Diagnostics for High Power Targets and Dumps

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Outline

- Introduction and Overview

- Examples of beam diagnostics at high power targets
  - CNGS
  - SNS
  - T2K

- Examples of beam diagnostics at high power dumps
  - LHC
  - FLASH

Introduction – Diagnostics for Targets

High power targets are used for production of secondary beams

- Objectives for Diagnostics for Targets
  1. Protection of targets from beam-induced damage

     Very demanding requirements on stability, since target design indicates that mechanical limit is exceeded for off-centred or too-high density beams.

  2. Quality assurance of secondary beams

     Instrumentation downstream of target is important feedback to primary beam

- Constraints for diagnostics systems
  – High radiation → Design has to include remote handling

Introduction – Diagnostics for Dumps

Dumps are needed for the safe disposal of the beam

→ Protect the machine in case of failure

→ Safely dump unstable beam before damage of equipment

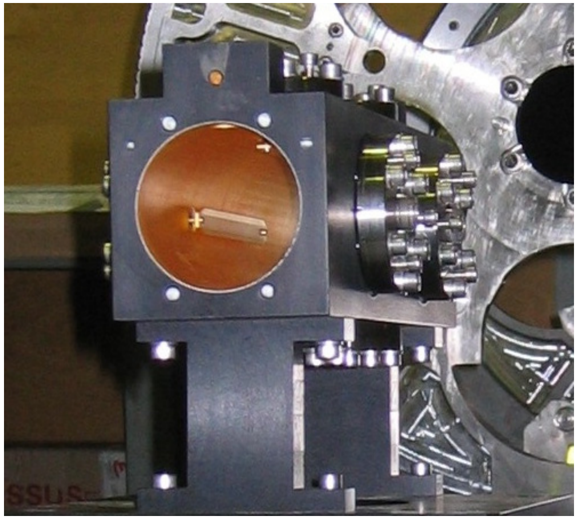
- Objectives for dump diagnostic systems
  1. Protection of beam dump and vacuum window
  2. Quality assurance of the beam dump system

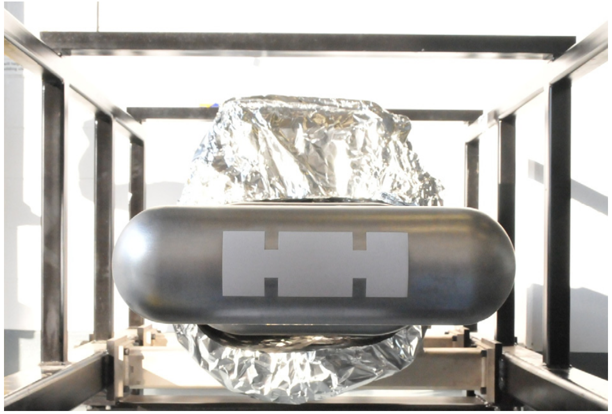
- Constraints for diagnostics system
  - High radiation → Design has to include remote handling

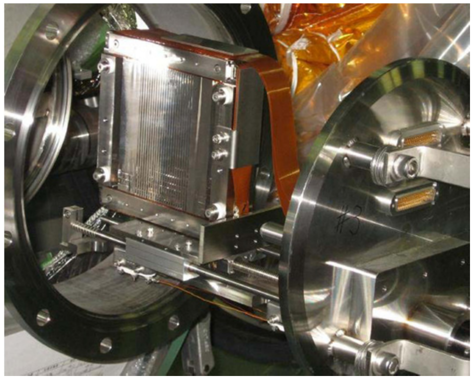
Overview of High Power Targets & Dumps Facilities

Facility	Physics	Beam	Beam energy	Beam power	Energy / pulse	Diagnostics
T2K ☆	neutrinos	p	30 (50) GeV	750kW (4MW)	0.4 MJ / ?	I, position, profile
NuMI / Nova		p	120 GeV	320 / 700 kW	0.7/0.9 MJ	I, position, profile, secondaries
CNGS ☆		p	400 GeV	510kW	3.1 MJ	I, position, profile, secondaries
SINQ (PSI)	spallation	p	0.59 GeV	1.2 MW	DC (50 MHz)	position, profile, “glowing sieve”
ISIS (RAL)		p	0.8 GeV	160 kW	3 kJ (50 Hz)	
SNS ☆		p	1.0 GeV	1.4 MW	23 kJ (60 Hz)	current density → profile
ESS		p	2 -2.5 GeV	5 MW	360 kJ (14 Hz)	current density → profile
CEBAF	fixed target	e^-	6 GeV	1 MW	DC	
PEPII	collider	e^-	$9(e^-)/3.1(e^+)$ GeV	n.a.		
ILC/CLIC		e^-	0.5 / 1.5 TeV	18/14 MW	3.6/0.28 MJ	spectrometer in post-coll. line
LHC ☆		p	7 TeV	n.a.	360 MJ	sweeping → profile
FLASH ☆	VUV, X ray	e^-	1.25 GeV	100 kW	20 kJ (5 Hz)	position, halo, beam loss
XFEL	FEL	e^-	20 GeV	2x300 kW	60 kJ (10Hz)	blow-up, sweeping → profile

Diagnostics for High Power Targets







Beam Diagnostics for Targets

1. Protection of targets from beam-induced damage
   - Make sure that beam hits target in correct place (usually center)

   → Beam position monitors

   - Ensure that beam density on target is smoothly distributed and safely below damage limit of the target

   → Beam profile monitors

   → Beam intensity monitors

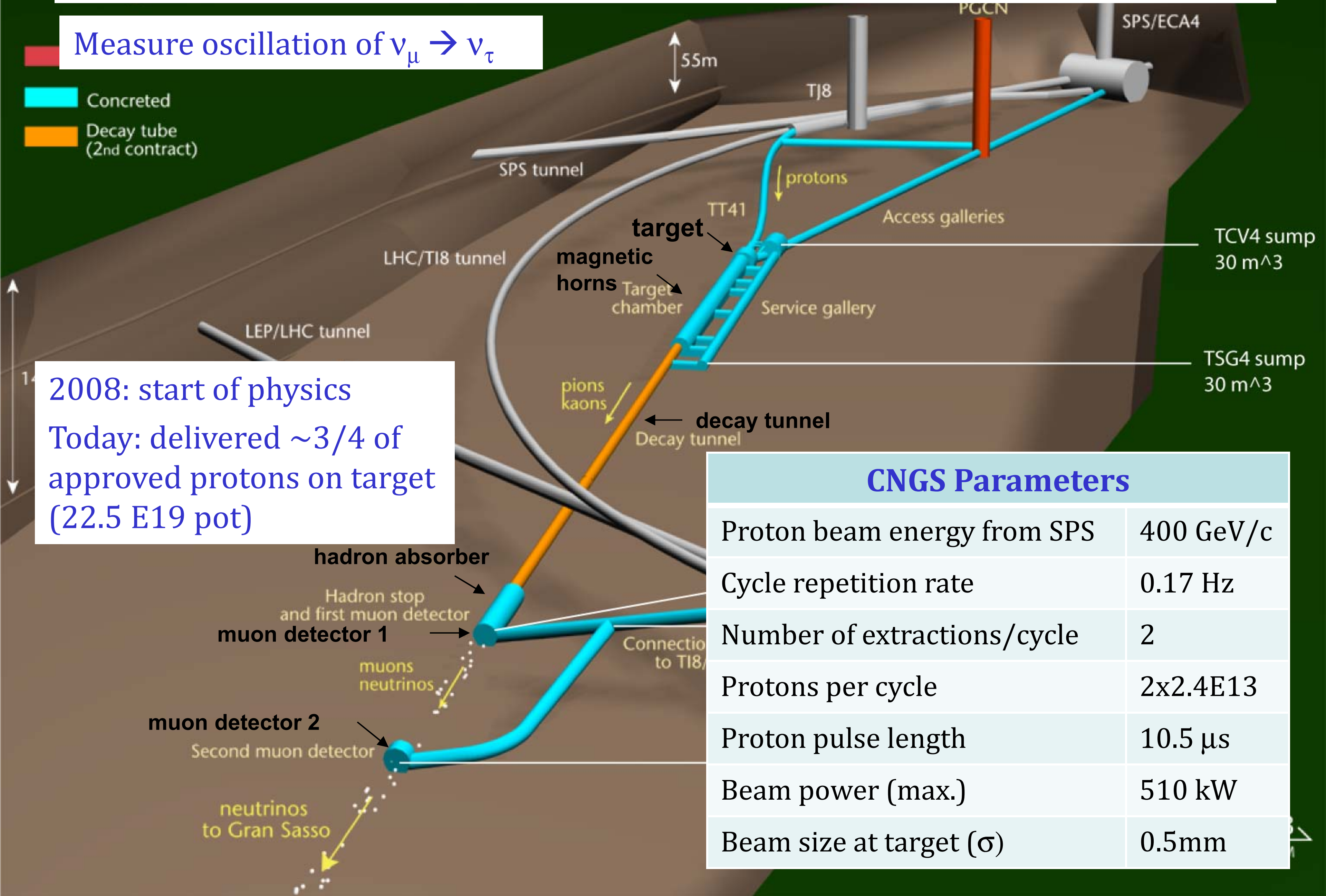
2. Quality assurance of secondary beams
   - Secondary beam instrumentation depends on type of particles required in secondary beam line

CNGS

CERN Neutrinos to Gran Sasso

CNGS – CERN Neutrinos to Gran Sasso

Measure oscillation of $\nu_\mu \rightarrow \nu_\tau$

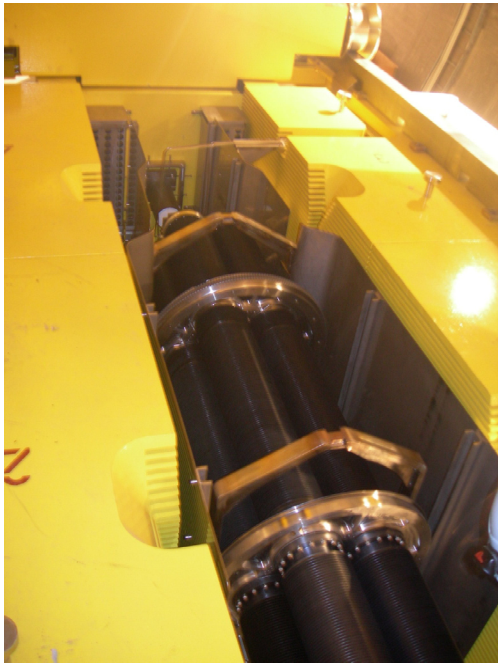


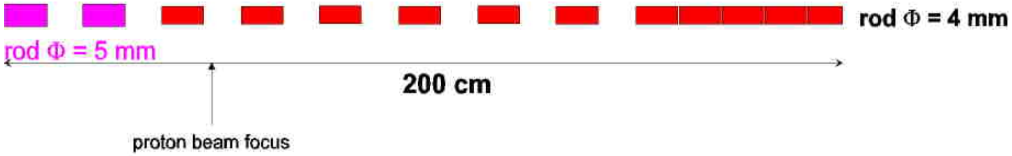
2008: start of physics

Today: delivered ~3/4 of approved protons on target (22.5 E19 pot)

CNGS Parameters	
Proton beam energy from SPS	400 GeV/c
Cycle repetition rate	0.17 Hz
Number of extractions/cycle	2
Protons per cycle	2x2.4E13
Proton pulse length	10.5 µs
Beam power (max.)	510 kW
Beam size at target (σ)	0.5mm

CNGS – Target





Target magazine: 1 unit in use, 4 in-situ spares

- 13 graphite rods, each 10cm long, Ø=5mm and/or 4mm
- Target rods in Al tube, closed with Be-window, filled with 0.5bar He

Critical issue for CNGS target:

- Off-axis beam
  - → Induces stress on target rod
  - → Worst case: beam hits 1.5mm off-axis, cold target, no damping

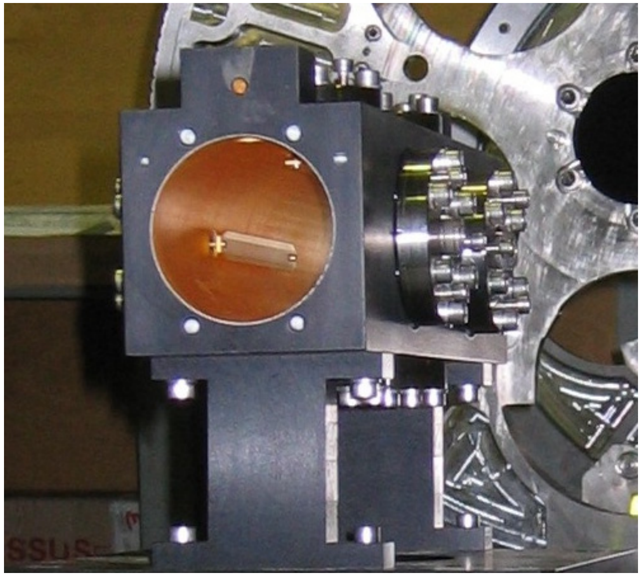
CNGS – Target Station Beam Position Monitor

Make sure that beam hits target well-centered

High radiation levels: ~5MGy/yr

→ Electromagnetic stripline pick-up beam position monitor operated in air

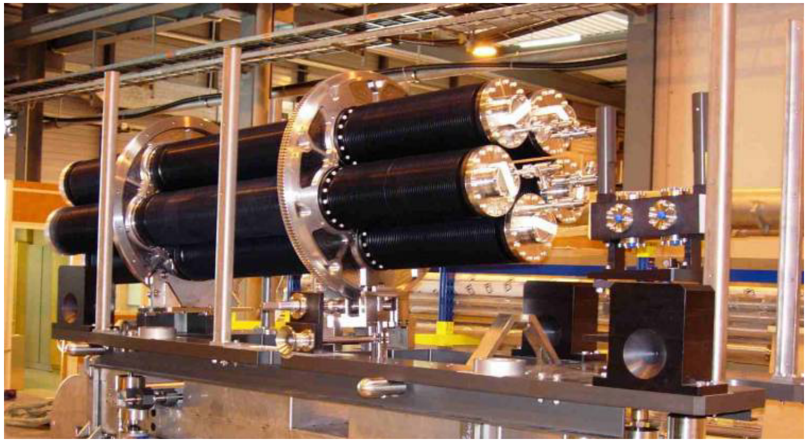
- –Pick-up body and electrodes: Aluminum alloy
- –30 μm gold layer on inner surface
- –Oxide layer on outer surface
- –3m semi-rigid ceramic insulated cables to patch panel outside target shielding



- –Resolution < 0.1mm, absolute precision: 0.2mm
- –Front-end: logarithmic amplifier
  - •Large dynamic range, no gain switching

- Directly mounted on target table

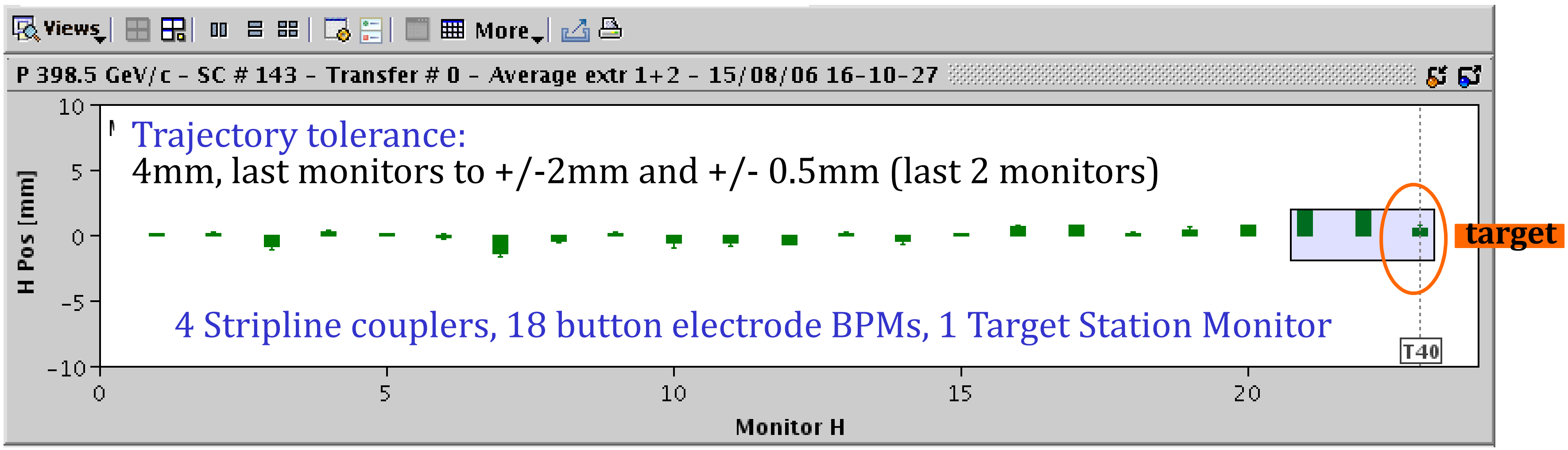
→ Exchange together with target



CNGS – Target Station Beam Position Monitor

- Operational experience
  - Required trajectory tolerance of +/-0.5mm well achieved.
  - After 4 years of physics run monitors are still performing well.
  - →Today: 14.9E19 protons on target (approved total: 22.5E19 pot)

CNGS extraction line: Horizontal plane



CNGS – Secondary Beam Monitoring

→ Muons are sister particles of neutrinos

CNGS Muon detectors:

Ionization chambers (LHC type BLMs, N_2 filled)

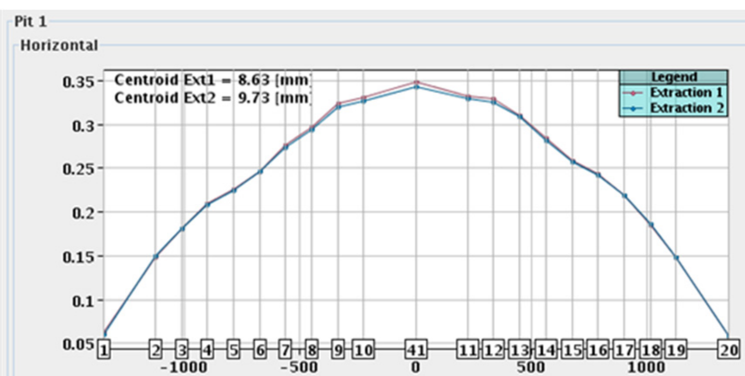
→system is very sensitive to any beam change

→ Online feedback on quality of the neutrino beam

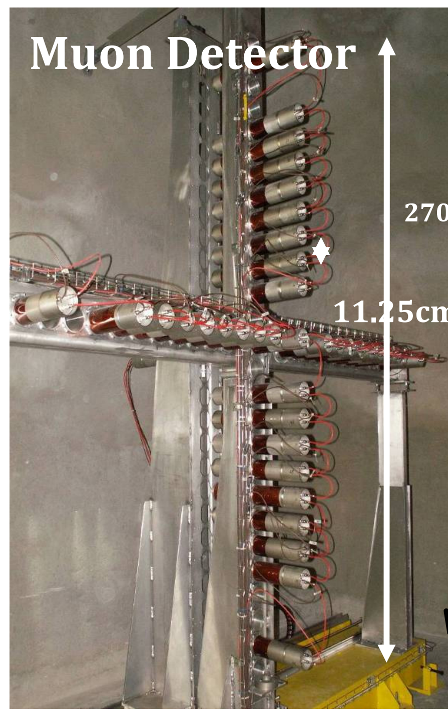
→ Offset of **beam vs target** at 0.05mm level

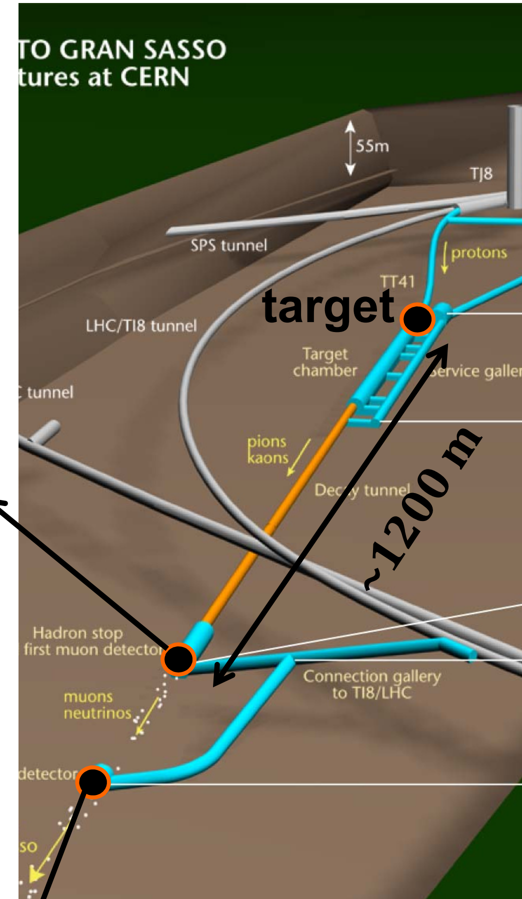
→ Offset of **target vs horn** at 0.1mm level

Horizontal muon profile



270cm

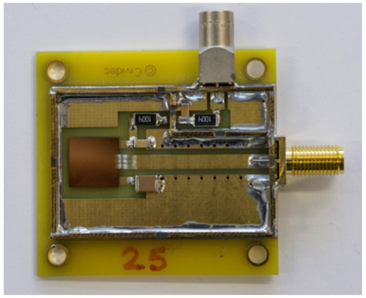


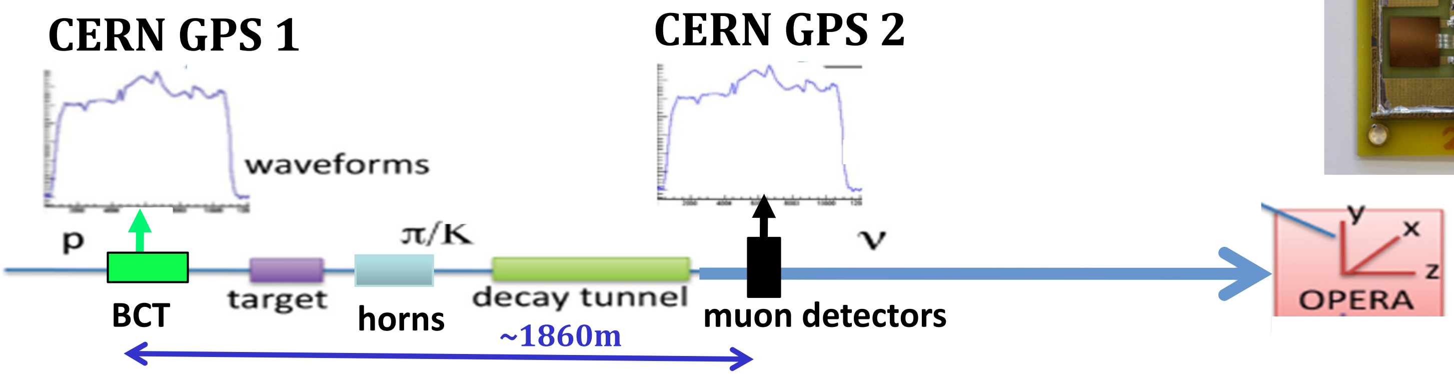


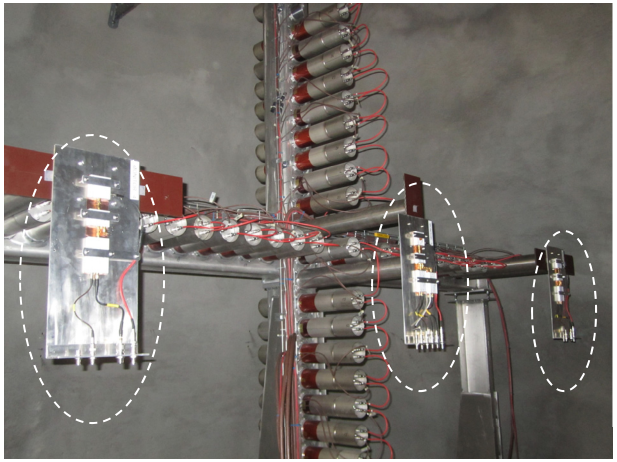
CNGS Activities as a Consequence of the Neutrino TOF Results

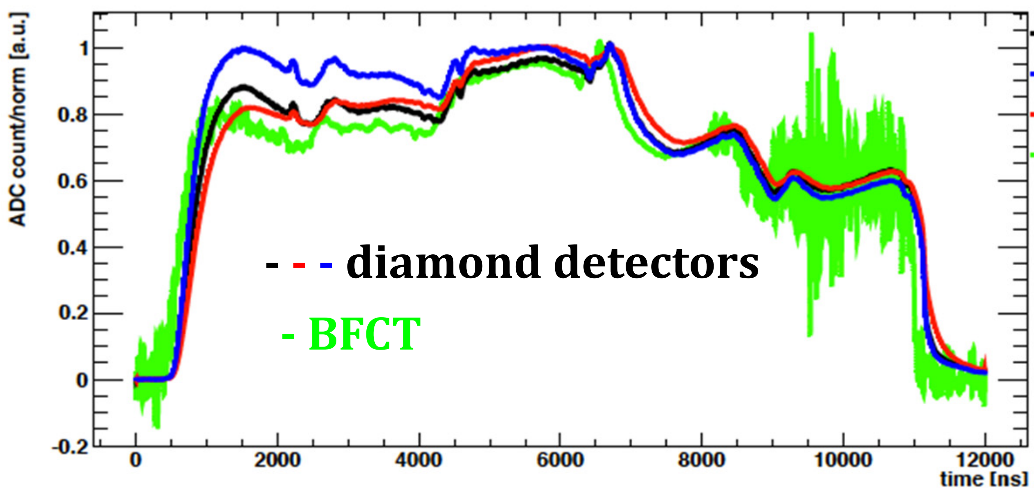
2011: Installation of new muon detectors (pCVD diamond detectors, 0.3x8x8mm^3)

- Measure the time structure of the muon spill
- Measure the GPS timing at CERN independently from the BCFT









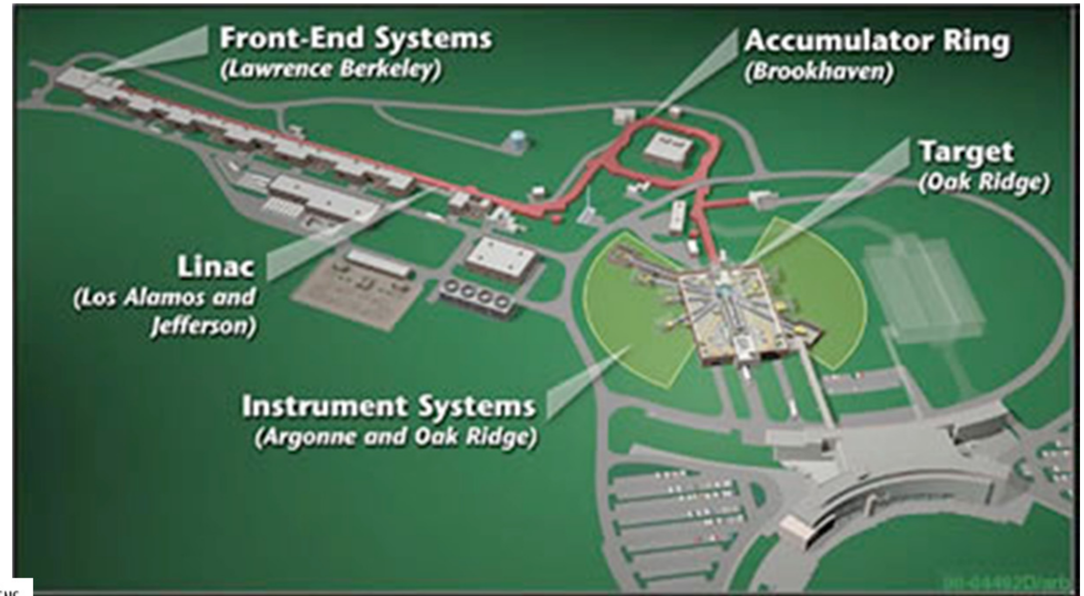
→ GPS timing measurement is consistent between the BFCT and the diamond detectors.

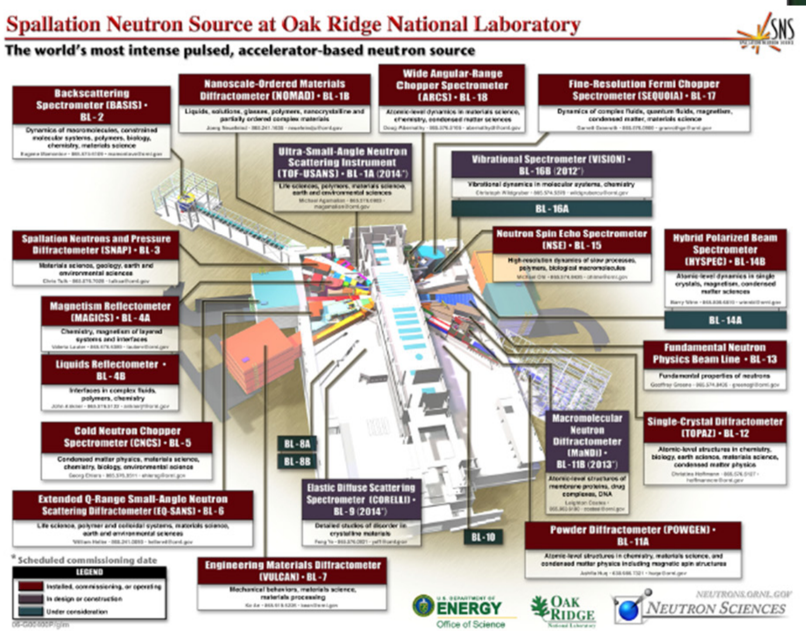
SNS

Neutron Spallation Source in Oak Ridge National Laboratory, Tennessee, USA

SNS – Spallation Neutron Source

SNS Parameters	
Proton beam kinetic energy	1.0 GeV
Proton beam power	1.4 MW
Pulse repetition rate	60 Hz
Protons per pulse	1.5E14
Proton pulse length	695 ns
Average beam current	1.4 mA





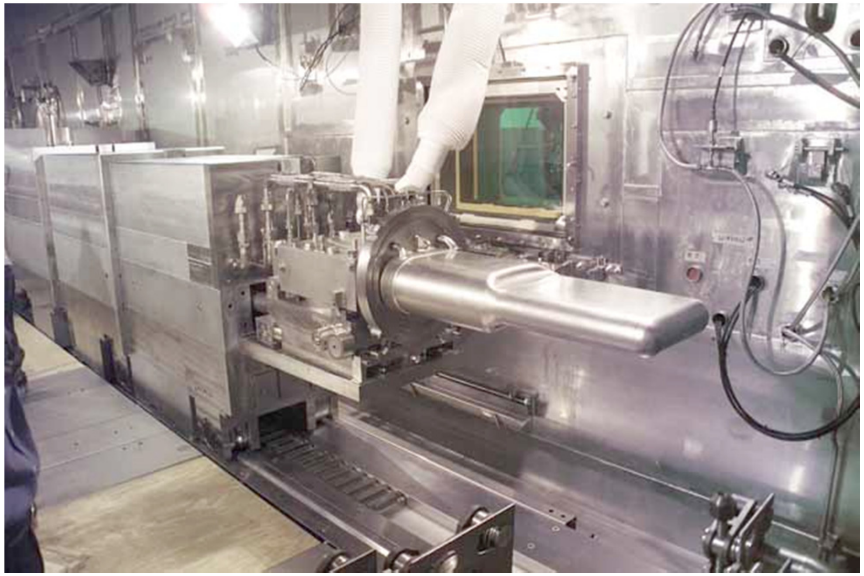
- Liquid mercury target
  - 1 thermal moderators (water)
  - 3 cold moderators (supercritical Hydrogen at 20K)
- → 24 beam-lines
  - E.g. FY11: 92% availability (88% committed)
- Currently operating at approximately 1MW

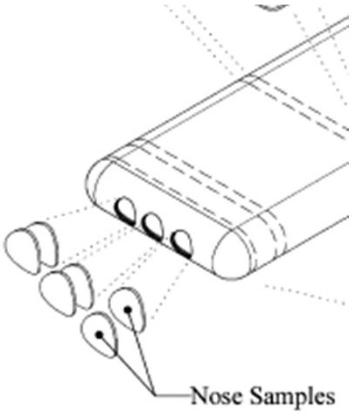
SNS – Liquid Mercury Target

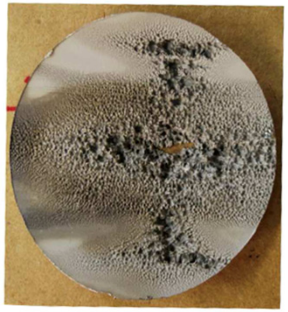
- Liquid Mercury container with water shroud around
- Target design goal: 2500 MWh operation (~5dpa in steel)
- Target front cross-section 104x399 mm^2
- Beam spot on target: 70x200 mm^2
- All targets exceeded design goal and target 5 is in use now

Critical issue of liquid mercury target:

- Experience of pitting damage by collapse of cavitation bubbles
  - Shown for short pulses operation (<1 μs)
  - Damage on target scales much faster than linear with the beam power density





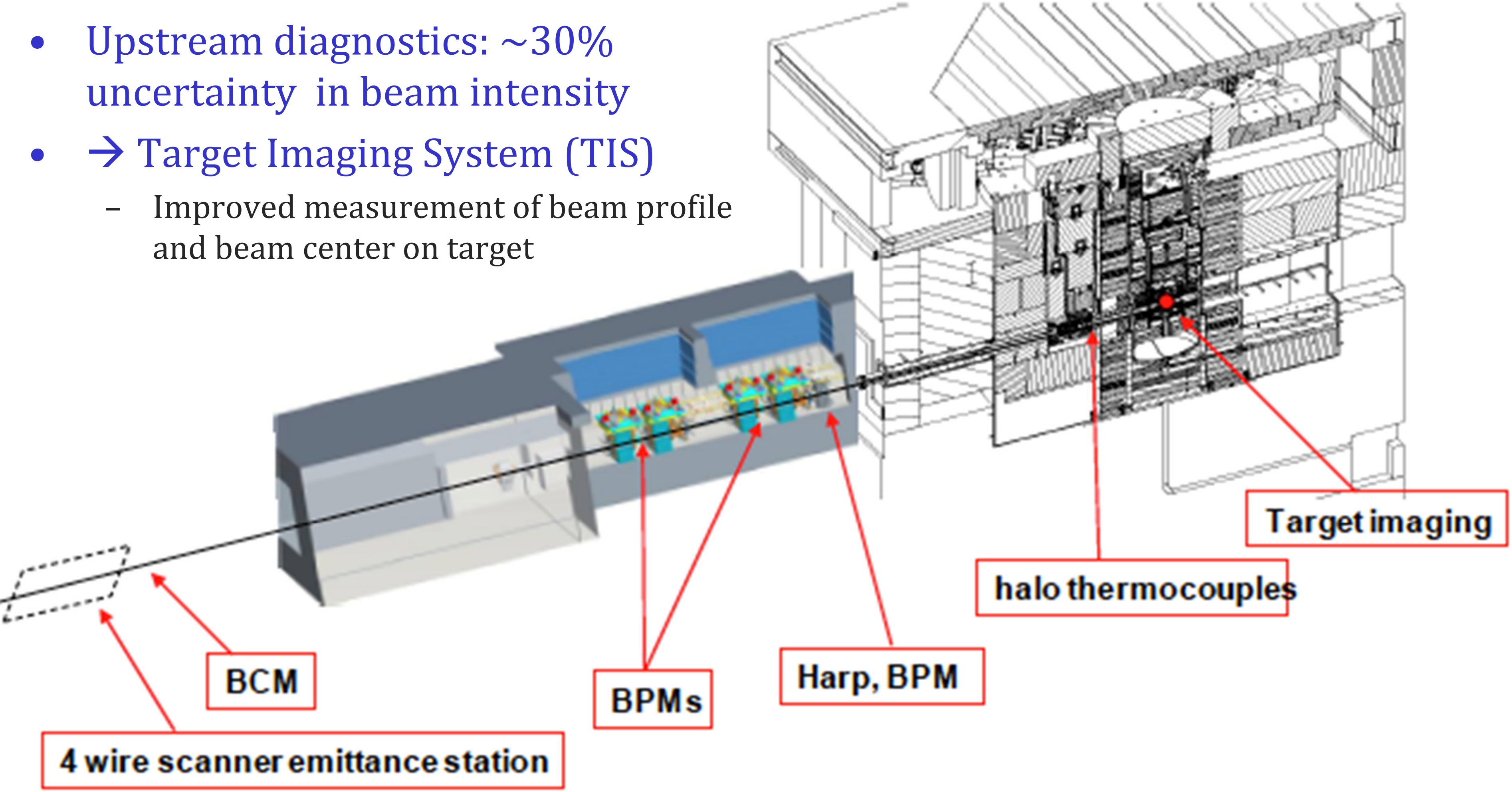


Target 1 center disk
Bulk flow side
After cleaning

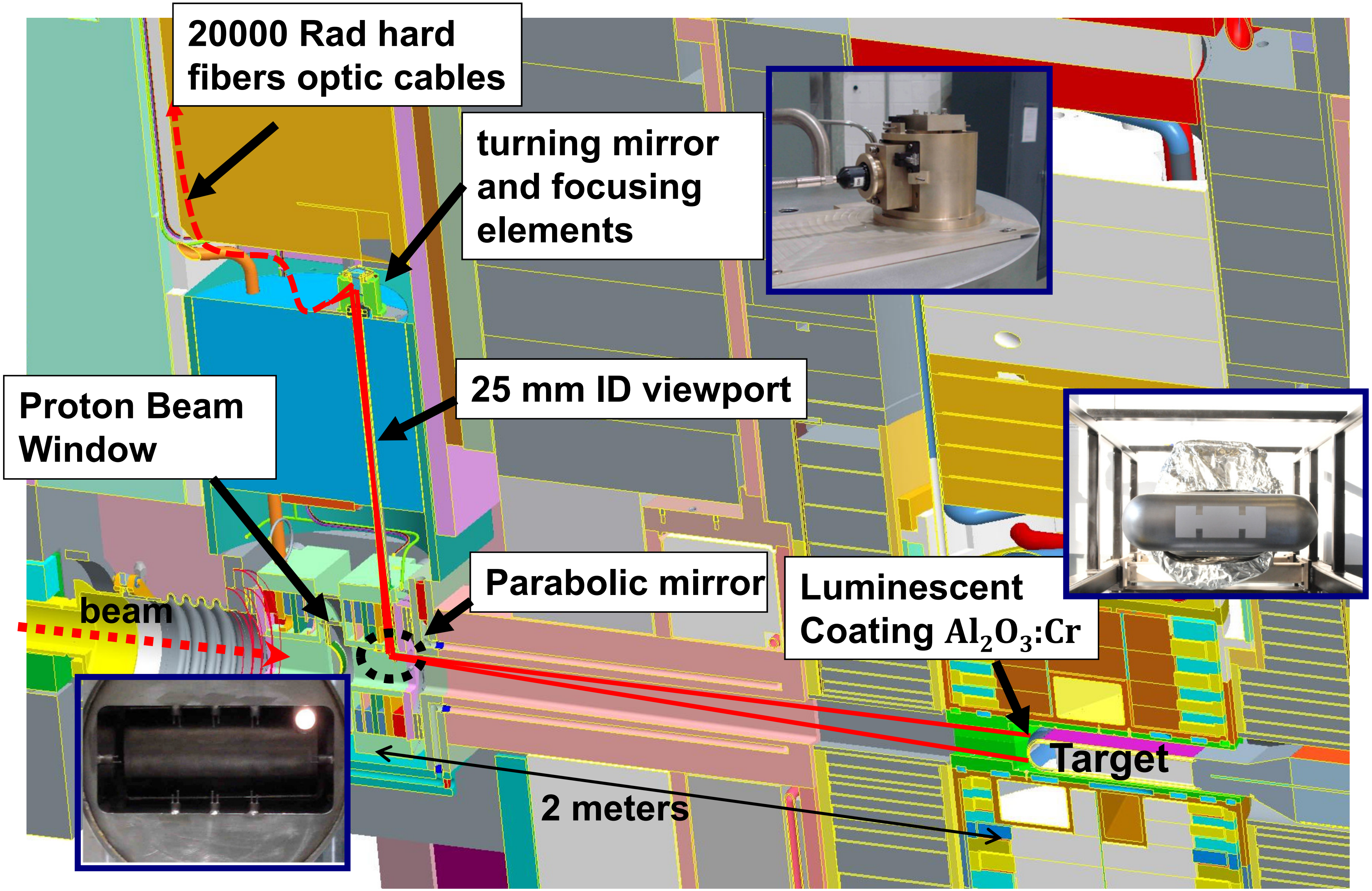
SNS – Beam Instrumentation around Target

Measurement and control of the beam intensity and beam distribution on target, in a region of extremely high radiation and very limited accessibility

- Upstream diagnostics: ~30% uncertainty in beam intensity
- → Target Imaging System (TIS)
  - Improved measurement of beam profile and beam center on target



SNS – Target Imaging System

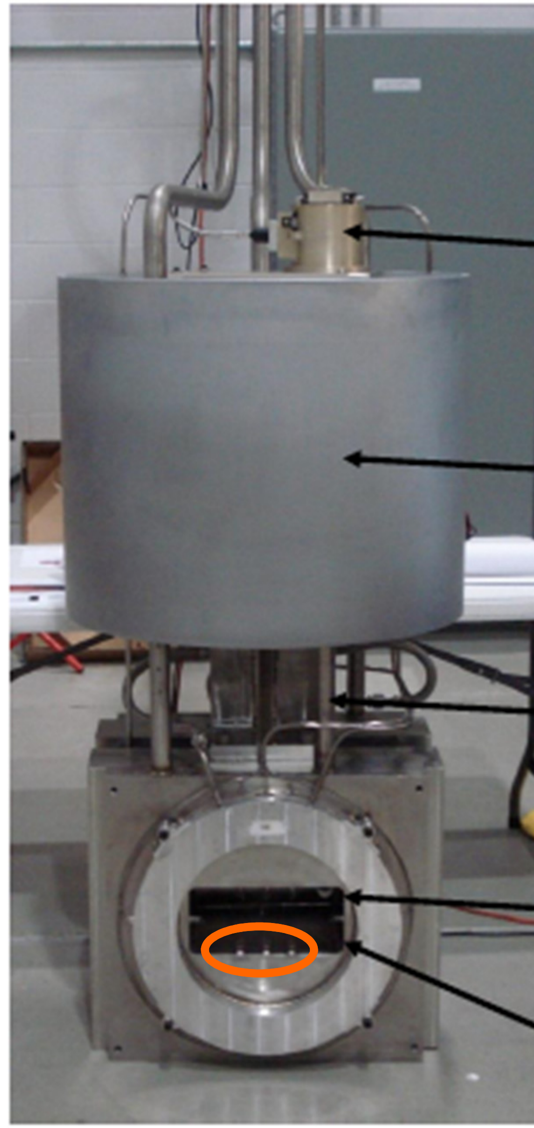


SNS – Target Imaging System

Photon source:

water shroud surrounding the target is coated with a thin luminescent material.

- Flame-sprayed Al_2O_3:Cr coating
  - 0.25 mm thick
  - Photon yield: 20 photons/proton/steradian



Imaging system:

Turning mirror, active hybrid lens, 20000 radiation hard fibers, 11.5 m long

1 m thick shielding plug

25 mm view tube

Off-axis parabolic mirror

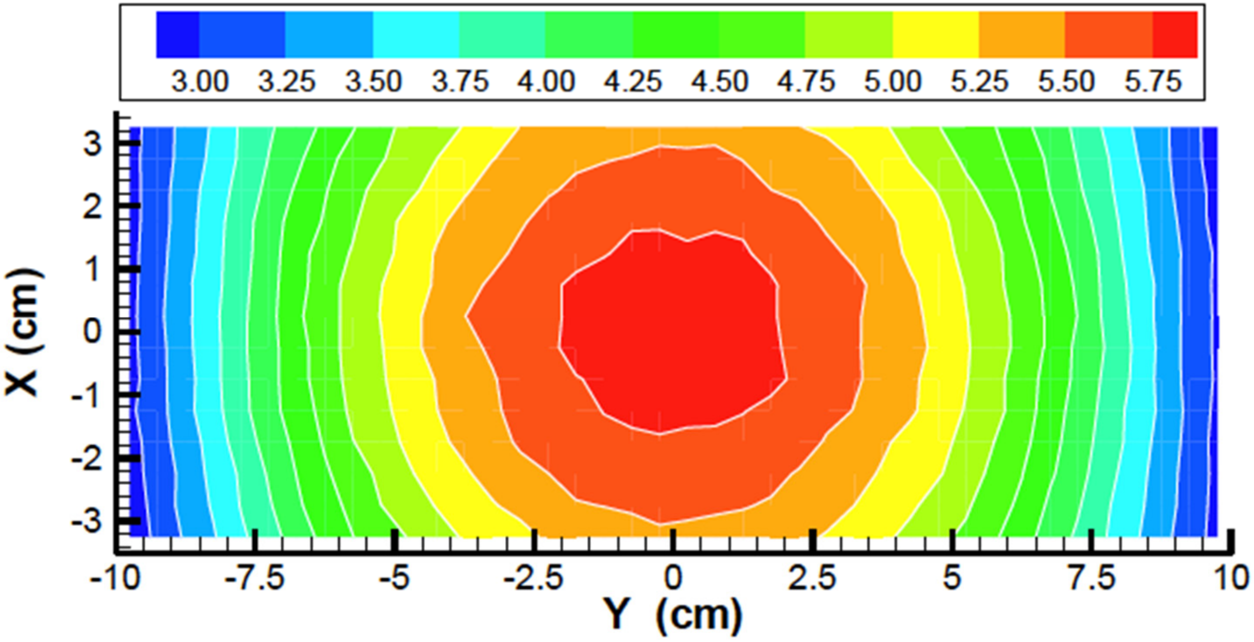
Proton beam window

Thermocouples for halo monitoring and beam centering

SNS – Operational Experience of Target Imaging System

- Mirror optics survives lifetime of window assembly:
  - Radiation environment near window at 1m above in Si is 1Gy for 1.5MW year

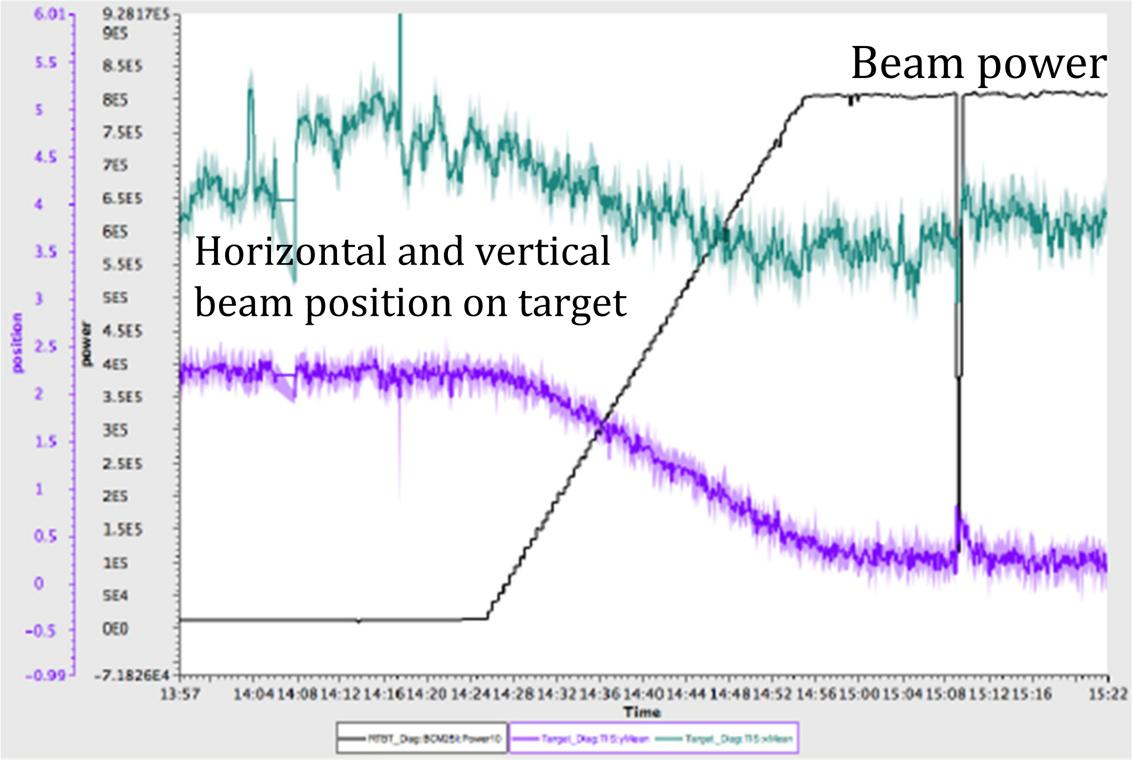
- Coating lasts the lifetime of the target



T. Shea

Calculated radiation damage to coating DPA in alumina spray (dpa/SNS yr/MW)

SNS – Operational Experience of Target Imaging System

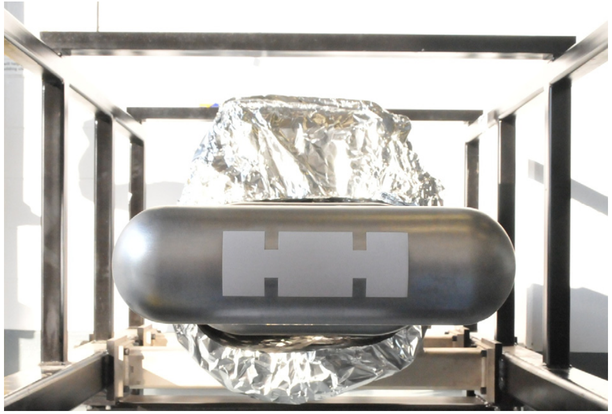


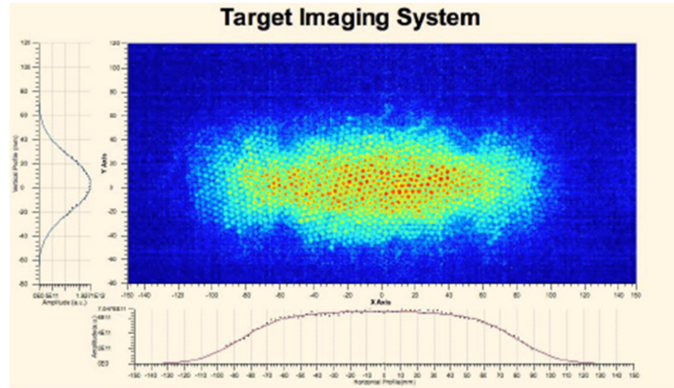
T. Shea

- 3mm accuracy on measured beam position (beam power dependent)
  - Due to thermally induced distortion of the parabolic mirror or the surface where mounted
  - → Corrected to better than 1mm with read-backs from nearby thermo-couplers on beam window

- Goal: 10% accuracy of peak intensity measurement → still working on this

SNS – Operational Experience of Target Imaging System





Display in Control Room

	Normal Condition	Off-normal	Action
Beam spot width height	200 mm 70 mm		
Beam power within nominal beam spot	>90 %	> 50% power outside spot	Immediate Shutdown – 2 pulses or less
Peak time-average beam current density	≤0.165 A/m^2	>0.165 and ≤0.181A/m^2	Correct within 30 min. or shutdown
		>0.181 A/m^2	Correct within 10 sec or shutdown
Peak single pulse density	≤1.72 x 10^16 protons/m^2	>2.15 x 10^16 prot/m^2	Immediate Shutdown – 2 pulses or less
Tolerance on beam horizontal centroid	±6 mm	> +/- 6 mm	Correct within 10 minutes or shutdown
Tolerance on beam vertical centroid	±4 mm	> +/- 4 mm	Correct within 10 minutes or shutdown

→ Using the TIS, tolerance on beam centroid is +/- 1mm

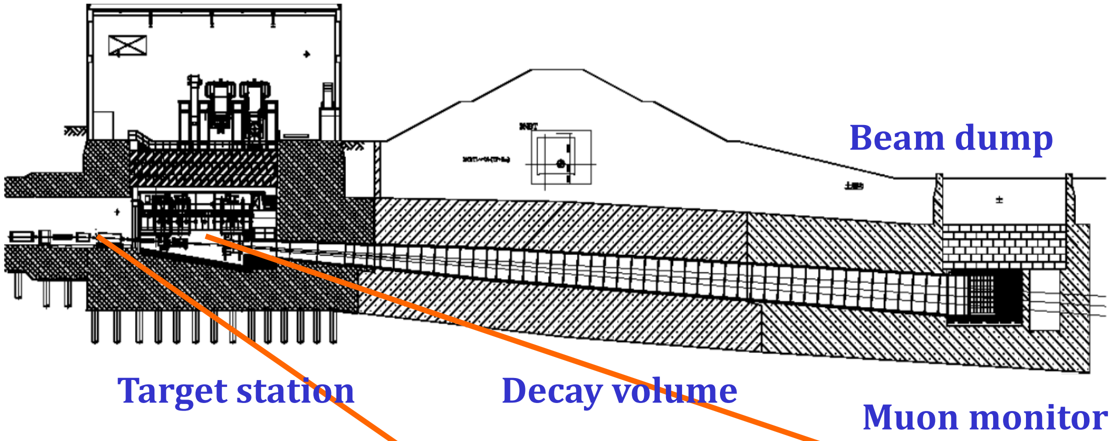
T2K

Neutrino Oscillation Experiment from Tokai to Kamioka, Japan

T2K – Remote Handling Example

Measure oscillation of $\nu_\mu \rightarrow \nu_e$

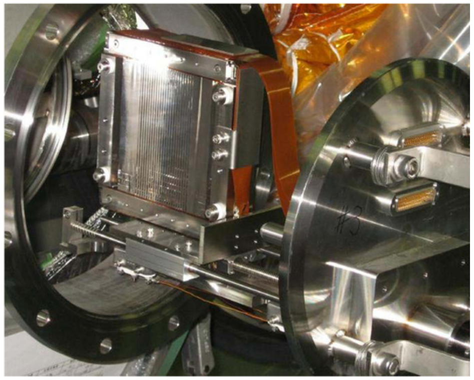
T2K Parameters	
Proton beam energy	30 GeV
Spill repetition rate	0.5 Hz
Number of bunches/spill	8
Protons per spill	3E14 p
Proton spill length	5 μs
Beam power (dedicated mode)	750 kW

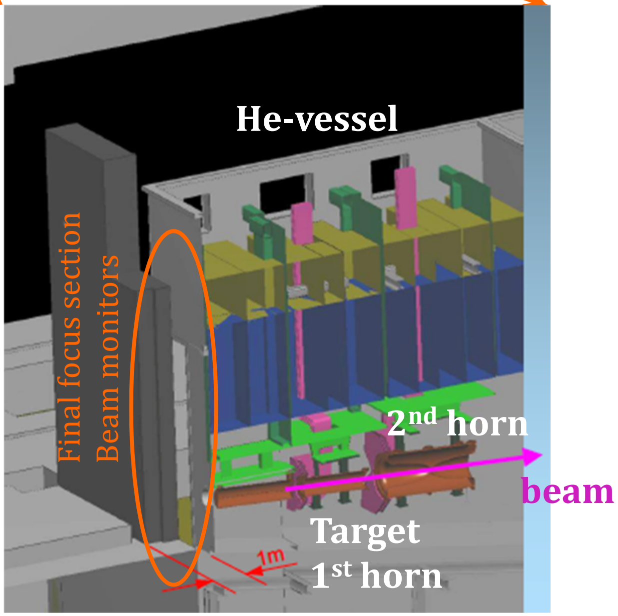


Final Focus Section Beam Monitors

→ Last meter upstream the target in vacuum area

- 1 Electrostatic BPMs
- 2 SSEM: segmented secondary emission foils for profiles
  - 5mm Ti strips, can be moved in/out

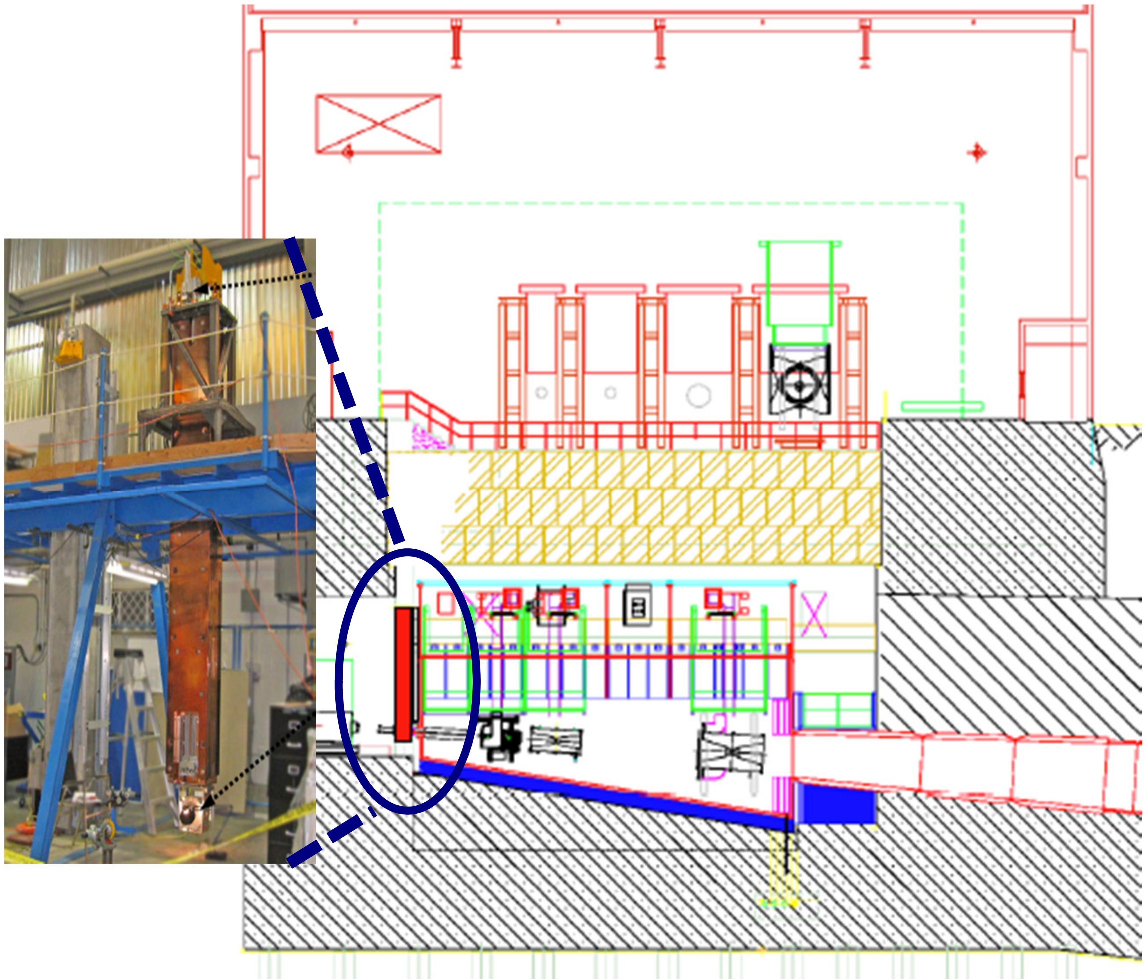




High radiation area → needs remote handling

T2K – Remote Handling

Final focus section beam monitors can be remotely removed/replaced/repaired



4.2m high steel shielding plug

→ Pulling out remotely from top of shield plug

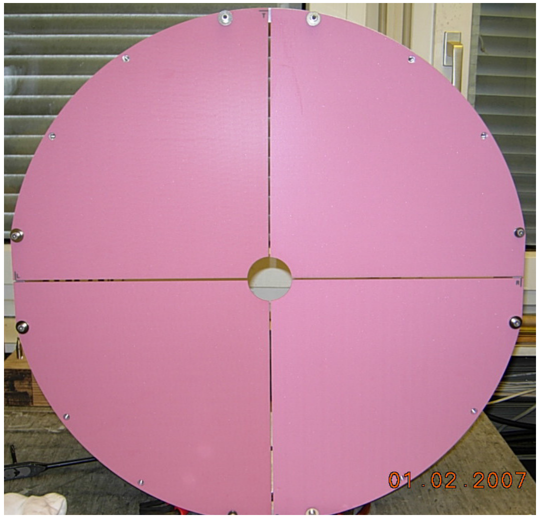
→ Disconnect/reconnect monitors remotely in hot cell

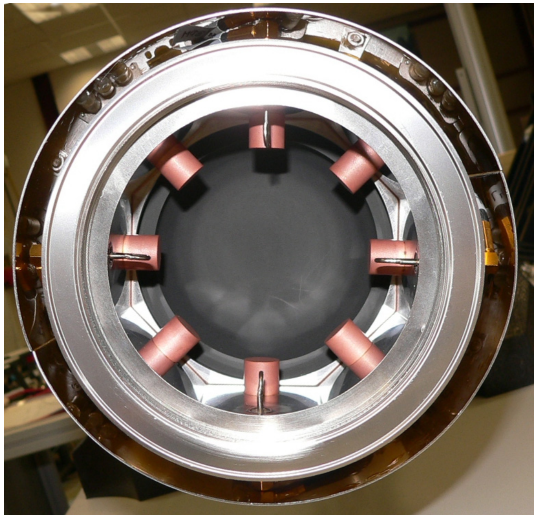
- Replacement is actuated from top of the shield plug with a mechanical clamp (SSEM) and screw draw-bolt (BPM) engagement.

→ Replacement alignment accuracy of the diagnostic monitors is +/- 0.1mm.

collaboration with **TRIUMF** and **RAL**

Diagnostics for Dumps





Beam Diagnostics for Dumps

Instrumentation often has to cover very large areas

- Beam is blown-up to a large size to reduce deposited energy density on the dump

1. Protection of beam dump and vacuum window
   - Measure beam profile on dump (beam dilution)

   → Beam screens

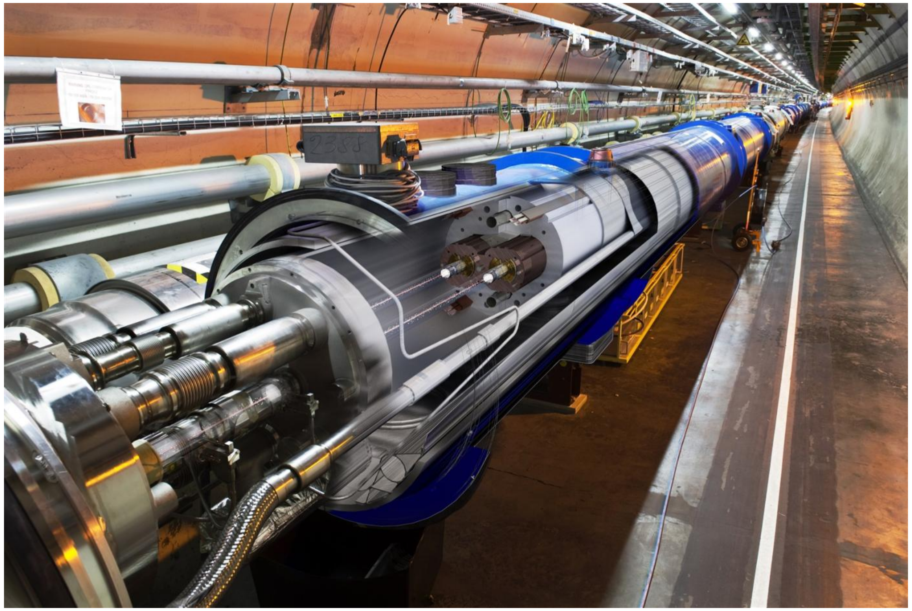
2. Ensure quality of beam dumping system

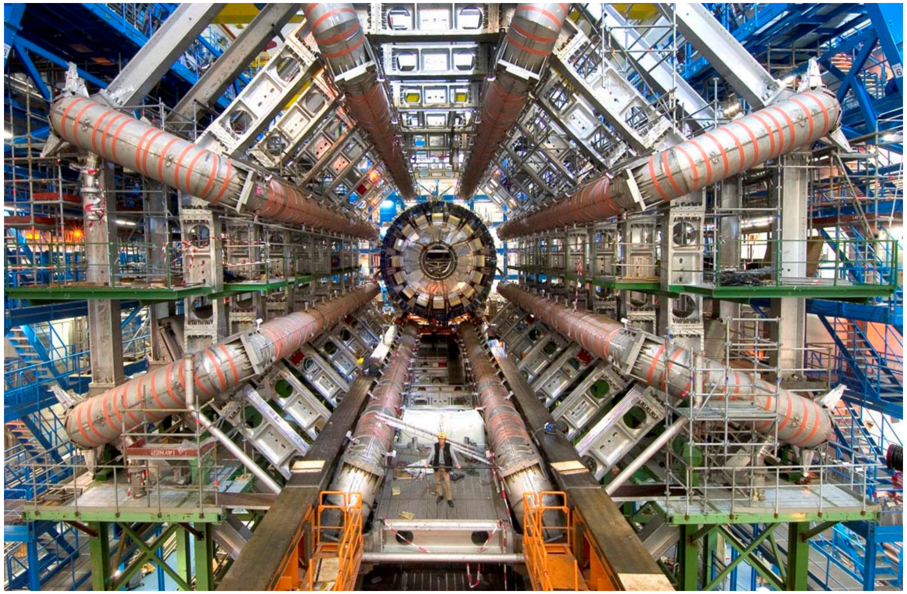
   → Beam halo monitors

   → Beam position monitors

   → Beam loss monitors

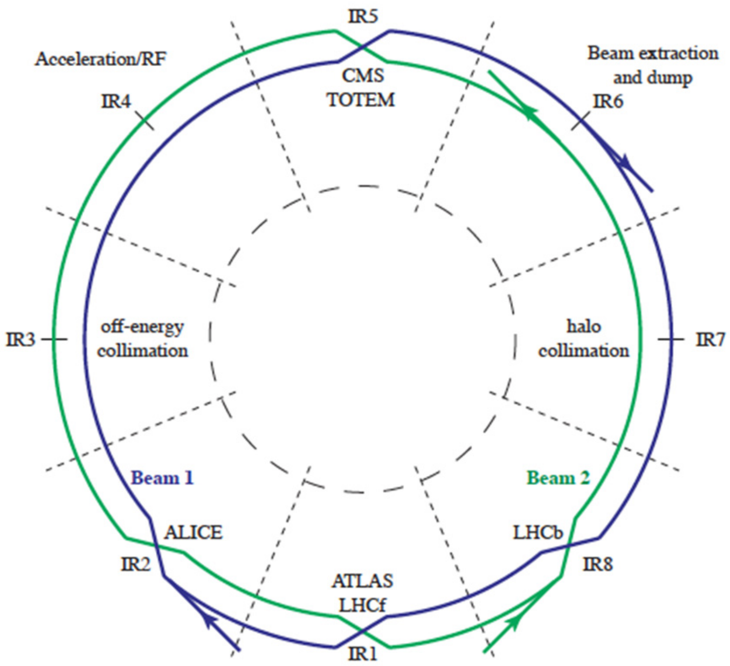
LHC
Large Hadron Collider
CERN





LHC

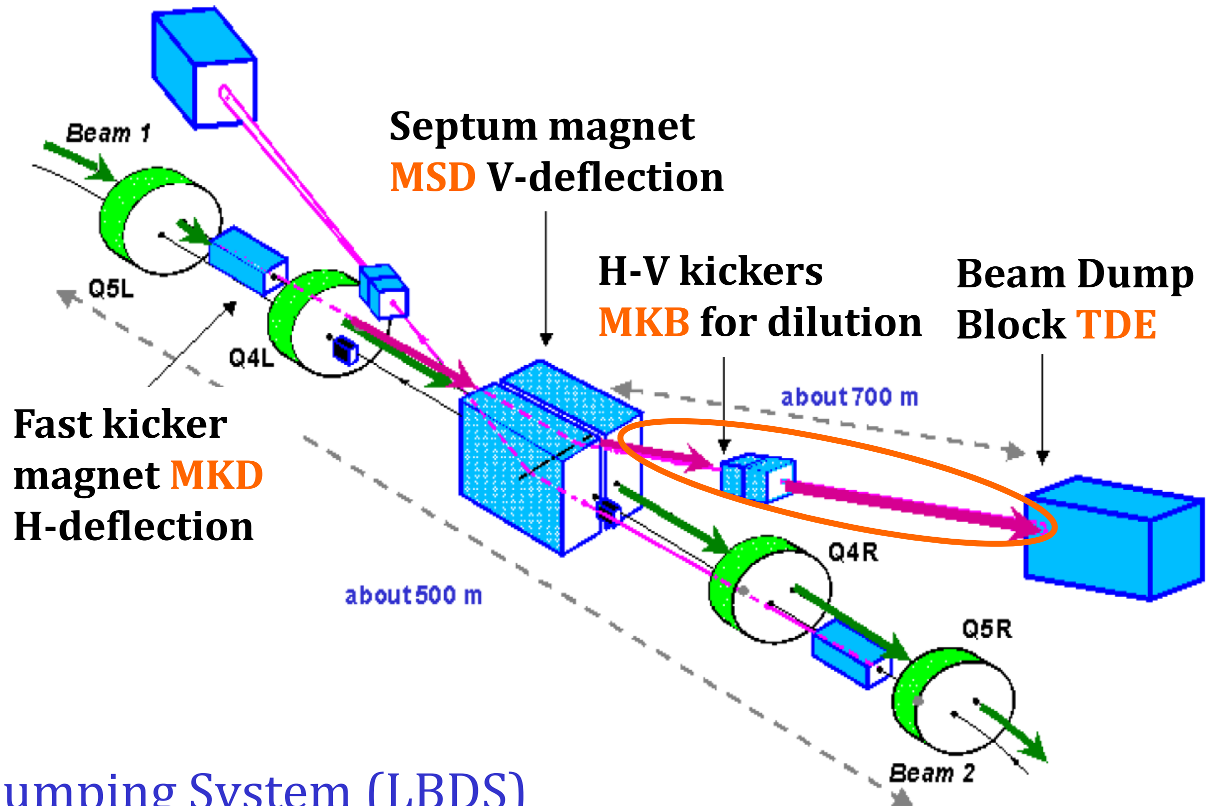
LHC Parameters	
Proton beam kinetic energy	7 TeV
Number of bunches	2808
protons per bunch	1.15E11
Bunch spacing	25ns
Peak luminosity	$10^{34}cm^{-2}s^{-1}$
Stored beam energy	360 MJ
Time of 1 LHC revolution	89 μs



→ Safely deposit the LHC beam with beam dump system

- Comply with Safety and Integrity Level 4, SIL4 (Probability of failure of demand $=10^{-4}$ - 10^{-5})

LHC – Beam Dump Principle



LHC Beam Dumping System (LBDS)

→ After every dump the signals of beam dumping control system and beam instrumentation measurements are automatically analyzed by the *eXternal Post-Operational Checks (XPOC)* system.

→ Ascertain that beam dumping system is 'as good as new' before new injection.

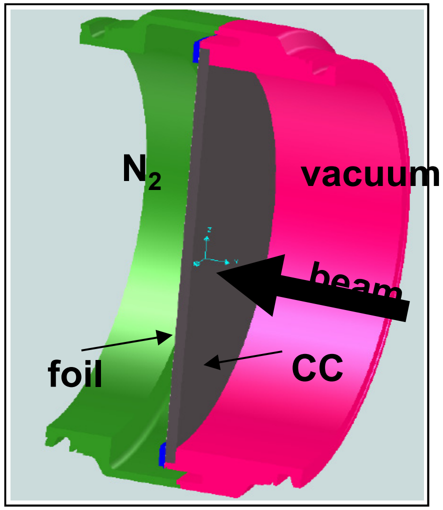
LHC – Beam Dump and Window

Beam dump

- 7.7m long, ⃠=700mm, graphite core
- Graded density of 1.1 g/cm^3 and 1.7g/cm^3
- 12 mm wall, stain-less steel welded pressure vessel, filled with N_2 @1.2 bar
  - Direct interlock on pressure of N_2 in gas-tank and bottle → always active
- ~1000 tons of concrete/steel shielding blocks

Beam dump entrance window

- 15mm thick, d=600mm, CC composite window, 0.2 mm stainless steel backing foil

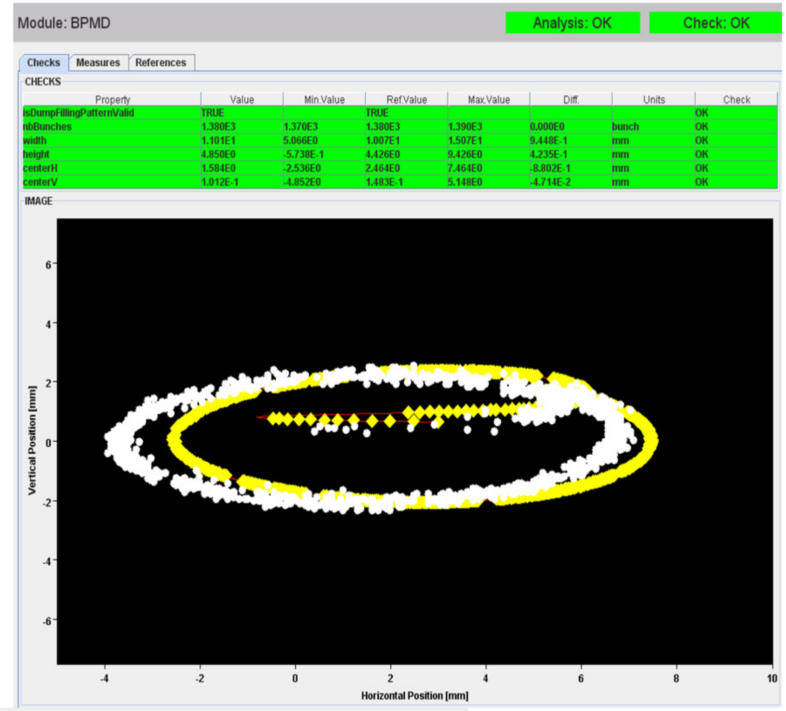


LHC – Beam Dump System

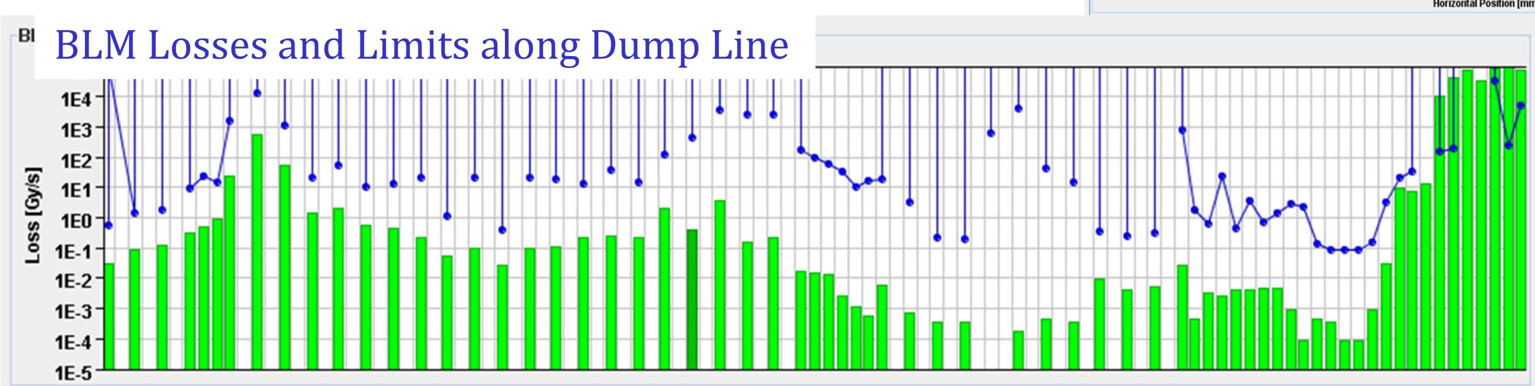
eXternal Operational Checks (XPOC) system analyses after every dump:

- Extraction and dilution kicker waveforms
- BPMs in dump line, also total number of bunches
- Beam intensities in dump line
- BLMs in extraction region, dump line and at collimators distributed over the machine
- Vacuum pressure in dump line and N_2 (over)pressure in dump itself
- Beam population in the 3μs abort gap required to accommodate the extraction kicker rise-time
- **Beam image on scintillation screen in front of dump**

BPM bunch count in dump line measured (white), expected (yellow)

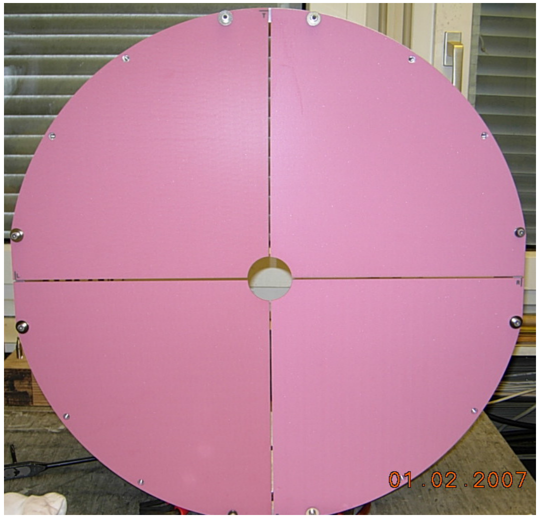


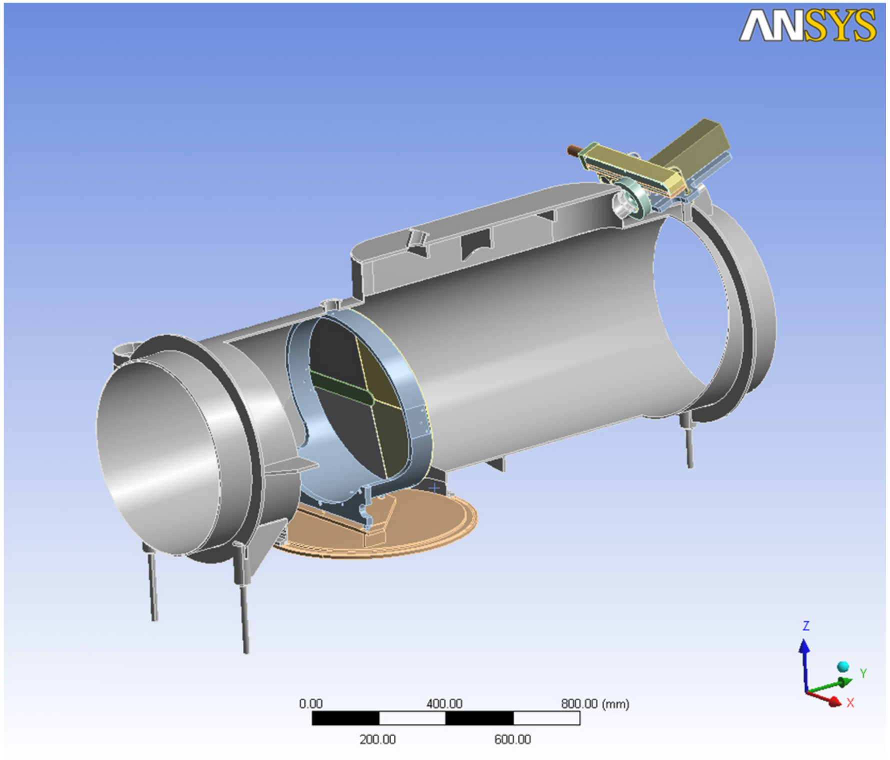
BLM Losses and Limits along Dump Line



19/04/2012
4 TeV
1380 bunches

LHC – Large Luminescence Screen, BTVDD





$Al_2O_3:Cr^{3+}$ screen

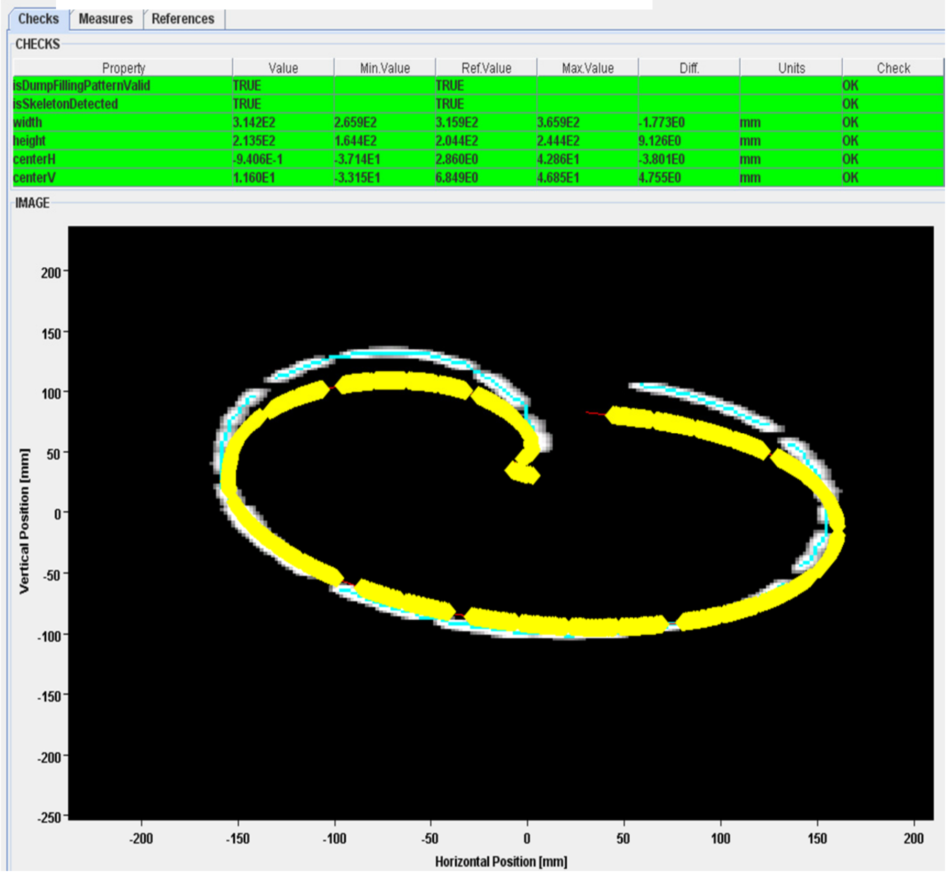
- 3mm thick, ⃠=600mm, 4 quadrants
- Central area open with ⃠=50mm
- Covered with $50x360mm^2$ rectangular screen
- Screen (camera): 80(20)° tilt angle
- Resolution of screen: <1mm
- Radiation hard: tested up to 10^{20} p/cm^2
- installed ~30m upstream of vacuum window

Radiation resistant camera (up to 10Mrad)

- Control unit for sensor 25m upstream of BTVDD tank
- Control with VME card 800m from BTVDD in technical gallery

LHC – Large Luminescence Screen, BTVDD

BTVDD – luminescence screen



Property	Value	Min.Value	Ref.Value	Max.Value	Diff.	Units	Check
isDumpFillingPatternValid	TRUE		TRUE				OK
isSkeletonDetected	TRUE		TRUE				OK
width	3.142E2	2.659E2	3.159E2	3.659E2	-1.773E0	mm	OK
height	2.135E2	1.644E2	2.044E2	2.444E2	9.126E0	mm	OK
centerH	-9.406E-1	-3.714E1	2.860E0	4.286E1	-3.801E0	mm	OK
centerV	1.160E1	-3.315E1	6.849E0	4.685E1	4.755E0	mm	OK

19/04/2012, 4 TeV, 1380 bunches

Sweeping beam with dilution kickers over 400mm diameter area

→ reduces beam density from ~10^{15} p/mm^2 to ~10^{11} p/mm^2

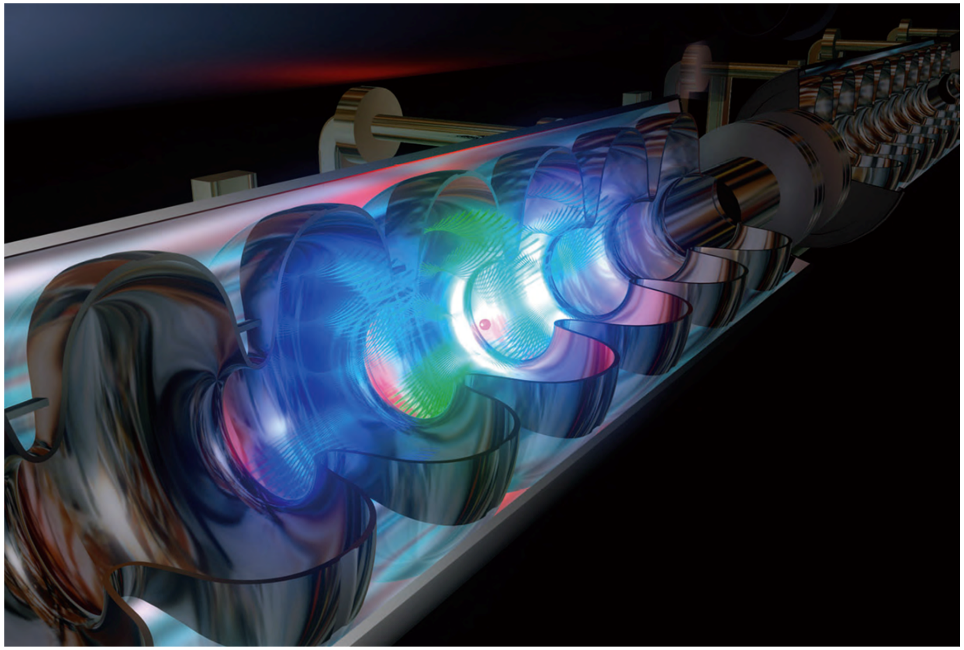
Crucial tool to perform an immediate 'on-line' diagnosis of the beam dump system

Experience with BTVDD:

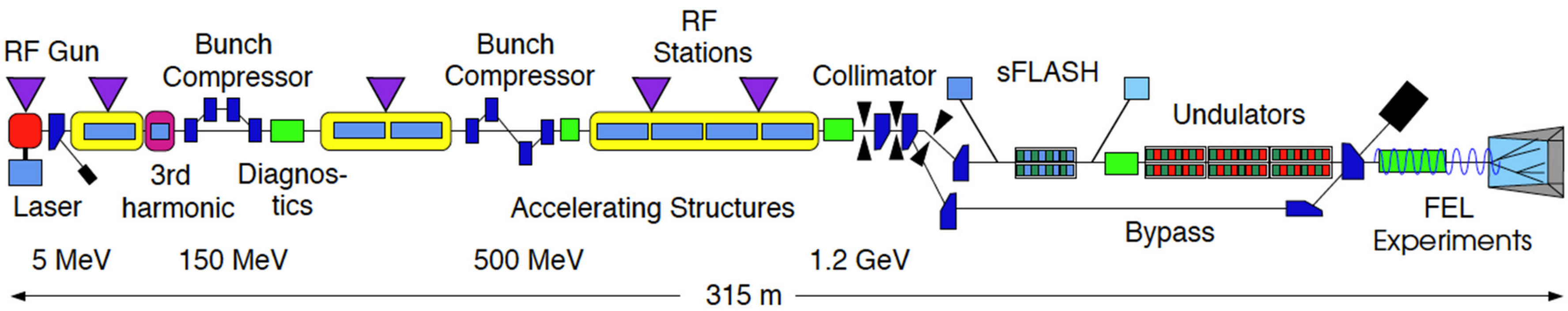
Best measurement result achieved when images are taken up to one second after the beam passage
→ Avoids radiation effects of the camera at the moment of beam passage

FLASH

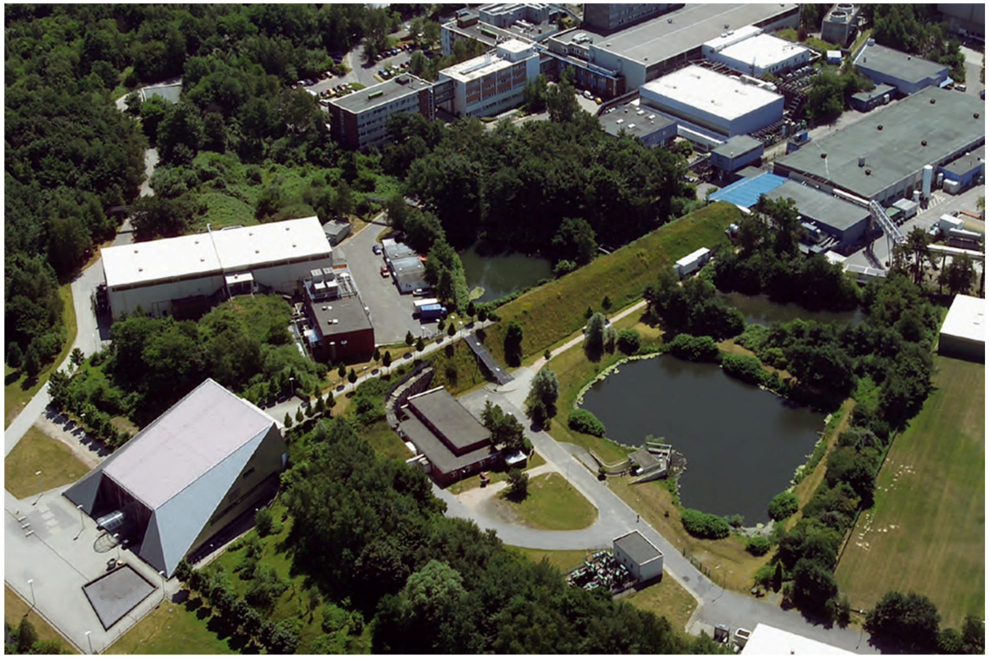
Free Electron Laser in Hamburg



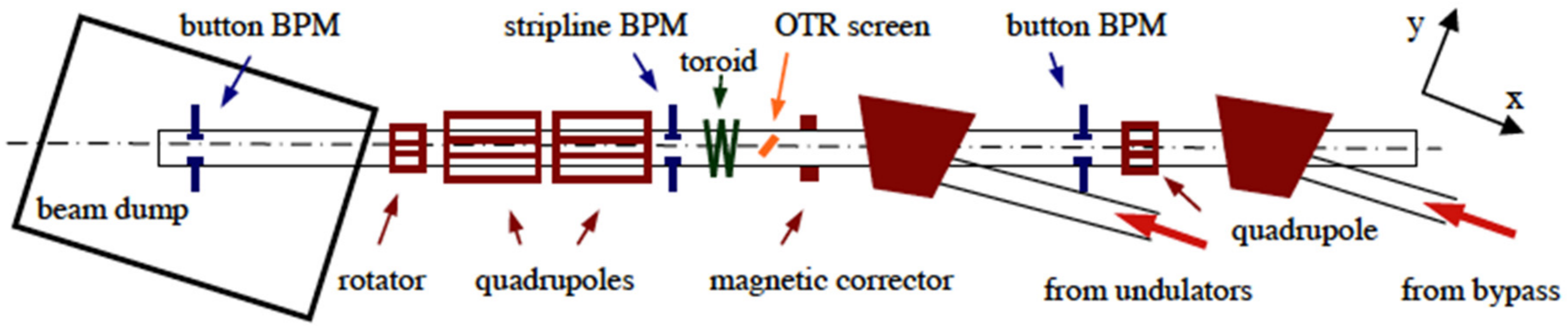
FLASH- Free-Electron LASer in Hamburg



- Facility:
  - Delivers ultra-short femtosecond coherent radiation in VUV and soft X-ray regime (44-4.2nm) to users
  - Also used for beam tests for XFEL and ILC → require long bunch trains.
- e-beam:
  - 1.25GeV, max pulse length: 800µs, 1-3nC/bunch, 0.1-1(3)MHz bunch repetition frequency



FLASH – Beam Dump Diagnostics



Damage due to a long high-current electron beam pulse happened in 2008

- Vaccuum leak occurred near the beam dump in autumn 2008

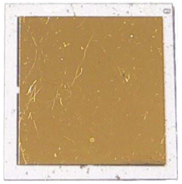
Beam halo monitors have been installed to make sure that beam and also beam halo stay inside the beam pipe close to the beam dump.

- Signals earlier than the other systems when the beam approaches the beam pipe.

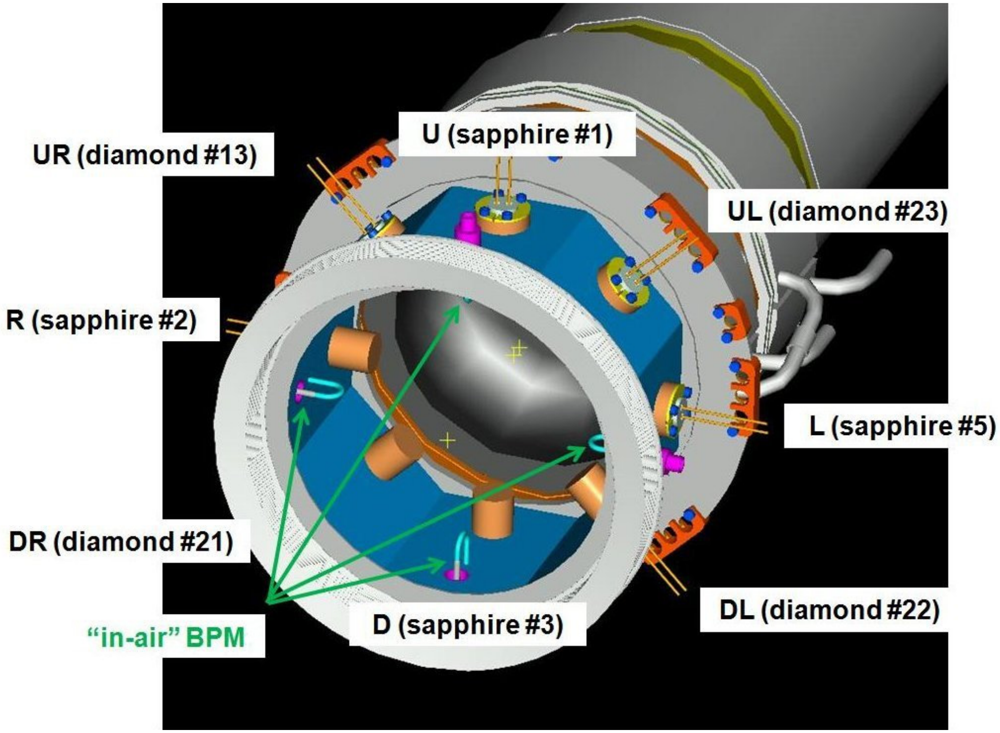
→ Also ionization chambers and glass fibers (beam loss monitor) were installed in the last section of the dump line.

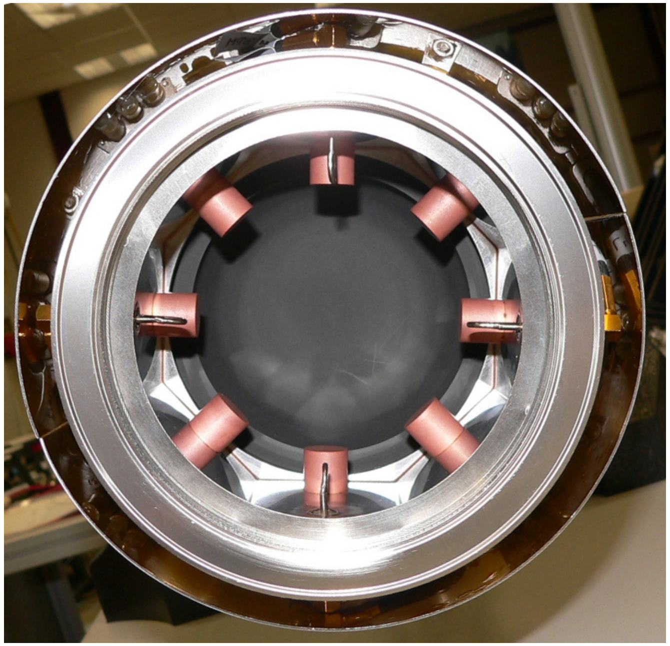
FLASH – Beam Halo Monitors, BHM

4 pCVD detectors
12x12x0.3mm^3
3.52 g/cm^3, 13.2eV e^-/hole
pair creation energy



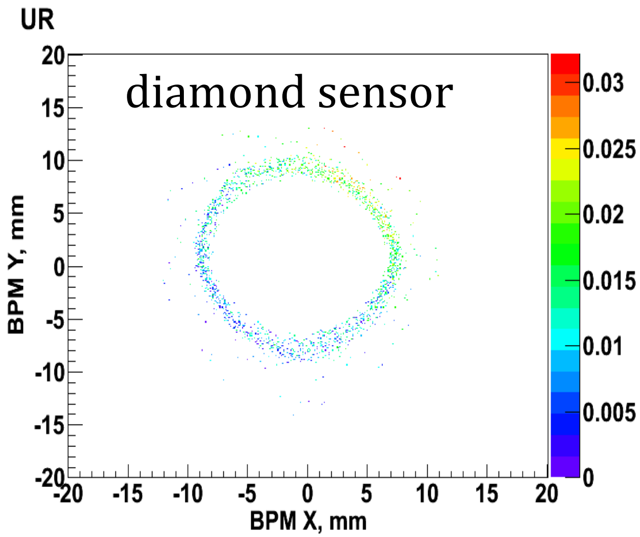
4 single crystal sapphire (Al_2O_3)
12x12x0.5mm^3
3.98 g/cm^3, 24.6eV e^-/hole
pair creation energy

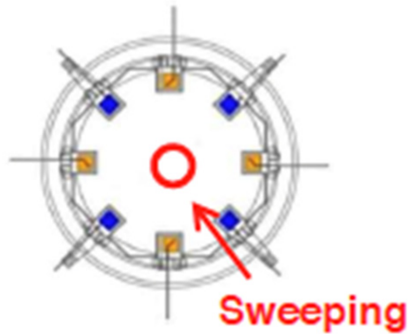




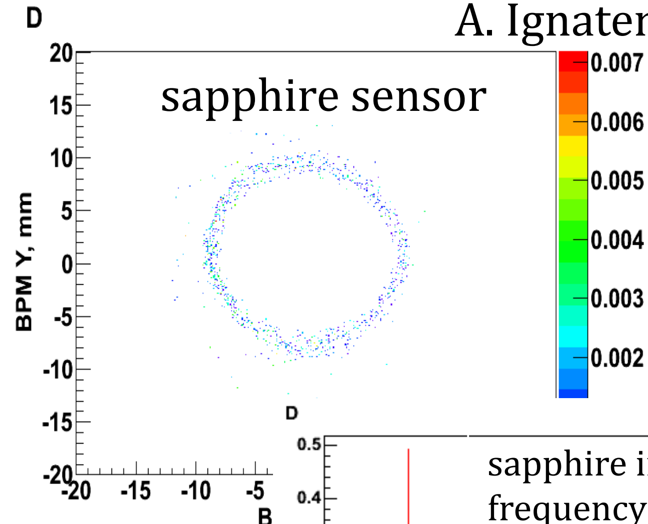
- Withstand several MGy
- BHM detect even small beam offsets inside last section of beam pipe

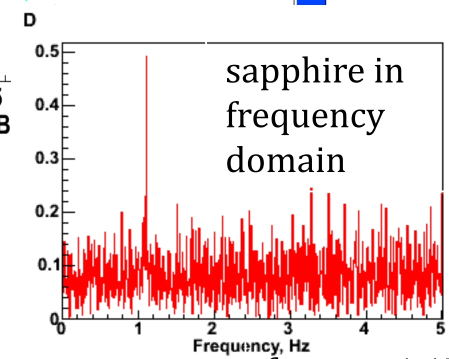
FLASH – BHM





A. Ignatenko





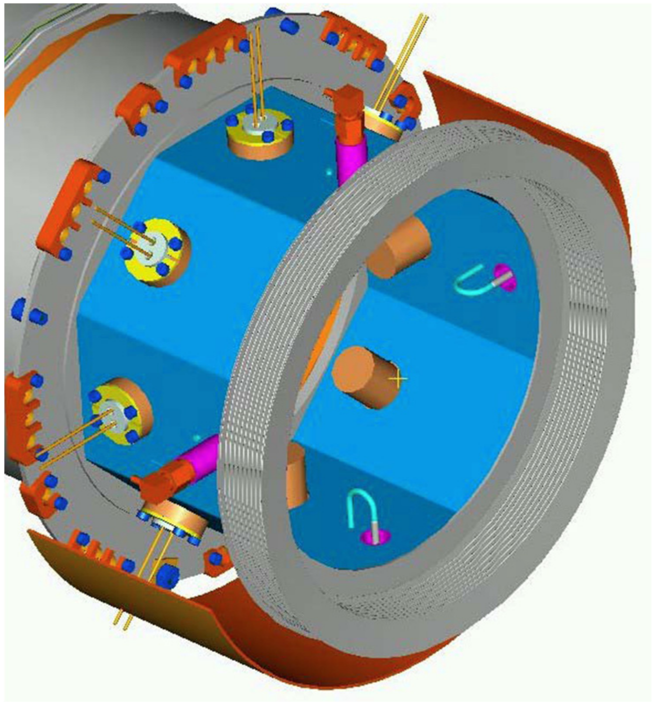
$f_{sweeping}$: 1.1Hz

- BHMs have been commissioned in September 2009
- Diamond sensors are more sensitive than sapphire detectors
  - Diamonds saturate at ~70pC hitting the sensor directly; while sapphires saturate at much higher charges (if at all)
  - Combination of diamond and sapphire enhances dynamic range
- Dependence on signal amplitude could be basis to abort the beam
- BHM also designed for FLASH II and XFEL (installed outside beam pipe)

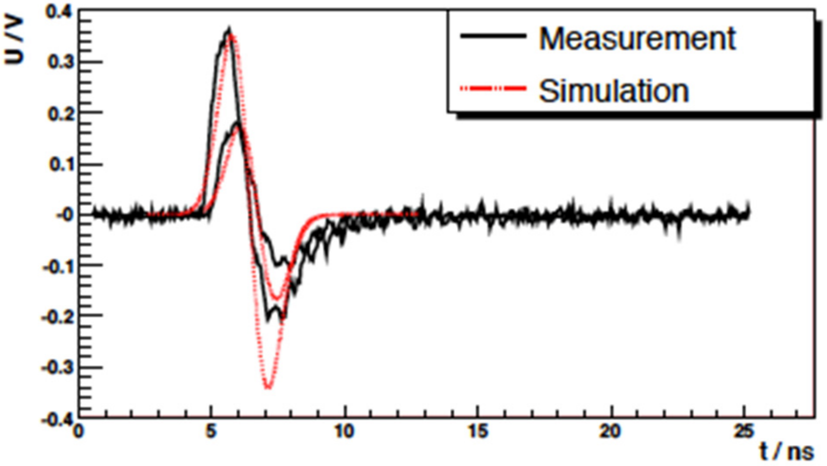
FLASH – Magnetic Coupled BPM

Magnetic coupled Beam Position Monitor

- After the vacuum window in area filled with dry Nitrogen N_2.
- Use magnetic field of bunches to generate position signal.
- 4 wire loops, placed parallel to the beam for optimal coupling.
- Each signal is low-pass filtered below 200 MHz to cut high frequency components of the compressed beam (also done for button BPMs)



D. Lipka



Measurements done during 9mA run:

- Agreement good in positive part

Summary

- Solutions for diagnostics depends on characteristics of each facility
  - Achieve redundancy by installing large number of monitors
  - Using fast and radiation hard materials: e.g. diamond detectors
  - Development towards optical signal transmission to monitors: e.g. screens & cameras.

- Common feature of diagnostics for high power targets and dumps
  - High radiation environment
  - Remote handling and repair/replacement of monitors in hot cells
  - Very close link between beam diagnostics and interlock system