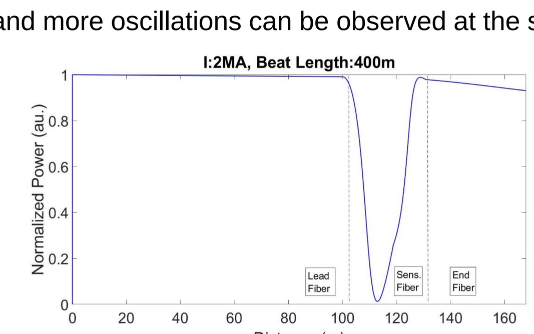


Figure 15: Complete POTDR trace for I=2MA.

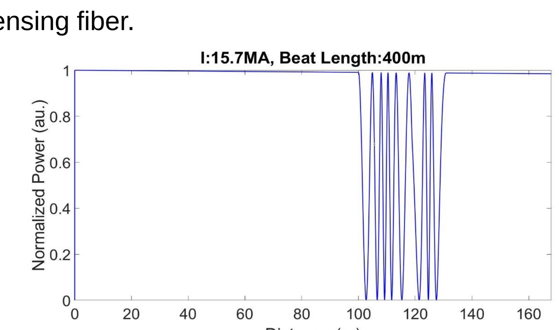


Figure 16: Complete POTDR trace for I=15.7MA.

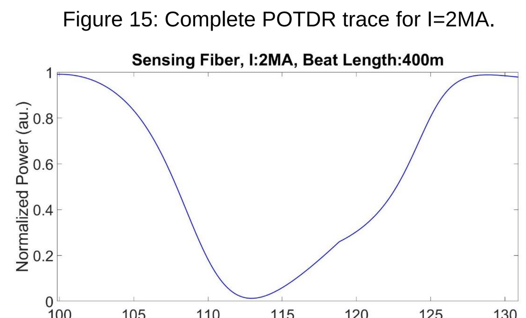


Figure 17: POTDR trace of the Sensing Fiber for I=2MA.

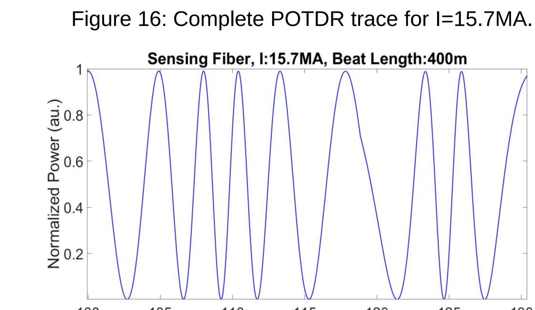


Figure 18: POTDR trace of the Sensing Fiber for I=-15.7MA.

Avg. Refractive index = 1.46
Beat Length = 400m
Fiber Radius = 125um

Lead Fiber = 100m
Sensing Fiber = 30.85m
End Fiber = 37.15m

Fiber attenuation = 0.2 db/km
Semicircle Radius = 6m

Current Sensing

To measure the current on simulation. Traces with the ideal conditions for the current range between 0-18.2MA with 10kA steps are stored. Least Squared Method is used to detect the current for the simulations. The difference between the ideal trace and simulation trace has been summed for all points and it is minimized to find the current.

Least Squared Method

$$\sum_i \left(P_{B_i}^{\text{ideal}} - P_{B_i}\right)^2$$

Resolution = 10kA

ITER Accuracy Requirements for Plasma Current I_P

	Current Range	Required Accuracy
High range	(1–17) MA	Relative accuracy of 1%
Low range	(0–1) MA	Absolute accuracy of 10 kA

Error Calculation

$$E_r = \frac{|I_P - I_{\text{mes}}|}{I_P}$$

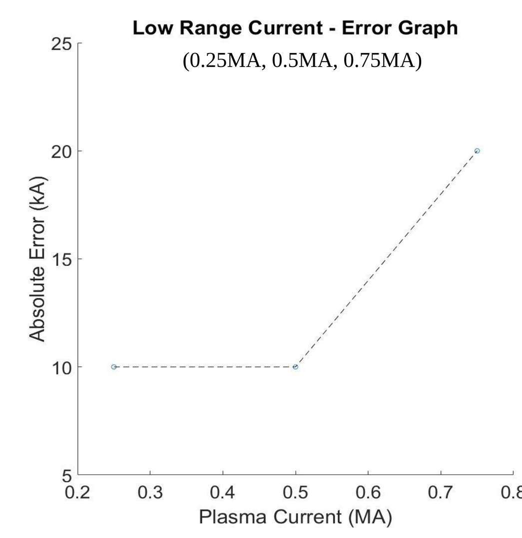


Figure 19: Absolute Error graph for low range current.

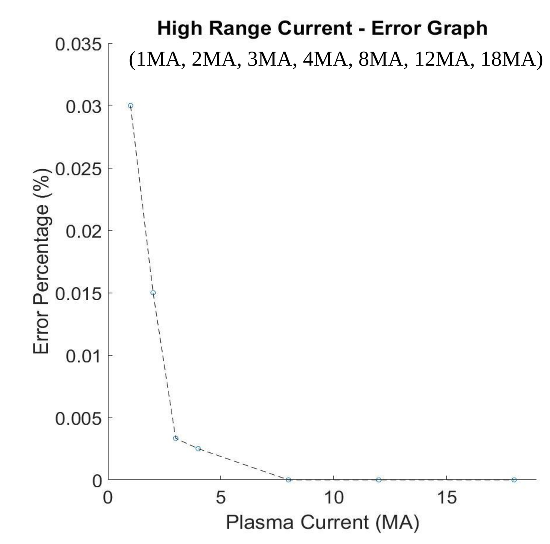


Figure 20: Absolute Error graph for high range current.

Bend-induced Birefringence

When a fiber is subjected to bending an additional linear birefringence is introduced to fiber and it can be calculated with the formula below and it depends on several parameters;

$$C_s = 0.5k_0 n_0^3(p_{11} - p_{12})(1 + v_p)$$

$$\delta_b = 0.5C_s\frac{r^2}{R^2}$$

k_0:Wavelength number
n_0:Avg. refrective index,
p_{11}-p_{12}:Strain-optical tensor parameters
v_p:Poisson ratio
r: Fiber diameter
R: Bending radius (1.865m)

Bend-induced birefringence is added to simulation and its effects are compared with the ideal case. For the high current range bend-induced birefringence is smaller than linear and circular birefringence in orders of magnitude therefore, its effect is negligible. For the low current range bend-induced birefringence is still smaller but it is effecting the accuracy of the sensor.

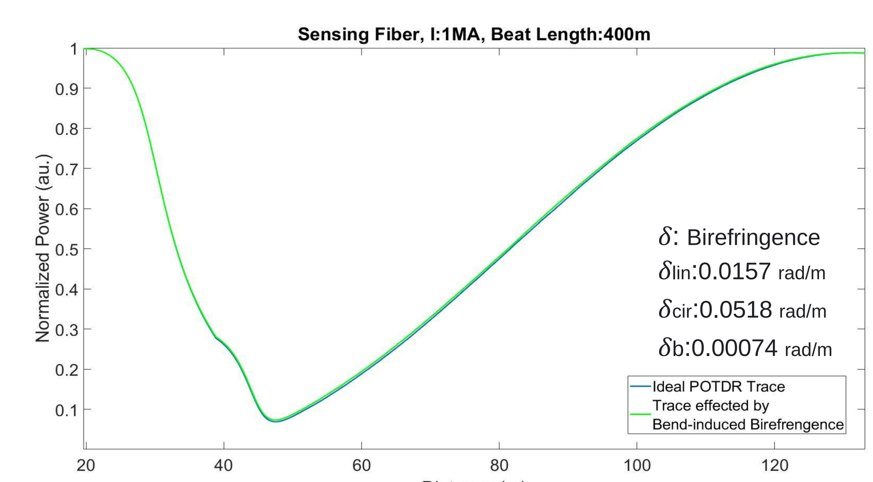


Figure 21: Both POTDR Trace with and without bending effects.

POTDR Photodetector Noise

To simulate the noisy trace, first the noise floor is calculated with the formula below by using different SNR values;

$$N = 5\log(\max\left(P_B(z)\right)/n + 1)$$

N: SNR, P_B: Power

After adding the noise floor to simulated trace, Additive White Gaussian Noise with zero mean is applied to it to find the noisy trace.

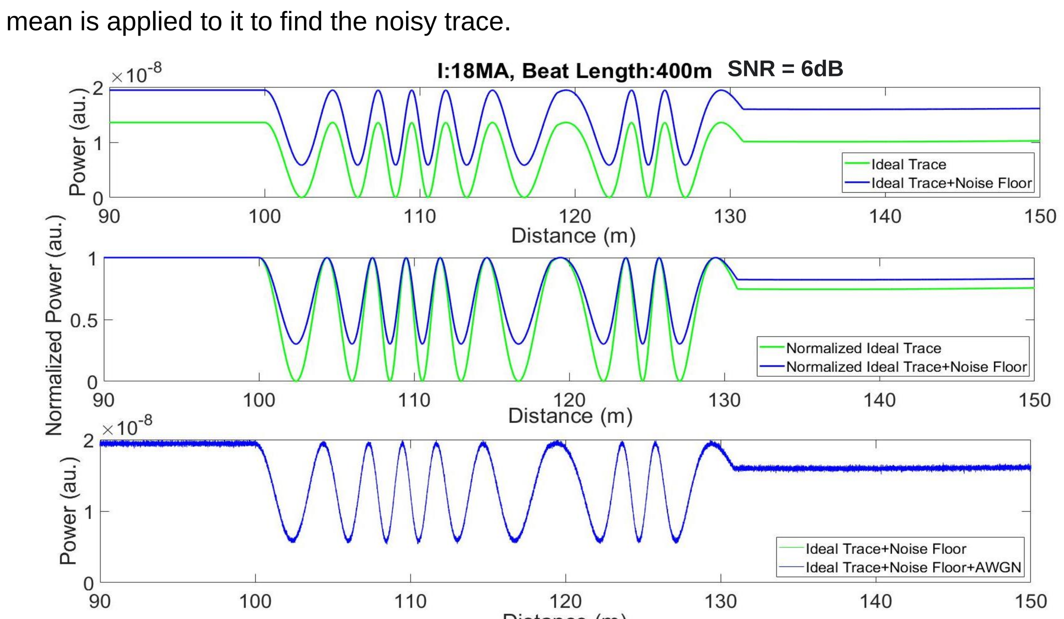


Figure 22: POTDR Traces with and without Photodetector Noise Floor and AWGN.

Conclusion

In this project, current sensing with D-shape sensing fiber, impacts of the bending induced linear birefringence, and impacts of the POTDR photodetector noise is implemented as add-ons to already-present POTDR simulator in MATLAB. Simulation current is detected with 10kA resolution by using least square method. An Error analysis is made on current measurement accuracy in the expected ITER operating range (0-17MA) and the requirements are satisfied by using low birefringent fiber (L_B>400m). Some simulations are made within the ITER operating range with the impacts of the bending induced linear birefringence. For L_B=400m, the accuracy requirements are satisfied in high current range. So, bending induced linear birefringence can be neglected in high current range but it can not be neglected in low current range. It is concluded that, fibers with low intrinsic birefringence performs better and by using spun fibers, which are resistent to external influences like fiber bending, ITER accuracy requirements can be satisfied for both low and high current ranges.

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