Current status of Large-scale Cryogenic Gravitational wave Telescope (LCGT) Project

Institute for Cosmic Ray Research and LCGT Collaboration

TAUP2011 @ Munich Sept 8th 2011

LCGT Collaborators

ICRR, Univ. of Tokyo
Nacional Astronomical Observatory of Japan,
High Energy Accelerator Research Organization,
Phys.S. Univ. of Tokyo,
GSFS Univ. of Tokyo,
F.Eng. Univ. of Tokyo,
Tokyo Institute of Technology,
Osaka City Univ.,
Phys.S. Kyoto Univ.,
Electro Communication Univ.,
ERI. Univ of Tokyo,
Astro. Univ. of Tokyo,
Hosei Univ., AIST,
NICT,
Phys.S. Osaka Univ.,
YITP Kyoto Univ.,
Phys.S. Ochanomizu Univ.,
ARISH Nihon Univ.,
S. Niigata Univ.,
Yamanashi-Eiwa Univ.,
CIT Nihon Univ.,
FST Hirosaki Univ.,
S. Tohoku Univ.,
S. Rikkyo Univ.,
S. Hiroshima Univ.,

S. Ryukyu Univ.,
FSE Waseda Univ.,
Gunma Astronomical Observatory,
Max Plank Inst. AEI,
California Institute of Technology,
Phys.S. Univ. of Western Australia,
Louisiana State Univ.,
CGRG Rochester Institute of Technology,
Astro. Beijing Normal Univ.,
Inter-University Center for Astronomy and Astrophysics, Moscow Univ.,
LATMOS/CNRS,
Univ. of Science and Technology of China,
Inst. for High Energy Physics of Chinese Academy of Sciences,
Peking Univ.,
CMS ITR Taiwan,
Maryland Univ.,
Columbia Univ.,
Glasgow Univ.,
Sannio Univ.,
LCGT highlights are ...

1. **Underground** → Stable Operation owing to low seismic noise.
2. **Usage of Cryogenic Mirrors and suspensions** → Reduction of Thermal Noise
3. **Collaboration with Geophysical Laser Strain-meter**
No problem (so far).

A half of year delay, but it was approved.

In the Univ. of Tokyo budget request item To MEXT. But not optimistic at all.

To be requested.

T.Kajita
LCGT Construction Schedule

<table>
<thead>
<tr>
<th>Year</th>
<th>LCGT</th>
<th>LIGO (H)</th>
<th>LIGO+ (S6)</th>
<th>Adv.LIGO</th>
<th>Virgo</th>
<th>Adv.Virgo</th>
<th>GEO</th>
<th>AIGO</th>
<th>ET</th>
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<tbody>
<tr>
<td>10</td>
<td>Initial-LCGT Construction</td>
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<td>baseline-LCGT Construction</td>
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</table>
Collaboration 1

● With LIGO
  • Some members visits and help, LIGO mirror rent, Design tool for IFO, Digital Control system, DCC access.

● With VIRGO
  • ICRR-VIRGO meeting, Exchange of academic agreement (Pro. Fidecaro, Pro. Flaminio, Pro Mours, Pro Ricci).
  • Italy-Japan conference will be held in October in Tokyo.

● With GEO
  • MOU with Glasgow Univ., (Pro.Hough) AEI., Collaboration on some R&Ds about suspension and optical coating mechanical loss.

● With University of Sannio
  • Academic agreement, Researcher exchange, and so on (Pro. De Salvo).

● With SUCA
  • Academic agreement, Collaboration on advanced IFO and data analysis (Pro. Ni).

K.Kuroda
Collaboration 2

- **With NIKHEF**
  - Collaboration on SAS system (Pro. Jo van den Brand).

- **With ET**
  - IRSES program between EU and Japan might be approved in 2012-2015?
  - Collaboration on SAS and suspension system.

- **With US group**
  - Collaboration on 3rd generation detector in USA (Pro. W. Johnson).

- **With Korean Group (KGWG, KIAS)**
  - Collaboration on laser and optics, data analysis (Pro. Yoon).
initial-LCGT (2010~2013)

- Fabry-Perot Michelson Interferometer
  - Mirrors and suspensions are set at room temperature.
  - SiO2 Mirrors.
  - 10W level laser sources
  - Negligible thermal distortion of mirror shape.
  - RF readout
  - Low frequency seismic noise isolation function in SAS are disable

- Targeted Sensitivity (for compact binary coalescences)
  - 5Mpc (SNR=8, Sky Averaged)
  - Displacement noise is limited by seismic and shot noise.

- Short Observation (for thrashing out problems)
baseline-LCGT (2013~2015~2016)

- Toward the Targeted Sensitivity
  - 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
Possible Sensitivity Limit of LCGT

- In order to attain the sensitivity to catch the event at \(~231\text{Mpc (SNR}=8)\), we need to reduce shot noise determined by 800kW optical power (400 kW).
- Thermal noise of the mirror, coating of the mirror, and suspension need to be suppressed by cryogenic temperature, 20K. Mechanical losses of these parts are required to satisfy this thermal noise limit; they are $10^{-8}$, $4\times10^{-4}$, $10^{-8}$
- Final sensitivity is limited by quantum noises in the observation frequency band, 230Hz. Radiation pressure noise is determined both by the optical power and by mass, 30kg $\Rightarrow$ ??
GW detection network

A part of budget of LCGT was approved. Anyway we can start LCGT!
LCGT contribution in the world network for GW detection

(1) Long distance between GWDs
   (20 mili-seconds time flight among North America, Europe and Asia)
(2) Angular dependence of GWDs

LCGT and LIGO/H-LIGO/L-Virgo can cover almost 100% of the sky.

By B. Schutz (@Fujihara seminar, May 2009)
LCGT Excavation

(Budget including excavation was finally approved in August 2011 (→ April 2011))

Location of Center (BS)
- latitude: 36.42°N, longitude: 137.30°.
- X arm direction: 300°, Y arm direction: 30°.
- Height from the sea level: about 372,000m.

- Over 200m ground coverage
- Tilt: 1/300

Water drain point

T.Uchiyama

Tilt: 1/300
Tunnel Design

The latest map of LCGT

1. Center parking
2. Center front room
3. Center experiment room A
4. Center experiment room B
5. Center experiment room C
6. Laser room (Deleted)
7. X-front cryostat room
8. X-front VI room (2F)
9. Front machinery room
10. Front VI preparation room (2F)
11. Y-front cryostat room
12. Y-front VI room (2F)
13. Approach for front VI room
14. Geo-phys X-front
15. Sakonishi front
16. Sakonishi front parking (Deleted)
17. Geo-phys X-end
18. X-end cubicle room
19. X-end cryostat room
20. X-end VI room (2F)
21. X-end machinery room
22. X-end VI preparation room (2F)
23. Approach for X-end VI room
24. X-end experiment room
25. X-end staff room
26. Geo-phys Y-front
27. Geo-phys Y-end
28. Y-end cryostat room
29. Y-end VI room (2F)
30. Y-end machinery room
31. Y-end VI preparation room (2F)
32. Approach for Y-end VI room
33. Y-end experiment room
34. Cryogenic experiment room (Deleted)
35. Y-end staff room
36. Y-end parking

Xarm and Yarm cross perpendicularly at the center of BS chamber.

3km:
- X: (25+2m) from BS - Center of X end cryostat room
- Y: (25-2m) from BS - Center of Y end cryostat room
**TBM will be used for all arm tunnels.**
Center Room Design

- Double layer structure for main mirror positions.
- Slope for the second floors.

Other notes:
- Shorter center exp. room C but Longer center exp. room B
- Wider crane span
- Longer center exp. room A
- Longer center front room but Shorter parking area
Double Layer Structure
Optical Layout for \textit{i.b.LCGT}

- ITM position is about 50 meters away from BS due to radiation shield duct that is extended from baseline ITM position.
A unit tube (12 m long and 0.8 m in diameter, SUS) production of the first lot (120 of 500) was started in this July.

- Chambers (2 m in dia.) //stack + D-Pendulum//
- Double chambers (2.4 and 1.5 m in dia.) //GASF + I-Pendulum + cryogenic//
- Chambers (1.5 m in dia./2 m for BS) //GASF + I-Pendulum//

Requirement: $10^{-7}$ Pa

Y. Saito
Vacuum Requirement
- Manufacturing of 12-m long tube -

* electro polishing and rinsing

Electro polishing
- current density; 20 A/dm²
- removal; 30-40 mm
- Ry ~ 2.5 mm

Rinsing
- pure water; 15 MW

A test product of 4-m long tube; a half of the inner surface was electro polished.

San-ai Plant Co., Kisarazu
Vacuum Requirement
- Manufacturing of 12-m long tube -

* pre-baking → dry air venting →
seal

Furnace
(200°C, ~3days)
Vacuum Tube Production
- Stock of 12-m long tubes -

- storage
(one year, or more, before installation)

→ in the railway tunnel

Mozumi tunnel of Kamioka Mining Railway (not in service)
Laser Power and wavelength
200W, 1064nm (→ 1550 nm ??)

Mirrors
Sapphire/Silicon(20K)

Finesse and Power in Cavity
1550, 400kW

One suspended
Mode Cleaner (13~26 m)

Rigid Pre-MCs will also be introduced.

Folding structure
For Power and Signal Recycling Cavities
• Length signal obtain position, phase, noise estimation are finished.

• ASC signal shows some problems to deteriorate sensitivity due to suspension pitch resonances. (to do item)
## Optimal Configurations

**ITM Spot: 3.5cm, ETM Spot: 4.0cm (IR=245Mpc)**

<table>
<thead>
<tr>
<th>(b) Positive (14km - 7.5km)</th>
<th>Displacement of mirrors:</th>
<th>PRM/SRM: 3.7cm, PR2/SR2: 1.8cm</th>
<th>PRC-Arm Mode Matching: 99.99%</th>
<th>Input beam - PRC Mode Matching: 99.97%</th>
<th>One-way Gouy phase: 21deg</th>
<th>Unstable Kopt: 24.4 N·m/rad</th>
</tr>
</thead>
</table>

| (b) Negative (1.68km - 1.87km) | Displacement of mirrors: | PRM/SRM: 34cm, PR2/SR2: 17cm | PRC-Arm Mode Matching: 99.99% | Input beam - PRC Mode Matching: 99.8% | One-way Gouy phase: 22deg | Unstable Kopt: 4.5 N·m/rad |

| **ITM Spot: 4.0cm, ETM Spot: 4.0cm (IR=248Mpc)** | (c) Positive (13.2km - 13.2km) | Displacement of mirrors: | PRM/SRM: 1.5cm, PR3/SR3: 2.2cm | PRC-Arm Mode Matching: 99.99% | Input beam - PRC Mode Matching: 95% | One-way Gouy phase: 30deg | Unstable Kopt: 33.4 N·m/rad |
|-----------------------------------------------|-----------------------------|---------------------------------|-----------------------------|----------------------------------------|--------------------------|--------------------------|

| (c) Negative (1.69km - 1.69km) | Displacement of mirrors: | PRM/SRM: 26cm, PR2/SR2: 13cm | PRC-Arm Mode Matching: 99.99% | Input beam - PRC Mode Matching: 92% | One-way Gouy phase: 34deg | Unstable Kopt: 4.3 N·m/rad |
Requirements for Folding Cavity
- to obtain separated alignment sensing signal for ITM and PRM -

For bLCGT configuration (1.6-1.9km arm cavity)

- Mode mismatch of PRC by ROC error
  - ROC error (1%) of PR2 reduce the mode match down to 98%
  - ROC error (1%) of PR3 reduce the mode match down to 88%.
  ⇒ ROC error of PR3 is serious

- Recovery of mode match by changing position of mirrors
  - It is possible to recover the mode match up to almost 100% by changing length of mirrors by ±14 cm for the ROC error (1%) of PR3.
  ⇒ PRM position need to move over 28 cm. It is possible.
  ⇒ Gouy phase aberration is ±0.3°
  - Error of correction length need to suppress within ±1 cm to recover the mode match up to 99%.

- Degeneracy with higher order modes
  - PRC does not degenerate with HOMs in order of (n+m)<10.
  - Requirement for the folding angle is less than 1 degree.

The similar result was obtained for iLCGT configuration (Flat-7km arm cavity)
Most of the main elements will be obtained by March 2012.

The first laser will be hopefully completed before March 2013.

Green lasers for green locking will be prepared by March 2012. They will be INNOLIGHT PROMETHEUS.
Items to be tested for Laser

- Performance of the fiber amplifier
  - 10-W one is OK but 40-W one has not been tested.

- Performance of the coherent addition system
  - The fringe contrast, phase stability and so on.

- Performance of the laser module when used as an amplifier.
  - Optimization of the beam profile for obtaining the best amplification performance.
  - Polarization stability, noise level should be tested.

- Fix the specifications for the control system (interfaces to a PC and other systems)
  - Discussion about the assembling with a company is necessary.
Mirrors for i.LCGT

• SiO2 Mirrors (substrate: \( \Phi 250 \times t100, 10kg \)) for PRs for folding in PRC, SRs in SRC and ETMs.
• Coating will be done in Japan.
• Polishing might be by a company or RIKEN Group in Japan.
  On the other hand.
• BS (\( \Phi 380 \times t120 \rightarrow t80?? \)),
• ITMs
• MC (\( \Phi 100 \times t30, \) flat & \( R=40m \) w2.5deg) are newly produced by “Asahi Glass” AQ2 Quality in Japan.
• Polishing and Coating might be by CSIRO ...

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12th International Conference on Topics in Astroparticle and Underground Physics 5 – 9 September 2011, Munich, Germany
Mirrors for b.LCGT
- Al2O3 -

$b.\text{LCGT}$ ( = LCGT)

- A-axis crystal ($\phi 25\text{cm} \times t 15\text{cm}$) has been ordered.
- Max size of C-axis crystal is now $\phi 22\text{cm} \times t 15\text{cm}$; this size is limited by the height of the boules.
- Absorption is still unclear; new small samples are being AR-coated. We need further days for obtaining the information (improved or not).
Vibration Isolation System

- Type-A: IP + GASF (4 stage) + Payload (23kg, cryogenic)
- Type-B: IP + GASF (2 stage) + Payload (10kg/20kg, room temp.)
- Type-C: Stack + Single/Double-pendulum (~1kg)
Pendulums (Type-A)

- **Type-A (2-layer structure)**
  - 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
Pendulums (Type-B)

- **Type-B**
  - IP base is supported by the outer frame.
  - Stack is used for small optics.
  - Pre-isolator is the same as Type-A’s.
Pendulums (Type-C)

- **Type-C**
  - Stack is designed based on TAMA’s one.
  - Rubber for stack is enclosed by bellows.
  - Differential evacuation is necessary for the bellows.
The isolation above 3Hz is due to a heat link of 0.03Hz.

The 1% coupling from vertical displacement is comparable with the horizontal one.

Predicted displacements are consistent with the IFO requirement above 5Hz.
Construction Status

- standard filter and top filter -
Isolation Performance (Type B)

- Calculation for the Type-B system does not contain the effects due to the support structure for the IP.

- Almost main optics are suspended by the Type-B payload on the stack in iLCGT.
## Expected Residual RMS

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<thead>
<tr>
<th></th>
<th>i.LCGT</th>
<th>b.LCGT</th>
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<tbody>
<tr>
<td><strong>Target</strong></td>
<td>Calculation</td>
<td>Requirement</td>
</tr>
<tr>
<td>Displacement @10Hz [m/rHz]</td>
<td>$3 \times 10^{-17}$</td>
<td>$4 \times 10^{-20}$</td>
</tr>
<tr>
<td>RMS (velocity) [μm/s]</td>
<td>$3.1$</td>
<td>$0.1$</td>
</tr>
<tr>
<td>RMS (displace.) [μm]</td>
<td>$2.2$</td>
<td>$0.1$</td>
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</tbody>
</table>
Rigid-Body Models of SAS

- Seismic noise induced motion of TM, with/without eddy current damping
Cryostats

- **Low vibration 4K cryocooler unit (prototype)**
  - Manufactured one unit
  - Performance test in progress at KEK, detail will be presented by N. Kimura.
- **Low vibration 4K cryocooler unit (actual)**
  - Manufacture 7 units in 2011fy.
  - Cost may be 33% larger than the initial estimation.
  - Bidding on 9/5, opening on 9/20
  - Candidate companies: 4?
- **Cryostat /Mirror chamber**
  - Machine 4 sets of components and partially assembling.
  - Cost may reduce 46% from the initial estimation by restriction of manufacturing period.
  - Bidding on 9/5, opening on 9/21
  - Candidate companies: 3?
- **Other expenses**
  - Purchase instruments for measurement, trial manufacture, preparation of samples, machining jigs, etc

Kimura
Required Issues for Cryostats
Conceptual Design

- 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.

Baffles for stopping thermal radiation

To SAS

Inner and Outer Shields

Ultra-low vibration Cryocooler (1W @ 4.2K)

T. Suzuki
Cryostats

Stainless steel t20mm
Diameter 2.4m
Height ~3.8m
M ~ 10 ton

Remote valve
Low vibration cryocooler unit

Drawn by S. Koike (KEK)

Cryocoolers
Pulse tube, 60Hz
0.9 W at 4K (2nd)
36 W at 50K (1st)

Cryostat accompany with the four cryocooler units
Inner Structure of Cryostats

Double radiation shields with hinged doors

Support rods

Heat path to cryocooler

View Ports

Al t=10mm

扉重量: Inner~18x2kg
Outer~24x2kg

S.Koike
Estimated Heat Budget

Estimated Heat Loads at the radiation shields and Support posts and rods

- 90 W by the top of the 80 K shield
- 2.2 W by the radiation at 8 K inner shield
- 2.4 W by the radiation and conduction (support posts and tension rods) at 8 K
- 24 W by the radiation and conduction (support posts and tension rods) at 80 K

Connection point with IM

dT_{1st} = 26 K

47 K at 1st stage of Cryo-cooler

7.4 K at the top of the 80 K outer shield

94 K

Very High Purity Aluminum Conductor

6.5 K at 2nd cold stage of Cryo-cooler

dT_{2nd} = 0.5 K

Low Vibration Cryo-cooler unit
## Estimated Heat Budget

### 1st Cold Stage

- **Outer Shield (W)**
  - Eleven View Ports: 22
  - Radiation from 300 K: 70
  - Support post and Rods: 24
  - Electrical wires: $3 \times 10^{-4}$

**Total**: 116 W/unit

### 2nd Cold Stage

- **Inner Shield (W)**
  - Duct Shields*: < 0.05 (Beam and SAS)
  - Eleven View Ports: 0.4
  - Radiation from 80 K: 2.2
  - Support post and Rods: 2.4
  - Electrical wires: $3 \times 10^{-4}$
  - Mirror Deposition: 0.9
  - Scattering Light: ?

**Total**: 5.9 W/unit

**W/unit**: 1.5
Proto-type cryocooler test

Plus tube type cryo-cooler with anti-vibration stage

Vacuum duct for very high pure aluminum thermal conductor

Tri-axial Laser Displacement meter
Results:

Cooling down to 8 K with 25 kg \( \Rightarrow \) 2.1 days

```
  to 80 K with 45 kg \( \Rightarrow \) 1.5 days
```

Estimated Cooling Speed:

Cooling down to 8 K with 410 kg \( \Rightarrow \) 9 days

```
  to 80 K with 880 kg \( \Rightarrow \) 11 days
```
Radiation Shield Duct Design

- to reduce 300K heat radiation to mirrors -

- Apertures of baffles change linearly
  \[ L = 17 \text{ m} \]
  \[ 2a = 900 \text{ mm}, \quad 2d_r = 800 \text{ mm}, \quad 2d_c = 250 \text{ mm} \]

R=0.94 at 10 um

<table>
<thead>
<tr>
<th>Position of baffles $x/L$</th>
<th>$P$ [W]</th>
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</thead>
<tbody>
<tr>
<td>No baffle</td>
<td>6.22</td>
</tr>
<tr>
<td>$0, \frac{8}{16}, \frac{9}{16}, \frac{10}{16}, \frac{14}{16}, 1$</td>
<td>0.0992</td>
</tr>
</tbody>
</table>

R=0.94±0.02
Worse case
R=0.96 $P=0.172$ W
Better case
R=0.92 $P=0.0615$ W

Thermal radiation can be sufficiently reduced by baffles

Sakakibara
Simulation of Inner Shield Cooling

- Model is constructed to estimate initial cooling time
- Heat is transferred by conduction in sapphire fibers and heat links and radiation
- Inner shield of 410 kg is connected to the 2nd stages of 4 cryocoolers
  - Cooling power is derived from test result of LCGT cryocooler

Vibration Isolation System

Heat Link

Sapphire Fiber

Platform

Intermediate Mass

Conduction

Radiation

Test Mass

Cryocooler

Inner Shield

\[
\frac{dT_{sh}}{dt} = -\frac{4 Q_{\text{cryo}}(T_{sh})}{M_{sh} C_{Al}(T_{sh})}
\]

Suspension system is excluded in this case
Simulation of Test Mass Cooling

- Increased radiation by platform, intermediate mass, and inside of inner shield coated with DLC (Diamond Like Carbon)
- Absorptivity of DLC at 10 um is 0.41 (cf. emissivity of Cu and Al is 0.03)
  - We assume that it equals emissivity

![Graph showing temperature over time for different components: TM, IM, Platform, Inner Shield]
1500m Baseline IFOs in both arms

- **Schedule**
  - 2011.10-2013.3: Laser assemble (partially)
  - 2011.10-2013.3: Optics assemble (partially)
  - 2012.11-2013.3: Benchmark, vacuum installation (2nd tunnel)
  - 2013.3-2013.7: Benchmark, vacuum installation (1st tunnel)
  - 2013.4-2013.9: Laser and optics installation
  - 2013.4-2013.9: Data acq. sys. Installation
  - 2013.10-2014.3: Observation

A. Araya
Iodine-stabilization System

Frequency stability $\frac{dv}{v} \sim 10^{-13}$

Iodine-stabilized Nd:YAG laser (532nm)
Summary

- Fundamental techniques for LCGT have been prepared by TAMA and CLIO and LCGT Collaborators.
- LCGT finally started in September 2010.
- 63% budgets was approved. A part of the rest 37% budget will be applied for 2011.
- Many LCGT parts are under designing.
- 5 years construction, and 2 years commissioning are planed. We hope observation from 2017.