# Operation Reliability of J-PARC Main Ring

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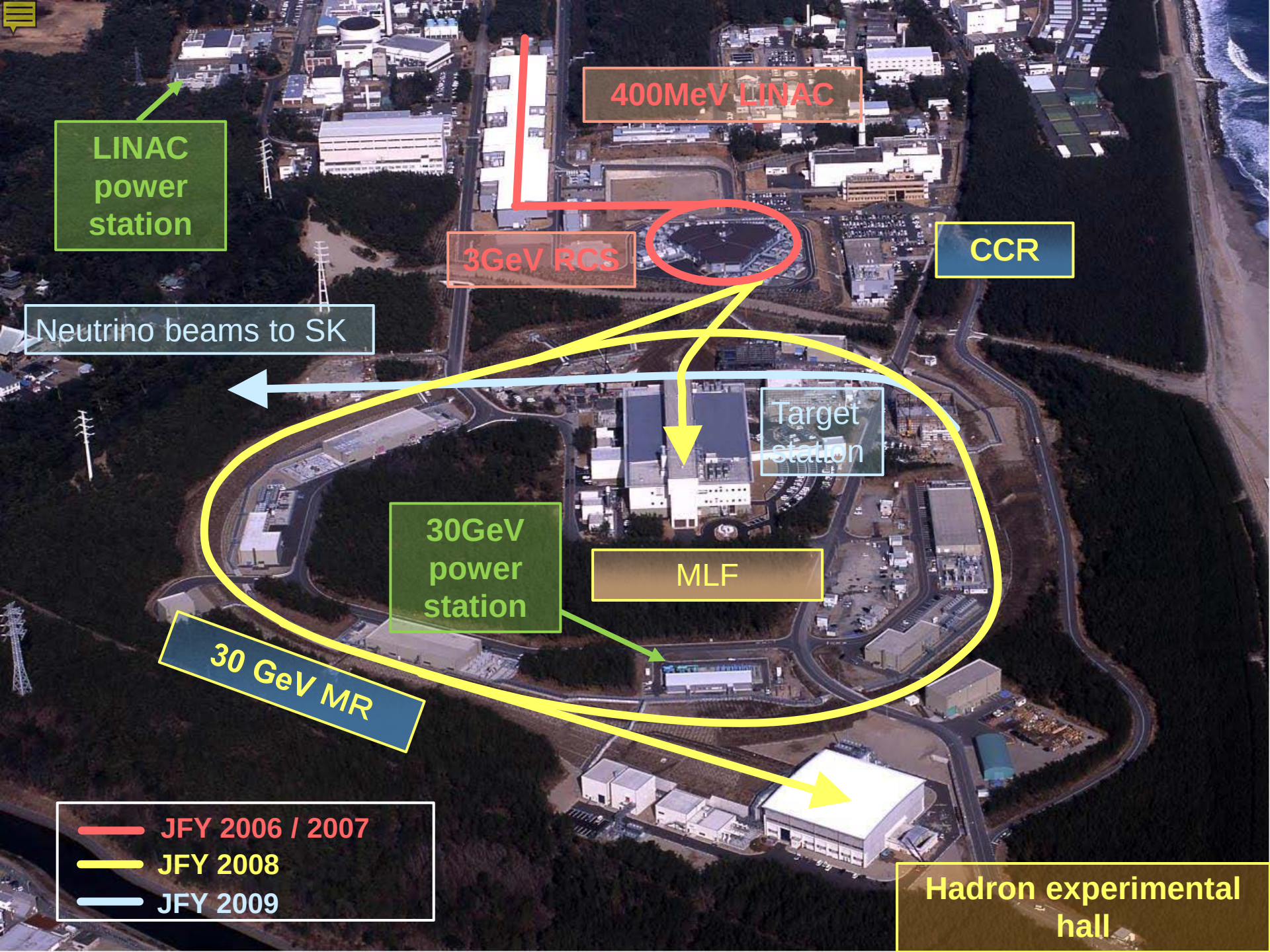
KEK/J-PARC

ARW2015 (27th April to 1st May)

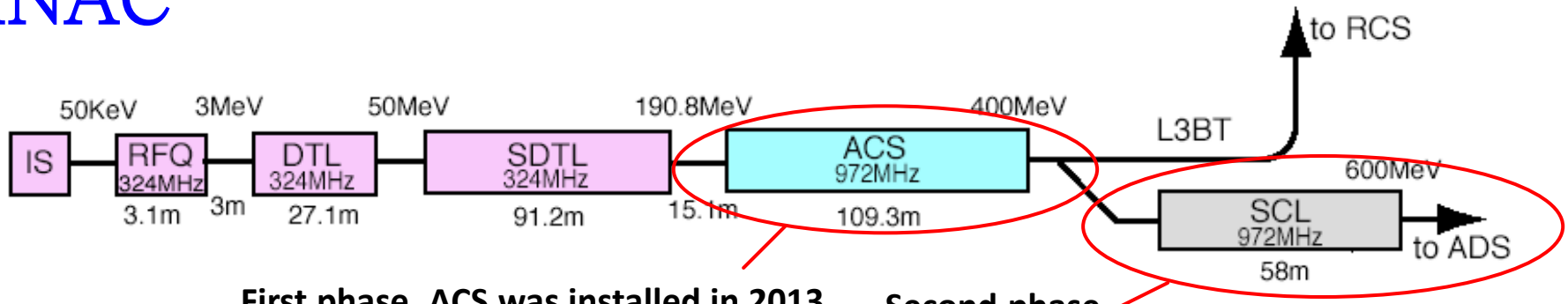
Crowne Plaza, Knoxville, Tennessee, USA

# Contents

# Introduction of J-PARC


LINAC power station
400MeV LINAC
3GeV RCS
CCR
Neutrino beams to SK
Target station
30GeV power station
MLF
30 GeV MR
JFY 2006 / 2007
JFY 2008
JFY 2009
Hadron experimental hall

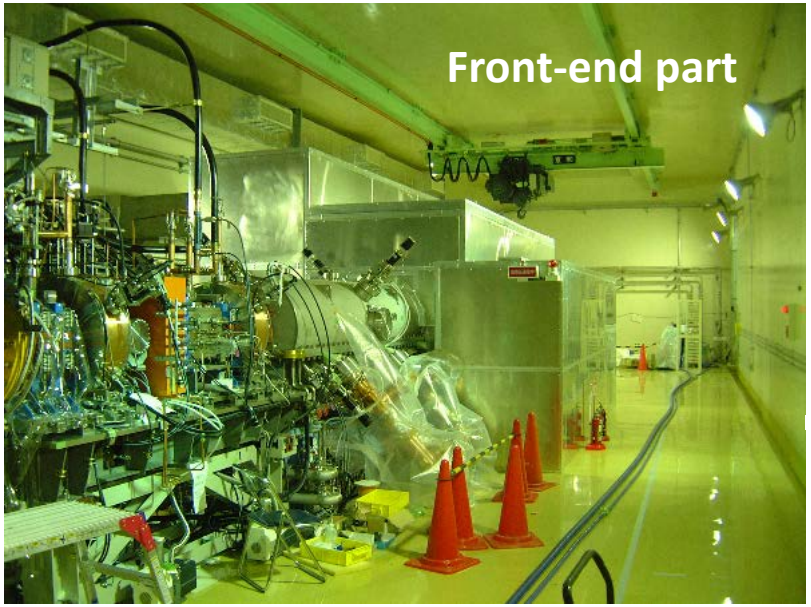
# LINAC



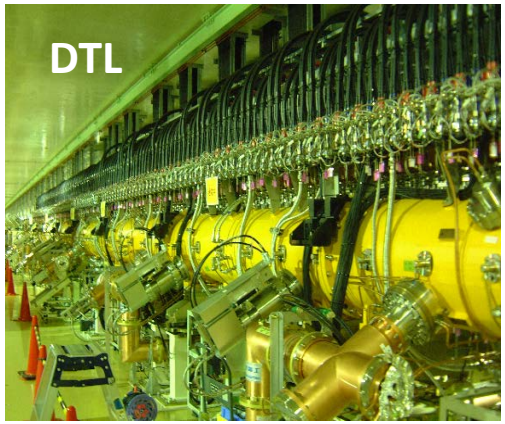

**First phase, ACS was installed in 2013 (Annular Coupled Structure)**

**Second phase (Superconducting Cavity Linac)**

**LINAC beam energy: 181 MeV -> 400 MeV with ACS**




**Ion source, LEBT, RFQ, MEBT(2 choppers, 2 bunchers)**





- **Particle**
  $H^-$ (Negative hydrogen)
- **Energy**
  - **on day-one** 181 MeV
  - **with ACS** 400 MeV
- **Peak current**
  - **at 181 MeV** 30 mA
  - **at 400 MeV** (50 mA)
- **Repetition** 25 Hz
- **Pulse width** 0.5 msec

Original by H. Oguri

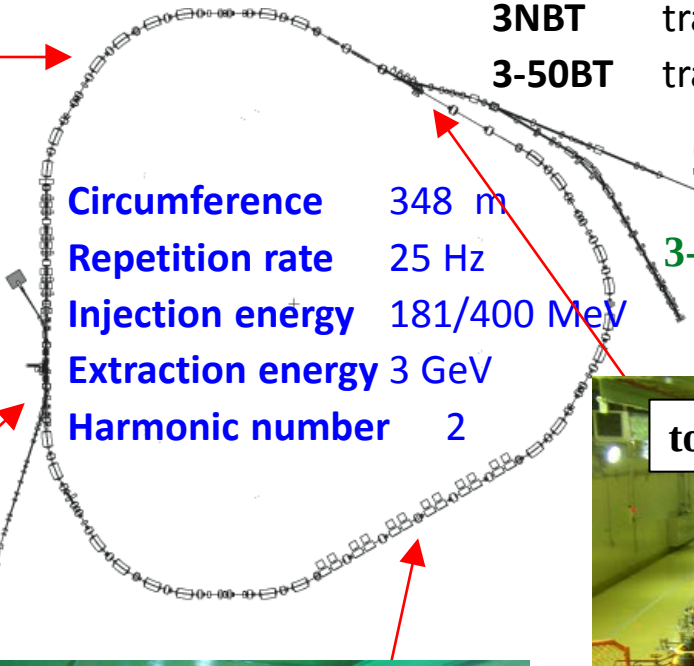
# RCS (Rapid Cycling Synchrotron)


**Neutron/Muon source** and **booster of the MR**

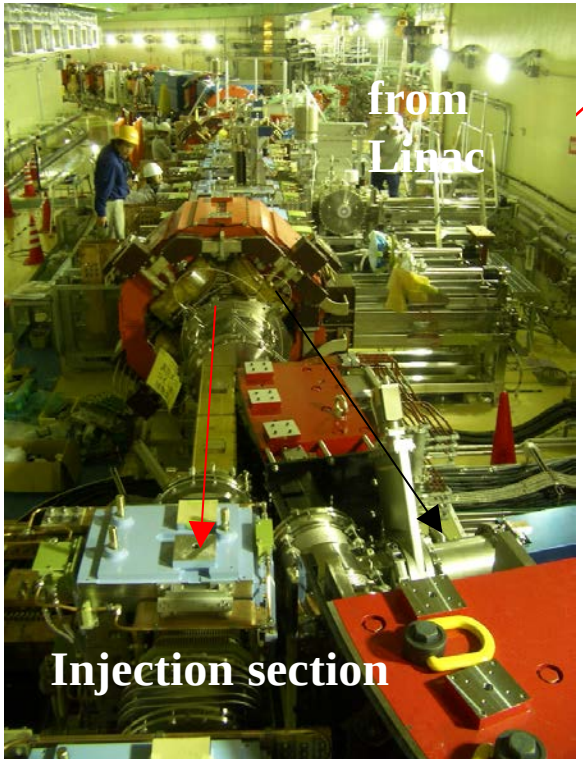
**Two beam transport lines:**

**3NBT** transport line to the MLF

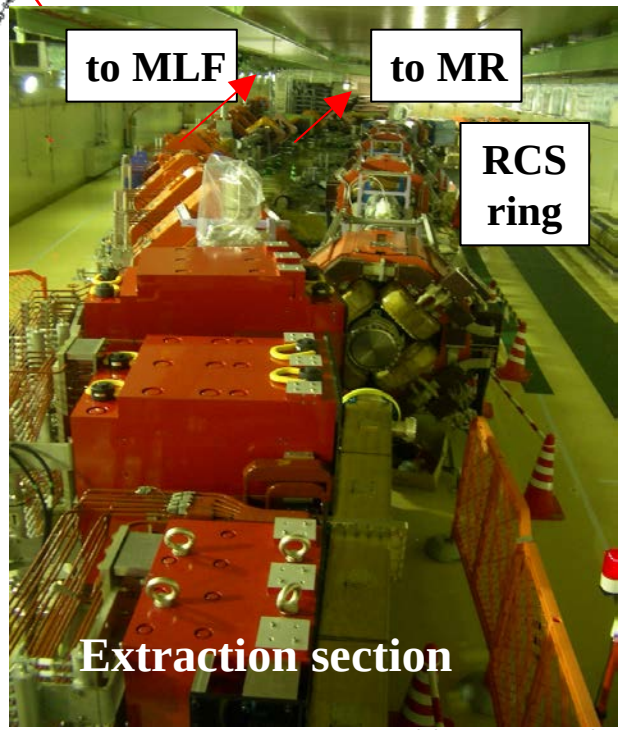
**3-50BT** transport line to the MR




| | |
|---|---|
| **Circumference** | 348 m |
| **Repetition rate** | 25 Hz |
| **Injection energy** | 181/400 MeV |
| **Extraction energy** | 3 GeV |
| **Harmonic number** | 2 |



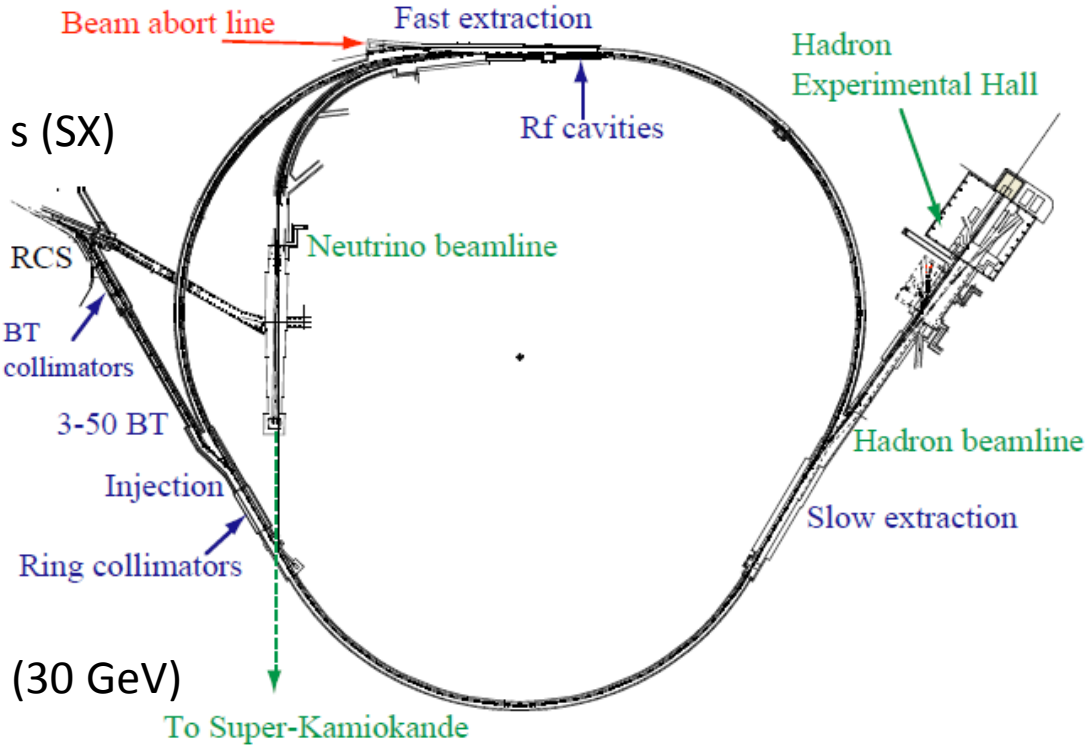





Original by M. Kinsho

# MR (Main Ring slow cycling synchrotron)

| | |
|---|---|
| **Circumference** | 1567.5 m |
| **Repetition cycle** | 2.48 s (FX), 6.00 s (SX) |
| **Injection energy** | 3 GeV |
| **Extraction energy** | 30 GeV |
| **Superperiodicity** | 3 |
| **harmonic #** | 9 |
| **No of bunches** | 8 |
| **Transition γ** | j 31.7 |
| **Typical tune (FX)** | (22.4, 20.8) |
| **Transverse emittance** | |
| **At injection** | <54 π mm mrad |
| **At extraction** | <10 π mm mrad (30 GeV) |




**Three dispersion free straight sections of 116-m long:**

- **Injection and collimator systems**
- **Slow extraction（SX）**
  - **to Hadron experimental Hall (Rare decay, hyper nucleus..)**
- **Rf cavities and Fast extraction(FX) (beam is extracted inside/outside of the ring)**
  - **outside: Beam abort line**
  - **inside: Neutrino beamline (intense n beam is send to SK located 300 km west)**

Original by T. Koseki

# Number of Main Components

**LINAC**

| name | number | power supply |
|---|---|---|
| RFQ | 1 | HVDC01 |
| DTL | 3( 3) | HVDC01 |
| SDTL | 32(16) | HVDC02-05 |
| ACS | 21(21) | HVDC06-12 |
| | ()klystron | |
| | | |
| Q | 77 (DTL1) | 60 |
| | 44 (DTL2) | 31 |
| | 28 (DTL3) | 20 |
| | 62 (SDTL) | 35 |
| Steering | 26 | 26 |

**RCS**

| name | number | power supply |
|---|---|---|
| BM | 24+(1) | BMDC+BMAC |
| QFN | 12 | QFN PS |
| QDN | 12 | QDN PS |
| QFX | 12 | QFX PS |
| QDX | 9 | QDX PS |
| QFL | 6 | QFL PS |
| QDL | 6 | QDL PS |
| QFM | 3 | QFM PS |
| | | |
| SM | 18 | SM PS |
| | | |
| RF | | |

**MR**

| name | number | power supply |
|---|---|---|
| BM | 96 | BM1-6 |
| | | |
| QFN | 48 | QFN PS |
| QDN | 48 | QDN PS |
| QFX | 48 | QFX PS |
| QDX | 27 | QDX PS |
| QFP | 6 | QFP PS |
| QFR | 9 | QFR PS |
| QDR | 6 | QDR PS |
| QFS | 6 | QFS PS |
| QDS | 6 | QDS PS |
| QFT | 6 | QFT PS |
| QDT | 6 | QDT PS |
| | | |
| SFA | 24 | SFA PS |
| SDA | 24 | SDA PS |
| SDB | 24 | SDB PS |
| | | |
| RF | 9 | |

And **Beam transport lines**

**LEBT, MEBT1, MEBT2, L3BT, 3NBT, 3-50BT, NU line, SY-HD line**
with many dipoles, quadrupoles, and other devices

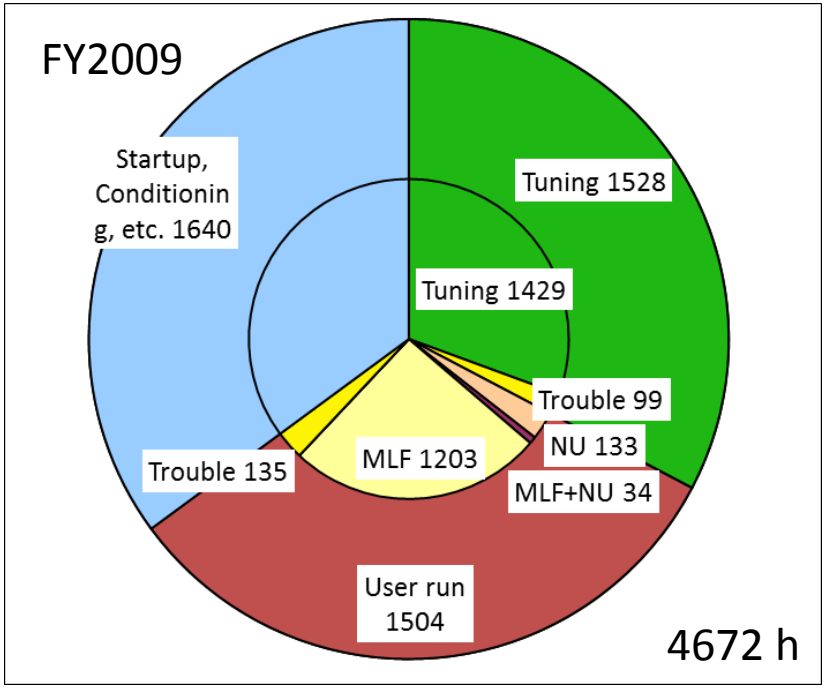
J-PARC is a big system.

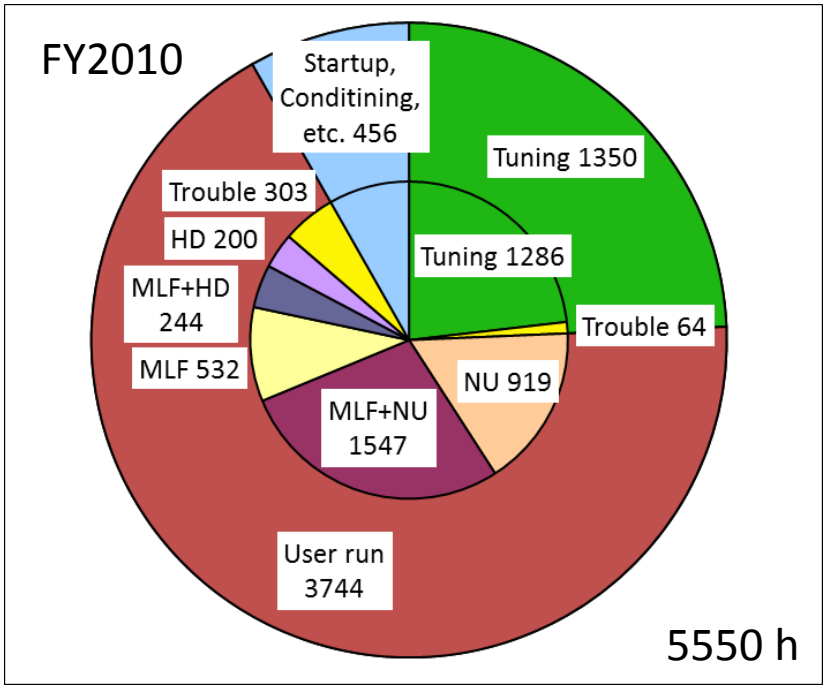
- Efforts which raises the reliability of each device are continued…
- For highly reliable operation, equipment of facilities is partly duplicated: cooling water pumps, fans, chillers, …

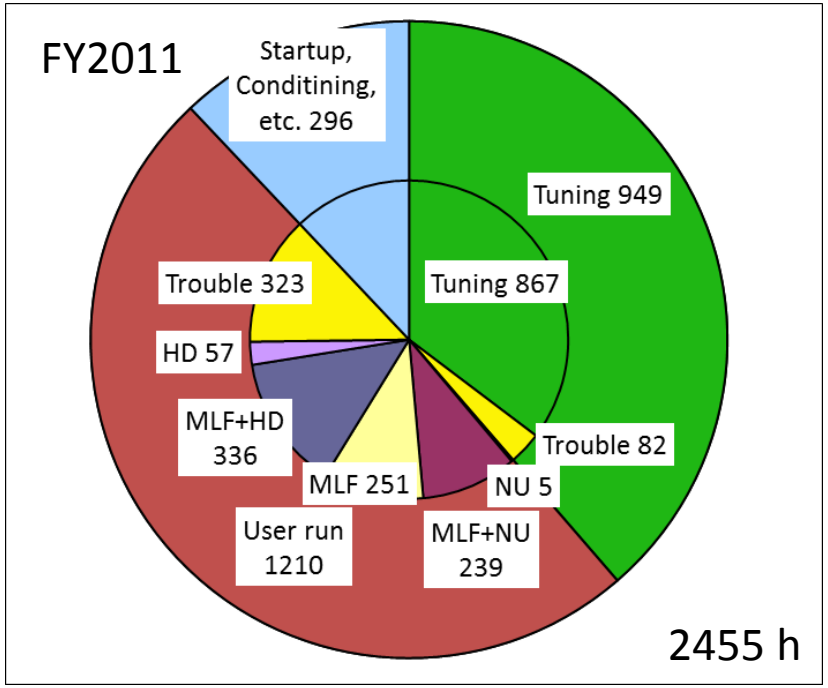
# Reliability review of J-PARC

# Operation Reliability [1]

Still early stage of J-PARC




- First physics run of NU
- Trouble was 135 hours (9.0%) in user time 1504 h.
- Mainly due to the RFQ conditioning in order to cure the discharge problem since 2008.

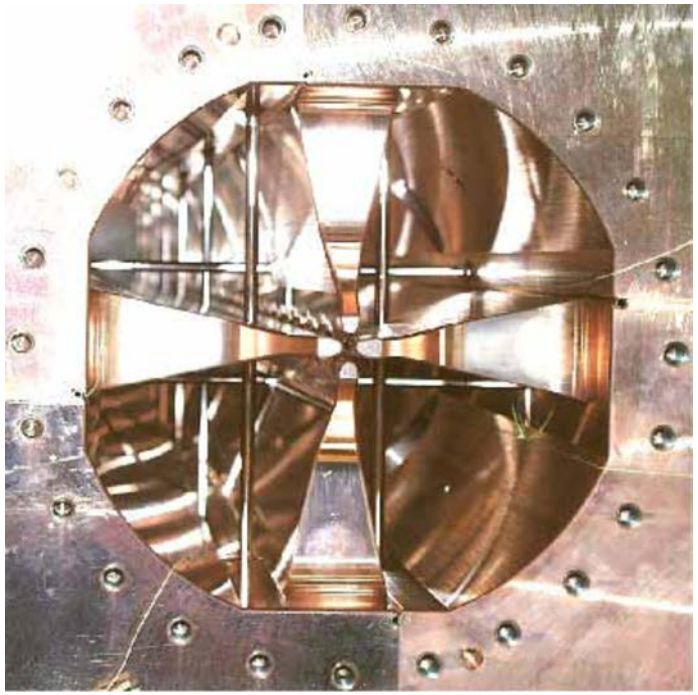
Operation data by M. Adachi

# Discharge problem in the RFQ

- The first severe discharge problem in the RFQ occured in September 2008.
- Before this problem, the availability of linac was more than 90 %.
- After the problem, we are suffering from sporadic unscheduled shutdown due to discharge problem in RFQ.
- A run cycle scheduled in Oct. 2008 was cancelled for RFQ conditioning.
- The RFQ downtime (both scheduled and unscheduled) dominated the machine time in runs in Dec. 2008 and Jan. 2009.

↓

"RFQ backup group" has been organized, who prepares the "backup RFQ" though it takes about one year.

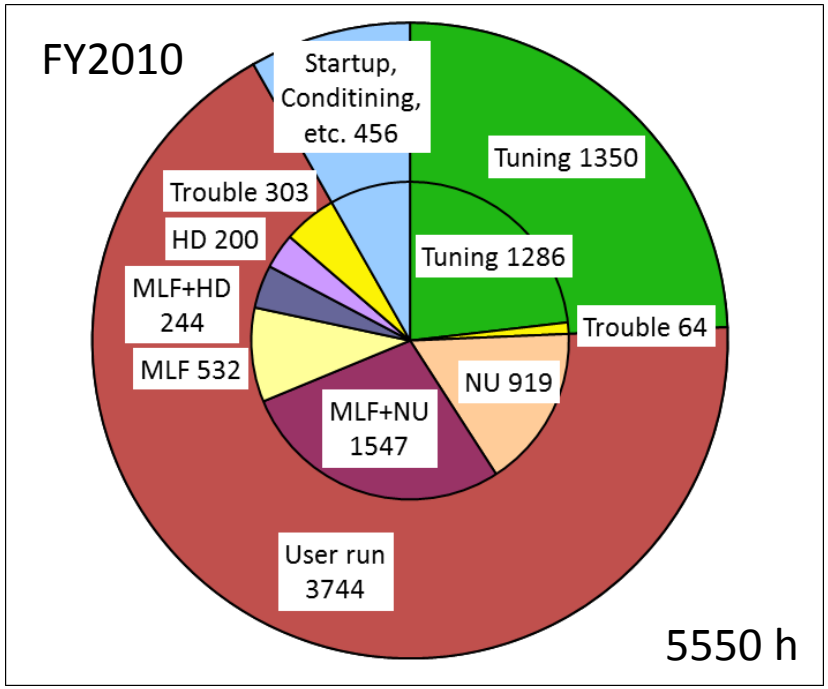


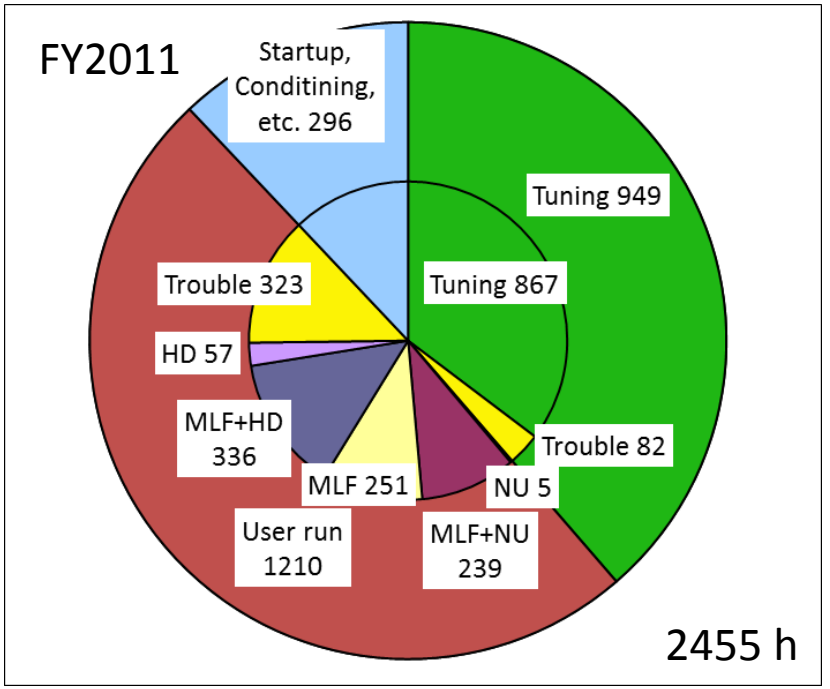
Inside view of RFQ

RFQ (Radio Frequency Quadrupole) uses electric quadrupole field for beam focusing. Discharge may occur at the surface with high voltage potential.

*Original slide by J-PARC LINAC group*

# Operation Reliability [1']



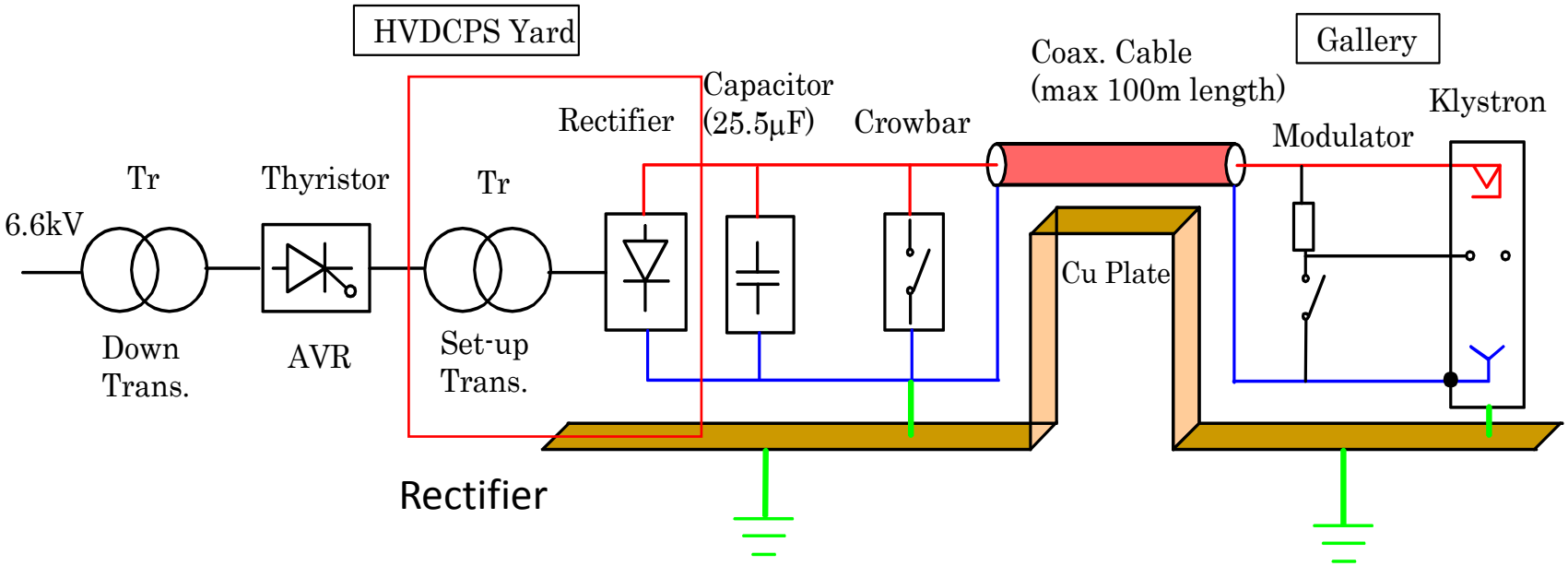




- In FY2010 and FY2011, time for "Startup and Conditioning" became shorter (~10%) because the machine operation got off the ground to a good start.
- Operation time of FY2011 was half of those of FY2009 and FY2010 because operation was cancelled (from March of FY2010) by Megaquake.
- In addition, user time from 4:10 22$^{nd}$ to 24:00 31$^{st}$ March (10 days) in 2012 (the last month of FY2011) was cancelled due to the trouble of DC power supply (HVDC01) of LINAC klystron.
- User availability was 91.9% in 2010, and 73.4% in 2011.

Operation data by M. Adachi

# Klystron DC power supply No.1 (HVDC01)

22nd March 2012, AM4:10 DC_over_current




Rectifier

(Phase-controlled AC 600V to DC 110kV)

HVDC1: power source of RFQ, DTL1, DTL2, and DTL3

*Original slide by H. Oguri and E. Chishiro*

# Step-up Rectifier

**Investigation**

Measurement of no-load current

⇩

Breakdown of diode

**Recovery**

30th March to 2nd April

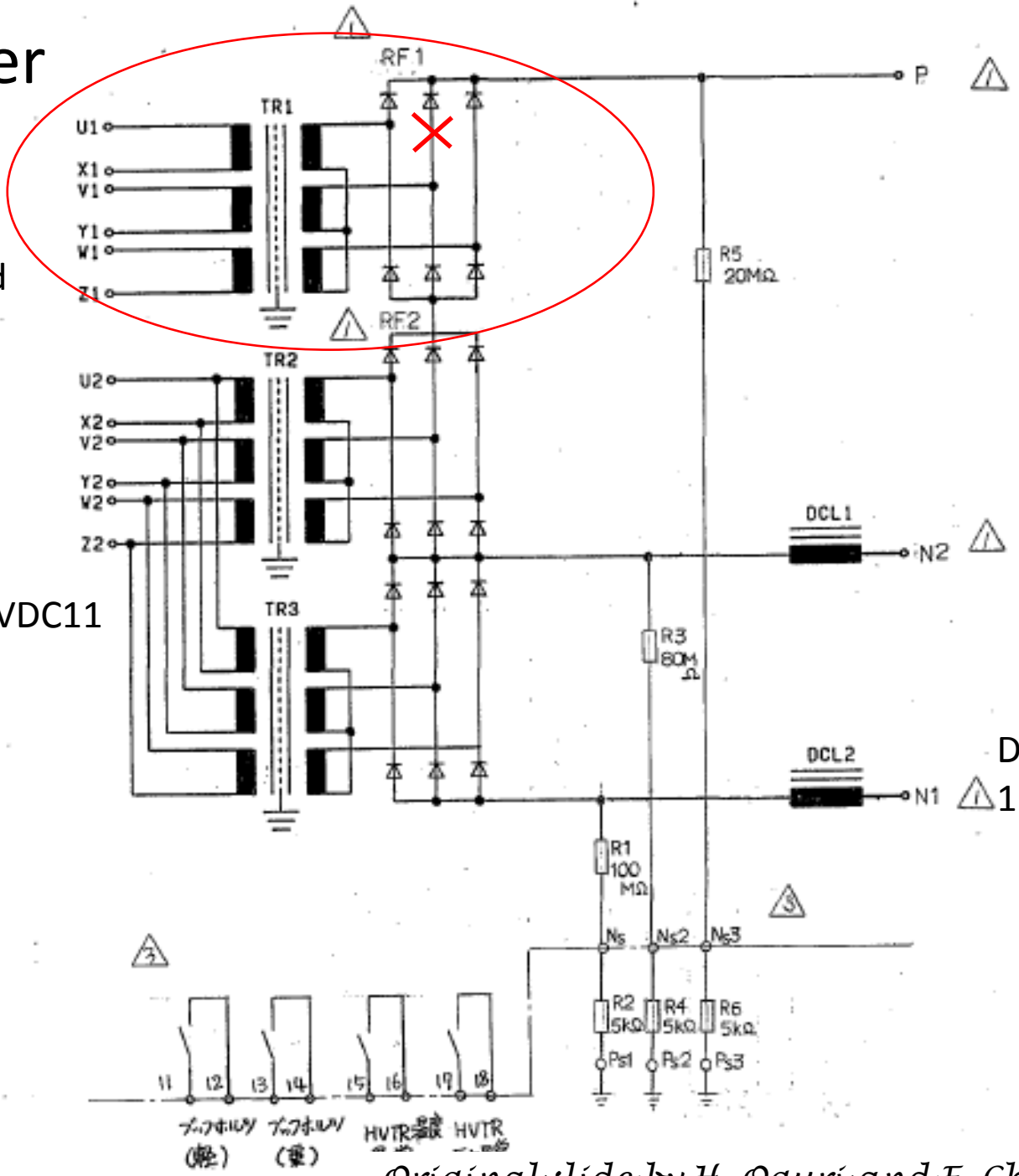
Exchange HVDC01 <-> HVDC11 (4 days)

3rd April Test operation

4th April Aging

5th April Beam ON

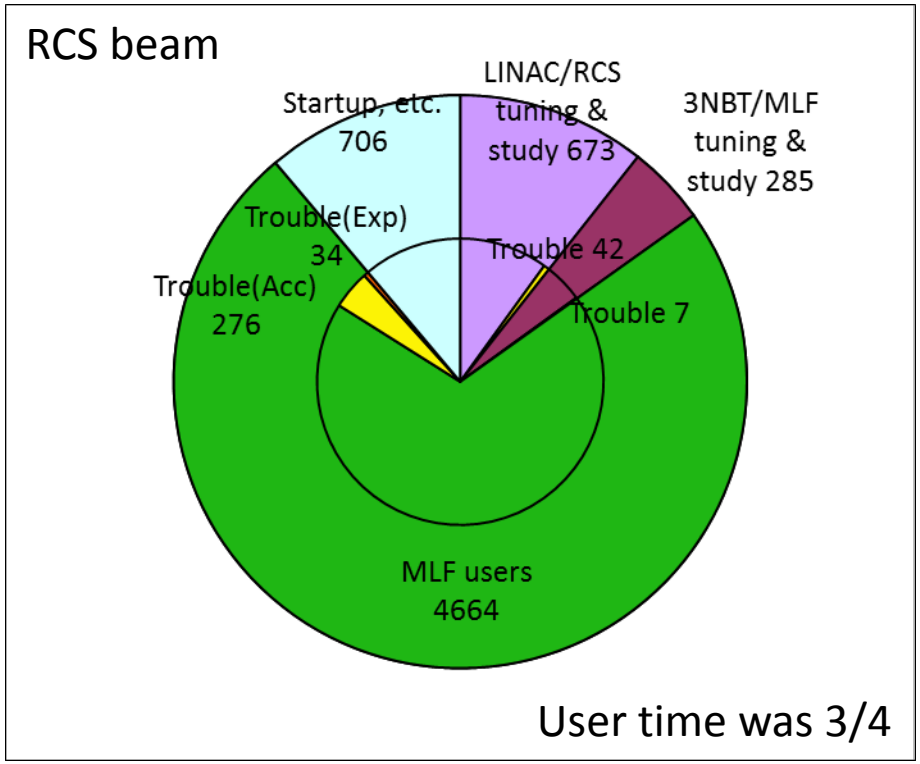
6 days for recovery

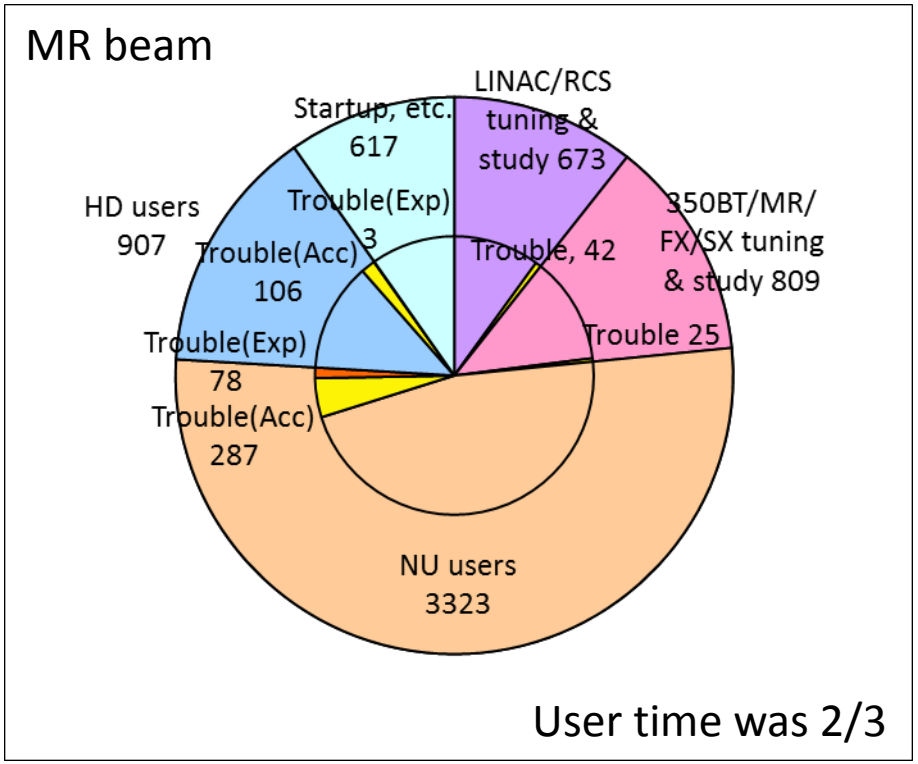



*Original slide by H. Oguri and E. Chishiro*

# Operation Reliability [2]

FY2012 One year after the Megaquake (6328 h)




| | MLF | NU | HD |
|---|---|---|---|
| User availability: | 93.4% | 89.0% | 88.0% |

Downtime mainly comes from MR SX(63 h), LINAC HVDC(59 h), RFQ(31 h)

| | |
|---|---|
| 16:25 25th Oct. 2012 | SX_SMS1 vacuum leak (19 h) |
| 00:51 14th Mar. 2013 | SX_SMS1 break down (37 h), HD beam was cancelled. |

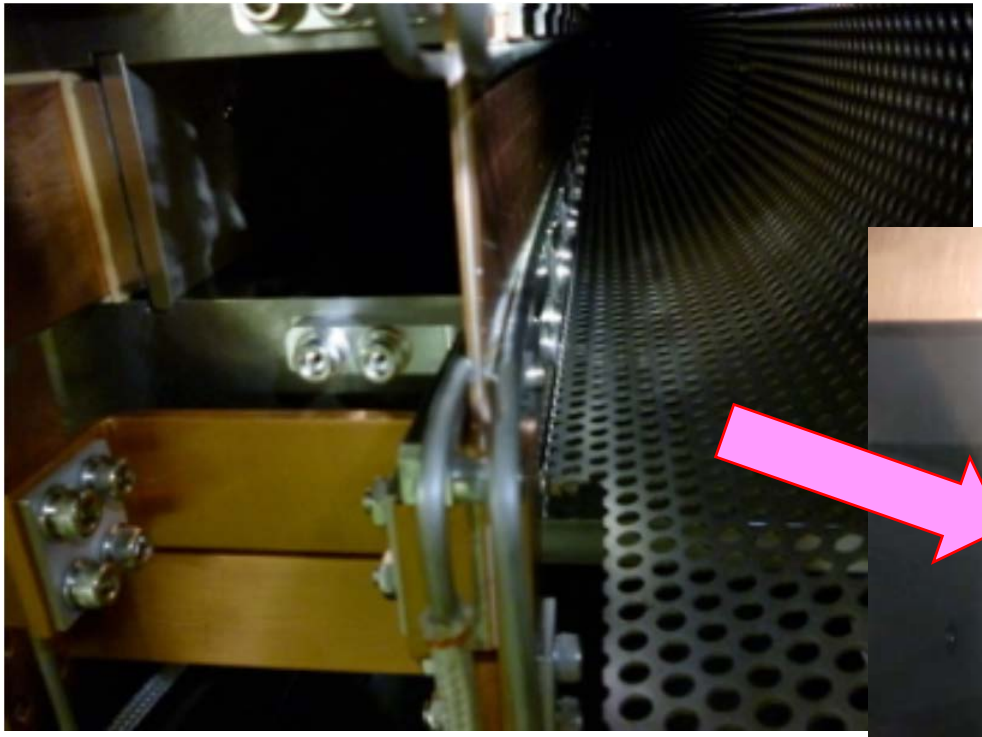
Operation data by M. Adachi

# Breakdown of septum conductor of SMS1

**SMS1**
Low field septum for slow beam extraction

Coil = 2 turns
Thickness= 3.5 mm (0.5 mm for ceramic)
Field strength= 1.38kG @3010A
Cooling
pipe= $\phi$3 mm(inner) t0.5 mm
$\Delta$t= 18 deg (2.1 L/min)

Nov. 2012



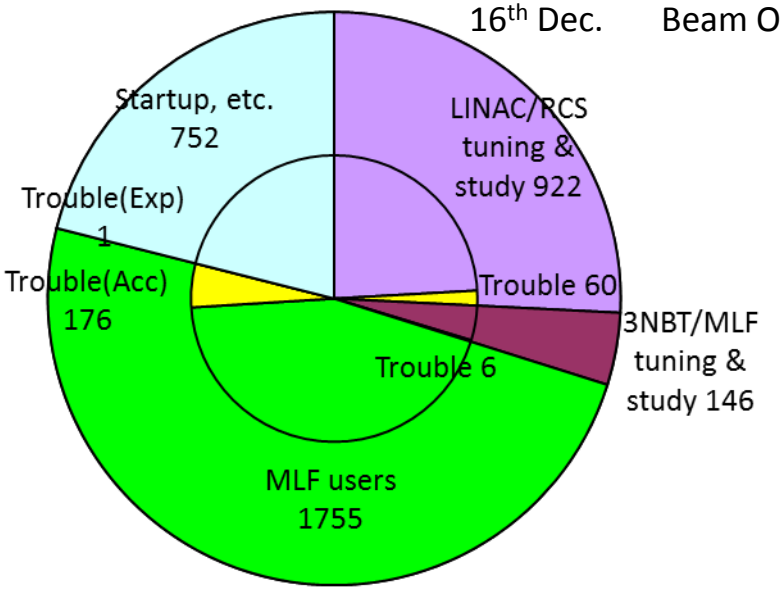
14th Mar. 2013

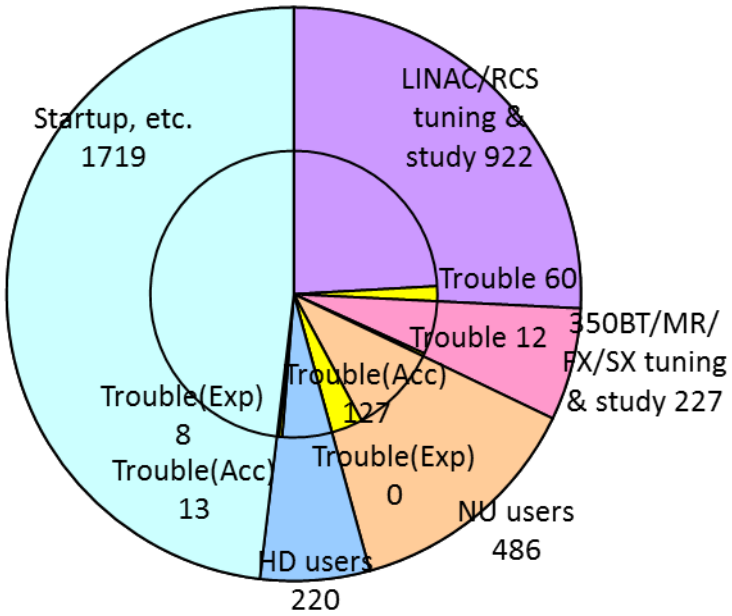
Conductor at the downstream bended out to the circulating beam!

# Operation Reliability [3]

FY2013 LINAC ACS installation and Radiation accident at Hadron hall (3574 h)

25th May All beam OFF due to the radiation accident at the Hadron hall
Long shutdown for the ACS installation
16th Dec. Beam ON at LINAC



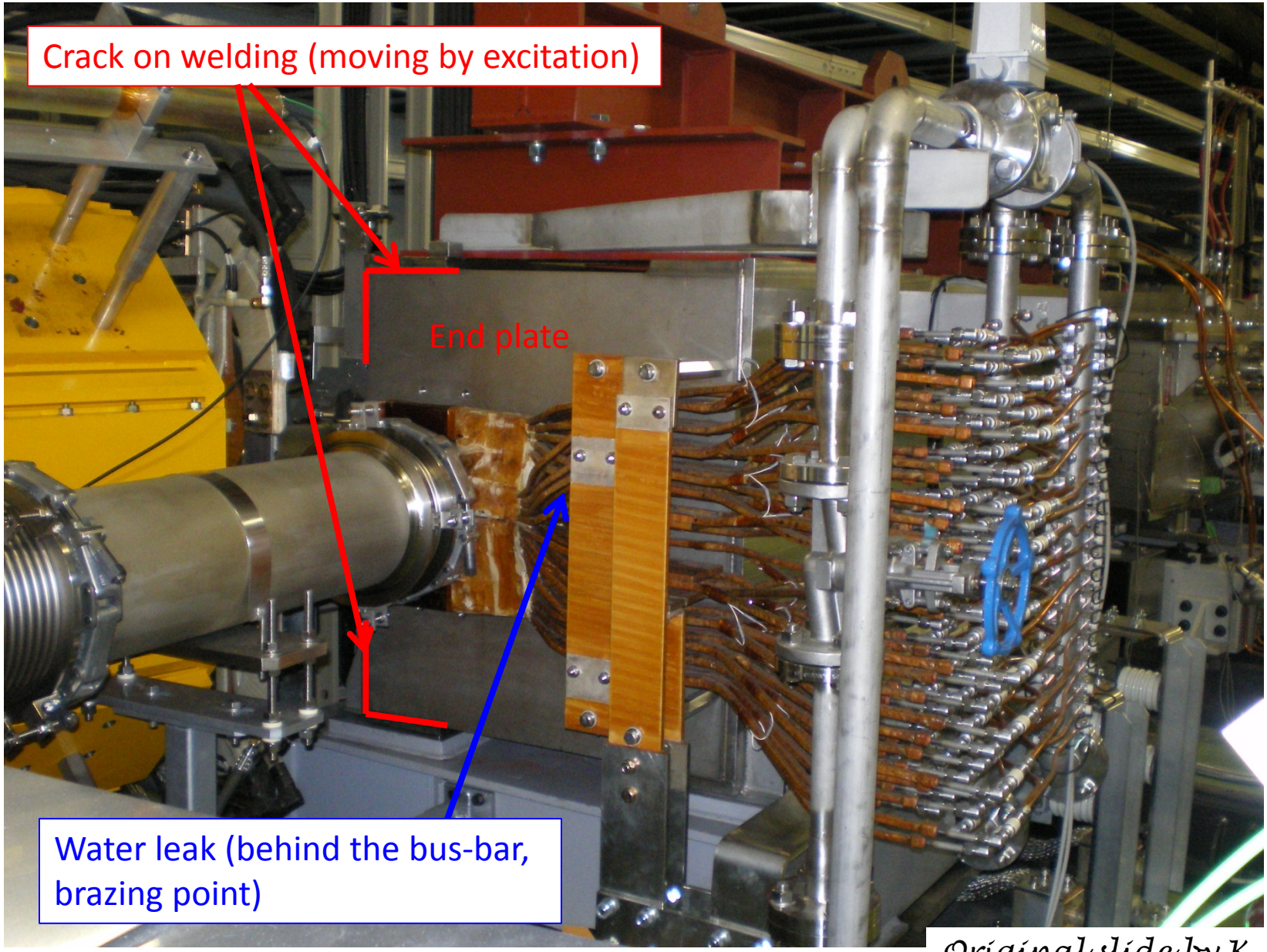

| | MLF | NU | HD |
|---|---|---|---|
| User availability: | 89.9% | 73.9% | 90.5% |

Downtime mainly comes from MR Inj.(114 h), LINAC HVDC(103 h), and RCS shift-bump(73 h)

13:50 8th May 2013 Water leak of MR Injection septum 1

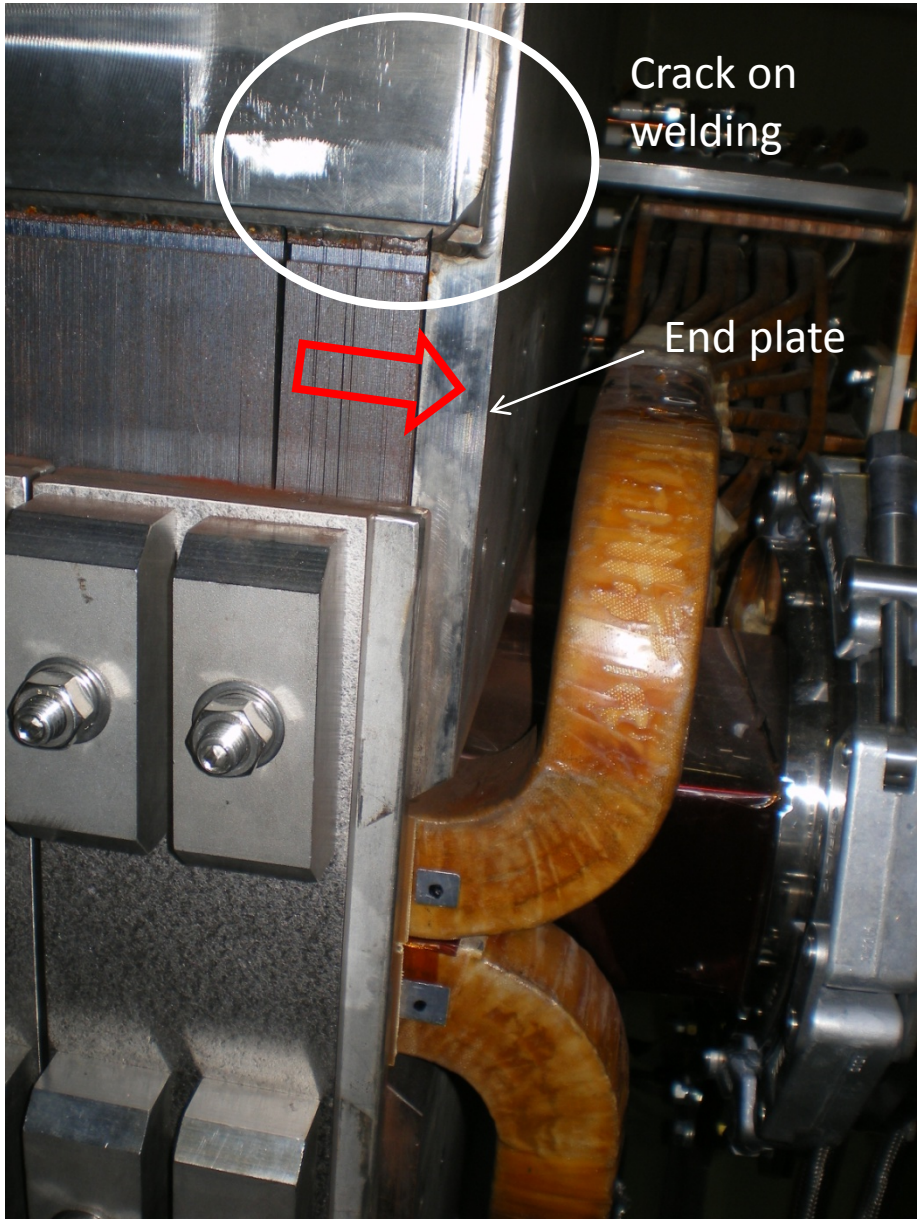
Operation data by M. Adachi

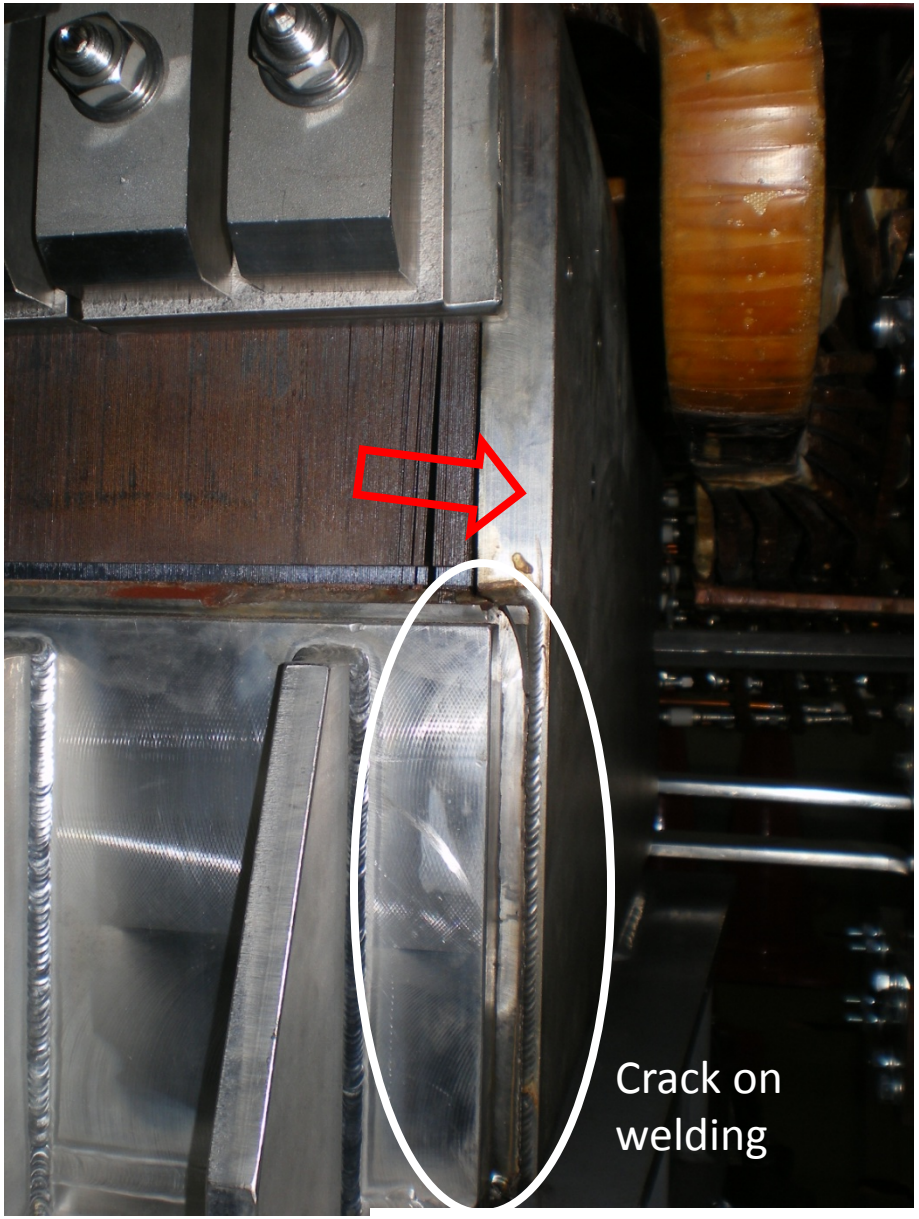
Injection septum 1




*Original slide by K. Ishii*

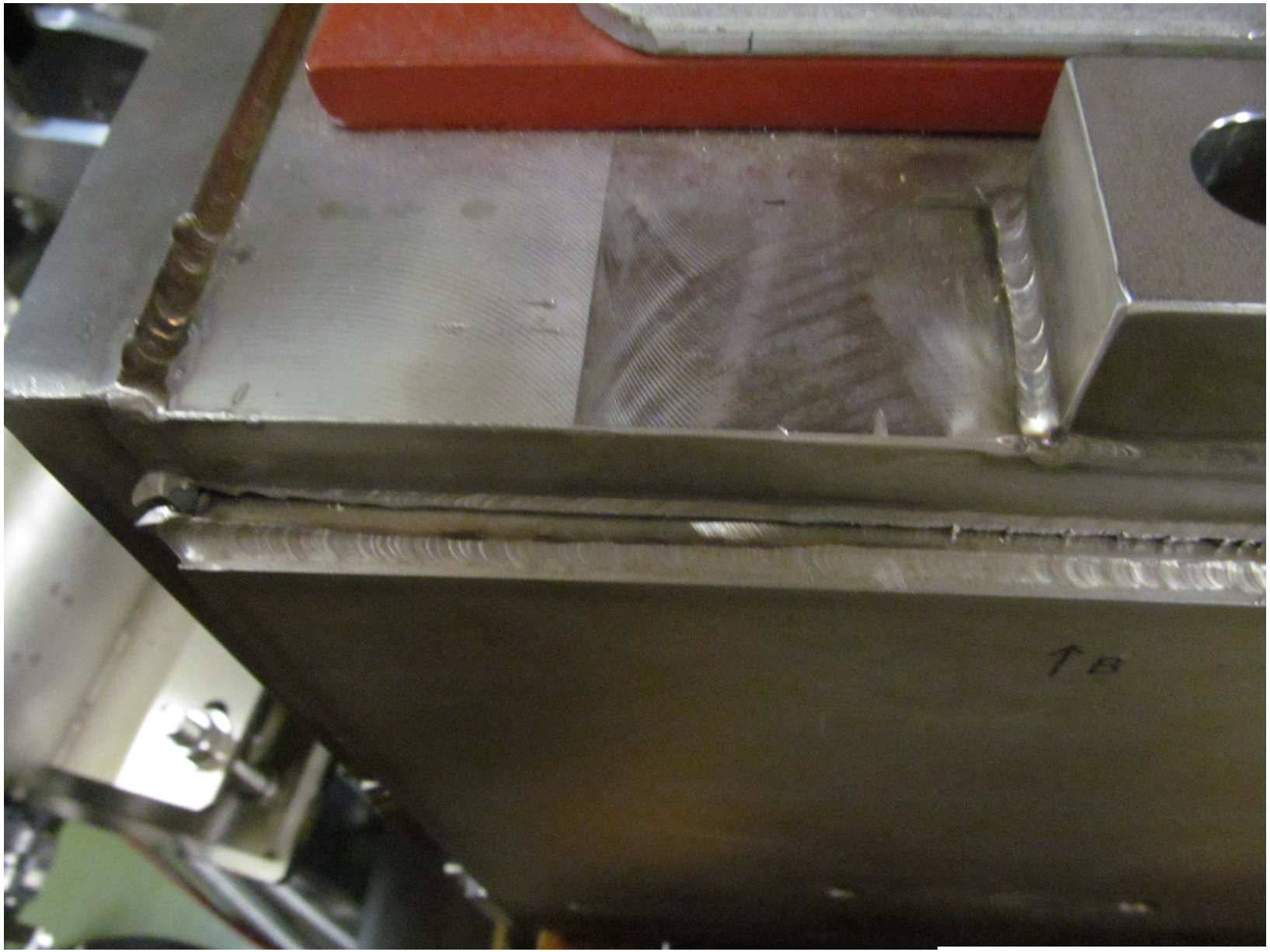
Injection septum 1




*Original slide by K. Ishii*

Injection septum 1

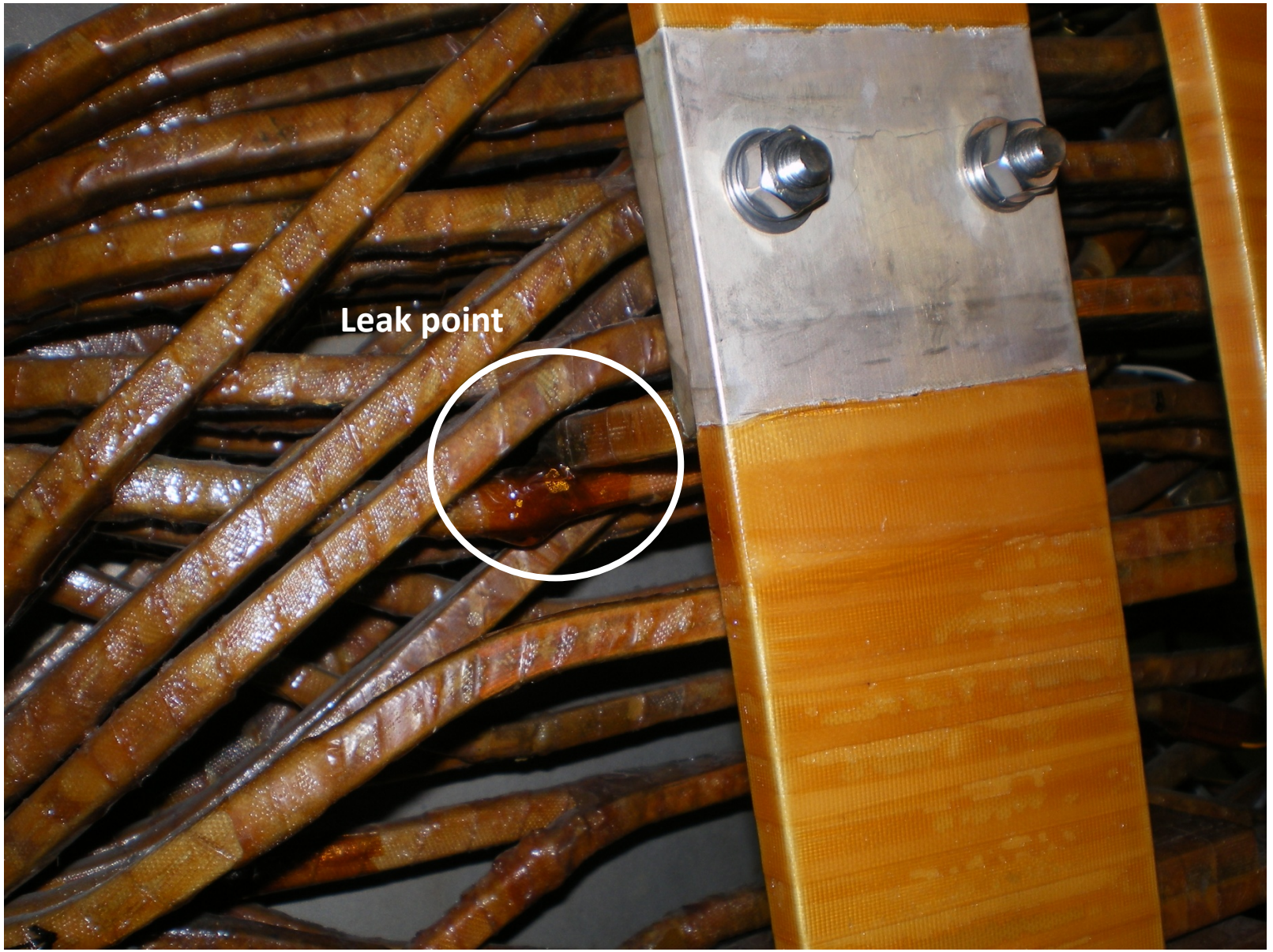


*Original slide by K. Ishii*

Injection septum 1

*Original slide by K. Ishii*

Injection septum 1

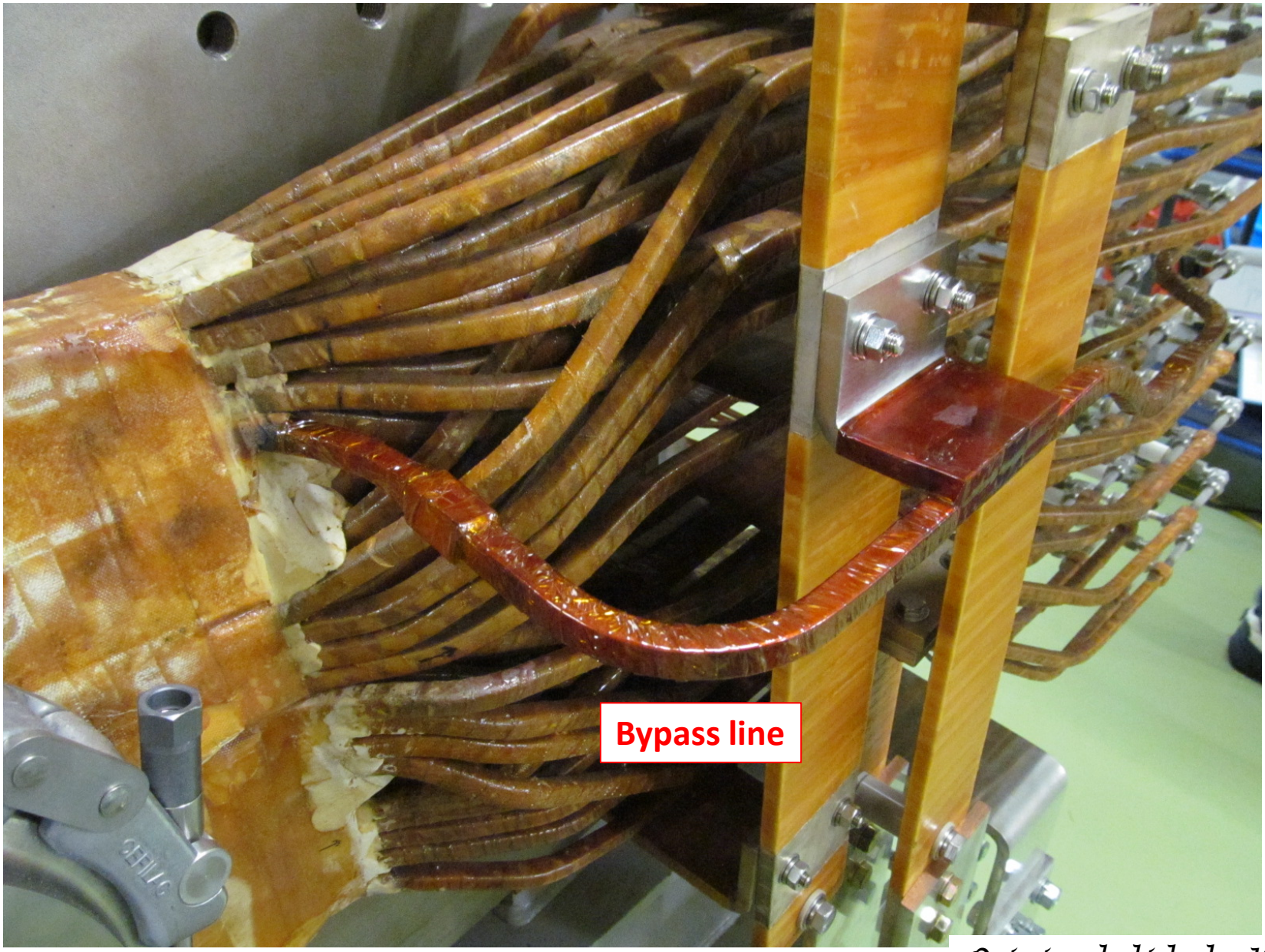



*Original slide by K. Ishii*

Injection septum 1

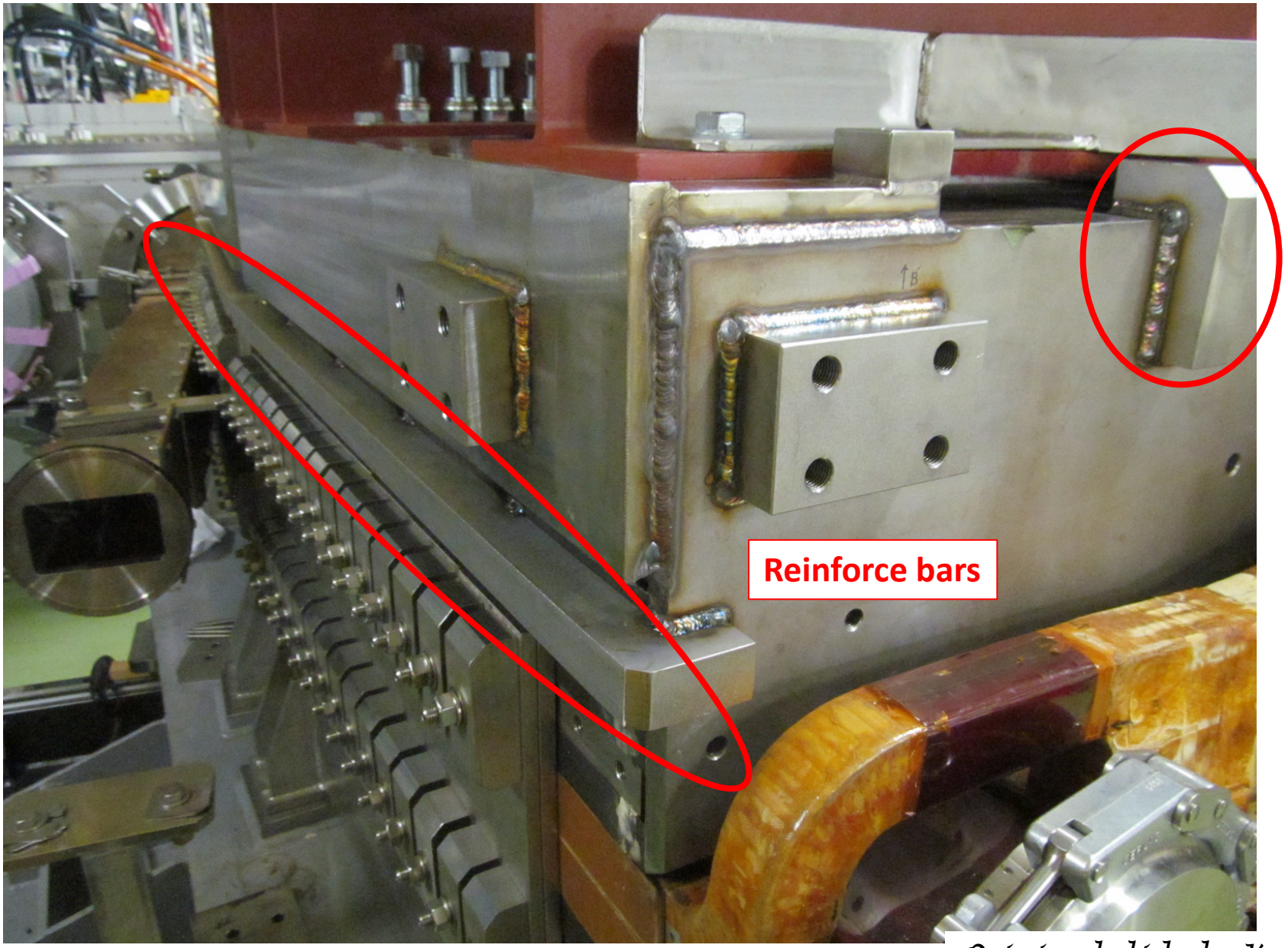
*Original slide by K. Ishii*

Injection septum 1




*Original slide by K. Ishii*

Injection septum 1




*Original slide by K. Ishii*

**Needed time for repair [Water Leak of MR Injection Septum 1]**

May 2013

| | |
|---|---|
| 8th | Revelation! of water leak and investigation |
| 9th | Design, scheduling, and applications for radiation and fire work |
| 10th | Education for workers, open flange, measurement, line-out, repair of hollow-conductor |
| 11th | Pressure test, re-welding the end plate, welding reinforce bars to the magnet, grinding |
| 12th | Welding reinforce pieces to the magnet, line-in, alignment, water check, vacuum leak check, current test (all night long) |
| 13th | Confirmation of recovery check |

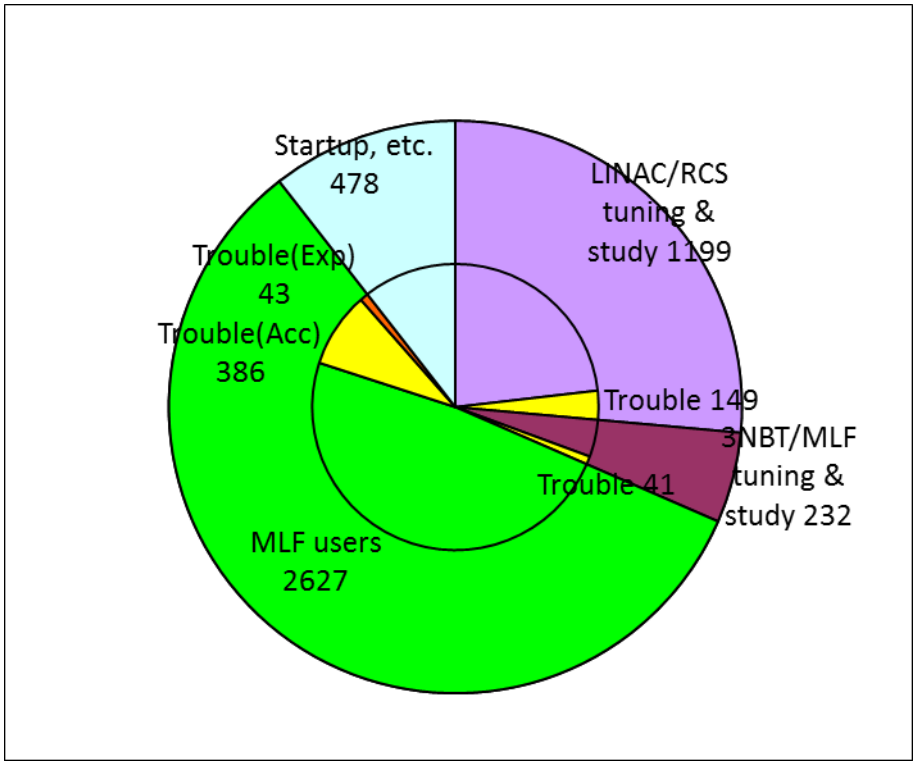
6 days for recovery

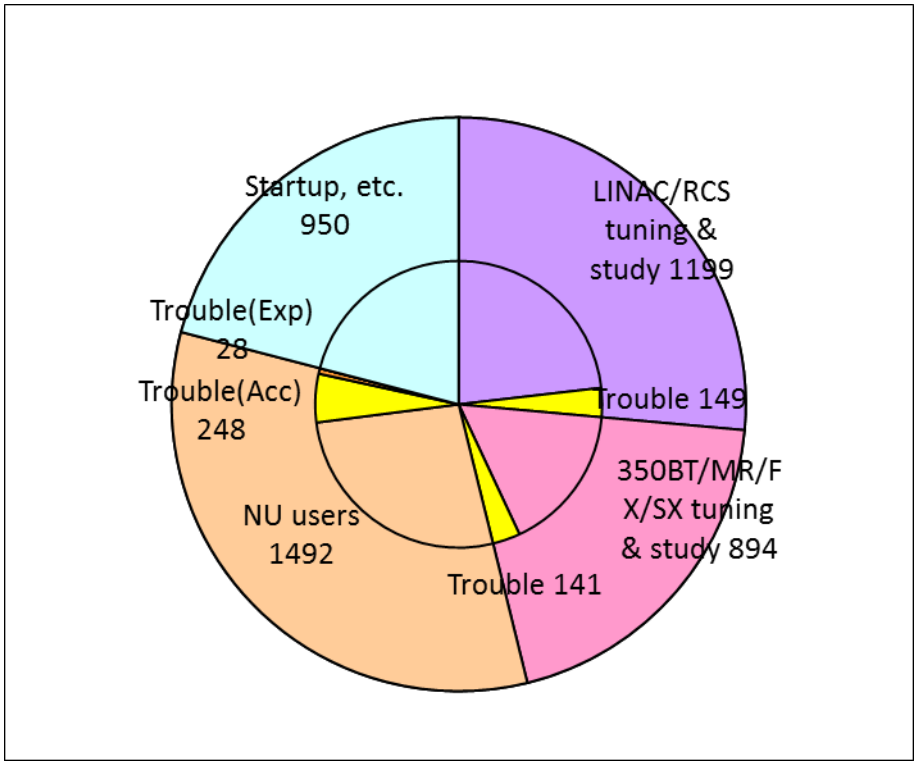
MR injection septum 1 was repaired and reinforced.
No trouble until now. (April 2015)

We have a plan to replace this by a new septum (all new designed) this summer.

# Operation Reliability [4]

FY2014 Ordinary year without HD experiments until 7th February 2015 (4535 h)




| | MLF | NU | HD |
|---|---|---|---|
| User availability: | 85.3% | 83.4% | 00.0% (No beam for HD users) |

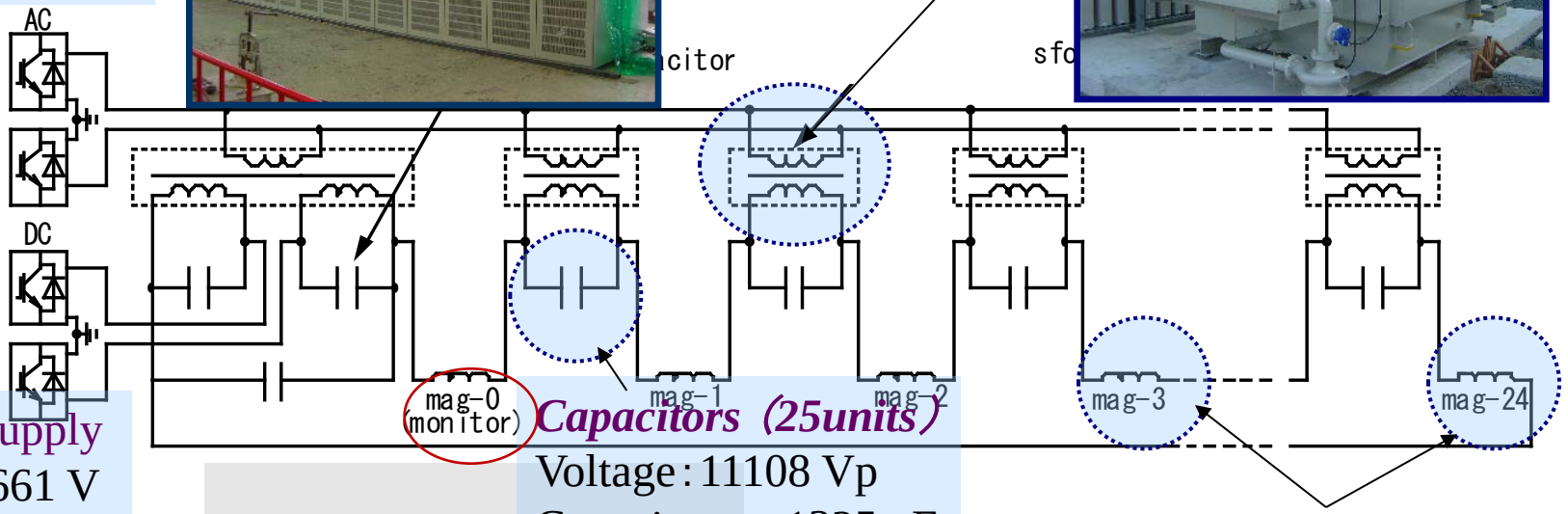
Downtime mainly comes from LINAC HVDC(154 h), RCS BM(115h), and LINAC ACS(63h)
MR worked well.

Operation data by M. Adachi

# Resonant network and power supply for BM

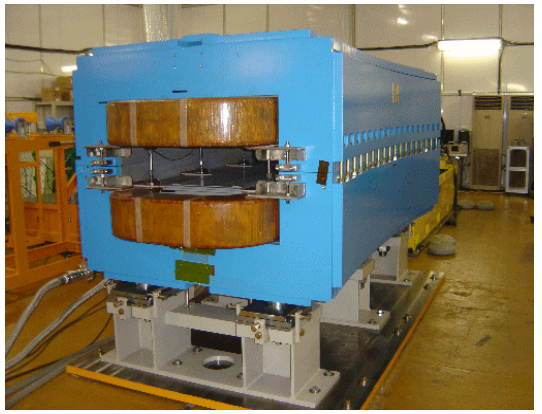
AC power supply
Voltage : 5832 Vp
Current : 1587 Ap
Rating : 3273 kW

***Chokes (25units)***
Inductance : 62 mH
Mass : 42 ton




DC power supply
Voltage : 2661 V
Current : 1667 A
Rating : 4436 kW

***Capacitors (25units)***
Voltage : 11108 Vp
Capacitance : 1325 uF
Mass : 11 ton



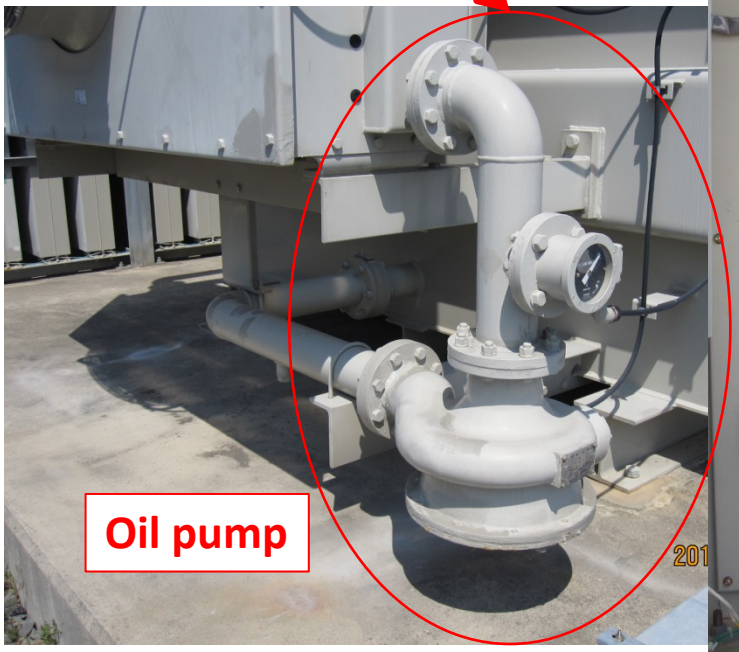
Bending Magnet

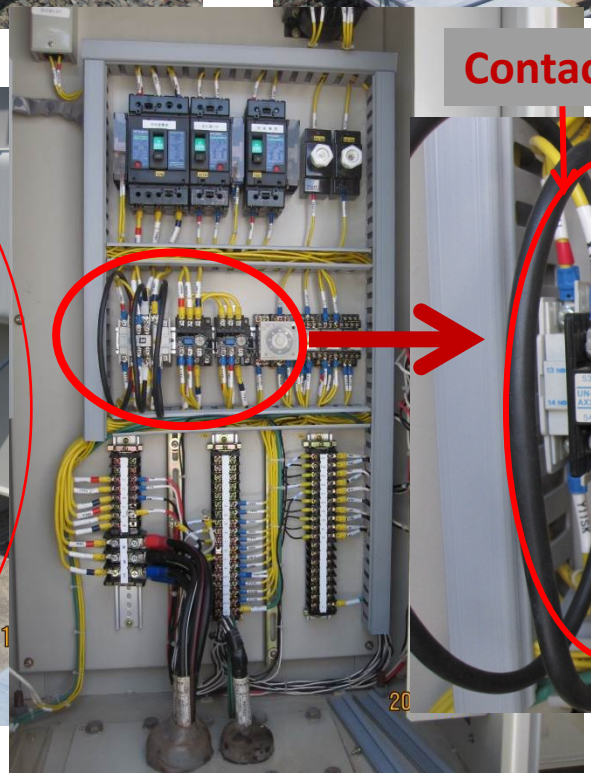
*Original slide by M. Kinsho*

Choke transformer（BMPS-CH11）



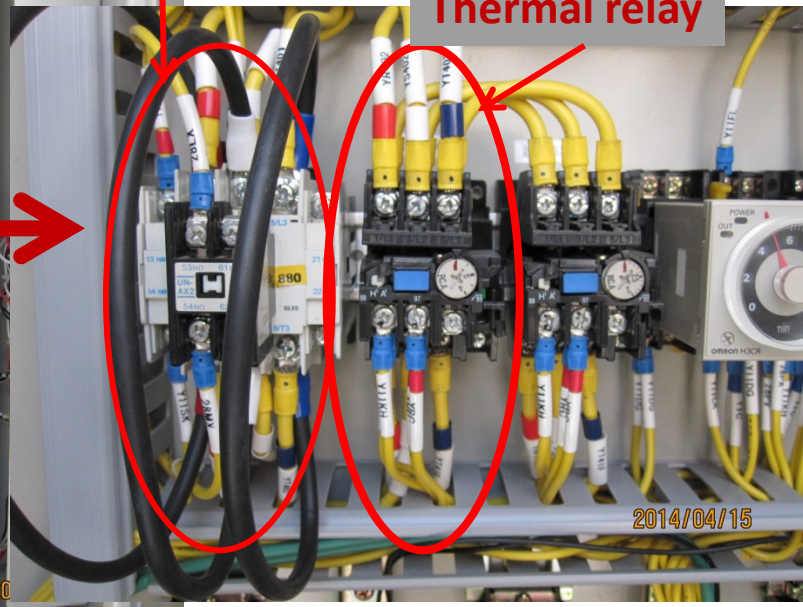
冷却器制御盤



Contactor

Thermal relay




*Original slide by M. Kinsho*

**Needed time for repair [RCS Bending Magnet]**

April 2014

11th 20:34 Electromagnetic contactor OFF for the oil pump and cooling fan of BMPS_CH11

12th 02:12 Recovered by a temporary expedient on that electromagnetic contactor

-------- **(Beam ON)** --------

15th 08:52 Breakdown of a thermal relay for the oil pump of BMPS_CH11
The cause was found out to be a breakdown of the oil pump.

16th, 17th Preparation and scheduling

18th Replace the pump

19th Current test, and startup magnets (It takes time to heat-up the magnets)

20th Beam tuning

21st 09:13 Recovery the user beam

6 days for recovery (after the 2nd beam down)

Spare parts are ready now. It takes 3 days for recovery at the next time.
No trouble until now. (April 2015)

# Investigation and Treatment of HVDC

**What's LINAC HVDC Power Supply?**

High Voltage DC power supply for klystrons.
Number of HVDCs: 12

**History of diode breakdown**

22nd Mar. 2012 #1 (FY2011)
7th Dec. 2013 #2
30th Jun. 2014 #5

Responsible: E. Chishiro

**Substantial reduction in downtime** can be expected.

**Major Causes of HVDC down**

1. Insufficient aging time
2. Noise distributed by AVR
3. Capacity decline of condenser in diode stack (cause of diode breakdown)

- #7 ~ #12: Newly installed with ACS in 2013. (They only need aging time.)
- Voltage clamp of main circuit of AVR
- Reinforced insulation of gate circuit of AVR
- Adoption of higher quality condenser

**HVDC IS OKAY NOW!?**

# Known Devices tend to be Broken Down

**LINAC HVDC Power Supply** ⟹ **We expect this term will disappear from here.**

| | |
|---|---|
| Weak point: | Diode in high voltage stack |
| Rate: | 1 /year |
| Backup: | 1 unit |
| Recovery time: | 2 days for swap and restart |

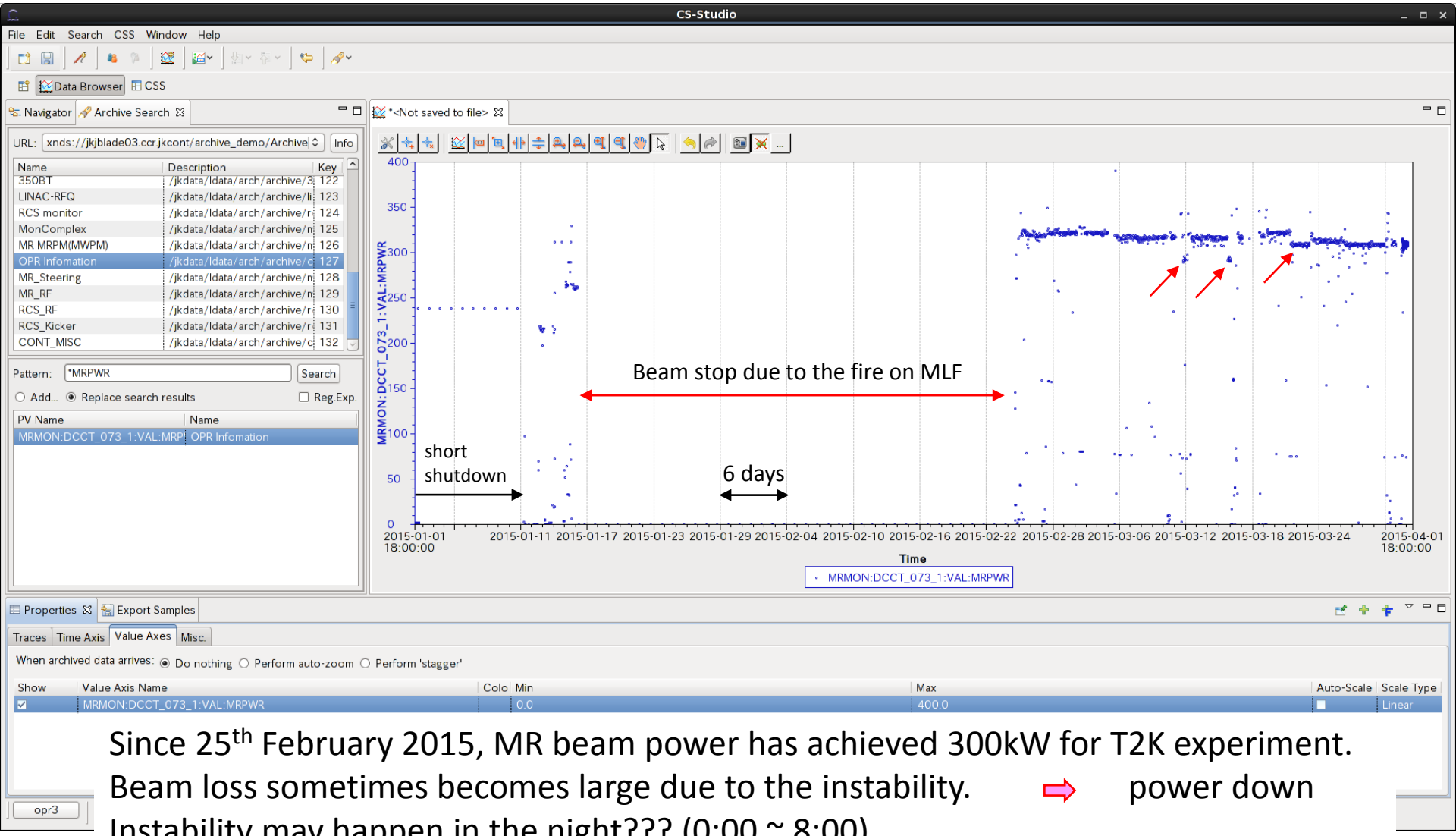
**RCS and MR RF**

| | |
|---|---|
| Weak point: | Vacuum condenser |
| Rate: | 0 or 1 or 2 /year |
| Backup: | several |
| Recovery time: | 4 hours for access to the accelerator tunnel |
| | 2 hours for replace |

**MR FX kicker**

| | |
|---|---|
| Weak point: | Diode in high voltage stack |
| Rate: | 0 or 1 /year |
| Backup: | 1 unit |
| Recovery time: | 3 hours for swap cables to the spare power unit |

# Operation Reliability [5] (Most recent MR)




Since 25th February 2015, MR beam power has achieved 300kW for T2K experiment.

Beam loss sometimes becomes large due to the instability. ⇨ power down

Instability may happen in the night??? (0:00 ~ 8:00)

# The Long Beam STOP

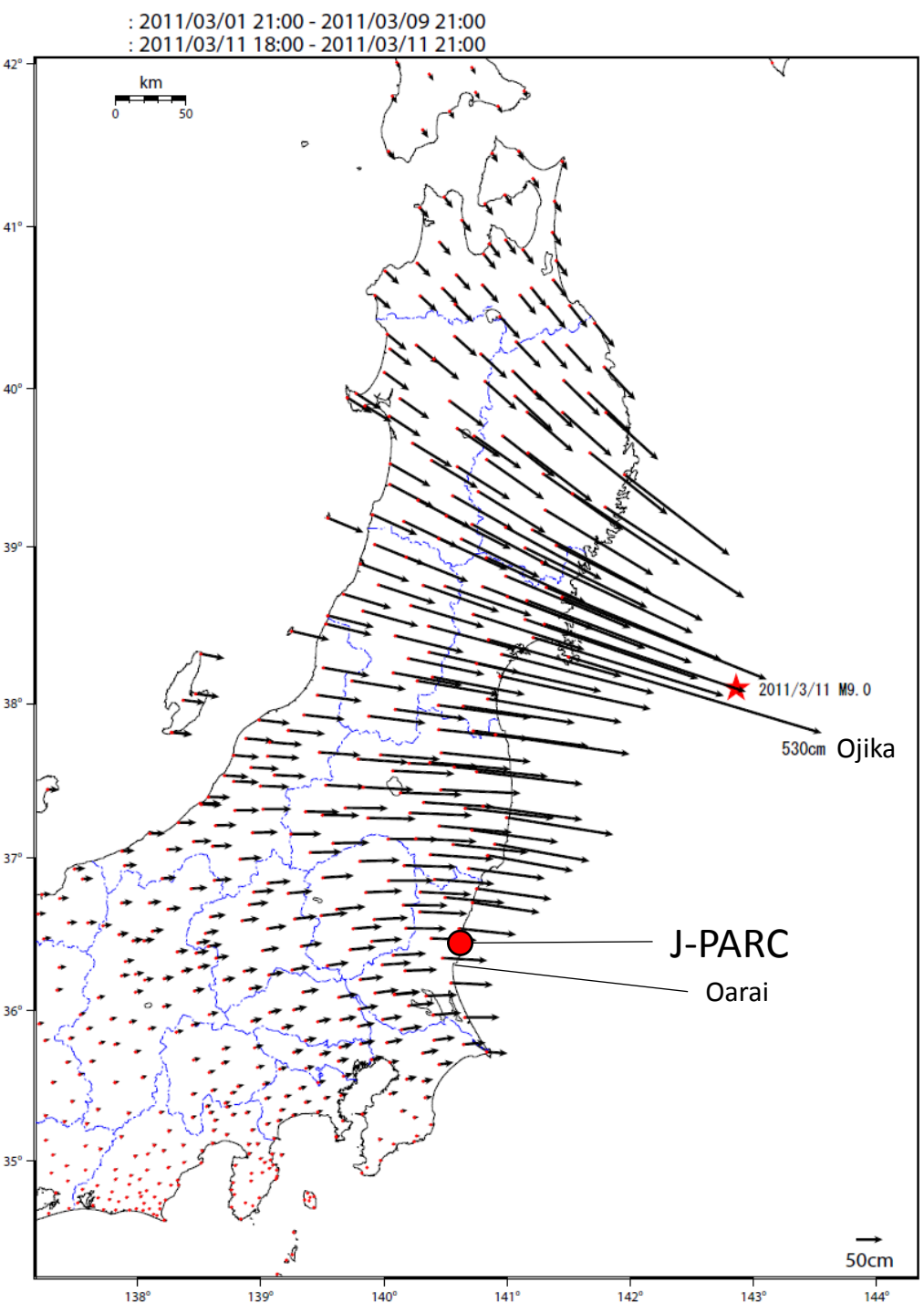
# The Long Be

**Mega Quake (3.1**

- On 3.11, 14:46 e" happened!
- The magnitude utes.
- One of the big
- The acceleratio l one were observed at th th of J-PARC.
- Fortunately, th vave was not so high at Tokai v of J-PARC was covered by the

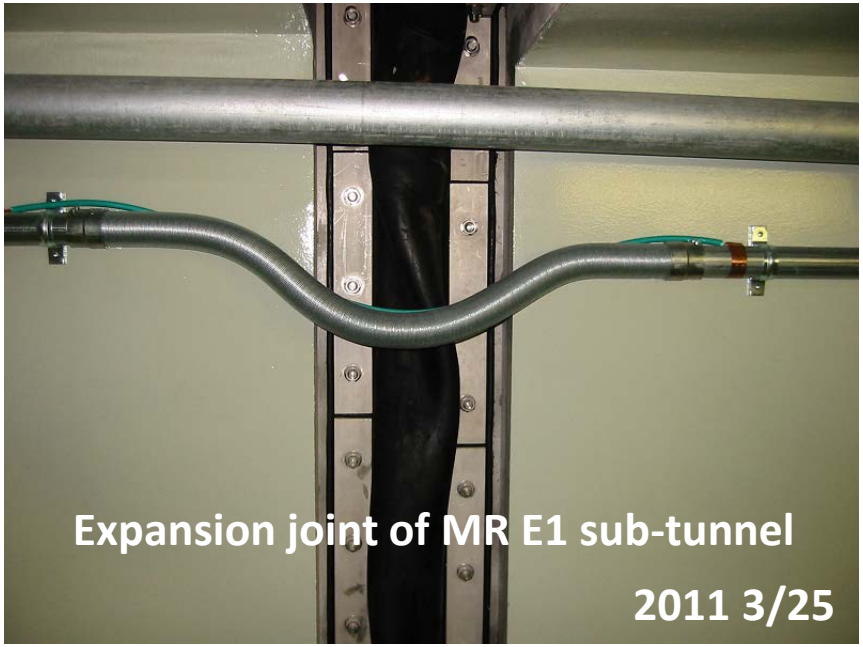
**Radiation Accide**

**Fire in the 2nd exp ty)**

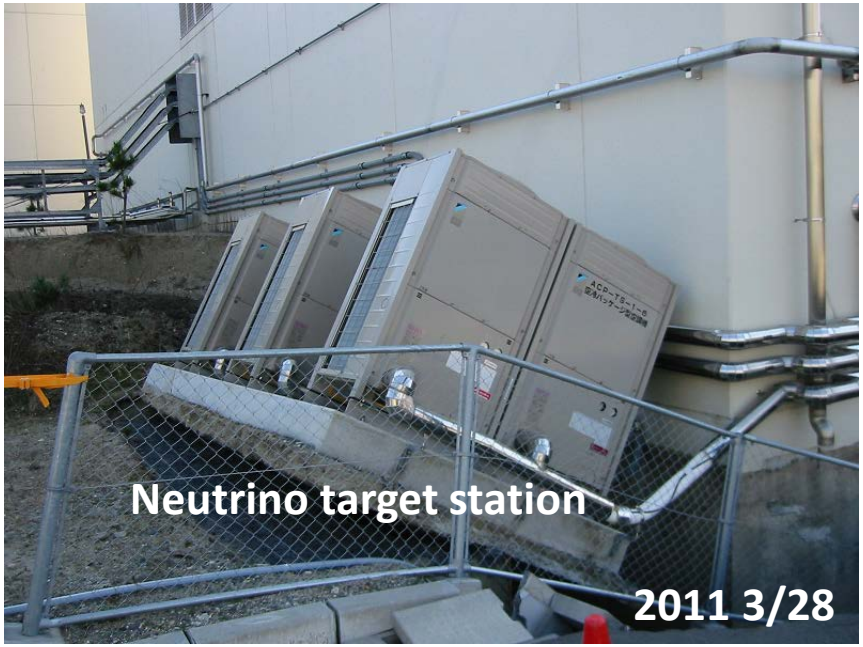



West road of LINAC
16:48
2011 3/11

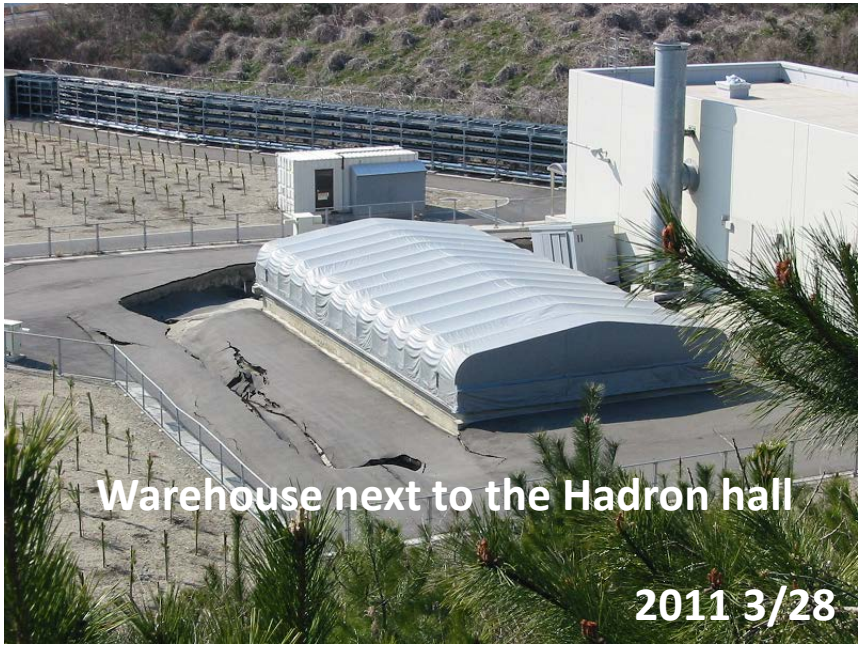

16:48
2011 3/11


Expansion joint of MR E1 sub-tunnel
2011 3/25


MR tunnel
2011 3/25

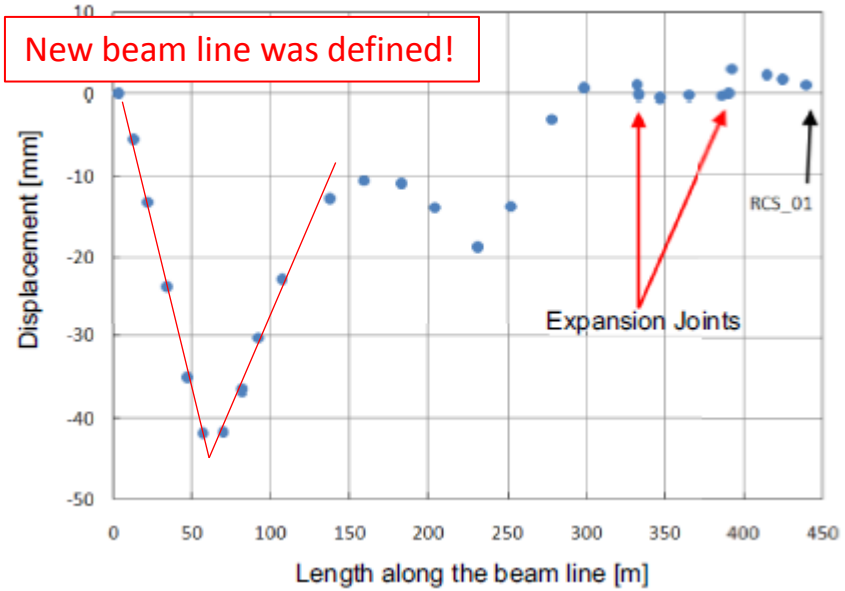

Neutrino target station
2011 3/28


Neutrino target station
2011 3/28


Warehouse next to the Hadron hall
2011 3/28


Neutrino target station
2011 3/28


Vertical displacement of LINAC

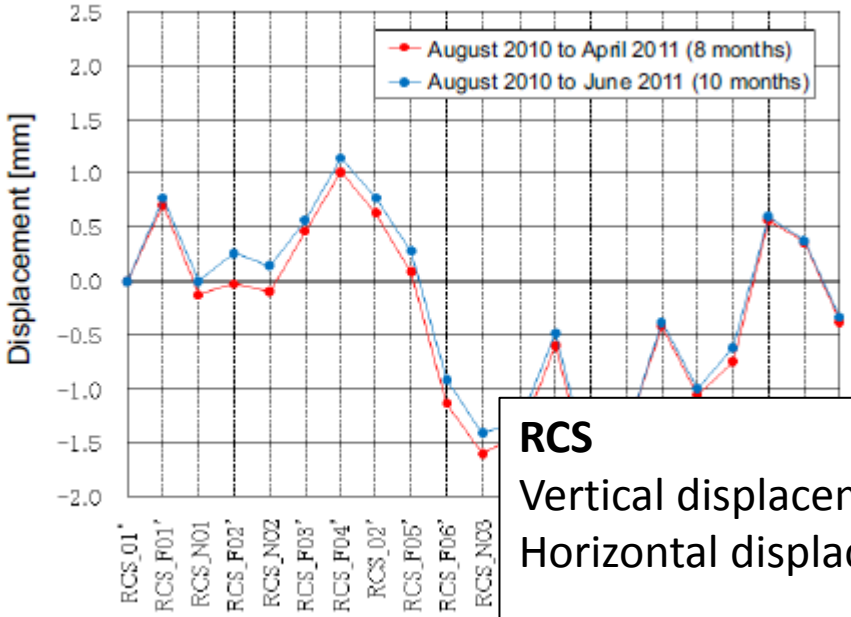


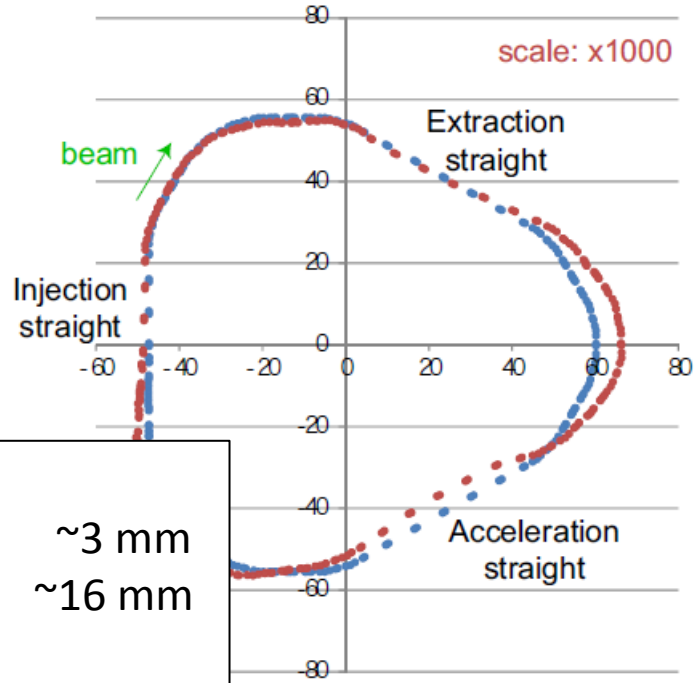

**LINAC**

The worst point subsided more than 40 mm at the upstream point of SDTL section.
The horizontal curve was also observed between the SDTL section and the ACS section.
The entrance of the first arc was displaced 25 mm to the east.

“The Displacement of J-PARC accelerators caused by Mega Quake” can be seen in Ref. M. J. Shirakata et al., TUPS057 IPAC 2011

# Deformation of rings




**RCS**

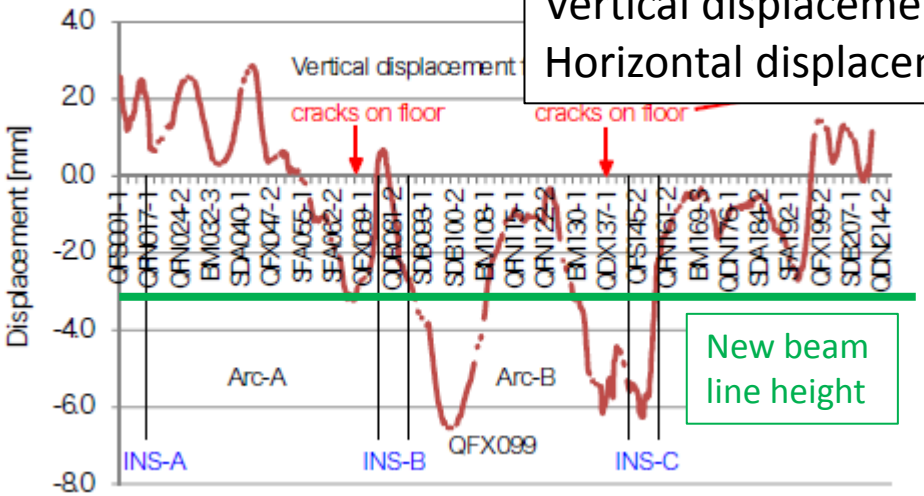
Vertical displacement: ~3 mm

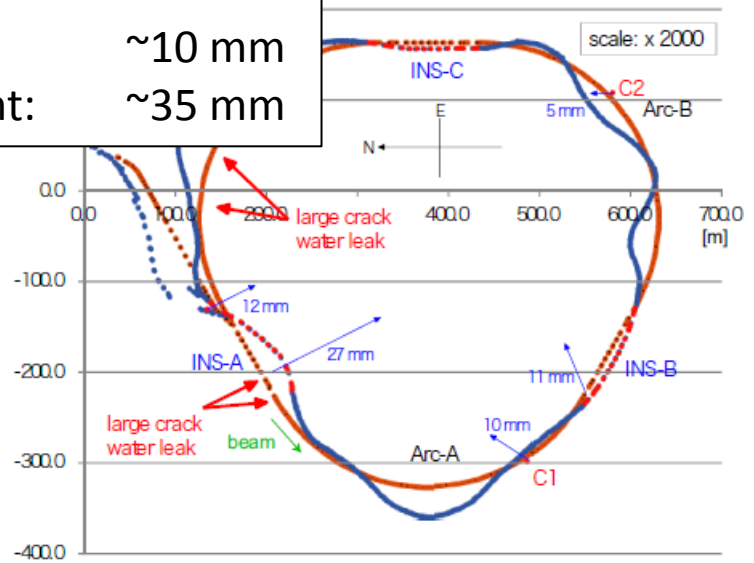
Horizontal displacement: ~16 mm

**MR**

Vertical displacement: ~10 mm

Horizontal displacement: ~35 mm



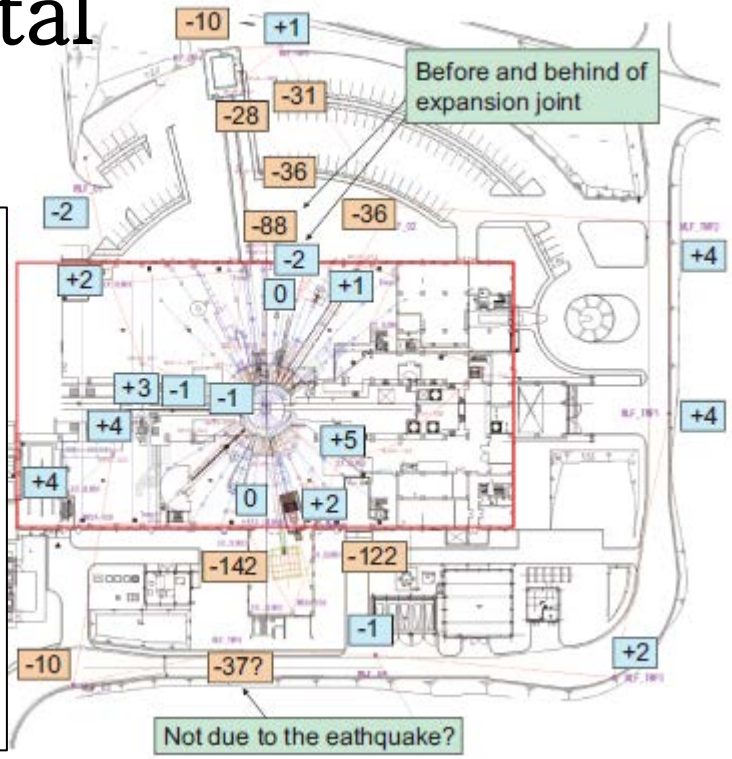



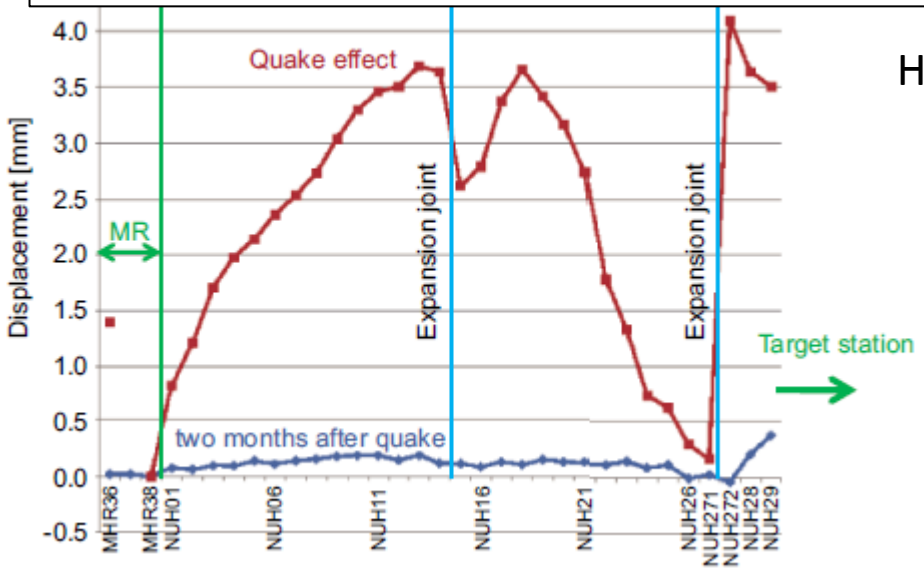
# Displacement of experimental hall and beam lines

**MLF**
Mainly vertical: ~4 mm
over 100 mm at the annexes for long beam line

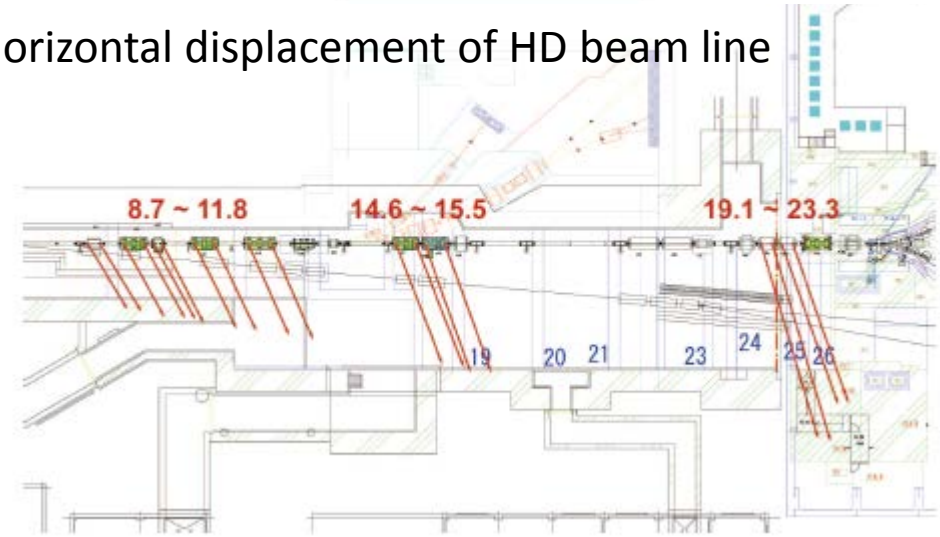
**NU**
Mainly vertical: ~4 mm (V-shaped)

**HD**
Mainly horizontal: ~25 mm (Direction was changed.)




Horizontal displacement of HD beam line



# Time Series [1/2]

**3/11 Earthquake!!**

J-PARC had completely closed. No electricity, No water, No gas stations!

3/17 **The first investigation** by division leaders. Still No electricity.

1. Large displacements of accelerators and beam lines were found, however, fortunately **ceramics components were not broken!**
2. The water could be used.
3. LINAC power station was largely damaged!

This is the key fact.
If some of them were broken, it took one more year…

**3/22 Recovery works started!!**

J-PARC site had opened. The LAN was back.

3/24 Internal telephone started recovering.

3/25 Electricity (for lights) started recovering. No air-conditioner.

3/29 LINAC power station was back. (more 5 months were needed for power devices)

3/30 Lights and local phone in acc. tunnel were back! (Still partially)
Water pump for drainage started.

3/31 Geometrical survey for acc. alignment check started.

4/01 Dehumidifiers were introduced.
Vacuum check for beam pipes started.

Water stop works in tunnel were also going on in parallel.

4/11 Access control level to the acc. tunnel was changed lower.

5/30 High power test started in the MR area

6/20 Re-alignment of cavities at LINAC started.

with new beam line shape

# Time Series [2/2]

8/24 Re-alignment of magnets at MR started.
10/11 Test operation of ion source started.
10/12 Test operation of RFQ started.
10/31 Alignment of MR main magnets finished.
11/15 Alignment of LINAC and L3BT finished.
11/28 RCS magnets started current test.
12/01 Ion source and RFQ got ready.
RCS magnets and vacuum got ready.
All cavities of LINAC started conditioning.
12/07 RCS full current test.
**12/09 LINAC started.**
10/10 MR current test.
12/12 RCS got ready.
12/14 MR vacuum was ready.
**12/17 RCS started.**
12/15 MR full current test.
12/19 MR got ready.
**12/21 MLF started.**
**12/22 MR started.**

with new beam line level

RCS was inferred that the deformation of ring was acceptable for 300kW operation.

Re-alignment of RCS was postponed to 2013.

All accelerators were back in 2011.
Recovery from the 3.11 was **286 days**.

# The Long Beam Stop [case 2]

**Mega Quake (3.11)**

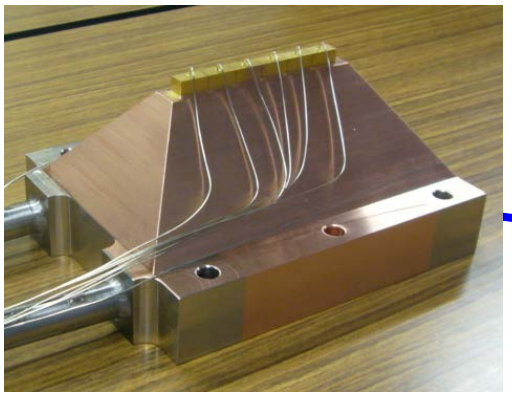
**Radiation Accident at Hadron Hall**

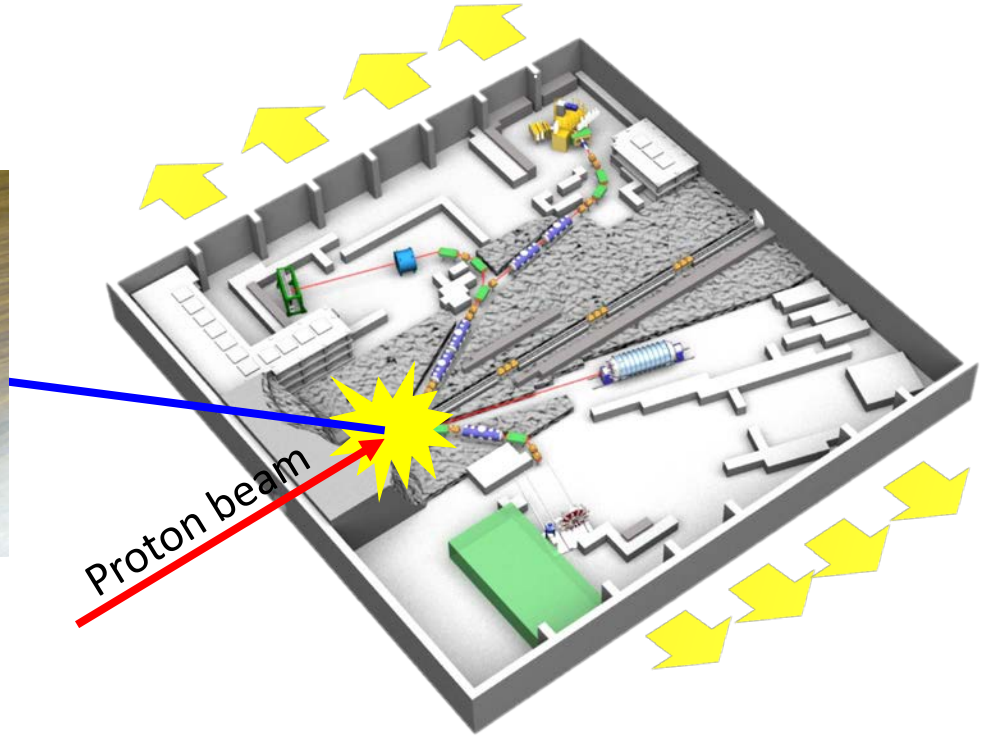
- The radiation monitoring level increased in the Hadron experimental hall.
- The experimental staff and students 36 of 104 people, who were in the hall at that time, were exposed to radiation from 0.1 to 1.7 mSV.
- An exposure doses were detected at the monitoring posts out of the Hadron experimental hall.
- The beam operation of all in May and June was cancelled.

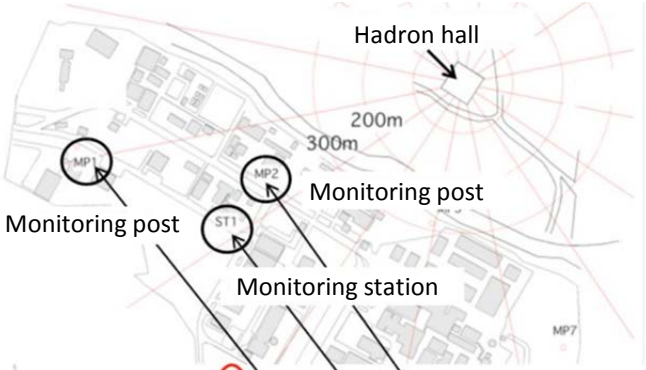
**Fire in the 2$^{nd}$ experimental hall of MLF (Meson and Life science Facility)**

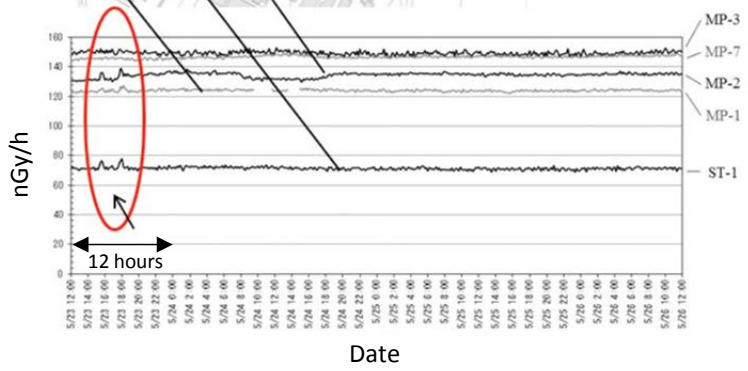
# Outline of the Fact

Au target





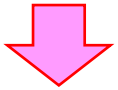




- J-PARC main ring provides 3 x 10^13 protons during 2 seconds in 24kW SX operation.
- At 11:55 23rd May, 2 x 10^13 protons were extracted in 5 ms by an accident.
- The Au-target was broken, and evaporated isotopes run away through ventilating fans.
- It was estimated to 20 GBq.
- An exposure dose was calculated to be 0.17μSv on the closest site boundary.

# The Long Way to the Return of Hadron Beam

**Beam for hadron experiments was stopped on 23rd May 2013.**
**All experiments were cancelled!**

- Investigation of causes and countermeasures
- Reports (by ordinance) to
  - the Nuclear Regulation Authority (NRA)
    - [because J-PARC is located in atomic energy agency (JAEA).]
  - Minister of Education, Culture, Sports, Science and Technology
  - Ibaraki-ken, Tokai village (local governments)
- Suggestions from the third party panel by distinguished citizens
- Proposals from the prefectural governor



- Organizational reformation for the safety
- Large-scale reform of the Hadron experimental hall
  - Radiation full controlled air-conditioning and ventilating system
  - Hand-foot monitoring system at the entrance
- Town meetings (several times, resident explanatory meetings)

**Beam recovery was at 23:11 9th April 2015. 686 days!!**
It has taken nearly 23 months!!

# The Long Beam Stop [case 3]

**Mega Quake (3.11)**

**Radiation Accident at Hadron Hall**

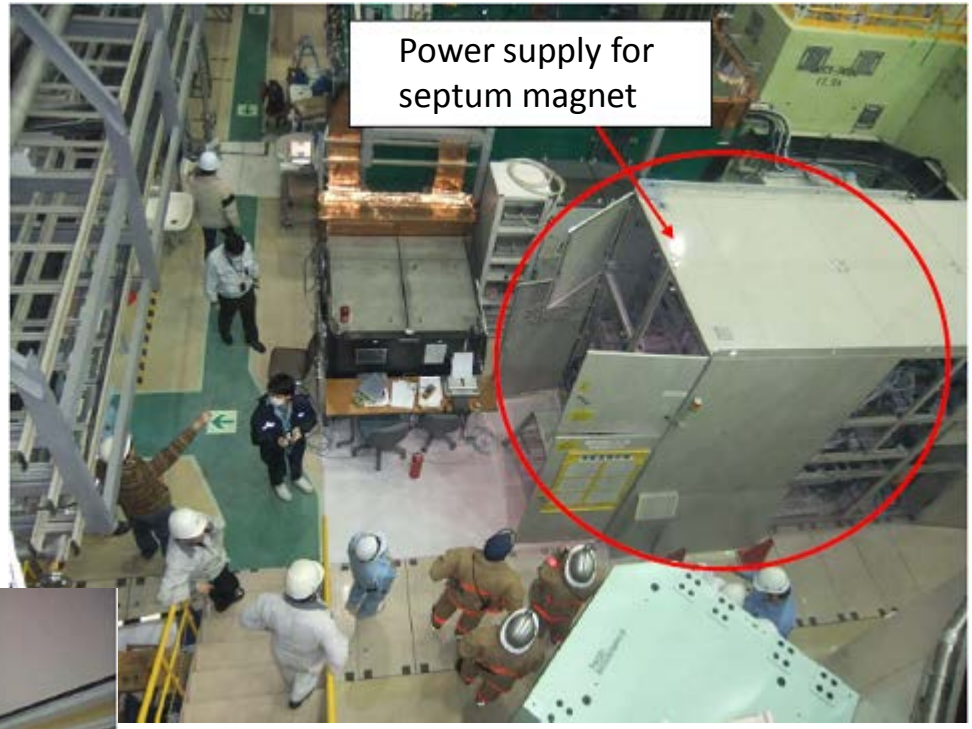
**Fire in the 2nd experimental hall of MLF (Meson and Life science Facility)**

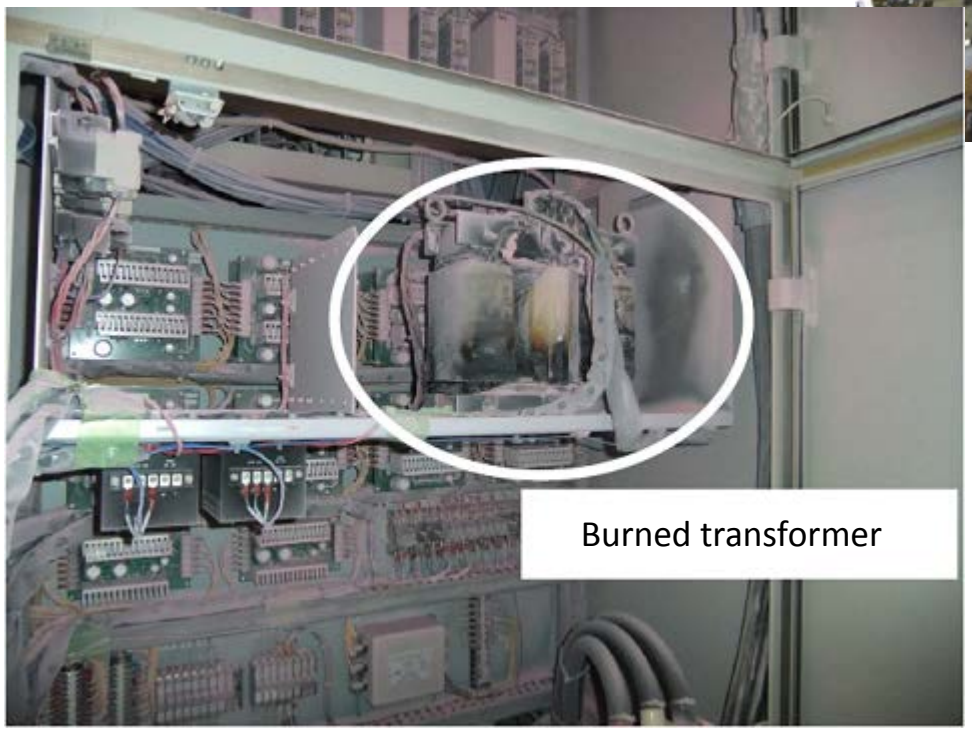
15:01 16th January 2015
A transformer in a power supply burned in the 2nd experimental hall where was a radiation controlled area of MLF.

- Immediately a staff put it out by a fire extinguisher.
- Nobody was injured.
- Nobody was irradiated.
- No spreads.

# Outline of the Fact

- Cause was a design mistake of modification of the power supply for septum magnet.
- Fire was immediately found out and put out by a fire extinguisher.
- There were no spreads.




Beam was back on 20th February.
It took **35 days**.

# Summary

- Reliability of J-PARC beam is about 90% for user operation.
- Rare case of breakdown tends to cause a long beam stop though spare parts are prepared.
- The cure of LINAC HVDC has done. We expect that it gets away from the worst top three in FY2015.

- Recovery from the Mega-quake was surprisingly fast.
- Some troubles bring an extremely long shutdown because the J-PARC was located in atomic energy agency.

**In addition, in 2015**

- T2K experiment achieved **10^21 POT** 15:15 26th March
- MR beam power achieved **300kW** to NU 22:54 25th February
- RCS beam power achieved **500kW** to MLF 11:00 14th April

# References

Sorry, most of all materials are written in Japanese!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- Y. Ikeda et.al　セプタム火災報告書配布版150123_県提出(最終）
- E. Chishiro　クライストロン電源フォルト対策　20141121_担当者打合せ
- M. Kinsho　RCS-BMPS_CH11故障-140425　20140425
- Y. Ikeda　ハドロン事故ー物理学会徳島報告　20130926_日本物理学会
- K. Ishii　入射セプタム1　トラブル報告　20130524 _担当者打合せ
- M. Tomizawa, T. Koseki
  SX低磁場セプタムのトラブル　20130412_担当者打合せ
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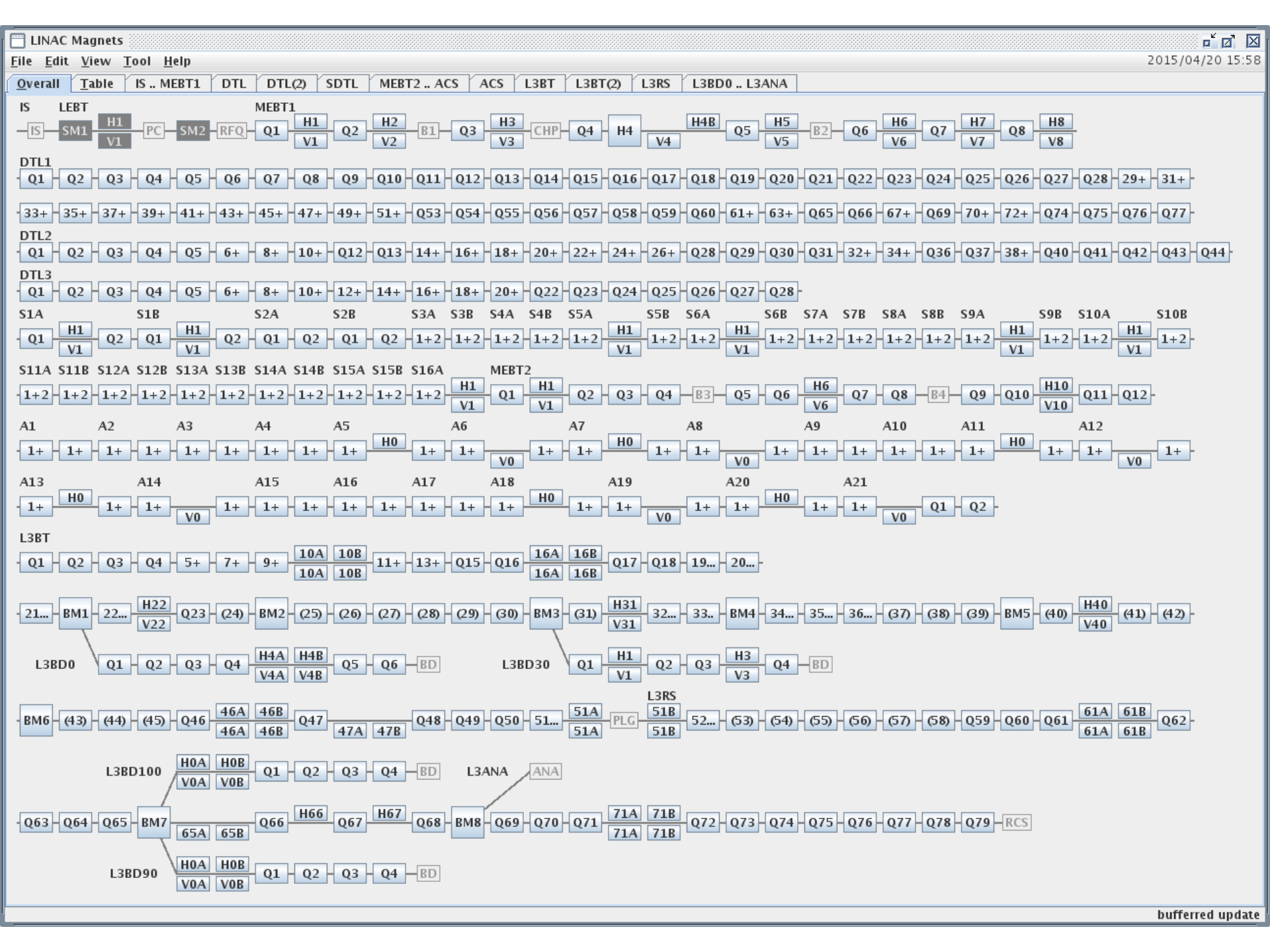
- H. Oguri　クライストロン電源1号機故障について_20120323
- M. J. Shirakata et al　TUPS057 IPAC 2011
- Geospatial Information Authority of Japan (GSI),
  http://www.gsi.go.jp/chibankansi/chikakukansi40005.html April 2011

Appendix


LINAC Magnets
File Edit View Tool Help
2015/04/20 15:58
Overall Table IS .. MEBT1 DTL DTL(2) SDTL MEBT2 .. ACS ACS L3BT L3BT(2) L3RS L3BD0 .. L3ANA
IS LEBT MEBT1
DTL1
DTL2
DTL3
S1A S1B S2A S2B S3A S3B S4A S4B S5A S5B S6A S6B S7A S7B S8A S8B S9A S9B S10A S10B
S11A S11B S12A S12B S13A S13B S14A S14B S15A S15B S16A MEBT2
A1 A2 A3 A4 A5 A6 A7 A8 A9 A10 A11 A12
A13 A14 A15 A16 A17 A18 A19 A20 A21
L3BT
L3BD0
L3BD30
L3RS
L3BD100
L3BD90
L3ANA
bufferred update

# Milestones

Linac Beam Commissioning started in Nov, 2006.
The linac accelerated the beam to a design value, 181 MeV on 24th Jan, 2007.
RCS Beam Commissioning started in Oct., 2007.
The RCS accelerated the beam to a design value, 3 GeV on 31st Oct, 2007.

Beam Commissioning of MR started in May, 2008.
Installation of FX and SX components were installed in summer, 2008.
Hadron and Neutrino beamline components were installed in summer, 2008.
MLF experiments started on 23rd Dec, 2008.

The MR accelerated the beam to a design value, 30 GeV on 23rd Dec, 2009.
Extraction to hadron beamline on 27th Jan, 2009.
Secondary beam was comfirmed 11th Feb, 2009.
Extraction to neutrino beamline on 23rd April, 2009.
Neutrino beam was comfirmed 23rd April, 2009.