Protection Related to High Power Targets

by

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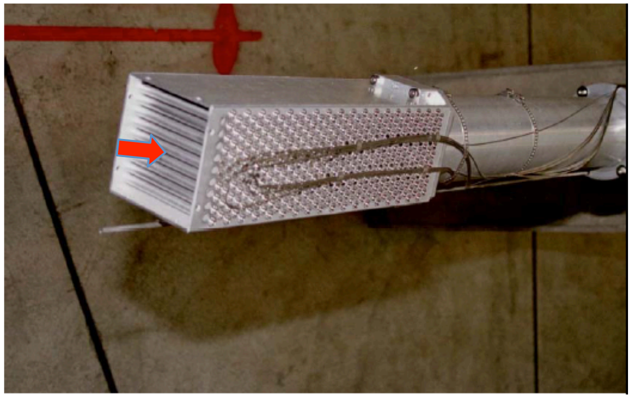
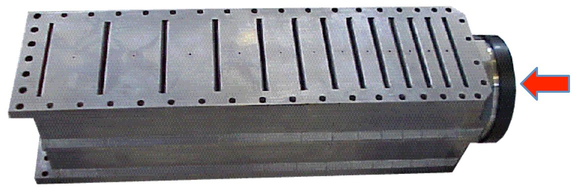
Introduction to high power targets

- In general, need high power targets to create either lots of secondary particles, or to make as many secondary particles as possible when the creation cross sections are very low
- High power targets come in many shapes and sizes, and have many uses
  - Neutron spallation targets (LANSCE, ISIS, SNS, J-PARC, PSI)
  - Muon production targets (J-PARC, PSI, TRIUMF, ISIS)
  - ISOL facilities (CERN, TRIUMF, IRIS, …)
  - Material irradiation studies (IFMIF, …)
  - Antiproton production (FNAL)
  - Neutrino production (FNAL, J-PARC, CERN)

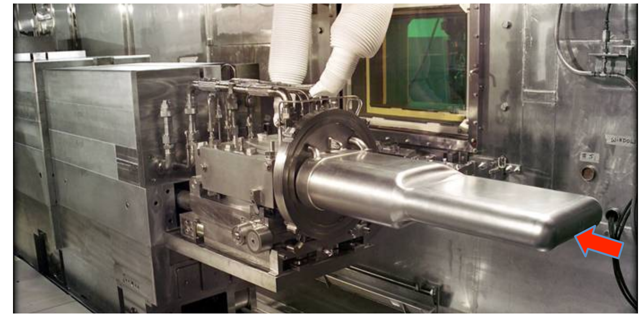
Some neutron spallation targets



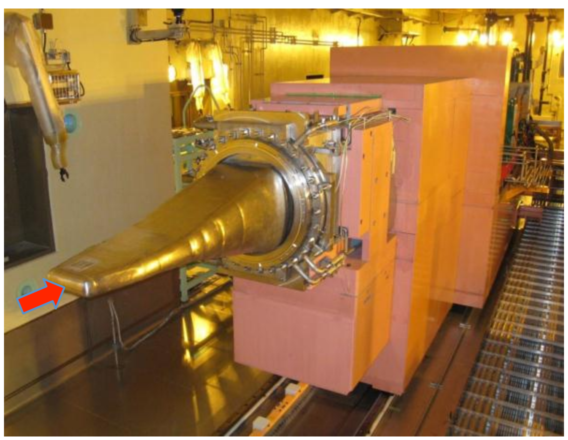
PSI's SINQ target
Lead rods, steel tube cladding



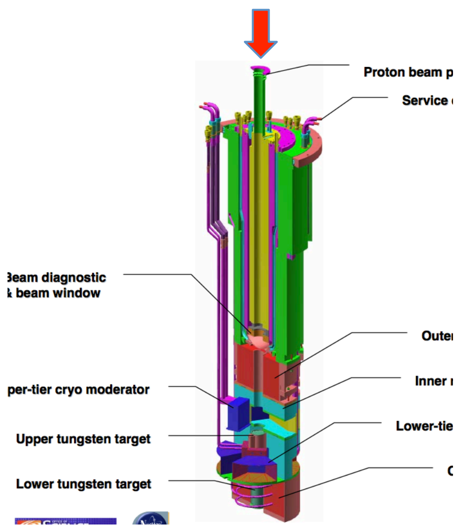
ISIS T1
Ta clad W



SNS mercury target

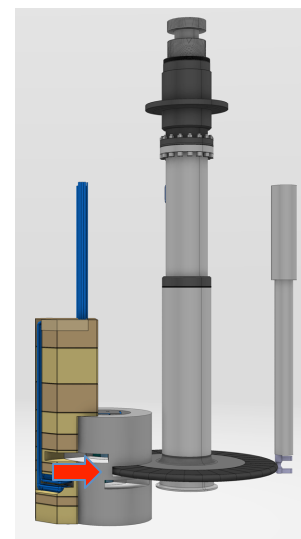


J-PARC mercury target



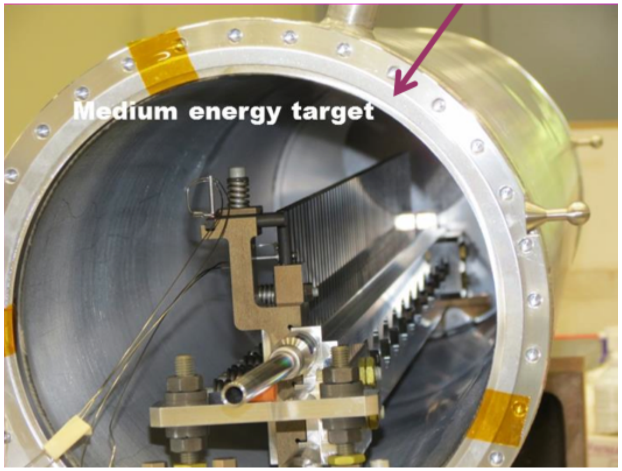
LANSCE
tungsten target

ISIS T2
Ta clad W

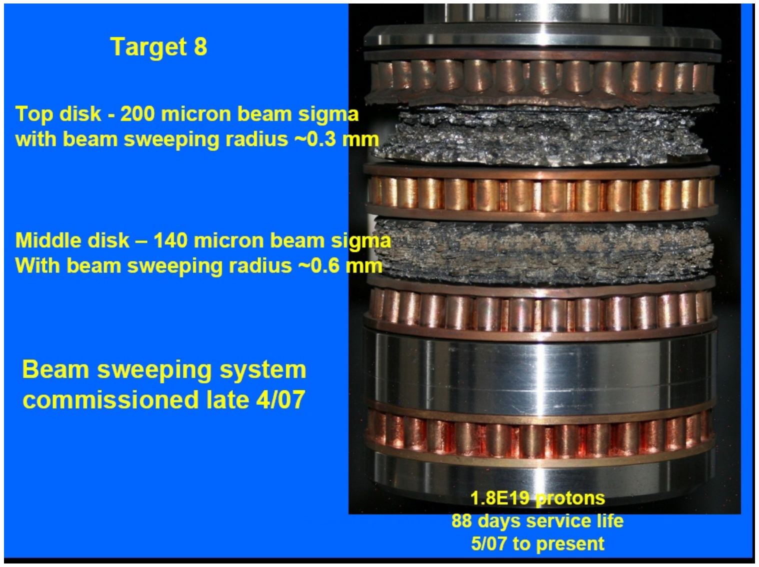


ESS tungsten target
(in design)

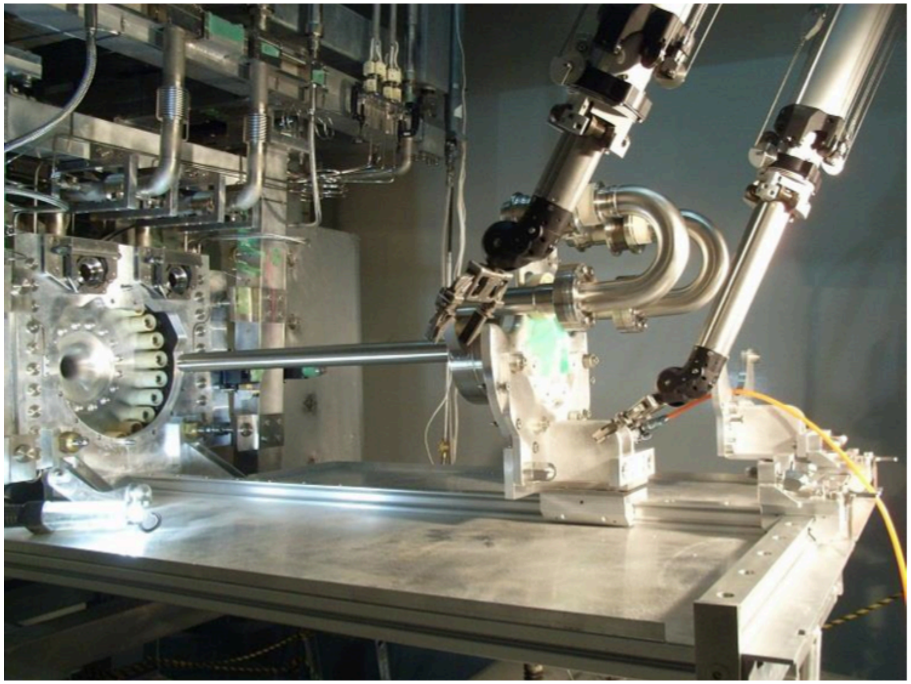
Some other high power targets



FNAL's NUMI carbon target



FNAL's pbar production target



J-PARC's T2K graphite target
26 mm dia x 910 mm long

Some ISOL targets

Rutherford RIST ISOL target
Stacks of Ta discs and washers

TRIUMF ISOL target
Diffusion bonded Mo foils

High power target challenges – the short list

- Removing the heat generated mainly by the beam, but also by nuclear decay
- Mechanical shock due to thermal stress from pulsed beams
- Radiation damage, including swelling & embrittlement
- Target handling (including installation and maintenance in a high radiation environment)
- Corrosive environment
- Beam parameters – matching target requirements to what the accelerator can deliver

Selected High Power Target Facilities with Proton Beam Power > 100 kW

Facility	Status	Target Material	Beam Pulse Duration (μs)	Beam Pulse Rep Rate (Hz)	Proton Energy (GeV)	Time Ave Beam Power (MW)	Peak Time Ave Power Density (GW/m^3)	Peak Energy Density (MJ/m^3)
ISIS TGT-1	Operating	W	0.4	40	0.8	0.16	1	25
ISIS TGT-2	Operating	W	0.4	10	0.8	0.04	1	100
LANSCE-Lujan	Operating	W	0.3	20	0.8	0.16	0.5	25
NuMi	Operating	C	8.6	0.53	120	0.7	0.32	600
SINQ/Solid Target	Operating	Pb, SS clad	CW		0.57	1	1	NA
SINQ/ MEGAPIE	Completed	Pb-Bi	CW		0.57	1	1	NA
JSNS	Operating	Hg		25	3	1	0.63	25
SNS	Operating	Hg	0.7	60	1	2	0.8	13
ESS - long pulse	Proposed	Hg	2,000	16.7	1.3	5	2.5	150
ESS - short pulse	Proposed	Hg	1.2	50	1.3	5	2.5	50
EURISOL	Proposed	Hg	3	50	2.2	4	100	2,000
IFMIF	Proposed	Li	CW		0.04 (D_2)	10	100	NA
LANSCE- MTS	Proposed	Pb-Bi/W	1,000	120	0.8	0.8	2.4	20
US Neutrino Factory	Proposed	Hg or C	0.003	15	24	1	3.8	1,080

Courtesy J. Haines

Target environment

- The target environment is often rough vacuum or helium
  - Vacuum is good because it does not interfere with the beams (primary or secondary)
  - Helium atmosphere is good because it helps cool components while minimizing its impact on the beams
    - However, impurities in helium can lead to corrosion of components
- Beam transport lines leading up to the target need good vacuum to minimize beam loss
  - So high power targets often involve windows to separate the beamline vacuum from the target environment
- Safety separation must also be considered – usually required for a liquid metal target

Corrosion in air and helium environments

- A partial pressure of air can result in the formation of nitric acid which can cause stress corrosion cracking in high strength steel or vacuum leaks in thin bellows exposed to stray beam with air outside.
- IPNS had a target bolt fail from stress corrosion cracking in a nominal helium atmosphere with air impurities when high strength steel was substituted for stainless steel.
- ISIS has observed corrosion around the target/reflector assemblies and limits impurities to below a couple of % in helium

Fermilab example

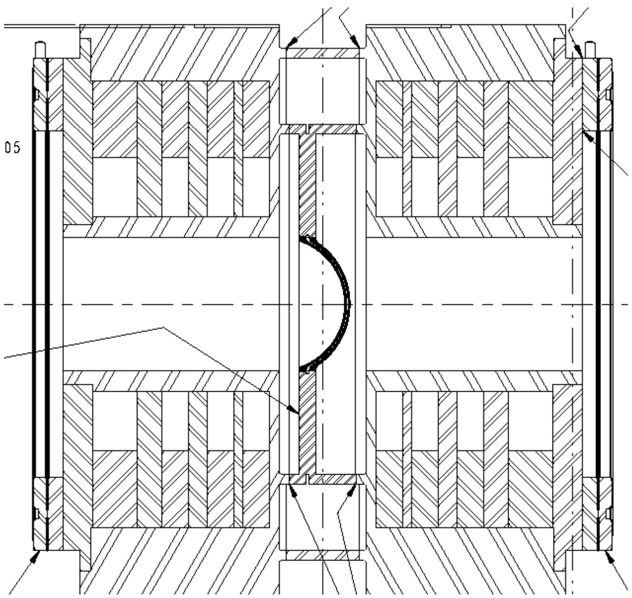
Additional Operational Concerns

- HS broken steel chain from hydrogen embrittlement caused by acidic vapors/condensate from air ionization (MiniBooNE 25 m absorber).

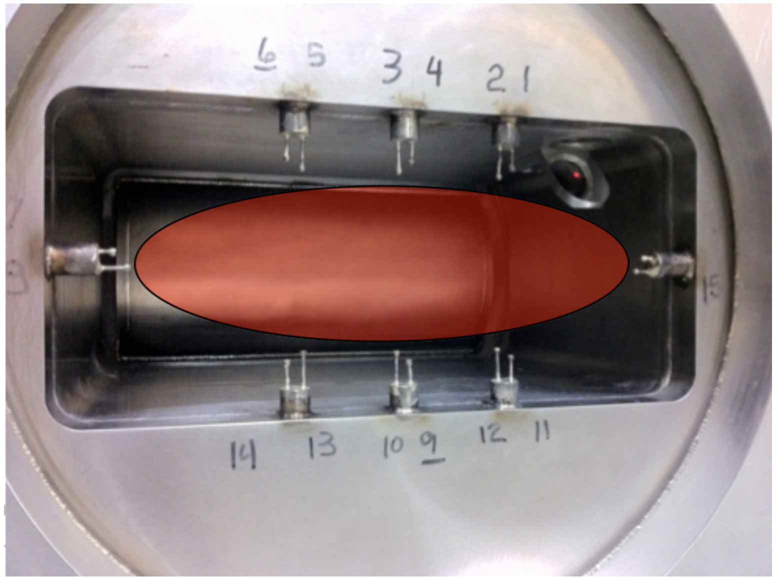
2007 HPT Workshop - P. Hurh/J. Hylen 22

Beam windows

- Just like the target, beam windows are also challenged by high power beams, due to heating, thermal stress, radiation damage, etc.
- Example: SNS target is in 1 atm He environment, uses Inconel beam window



SNS window side view



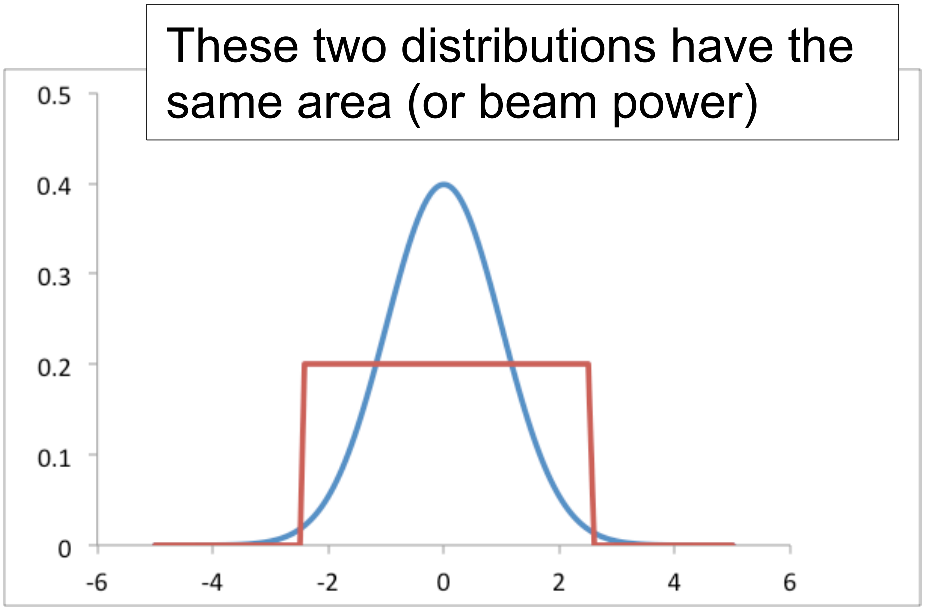
View from downstream side

Most important beam parameters

- The highest power targets push the edge of achievable technology, and to live on the edge requires a very narrow range of beam parameters to avoid overpowering the target
- High power targets want the nominal beam distribution to be in the right place, and must not exceed the maximum beam current
- The most important beam parameters are
  - Beam position
  - Beam size and shape (i.e. distribution)
  - Beam energy
  - Beam current
  - Beam pulse length, rep rate, energy per pulse (short pulses cause pressure pulse)

Importance of beam distribution

- High power targets often prefer flat or uniform beam distributions, because they minimize the beam density and thereby minimize the energy density deposited in the target
- Unless special measures are taken in the accelerator / beam delivery systems, the beam distribution will usually be mostly Gaussian
- Possible target protection system requirement: monitor beam distribution, do not allow off-normal distributions

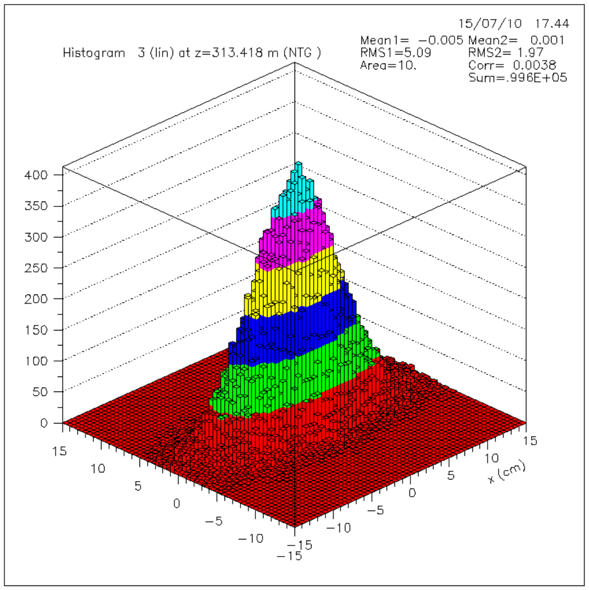


Methods to flatten beam distribution

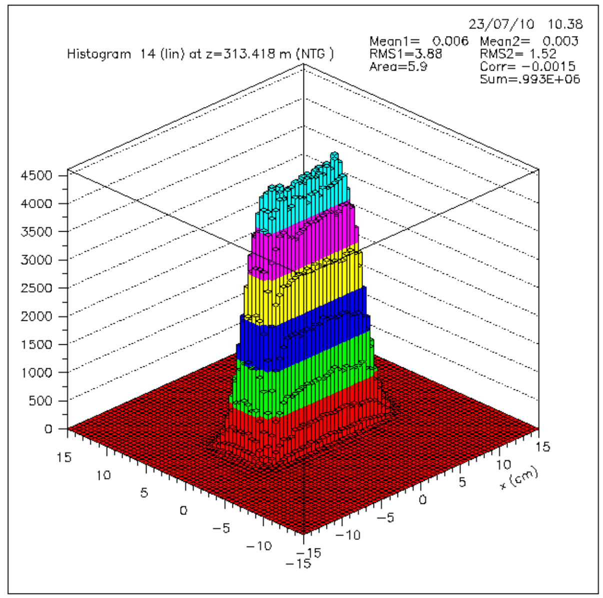
- Injection painting in storage rings and synchrotrons (e.g. SNS, J-PARC)
- Multipole magnets (e.g. octupoles) in beam transport line to target (e.g. J-PARC)
  – Note that beam must usually be well-centered in the octupoles for proper flattening. Off center beams will produce skewed distributions.
- Raster system (e.g. ESS)
- Possible target protection system requirement: monitor and interlock beam flattening system. For octupole-based flattening systems, consider monitoring beam position in the octupoles.

Octupoles at J-PARC

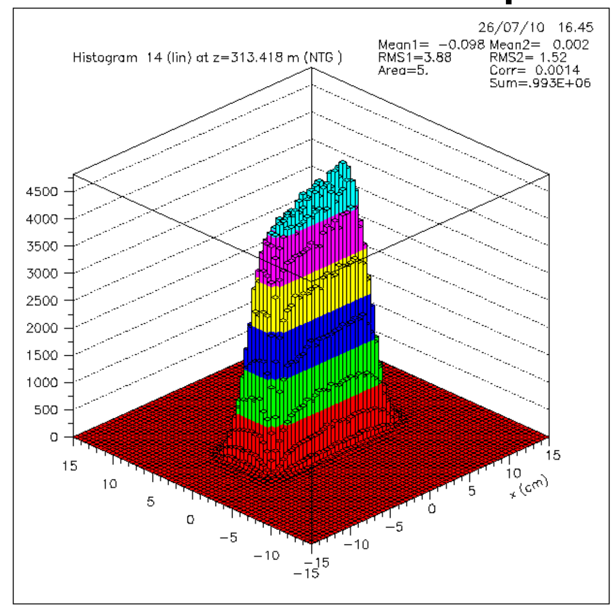
No octupoles



With octupoles



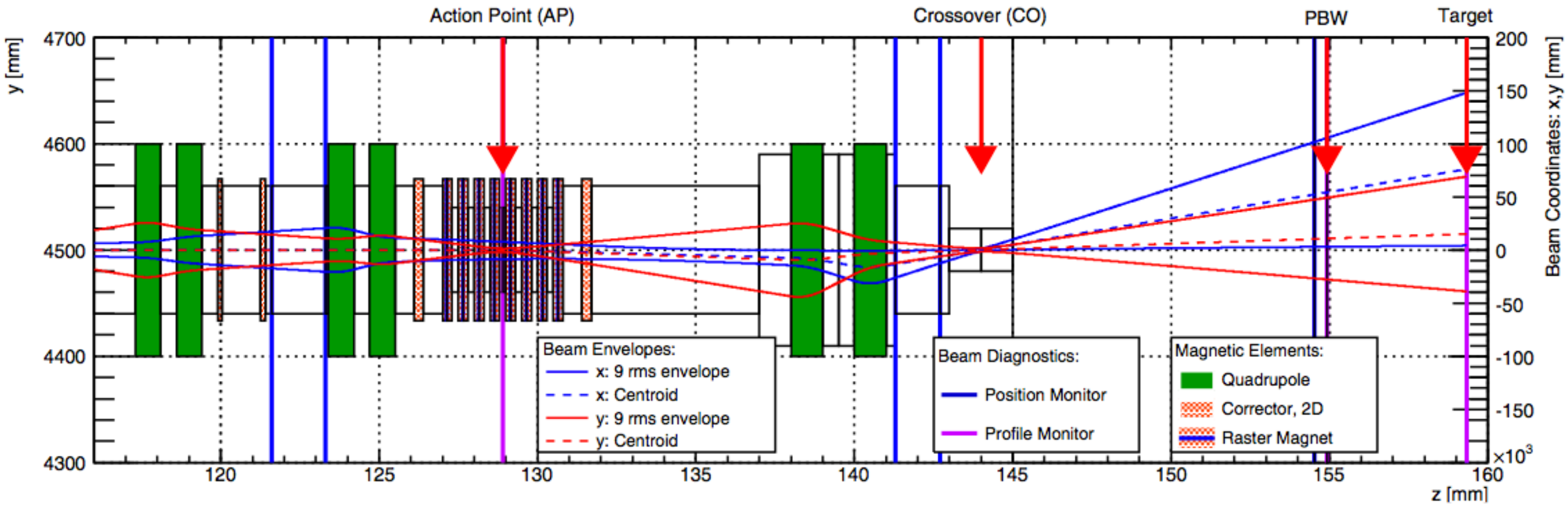
2 mm offset in octupole



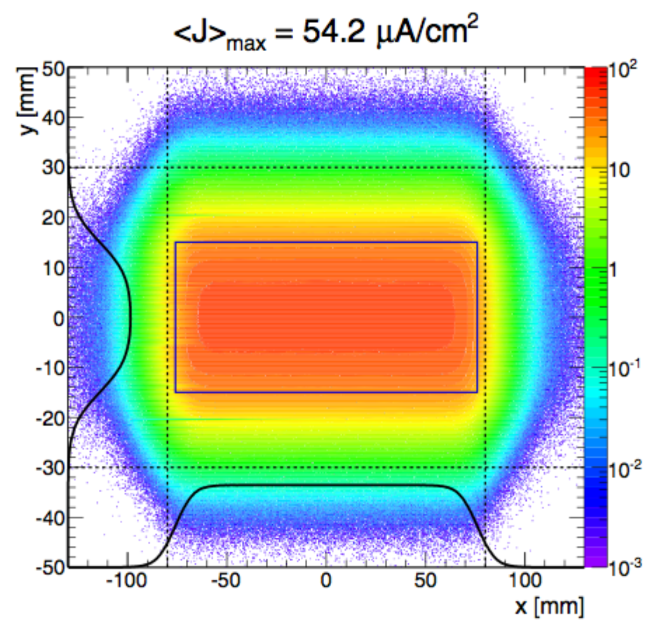
In 2013, J-PARC added two octupole magnets to flatten the beam distribution on the neutron spallation target

(Shin-ichiro Meigo et al., AccApp 2013)

Beam raster system planned for ESS



Possible sweep frequencies 29.05 and 39.55 kHz



(H.D. Thomsen et al., IPAC13)

What can go wrong? Some examples…

- J-PARC overpowered Hadron Hall gold target 2013
- ISIS exceeded design beam density 2010
- PSI exceeded nominal beam density 2004

J-PARC target failure May 23, 2013

Instead of the normal 2-second slow extraction from the Main Ring, all the beam was extracted in 5 ms, overheating the target.

Result: ALL BEAMS off until 9 months later, Feb. 17, 2014. Hadron Hall operations expected to be restart Autumn 2014.

December 17, 2013
J-PARC Center

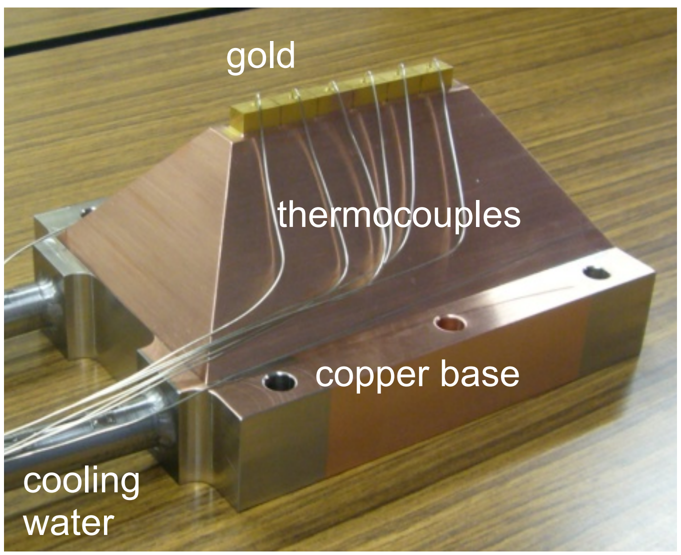
The Observation of the Gold Target at the Hadron Experimental Facility

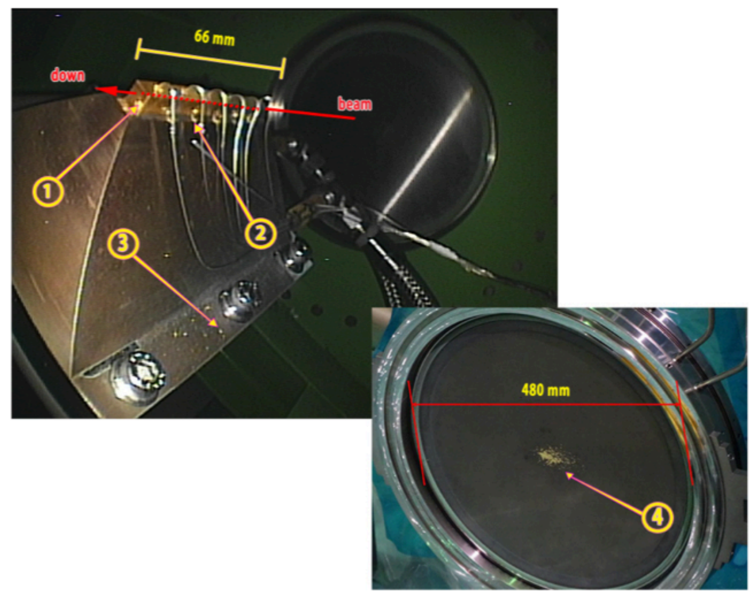
On December 12 and 13, we observed the gold target at the Hadron Experimental Facility by a fiberscope for the first time after the radioactive material leak accident that occurred at Hadron Experimental Facility on May 23, 2013.

As we reported previously, it has been considered that the target was damaged and partially evaporated by an accidental injection of a large amount of protons for a very short period (i.e., 5 micro sec.), and several simulations were carried out.

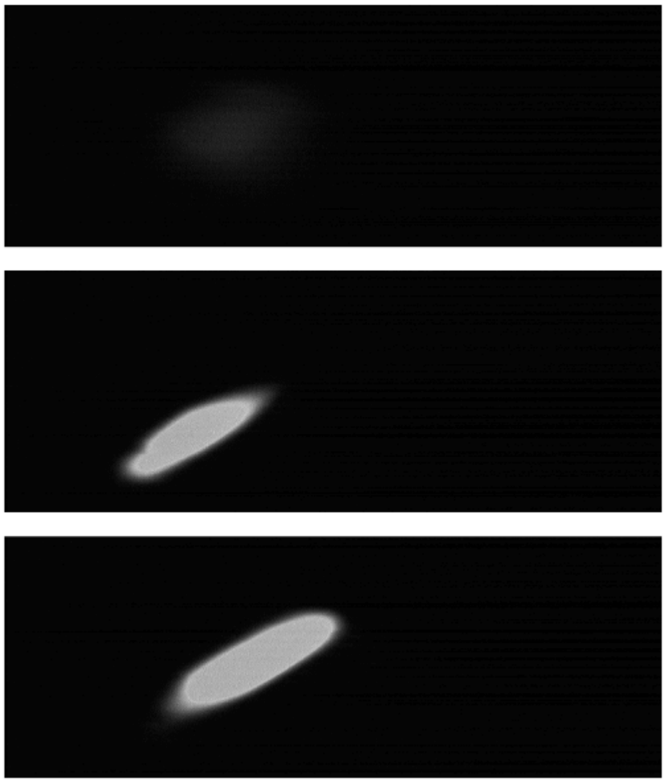
During the observation, we verified: 1) a hole 1 mm in diameter at a downstream end of the gold target, 2) gold-colored nubs, which probably are traces of dripped out melting gold from slits of a gold rod of the target, 3) probably droplets of melted gold on the copper base block and 4) traces of sprayed out melting gold on a beryllium window at the downstream of beam. Please note that these droplets marks are observed only on the right side of the target as viewed from the downstream.

These observations nicely match with our simulation results. Consequently, we consider that, at the injection, temperature of the gold target partially exceeded melting and further vaporizing points, and melted gold was pushed outward due to a rapid volume expansion resulted from vaporization of the melted gold.





VIMOS saw wrong Parameter File



```
Wed Oct 27 21:20:52 2004

Lost frames: 0
bm1_30911: Mean1:131.175100, Mean2:46.695600, Ratio:2.809153
bm2_30911: Mean1:129.106525, Mean2:46.758324, Ratio:2.761145
bm3_30911: Mean1:130.704061, Mean2:46.765639, Ratio:2.794874
bm4_30911: Mean1:129.476032, Mean2:46.566844, Ratio:2.780434
bm5_30911: Mean1:131.050932, Mean2:46.630073, Ratio:2.810438
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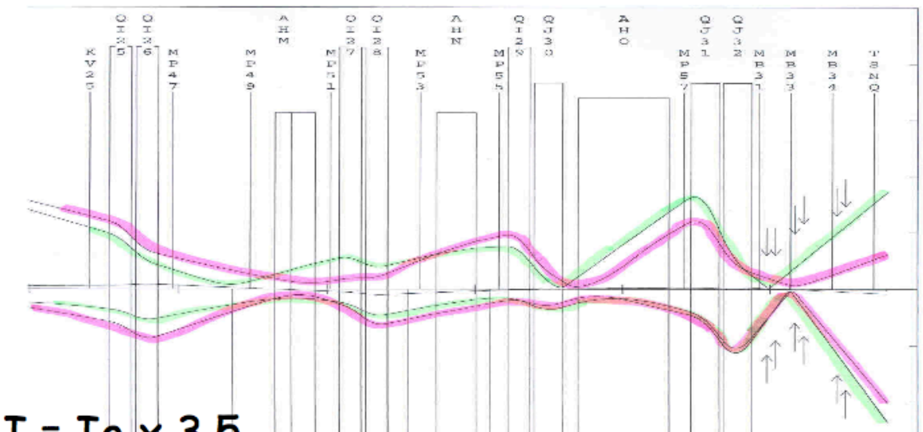


Result: The maximum in the beam density was boosted by a factor of 3.5 resulting in overheating of the center volume inside the target with subsequent damage to some rods and specimens therein.

(K. Thomsen, NIM A 575, p. 347 (2007))

ISIS target failure January 2010 Second Target Station MKI Target cladding failure

Failure was likely a combination of design error and leaks – possibly analyzed for uniform beam but actual profile gave much higher temperature. Also there was a moderator system water leak which put water in the beam which then disassociated at the high temperature to produce oxygen to attack tantalum grain boundaries.

Result: tantalum cladding fell apart, making a hole

Loss-of-coolant failures in tungsten targets

- Loss of coolant could result in tungstic acid vapor (WO_3*H_20) being produced as a result of tungsten vaporization at an elevated temperature (> 800 ^oC) in the presence of steam. This reaction also produces hydrogen which can burn or detonate creating elevated pressures for discharges.
- Highly activated powder generated by the condensing acid vapor dispersed to the site boundary is an unacceptable condition if a large fraction of the tungsten is involved.
- The LOCA failure mode has been studied and documented by LANL; but has not occurred.

Beam windows – what can go wrong?

- We also need to be concerned with beam windows. They are often part of the target system, and can also be damaged by the beam
- High power beam windows must be cooled, usually with water
- Windows can fail due to over-focused or off-center beams
- Radioactive water can be spilled into the beam line vacuum and/or the target environment

LAMPF beam window failure

- 800 MeV protons, 800 kW, 120 Hz
- Window installed in 1995
- In 1996, beam size reduced from σ = 20 mm to 15 mm to increase fluence on some samples to be irradiated
- Window failed after 6 months of operation, probably at weld joint where a thermocouple was attached, on the air side of the window

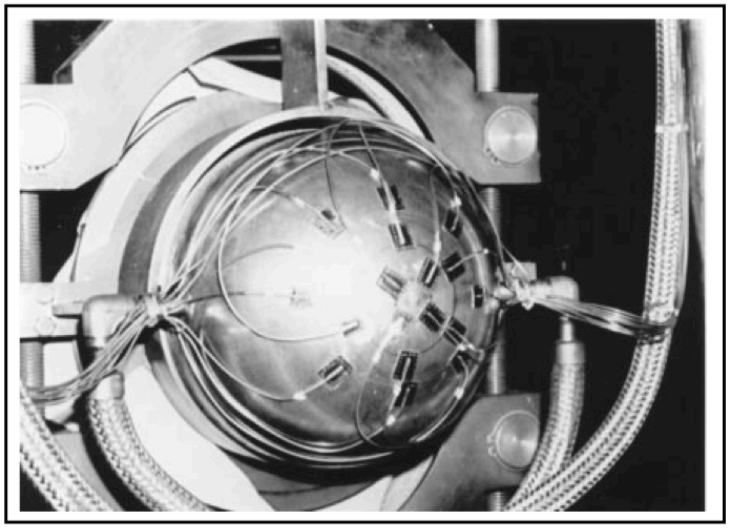


Fig. 2 *Outer face (atmosphere side) of the LANSCE double-walled hemispherical beam exit window showing placement of the thermocouples. Note that several spot welds were used to affix the thermocouple pads to the window surface.*

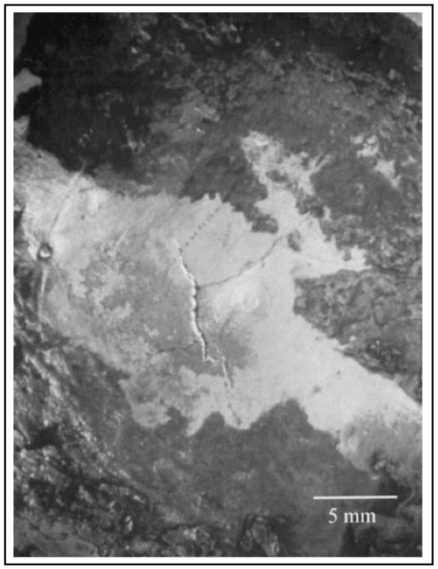


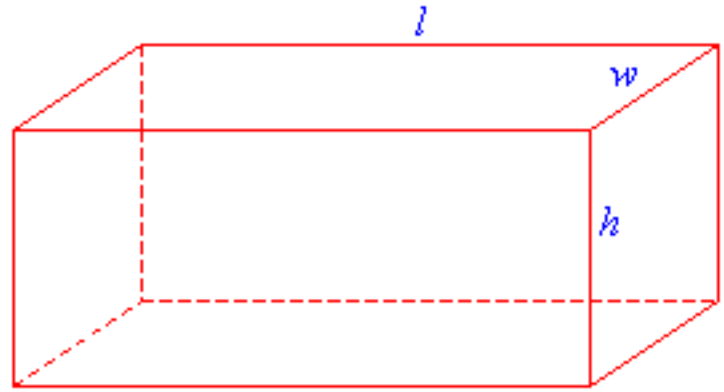
Fig. 12 *The crack near both the mechanical center and dose maximum seen from the waterside following removal of some of the deposits*

(W. Sommer et al., PFANF8 (2003) 1:71-80)

Example: rectangular dc beam

Assume:

2 MW beam
1 GeV protons
dc beam
Rectangular shape 2 cm x 2 cm
Stops 0.75 m into target
Assume uniform energy deposition
and no scattering



1-second power density = (2 MW)/(2 cm)/(2 cm)/(0.75 m) = 6.67 GW/m^3

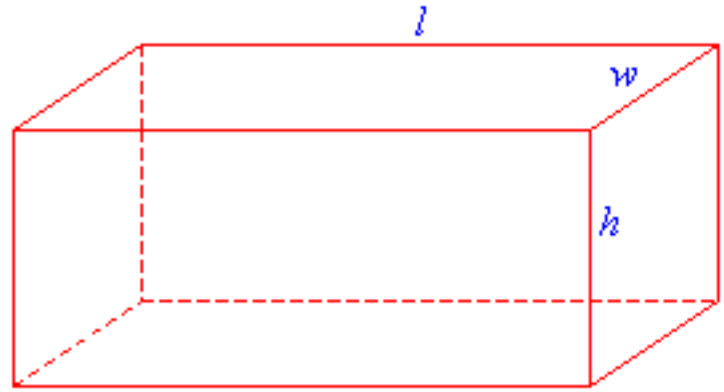
Assume off-center beam must be shut off before it can deposit 100 J

(100 J) / (2 MJ/s) = 50 us = required turn off time

Example: rectangular pulsed beam

Assume:

2 MW beam
1 GeV protons
10 Hz
Rectangular beam pulse 2 cm x 2 cm
Each pulse 1.5 us long
Stops 0.75 m into target
Assume uniform energy deposition and no scattering



$$V = l \cdot w \cdot h$$

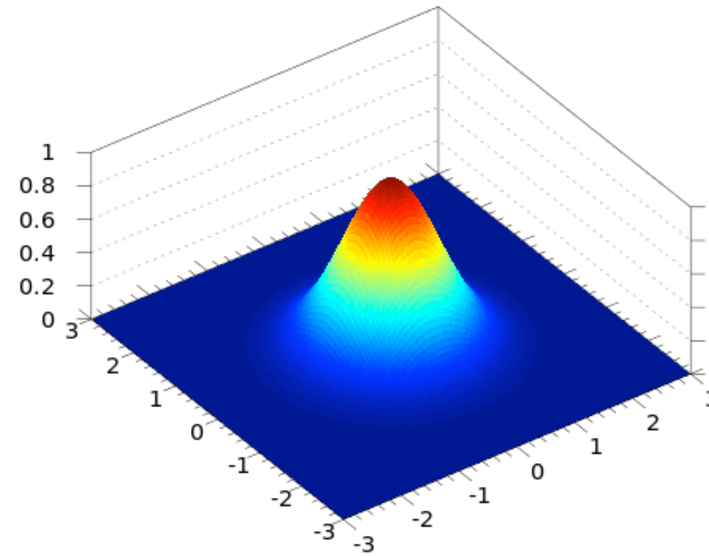
1-second power density = (2 MW)/(2 cm)/(2 cm)/(0.75 m) = 6.67 GW/m^3
Energy per pulse = 2 MW / 10 Hz = 0.2 MJ
Per pulse energy density in target = (0.2 MJ)/(2 cm)/(2 cm)/(0.75 m) = 667 MJ/m^3
Peak power density = (667 MJ/m^3) / (1.5 us) = 4.45e14 W/m^3

With 1.5 us pulses, it is not practical to shut off the beam mid-pulse. Can only prevent the next pulse from occurring.

Example: Gaussian beam

Assume:

2 MW beam
1 GeV protons
10 Hz
Gaussian beam pulse $\sigma_x = \sigma_y = 0.5$ cm
Each pulse 1.5 us long
Stops 0.75 m into target
Assume uniform energy deposition
and no scattering



$$f(x,y) = A\left[-\left(\frac{(x-x_0)^2}{2\sigma_x^2} + \frac{(y-y_0)^2}{2\sigma_y^2}\right)\right]$$

1-second power density =
(2 MW)/(2π)/(0.5 cm)/(0.5 cm)/(0.75 m) = 17 GW/m^3

$$V = \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy\, f(x,y) = 2\pi A \sigma_x \sigma_y$$

Note: more realistic calculations will take into account beam scattering, energy deposition as a function of energy, and heating by the secondary particles. That is beyond the scope of this lecture.

Target protection

- For the beam-related protection, main parameters of concern are: beam density (beam profile), beam size, beam position, beam current (power).
- Protection involves control over these parameters, monitoring these parameters, and turning off the beam if these parameters move outside allowable limits
- The targets themselves often have their own separate non-beam-related protection system

Types of beam-related target protection

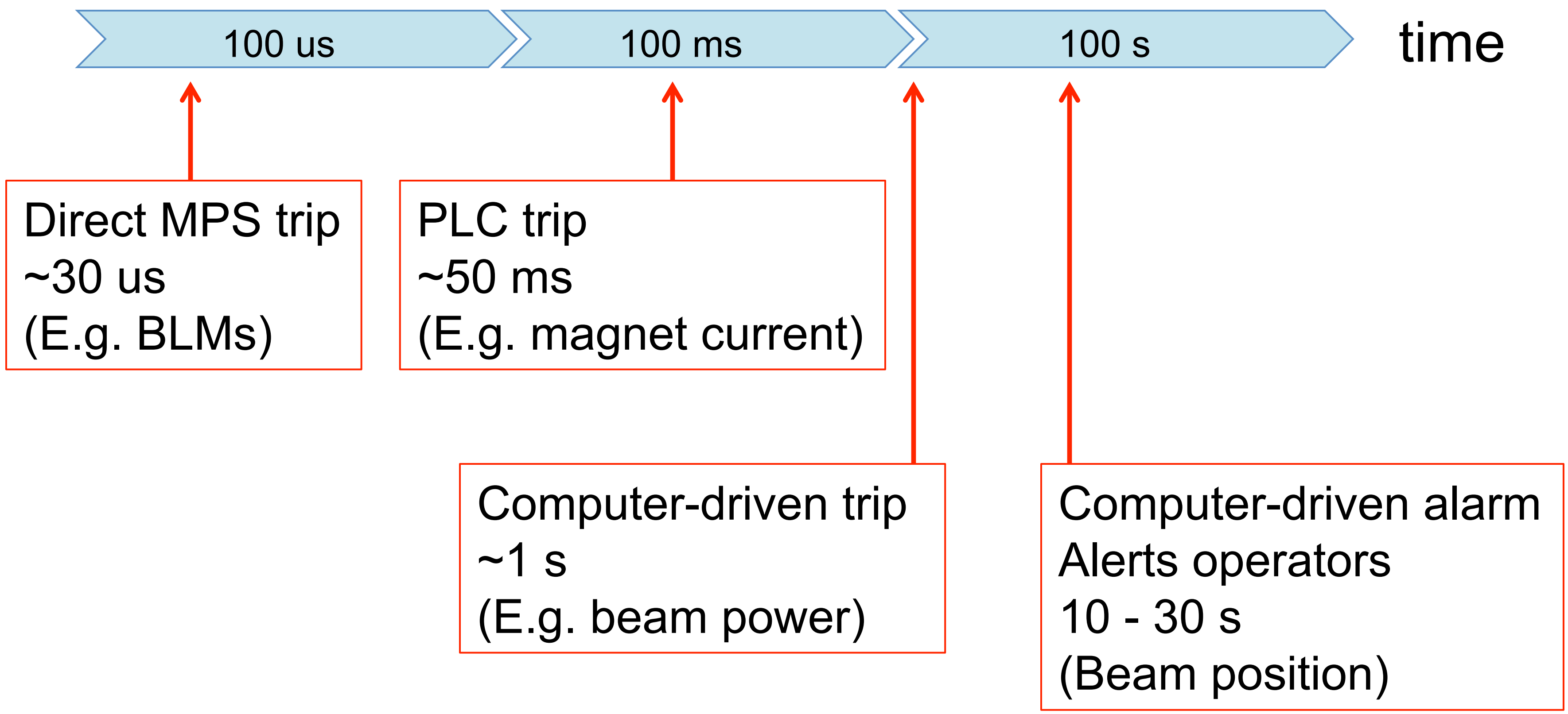
- Rapid and automatic beam turn off for off-normal beams
- Equipment and operating parameter lock down to prevent accidental changes
- Alarms that alert operators when parameters move outside of pre-defined limits
- Collimators to partially intercept off-normal beams
- Beam transport designs that avoid high sensitivity – don't want to live on the edge, don't want to be very sensitive to small magnet changes
- Target designs that can tolerate off-normal beam for a short period of time

Protection by interlocking on off-normal measured beam parameters

- Continuously monitor and interlock on critical beam parameters
  - Beam loss monitors (everybody)
  - Beam current monitors (everybody)
  - Beam position monitors (PSI has automatic beam centering based on BPM signals)
  - Amount of beam intercepted by collimator (PSI)
  - Harp profile monitors (J-PARC, SNS)
  - Ionization profile monitors (PSI)
  - Glowing screen just upstream of target (PSI)
  - Halo thermocouples (SNS)

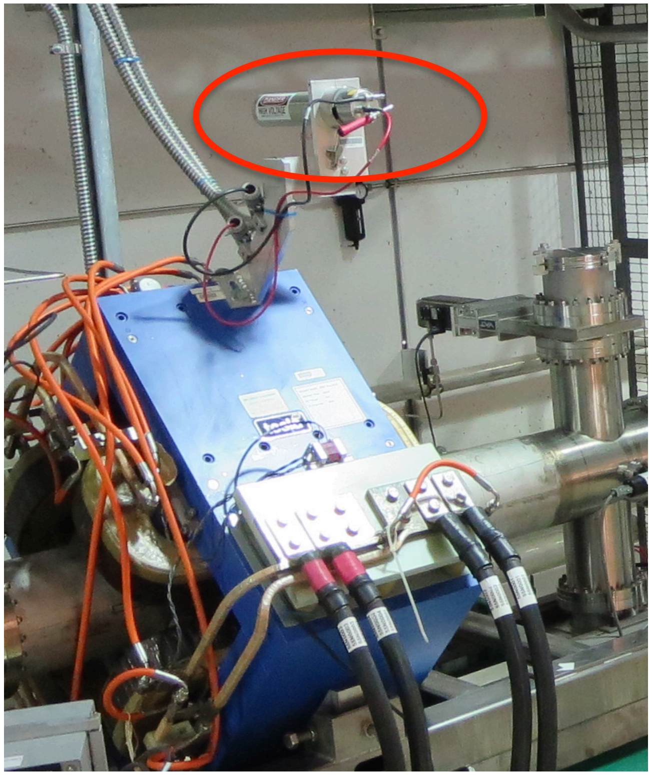
Different types of profile monitors

Time to trip beam



Protection by rapid beam turn-off

- Fastest is direct MPS trip
  - Example: At SNS linac beam stops 20 – 30 us after BLM trip
  - If trip occurs upstream of or within the accumulator ring, can stop accumulation, but beam that has already accumulated will be sent to target – anywhere from small to full intensity
  - If trip occurs downstream of ring, can only prevent the next pulse from beginning the accumulation process



Protection by rapid beam turn-off (cont.)

- Next fastest is PLC inputs to MPS system
  - Example: At SNS, PLCs monitor separate current transformers on the power supplies for the last few magnets in the transport line to the target.
  - Estimated time to turn off beam is 50 ms
  - PLC trips also turn off high voltage to ion source and turn off the high voltage to the first few klystrons

Protection by rapid beam turn-off (cont.)

- Third-fastest is faults detected by computers. Beam turn off is still through MPS system.
  - Example: At SNS, computers monitor all magnet power supply currents in the beam transport to the target (as read by the power supply controller – not by separate current transformers). Estimated beam turn off time is about 1 second.

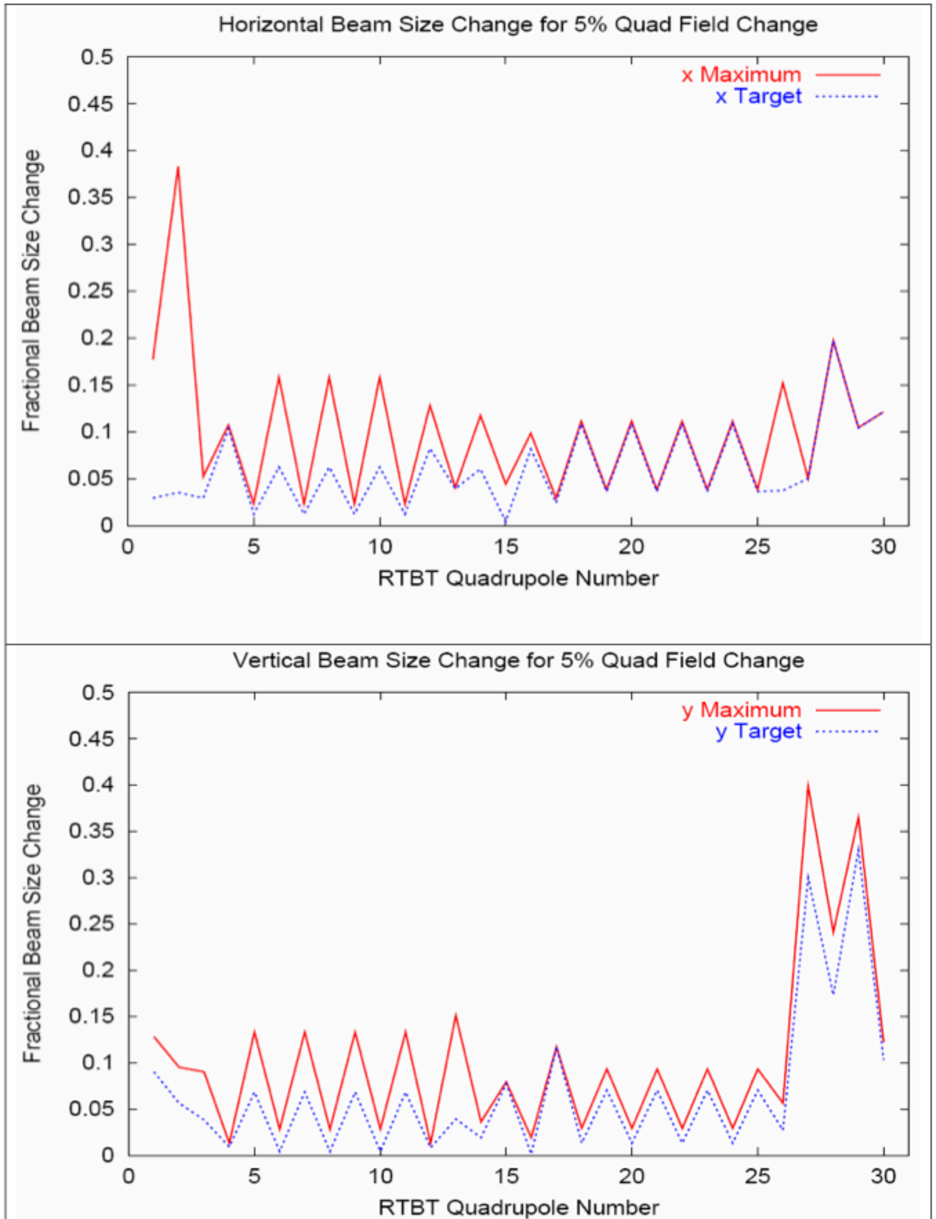
Protection by rapid beam turn-off (cont.)

- Fourth-fastest is alarms to the operators, generated by the control system
  - The control system can monitor a huge number of parameters, and values derived from those parameters
  - And then alert operators, who can take action to correct the alarm state or manually shut off the beam
  - Example: At SNS, the control system alarms on beam position on target
  - Estimated time to correct alarm state is 10 to 30 seconds, or possibly longer

Protection by BLMs

- BLMs are a standard part of any beam transport system, mainly used to protect beam line components
- BLMs can also be used to protect a target
  - Idea is that a quadrupole change that can cause the beam to be too small or too large at the target will cause beam loss upstream of the target
  - Also deviations from the nominal beam trajectory that could result in a bad position on the target can cause beam loss
  - At SNS, BLMs are located, and thresholds are set, such that some of the quadrupole magnet set points that can result in off-normal beams at the target will trip the BLMs

SNS quad sensitivity study



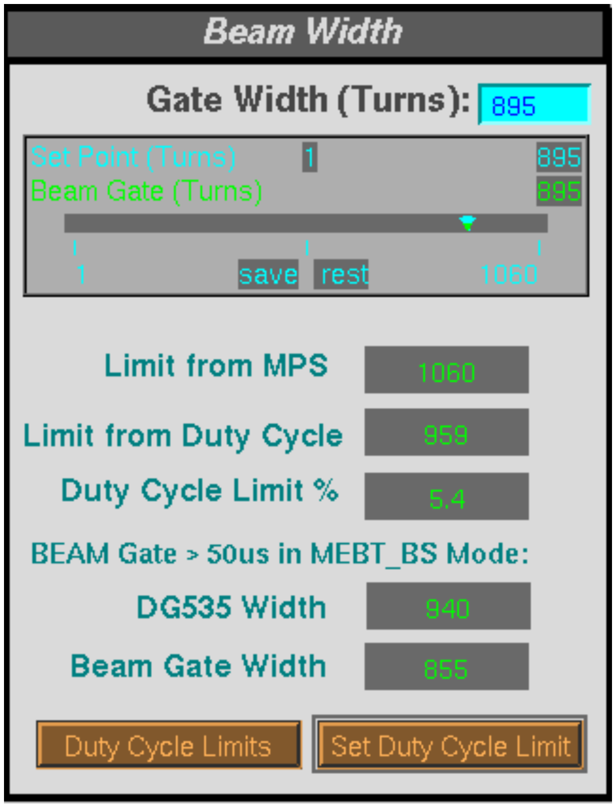
Six of the 19 quad magnet power supplies will cause BLM trips (>0.1% beam loss) before causing dangerous beam parameters at the target

Magnet	Constraint %	Reason
QV1		Upstream beam loss at -30%, +15% field strengths
QH2		Upstream beam loss at -10%, +15% field strengths
QV3		Upstream beam loss at -50%, +40% field strengths
QH4	7	Peak current too high at -7% field strength
QV5, 7, 9, 11	12	Peak current too high at -12% field strength
QH6, 8, 10		Upstream beam loss at -20%, +10% field strengths
QH12		Upstream beam loss at -20%, +20% field strengths
QV13		Upstream beam loss at -40%, +30% field strengths
QH14	12	Peak current too high at +12% field strength
QV15	16	Peak current too high at -16% field strength
QH16	8	Peak current too high at -8% field strength
QV17	8	Peak current too high at +8% field strength
QH18, 20, 22, 24	24	Peak current too high at +24% field strength
QV19, 21, 23, 25	32	Beam on target too low at +32% field strength
QH26	40	Beam on target too low at -40% field strength
QV27	8	Beam on target too low at -8% field strength
QH28	7	Peak current too high at +7% field strength
QV29	8	Beam on target too low at -8% field strength
QH30	9	Peak current too high at +9% field strength

(J. Holmes, SNS Tech Note 162, 2005)

Protection by equipment lock-down

- Another method to protect the target is to lock down certain control parameters
- Example: At SNS, the operators set a gate generator at the ion source to limit the possible beam pulse length



Beam gate width and duty cycle limits, set by operators

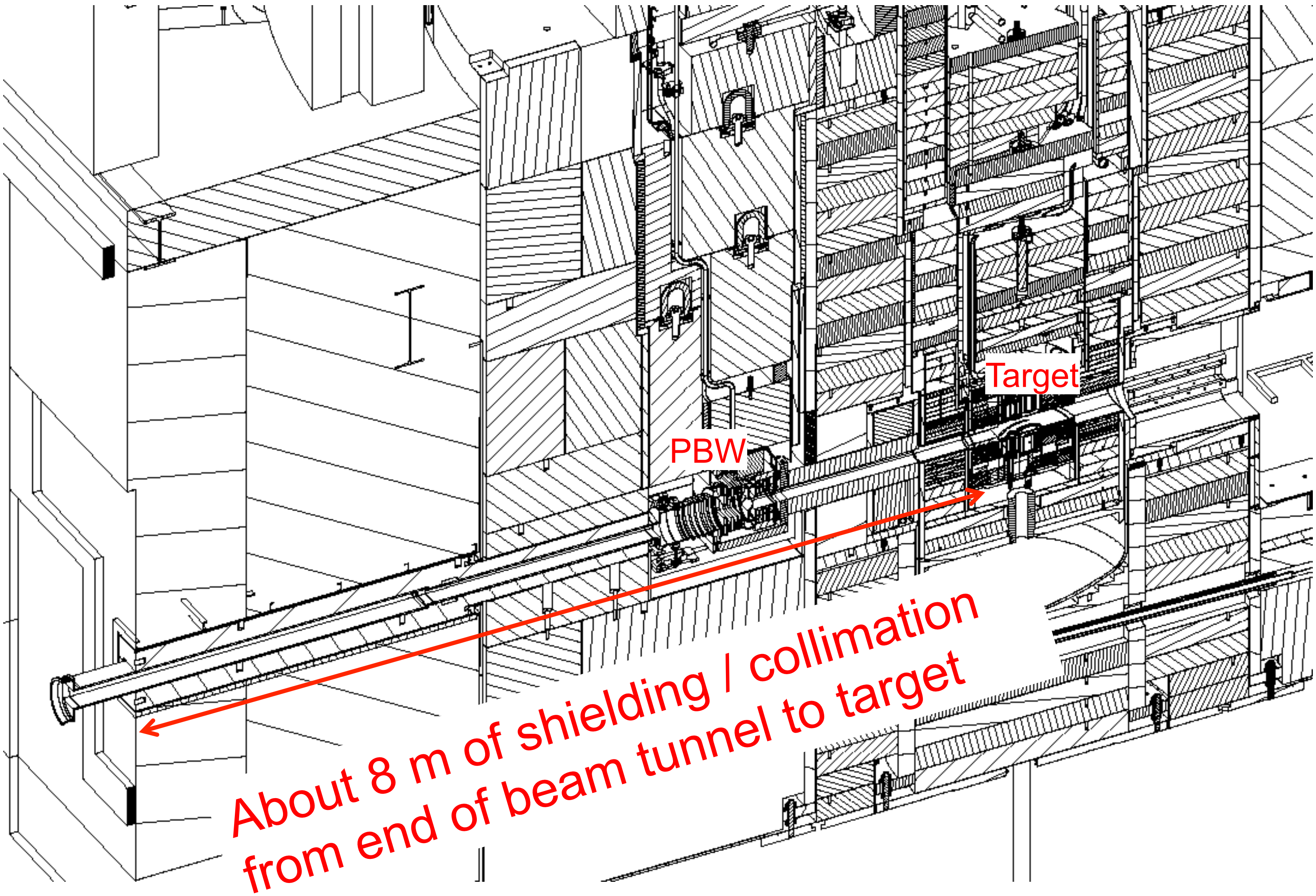
Protection by alarms

- Control system can monitor many parameters, and alert operators when these parameters stray outside of pre-defined limits
- These are separate from the automatic interlocks. Alarms do not automatically turn off the beam.
- Alarms may be set to alert operators before parameters reach the interlock limits, or may be set on some less-rigorous parameters

Protection by collimation

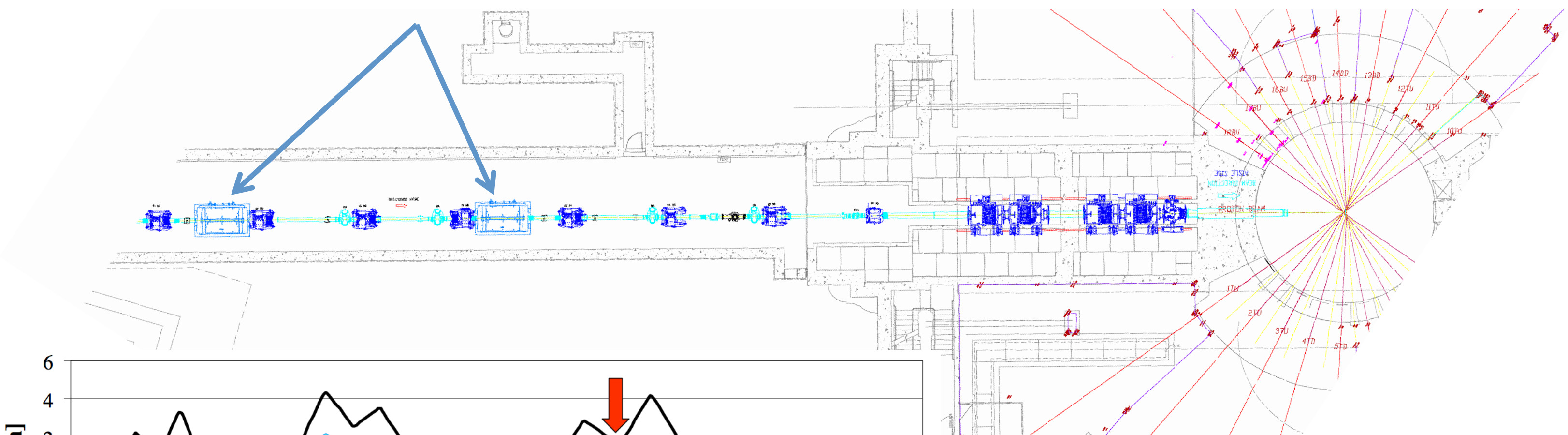
- Often have collimators in last part of beam transport leading to target
  - Prevent large beam position variations
  - Ensure beam hits central region of target
  - Example: SNS, has collimator 27.9 x 12.7 cm^2, compared to requirement of 90% of beam inside a 20 x 7 cm^2 rectangle centered on target
  - SNS also has collimators in beam transport line that intercept a portion of beam that does not receive the nominal kick angle from the extraction kickers

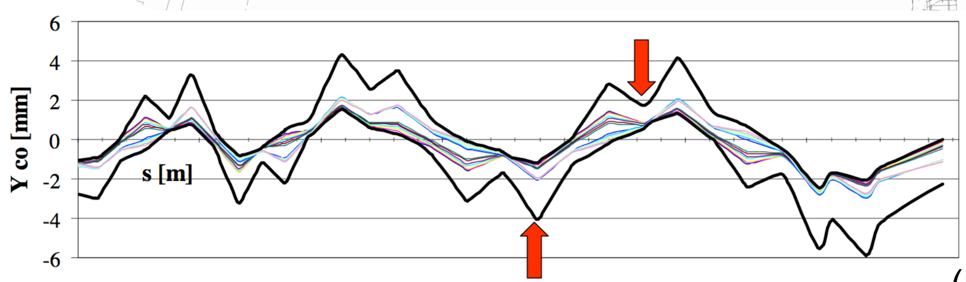
Cross section from harp to SNS target



SNS beam line collimators

- RTBT collimators are designed to intercept beams that are off-center due to extraction kicker mis-fires.
- This protects the target from off-center beams.





(N. Catalan-Lasheras & D. Raparia, PAC 2001)

Protection by beamline design

- It can be desirable to design the beam transport to avoid high sensitivity for beam parameters at target
  - Don’t want to live on the edge, don’t want to be very sensitive to small magnet changes, don’t want high magnification in beam optics
  - Example from SNS: phase advance from extraction kickers to target is a multiple of pi

Protection by beam line design

Example: mis-fires of extraction kickers in the ring cause trajectory oscillations in the beam transport line. The beam line is designed for n*pi phase advance so that the position change on the target will be minimized.

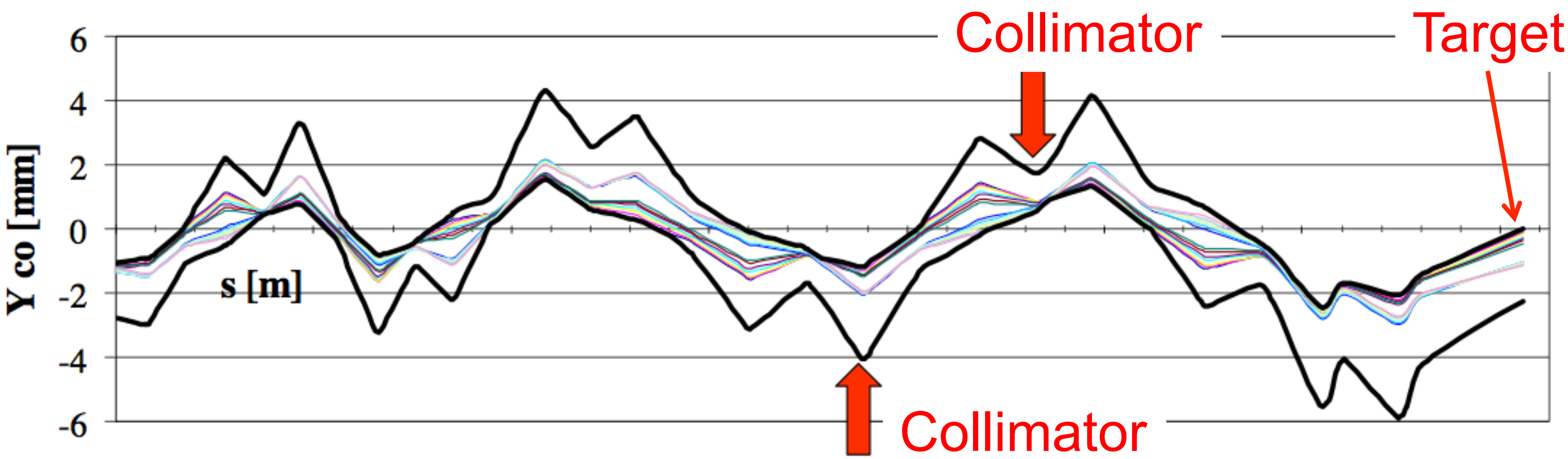


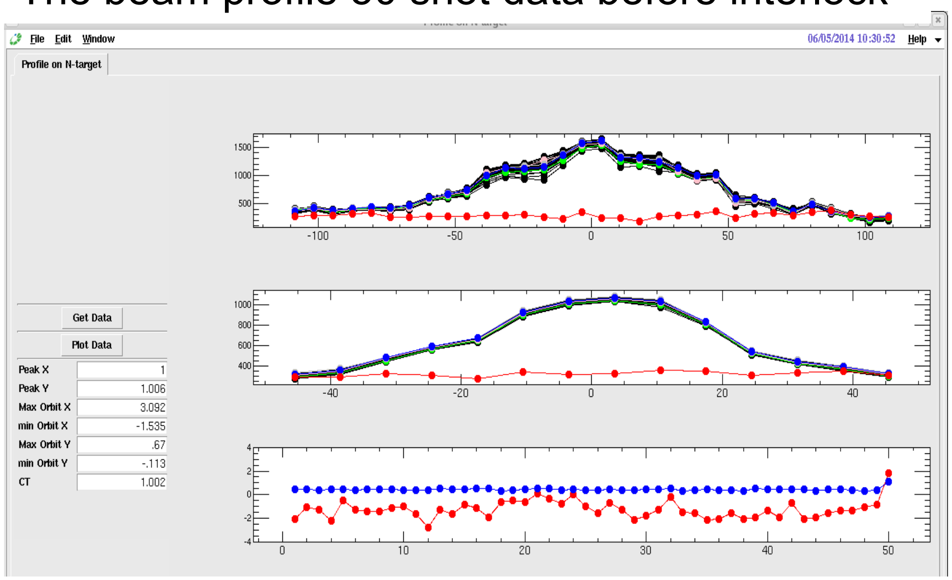
Figure 2: Vertical closed orbit deviation along the RTBT. Thin lines correspond to one kicker mis-fire. Bold lines are the maximum and minimum closed orbit deviation when two kickers fail simultaneously.

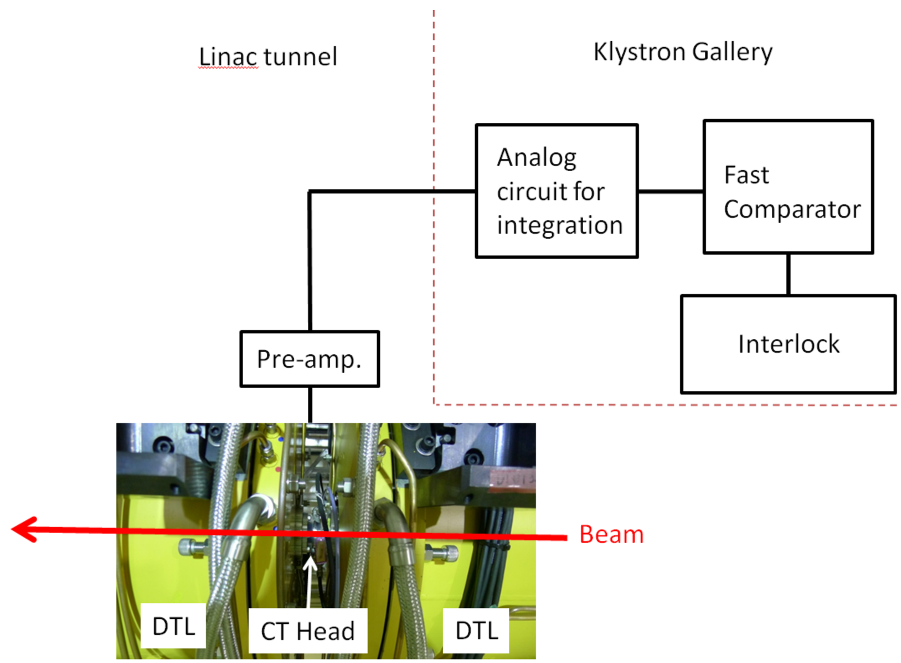
(N. Catalan-Lasheras & D. Raparia, BNL Tech Note 095, 2001)

Example: J-PARC target protection

- 1 MW, 25 Hz, 3 GeV mercury target
- Waveform monitor on extraction kickers of RCS
- PLC monitors some of the quadrupole and dipole currents
- PLC monitor for beam profile. It is possible to connect the machine protection system, but don't do it currently.
- New fast beam current interlock

The beam profile 50 shot data before interlock





Fast beam current interlock system

Example: FNAL NuMI target protection

- NuMI target is now 120 GeV, 700 kW. >1 MW is planned.
- Prior to beam extraction from Main Injector, check >250 inputs to the Beam Permit System. Send beam to abort dump if inputs are not correct.
  - Beam position and angle for extraction channel
  - Excessive residual MI beam in NuMI kicker gap
  - Extraction kicker status
  - NuMI power supplies ramped to proper flattop values
  - Target station and absorber beam readiness
  - All beam loss monitors readings from the previous extraction
  - Previous pulse position and trajectory at targeting
- Also has automatic beam steering to keep beam centered on target
- If a beam pulse is >1.5 mm off center, turn off beam

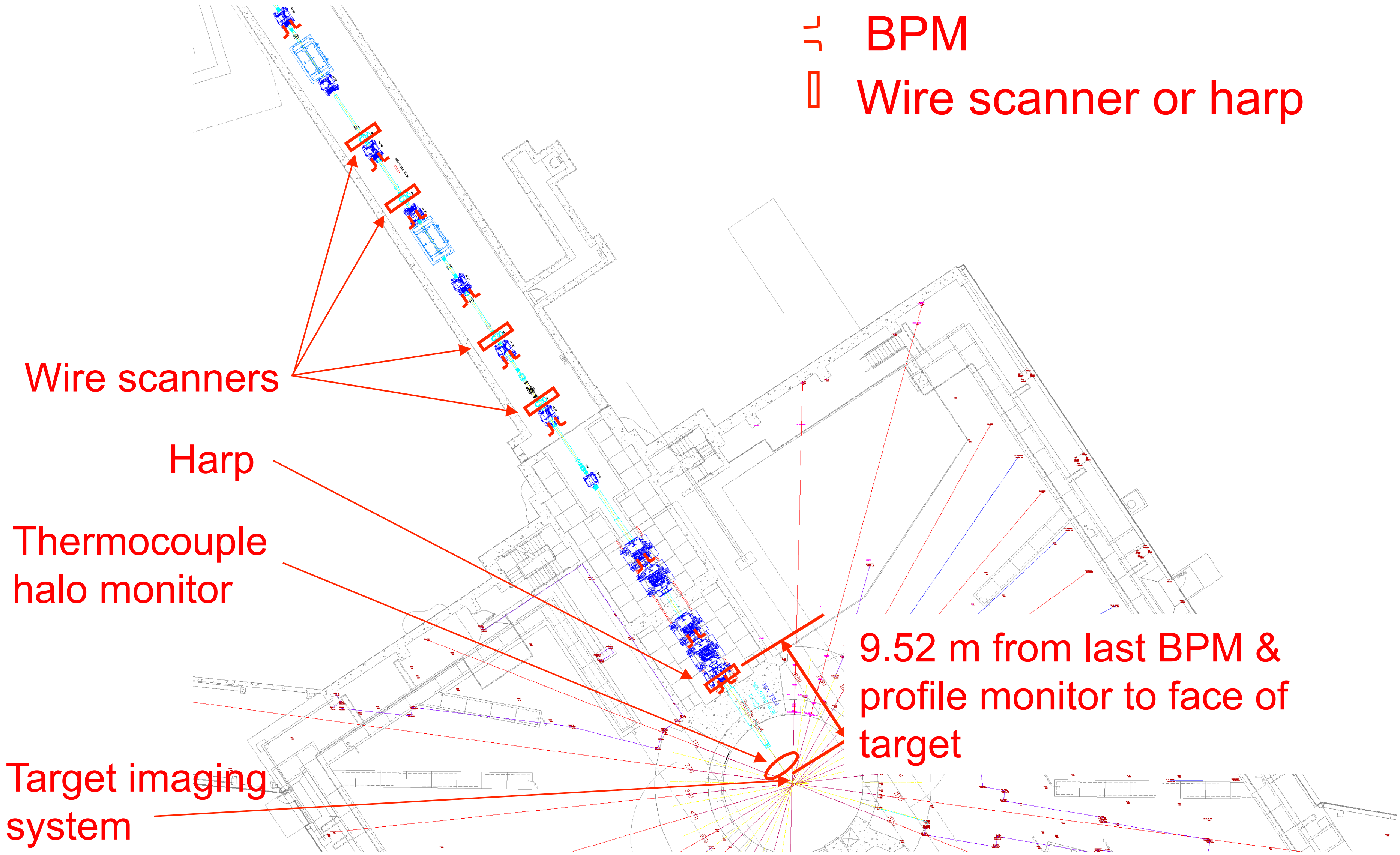
(Courtesy S. Childress)

Example: ISIS target protection

- TS1: 800 MeV, 160 kW, 40 Hz. TS2: 800 MeV, 40 kW, 10 Hz.
- Beam Halo monitor (8 equally spaced thermocouples in the penumbra of the beam ~100 mm upstream of the target) indicate mis-focus and mis-steer. Suitable trip levels of thermocouple values feed into the protection systems if such events occur.
- It is capable of turning off the machine within 2 ms and hence inhibits the next beam pulse from the ion source in the 50 Hz cycle.
- Also have a steering servo system to accommodate variations in the upstream beam. The servo and trip system is slow running at ~ 2s.
- On Target 2 there is also a HARP profile monitor which sits permanently in the beam but this isn't interlocked. A similar harp is planned for Target 1 as part of an upgrade project.

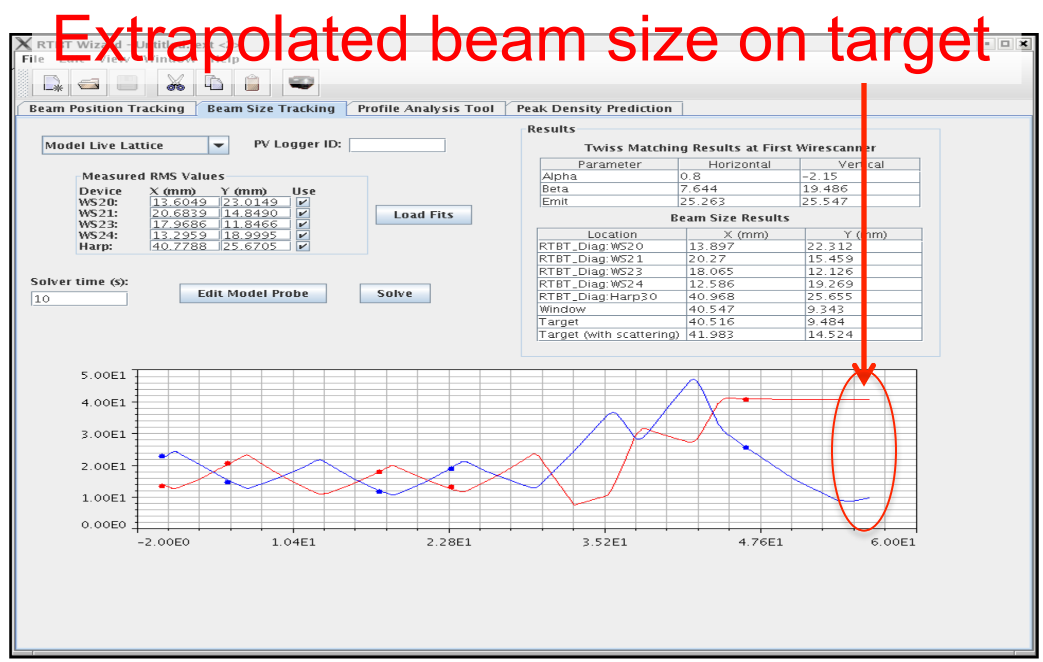
(Courtesy Dean Adams)

SNS beam transport to target



Example: SNS target tune up

- Send low intensity, 1 Hz beam (< 1 kW) to target, and center the beam on the target using BPMs
- Slowly increase the power at 1 Hz to full intensity (~23 kW)
  - Check beam centering using Target Imaging System
  - Check beam size on target using wire scanners and harp to measure profiles, then use on-line model to extrapolate to target



Example: SNS target tune up (cont.)

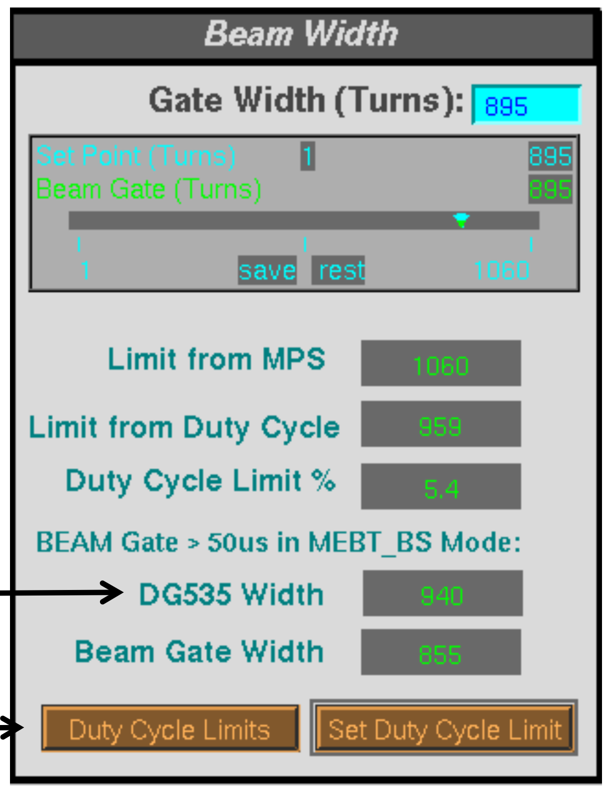
- Check peak beam density on target
  - On-line model extrapolates peak density measured with harp to determine peak density at target
- Now have met critical beam parameters on target:
  - Beam centered within 6 mm horiz. and 4 mm vertical
  - rms beam size < 49 mm horizontal and < 17 mm vertical
  - Peak density on target less than 2e16 protons/m^2 (for 1 GeV case)
  - Peak density on proton beam window less than 2.9e16 protons/m^2

Example: SNS target tune up (cont.)

- Lock down equipment and other parameters before increasing beam power beyond 100 kW. All these cause automatic trips.
  - Last 5 quad power supplies monitored by PLC with current limit set to +/-7%
  - Both large dipoles monitored by PLC with current limit set to 2 A
  - Last 2 horizontal dipole correctors and last 2 vertical dipole correctors monitored by PLC with current limit set to +/-5 A
  - Injection kicker waveform monitor engaged. If waveforms stray outside of pre-defined windows, MPS system trips beam
  - Extraction kicker waveform monitor engaged. If waveforms stray outside of pre-defined windows, MPS system trips beam
  - All RTBT magnets monitored by computer with current limits set to +/-5% on quads, +/-5% on large dipole magnets, and +/-0.5 A on dipole correctors
  - Beam power limit set into control system, monitored by computer

Example: SNS target tune up (cont.)

- Equipment lock down that does not cause automatic trips, but does limit range of allowable beam parameters
  - Beam pulse length limit set by gate generator at ion source
  - Beam duty factor limit set into control system, monitored by computer



Hardware limit

Software limit

Beam gate width and duty cycle limits, set by operators

Magnet current lockdown by PLC

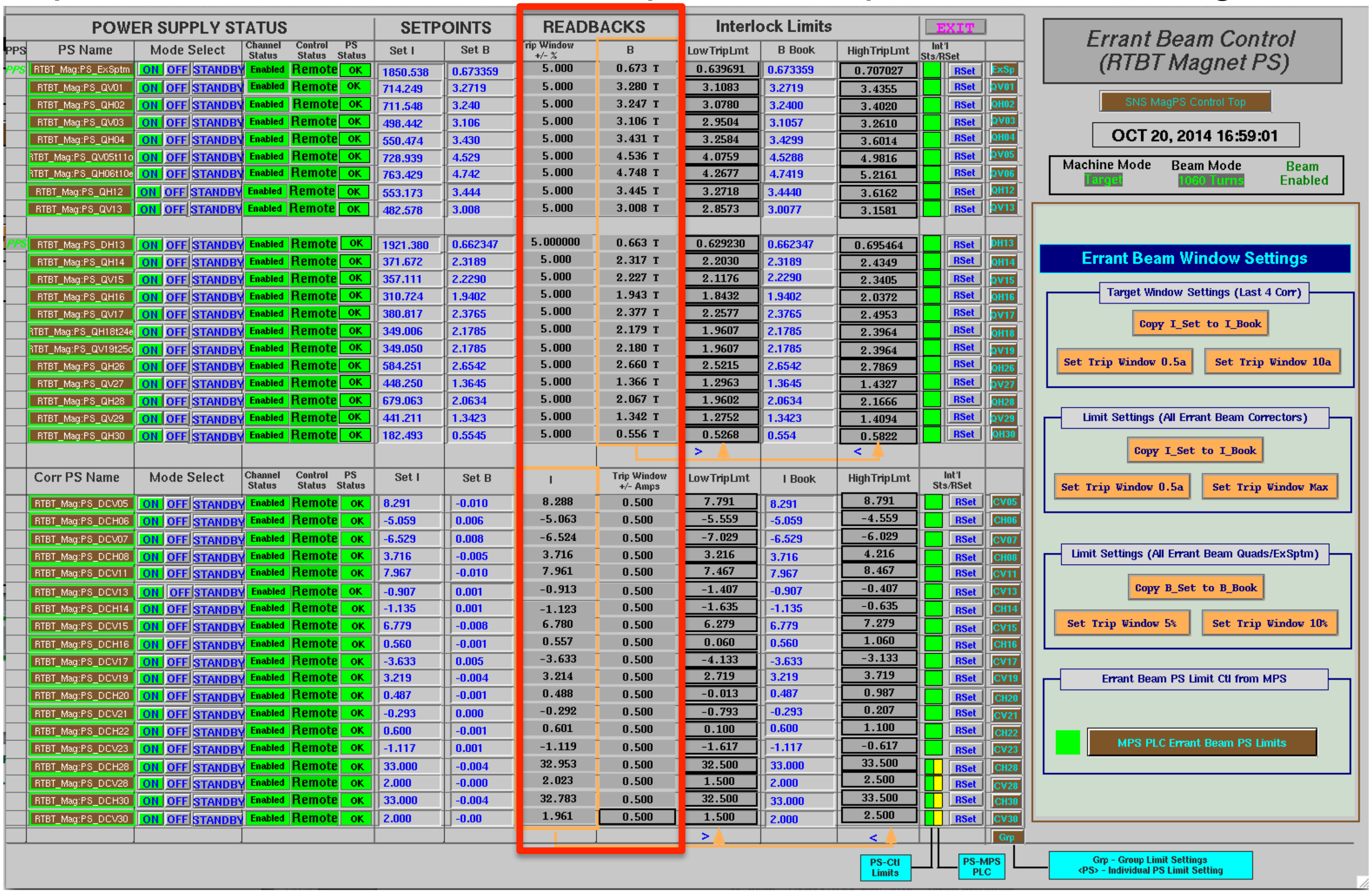
Example: SNS lock-down of RTBT quad and dipole corrector magnet currents

PLC limits on:

- Last 5 quads
- Last 4 steerers
- Large dipole magnet

Magnet current lock-down by computer

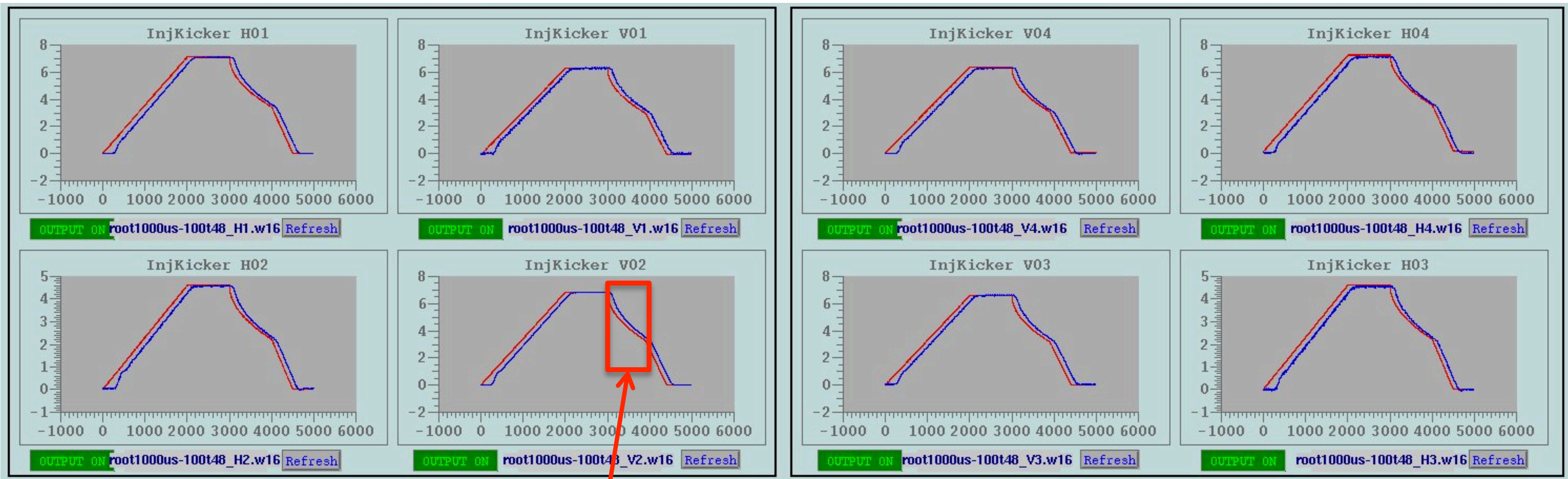
Example: SNS lock-down of RTBT quad and dipole corrector magnet currents



Trip limits set to +/-5% on quads and +/-0.5 A on dipole correctors

Injection kicker lock-down

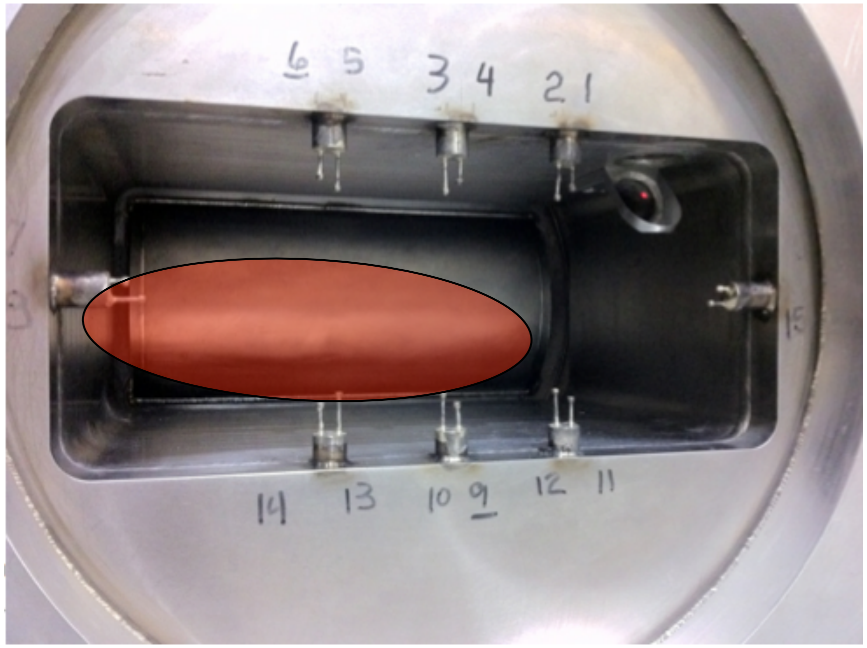
Example: SNS injection kicker production waveforms. Directly impact the beam distribution on the target.



- Injection occurs during exponential ramp down of injection kicker amplitude
- Oscilloscopes with waveform masks monitor the readback waveforms and trip the beam if they stray outside or pre-defined limits

Other interlocks always in effect

- Beam loss monitors (direct MPS interlock)
- Proton beam window thermocouple halo monitors (PLC interlock)
- Target system parameters (mercury flow, water cooling, etc.) (PLC interlock)



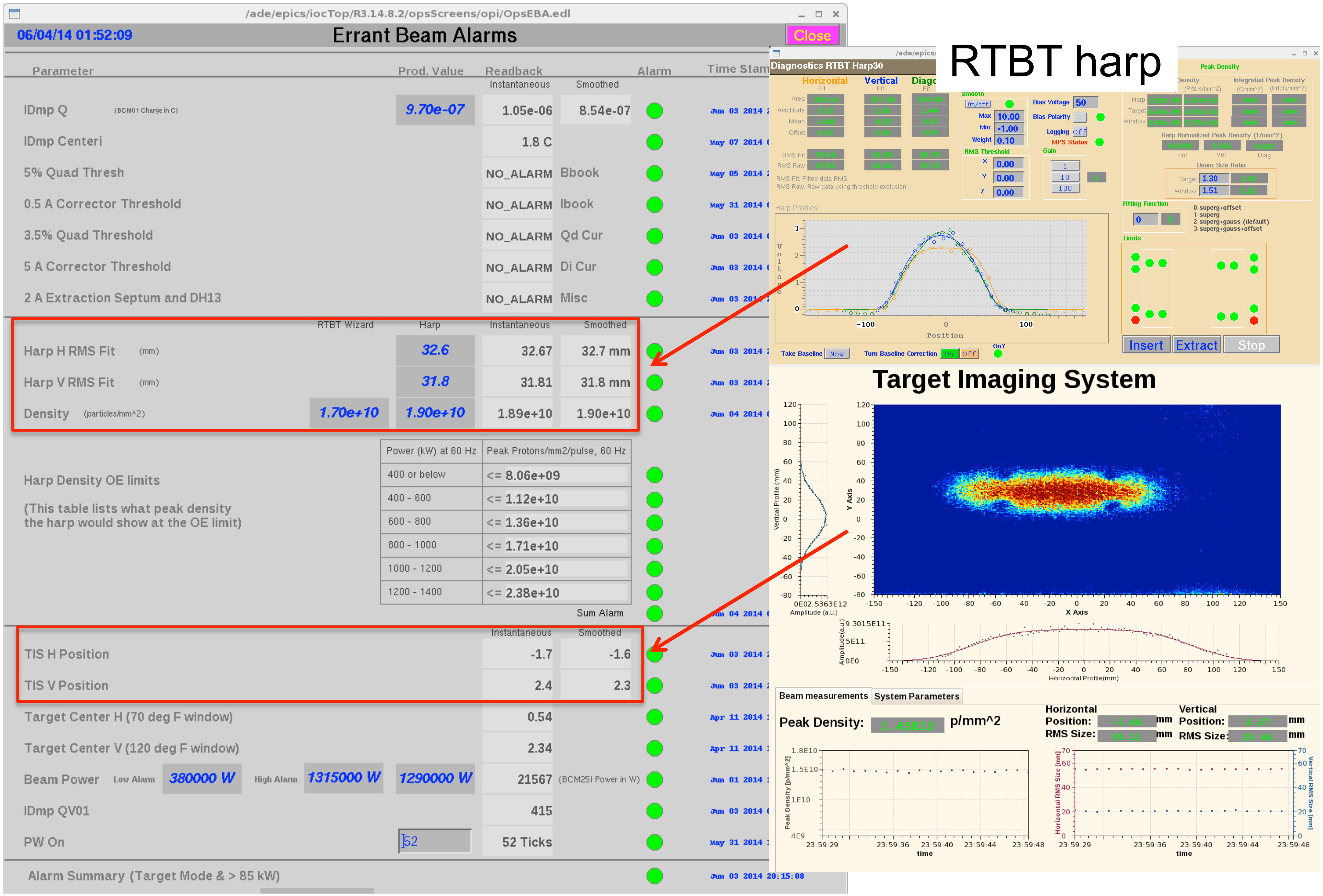
Proton beam window halo thermocouples

SNS target protection alarms

- The control system monitors the following parameters, and alerts operators if they stray outside of pre-set bounds:
  - Beam position on target calculated by the Target Imaging System
  - The beam density at the harp 9.52 m upstream of the target. Should be proportional to the beam density at the target.
  - The beam size at the harp 9.52 m upstream of the target, should be proportional to the beam size on the target
  - Beam power
  - Beam centering estimated from proton beam window halo thermocouples (top – bottom, left-right)
  - Some magnet currents

[Alarms in blue are to prevent interlock trips (alarm threshold is lower than trip threshold)]

SNS alarm summary screen



Summary

- High power targetry is an active field that is continuously advancing
- The highest power targets require tight control over the beam position, density, and distribution – even then the target lifetimes can be short (e.g. 6 months at SNS)
- Machine protection systems must monitor these beam parameters and quickly activate interlocks if they stray outside of limits
- Protection can include
  - Monitoring equipment set points, equipment readback parameters, beam parameters
  - Locking down certain controls
  - Beam line design, collimator systems

Thank you for your attention!

Back up slides