Cryogenic Study of the LXe TPC at KEK

Sara Diglio and Lucia Gallego
KEK December 1st 2015
KEK Experimental Set-up

Control system of cryogenics

pump of the gas circulation

Heat exchanger with vacuum insulation

Xe Pre-cooling system

PT2

PT3

PT1

PT4

PT6

PT5

PT7

LXe Cryostat

PDC08

PTR (24W@165K, 108.15°C)

LXe

Power supply and Control

PT2

PT3

PT1

PT4

PT6

PT5

PT7

TWINBIRD SC-UE15

173K@30W

TWINBIRD SC-UE15

173K@30W
Cooling Power Iwatani PTR PDC08 (8W at 77K)

PDC 08+C100K Cooling Power

<table>
<thead>
<tr>
<th>Cold Head Temperature(K)</th>
<th>Cooling Power(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>76,8</td>
<td>10</td>
</tr>
<tr>
<td>93,5</td>
<td>15</td>
</tr>
<tr>
<td>117,1</td>
<td>20</td>
</tr>
<tr>
<td>140,19</td>
<td>25</td>
</tr>
<tr>
<td>164,5</td>
<td>29,1</td>
</tr>
<tr>
<td>169</td>
<td>30</td>
</tr>
</tbody>
</table>

Approx. 29W at 164 K

Volts….200  
Hertz…50    
Phase…1     
Compressor Suzuki Shokan co..Ltd.  C100K  
Cryocooler Iwatani PDC-08

Static Pressure:1.60MpaG  
Measured by KEK on 2014/07/11

KEK 01 / 12 / 2015
Cooling Power TWINBIRD Stiring Cooler

Cooling temperature range: -120 °C to +70 °C

(Measured by TWINBIRD)

- Cooling Capacity
  - Approx. 120W (at the cold side temperature of -23.3°C)
  - Approx. 50W (at the cold side temperature of -80°C)

Approx. 12W at -125 °C
2015 3/27 - 4/7
Maximum : 4.69 ℓ /min

Operation for 10 days
PDC08: SV=164K
stable operation, 3/27 - 4/7
Heat exchanger in vacuum
4.0x10^-4Pa

LXe Cryostat
T2 -107.9℃
PT1=164K
-99.2℃
PT5 -105.4℃
PT6 -110.82℃
PT7 -126.39℃
LXe height ~131mm
vacuum 2.53x10^-4Pa

PDC08 (PTR)
PTR (29.1W@164.5K)
PT:86kPaG
4.69 ℓ /min[FM]
PT:-15kPaG
PT2 -59.0℃
PT1 -109℃
PT3 -1.6℃
PT4 105.7℃
PT5 -109.4℃
PT6 -110.82℃

DB1000
No.1,Pt7 CH
PV=146.78K
SV=140.00K
No.2 Pt6 ボイル
PV=162.34K
SV=162.00K

note: SV=Setting Value
PV=Monitor Value

KEK 01 / 12 / 2015
Temperature profile during pre-cooling and liquefaction

Temperature of the Cold Head T1 [K] vs Time

- Cold head temperature reaches 165 K in about 12 h
- Reached stability at 165 K
- Maintains stability at 164 K
Internal cryostat
Temperature reaches \( \sim -109^\circ\text{C} \)
in about 12 h
Temperature profile during all data-taking

Holidays

- T1 Xe chamber IN TEMP
- T2 Xe chamber OUT TEMP
Temperature profile during all data-taking

Holidays

Date

Temperature (ºC)

T1 Xe chamber IN TEMP
T2 Xe chamber OUT TEMP
Temperature profile during pre-cooling and liquefaction
Temperature profile during pre-cooling and liquefaction

Less than 24 h to cool down the system.
Pressure profile inside cryostat during pre-cooling and liquefaction
Estimated time needed to increase the LXe level of 100 mm: ~ 12h
Flow Rate vs Time. Data from 18/11 to 29/11

- ~ 4.5 l/min
- ~ 7.5 l/min
- ~ 11 l/min
- from ~ 4.25 to 5.5 l/min

KEK 01 / 12 / 2015
Temperature profile during circulation

Temperature stability during relative long period

Temperature (°C) vs Time

T1 [°C]
T2 [°C]

23/11/15 00:00
24/11/15 00:00
25/11/15 00:00
26/11/15 00:00
27/11/15 00:00
28/11/15 00:00
29/11/15 00:00

PTR
24W@165K,
0.815°C

LXe

KEK 01 / 12 / 2015
Pressure profile during circulation

Pt-1: pressure inside cryostat
Pt-3: pressure at exchanger inlet

Pressure stability during relative long period

![Graph showing pressure profile and stability over time.](image)
Pressure profile during circulation

Pt-1: pressure inside cryostat
Pt-3: pressure at exchanger inlet
LXe level profile during circulation
Flow rate vs Time

Flow Rate [l/min]

~ 7.5 l/min

~ 4.5 l/min


KEK 01 / 12 / 2015
Flow rate vs Time

Flow Rate [l/min]

~ 4.5 l/min

~ 7.5 l/min

KEK 01 / 12 / 2015
Flow rate of 4.5 l/min
The two curves have a similar trend
Flow rate of 7.5 l/min

Temperature vs Time

- PT1: 1st-IN TEMP
- PT2: 1st-OUT TEMP
- PT3: 2nd-IN TEMP
- PT4: 2nd-OUT TEMP
- PT5: Heat exchanger OUT TEMP
- PT6: Xe Coil DC TEMP
- PT7: Cold Heater TEMP

Flow rate of 7.5 l/min
Heater vs Time and Heater vs Flow rate

Flow rate of 7.5 l/min

The two curves have different trend
Flow rate around 4.5 l/min
Flow rate around 4.5 l/min
Flow rate around 7.5 l/min
Flow rate around 11.0 l/min

-0.001
-0.0011
-0.0012
-0.0013


Pression in chamber [Mpa] / T1 [°C]
Pression in chamber [Mpa] / T2 [°C]
Flow rate vs Time

Flow rate around 11.0 l/min
8 h 30 min

Flow rate around 11.0 l/min
8 h 30 min
Cryogenics Study

By courtesy of Eric Morteau

<table>
<thead>
<tr>
<th>SUBATECH</th>
<th>KEK</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gas flow (l/min)</strong></td>
<td>31.3</td>
</tr>
<tr>
<td>T inside cryo T2 (°C)</td>
<td>-100.7</td>
</tr>
<tr>
<td>PT1 (°C)</td>
<td>-106.0</td>
</tr>
<tr>
<td>PT2 (°C)</td>
<td>18.1</td>
</tr>
<tr>
<td>PT3 (°C)</td>
<td>24.5</td>
</tr>
<tr>
<td>PT5 (°C)</td>
<td>-104.4</td>
</tr>
<tr>
<td>T1 (°C)</td>
<td>-104.4</td>
</tr>
</tbody>
</table>

*Average values during stability

By courtesy of Eric Morteau

**TWINBIRD**

<table>
<thead>
<tr>
<th><strong>Gas flow (l/min)</strong></th>
<th>4.5</th>
<th>7.5</th>
<th>11.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT7 (°C)</td>
<td>-124.8</td>
<td>-125.1</td>
<td>-124.9</td>
</tr>
<tr>
<td>PT6 (°C)</td>
<td>-109.6</td>
<td>-109.5</td>
<td>-109.2</td>
</tr>
<tr>
<td>PT4 (°C)</td>
<td>-104.7</td>
<td>-104.5</td>
<td>-104.3</td>
</tr>
<tr>
<td>PT5 (°C)</td>
<td>-104.4</td>
<td>-104.3</td>
<td>-104.0</td>
</tr>
<tr>
<td><strong>Cooling Power (W)</strong></td>
<td>~ 12</td>
<td>~ 12</td>
<td>~ 12</td>
</tr>
<tr>
<td><strong>Heater (W)</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Average values during stability

*PTR Cooling power from data sheet

Thermal loss between cryostat and heat exchanger

Thermal conduction inside heat exchanger

Thermal loss between exchanger outlet and cryostat inlet

KEK 01 / 12 / 2015
KEK Cryogenics Set-up — Data (18 - 26/11/2015)

<table>
<thead>
<tr>
<th>SUBATECH</th>
<th>KEK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas flow (l/min)</td>
<td></td>
</tr>
<tr>
<td>31.3</td>
<td>4.5</td>
</tr>
<tr>
<td>T inside cryo T2 (°C)</td>
<td></td>
</tr>
<tr>
<td>-100.7</td>
<td>-106.9</td>
</tr>
<tr>
<td>PT1 (°C)</td>
<td></td>
</tr>
<tr>
<td>-106</td>
<td>-107.9</td>
</tr>
<tr>
<td>PT2 (°C)</td>
<td></td>
</tr>
<tr>
<td>18.1</td>
<td>-58.5</td>
</tr>
<tr>
<td>PT3 (°C)</td>
<td></td>
</tr>
<tr>
<td>24.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>PT5 (°C)</td>
<td></td>
</tr>
<tr>
<td>-104.4</td>
<td>-104.7</td>
</tr>
<tr>
<td>T1 (°C)</td>
<td></td>
</tr>
<tr>
<td>-104.4</td>
<td>-98.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PTR (164 K@24 W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas flow (l/min)</td>
</tr>
<tr>
<td>4.5</td>
</tr>
<tr>
<td>Cold Head T (°C)</td>
</tr>
<tr>
<td>164</td>
</tr>
<tr>
<td>PTR Power (W)</td>
</tr>
<tr>
<td>29</td>
</tr>
<tr>
<td>Heater (W)</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>Cooling Power (W)</td>
</tr>
<tr>
<td>18</td>
</tr>
</tbody>
</table>

*Average values during stability
*PTR power from KEK measurements
Heat Exchanger Efficiency

By courtesy of Kasami-san

<table>
<thead>
<tr>
<th>SUBATECH</th>
<th>KEK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas flow (l/min)</td>
<td>31.3</td>
</tr>
<tr>
<td>PT2 (°C)</td>
<td>18.1</td>
</tr>
<tr>
<td>PT3 (°C)</td>
<td>24.5</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>99.9</td>
</tr>
<tr>
<td>Cp (J/g/K)</td>
<td>0.34</td>
</tr>
<tr>
<td>Lp (J/g)</td>
<td>96.26</td>
</tr>
</tbody>
</table>

\[
\varepsilon = 1 - \frac{C_p \times \Delta T_{\text{warm}} \times F(\text{g/s})}{Q(\text{W})}
\]
**Heat Exchanger Efficiency**

**Figure 1:** (left) 3D drawing of the PTR, heat exchanger and the connection with cryostat. (right) Schematic of SUBATECH.

*By courtesy of Kasami-san*

<table>
<thead>
<tr>
<th>SUBATECH</th>
<th>KEK</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gas flow (l/min)</strong></td>
<td>31.3</td>
</tr>
<tr>
<td><strong>PT2 (°C)</strong></td>
<td>18.1</td>
</tr>
<tr>
<td><strong>PT3 (°C)</strong></td>
<td>24.5</td>
</tr>
<tr>
<td><strong>Efficiency (%)</strong></td>
<td>99.9</td>
</tr>
<tr>
<td><strong>Cp (J/g/K)</strong></td>
<td>0.34</td>
</tr>
<tr>
<td><strong>Lp (J/g)</strong></td>
<td>96.26</td>
</tr>
</tbody>
</table>

**Gas Flow (l/min)**

\[
\varepsilon = 1 - \frac{C_p \times \Delta T_{\text{warm}} \times F (\text{g/s})}{Q (\text{W})}
\]
### Heat Exchanger Efficiency

**Efficiency (%):**

- **SUBATECH:**
  - Gas flow (l/min): 31.3
  - PT2 (°C): 18.1
  - PT3 (°C): 24.5
  - Efficiency (%): 99.9

- **KEK:**
  - Gas flow (l/min): 4.5, 7.5, 11.0, 4.5
  - PT2 (°C): -58.5, -50.3, -44.1, -58.5
  - PT3 (°C): -1.5, 6.7, 11.7, -2.1
  - Efficiency (%): 86.1, 86.1, 86.5, 86.3

**Cp (J/g/K):**

- **SUBATECH:** 0.34
- **KEK:** 96.26

**Lp (J/g):**

- **SUBATECH:**
  - Gas flow (l/min): 31.3
  - Eff. (%): 99.9

**Equation:**

\[ \varepsilon = 1 - \frac{C_p \times \Delta T_{\text{warm}} \times F}{Q} \]

**Notes:**

- By courtesy of Kasami-san
Thermal Losses

By courtesy of Eric Morteau

*Temperature values for a gas flow of 4.5 l/min

KEK 01 / 12 / 2015
Thermal Losses

By courtesy of Eric Morteau

*Temperature values for a gas flow of 4.5 l/min

KEK 01 / 12 / 2015
**Thermal Losses**

**Assumptions:**
- Negligible resistance between the tube wall and the LXe.
- Constant properties
- Negligible radiation heat loss
- Stability

<table>
<thead>
<tr>
<th>Thickness insulator (mm)</th>
<th>40</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T2 - PT1</strong></td>
<td>1.80 W</td>
<td>1.57 W</td>
</tr>
<tr>
<td><strong>PT5 - T1</strong></td>
<td>2.48 W</td>
<td>-</td>
</tr>
</tbody>
</table>
ありがとうございました

Thank you!
Slow Control
The measurement indicates that the performance of the present heat exchanger is very efficient. It is 99% even at high flow, which is even better than the performance of other heat exchangers. The measurement of cooling power is shown in Figure 1 (left). The pressure drop is shown in Figure 2 (left). The temperature of the pressure drop is shown in Figure 2 (right). The temperature at the cold end for the design of heat exchanger (0.5 m, 100 bar, 2 K) is quite stable (tube side: ~-103 ºC, shell side: ~ -101 ºC), which indicates that there is heat exchange between LXe and GXe inside heat exchanger even at small flow (~2.5 NL/min). Coaxial heat exchanger is better than its designed plate heat exchanger described in [6].

To estimate the performance of the present heat exchanger, the coaxial heat exchanger described in [6], the pressure drop is proportional to the difference of pressure difference (Δp) as a function of recirculation rate, it is nearly unobservable at high flow.

<table>
<thead>
<tr>
<th>PTR (200W@164K)</th>
<th>Coaxial Heat Exchanger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas flow (l/min)</td>
<td>31</td>
</tr>
<tr>
<td>Cooling Power (W)</td>
<td>70</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>99</td>
</tr>
</tbody>
</table>

The outlet of tube side and the inlet of shell side, which are close to room temperature (~50 cm). The measurement of temperature at inlet and outlet can only be measured directly by courtesy of Eric Morteau.

By courtesy of Eric Morteau

References

6. Supported by the region of Pays de la Loire, France.
Reached stability

Temperature of the Cold Head T1 [K] vs Time

164 K

Pressure within the Cryostat [MPa] vs Time

1.12 kPa

Reached stability
Temperature profile during liquefaction

- T1 [K] temperature of the Cold Head
- Lt-1 [K] temperature in the vessel
Flow rate 11 l/min : 8h 30min
Flow rate 7.5 l/min : 16h

Flow Rate [l/min]
Flow rate 5.5 l/min : 5h 30min
Flow rate 5.5 l/min : Ratio pressure/temperature VS time
Pressure in the chamber / Temperature VS Time

Pression in chamber [Mpa] / T [° C] vs Time

- Pression in chamber [Mpa] / T1 [° C]
- Pression in chamber [Mpa] / T2 [° C]
Pressure in the chamber / Temperature in the vessel (low) VS Time
Pressure in the cryostat / Temperature in the vessel (low) VS Flow Rate
Pressure in the chamber / Temperature in the vessel (low) VS Flow Rate

Region 4.2-4.7 l/min

Pt-1(MPa)/Lt-1(K) vs Flow Rate [l/min]
Pressure in the chamber / Temperature in the vessel (low) VS Time

Region 4.2-4.7 l/min

Pt-1(MPa)/Lt-1(K)
Pressure in the chamber / Temperature in the vessel (low) VS Time

11 l/min

Pt-1(MPa)/Lt-1(K) vs Time

11/25/15 7:56
11/25/15 10:21
11/25/15 12:45
11/25/15 15:09
11/25/15 17:33