Koeberg Nuclear Power Station

- currently the only one in the country, and the only one on the entire African continent.
- located 30 km north of Cape Town, on the west coast of South Africa.

- Koeberg is owned and operated by the country's only national electricity supplier, Eskom.
Project Overview: Needs and Requirements

- Sensing HIGH Temperature and HIGH DOSES
  - In-core for Pressurized Water Reactors (PWR)
  - In-core for Advanced High Temperature Reactors (AHTR)

- Dosimetry mapping
  - Guaranteeing efficient operations, with substantial monetary savings.
  - Improving safety, avoiding accidents or, providing information in case of accidents (safer reactor both in normal operation and in an accident scenario)

Expectations:
- Finding the right technology adaptable to such harsh environment, with sensors surviving from 2 weeks to month in-core
Project overview: Goals and Objectives

• Individuation of the most suitable fiber optical-based technology for in-core reactors temperature and dose monitoring

• Application of optical fiber-based sensors in PWR Koesberg Reactor:
  - Temperature sensing and mapping (short term objective- 3 months to start)
  - Dose mapping (long term objective)
The whiteboard picture is the Koeberg PWR Reactor core (3mx3m) which has 24 blind tubes inserted into the core penetrating the pressure vessel. Only one tube is shown. Then there is a manifold that can approach each tube in turn and connect to the tube so that one can send up a sensor. There is an emergency crimp sealer on the tube in case there is a safety issue. The other end of the manifold penetrates the shielding, and so the sensor has to be about 5 m long for the in-core + in-radiation-field section. We could easily insert in a pilot experiment sensor line as a test in one tube with very little overhead. We expect we should also easily get regulatory clearance due to a previous similar test which was investigate and granted.

5 m long sensor (guess he’s refering to fiber!) ➔ 5 meters should be the distance from the shielding and the core (which is already 3 m) (TO BE CLARIFIED)
FOS FOR IN-CORE T MONITORING

In the first part of the project (short term) the focus will be the in-core temperature sensing and mapping

Fiber Bragg Gratings (FBGs) as sensing solution for high temperature monitoring in PWR

- ‘Moderate’ Temperature (300- 400 °C)
- Strong radiations (neutron flux of $10^{20}$ neutrons/cm$^2$)
WHY FBGs FOR IN-CORE T MONITORING?

- Immunity to electro-magnetic interference
- Compact size
- Intrinsically safe
- Ease of multiplexing
- Remote multi-point sensing
- Resistance to harsh environments:
  - Suitable for high temperature operation
  - Suitable for radiation environments
From literature...

- FBGs written on several types of fiber using different fabrication technique:
  1. UV Ge doped core fiber
  2. FEMTO Ge- doped core fiber
  3. FEMTO F doped core and F doped cladding
  4. FEMTO Pure silica core F doped cladding

- γ-irradiation up to 1 MGy

1. **UV-GE DOPED FIBER**: red shift ~150 pm, tendency to saturation at doses 1 MGy
2. **FEMTO FBGS**: blue shift much smaller than the UV written gratings
   - FS-PS core F doped cladding: initial red shift and after 23 kGy inversion of direction;
   - shift at the end of the experiment of 10 pm
   - FS-Ge doped core: initial red shift and after 56 kGy inversion of direction; shift at the end of the experiment of 24 pm
   - FS- F doped core/cladding: blue shift; shift at the end of the experiment of 32 pm
From literature...

IRRADIATION UP to 3 MGy @25 °C

IRRADIATION UP to 3 MGy at 230 °C (pre-thermal treatment @ 750 °C)

- Radiation tolerant optical fiber:
  a) F doped core
  b) Pure silica core
- FEMTO SECOND (Ti:sapphire laser)
- Pre-irradiation (x-ray up to 1,5 MGy)+
  Thermal treatment after fabrication @ 350 or 750 °C for 15 minutes
- Irradiation at room temperature /irradiation at 230 °C

IRRADIATION UP to 3 MGy @25 °C

1. Pre-thermal treatment increases the radiation resistance of FS-FBGs
2. For the F-doped core, the amplitude is almost unaffected by radiation (with pre-thermal treatment at 750 °C, amplitude variations smaller than 0,1 dB)

IRRADIATION UP to 3 MGy @230 °C

1. Saturating tendency of the BWS
From literature...

- Radiation tolerant optical fiber: pure silica core, F doped cladding + metallic coating
- FEMTO SECOND (Ti:sapphire laser)
- Pre-irradiation (x-rays up to 1MGy) + Thermal treatment after fabrication @ 500 °C for 15 minutes
- $\gamma$-irradiation at room temperature / irradiation at 335 °C up to 200 kGy
From literature...

**PROOF-OF PRINCIPLE OF T MONITORING IN RADIATION ENVIRONMENT AND HIGH T**

- Irradiation performed in the SCK•CEN BR2 reactor (Belgium)
- **Neutron** Irradiation @ $2.83 \times 10^{19} \text{n} \cdot \text{cm}^{-2}$ at 291°C for 21 days
- **Total dose of 3.8 GGy**
- FEMTO (Ti:sapphire laser)
- Radiation resistant fiber

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### Compaction in Optical Fibres and Fibre Bragg Gratings Under Nuclear Reactor High Neutron and Gamma Fluence

Laurent Remy, Guy Cheyns, Andrei Gusarov, Adriana Morana, Emmanuel Marin, and Sylvain Girard, Senior Member, IEEE

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 63, NO. 4, AUGUST 2016

#### Shift of the Irradiated FBG

<table>
<thead>
<tr>
<th>FBG</th>
<th>Pre-Irradiation X ray</th>
<th>λ_B before irradiation (nm)</th>
<th>λ_B after irradiation (nm)</th>
<th>Shift (pm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC-1</td>
<td>F-doped core</td>
<td>750</td>
<td>1539.360</td>
<td>+ 40</td>
</tr>
<tr>
<td>HC-2</td>
<td>F-doped core</td>
<td>350</td>
<td>1539.143</td>
<td>- 155</td>
</tr>
<tr>
<td>HC-3</td>
<td>pure silica core</td>
<td>350</td>
<td>1538.988</td>
<td></td>
</tr>
<tr>
<td>HC-4</td>
<td>pure silica core</td>
<td>750</td>
<td>1543.804</td>
<td>+ 770</td>
</tr>
</tbody>
</table>

#### Attenuation of the Irradiated FBG

<table>
<thead>
<tr>
<th>FBG</th>
<th>Reflectivity before irradiation (%)</th>
<th>Reflectivity after irradiation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC-1</td>
<td>8.8%</td>
<td>1.3%</td>
</tr>
<tr>
<td>HC-2</td>
<td>62.8%</td>
<td>7.9%</td>
</tr>
<tr>
<td>HC-4</td>
<td>18.7%</td>
<td>0.4%</td>
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</tbody>
</table>
• FBGs designed specifically to be minimally impacted by ionizing radiation.
  ✓ Radiation hard SM fiber
  ✓ FEMTO LASER grating inscription technique

• Commercial suppliers of FEMTO FBGs for T monitoring in harsh environment
Based on previous studies reported in literature, the research/operative plan proposal is the following:

- **FEMTO FBGs SAMPLES PROCUREMENT**
- **THERMAL TREATMENT**
- **IRRADIATION EXPOSURES**
- **TEMPERATURE CHARACTERIZATION**
- **IDENTIFICATION OF THE MOST SUITABLE DEVICE FOR IN-CORE T MONITORING AND FINAL VALIDATION IN PWR REACTOR**

No thermal treatment is also considered in the process.
Research/operative Plan: details (1)

- Procurement of sensors without any thermal treatment applied
- 2 types of gratings to be investigated:
  - FBGs written in Pure silica core and F-doped cladding optical fiber
  - FBGs written in F-doped core/cladding optical fiber
Research/operative Plan: details (2)

- Thermal treatment at high T (500-700 °C)
- Facility for the thermal treatment to be decided with the partners
  Can we use the reactor itself?
Research/operative Plan: details (3)

- Possibly, dose exposures at controlled T - is it possible to extract fibers during the run of the reactor? (.. gratings exposed to different levels of radiations..)

- To be performed directly in the reactor
Research/operative Plan: details (4)

- Range of calibration to be decided with the partners
- Calibration facility to be decided with the partners
  Can we use the reactor itself?
Based on the results of the irradiation and of eventual thermal treatments, the best configuration of FEMTO FBGs (written on pure silica core fiber or F-doped core/cladding optical fiber) will be selected for the application of in-core T monitoring in PWR reactor.
Profiting of the opportunity of the FBGs installation in the PWR reactor, we propose to test in real conditions also a few samples of LPG-based sensors (under investigations @ CERN)

- Custom sensors:
  - Pure silica core SM optical fiber
  - F doped core/cladding SM optical fiber
- FEMTO LASER grating inscription technique
Optoelectronic interrogation system

- Commercial optoelectronic interrogation system
- Robust, compact, high precision
- Suitable for both FBG and LPG technology

University of Sannio is going to lend the optical interrogator to the partners for the duration of the experimental tests/data taking in the PWR
Organization & schedule

Duration of the project: 12 months

Task T1: Project requirements definition (operative ranges/package if needed/needs of installation in reactor...) and FEMTO FBGs/LPGs procurement

Task T2: Experiments:
- thermal treatment
- preliminary irradiation exposures
- T-characterization

To identify the best configuration to be installed in the reactor in terms of higher resistance to radiation and lower radiation sensitivity

Task T3: Final validation in PWR reactor
## Organization & schedule: details

<table>
<thead>
<tr>
<th>Task</th>
<th>Task Denomination</th>
<th>Responsible</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project requirements definition and sensors procurement</td>
<td>T1</td>
<td></td>
<td>3 months</td>
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<tr>
<td>Experimental tests</td>
<td>T2</td>
<td></td>
<td>6 months</td>
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<tr>
<td>Final validation in PWR reactor</td>
<td>T3</td>
<td></td>
<td>3 months</td>
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<tr>
<td>T FOS FOR NUCLEAR PLANTS</td>
<td>TOTAL BUDGET</td>
<td>€ 70,000.00</td>
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<tr>
<td>Costs for Personnel</td>
<td>€ 30,000</td>
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<tr>
<td>Costs for Sensors (FBG/LPG)</td>
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<tr>
<td>Costs for Optical interrogator</td>
<td>€ 0,000*</td>
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<tr>
<td>Travel costs (personel/instrumentation)</td>
<td>€ 20,000</td>
<td></td>
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</tbody>
</table>

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