RISK ASSESSMENT IN THE NEXT INJECTORS COMPLEX

MACHINE PROTECTION WORKSHOP
8-6-2012

ANDREA APOLLONIO
TE-MPE-PE

Thanks to: J.B. Lallement, V. Vlachoudis, J. Humbert

OUTLINE

- Introduction
- Overview of the Injector Complex (Linac 4, TL, PSB)
- Reliability Analysis
- Test Case
- Risk assessment: considerations
- Website
- Conclusions and future developments

DEPENDABILITY...

...is the term used to describe many aspects of safety engineering; the most commonly known terms related to it are:

- Safety - linked to the consequences of system failure.
- Reliability - The continuity of system operation.
- Maintainability - The ability of a system to be modified and repaired.
- Availability - The readiness of a system for operation.
- Mean Time Between Failures (MTBF) or Failures in Time (FIT) - A measure of the statistically predicted time between failures.
- Failure Modes - The way in which a system fails.

FAILURE MODES: CLASSIFICATION

Failure modes can be classified according to the **cause of the failure**.

Most common examples:

- Powering failures (PC for magnets, Klystrons for accelerating structures,…)
- Mechanical failures (Movable devices, Vacuum valves,…)
- Electronic failures (Interlock Systems, User Systems,…)
- Detection failures (BLMs, Magnet Current Acquisition System,…)

RISK CLASSIFICATION [1]

The specification of the LHC Machine Protection System gives the dependability requirement in the form of a Safety Integrity Level (SIL). Four possible levels exist, from 1 to 4. SIL 4 is the most strenuous. These are defined by the IEC-61508 standard.

Frequency	per year	Catastrophic	Critical	Marginal	Negligible
Frequent	1	SIL4	SIL3	SIL3	SIL2
Probable	0.1	SIL3	SIL3	SIL3	SIL2
Occasional	0.01	SIL3	SIL3	SIL2	SIL1
Remote	0.001	SIL3	SIL2	SIL2	SIL1
Improbable	0.0001	SIL3	SIL2	SIL1	SIL1
Not Credible	0.00001	SIL2	SIL1	SIL1	SIL1
cost [Millions of CHF]		>50	1-50	0.1-1	0-0.1
downtime [days]		>180	20-180	3-20	0-3

B. Todd

A single 10 hour operation of the LHC is referred to as a mission, some 400 missions per year are expected, a SIL 3 Machine Protection System has less than a 1% chance of failure in the 8000 missions that are expected in the 20 year lifetime of the LHC.

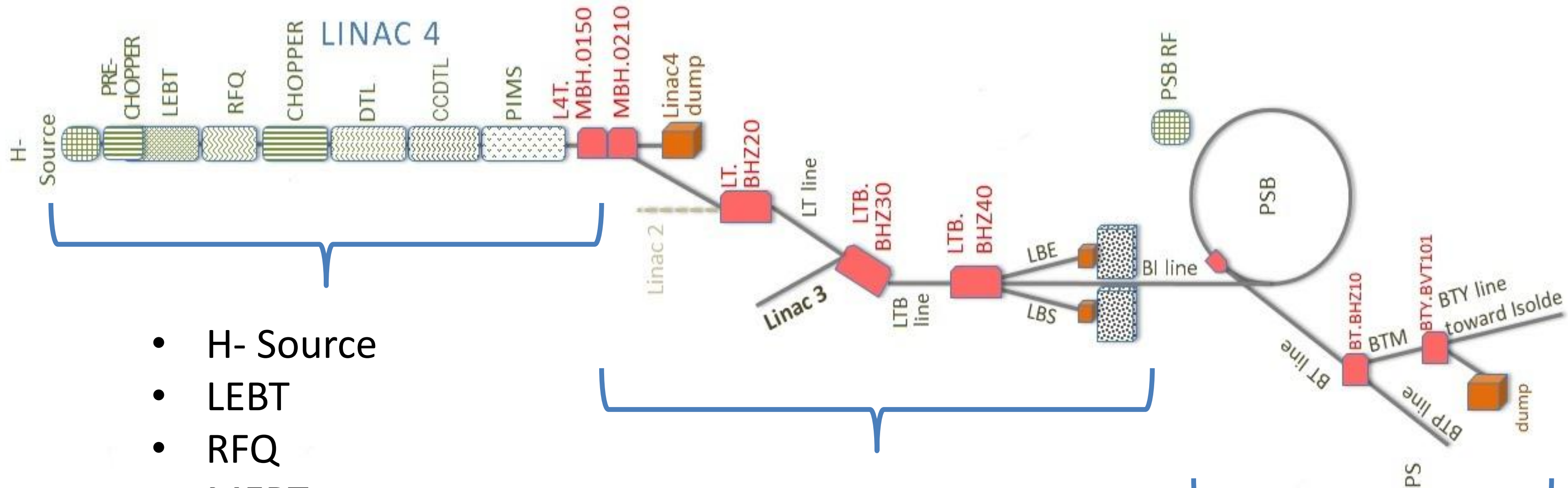
NEW INJECTOR COMPLEX AT CERN: LINAC4-TL-PSB

Linac 4 is the new linear accelerator that will replace Linac 2 for injection in the PSB

LINAC 4 MAIN PARAMETERS	
Ion species	H-
Output energy	160 MeV
Bunch frequency	352.2 MHz
Repetition Rate	1.1 Hz
Beam pulse length	400 µs
Source current	80mA
RFQ output current	70mA
Linac current	40mA

The beam coming from Linac 4 will join the existing Linac 2 Transfer Line through a new dedicated TL section (L4T) before injection in the PS Booster.

NEW INJECTOR COMPLEX AT CERN: LINAC4-TL-PSB



- H- Source
- LEBT
- RFQ
- MEBT
- Accelerating Structures (DTL, CCDTL, PIMS)
- Vacuum

- Bending Magnets (H+V)
- Quadrupoles
- Steerers
- Debunching Cavity
- Vacuum

- Stripping Foil
- Kickers (Inj+Extr)
- Septa
- Bending Magnets
- Quadrupoles
- Steerers
- Accelerating cavities
- Vacuum

RELIABILITY ANALYSIS

Approach:

- Study the system under investigation (every component!)
- Derive possible Failures and Failure Modes
- Identify Failure 'Categories' (e.g. cavities, quadrupoles, etc.)
- Consider several Test Cases for each category
- Identify the Worst Cases for each category
- Evaluate possible damage in these scenarios (FLUKA, particle physics MonteCarlo simulation package) in case of Protection Systems working or not

Difficulties:

1. Retrieve and collect informations (contact experts, components still under design,…)
2. Identify the Failure Categories and evaluate the impact of failures in circular accelerators
3. Cover all possible failure scenarios with 'adequate' accuracy

FAILURES: TEST CASES

Test cases which have been studied:

- Quadrupoles
- Cavities
- Chopper – Quadrupole
- Bending magnets

Approach:

1. Simulate the failure of a component in a Tracking Code (*TraceWin*, CEA, *Travel*, CERN)

2. Quantify and localize the losses (percentage of particles and power)

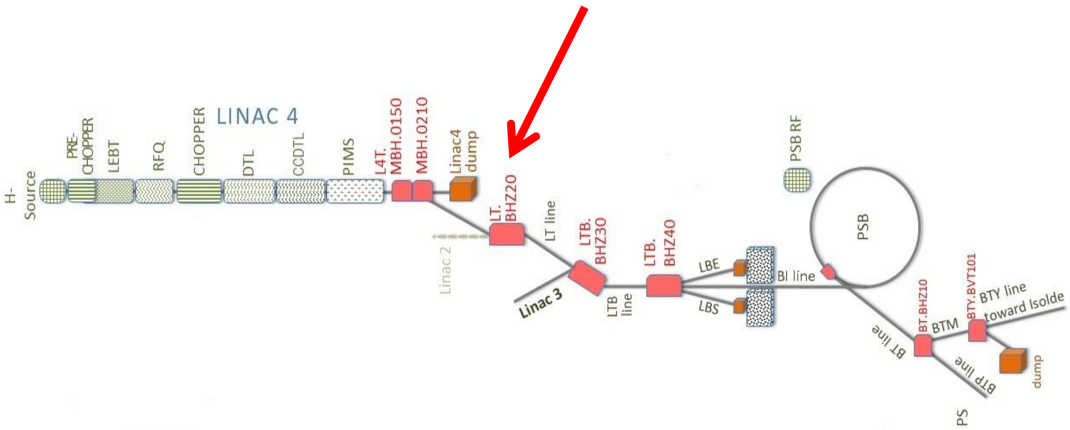
3. Run simulations (FLUKA) in the worst cases to verify the possibility of damage of the equipment

Note 1: Only single failures have been considered in these first studies

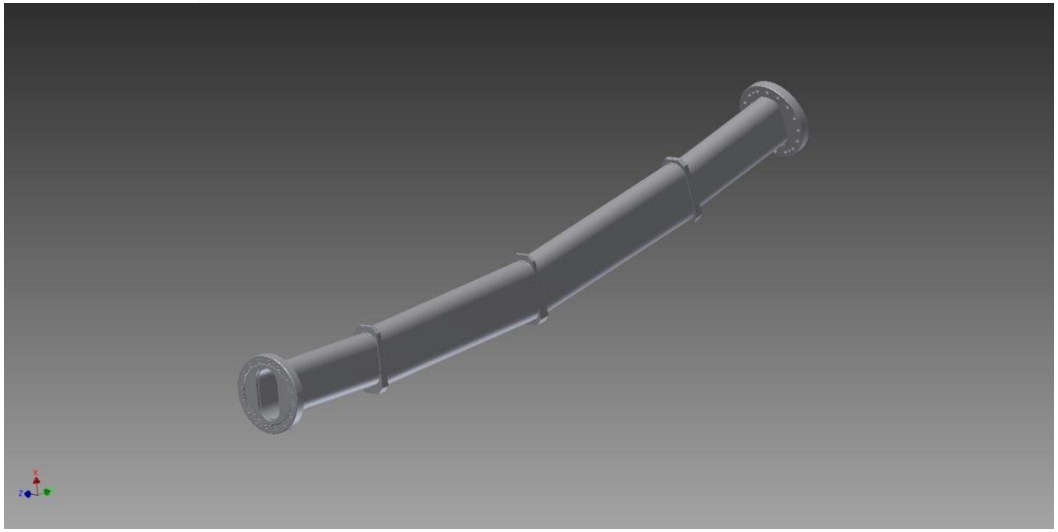
Note 2: tracking codes are not made to simulate failures therefore expedients are used. The results have then to be interpreted as estimates of the losses for the given failure cases.

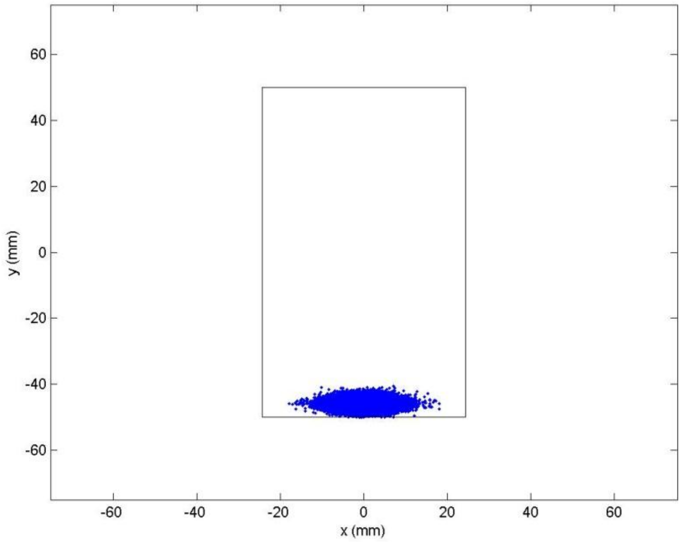
WORST CASE: MBV FAILURE

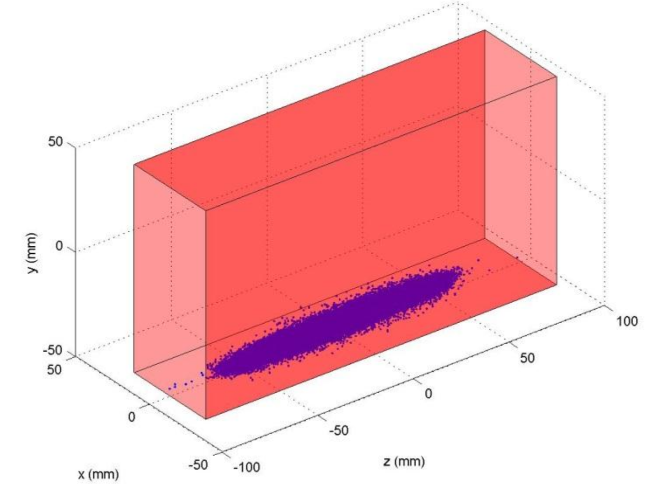
First Vertical Bending Magnet Failure in the TL



J. Humbert

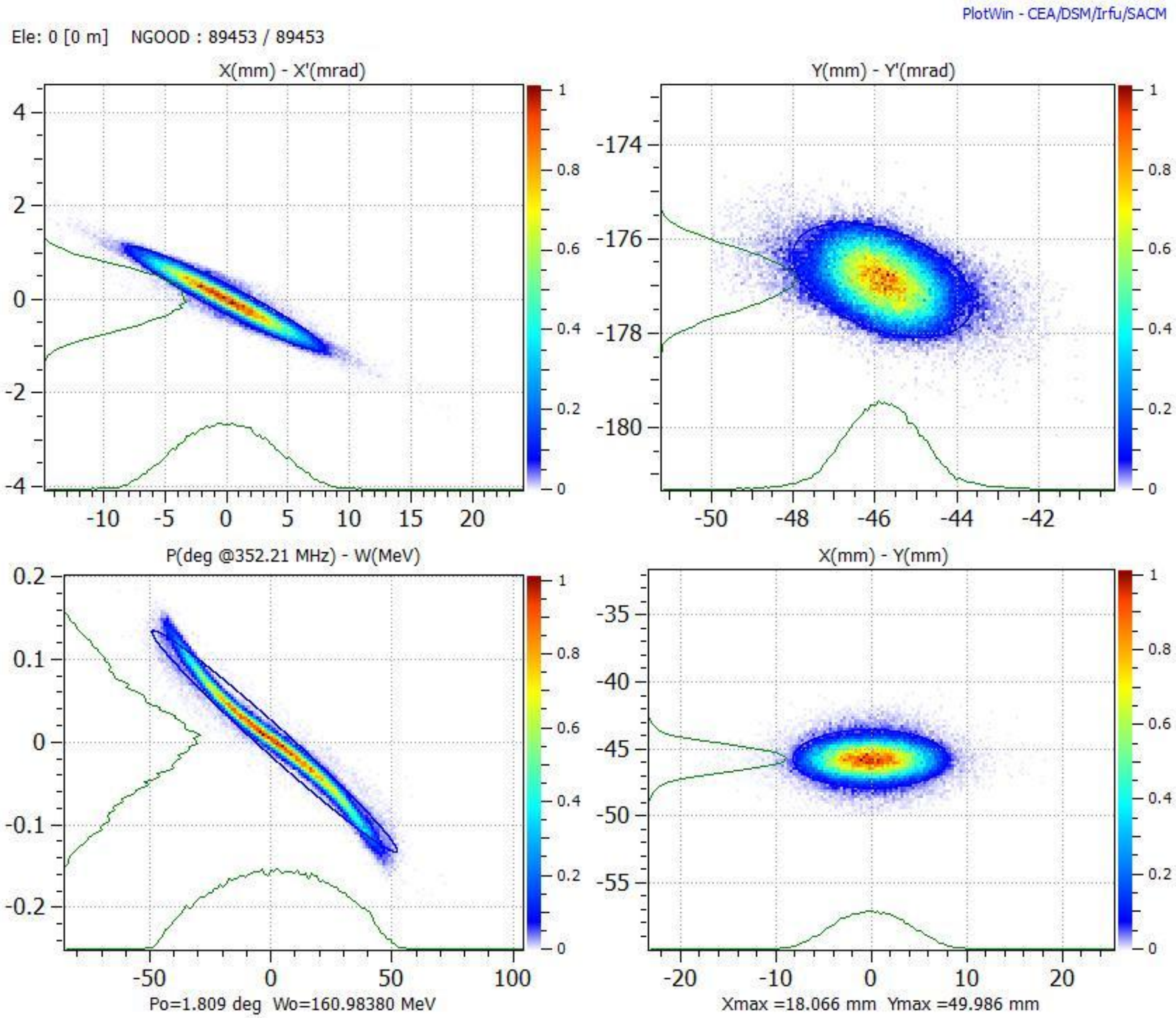






WORST CASE: BEAM FILE

J. B. Lallement



BEAM DISTRIBUTION IN THE WORST CASE FROM THE BEAM FILE

ENERGY: 160 MeV

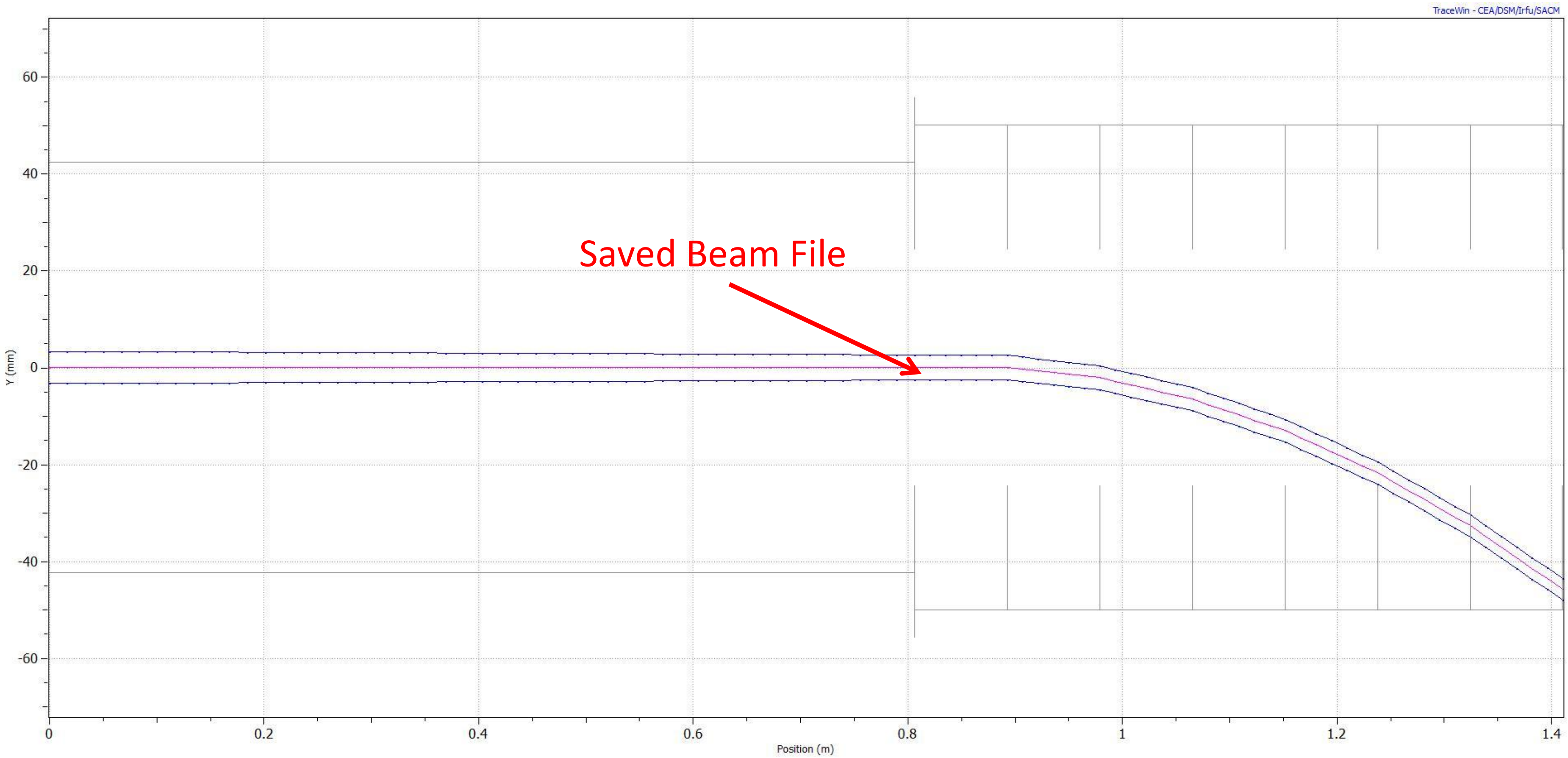
RMS SIZE (X*Y):
3.6194 mm * 0.9781 mm

POSITION: 120.8m

All beam lost after 60 cm in the MBV with a grazing angle of about 200 mrad

WORST CASE: MBV FAILURE

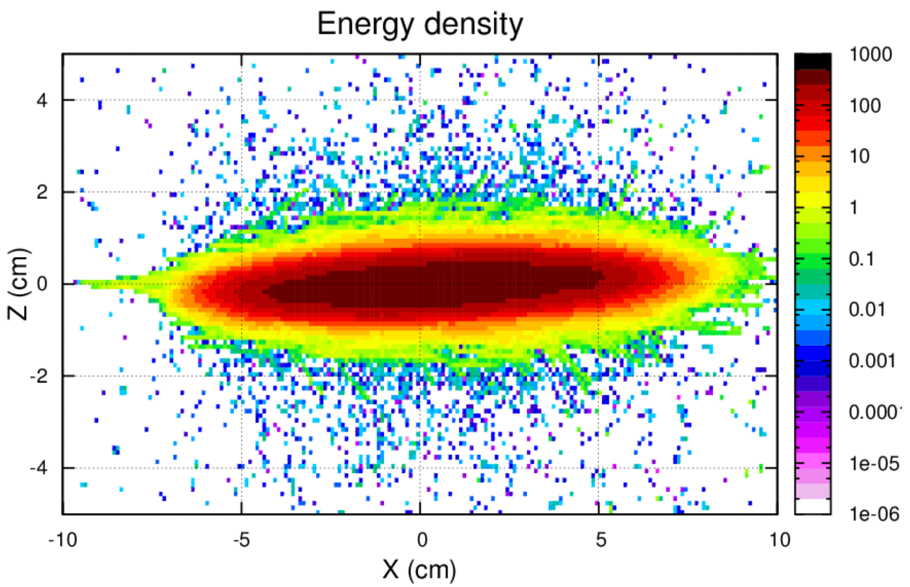
VERTICAL STEP OFF: Losses in MBV.1250 → Failure Simulation Expedient

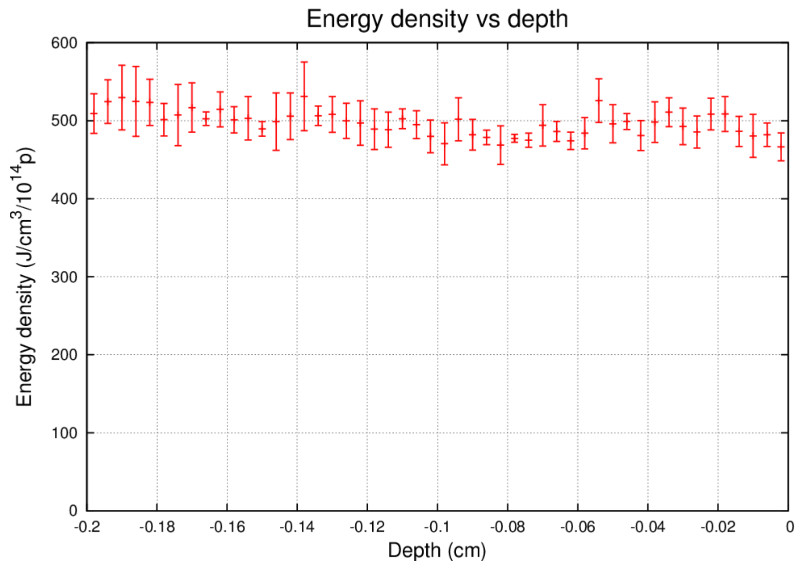


J. B. Lallement

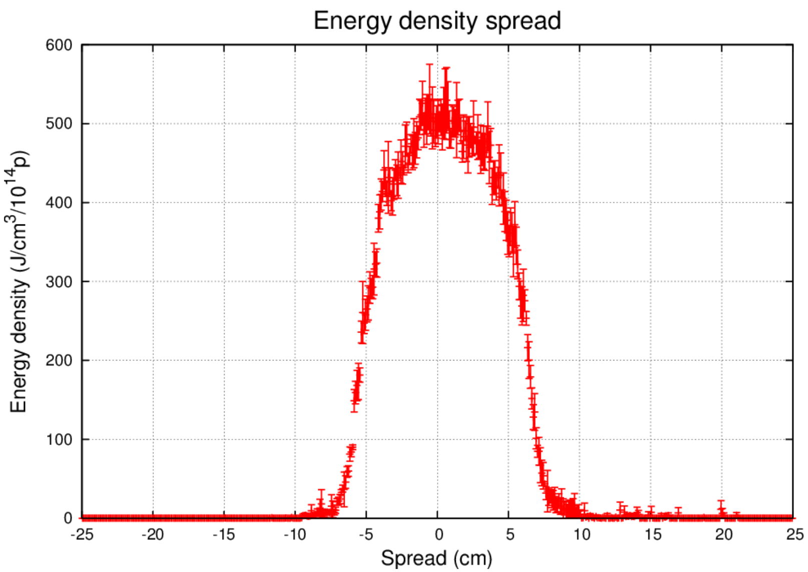
All beam lost after 60 cm from the beginning of the MBV with a grazing angle of 200 mrad (the code crashes!)

WORST CASE: FLUKA ANALYSIS





V. Vlachoudis



- Total energy: 160MeV *10^14p = 2.56 kJ 70% (~1.8 kJ) of the energy escapes the 2mm beam pipe downstream.
- Peak energy deposition ~530 J/cm3: adiabatic temperature rise of about 130 K.
- Critical temperature for 316LN SS: 833 °C
- Melting point for 316LN SS: 1390 °C
- Next step will be to verify the impact of the 70% of the energy on the magnet around the pipe

RISK ASSESSMENT IN LINAC4

A definitive assessment of the risk in Linac4 (SIL) still needs to be defined:

- Further studies and simulations for worst cases are ongoing
- The failure catalogue is being compiled as the knowledge on the system increases and the design is updated

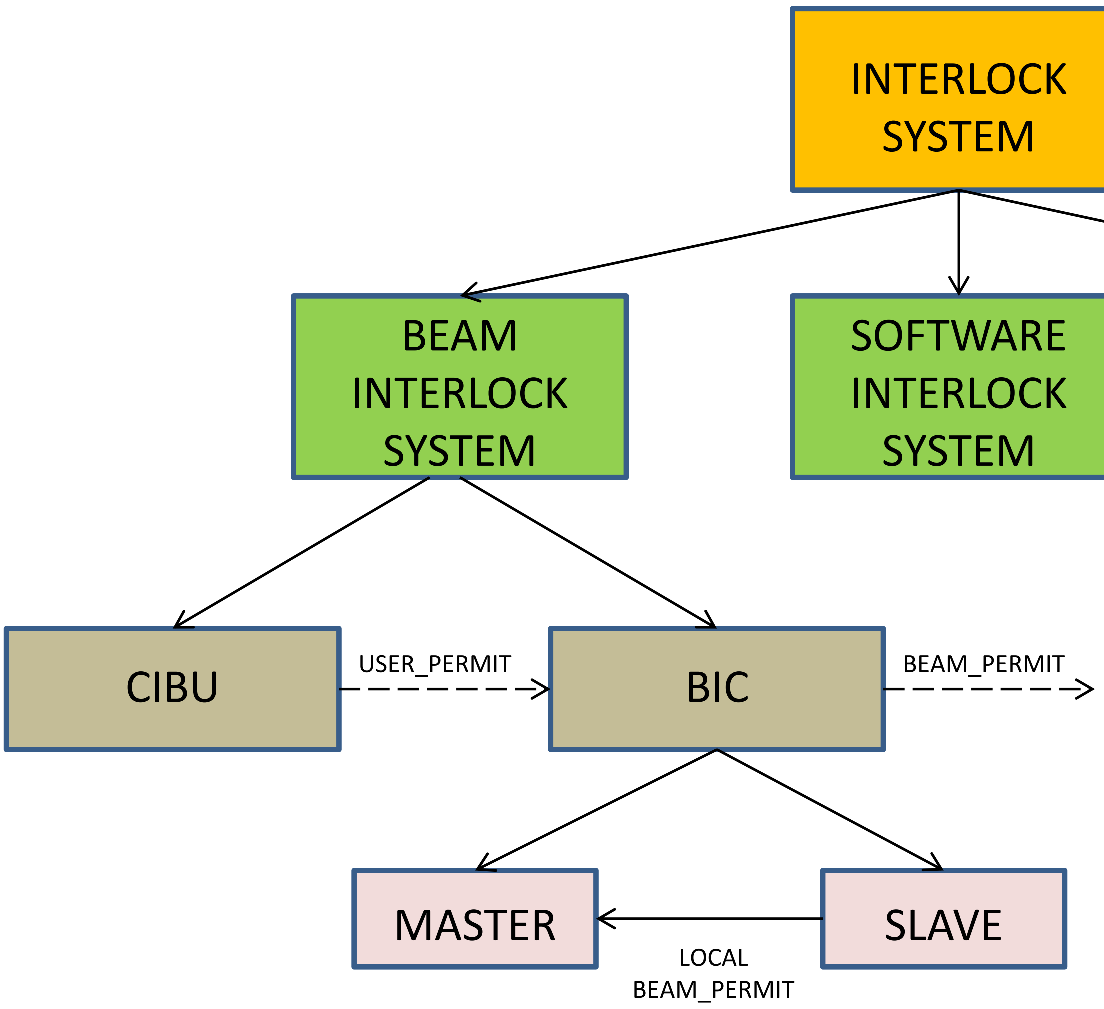
The objective is to obtain a risk matrix similar to the one for the LHC which will allow the determination of the SIL for Linac4.

Estimates for SIL are strictly related to the project, so risk assessment has to be carried on depending on many factors (project budget, dependability requirements, availability of spare parts,…).

One preliminary comment: the SIL level for Linac 4 will be mainly determined by the requirements on availability (more than cost).

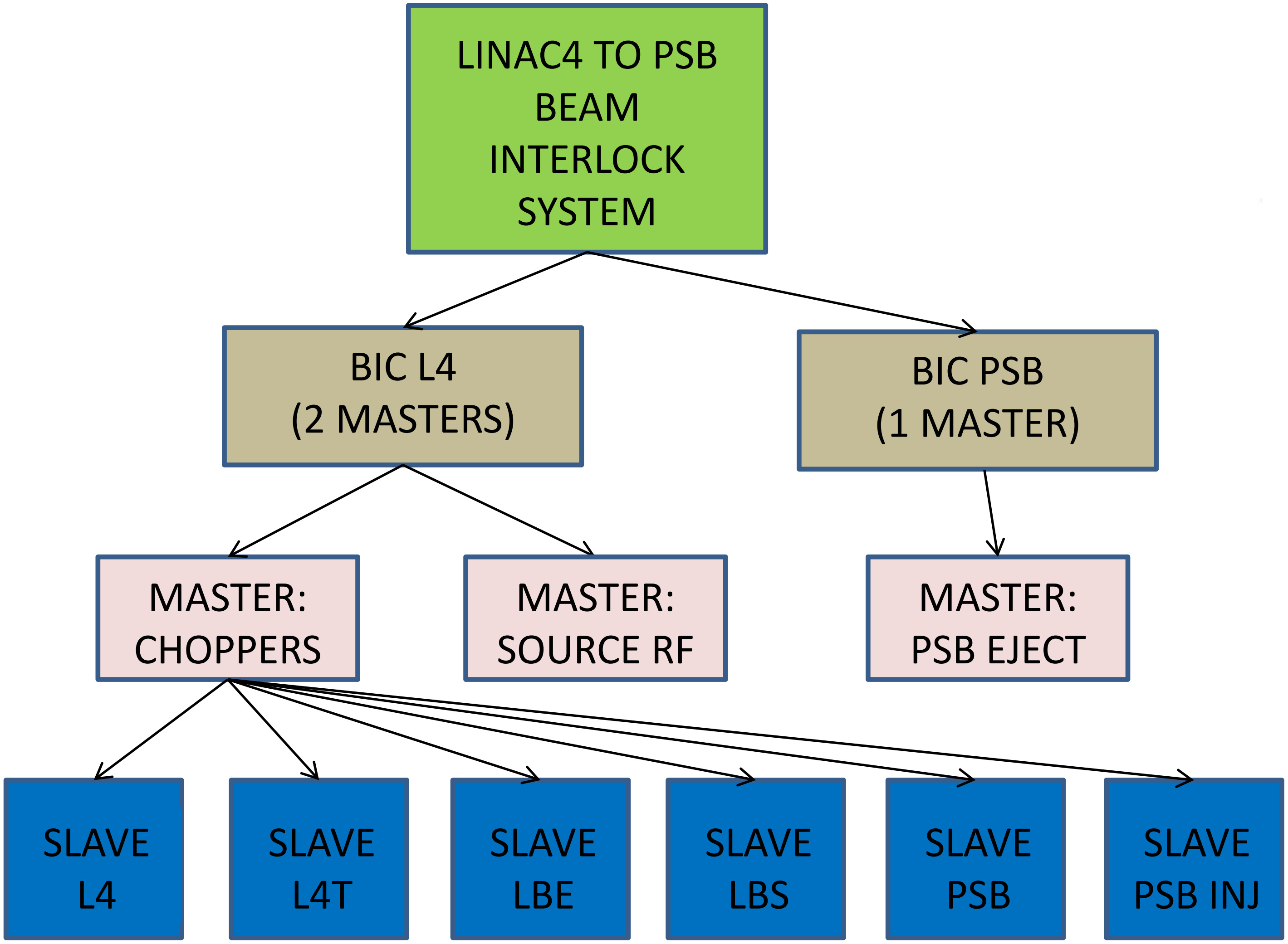
Machine Protection Systems are being designed according to what already done for the LHC (SIL3), so big margins are expected in this case.

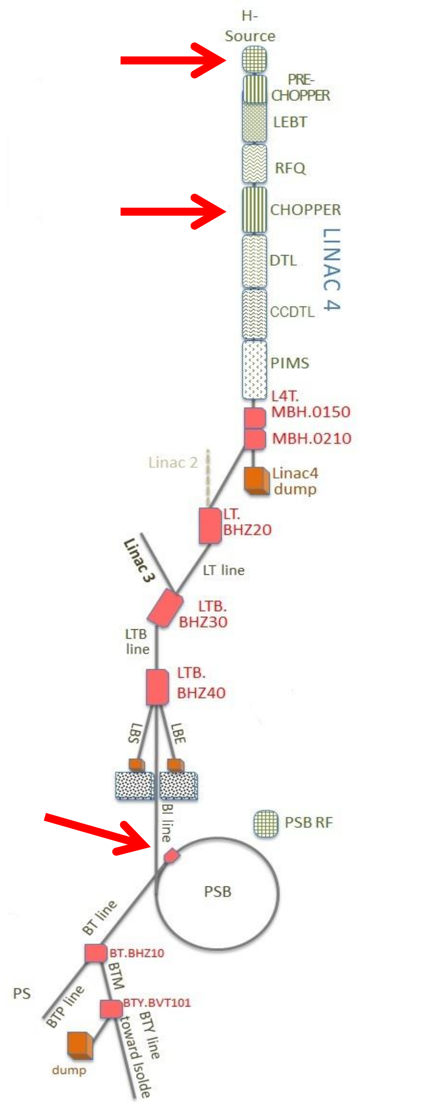
INTERLOCK SYSTEM: GENERAL OVERVIEW



- BIS: fast reaction times or minimization of machine activation needed
- SIS: monitor slow-changing parameters or for complex logic implementation
- EC: Optimization (Users requests,…)

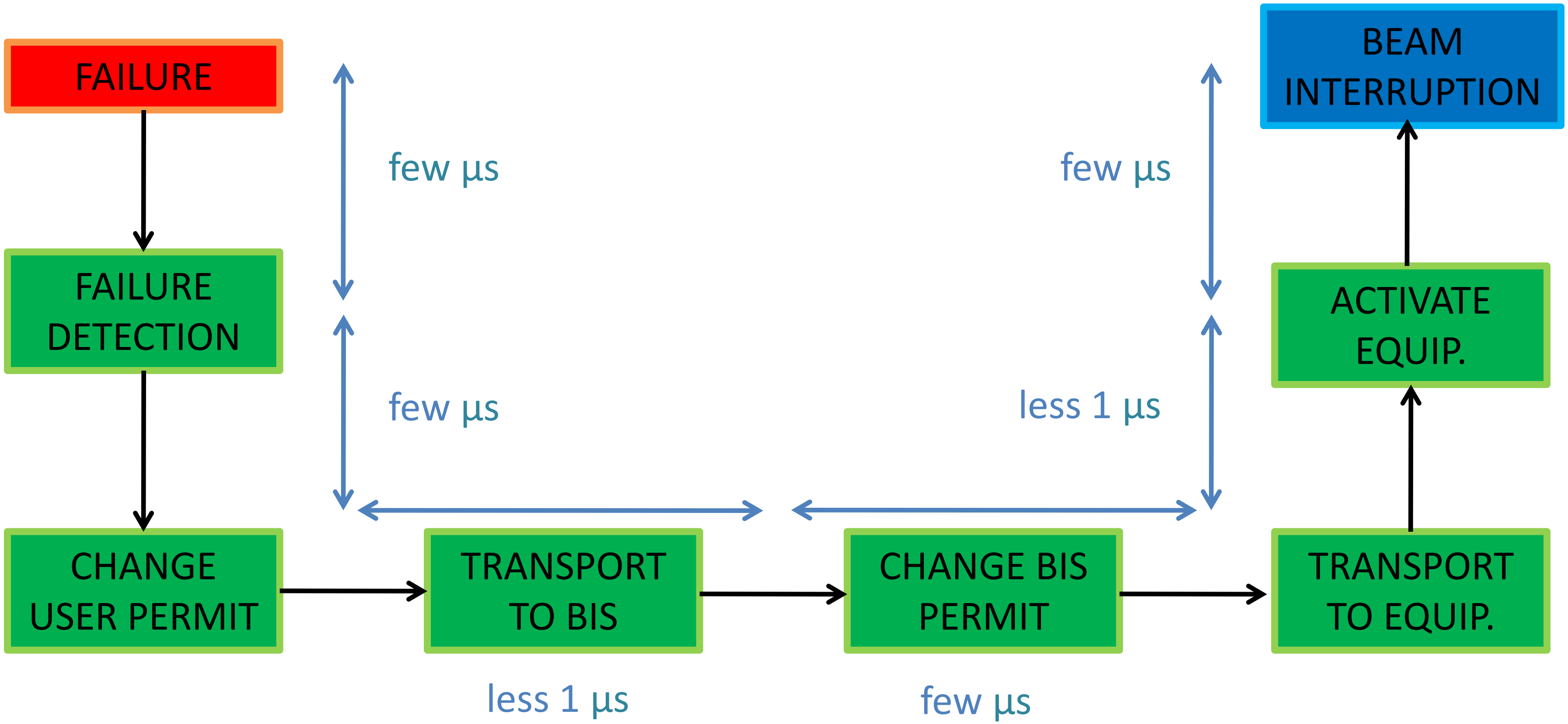
LINAC4 TO PSB BEAM INTERLOCK SYSTEM [2]





The BIS is able to react within the same pulse as the failure is detected!

MACHINE PROTECTION: TIMING



Total time: 10-20 µs Pulse length: 400 µs

RETRIEVING AND COLLECTING INFORMATIONS: WEBSITE (1/2)

A dedicated website has been developed to:

- Keep trace of all the studies performed
- Collect the big amount of informations retrieved
- Give easy access to the reference documents

https://espace.cern.ch/linac4-and-machine-protection/SitePages/Home.aspx

Why a website?

- Easy to consult
- Interactive
- Easy to update and maintain (Linac4 is still under development)
- All references to documents immediately available

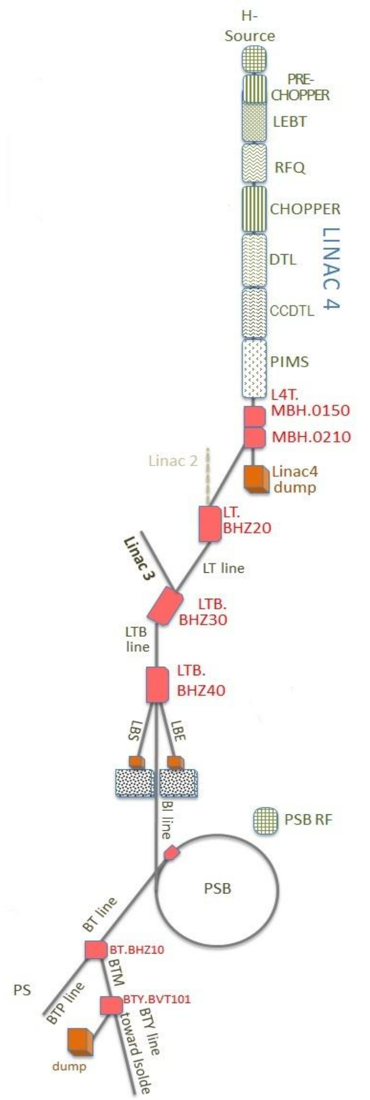
RETRIEVING AND COLLECTING INFORMATIONS: WEBSITE (2/2)

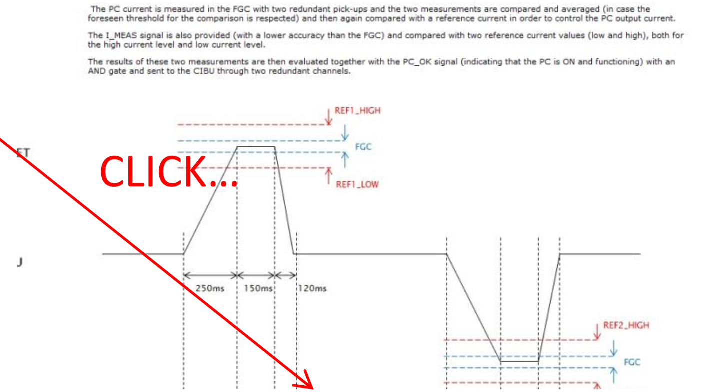
HOME:
- Introduction
- Acronyms
- Glossary

LINAC4 to PSB:
- Components description
- Images

MACHINE PROTECTION:
- Failure catalogue
- Components and interlocks
- Failure simulations

OPERATION MODE	BEAM CONDITION	EQUIPMENT	
		COMPONENT	FAILURE
2) MBV.1250 (WORST CASE)			Powering Fail





CLICK...

RFQ (Radio Frequency Quadrupole)
Purpose: accelerate, capture and bunch low enery particles up to 3MeV.
Function: The resonating mode of the cavity is a focusing mode; alternating the voltage on the lectrodes poduces a field in the direction of propagation of the beam which bunches and accelerates the beam. The RFQ is the only linear accelarator structure that can accept a low energy continuous beam of particles.
Input: Powering, Voltage
Output: applied electro-magnetic field
Location:
Components:
Failures: Powering Failure

ASURES | VENTION | T./COMP | - | L4T.MBV | CES |)) | lost in

CONCLUSIONS

Injector Complex Analysis:

- Elements study
- Failure Modes
- Optics Simulations + FLUKA Simulations for worst cases
- Risk Assessment

Further studies on worst case scenarios are necessary to assess the Linac4 SIL:

- Study of the impact of particles escaping the beam pipe in case of the MBV failure (no protection)
- Same study in case Protection Systems are in place (only a portion of the particles will be lost in this case)

From this preliminary analysis the currently foreseen Protection Systems seem to guarantee safety margins for machine operation: design and experience gained from the LHC have been exploites.

A website to collect and share informations on the project seems the most efficient way for this purpose.

FUTURE DEVELOPMENTS

Can this approach be easily extended to other machines?

The next injector complex has been an ideal test bench for the developed approach:

- It is a relatively 'small' machine → failure cases can be handled more easily
- It's still under design for many aspects → collected informations have to be continuously updated

Extend such studies to bigger machines is a challenge, considering all the possible failure cases. A very systematic approach is needed, as well as the collaboration of several experts for the different related studies.

Next steps:

- Conclude the studies related to Linac 4
- CLIC study
- LHC study (already started, S. Wagner)

THANK YOU FOR YOUR ATTENTION

References:

[1] "A Beam Interlock System for CERN High Energy Accelerators", B.Todd, CERN, 2006.

[2] "Beam Interlock Specifications for Linac4, Transfer Lines and PS Booster with Linac4", B.Mikulec, J.L.S.Alvarez, B.Puccio, CERN, 2011.

ADDITIONAL SLIDES

LINAC4: NOMINAL PARAMETERS

Linac 4 is the new linear accelerator that will replace Linac 2 for injection in the PSB

LINAC 4 PARAMETERS	
Ion species	H-
Output energy	160 MeV
Bunch frequency	352.2 MHz
Max. rep.-rate	2 Hz
Beam pulse length	400 us
Max. beam duty cycle	0.08%
Chopper beam-on factor	62%
Chopping scheme	222/133 full/empty buckets
Source current	80mA
RFQ output current	70mA
Linac current	40mA
Average current	0.032mA
Beam power	5.1kW
No. particles per pulse	10^14
No. particles per bunch	1.14*10^9
Source transverse emittance	0.2 pi mm*mrad
Linac transverse emittance	0.4 pi mm*mrad

Operational repetition rate will be 1.1 Hz

FAILURE MODES: EXAMPLE FOR THE LHC [1]

Failure modes are classified by **beam loss time constants**. The fastest of these failures relies on passive protection through **collimation**, the others must be caught by the **Machine Protection System**.

1. Ultra-Fast Losses could occur during a beam injection or extraction process. In these cases the beam is completely lost within 100 μs.

→ Passive Protection (collimators)

2. Fast/Very Fast Losses are failures that drive the beam unstable within around ten turns of the machine. A typical cause could be a magnet quench.

→ Beam Loss Monitors

3. Slow Losses take many turns of the machine to develop, having beam loss timescales of at many milliseconds.

→ Many elements from the Machine Protection Systems

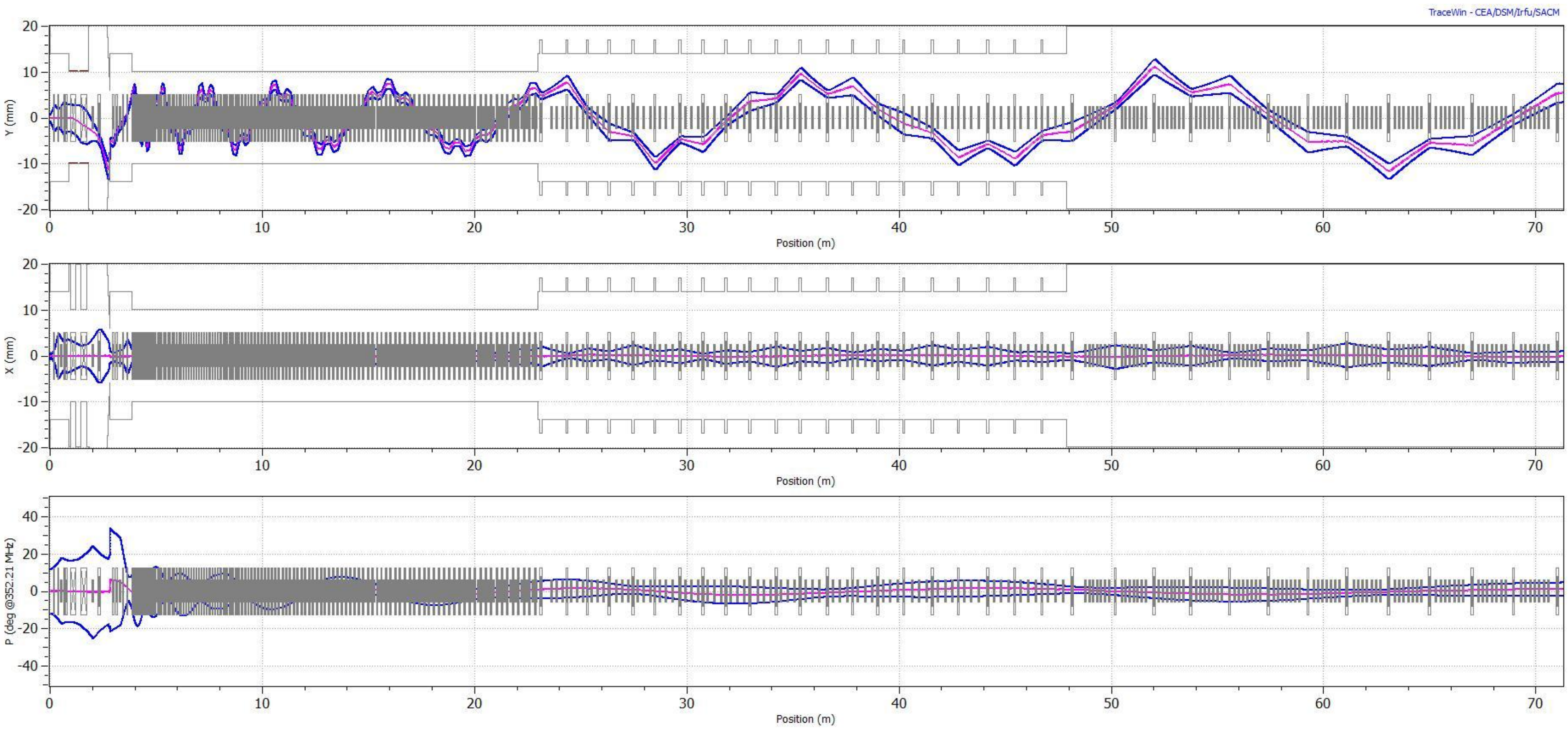
FAILURES: EXAMPLE FOR THE LHC

System Name	Approximate Fastest Response Time	Cause of Interlock
Beam Loss Monitor System	40µs	beam losses outside of tolerances
Experiment Detectors	40µs	beam loss in an experimental area outside of tolerances
Beam Lifetime	60 - 180µs	lifetime of the beam is outside of tolerances
Fast Magnet Current-Change Monitor	60µs	rate of change of critical magnet field is outside tolerances
Transverse Feedback	60 - 120µs	bunch feedback shows bunches outside of tolerances
Powering Interlock Controllers	100µs - 1ms	failure of superconducting magnet power converter
Vacuum System	1 - 10ms	vacuum outside of tolerances, or valve not in safe position
Experiment Movable Devices	1 - 10ms	experiment movable devices are not in safe position
Collimation System	1 - 10ms	collimator jaws are not in safe position
Safe LHC Parameters	1ms 1000 - 10000ms	beam presence flag is inconsistent other machine safety parameter is inconsistent
Beam Television	1 - 10ms	invasive beam diagnostic equipment is not in safe position
Experiment Magnets	10 - 100ms	magnet failure in an experimental area
Warm Magnet Interlock Controllers	10 - 100ms	failure of normal conducting magnet or power converter
Access System	100ms	machine access violation endangering personnel
CERN Control Room	1 - 10s	operator beam dump request
LHC Beam Dumping System	60 - 180µs	LHC Beam Dumping System is not ready to operate

B. Todd

LINAC4: SIMULATIONS OF FAILURES (1/5)

One component failing in each simulation (chopper, EMQs, cavities):



J.B. Lallement

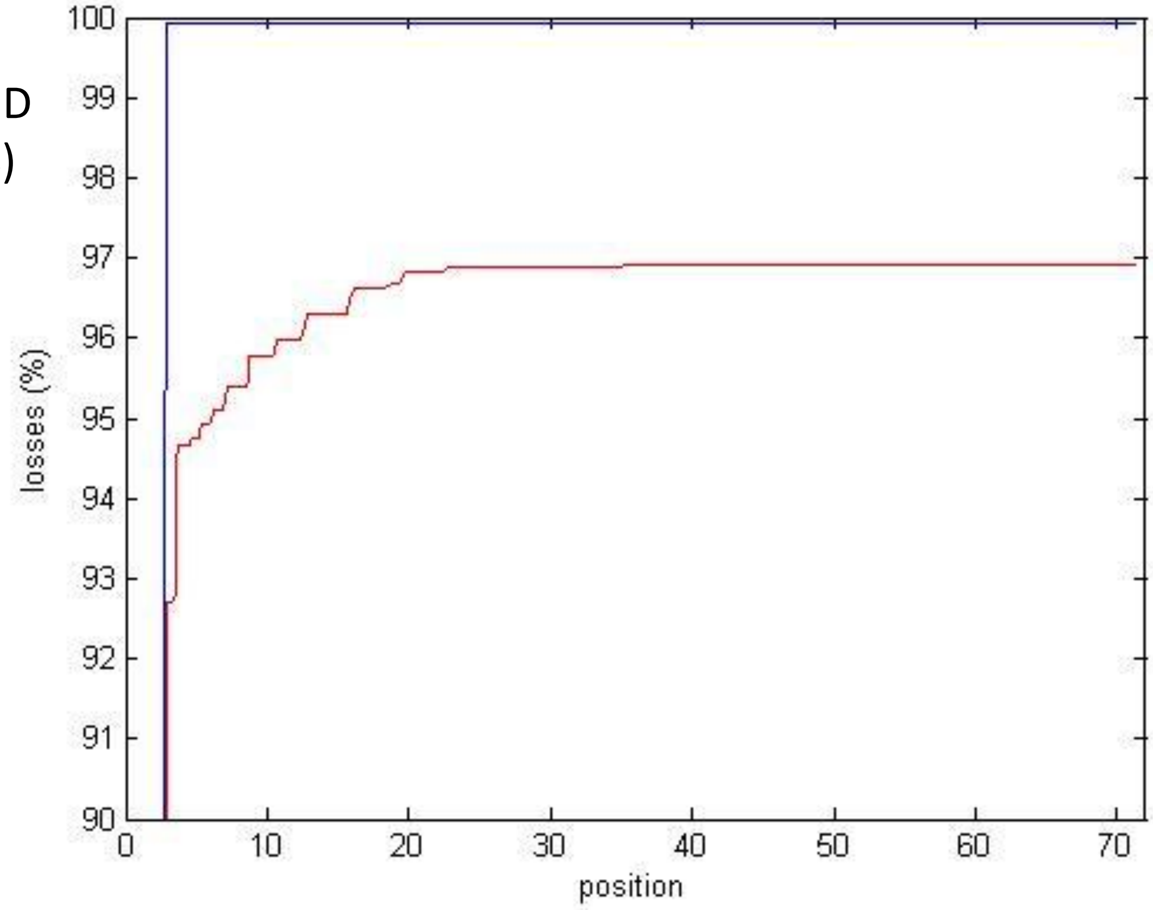
Example: CHOPPER ON + DEFOCUSING QUADRUPOLE (ON/OFF)

NOTE: for cavity failures it is assumed that the only effect on the beam is caused by the absence of the accelerating field.

LINAC4: SIMULATIONS OF FAILURES (2/5)

Example: CHOPPER ON + DEFOCUSING QUADRUPOLE (ON/OFF)

INTEGRATED LOSSES (%)



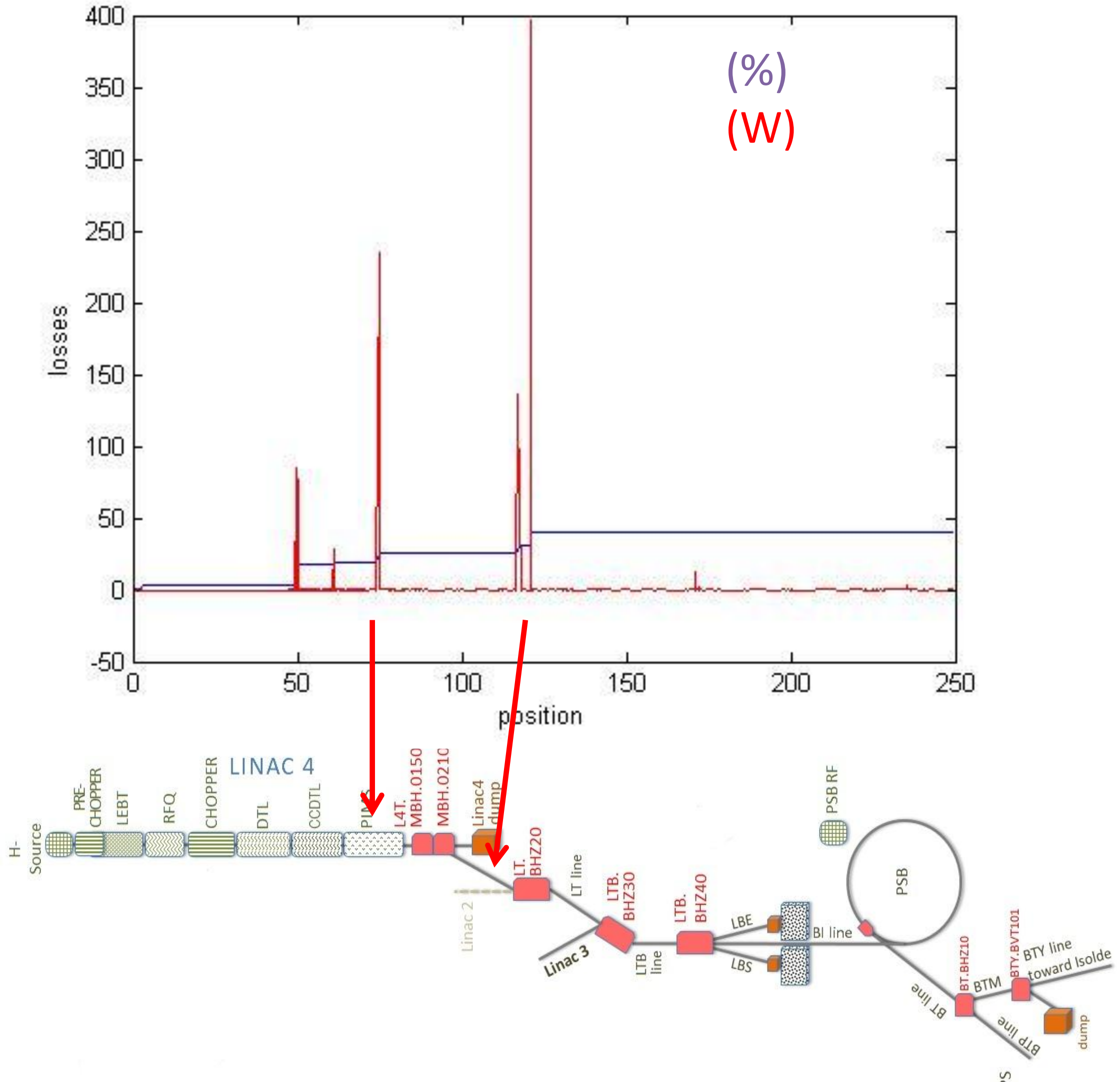
QD ON
QD OFF

MEBT 0m
DTL 3.9m
CCDTL 25.5m
PIMS 48.8m
END PIMS 70.6m

Losses propagate also in the transfer line if the QD is OFF

LINAC4: SIMULATIONS OF FAILURES (3/5)

Example: LAST CCDTL EMQ OFF



MEBT 0m
DTL 3.9m
CCDTL 25.5m
PIMS 48.8m
END PIMS 70.6m

1st BENDING M 77.7m
2nd BENDING M 81.8m
3rd BENDING M 85.9m

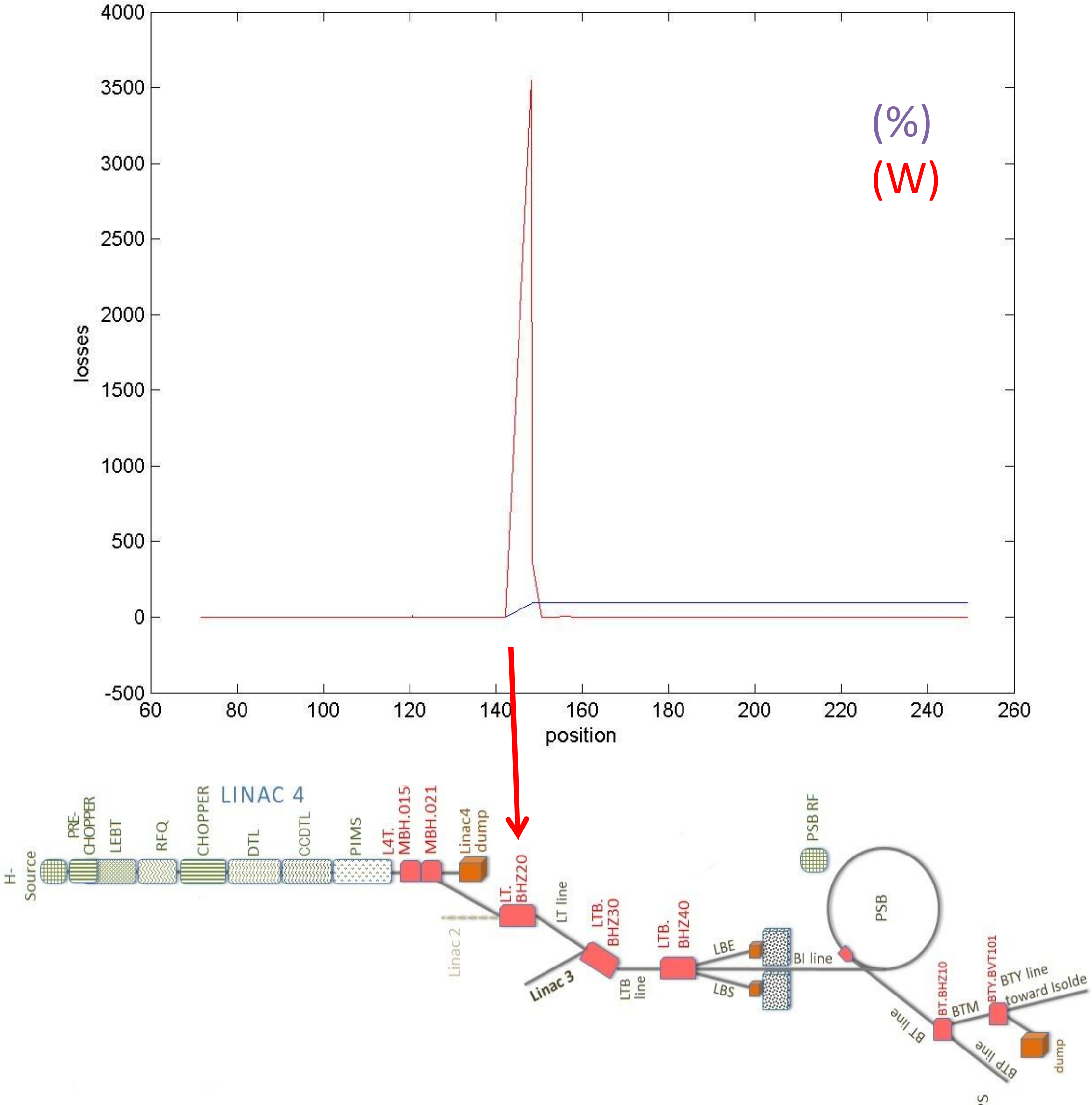
VERICAL STEP:
1st BENDING M 120.8m
2nd BENDING M 130.8m

BHZ20 141.1m
BHZ30 171.1m
BHZ40 237.5m

30% of the beam lost in the PIMS, 20% in BVT.1250

LINAC4: SIMULATIONS OF FAILURES (4/5)

Example: LAST PIMS MODULE OFF



MEBT 0m
DTL 3.9m
CCDTL 25.5m
PIMS 48.8m
END PIMS 70.6m

1st BENDING M 77.7m
2nd BENDING M 81.8m
3rd BENDING M 85.9m

VERICAL STEP:
1st BENDING M 120.8m
2nd BENDING M 130.8m

BHZ20 141.1m
BHZ30 171.1m
BHZ40 237.5m

100% Beam lost in BHZ20