KAGRA Large-scale Cryogenic Gravitational wave Telescope Project in Japan

KAGRA Collaborators

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GSFS Univ. of Tokyo,
F.Eng. Univ of Tokyo,
Tokyo Institute of Technology,
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Phys.S. Kyoto Univ.,
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ERI. Univ of Tokyo,
Astro. Univ. of Tokyo,
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YITP Kyoto Univ.,
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S. Rikkyo Univ.,
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KAGRACollaborators

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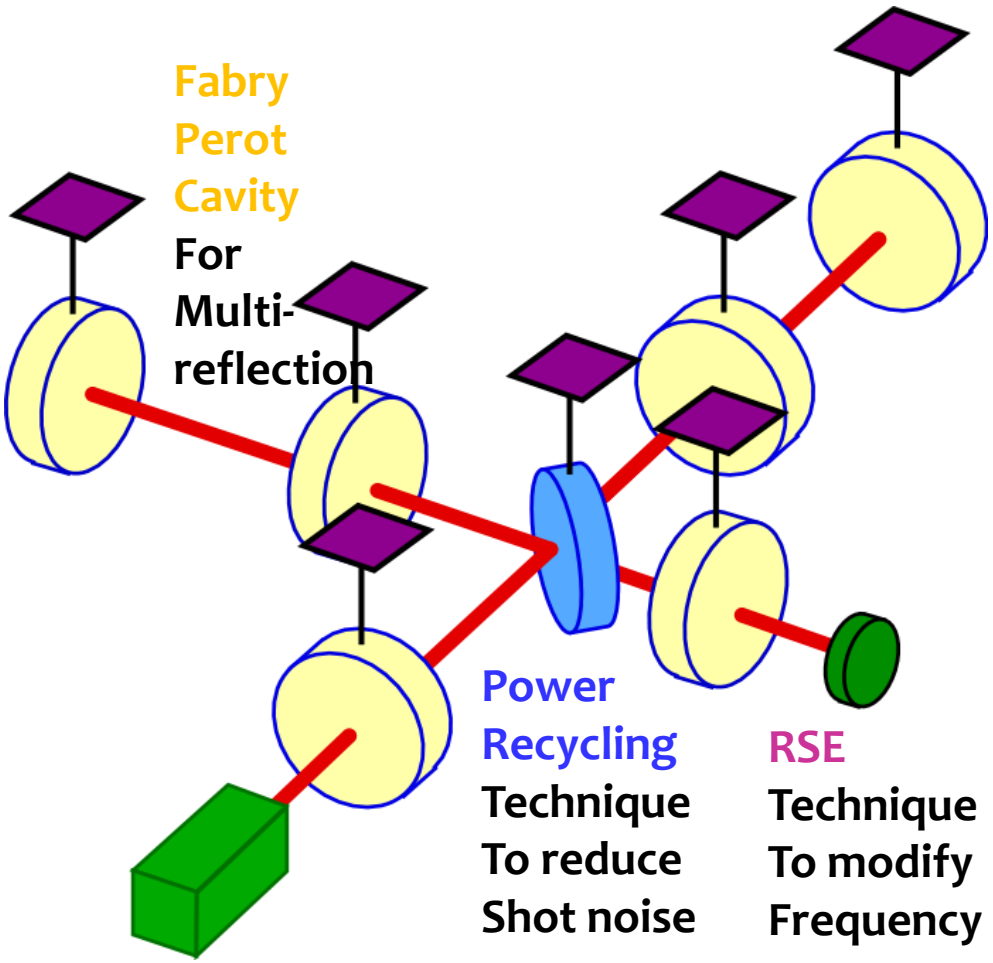
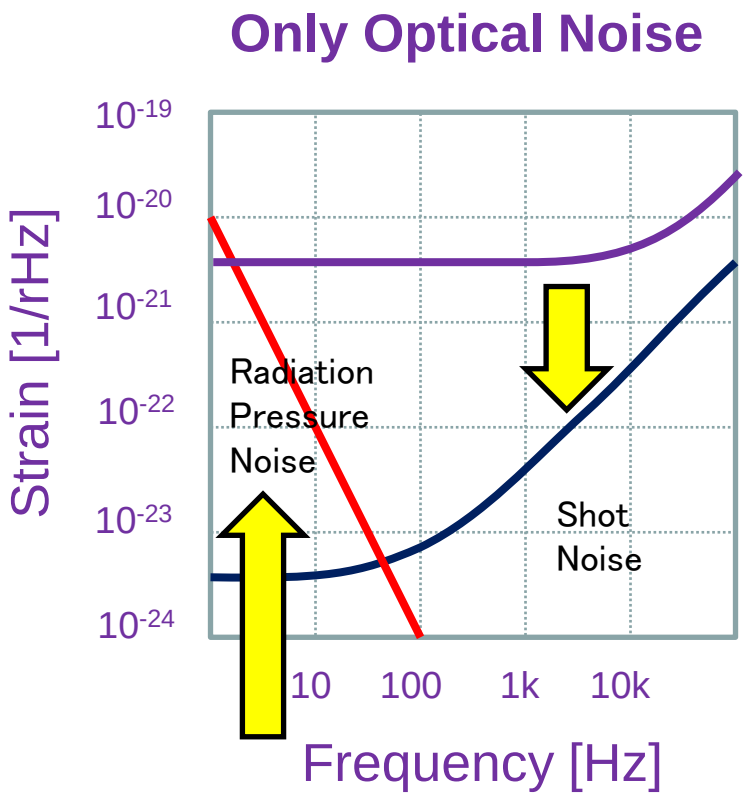
Inst. for High Energy Physics of Chinese Academy of Sciences,
Peking Univ.,
CMS ITR Taiwan,
Maryland Univ.,
Columbia Univ.,
Glasgow Univ.,
Sannio Univ.,
Shanghai Normal Univ.,
National Tsing Hua Univ.,
Korea Univ., KIAS,
Inje Univ., Korea Univ.,
Yongji Univ.,
Seoul National Univ.,
Korea Atomic Energy Research Institute ,
Hanyang Univ.,
Pusan National Univ.,
KISTI , Korea NIMS,
Kyungpook National Univ.,
Kunsan National Univ.,
KIAS , IISER-TVM,

GW Detector Engineering Aspects

- **Recycled Fabry-Perot Michelson Interferometer with Resonant Sideband Extraction Technique.**





Km scale-GWDs in the world

Merits of GW detection network

- **Convincing "True detection"**
  - **By coincidence of independent detectors.**

- **Determination of**
  - **Arrival time,**
  - **Polarization of GWs,**
  - **(in case of inspiral binary,) absolute amplitude and inclination angle of orbit.**

- **Duty time of observation**
  - **More GW events,**
  - **Chance of follow up observation.**

- **Sky coverage enhancement**

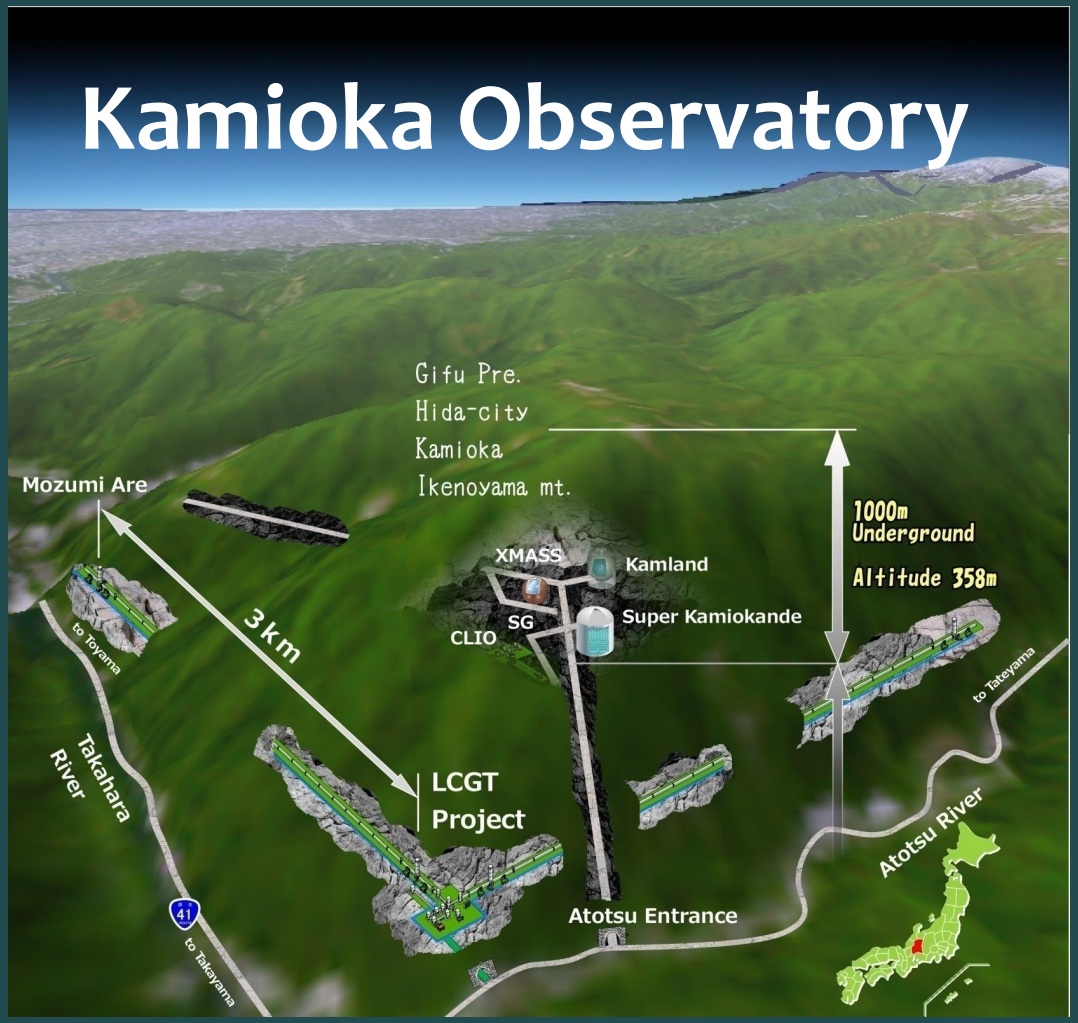
KAGRA Highlights

KAGRA highlights that are different from other GWDs such as aLIGO,a VIRGO are …

(1) Underground
→ Stable Operation owing to low seismic noise.

(2) Usage of Cryogenic Mirrors and suspensions
→ Reduce Thermal Noises

(3) Collaboration with Geophysical Laser Strain-meter



Merits (& demerits) of Underground

- **Out-band frequency range seismic noise at low frequency has nonlinear effect on in-band frequency range sensitivity in GWD. So lower seismic noise in out-band is desirable.**

  →Smaller low-frequency motion of mirror

  → Lower gain of control system necessary

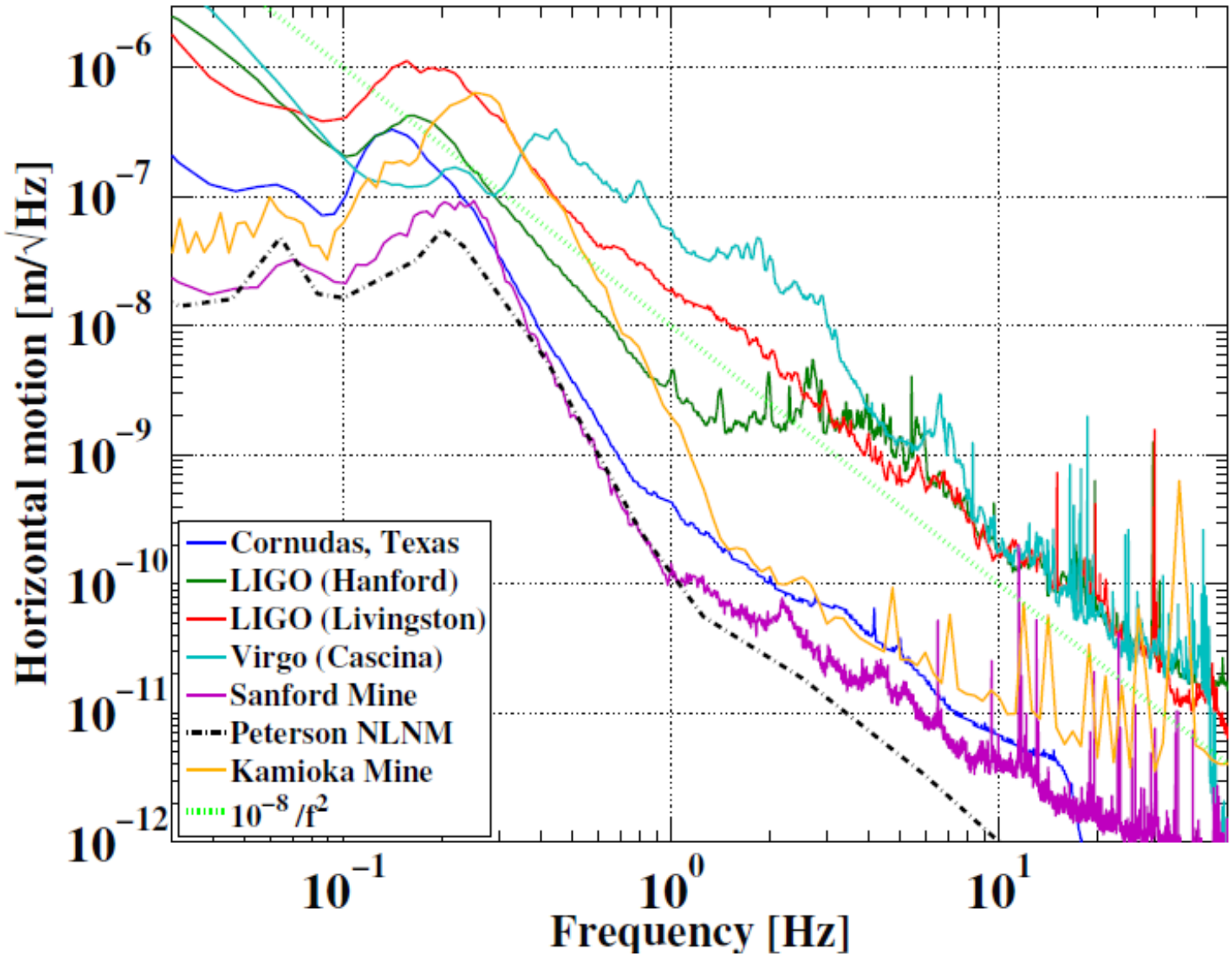
  →Lower in-band noise imposed by control system

- **Low Gravity Gradient Noise**

on the other hand,

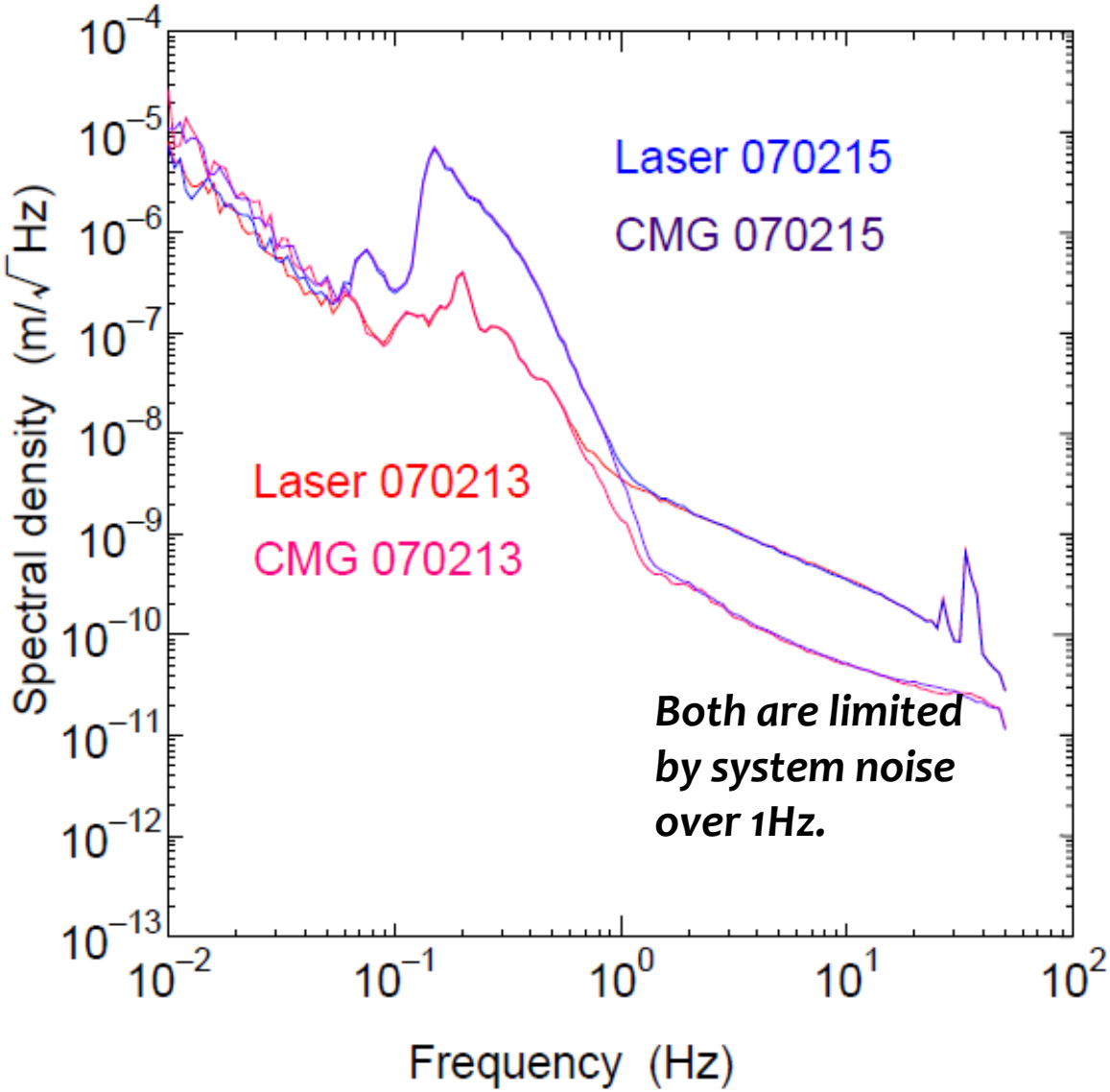
- **We found the "water" in the mountain is annoying source in many practical aspects.**
- **We should check the "Gravity Gradient Noise" due to water flow near mirrors**

Low Seismic noise Underground



By Rana (LIGO)

Kamioka Seismic Noise



Strain Meter Data (< 20Hz)

070215 : Stormy day

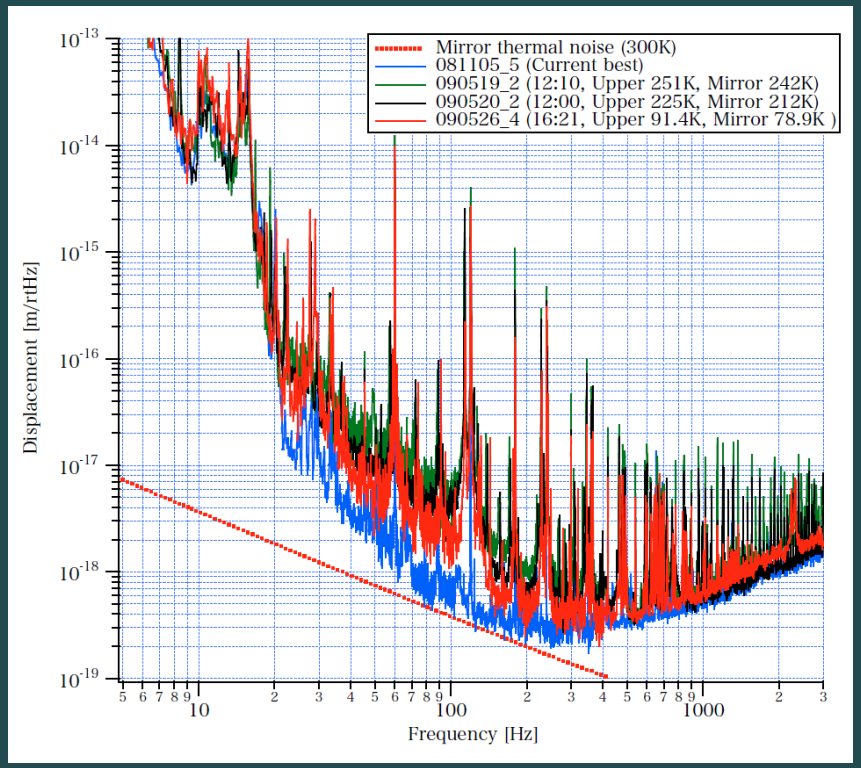
070213 : fine day

10 times enhancement of micro seismic noise due to ocean waves can be observed.

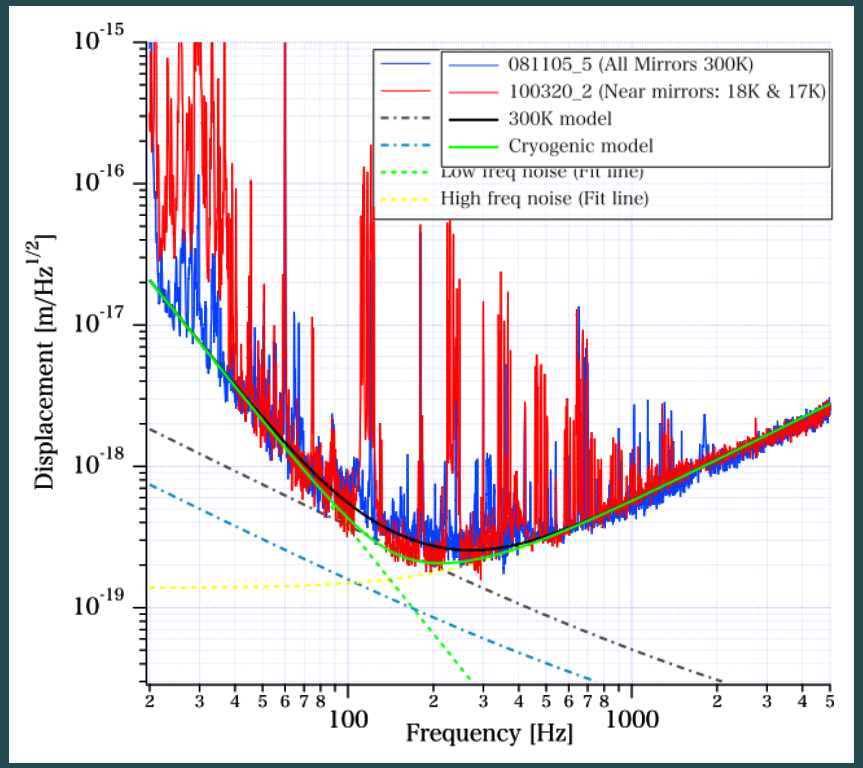
Cryogenic Mirror and Suspension

- **Thermal noise reduction using cryogenic mirror and mirror suspension.**
- **CLIO proto-type verified these properties.**

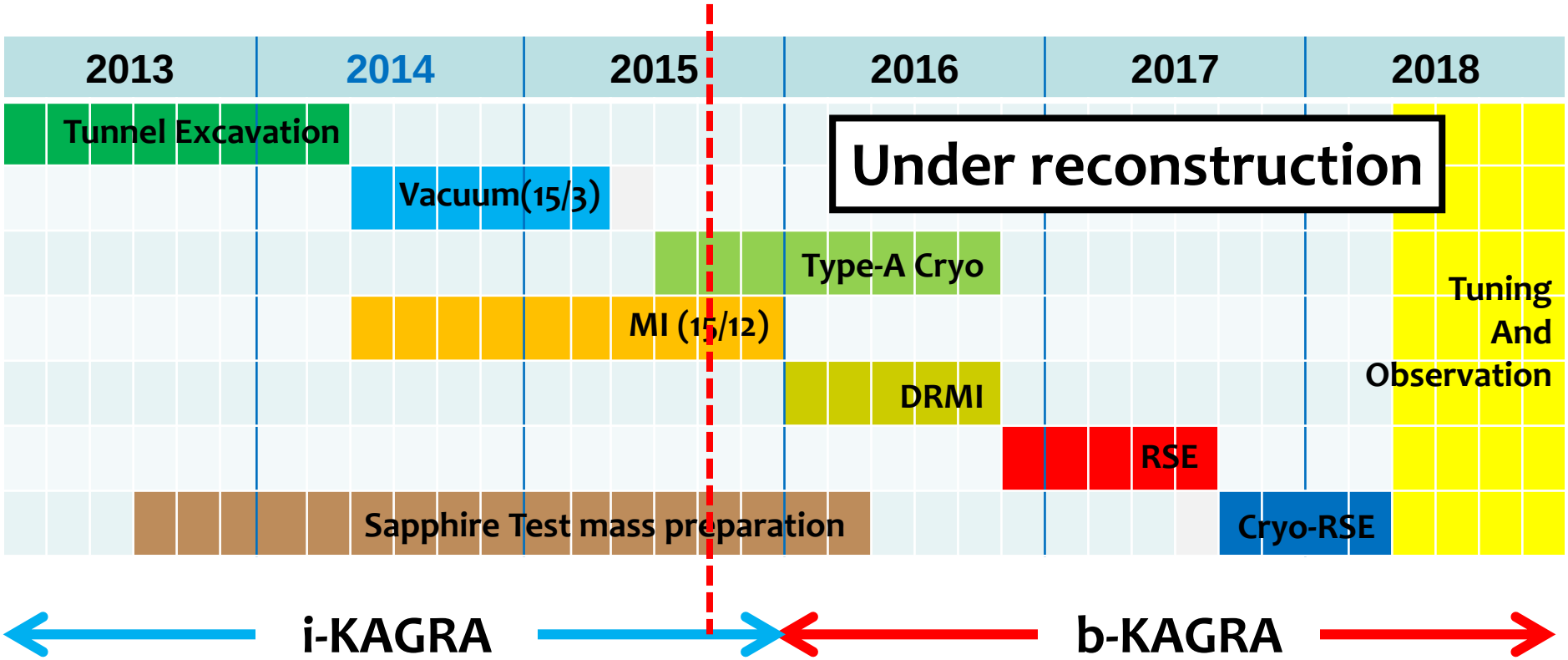
Suspension Thermal Noise



Mirror Thermal Noise



KAGRA Road Map



Experience of km-scale laser interferometer.
Michelson Interferometer Construction

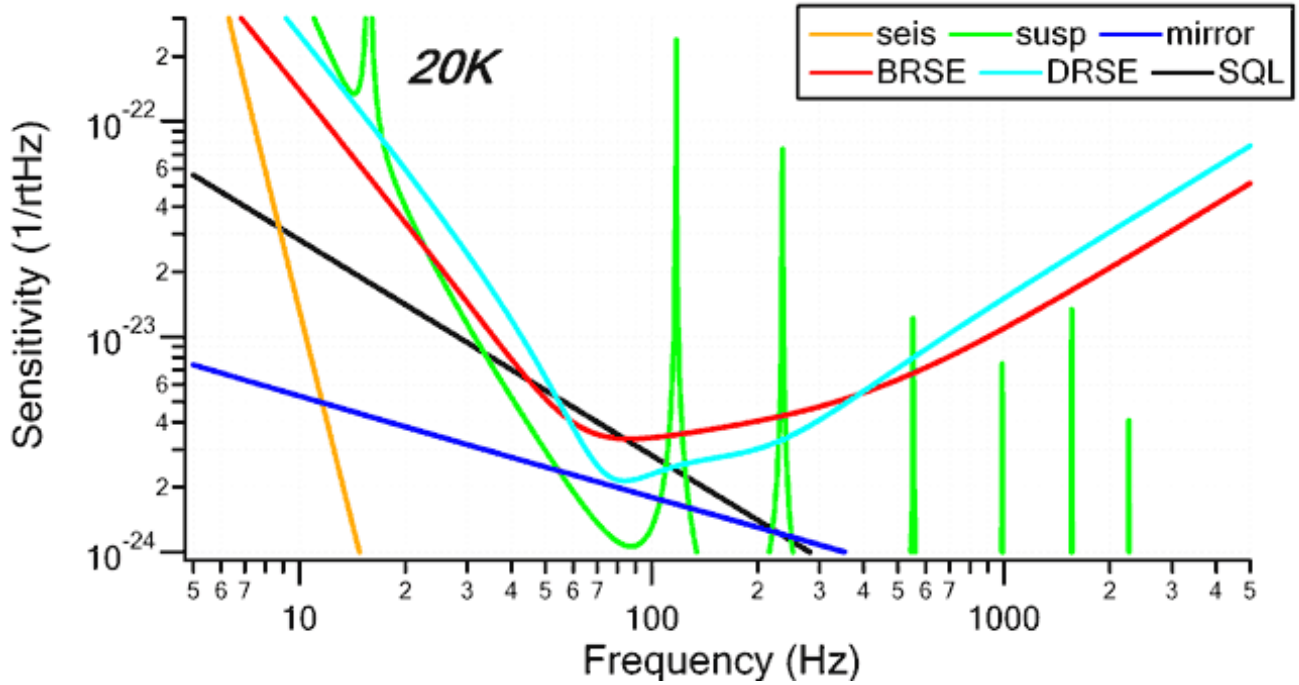
Introduction of cryogenic mirrors and RSE technique to reach the targeted sensitivity.

initial-KAGRA (2010~2015.12)

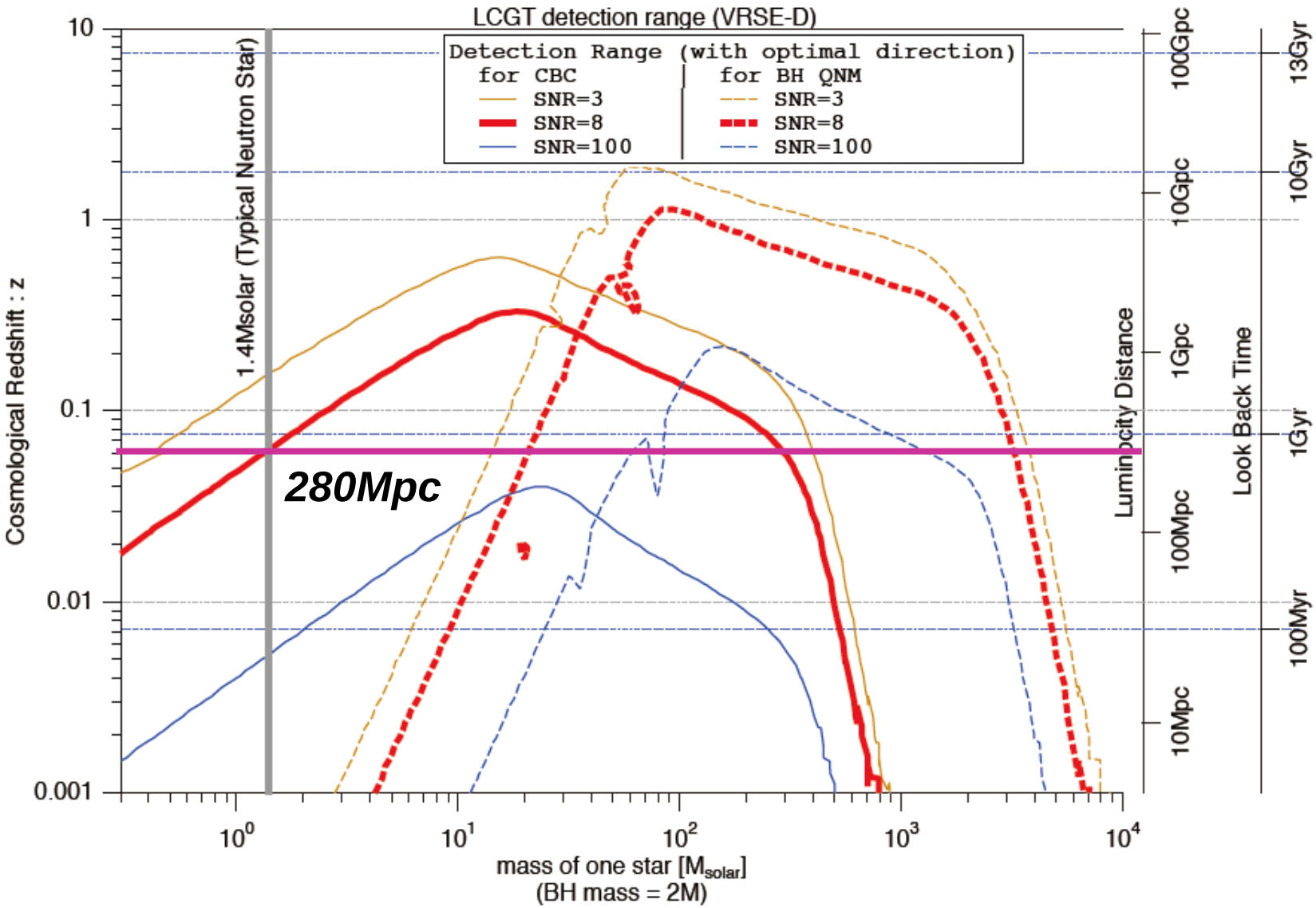
- **Construction Phase.**
  - **Tunnel**
  - **Vacuum**
  - **Facility**
- **Interferometer component design.**
- **3km arm Michelson Interferometer construction.**
  - **Mirrors and suspension are set at 300K.**
  - **SiO_2 Mirrors.**
  - **2W level laser sources**
  - **Simple Mirror Suspension**
- **Short Observation (for thrashing out problems)**

baseline-KAGRA (2016~2017,18)

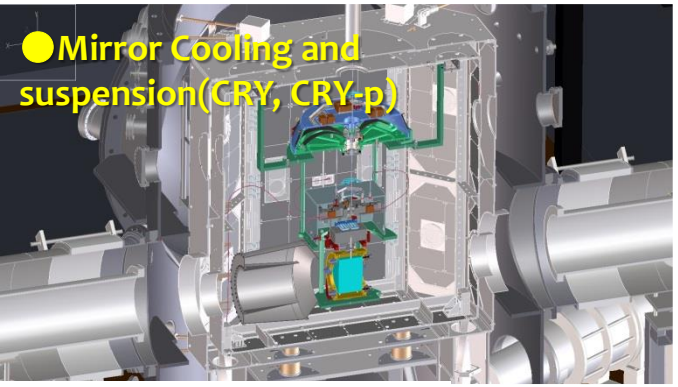
- **Toward the Targeted Sensitivity ~ 280Mpc**
  - Cryogenic mirrors and suspensions (sapphire)
  - 200W~ 25W Laser (Mitsubishi-Amp or Fiber-Amp)
  - RSE technique (Broadband or Detuned in Variable RSE)
  - DC readout technique
  - Output Mode Cleaner
  - SAS full operation

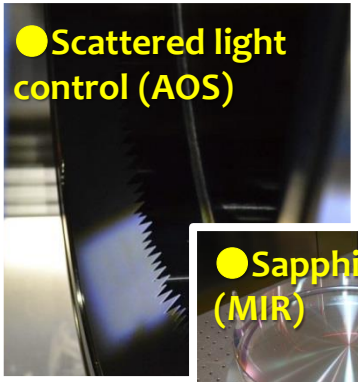


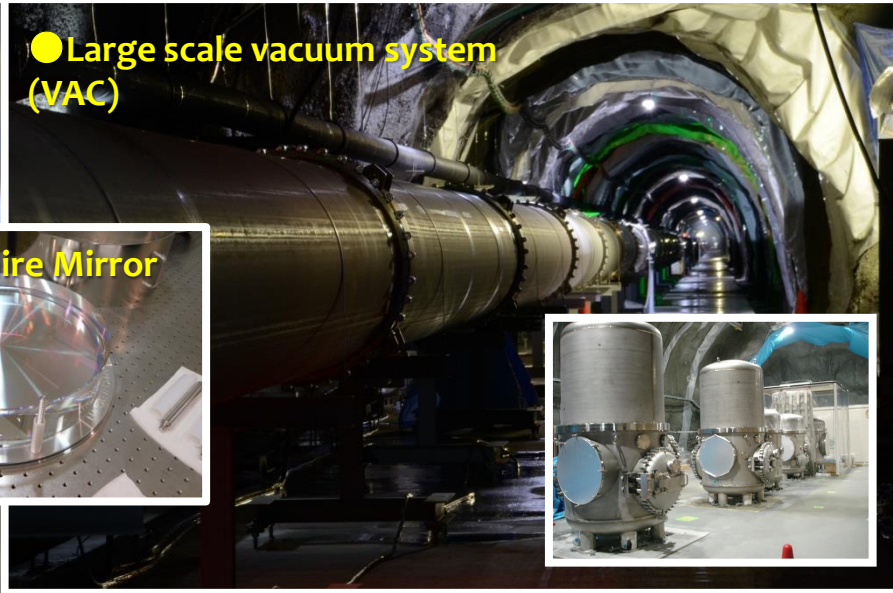
Inspiral Range of KAGRA

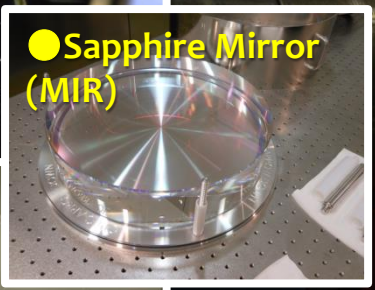


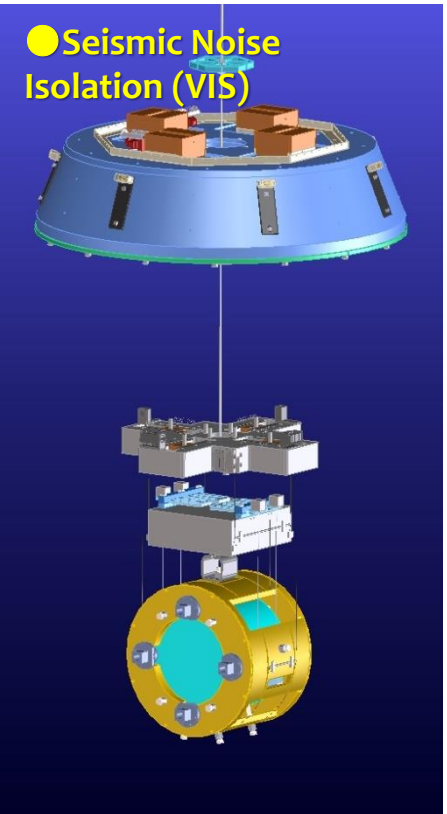
Construction Status of KAGRA

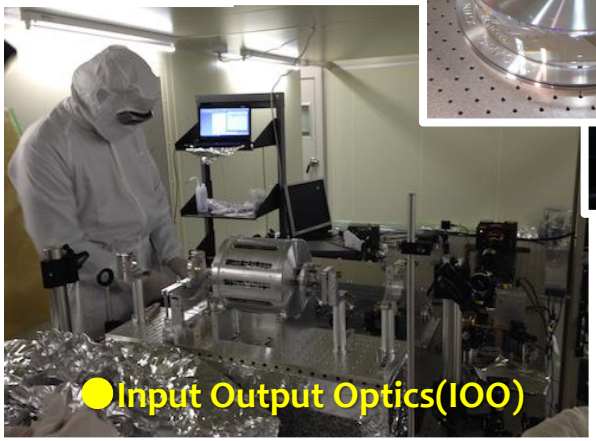


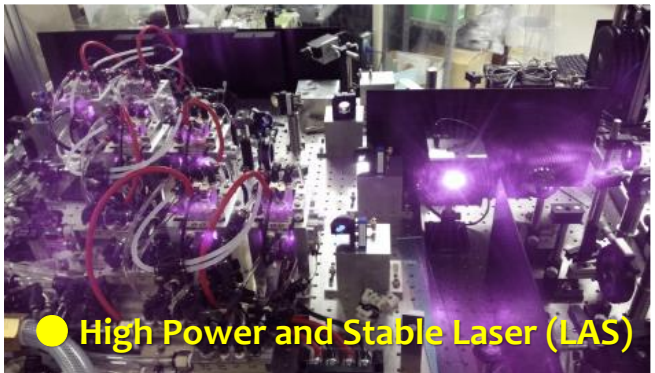


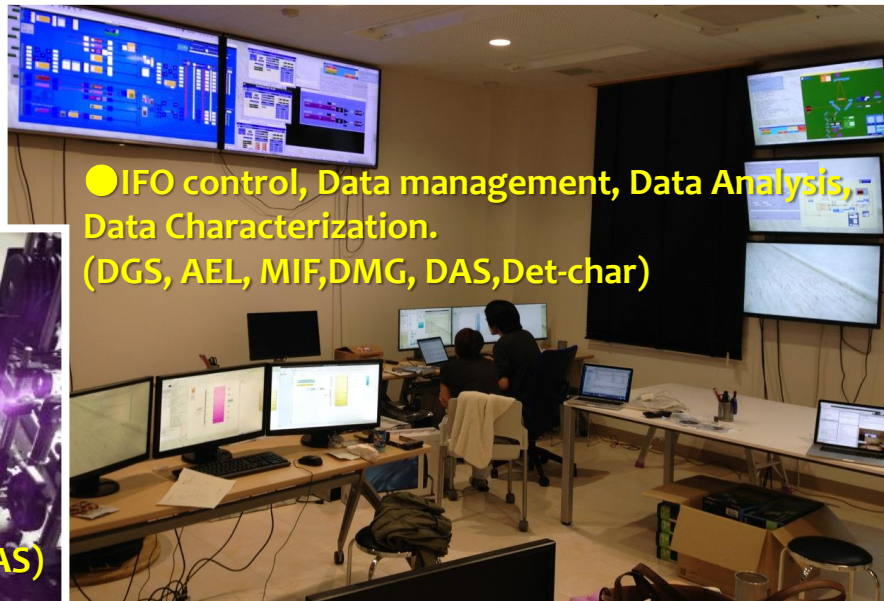








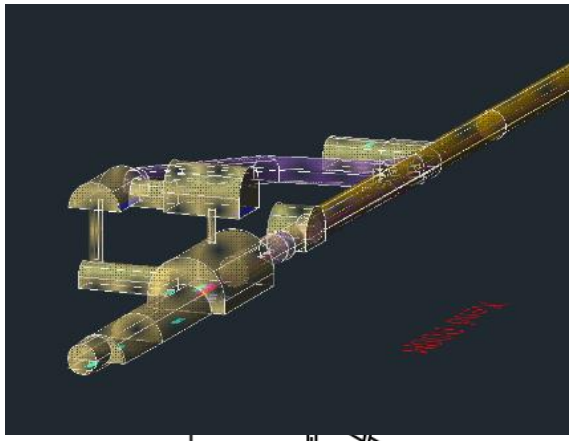




Tunnel Excavation

- Tunnel Design -

- Excavation has started in May 2012.
- Sometimes, we got a lot of water.

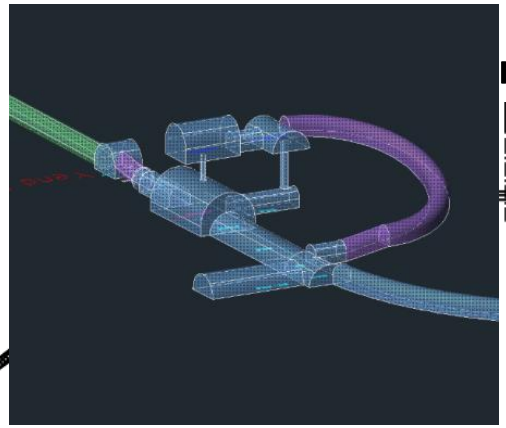


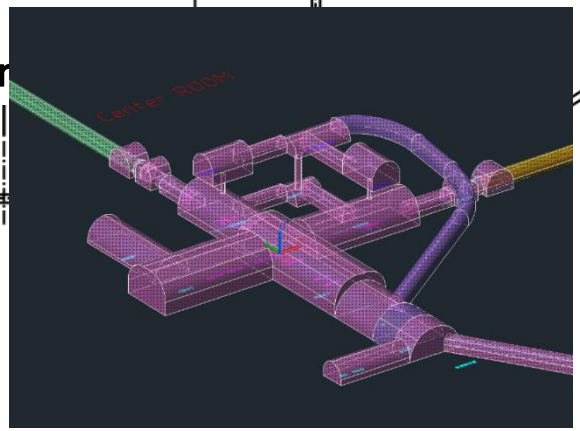
X End Station (Sakonishi)

GW Atotsu Entrance

~500m

GW Atotsu Access Tunnel





Mozumi Access Tunnel

Mozumi Entrance

~900m

Y End Station (Mozumi)

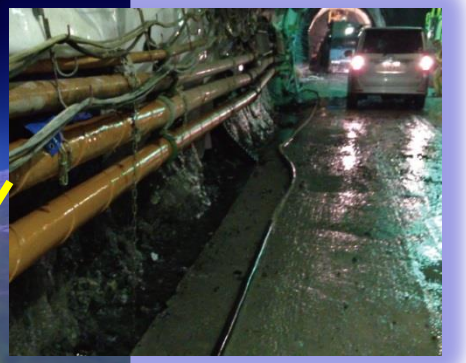
Corner Station (Atotsu)

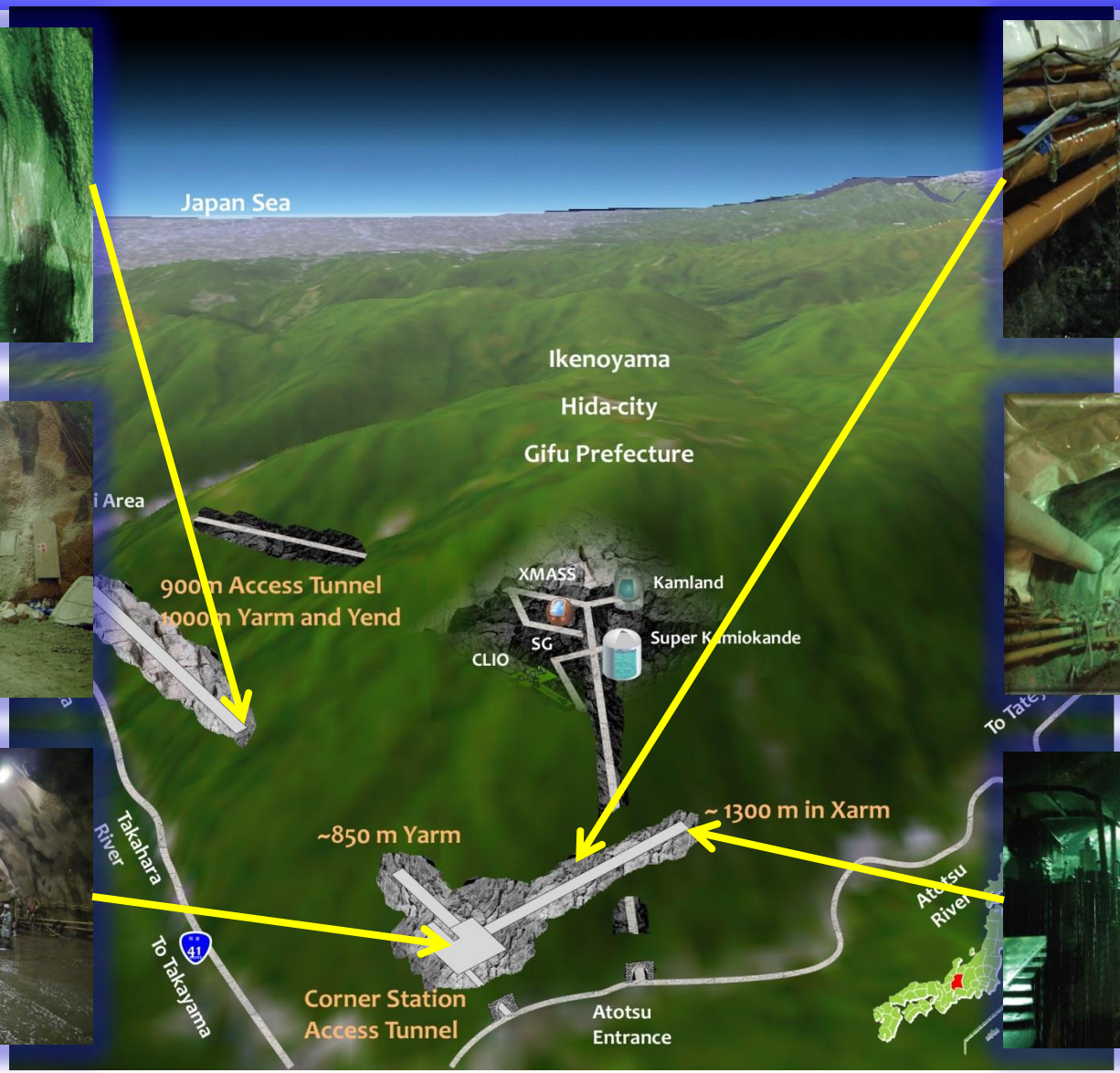
TUN, VAC Group

Blasting for 22 months from May 2012

Tunnel Group

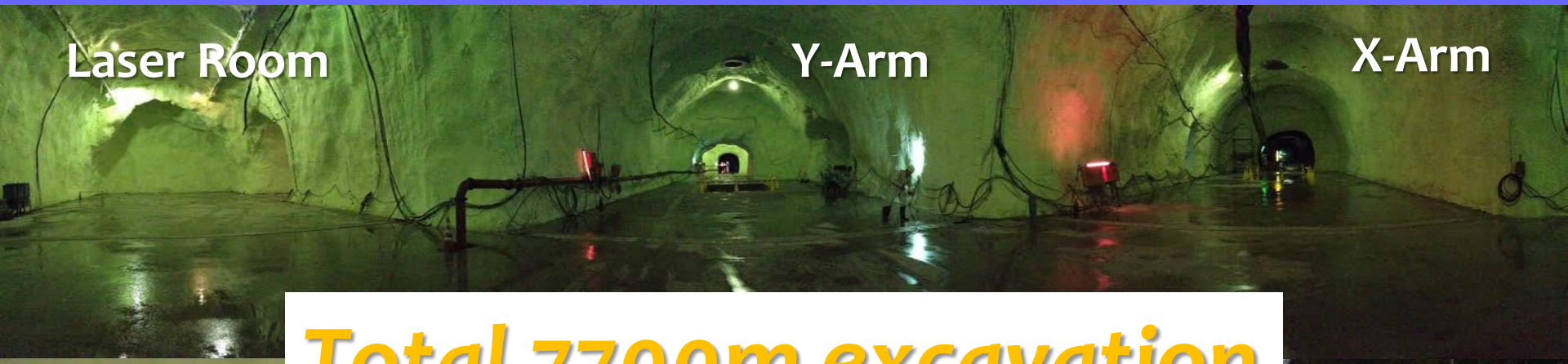
Tunnel Excavation around 2013 August





Tunnel Group

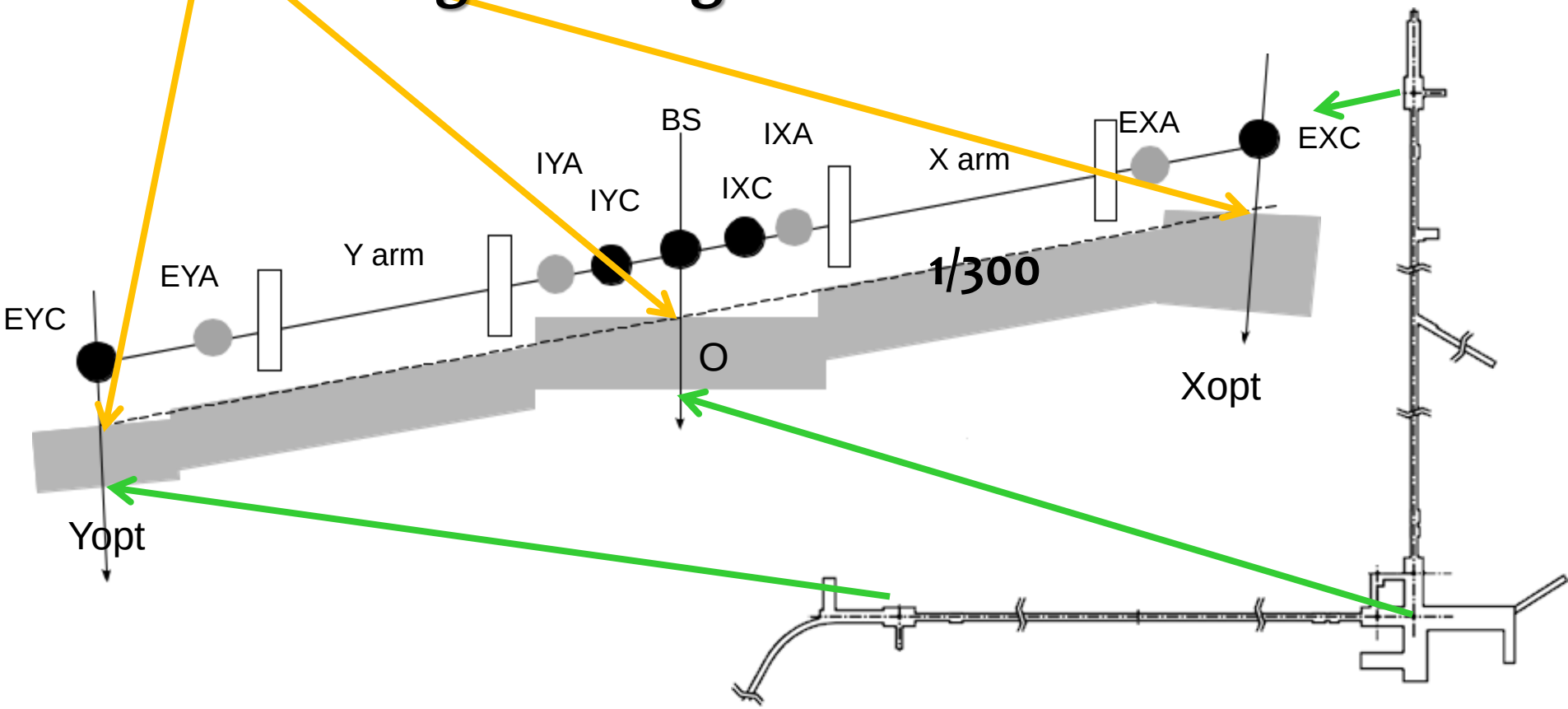
Tunnel Completed in March 2014



Total 7700m excavation

Tunnel Design

- Slope of 1/300 was selected to drain the water to rivers.
- Horizontal planes for each station are prepared for easiness during installing vacuum tanks

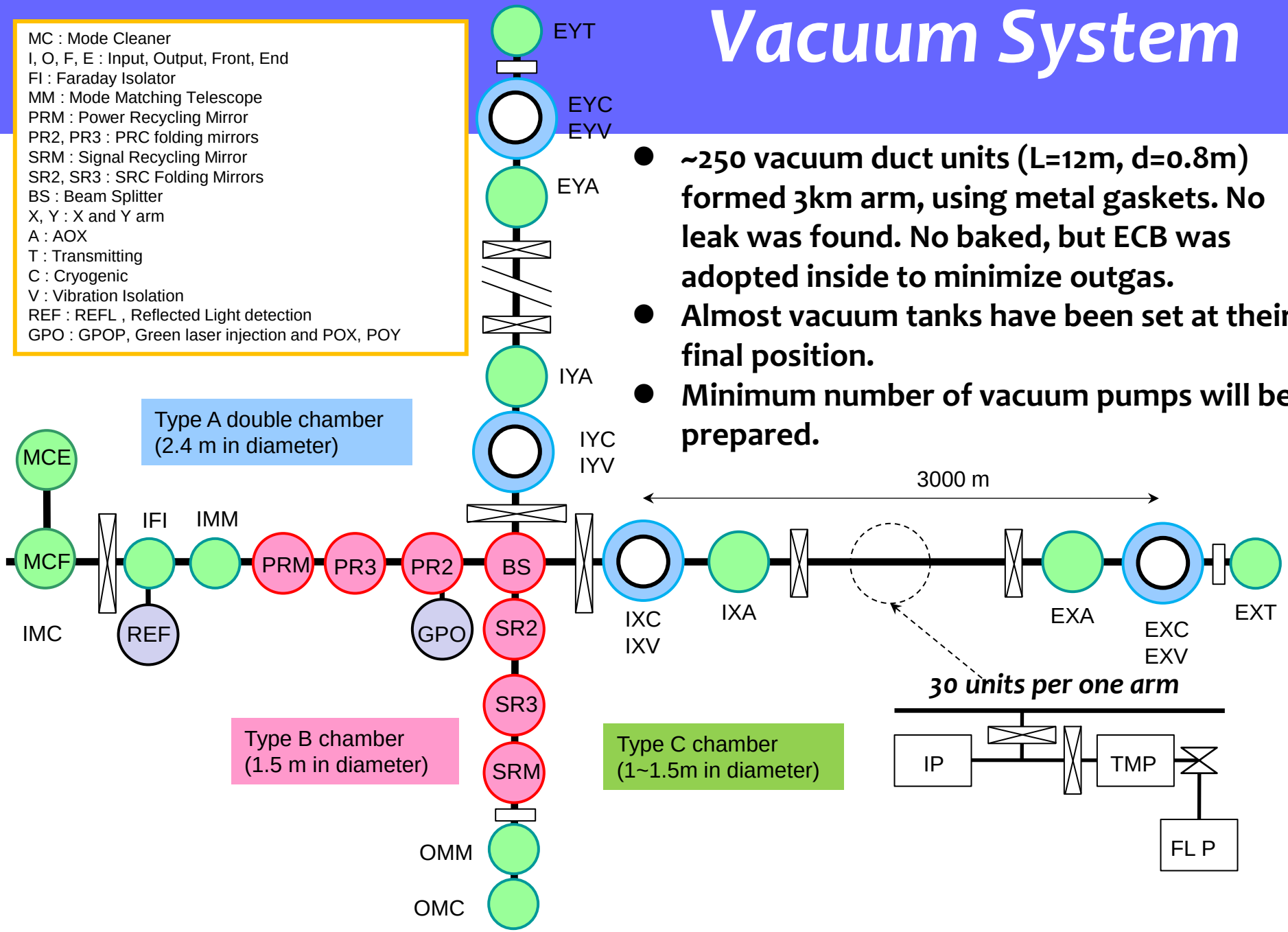


New Building for GWPO

Vacuum System

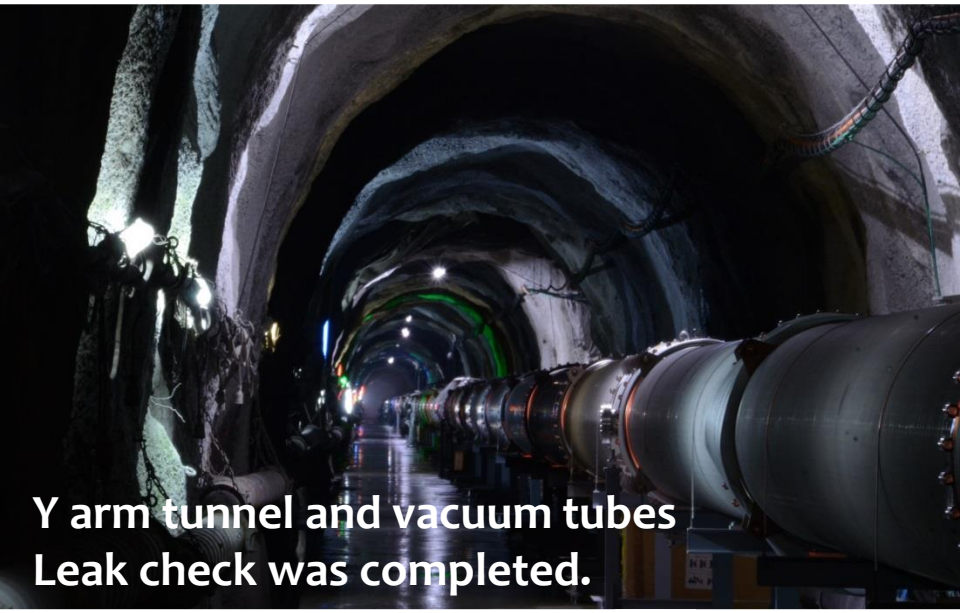
MC : Mode Cleaner
I, O, F, E : Input, Output, Front, End
FI : Faraday Isolator
MM : Mode Matching Telescope
PRM : Power Recycling Mirror
PR2, PR3 : PRC folding mirrors
SRM : Signal Recycling Mirror
SR2, SR3 : SRC Folding Mirrors
BS : Beam Splitter
X, Y : X and Y arm
A : AOX
T : Transmitting
C : Cryogenic
V : Vibration Isolation
REF : REFL , Reflected Light detection
GPO : GPOP, Green laser injection and POX, POY

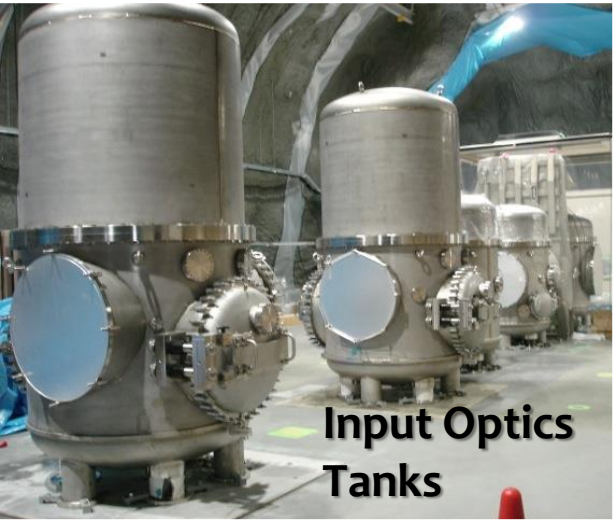
- ~250 vacuum duct units (L=12m, d=0.8m) formed 3km arm, using metal gaskets. No leak was found. No baked, but ECB was adopted inside to minimize outgas.
- Almost vacuum tanks have been set at their final position.
- Minimum number of vacuum pumps will be prepared.



VAC Group

Vacuum Ducts and Chambers Set in FY2014





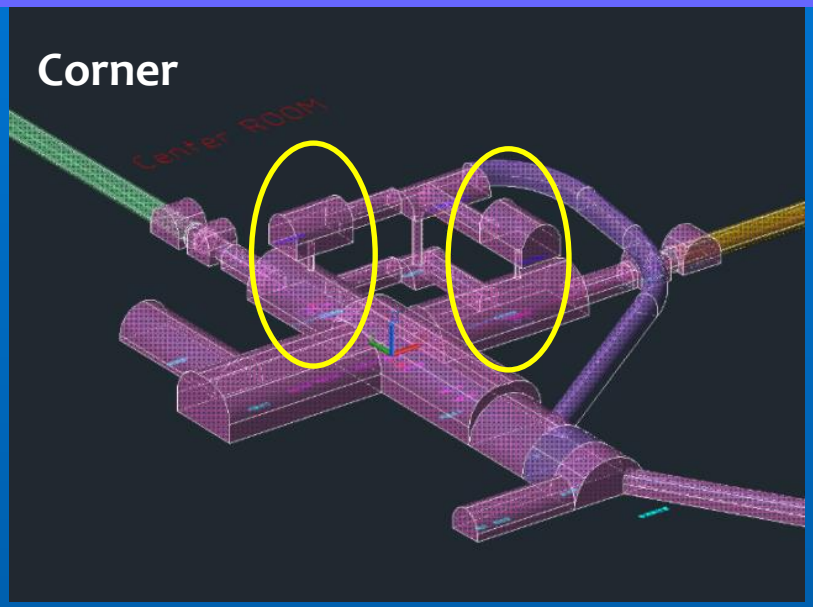
Vibration Isolation System

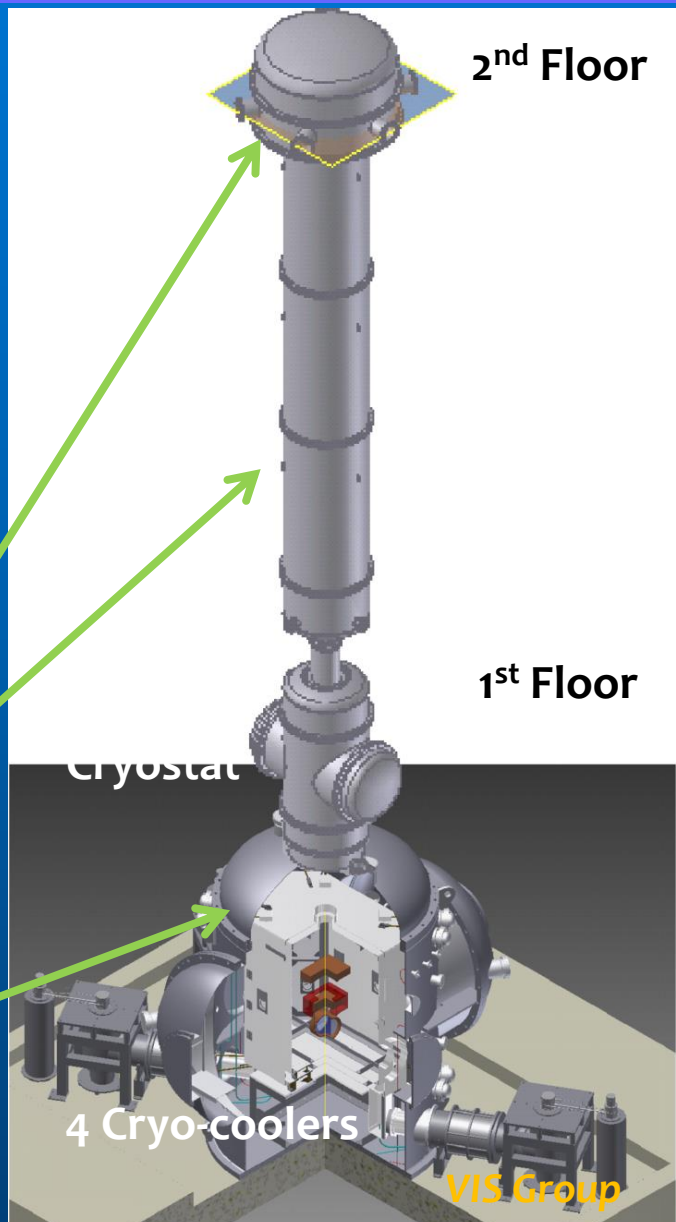
Seismic noise isolation is one of essential requirements in GWDs. Not only in-band frequency range (10Hz ~ several kHz), but also out-band frequency (below 10Hz), it is important to obtain low seismic noise to avoid "up-conversion seismic noise".

- **Highest performance SAS for the main four sapphire mirrors (type-A).**
- **Less performance isolators than Type-A for silica mirrors that form main parts of IFO (Type-B, Type-Bp, Type-Bp').**
- **Simple isolators for MC mirrors and small optics. (Type-C)**

Super Attenuation System (Type-A)

- for sapphire mirrors -

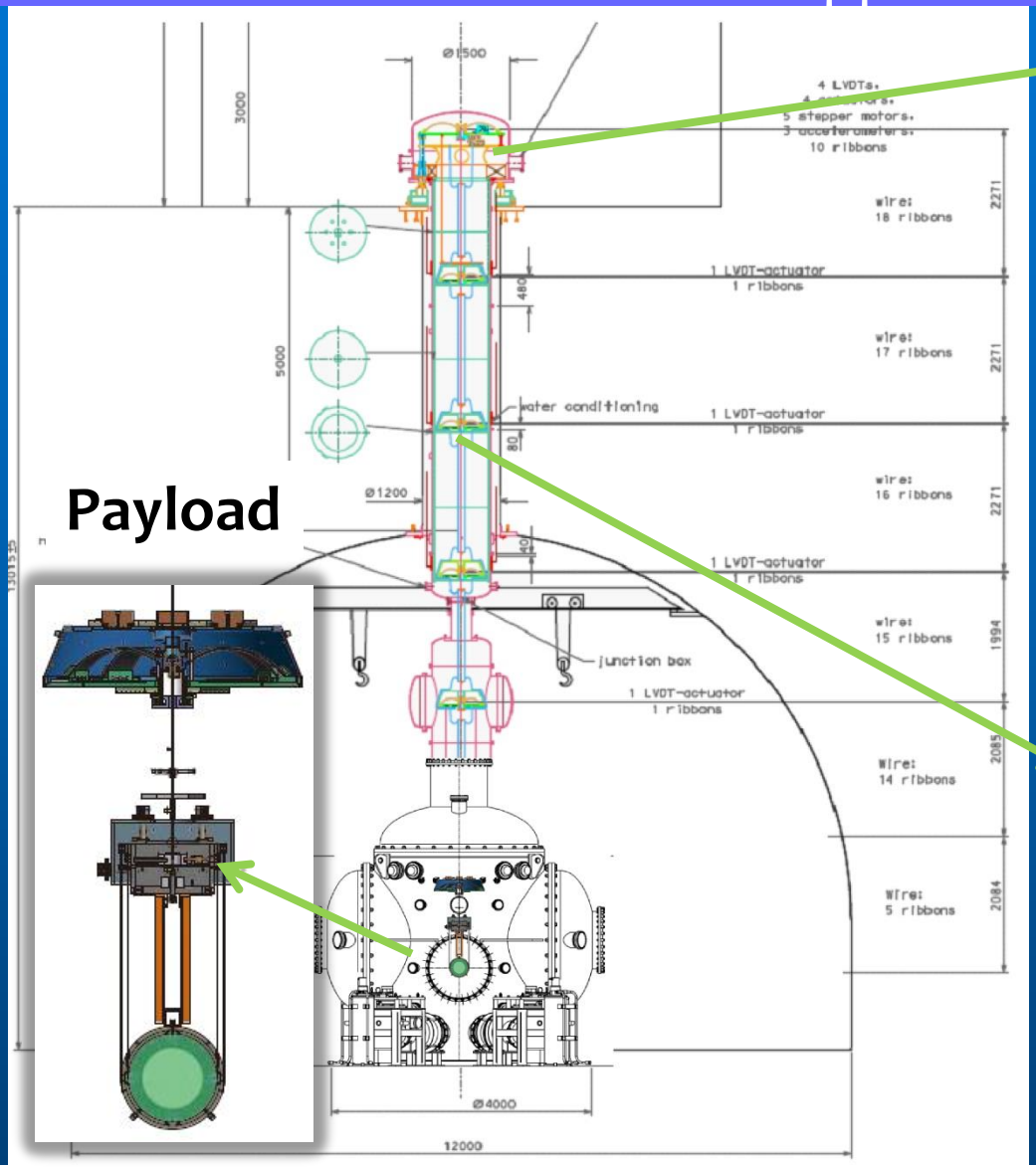




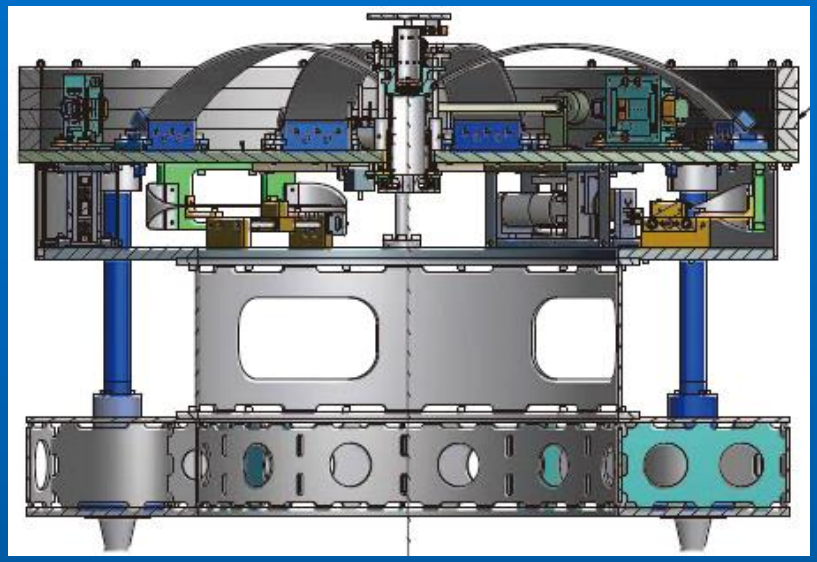
- Upper tunnel containing pre-isolator (short IP and top filter)
- 1.2m diameter 5m tall borehole containing standard filter chain
- Lower tunnel containing cryostat and payload

Super Attenuation System (Type-A)

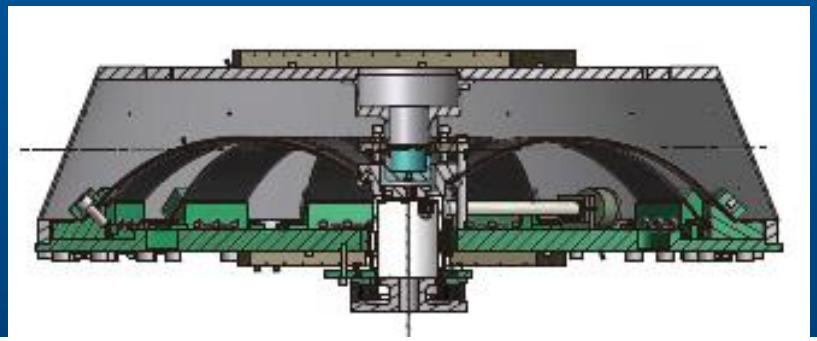
- for sapphire mirrors -



Top filter [Filter0] and Inverted Pendulum (IP)



Geometric Anti-Spring (GAS) Filter1 (Filter1~3 in Type-A)



Pendulums (Type-B)

- Simplified Type-A -

Pre-isolator

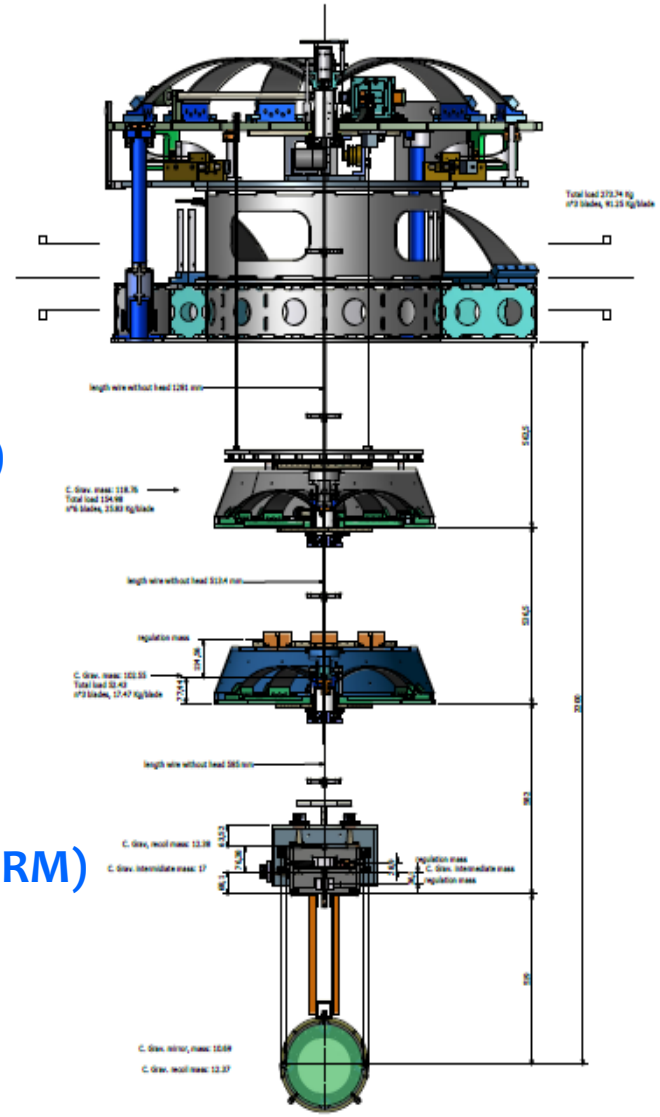
- Top filter [Filter0]
- Inverted Pendulum (IP)

Filter chain

- Geometric Anti-Spring (GAS)
- Filter1 (Filter1~3 in Type-A)

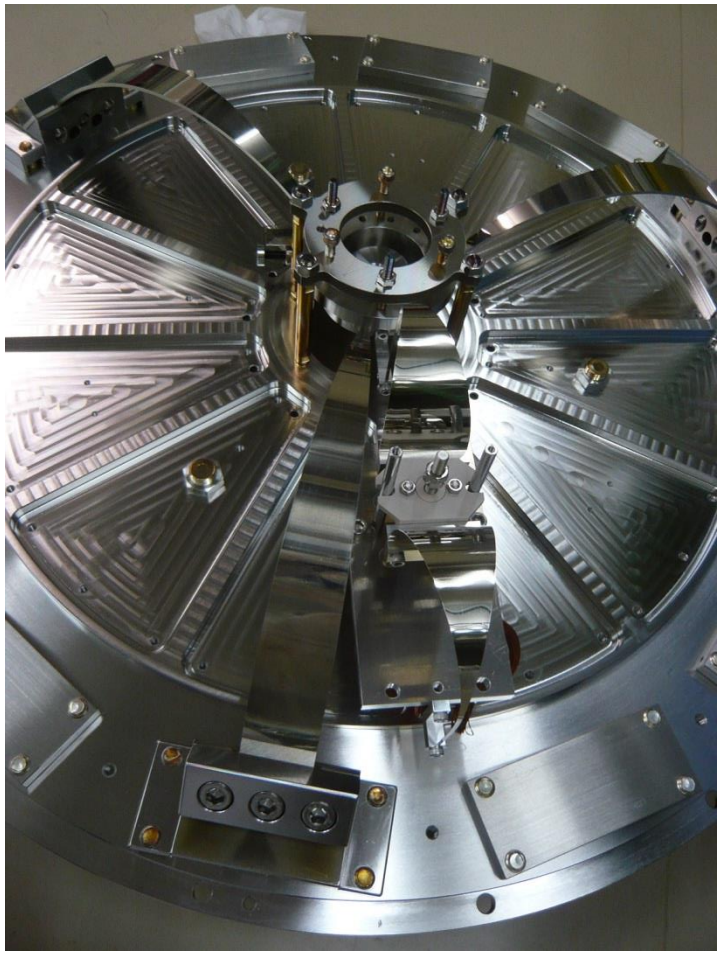
Payload

- Bottom Filter (BF)
- Intermediate Mass (IM)
- Intermediate Recoil Mass (IRM)
- Test Mass (TM)
- Recoil Mass (RM)



VIS Group

Bottom Filters



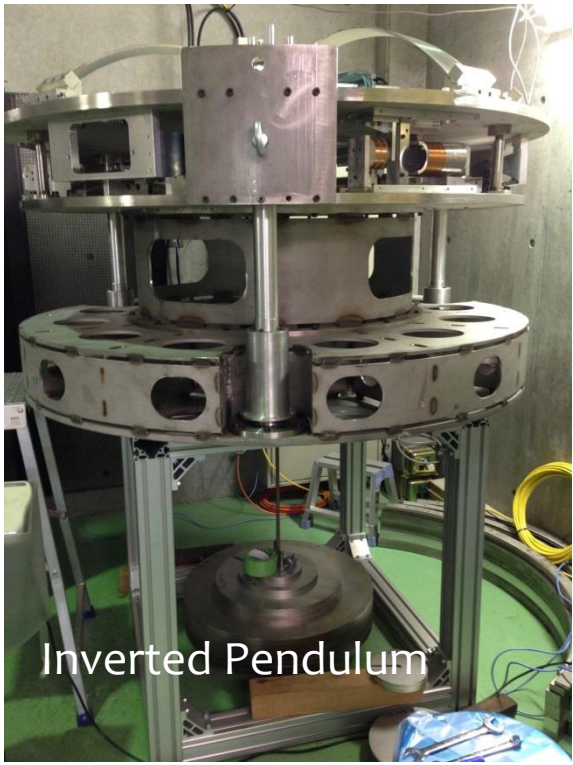
Blades and fishing rod are mounted onto the base plate.

Maraging blade springs made by NAOJ-ATC

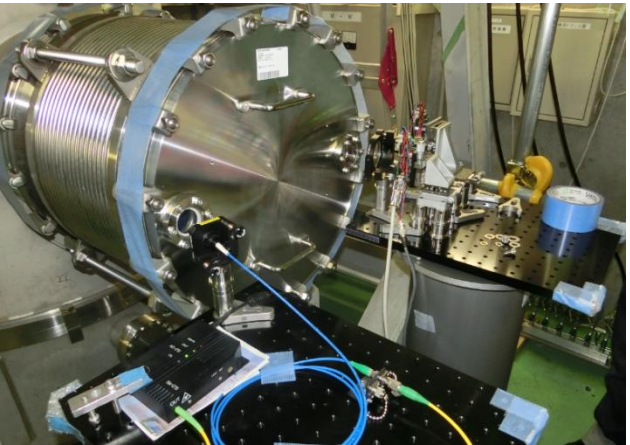
Assembled bottom filters in ATC

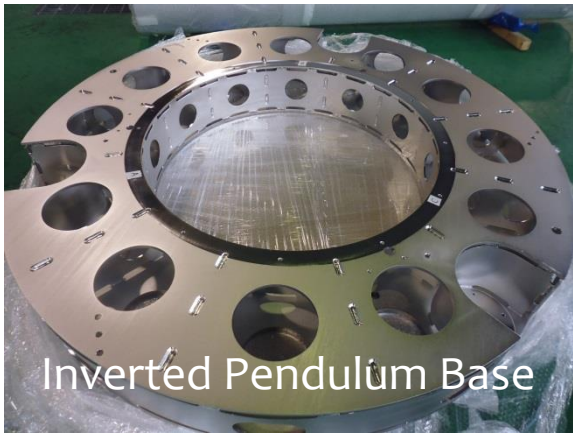
Full Type-B Test in TAMA

All of system was assembled with cabling by the side of the chamber. The full system was hung by a crane and installed into the chamber from the top. The system is working in vacuum now.

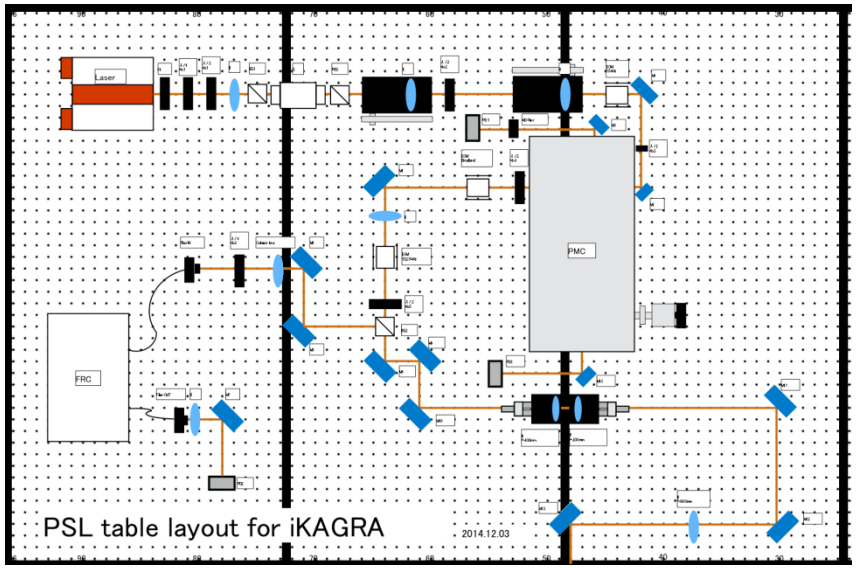


VIS Group

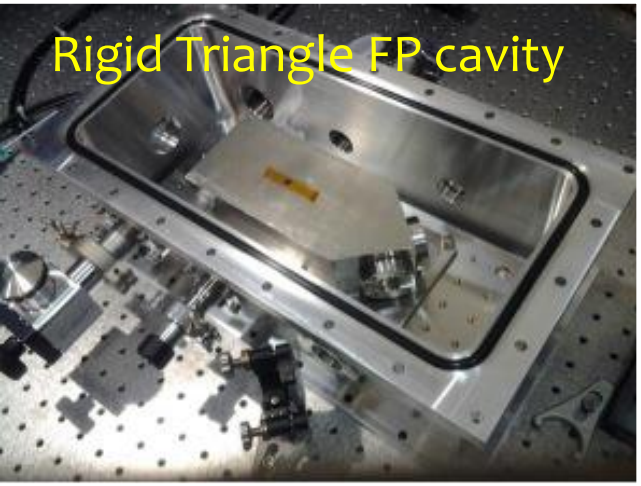


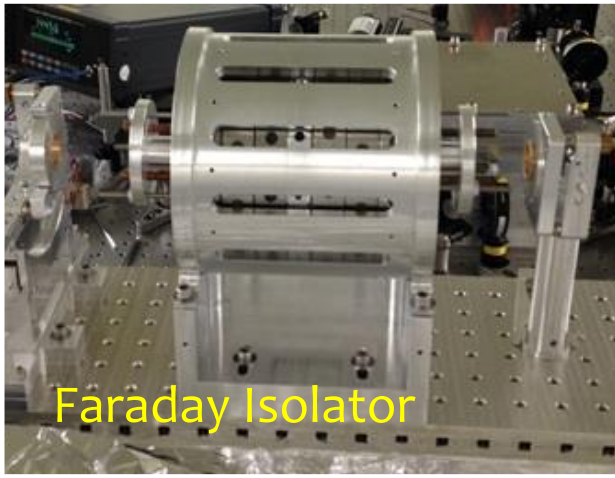


Input Output Optics for iKAGRA



- Pre-stabilized laser (PSL) was developed and tested at Kashiwa, and the performance was OK.
- PSL is being installed in Kamioka. The pre-mode cleaner was locked.
- Input Faraday isolator has been assembled, and the performance was measured to be OK.
- The mode cleaner suspensions were assembled and tested at NAOJ. One suspension system has been installed in Kamioka.

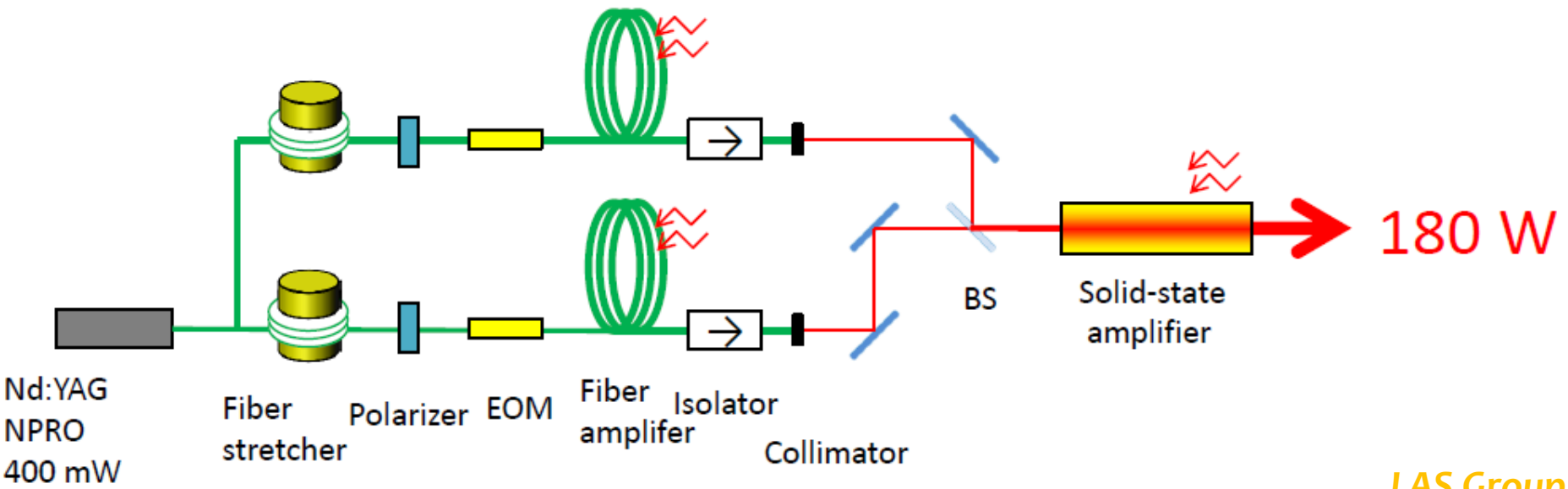




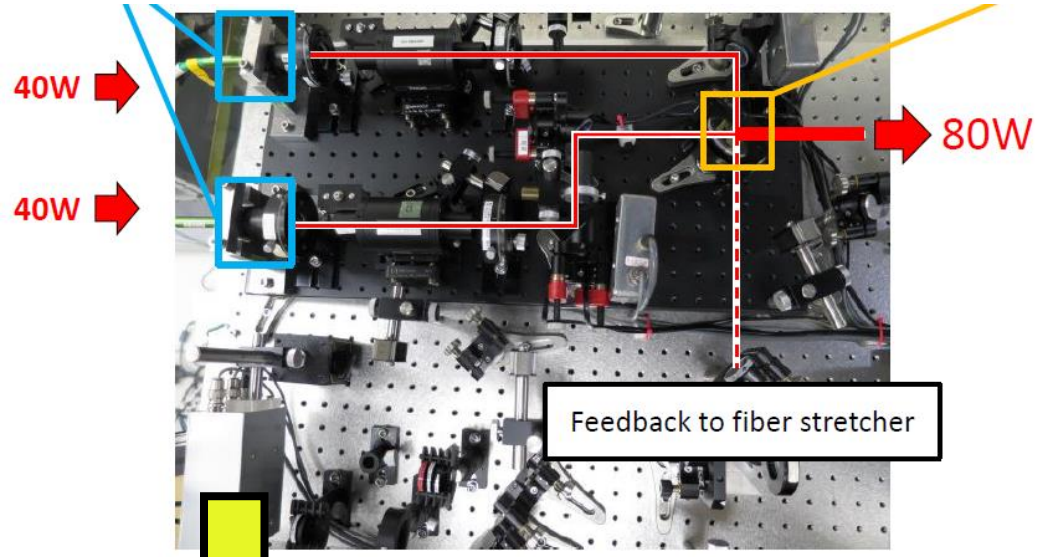
Laser Source for bKAGRA

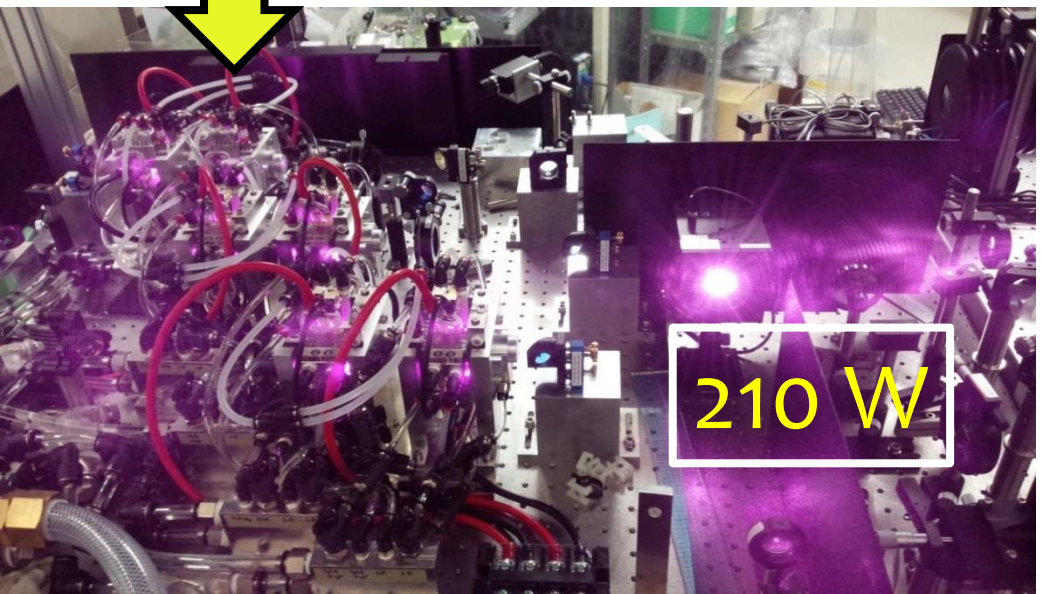
Laser should has…

- Power > 180 W
- Single frequency of 1064nm
- Low frequency noise
- Stable linear polarization
- Stable single transverse mode (TEM00)
- Low intensity noise
- Wide-band control for stabilization systems
  - About 1MHz for frequency control
  - About 100kHz for intensity control



Preliminary Result of Laser



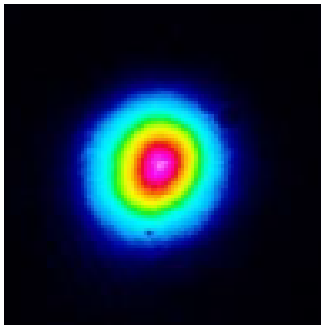


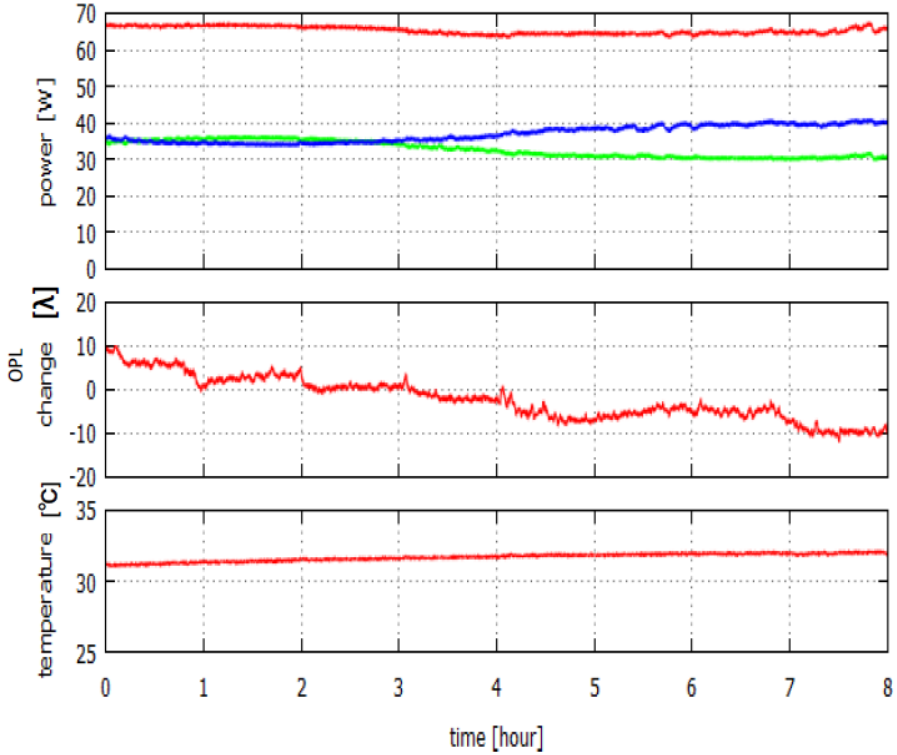
- 78.9 W was achieved by coherent addition
- 210 W was achieved by solid-state amplifiers
- Coherent addition was maintained for 8 hours
- Output power changed in time
- Atmosphere temperature changed in time
- Noise peak in Intensity & phase noise–18 kHz

- Stabilize output power–Stabilize temperature?
- Evaluate the noise of the 210-W beam
- Beam quality is ugly.
- Diminish the 18 kHz noise peak–Change fiber stretchers?

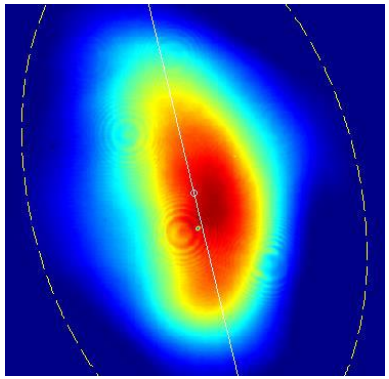
Laser Quality

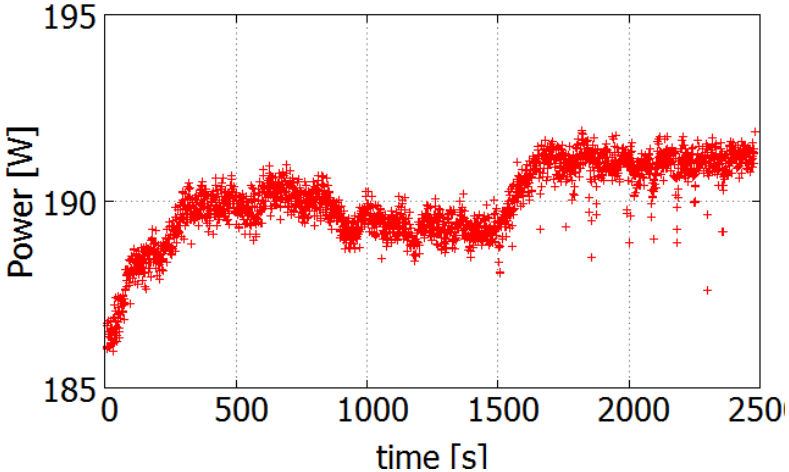
- 78.9 W Coherent Addition Laser





- 190 W amplified and mode improved Laser (210 W -> 190W because of realignment of the Amplifiers)



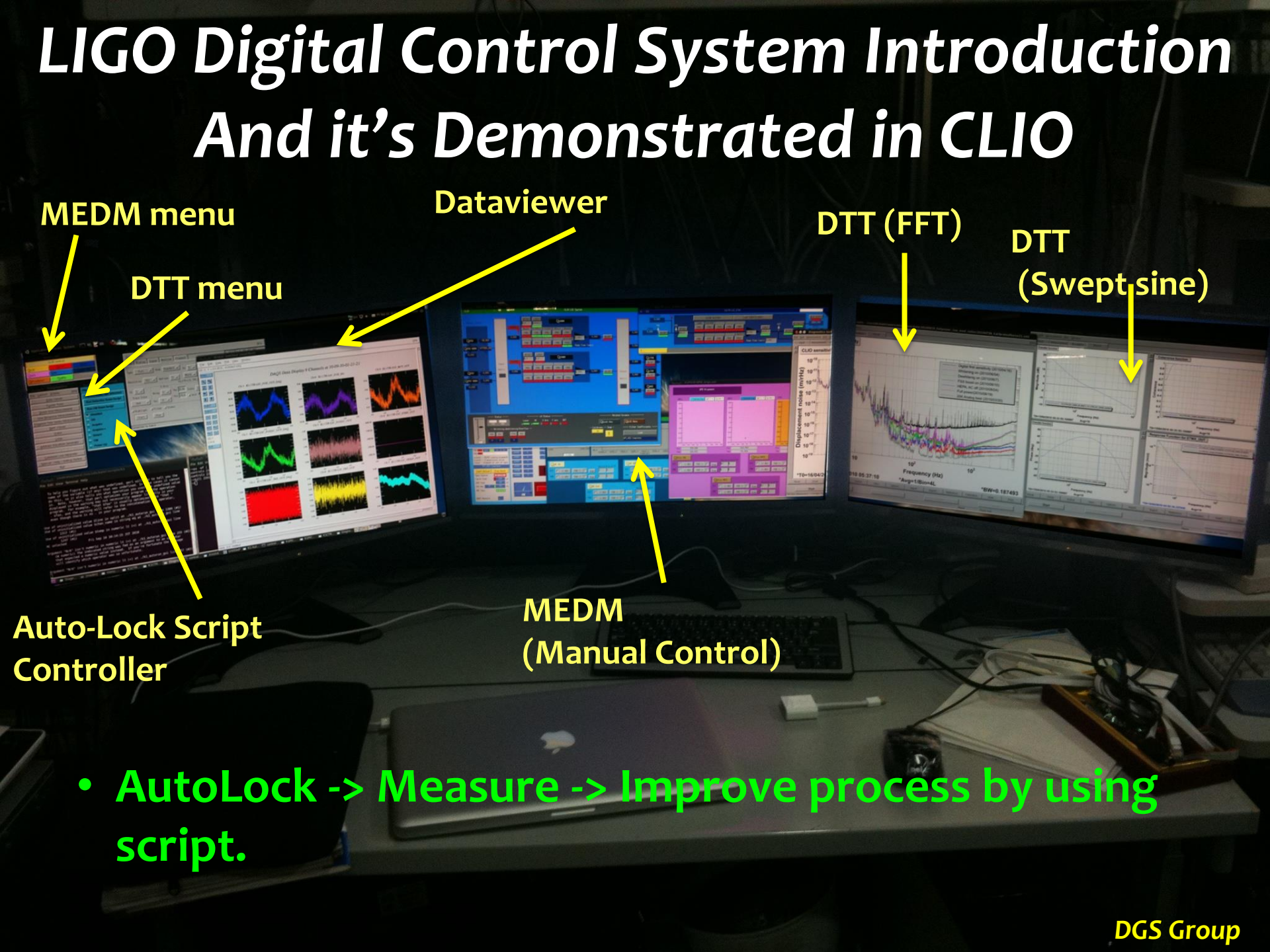


Digital Control System

DGS is indispensable for GWD control including many of freedoms, quick trouble shooting, quick trial and error, data storage, GW signal analysis and GW signal evaluation.

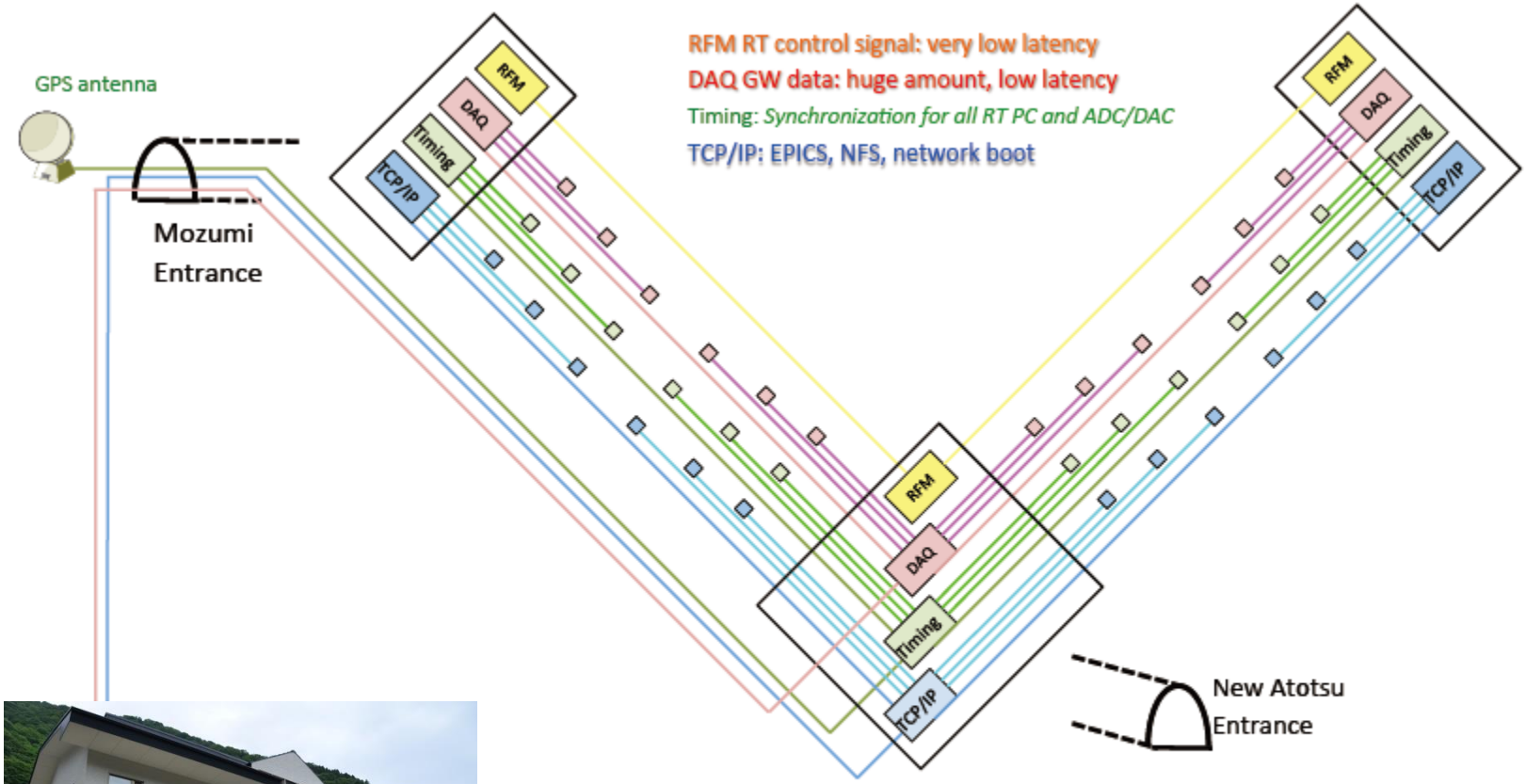
- **KAGRA DGS is based on aLIGO helps.**
- **Real time control of SAS, IFO length and alignment, pre-stabilized laser using reflective memory, and sequence control of an interlock system.**
- **Data taking and storage of IFO output (= GW signals) and many detector characterization data in IFO,**
- **Timing control.**
- **Mainly signals less than ~ 10kHz management.**

LIGO Digital Control System Introduction And it's Demonstrated in CLIO



- AutoLock -> Measure -> Improve process by using script.

Network Design for Controls and DAQ



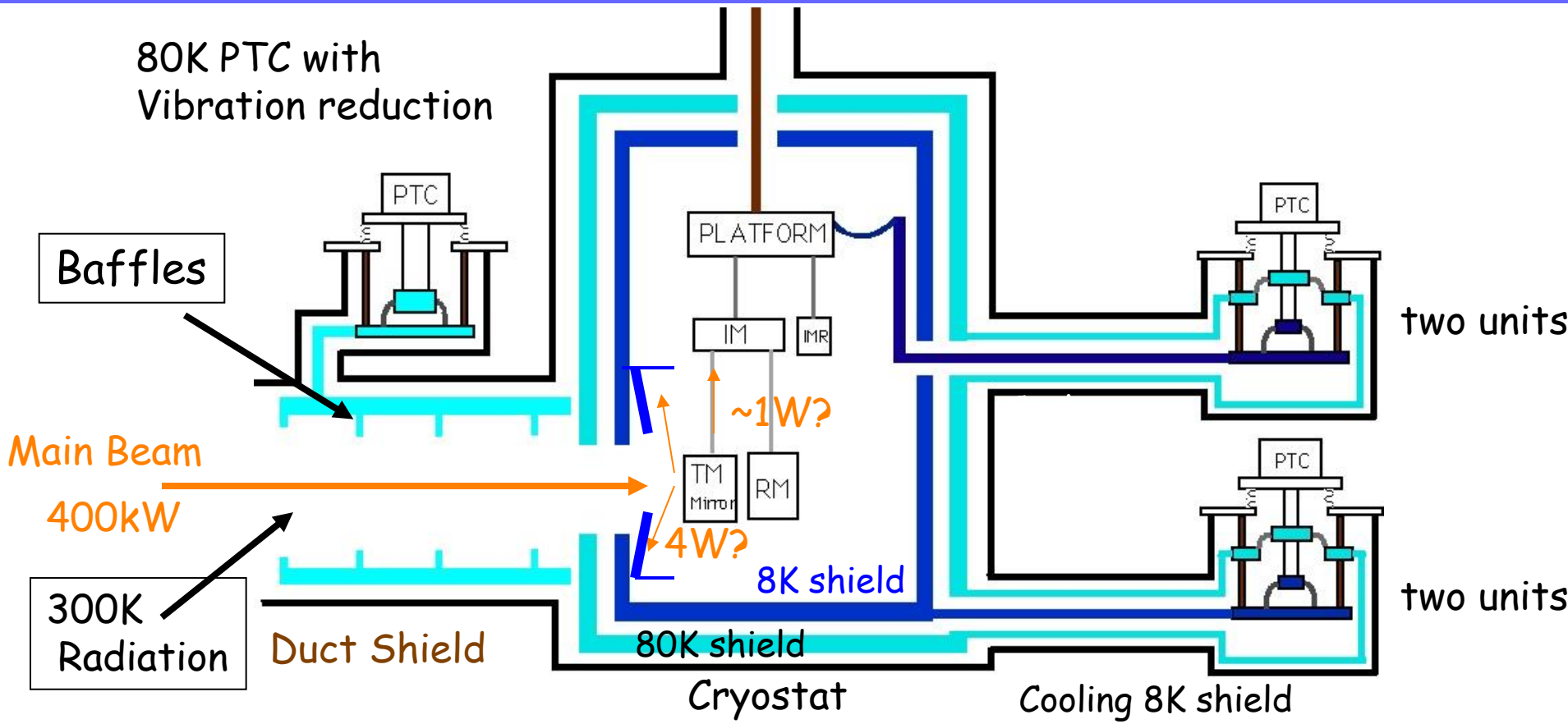
Remote Control Room in DAB

Cryostats

Cryostat for mirror cooling is essential in KAGRA. Requirement for cryostats are …

- Temperature of the test mass/mirror < 20 K.
- Inner radiation shield have to be cooled < 8 K.
- The mirror have to be cooled without introducing excess noise, especially vibration from the cryo-coolers.
- Accessibility and enough volume for the installation work around the mirror.
- Satisfy ultra high vacuum specification < 10^{-7} Pa.

Conceptual Cooling System



- Four 4K cryocooler units per one cryostat
- Baffles against wide scattering is cooled via 8K shield.

→ 2 units for cool cryo-payload
2 units cool for 8K shield
4 units cool for 80K shield

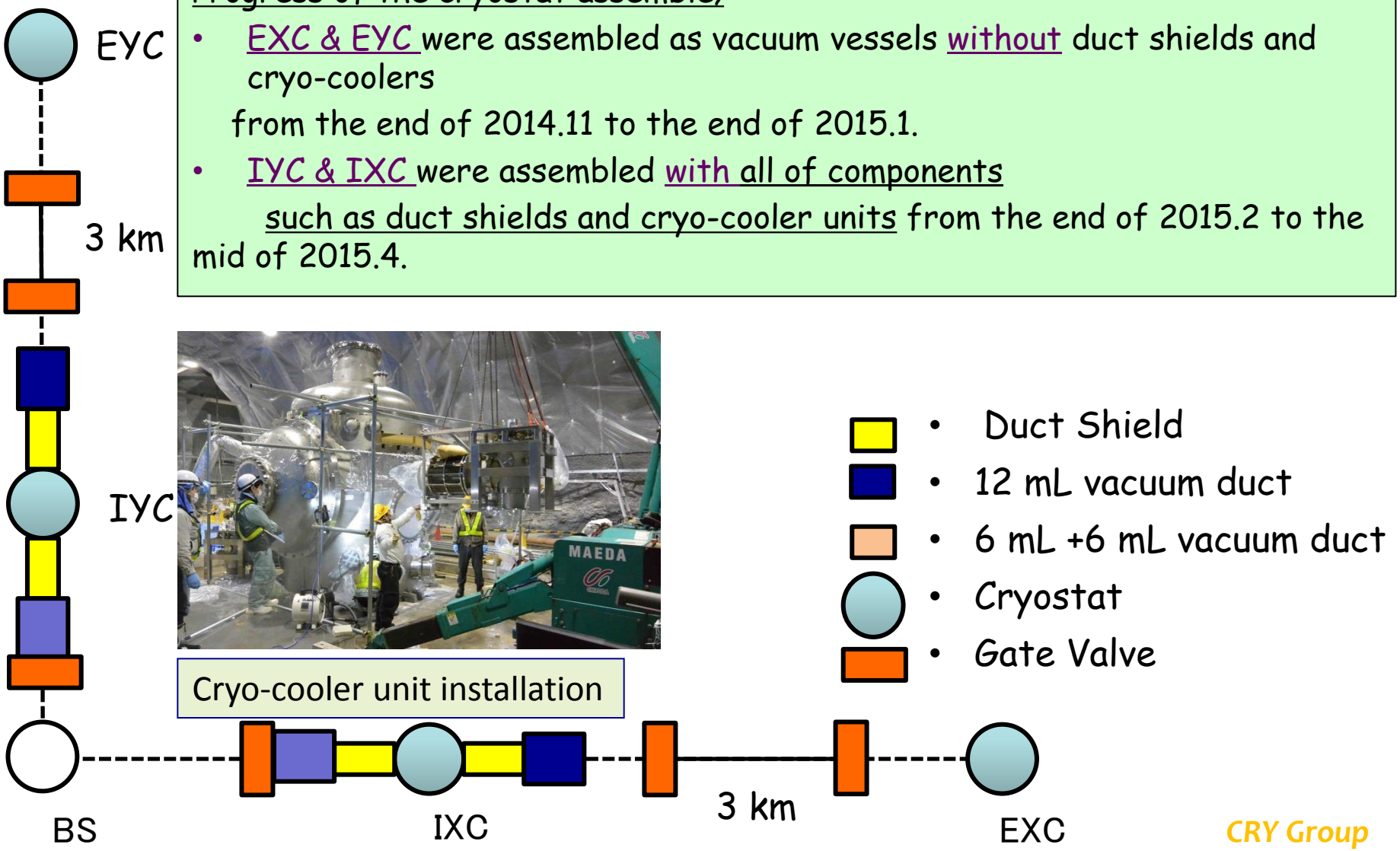
Cryostat Installation in KAGRA

Progress of the cryostat assemble;

- EXC & EYC were assembled as vacuum vessels without duct shields and cryo-coolers

  from the end of 2014.11 to the end of 2015.1.
- IYC & IXC were assembled with all of components

  such as duct shields and cryo-cooler units from the end of 2015.2 to the mid of 2015.4.

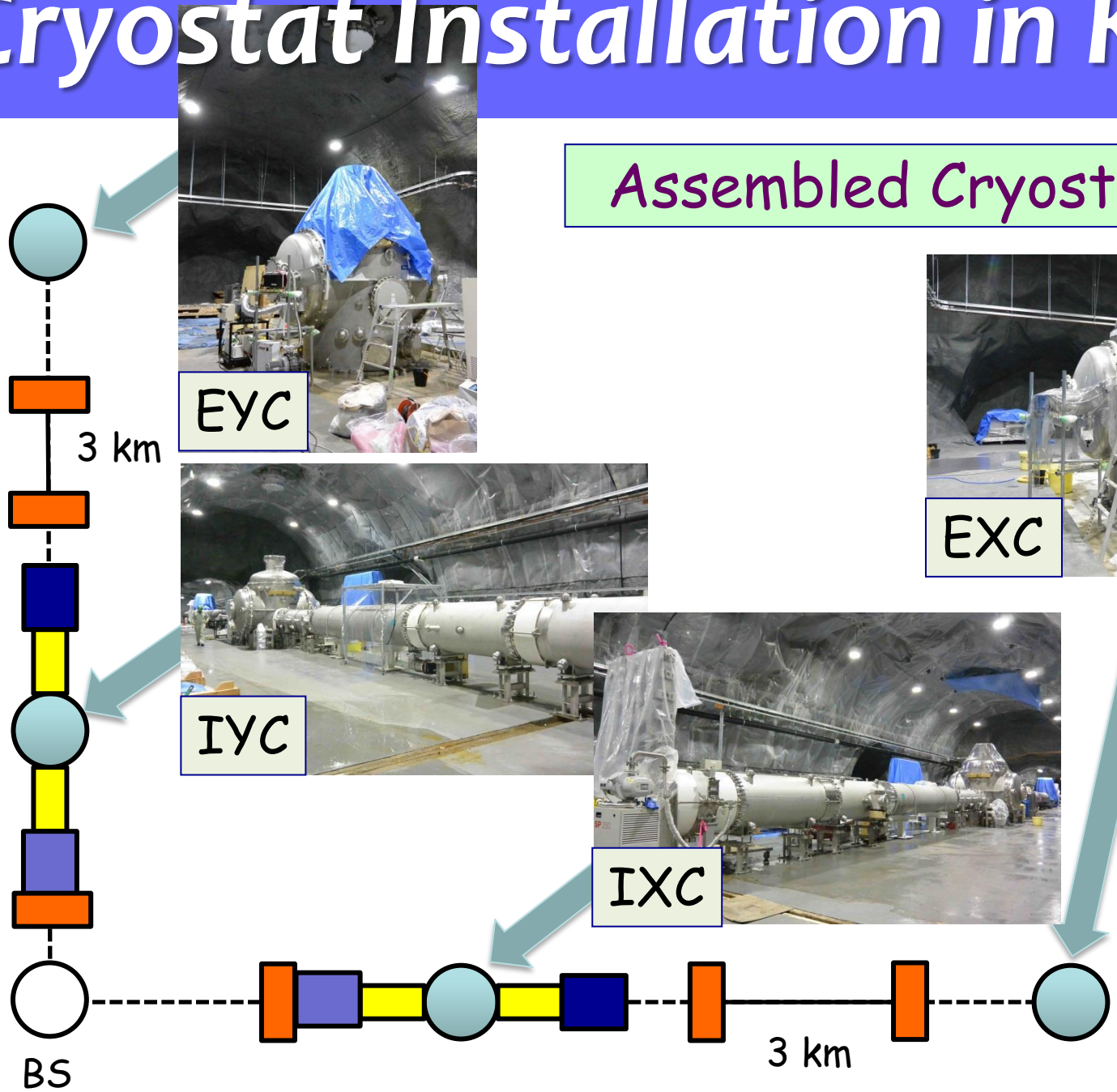


Cryo-cooler unit installation

CRY Group

Cryostat Installation in KAGRA

Assembled Cryostat Photos



Reached pressure
in the Y-front cryostat
3.7×10^{-7} kPa

CRY Group

Cryostat and Clean Booths

Y arm End Cryostat

X arm End Cryostat

Y arm Near Cryostat

X arm Near Cryostat

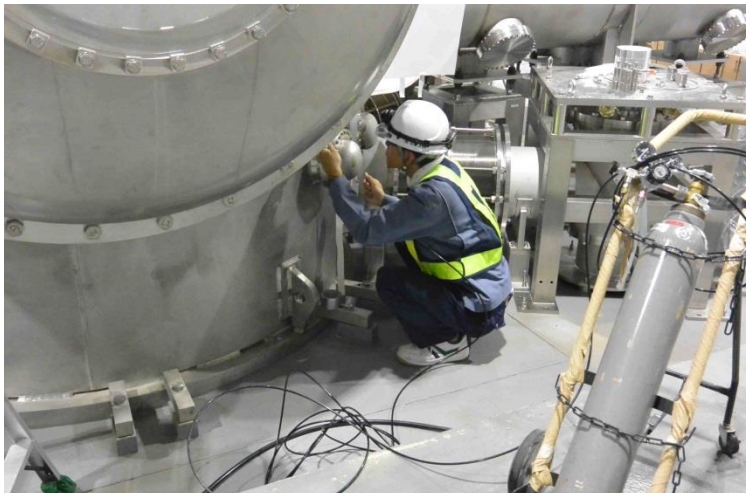
Leak Test of Cryostats

X&Y-end cryostats

- Leak test were cleared based on KAGRA requirement
  $< 1\times10^{-10}$ Pa*m^3/sec
- No excess leak found above the background
  ($\sim1\times10^{-12}$ Pa*m^3/sec)

X&Y-front cryostats

- At leak test,
  two small leak spots $< 1\times10^{-9}$ Pa*m^3/sec were founded by the reason of malfunction of gaskets.
- It should be replace until mid of September 2015.



Sapphire Mirror Suspension

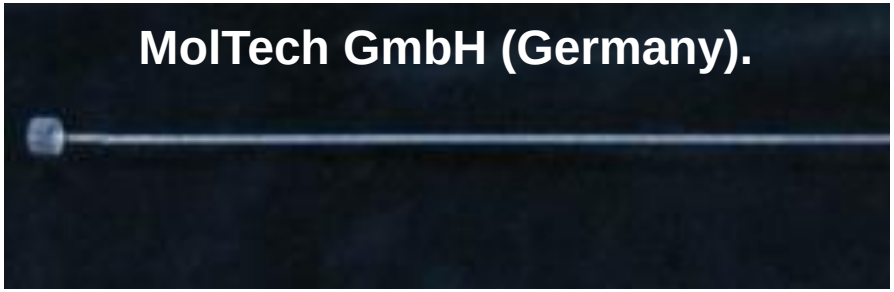
Sapphire mirror suspension is essential in KAGRA. Requirement for sapphire mirror suspension (wires) are …

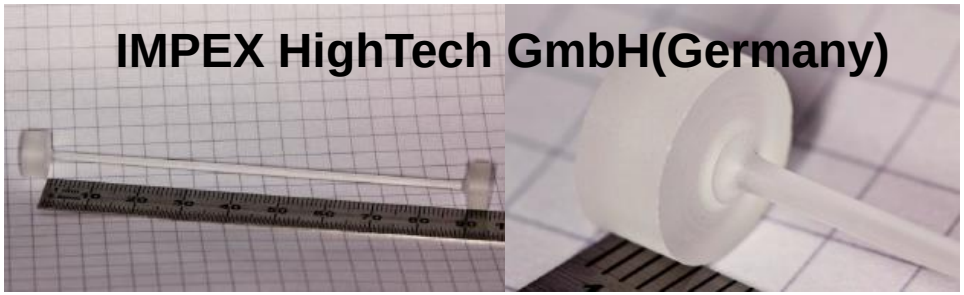
- High tolerance for tension to suspend 30kg sapphire mirror.
- High thermal conductivity to extract heat from the mirror.
- Low mechanical loss of fibers (wires) and their fixing on mirrors ($< 10^{-8}$).
- Easy assembly.
- Satisfy ultra high vacuum specification $< 10^{-7}$ Pa.

The solution is to use sapphire fibers (almost rods)

Mirror Suspension using Sapphire Fibers

- KAGRA Sapphire mirrors are designed to be suspended by sapphire fibers to obtain heat drain path and to reduce suspension thermal noise.
- Because bonding attachment is hopeless for sapphire fibers, nail heads shape is desired to huck sapphire mirrors.





Property Checks are required about ...

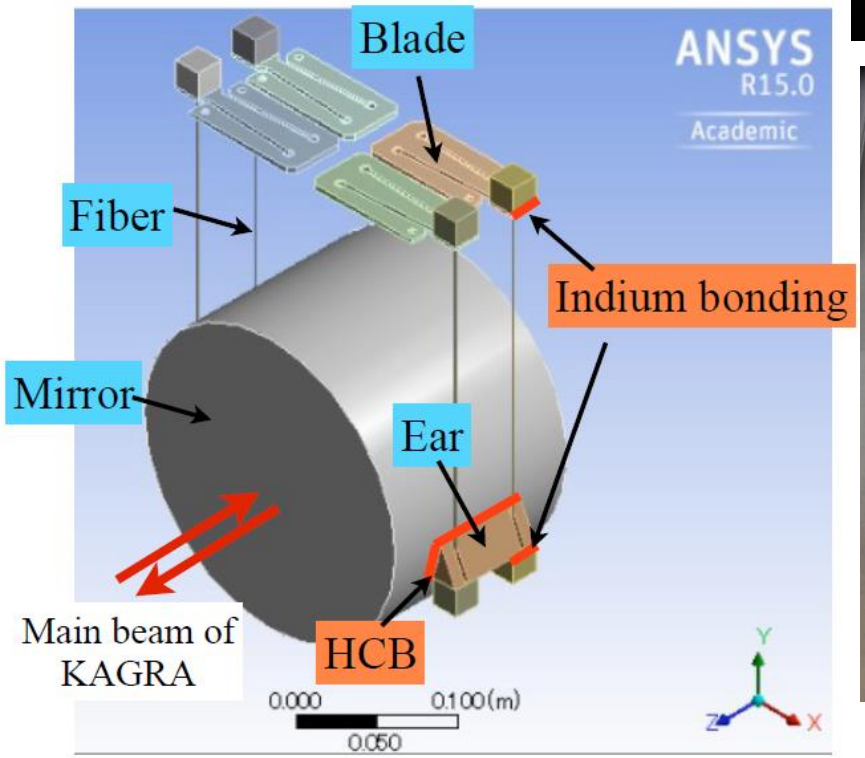
- Mechanical Loss
- Thermal Conductivity
- Strength (bending, sheer, tensile)

in Univ. of Tokyo, Jena Univ. and Roma Univ.

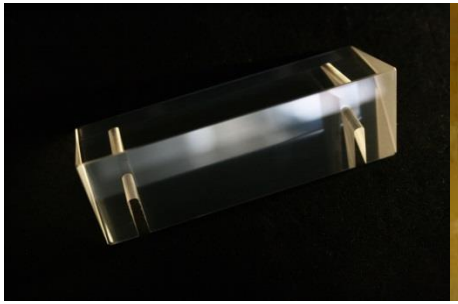
Mirror Suspension using Sapphire Fibers

(1) Sapphire lop-eared suspension

- A part of cryo-payload
- Main sapphire mirrors are included.
- All parts are made from sapphire.

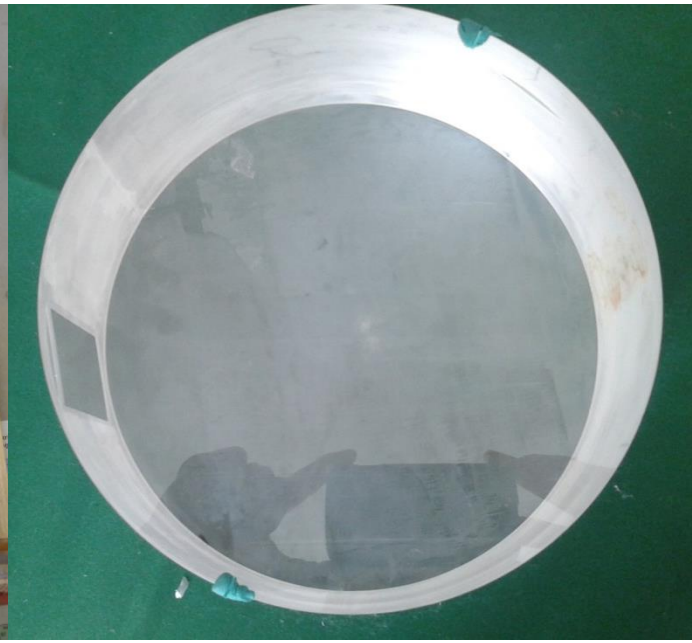


Sapphire Ear



Sapphire Blade

Sapphire rod



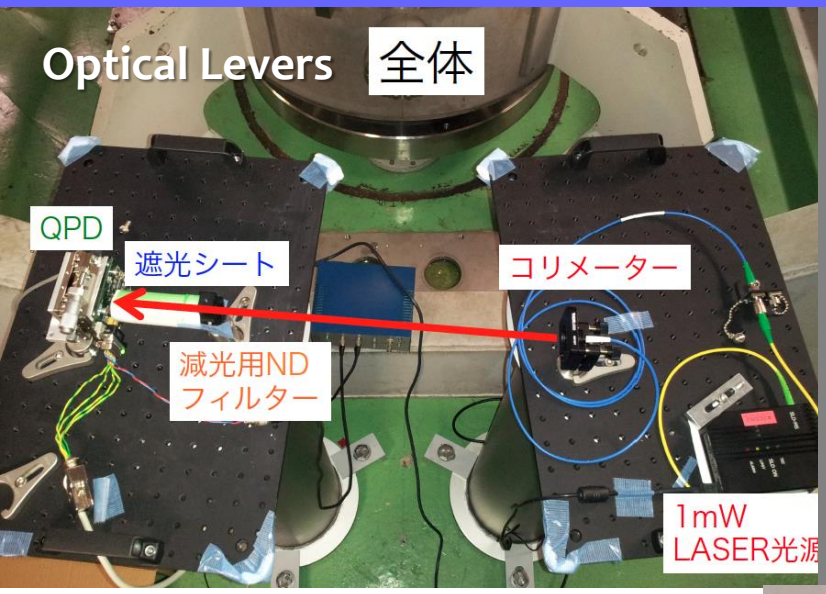
Sapphire Mirror Substrate

Auxiliary Optics

IFO control is supported by many auxiliary systems including…

- Stray Light Control (SLC) mainly to reduce scattered light noise in the sensitivity, and to avoid hazard (damage on optics, fibers) in IFO and suspension.
- Beam Reducing Telescopes to handle the large diameter laser beam from the both Fabry-Perot cavities in small size optics to monitor the FP cavity resonance and stability.
- Optical Levers to identify the mirror alignment at their local position to keep IFO mirrors' best positions.
- Viewports to inject and extract laser beams into/from vacuum area.
- Monitors (CCD cameras) and Illumination to know the many cavities resonances in IFO from the brightness on mirrors.

Scattered Light Control and Others



- Viewports
- Optical Levers (OpLev)
- iKAGRA Beam Reducing Telescopes (BRT)
- Stray Light Control (SLC)
- …

Mirror Substrate for b.KAGRA

- Al_2O_3 -

- Sapphire for b.KAGRA (= KAGRA)
  - A-axis crystal (ϕ22 cm x t15 cm) has been obtained.
  - Max size of C-axis crystal is now ϕ22cm x t15cm; this size is limited by the height of the boules of a machine in Crystal Systems LAOS Inc.
  - Several C-axis crystals (ϕ22 cm x t15 cm) have been also obtained. Now the quality check is on going.
  - Shinkosha (Japanese Company) might be able to large size low loss sapphire substrate. Shinkosya can make C-axis growing crystal.

Mirror Substrate for Others

- SiO_2 -

- SiO_2 Mirrors (ϕ250 x t100) for PR2, PR3, SR2, SR3 (Corning)., ITMs and ETMs (Heraeus).
- Coating was done in ICRR and LMA.
- Polishing by ZYGO.

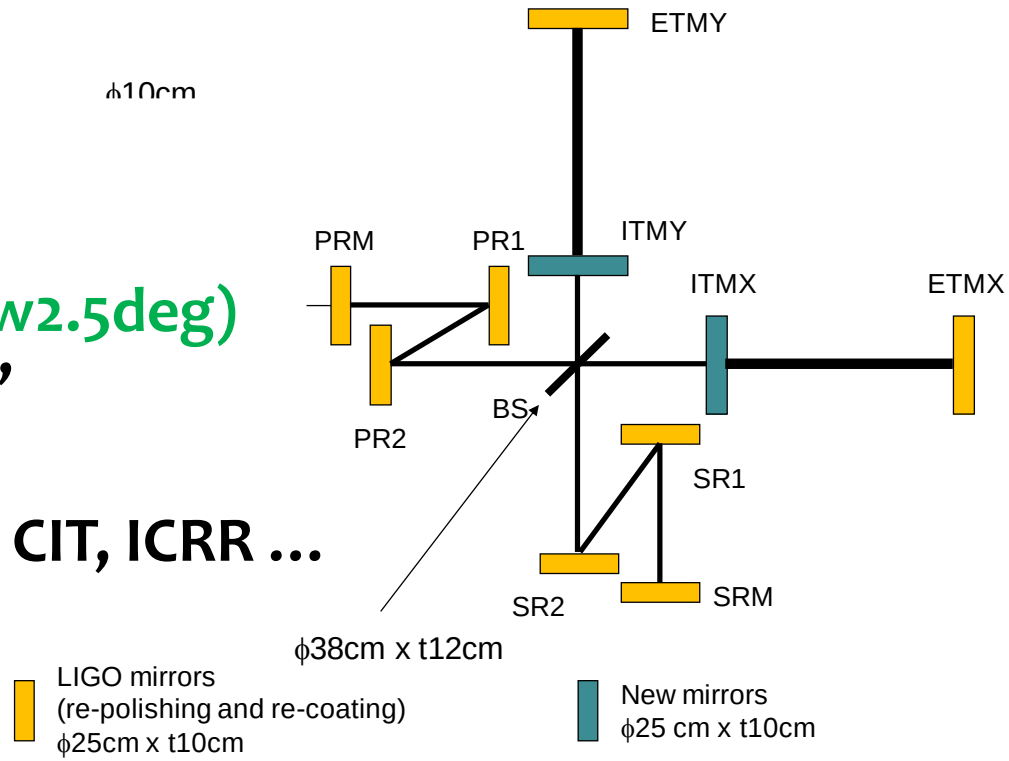
On the other hand.

- BS (ϕ370 x t80),
- PRM, SRM
- MC(ϕ100 x t30, flat & R=37.3m, w2.5deg)

were produced by "Asahi Glass"

AQ2 Quality in Japan.

- Polishing and Coating by ZYCO, CIT, ICRR …



Mirror Summary

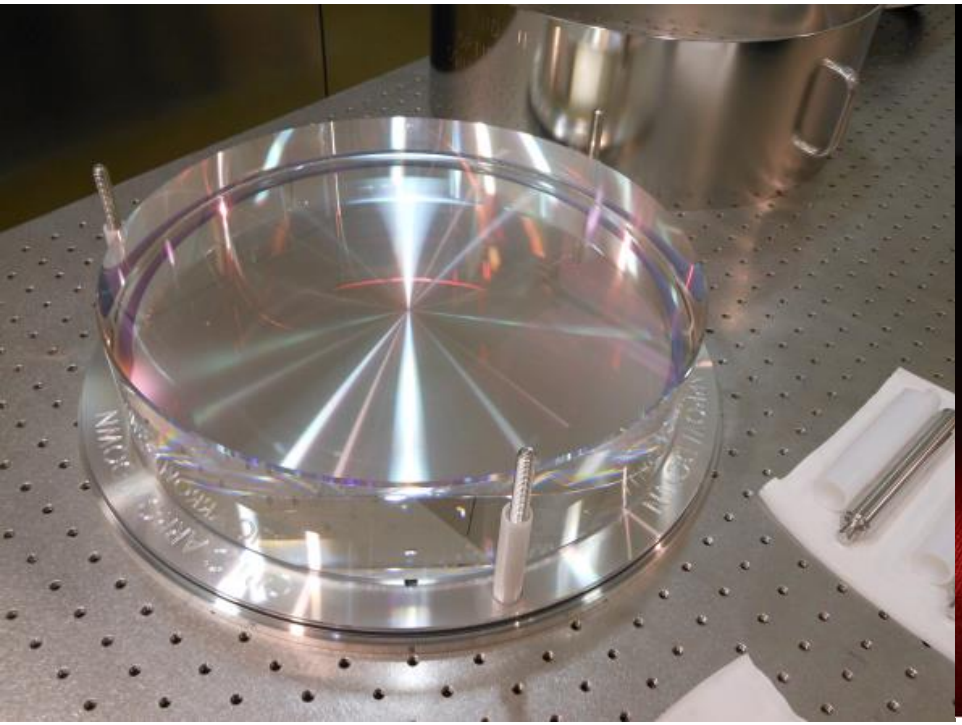
N	optic type	diameter (mm)	thickness (mm)	wedge (degrees)	mass	ROC	substrate	drawing	figure(nm) / aparture(mm)	micro roughness	test report	scatter (TIS)	absorption (coating)	HR transmission	AR reflection	absorption (bulk)	notes	status	location
1	BS	370.15–370.18	80.49 (thick end)	0.0796		S1: 689.7km@220mm, S2: 179.6km@220mm	AGC AQ2		S1: 0.705@220mm, S2: 1.58@220mm	0.23 nm		5.5–5.6 ppm		49.96%@1064nm, 99%@532nm	<30ppm@1064nm, 0.3%@532nm			completed, being characterized	CIT
2	ETM01	250.75	99.63	2		7.26km	Corning 7980										WA4K-X	as is	ICRR
3	ETM02	250.88	99.93	2		7.32 km	Corning 7980										WA4K-Y	as is	ICRR
4	ITM05m	250.97		0.042 (+-0.01)		13.9km	Heraeus Suprasil 312S										WA4K-X	modified	ICRR
5	ITM06m	250.95		0.042 (+-0.01)		13.6km	Heraeus Suprasil 312S										WA4K-Y	modified	ICRR
6	PR3	249.98	94.6 (center)	2.019		24.9165m@220mm	Corning 7940	D1402293	S1: 0.88nm@220mm, S2: 5.9nm@225mm								SPETM02, LF=49.9ppm	being coated	LMA
7	PR2	249.97	94.3 (center)	2.042		-3.076m@40mm	Corning 7940	D1402292	S1: 0.41nm@40mm, S2: 16.6nm@225mm								SPETM01, LF=20.2ppm	being coated	LMA
8	SR3	249.83	94.5 (center)	2.026		24.917m@220mm	Corning 7940	D1402296	S1: 1.09nm@220mm, S2: 5.99nm@225mm								SPETM08, LF=71.0ppm	being coated	LMA
9	SR2	250.49	95.1 (center)	2.096		-2.991m@40mm	Corning 7940	D1402295	S1: 0.44nm@40mm, S2: 3.78nm@225mm								SPETM04, LF=34.3ppm	being coated	LMA
10	MCe	95.95	29.45 (thick end)	2.5		37.3m@30mm	AGC AQ		6.7nm@50mm (w/o power)	0.1293nm@30mm		1.5ppm@70mm		4.7ppm@center	17(+-3)ppm@60mm	N/A		completed	ICRR
11	MCi	95.97	29.45 (thick end)	2.5		N/A	AGC AQ2		0.33nm@50mm (w/o power)	0.0939nm@30mm		4.5ppm@60mm		6019(+-48) ppm@50mm	410(+-68) ppm@60mm	N/A		completed	ICRR
12	MCo	95.95	29.50 (thick end)	2.5		N/A	AGC AQ2		0.30nm@50mm (w/o power)	0.1017nm@30mm		2.8ppm@60mm		6098(+-32) ppm@50mm	302(+-30) ppm@60mm	N/A		completed	ICRR
13	ETM01						CSI LAOS										sapphire		
14	ETM02						CSI LAOS										sapphire		
15	ITM01						CSI LAOS										sapphire		
16	ITM02						CSI LAOS										sapphire		
17	PRM						AGC AQ2	D1402291											
18	SRM						AGC AQ2	D1402294											
19	IMMT1																		
20	IMMT2																		

MIR (Mirror)

Check : surface radius, roughness, homogeneity, birefringence, heat absorption.

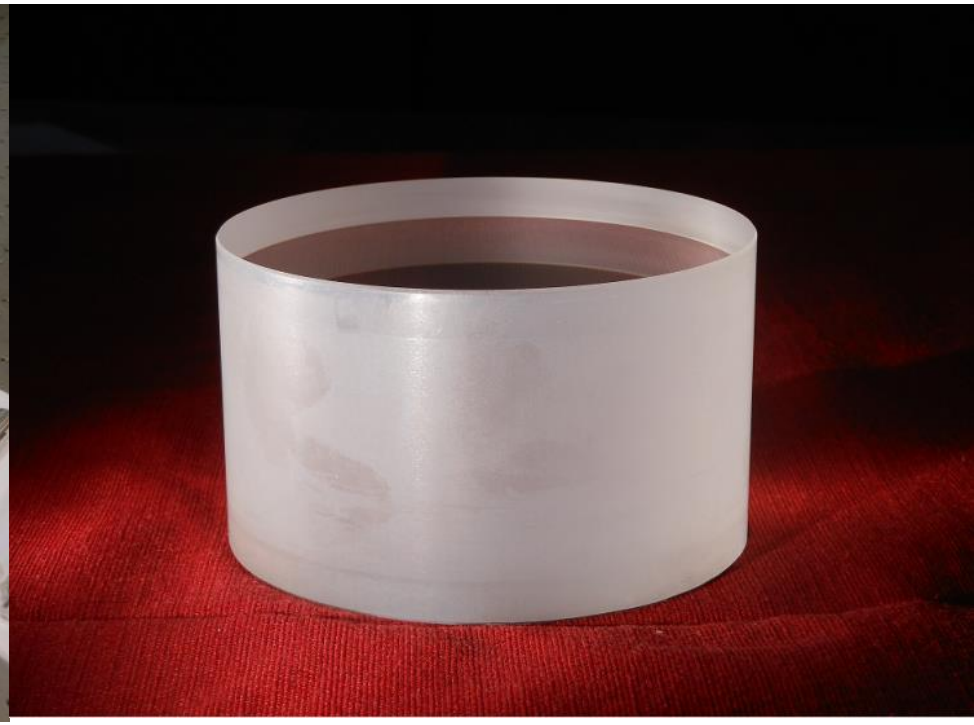
Beam Splitter

(37cmx8cm, SiO_2)



Sapphire

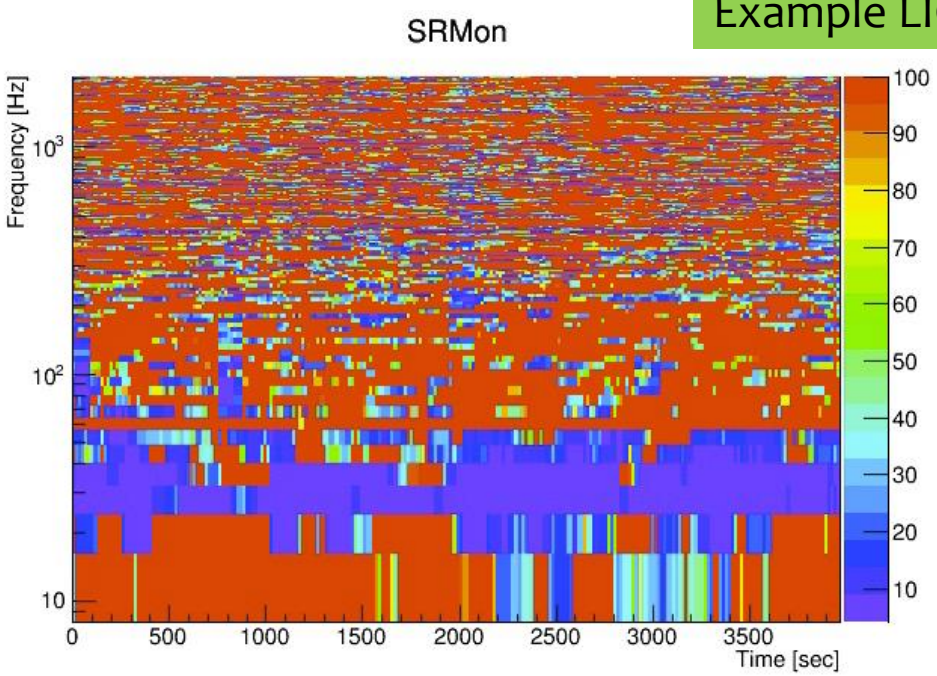
(22cmx15cm, Al_2O_3)

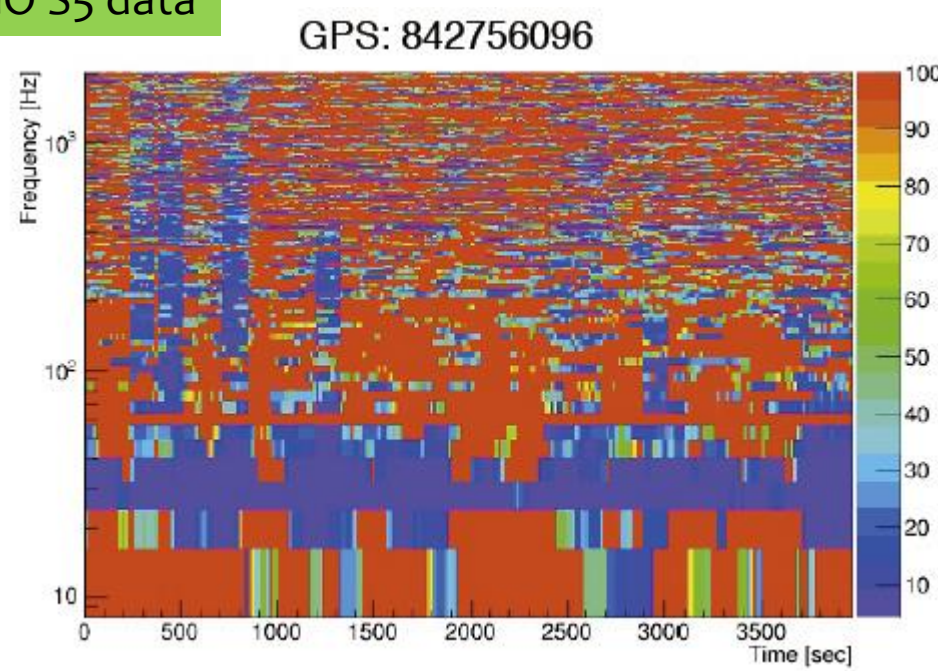


Detector Characterization

- **Development of monitor tools**
  - Non- gaussianity monitor tools and ν estimation process (non-gaussianity parameter) was verified using non-gaussian noise model.
  - Online DetChar cluster is installed.
  - Almost all important diagnostics tools are prepared.
  - Magnetic fields and seismic activities at the KAGRA site were measured

Example LIGO S5 data





DetChar Group

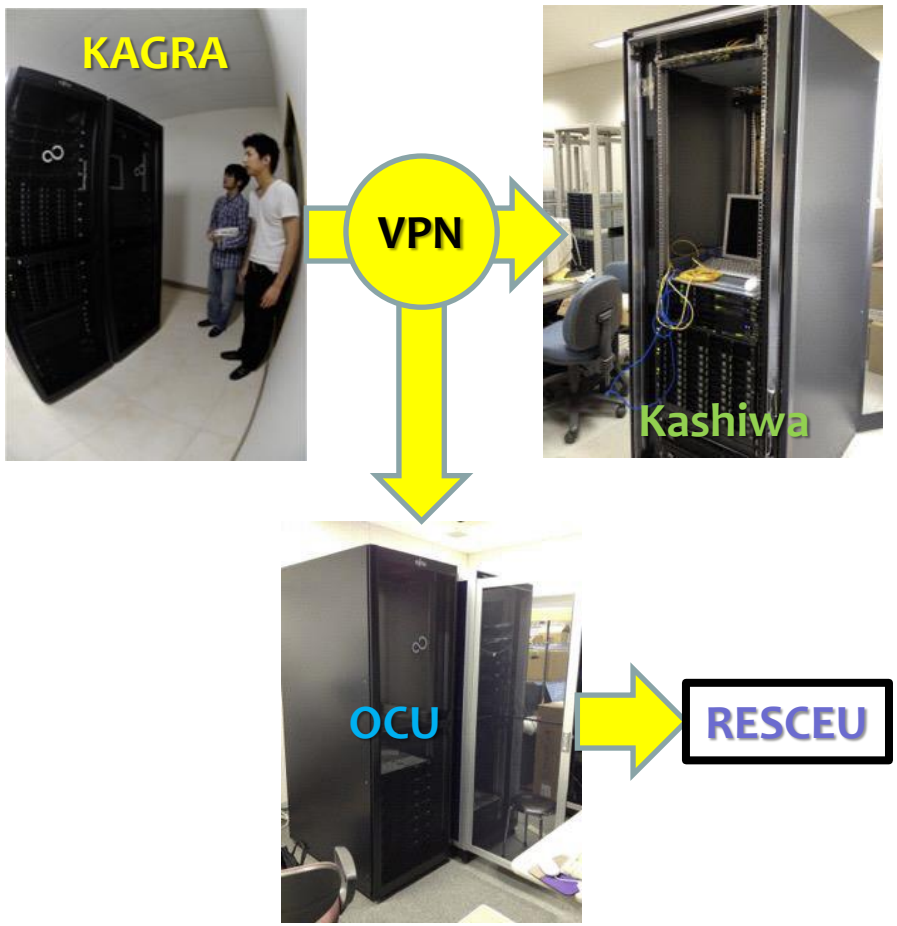
Data Analysis

- **Compact Binary Coalescence (CBC) status**
  - Frequency domain matched filtering(MF) (ICRR Cluster) : pipeline development.
  - Low latency analysis (time domain MF) (Osaka CU) : components preparation.
  - Bayesian parameter estimation : Basic study with KOREAN group
  - Alert sending system for EM partners (multi-messenger astronomy) : investigation about LIGO VIRGO case.
- **Burst status**
  - Development of single detector search pipeline.
  - Data Retrieving, Data Conditioning, Event Selection : implemented.
  - Parameter Estimation : In progress.
- **Continuous Wave(CW) status**
  - Study of LAL.
  - Development of Matlab codes using the resampling technique.
  - Radiometry GPGPU code has been developed.
- **KAGALI Development**

  KAGRA data analysis subsystem develops our own data analysis library called KAGra Algorithmic LIbrary or “KAGALI” in short.

Data Management

- **Data transfer between each computer system (ICRR-KAGRA, ICRR-Kashiwa, OCU, RESCEU).**



- **GRID transfer Tests (Nagaoka, RESCEU)**

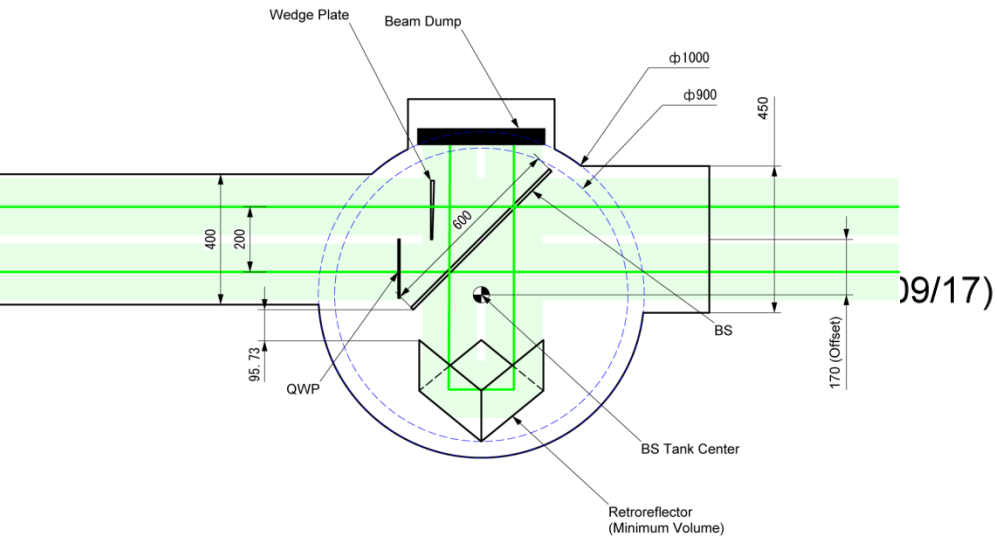
✓ Simple transfer test succeeded in 2014.
✓ Overview design is proceeding.
✓ Software (DMG pipeline) development must be done fast!
✓ Pipeline includes a processing of 'calibrated data'.

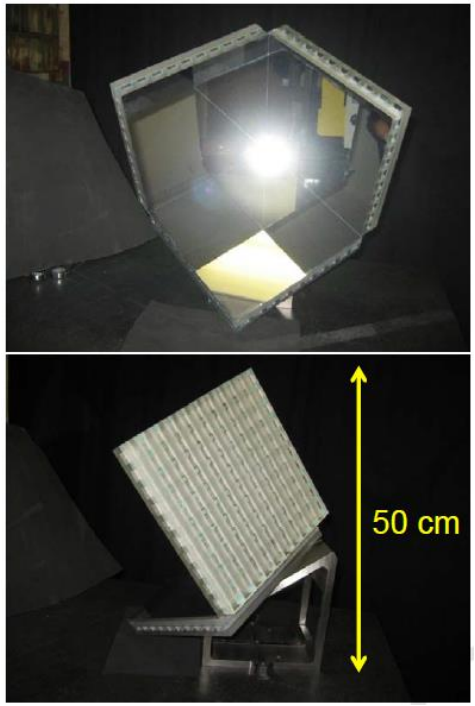
Baseline Interferometer

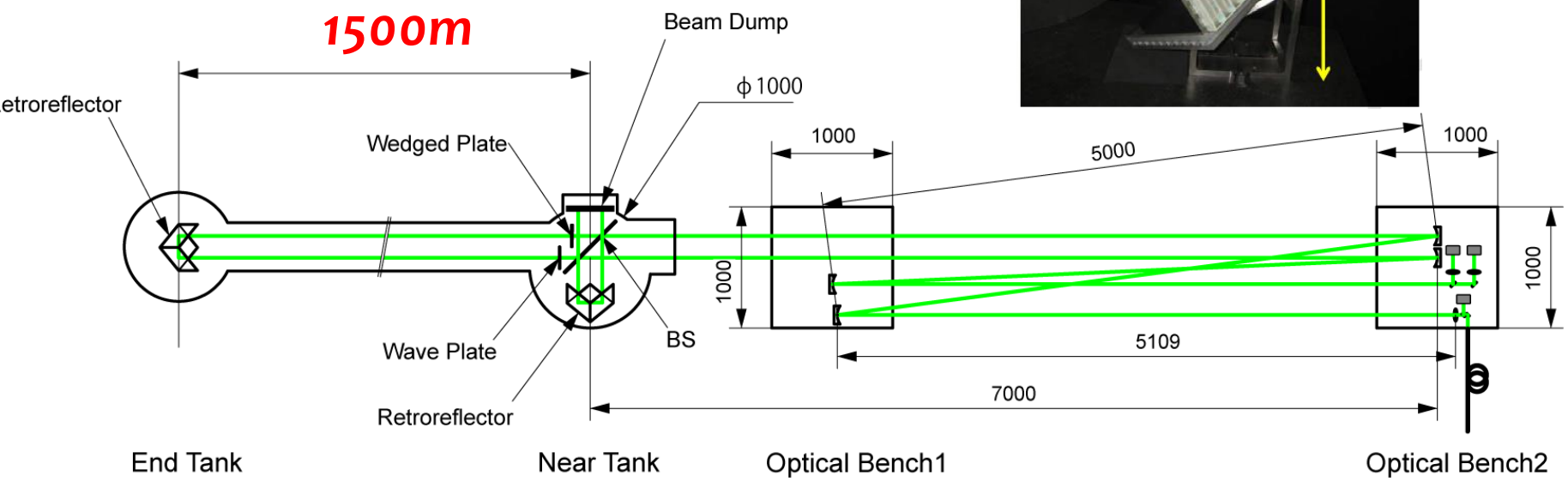
Purpose and Targets

1. Baseline monitor for KAGRA (Tides, earthquakes, crustal deformation…in the middle of Niigata Kobe Tectonic Zone)
2. Fault-creep monitor for the Atotsu fault
3. Deep interior of Earth (Monitoring Earth's free oscillations)

1500m Baseline IFOs in both arms

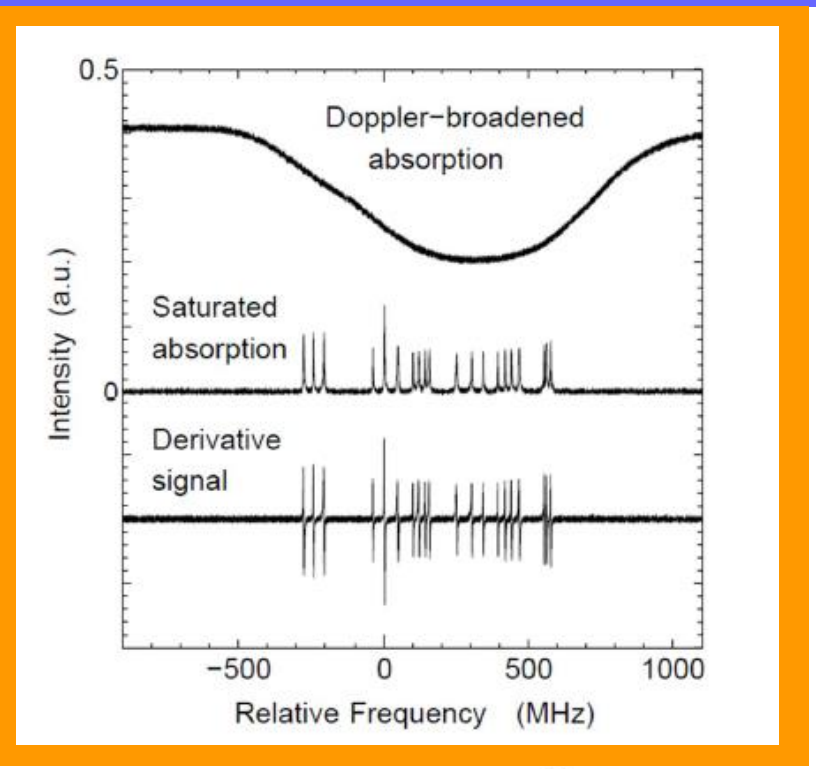




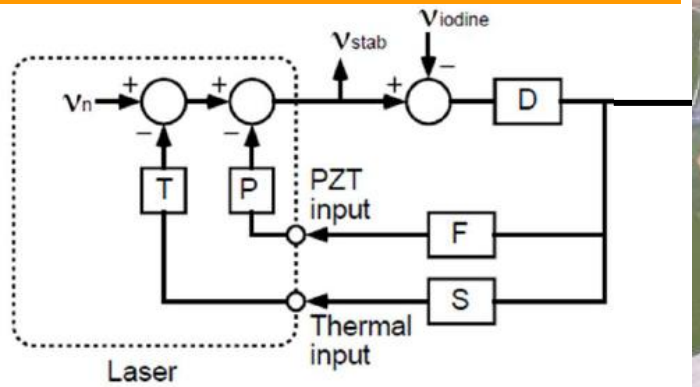


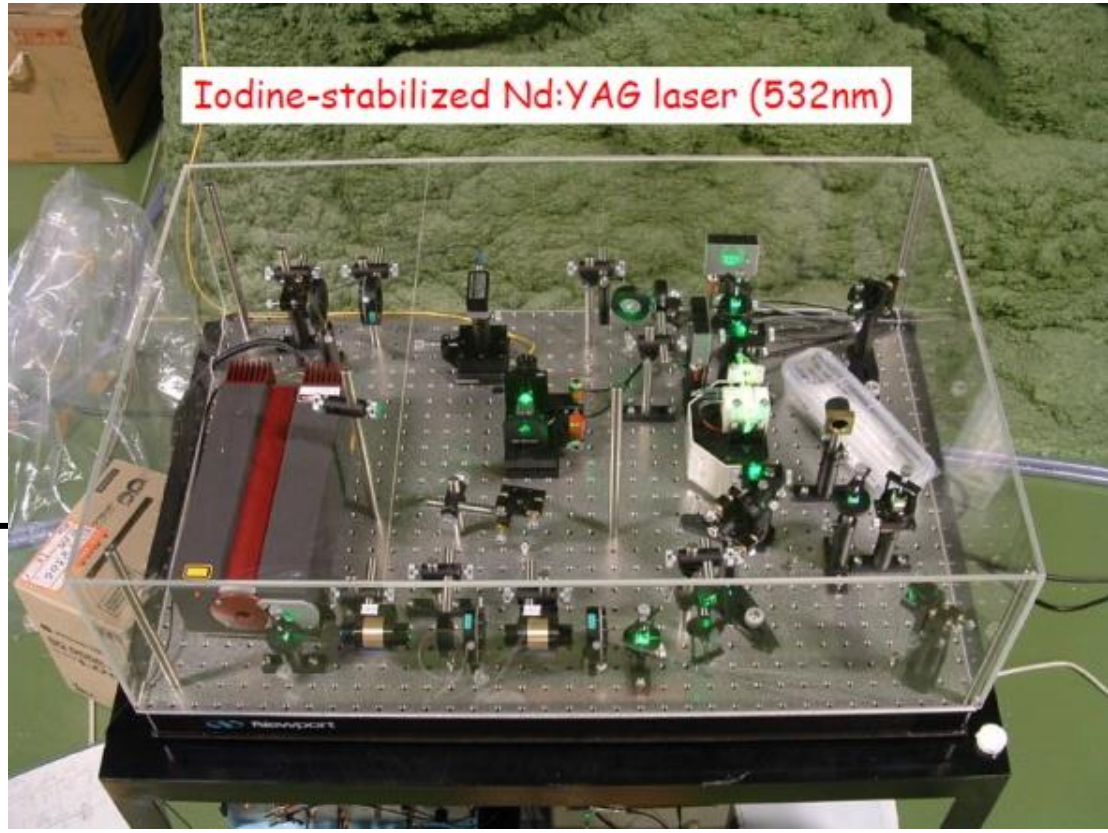
GIF Group

Iodine-stabilization System in CLIO



Frequency stability $d\nu/\nu \sim 10^{-13}$

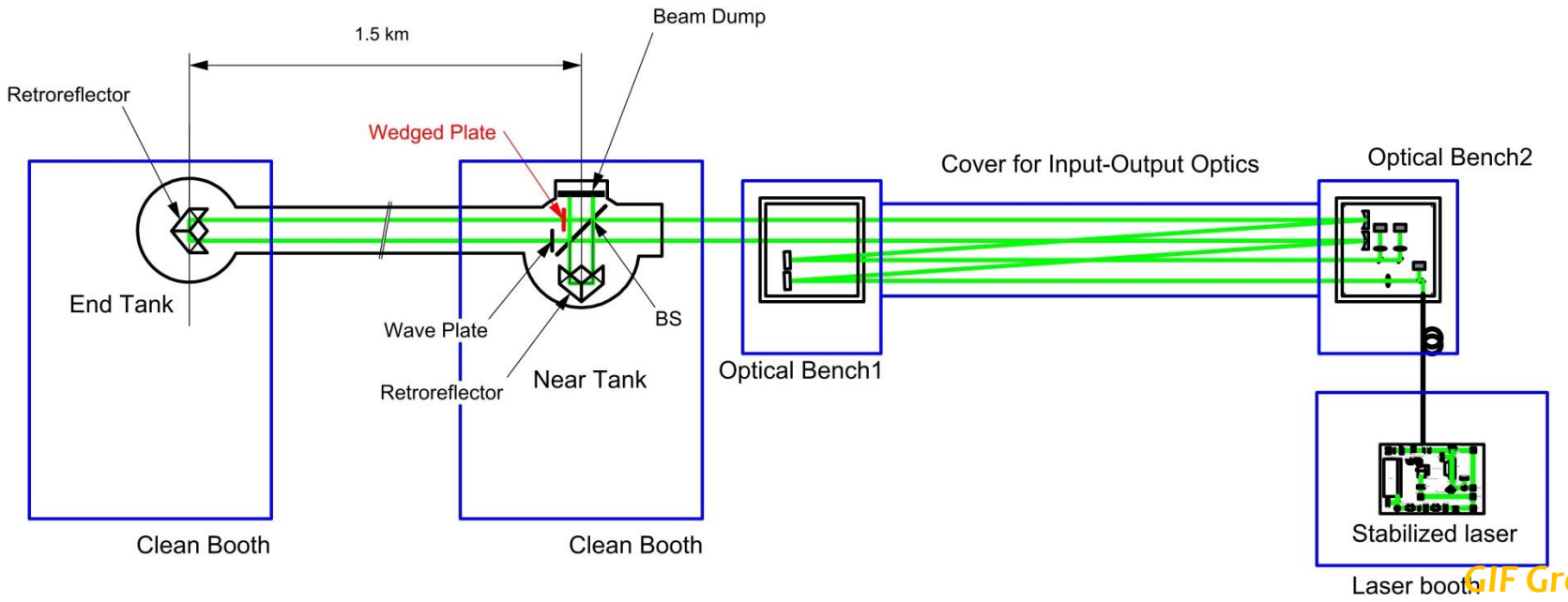




GIF Group

Construction Status in KAGRA

- **Site construction (X-arm)**
  - Clean booth construction underway
- **I_2 stabilized lasers**
  - Two units being ready for stability evaluation (beat measurement)
- **Optical components**
  - In-vacuum optics: to be installed after vacuum test
  - Out-vacuum optics: ready for installation



GIF Group

Summary

- *Fundamental techniques for KAGRA have been prepared by TAMA and CLIO and KAGRA Collaborators.*
- *KAGRA started in 2010.*
- *Tunnel was finished in FY2013, facility including clean booths and vacuum system were done in FY2014.*
- *The iKAGRA is planed in December 2015.*
- *The bKAGRA will start after iKAGRA short observation.*
- *Although there are many to do in the future tasks and problems in the finished tasks, we keep proceedings and improving them step by step.*