HK Secondary Beam Issues

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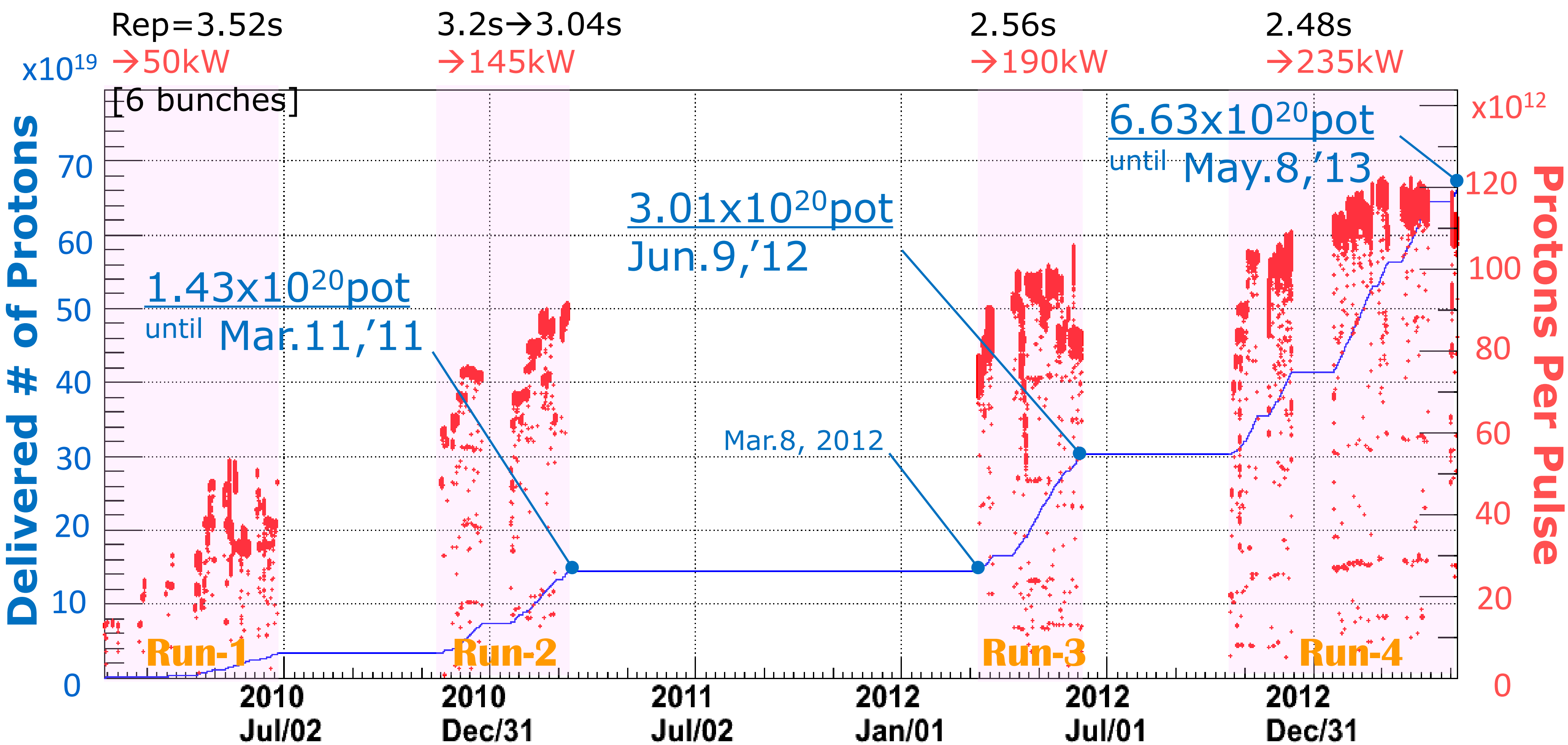
STFC Rutherford Appleton Laboratory

T2K Operation History



Total # of pulses 2.2×10^6 4.7×10^6 7.7×10^6 1.2×10^7

Existing target & horns used from 2009. → **1.2×10^7 pulses**

Mid-term plan of MR for the next five years

FX : We adopt the high repetition rate scheme to achieve the design beam intensity, 750 kW. Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's and RF cavities.
SX : After replacement of some SUS ducts to Ti ducts to reduce residual radiation dose, 50 kW operation for users will be started. Beam power will be gradually increased toward 100 kW carefully watching the residual activity. Local shields will also be installed if necessary.

JFY	2011	2012	2013	2014	2015	2016	2017
			Li. upgrade				
FX power [kW] **SX power : User op. (study) [kW]**	**150** **3 (10)**	**200** **10 (50)**	**300** **<50**	**400** **50 (100)** →			**750** **100**
Cycle time of main magnet PS **New magnet PS for high rep.**	**3.04 s**	**2.56 s** R&D →	**2.4 s**	→	Manufacture installation/test →		**1.3 s**
Present RF system **New high gradient rf system**	Install. #7,8	Install. #9 R&D →	→		Manufacture installation/test →		
Ring collimators	Additional shields	Add.collimators and shields (2kW)	Add.collimators (3.5kW)				
Injection system **FX system**	New injection kicker	Kicker PS improvement、Septum 2 manufacture /test → LF septum, PS for HF septa manufacture /test →					
SX collimator / Local shields	SX collimator				Local sheilds →		
Ti ducts for SX devices		Septum endplate	ESS				

T2K Long Term Plan (~2018)

Scenarios for Multi-MW output beam power are being discussed (unofficially and quietly!) :

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

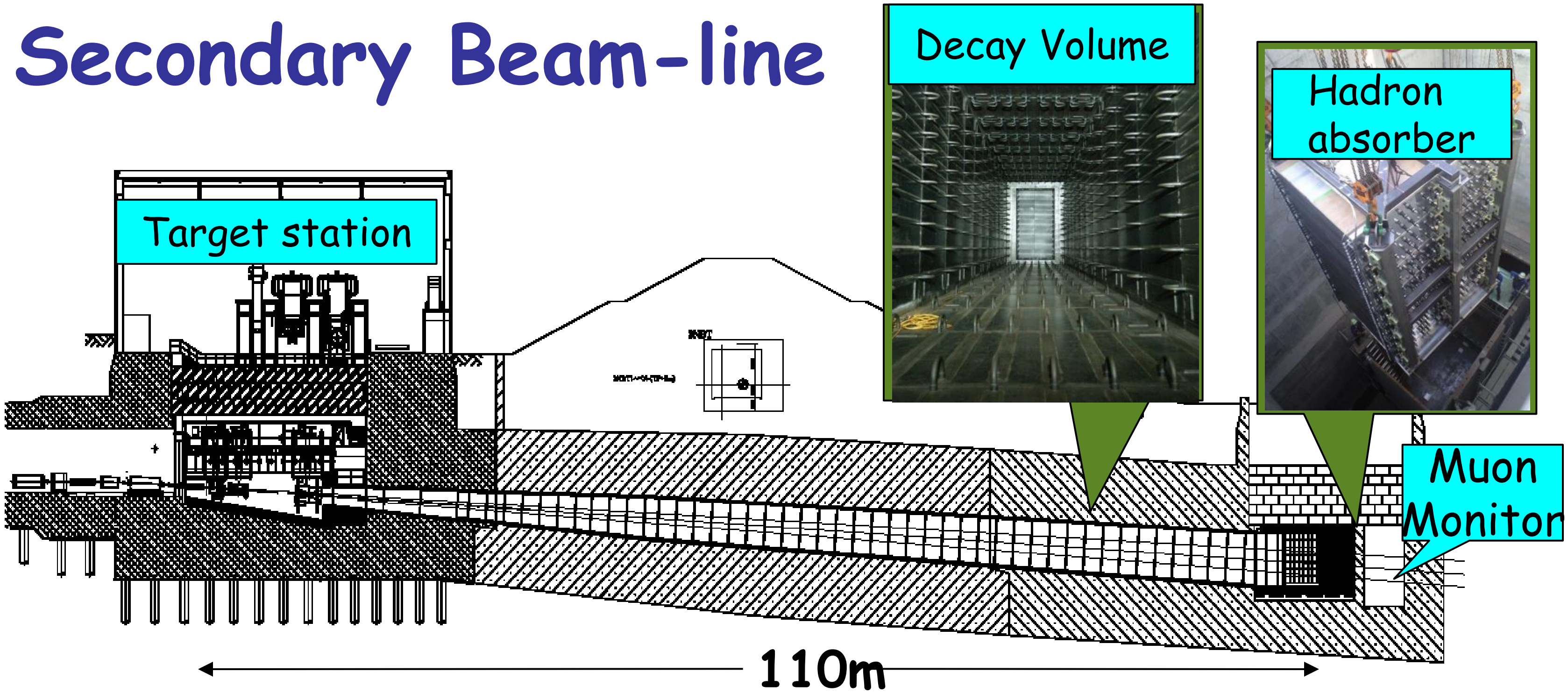
Linac with an beam energy > 9 GeV!

MR operated only for SX users

…

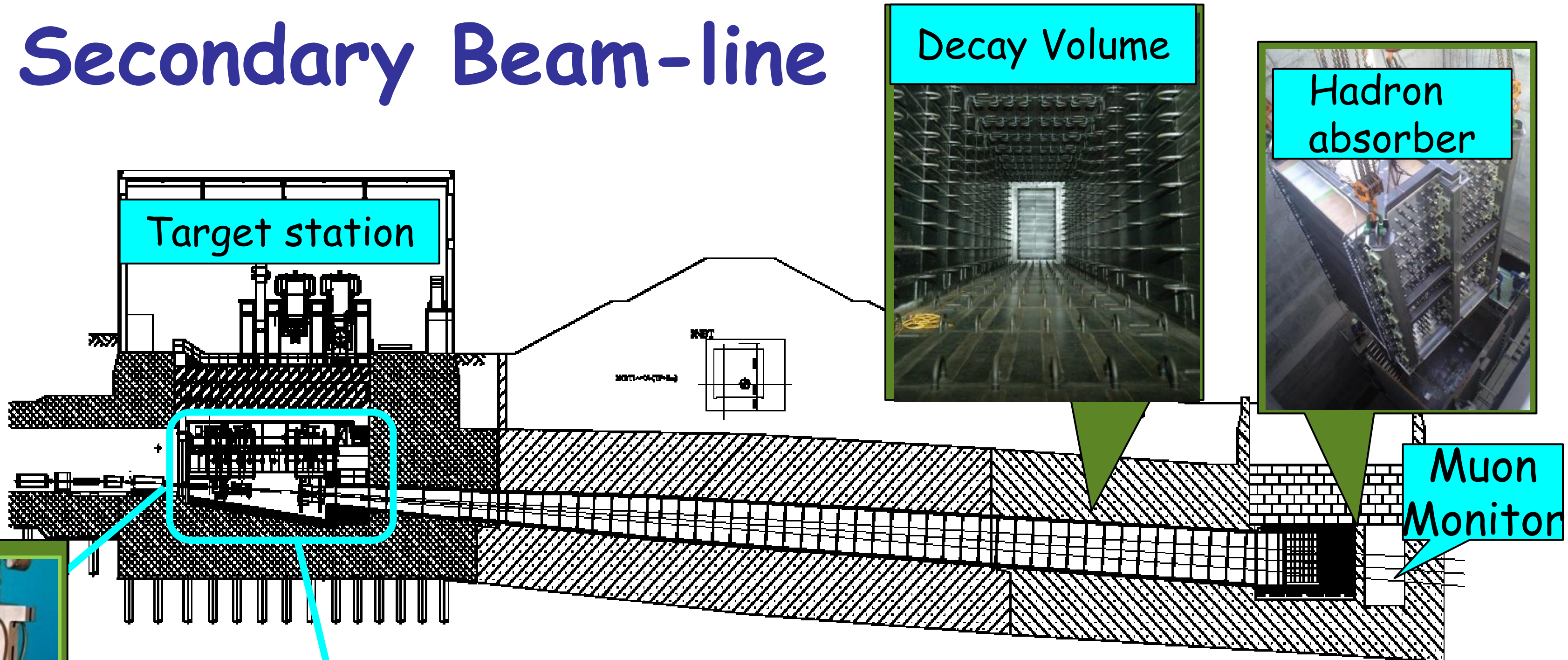
One idea: 8 GeV Booster/Damping Ring

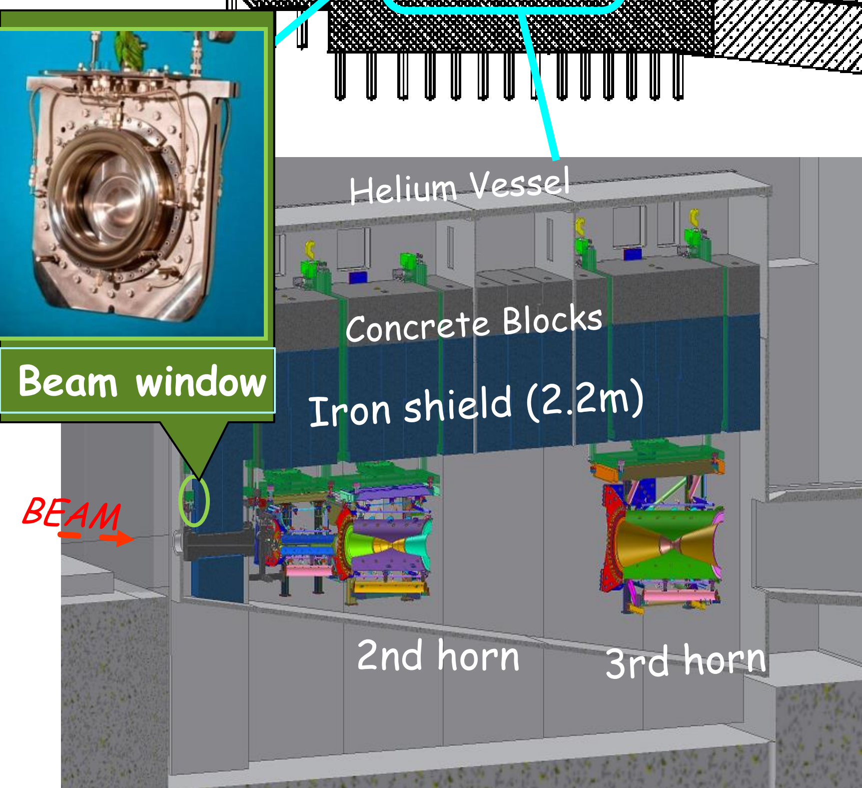
T2K Secondary Beam-line



Target station (shielding, hadron absorber) designed & constructed for **3-4 MW beam power**

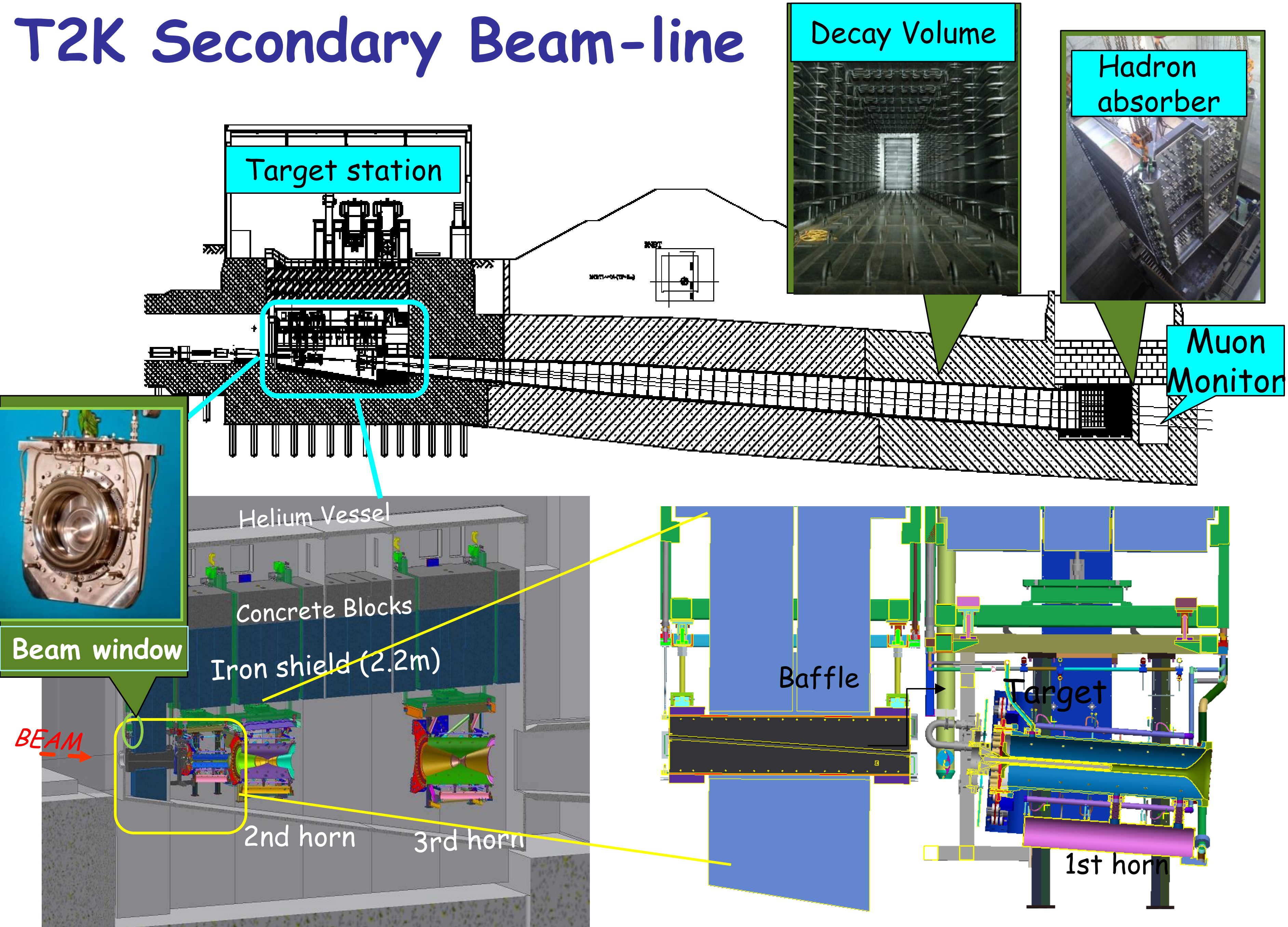
T2K Secondary Beam-line





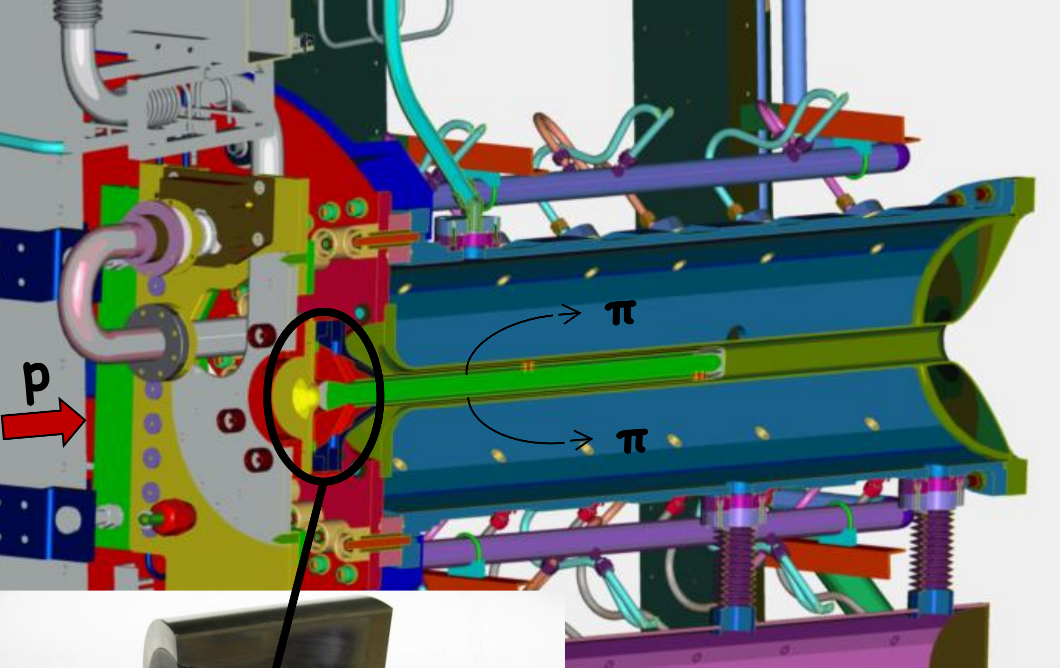
Most components in secondary beamline would need to be upgraded for MW operation:
beam window, target, horns
- NB activated air & water handling

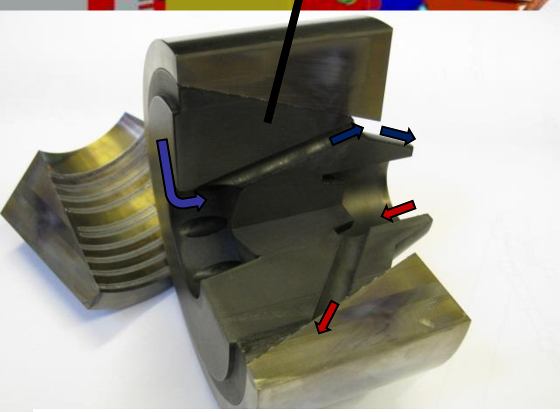
T2K Secondary Beam-line

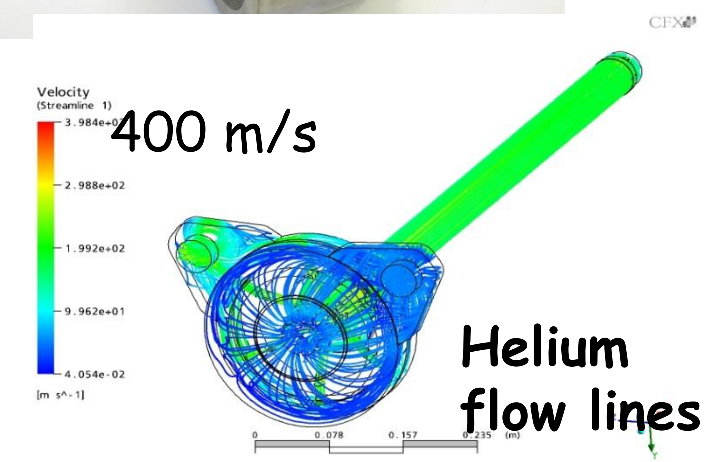


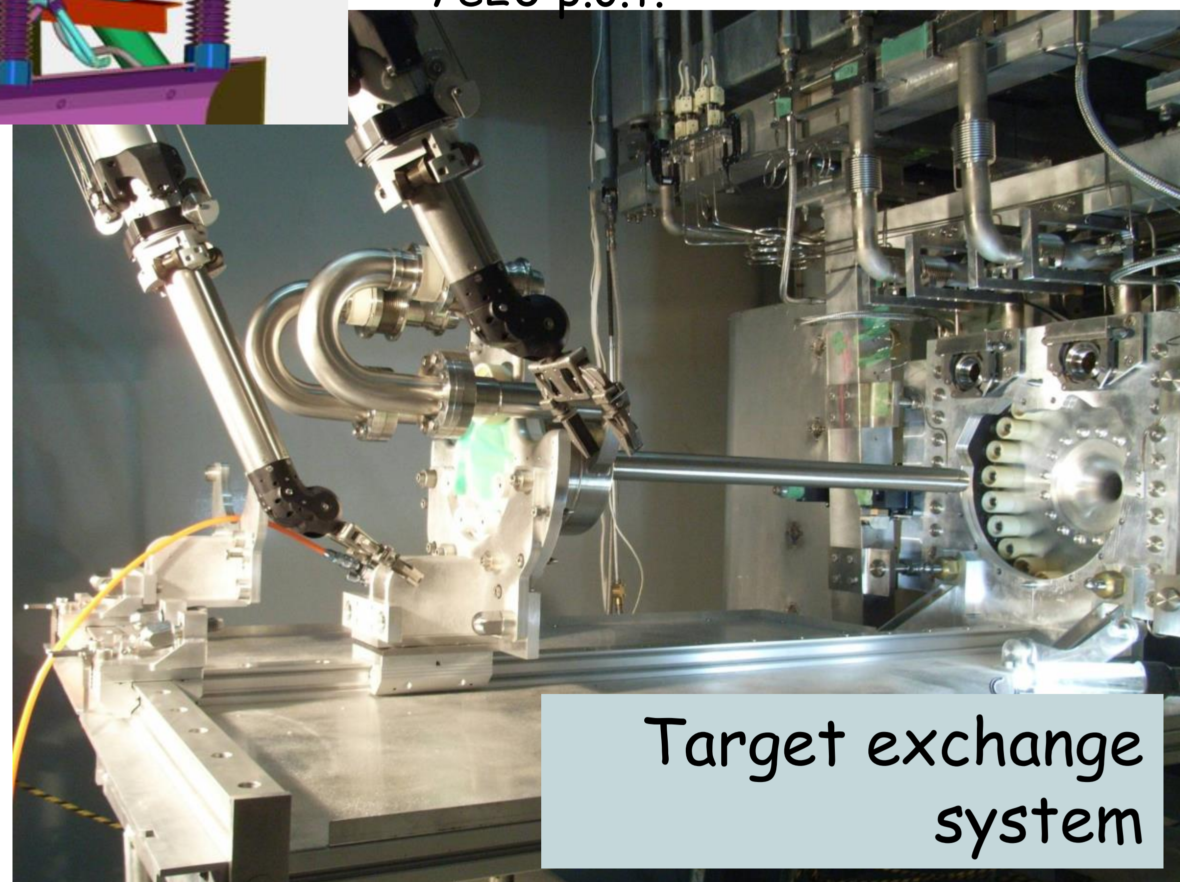
T2K Target & horn

- 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 being replaced after 4 years operation, 7e20 p.o.t.









Target exchange system

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
- OTR, beam monitors
- Target station emission limitations

Horn Problems/Limitations (T.Sekiguchi)

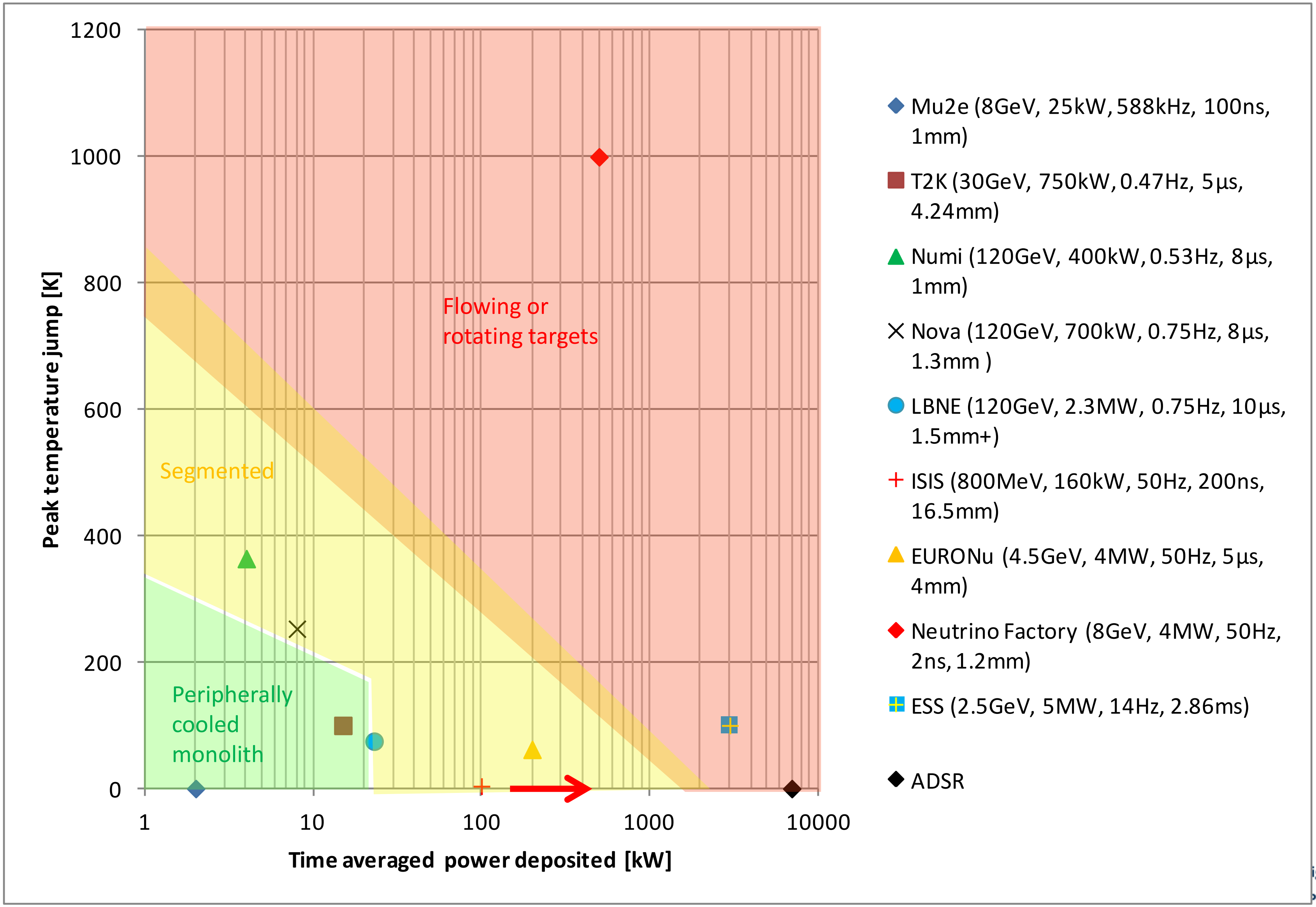
- **What are real problems for horns in a high power beam?**
  - One tends to consider about these things for a high power beam.
    - Cooling to survive a large heat deposit.
    - Mechanical strength for a high current (~300kA)
    - Fatigue due to a repetitive stress of $O(10^8)$.
  - These issues are actually major consideration, but…
  - **Real problems in a high power beam do happen due to**
    - Radio-activation:
      - A treatment of radioactive waste (tritium and ^{7}Be, etc).
      - No more manual maintenance → **Remote maintenance needed**.
    - **Hydrogen production by a water radiolysis.**
    - NO_x production in case of air environment.
      - Acidification of water.

Horn issues for >1MW beam (T.Sekiguchi)

- T2K horn is designed for 750kW beam.
- Currently hydrogen production and poor stripline cooling limit an acceptable beam power.
- However, some modifications are made for new horns to resolve these problems.
- In order to achieve 750kW beam power, replacing with new horns and new power supplies are necessary.
- New horns will be replaced in FY2013 and new power supplies will be operated from fall 2014.
  - Update – new 3rd horn successfully installed, 2nd & 1st horns to be replaced in January 2014
- Possibility for beam power beyond 1MW is considered. An acceptable beam power for horn is estimated to be 1.85MW.

New 3rd horn being installed last month

Limitations of target technologies



‘Divide and Rule’ for increased power

Dividing material is favoured since:

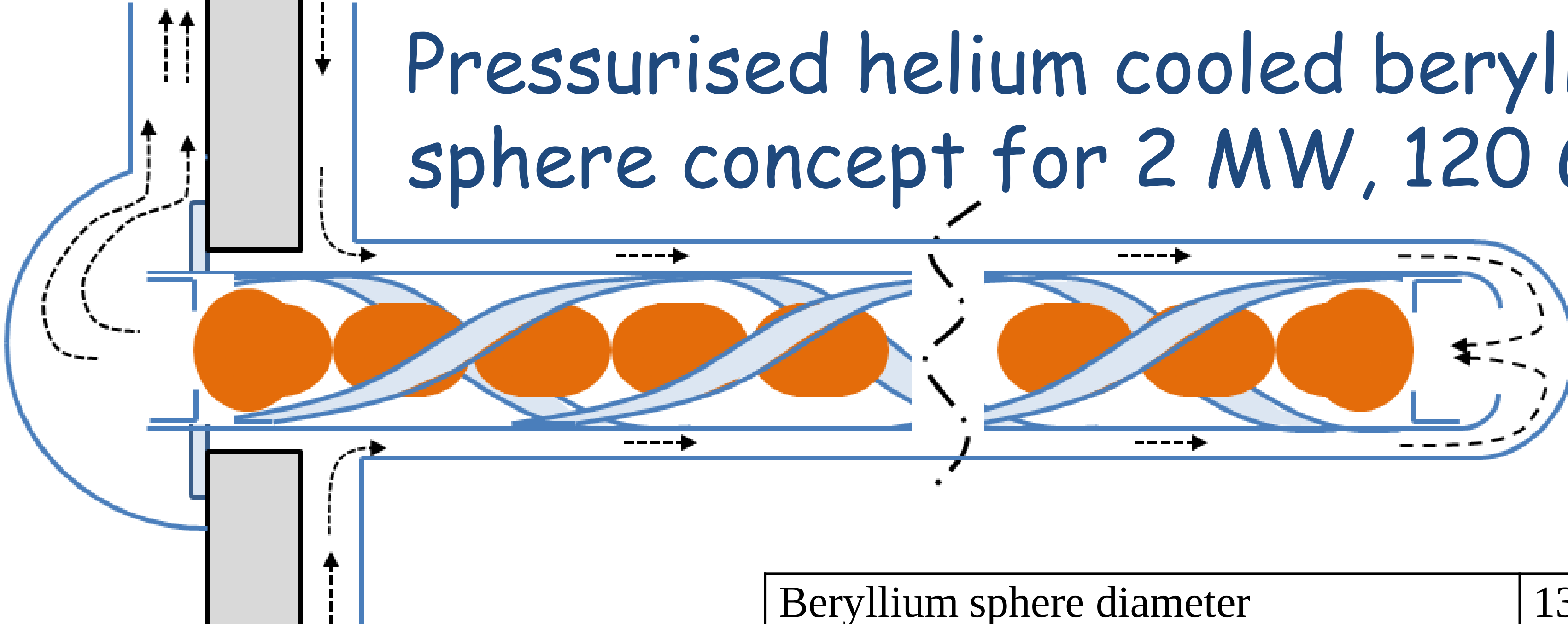
- Better heat transfer
- Lower static thermal stresses
- Lower dynamic stresses from intense beam pulses

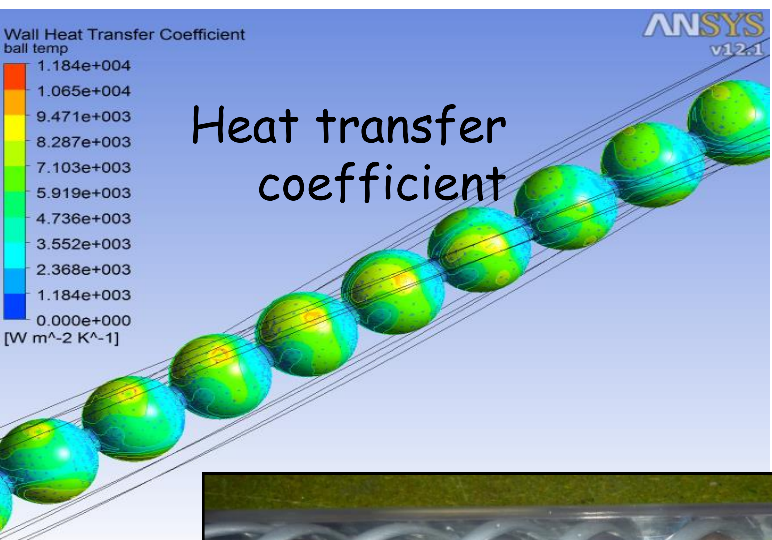
Helium cooling is favoured (cf water) since:

- No ‘water hammer’ or cavitation effects from pulsed beams
- Lower coolant activation, no radiolysis
- Negligible pion absorption – coolant can be within beam footprint
- For graphite, higher temperatures partially anneal radiation damage

Low-Z target concepts preferred (static, easier)

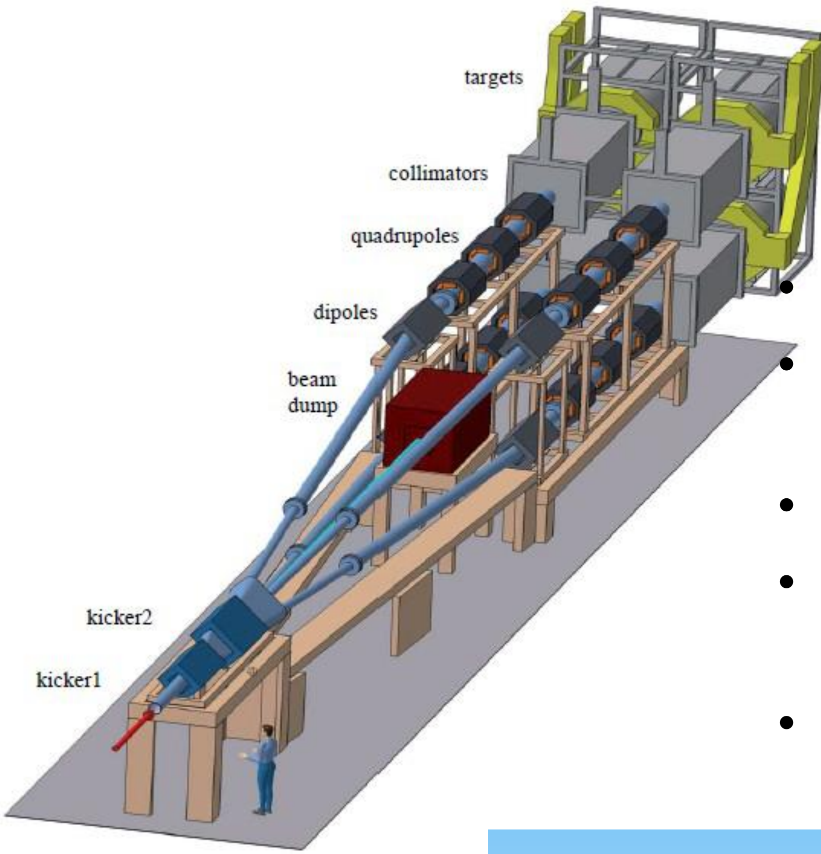
Pressurised helium cooled beryllium sphere concept for 2 MW, 120 GeV



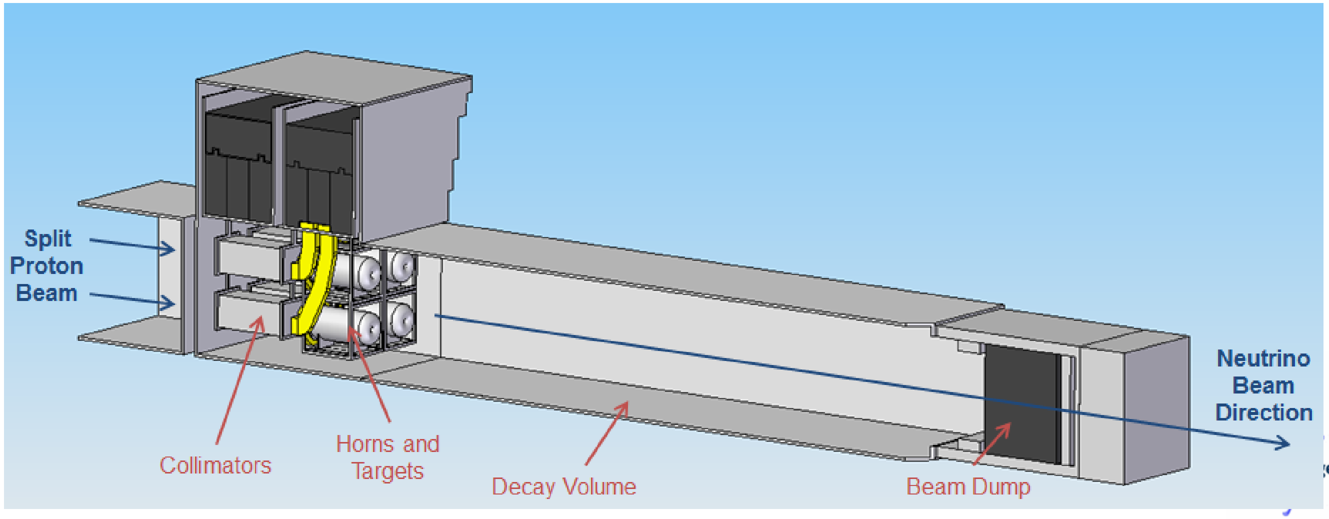


Beryllium sphere diameter	13 mm
Beam sigma	2.2 mm
Helium mass flow rate	17 g/s
Inlet helium pressure	11.1 bar
Outlet helium pressure	10 bar
Inlet velocity	40 m/s
Maximum velocity	185 m/s
Total heat load	9.4 kW
Maximum beryllium temperature	178 C
Helium temperature rise, ΔT (T_{in}-T_{out})	106 C

CERN SPL Superbeam study



- 4 MW beam power at 4.5 GeV
- 4 targets in 4 horns considered feasible
- ~50 kW heat load per target
- Particle bed only viable static target option
- Concept recycled for ESS SB proposal, candidate for HK



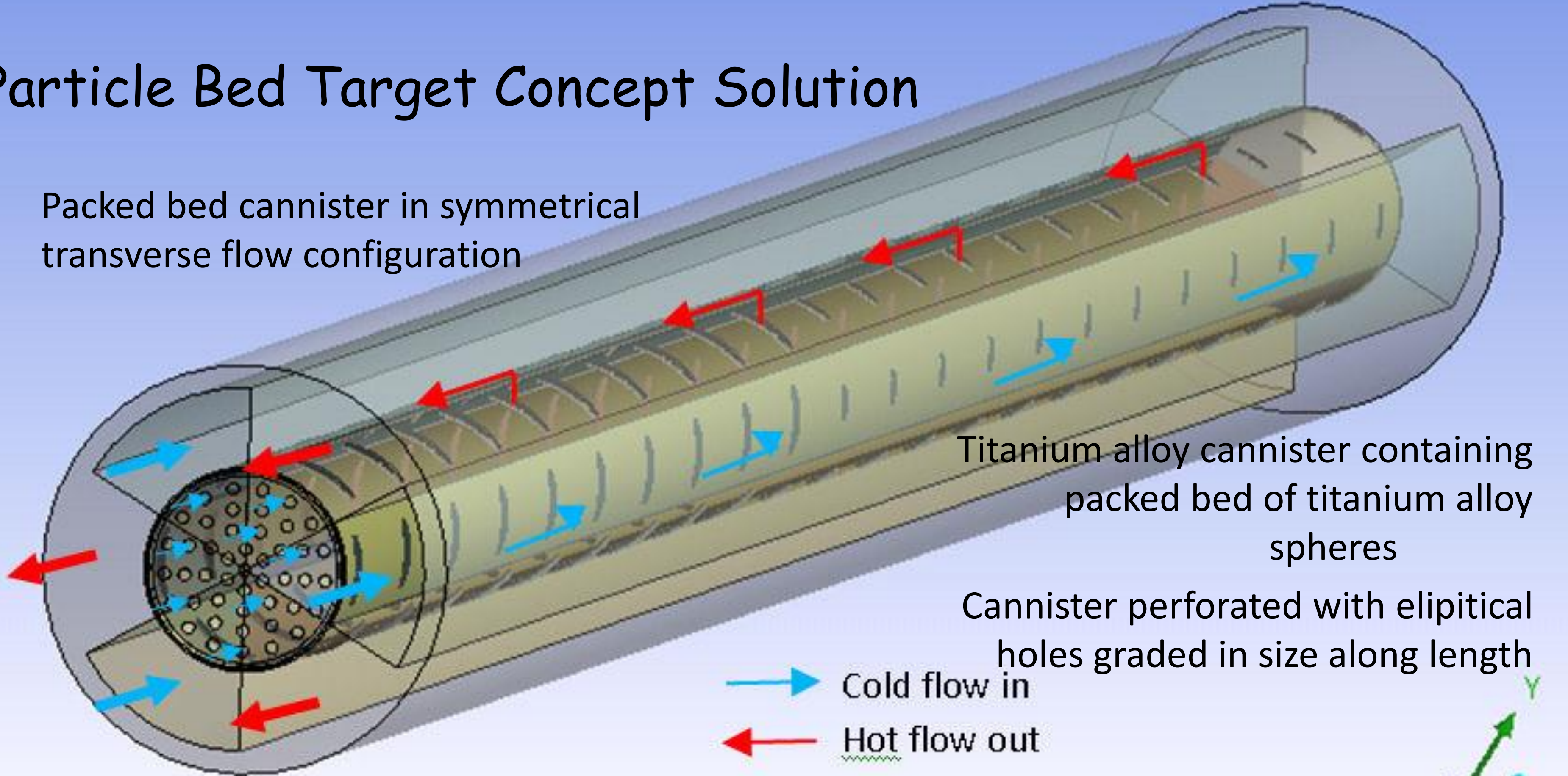
Particle bed advantages

- Large surface area for heat transfer
- Coolant can pass close to maximum energy deposition
- High heat transfer coefficients
- Low quasi static thermal stress
- Low dynamic stress (for oscillation period <<beam spill time)

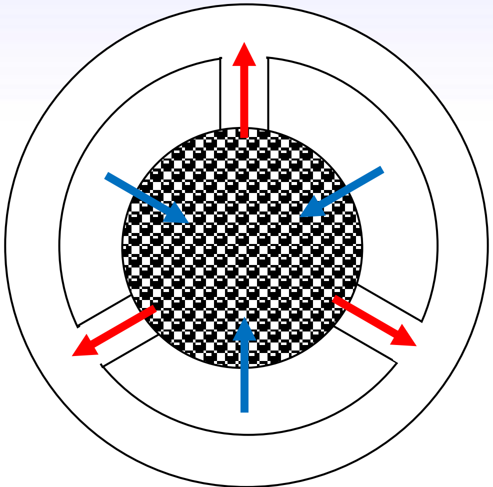
… and challenges

- High pressure drops, particularly for long thin Superbeam target geometry
  - Need to limit gas pressure for beam windows
- Transverse flow reduces pressure drops – but
  - Difficult to get uniform temperatures and dimensional stability of container

Particle Bed Target Concept Solution



T.Davenne



Model Parameters

Proton Beam Energy = 4.5GeV

Beam sigma = 4mm

Packed Bed radius = 12mm

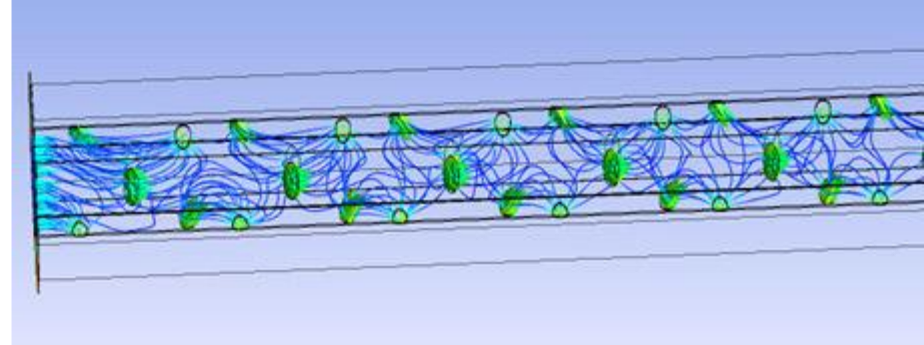
Packed Bed Length = 780mm

Packed Bed sphere diameter = 3mm

Packed Bed sphere material : Titanium Alloy

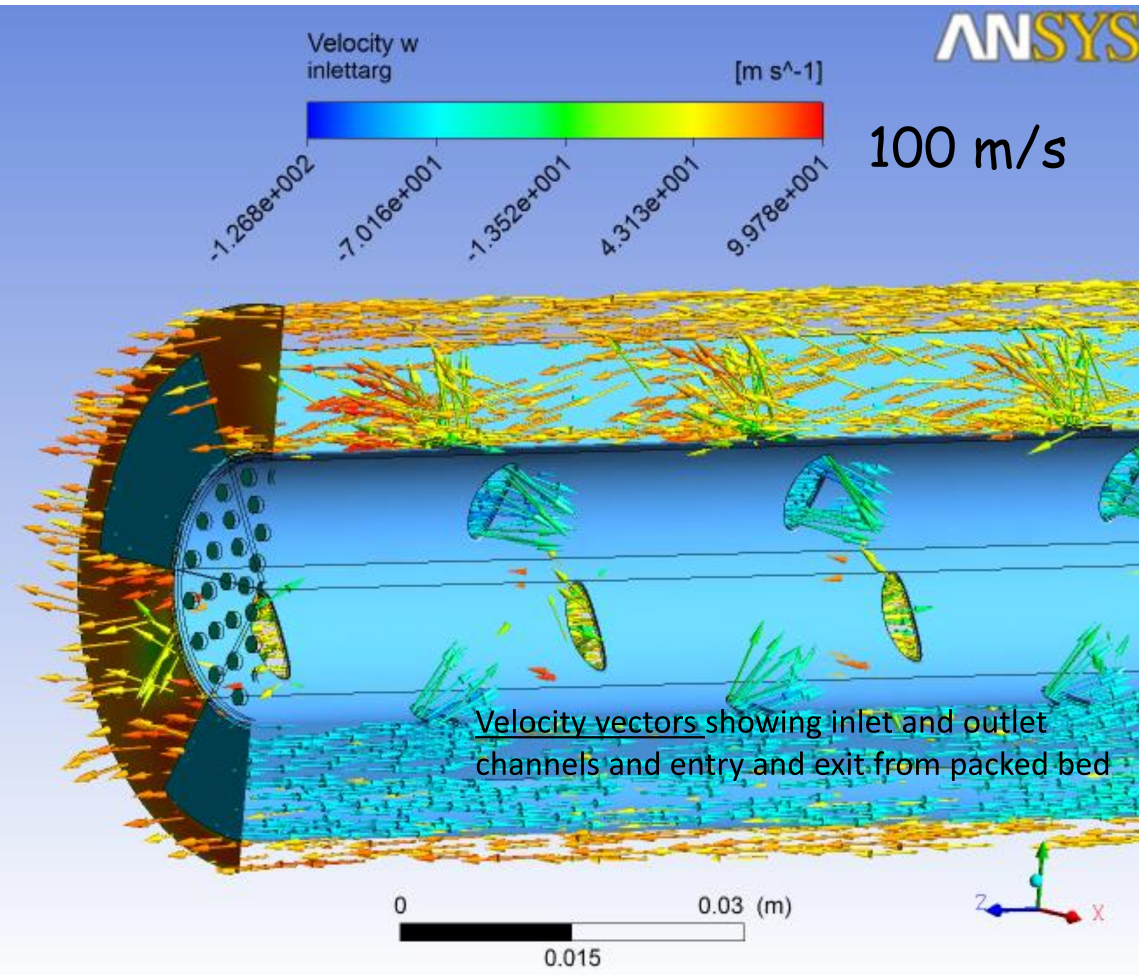
Coolant = Helium at 10 bar pressure

Packed Bed Model (FLUKA + CFX v13)



Streamlines in packed bed

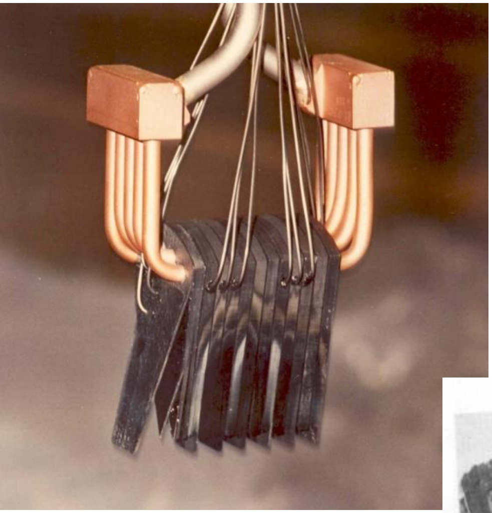
- Packed bed modelled as a porous domain
- Permeability and loss coefficients calculated from Ergun equation (dependant on sphere size)
- Overall heat transfer coefficient accounts for sphere size, material thermal conductivity and forced convection with helium
- Interfacial surface area depends on sphere size
- Acts as a natural diffuser - flow spreads through target easily



Velocity vectors showing inlet and outlet channels and entry and exit from packed bed

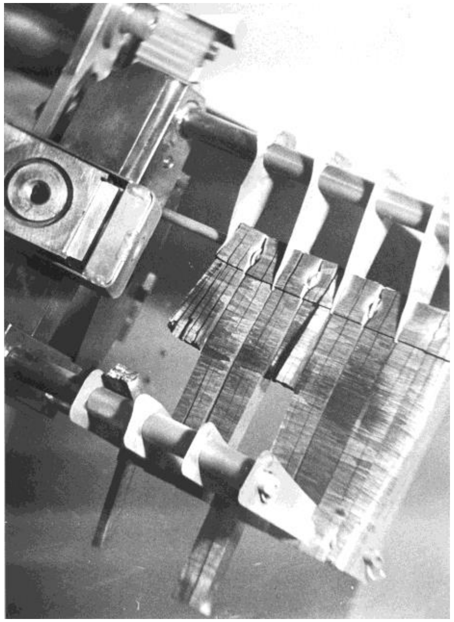
Ashes to ashes, dust to dust...

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

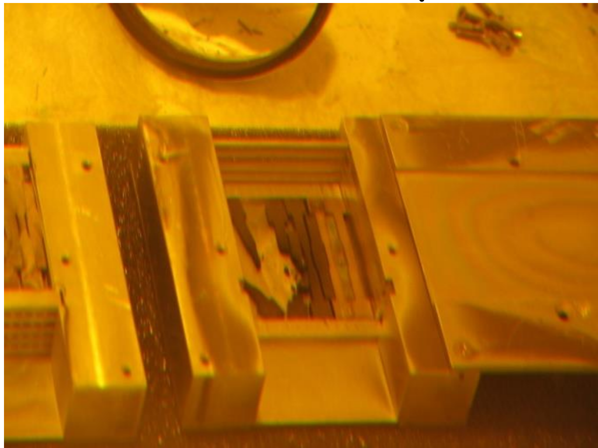


LAMPF fluence 10^22 p/cm2

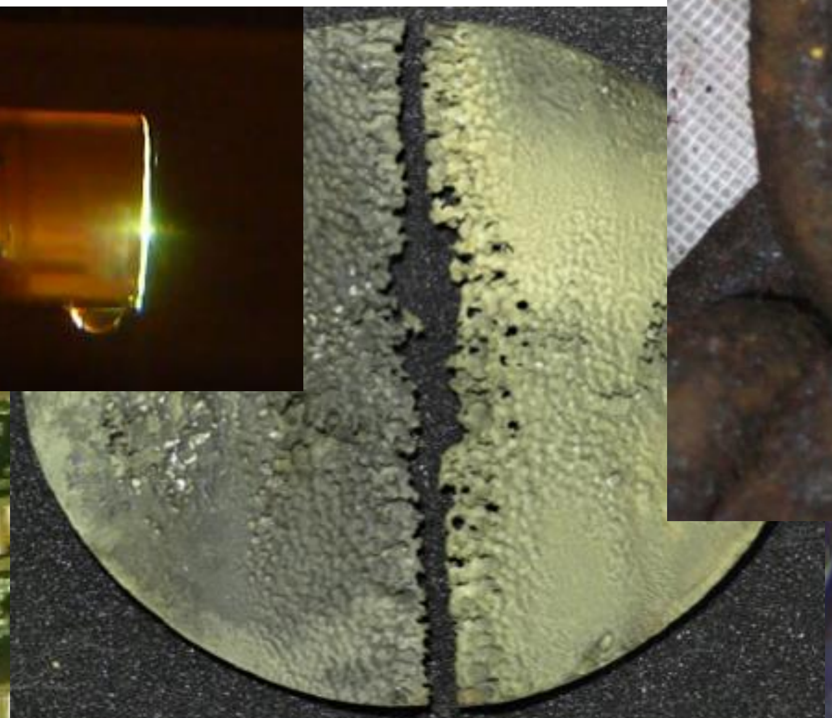
PSI fluence 10^22 p/cm2

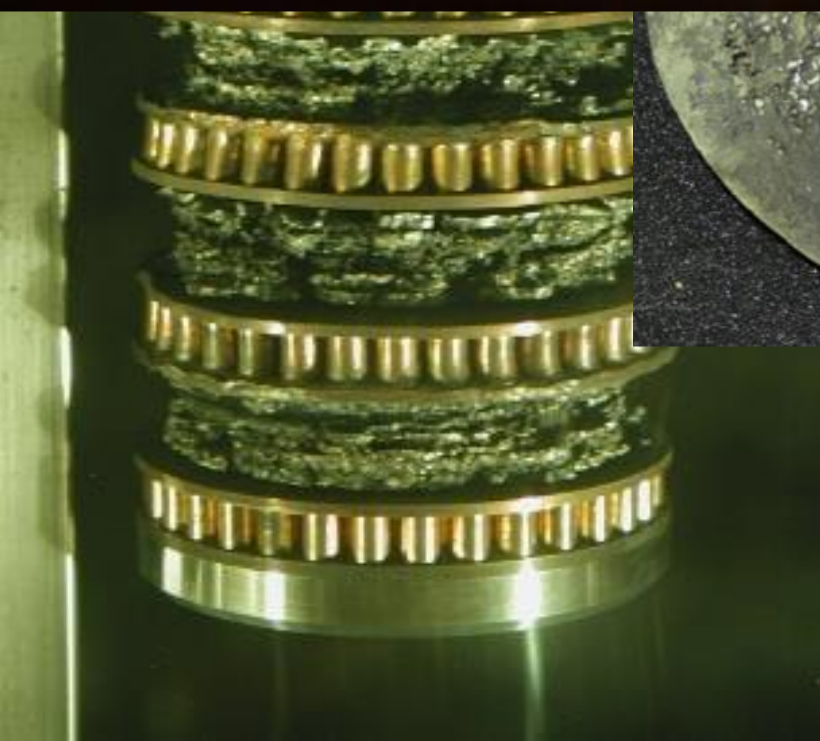


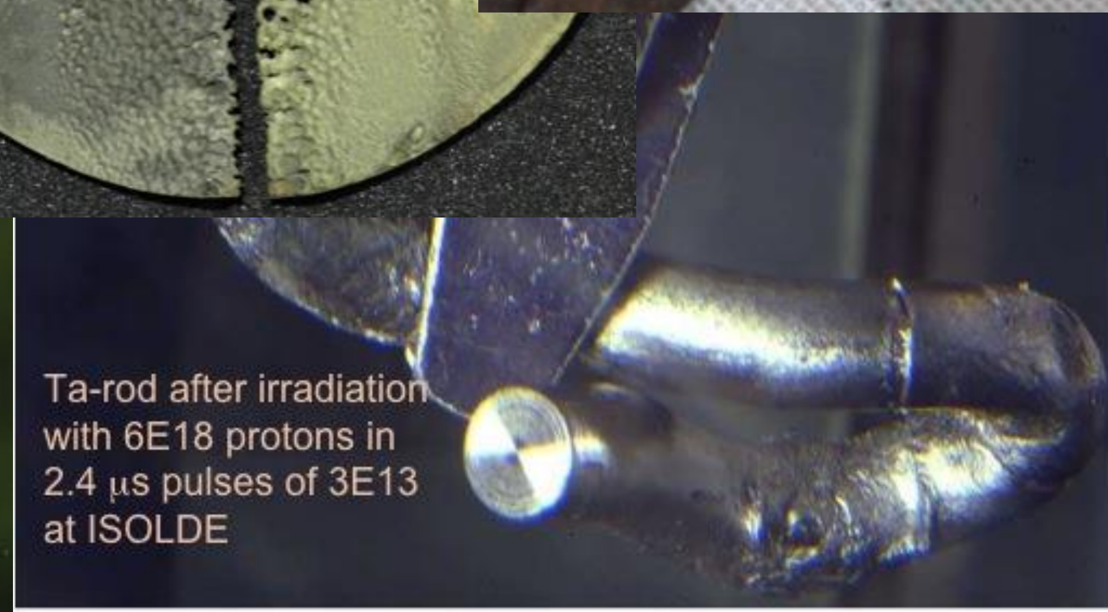
BNL tests (in water): fluence ~10^21 p/cm2



Interaction of proton beams with metals







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

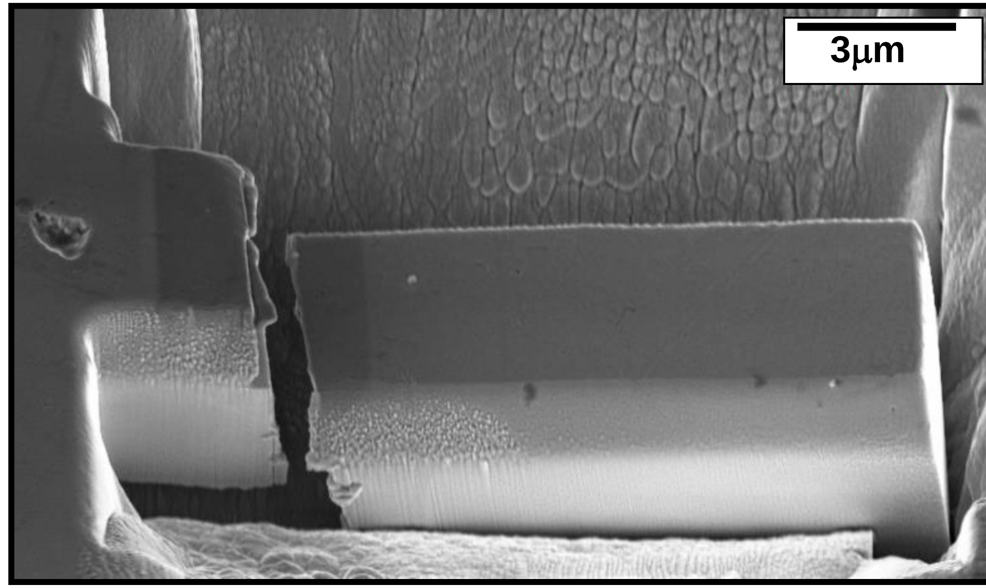
MoU signed by 5 US/UK institutes – Fermilab, BNL, PNNL, RAL, Oxford Materials Department

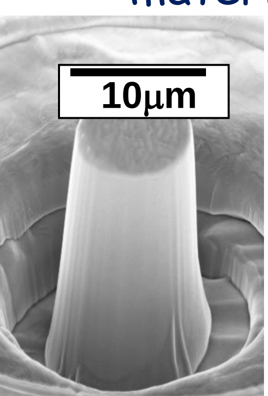
New Post-doc recruited at Oxford to study beryllium

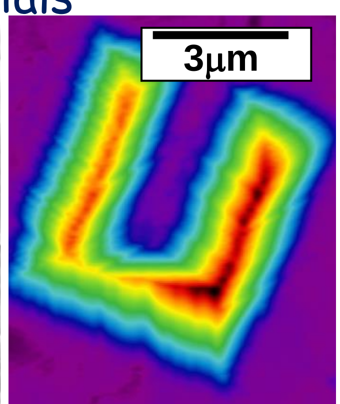
Working groups on graphite, beryllium, tungsten, new collaboration on Ti alloys

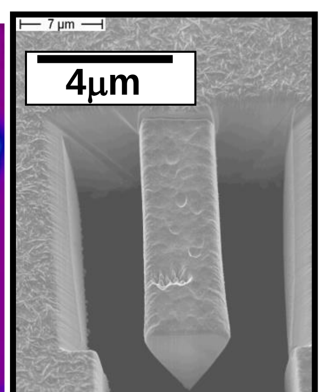
Micro-mechanical testing

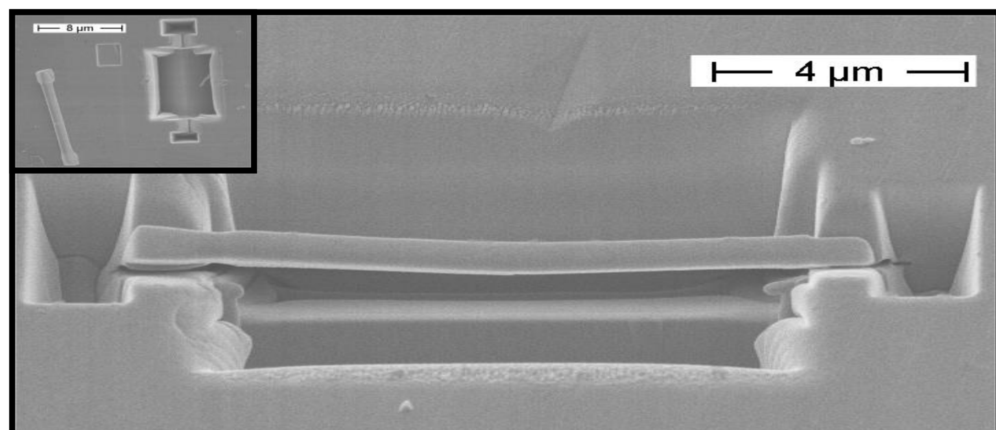
- Unique materials expertise at Oxford (MFFP Group)
- Micro-cantilevers machined by Focused Ion Beams
- Compression tests
- Tension tests
- Three Point Bend
- Cantilever bending
- New facility NNUF (National Nuclear User Facility) under construction at Culham to carry out such testing of small quantities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











Secondary beam component limitations for >1MW operation

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  - 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

Beam 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

1. Beam Windows

- Ti6Al4V and Ti6Al4V1B
  - Ti6Al4V used in T2K beam windows for resilience to pulsed beams
  - MSU/FRIB intend to use Ti alloy for beam dump window, will see very high radiation damage rates
  - Collaboration between RAL, KEK, Fermilab and MSU via RaDIATE/PASI collaboration to perform:
    - Neutron damage experiments
    - Heavy ion damage experiments at MSU
    - Investigation of relevance to T2K beam parameters, **possibility to test sample from used T2K beam windows?**
- Beryllium:
  - Attractive as low-Z, high strength, high thermal conductivity
  - Report nearly complete on radiation damage literature (by Oxford MFFP Group/NNL)
  - Post-doc recruited at Oxford to start Jan 2014 (formerly at PSI with Yong Dai)
  - In-beam experiment scheduled for HiRadMat facility at CERN

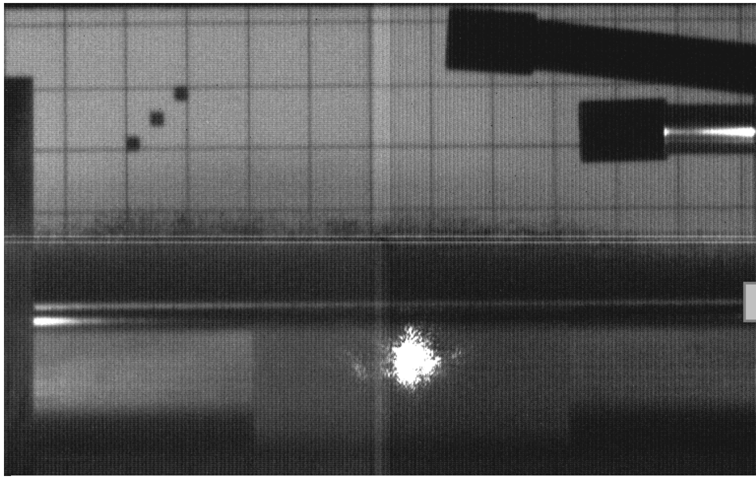
2. Study limits of existing target

- How far can existing T2K design be pushed?
  - Design developments may push current design towards 1 MW operation
  - But for how long? Graphite radiation damage issues
  - Exploit strand of RaDIATE collaboration – e.g. of interest to Fermilab for NOvA target
  - Thermal-hydraulic/CFD simulations:
    - Higher pressure helium -> higher power operation
    - But: extra stresses in window (from pressure and thermal stresses) and target material (thermal stresses)

3. Target research

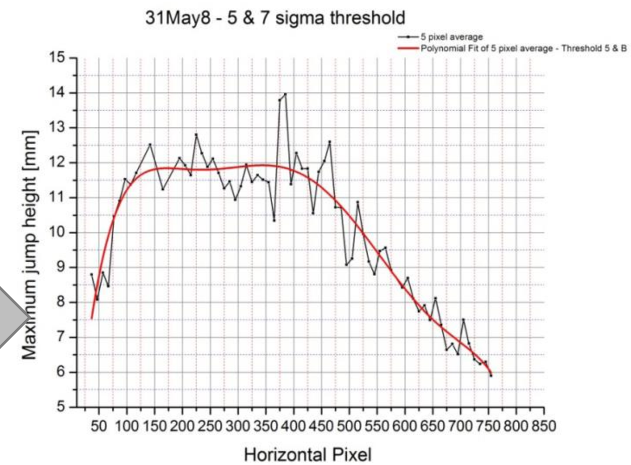
- Study static, packed bed, low-Z targets
  - Beryllium, AlBeMet alloys, titanium alloys are only realistic long lifetime alternatives to graphite
- Conceptual design, engineering simulations
- Physics vs engineering performance (high pion yield, long enough lifetime)
- Manufacturing prototyping
- Off-line heating & cooling experiments involving:
  - Induction heater
  - Prototype helium cooling plant
  - Calorimetric measurements
- On-line pulsed beam experiment at HiRadMat, CERN

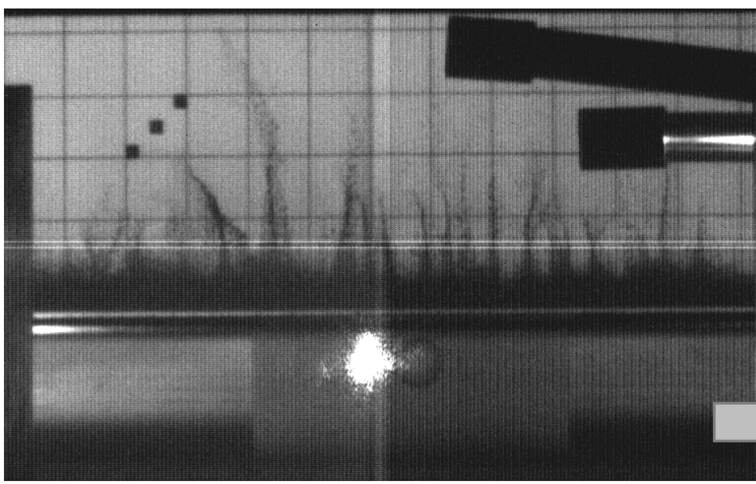
2012 HiRadMat pulsed beam experiment with tungsten powder



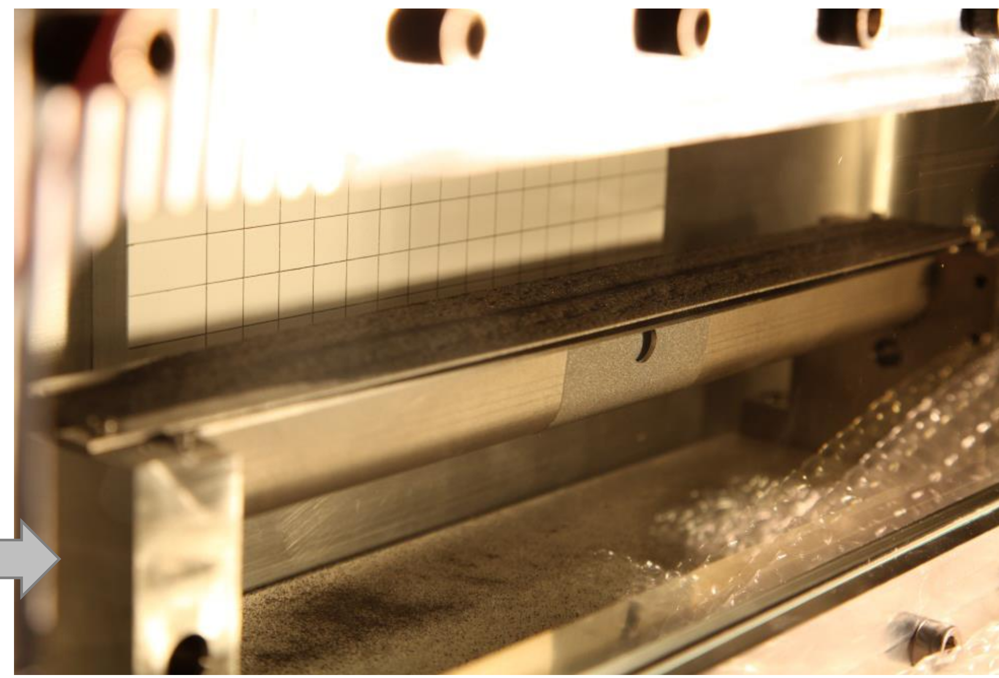
Shot #8, 1.75e11 protons
Note: nice uniform lift

Lift height roughly correlates with deposited energy





Shot #9, 1.85e11 protons
Note: filaments!



Trough photographed after the experiment.
Note: powder disruption