HK Beam

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Credits:

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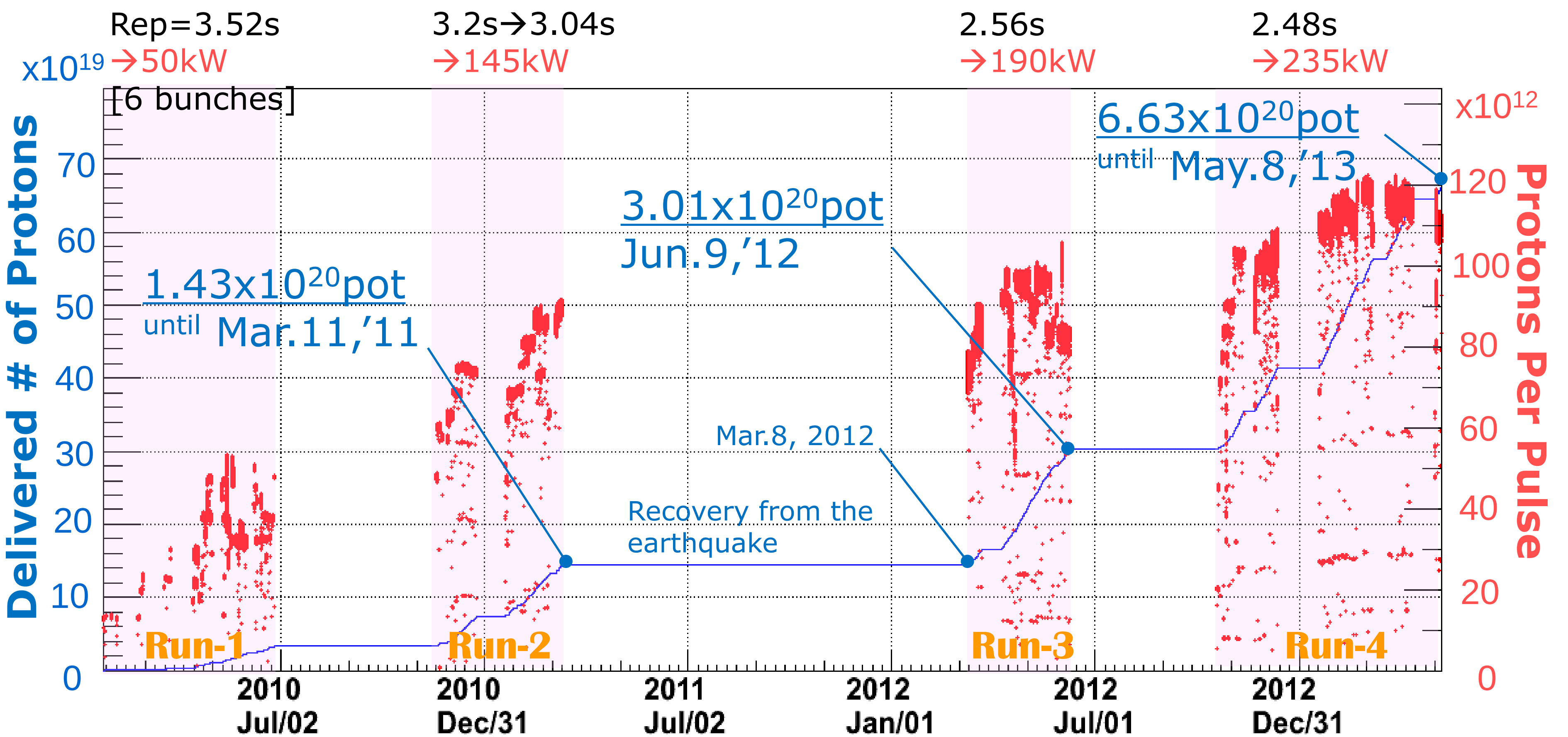
Delivered POT to neutrino facility



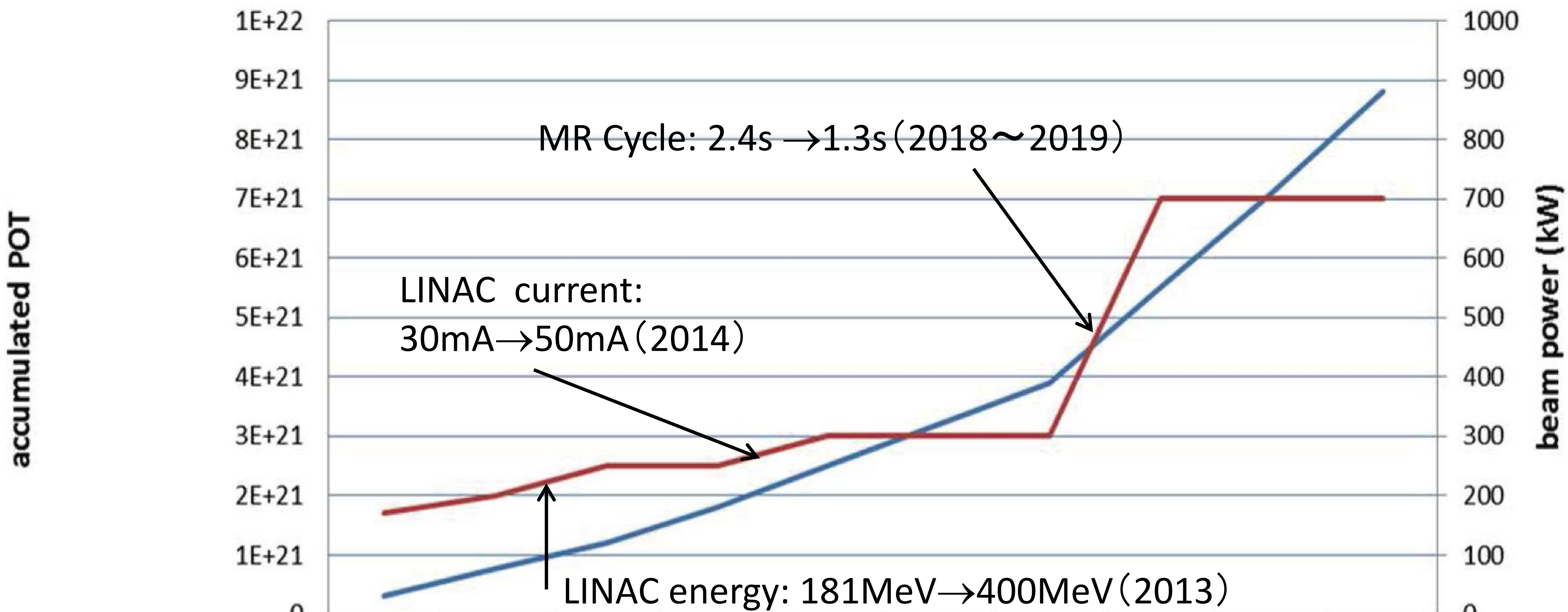
- **Stable operation at ~220kW (235kW for trial)**
  - >1.2x10^{14}ppp (1.5x10^{13}x8b) is the world record of extracted protons per pulse for synchrotrons.
- **Accumulated *pot* : 6.63x10^{20} by May.8 (6.39x10^{20}pot by Apr.12).**
- **Accumulated # pulses : 1.2x10^{7}, original horns/target**

Mid-term plan of Main Ring

JFY		2011	2012	2013	2014	2015	2016	2017
				400MeV Linac	IS/RFQ			
Beam Power(FX)[kW]		150	200	240	250~400			750
	rep. rate	3.04 s	2.56 s	2.48 s	2.40s	2.32s		1.3 s
	New PS			R&D		construction/Test		
	RF Cavity	#7,8	#9					
	High Grad. Cav.		R&D		Production, Construction, Test			
	Collimator	addition sheild	collimator (2kW)	collimator(3.5kW)				
	Inj. & FX	New Inj. Kickers		Kicker PS rework/ New Septum construction				
Beam Power(SX) :[kW]		3	10	25	25~50			100
	Collimator/ Shielding	SX Collimator		septa Power supplies				
	Replace. Equi. made of Titanium		Sept. Mg. Endplate	ES septum		Local shielding		

- **FX: rep rate: 0.4→ ~1Hz by replacing magnet PSs / RF cavities**
  - A new budget is needed for replacing MR main magnet power supplies.

Future Improvements for higher power



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
accumulated POT	3.1E+20	7.8E+20	1.2E+21	1.8E+21	2.50E+21	3.20E+21	3.90E+21	5.50E+21	7.10E+21	8.80E+21
beam power	170	200	250	250	300	300	300	700	700	700

- Original (old) planed parameters for 750kW was:
  MR cycle: 2.1s, PPP: $3.3\text{x}10^{14}$ ←Nu facility was designed
- Present expected beam parameters for 750kW will be:
  MR cycle: 1.28s, PPP: $2.0\text{x}10^{14}$→Reduce thermal shock by 60%

T2K Long Term Plan (>2018)

Scenarios for Multi-MW output beam power are being discussed:

K. Hara, H. Harada, H. Hotchi, S. Igarashi, M. Ikegami,

F. Naito, Y. Sato, M. Yamamoto, K.Tanaka, M. Tomizawa

1. Large aperture MR

Enlarging the physical aperture from 81 to > 120 πmm.mrad - a new synchrotron in the MR tunnel

2. Second booster ring for the MR (emittance damping ring)

BR with an extraction energy ~ 8 GeV, between the RCS and the MR

3. New proton linac for neutrino beam production

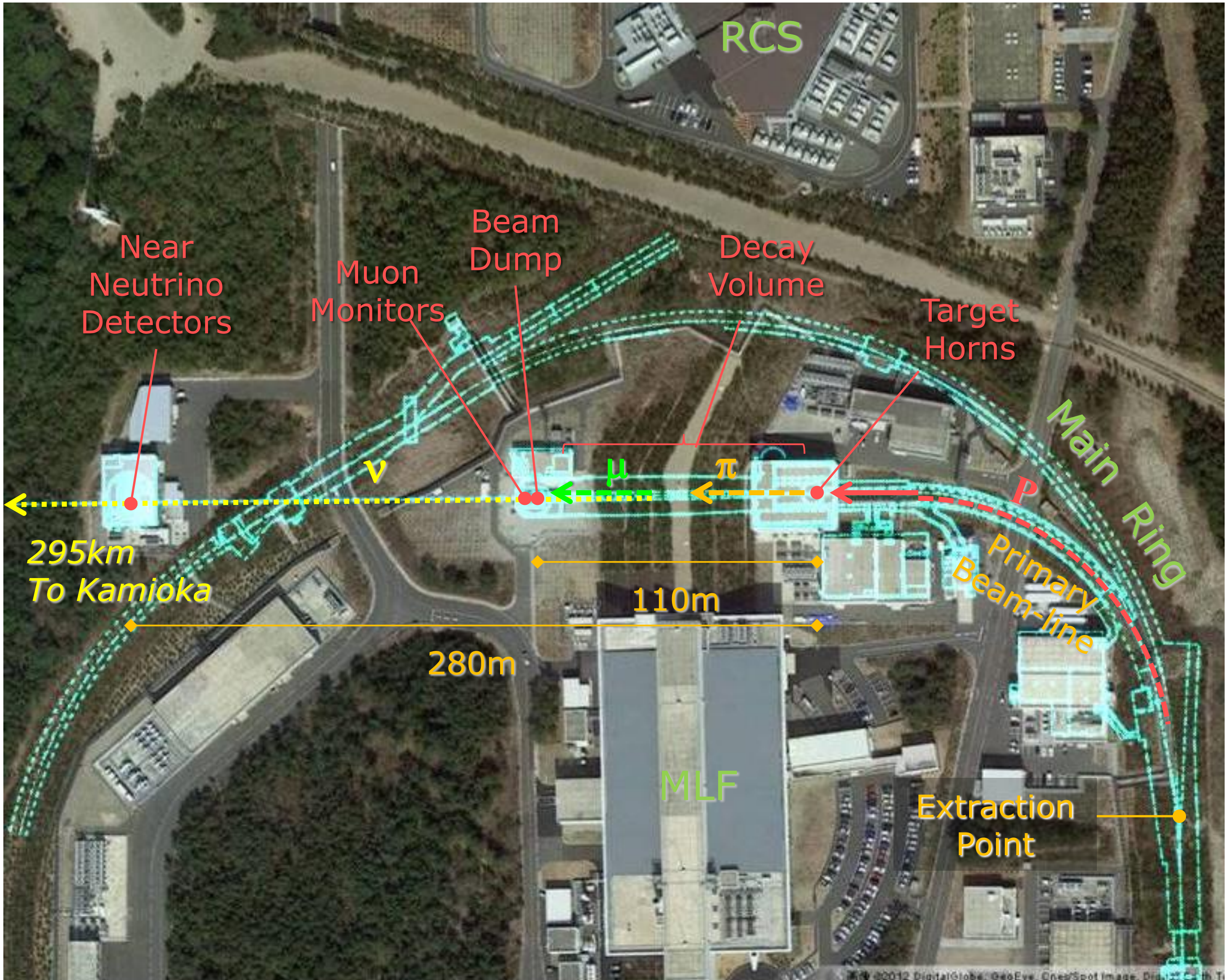
Linac with an beam energy > 9 GeV!

MR operated only for SX users

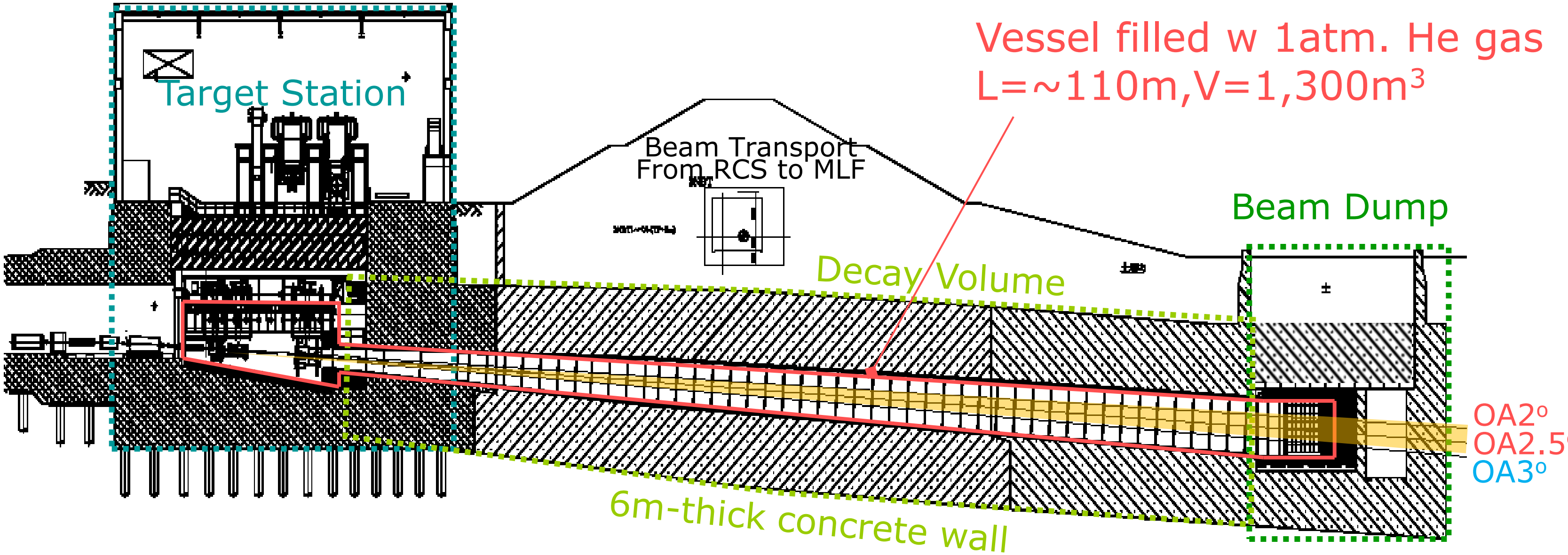
…

One idea: 8 GeV Booster/Damping Ring

The neutrino experimental facility

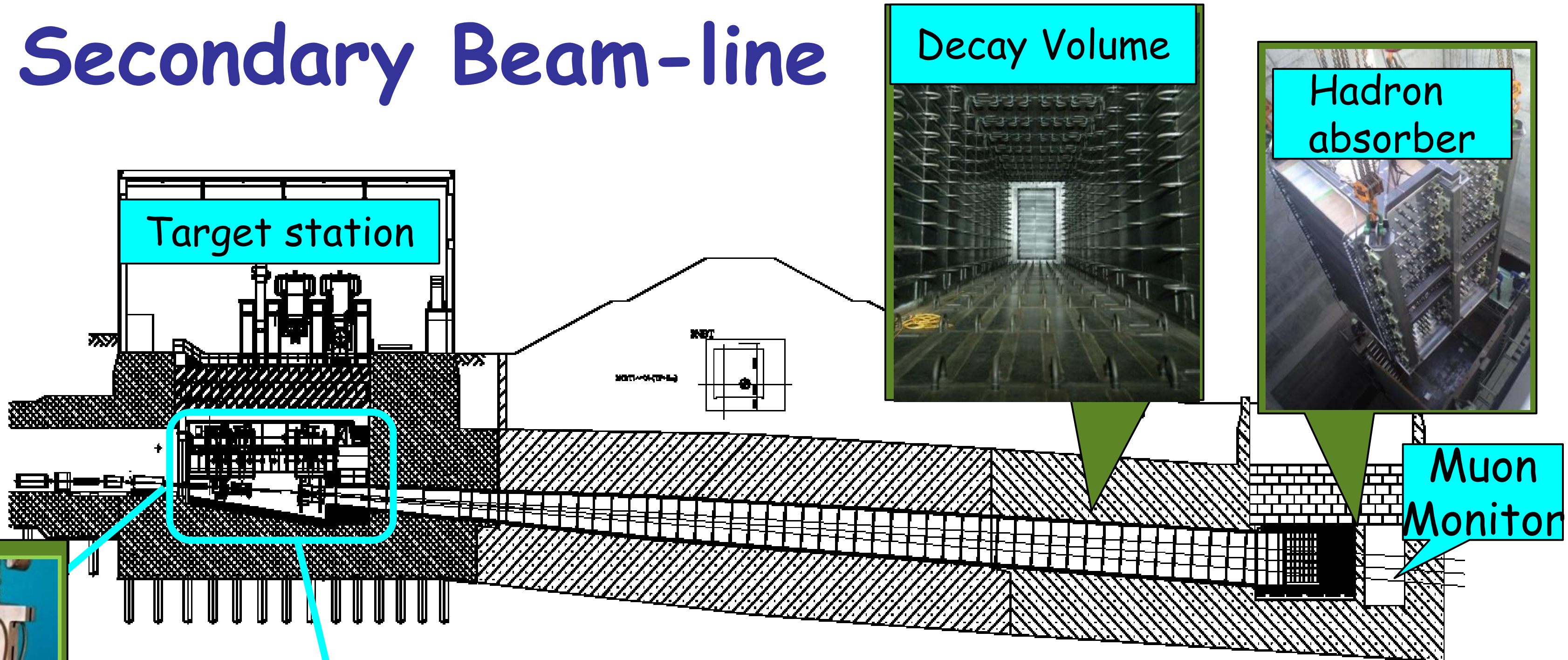


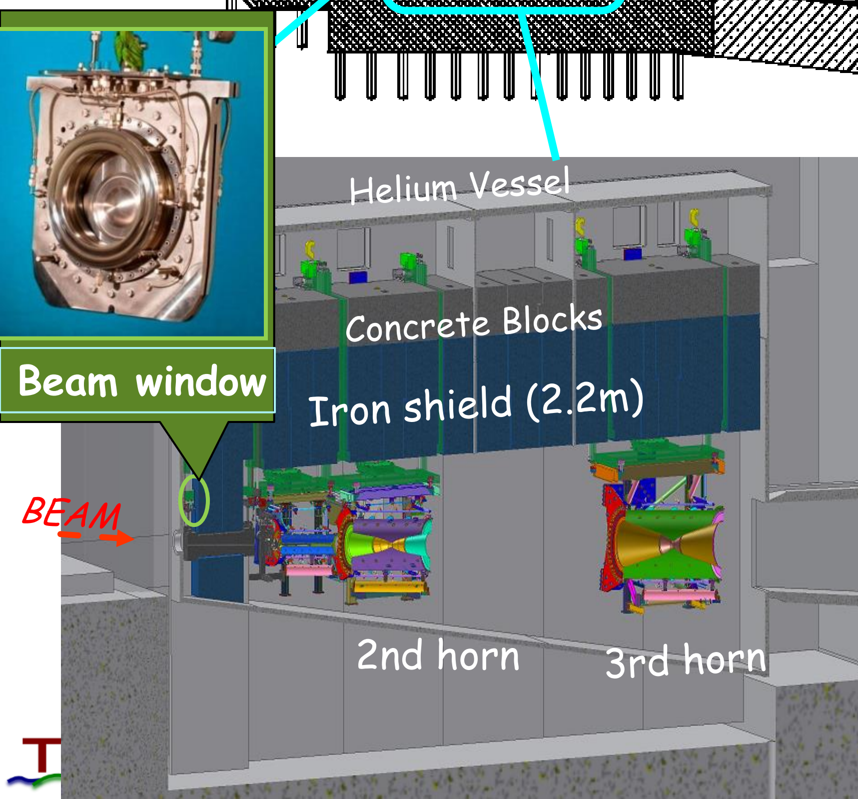
Secondary Beam-line



- Target Station(TS), Decay Volume(DV), & Beam Dump(BD)
  - TS: He-cooled graphite target, 3 magnetic horns, remote maintenance
  - DV: 94m-long tunnel with rectangular cross section
  - BD: hadron absorber made of large graphite blocks, surrounding iron shields
- Enclosed in large water-cooled steel helium vessel.
  - He atmosphere prevents nitrogen oxide (NO_x) production / oxidization of apparatus.
- Iron plates of the vessel are cooled by water circuits.
  - Maintenance is not possible after beam operation due to activation.
  - Radiation shielding / cooling capacity were designed for ~4MW beam.

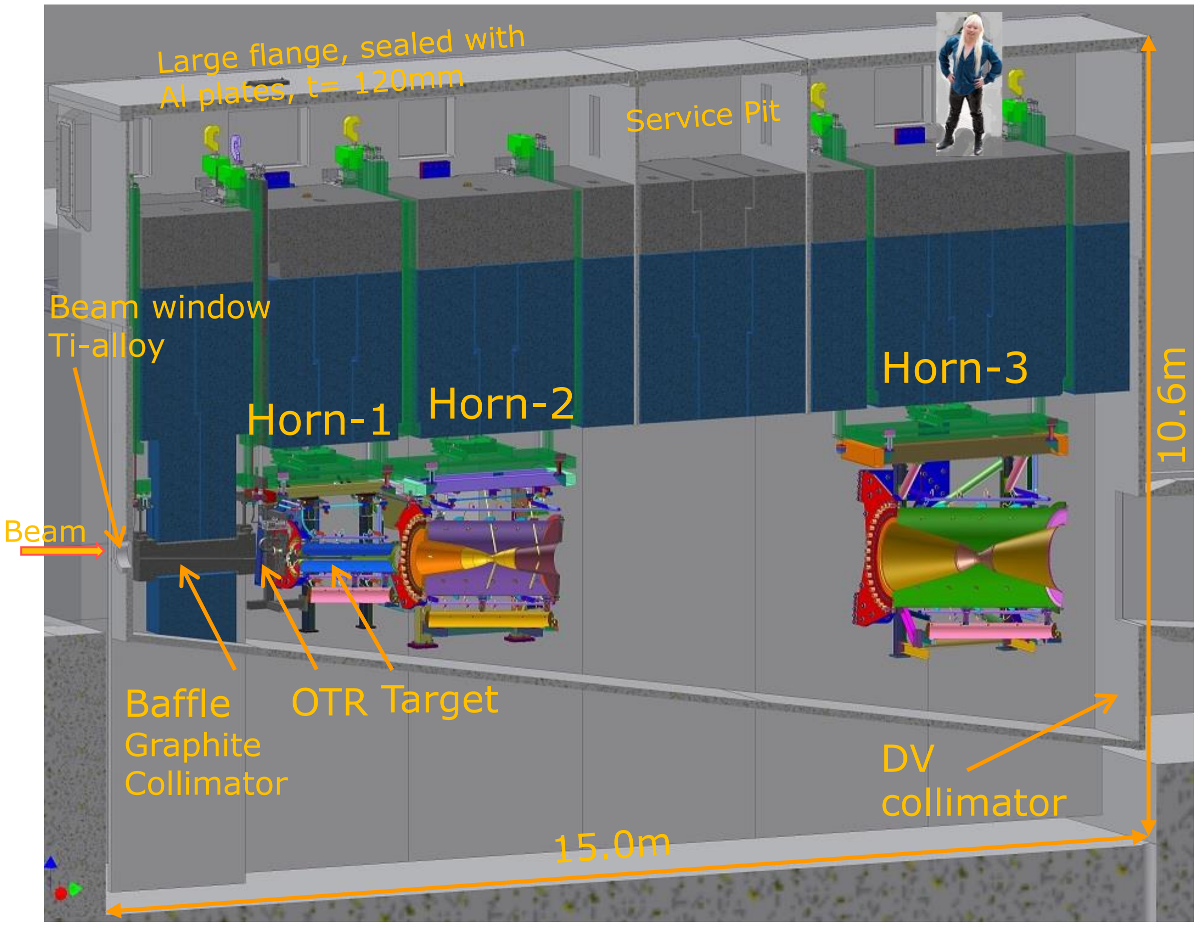
T2K Secondary Beam-line

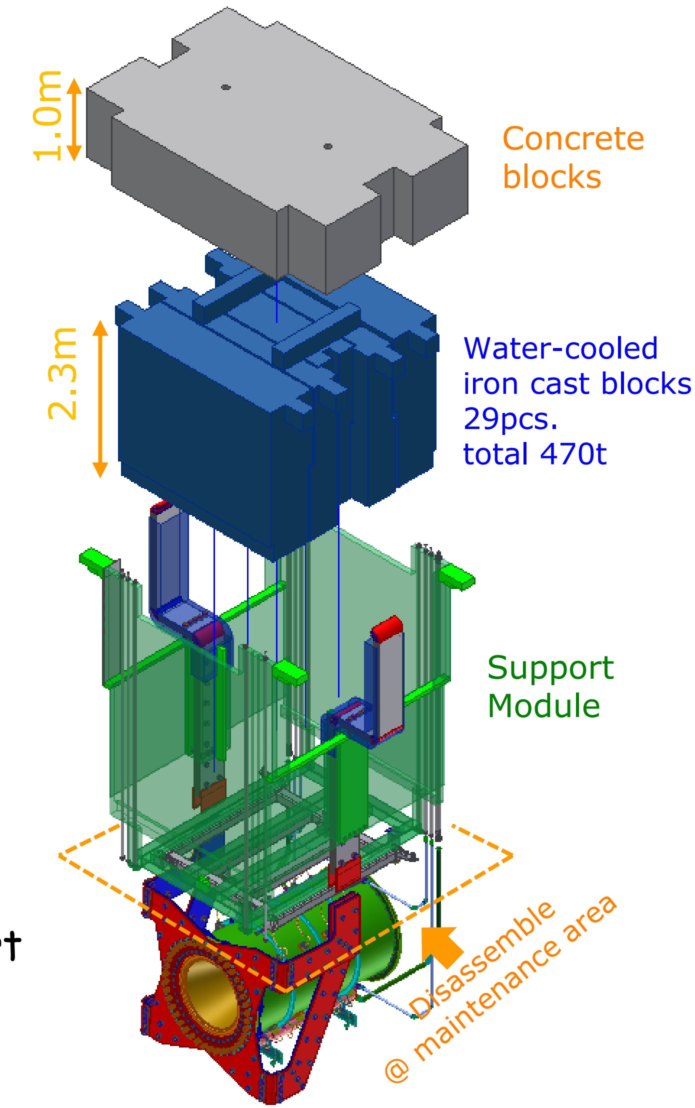




Most components in secondary beamline would need to be upgraded for MW operation:
beam window, target, horns
- NB activated air & water handling

Target Station (TS)





- Horns / a baffle are supported within vessel by support modules.
- Apparatus on the beam-line are highly irradiated after beam. Remote maintenance required.

Horn Problems/Limitations

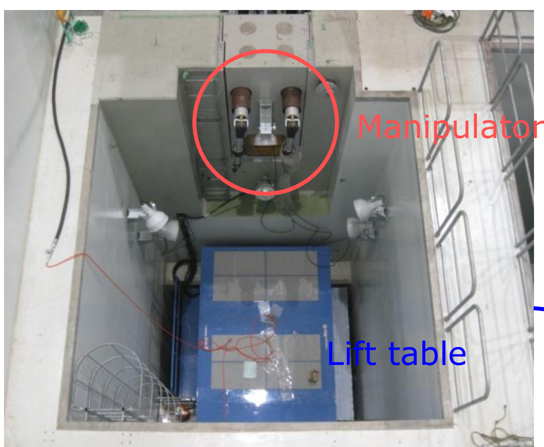
- Issues operating horns in a high power beam:
    - Cooling to survive a large heat deposit.
    - Mechanical strength for a high current (~300kA)
    - Fatigue due to cyclic stress (10^8).
  - These issues are a major consideration, but…
  - **Real problems in a high power beam result from**
    - Radioactivation:
      - Treatment of radioactive waste (tritium and ^{7}Be, etc).
      - No more manual maintenance → **Remote maintenance needed**.
    - **Hydrogen production by a water radiolysis** ($2H_2O \rightarrow 2H_2 + O_2$)
    - NO_x production in case of air environment.
      - Acidification of water.

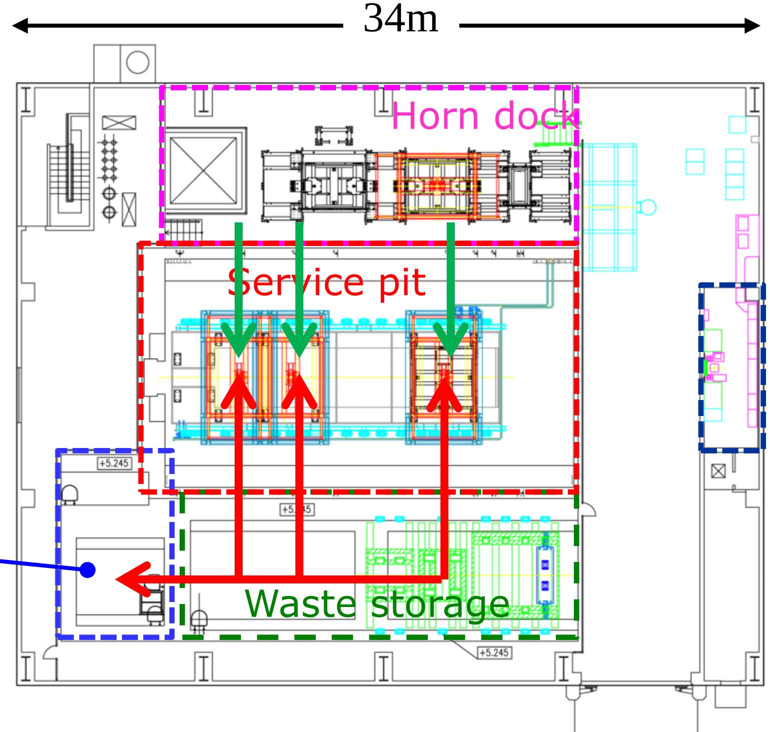
T2K

Replacement of all horns
2013 shutdown – Apr. 2014

- H_2 production by water radiolysis H_2 density after 1 week of 220kW beam: **1.6%** (near horn)
  - Need to two ports to circulate gas flow in horns
- Small water leak (5~10L/day) since autumn 2012
  - More leak with beam
    - *all horns + target replaced with spares*

Maintenance area



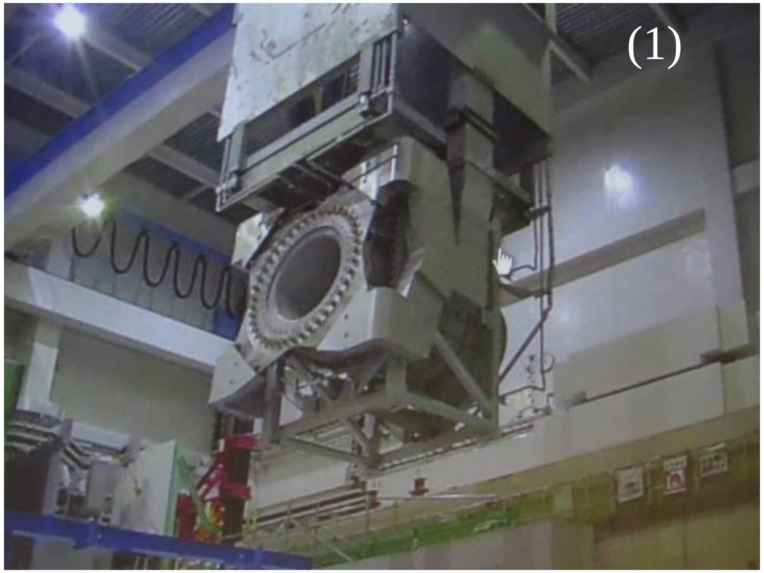


Control room

All processes managed remotely at control room

T2K

Remote replacement of horns

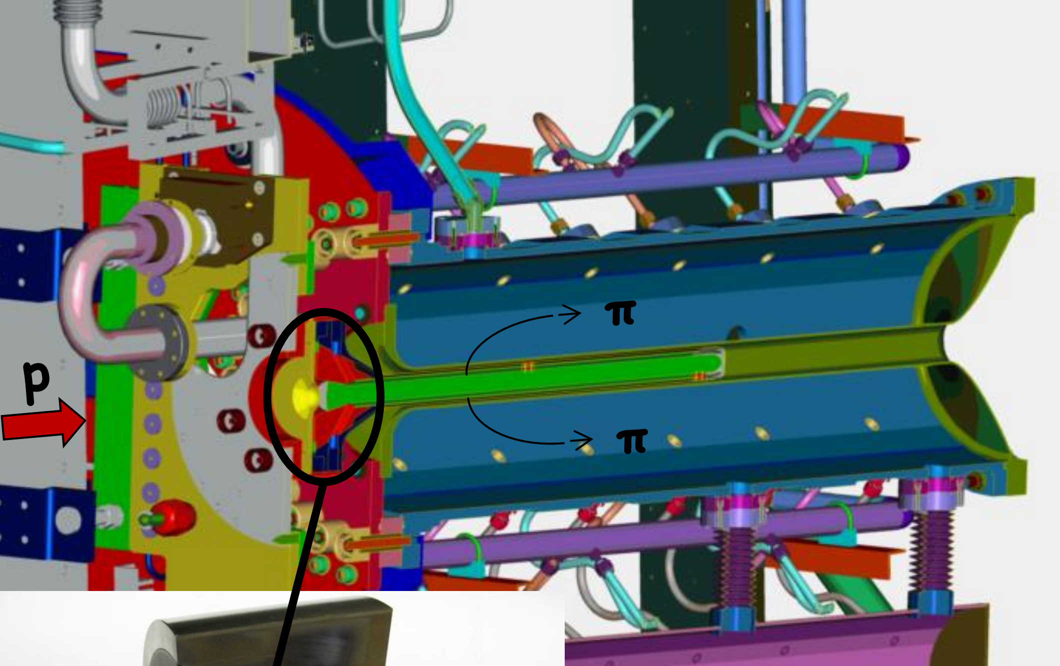


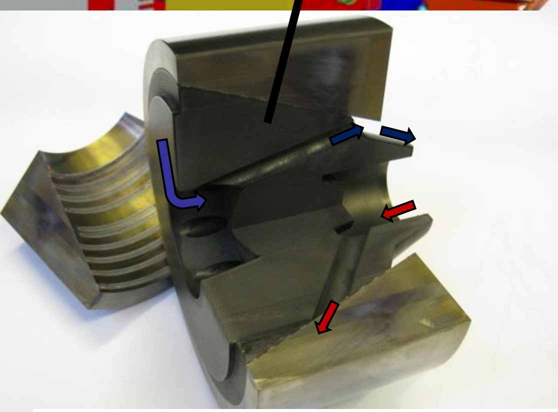
- Work started with horn-3, as less radio-active.

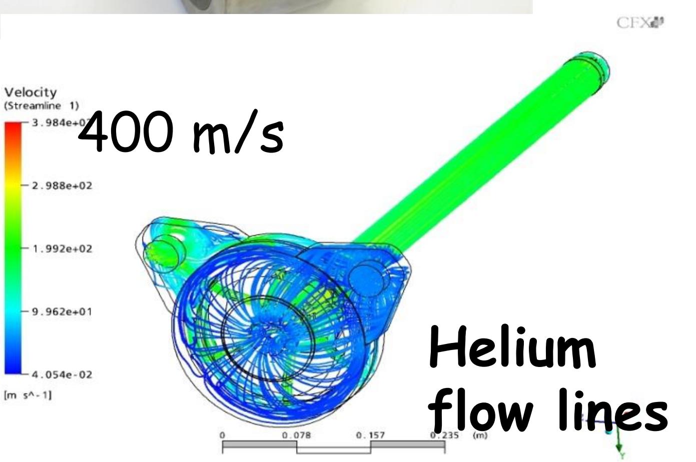
(1)Take out old horn (Nov.26)
(2) insert new horn (Nov.29)
(3) old horn to casket (Dec.10)

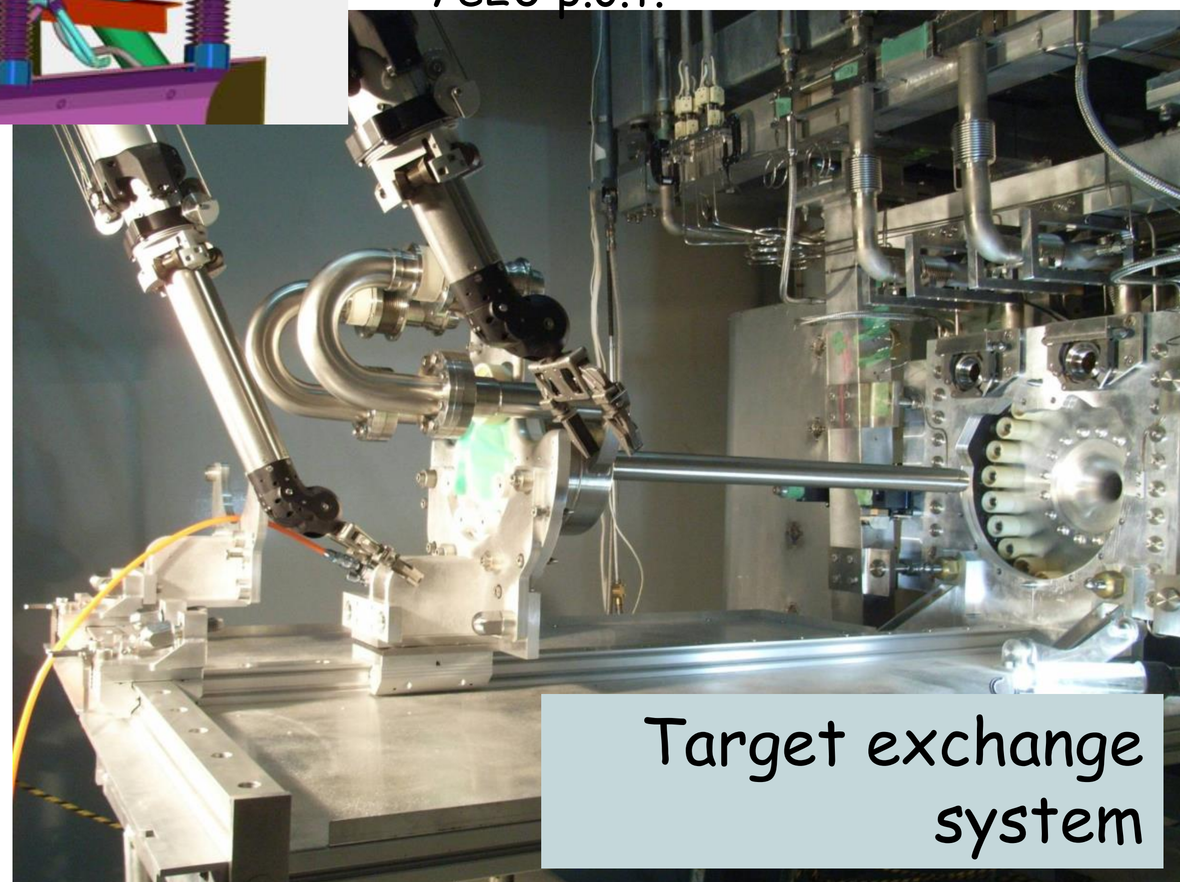
T2K Target & horn

- Helium cooled graphite rod
- Design beam power: 750 kW
  (heat load in target c.25 kW)
- Beam power so far: 230 kW
- 1st target & horn currently now replaced after 4 years operation, 7e20 p.o.t.





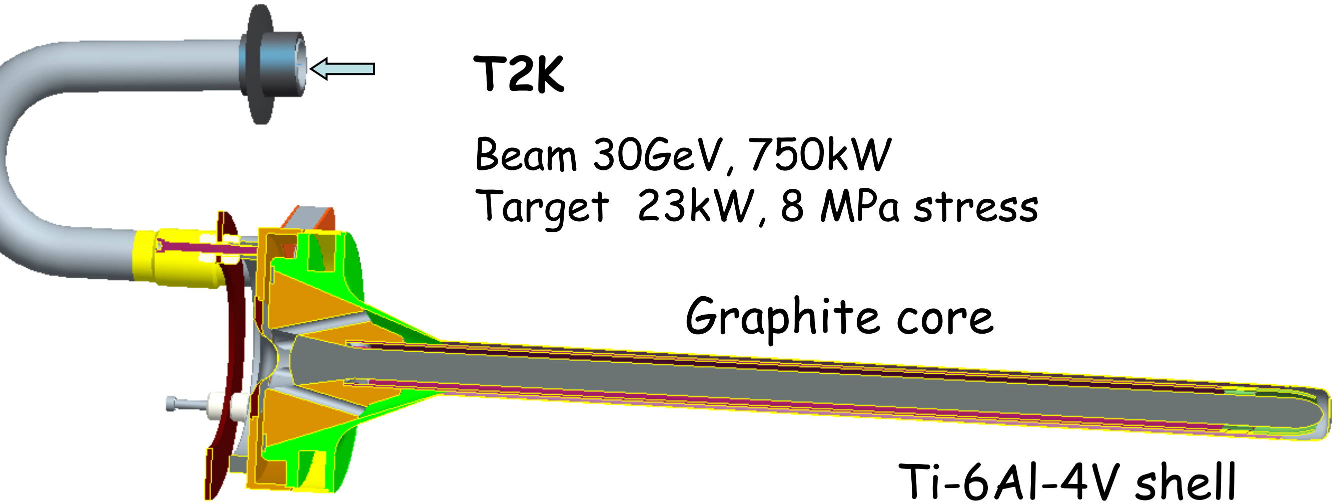




Secondary beam component limitations for >1MW operation

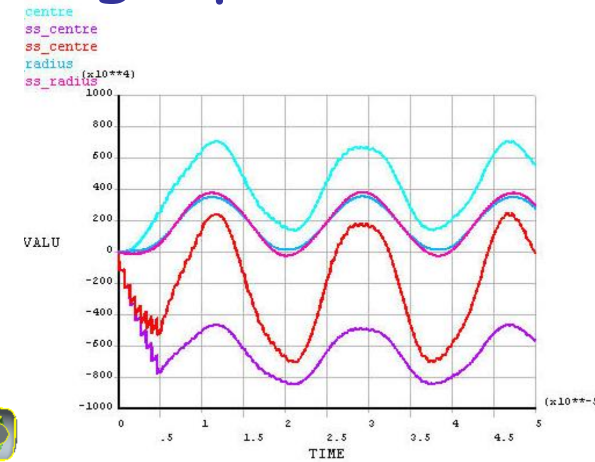
- Beam windows (target station and target)
  - Radiation damage & embrittlement of Ti6Al4V alloy
  - Stress waves from bunch structure
  - Is beryllium a better candidate?
- Target
  - Radiation damage of graphite
    - Reduction in thermal conductivity, swelling etc
  - Structural integrity & dimensional stability
  - Heat transfer
  - High helium volumetric flow rate (and high pressure or high pressure drops)
- 1st Horn – 1.85 MW beam power estimated limit
- OTR, beam monitors
- Target station emission limitations

Current target – helium cooled solid graphite rod



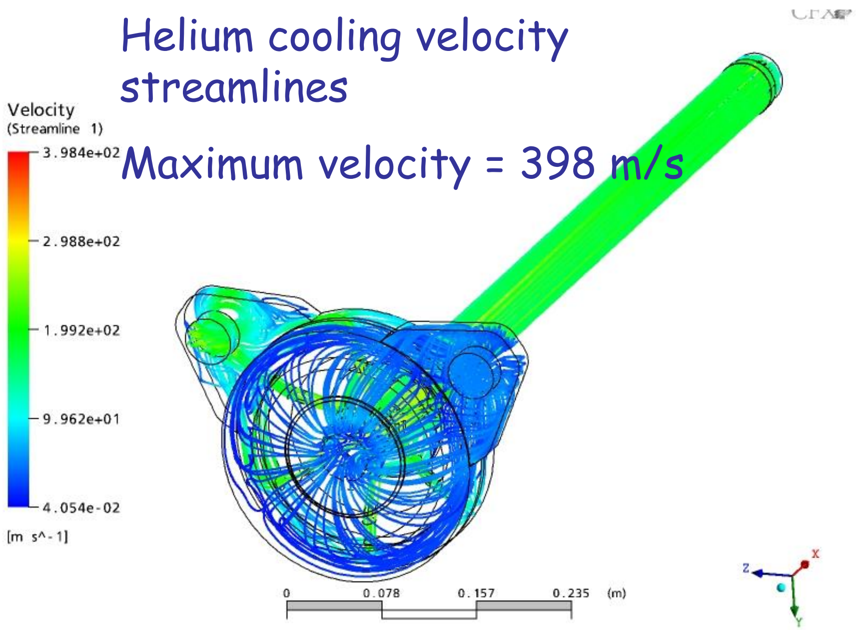
T2K

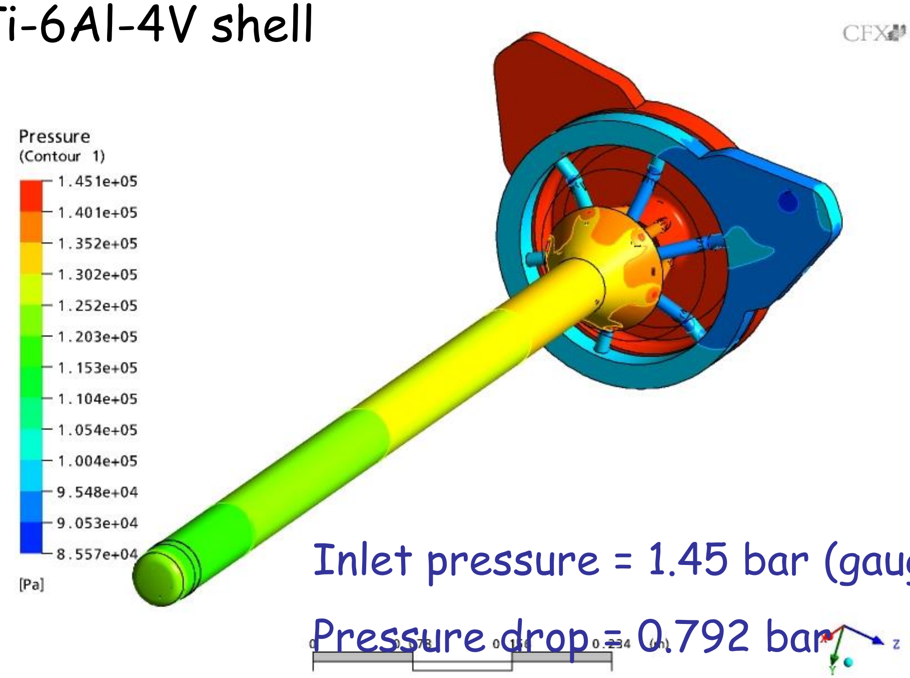
Beam 30GeV, 750kW
Target 23kW, 8 MPa stress



Helium cooling velocity streamlines

Maximum velocity = 398 m/s





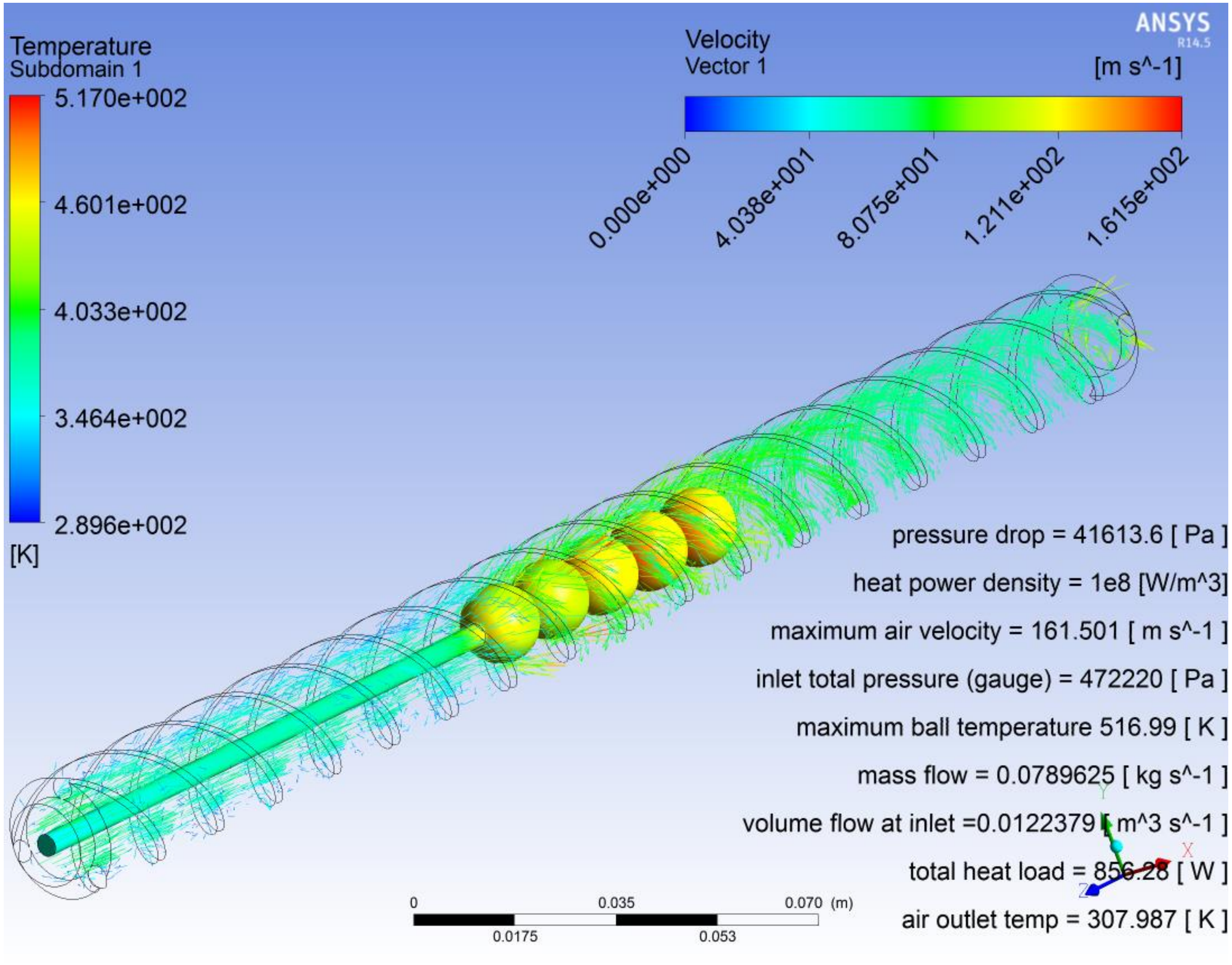
Inlet pressure = 1.45 bar (gauge)

Pressure drop = 0.792 bar

Plan: Investigate higher pressure helium for higher powers

T2K

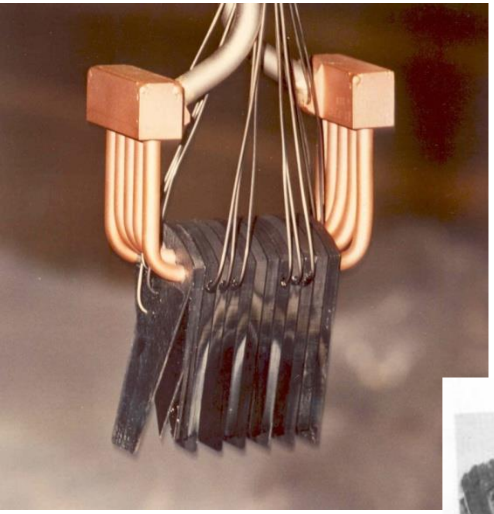
Possible target design concept for higher power operation



Helical helium flow around spherical target material

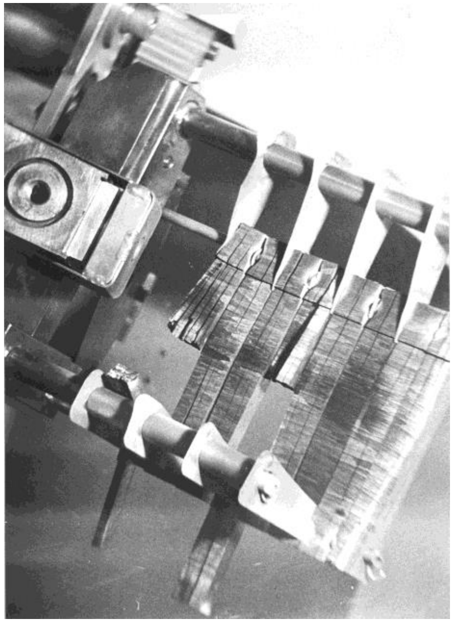
Ashes to ashes, dust to dust...

The ultimate destiny for all graphite targets (T2K c.10^{21} p/cm^2 so far)

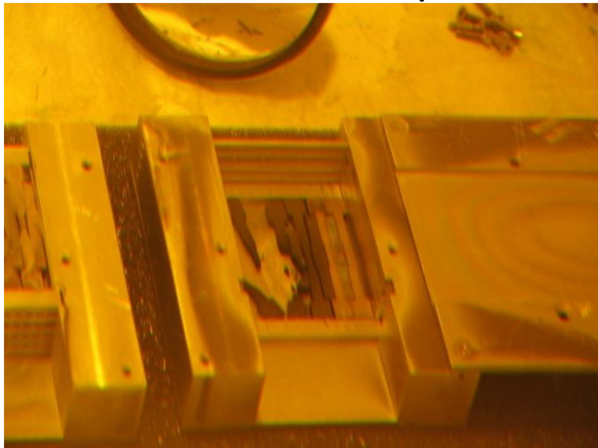


LAMPF fluence 10^22 p/cm2

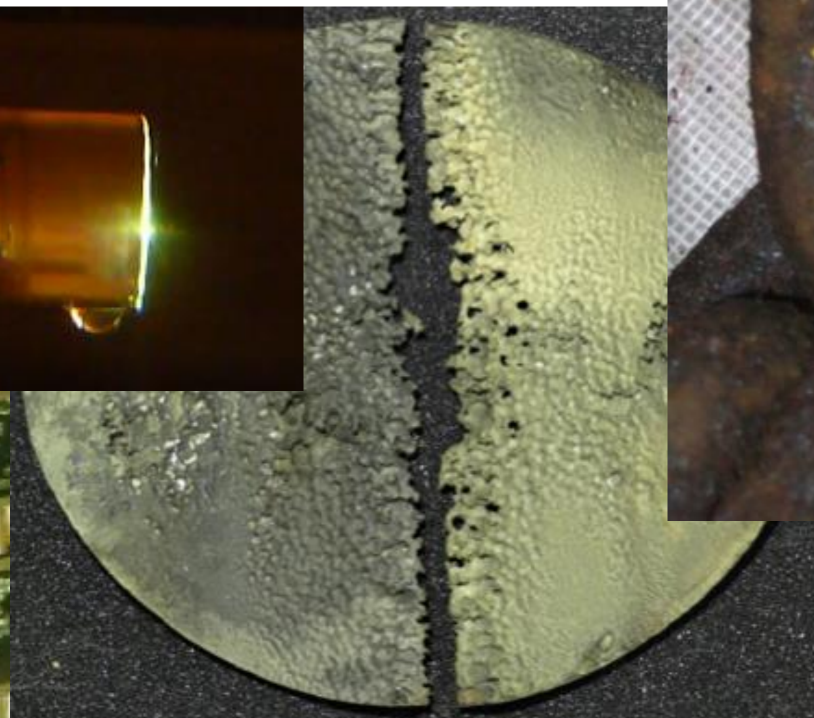
PSI fluence 10^22 p/cm2

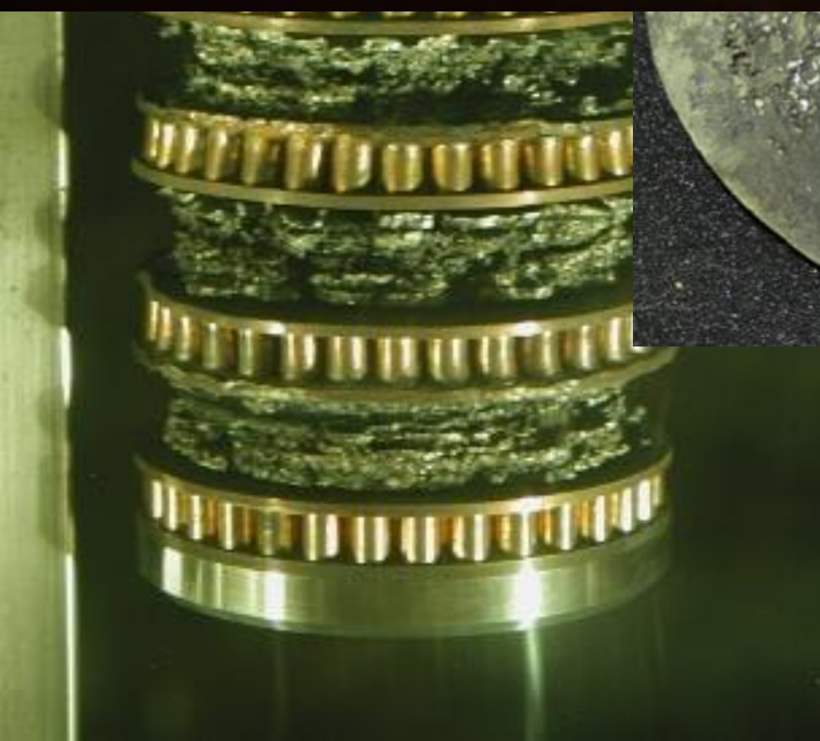


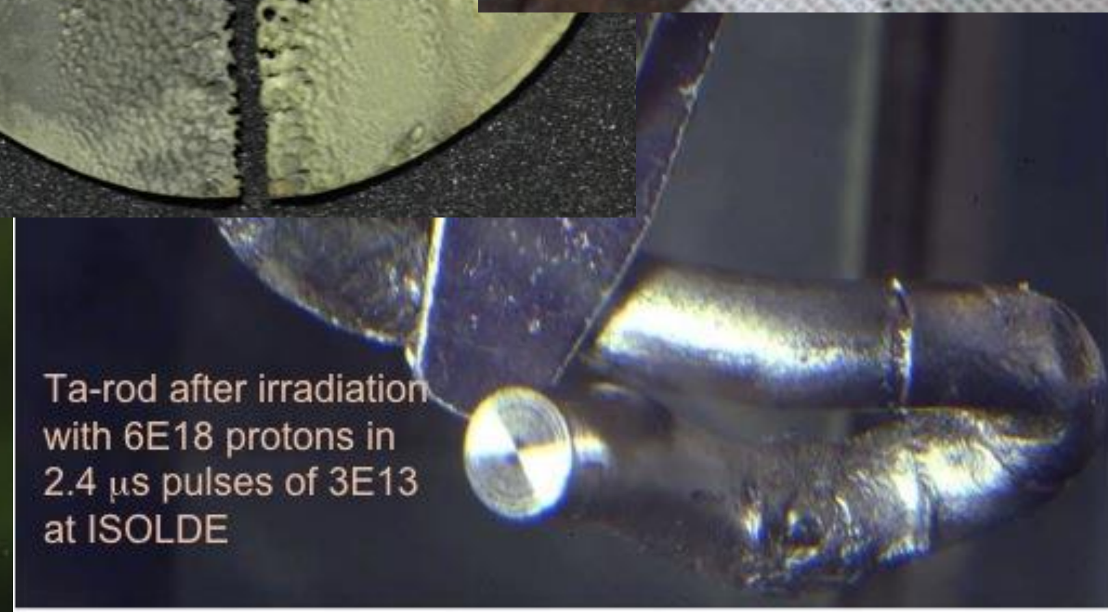
BNL tests (in water): fluence ~10^21 p/cm2



Interaction of proton beams with metals

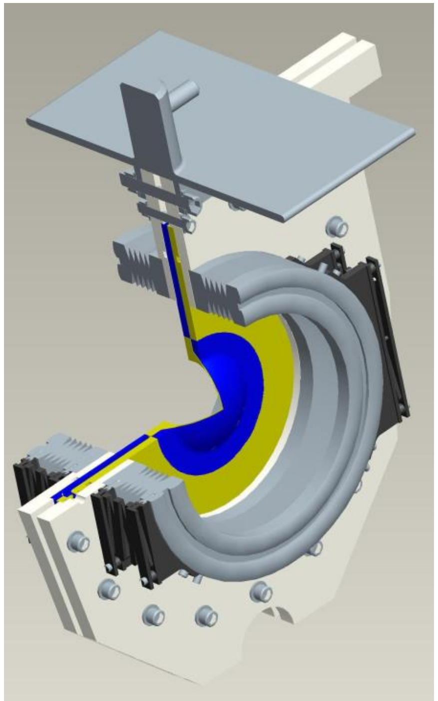


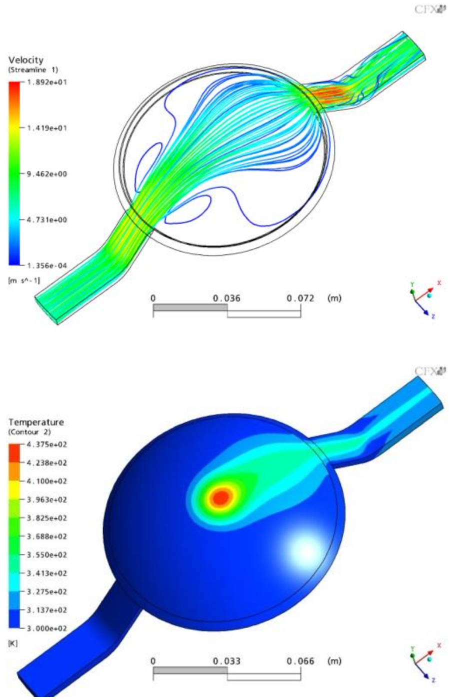


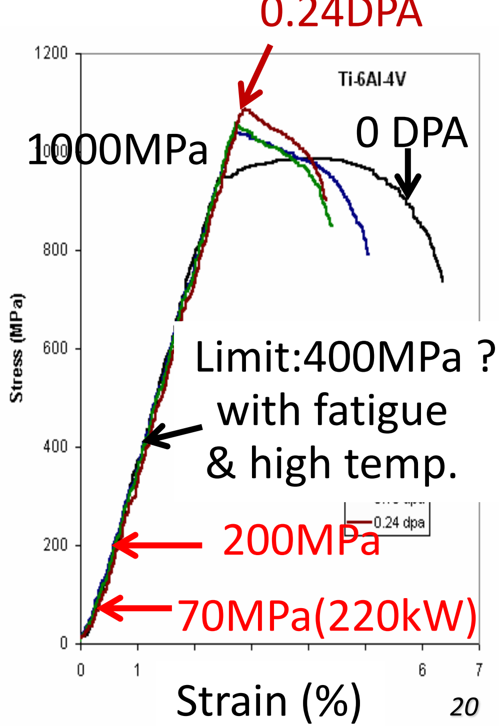


Beam Window

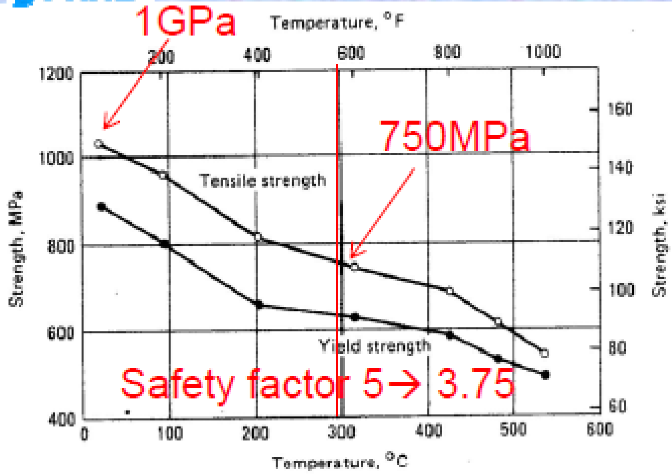
- Separates He vessel from vacuum in primary line with pillow seals
- Double skin of 0.3mm thick Ti-6Al-4V, cooled by He gas (0.8g/s)
- 300°C/200MPa, Safety factor 2 for 750kW($3.3x10^{14}$)
  ~ Safer for 750kW($2.0x10^{14}$)
- Reduction of Ductility reported with 0.24DPA
  $6x10^{20}$pot≈1DPA?: Replacement cycle should be considered.
- Same window in front of Target, Same material with OTR, SSEM

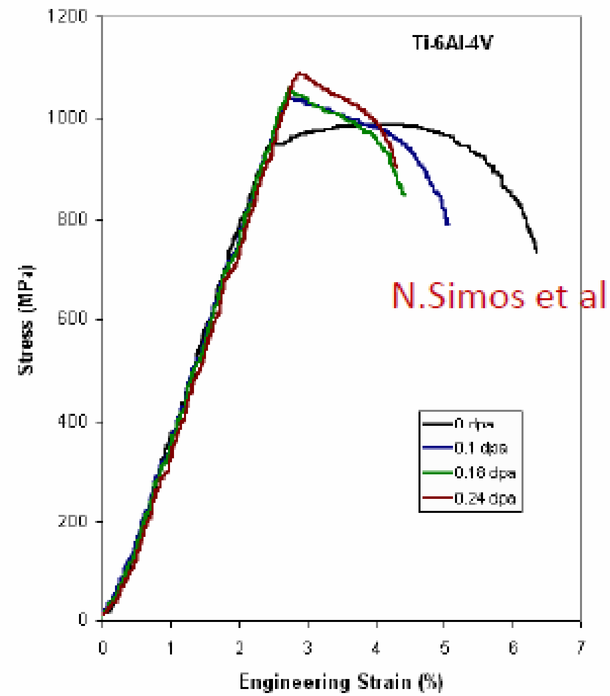


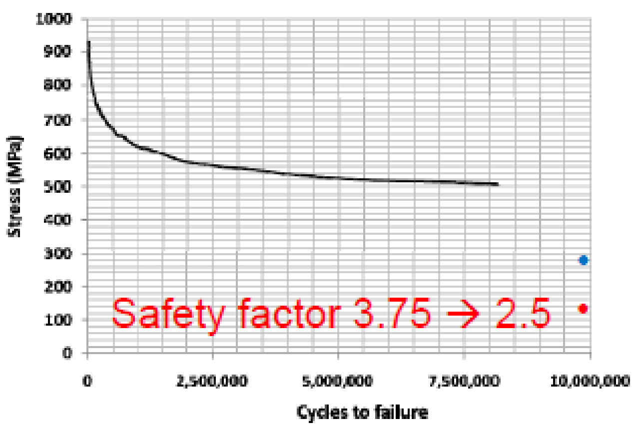




Strength of Ti-6Al-4V





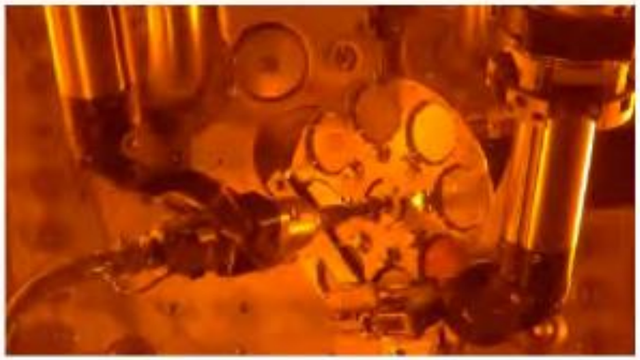


Reduction of Ductility was reported with 0.1~0.24DPA

T2K after Run-4: 6×10^{20}pot≈1DPA(?)

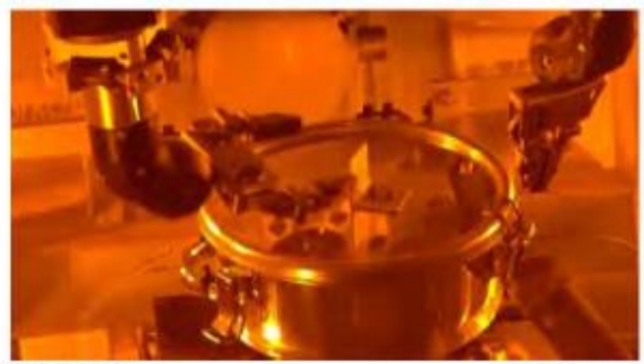
This could increase the effect of transient stress waves by making the material more susceptible to crack propagation, thus increasing the likelihood of fatigue failure. Therefore, an assessment of the effect of radiation on this alloy must be the key factor in determining the operational lifetime of a Ti-6Al-4V beam window.

OTR 1 Disk Removal



- OTR 1 disk was removed from 1st horn on March 24th by Tada-san and his crew, using the TRIUMF remote manipulator arms

- Stored in container so irradiated Ti foils can be mechanically tested (beam window is the same Ti alloy)



17 April 2014 T2K Collaboration Meeting 10

- ~5mSv/h out of pan
- On-contact: a few Sv/h (Φ~4mm) (?)

RaDIATE Collaboration

Radiation **D**amage **I**n **A**ccelerator **T**arget **E**nvironments

Collaboration on accelerator target materials as part of **P**roton **A**ccelerators for **S**cience & **I**nnovation (PASI) initiative.

http://www-radiate.fnal.gov/index.html

Key objectives:

- Introduce materials scientists with expertise in radiation damage to accelerator targets community
- Apply expertise to target and beam window issues
- Co-ordinate in-beam experiments and post-irradiation examination

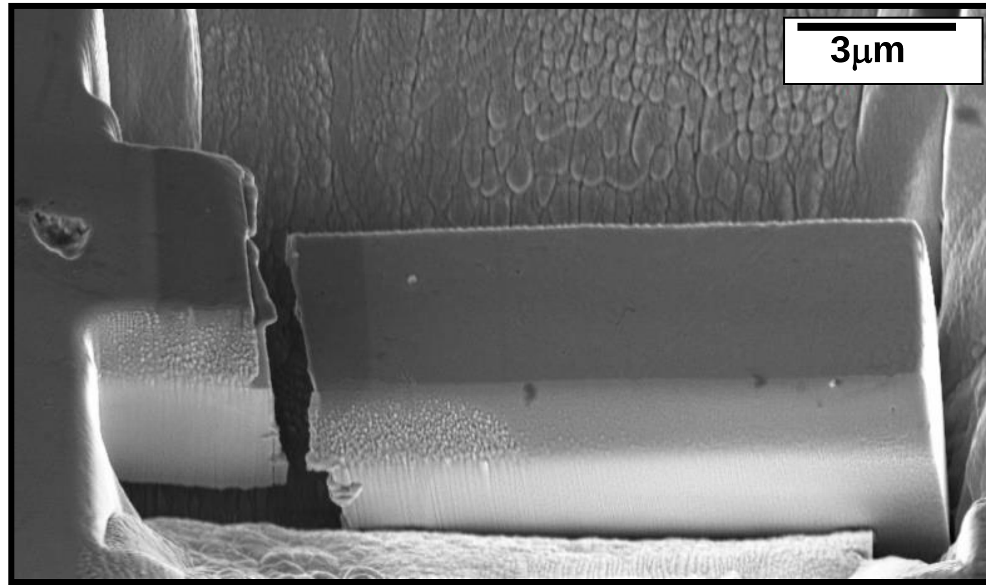
MoU signed by 5 US/UK institutes – Fermilab, BNL, PNNL, RAL, Oxford Materials Department

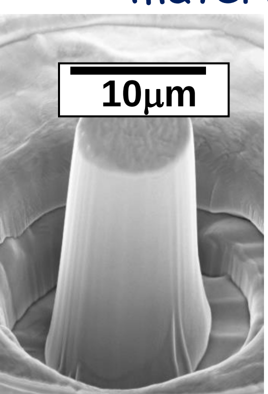
New Post-doc recruited at Oxford to study beryllium – good beam window candidate for T2K

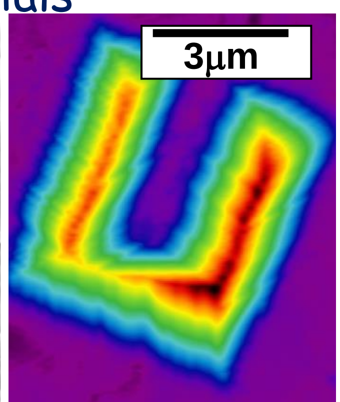
Working groups on graphite, beryllium, tungsten, new collaboration on Ti alloys (KEK, MSU, Fermilab, RAL)

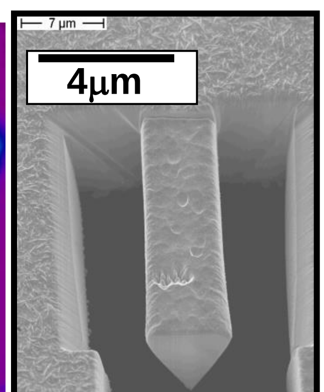
Micro-mechanical testing

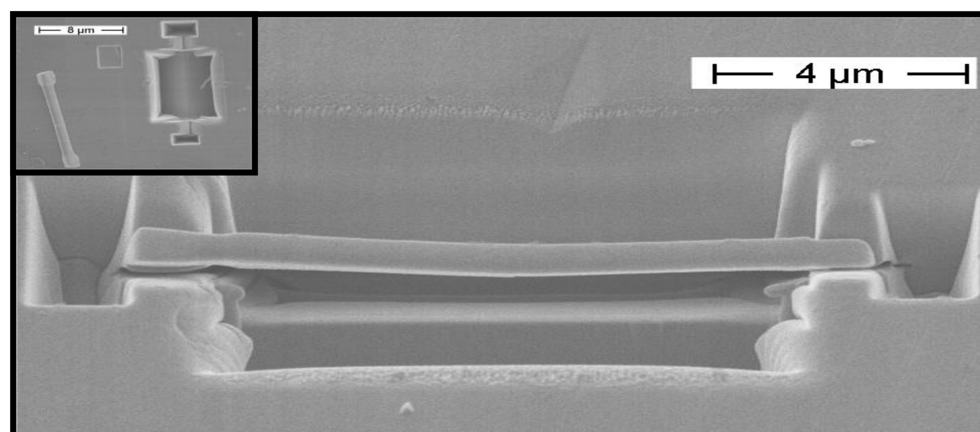
- Unique materials expertise at Oxford (MFFP Group)
- Micro-cantilevers machined by Focused Ion Beams
- Compression tests
- Tension tests
- Three Point Bend
- Cantilever bending
- New facility NNUF (National Nuclear User Facility) under construction at Culham to carry out such testing of small quantities highly active materials



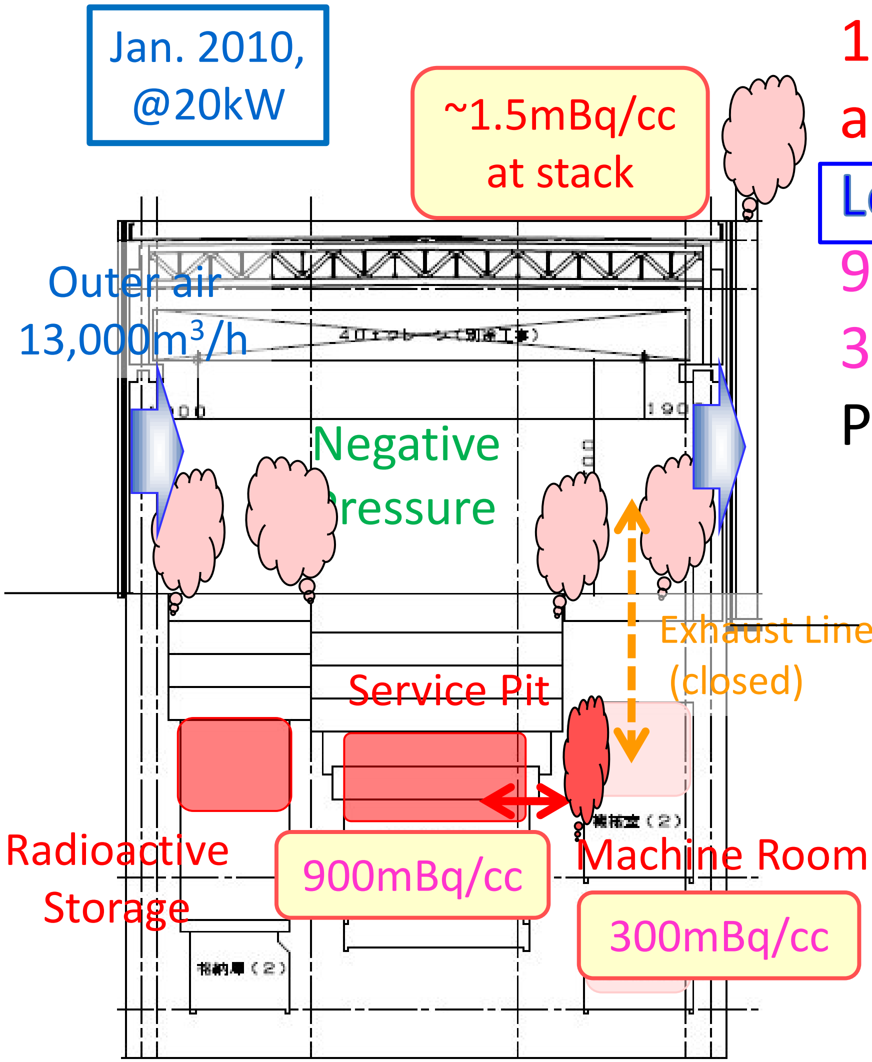








Radioactivity of exhausted air



1.5mBq/cc ^{41}Ar was observed at TS stack and beam time was restricted.

Legal limit : 0.5mBq/cc in 3-month ave.

900mBq/cc at Service pit,

300mBq/cc at machine room

Possible sources:

- Gap between concrete blocks
- Cable penetration part between
  - 1st floor and machine room
  - Service pit and machine room
- Closed dumper for underground exhaust
- Door to machine room

Improvement of acceptable power

	Radioactivity in exhaust (<0.5mBq/cc)	Acceptable power
2010 Jan. ~ Feb.	1.5mBq/cc (20kW)	7kW
* Fill resin into gap of concrete blocks and cable penetration part		
2010 Feb. ~ Mar.	0.5(20kW)→0.8(27kW)	17kW
* Water-tight sheets over concrete blocks, air-tight dumpers		
2010 Jun.	0.15(50kW)	170kW
* Maintenance, Air-tight door for stairway room, water-tight sheet at service pit ceil		
2010 Nov. ~ 2011 Feb.	0.28(105)→0.4(125kW)	160kW
* Second layer of water-tight sheet on concrete blocks		
2011 Mar.	0.3(145kW)	240kW
* Earthquake, Maintenance, Bypass of ventilation		
2012 Mar. ~ Apr.	0.13(145)→0.16(176kW)	550kW
* Seamless Air-tight sheet over concrete blocks		
2012 May. ~ Jun.	0.1(190kW)	950kW
* Maintenance, Remove water-tight sheet at service pit ceil		
2012 Nov. ~ 2013 Apr.	0.3(230kW)	400kW

Secondary beam component limitations for >1MW operation

- Beam windows (target station and target)
  - Radiation damage & embrittlement of Ti6Al4V alloy
  - Stress waves from bunch structure
  - Is beryllium a better candidate?
- Target
  - Radiation damage of graphite
    - Reduction in thermal conductivity, swelling etc
    - Try beryllium?
  - Structural integrity & dimensional stability
  - Heat transfer
  - High helium volumetric flow rate (and high pressure or high pressure drops)
- 1st Horn
- Target station emission limitations

Target & Beam Window Programme Topics

- Collaboration between experts regarding:
  - Physics performance
  - Engineering performance
  - Materials performance
- Engineering studies
- Materials – Radiation damage studies
  - DPA/He/H2 calculations
  - Cross-referencing with literature data
  - Devise suitable experiments with irradiation and Post Irradiation Examination (PIE)
- Prototyping
- Heating/cooling tests

Study limits of existing & new target designs

- How far can existing T2K design be pushed?
  - High pressure helium flow may push current design beyond 1 MW operation
  - But for how long? Graphite radiation damage issues
  - Need to consider new designs & materials (beryllium?)
  - Thermal-hydraulic/CFD simulations:
    - Higher pressure helium -> higher power operation
    - But: higher stresses in window & target
  - Off-line heating/cooling/stress experiments
  - On-line experiment (Be window on HiRadMat, CERN)

Summary of T2K beam status

- Successful beam for user operation:
  - 235kW max. so far for the T2K experiment
- To increase #p/bunch
  - MR collimator capability 3.5kW
  - LINAC energy upgrade to 400MeV, frontend upgrade to be in 2014
- MR 750kW operation → doubled rep rate, maybe 1 Hz possible
  - R&D for MR magnet power supplies well in progress
  - Higher gradient RF core to be ready for installation in 2015
- Neutrino beam-line
  - No critical problems for essential components so far.
  - All 3 horns/target. replaced
  - Replacement of Horn-3 completed, radiation well under control.
- Upgrade of Neutrino beam-line
  - Doubled rep.rate: less thermal shock for target / beam window.
  - Horn: triple PS operation is necessary for 1 Hz (320kA) operation.
  - New facility buildings are needed with larger DP tanks
  - Worth to start discussion / investigation ASAP to make concrete upgrade plan. Contribution from international community is highly appreciated (from KEK side)