COMPASS Upgrade

INSTITUTE OF PLASMA PHYSICS OF THE CAS

System Overview of DIAG-075-077 Fast IR Thermography

CU_DIAG-075-077_PMC_SystemOverview

Revision 1

Log of revisions

Revision	Date	Description	Responsible
2	23 Jun 2025	Marked proprietary documents	Milan Berta
1	21 Jun 2025	Initial edit in the new template	Milan Berta

Content

Related documents

[1] CU_DIAG-075-077_PMC_ImpactMatrix

[2] CU_DIAG-075-077_PMC_IntroductoryCall

List of abbreviations

Official list of COMPASS-U abbreviations can be found in CU_DOC_Abbreviations

- MWIR mid-wave infrared
- FIRCam fast infrared thermography camera
- UHV ultra-high vacuum
- MN#6 mid-plane narrow port number 6
- FOV field of view
- CAD computer-aided design

1. Introduction

This system represents the telescope and steering assembly for fast infrared thermography diagnostics (FIRCam), designed to collect and guide incoming mid-wave infrared (MWIR) radiation emitted from the plasma-facing components inside the tokamak vessel — primarily targeting the lower outer vertical divertor tiles, but also allowing flexible coverage of the upper divertor and first-wall limiters. The system is integrated into midplane narrow port MN#6, with the baseline line-of-sight oriented to the lower divertor region.

The system is mounted in the horizontal midplane of the tokamak chamber and is oriented towards the central axis of the chamber column. Infrared radiation originating from the lower or upper divertor tiles is reflected by two mirrors into the telescope's optical train, and exits toward the IR camera. The design accommodates ultra-high-vacuum conditions and includes mechanical actuation for remote mirror steering through a cryostat diagnostic port.

The final system includes a rotatable mirror head for flexible field-of-view steering. To allow early deployment, the first phase uses fixed mirrors, but the design already reserves space and interfaces for future installation of the rotatable head.

2. System operating principle

The FIRCam system is designed to measure and monitor surface temperatures and heat flux profiles at critical plasma-facing components inside the tokamak vessel. Its primary diagnostic targets are the outer vertical divertor tiles, particularly in the lower divertor region, where high heat loads and strong plasma-surface interactions occur.

Using high-speed mid-wave infrared (MWIR) thermography, the system captures the temperature evolution of the divertor target plates with sufficient spatial and temporal resolution to resolve fast transient phenomena such as Edge Localised Modes, disruptions, or power modulation events.

The system provides both:

- Temperature profiles over the lower outer vertical divertor target.
- Heat flux profiles, derived through post-processing using inverse heat conduction models.

These measurements support both physics research and machine protection.

3. System location and field-of-view steering

The complete FIRCam assembly is installed at machine port MN#6, utilising available diagnostic access in the horizontal midplane. The mirror steering sub-assembly allows controlled re-orientation of the field of view towards:

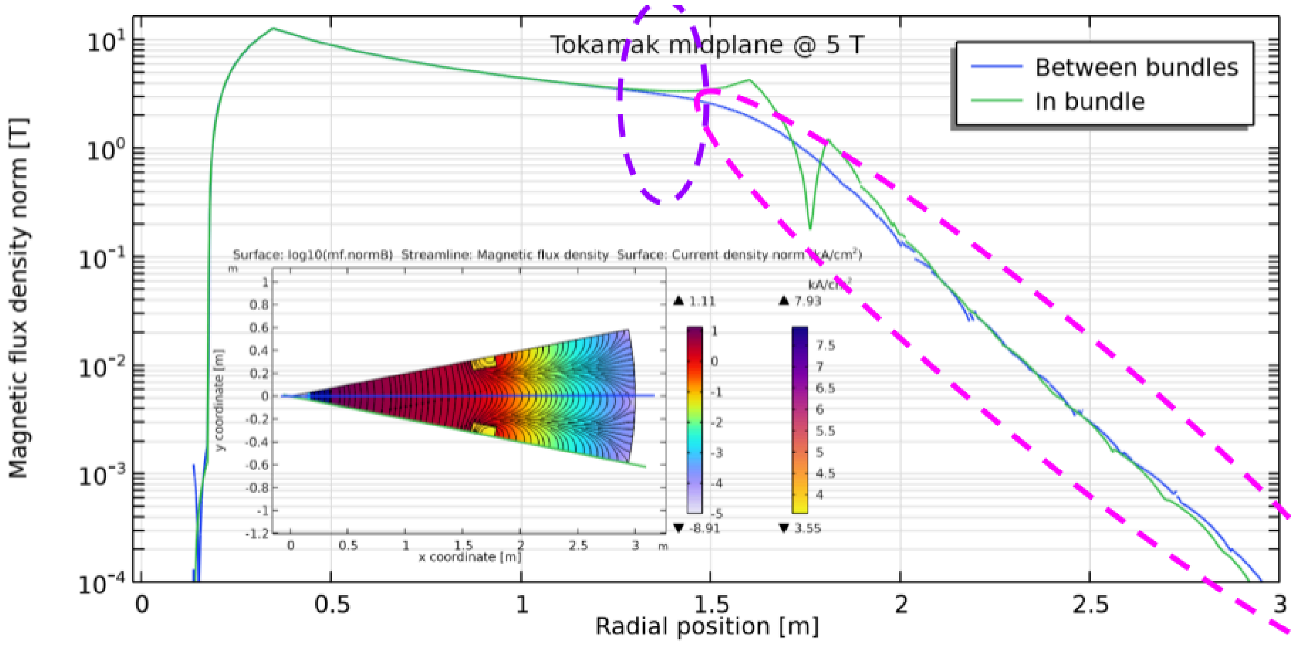
- The lower divertor target
- The upper divertor target
- The outer wall limiters
- Other poloidal locations depending on scientific and operational needs

4. Environmental conditions

The FIRCam system operates in ultra-high vacuum (UHV, down to 10^{-6} Pa) inside the tokamak vessel. All components comply with vacuum compatibility and outgassing requirements.

Temperature exposure ranges from room temperature up to 500 °C, depending on operational scenarios (commissioning, plasma discharges, baking). This refers to the temperature of surrounding structures; the telescope and camera are expected to remain at reasonable operating temperatures ensured by radiation shielding and cooling – to be defined in further agreement. Materials and mechanical design accommodate thermal expansion and maintain optical alignment across this range.

The system design shall account for long-term operation in strong magnetic fields up to 3.7 T at the midplane and at the port entrance. The magnetic field rapidly decays in the cryostat, but necessary electromagnetic shielding shall be applied to protect camera electronics even outside of the cryostat, too. Toroidal magnetic field direction and magnitude close to 3.7 T at the midplane and port entrance is shown in the following figure.



Toroidal magnetic field map at the midplane with depicted regions of interest for the **head with mirrors** (purple) and for the **telescope with lenses** (pink).

For radiation shielding requirements, the expected maximum neutron rate (instantaneous flux) is 5×10^{9} neutrons/cm$^{2}\cdot$s, and the total maximum annual dose (yearly fluence) with realistic shot count 6×10^{12} N/cm$^{2}\cdot$y, with N standing for neutrons.

5. Basic optical and mechanical requirements

The system shall consist of two primary assemblies:

- The diagnostic head, mounted at the tokamak cryostat vessel and cryostat tube.

- The telescope assembly, which contains the internal optical train and the MWIR camera.

The telescope must be removable and reinsertable from the cryostat tube without disassembling the full support structure.

The mechanical interface shall ensure repeatable optical axis alignment and preserve the optical path integrity after reinsertion.

The distance between the inner and outer opening of the MN#6 port in the cryostat is about 1.1m. That shall be the minimal distance for the rotatable head and the telescope with the optical train. The coupled MWIR camera is outside the cryostat vessel envelope, see scheme below. The diagnostic head (MWIR camera) is located approximately 1.3–1.5 m from the input port and the rotatable mirrors.

The system shall provide a field of view (FOV) of 160 mm width at a distance of ~ 1400 mm from the front mirror. This should correspond to spatial resolution of 0.5 mm/pixel at the divertor surface).

The highest image quality is required in the vertical center region of the detector, as sub-frame readout – used to reach high frame rates – utilizes the detector center).

The first wall limiters near the MN#6 port are located at R = 1233 mm (radial distance). The most inner part of the FIRCam shall be recessed by at least 20 mm to ensure that the innermost component lies at R ≥ 1253 mm.

The camera shall support manual rotation to align the detector axis vertically with the outer divertor tile surface.

Mirror rotation must be manually adjustable with the vacuum vessel at room temperature. The system must maintain a fixed FOV when operating at vacuum vessel wall temperatures up to 500 °C.

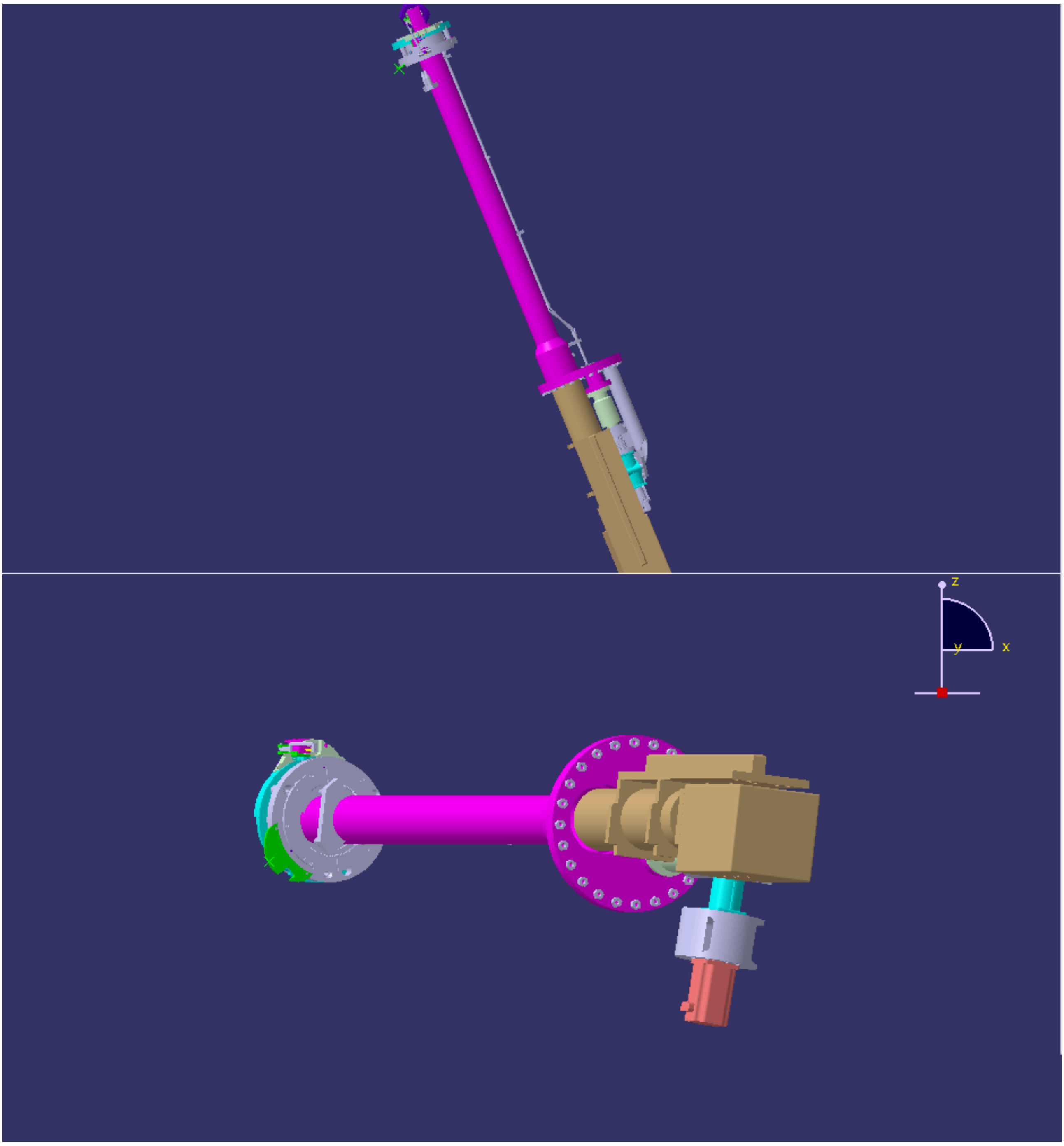
6. CAD isometric and multiview

The CAD model of the telescope and camera was based on the ASDEX tokamak telescope. This model was subsequently extended and adjusted to align with the COMPASS Upgrade ports and the cryostat size.

CAD isometric and multiviews of the system are included below. The rotatable endoscope incorporated into the design is based on a design from ASDEX Upgrade, with CAD data provided by Albrecht Herrmann in 2020.

The STP format CAD file for the FIRCam is

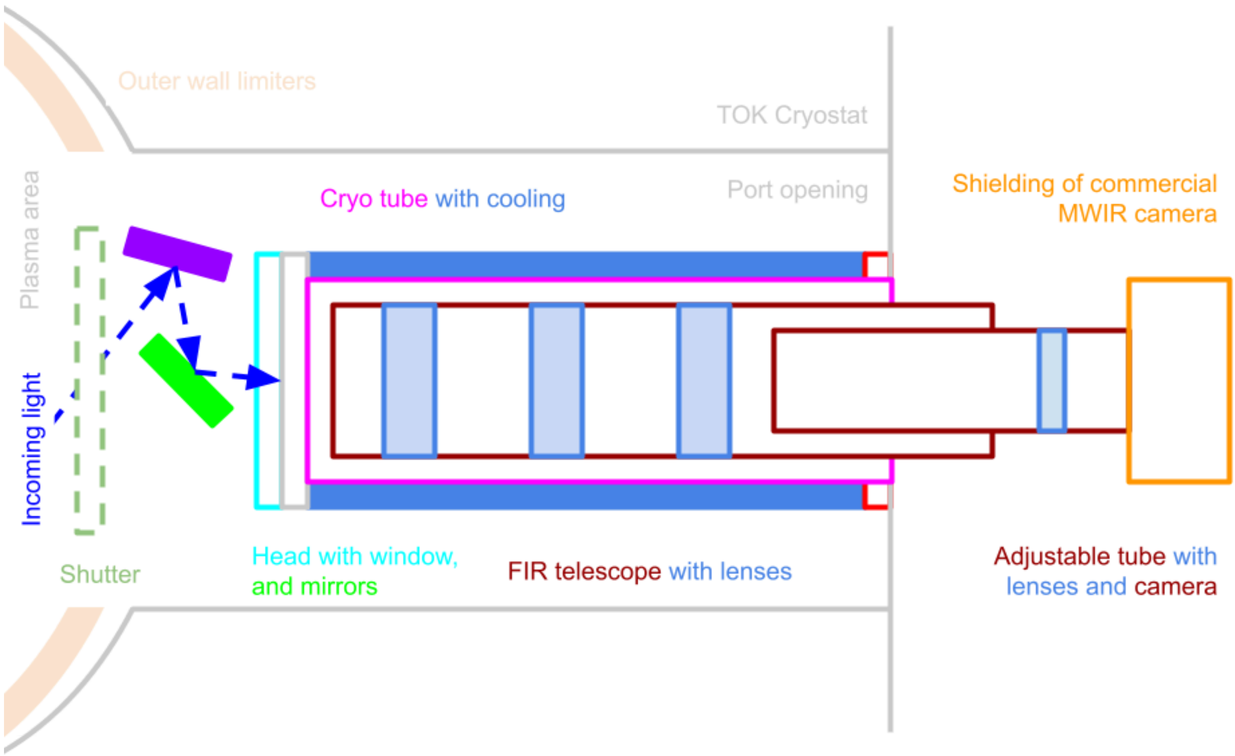
- 103223_V01_PRT.stp



7. Optical path and component description

Schematics drawing of the FIRCam positioned in the tokamak vacuum vessel and cryostat chamber.

- CU_DIAG-075-077_SDD_DRW_Schematics



First mirror – Entry point (purple)

- Function: Collects the incoming IR radiation from the plasma chamber and redirects it toward the **second mirror**.
- Mounting: Positioned at the inner end of the telescope; mounted on a rotatable circular frame.
- Adjustment axis: Vertical tilt (azimuthal steering).
- Mechanism: Rotation angle adjusted manually before closing the tokamak chamber. The first deployment phase uses manually pre-set mirror positions; provision for future motorized or remotely controlled actuation is reserved in the mechanical design.

Second mirror – Top deflection (green)

- Function: Redirects the light beam horizontally into the optical axis of the IR camera.
- Mounting: Fixed on a concentric **rotatable ring**
- Adjustment axis: Horizontal tilt (elevation, POV camera).
- Mechanism: Rotation angle adjusted manually before closing the tokamak chamber. The first deployment phase uses manually pre-set mirror positions; provision for future motorized or remotely controlled actuation is reserved in the mechanical design.

Mirror steering and support interfaces

- **Shutter**'s (light green) role is to cover the elements of the diagnostics (the lenses and the **input window**) that can degrade due to sputtering during boronisation.
- **Rotating flange** with bearing elements (light blue): Enables smooth steering of the **second mirror**.

- Inner interface flange (grey): Provides mechanical stabilization and sealing at the vacuum barrier (cryostat-to-plasma side).

Telescope tube and vacuum interface

- **Main tube** (pink): Acts as a vacuum-tight housing and support for the inner telescope. Runs from the cryostat **outer flange** to the tokamak window (plasma-facing window). Supports potential **thermal insulation and/or active cooling**.
- **Outer flange** (red): Fixation to the outer wall of the cryostat, ensuring system alignment and sealing.
- **Support housing and joint block** (brown, not fully depicted): Mechanically connects the telescope system to the IR camera housing, supports precise optical alignment of the IR lenses. Two concentric tubes enable manual fine-tuning the camera focus plane to the image plane.
- The **telescope system** (not in the STP file, inside the **main tube**): acts as a mechanical support for the focusing optical components.
    - ZEMAX optical simulation file AUG_endos_03_mirr_exp_B_performence calculation.ZDA

Fast MWIR camera TELOPS FAST-IR 2K and anti-magnetic and anti-neutron shielding

- Fast MWIR camera TELOPS FAST-IR 2K (3-5 um InSb detector, 2 kHz @ 320 × 256 px, up to 90 kHz in subframe mode) is used for image recording. See separate section for camera technical details.
- Tokamak-relevant **shielding** (light brown) required for electronics.

Cooling system (planned)

- **Cooling system**: A thermal control system (likely passive thermal jacket or active cooling spirals/coils) is intended for integration around the **main tube**, to mitigate heat load from the environment and maintain thermal stability of the telescope structure and optics. A passive thermal jacket is foreseen for initial implementation, with optional active cooling integration under evaluation for future operation.

8. Fast MWIR camera and detector system

The FIRCam system utilizes a commercial high-speed cooled mid-wave infrared (MWIR) camera: TELOPS FAST-IR 2K (TEL-4232)

The camera operates in the 3–5 μm spectral range, based on an InSb (Indium Antimonide) focal plane array detector. For the baseline configuration, the camera provides:

- Full-frame resolution of 320 × 256 pixels.
- Frame rates up to 2000 frames per second (fps) at full resolution.
- Subwindowed operation allows frame rates up to 90 kHz depending on window size.
- Real-time temperature calibration (RTTC), enabling direct radiometric measurements of surface temperatures.

The camera design incorporates:

- Rugged, sealed metal enclosure suitable for laboratory and industrial environments.
- Conduction-cooled housing (external cooling integration handled by telescope system design).
- Standardized optical interface (bayonet) compatible with commercial MWIR lenses.
- Full software control and autonomous operation via external computer systems.
- Available OEM support for integration into customized diagnostic setups.

The TELOPS camera head is integrated into the telescope assembly through a dedicated interface block providing:

- Precise alignment of the optical path.
- Mechanical support and vibration damping.
- Heat sinking and thermal management interface.
- Electromagnetic shielding to mitigate stray magnetic fields from the tokamak environment.

The camera is operated from a dedicated control and acquisition computer, located outside the experimental hall. Data acquisition and real-time processing are performed via standard manufacturer software, with possible extensions for integration into the tokamak central control and data handling systems.

Camera data sheets and user guide

- User guide Telops - 2011 - Telops Infrared Camera Series User's Guide.pdf
- Technical datasheet Telops - 2015 - Fast High Performance Infrared Camera - FAST-IR 2K Datasheet....
- Technical drawings TELOPS - 2003-09-19 - TEL2000 Coque rev0.pdf (proprietary information, subject of NDA, available on request)
- Technical drawing to the bayonet FAST-IR-2K bayonet.png (proprietary information, subject of NDA, available on request)
- Test report of the calibration FAST-IR-2K_TEL-4232-0001-d (Test Report).pdf (proprietary information, subject of NDA, available on request)

9. Component ownership overview

In-house provided components:

- MWIR camera: TELOPS FAST-IR 2K, including shielding interface.
- Port flanges: Structural elements securing the telescope and cryotube within the cryostat.
- Electromagnetic shielding: Protection for the camera electronics in the magnetic field environment.
- Optional neutron shielding: Shielding for high-radiation scenarios.
- Cryotube cooling: Infrastructure for passive or active thermal management of the cryotube.

Components to be procured from third parties:

- Rotatable mirror head: Includes first and second steering mirrors and mechanical actuation features.
- Cryotube (vacuum-optics barrier): Provides vacuum sealing and thermal isolation between vessel and optical components.
- Optical telescope assembly: Complete optical train including lenses, supports, and focusing mechanics.
- Camera fixture block: Precision interface for mechanically and optically coupling the MWIR camera to the telescope.

10. Installation, assembly, and serviceability notes

The FIRCam diagnostic system is installed through the dedicated midplane narrow port MN#6 on the tokamak cryostat. The main telescope assembly is inserted as a pre-aligned unit and fixed to the external cryostat flange. The mirror positions are pre-adjusted manually prior to vacuum closure of the tokamak chamber. In the first deployment phase, no remote or in-vacuum actuation is included; future upgrades may introduce motorized remote mirror steering.

Routine maintenance or replacement of internal optical components shall prevent venting and opening of the cryostat vacuum chamber. The critical optical surfaces are protected by a shutter during bake out to minimize deposition and degradation. The diagnostic head remains externally accessible for service, adjustment, and replacement without venting the main vacuum system.

Thermal control system components (passive jackets or active cooling loops, once implemented) are integrated with accessible service interfaces at the cryostat flange level (venting required).

11. Impact analysis

A preliminary impact analysis and a loose Failure Mode and Effects Analysis (FMEA) was performed, identifying key risks related to vacuum, optics, mechanics, and measurement reliability. Full FMEA shall be pursued as part of the design documentation.

- CU_DIAG-075-077_PMC_ImpactMatrix

The impact analysis file provides a structured component-by-component breakdown of the FIRCam infrared diagnostic system for tokamak applications. Each system element is listed with its functional role, technical description, and interconnections within the complete assembly. The document serves as a preliminary feasibility assessment, identifying environmental effects, potential issues, and posing technical questions and open points for further design development and risk evaluation.

12. Supporting materials

Less technical but visually more appealing presentation of the system. Slides & notes used for vendor communication:

- CU_DIAG-075-077_PMC_IntroductoryCall