Reliable Beam Extraction

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Workshop on Machine Protection, focusing on Linear Accelerator Complexes

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Extraction kickers

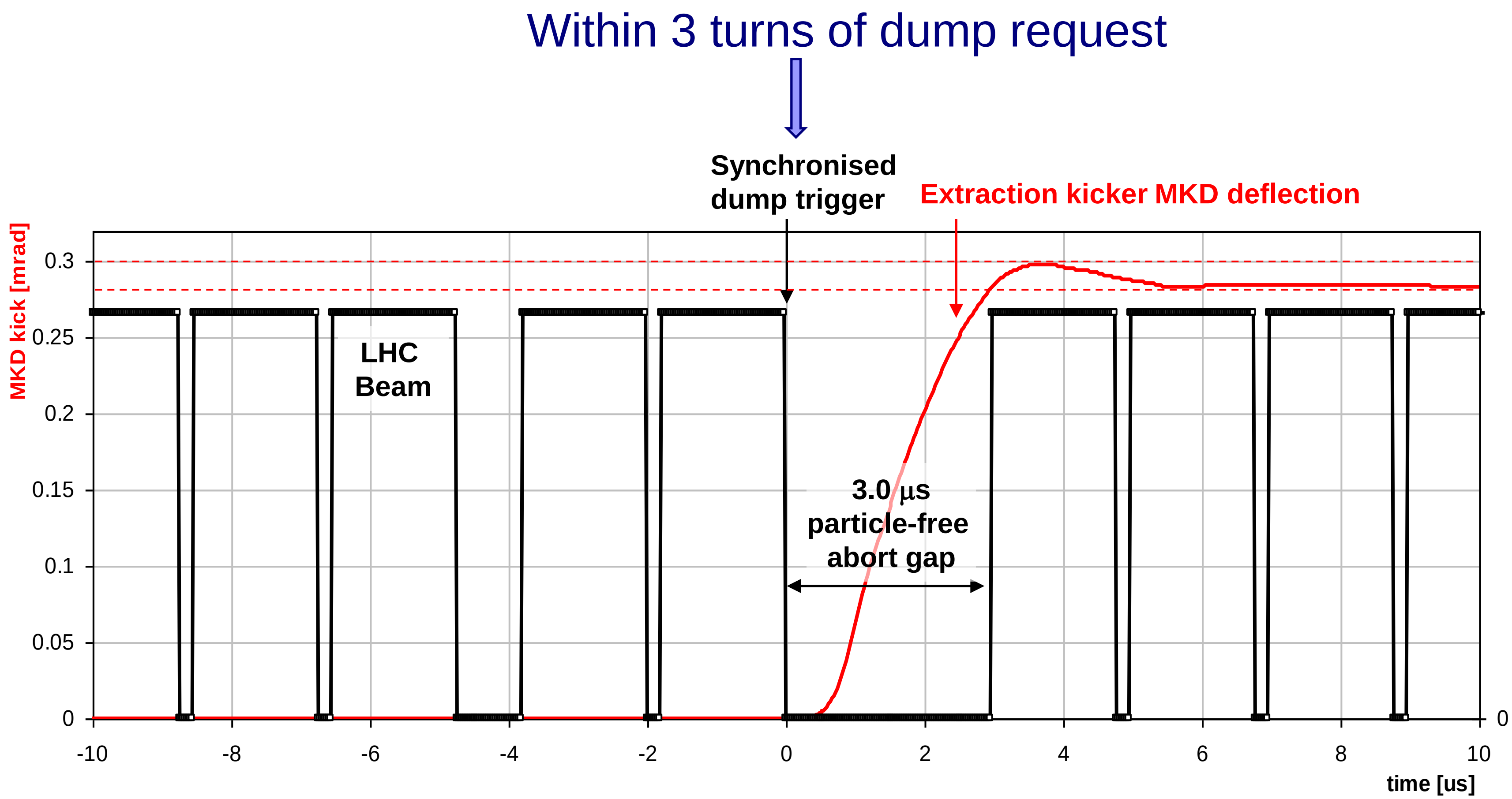
- Fast kickers used at many places in linear collider systems
  - Combiner rings
  - Damping rings
  - Beam distribution (drive beam)
  - Emergency dumps
    - Cannot be used for CLIC: 0.5 ns bunch spacing (2 GHz baseline)
    - Possibly be used for ILC – 369 ns bunch spacing
- Safe extraction required
  - High brilliance beams can cause damage to equipment when extraction kickers don't function as expected
- This talk: how to make safe(r) extraction kickers
  - Example of LHC beam dump extraction kickers – operational
  - Example of CLIC damping ring extraction kickers – design phase

Extraction kicker failure modes

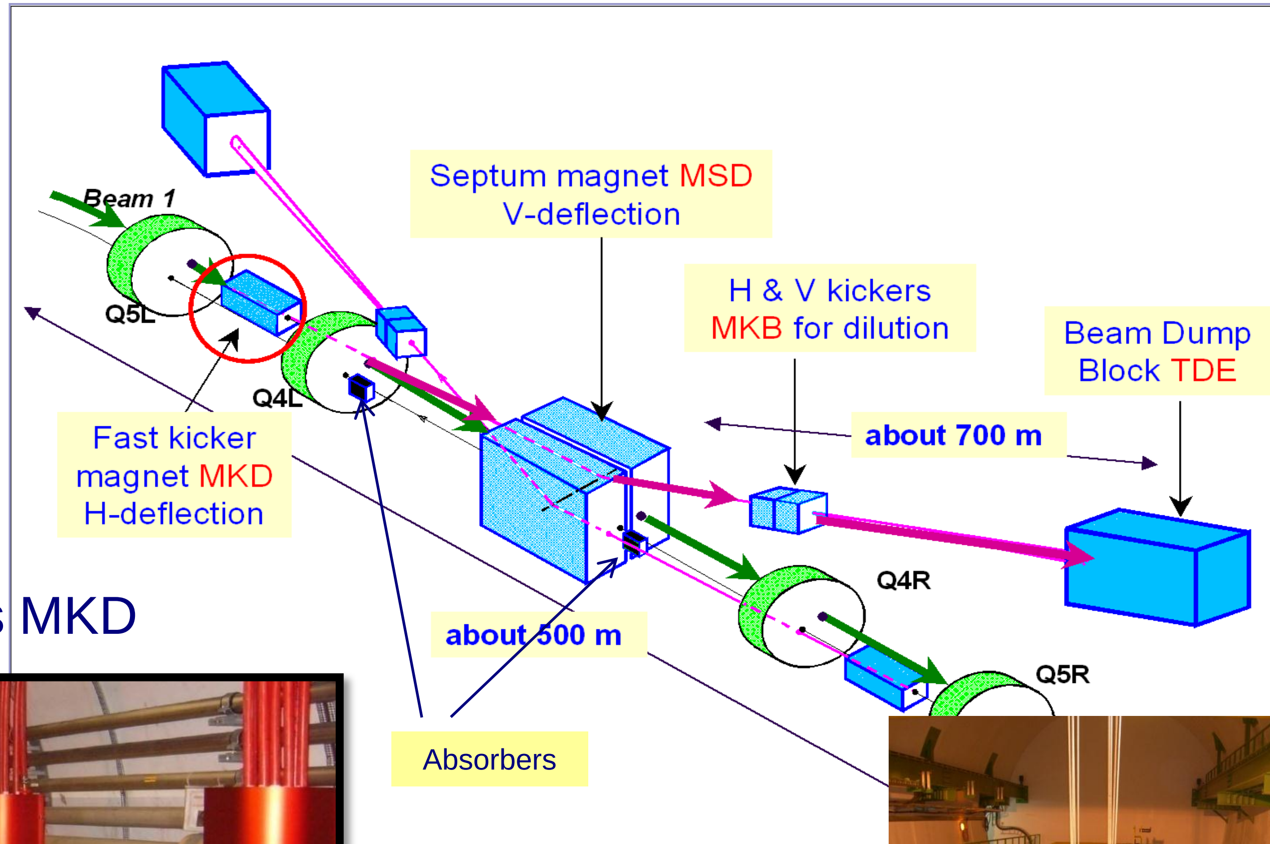
- Different failures modes to be analysed
  - Not triggering (bad for emergency beam dump)
  - Unsynchronised triggering
    - Rise time of the kicker pulse during period with beam
    - Part of the beam not deflected with nominal kick
  - Amplitude not correct
    - Complete beam not deflected with nominal kick
- Failures modes in two families
  - Control system problems
    - Triggering system, synchronisation, reference amplitude
  - Hardware problems
    - Break-down of the kicker element, within the generator, or the interconnections

Synchronised extraction kick

Example for the LHC extraction kickers MKD



LHC Beam Dumping System

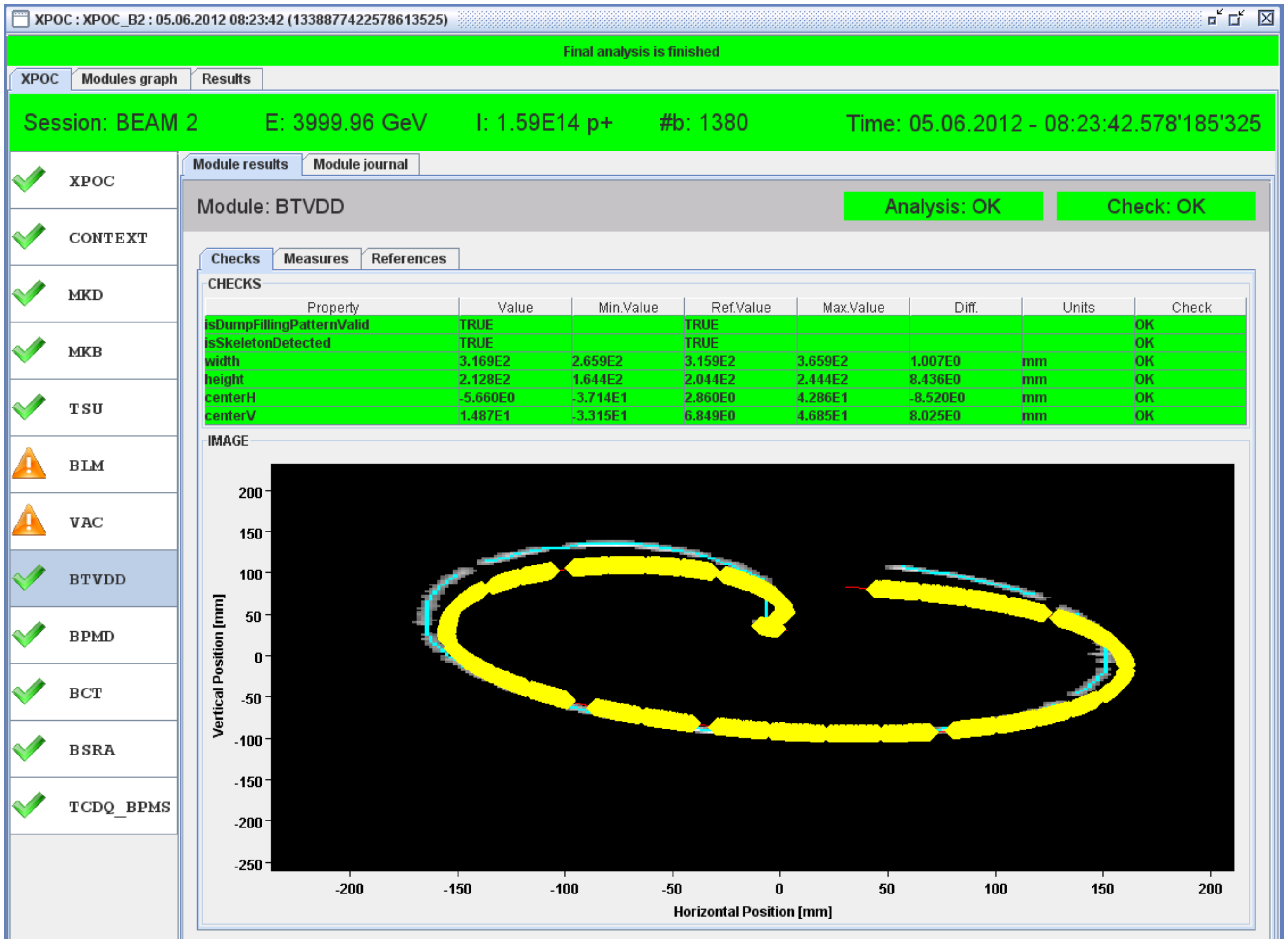


Extraction kickers MKD

Dump block

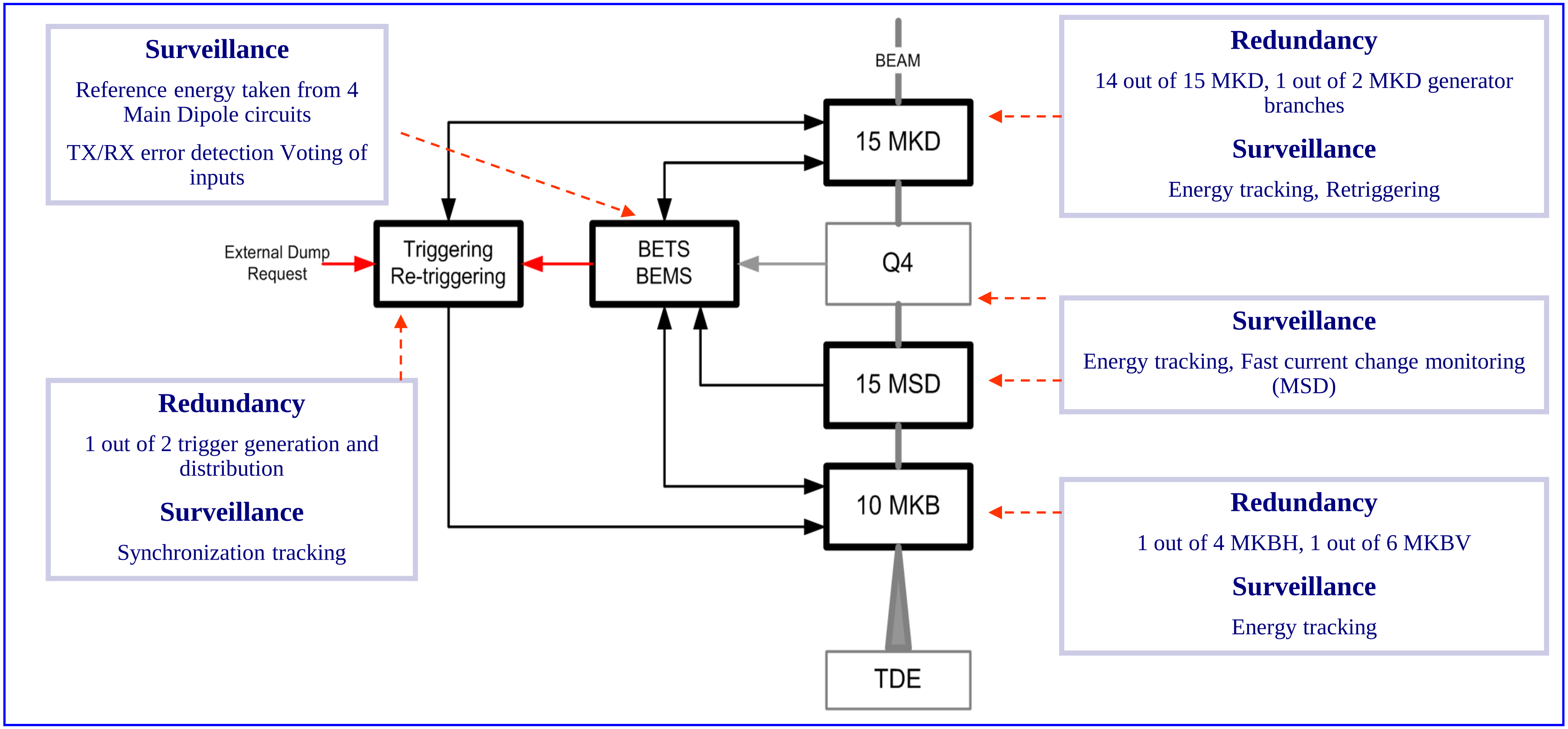
Image of dumped beam

Automatic analysis within eXternal Operational Check (XPOC)



LHC Beam Dumping System

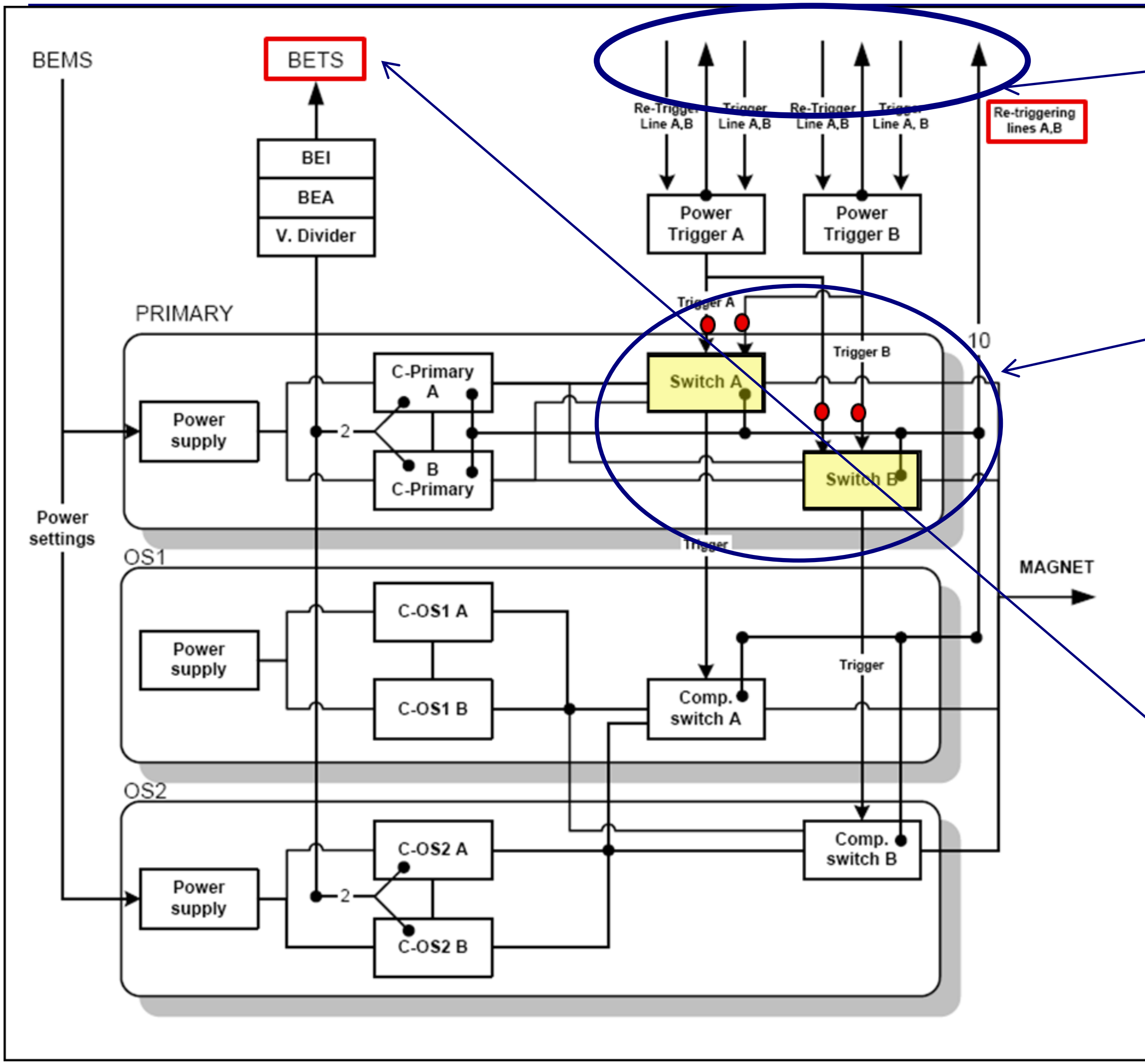
- System safety is based on:
  - Built in redundancy
  - Continuous surveillance
  - Post Operational Checks (IPOC/XPOC)



Extraction Kicker NOT firing

- One kicker not firing is covered by
  - System redundancy: can dump correctly with 14/15 MKD systems
- It is very unlikely that one, or even more unlikely more than one, kicker will not fire because of:
  - Choice of switch type:
    - The GTO Thyristor switch stack consisting of 10 discs
    - Manufacturer failure rate for 1 disc → *$2.4 \cdot 10^{-6}$ failures per hour for 1 switch*
  - Redundancy within each kicker generator
    - Each generator has two solid state switches in parallel, which can each take the full current
  - Redundancy in triggering system
- Complete system not firing due to no trigger from Beam Interlock System not treated here
  - Fault external to beam dumping system
  - See presentation on Friday morning by Benjamin Todd: "Reliability of the CERN Beam Interlock System"

Functional Architecture of 1 MKD Generator



4 triggers coming in from BIS (and 2 going out)

Two parallel switches, full redundancy in each generator

Surveillance of voltage = kick angle

Kicking with wrong strength

- Probably one of the worst scenario's
- Covered by comprehensive Energy Tracking System (BETS)
  - Energy is calculated from the main dipole currents in the four 'adjacent' octants
  - Large redundancy in generation of energy reference and in verification of power supply voltage, which determines kicker strength, while being ready for the next dump
  - Kicker settings and Energy Interlock values both hardcoded in the Front Ends, using separate tables
    - No remote access to these tables
    - "There are no operator buttons on the beam dumping system!"

Erratic firing of kicker

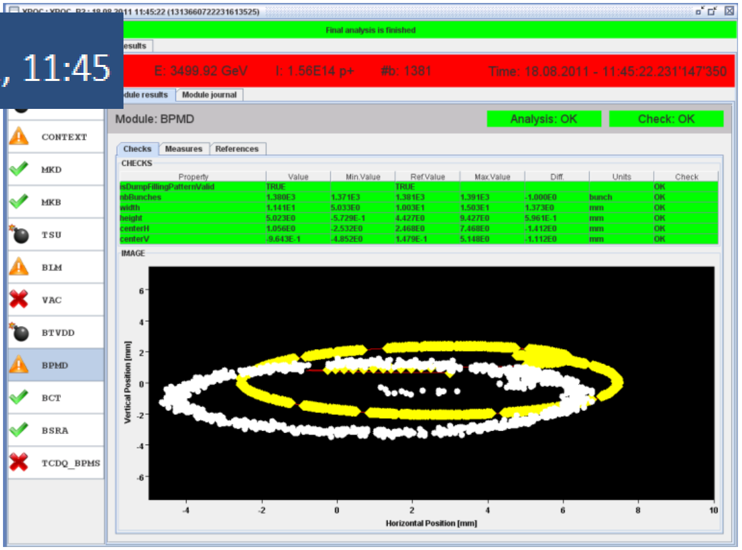
- Re-triggering system which detects any ‘spontaneous’ firing of an MKD kicker magnet
- Within 700 ns all switches will be fired asynchronously
  - During this delay and the 3 μs rise time of the MKD kickers, the bunches swept over the aperture will be intercepted by the TCDQ and TCDS absorbers.
- Again redundant signal paths

Power Cut

- In this case the beam will clearly need to be dumped because most other equipment will stop working
- Beam dumping system kickers are on 2 parallel, redundant Uninterruptable Power Supplies (UPS)
- UPS required:
  - Trigger Synchronisation Unit needs power from UPS to start the trigger of the beam dump
  - All other power is stored in capacitors, ready to be ‘released’ at the moment of trigger

Total power cut at LHC - 18 August 2011, 11:45

  - Beams were correctly dumped:



Property	Value	Min.Value	Ref.Value	Max.Value	Diff.	Units	Check
isDumpFillingPatternValid	TRUE		TRUE				OK
nbBunches	1.380E3	1.371E3	1.381E3	1.391E3	-1.000E0	bunch	OK
width	1.141E1	5.033E0	1.003E1	1.503E1	1.373E0	mm	OK
height	5.023E0	-5.729E-1	4.427E0	9.427E0	5.961E-1	mm	OK
centerH	1.056E0	-2.532E0	2.468E0	7.468E0	-1.412E0	mm	OK
centerV	-9.643E-1	-4.852E0	1.479E-1	5.148E0	-1.112E0	mm	OK

Safety Study Beam Dumping Study

- Ph.D. thesis Roberto Filippini (CERN-THESIS-2006-054)
- FMECA analysis
  - More than 2100 failure modes at component levels
    - Components failure rates from standard literature (Military Handbook)
  - Arranged into 21 System Failure modes
- Operational Scenarios with State Transition Diagram for each Mission = 1 LHC fill
- State Transition Diagram for Sequence of Missions and checks

Likelihood of any unacceptable failure

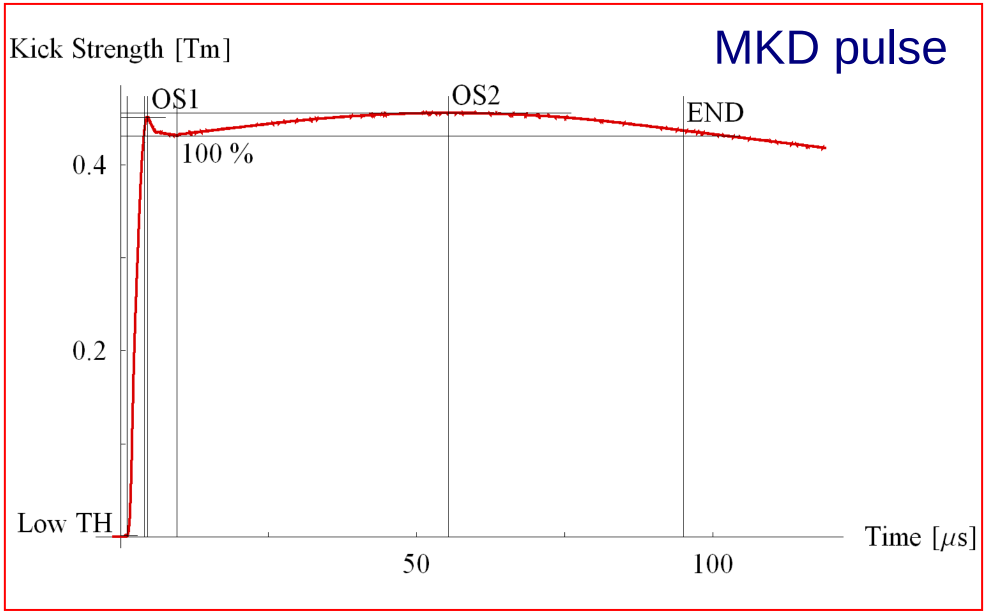
Availibility

Case studied	Unsafety/year	False dumps/year
Default scenario	2.41×10^{-7} (> SIL4)	4.06
No redundant power triggers	2.34×10^{-6} (SIL4)	3.02
No redundant triggering sys.	4.68×10^{-4} (SIL2)	4.02
14 MKD	0.011 (SIL1)	3.89
No BETS	0.059 (< SIL1)	3.40
No RTS	0.32 (< SIL1)	4.06

Can learn a lot from relative numbers !

Obligatory !

Reliability Run before first beam

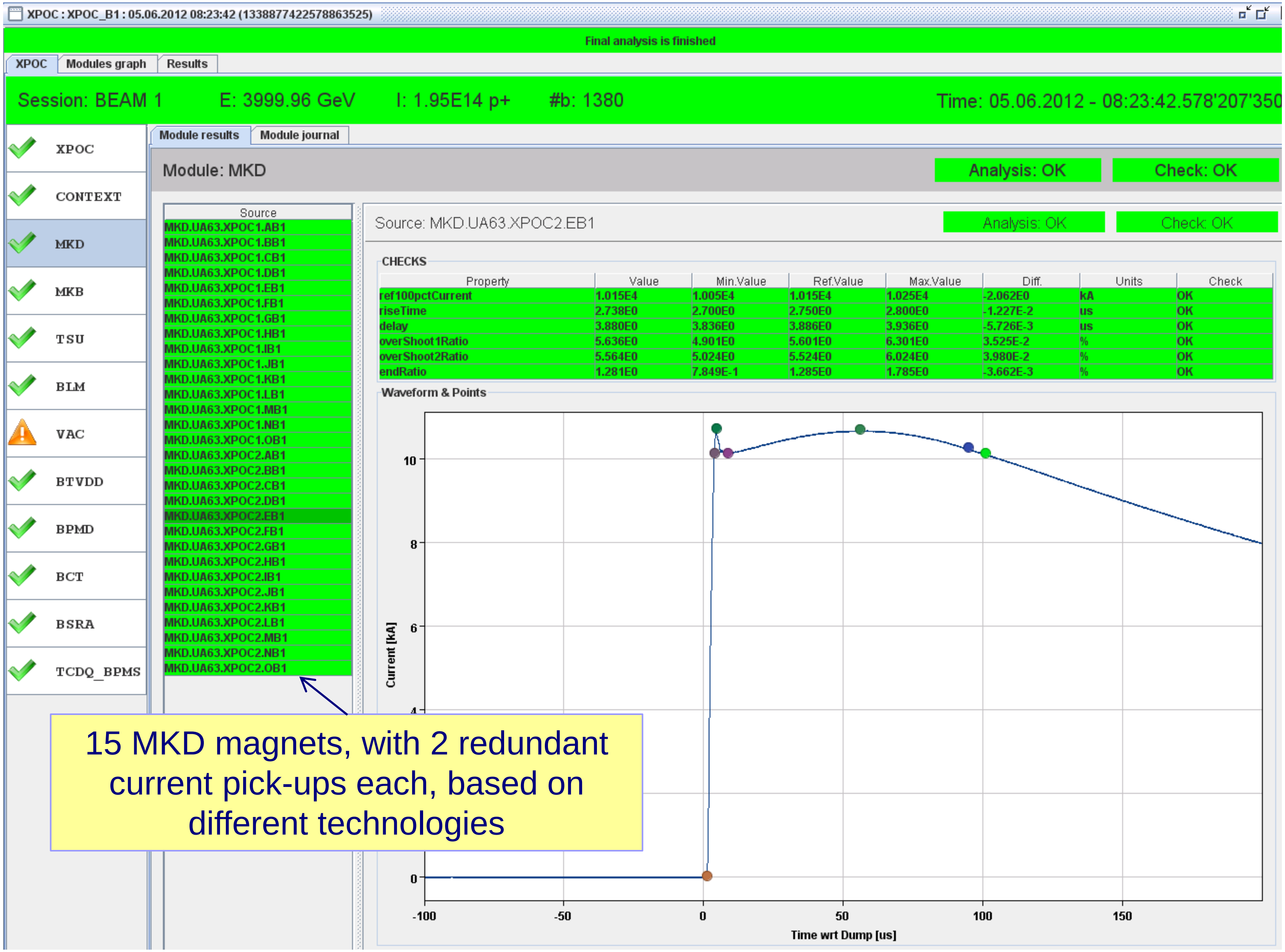


- **741'057** Magnet Pulses Analysed with IPOC and XPOC Systems
  - > 10 years of operation
- Some hardware problems discovered
  - Contact erosion -> replacement program
- No critical failures, but some weaknesses detected with the IPOC/XPOC systems during the reliability run
- Global confirmation of assumed component failure rates

Post Operational Checks

- Every beam dump (extraction) is automatically analysed
- Any out of tolerance kicker waveform, or more than usual beam losses, will block the next injection
- Kicker waveform failures can only be reset by the system experts
  - Not the Engineer In Charge in the control room
  - Not the piquet / technician from the standby service
- This provides the ‘as good as new’ assumption used in the reliability calculations leading to SIL4 classification

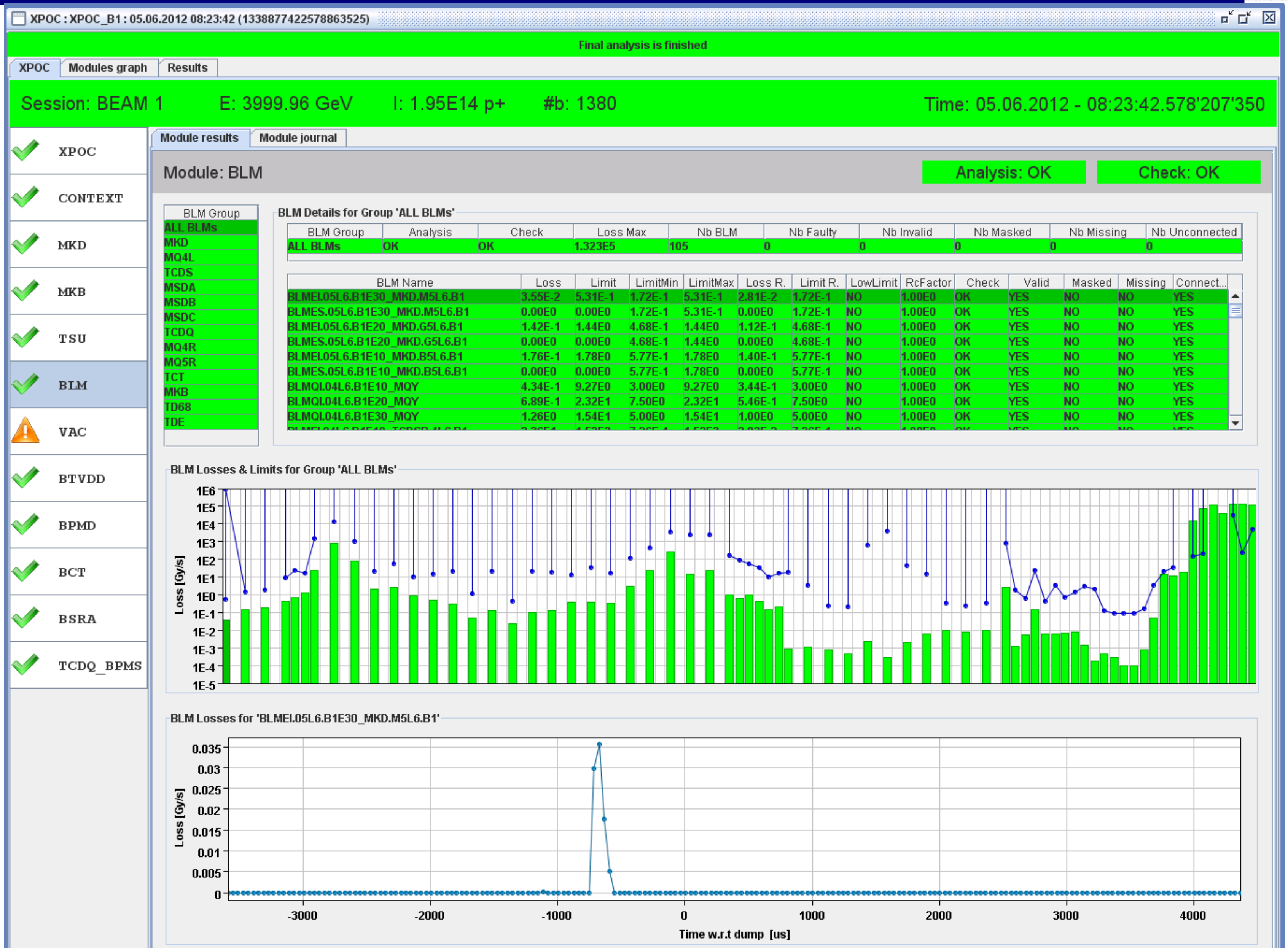
XPOC check of extraction kicker



Property	Value	Min.Value	Ref.Value	Max.Value	Diff.	Units	Check
ref100pctCurrent	1.015E4	1.005E4	1.015E4	1.025E4	-2.062E0	kA	OK
riseTime	2.738E0	2.700E0	2.750E0	2.800E0	-1.227E-2	us	OK
delay	3.880E0	3.836E0	3.886E0	3.936E0	-5.726E-3	us	OK
overShoot1Ratio	5.636E0	4.901E0	5.601E0	6.301E0	3.525E-2	%	OK
overShoot2Ratio	5.564E0	5.024E0	5.524E0	6.024E0	3.980E-2	%	OK
endRatio	1.281E0	7.849E-1	1.285E0	1.785E0	-3.662E-3	%	OK

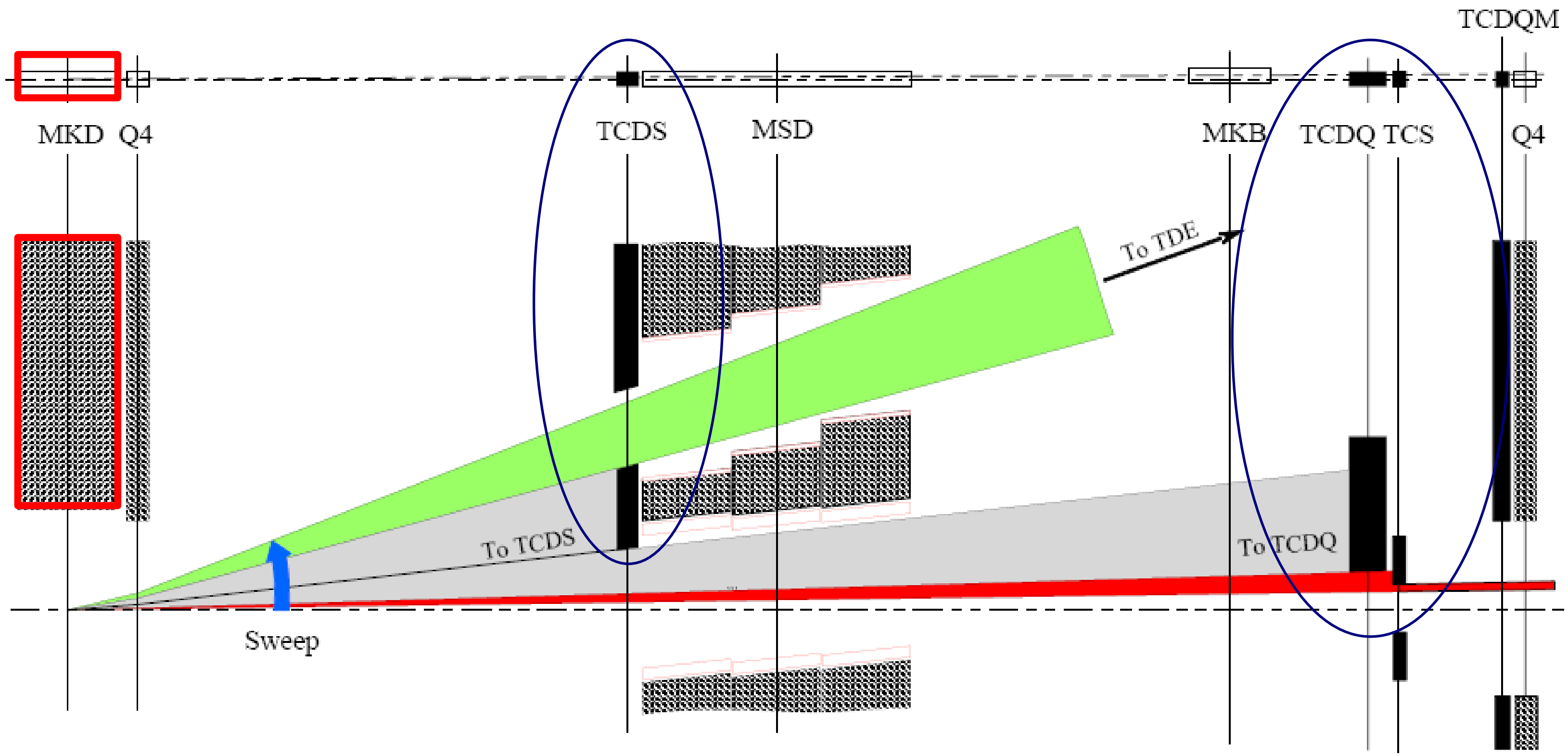
15 MKD magnets, with 2 redundant current pick-ups each, based on different technologies

XPOC check of Beam Losses



Mitigation by absorbers / diluters

- Mitigation only possible for some failure modes
  - Beam in the Abort Gap
  - Asynchronous beam dump → quench or damage
- Precautionary measures include:
  - TCDS (fixed) – 6 m long diluter protects extraction septum
  - TCDQ/TCS (**mobile**) – 7 m long diluter kept at about **7-8 σ from the beam at all times**

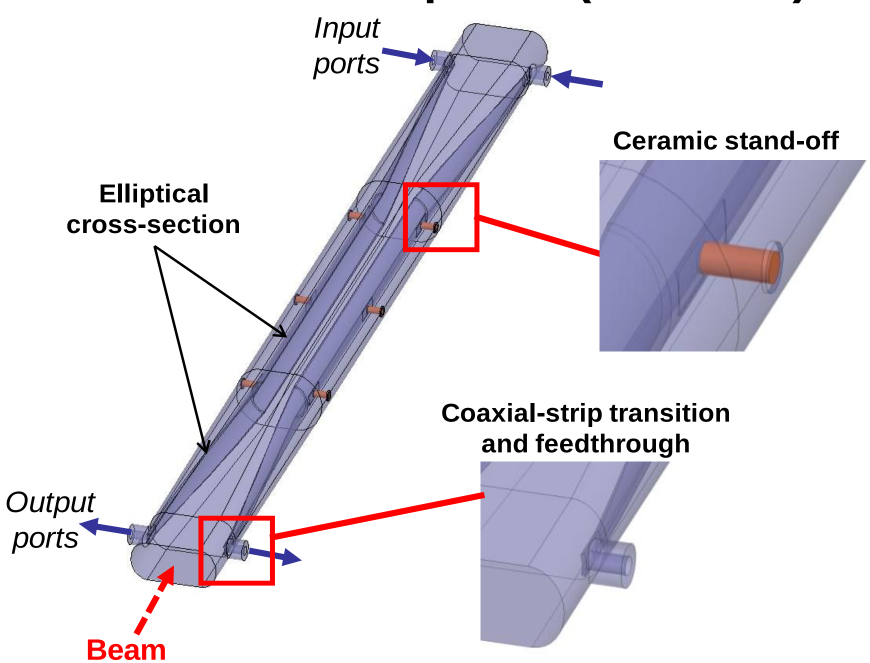


Extraction kickers CLIC damping rings

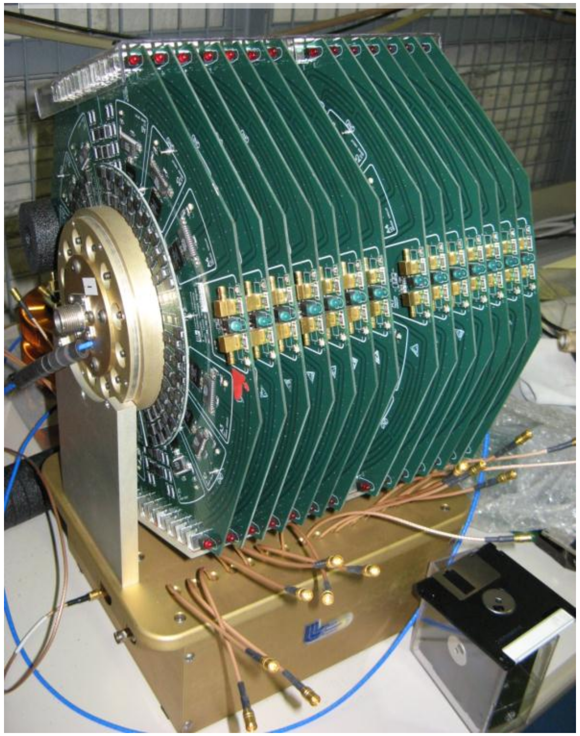
M.Barnes, J.Holma, CERN and C. Belver-Aguilar, A. Faus-Golfe IFIC

- Magnet: Striplines have been chosen for the CLIC DR & PDR extraction kickers
  - Low beam coupling impedance
  - Reasonable broadband impedance matching to the electrical circuit
- Pulsed power supply: **Inductive adder**

Striplines (DAPHNE)

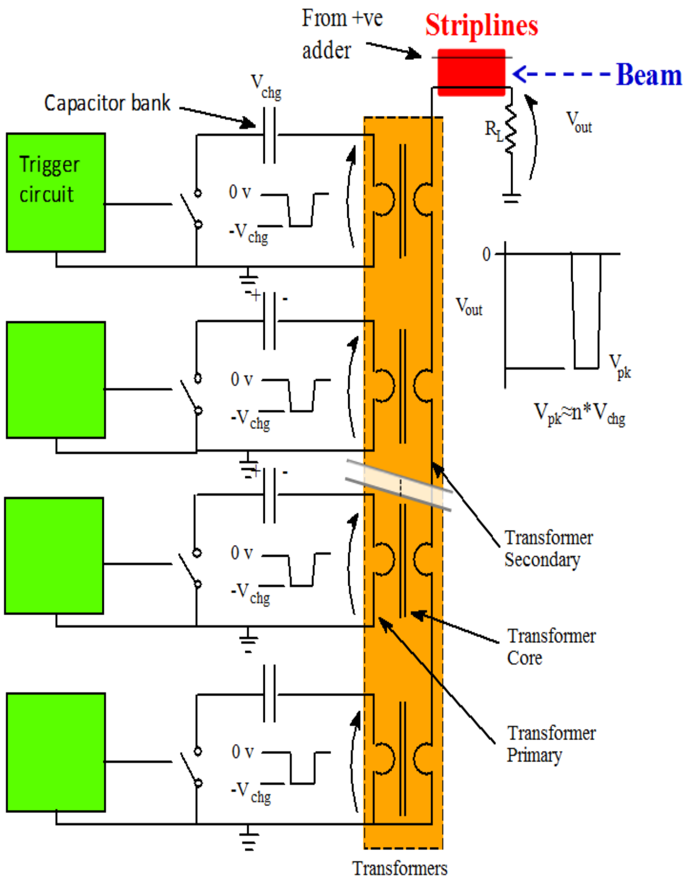


Inductive Adder



Inductive Adder

- Parallel circuits: Reduce the effect of single switch failures:
  - 20 levels which work individually on the primary side of the transformer, two levels redundant
  - 20 x 700 V max.
- Redundancy:
  - 12 switches per level, most likely high current MOSFETs
  - Two switches redundant
- Analogue modulation layer to reduce droop and ripple
  - IPOC system to detect failure of such system
- Fast rise and fall times
  - In case of timing problems: a fast rise and fall time will result in beam being swept faster across downstream materials and devices, minimizing potential damage.
  - Expected field rise-time of a few 100 ns.
- Weak points:
  - Striplines and cables from the inductive adder to the striplines, and coaxial connectors are potential weak points – a single failure of one of these components could result in only 50% deflection
  - Can have multiple systems but this will increase the length of the system = ring circumference. Presently two systems per damping ring.

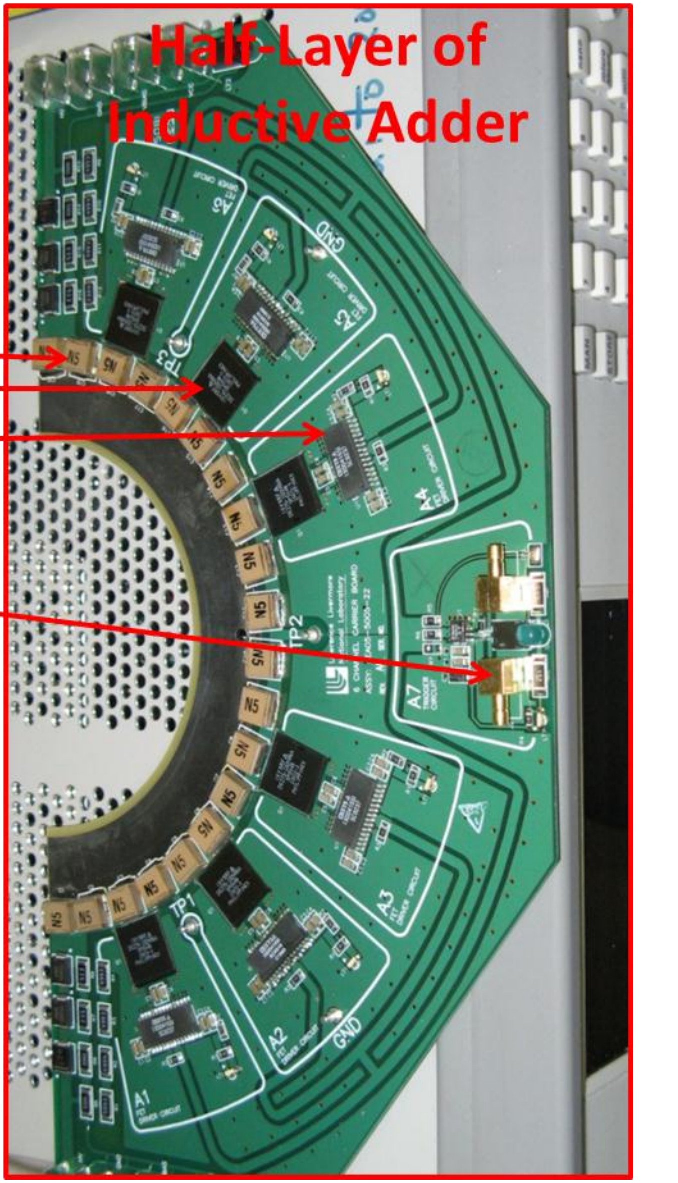


Inductive Adder based on Redundancy

The inductive adder primary windings consists of stacked layers of PCBs, each layer will include:

- ✓ multiple capacitors;
- ✓ multiple high power and fast solid-state switches;
- ✓ multiple driver circuits;
- ✓ multiple (4) receivers per layer – number could maybe be increased to improve redundancy.

Hence, although complex, there is redundancy built into the design of the Inductive Adder.



Conclusions

- Reliable beam extraction systems can be made
  - LHC beam dumping system as example
- The tools are
  - Redundancy
  - Surveillance
  - Post Operational Checks

- Certain failure modes can be mitigated by using absorbers
- Dependability studies are useful
  - SIL levels concerning safety can be attributed
  - Put all the different sub-systems together to get over-all number for safety and availability: complex wide
  - Trust relative results of safety and availability
- Reliability run to check assumptions in dependability analysis and discover infant weaknesses
- CLIC damping ring extraction kicker pulse generator based on redundancy and parallel systems