Machine Protection Systems for Modern Light Sources

Timmy Lensch
IBIC 2026 | Whistler
September 2, 2026

HELMHOLTZ

IBIC 2026

15TH INTERNATIONAL BEAM INSTRUMENTATION CONFERENCE

Whistler Conference Centre

August 30th to September 3rd

Whistler BC, Canada

DESY.

Machine Protection Systems for Modern Light Sources

Outline

Motivation

- What is and why machine protection?
- damage potential of stored beam

3rd Generation Synchrotron Light Sources

- MPS: Concept and technical solutions (e.g. PETRA III)

4th Generation Synchrotron Light Sources

- challenges for 4th generation
- changes of MPS (e.g. PETRA IV)
- dump schemes for 4th generation

(from now on, light source means synchrotron light source)

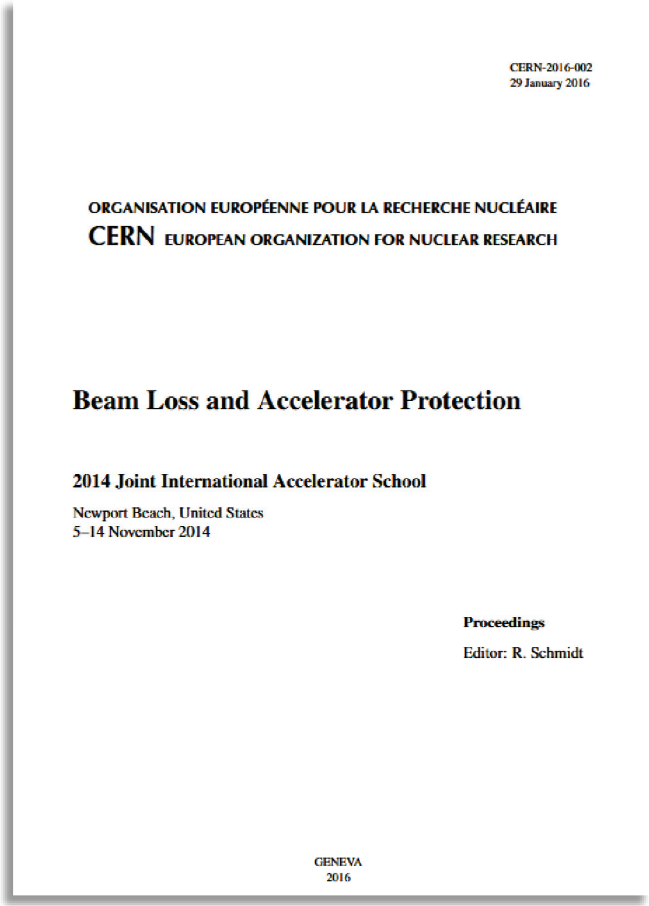
Motivation

Why Machine Protection?

Introduction to Machine Protection, R.Schmidt:

Proceedings Joint International Accelarator School, 2014
Machine Protection, CAS Norway, 2013, R.Schmidt

- no protection of …
  - people → Personnel Access System (typ. SIL* based)
  - environment → follow legal requirements
- protection of
  - **accelerator equipment** and **experiments** (the invest)
    → **Machine Protection System**
- What to protect?
  - equipment when there is a significant amount of stored energy in the components (e.g. super conducting magnets)
    → not so much important at a light source (e.g. no quench protection)
  - from uncontrolled beam losses in case of significant amount of stored energy in the beam
    → depends on beam size (e.g. 3rd vs. 4th generation light source)
  - from synchrotron radiation (e.g. on absorbers)
    → **3rd and 4th generation light sources!**
  - risk of performance degradation for undulators using permant magnets
    → **use of permanent magnet dipoles at 4th generation light sources**


CERN-2016-002
29 January 2016

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Beam Loss and Accelerator Protection

2014 Joint International Accelerator School

Newport Beach, United States
5–14 November 2014

Proceedings

Editor: R. Schmidt

GENEVA
2016

* SIL: Signal Integrity Level

Motivation

Example: Stored Beam Energy of Protons at LHC ...

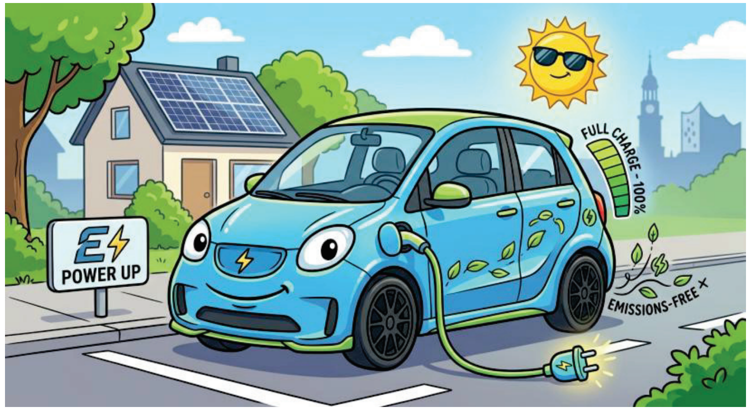
- stored beam energy E [J]

$$E[J] = \frac{I_{DC}[A]}{f_{rev}\,[Hz]} \cdot U[V]$$

- Nominal LHC:
  - beam current: 0.58 A
  - voltage: 7 TV
  - revolution frequency: 11245 Hz

$$E = \frac{0.58\ A}{11245\ Hz} \cdot 7\ TV = \mathbf{361\ MJ}$$

- *HL-LHC Ultimate* even factor 2 in energy!



Picture generated using Gemini

EV Equivalent:

One stored LHC beam (361 MJ) can charge a **100 kWh EV battery to 100%!**

(e.g., Tesla Model S / 500 km range)

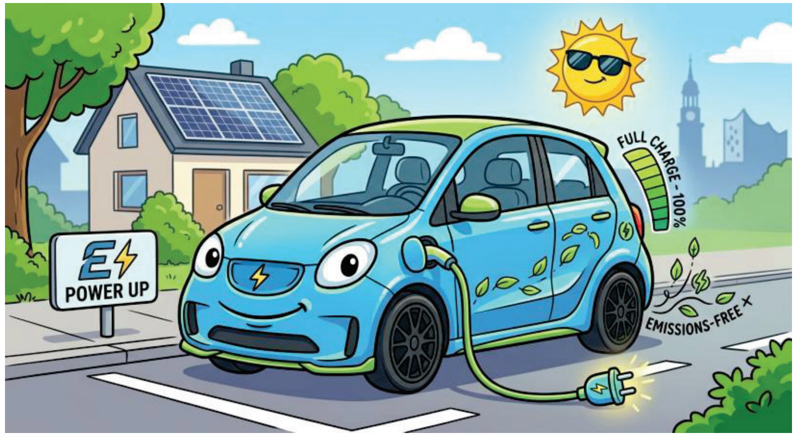
An energy the accelerator releases in under **90µs.**

- pistol bullet: ~500J
- 1kg TNT: ~4MJ
- 1l of fuel: ~36 MJ

Motivation

Stored Beam Energy in a 3rd Generation Electron Machine

Facility (3rd Gen)	Circumference [m]	E [kJ]
PETRA III	2304	5.53 (@120 mA)
Spring-8	1436	3.83 (@100 mA)
APS	1104	2.58 (@100 mA)
ESRF	844	3.38 (@200 mA)
NSLS-II	792	3.96 (@500 mA)
Diamond	561	1.68 (@300 mA)
SOLEIL	354	1.62 (@500 mA)
SLS	288	0.92 (@400 mA)
CLS	**171**	**0.28 (@220 mA)**



Example: Canadian Light Source

EV Equivalent: A 100 kWh EV battery can be charged to **0.00007778 %**

→ Range: **40 cm**

→ need **1.29 million revolutions (733 ms) in CLS** to fully charge the battery

Picture and data collection with help of Gemini

Motivaion

Damage Potential of an Electron Beam

- stored electron beam energy << proton beam (e.g. LHC)

Challenges 3rd generation light sources

- horizontal beam emittance
  → some nm rad → energy density close at melting points, beam not at single spot …
  → not critical

➢ protect absorbers (synchrotron light)

➢ protect permanent magnets (radiation)

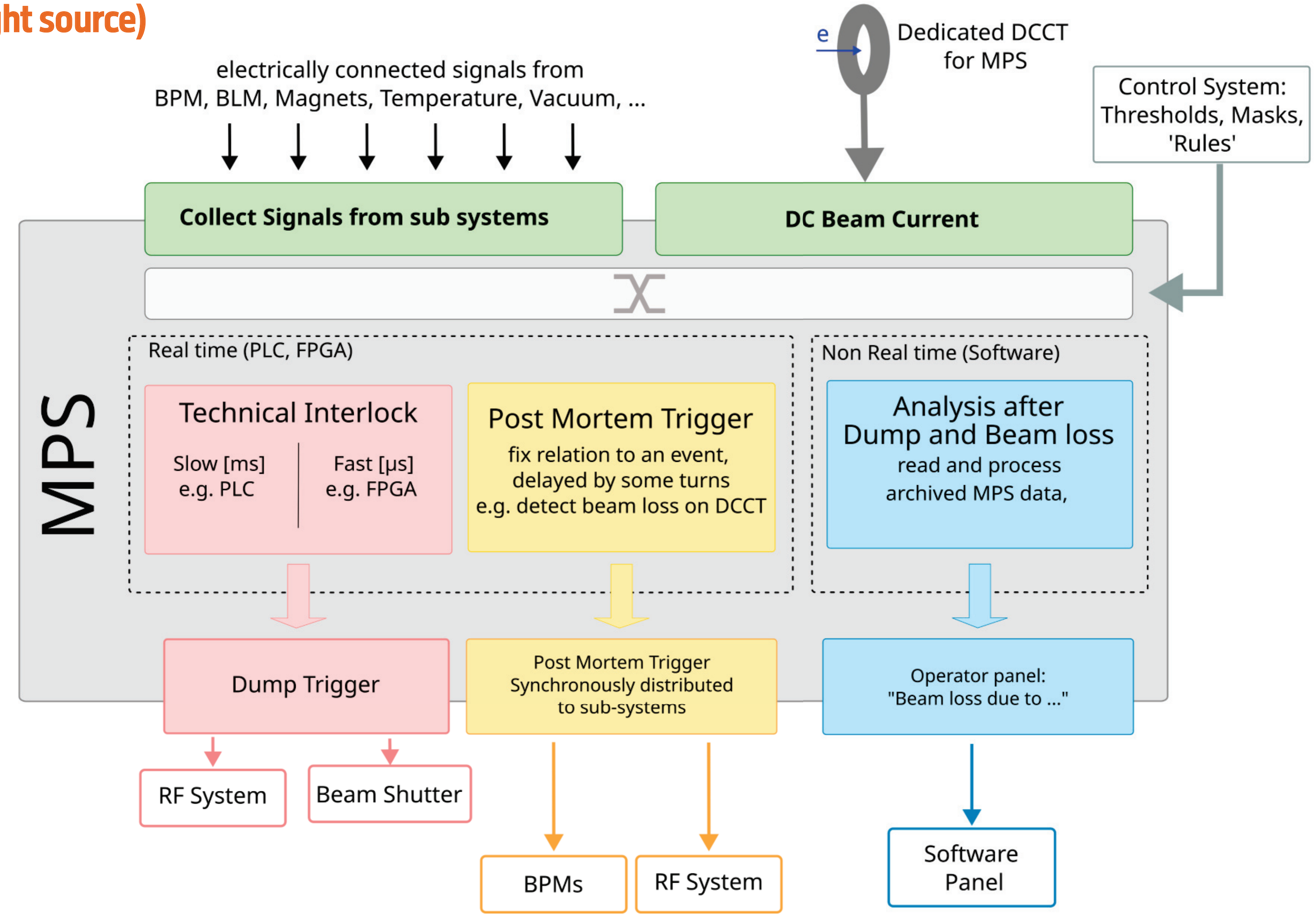
➢ **Focus on the technical realization of a MPS (PETRA III)**

The Generic Beamline Concept of the PETRA III Undulator Beamlines, U.Hahn et al.
Radiation Damage of Undulators at PETRA III, IPAC2014, M.Tischer et al.

Machine Protection – Technical

Machine Protection System in general

Overall View (3rd gen light source)



Machine Protection System

System or *Philosophy?*

A Machine Protection System is not only ONE single system

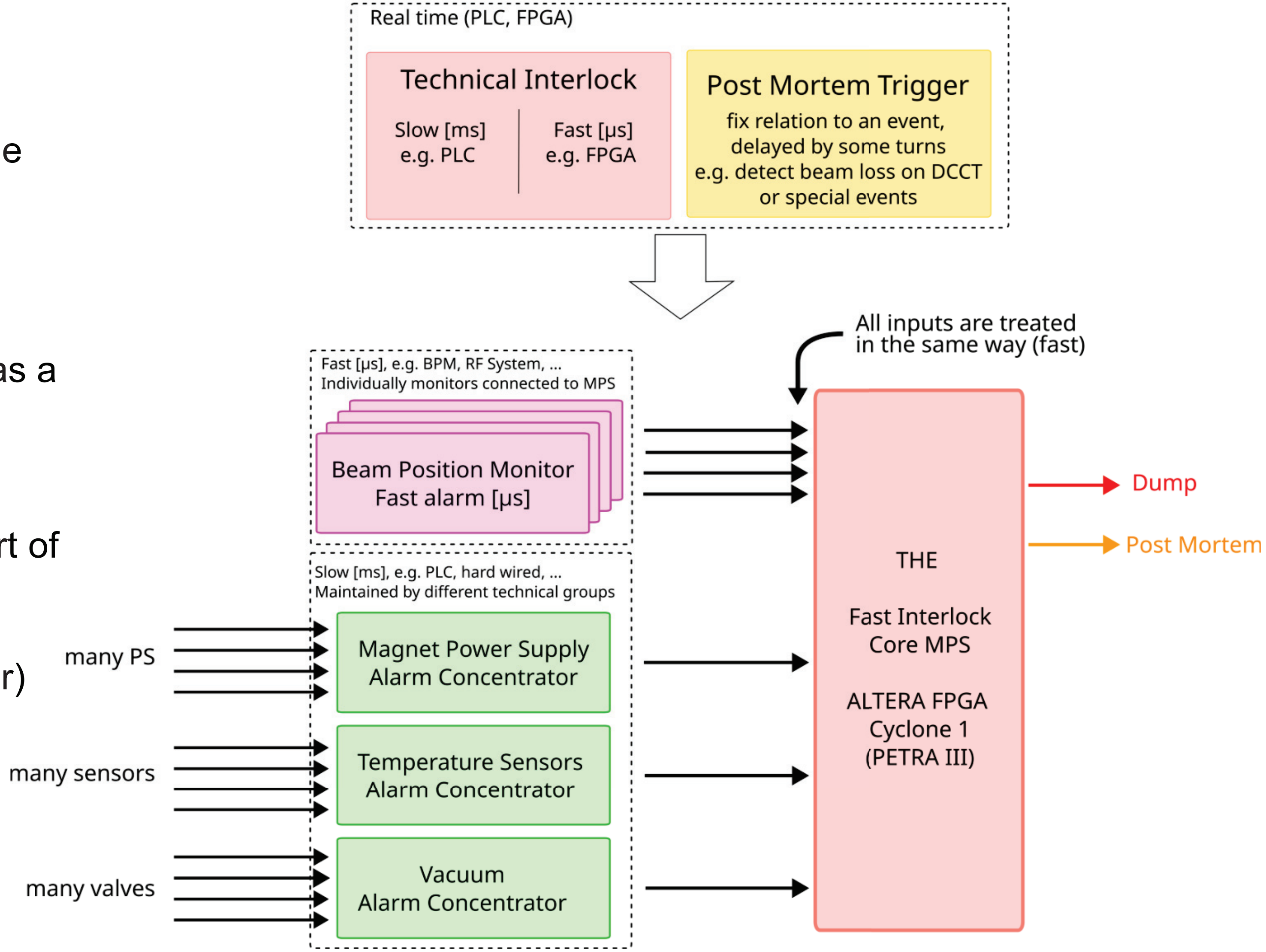
- set of several ***systems***

But, ***Machine Protection*** can also be understood as a ***philosophy!***

Every *system* (HW, FW, SW), every *cable* but also subsequent *analysis* needs to be considered as part of the interlock!

This also *includes dump components* (RF off, kicker)

„Systemic safety culture“



Alarms connected

Typical (?) 3rd Generation

PETRA III, 2009 (extension 2015)

Sensor	Quantity on MPS	Type ***
BPM (IDs and Damping Wiggler)*	60	Fast
RF System	8	Fast
Beamlines (Undulator Gap, Fast Shutter, Vacuum)	100	Slow
Temperature Sensors **	30	Slow
Magnet Power Supplies **	52	Slow
Vacuum **	40	Slow
Absorber Water Flow **	10	Slow
Total	**300**	

*total BPMs: ~230
**pre-combined out of bigger number
*** with regard to influencing the beam

APS Machine Protection System:

THE SENSORS

A list of the sensors in use around the ring appears below.

Sensor	Quantity
Absorber Water Flow	320
Vacuum Chamber Water Flow	76
Storage Ring Flags	10
Isolation Valves	80
Beam Position Limits Detector	7
Experiment Hall Front Ends	14 BMs
Experiment Hall Front Ends	9 IDs

The APS Machine Protection System, R.Fuja et al. 1996

Overall Design Concepts for the APS Storage Ring Machine Protection System, Proceedings of the I995 IEEE PAC, A.Lumpkin et al.

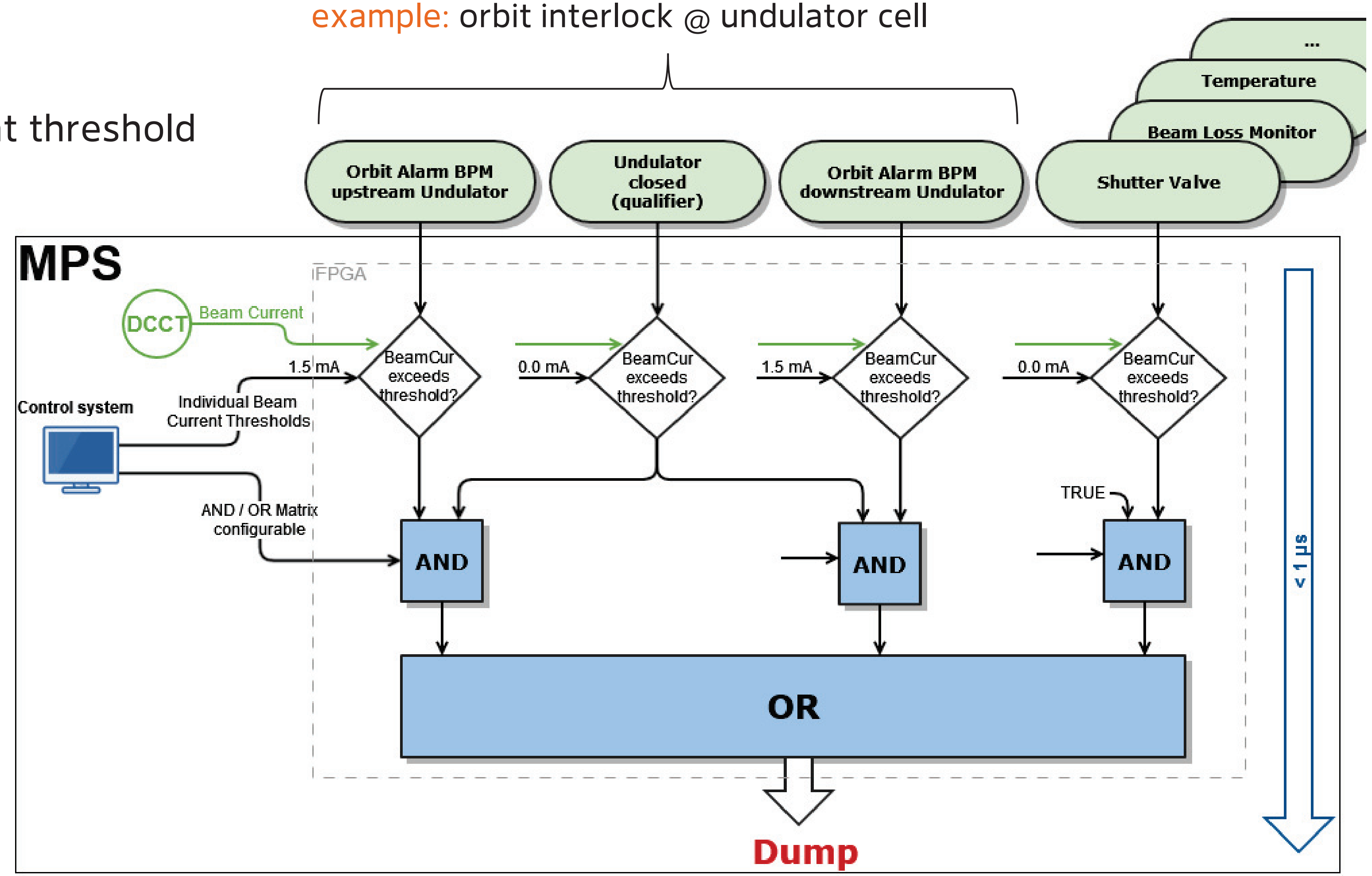
→Beam Position Monitors gained prominence in 3rd-generation light sources

Alarm Processing

e.g. PETRA III concept

- PETRA III MPS concept
  - each input with individual beam current threshold
  - configurable AND/OR matrix
- MPS signal types are treated internally
  - **alarms**
    - → can trigger beam dump
      e.g. BPM, BLM, shutter, temperatures,…
  - **qualifiers**
    - → masks alarm for special conditions
      e.g. undulator gap „open“
  - **status**
    - → do not trigger beam dump
    - → used for analysis of beam loss
    - → example …

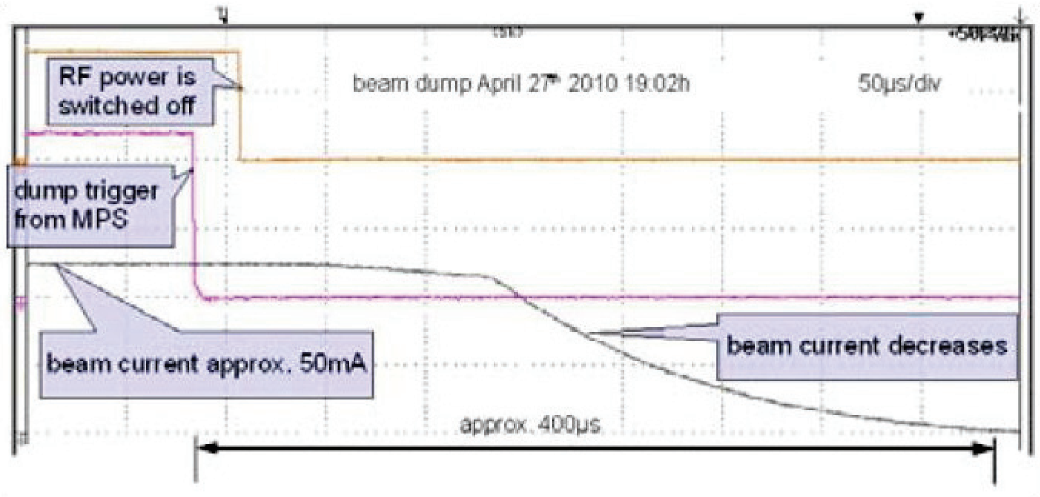
example: orbit interlock @ undulator cell



3rd Generation Dumping

Masking RF

PETRA III:
- MPS sends a dump trigger
- RF power is switched off (5 ms)
- beam looses energy and spirals inwards, hitting scaper
- beam fully lost after **~400 µs (~58 turns)**



- backup and injection inhibit:
  close beam shutter (takes ~200 ms)

APS Dump Scheme:

II. BEAM ABORT INTERLOCK

The beam abort interlock associated with beam missteering is part of the overall machine protection system (MPS), which encompasses all mechanisms which can potentially damage the machine. Common to all MPS input is a method for turning off the beam; at the APS the chosen method is to momentarily interrupt the rf system. This ensures that the beam will lose energy and spiral inwards, to be totally lost in less than 300 microseconds [1]. This process can be made even faster and the loss localized by placing a horizontal aperture limitation, or scraper, at a location of large horizontal dispersion [2].

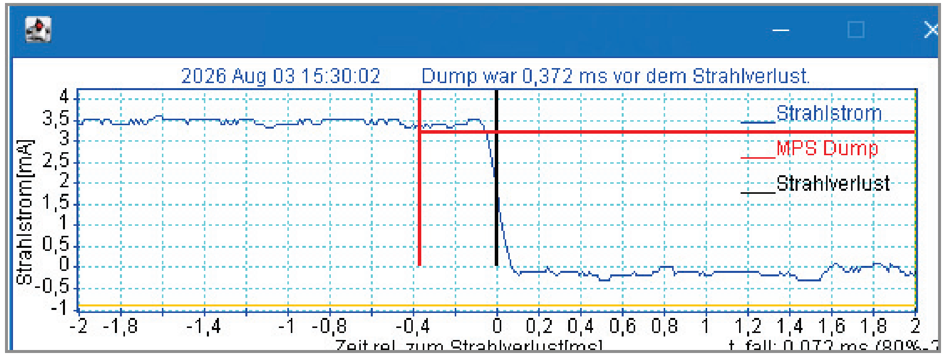
Abort Interlock Diagnostic for Protection of APS Vacuum Chamber, PAC 1993, G.Decker

Similar at SOLEIL, SPring-8, ESRF, …

MPS: Post Mortem

PETRA III concept

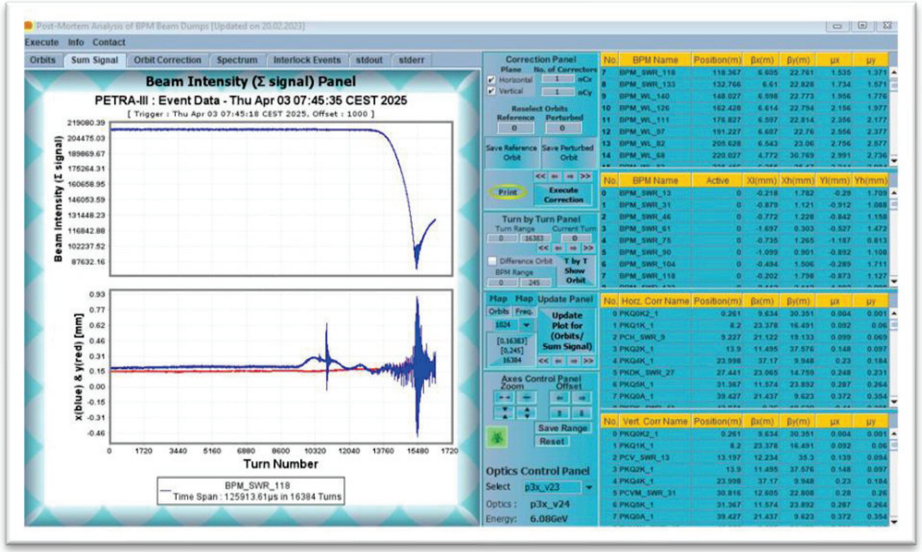
- MPS measures with dedicated DCCT
- if current drops by 3% / ms MPS triggers an internal Post Mortem event
- event is send delayed to all sub-systems synchronously
- sub-systems stop their ring-buffers with tbt data

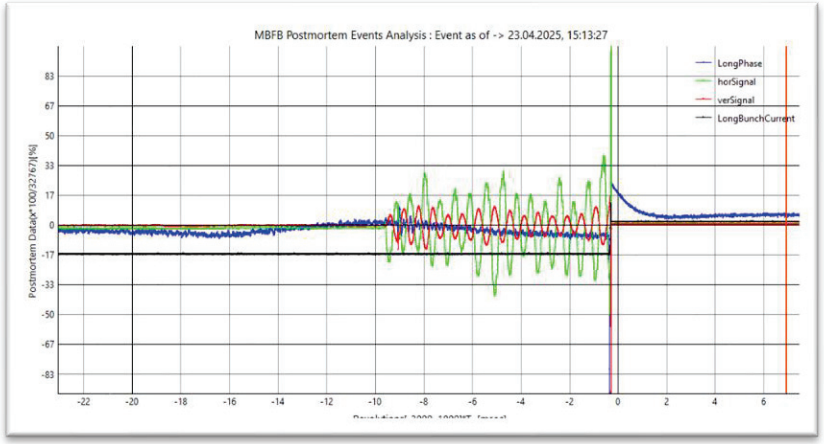


DC beam current measured by the MPS
X-axis: time in [ms]
Blue: beam current from MPS DCCT [mA]
Red: time of BPM alarm due to orbit deviation
Black: beam loss detected and synchronoulsy sent to other systems

Synchronized Post Mortem Trigger of the PETRA III MPS, BIW12, T.Lensch et al.

PETRA III operation examples:
Post Mortem analysis with tools from Gajendra Sahoo
(top: BPM data, bottom MBFB data)





MPS: Analysis

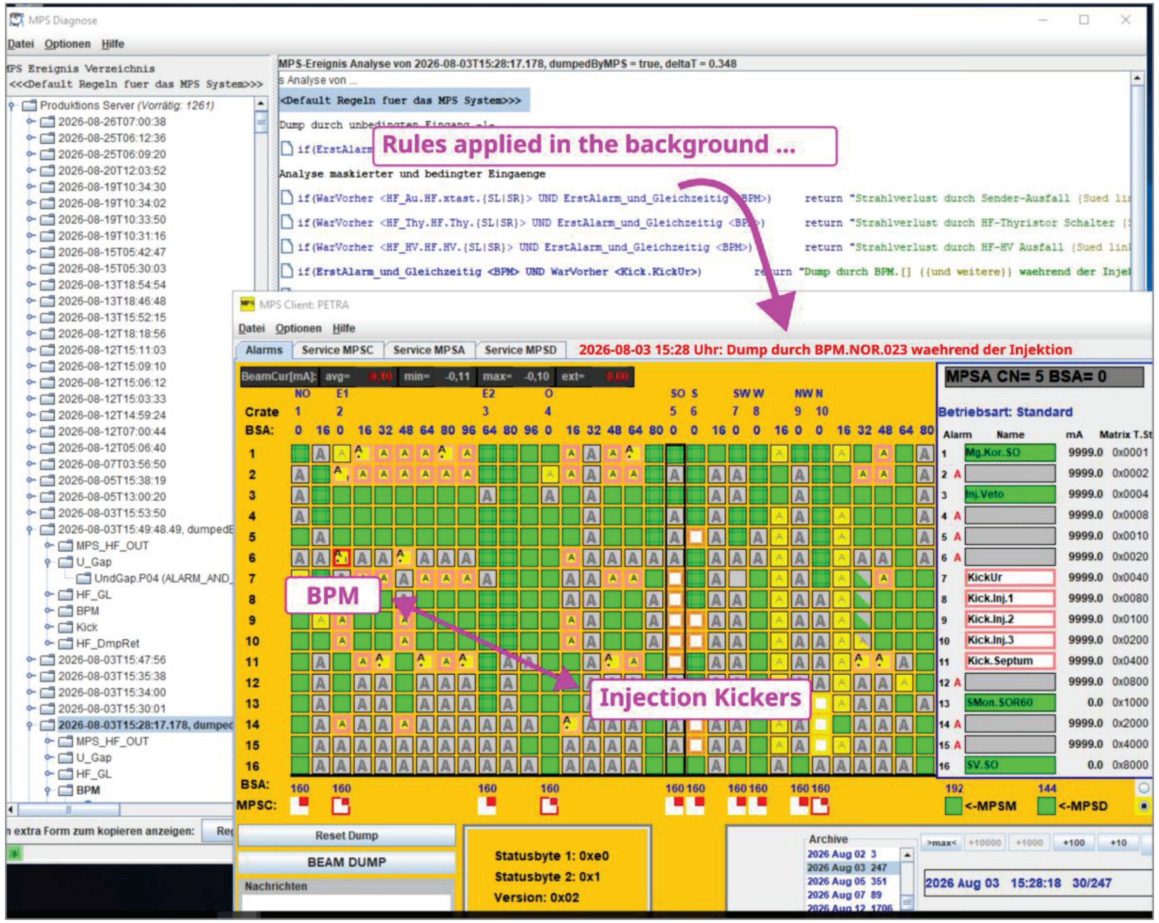
PETRA III concept (~2010)

- software tool with *domain specific language (DSL)* architecture
  (if-this-then-that style)
- evaluates MPS input data from the event archive before and after a beam loss
- generates a human (=operator) understandable output

→ **avoiding misinterpretation!**

Example: Beam loss because injection kicker (*status*) caused orbit deviation, detected by a BPM (*alarm*)

- BPM detected bad orbit → dump trigger
- the tool detects the timing relationship using the defined rules



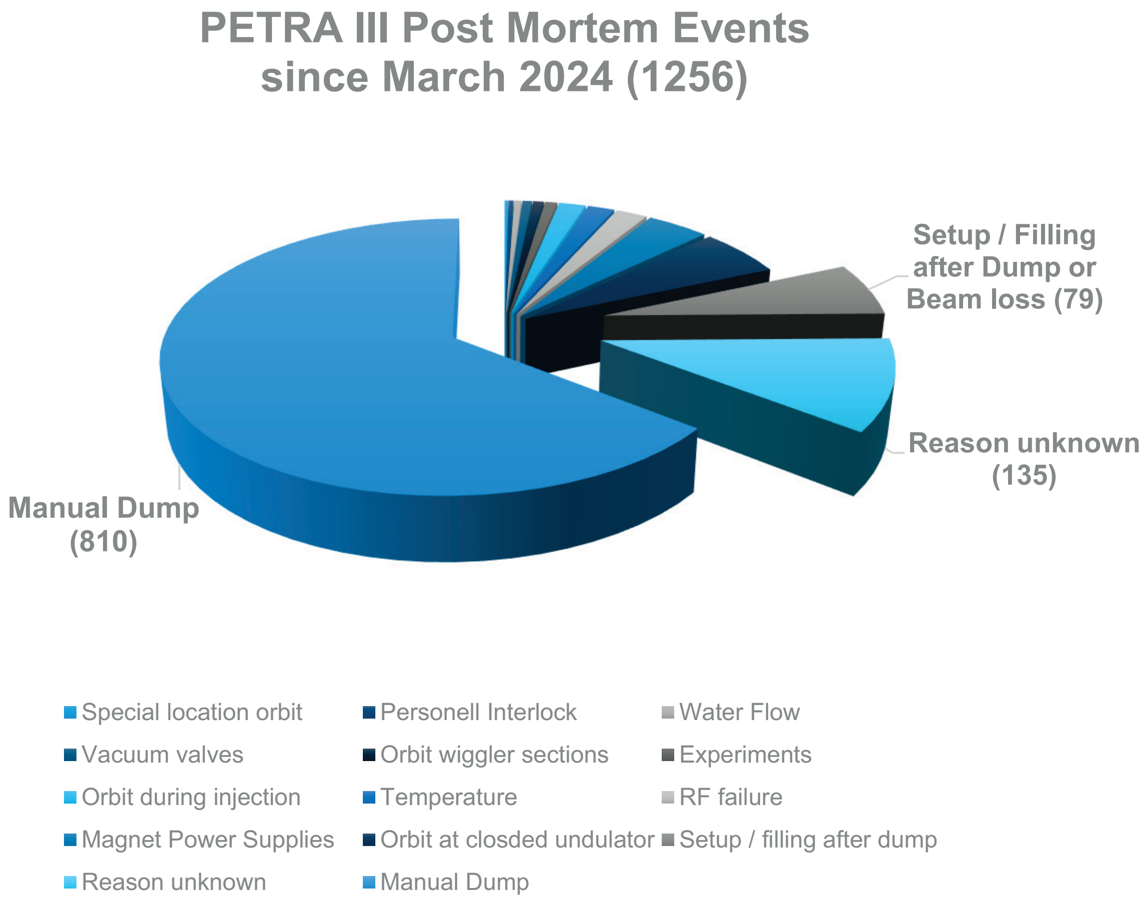
Machine Protection Diagnostics on a Rule Based System, ICALEPCS2013, Marcus Walla et al.

MPS: Analysis

Some statistics from PETRA III

- 1256 events in the last 2.5 years
- ignore
  - manual dumps (machine studies, setup, …) (810)
  - dump or losses during setup / filling (79)

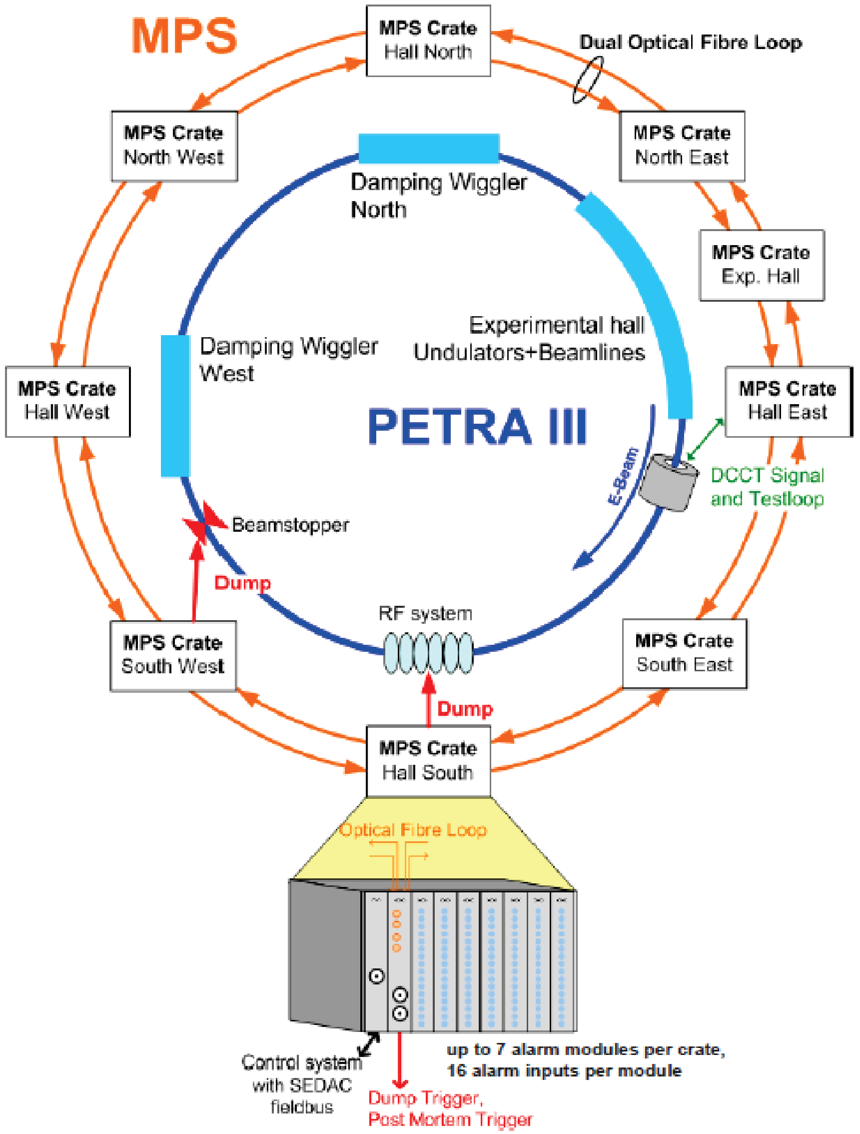
- 135 the unknown reasons! (~10%)
  - no alarms indicating any reason
  - average ~1/week (but often during studies and setup)
  - some mains problems, feedback
  - ok, as long as availability not negatively affected
  - ➢ **have in mind for 4th gen LS: understand 100%**



Machine Protection System

PETRA III MPS in a nutshell

- SEDAC field bus based system (250 kbit/s), TINE controls
- NIM cassetts in dedicated chassis, distributed over PETRA
- collecting local alarms, local *dump decision*
  - static signalling from sub-systems!
- dual optical link for
  - link broken → MPS sends dump trigger (*integrated heartbeat*)
  - DC beam current transmission
  - post mortem trigger (synchronous)
  - dump trigger
  - delay on optical link: worst-case ~4 turns (28 μs) to send the dump trigger to the RF system



PETRA III MPS Core Hardware

Do's and Don't's for the Core MPS

- MPS fully based on inhouse developed FPGA board 👍
  - widespread acceptance after 17 years (using FPGA)
- simple (PCB, FW, SW) design 👍
- process slow and fast alarms on the same hardware 👍
  - (the core MPS hardware; slow done by other techn. group)
  - reduce variety of components to develop and maintain

- alarm inputs: static signals (potential free contact) 😳
  - improve fail-safe behavior
- 2 pin LEMO-00 connectors 😳
  - sophisticated assembly of connectors
- not needed: robust, dedicated chassis 😳

NIM modules developed for PETRA III MPS

Other machine's 3rd Generation MPS

(Selection)

ALBA https://proceedings.jacow.org/icalepcs2011/papers/wepmu005.pdf
- **EPS Equipment Protection System → ms**
- **FIS Fast Interlock System → µs → combined with Timing System**
- **Dump:** RF off (https://www.ipac26.org/prepress/pdf/THP2047.pdf)

APS https://digital.library.unt.edu/ark:/67531/metadc664849/m2/1/high_res_d/286268.pdf
- **Dump:** RF off some ~100 turns in vacuum chamber

SOLEIL MACHINE PROTECTION AND INTERLOCK SYSTEMS AT SYNCHROTRON SOLEIL, https://proceedings.jacow.org/icalepcs2009/papers/wep089.pdf
- **MPS based on Siemens S7 with „FPGA Extension" for fast signals**
- **Dump: RF off**

Spring-8 https://spring8.jp/archive/pdf/en/ann_rep/96/P235-236.pdf
- **Fast + Slow MPS**
- **Dump:** RF off

INTRODUCTION

ALBA is a third generation, 3 GeV synchrotron light source with a natural emittance of 4.6 nm [1,2]. At ALBA, and in most of the 3rd generation of synchrotron light sources, in case of a sudden beam loss the interlock system generally sends a signal to switch off the RF system. The beam then starts t… turns, the beam hits the… celerator and is lost. Ov… none of the electron be… pipe or nearby objects.

The APS Machine Protection System (MPS) *

R. Fuja, B. Berg, N. Arnold, G. Decker, B. Dortwegt, M. Ferguson, N. Friedman, J. Gagliano A. Lumpkin, G. Nawrocki, X. Wang

Argonne National Laboratory, 9700 South Cass Ave., Argonne, IL 60439 USA

RECEIVED AUG 12 1996 OSTI

Abstract. The machine protection system (MPS) that protects the APS storage ring vacuum chamber from x-ray beams, is active. There are over 650 sensors monitored and networked through the MPS system. About the same number of other process variables are monitored by the much slower EPICS control system, which also has an input to the rf

WEP089 Proceedings of ICALEPCS2009, Kobe, Japan

MACHINE PROTECTION AND INTERLOCK SYSTEMS AT SYNCHROTRON SOLEIL

Y.M. Abiven, F. Dohou, P. Rommeluère, Synchrotron SOLEIL[#], Saint Aubin, France.

High Speed Interlock System for the SPring-8 Beamline

Togo KUDO, Takeo TAKASHIMA, Hiroaki KIMURA, Hiroyuki KONISHI, Hideki AOYAGI, Yoshiharu SAKURAI, Hideo KITAMURA

SPring-8, Kamigori, Ako-gun, Hyogo, 678-12, JAPAN

1. Introduction

In the Spring-8 beamline, there are some cases that photon beam should be rapidly stopped; irradiation of synchrotron radiation (SR) to a vacuum chamber wall; a large vacuum leakage, etc. In such cases, RF power supply to the accelerating cavities is stopped by Beam Abort System (BAS)[1].

BAS consists of eight Beam Interlock Modules (BIMs) [2], which are linked each other with photo-fiber cables. The BIMs are installed at the Safety PLC racks around the SPring-8 Storage Ring, and given the Beam Abort Request from the nearest beamline or other systems. The BIMs don't only stop the RF supply, but also inform to the safety PLC where the accidents happen.

changed by miss-steering of the electron … the Storage Ring. In these cases, the SR … hit the beam pipes or the other componen… do not have heat-proof structures. Ther… front-end should have an interlock system… to abort the electron beam in the Stor… immediately. The interlock X-ray moni… designed to detect miss-steering of the … excess the acceptance and send a interlo… to the BAS.

The diagram of the Interlock X-ray … signal processing is shown in Figur… monitor head is electrically floated … voltage(0~-1kV) by use of i… amplifier(ISO122:Bar Brown). The thre… the current signal is valuable(0~10mA). … constant of the current-voltage converting

Motivation Pt. 2

4th Generation Light Sources

- beam current: same
- energy: same or lower
- vertical emittance same or lower
- horizontal emittances between 10 – 70 times lower

➢ energy density increased!

APS-U based, more physics: **Machine Protection for Synchrotron Light Sources, US Particle Accelerator School 2023, Louis Emery**

Damage potential increased !!

But again:

→ **what does that mean for our MPS'?**

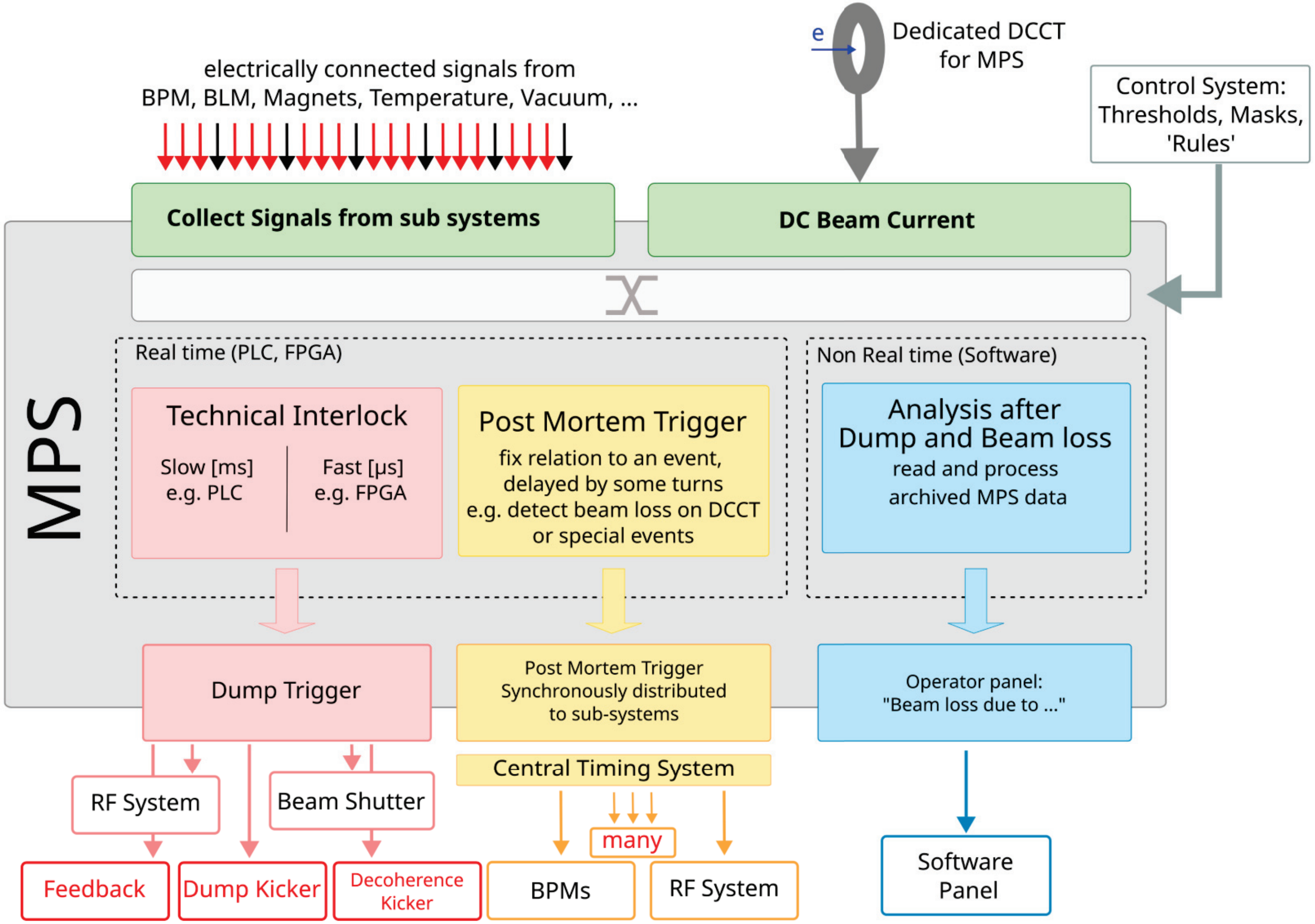
(here: current plan PETRA IV)

Facility (3rd Gen)	Facility (4th Gen)	σ_x 3rd [pm rad]	σ_x 4th [pm rad]
PETRA III	PETRA IV 2031/32	1000	~ 20
SPring-8	SPring-8-II 2028/29	2800	~100
APS	APS-U (2024)	3100	~42
ESRF	ESRF-EBS (2020)	4000	133
NSLS-II	NSLS-II-U >2030	1000	<100
Diamond	Diamond-II 2027/28	2700	160
SOLEIL	SOLEIL II 2030	3900	~80
SLS	SLS 2.0 (2025)	5500	150
CLS	CLS 2.0 >2030	18100	<300

Machine Protection System – 4th Generation

Same concept like 3rd generation, but …

- collect more information
  → number of input signals increases
  - all BPMs to MPS
  - beam losses without „dump scheme“ not allowed anymore !?
- more systems to dump the beam
  → extent beam dump scheme
- more information
  → more Post Mortem customers
  → increase fan out of signal
- analysis more extensive
  - AI ?



Machine Protection System – 4th Generation

Number alarms increased – here for PETRA IV

- >5000 alarms in total that may dump the beam
- >1100 sub-systems are directly connected to the MPS

Sensor	Quantity PETRA III	Quantity PETRA IV	Type ***
BPM (PETRA III only BPMs at IDs and Damping Wiggler)* (PETRA IV all BPMs)	60	780	Fast
RF System	8	12	Fast
Feedbacks (no alarms at PETRA III)		2	Fast
BLM (total 600 BLM sensors) (no BLMs at PETRA III)		300	Fast
Beamlines (Undulator Gap, Fast Shutter, Vacuum)	100	150	Slow
Temperature Sensors **	30	50	Slow
Magnet Power Supplies **	52	60	Slow
Vacuum **	40	60	Slow
Absorber Water Flow **	10	20	Slow
Total	**300**	**1134**	

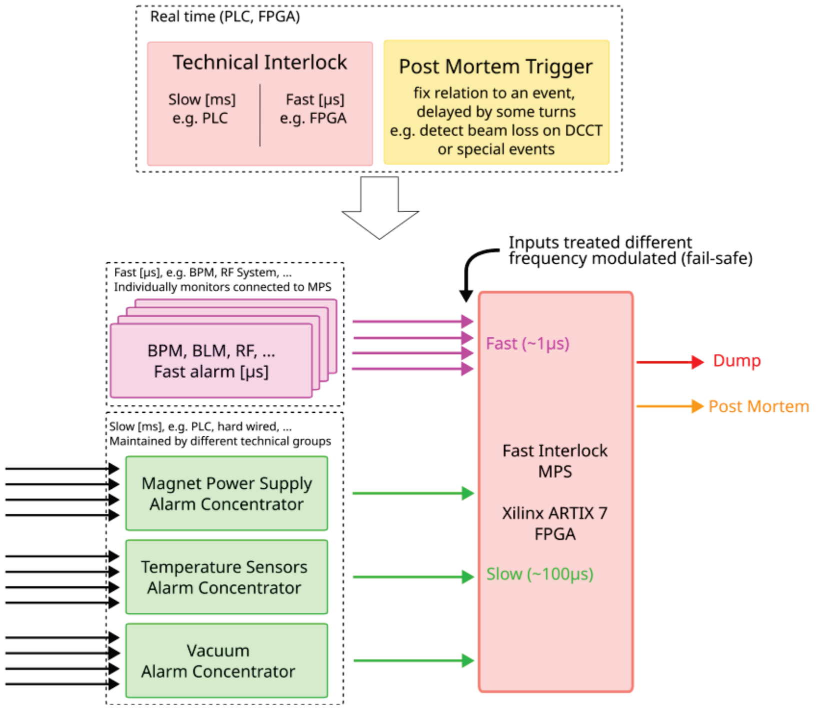
*total BPMs: ~230 (PETRA III)
**pre-combined out of bigger number
*** with regard to influencing the beam

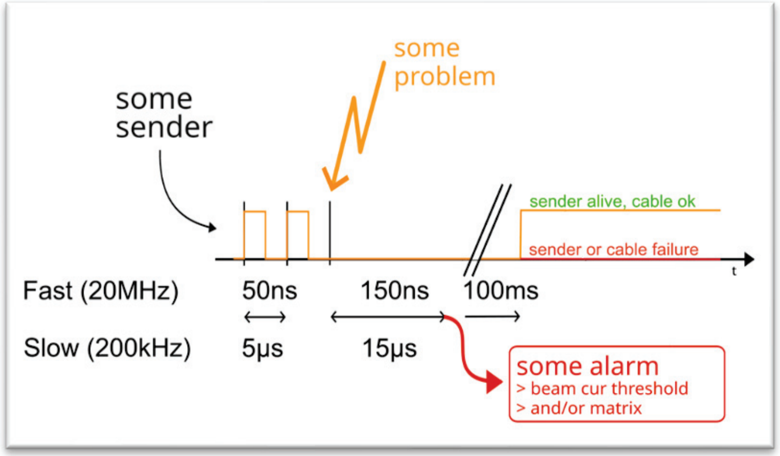
→4th generation light sources much more related on fast alarms like BPM, feedbacks, RF!

PETRA IV Machine Protection System

Enhanced alarm handling including fail-safe

- replace simple *on/off* static signaling with
  - frequency-modulated signals
  - differential RS422
- input signals are defined as …
  - *fast*: turn / few turns (µs) affect on beam (or beam is already affected)
    - i.e. BPM, BLM, …
    - 20 MHz (healthy) vs. 10 Hz (alarm)
    - latency: << 1 turn
  - *slow*: several turns (ms) affect on beam
    - i.e. magnets, vacuum, temperature
    - 200 kHz (healthy) vs. 10 Hz (alarm)
    - latency: ~2 turns
  - *static:* indicates either broken cable or dead sender (alarm)
- ***Enhanced fail-safe detection***

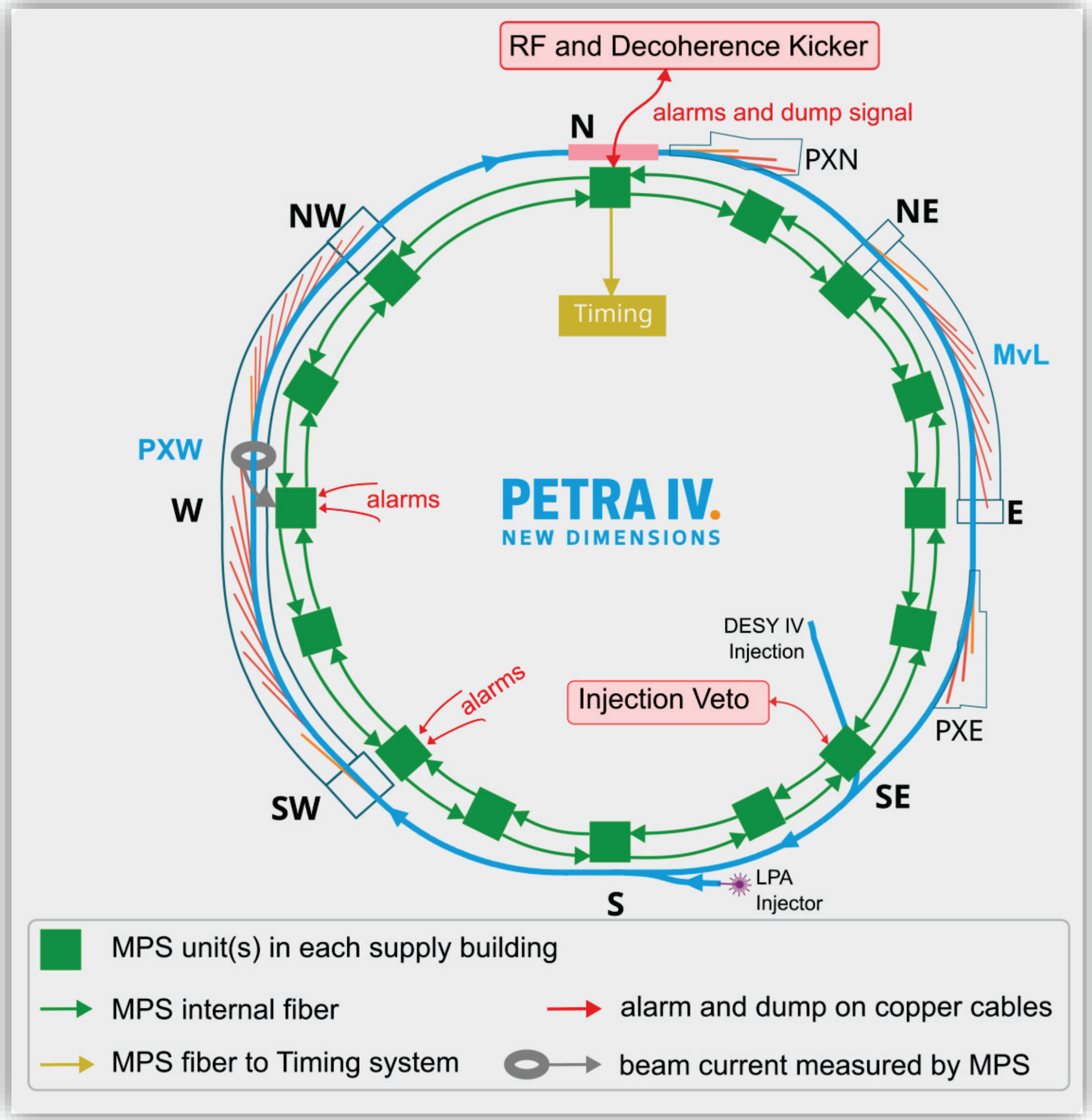




PETRA IV MPS Overview

Distribution and Connections

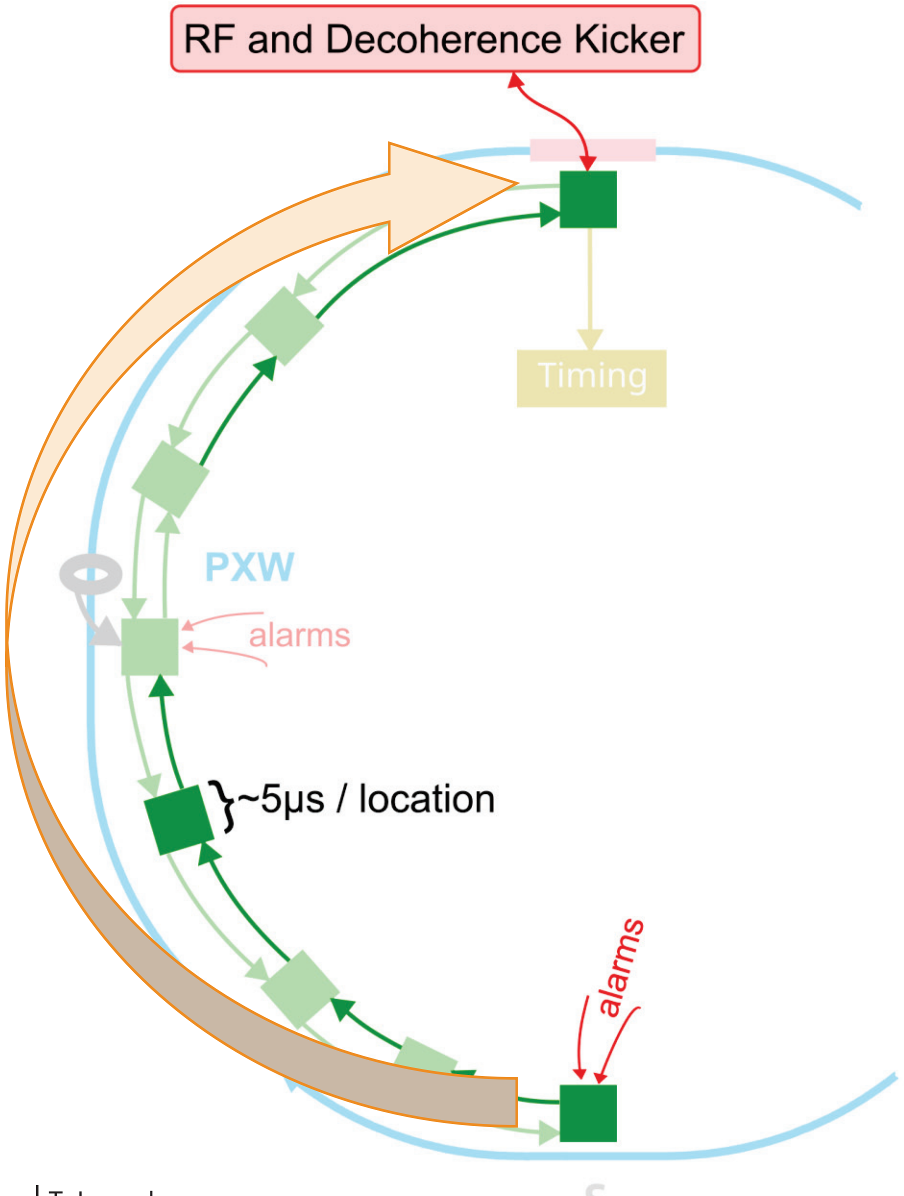
- ~80 distributed MPS units (MTCA.4 card)
- integrated into MTCA.4 chassis alongside BPMs and BLMs
- connected with dual fiber, broadcast of …
  - beam current (measured in PXW with DCCT)
  - locally generated dump signal
  - Post Mortem trigger
    - from beam loss or other event
- extract dump signals and injection veto everywhere
- send to timing system via fiber link
  - DC beam current
  - Post Mortem, dump signal, …
  - ➢ increased fan out



Machine Protection System

Electronic and fiber transmission latency

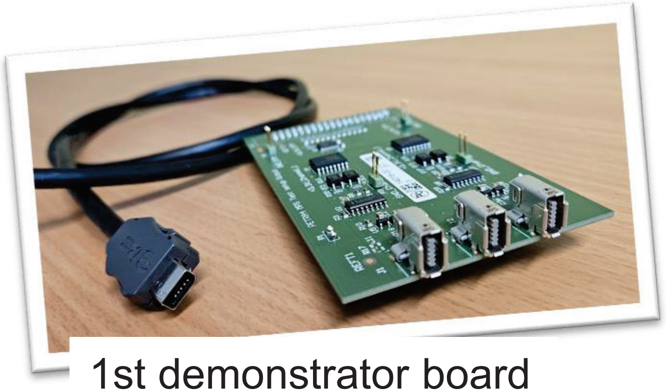
- MPS unit: FPGA logic internally
  - ~800ns preparation of data to fiber per MPS unit
  - ~40 units (south to north) x 800ns = **~32μs**
- fiber approximately 1.6 km
  - 5ns/m → **~8μs**
- worst case delay: **40μs (~6 turns)**
  alarm from south to north



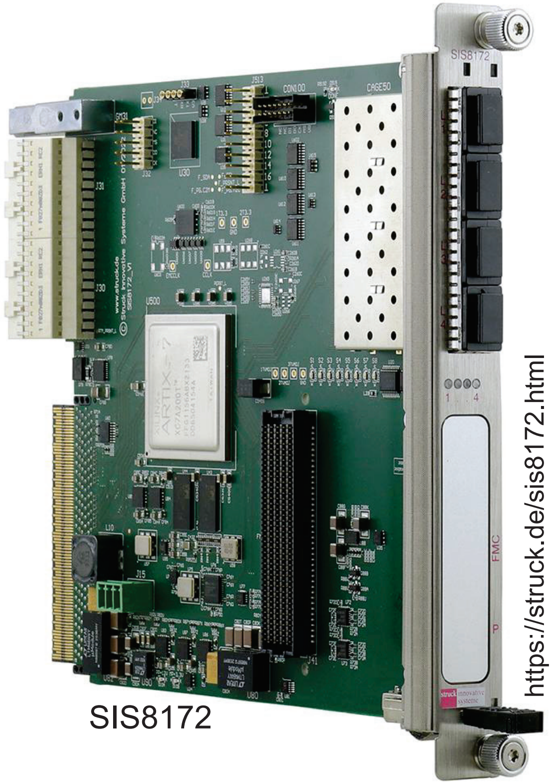
Machine Protection System

Hardware

- MTCA.4 standard
- similar approach like E-XFEL MPS
- use COTS board: SIS8172, ARTIX FPGA
  - 4x SFP+ connectors → fiber loop
  - FMC connector → DCCT measurement
  - Zone3 D1.0 connector → alarm collector RTM …
- … inhouse RTM development
  - 12 ix industrial® connectors for RS422 inputs and output
    - cable and connector easy to assemble (similar RJ45 but smaller)
  - individual galvanic isolation of inputs
- development of interface boxes (24V → RS422)
  - PLC based alarms i.e. vacuum, temperature, beamlines, …
  - implement fail-safe behavior (200kHz frequency modulation)



1st demonstrator board



SIS8172

https://struck.de/sis8172.html

Dump Scheme

Damage potential 4th generation light sources

horizontal emittance up to **70x smaller**!

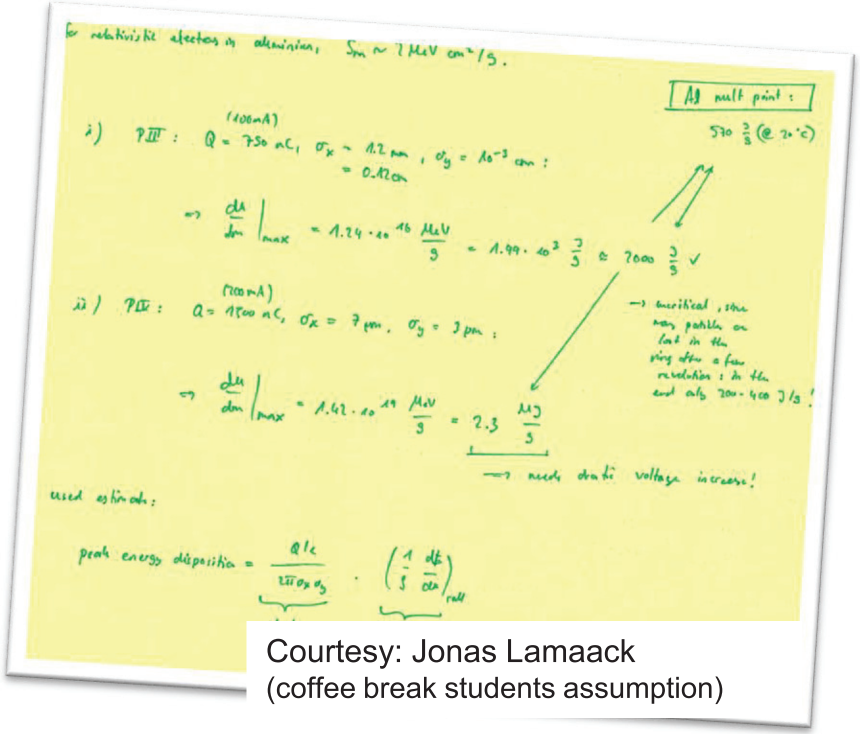
‚Naive assumption‘: beam hits Al single spot

- Al melting point 570 J/g
- PETRA III: 2 kJ/g
- **PETRA IV: 2.3 MJ/g**

➢ **in the future the energy density up to 1000x higher!**

➢ simple RF off + scraper not allowed anymore

➢ simulate or make test in other machine (or both)



Courtesy: Jonas Lamaack
(coffee break students assumption)

Damage Potential of an Electron Beam

Titianium as potential PETRA IV collimator material

Simulations and Tests

Example of e⁻ beam on copper with

- 18 GeV
- 2mm diameter
- 500 kW for 1.3s (650kJ)

Figure 3 depicts a 30 cm long copper block onto which a beam damage test was performed in 1971 at SLAC [8]; the block was meant to simulate a collimator. An 18 GeV/*c* e⁻ beam of ≈2 mm diameter, with a power of roughly 500 kW, impinged the edge of the block. The impact lasted roughly 1.3 s and led to extensive melting in the impacted area. Although this was a relatively slow accident, the type of damage it generated can be compared to those created by faster events.

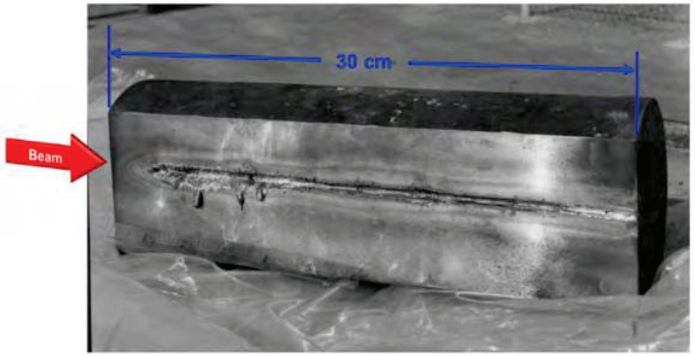
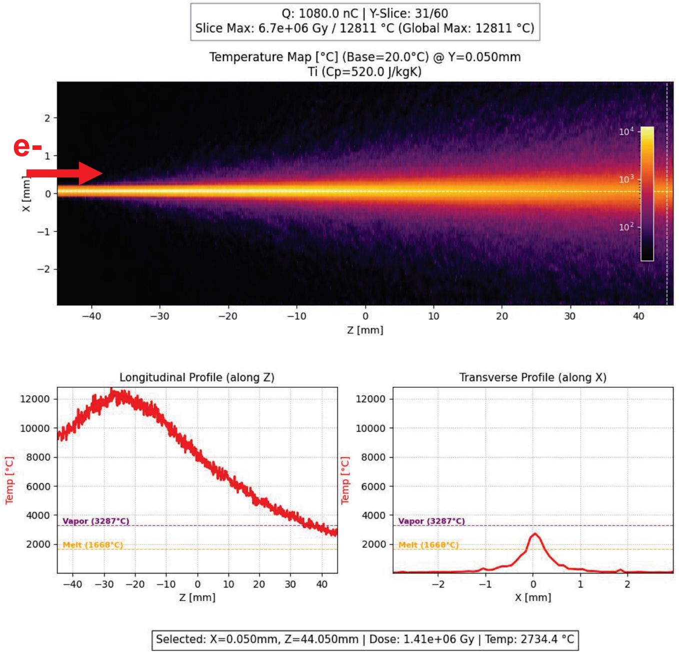


Fig. 2: Copper block used for damage test at SLAC in 1971

Beam-Induced Damage Mechanisms and their Calculation,
Beam Loss and MPS Joint Accelerator School 2014, A. Bertarelli

→ Collimation and Machine Protection for Low Emittance Rings, IBIC22, J.C. Dooling et al.

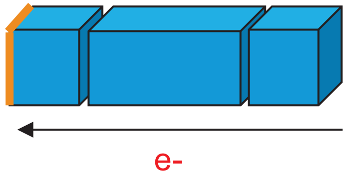
Simulate dose and thermal distribution

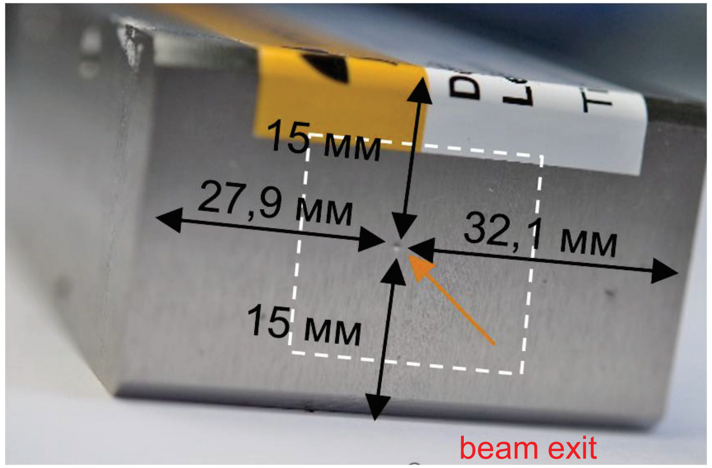


Expectation

- temperature exceeds vaporization threshold
- channel is expected to be formed

Test in European-XFEL (90 mm Ti block)





Extremly early statement after inspection:

- significant internal heating (no damage)
  → Suitable for beam dumps
- grazing incidence: Risk of melting and damage

Courtesy: Sergey Strokov, Alexey Ermakov, Elena Ermakov

Dump Scheme 4th Generation

Selection of 4th generation …

- **ALBA-II:** Simulations showed no damage potential without dedicated fan out or decoherence kicker due to non-linearities in the beam
  Heat Load Distribution in Case of Sudden Beam Loss for ALBA-II, IPAC2026, O.Blanco-Garcia et al.

- **APS-U:** vert. fan-out kicker + Rf off + collimators
  Measuring the Effects of Fast Beam Loss on the Advanced Photon Source Upgrade Storage Ring Collimators, IBIC2025, J.C.Dooling et al.
  Collimator irradiation studies in the Argonne Advanced Photon Source at energy densities expected in next-generation storage ring light sources, Phys. Rev. Accel. Beams 25, 043001 – Published 8 April, 2022, J.C.Dooling et al.

- **ESRF-EBS:**
  - interlock: RF off + decoherence kicker, lost on collimators
  - intentionally beam dump: slowly scraping the beam by gradually closing the collimators, likely less harmful to the collimators.

  Private communication with Benoit Roche, ESRF

- **SLS 2.0:** Beam Dump Kicker, beam is lost in ~1μs on dump, dedicated vacuum valve as backup, no dedicated decoherence kick
  SLS 2.0 Machine Protection, IPAC2023, F.Armborst et al.

- **Diamond II:** Dump Kicker, beam lost within 2 turns on beam dump and hor.+vert. collimators
  A Beam Abort System for the DIAMOND-II Storage Ring, IPAC2026, H.Ghasem et al.

- **Preliminary Dump Scheme for PETRA IV …**

Dump Scheme PETRA IV

Currently foreseen

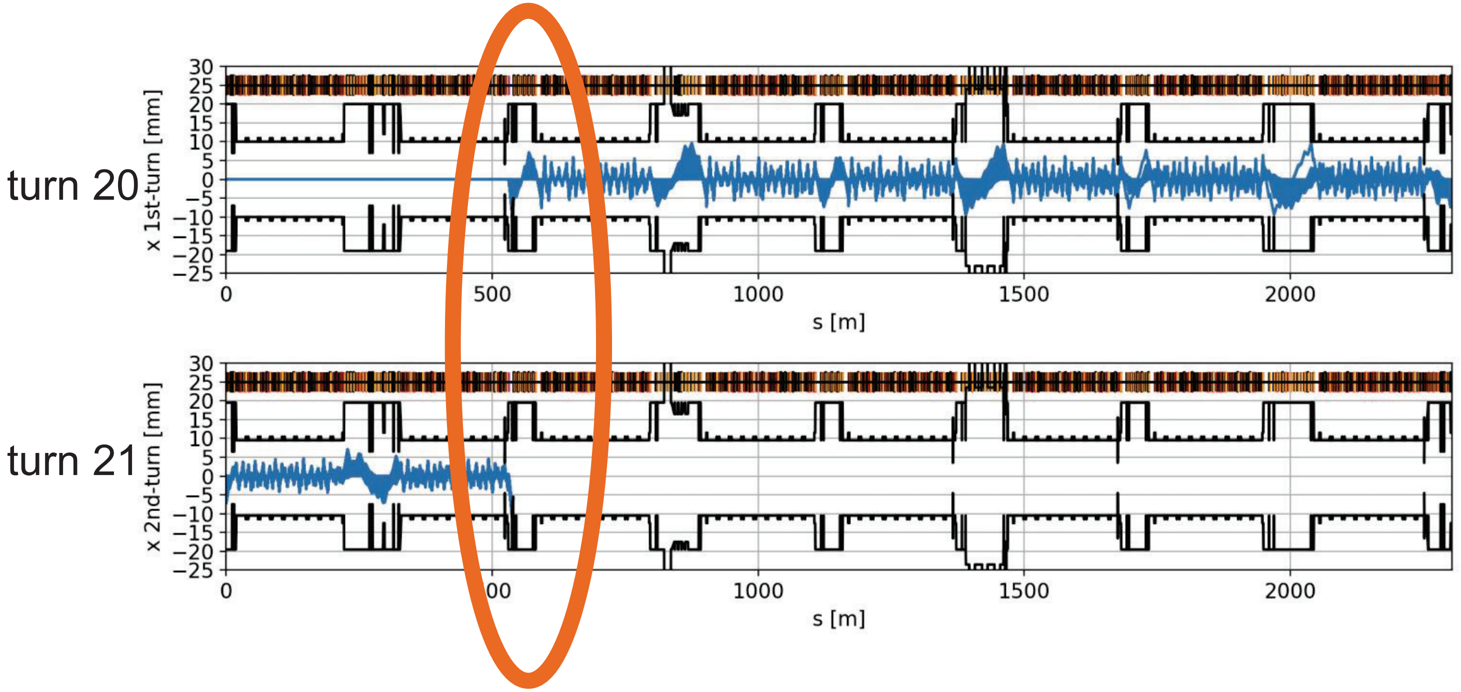
Dump Scheme currently studied

- turn 0: switch off RF
- turn 1: fire decoherence kicker
  (beam blow up)
- turn 20: fire dump kicker
- turn 21: beam is lost

First simulation results on losses
(80 bunches, 80 mA):

- 96.3% of the beam goes into dump
  (hor. / vert. along dump: ca. spread ±1mm)
- 3.2% in horizontal collimator
- 0.5% other components

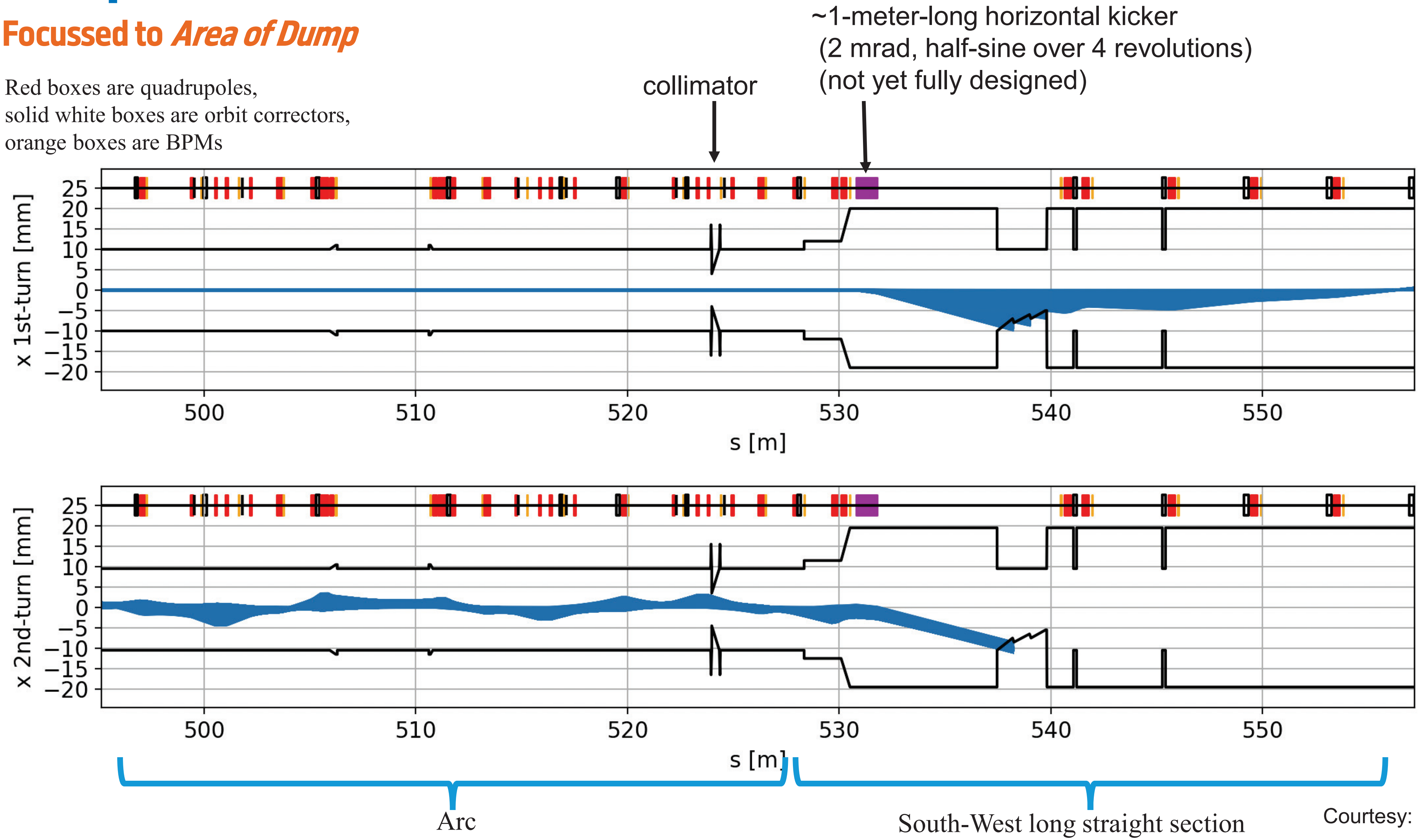
Courtesy: Chao Li, Konstantinos Paraschou



Dump Scheme PETRA IV

Focussed to *Area of Dump*

Red boxes are quadrupoles,
solid white boxes are orbit correctors,
orange boxes are BPMs



Courtesy: Chao Li, Konstantinos Paraschou

Summary

- 3rd generation light sources
  - need for MPS: protect against synchrotron-induced damage (absorbers) or secondaries (e.g. permanent magnets)
  - typical MPS design:
    - fast interlocks, PLC-based or slow systems (e.g. PETRA III)
  - dump scheme: masking RF power for safe beam termination

- challenges for 4th generation light sources
  - higher damage risk: much lower emittance → localized energy deposition
  - MPS adaptations
    - faster response, more sensors (e.g. PETRA IV plan)
  - dump scheme extended
    - decoherence and dump kickers

- briefly included other light sources MPS‘ and dump schemes

Open questions:

Role of AI in analysis and Post Mortem business —are there emerging approaches?

Your input welcome! Feedback, comments, and ideas are highly appreciated.

Thank you

Acknowledgements: would like to express our gratitude to all authors of the publications cited herein. Special thanks go to Kees Scheidt and Benoît Roche (ESRF) for their insightful explanations regarding their dump schemes. We are also indebted to Chao Li and Konstantinos Paraschou from the DESY Beam Physics Group for sharing their pioneering results on the PETRA IV dump scheme.Our appreciation extends to Jonas Lamaack for his illuminating coffee-break discussions on energy density and for meticulously reviewing this paper.Lastly, we thank everyone who contributed, knowingly or unknowingly, to this work. unknowingly.

Gemini

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Timmy Lensch
Beam Diagnostics
timmy.lensch@desy.de

Gero Kube
Beam Diagnostics
gero.kube@desy.de

Ilya Agapov
Beam Physics
Ilya.agapov@desy.de

References

B. Roche, ESRF, private communication, 2026.

Struck Innovative Systeme GmbH, "SIS8172 - MTCA.4 AMC Board with Artix FPGA," `https://struck.de/sis8172.html`, accessed: 2026-09-01.

G. Decker, "Abort Interlock Diagnostic for Protection of APS Vacuum Chamber," in *Proc. PAC1993*, Washington, DC, USA, May 1993, pp. 2196–2198.

R. Fuja et al., "The APS Machine Protection System," *Nucl. Instrum. Methods Phys. Res. A*, vol. 372, no. 2, pp. 367–372, 1996. 10.1016/0168-9002(95)01480-8

A. Lumpkin et al., "Overall Design Concepts for the APS Storage Ring Machine Protection System," in *Proc. IEEE PAC1995*, Dallas, TX, USA, May 1995, pp. 1234–1236.

U. Hahn et al., "The Generic Beamline Concept of the PETRA III Undulator Beamlines," in *Synchrotron Radiation Instrumentation*, 2007.

T. Lensch et al., "Synchronized Post Mortem Trigger of the PETRA III MPS," in *Proc. BIW2012*, Newport News, VA, USA, Apr. 2012, pp. 456–458. 10.18429/JACoW-BIW2012-MOPG032

M. Walla et al., "Machine Protection Diagnostics on a Rule-Based System," in *Proc. ICALEPCS2013*, San Francisco, CA, USA, Oct. 2013, pp. 789–791. 10.18429/JACoW-ICALEPCS2013-THPPC071

A. Bertarelli, "Beam-Induced Damage Mechanisms and Their Calculation," in *Proc. CAS School on Beam Loss and MPS*, 2014. 10.5170/CERN-2016-002

M. Tischer et al., "Radiation Damage of Undulators at PETRA III," in *Proc. IPAC2014*, Dresden, Germany, Jun. 2014, pp. 123–125. 10.18429/JACoW-IPAC2014-WEPRO035

J. C. Dooling et al., "Collimation and Machine Protection for Low Emittance Rings," in *Proc. IBIC2022*, Kraków, Poland, Sep. 2022, pp. 234–236. 10.18429/JACoW-IBIC2022-TU2T1

F. Armborst et al., "SLS 2.0 Machine Protection," in *Proc. IPAC2023*, Geneva, Switzerland, May 2023, pp. 345–347. 10.18429/JACoW-IPAC2023-MOPM018

J. C. Dooling, "Measuring the Effects of Fast Beam Loss on the Advanced Photon Source Upgrade Storage Ring Collimators," in *Proc. IBIC2025*, 2025, to be published.

O. Blanco-García et al., "Heat Load Distribution in Case of Sudden Beam Loss for ALBA-II," in *Proc. IPAC2026*, 2026, to be published. 10.18429/JACoW-IPAC2026-THP2047