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BM18, THE NEW ESRF-EBS BEAMLINE FOR HIERARCHICAL PHASE-CONTRAST TOMOGRAPHY

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Abstract

BM18 is an ESRF-EBS beamline for hierarchical tomography, it will combine sub-micron precision and the possibility to scan very large samples. The applications will include biomedical imaging, material sciences and cultural heritage. It will allow the complete scanning of a post-mortem human body at 25 µm, with the ability to zoom-in in any location to 0.7 µm.

BM18 is exploiting the high-energy-coherence beam of the new EBS storage ring. The X-ray source is a short tripole wiggler that gives a 300mm-wide beam at the sample position placed 172m away from the source. Due to this beam size, nearly all of the instruments are developed in-house. A new building was constructed to accommodate the largest synchrotron white-beam Experimental Hutch worldwide (42x5-6m). The main optical components are refractive lenses, slits, filters and a chopper. There is no crystal monochromator present but the combination of the optical elements will provide high quality filtered white beams, as well as an inline monochromator system. The energy will span from 25 to 350 keV.

The Experimental Hutch is connected by a 120m long UHV pipe with a large window at the end, followed by a last set of slits. The sample stage can position, rotate and monitor with sub-micron precision samples up to 2,5x0.6m (H x Diam.) and 300kg. The resulting machine is 4x3x5m and weighs 50 tons. The girder for detectors carries up to 9 detectors on individual 2-axis stages. It moves on air-pads on a precision marble floor up to 38m behind the sample stage to perform phase contrast imaging at a very high energy on large objects.

The commissioning is scheduled for the beginning of 2022; the first “friendly users” are expected in March 2022 and the full operation will start in September 2022.

BM18, HIERARCHICAL PHASE-CONTRAST TOMOGRAPHY

General Concept

BM18 is a project that developed within the ESRF-EBS project. It aims at benefiting from the new capabilities of the “bending magnet (BM)” X-ray sources from the new lattice. Indeed, the ESRF-EBS is reaching a new level in terms of X-ray coherence in a storage ring. The progress is impressive for undulators in the straight sections of the machine, but in fact, the smallest possible X-ray sources (and then the highest spatial coherence) are obtained using short wigglers installed on the BM ports of the previous machine. As coherence depends on the X-ray source size and of the distance between the sample and the source, the BM18 concept has been developed to combine the smallest possible X-ray source with the longest possible beamline at the ESRF (220m in total).

The ESRF has a long tradition of X-ray full-field imaging at high energy, especially using propagation phase contrast. During the past two decades, important efforts have been made in order to increase the maximum size of the sample from a few mm up to about 20 cm in diameter and 50 cm vertically.

X-ray Source

This new beamline will allow a dramatic increase of sample sizes (up to 0.7m in diameter, 2.5m vertically and a total weight of 300 kg), while also increasing the sensitivity, especially at high energy. The source was then selected as a tripole wiggler with the central pole at 1.56T (the two lateral poles being at 0.85T) in order to produce a continuous X-ray spectrum optimized for very hard X-rays.

Optical Scheme

The beamline has been designed to be operated only in polychromatic mode in order to maximize the average usable energy, as well as to preserve the coherence as much as possible. The optical scheme is then based on mirror polished filters with different materials (C, SiO2, Al2O3, Al, Ti, Cu, Mo, Ag, W, Au), with different thicknesses and shapes allowing the energy to be tuned from 25 keV to 350 keV. In addition, several systems of inline monochromators have been implemented using refractive lenses and high precision slits to be able to tune the bandwidth and beam geometry when needed. A chopper is integrated in order to fine tune the beam power without changing its spectrum. All in all, these optical combinations bring most of the functionalities from a classical insertion device beamline with a moveable gap, even if BM18 will be on a fixed gap system.

Experimental Hutch

Considering the large energy range and foreseen applications, the experimental hutch has been designed to be as long as possible (45m). This allows a propagation distance up to 38m between the centre of the sample and the most distant position of the detectors. The extremely small size of the X-ray source on this beamline makes it possible to exploit this long propagation distance for pixel size down to 13 µm. For smaller pixel sizes, the propagation distance can be reduced as required.

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Detectors and Automation

The main purpose of this new beamline is to offer a highly automated multi-resolution platform to investigate large samples through a hierarchical approach. The different detectors (up to 9 in total, covering from 100µm down to 0.7µm) will all be based on indirect detector principle. A scintillator screen is observed by CMOS sensors via different optical mounting systems (microscope, zoom, tandem optics, macro optics). These various optics will be installed on a large motorized detector stage that will be able to move along the entire hutch on a polished marble floor. The concept is to automatically change from one configuration to the next, without having to enter the hutch, making it possible to zoom-in anywhere on a sample via a graphical user interface.

Applications

BM18 will make hierarchical imaging possible in a large range of diverse samples, as well as high-throughput imaging of a large series of samples. The main scientific topics that motivated the construction of BM18 are material sciences (for both academic and industrial applications), cultural heritage (especially palaeontology which is a long standing tradition at the ESRF), as well as more recently geology, and biomedical imaging. This last topic emerged recently on BM18 following the covid-19 pandemic when it appeared that this beamline would have the capabilities to completely scan a human body (post-mortem), with an accuracy that's never been reached, and with the possibility to zoom-in down to the cellular level using the hierarchical imaging system.

The last important topic on BM18 is the industrial applications that span across many different fields, even if the material sciences remain the dominant topic.

BEAMLINE COMPONENTS

The components of the beamline are grouped into two zones, the ones located in the Optical Hutch (OH) and the ones in the Experimental Hutch (EH). They are connected by a 120m in-vacuum transfer pipe.

The first hutch is the OH (Fig. 1). It is a shielded hutch in the ESRF Experimental Hall, located in the vicinity of the storage ring and front-end wall. It contains 4 sets of slits, 15 axis of filters, 2 sets of lenses (1D and 2D respectively), a chopper, a beam enlarger and the safety and vacuum standard beamline equipment.

The second zone is the EH. It is placed in a new remote satellite building in order to put the sample at the maximum possible distance (172m) from the source on the ESRF site. It contains the final window, a last set of slits, two sample stages for tomography (the large one and a smaller one equivalent to the systems already installed on BM05, ID19 and ID17 at the ESRF) and the detectors on a movable girder (Fig. 2).

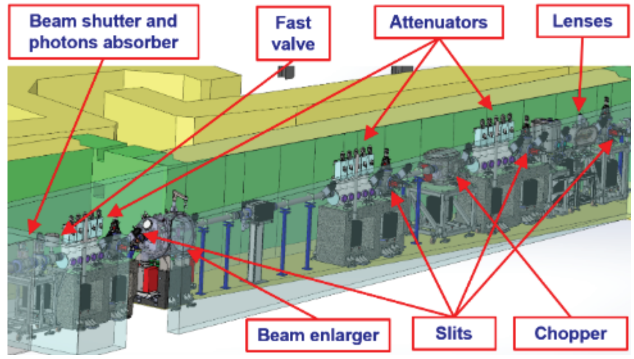

Figure 1: Optical hutch layout.

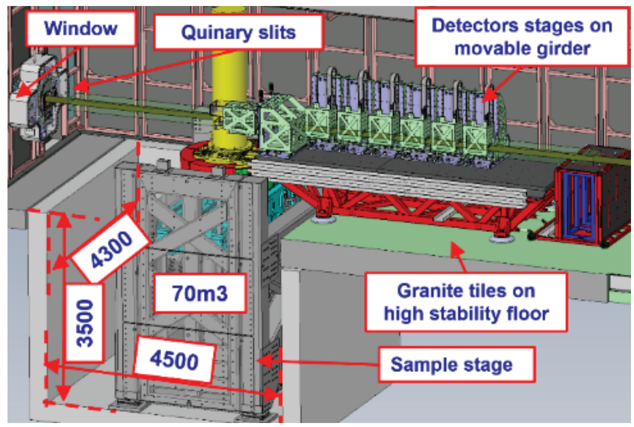

Figure 2: Experimental hutch layout.

Optical Hutch Slits

Four sets of identical slits are placed in the Optical Hutch. The design, including manufacturing drawings, was made by the ESRF. The construction was assigned to CINEL S.R.L. (Italy). The characteristics are listed in Table 1, and the design is shown in Fig. 3.

The main technical difficulty was to make a vertical scan with a minimum gap of 10 µm. As the vertical blades are 100 mm wide, the wobbling around the beam axis shall be in the order of 10 µrad. This result was obtained by: a) guiding the blades by precision rails put directly in vacuum and well-spaced carriages, b) careful cooling to reduce thermal deformation, c) actuating one of the blades with respect to the other, to have a motor to set the position and a second one to set the offset. This permits the beam to be scanned with nearly absolute constant aperture.

The motors (2-phase stepper) have very high reduction ratio gearboxes to ensure the irreversibility of the stages, leading to very high resolution (0.25 µm/step horizontally, 0.15 µm/step vertically) but relatively small maximum speed.

The test carried out by the supplier and repeated at the ESRF indicated that the maximum wobbling is about 20 µrad. This value is slightly higher than expected but small enough to ensure the proper functioning. The lower than expected performance could be due to a relatively bad running parallelism of the guides.

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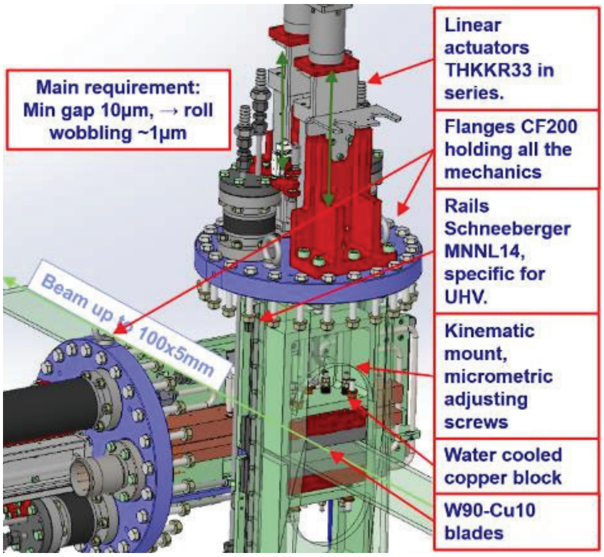

Figure 3: OH slits.

2D (2x1D) Cross-Lenses

The 2x1D Cross Lenses shown on Fig. 4 are composed of two sets of lenses: a horizontal block and a vertical block. Each of these blocks can hold two micro-lens chips intended to be made from sapphire, silicon or glassy carbon, with the dimensions: 100x50x2mm. The chips are clamped into water-cooled copper blocks and can be actuated along 5 degrees of freedom thanks to a stack of linear and rotary stages. To increase the thermal conductivity between the chip and the copper blocks, a pyrolytic graphite sheet is inserted (which can withstand a temperature of 400°C instead of the standard indium which would melt on the chip). The homogenous 2MPa pressure is obtained, over the whole chip, thanks to an assembly of 32 spring-pistons forming an elastic "bed".

Each motor is linked via a copper thermal braid to a water-cooled loop to avoid a global heating of the positioning system.

The ESRF has made the design and carried out the assembly.

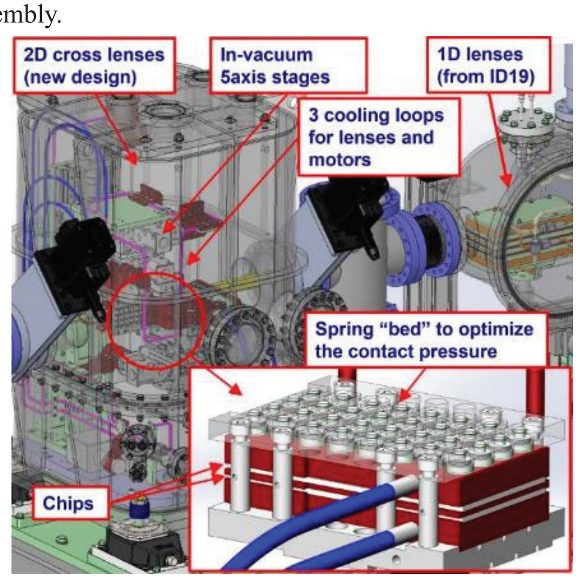

Figure 4: 2D Cross lenses – spring bed.

Attenuators

The attenuators system is composed of 5x3 movable axis (3 chambers with 5 axis each) carrying 3 types of filters of various materials. The filters have 3 possible shapes: a) thin sheet (up to 5mm thickness in the beam direction), b) blocks (from 5 to 100mm), c) rods (5mm diameter, with the cylinder axis placed horizontally, normal to the beam).

conceptual design of the chamber and axis was made by the ESRF, while the detailed design and manufacturing was assigned to CINEL S.R.L.

The ESRF has made the detailed designed of the brackets for the filters. The challenge was managing the cooling of different types of filters and many materials, keeping the design simple and affordable. The mechanical solution to hold thin filters is a simple copper bracket, cooled by water. For the other types (blocks and rods), a multilayer design was selected, alternating the filters with water cooled blocks of copper and uncooled intermediate plates (Fig. 5).

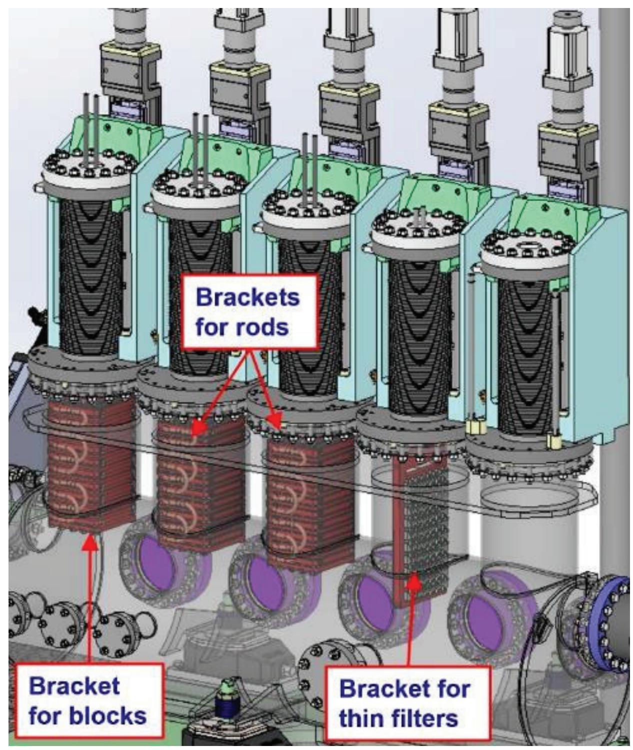

Figure 5: Attenuators.

Chopper

The aim of the chopper in BM18 is to reduce the average power of the beam without changing the beam characteristics, by cutting the beam temporally.

The design (Fig. 6) is based on 2 rotating wheels, in which radial slots reduce half of the total contact surface with the impinging beam. When the slots of the 2 wheels are aligned and are in rotation, 50% of the beam can pass through. When the phase difference is equal to the slot step, no beam is transmitted. The intermediate beam position allows the power to be adjusted between 0% and 50%. The entire beam can pass through when the wheels are aligned and stopped with a slot in the beam position. The requested

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aperture frequency is 2 kHz. As the wheels have 100 slots, the angular velocity is 20rps -1200rpm.

The wheels are rotated together by a stepper motor. They are cooled by forced airflow, placed outside the vacuum chamber; a magnetic feedthrough transmits the torque. The phase is adjusted with a mechanism that transforms the axial movement of one-wheel in respect to the other to an angle, using the principle of a long pitch threading. The wheels are made in tungsten alloy. The cooling is secured only by radiating from a water-cooled cage located between the wheels and the chamber. As the temperature of the wheels can rise up to 200ºC, ceramic bearings are used.

The complete design was made internally at the ESRF, including the manufacturing drawing. The instrument was produced and assembled by Alca Technology S.R.L. (Italy).

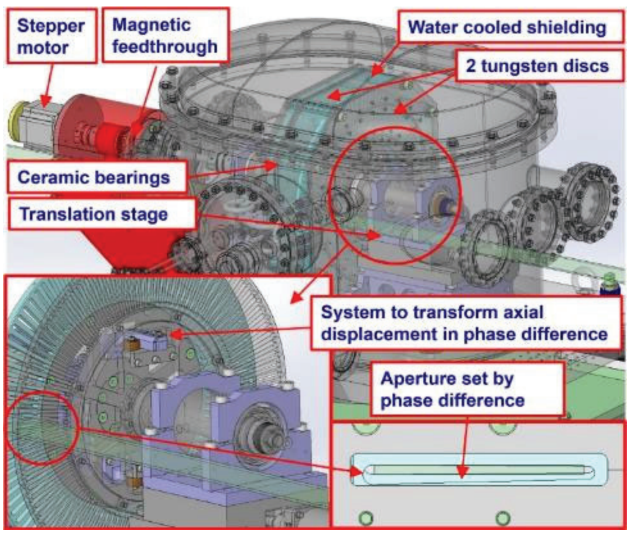

Figure 6: Chopper.

Window

A large window (in development) will be placed at the end of the transfer pipe in the OH. Its role is to separate the vacuum part of the beamline from the in-air part, with the minimum impact on beam quality and intensity. Table 1 contains the main requirements for the design of the window.

Several possible materials were investigated. Finding one with a high transparency to X-rays, low thickness and possibility of mirror polishing at a reasonable price is challenging. The best material candidate is 1050' series aluminium (even if reducing the thickness to a reasonable value in terms of X-ray absorption is challenging) and beryllium (for this material the challenges are the safety and cost). Vitreous Carbon was also studied and samples were tested however, this material was not available in the required dimensions.

In order to start the operation of the beamline as soon as possible, a preliminary smaller beryllium window (330x30x0.6mm), was installed.

Table 1: Window Specifications

Requirement	Dimension
Beam dimension	360×200mm
Max thickness (Z=13)	2 mm
Max thickness (Z=6)	6 mm
Mirror polishing	Ra min=0.1 µm
Homogeneity @ tomography resolution (0.5 µm)	
Radiation resistance	
Vacuum pressure mechanical resistance	
Low leak rate for UHV	
Safety (resistance to impacts…)	
Good thermal conductivity and high T resistance	

Experimental Hutch Slits

A large set of slits (Fig. 7) is settled at the very beginning of the EH. The whole assembly, and its nitrogen chamber (300kg total weight), are fixed on the concrete wall, to reserve space on the floor for the Sample Stage and its movable floor.

The main characteristic of this set of slits is its large dimensions, as the beam can have dimensions of 400x200mm. The minimum gap of 50 µm needs high precision guiding (max yaw error 12 µm), and fine resolution (0.5 µm/step). To reduce the thermal deformation on the edge of the slits the 20mm-thick tungsten blades have an inner cooling loop that should reduce the thermal bump to 5µm. All of the translated parts are lubricated with a special radiation-resistant grease (Lubcon - Turmotemp II/400 CL2).

The whole design is owned by the ESRF and produced by KINKELE GmbH & Co KG (Germany).

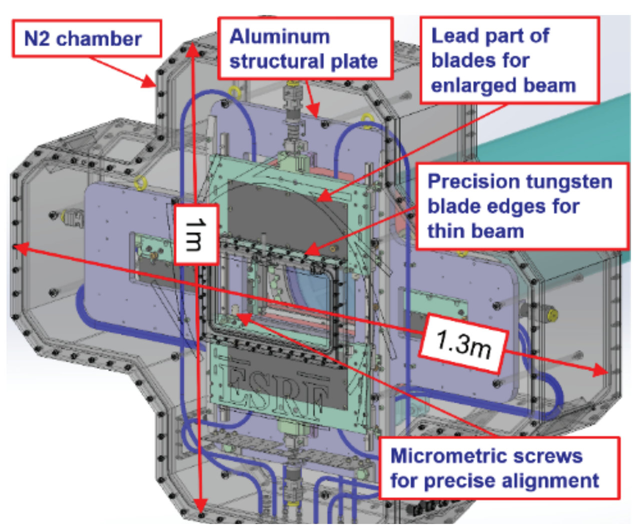

Figure 7: Experimental hutch slit.

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Sample Stage

The Sample Stage is used to position and rotate a large sample in the beam in order to perform tomography. The combination of high precision and large (and heavy) samples is very challenging from a mechanical point of view (Table 2).

The ESRF made a call for tender to assign the supply of this machine to a single supplier, LAB Motion Systems (Belgium).

The proposed machine, currently in construction, (Fig. 8) weights approximately 50T and it will be placed in a 70m3 pit at the beginning of the EH. The main structure is made from steel, and the translation axies are obtained with balls linear rails and balls screws (Fig. 8).

The most innovative part is the air bearing spindle. It is based on 3 rotating air-pads on a granite table to hold the axial load (sample weight + magnetic preload). A central air bearing holds the axial load. A counterweight system is added to avoid static eccentricity, which can affect the sphere of confusion. The stage over the spindle is connected with a kinematic mount to avoid the propagation of deformations.

A metrology system was added to continuously monitor the sample error and use this information for data correction and to adjust the position of the counterweight. This system is composed of 8 capacitive sensors (6 axial and 2 radial, normal to the beam) mounted on a kinematic support, targeting a quasi-kinematic ring machined on the top plate of the spindle stage. The kinematic mounts should avoid transmitting the deformation of the spindle itself and provide the pure location of the rotation axis.

The Z stage is actuated by 4 vertical ball-screws, in order to finely level the Y stage and ensure verticality of the tomography axis.

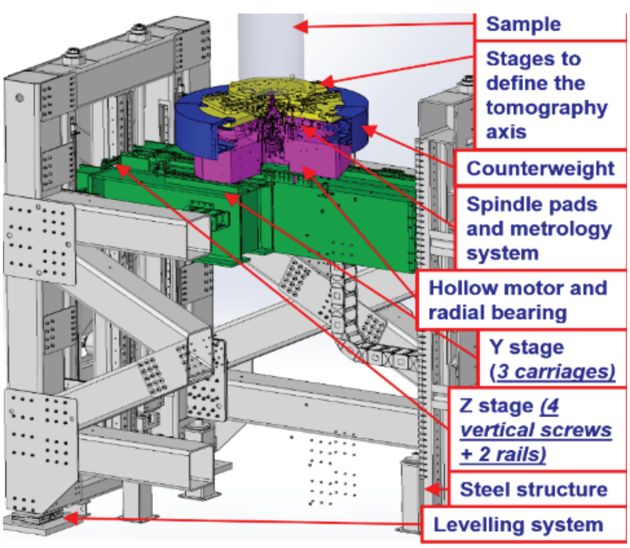

Figure 8: Sample stage.

Detector Supports

Each of the 6 "generic" detectors are placed on an individual 2 axis positioning stage. This allows the detector position to be adjusted laterally and vertically through the beam and the removal from the beam when using the downstream detectors. All of the stages are mounted on a unique girder (5.5x1.9m) that moves 30m along the beam axis.

Table 2: Sample Stage Specifications

Data	Dimension
Max sample weight	300 kg
Max sample dimensions	H=2.5 m, D=0.6 m
Z stage stroke	2.5 m
Y stage stroke	+/- 0.7 m
Z-Y stage precision	10 µm
Sample positioning on spindle	+/- 0.3 m
Spindle sphere of confusion	0.5 µm @ 2.5 m

The girder was designed by the ESRF. It is composed of a granite table (produced by Zali S.R.L., Italy), supported by a steel structure (made by Nortemecanica, Spain [1]), sustained by precision air-pads on a stone tiled floor. A THK JR45 rail is used to guide the movement. The motion is driven by a friction wheel located between the structure and the floor (Fig. 9). The air-pad system is being studied.

The system is supplemented by an additional carriage on wheels for the electronics racks. This separation minimizes the thermal deformation of the girder and reduces the load on the precision air-pads.

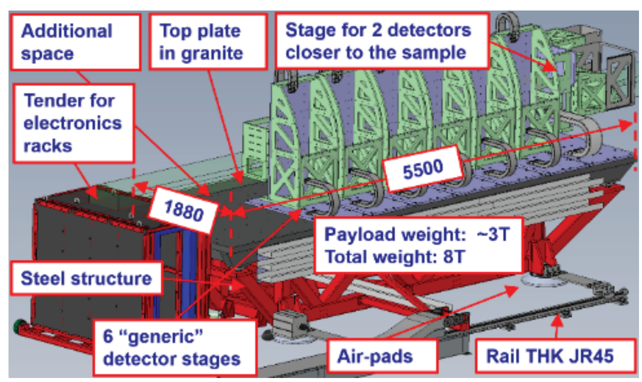

Figure 9: Detectors girders and stages.

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