# Summary of the Operation of the SKS Cryogenic System at 12-GeV PS in KEK

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Contents:

# 1. Overview of the SKS cryogenic system

The cryogenic system for the SKS (Superconducting Spectrometer Magnet) had been designed and constructed from 1989 to 1991 at K6 beam line of the 12-GeV PS in KEK for nuclear physics experiments.

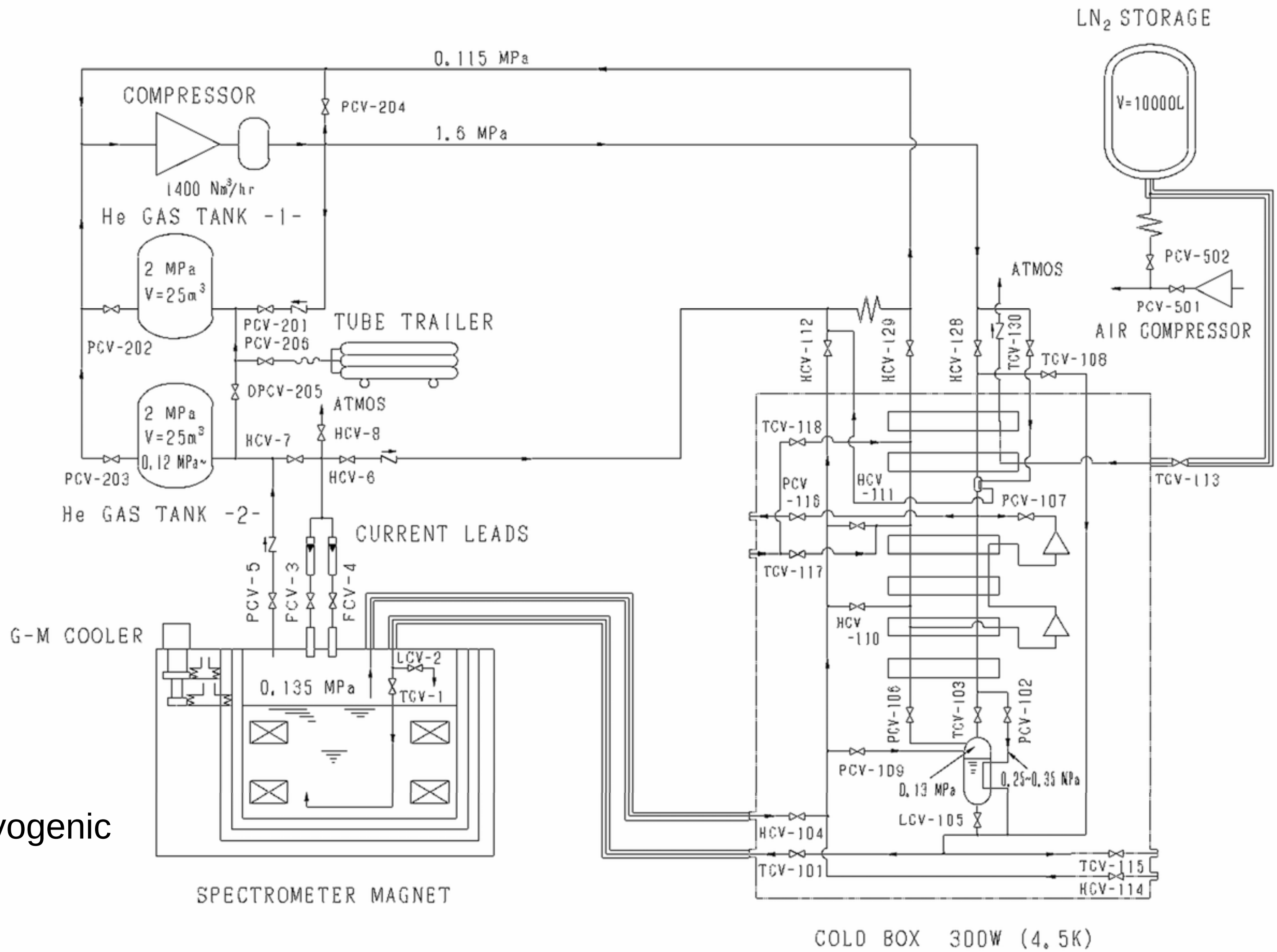



Fig. 1-1

SKS cryogenic system

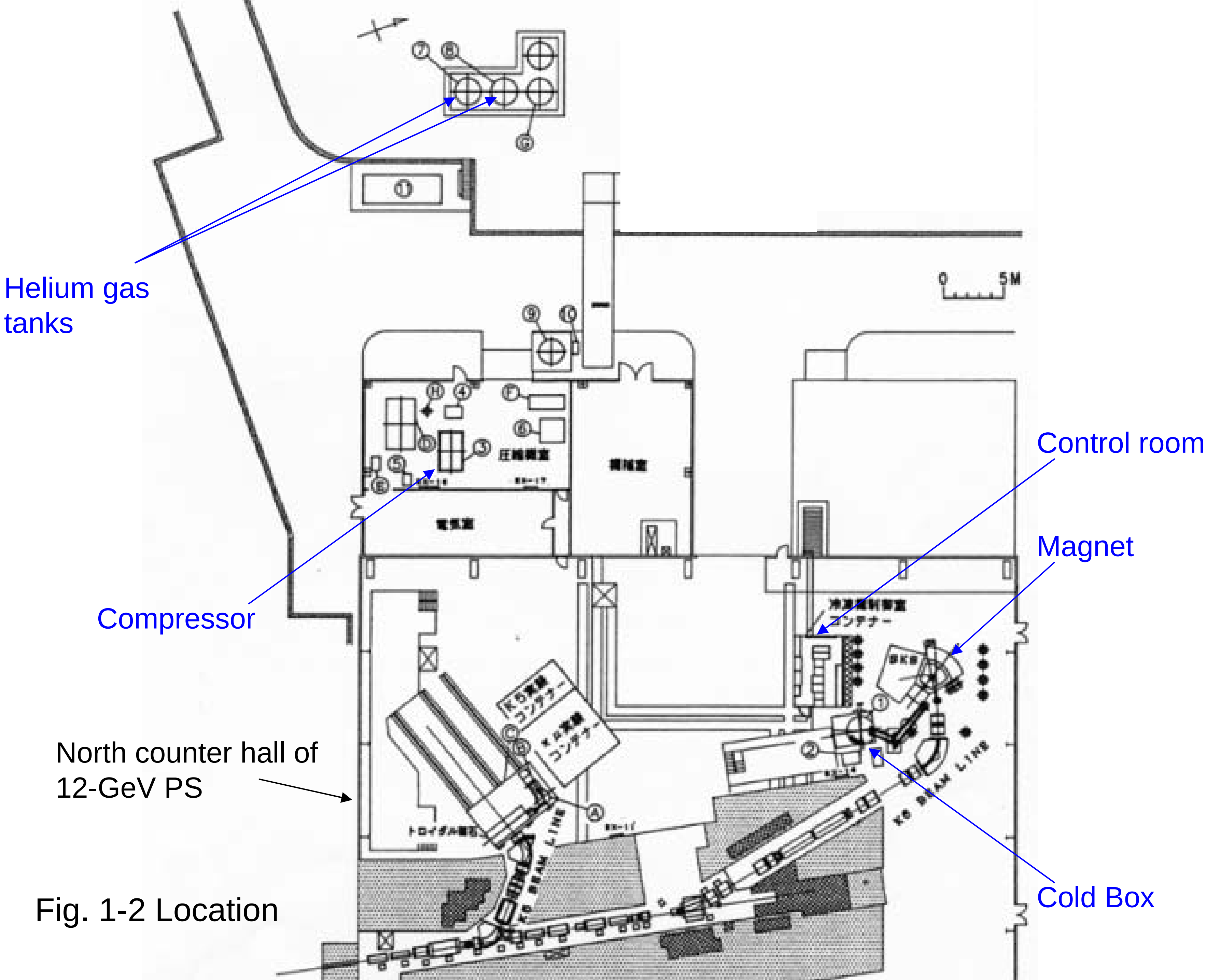



Fig. 1-2 Location

## Magnet parameters

G-M cooler for shield cooling:

- ♦Refrigeration 6 W at 20 K + 60 W at 80 K

Magnet (large sector type dipole):

- ♦Cooling method Pool boiling
- ♦LHe Capacity 156 L
- ♦Cold mass 4.5 ton (SS, Cu)
- ♦Thermal load (not including transfer lines) 5 W + 1.5 L/h

  Very low
- ♦Cooling-down time 50 hours
- ♦Central filed 3 T
- ♦Current 498 A
- ♦Stored energy 11.2 MJ

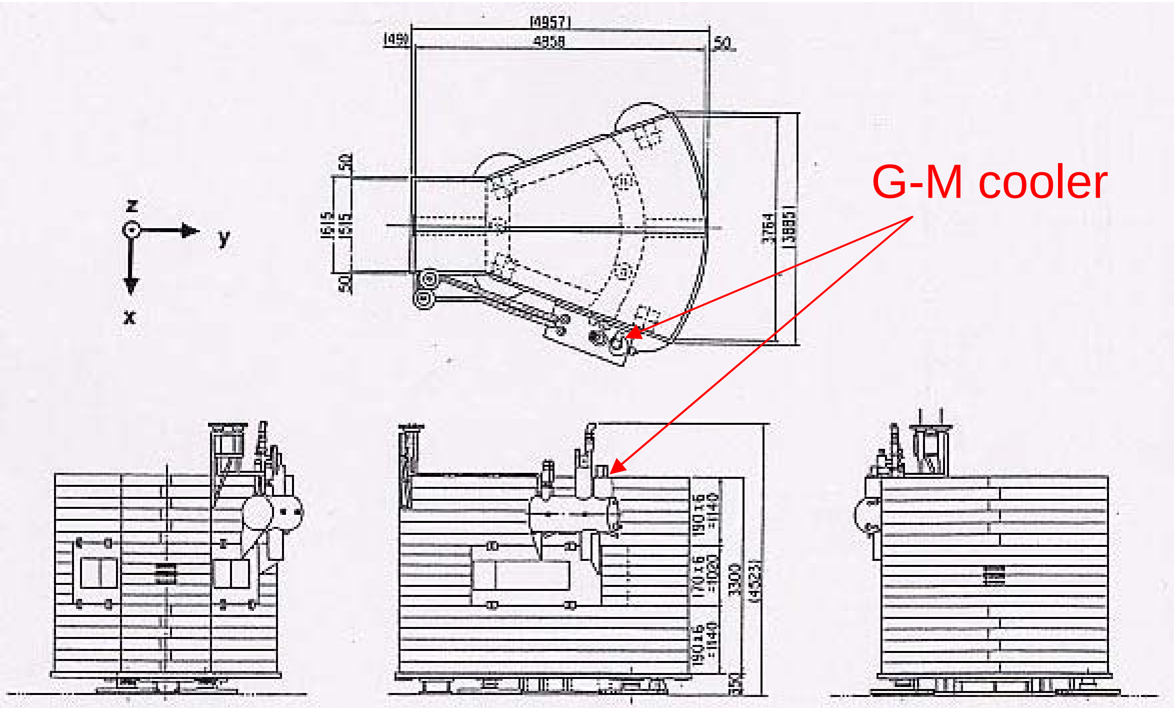



Fig. 1-3 Magnet

# Main refrigerator parameters

| | |
|---|---|
| ♦Type of refrigerator | Claude cycle |
| ♦Cold box: Refrigeration | 300 W at 4.5 K (using $LN_2$), 180 W at 4.5 K (without $LN_2$) |
| Liquefqction rate | 100 L/h (using $LN_2$), 40 L/h (without $LN_2$) |
| ♦Compressor: Type | Screw compressor |
| Flow rate | 1,400 $Nm^3/h$ |
| ♦$LN_2$ storage | 10,000 L |

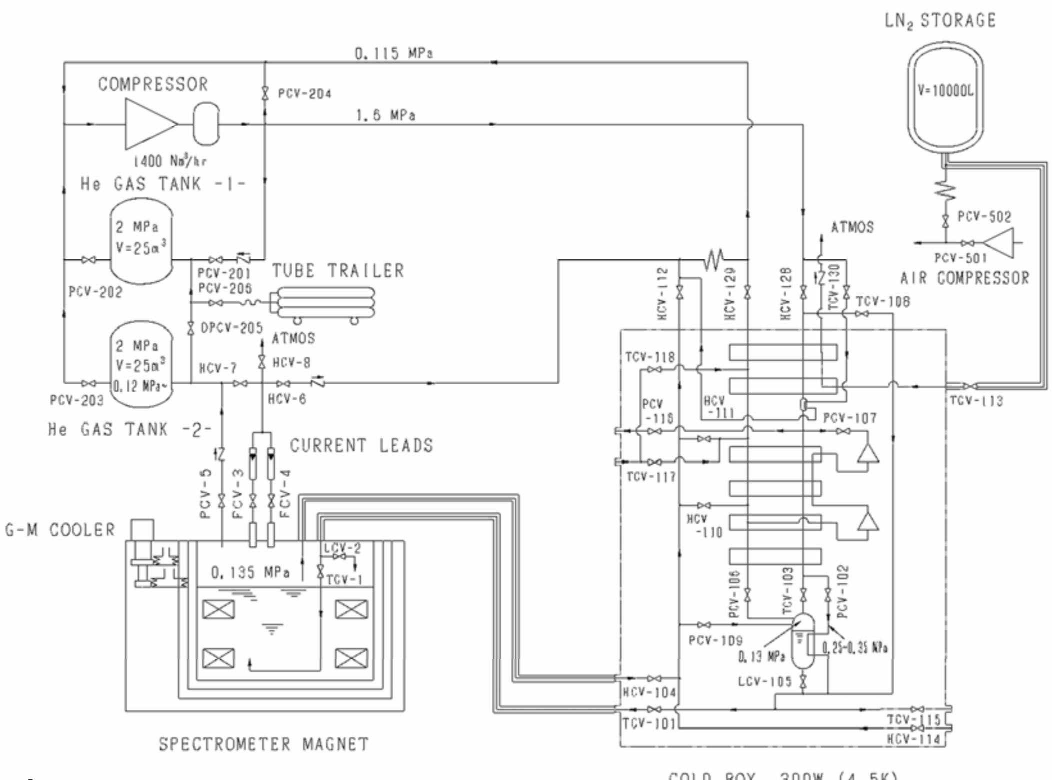



Fig. 1-4 System

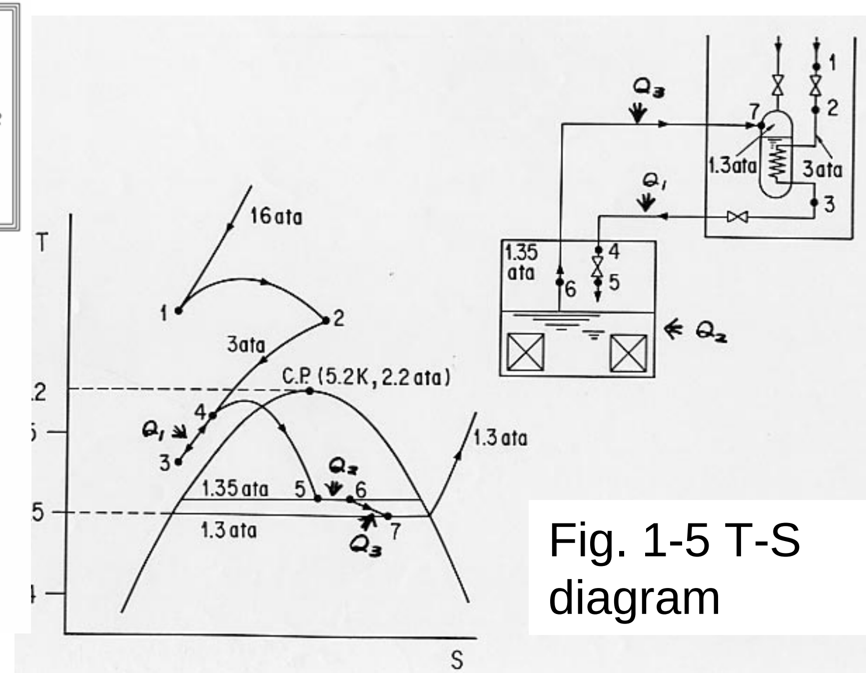



Fig. 1-5 T-S diagram

## Features

♦The magnet is **rotatable from -10 degree to +40 degree** around target point.
The magnet has 4 transpositioners at bottom.
Transfer lines have rotatable bayonets. A G-M cooler is used for shield cooling.

♦Thermal load of the magnet is **low. (5 W)**
Low current (498 A), but Many Ampere turns (2.1 MA) and large stored energy (11.2MJ)

♦**Full automatic control** with a large process controller
Operation by nuclear experiment group members who are not cryogenic experts.

## History

1989-1991 **Construction.**

1991 Test operation and field mapping of the magnet started without beam.

1992 After tuning with beam, **experiments (2 week mode) started**.

1993 **4$^{th}$ quench ("Big quench") occurred**. The GFRP supports were broken.

1993-1994 **Repair.** After test operation, **experiments restarted.**

1997 **4 week mode** (for experiments) started.

1998-1999 **Experiments stopped for 1 year** to construct another beam line (K2K)

1999 Experiments restarted but beam time decreased to share the beam.

2001-2002 **Beam time concentrated** because of K2K repair.

2003-2005 After K2K repair, SKS beam time decreased.

2005 **Last experiment in 12-GeV PS**. In Mar. 2006, 12-GeV PS terminated operation.

## Future plan

We have a plan to change cooling method **from a 300 W refrigerator to GM/JT cryocoolers** for the use in **J-PERC**.

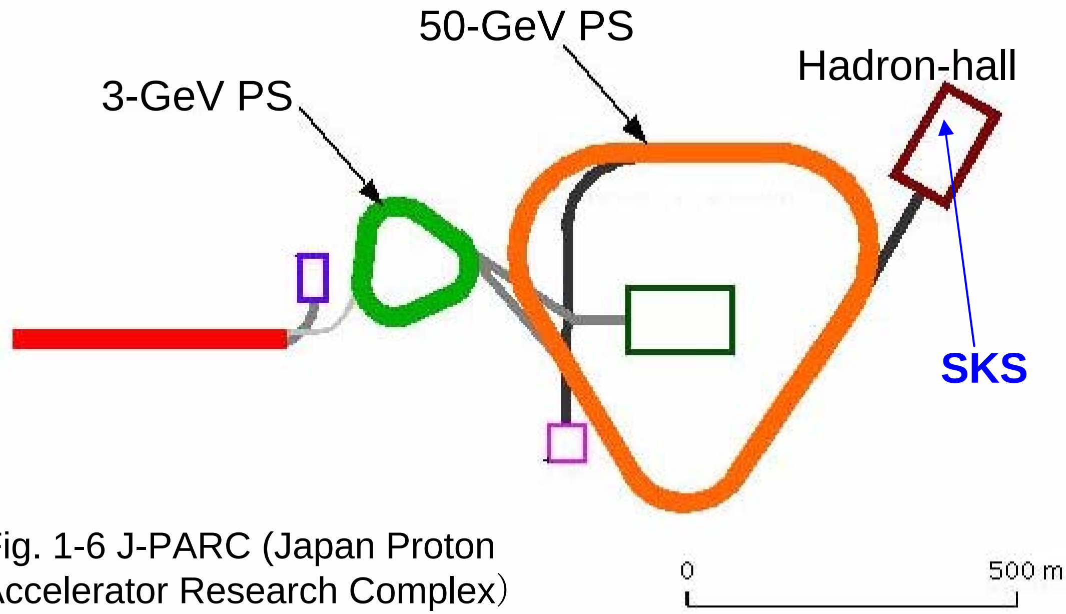



Fig. 1-6 J-PARC (Japan Proton Accelerator Research Complex)

Schedule:

Now Accelerators are under construction.

- 2007-2008

  SKS reconstruction

- 2009

  Experiment start

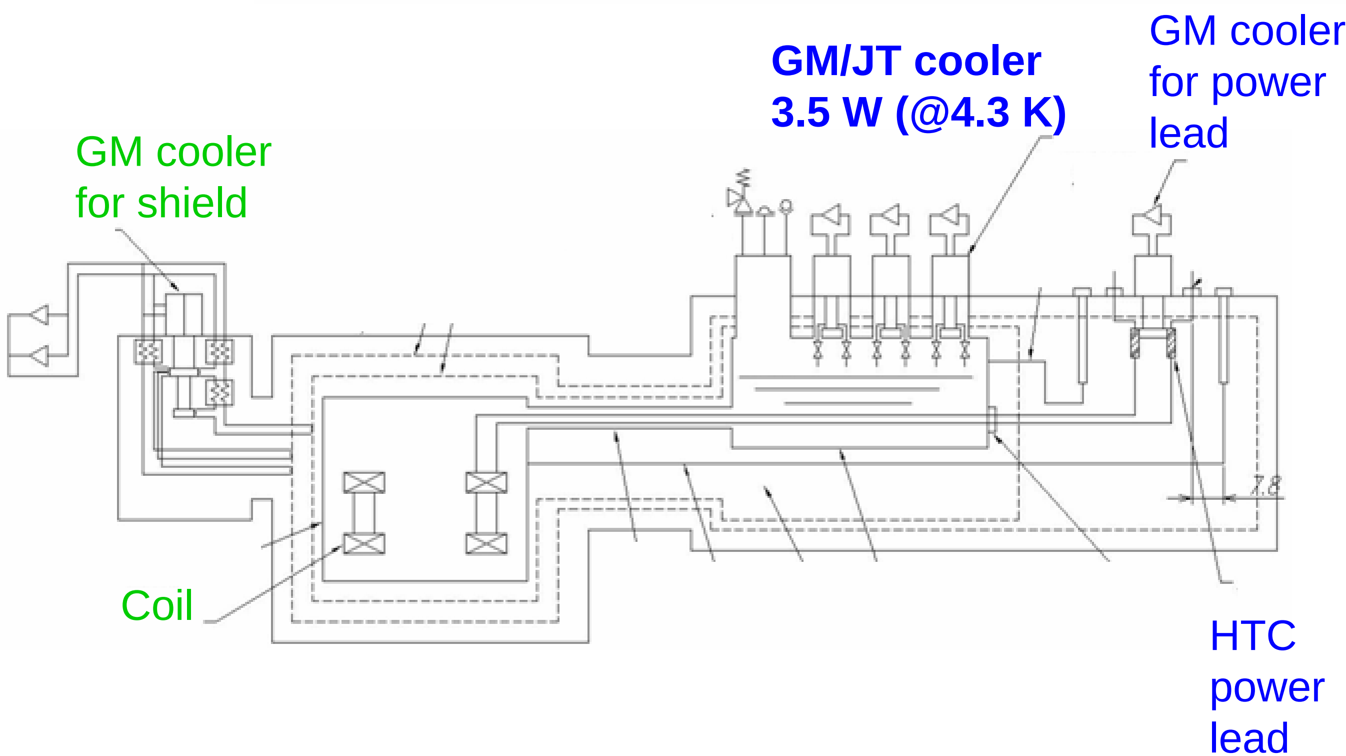



Fig. 1-7 New SKS

# 2. Reliability of the SKS cryogenic system

Compared with the other cryogenic system in KEK of the previous TRISTAN detector systems and the running BELLE detector system, **two points in operation style are different**:

- Operation is made up of **a large number of short periods**.

  (Since 1997, it has been repeating a long rest period and a short operation period.)
- The system is **operated by experiment group members who are not cryogenic experts**.

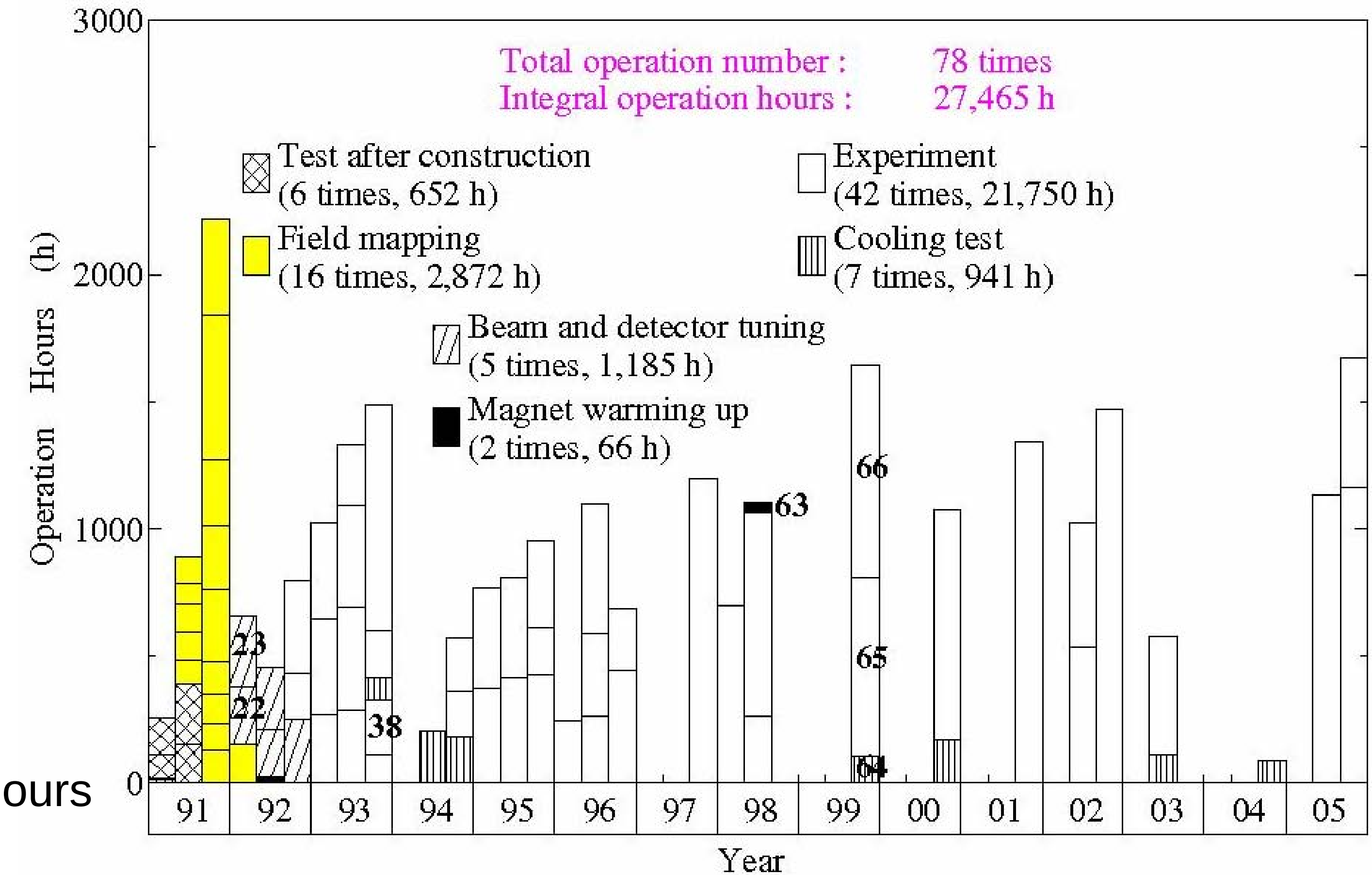



Fig. 2-1
Operation hours

**Yearly record of numbers of failures:**

Failures that **only occurred during the operation period (218 failures) were used** to evaluate the reliability.

Period A: many failures in the cooling tests after repair of the 4th quench.

("Big quench" the most serious failure – repair of the magnet took almost 1 year)

Period B: many failures in the period repeating a long rest and a operation.

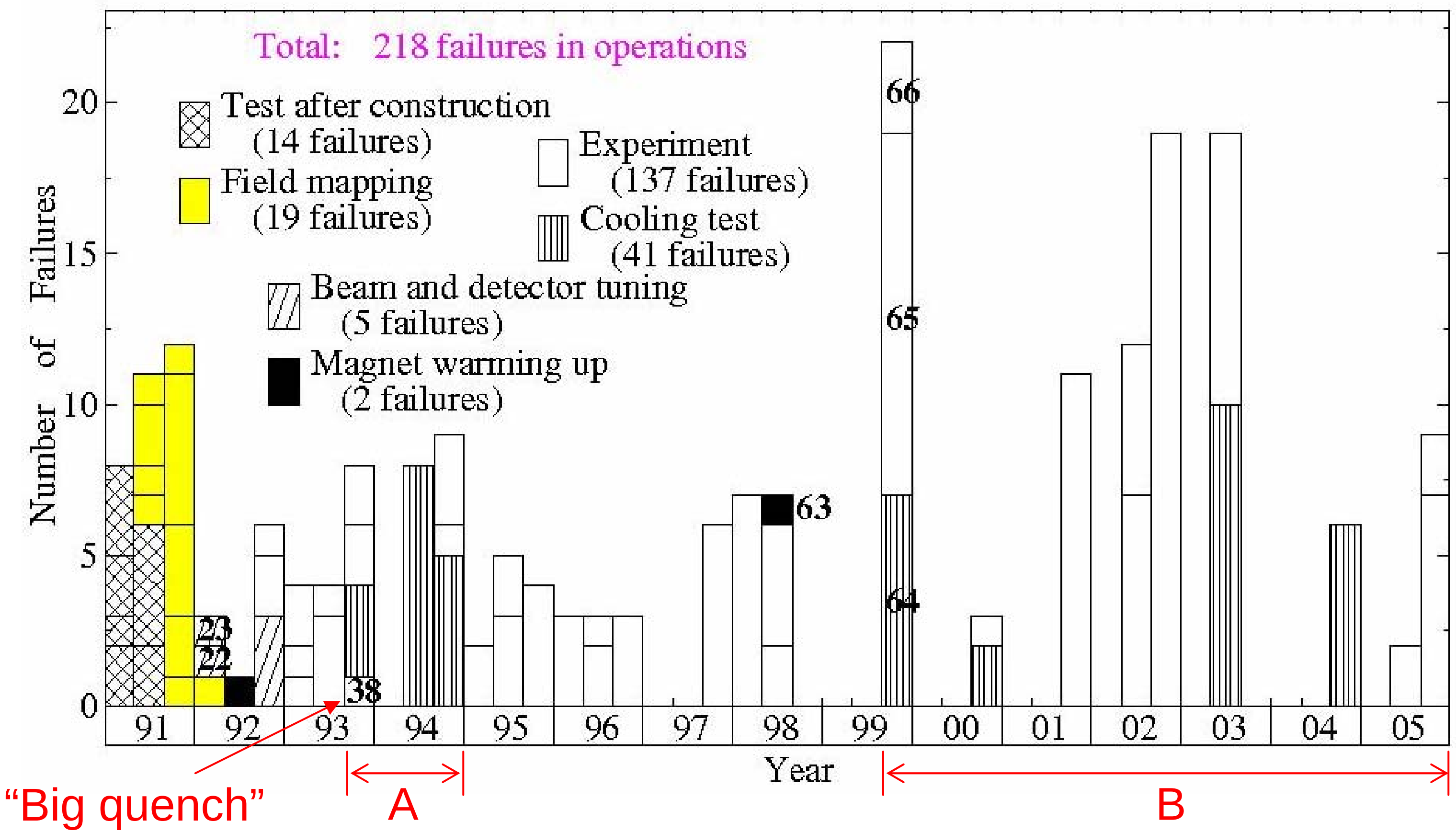



Fig. 2-2

Failure record

**Failure occurrence rate (failure numbers divided by hours in a operation ) :**

**DFR (Decreasing Failure Rate)** – initial rapid decreasing period.

We defined DFR period from #1 to #22.

**CFR (Constant Failure Rate)** – base is almost constant besides peaks.

After 4th peak, peaks were observed in the short cooling test after long rest.

We defined CFR period from #23 to the end.

W

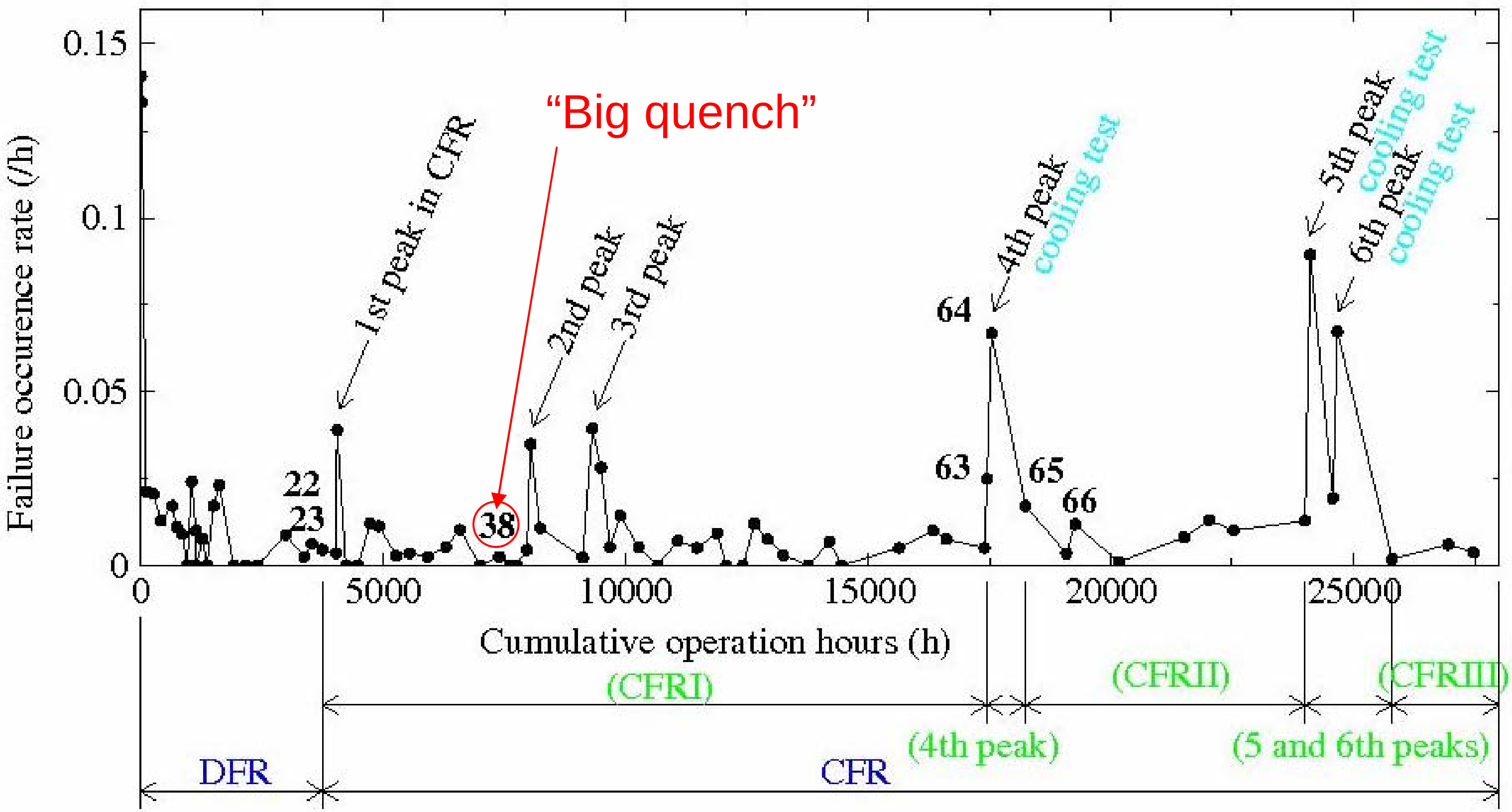



Fig. 2-3 Failure occurrence rate vs. cumulative operation hours

**Evaluation of reliability:**

The method calculates **A (Availability)** with **MTBF (Mean Time Between Failures)** and **MTTR (Mean Time To Repair)** to evaluate **the system working ratio**.

**MTBF (Mean Time Between Failures)**

$\lambda$ : the mean failure rate during CFR form period.

$$MTBF = \frac{1}{\lambda}, \quad \text{where} \qquad \lambda = \frac{number\ of\ \ failures\ during\ CFR\ \ form\ \ period}{cumulative\ operation\ time}$$

For SKS, $\lambda = 7.6 \times 10^{-3}$ (1/h), MTBF = 129 h

Cf. for TRISTAN, $\lambda = 1.1 \times 10^{-3}$ (1/h), MTBF = 909 h

**Growth rate of reliability** during the early DFR form period can be evaluated.

$$cumulative\ MTBF = \frac{T^{\alpha}}{K}$$ , where T: cumulative test hours,

$\alpha$ : growth rate,

K: a constant

This equation was empirically derived by Duane [1] for the relationship between the failure rate and early test period of the engine, generator, fluid machines, etc.

For SKS, from Fig. 2-4, $\alpha = 0.49$

Cf. for TRISTAN, $\alpha = 0.65$

According to Duane, around $\alpha = 0.5$ shows standard growth of the reliability.


REFERENCE

1. Duane, J. T., IEEE Trans. Aerosp. (1964) 24-2 563

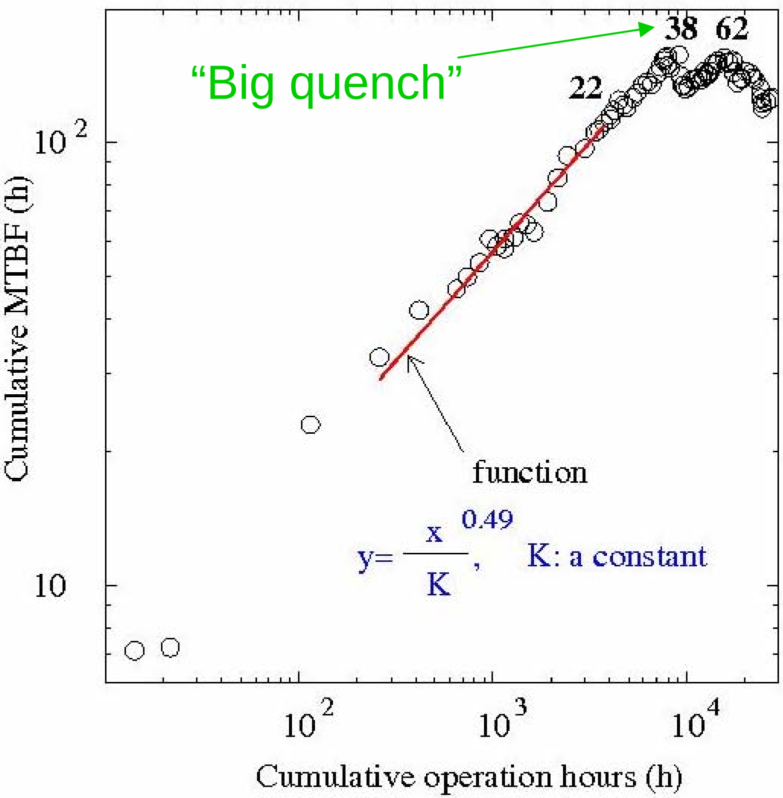




Fig. 2-4 Cumulative MTBF

## MTTR (Mean Time To Repair)

**87 of 218** failures during the operation period stopped the operation to repair.

1. Light failure: the operation restarted within the scheduled operation period. 73 cases
2. Middle-light failure: the operation did not restart because the repair took time. 13 cases
3. Serious failure: repair took long time and succeeding schedule was terribly changed. 1 case – “Big quench”

The mean repair rate during random repair time (=CFR): $\mu = 2.1 \times 10^{-2}$ (1/h)
MTTR = 32.0 h for SKS

Cf. For TRISTAN,

$\mu = 0.14$ (1/h)

MTTR = 7.1 h

Equation:

$$MTTR = \frac{1}{\mu}, \quad \text{where}$$

$$\mu = \frac{number\ of\ \ failures\ during\ CFR}{cumulative\ repair\ time}$$

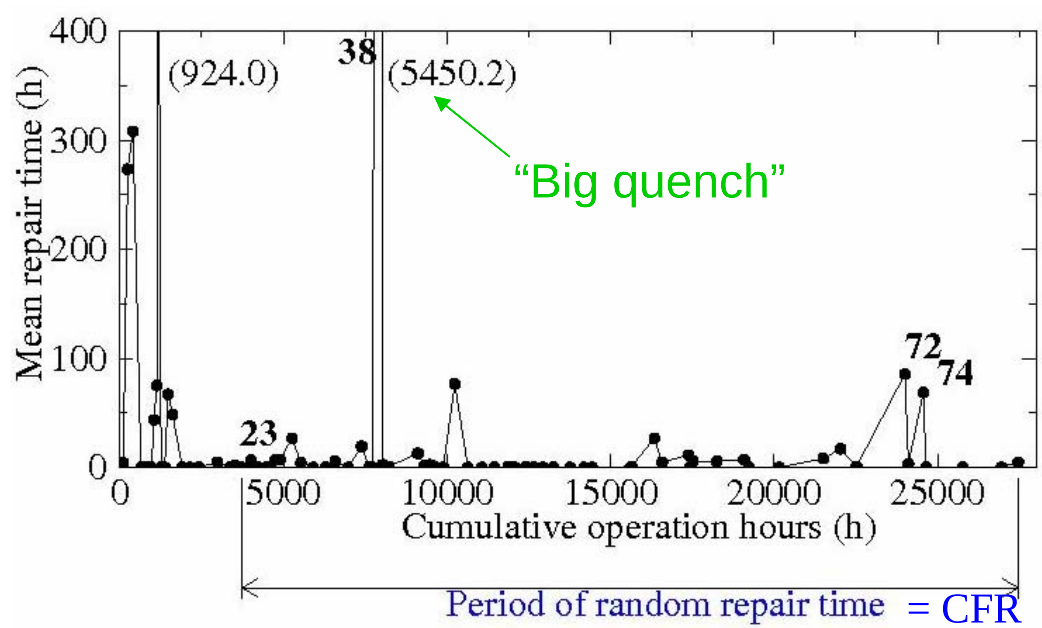



Fig. 2-5 Mean repair time of each operation

Availability: $A = \frac{MTBF}{MTBF + MTTR}$

Result: A= 80.1 % for SKS

Cf. A = 99.2% for TRISTAN

Table 2-1 Comparison of the result

| System and period | Cumulative Operation Hours (h) | Number of operations | Number of failures | MTBF (h) | MTTR (h) | Availability (%) |
|---|---|---|---|---|---|---|
| **TRISTAN*** <br> **(VENUS)** 05/1985-05/1995 <br> **(TOPAZ)** 03/1985-05/1995 <br> **(AMY)** 12/1986-07/1994 | <br> **49,187** <br> **45,669** <br> **41,769** | <br> **22** <br> **20** <br> **17** | **155** in total | **909** on average | **7.1** on average | **99.2** on average |
| **SKS*** 02/1991-12/2005 | **27,465** | **78** | **218** | **129** | **32** | **80.1** |
| **BELLE**** 09/1997-12/2001 | **23,947** | **10** | **32** | **1,376** | **4.6** | **99.7** |

*: terminated systems. **: running system but data were taken from the operations until Dec. 2001.

**Conclusion from this analysis:**

- SKS growth rate was standard. The large number of failures and one serious failure caused lower availability than TRISTAN and BELLE.

- Operation style and cycle might cause a such large number of failures.

# 3. A failure example – radiation effect for the control system

Outline:

1) The control system of the SKS cryogenic system is using a large process controller with all dual system ( two CPU boards, two power supplies, two busses, etc). But it was constructed in 1989 and has no ECC (Error-Correcting Code) function.

2) Occasional failures of one CPU stop are a known problem. But it was not a big problem since the SKS operation cycles were relatively short. (about 14 days until 1996 and 28 days after 1996 on average)

3) In 2001, we had the longest continuous operation (operation#69 – 56 days) and experienced one and the other CPU down in succession. The whole cryogenic system was left with no active control for a period. After that, the diagnosing program was installed on the process controller.

4) In 2002, we experienced the same phenomena two times (both operation#72 – 61 days). The diagnosing program showed that the cause was a parity-check-error.

5) At this time, we studied the radiation effect (SEU, Single Event Upset) case estimated by ATLAS cryogenic group of CERN.

6) We counted the Neutron flux at the control room, found the SEU data of our memories on CPU board and applied them for our control system. The calculated SEU rate explains our observation- SEU probability on both CPU boards in 60 day operation is 73%.

7) Some measures were taken. One measure was to shield against the expected radiation source. After counting the Neutron flux again, the shielding measures proved not to be sufficient yet.

1) The control system of the SKS cryogenic system is using a large process controller with all dual system ( two CPU boards, two power supplies, two busses, etc). But it was constructed in 1989 and has no ECC (Error-Correcting Code) function.

ECC (Error-Correcting Code) – redundant, auto-correct function

(Since mid 1990s, we have been requesting ECC for process controllers. )

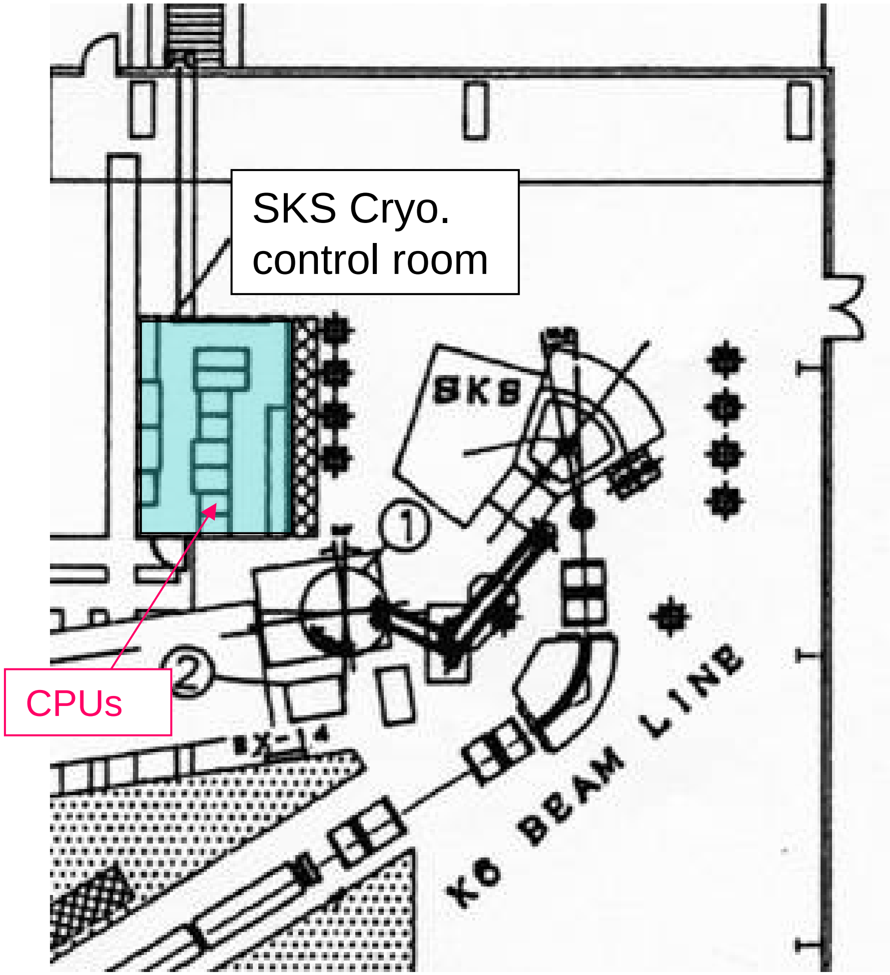



Fig. 3-1 Control room location

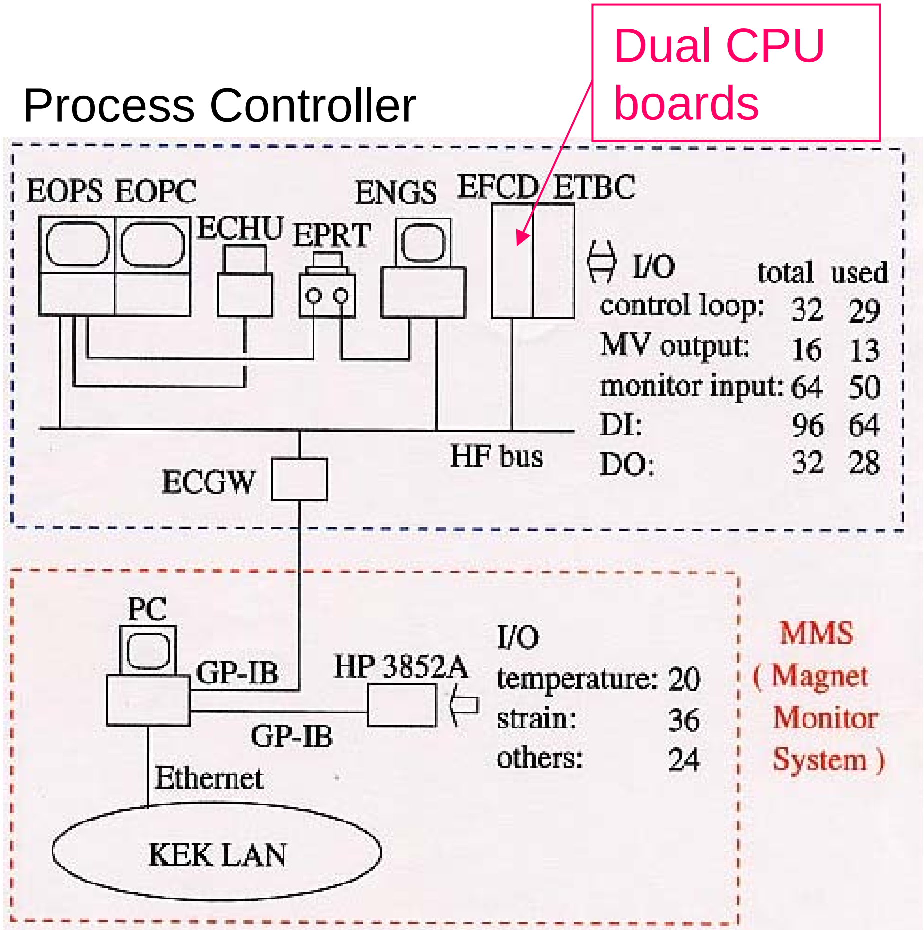



Fig. 3-2 Process controller

2) Occasional failures of one CPU stop are a known problem. But it was not a big problem since the SKS operation cycles were relatively short. (about 14 days until 1996 and 28 days after 1997 on average)

- Before 2001, we observed 11-times CPU stops.
- Many experiments concentrated in 2002.

Table 3-1 CPU stop history

| No. | Date | Down CPU R or L | Control CPU | Operation | Beam | Cause | notes |
|---|---|---|---|---|---|---|---|
| #12 | 13/10/2001 | R | R | run (#69) | on | unknown | |
| #13 | 03/11/2001 | L | L | run (#69) | on | unknown | Two CPUs down. |
| #14 | 11/04/2002 | L | R | run (#70) | on | contact less? | |
| #15 | 17/04/2002 | R | R | run (#70) | on | contact less? | |
| #16 | 23/05/2002 | R | R | run (#71) | on | Parity check error | Diagnosing program was installed. |
| #17 | 15/09/2002 | R | R | run (#72) | on | Parity check error | |
| #18 | 02/10/2002 | L | L | run (#72) | on | Parity check error | Two CPUs down. |
| #19 | 08/10/2002 | R | R | run (#72) | on | Parity check error | Two CPUs down. |
| #20 | 15/10/2003 | L | R | stop | off | Parity check error | |
| #21 | 22/12/2005 | R | unknown | run (#78) | on | Parity check error | Shield was constructed. |

3) In 2001, we had the longest continuous operation (operation #69 – 56 days) and experienced one and the other CPU down in succession. The whole cryogenic system was left with no active control for a period. After that, the diagnosing program was installed on the process controller.

4) In 2002, we experienced the same phenomena two times (both operation #72 – 61 days). The diagnosing program showed that the cause was a parity-check-error of the memories on a CPU board. When the first CPU down occurred, we set the CPU standby. If another CPU had stopped, the control would have switch to the other standby CPU. But in this time, it did not work well.

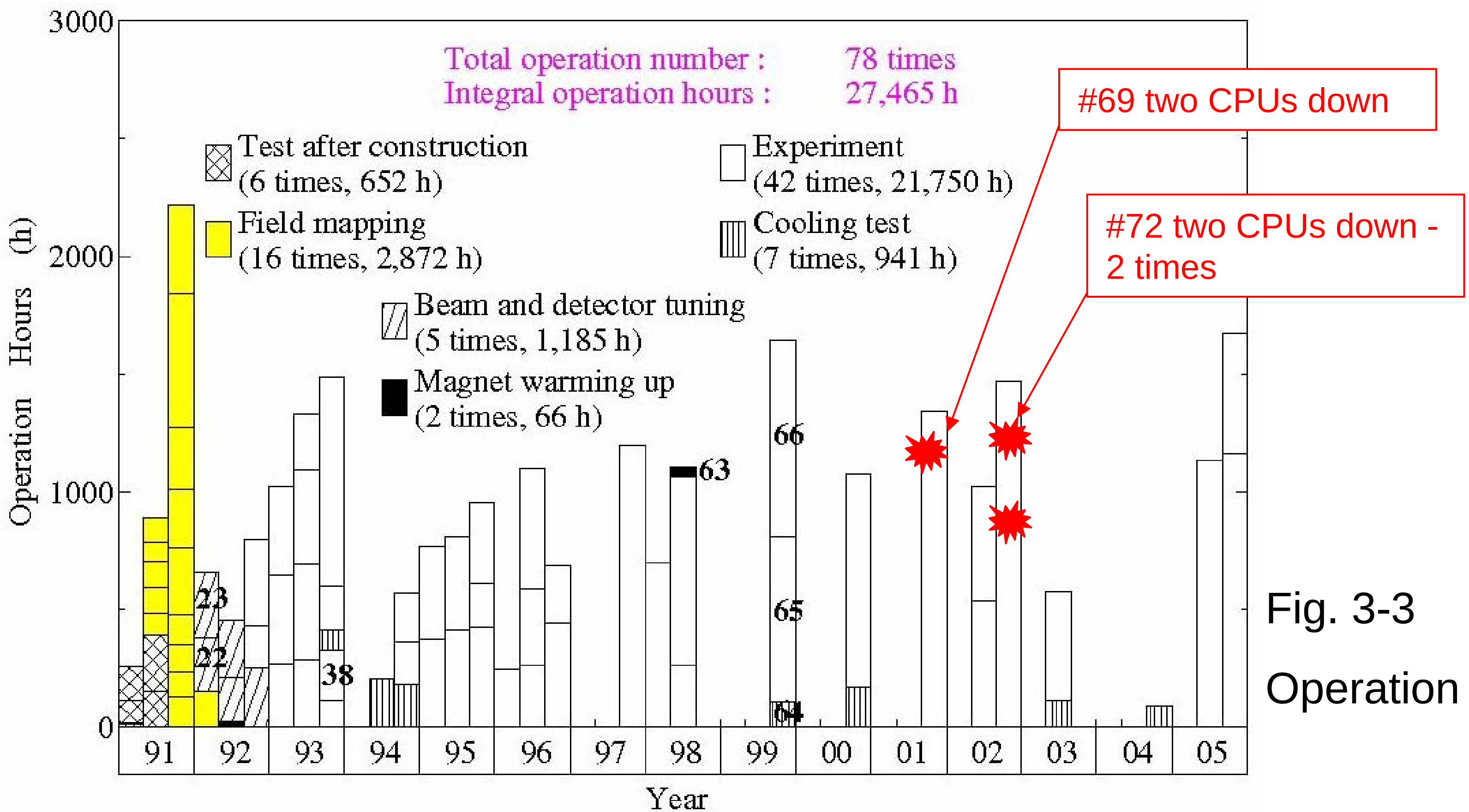


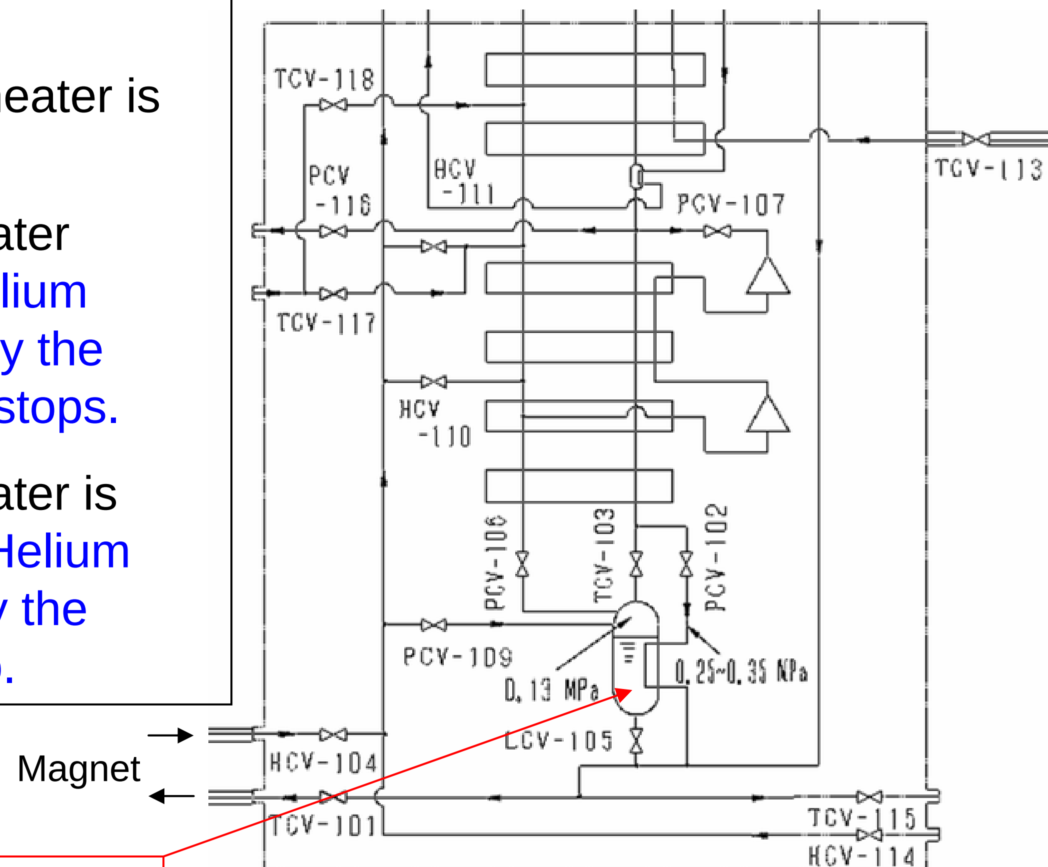

Fig. 3-3

Operation hours

- When two CPUs stop, the alarm was not equipped originally. At once, the process controller automatically restarts, holding the same output values as just before two CPU stopped. But controls states were all changed to manual control.

For SKS, only heater output of a separator in the Cold Box controls the liquid Helium volume.

- After restart, output value of the heater is fixed.
- If the fixed output value of the heater exceeds the average, the liquid Helium volume gradually decreases. Finally the interlock acts and the compressor stops.
- If the fixed output value of the heater is lower than the average, the liquid Helium volume gradually increases, Finally the interlock acts and the turbines stop.




Separator in the Cold Box

Fig. 3-4 Cold Box

5) At this time, we studied an radiation influence (SEU) on “intelligent” valve positioners estimated by ATLAS cryogenic group of CERN.

Sorts of the radiation effects on semiconductors:

| | |
|---|---|
| A) TID (Total Ionizing Dose) | permanent |
| B) NIEL (Non-Ionizing Energy Loss) | permanent |
| C) SEE (Single Event Effects) | |
| C-1) SEU (Single Event Upset) | transient |
| When Hadron-Nucleus reaction occurs in a sensitive area of the semiconductors, large energy deposit by nuclear fragments upsets bit information. | |
| C-2) SEL (Single Event Latch-up) | permanent |
| C-3) SEGR (Single Event Gate Rupture) | permanent |
| C-4) SEB (Single Event Burnout) | permanent |

6) We counted the Neutron flux at the control room, found the SEU data of our memories on CPU board and applied for our control system. The calculated SEU rate explains our observation- SEU probability on both CPU boards in 60 day operation is 73%.

- Always 1 $\mu$ Sv/h has been observed in the control room.
- Counted Neutron flux (more than 20 MeV)– 0.625 particle/cm$^2$·s
- A CPU board uses 6 SRAMS
  - HITACHI SRAM HM628128LP-8 (128k $\times$ 8 bit)
- SEU data for HM628128LP was found in a database, "http://radnet.jpl.nasa.gov/Compendia/P/srams.pdf"
  Original data was derived from "R. Harboe-Sorensen, et al.: IEEE Trans. Nucl. Sci. Vol.40 (1993) 1498"
- We took 1E-13 cm$^2$/bit as a SEU cross section.

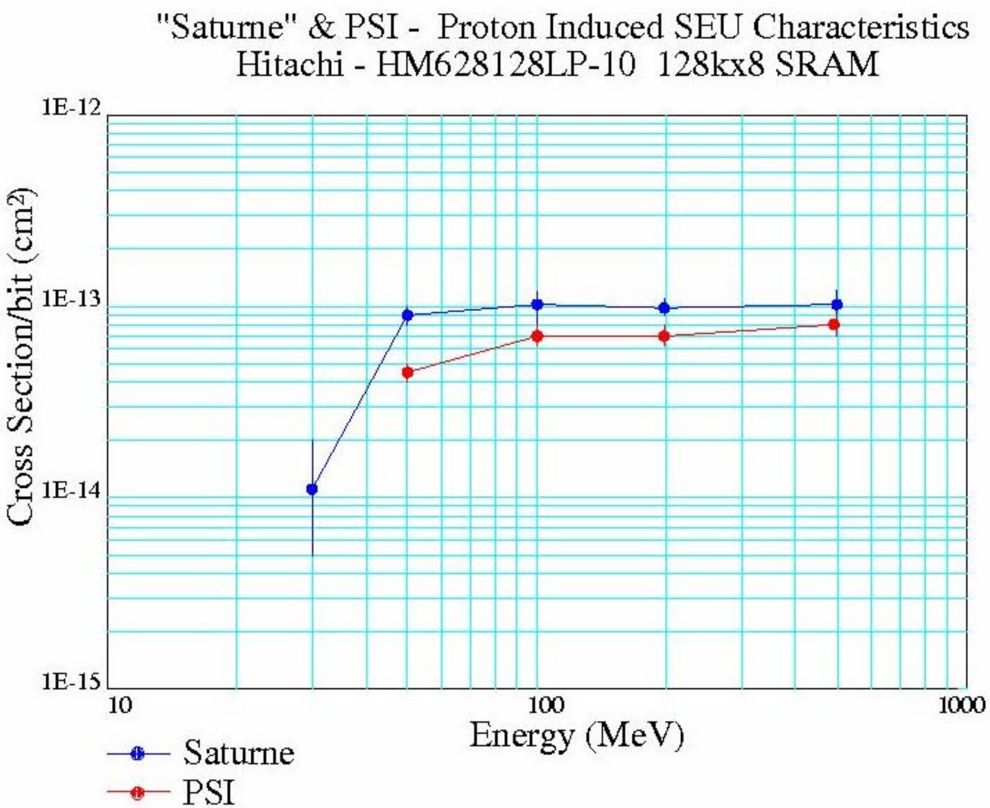



Fig. 3-5 Original Data of SEU by Harboe-Sorensen

Calculation:

- SEU rate more than once in a CPU board .

1E-13 $cm^2$/bit × 1 Mbits × 0.625 particle/$cm^2 \cdot s$ × 6 memories = 3.24E-2 upsets/day (1)

It means SEU occurs in a board once in 30.9 days on average.

- In detail, SEU events follows Poisson distribution.

From equation (1), for 60days,

1.944 upsets/board/60days

Probability of SEU occurrence more than once in a CPU board in 60 days

1-P(0;1.944) = 0.8569

Probability of SEU occurrence more than once in each board of two boards in 60 days

$0.8569^2 = 73\ \%$

The calculated SEU rate explains our observation.

7) Measures - we took two main measures:

1. **New alarm function** – when both CPUs stop, alarm keeps beeping.
2. **Iron shield to suppress Neutron flux.**

Because it is so narrow space in the neighbor of the control room, we set the Iron shield on the expected radiation source. This expectation was based on the Neutron radiation map. GEANT simulation showed that 20 cm thickness Iron stops half of the inlet neutrons having energy more than 20 MeV.

Shield 1: set on the old shield.

50 cm x 300 cm x 50 cm

covers from 250cm to 300cm height from the floor level.

Shield 2: All new shield.

100cm x 100cm x 300cm

Covers from floor level to 300cm height.

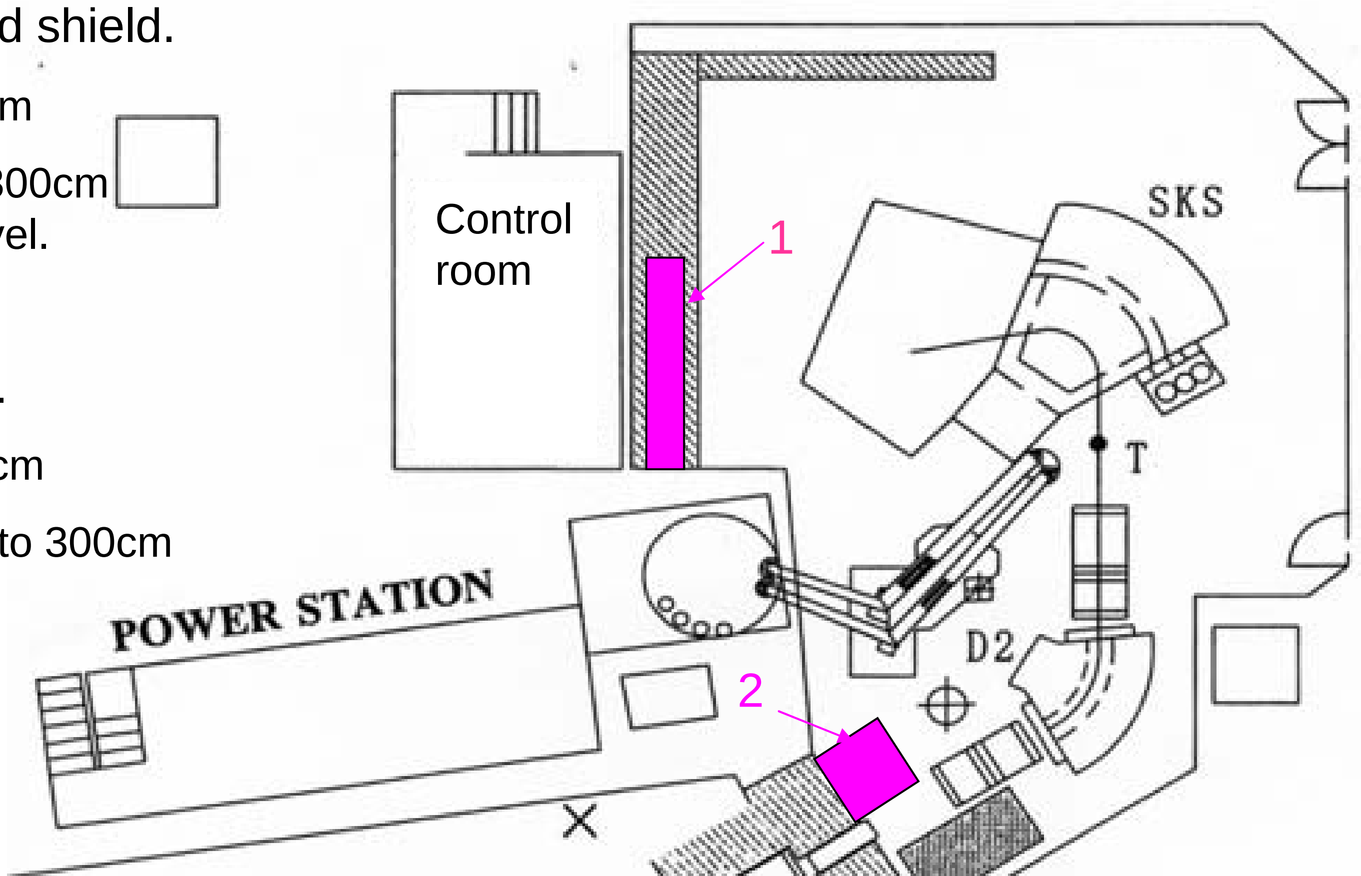



Fig. 3-6 Shield

**Effect of the shield:**

We counted Neutron flux again and estimated the SEU probability.

1) Counted Neutron flux after measures: 0.527 particle/cm$^2$

Cf. 0.625 particle/cm2 before taking measures.

2) Probability of SEU occurrence more than once in each board of two boards in 60 days after measures: 65 %

Cf. 73 % before taking measures.

We could diminish only 8 % probability.

**Conclusion from this experience:**

- ECC function is necessary for control systems.
- To avoid radiation effect on semiconductors, the best way is to locate controller far from the radioactive area. In the radioactive area, point shielding is not effective.

In the **J-PARC,** now under construction, radiation is supposed to be **more serious problem**.
We are going to locate our new GM/JT controllers and other controllers **outside of the Hadron Hall to avoid such radiation effects**.

# 4. Database development for cryogenic systems

In our radiation effect problem, we studied much from data made by ATLAS group of CERN and database developed by NASA. Both data are open to the public with WWW.

Based on our SKS experience and beyond our own system, we are developing **a database of cryogenic systems for superconducting magnets**.

**Aim:** To **share** the information of **parameters, failure examples and measures**.

**Schedule:** The database will open with **WWW** in **March 2007**.

**Contents:**

1. **Parameter information** – **generally open to the public.**
2. **Failures and measures information** –

   **protected information. User needs to submit his or her purpose to use.**

**Please cooperate with us.** If it is difficult to open your failure information, please tell us your parameter information of the system.

**We thank contributors.**

# 5. Summary

1. The SKS cryogenic system **terminated 15 year operations at 12-GeV PS** in KEK.

   We have a plan to change cooling method **from a 300 W refrigerator to GM/JT cryocoolers** for the use in **J-PARC**.

2. We analyzed 15 year operations **from the view point of the reliability**.

   It was proved that the large number of failures and one serious failure caused **lower availability than TRISTAN and BELLE**.

   **Operation style and cycle  of the SKS might cause a such large number of failures**.

3. We suffered **failures caused by the radiation effect (SEU) for the control system**. Through this experience, we recognized that **ECC function is necessary for control systems** to avoid radiation effect on semiconductors and the best way is **to locate controller far from the radioactive area**.

4. Based on our SKS experience and beyond our own system, we have been **developing the database for cryogenic systems**. Contents have two parts, **parameter information** and **protected failure information**.

   **Please cooperate with us.**