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ROBOTS FOR SAFETY IN FCC

O. Rios, A. Henriques, M. Widorski, R. Losito, M. Di Castro, A. Masi, M. Nas, T. Otto

gratefully acknowledging the contributions of the FCC Infrastructure
and Operation WG and sub-WGs, all FCC study teams
and the collaborating partners (list in annex)

Outline

- Intro: Root and Motivation
- Robotic Monitoring and Maintenance for FCC
  - Current examples of remote monitoring and maintenance
- Robotic possible solutions for installation, Installations Workflows
  - Inverted Assembly Line
- Robots in Emergency Situation
  - Ceiling rail-mounted Robot in a Fire Emergency (prototypes)
  - CFRS robot testing
- Safety Hazards from Robots
- Challenges for (Safety) robots integration

Challenges for Personal Safety in FCC Arcs

Main Factors

- Nearly 10 km arc length
- Long distance between shafts (>10km):
  - Transport safety. Reaching the workplace while keeping full attention in the repetitive structure
  - Being exposed to workplace hazards
  - Receiving help in case of emergency
  - Emergency response and intervention time
  - Occupants evacuation
- Augmented by the relatively narrow transport corridor
  - Two-way traffic at reasonable speed not possible
  - Overtaking a parking vehicle is difficult

SPS Fire Safety Study Group / Firefighting Tactical Approach , July 2015

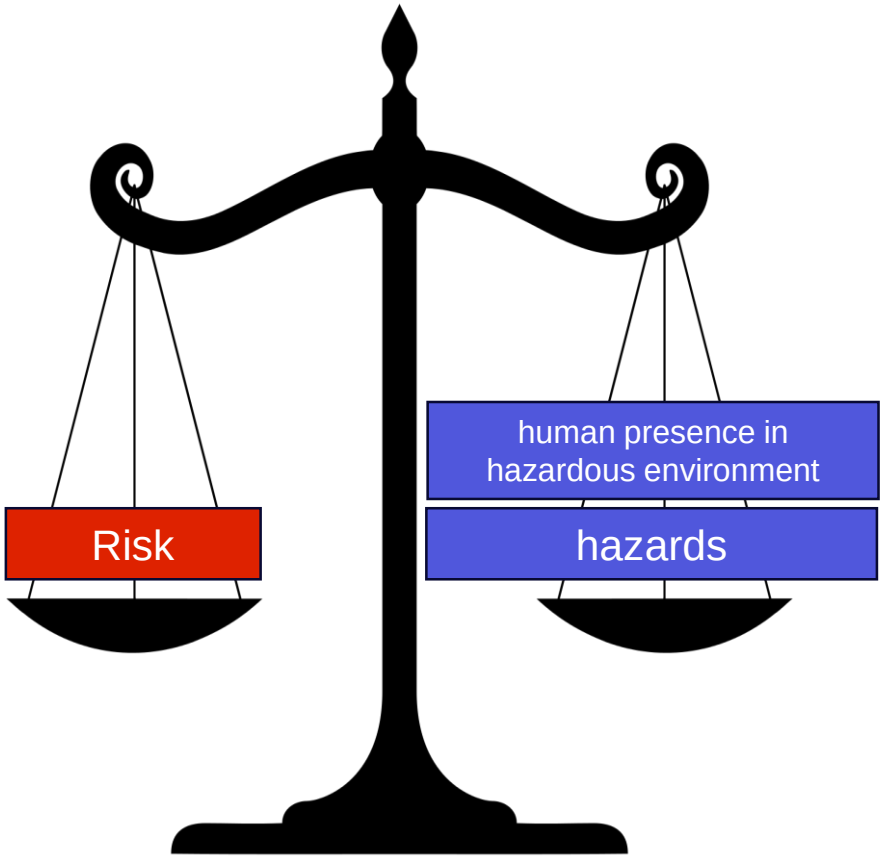
Root causes

The root causes are:

- Routine presence of workers in the arcs
- Distance and complexity of facility (where hazards are present)

Reducing workers exposure to risk:

Robots can reduce human presence (while not augmenting the hazards)



Two Operational Phases in the Arcs

- **Installation**: (Starting from an empty tunnel)
  - Installing Services (electricity, HVAC, fluids)
  - Transporting and placing magnets and other components
  - Connecting the components
  - Testing and Commissioning
- **Monitoring and Maintenance during operation breaks (Technical Stop, YETS, LS)**
  - Monitoring and measurement (photo, film, dimensions, environmental parameters)
  - Exchange of standardised components
  - Complex manipulations
  - Preparation of human intervention

Up to which extent can those tasks be robotized (or highly automatized) ?

Installation phase: Inverted Assembly Line

- The installation of an accelerator arc can be described as an “inverted assembly line” where the product is static and the robots / manipulators advance from place to place

- Automated installation of the services in an empty tunnel should be explored (taking industry examples: oil/gas pipe, sea cabling, TBM..)

- The sheer number of components and connections is so high (> 6000) that the necessary investment in automatization of accelerator installation may/will pay off:
  - Theoretically, 24/7 working time
  - Reduced hazard exposure and risk for worker safety
  - Human-Robot interaction

- Increase of standardization will facilitate dismantling

Installation workflow in FCC arcs

- Install Services in the empty tunnel
  - Electricity, HVAC, Fluids
- Repeat n-times (accelerator arc is a repetitive structure):
  - Transport component (magnet, or assembly of magnets on girder)
  - Place and align component
  - Connect with neighbouring components
    - FCC-ee: connect beamlines, signal and power cables
    - FCC-hh*: connect beamlines, bus bars, cryogenic lines, signal cables
- FCC-ee: n >> 10 girders in one arc
- FCC-hh: n >> 10 Dipoles and Quadrupoles in one arc

* Assuming that FCC-hh components are a scaled-up version of LHC components

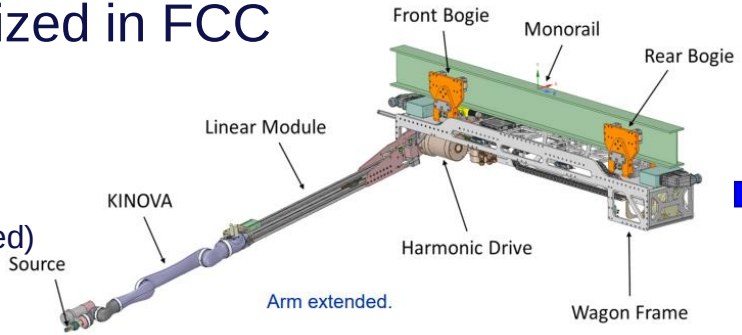
Current Monitoring and Maintenance

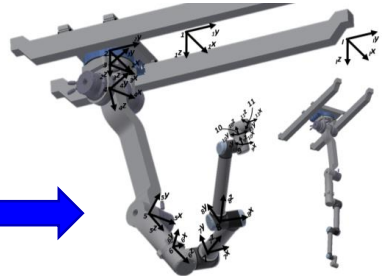
that are (or should be) robotized in FCC

Courtesy: A. Infantino, M. Di Castro et al.

❑ RP measurements

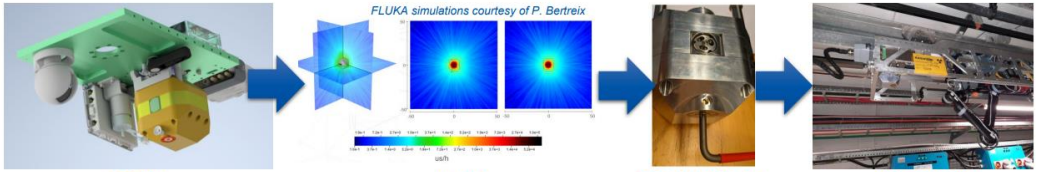
- BLM and radiation monitor calibrations:
  - TIM for the BLM (recently implemented)





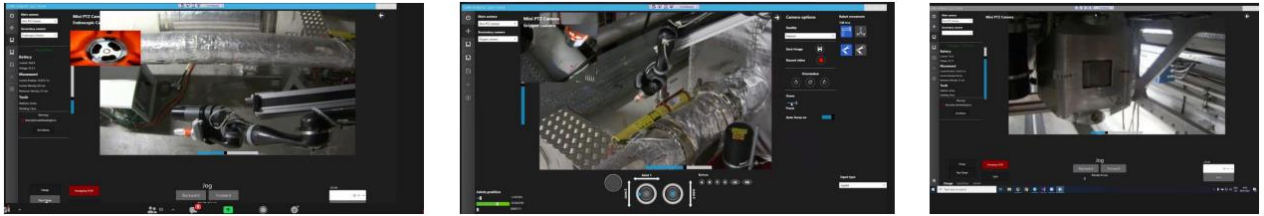
FCC arm concept.
H. Gamper PhD work

TIM source shielding design



- ✓ reduction of individual dose
- ✓ reduction of ODH risk
- ✓ reduction of risk of travel-related accidents.

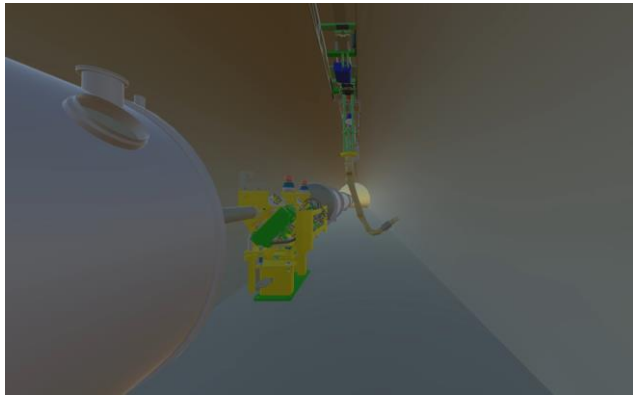
Operation during LS2



Current Monitoring and Maintenance

that are (or should be) robotized in FCC

Courtesy: A. Infantino, M. Di Castro et al.



❑ RP measurements

- BLM and radiation monitor calibrations:
  - TIM for the BLM (recently implemented)
- Rapid inspections in closed areas
  - to avoid flushing the air from sector
  - avoid stopping the machine (if rad-hard!)

Novel robotic arm for RP sensor deployment

- ✓ Dynamic change of height and distance to the beam while running
- ✓ Integration in TIM already done
- ✓ Possibility to map specific area

Current Monitoring and Maintenance

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- Radiation survey measurements
  - already partially done now at LHC
  - reduce waiting time before authorising access, due to faster survey measurements in the tunnel
  - support human intervention (*scouting* RP robot)

Current Monitoring and Maintenance

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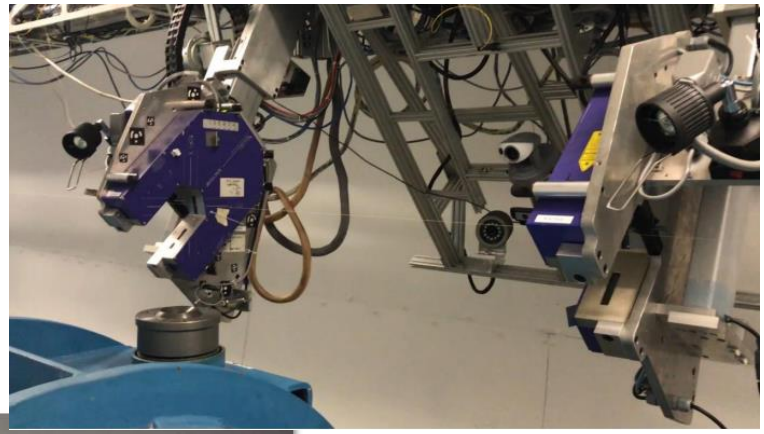
All interventions, especially in the high radiation areas (dump, collimator, areas next to the IP), which can be done by robots will lead to reduced exposure of personnel.

Current Monitoring and Maintenance

that are (or should be) robotized in FCC

- Replacement of faulty components
- Survey and alignment
- Safety patrol before closure of the beam area
- CE defects detections (crack, leaks, deterioration…)

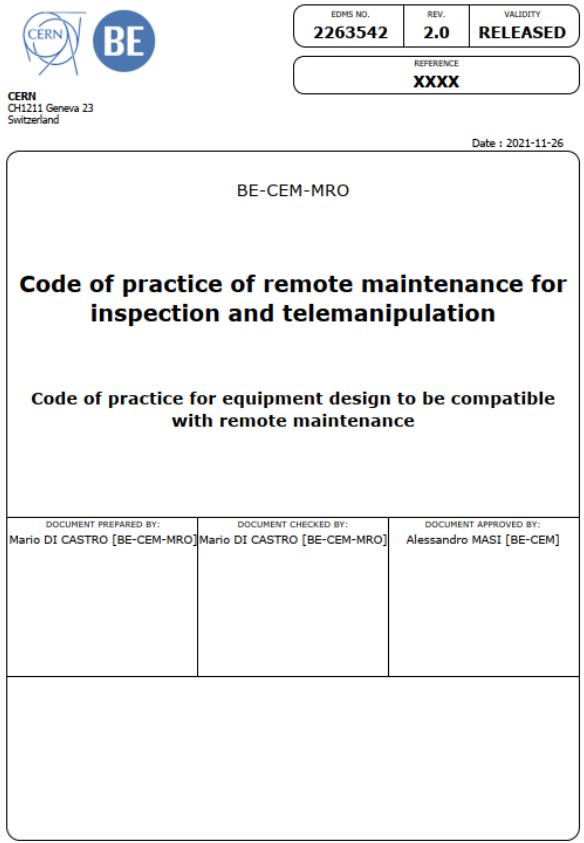


Survey measure position of a collimator

Example of water leaks and cracks found using vision-based machine learning techniques

Monitoring and Maintenance for FCC

- Robots and remote manipulation can keep persons out of the arcs
- To make these techniques possible, it is required to follow a guideline to all equipment
- BE-CEM developed a "*Code of practice of remote maintenance*". It is a living document, continuously updated with new areas of robotics applications. (→)
- The code is field-tested in the existing accelerators and **should be evolved towards FCC**



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2263542	2.0	RELEASED

REFERENCE: XXXX

Date : 2021-11-26

BE-CEM-MRO

Code of practice of remote maintenance for inspection and telemanipulation

Code of practice for equipment design to be compatible with remote maintenance

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
Mario DI CASTRO [BE-CEM-MRO]	Mario DI CASTRO [BE-CEM-MRO]	Alessandro MASI [BE-CEM]

Robots in Emergency Situation

FCC CDR foresees different ceiling-mounted robots for tasks such as:

- Monitoring
- Handling light components
- Alignment: measurement and correction
- **Assistance in emergency situations**
  - **Early monitoring of the fire event. Support CFRS initial tactical plan**
  - **Early fire suppression with extinguishing substances**
  - **Evacuation guidance**

Speed is key!

Early intervention robots

Courtesy: M Di Castro et al. (BE-AMS)

With such **large distances** and **show up times, early intervention systems are necessary** for example in case of accident or fire

- **Human fire response** (Fire Service) in accelerator facilities is judged **fundamental but not enough** due to **response delay**, personal risk assessment.
  - **Robotic** firefighting allows fire **inspection**, **victim** search and initial fire **suppression**.
  - **Robotic** firefighting could guide fire service giving environmental information (+ augmented reality)
  - **Human** firefighting remains necessary for **rescue** operations and **final extinguishing.**

However, there are some **strong requirements** to the robotic solution

→ It cannot hamper **evacuation** (nor in case of failure)
→ It cannot hamper **intervention** (nor in case of failure)

Ceiling rail-mounted solution

Ceiling Robot in a Fire Emergency

1. **Locate** and **inspect** the seat of the fire

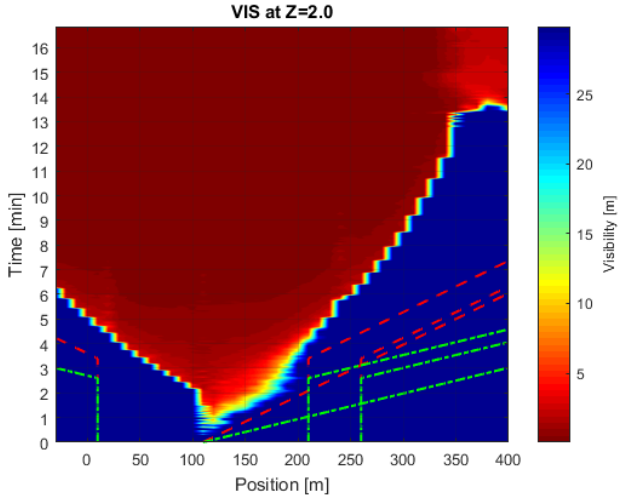
2. Attempt **fire extinguishing**, smoke fire/spread mitigation
   - Deploy extinguishing media (aerosol based media) to temporally **suppress fire**.
   - **Deploy smoke curtains** to avoid smoke damage and retain extinguishing media in desired areas

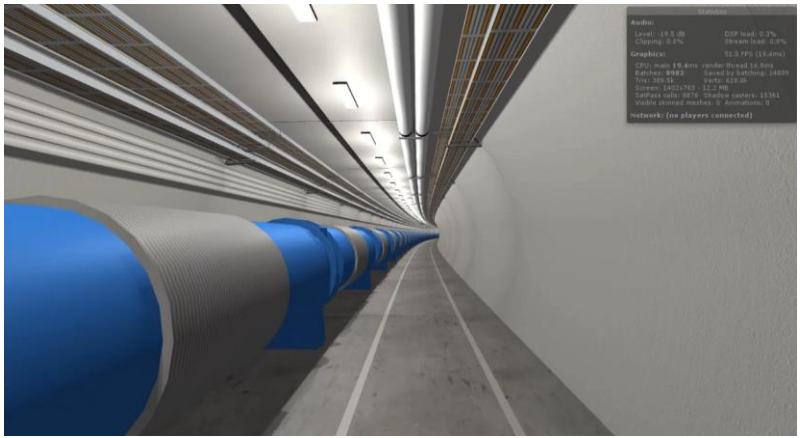
3. **Search for and detect human life** inside the tunnel based on thermal imaging, movement sensors and **guide** them to the closest exits

4. **Follow** and support **intervening firefighting teams**, to monitor, relay communications and explore ahead.

Ceiling Robot in a Fire Emergency

- **Locate** and **inspect** the seat of the fire (in ~5-10 minutes)
  - Several robots that can travel at high speed (train system?)
  - Overtaking existing robots in the rails
- **Guide** and **support** evacuation

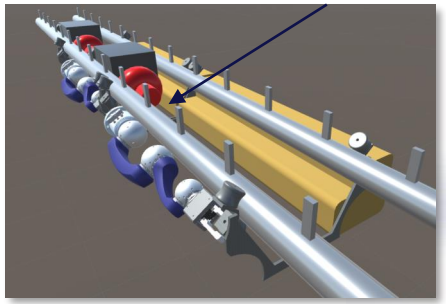


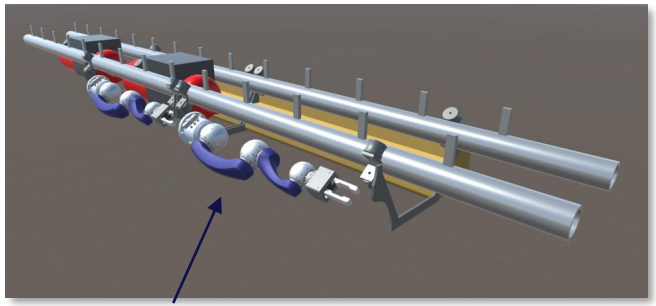


Checking guiding capabilities on VR

TIM for First Intervention

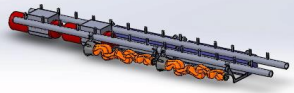
"Internal" part for **early intervention**

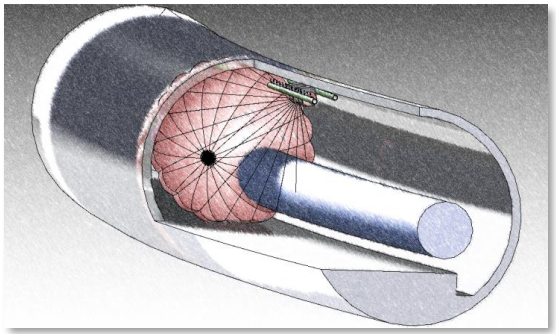




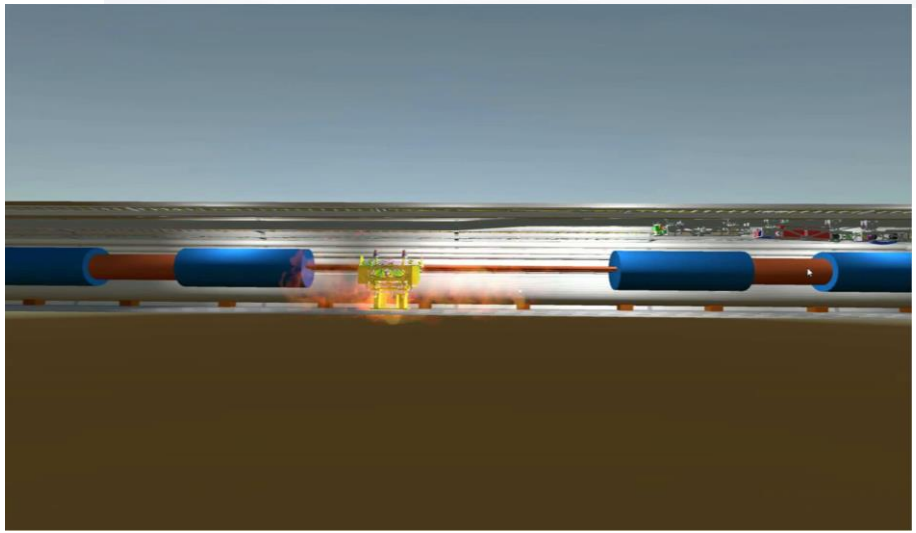
"External" part for **maintenance, measurements and inspections**

2 in 1 concept
Or taking over other robots for rapid deployment





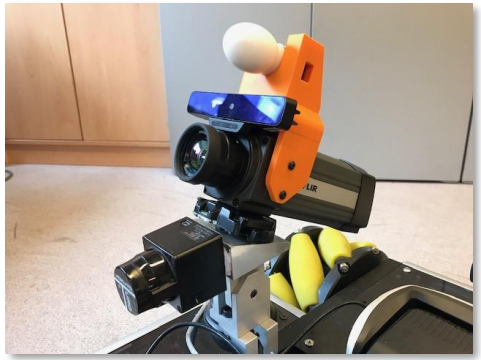
Fire fighting initial concept



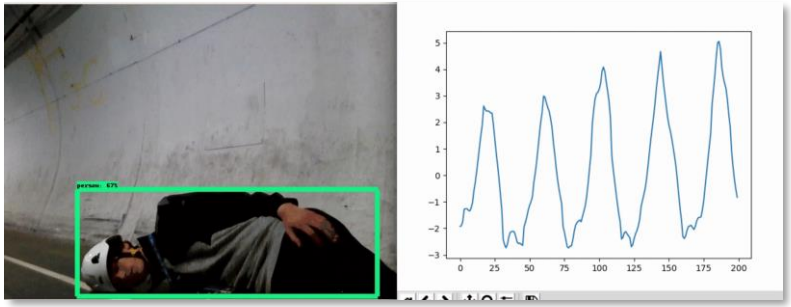
Courtesy: M Di Castro et al. (BE-AMS)

People recognition and vital monitoring

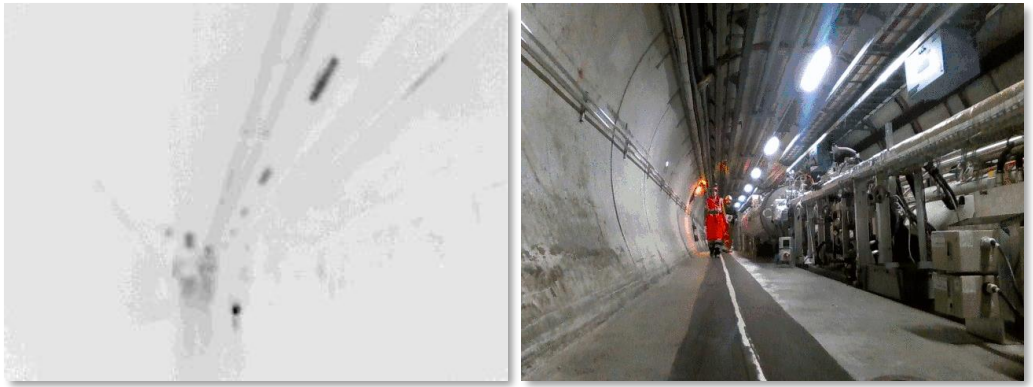
- Machine learning techniques enhance people detection and vital signals monitoring at distance
- People search and rescue is of primary interest in disaster scenarios



Vision system (2D Laser, radar, thermal and 2D-3D camera)



Online respiration monitoring

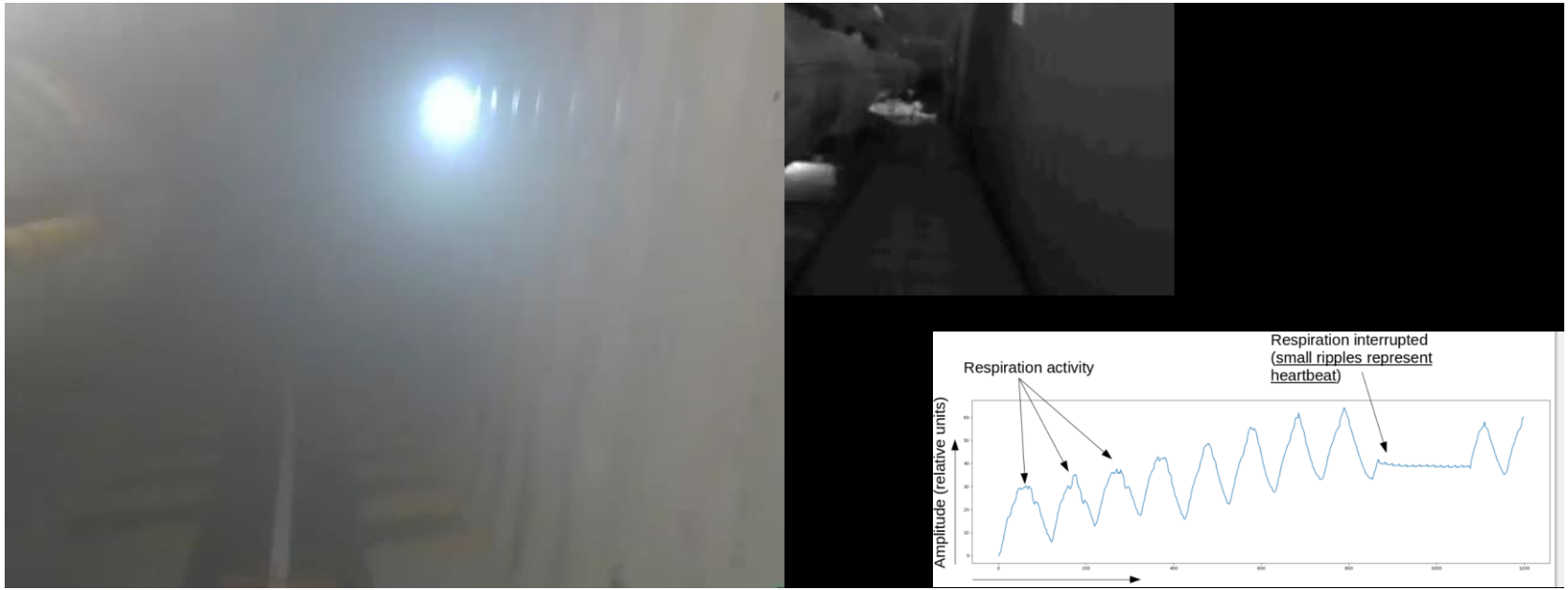


Online people recognition and tracking

Courtesy: M Di Castro et al. (BE-AMS)

Robots for Search and Rescue

Collaboration with HSE-FRS



2D IMAGE

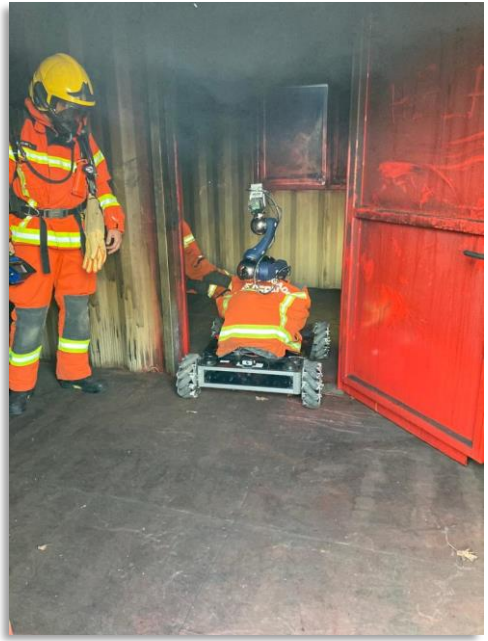
IR+RADAR (for respiration and heart beat monitoring

Video of CERNbot searching for victims in disaster zones with presence of heavy smoke, comparison of standard 2D image with IR+RADAR

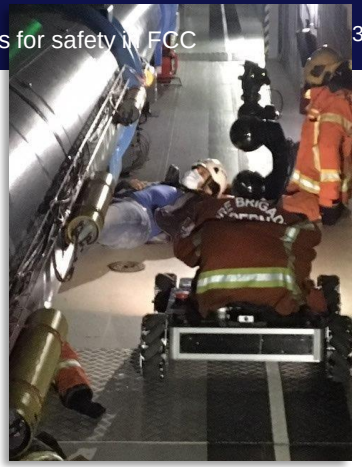
Courtesy: M Di Castro et al. (BE-AMS) and M. Nas

Robots for Search and Rescue

- First test of for **FB-CERNbot** collaboration for search and rescue in disaster zones



Collaboration with HSE-FRS



Courtesy: M Di Castro et al. (BE-AMS) and M. Nas

Safety Hazards from Robots

- Some interventions may require co-operation between robots or remote manipulation and human workers. Human-robot interactions shall be made ‘safe’
- If robots are used as ‘safety system’ (intervention, emergency) they need to show a given reliability level (SIL2 is already being used for the *self*-safety)
- Robots must adhere to ISO 10218 “Safety Requirements for Industrial Robots”
- FAIL SAFE.
  - Robot does not obstruct evacuation! → Rail mounted is best solution.
- Interaction between robots interventions and evac.
- If ceiling mounted, risk of falling objects (also during Fire Brigade intervention)
- Fire risk: Battery powered (rapid learning curve of new battery technologies)

Challenges for (safe) robots integration

- Doors and compartments: FCC fire safety concept relies on doors every 440m. Those need to be prepared for robot automatic crossing (and shutting close afterwards)

- Temperature/heat resistance for Fire Intervention (initial Ta potentially encountered is already available).

- Degraded intervention scenarios (heat, communication…).
  - The faster response, the less degraded scenario

- Ceiling-rail-mounted robot is the preferred solution, yet:
  - Smoke will firstly accumulate below the ceiling, need for IR and adapted sensors
  - Higher temperatures are expected near the ceiling (robot heat resistance, as well as hosting infrastructure)

- Intervention robots need to be spread out and safely parked in radiation-protected areas throughout the infrastructure

Summary

- Robots and remote manipulation can also play a major role in accelerator installation
  - **Reduce hazard** exposure
  - **Optimize** manpower, extended working time (**while not increasing exposed risk**!)

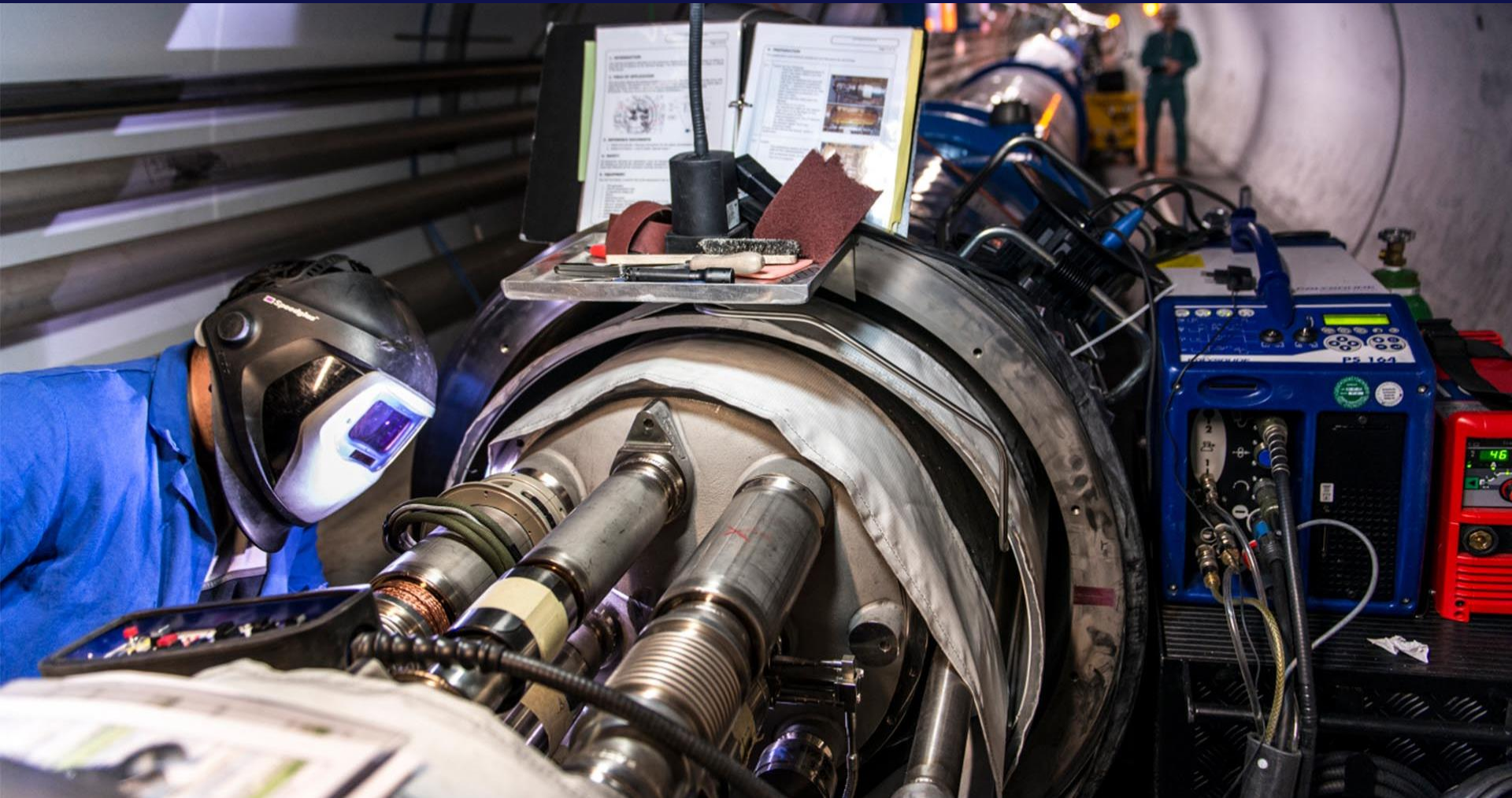
- **Advancements** are already **present** in **LHC** technology updates, yet, **journey** is still **long** for FCC operation!

- **Technologies** developed in this context are **transferable**

- Robots and remote manipulation can mitigate the safety hazards to personnel in the FCC arcs:
  - Keep **persons out of the arcs** for routine tasks (monitoring, patrols, standard repair)
  - **Standardize** all **equipment** so that exchange can be remotely executed

- Robots are **key part** on **emergency concept** in FCC
  - **Provide crucial** first data on scenario (very long human response time)
  - Assist in early fire suppression and evacuation

Thank you
for your attention.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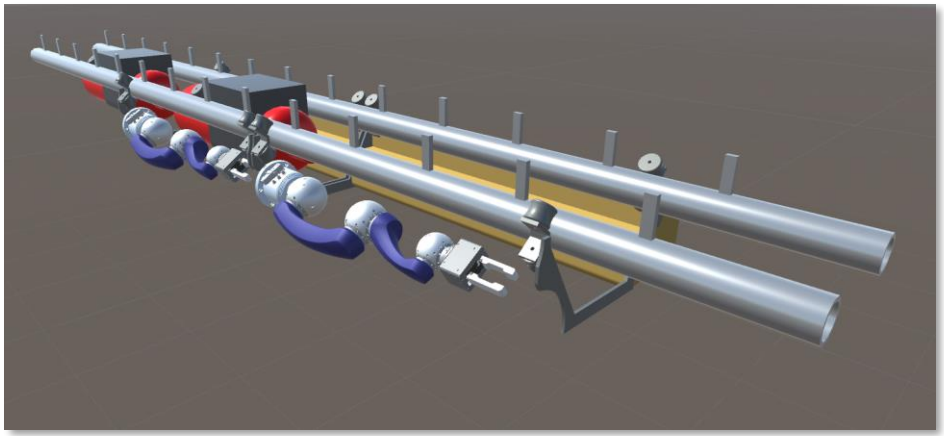
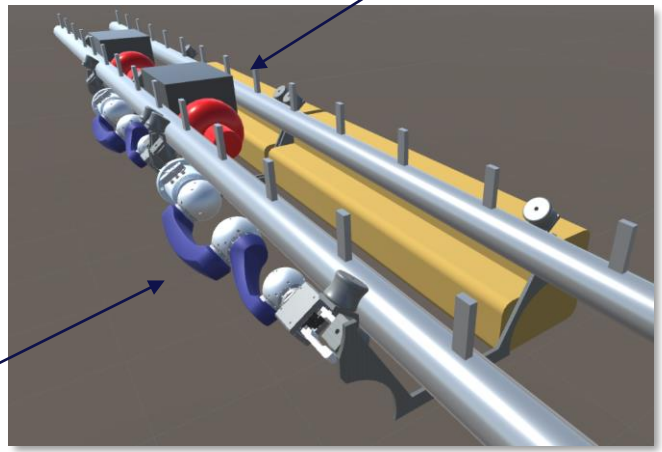
Novel Robot design for FCC

- With such large distances in FCC, it is not possible to have human quick inspection/maintenance interventions
- Preliminary design of an overhead robot running on a ceiling support
  - ✓ Choice made from the operational experience over recent years (TIM/monorail vs ground robot interventions)
- 2in1 robot for inspection, environmental measurements, in-situ maintenance and early intervention in case of accident



“Internal” part for **early intervention**



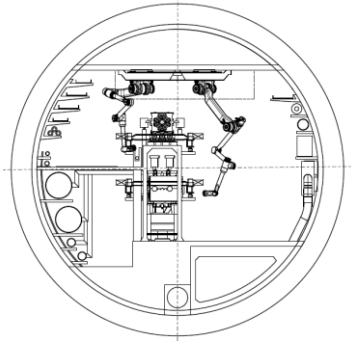
“External” part for **maintenance, measurements and inspections**

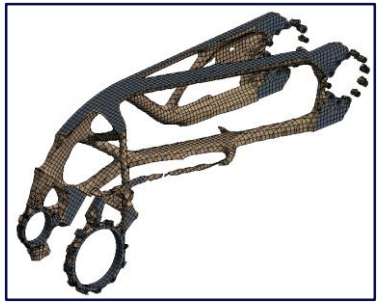
Robots for Future Accelerators (FCC)

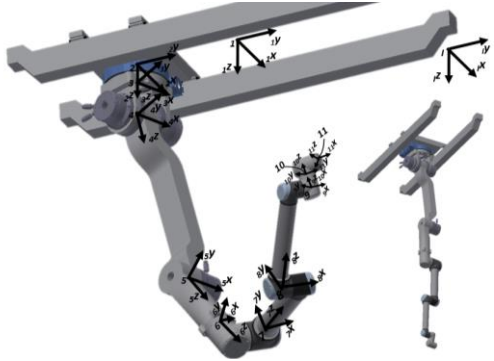
H. Gamper PhD work

$$\min_{\mathbf{x},\,\mathbf{p}_l} \quad J(\mathbf{x},\,\mathbf{p}_l)$$

$$\begin{aligned} \text{s.t.} \quad \mathbf{f}(\mathbf{x},\,\mathbf{p}_l) - \mathbf{z}_{des} &= \mathbf{0} \\ -\mathbf{c}(\mathbf{x},\,\mathbf{p}_l) &\leq \mathbf{0} \\ \mathbf{ub}(\mathbf{x},\,\mathbf{p}_l) &\leq \mathbf{0} \\ \mathbf{lb}(\mathbf{x},\,\mathbf{p}_l) &\leq \mathbf{0} \end{aligned}$$







$$J(\mathbf{x},\,\mathbf{p}_l) = \underbrace{\mathbf{Q}^T(\mathbf{x},\,\mathbf{p}_l)\mathbf{K}_Q\mathbf{Q}(\mathbf{x},\,\mathbf{p}_l)}_{J_1} + \underbrace{\mathbf{k}_p^T \arctan(\mathbf{p}_l)}_{J_2} + \underbrace{\mathbf{k}_w^T\mathbf{w}(\mathbf{x},\,\mathbf{p}_l)}_{J_3}$$

General version of this algorithm was used to find the optimal design of a cavity inspection manipulator

Gamper, H.; Gattringer, H.; Müller, A. and Di Castro, M. (2021). **Design Optimization of a Manipulator for CERN's Future Circular Collider (FCC),** ICINCO 2021

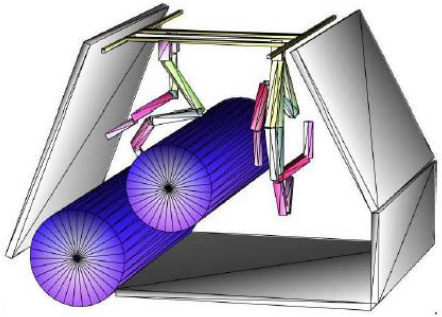
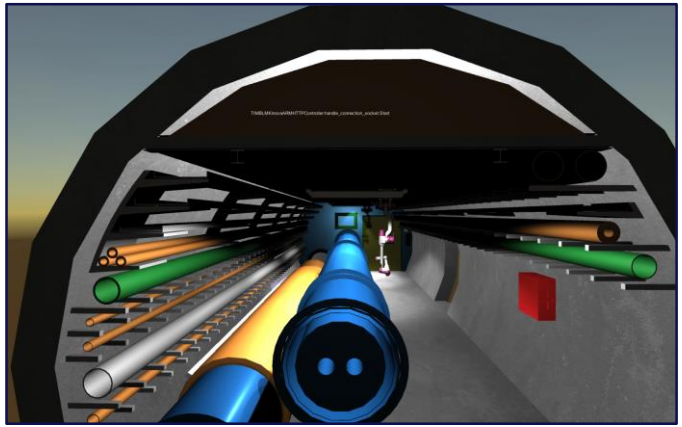
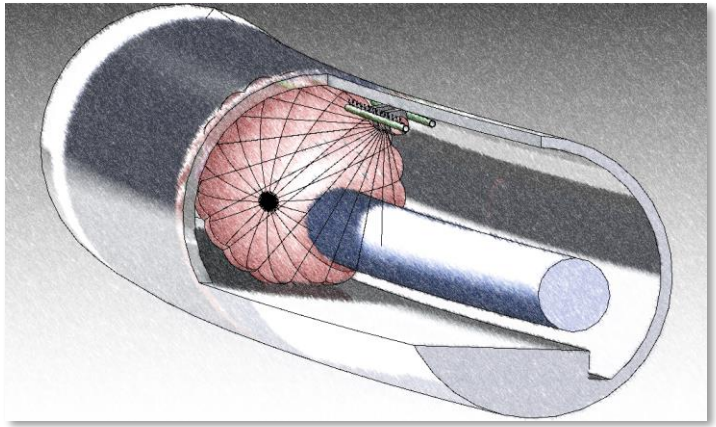


Figure 11: Optimization results FCC-hh (collision objects)

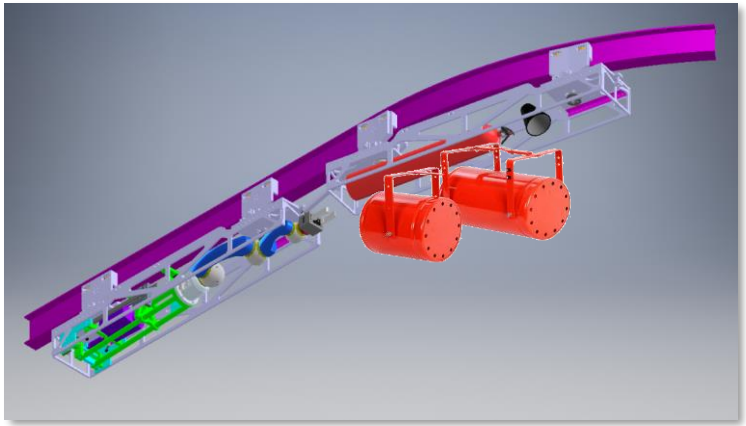


TIM for First Intervention

- Locate and inspect the seat of the fire
  - ✓ Precise environmental information given to Fire Brigade
- Deploy smoke curtain to confine the zone
- Deploy extinguish media



Sketch of TIM deploying a smoke delimitation curtain



3D of TIM equipped with powder extinguish media

Courtesy: M Di Castro et al. (BE-AMS)

Visibility and Temperature: Fire#3

Life Safety objective met !