

Protection Related to High Power Targets

by

Michael Plum
ORNL/SNS

USPAS / Joint International
Accelerator School: Beam Loss and
Accelerator Protection
Newport Beach, California
Nov. 5-14, 2014



U.S. DEPARTMENT OF
ENERGY

 **OAK RIDGE NATIONAL LABORATORY**
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

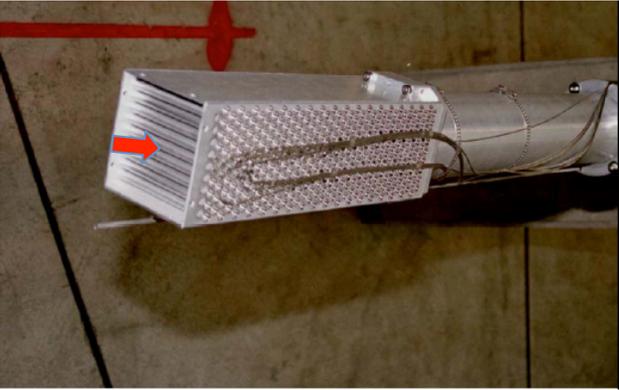
Table of contents

- Introduction to high power targets
- What can go wrong, what are the risks?
- Controlling the beam-related risk
- Examples from some other labs
- Detailed example of SNS target tune up and protection

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



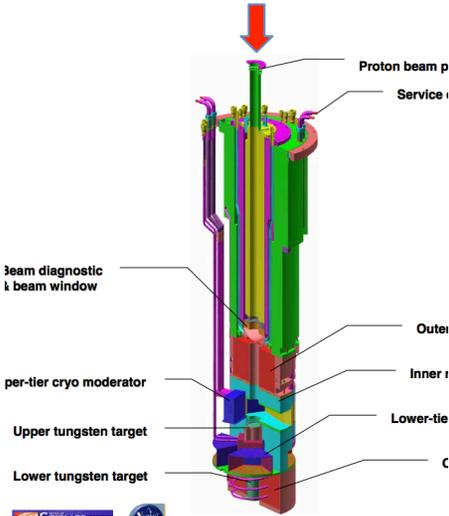
ISIS T1
Ta clad W



SNS mercury target



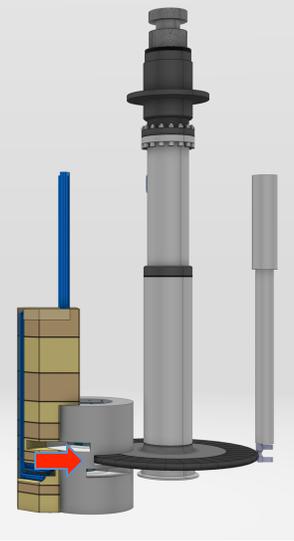
J-PARC mercury target



LANSCE
tungsten target

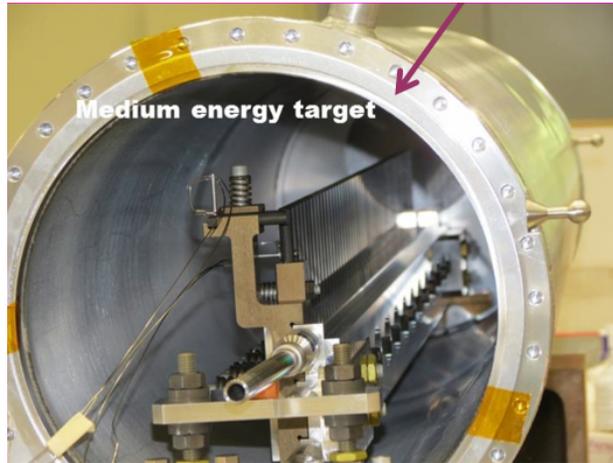


ISIS T2
Ta clad W

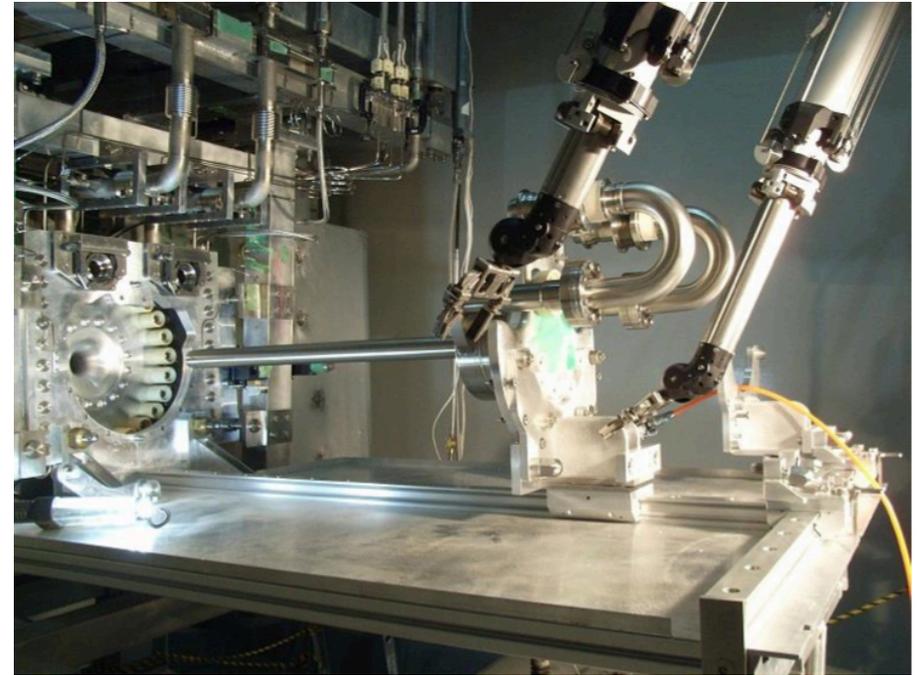


ESS tungsten target
(in design)

Some other high power targets



FNAL's NUMI carbon target



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

Target 8

Top disk - 200 micron beam sigma
with beam sweeping radius ~0.3 mm

Middle disk - 140 micron beam sigma
With beam sweeping radius ~0.6 mm

Beam sweeping system
commissioned late 4/07

1.8E19 protons
88 days service life
5/07 to present

FNAL's pbar production target

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		Proton Energy (GeV)	Time Ave Beam Power (MW)	Peak Time Ave Power Density (GW/m ³)	Peak Energy Density (MJ/m ³)
			Duration (μs)	Rep Rate (Hz)				
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

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



Additional Operational Concerns

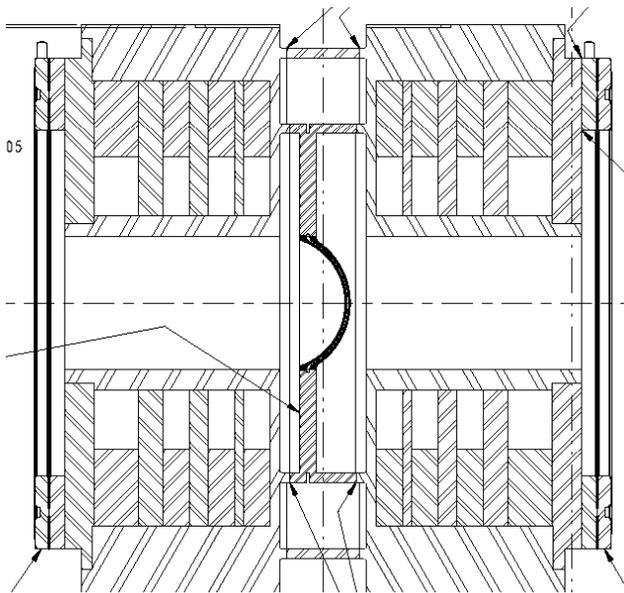
Fermilab example



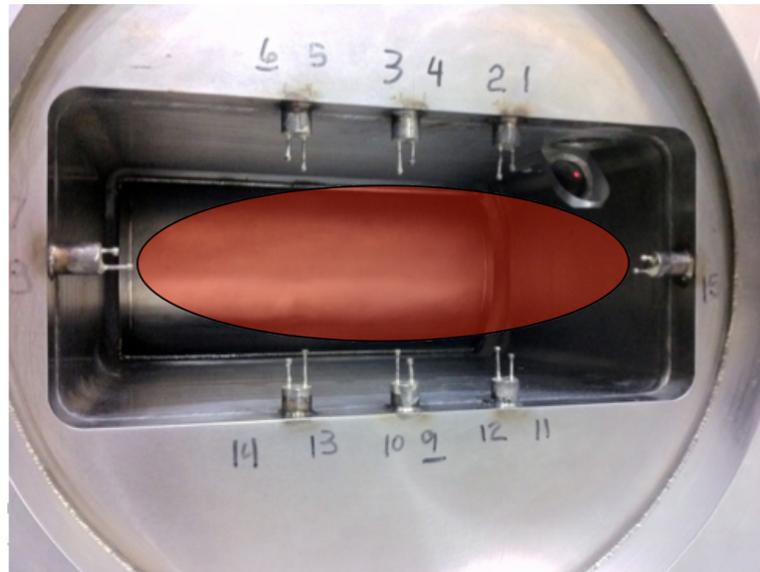
- HS broken steel chain from hydrogen embrittlement caused by acidic vapors/condensate from air ionization (MiniBooNE 25 m absorber).

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



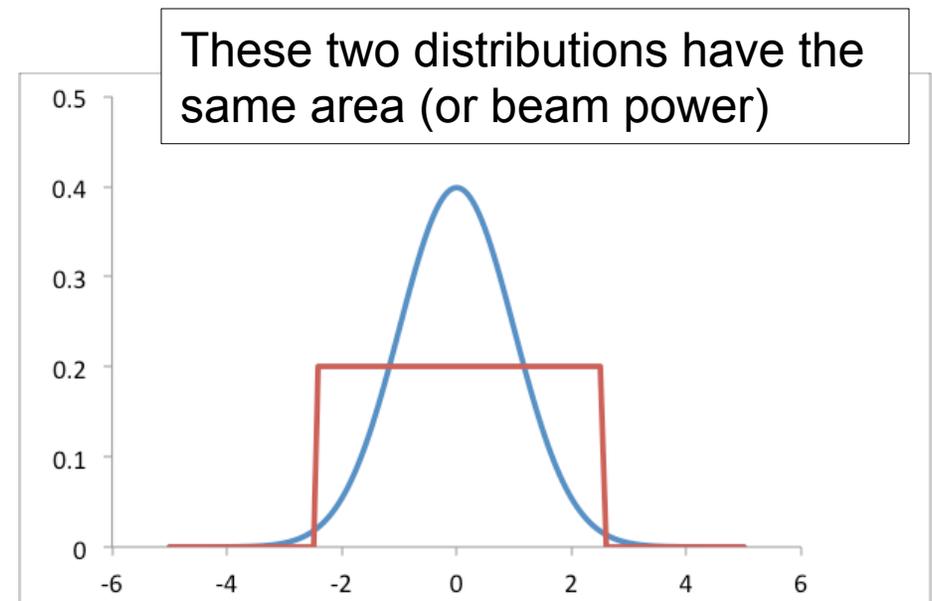
View from downstream side

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

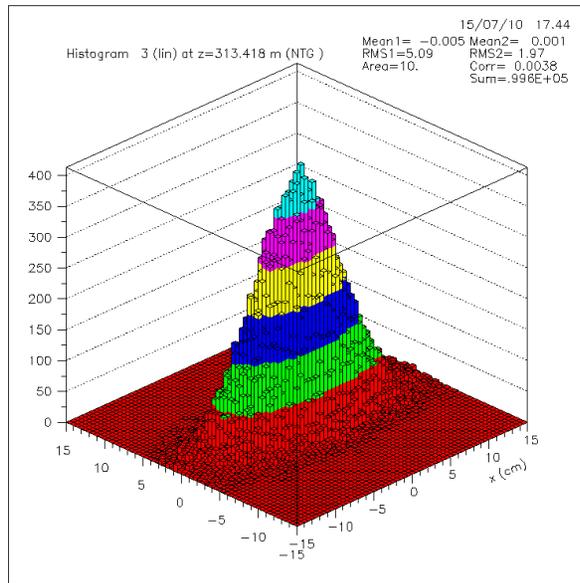


Methods to flatten beam distribution

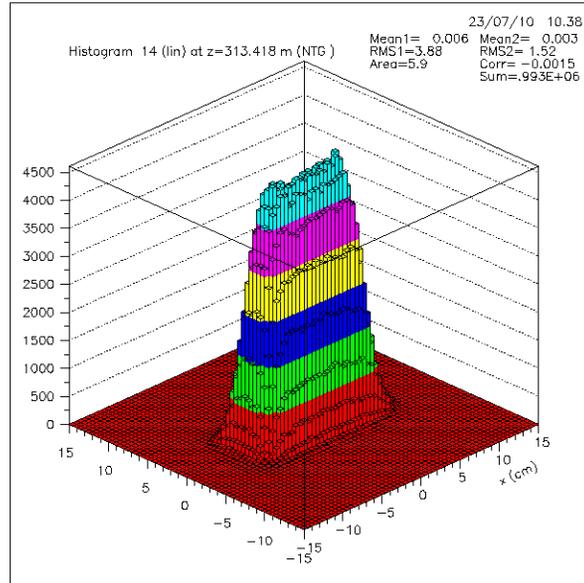
- Injection painting in storage rings and synchrotrons (e.g. SNS, J-PARC)
- Multipole magnets (e.g. octupoles) in beam transport line to target (e.g. J-PARC)
 - Note that beam must usually be well-centered in the octupoles for proper flattening. Off center beams will produce skewed distributions.
- Raster 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

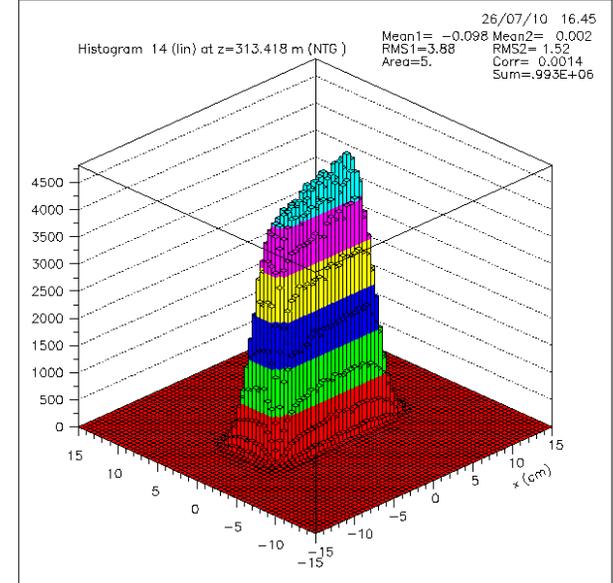
No octupoles



With octupoles

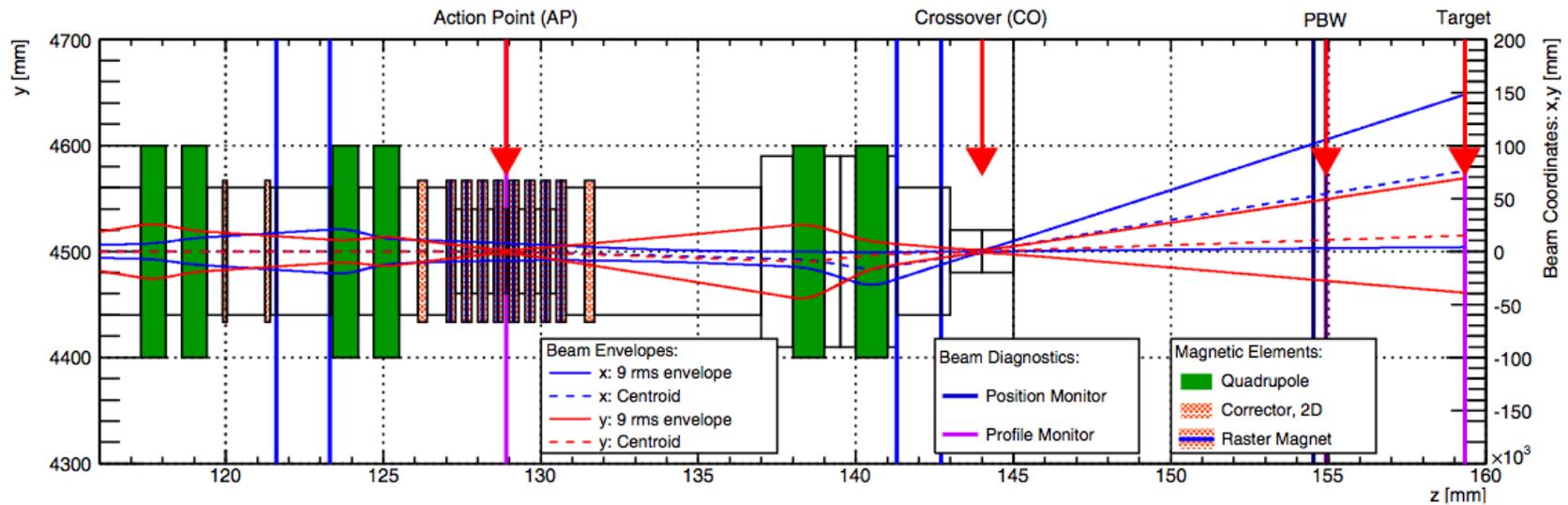


2 mm offset in octupole

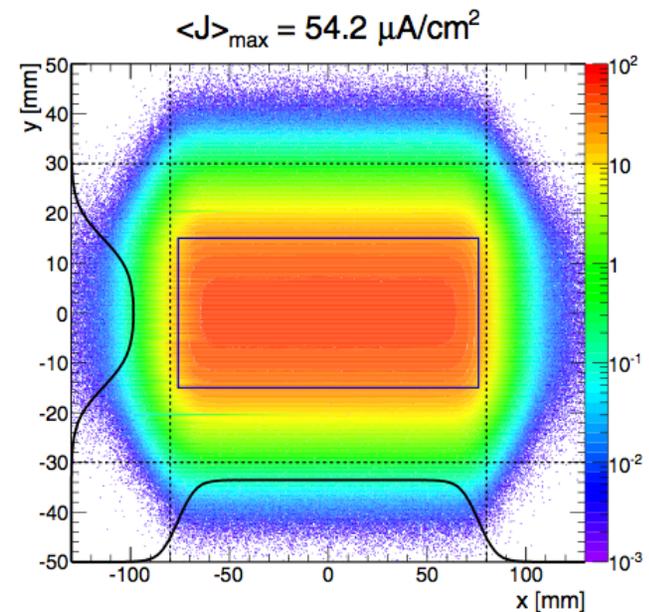


In 2013, J-PARC added two octupole magnets to flatten the beam distribution on the neutron spallation target

Beam raster system planned for ESS



Possible sweep frequencies 29.05 and 39.55 kHz



What can go wrong? Some examples...

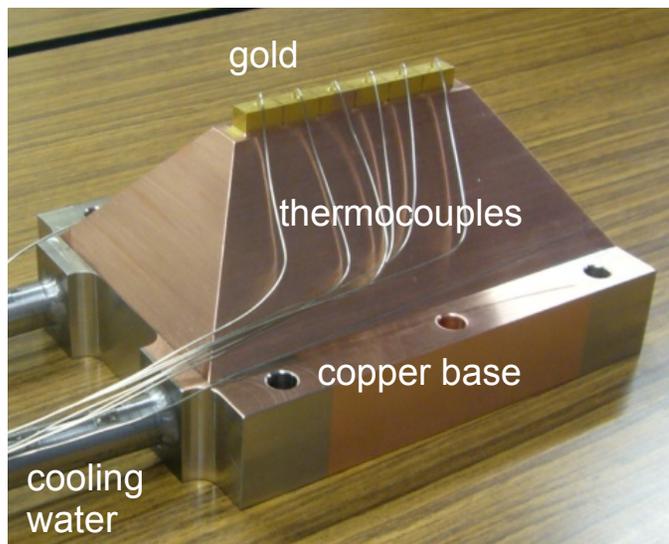
- J-PARC overpowered Hadron Hall gold target 2013
- ISIS exceeded design beam density 2010
- PSI exceeded nominal beam density 2004

J-PARC target failure May 23, 2013

December 17, 2013
J-PARC Center

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.



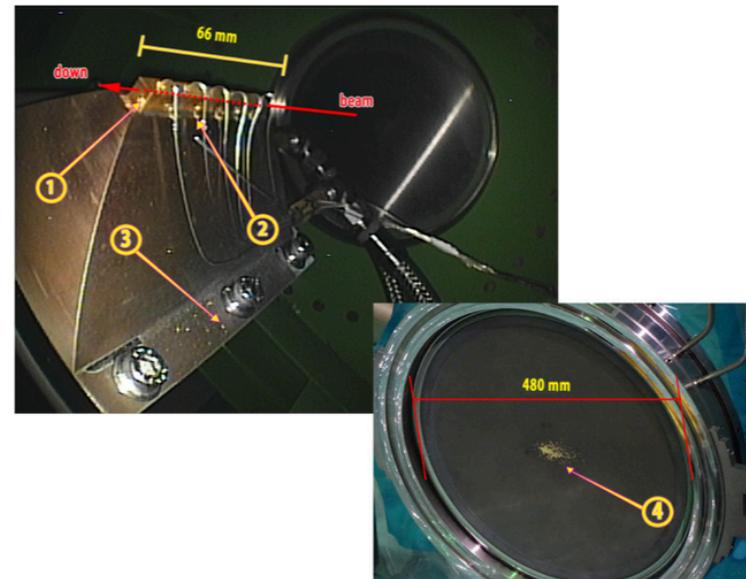
The Observation of the Gold Target at the Hadron Experimental Facility

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.

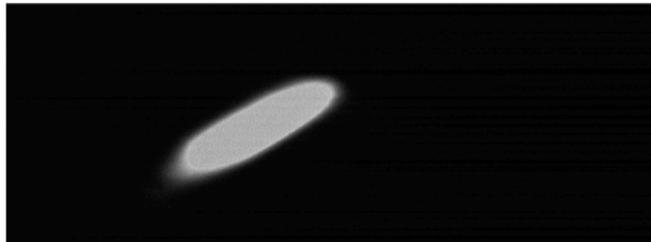
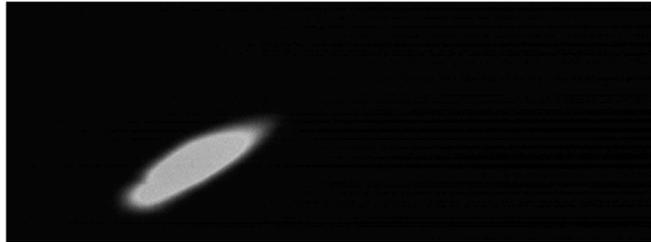
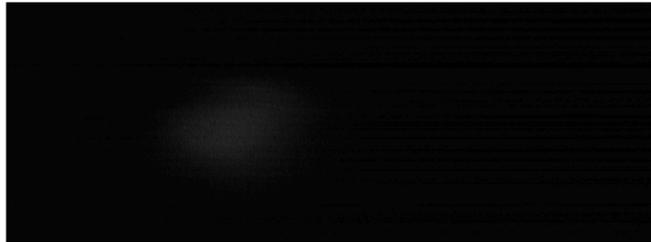
As we reported previously, it has been considered that the target was damaged and partially evaporated by an accidental injection of a large amount of protons for a very short period (i.e., 5 micro sec.), and several simulations were carried out.

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.



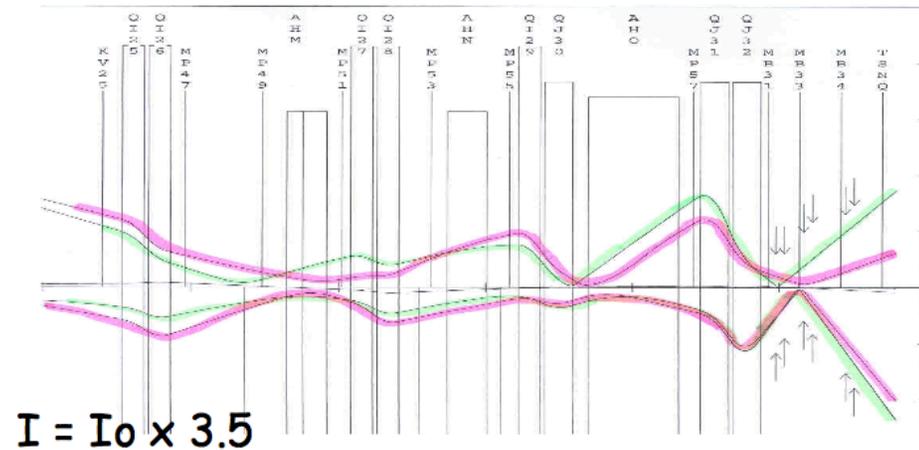
VIMOS saw wrong Parameter File



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
  
```



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.

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 ($\text{WO}_3 \cdot \text{H}_2\text{O}$) being produced as a result of tungsten vaporization at an elevated temperature ($> 800 \text{ }^\circ\text{C}$) 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 $\sigma = 20$ 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

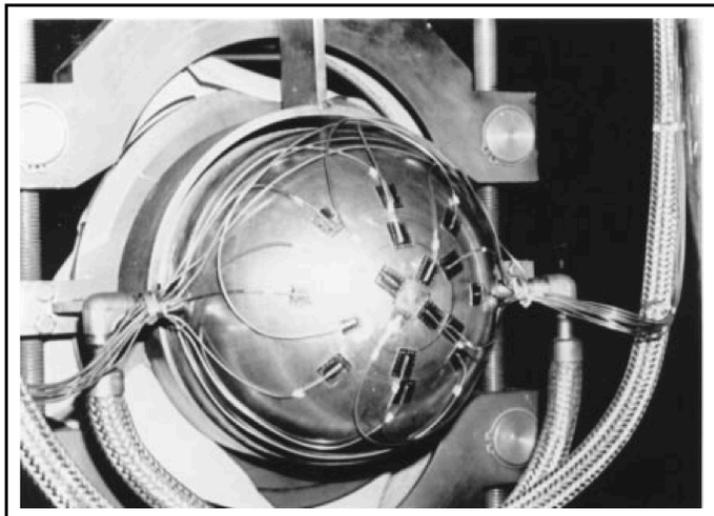


Fig. 2 Outer face (atmosphere side) of the LANSCE double-walled hemispherical beam exit window showing placement of the thermocouples. Note that several spot welds were used to affix the thermocouple pads to the window surface.

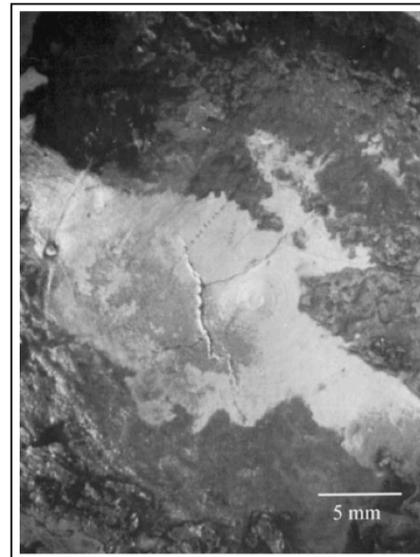


Fig. 12 The crack near both the mechanical center and dose maximum seen from the waterside following removal of some of the deposits

Example: rectangular dc beam

Assume:

2 MW beam

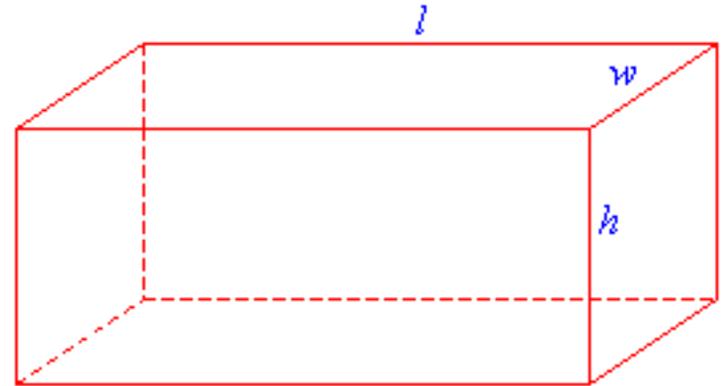
1 GeV protons

dc beam

Rectangular shape 2 cm x 2 cm

Stops 0.75 m into target

Assume uniform energy deposition
and no scattering



$$\text{1-second power density} = (2 \text{ MW}) / (2 \text{ cm}) / (2 \text{ cm}) / (0.75 \text{ m}) = 6.67 \text{ GW/m}^3$$

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

$$(100 \text{ J}) / (2 \text{ MJ/s}) = 50 \text{ us} = \text{required turn off time}$$

Example: rectangular pulsed beam

Assume:

2 MW beam

1 GeV protons

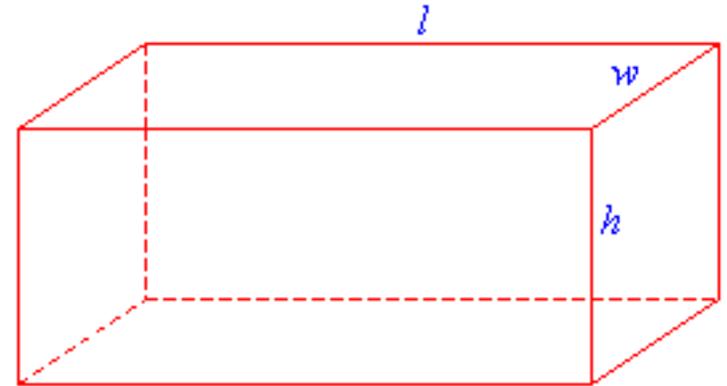
10 Hz

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 = $(2 \text{ MW}) / (2 \text{ cm}) / (2 \text{ cm}) / (0.75 \text{ m}) = 6.67 \text{ GW/m}^3$

Energy per pulse = $2 \text{ MW} / 10 \text{ Hz} = 0.2 \text{ MJ}$

Per pulse energy density in target = $(0.2 \text{ MJ}) / (2 \text{ cm}) / (2 \text{ cm}) / (0.75 \text{ m}) = 667 \text{ MJ/m}^3$

Peak power density = $(667 \text{ MJ/m}^3) / (1.5 \text{ us}) = 4.45 \times 10^{14} \text{ W/m}^3$

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

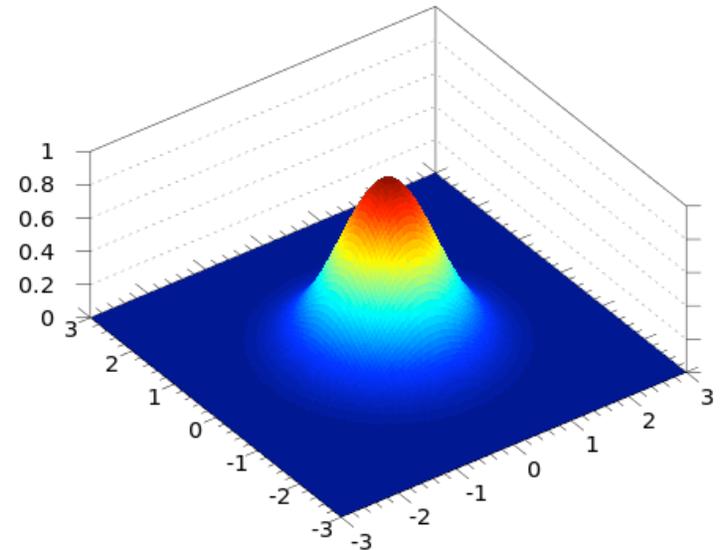
10 Hz

Gaussian beam pulse $\sigma_x = \sigma_y = 0.5$ cm

Each pulse 1.5 μ s 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 =

$$(2 \text{ MW}) / (2\pi) / (0.5 \text{ cm}) / (0.5 \text{ cm}) / (0.75 \text{ m}) = 17 \text{ GW/m}^3$$

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

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

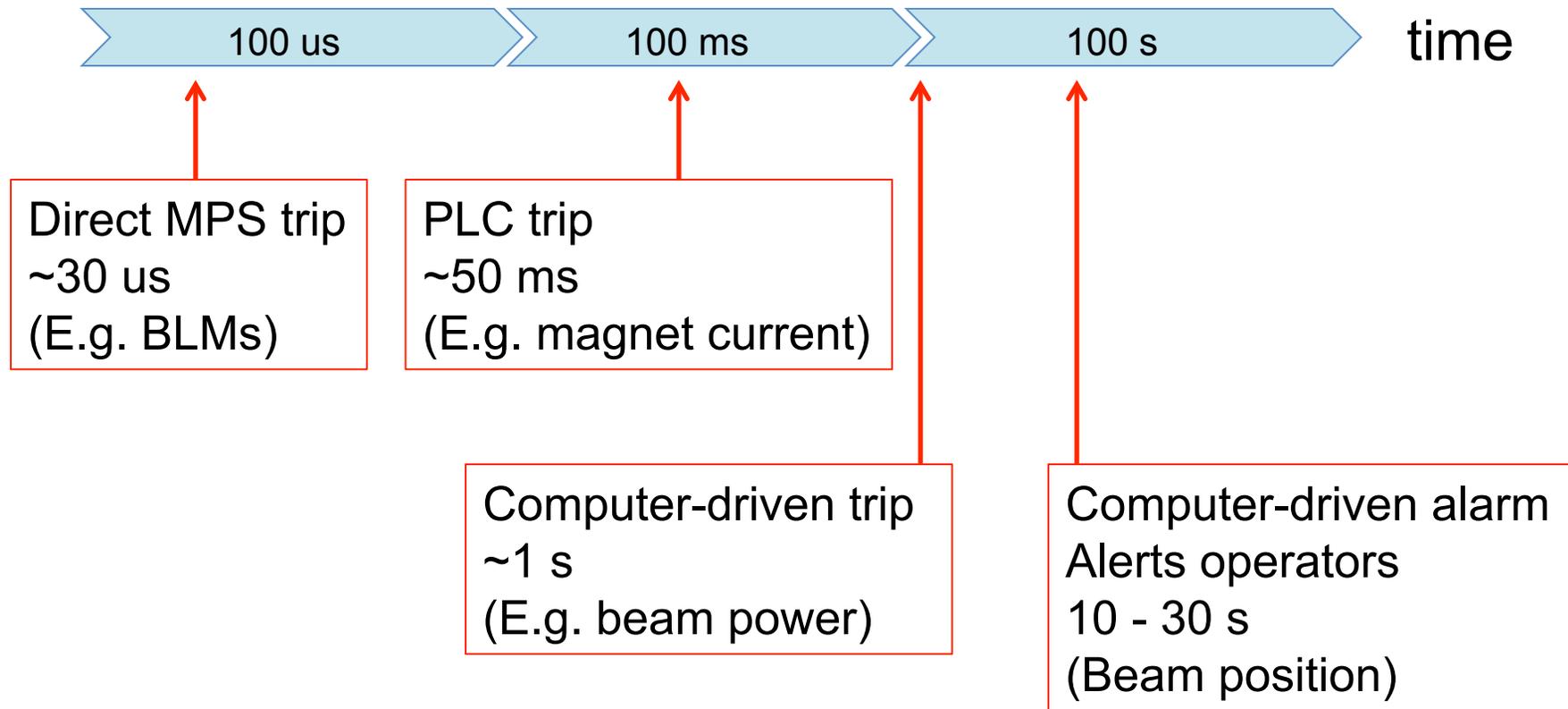
Types of beam-related target protection

- 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

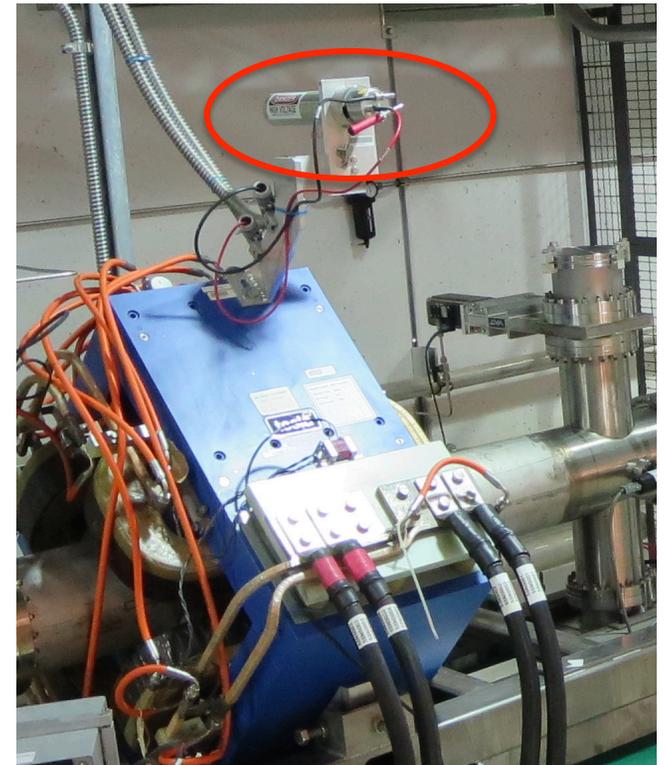
- Continuously monitor and interlock on critical beam parameters
 - Beam loss monitors (everybody)
 - Beam current monitors (everybody)
 - Beam position monitors (PSI has automatic beam centering based on BPM signals)
 - Amount of beam intercepted by collimator (PSI)
 - Harp profile monitors (J-PARC, 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.

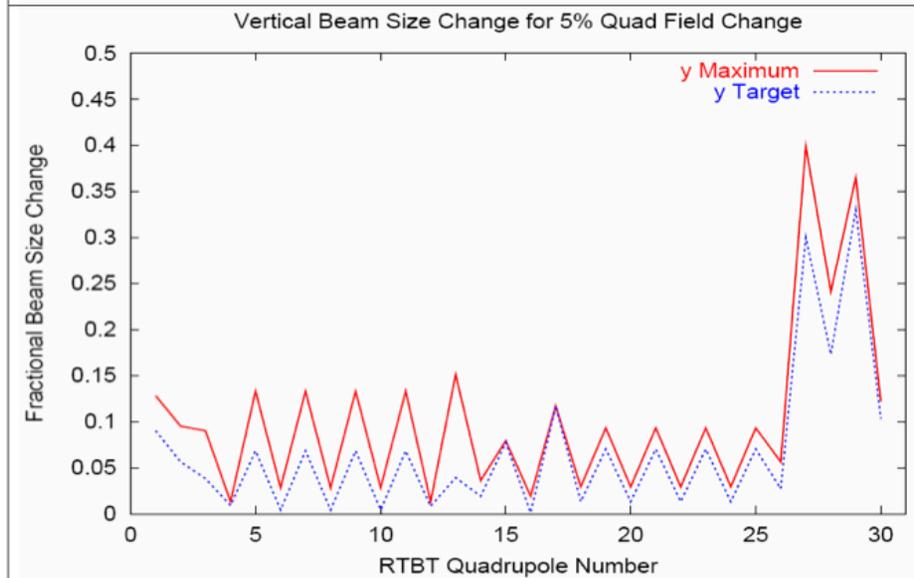
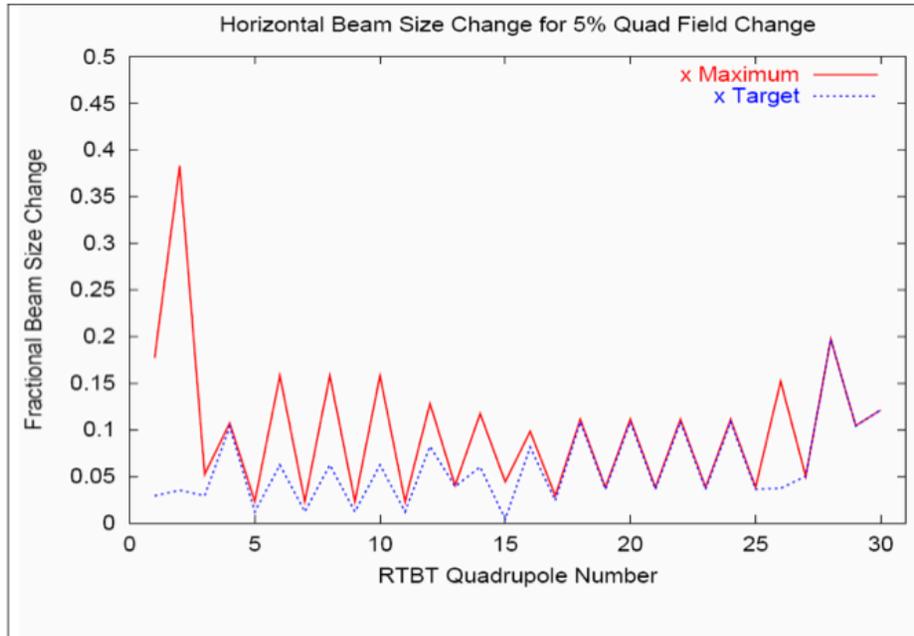
Protection by rapid beam turn-off (cont.)

- 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

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

The screenshot displays a control interface for 'Beam Width'. At the top, 'Gate Width (Turns):' is set to 895. Below this, a 'Set Point (Turns)' is set to 1, and 'Beam Gate (Turns)' is set to 895. A horizontal slider bar is visible, with 'save' and 'rest' buttons below it. Further down, several limits are shown: 'Limit from MPS' is 1060, 'Limit from Duty Cycle' is 858, and 'Duty Cycle Limit %' is 5.4. A section for 'BEAM Gate > 50us in MEBT_BS Mode:' includes 'DG535 Width' at 840 and 'Beam Gate Width' at 855. At the bottom, there are buttons for 'Duty Cycle Limits' and 'Set Duty Cycle Limit'.

Beam gate width and duty cycle limits, set by operators

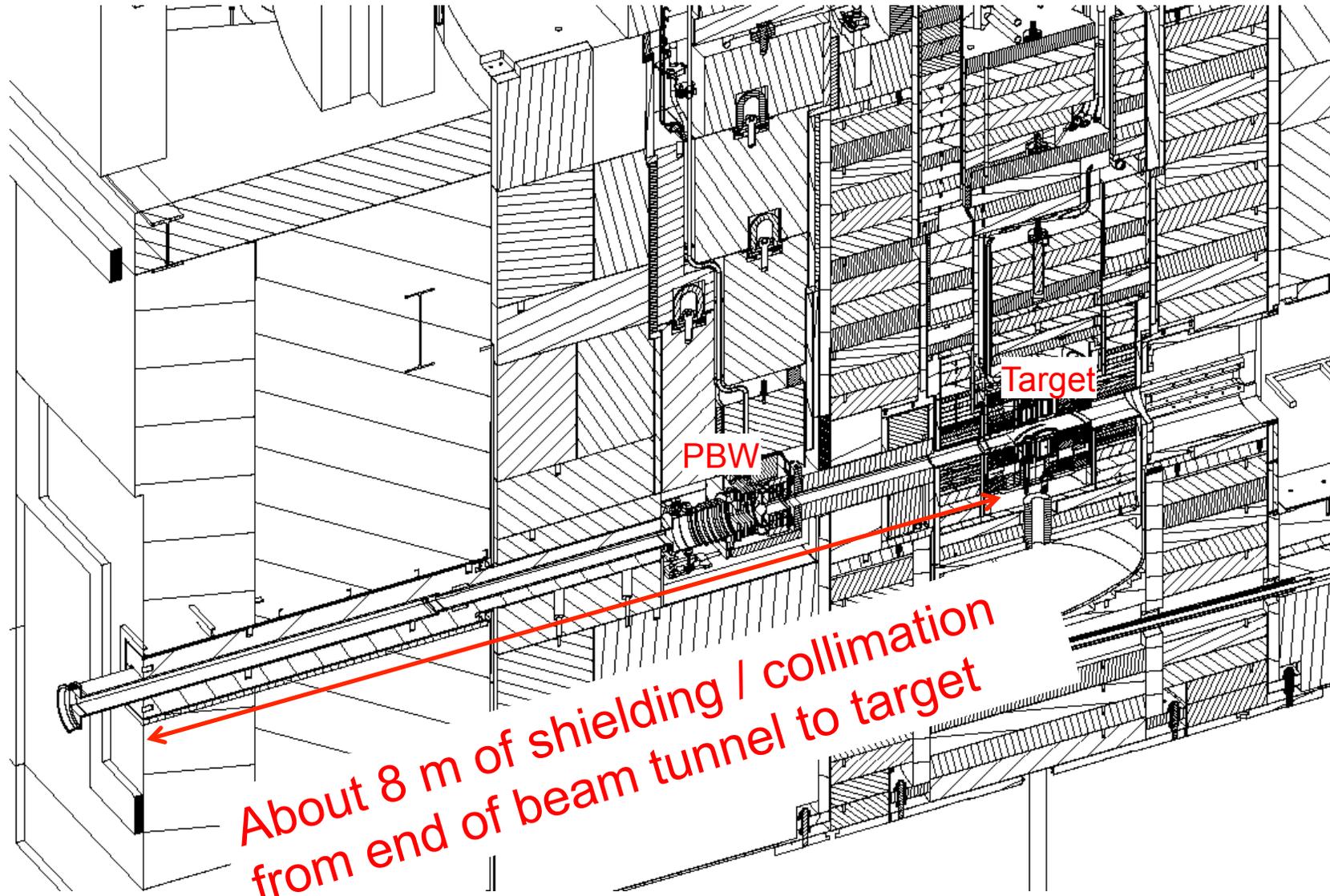
Protection by alarms

- 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 $27.9 \times 12.7 \text{ cm}^2$, compared to requirement of 90% of beam inside a $20 \times 7 \text{ cm}^2$ 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

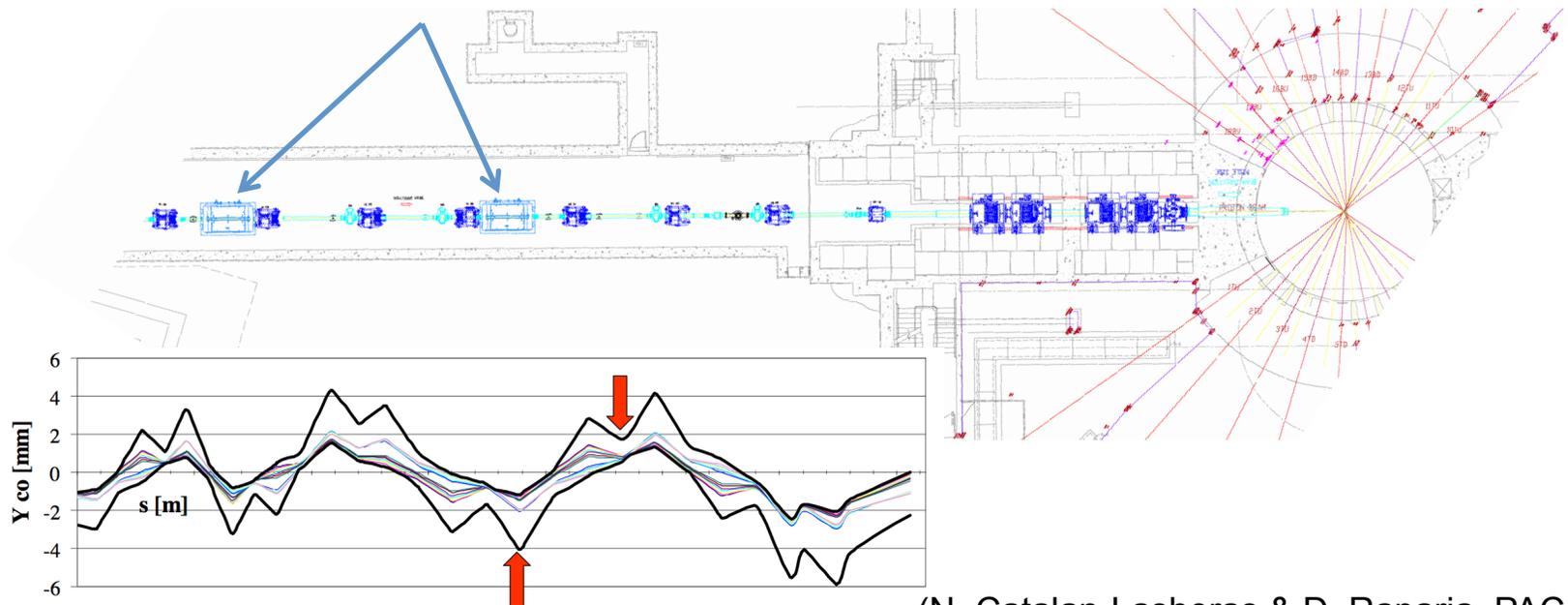


About 8 m of shielding / collimation
from end of beam tunnel to target

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 π

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.

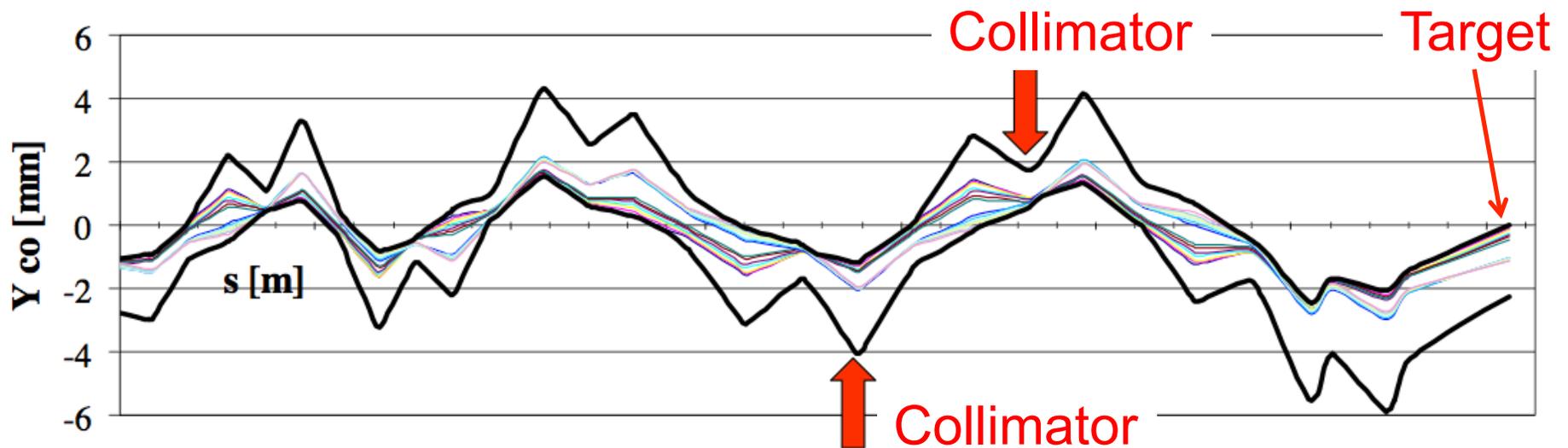


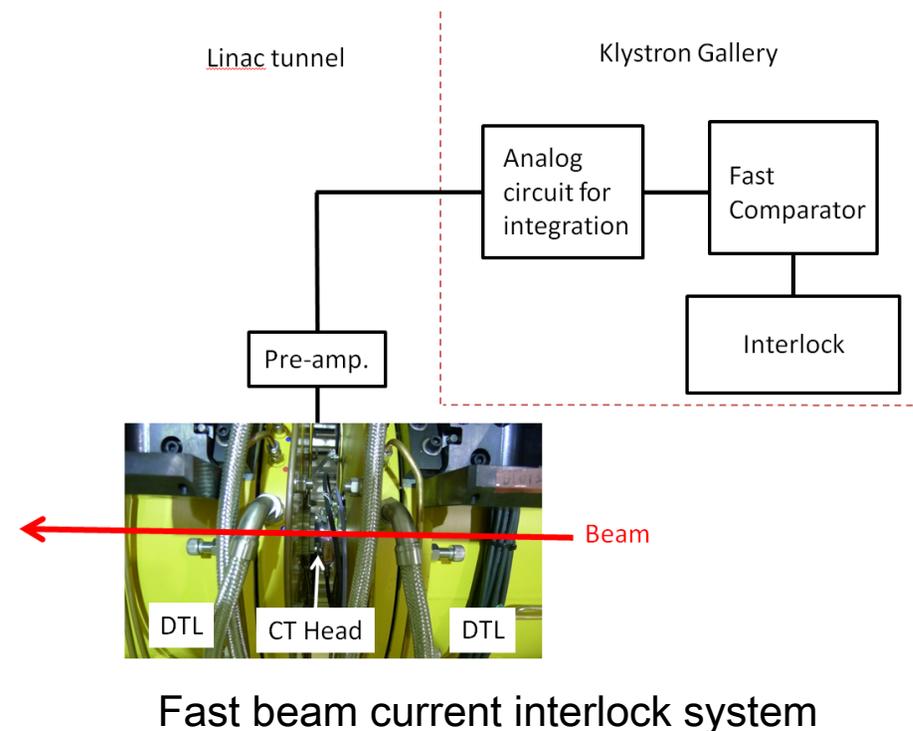
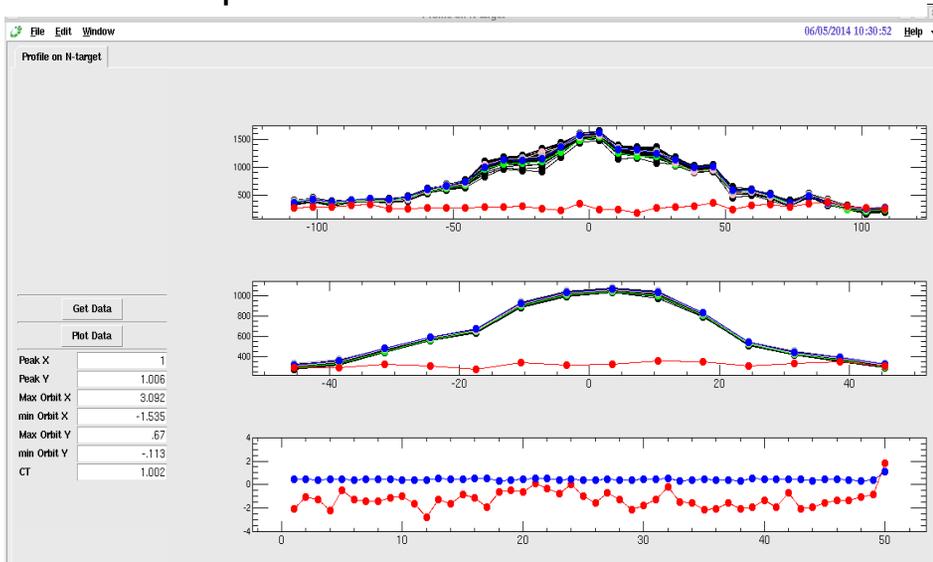
Figure 2: Vertical closed orbit deviation along the RTBT. Thin lines correspond to one kicker mis-fire. Bold lines are the maximum and minimum closed orbit deviation when two kickers fail simultaneously.

(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



Example: FNAL NuMI target protection

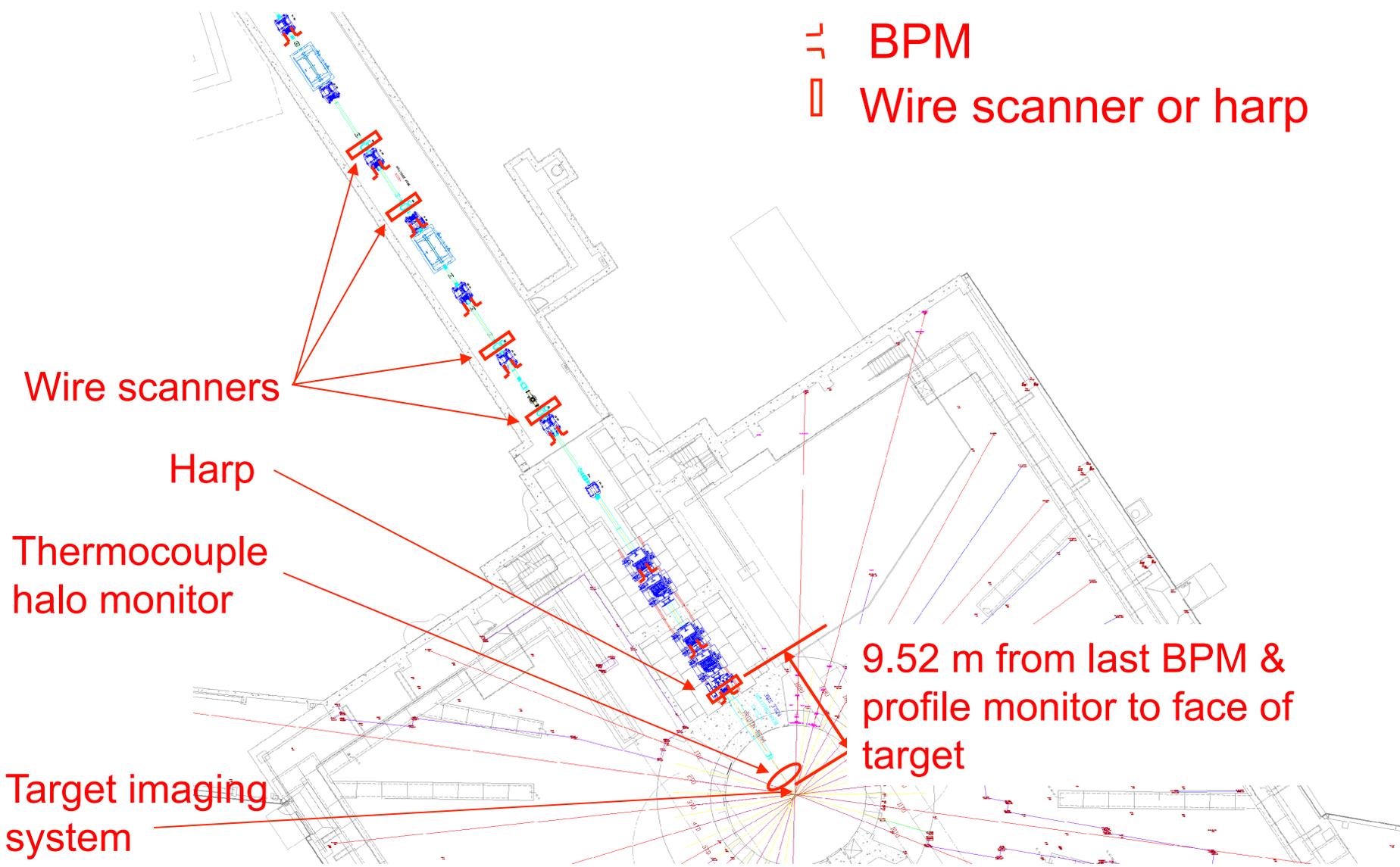
- NuMI target is now 120 GeV, 700 kW. >1 MW is planned.
- Prior to beam extraction from Main Injector, check >250 inputs to the Beam Permit System. Send beam to abort dump if inputs are not correct.
 - Beam position and angle for extraction channel
 - Excessive residual MI beam in NuMI kicker gap
 - 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



Example: ISIS target protection

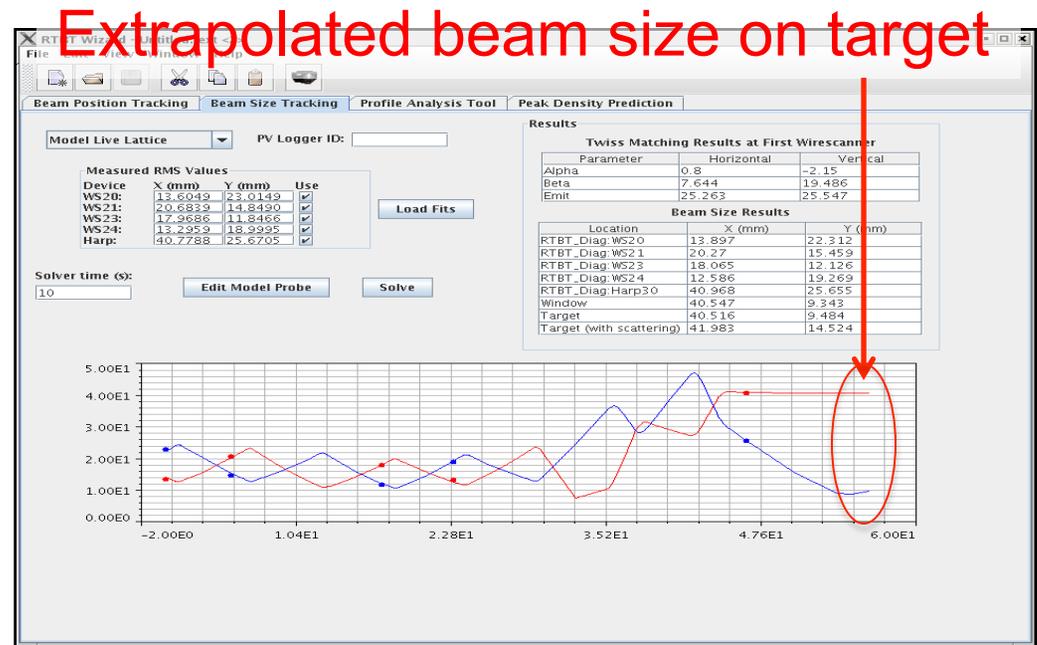
- TS1: 800 MeV, 160 kW, 40 Hz. TS2: 800 MeV, 40 kW, 10 Hz.
- Beam Halo monitor (8 equally spaced thermocouples in the penumbra of the beam ~100 mm upstream of the target) indicate mis-focus and mis-steer. Suitable trip levels of thermocouple values feed into the protection systems if such events occur.
- 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.

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/m² (for 1 GeV case)
 - Peak density on proton beam window less than $2.9e16$ protons/m²

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 $\pm 7\%$
 - 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 $\pm 5\%$ on quads, $\pm 5\%$ 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

The screenshot displays the 'Beam Width' control interface. At the top, 'Gate Width (Turns):' is set to 895. Below this, a 'Set Point (Turns)' is set to 1, and the 'Beam Gate (Turns)' is shown as 895 on a slider scale from 1 to 1000. Further down, several limits are listed: 'Limit from MPS' at 1000, 'Limit from Duty Cycle' at 850, and 'Duty Cycle Limit %' at 5.4. A section titled 'BEAM Gate > 50us in MEBT_BS Mode:' contains 'DG535 Width' at 940 and 'Beam Gate Width' at 855. At the bottom, there are buttons for 'Duty Cycle Limits' and 'Set Duty Cycle Limit'. Annotations include 'Hardware limit' pointing to 'DG535 Width' and 'Software limit' pointing to the 'Duty Cycle Limits' button. A bracket on the right groups the 'Limit from Duty Cycle', 'Duty Cycle Limit %', and 'Beam Gate Width' parameters, with the text 'Beam gate width and duty cycle limits, set by operators'.

Parameter	Value
Gate Width (Turns)	895
Set Point (Turns)	1
Beam Gate (Turns)	895
Limit from MPS	1000
Limit from Duty Cycle	850
Duty Cycle Limit %	5.4
BEAM Gate > 50us in MEBT_BS Mode:	
DG535 Width	940
Beam Gate Width	855

Magnet current lockdown by PLC

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

MPS PLC Inputs

Machine Mode: **Target**
 Beam Mode: **RTBT Turn**

Magnet PS Limit Sets: **Run**

Crash Buttons

Key Switch Panel: **Run**
 South Arc: **Run**
 North West Arc: **Run**
 North East Arc: **Run**

CCL Beamstop

CCL BS Intlk Latch: **OK** (Reset)
 CCL BS In: **ON**
 CCL BS Out: **ON**
 CCL Beamstop Downstream Valve: **Open**

CCL Beamstop Water

CCL BS Water Intlk: **OK**
 CCL BS Water OK: **OK**

Linac Dump

LDmp Quad Status: **OK**
 LDmp Thermocouple Sum: **OK**
 HEBT CCWS Status: **OK**
 PPS HEBT DIPOLES Sts: **OFF** (PPS Critical Device)

	Readback	Low Limit	High Limit
LDmp QH01A05 Window	93.07	89.81	96.32
LDmp QV02 Window	14.15	13.65	14.65
LDmp QV03a06 Window	70.56	69.00	73.00
LDmp QV04 Window	32.11	30.99	33.23

HEBT DH11 LOW Trip: **OFF** (Note: DH11 Low has to be satisfied to run only into the Linac Dump)

Injection Dump

IDmp Sum Status: **OK**
 HEBT CCWS Status: **OK**
 PPS HEBT DIPOLES Sts: **ON** (PPS Critical Device)
 PPS Ring DIPOLES Sts: **OFF** (PPS Critical Device)
 Ring DH A12 LOW Alarm: **OFF**

	Readback	Low Limit	High Limit
IDmp QV01 Window	414.29	400.00	455.72
HEBT DH11 Window	525.27	24.00	545.00

DH A12 LOW Trip: **OFF** (Note: DH A12 only has to be satisfied to run only into the Injection Dump)

Ring

Ring CCWS Status: **OK**
 PPS Ring DIPOLES Sts: **ON** (PPS Critical Device)
 PPS Ex Sept Sts: **OFF** (PPS Critical Device)
 Ring DH A12 HI Alarm: **OFF** (Note: Ring DH A12 is only a warning!!! Will not trip MPS)

	Readback	Low Limit	High Limit
DH A12 Window	111.11	111.11	111.11
Ext Septum LOW Trip	111.11	111.11	111.11

(Note: Ext Septum Low has to be satisfied to run only into the Ring)

Extraction Dump

EDmp Thermocouple Sum: **ON**
 PPS Ex Sept Sts: **ON** (PPS Critical Device)
 PPS DH13 Sts: **OFF** (PPS Critical Device)

	Readback	Low Limit	High Limit
EDmp QH01 Window	463.71	447.23	479.67
EDmp QV02 Window	407.16	397.00	417.00
Ext Septum Window	1850.71	1848.71	1852.71

RTBT DH13 Low: **OFF** (Note: DH13 Low has to be satisfied to run only into the Extraction Dump)

Target

Tgt PLC Sts: **OK**
 PPS DH13 Sts: **ON** (PPS Critical Device)
 RTBT CCWS Status: **OK**

	Readback	Low Limit	High Limit
RTBT DH13 Window	1919.75	1918.00	1922.00
RTBT QH26 Window	560.69	541.07	580.31
RTBT QV27 Window	431.43	416.21	446.40
RTBT QH28 Window	699.17	674.70	723.65
RTBT QV29 Window	395.97	382.11	409.83
RTBT QH30 Window	174.78	168.66	180.90
RTBT DCH28 Window	36.85	31.80	41.80
RTBT DCV28 Window	11.37	6.37	16.37
RTBT DCH30 Window	32.60	27.55	37.55
RTBT DCV30 Window	2.06	-2.94	7.06

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

POWER SUPPLY STATUS						SETPOINTS		READBACKS		Interlock Limits			PS-UI
PPS	PS Name	Mode Select	Channel Status	Control Status	PS Status	Set I	Set B	Trip Window +/- %	B	LowTripLmt	I Book	HighTripLmt	Int'l Sts/RSet
PPS	RTBT_Mag_PS_ExSptm	ON OFF STANDBY	Enabled	Remote	OK	1850.538	0.673359	5.000	0.673 T	0.639691	0.673359	0.707027	RSet CV01
	RTBT_Mag_PS_QV01	ON OFF STANDBY	Enabled	Remote	OK	714.249	3.2719	5.000	3.280 T	3.1083	3.2719	3.4355	RSet CV01
	RTBT_Mag_PS_QH02	ON OFF STANDBY	Enabled	Remote	OK	711.548	3.240	5.000	3.247 T	3.0780	3.2400	3.4020	RSet CV02
	RTBT_Mag_PS_QV03	ON OFF STANDBY	Enabled	Remote	OK	498.442	3.106	5.000	3.106 T	2.9504	3.1057	3.2610	RSet CV03
	RTBT_Mag_PS_QH04	ON OFF STANDBY	Enabled	Remote	OK	550.474	3.430	5.000	3.431 T	3.2584	3.4299	3.6014	RSet CV04
	RTBT_Mag_PS_QV051to	ON OFF STANDBY	Enabled	Remote	OK	728.939	4.529	5.000	4.536 T	4.0759	4.5288	4.9816	RSet CV05
	RTBT_Mag_PS_QH061to	ON OFF STANDBY	Enabled	Remote	OK	763.429	4.742	5.000	4.748 T	4.2677	4.7419	5.2161	RSet CV06
	RTBT_Mag_PS_QH12	ON OFF STANDBY	Enabled	Remote	OK	553.173	3.444	5.000	3.445 T	3.2718	3.4440	3.6162	RSet CV12
	RTBT_Mag_PS_QV13	ON OFF STANDBY	Enabled	Remote	OK	482.578	3.008	5.000	3.008 T	2.8573	3.0077	3.1581	RSet CV13
PPS	RTBT_Mag_PS_DH13	ON OFF STANDBY	Enabled	Remote	OK	1921.380	0.662347	5.000000	0.663 T	0.629230	0.662347	0.695464	RSet CV13
	RTBT_Mag_PS_QH14	ON OFF STANDBY	Enabled	Remote	OK	371.672	2.3189	5.000	2.317 T	2.2030	2.3189	2.4349	RSet CV14
	RTBT_Mag_PS_QV15	ON OFF STANDBY	Enabled	Remote	OK	357.111	2.2290	5.000	2.227 T	2.1176	2.2290	2.3405	RSet CV15
	RTBT_Mag_PS_QH16	ON OFF STANDBY	Enabled	Remote	OK	310.724	1.9402	5.000	1.943 T	1.8432	1.9402	2.0372	RSet CV16
	RTBT_Mag_PS_QV17	ON OFF STANDBY	Enabled	Remote	OK	380.817	2.3765	5.000	2.377 T	2.2577	2.3765	2.4953	RSet CV17
	RTBT_Mag_PS_QH1824e	ON OFF STANDBY	Enabled	Remote	OK	349.006	2.1785	5.000	2.179 T	1.9607	2.1785	2.3964	RSet CV18
	RTBT_Mag_PS_QV1925e	ON OFF STANDBY	Enabled	Remote	OK	349.050	2.1785	5.000	2.180 T	1.9607	2.1785	2.3964	RSet CV19
	RTBT_Mag_PS_QH26	ON OFF STANDBY	Enabled	Remote	OK	584.251	2.6542	5.000	2.660 T	2.5215	2.6542	2.7869	RSet CV26
	RTBT_Mag_PS_QV27	ON OFF STANDBY	Enabled	Remote	OK	448.250	1.3645	5.000	1.366 T	1.2963	1.3645	1.4327	RSet CV27
	RTBT_Mag_PS_QH28	ON OFF STANDBY	Enabled	Remote	OK	679.063	2.0634	5.000	2.067 T	1.9602	2.0634	2.1666	RSet CV28
	RTBT_Mag_PS_QV29	ON OFF STANDBY	Enabled	Remote	OK	441.211	1.3423	5.000	1.342 T	1.2752	1.3423	1.4094	RSet CV29
	RTBT_Mag_PS_QH30	ON OFF STANDBY	Enabled	Remote	OK	182.493	0.5545	5.000	0.556 T	0.5268	0.554	0.5822	RSet CV30
	Corr PS Name	Mode Select	Channel Status	Control Status	PS Status	Set I	Set B	I	Trip Window +/- Amps	LowTripLmt	I Book	HighTripLmt	Int'l Sts/RSet
	RTBT_Mag_PS_DCV05	ON OFF STANDBY	Enabled	Remote	OK	8.291	-0.010	8.288	0.500	7.791	8.291	8.791	RSet CV05
	RTBT_Mag_PS_DCH06	ON OFF STANDBY	Enabled	Remote	OK	-5.059	0.006	-5.063	0.500	-5.559	-5.059	-4.559	RSet CV06
	RTBT_Mag_PS_DCV07	ON OFF STANDBY	Enabled	Remote	OK	-6.529	0.008	-6.524	0.500	-7.029	-6.529	-6.029	RSet CV07
	RTBT_Mag_PS_DCH08	ON OFF STANDBY	Enabled	Remote	OK	3.716	-0.005	3.716	0.500	3.216	3.716	4.216	RSet CV08
	RTBT_Mag_PS_DCV11	ON OFF STANDBY	Enabled	Remote	OK	7.967	-0.010	7.967	0.500	7.467	7.967	8.467	RSet CV11
	RTBT_Mag_PS_DCV13	ON OFF STANDBY	Enabled	Remote	OK	-0.907	0.001	-0.913	0.500	-1.407	-0.907	-0.407	RSet CV13
	RTBT_Mag_PS_DCH14	ON OFF STANDBY	Enabled	Remote	OK	-1.135	0.001	-1.123	0.500	-1.635	-1.135	-0.635	RSet CV14
	RTBT_Mag_PS_DCV15	ON OFF STANDBY	Enabled	Remote	OK	6.779	-0.008	6.780	0.500	6.279	6.779	7.279	RSet CV15
	RTBT_Mag_PS_DCH16	ON OFF STANDBY	Enabled	Remote	OK	0.560	-0.001	0.557	0.500	0.060	0.560	1.060	RSet CV16
	RTBT_Mag_PS_DCV17	ON OFF STANDBY	Enabled	Remote	OK	-3.633	0.005	-3.633	0.500	-4.133	-3.633	-3.133	RSet CV17
	RTBT_Mag_PS_DCH18	ON OFF STANDBY	Enabled	Remote	OK	3.219	-0.004	3.214	0.500	2.719	3.219	3.719	RSet CV18
	RTBT_Mag_PS_DCV20	ON OFF STANDBY	Enabled	Remote	OK	0.487	-0.001	0.488	0.500	-0.013	0.487	0.987	RSet CV20
	RTBT_Mag_PS_DCH21	ON OFF STANDBY	Enabled	Remote	OK	-0.293	0.000	-0.292	0.500	-0.793	-0.293	0.207	RSet CV21
	RTBT_Mag_PS_DCV22	ON OFF STANDBY	Enabled	Remote	OK	0.600	-0.001	0.601	0.500	0.100	0.600	1.100	RSet CV22
	RTBT_Mag_PS_DCH23	ON OFF STANDBY	Enabled	Remote	OK	-1.117	0.001	-1.119	0.500	-1.617	-1.117	-0.617	RSet CV23
	RTBT_Mag_PS_DCV28	ON OFF STANDBY	Enabled	Remote	OK	33.000	-0.004	32.953	0.500	32.500	33.000	33.500	RSet CV28
	RTBT_Mag_PS_DCH28	ON OFF STANDBY	Enabled	Remote	OK	2.000	-0.000	2.023	0.500	1.500	2.000	2.500	RSet CV28
	RTBT_Mag_PS_DCV30	ON OFF STANDBY	Enabled	Remote	OK	33.000	-0.004	32.783	0.500	32.500	33.000	33.500	RSet CV30
	RTBT_Mag_PS_DCH30	ON OFF STANDBY	Enabled	Remote	OK	2.000	-0.00	1.961	0.500	1.500	2.000	2.500	RSet CV30

Errant Beam Control (RTBT Magnet PS)

SNS MagPS Control Top

OCT 20, 2014 16:59:01

Machine Mode ON Beam Mode ON Beam Enabled ON

Errant Beam Window Settings

Target Window Settings (Last 4 Corr)

Copy I_Set to I_Book

Set Trip Window 0.5a Set Trip Window 10a

Limit Settings (All Errant Beam Correctors)

Copy I_Set to I_Book

Set Trip Window 0.5a Set Trip Window Max

Limit Settings (All Errant Beam Quads/ExSptm)

Copy B_Set to B_Book

Set Trip Window 5% Set Trip Window 10%

Errant Beam PS Limit Ctl from MPS

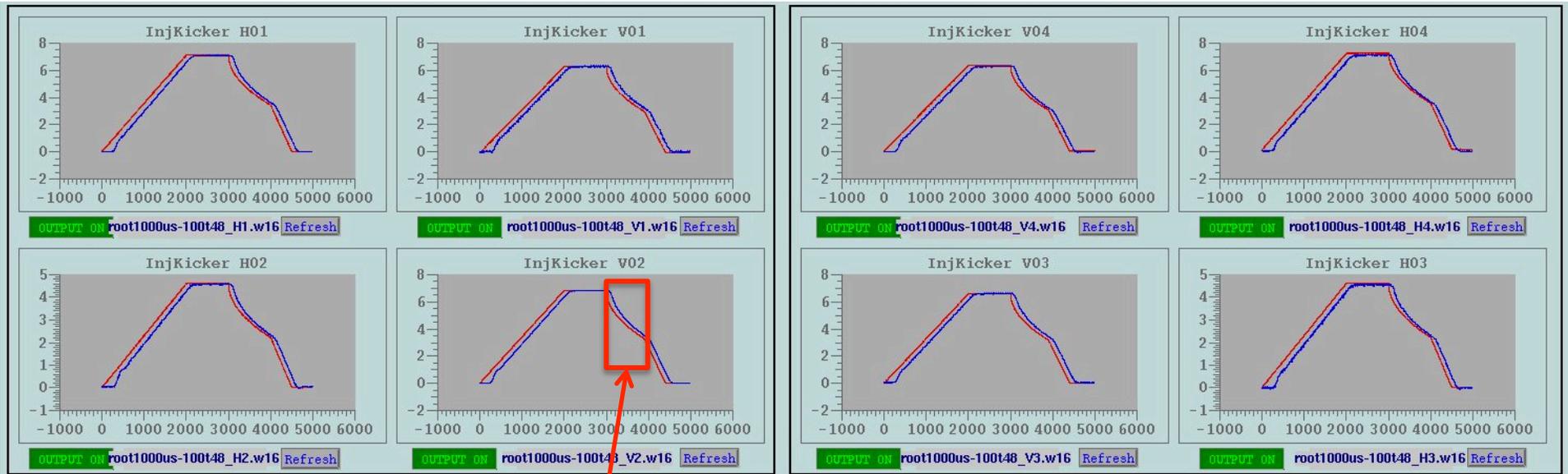
ON MPS PLC Errant Beam PS Limits

PS-UI Limits PS-MPS PLC Grp - Group Limit Settings <PS> - Individual PS Limit Setting

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

Injection kicker lock-down

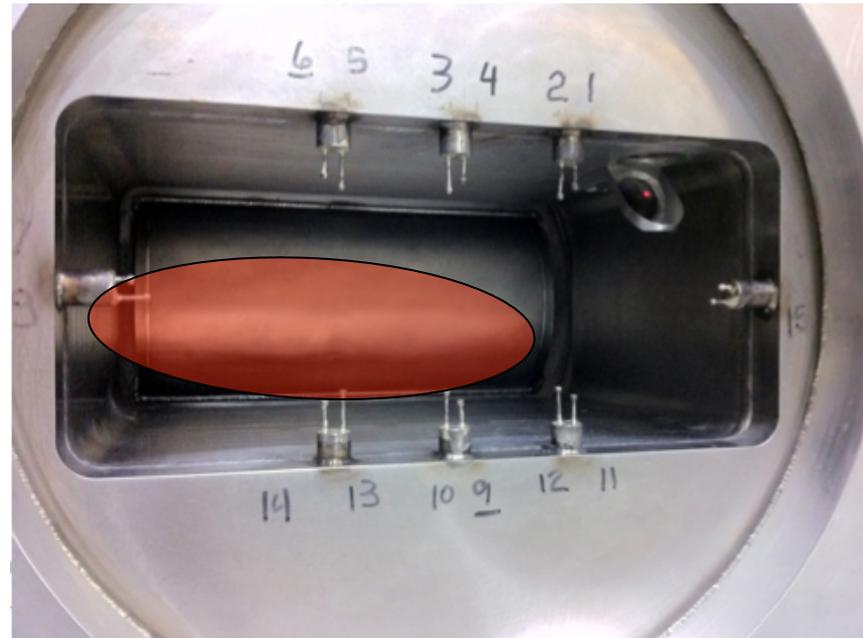
Example: SNS injection kicker production waveforms. Directly impact the beam distribution on the target.



- 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

06/04/14 01:52:09 Errant Beam Alarms

Parameter	Prod. Value	Readback		Alarm	Time Stamp
		Instantaneous	Smoothed		
IDmp Q (BCM01 Charge in C)	9.70e-07	1.05e-06	8.54e-07	●	Jun 03 2014
IDmp Centeri		1.8 C		●	May 07 2014
5% Quad Thresh		NO_ALARM	Bbook	●	May 05 2014
0.5 A Corrector Threshold		NO_ALARM	lbook	●	May 31 2014
3.5% Quad Threshold		NO_ALARM	Qd Cur	●	Jun 03 2014
5 A Corrector Threshold		NO_ALARM	Di Cur	●	Jun 03 2014
2 A Extraction Septum and DH13		NO_ALARM	Misc	●	Jun 03 2014
RTBT Wizard					
		Harp	Instantaneous	Smoothed	
Harp H RMS Fit (mm)		32.6	32.67	32.7 mm	●
Harp V RMS Fit (mm)		31.8	31.81	31.8 mm	●
Density (particles/mm ²)	1.70e+10	1.90e+10	1.89e+10	1.90e+10	●
Harp Density OE limits					
	Power (kW) at 60 Hz	Peak Protons/mm2/pulse, 60 Hz			
	400 or below	<= 8.06e+09		●	
	400 - 600	<= 1.12e+10		●	
	600 - 800	<= 1.36e+10		●	
	800 - 1000	<= 1.71e+10		●	
	1000 - 1200	<= 2.05e+10		●	
	1200 - 1400	<= 2.38e+10		●	
Sum Alarm					
		Instantaneous	Smoothed		
TIS H Position		-1.7	-1.6	●	Jun 03 2014
TIS V Position		2.4	2.3	●	Jun 03 2014
Target Center H (70 deg F window)		0.54		●	Apr 11 2014
Target Center V (120 deg F window)		2.34		●	Apr 11 2014
Beam Power	Low Alarm 380000 W High Alarm 1315000 W	1290000 W	21567	(BCM251 Power in W)	●
IDmp QV01		415		●	Jun 03 2014
PW On	52	52 Ticks		●	May 31 2014
Alarm Summary (Target Mode & > 85 kW)					

RTBT harp

Diagnosics RTBT Harp30

Horizontal FS	Vertical	Diag
Area: 259.00	257.45	259.08
Amplitude: 2.12	1.96	1.44
Mean: -0.98	-6.52	-5.87
Offset: 0.00	0.00	0.00

RMS Fit: 32.64 31.84 30.76
 RMS Raw: 32.50 31.54 30.73
 RMS Fit: Fitted data RMS
 RMS Raw: Raw data using threshold exclusion

Harp Profiles

Peak Density
 Density (Ptics/mm²): 2.95e-08, 1.47e+10, nan, nan
 Integrated Peak Density (C/mm²): nan, nan
 Harp Normalized Peak Density (1/mm²): 0.0096, 0.011, 0.012
 Beam Size Ratio: Target 1.30, 1.30; Window 1.51, 1.51

Target Imaging System

Target Imaging System

Beam measurements System Parameters
 Peak Density: 1.45810 p/mm²
 Horizontal Position: -1.44 mm Vertical Position: 2.27 mm
 RMS Size: 55.11 mm RMS Size: 20.64 mm

Peak Density [p/mm²] vs time
 Horizontal RMS Size [mm] vs time
 Vertical RMS Size [mm] vs time

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