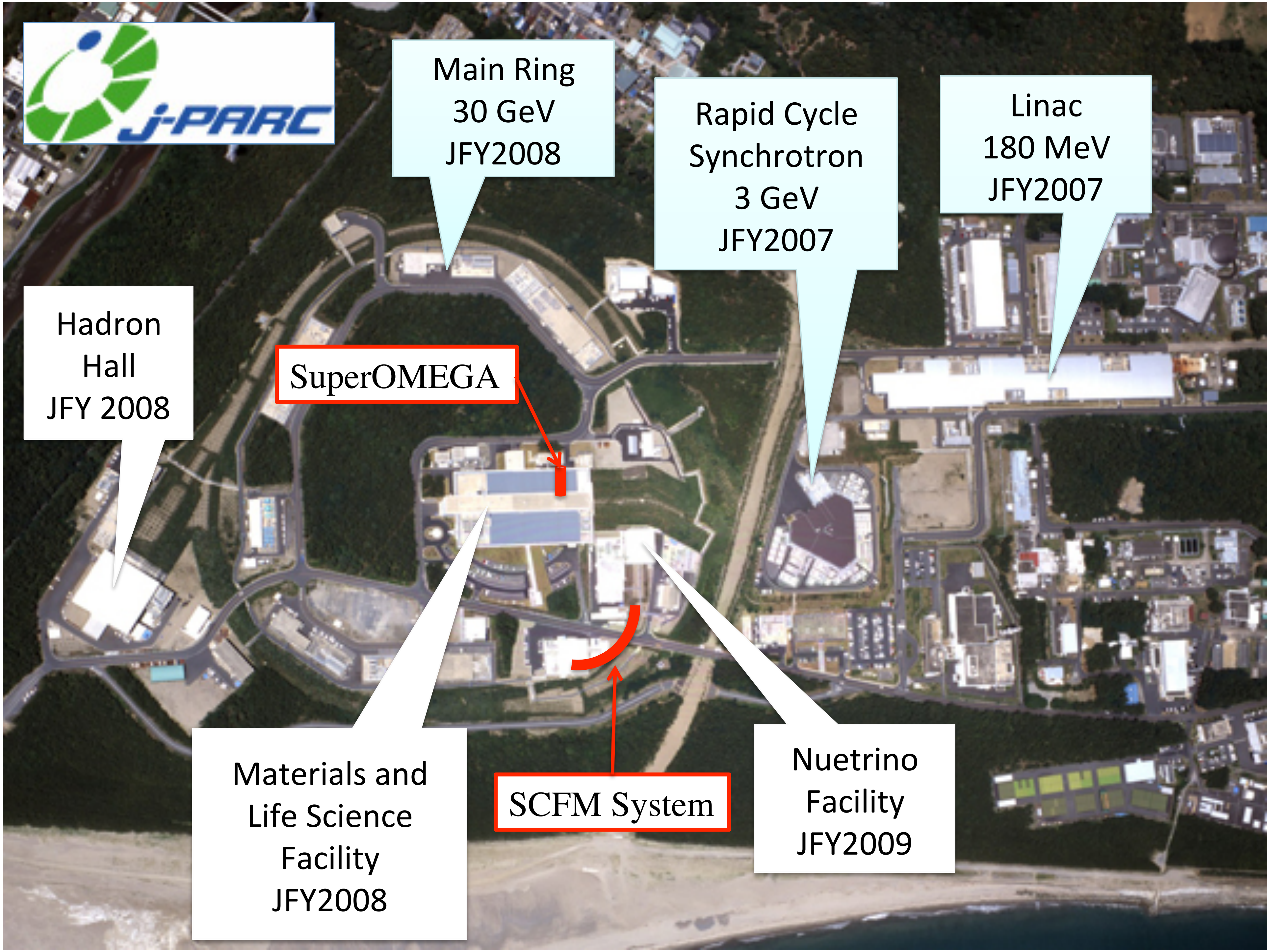
Superconducting magnets in J-PARC and their radiation protections

Toru Ogitsu
J-PARC Cryogenic Section

Superconducting Magnets in J-PARC

- In Operation
  - Neutrino Beam Line SCFM system
  - SKS spectrometer
  - Large OMEGA muon beam line solenoid
- Under Construction
  - Super OMEGA muon beam line
- Proposed
  - COMET (Makoto's Talk)
  - HFS, g-2


J-PARC
Main Ring
30 GeV
JFY2008
Rapid Cycle
Synchrotron
3 GeV
JFY2007
Linac
180 MeV
JFY2007
Hadron
Hall
JFY 2008
SuperOMEGA
Materials and
Life Science
Facility
JFY2008
SCFM System
Nuetrino
Facility
JFY2009

Superconducting Magnets in J-PARC

- In Operation
  - **Neutrino Beam Line SCFM system**
  - SKS spectrometer
  - Large OMEGA muon beam line solenoid
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- Proposed
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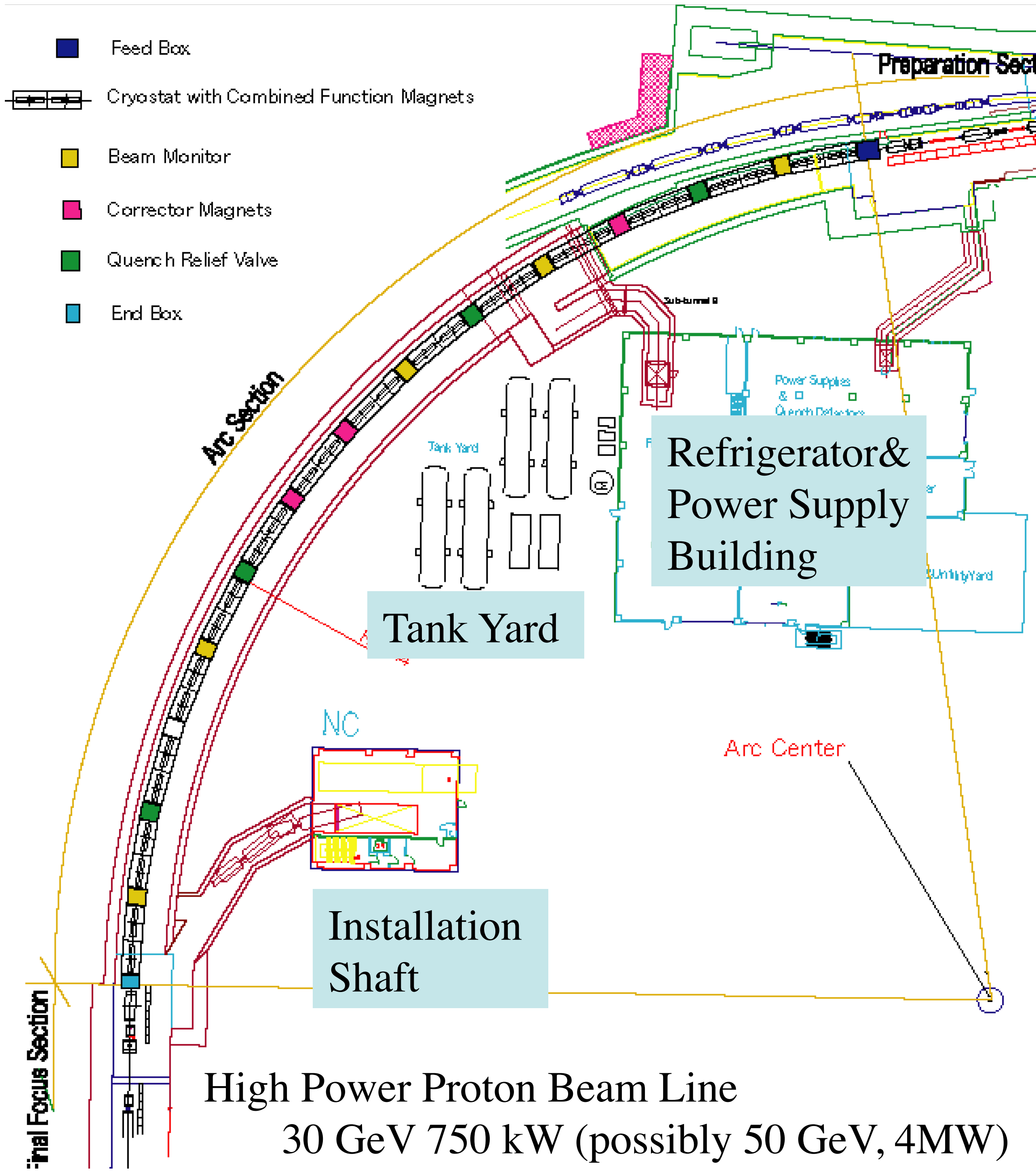


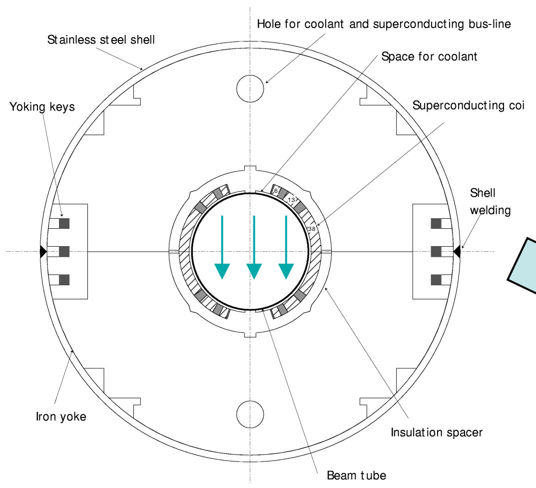
High Power Proton Beam Line
30 GeV 750 kW (possibly 50 GeV, 4MW)

System Overview

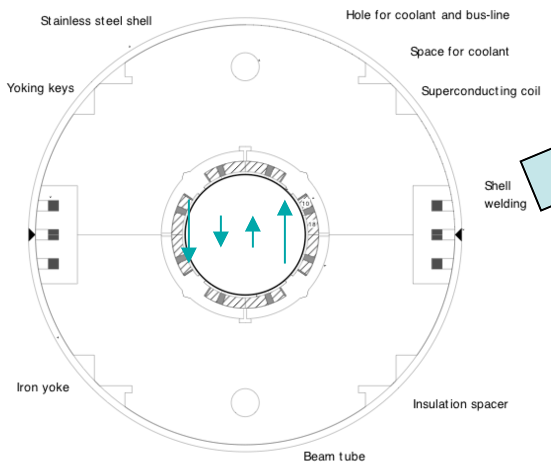
- 28 SCFMs
  - Dipole 2.6 T
  - Quad 18.6 T/m
  - Length 3.3 m
  - 2 in 1 Cryostat
  - Total Stored Energy: 10MJ (50GeV)
- 13 interconnects
  - 5 beam monitor
  - 3 correctors
  - 4 quench valve
  - 1 none

SCFM: Superconducting Combined Function Magnet

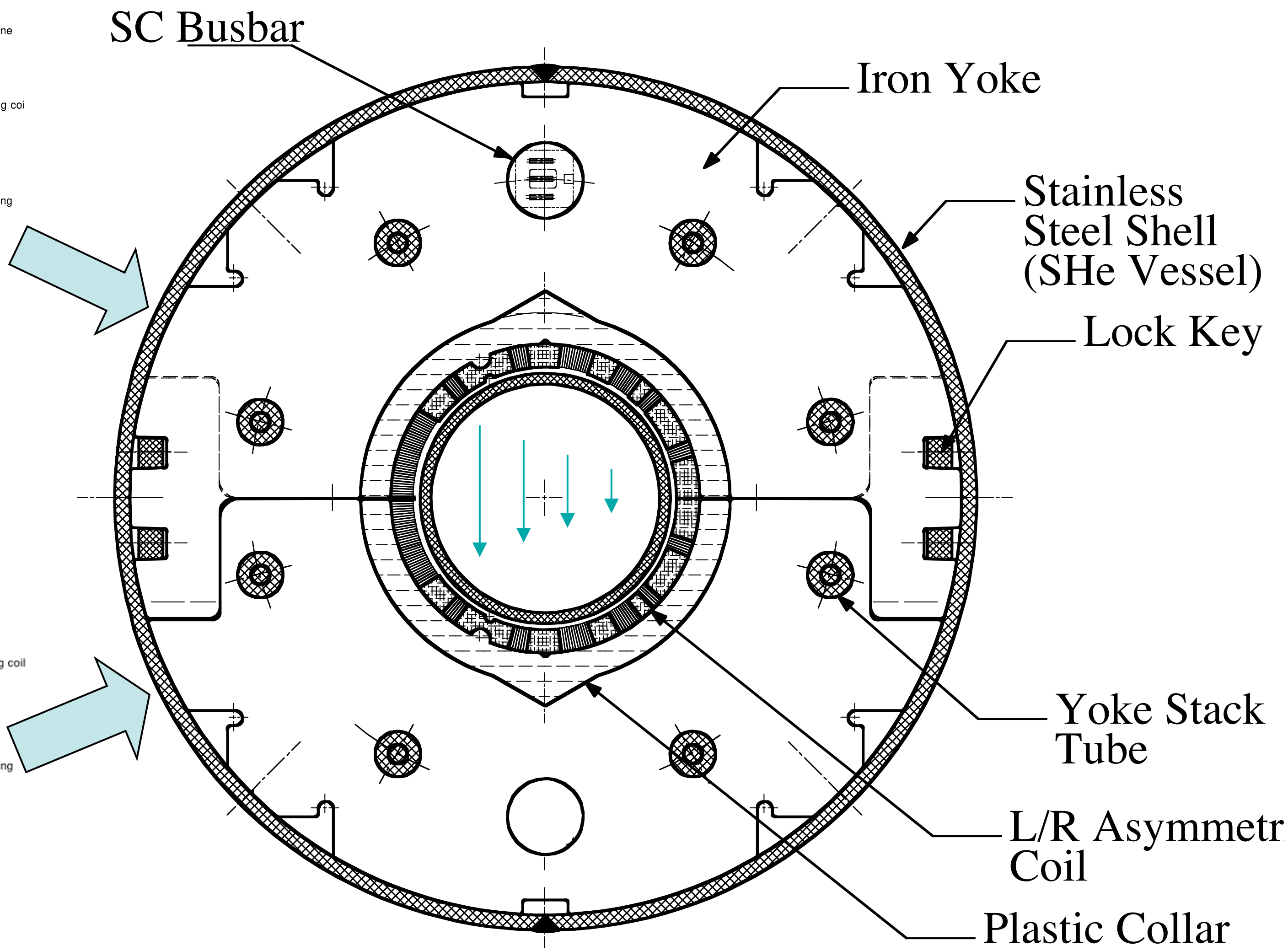
SC Combined Function Magnet



Dipole (Bending)

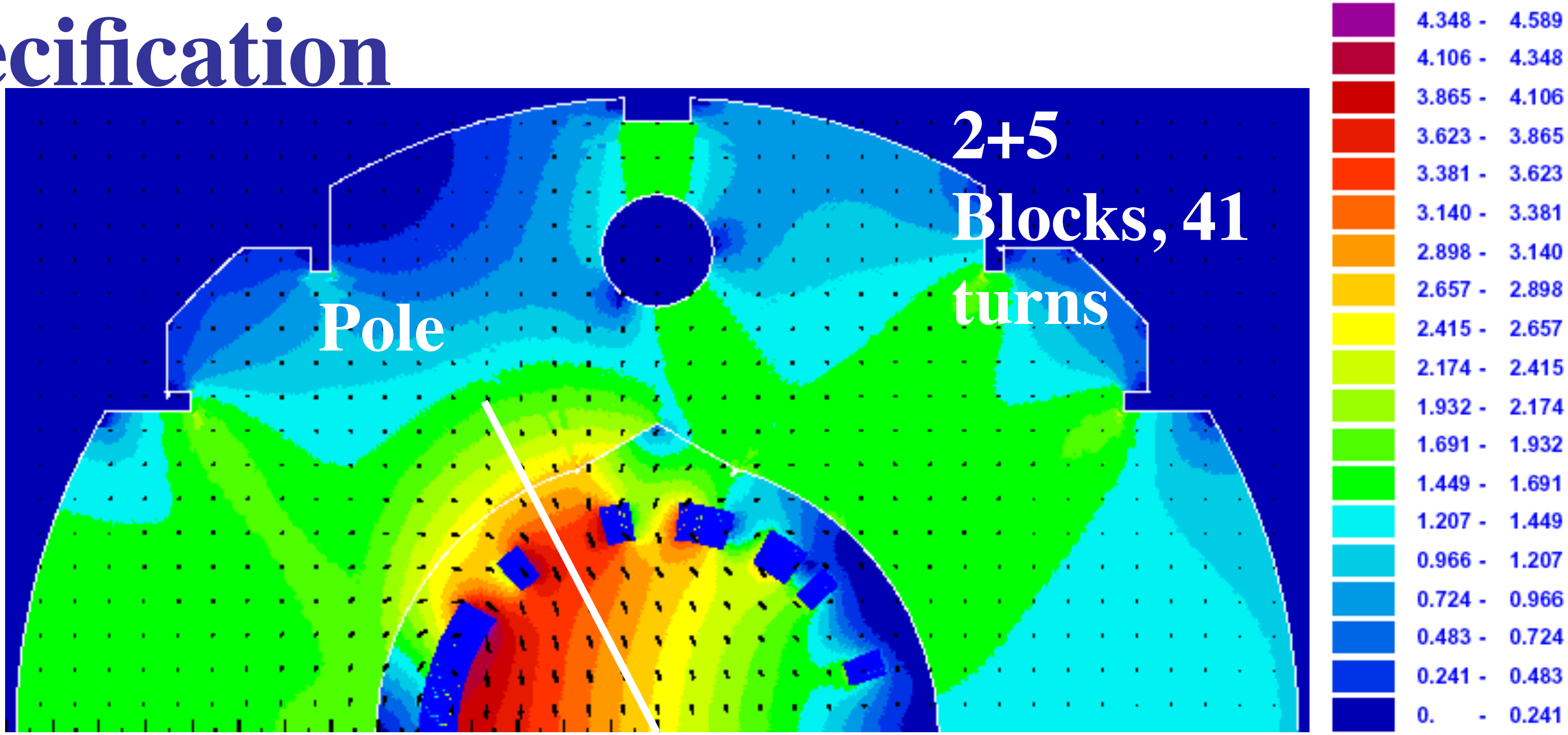


Quadrupole (Focusing)



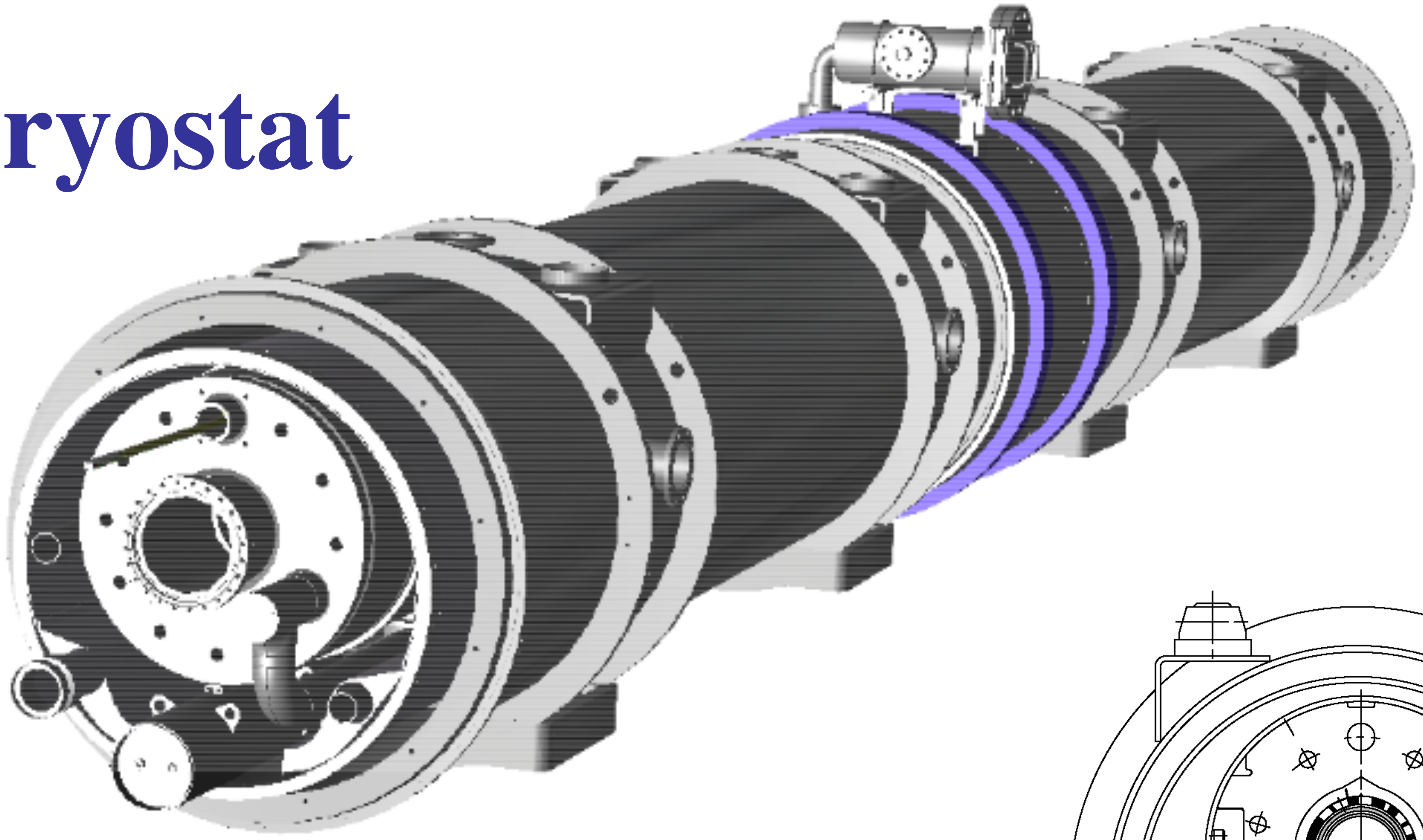
Dipole/Quadrupole Combined
Bending + Focusing

Specification

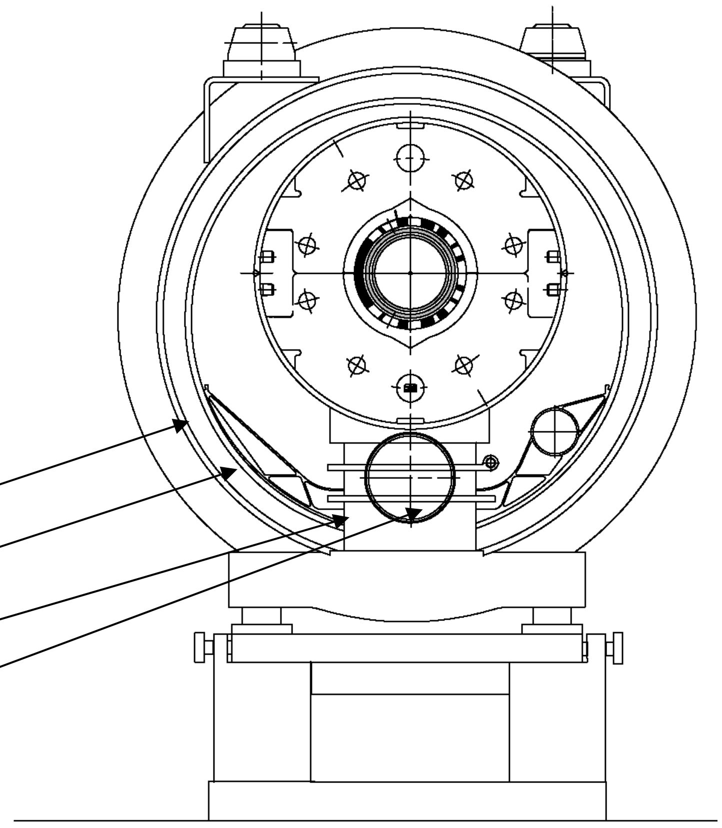


Coil ID.:	173.4mm	Op. Current:	7345 A
Mag. Length:	3300 mm	Op. Margin:	72%
Mech. Length:	3630 mm @RT	Inductance:	14.3 mH
Tmax:	< 5.0K	Stored Energy:	386 kJ
	(Supercritical Helium)	# of Magnet:	28
Dipole Field:	2.59 T	SC Cable:	NbTi/Cu for LHC
Quad. Field:	18.6 T/m		Dipole Outer-L
Field Error:	< 10^-3		

Cryostat

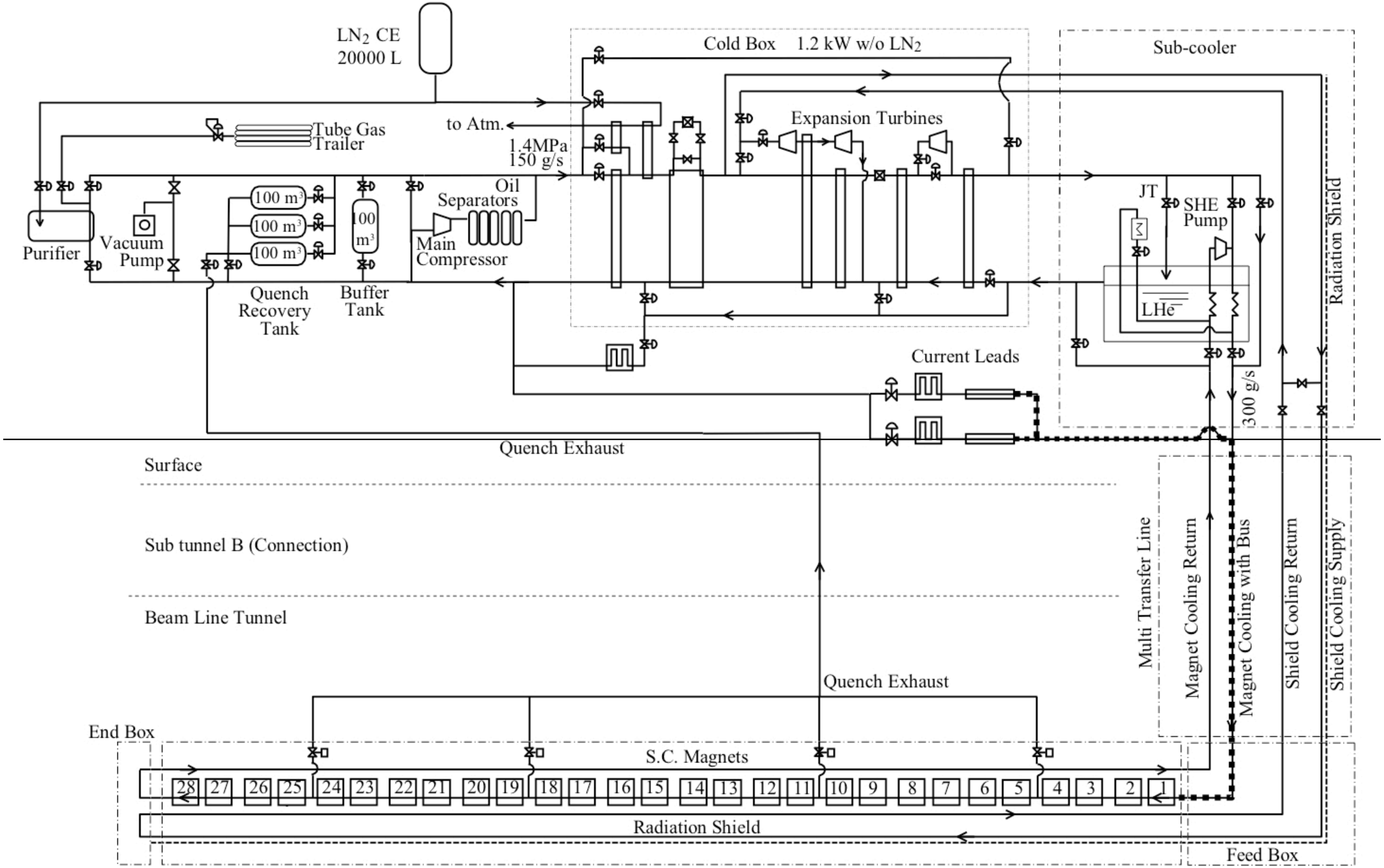


- 2 magnets in 1 cryostat
  - F & D magnets (doublet optics)
- Common Design with LHC
  - Vacuum Vessel
  - Shield Tray
  - Support Post
  - Cold Diode



Cryogenics

- Refrigerator Power；1.2kW@4.5K、2.5kW@80K
- Supercritical Helium Pump，300~400 g/s 400kPa



Neutrino Beam Line SCFM System Beam loss associated Issues

- High Power Proton Beam Line
  - 30 GeV 750 kW (possibly 50 GeV, 4MW)
  - Beam loss 1W/m (10W per point) by tunnel shield
- Issues associated with beam loss
  - Average loss = irradiation
    - Material durability
    - Component durability
    - Tritium Creation in Helium
  - Accidental loss

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    - Component durability
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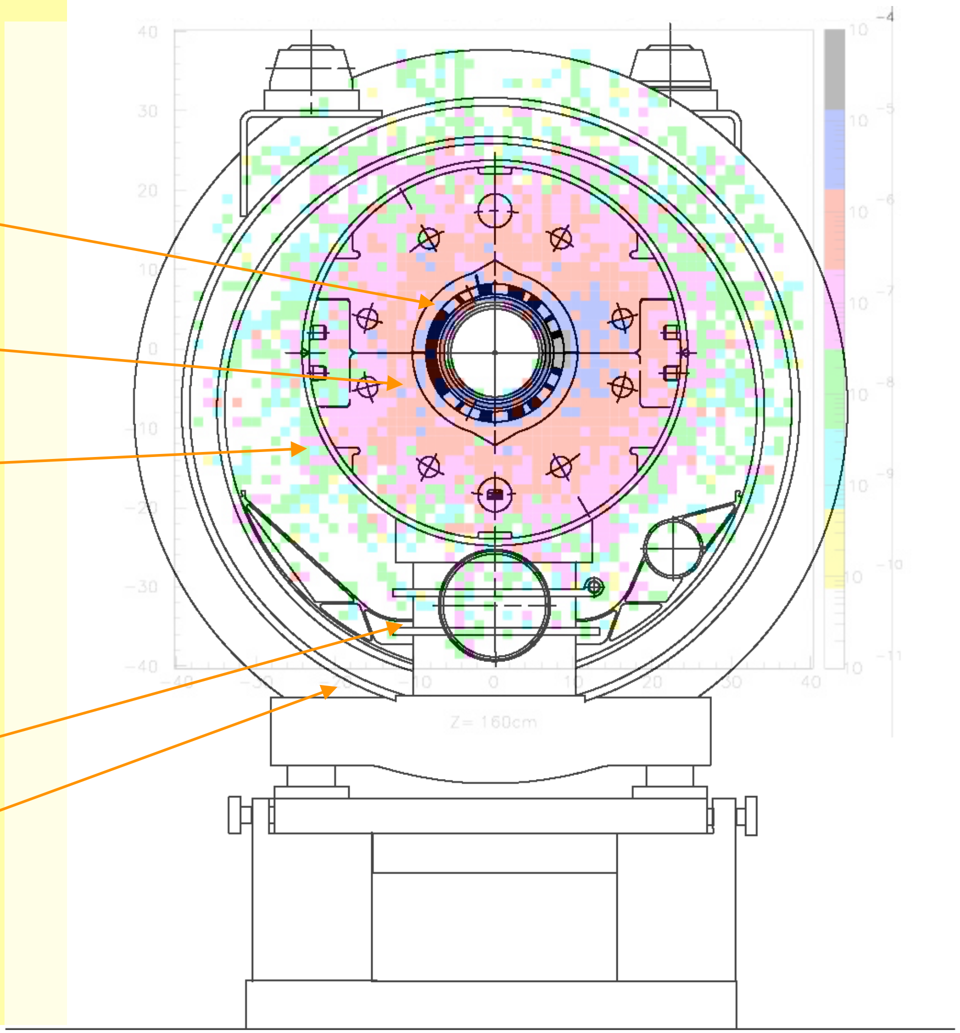
Irradiation by beam loss

Computed using MARS

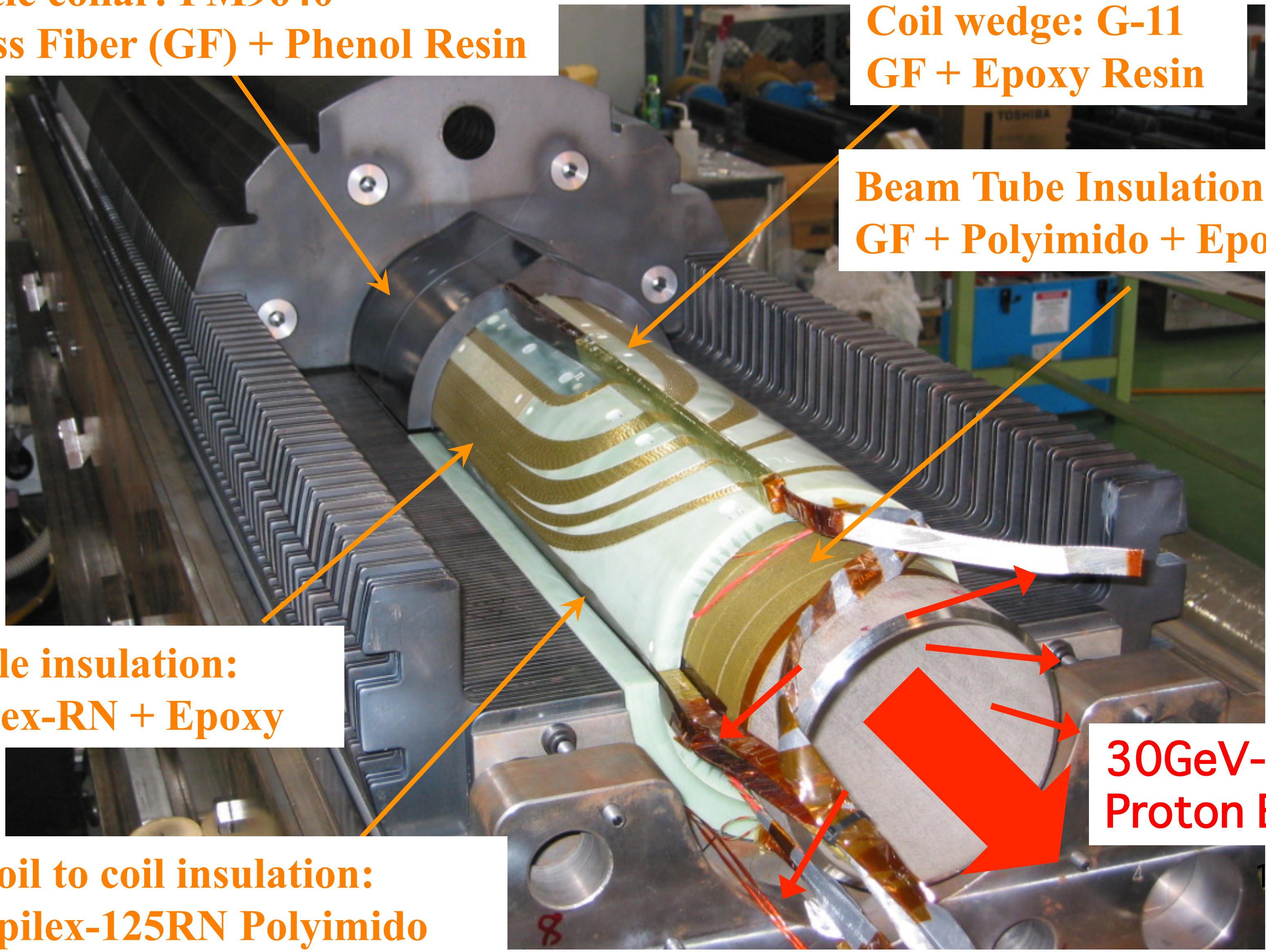
1 w/m, 4000 hr/year

- Coil (~30kGy/y)
  - GFRP (~10^7Gy)
  - Polyimide (~10^7Gy)
- Plastic Collar (~10kGy/y)
  - Glass Filled Phenol (~10^7Gy)
- Super Insulator
  - Body (~200Gy/y)
    - Polyester (10^5~10^6Gy)
  - End (~30kGy/y)
    - Polyimide (~10^7Gy)
- Support Post (~200Gy/y)
  - GFRP (10^7Gy)
- O-ring (~200Gy/y)
  - EPDM (~10^6 Gy)



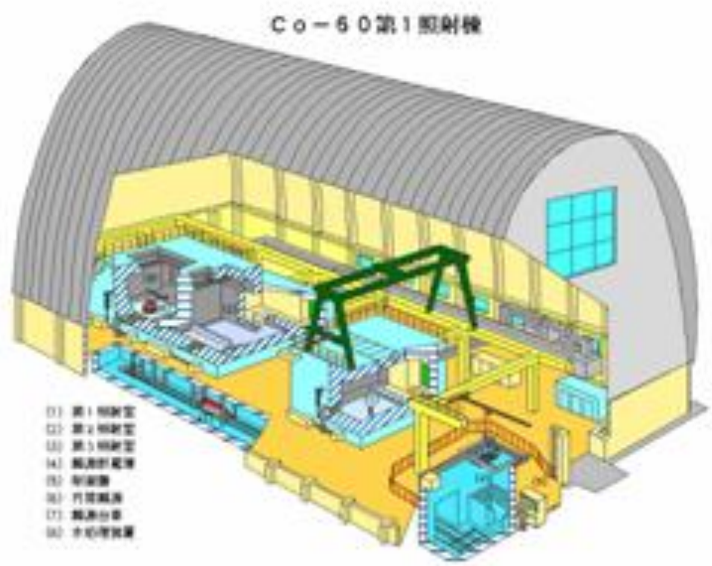
Organic Materials in SCFMs

: Evaluated in this study

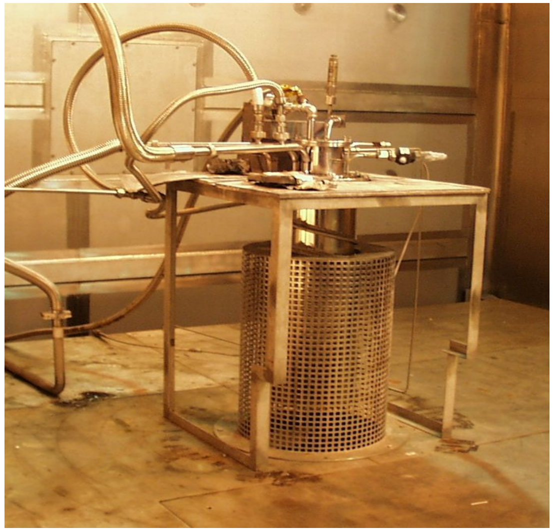


Material Test

- Test Facility
  - JAEA Takasaki Co-60 γ-ray irradiation facility
  - <10kGy/hour
  - Room & LN_2 temp.
- Test Items
  - Sample: Organic Mat.
  - Evolve Gas
  - Mechanical test

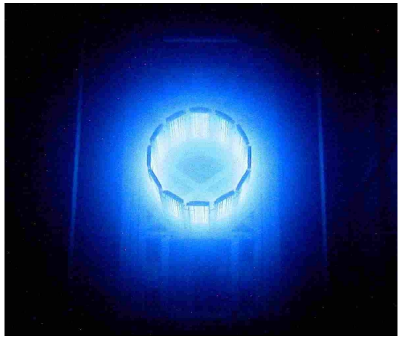


Gamma-ray Irradiation @JAEA-Takasaki

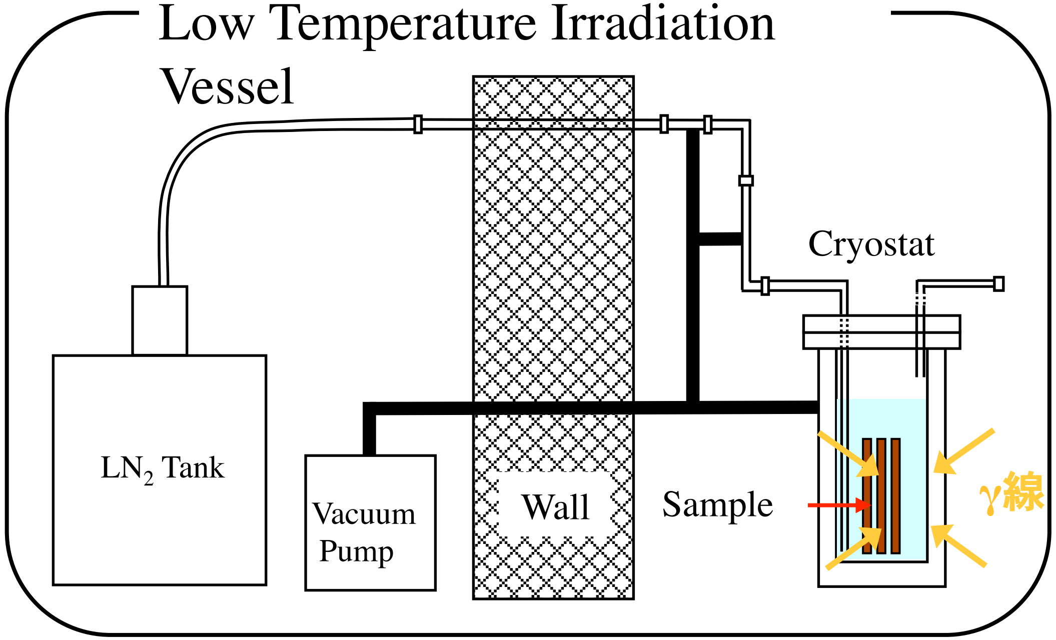


Co-60γ-ray irradiation
under Liq. N2 temp

Co-60γ-ray
source

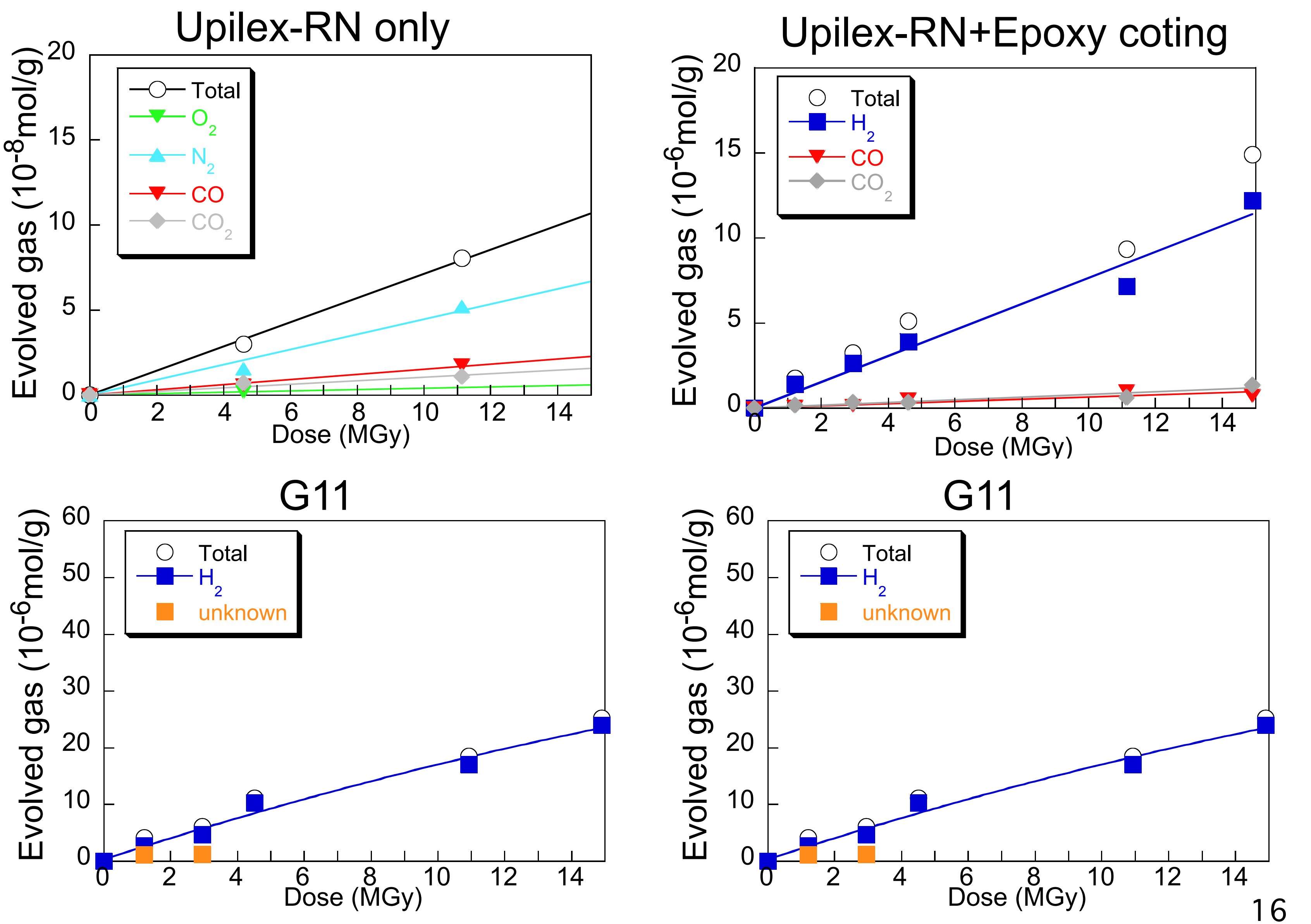


Sample in the glass tube

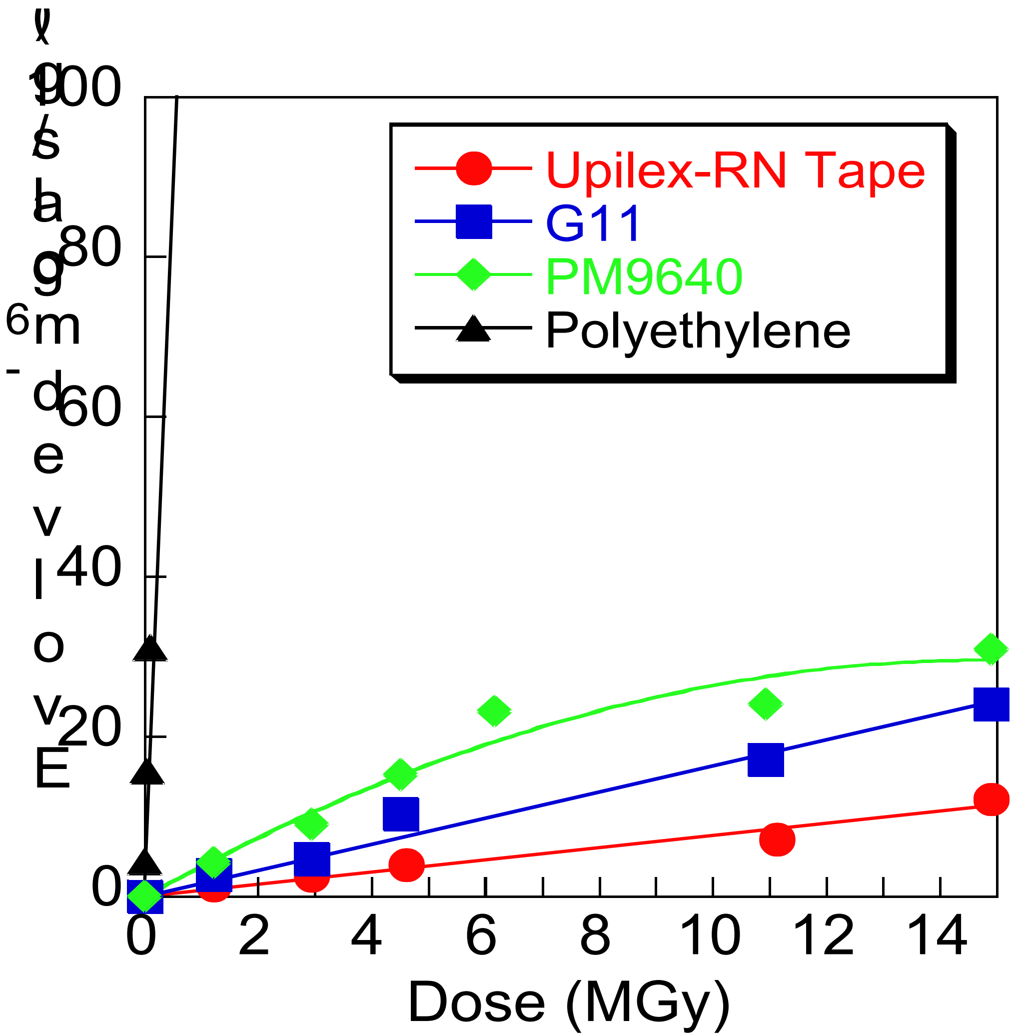


Irradiation
↓
Gas analysis
↓
Mechanical Test

Evolve Gases from the organic materials



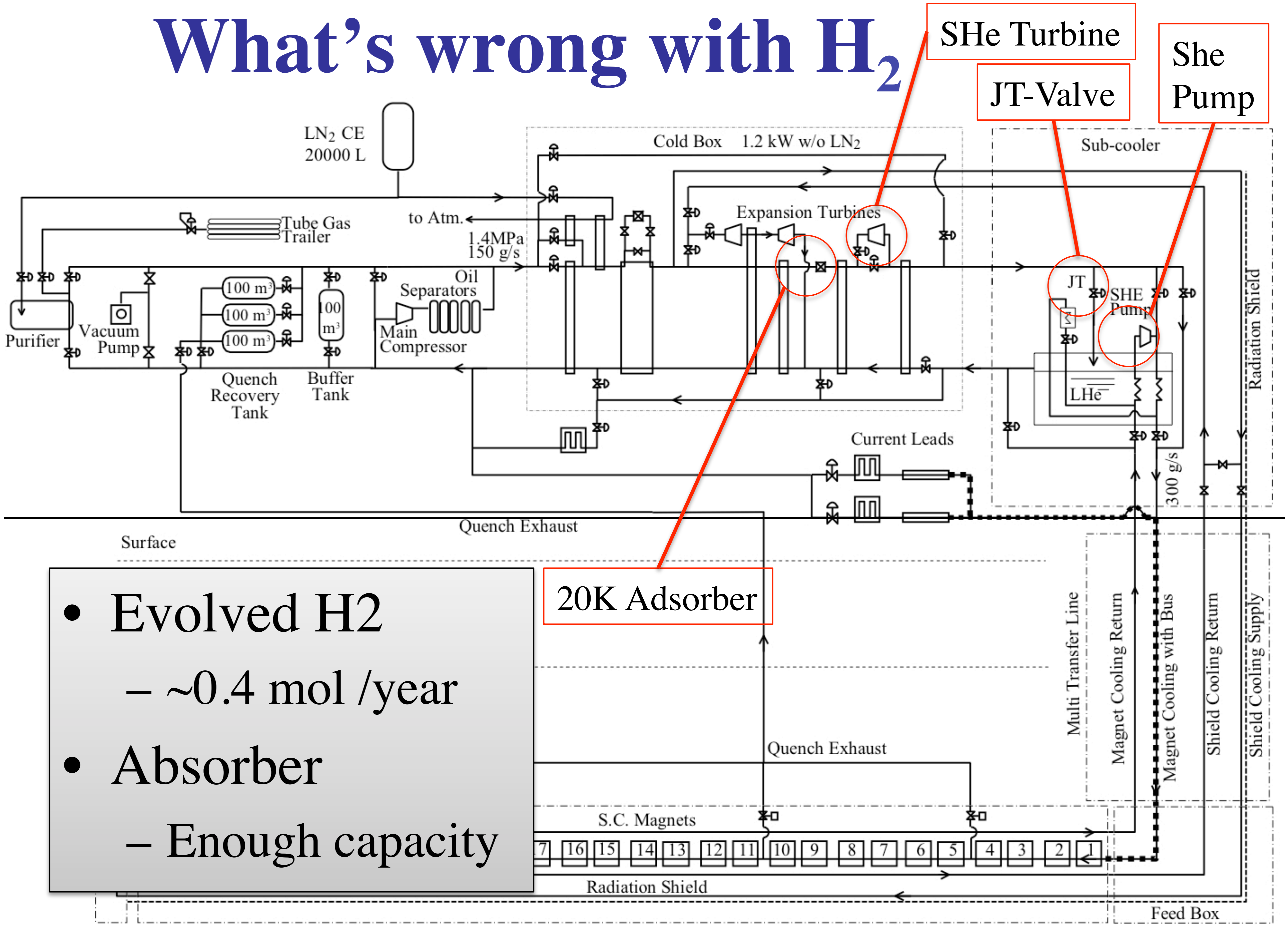
Comparison to Polyethylene



Sample	G (H_2)
Upilex-RN Tape	1.13×10^{-2}
G11	2.18×10^{-2}
PM9640	3.35×10^{-2}
Polyethylene	4.19

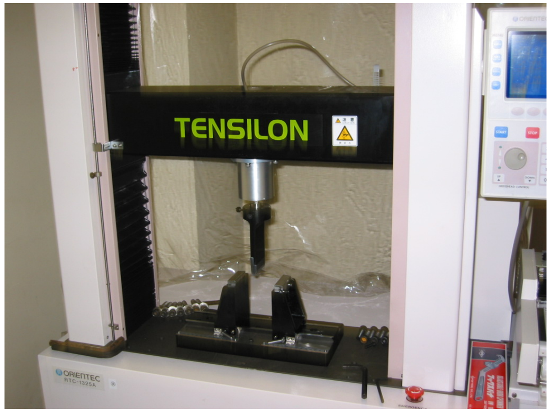
- Majority of the evolved gas is Hydrogen
- Level is quite small compare to polyethylene

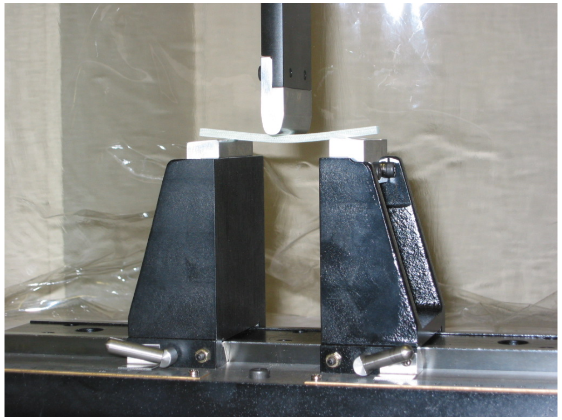
What's wrong with H_2

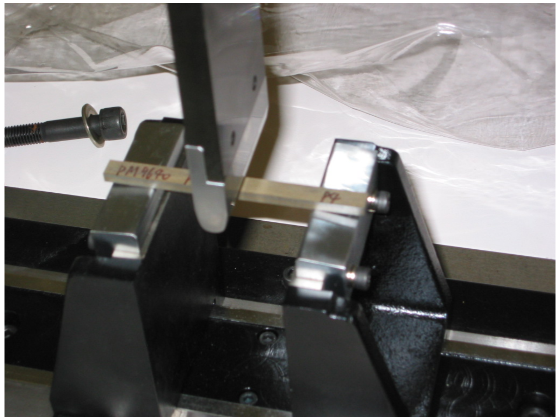


- Evolved H2
  - ~0.4 mol /year
- Absorber
  - Enough capacity

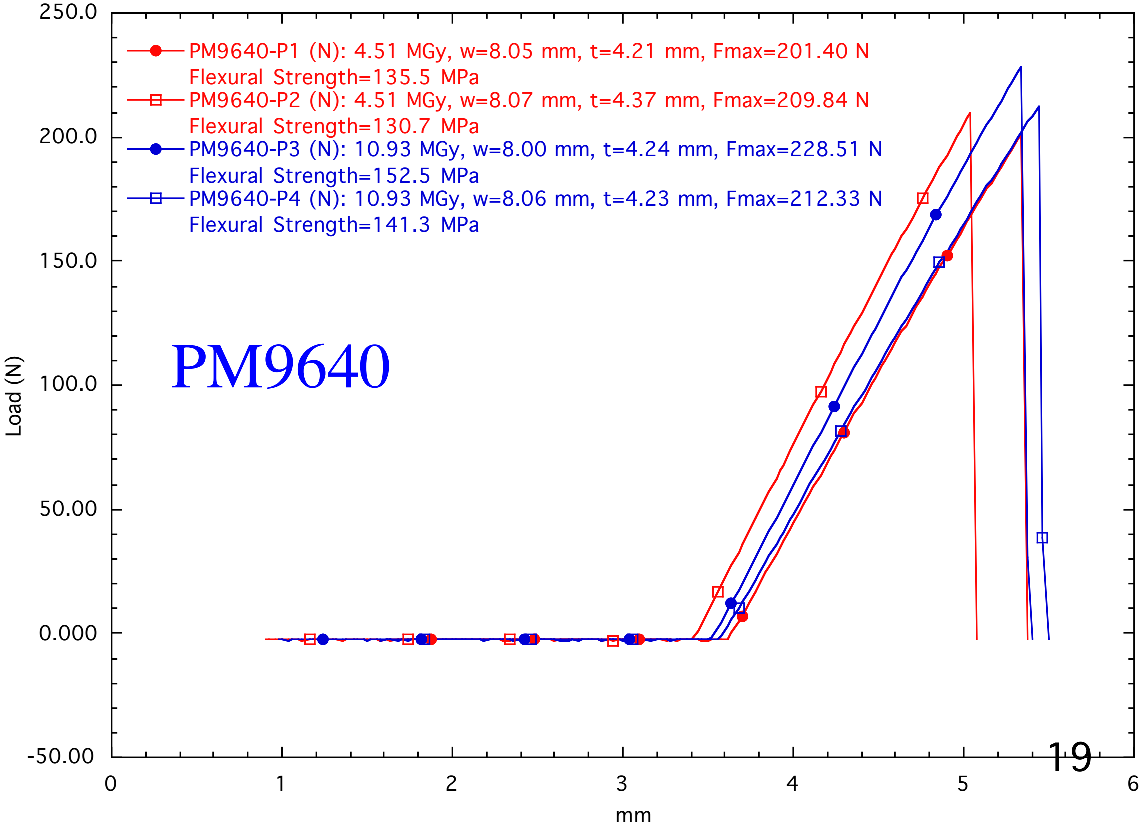
Mechanical Tests





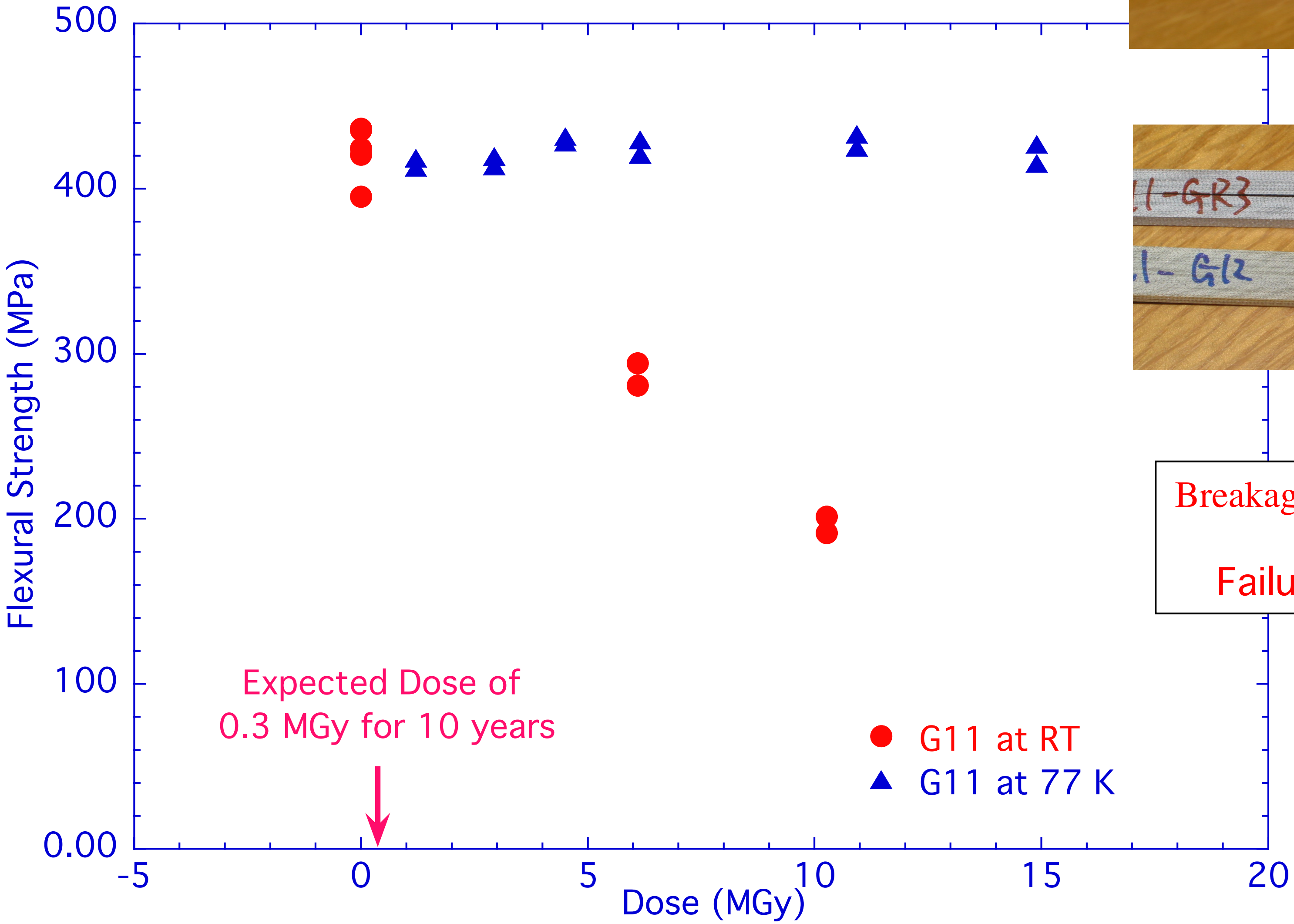


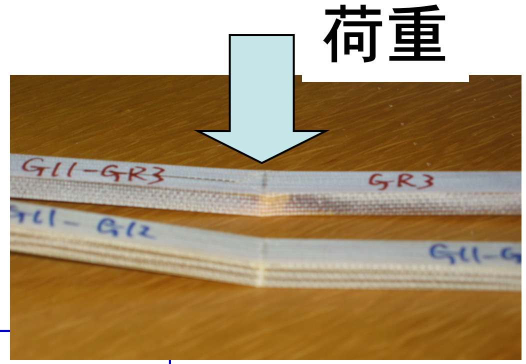
- Bending Test（JIS-K6911）
  push bar speed：2 mm/min.
- Sample：PM9640、G-11
- Size：8 mm x 4 mm x100 mm
  Size limited by glass tube

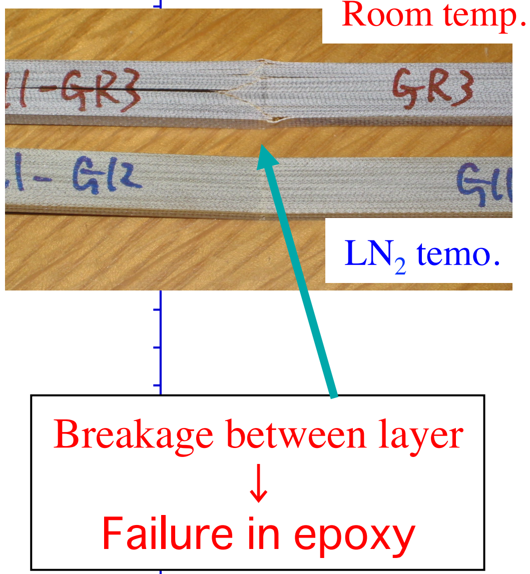


G-11

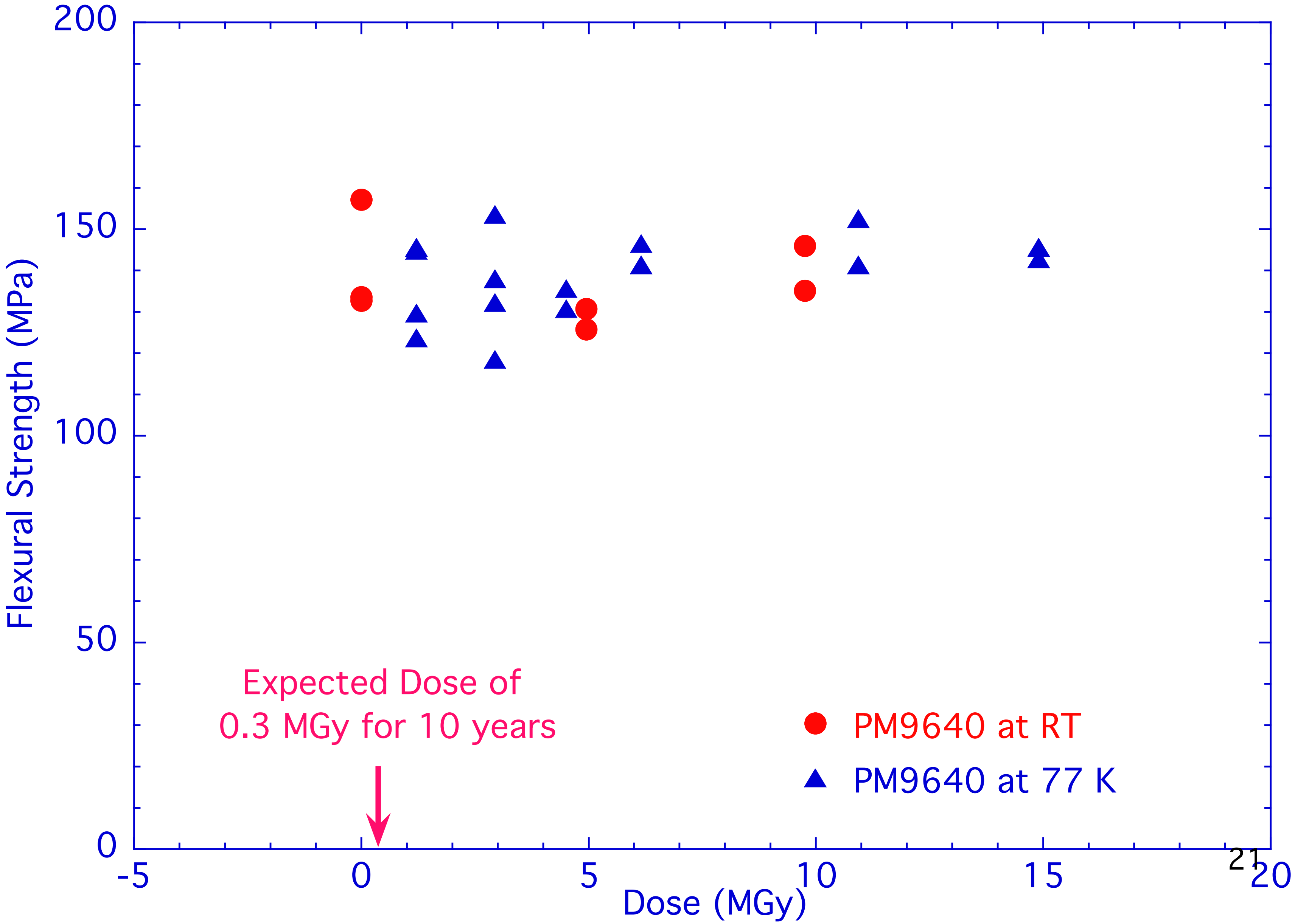
No degradation with LN_2 temp. irradiation
Clear degradation with room temp. irradiation







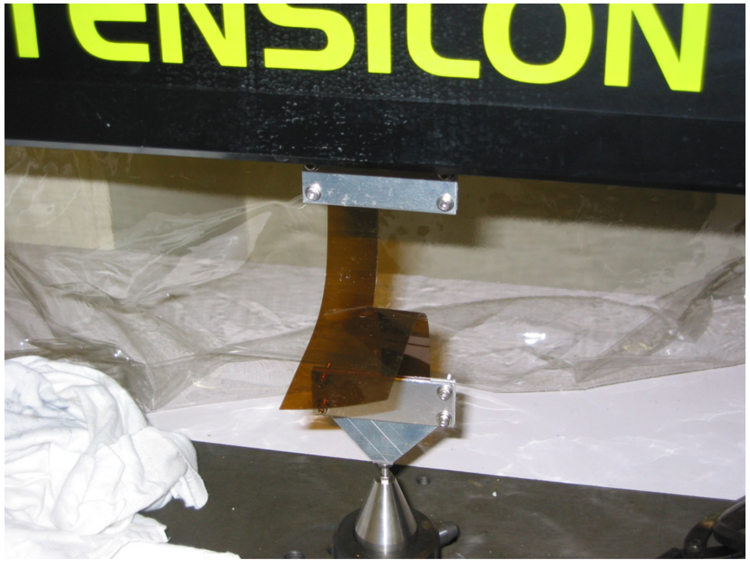
PM9640

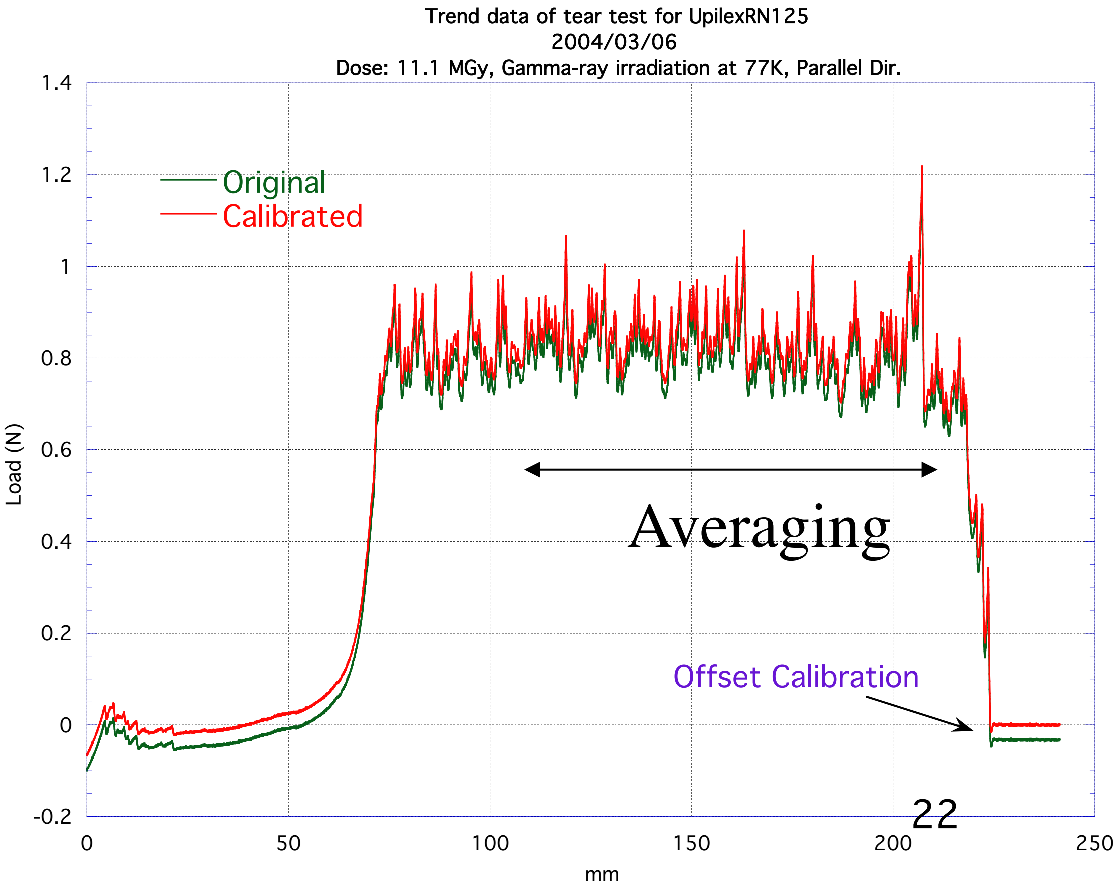


Flexural Strength (MPa)
200
150
100
50
0
-5
0
5
10
15
20
Dose (MGy)
Expected Dose of
0.3 MGy for 10 years
PM9640 at RT
PM9640 at 77 K

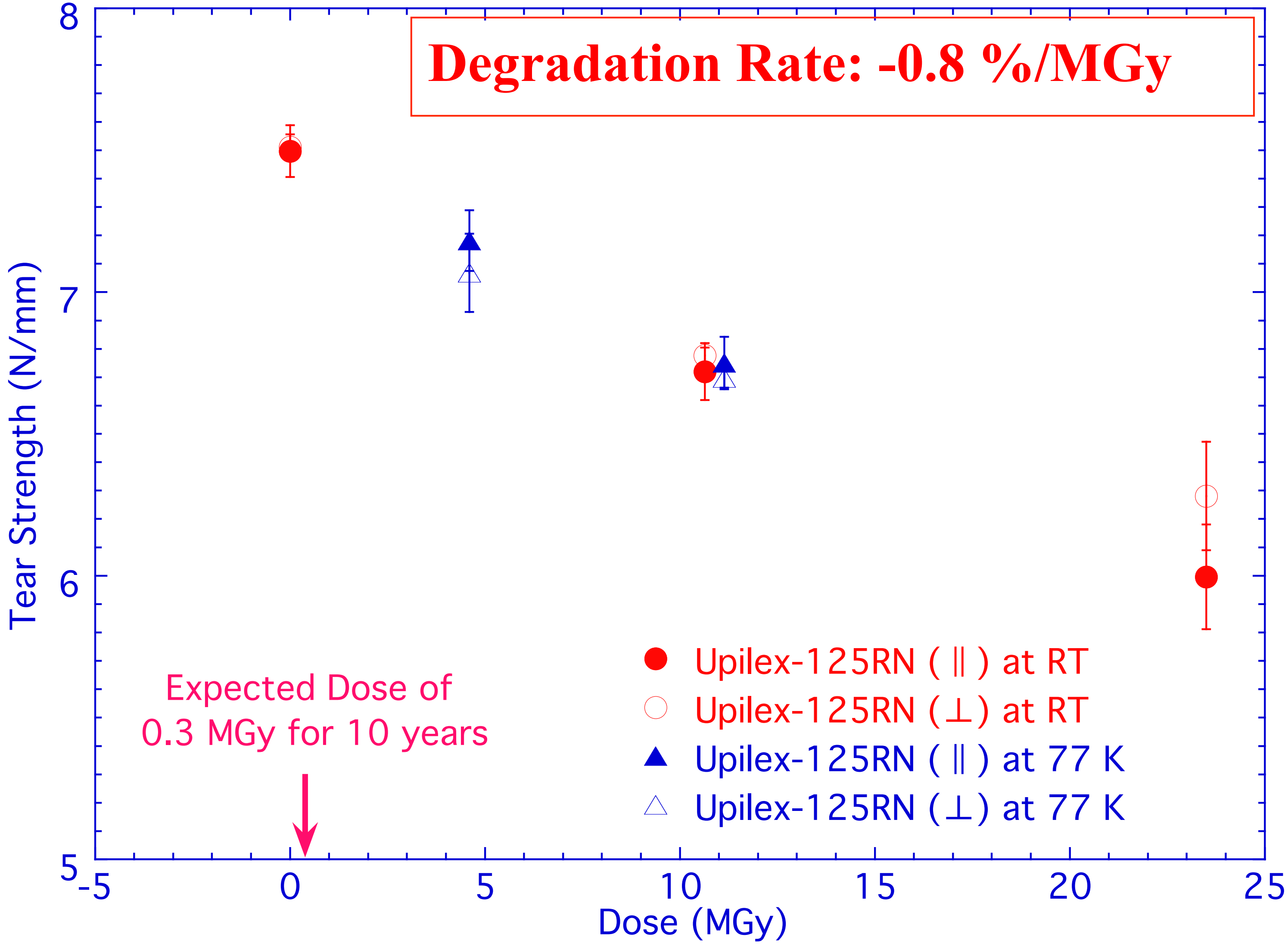
Tearing Property of Film

JIS-K7128-1 Trouser tear method
Tearing Speed：200 mm/min.
Sample size：150 mm×50 mm、slit length 75 mm



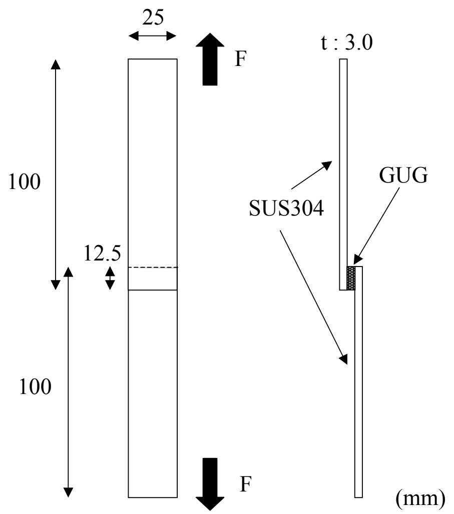


UpilexRN125

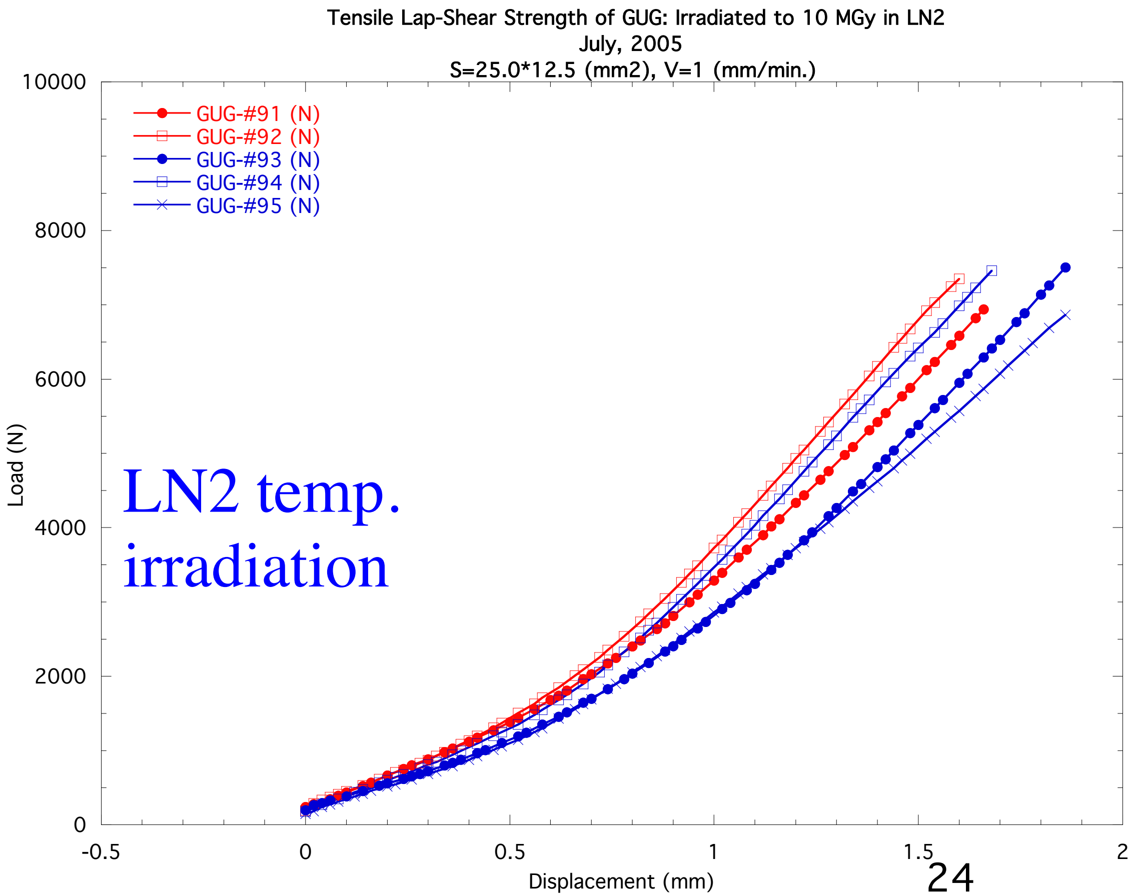


※No difference in role direction

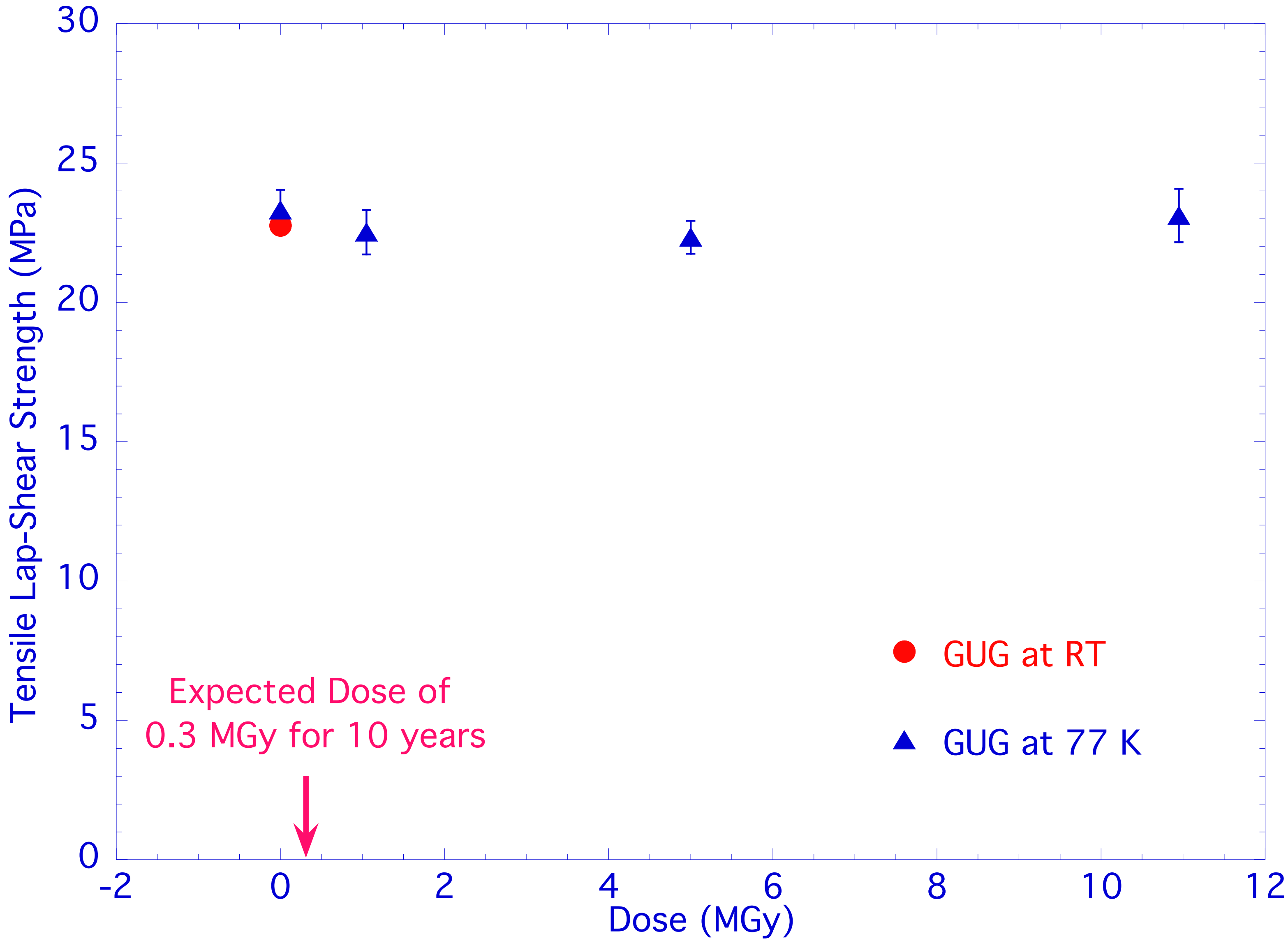
Bonding Strength



- Bonding Strength Test（JIS-K6850）
  Speed：1 mm/min.
- GUG（Glass Fiber+UpilexRN+Epoxy）
  Curing Condition：130°C, 5 hours



GUG (Glass fiber + Polyimido + Epoxy)



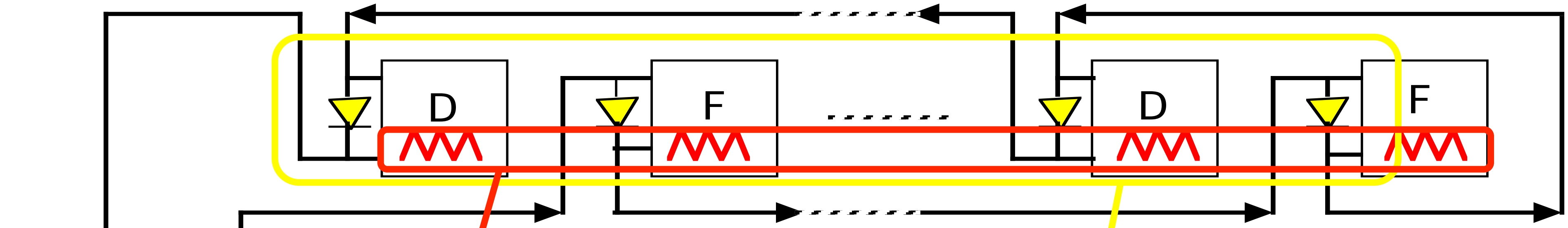
Material Test Summary

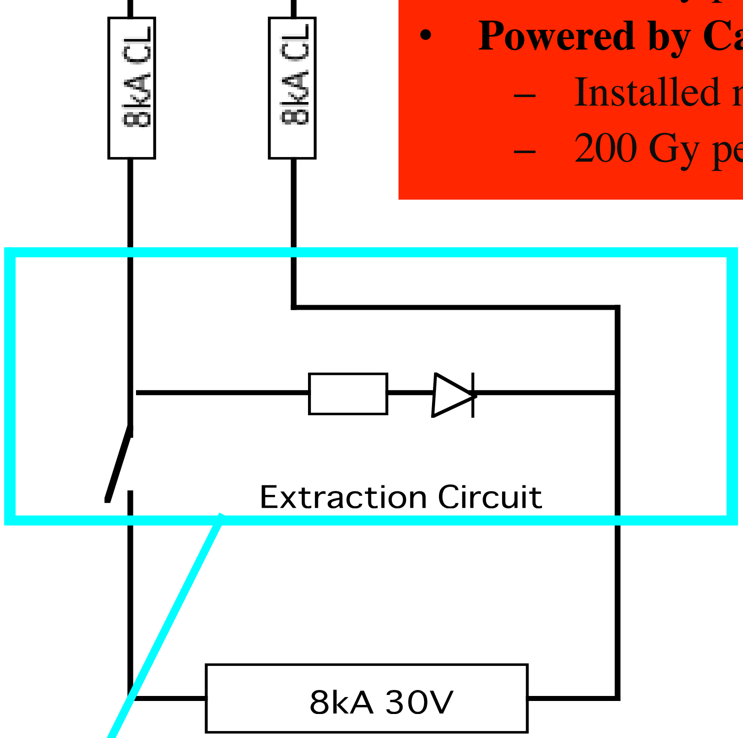
- Material Irradiation Hardness
  - Most of them are tested at Takasaki
    - Almost all organic material in Magnet Cold Mass
      - With both room and LN2 temp irradiation (presented here)
    - Super-insulation (by JAEA team)
    - EPDM O-ring
  - They all show enough durability with sufficient margin

Neutrino Beam Line SCFM System
Beam loss associated Issues

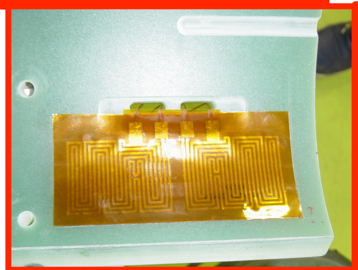
- High Power Proton Beam Line
  - 30 GeV 750 kW (possibly 50 GeV, 4MW)
  - Beam loss 1W/m (10W per point) by tunnel shield
- Issues associated with beam loss
  - Average loss = irradiation
    - Material durability
    - **Component durability**
    - Tritium Creation in Helium
  - Accidental loss

Quench Protection System





- **Quench Protection Heater**
  - 10 kGy per year
- **Powered by Capacitor Bank**
  - Installed near SCFM
  - 200 Gy per year

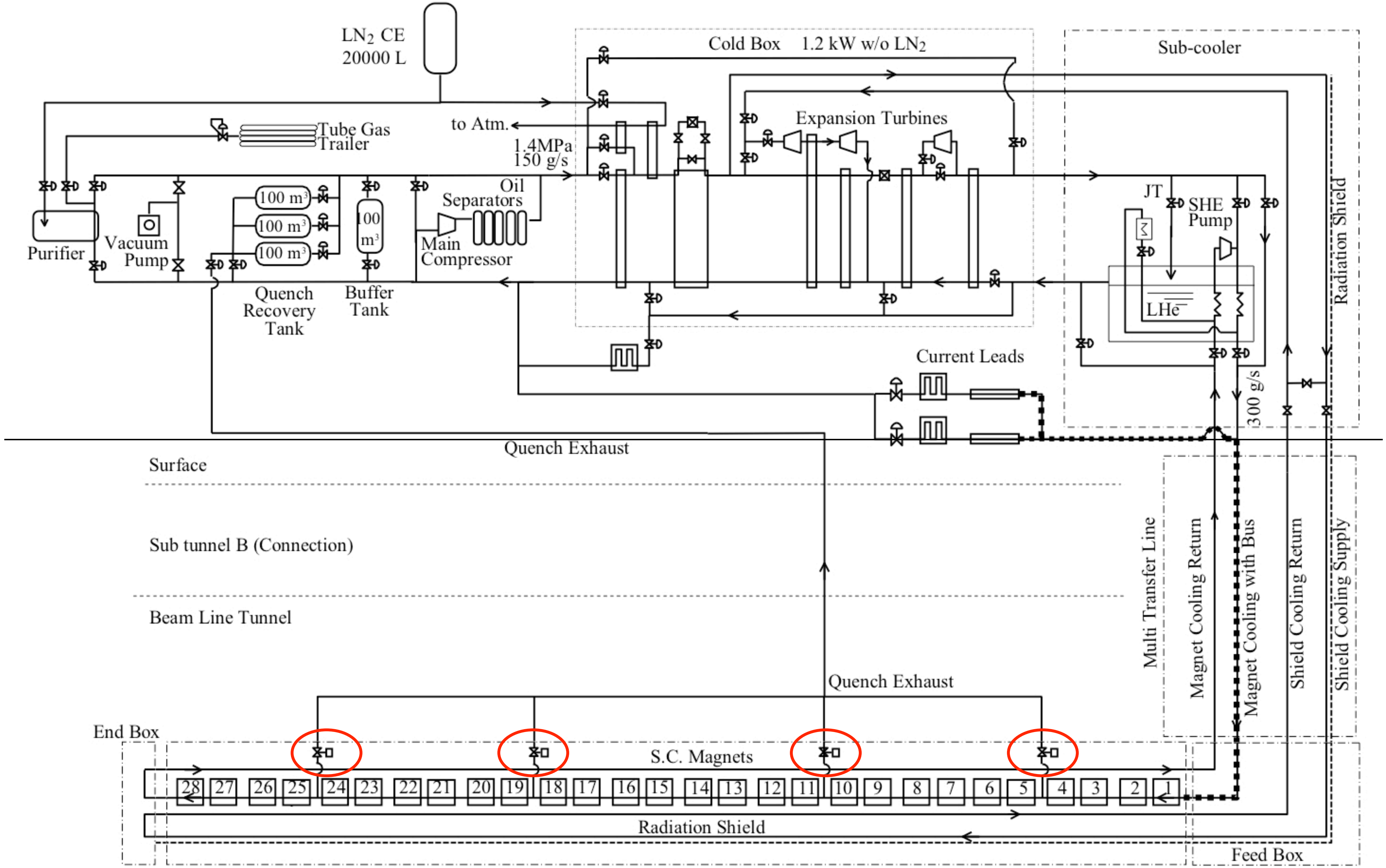


- **Cold Diode**
  - Turn On Voltage: 6V
  - Forward Voltage: 1V
  - $1.2 \cdot 10^{13}$ n/cm^2/year

- **Dump Circuit**
  - Protect Cold Diodes and SC Bus Bars
  - Time Constant: 10 sec

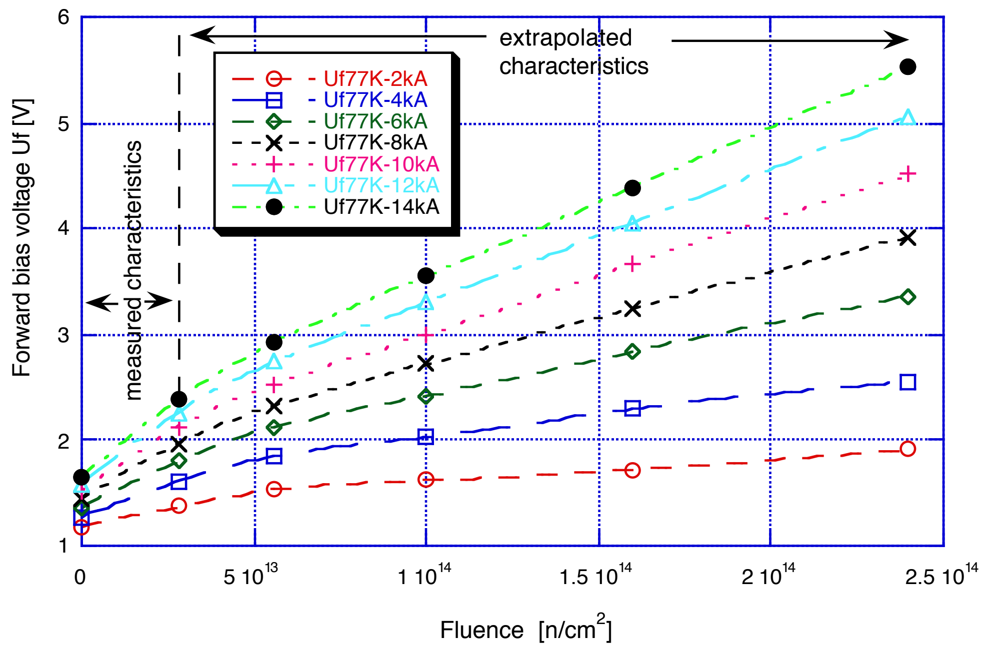
Quench Relief Valve

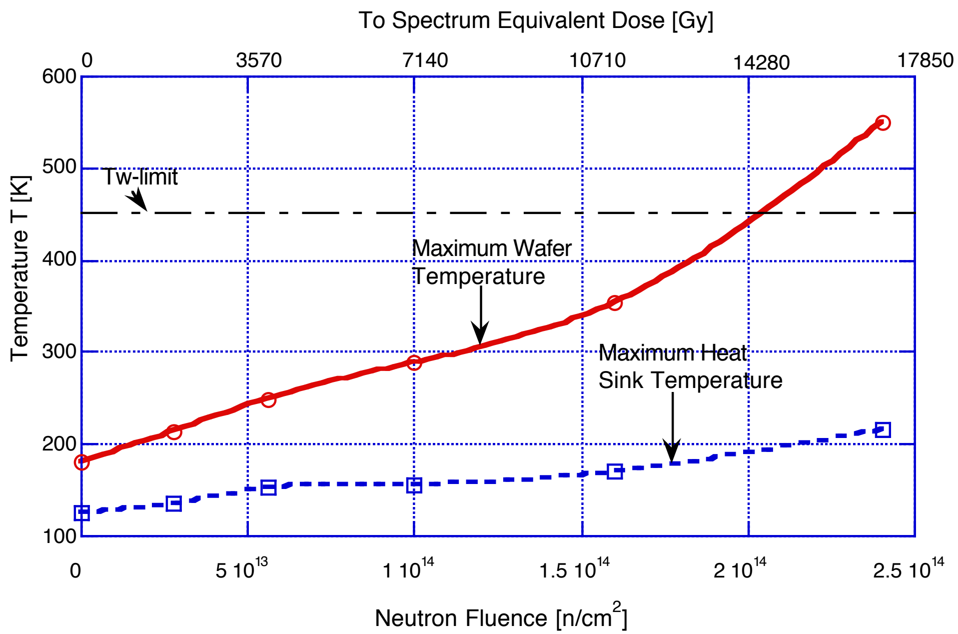
- Release pressurized helium to bu
- 10kGy per year



Radiation to Cold Diode

- Influence of Neutron to Cold Diode
  - Intensively studied at CERN by D. Hagedorn
    - Change Forward Voltage
  - Using LHC Arc Quad Assembly
    - 7.5kA Operation
    - Limit; 2• 10^{14} n/cm^2

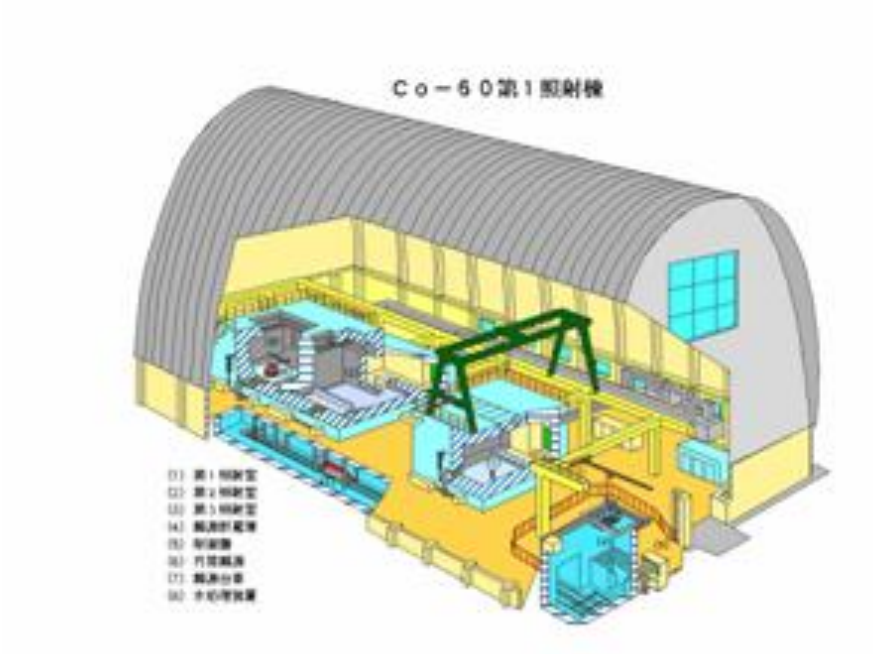




Courtesy D.Hagdorn

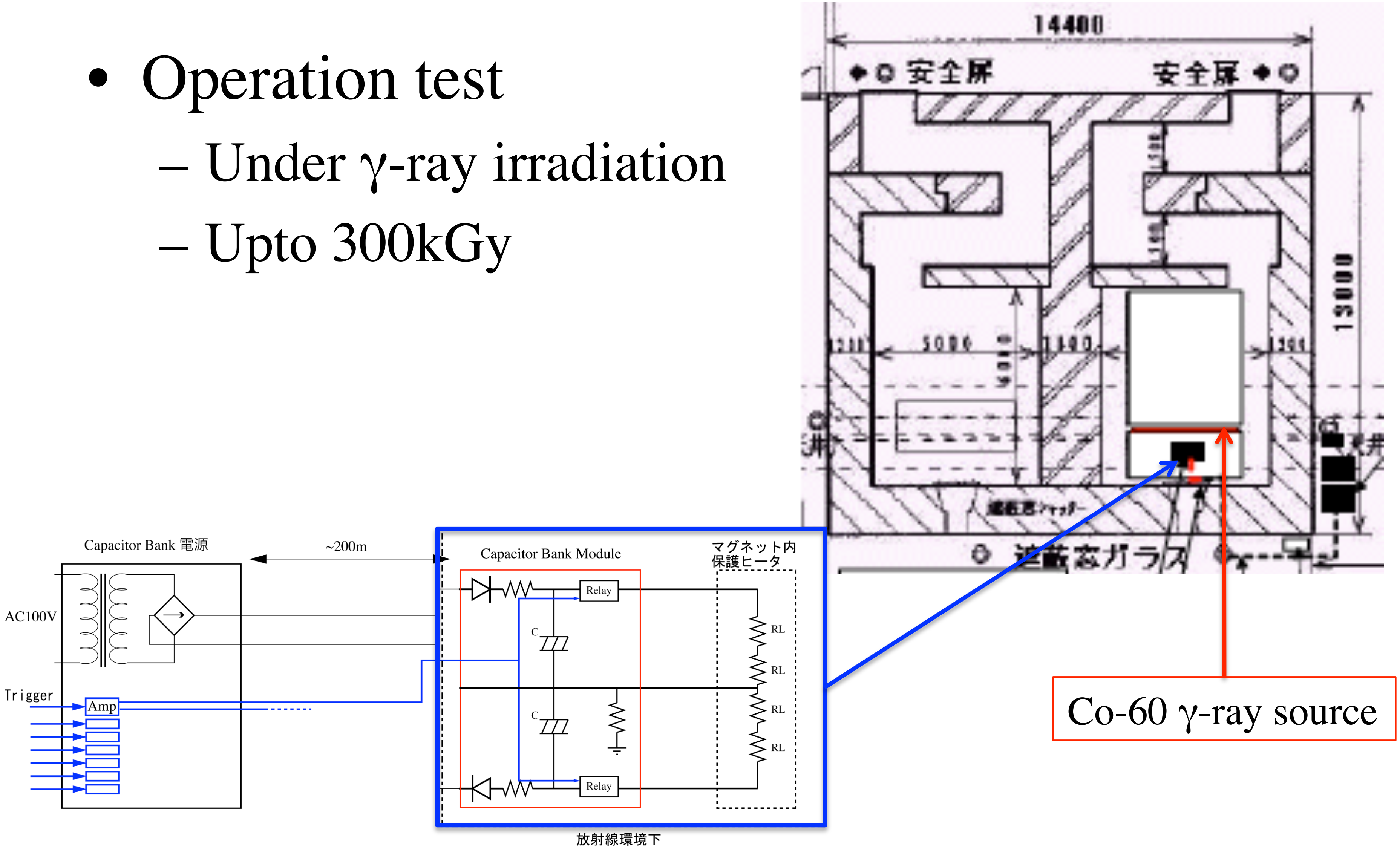
Components Test

- Test Facility
  - JAEA Takasaki Co-60 γ-ray irradiation facility
  - <10kGy/hour
- Test Items
  - Capacitor Bank
  - Quench Relief Valve

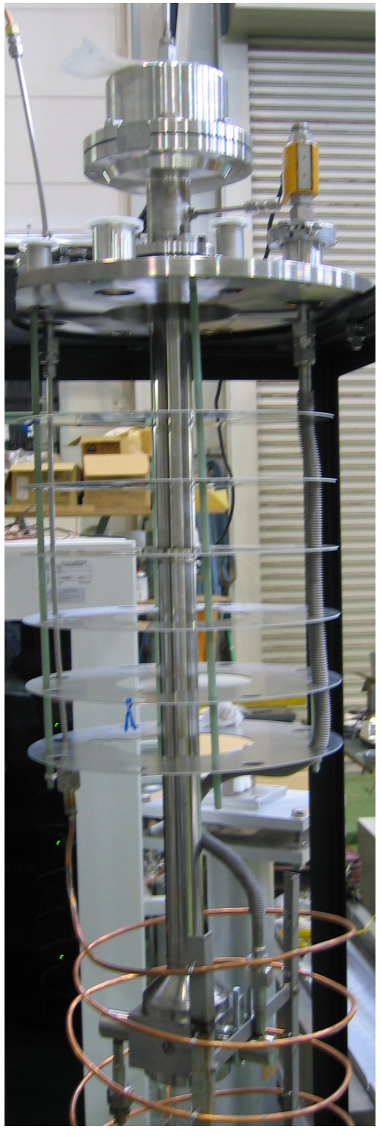


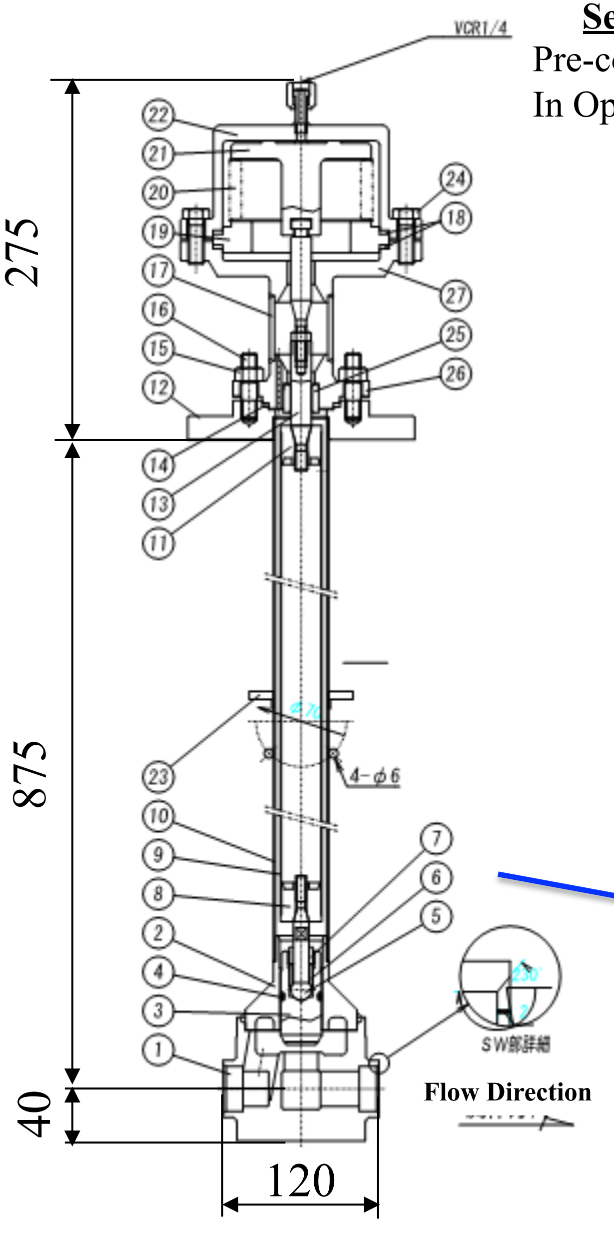
Irradiation test of Capacitor Bank

- Operation test
  - Under γ-ray irradiation
  - Upto 300kGy



Relief Valve (Kimura Valve)





Setting Pressure

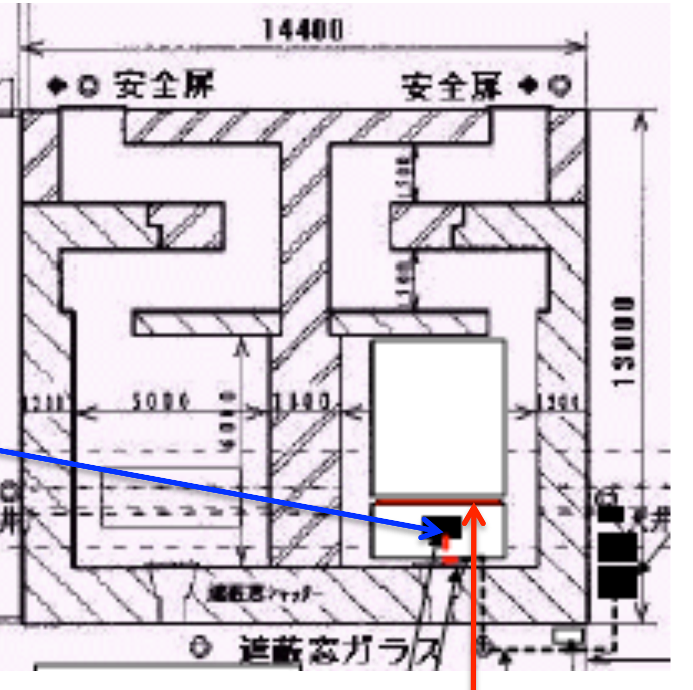
Pre-cooling: 1.2 MPa

In Operation: 0.45 MPa

Operation test

Under γ-ray irradiation

Upto 300kGy



Co-60 γ-ray source

Components Summary

- Cold Diode
  - Use exactly the same one as CERN LHC arc quadrupole magnets
  - Radiation hardness was tested and evaluated by CERN
    - May not survive for long term operation >20 years
    - Needs routine check and eventual replace
- Other components
  - Capacitor Bank and Quench Relief Valve
  - Tested at Takasaki and confirmed enough durability

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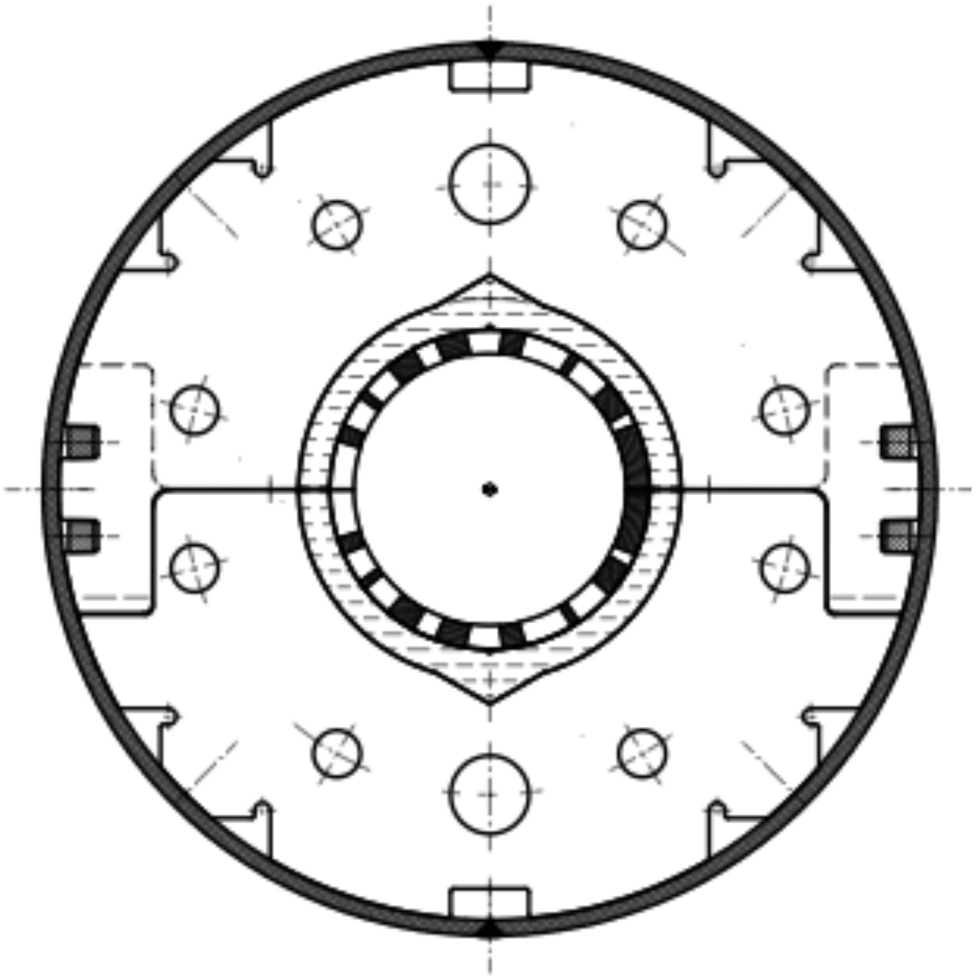
    - Material durability
    - Component durability
    - **Tritium Creation in Helium**
  - Accidental loss

Tritium Issue

- After 4000 hour 1w/m loss
  - Beam Tube Periphery
    - 180 Bq/cc * 5 litter = 900 kBq
  - Cooling Holes
    - 25 Bq/cc * 20 litter = 400 kBq
  - End Space
    - 30 Bq/cc * 60litter = 1800 kBq
  - Cooling Tube
    - 20Bq/cc * 15litter = 300 kBq
  - 3He to tritium
    - 7 Bq/cc * 100litter = 700 kBq
  - Total
    - ~4 MBq / 100 litter
    - ~ 40 Bq/cc



Tritium Issue: Regulation

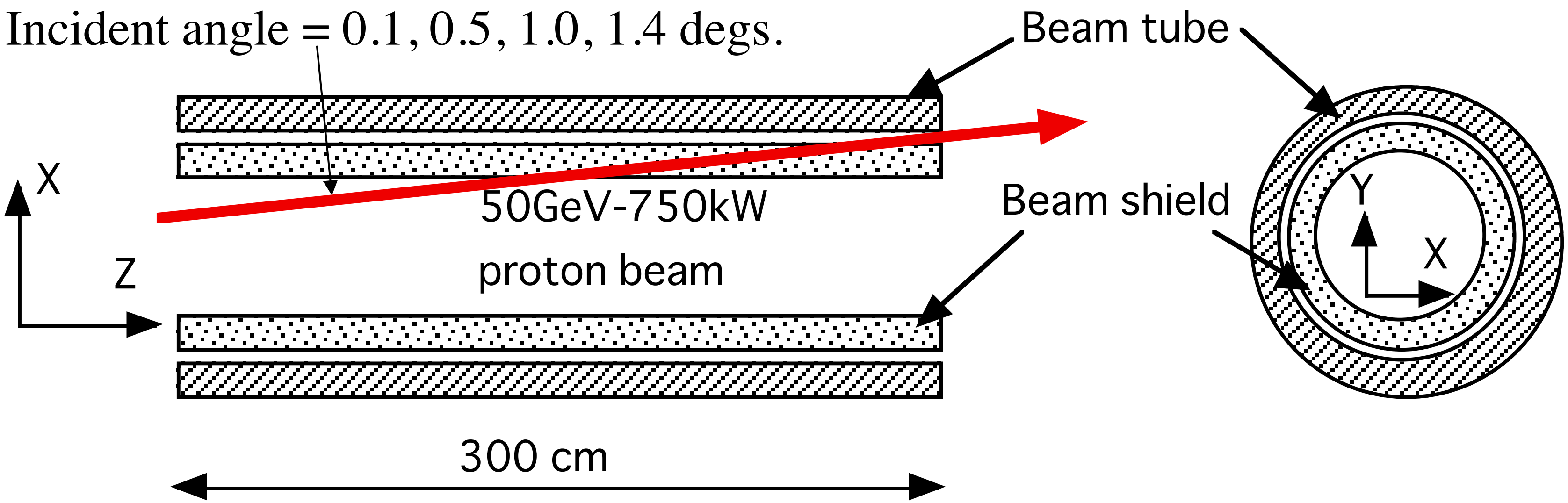
- Estimated value after 4000 hour operation
  - 40 Bq/cc at 3.6 atm 5 K in 2800 litter
  - ～0.035 Bq/cc ；1 atm 300K ／ 3200 m^3
- Regulation
  - HT ；7 Bq/cc
  - HTO ；5 mBq/cc
- HTO regulation is very stingy
  - May exceed in worst case
  - Routine check
    - Sampled helium gas during warm condition
    - Regeneration gas of 20K adsorber

Neutrino Beam Line SCFM System
Beam loss associated Issues

- High Power Proton Beam Line
  - 30 GeV 750 kW (possibly 50 GeV, 4MW)
  - Beam loss 1W/m (10W per point) by tunnel shield
- Issues associated with beam loss
  - Average loss is reasonable
    - Material = Price vs adequate radiation harness
    - Component durability
    - Tritium Creation in Helium
  - **Accidental loss**

Full Beam Loss

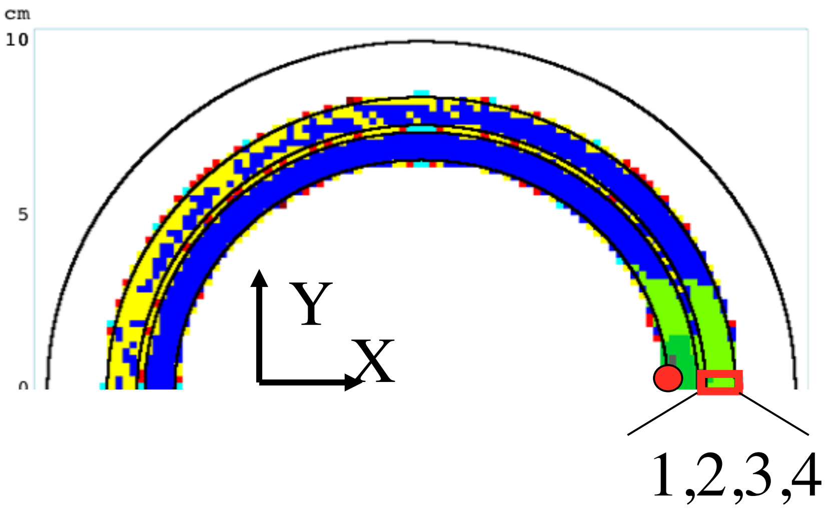
Incident angle = 0.1, 0.5, 1.0, 1.4 degs.

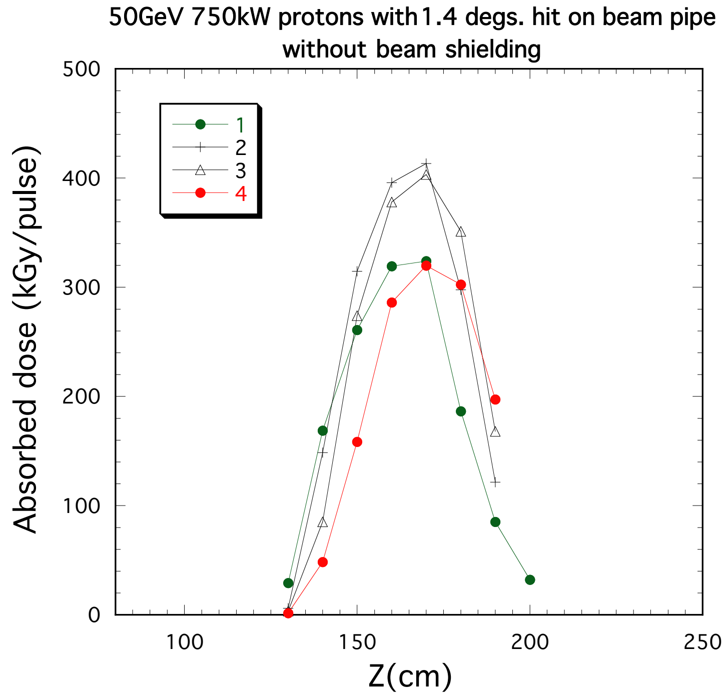


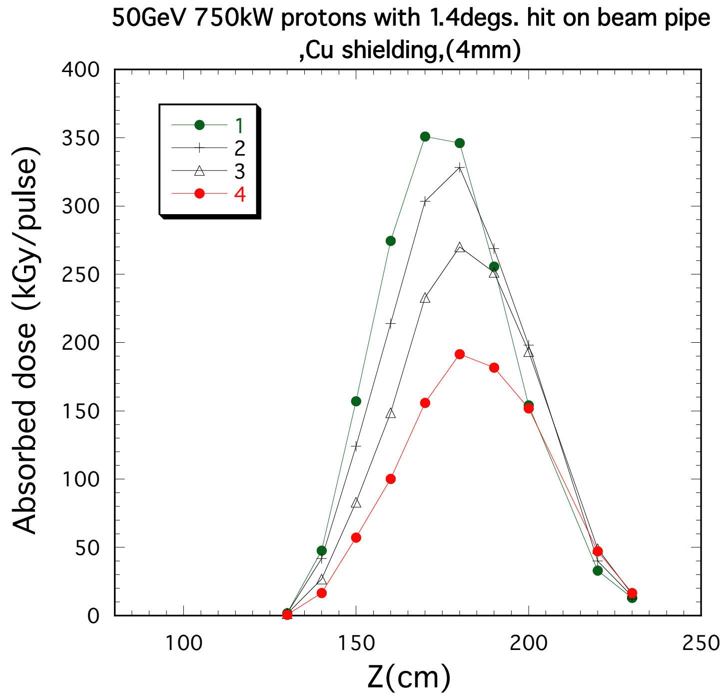
The beam is distributed uniformly rectangular area. dX=1cm,dY=2cm

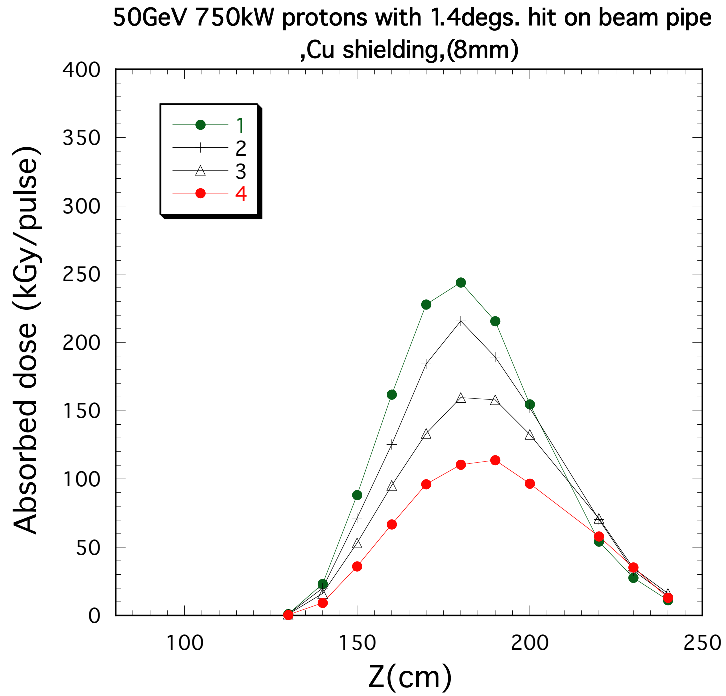
-	Beam shield	Beam tube
Material	Copper	Stainless
Radius (mm)	~74	76~84
Thickness(mm)	0, 4, 8, 10	8

Thermal Input









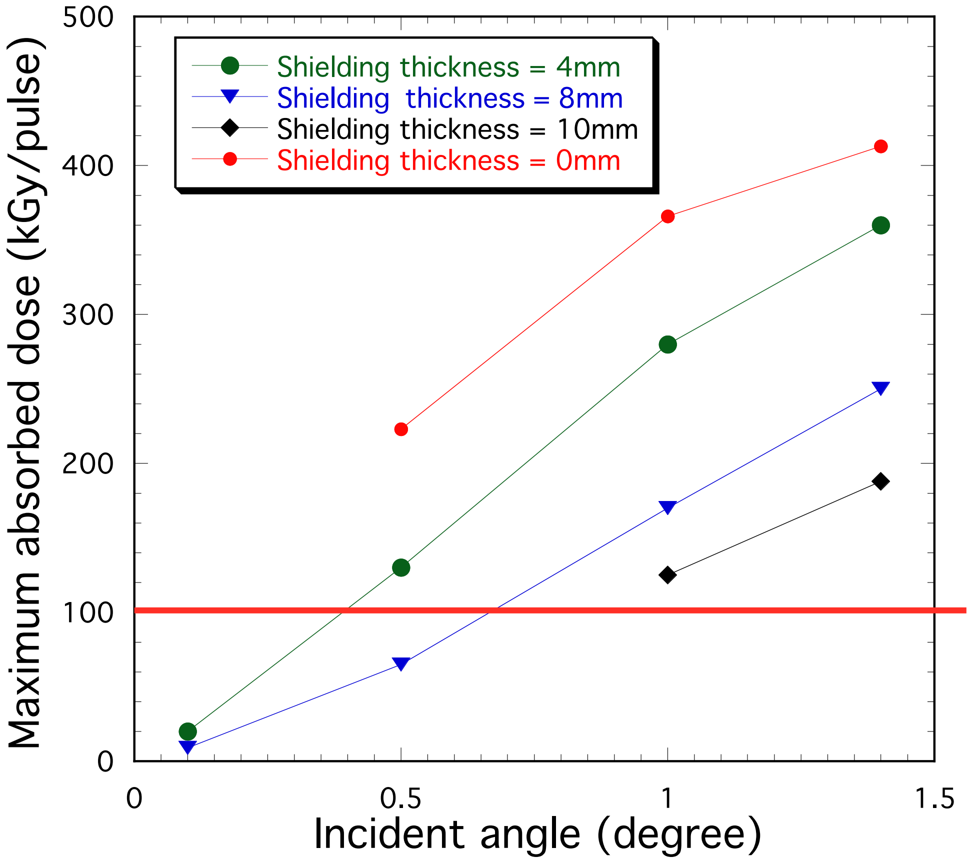
Thermal Stress Limit

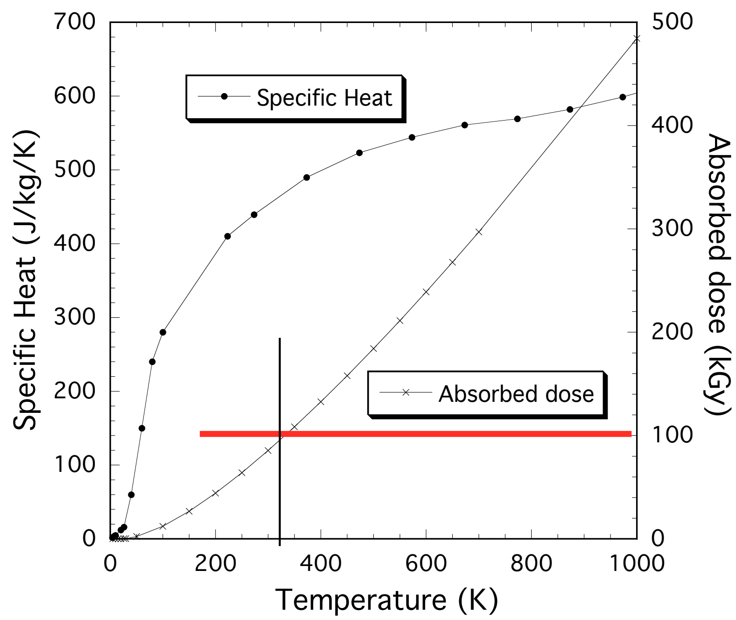
Simple estimation: $$\sigma_{th} = \frac{2-\nu}{3(1-\nu)} \cdot E \cdot \int_0^T \alpha \cdot dT$$

100kGy/pulse

$\sigma_{th} = 0.52\text{GPa}$

~ Tensile Strength @ 300K





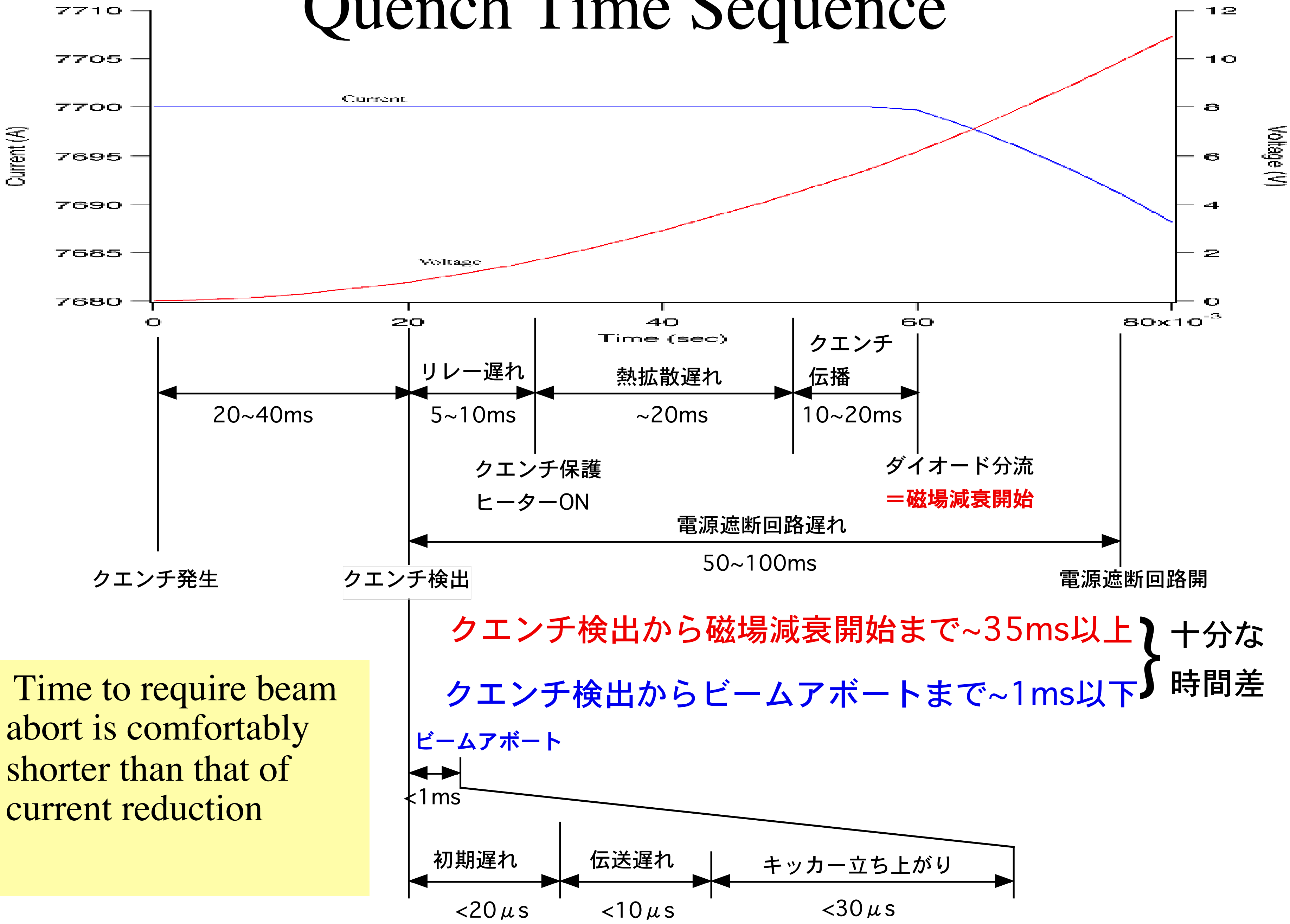
Accidental Loss

- Beam incident angle is important
  - Worst case is the beam without SCFM operation: 1.4 degree
  - 10mm thick beam shield does not help (accepted limit)
    - No shield

- Beam that are passed through the preparation section
  - Will pass through SCFM section if the operation current is correct

- Interlock system
  - No beam without correct SCFM operation current
  - Time sequence for quench interlock should be checked

Quench Time Sequence



Time to require beam abort is comfortably shorter than that of current reduction

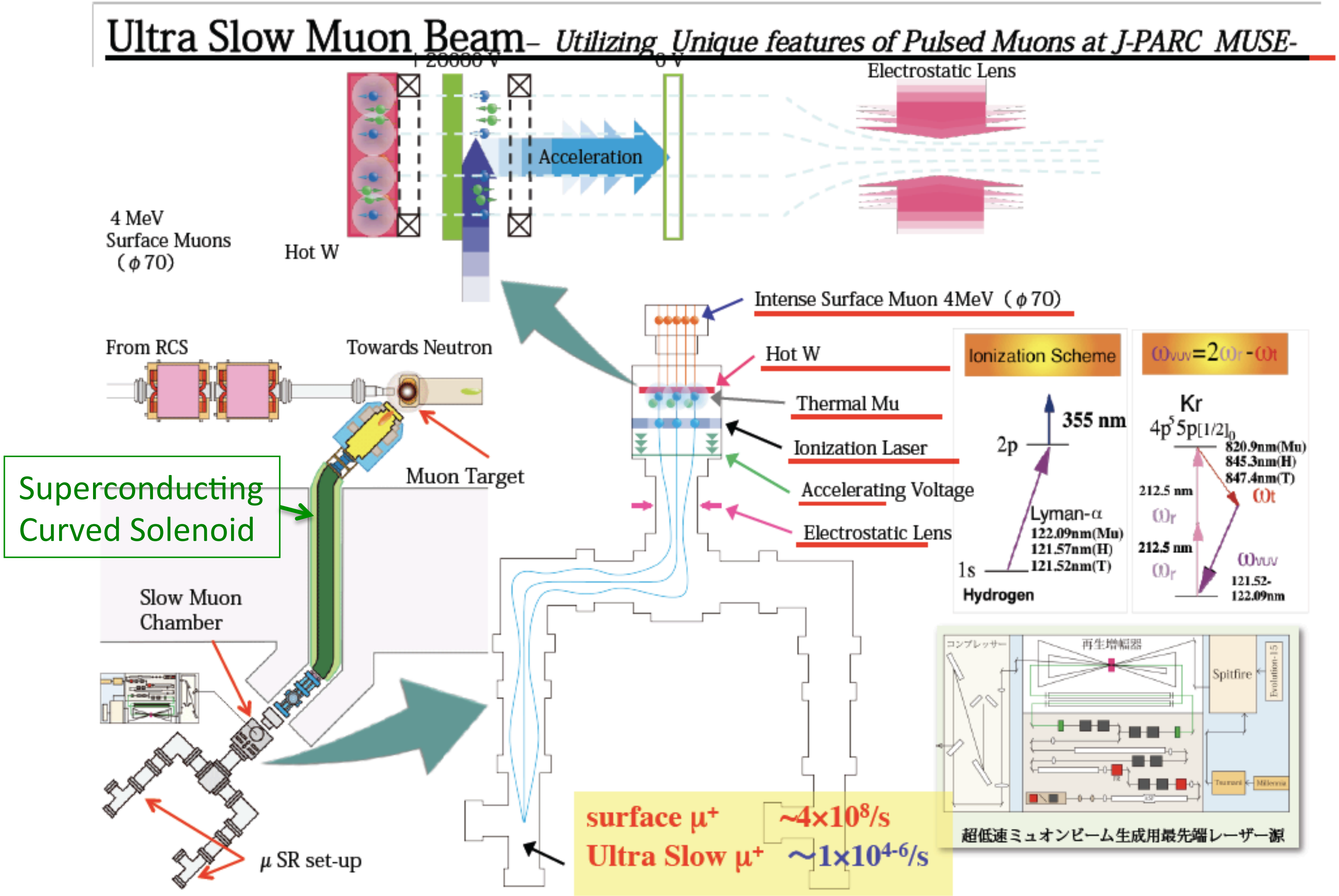
Neutrino Beam Line SCFM System
Beam loss associated Issues Summary

- Issues associated with beam loss
  - Irradiation hardness was checked for
    - Materials and Components
      - Cold diode may be the only issue and will be checked routinely
  - Tritium Creation in Helium
    - May exceed regulation in worst case
      - Routine checking
  - Accidental loss is huge
    - Full beam loss is not acceptable = Interlock System

Superconducting Magnets in J-PARC

- In Operation
  - Neutrino Beam Line SCFM system
  - SKS spectrometer
  - Large OMEGA muon beam line solenoid
- Under Construction
  - **Super OMEGA muon beam line**
- Proposed
  - COMET (Makoto's Talk)
  - HFS, g-2

Super Ω


Ultra Slow Muon Beam– Utilizing Unique features of Pulsed Muons at J-PARC MUSE-
Electrostatic Lens
Acceleration
4 MeV
Surface Muons
(φ70)
Hot W
From RCS
Towards Neutron
Muon Target
Superconducting
Curved Solenoid
Slow Muon
Chamber
μ SR set-up
Intense Surface Muon 4MeV（φ70）
Hot W
Thermal Mu
Ionization Laser
Accelerating Voltage
Electrostatic Lens
Ionization Scheme
355 nm
2p
Lyman-α
122.09nm(Mu)
121.57nm(H)
121.52nm(T)
1s
Hydrogen
ωVUV=2ωr-ωt
Kr
4p⁵5p[1/2]₀
820.9nm(Mu)
845.3nm(H)
847.4nm(T)
212.5 nm
ωr
ωt
212.5 nm
ωr
ωVUV
121.52-
122.09nm
コンプレッサー
再生増幅器
Spitfire
Evolution-15
超低速ミュオンビーム生成用最先端レーザー源
surface μ+ ~4×10⁸/s
Ultra Slow μ+ ~1×10⁴⁻⁶/s

Ultra-slow Muon Facilities SuperOMEGA 2008~

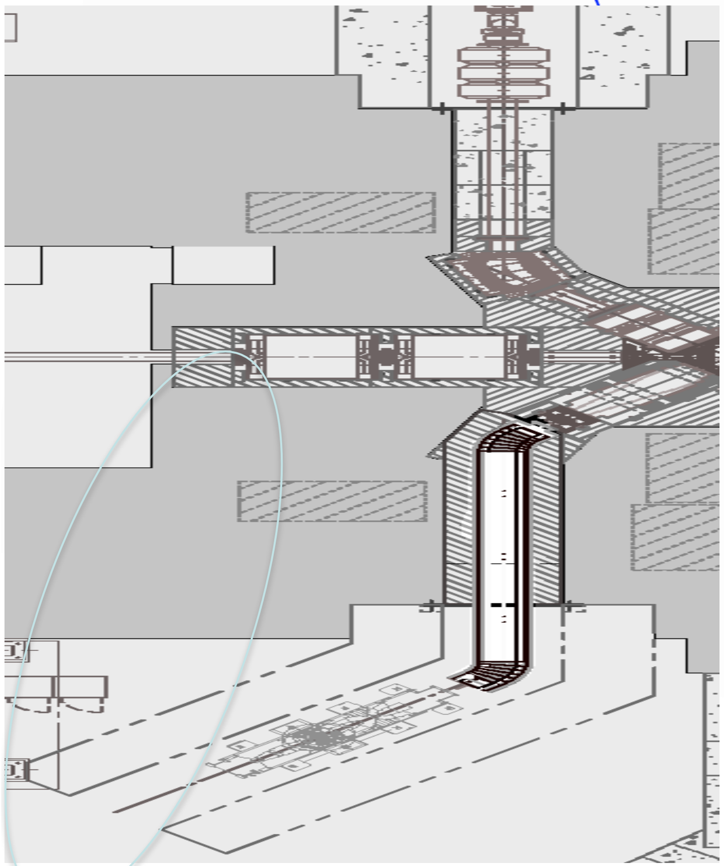
Capture Solenoid

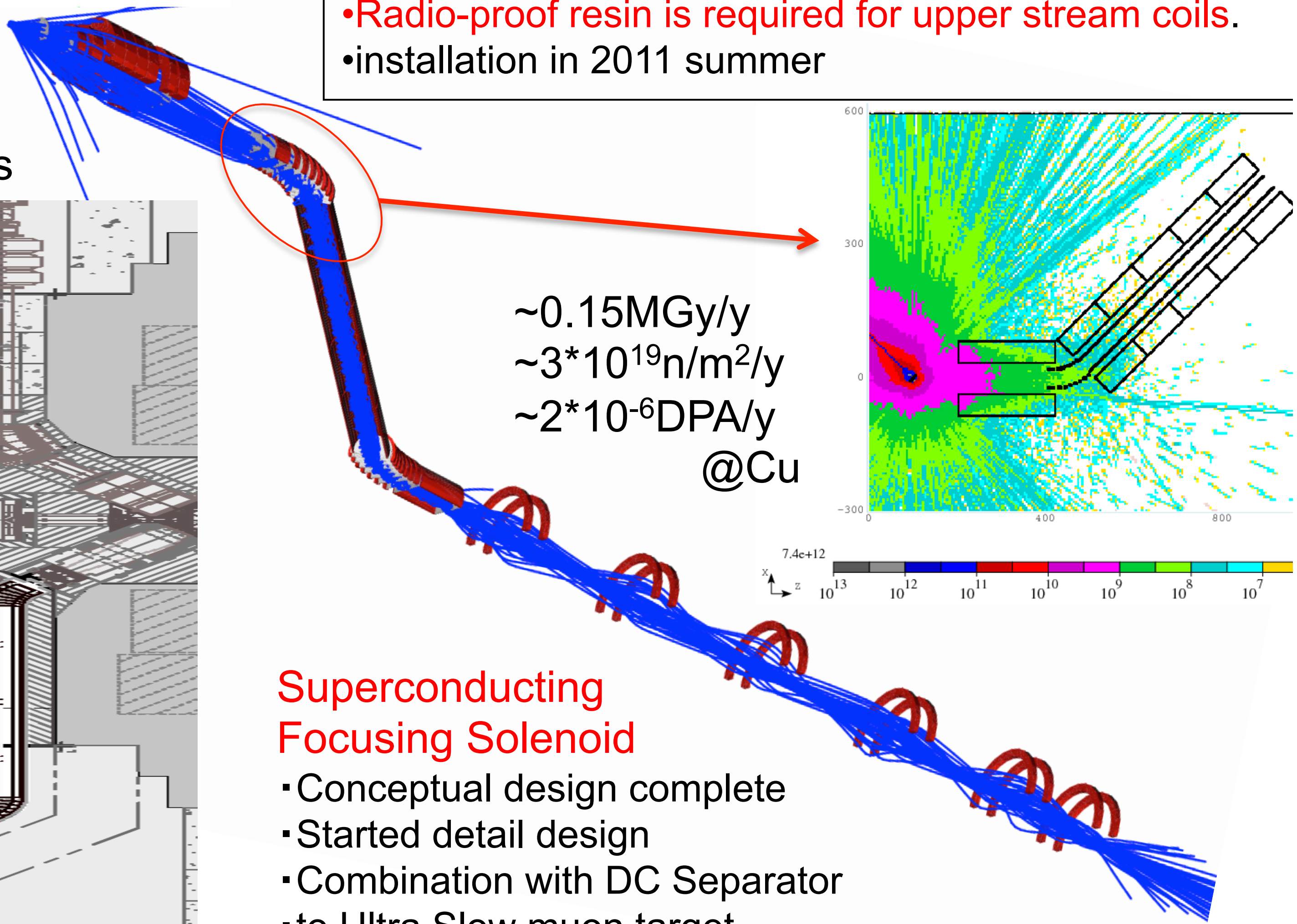
- MIC insulation normal solenoid
- Installed in 2009

Superconducting Transport Solenoid

- Transporting captured muons with high efficiency > 80 % by solenoid field.
- Dipole field separates +/- muons.
- Radio-proof resin is required for upper stream coils.
- installation in 2011 summer

MLF Muon Beam Lines





~0.15MGy/y
~$3*10^{19}$n/m^2/y
~$2*10^{-6}$DPA/y
@Cu

Superconducting Focusing Solenoid

- Conceptual design complete
- Started detail design
- Combination with DC Separator
- to Ultra Slow muon target

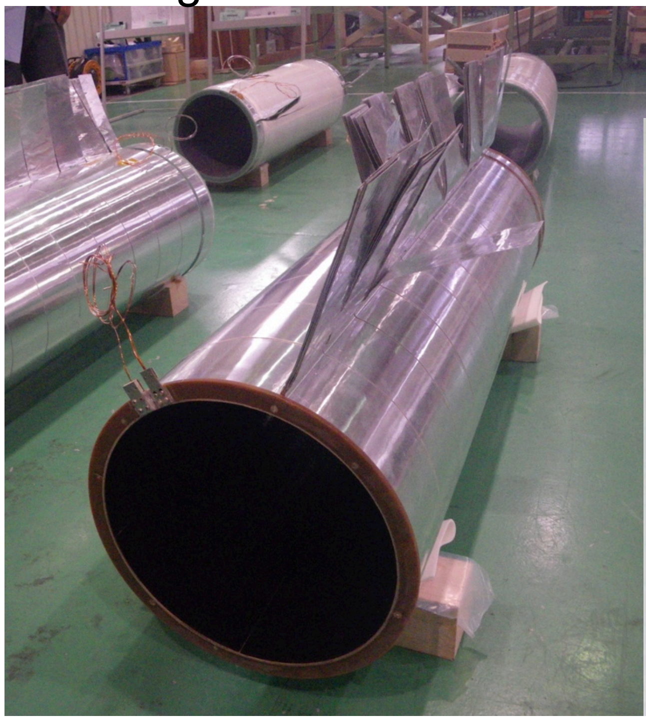
Super OMEGA

- Muon Beam Transport
  - Close to Production target
  - Large acceptance using solenoidal field
  - GM cryo-cooler cooling
- Issues
  - Continuous radiation doze
    - Radiation damage: organic material and metals
  - Heat load by radiation (~0.5W)

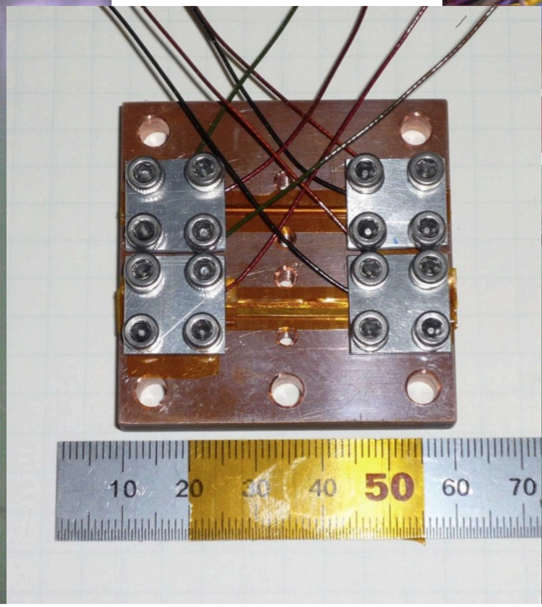
SuperOMEGA Beam Line

- GM indirect cooling with pure Al, Cu stabilized coil, extra heat load margin 2W
- Design magnet system with degraded RRR
- High radiation part: glued by Bismaleimide-Triazine resin, polyimide base composite end plate, replaceable coil, watch sample of Al and Cu
- Low radiation part: glued by epoxy resin, epoxy base composite end plate, not removable, correction dipoles
- **Operation starts 2012**

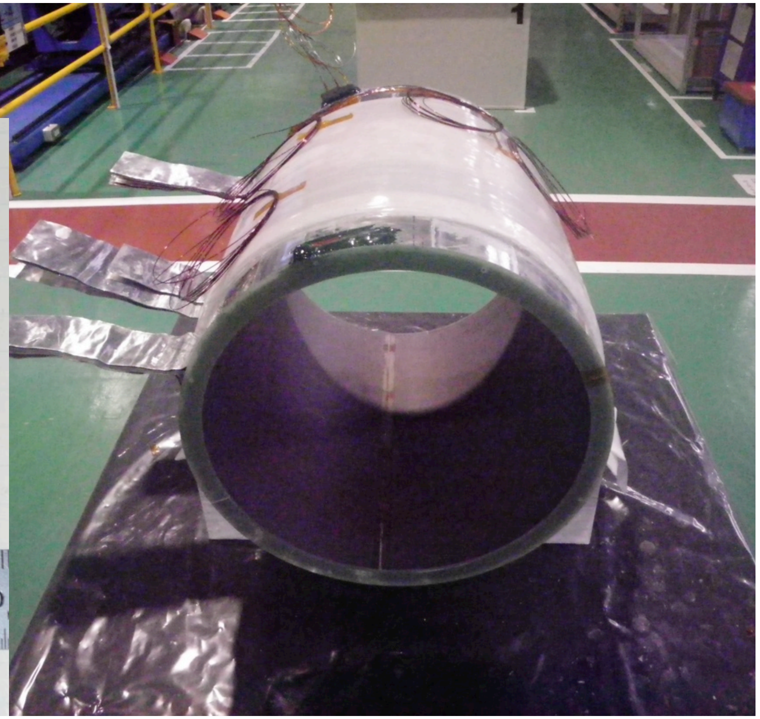
High Radiation Part



Watch Sample



Low Radiation Part



Summary

- Neutrino SCFM System
  - Extensive irradiation tests at Takasaki
    - Organic materials and components
  - Issues
    - Cold diode, Tritium, Full beam loss
      - Can be controllable
- Super OMEGA
  - Degradation on pure metals
    - Irradiation tests at Kyoto-Univ. KURRI
    - Watch sample
- Important point
  - Accumulation of Experiences and Collaborators