THPB091

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MACHINE PROTECTION

ISSUES AND SOLUTIONS FOR LINEAR ACCELERATOR COMPLEXES

First workshop on machine protection held at CERN June 2012

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Abstract

The workshop “Machine Protection focusing on Linear Accelerator Complexes” was held from 6-8 June 2012 at CERN. This workshop brought together experts working on machine protection systems for accelerator facilities with high brilliance or large stored beam energies, with the main focus on linear accelerators and their injectors. An overview of the machine protection systems for several accelerators was given. Beam loss mechanisms and their detection were discussed. Mitigation of failures and protection systems were presented. This paper summarises the workshop and reviews the current state of the art in machine protection systems.

Motivation and Objectives

Machine protection: **major concern** for high power linear accelerators in construction or planned (ESS, XFEL, ILC, CLIC).

Increased beam power ⇒ machine protection imperative.

Bring together for the first time experts on machine protection from various origins and disciplines

- exchange experience and ideas
- profit from recent experience of LHC

Workshop Organisation

60 participants with a significant number from outside CERN .
30 presentations & discussion in 6 half day sessions:

- **Introduction:**
  - objectives for machine protection
  - existing solutions and challenges for future installations.
- **Beam loss mechanisms:** existing installations and expectations for future accelerator.
- **Failure detection:** failures leading to uncontrolled beams.
- **Failure mitigation:** failure dependent mitigations strategies.
- **Operational aspects:** commissioning, intensity ramp, availability, risk assessment and management.
- **Summing up and closing**

Beam Loss Mechanisms

to be studied first: key role in failure scenarios

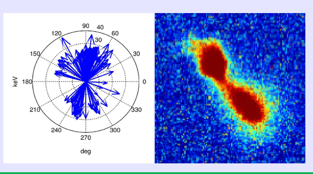
Operational beam losses: inherent quasi continuous losses (loss background). Not primary concern for failure studies, but **induced radiation** contributes to long term failure, and may pose problems to electronics.

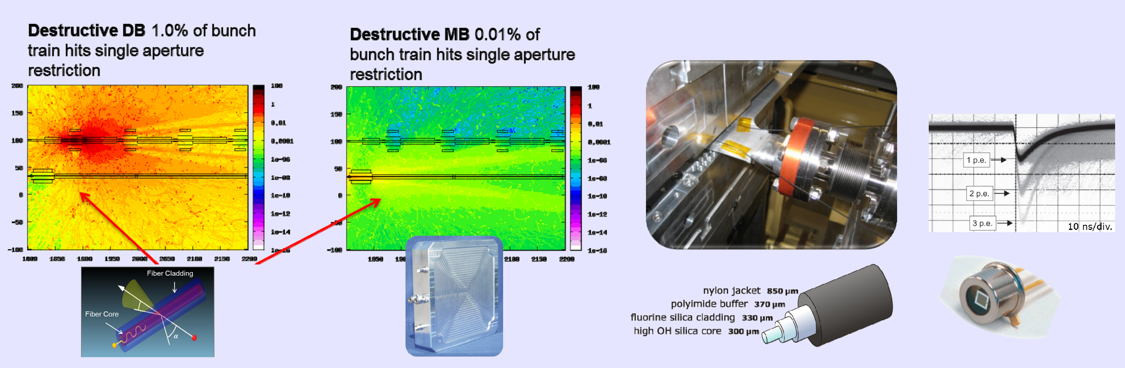
Sources: dark current, un-captured beam, satellite bunches, beam gas induced beam halo, ...

Equipment failure: ⇒ major damage

Transient beam losses: temperature , ground motion, UFOs, ...

- Software tools and methods to simulate beam behaviour & losses.
- LHC experience
- First measurement of beam kick induced by RF breakdown in CLIC structures.





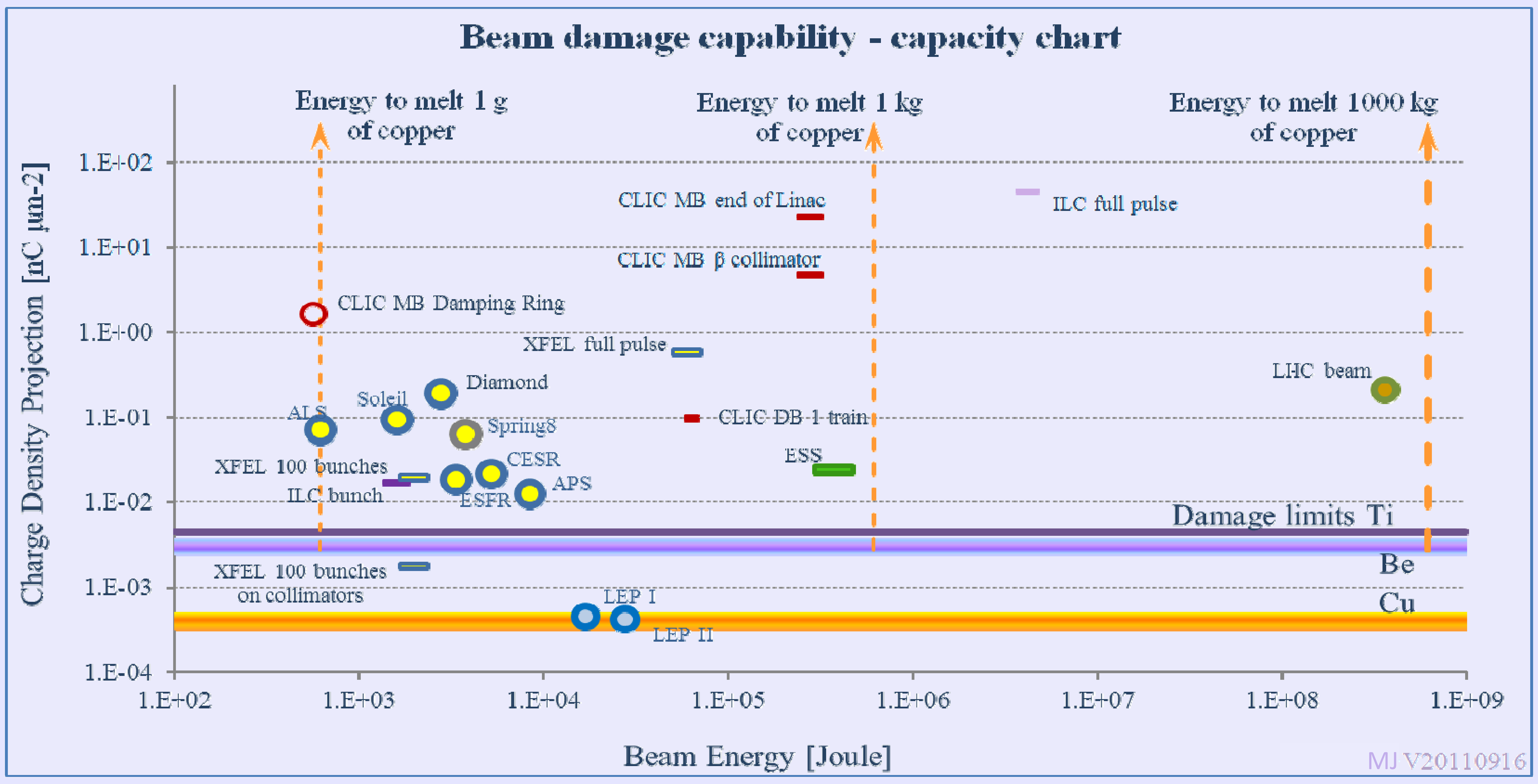
Failure Detection

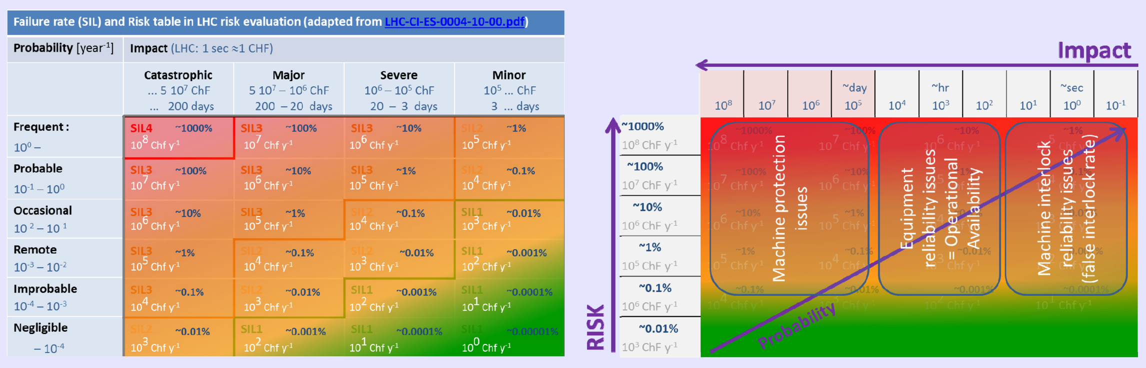
most effective: act before failure leads to damage

Equipment failures: for beam interlock.

Beam quality: not always applicable for RT beam abort in linear accelerators, but fundamental for a beam permit system to protect against upcoming instabilities. Example from LHC transfer line and injection beam permit.

Beam diagnostics instruments: large emphasis on beam loss detection. **Scintillating fibre**: economic solution for large beam loss observation systems (e.g. CLIC drive-beam decelerators).





Machine Protection

protect accelerator from beam induced damage

Not: equipment protection, quench protection, ...
Not: personnel protection (stringent legal requirements and basic solutions).
Not limited to the interlock system:

1. **Passive protection** (collimators and masks) limits damage caused by unmanageable failures.
2. Active **beam-abort systems** to dispose of any beam present (beam observation , abort kickers, beam dumps, ...
3. **Beam interlock**: inhibits the beam in case of equipment failures.
4. Strategy to **limit rate of change** for magnetic fields and device positions.
5. **Post cycle quality assessment** (beam and equipment), inhibit next cycle when performance is outside predefined limits.
6. A **beam-stop restart system**: i.e. intensity ramp sequence providing protection depending on machine status.
7. Version control and parameter change authorization.
8. **Fault recording**, analysis and playback system.
9. Written **procedures to introduce changes** in the parameters that control the machine protection system.
10. **Test procedures** to thoroughly test the components of the machine protection system after each change in the system.
11. **Spares policy** to reduce loss of operational availability caused by unavoidable damage to equipment.

Failure Mitigation

reducing risk = reducing (frequency or impact)

Frequency reduction

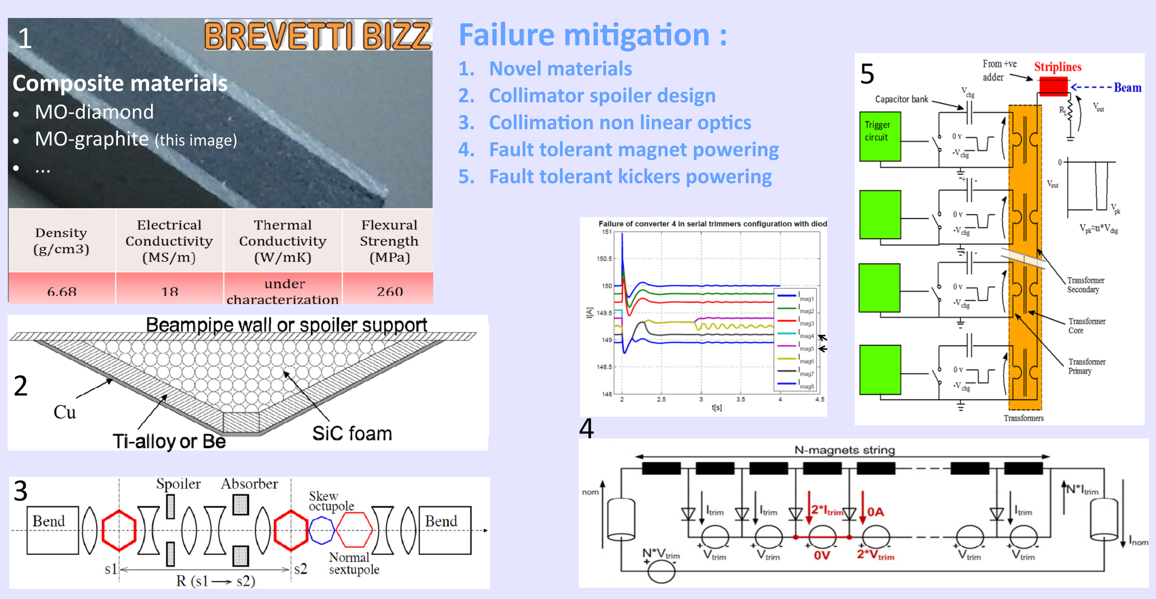
Improved equipment reliability: kicker pulsing circuit, fault-tolerant powering configuration, ... (these also contribute to better system availability).

Beam interlock: reduce the frequency of dangerous beam failures (need efficient detection, decision and beam abort).

Impact reduction

Passive protection (masks and collimators) for ‘in-flight’ failure protection. Often close or above material damage threshold (high beam brilliance). Examples of possible improvements: new collimator designs, nonlinear collimation optics, novel material.

Spare policies: reduce impact in case of unavoidable damage. Examples: spare collimator surface, build-in hot spares in powering configurations.



Risks Normalization

Risk = Frequency x Impact (expectation value of impact)

Damage potential: amount of energy that can be released before the system can safely shut down.

Risk (in statistical terms) expectation value of the impact

Risk = Impact x Probability

impact: - cost of repair [risk] = [money]/[time]
- operational downtime. [risk] = [downtime]/[time]

Normalize by available financial resources and scheduled operation time. [Risk] ⇒ [fraction of available resources].

- prioritize risk mitigation
- risk reduction pays off where risk reduction > investment.

Risk metrics can be made dimensionless

⇒ Risk management is scale invariant

Low probability high impact risk, estimation errors: ⚠

- Probability : aging, human errors, unanticipated configuration changes or coincidences with other failure modes.
- Impact: Collateral damage

Implementation and Operation

key to success & performance

SLC experience: machine protection ⇒ unstable operation:
beam inhibit ⇒ thermal change ⇒ beam instability ⇒ beam inhibit

⇒ **Beam-stop recovery** important. Discussed at workshop: recovery of RF breakdowns, beam intensity ramp up procedures.

Analysis & tools

- Post mortem analysis, performance analysis
- Risk classification and evaluation (prioritization of mitigation
- Machine availability analysis.
  (last 2 are very similar: failure catalogue, frequency, impact, possible redundancies, knock-on effects).

System complexity ⇔ **reliability**. Often came up at the workshop. Machine protection implementation must follow a system approach. Example: incorrect to simplify the interlock system while creating hidden complexity elsewhere in the system.

Conclusions

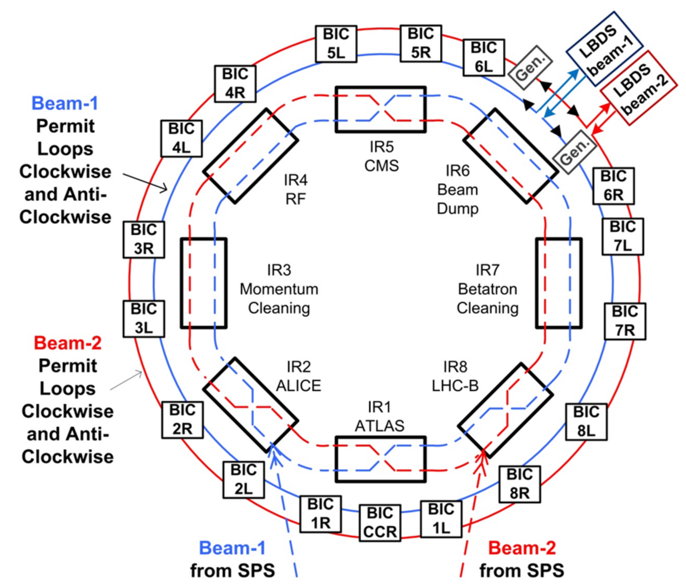
Machine protection (MP) plays a crucial role in future high power linear accelerators and poses many new challenges, e.g. robust collimator designs; large scale beam loss detection systems; intensity ramp-up whilst following beam performance and environmental changes; improving equipment reliability and managing system complexity. Some challenges will be addressed through R&D programs, while others will need learning in realistic machine environments.

The workshop has shown that MP must be an integral part of the accelerator design stage and include well-planned and engineered instrumentation. Such instrumentation is crucial to understand the dynamics of the machine and will allow the MP to evolve in parallel with the commissioning of the machine at increasing stored beam energies.

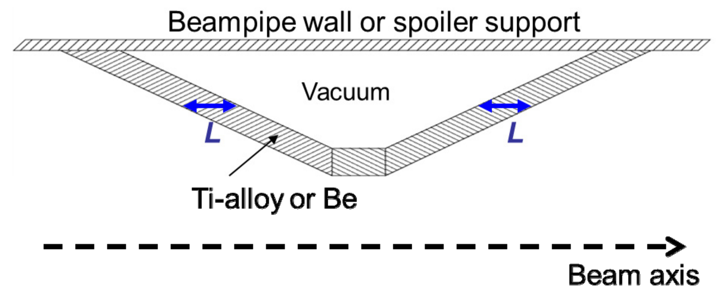
The workshop allowed a fruitful exchange of experience and was highly valued by the participants. It is foreseen to repeat the workshop in two or three year. More details will be made available on the workshop website or can be obtained by contacting the authors.

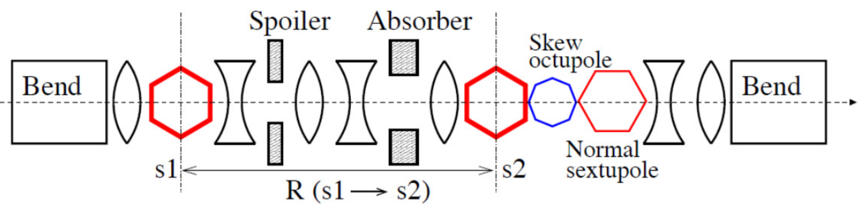
Reference

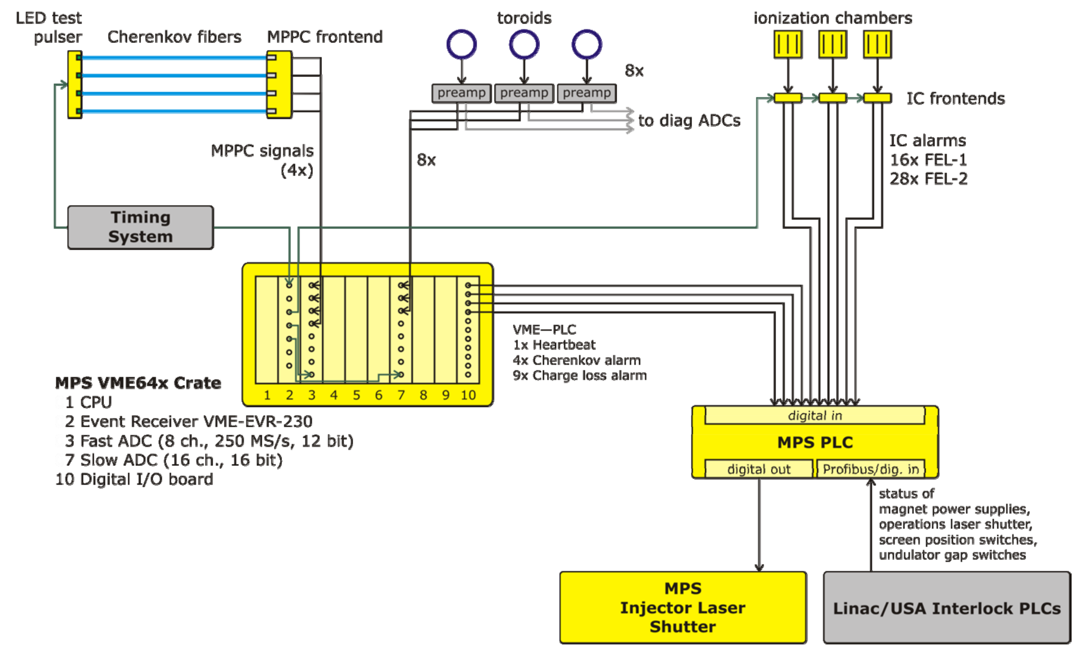
Conference web site and presentations repository:
http://indico.cern.ch/conferenceDisplay.py?confId=185561



- "Hollow" spoilers







Mo-CD Composites

BREVETTI BIZZ

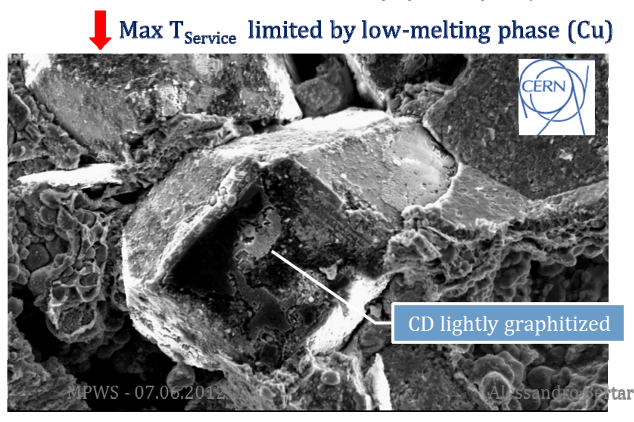
- Co-developed by **CERN** and a SME, **Brevetti Bizz**, Verona, Italy
- High sintering T of Mo (~**1700 °C**) leads to diamond graphitization. 2 alternative processes: **Liquid Phase Sintering (LPS)** or **Assisted Solid-state Sintering (ASS)**

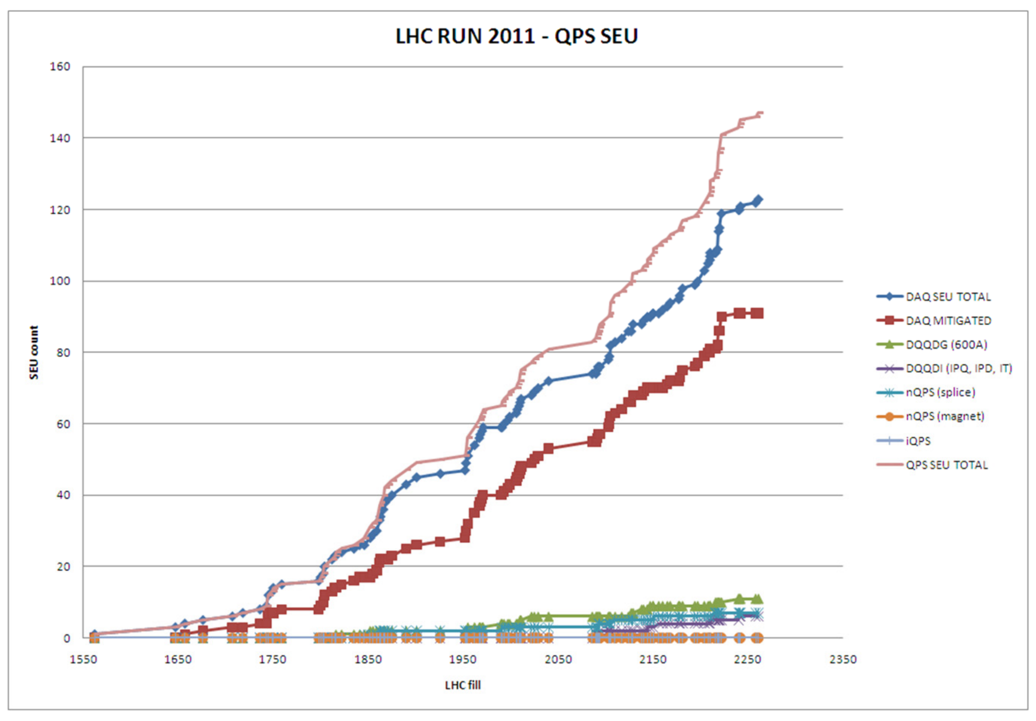
LPS

- ↑ Addition of low-melting phase (Cu) to fill in the pores between Mo and CD
- ↑ Good mechanical strength (400+ MPa) and fair Thermal Conductivity (185 W/mK)
- ↓ Max $T_{Service}$ limited by low-melting phase (Cu)

ASS

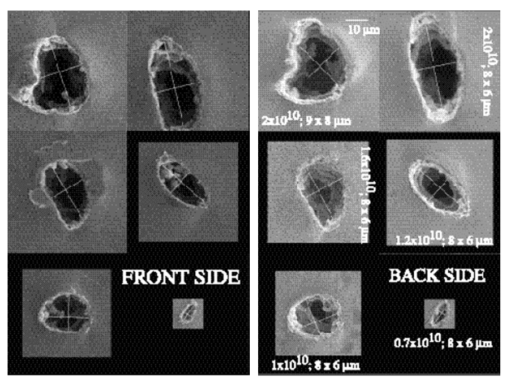
- ↑ Addition of activating elements (Ni, Pd) enhances Mo sintering at low T (~1300 °C)
- ↑ Absence of low-melting phase increases $T_{Service}$ up to ~2600 °C
- ↓ Large diamond particles interfere with Mo compaction.
- ↓ Diamond graphitization not fully avoided.





- What makes a beam destructive is its brilliance (projected beam charge density)
- Concentrated beams of even modest energy can damage the material (more beam energy just implies drilling deeper holes, i.e. more damage)
- Projected charge density damage threshold :

$\sigma_{yield} = \Delta T_{yield} \times c \,/\, (1.4 \times dE/dx)$



Single Pulse Damage in 1.4 mm Cu

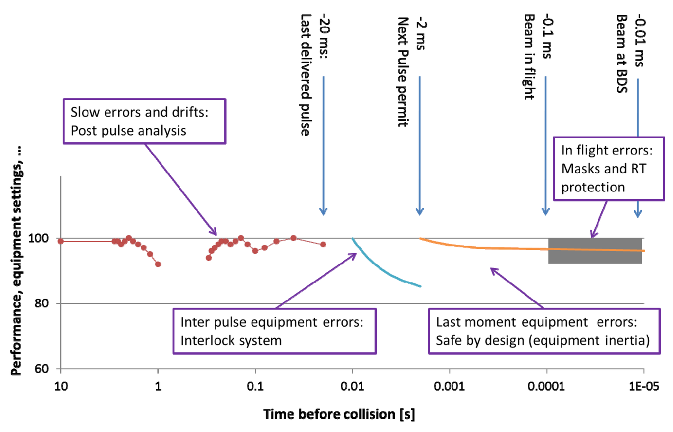
Scanning Electron Microscope images.

Charge density of beam impacts 1 … 3 nC µm⁻²

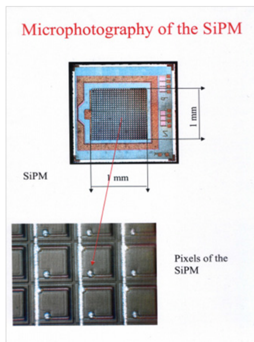
Source: XX International Linac Conference, Monterey, California

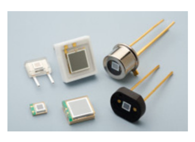
	σ_{yield} [nC µm^{-2}]	ΔT_{yield} [°C]	c_{th} [J °C^{-1} g^{-1}]	dE/dx_{min} [MeV g^{-1} cm^2]
CU	0.39 10^{-3}	201	0.38	1.40
BE	3.02 10^{-3}	370	1.82	1.60
Ti-alloy	4.45 10^{-3}	1710	0.46	1.45

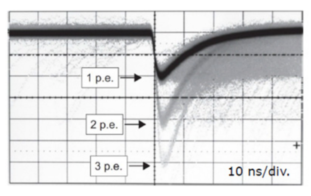
Yield temperature rise take from EUROTeV 2008-050



Downtime	Frequency	Risk Equivalent (for 6 month running per year)
3 month	1 per 5 years	7.5%
1 day	10 per year	5.5%
2 years	1 per 10000 years	0.02%







- Array of avalanche photodiodes (APDs) connected in parallel
- Reverse bias → photon causes APD breakdown
- Photomultiplier-like gain
- Dynamic range limited by number of APDs
- Rise time: some 100 ps
- Hamamatsu S10362-11-050U: 400 APDs at ~70 V reverse bias