Machine Protection system in CLIC

M.Jonker 2009 06 03
CLIC Beam Instrumentation Workshop

With many slides borrowed from presentation ACE 2009 05 27:

Machine Protection and Operational Aspects
or what can be done before the CDR in 2010

Outline

- The issues
  - Operational aspects
    - Availability
    - Machine commissioning
    - Safety
  - Machine protection
- Working group, mandate & participation
- Priorities, what can and must be done before the CDR in 2010

Operational aspects

Concerns related to the operational aspects of the machine:

- Construction staging and energy staging
- Machine commissioning
  - Safety elements and location of beam stoppers for partial operation
  - Required beams and procedures
- Radiation issues (Personnel: maintenance, electronics: MTBF)
- Safety
- Availability

  (a machine which has a low expected availability, will not be very attractive to the physics community)

CLIC Machine Protection

An extensive topic:

- Many different accelerator component types (linacs, combiner rings, transport lines, decelerator, damping rings, main linac, beam delivery and diagnostics system, post collision lines).
- Many different beams with different characteristics (energy intensity, brilliance)
- Impressive beam power and energy density

CLIC Machine Protection

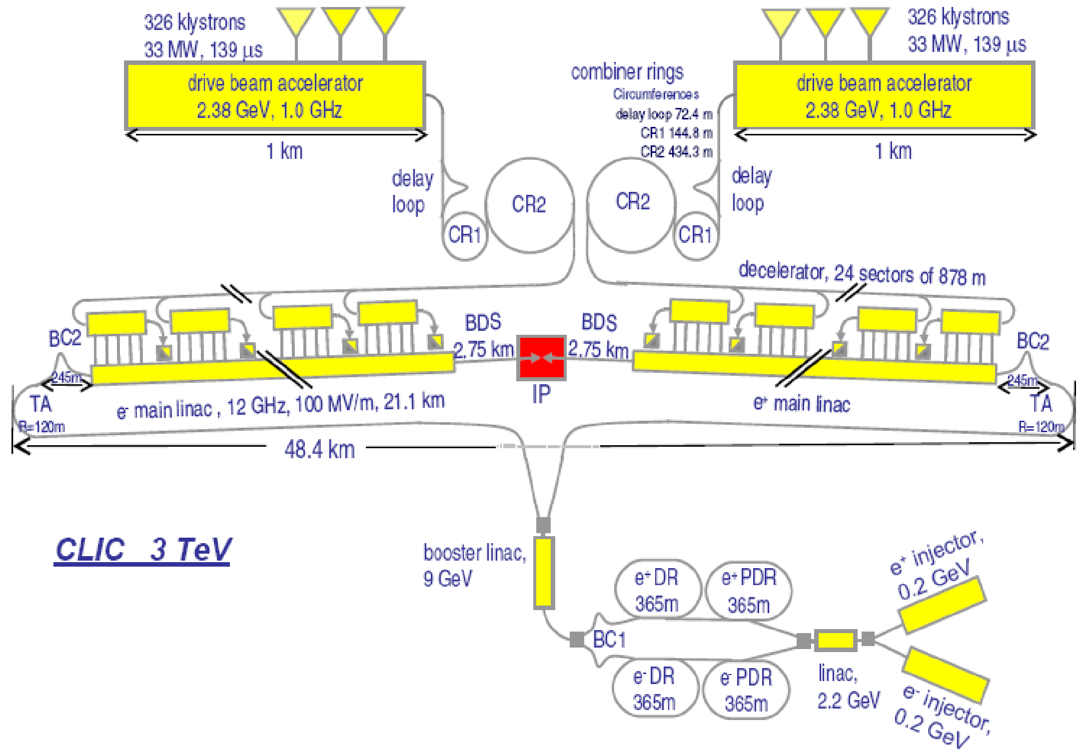
Main Beam

- 2 injectors $e^+ e^-$
- 1 Linac, 2.2 GeV, 234 m, 2 GHz
- 2 Pre-damping rings 365 M

  NB: Synchrotron power from damping rings: 3.857 Mev turn^{-1} x 204 nC /1.2 ms turn^{-1} = 656 KW, (13 KJ pulse^{-1}).
- 2 Damping rings 365 M (same as PDR)
- 2 Bunch compressors (4 GHz RF)
- 1 Booster linac, 6.6 GeV, 561m
- 2 Transport lines (24.2 km)
- 2 Turn around loops
- 2 Bunch compressors (245 m, 12 GHz RF)
- 2 Main linacs (24.2 km 12 GHz RF from Pets)
- 2 Beam delivery (2.75 km diagnostics, collimation, final focus)
- 2 Post collision lines (beam dumps)

Drive Beam

- 2 Drive beam linac (2x326 klystrons, 139 us)
- 2 Delay loops (2 RF kickers)
- 2 Combiner rings 144.8 m (2 RF kickers)
- 2 Combiner rings 434 m (2 RF kickers)
- 2 Transport line with 24 extraction kickers
- 2x24 Decelerator sectors, each n PETS structures and dump.



CLIC beams

Drive Beam

- Uncombined beam 1 out of 24 pulses with reduced pulse length (~ 50 ns): just to reduce the intensity to a safe level.
- …
- Full combined beam

Main Beam

- Reduced intensity /enlarged emmittance
- …
- Nominal beam

Beams and beam power

CLIC drive beam (2.4 GeV)	bunch	train	pulse	second
Bunches	1	2922	7 0128	3 506 400
Charge [nC]	8.4	**24 544**	58 9075	29 453 760
Time [ns]	0.083	244	140 300	1 s
Current [A]	100	100	4.20	0.029
Beam Energy [kJ]	0.020	**59**	1 413	70 689

CLIC main beam	bunch	pulse	second
Bunches	1	312	15600
Charge [nC]	0.60	**186**	9285
Time [ns]	0.5	156	1 s
Current [A]	1.2	1.2	$9.3\ 10^{-6}$
Beam Energy @2.8 GeV [kJ]	0.0014	0.45	22.3
Beam Energy @9 GeV [kJ]	0.0053	1.69	83.6
Beam Energy @1.5 TeV [kJ]	0.89	**278**	13927

LEP (100 GeV)	bunch	beam	total
Bunches	1	8	16
Current [μA]	600	5000	10000
Charge [nC]	53.4	**445**	890
Beam Energy [KJ]	5.4	**45**	90

Effect of beam in matter

Note: in energy density in cupper for Melting : 400 J g-1, Structural yield 62 J g-1

Material	**C**	**Al**	**Cu**	**W**
LEP Beam (100GeV, 445 nC)				
Energy Density @ shower core [J g^{-1}]	0.64	1.68	22	112
Energy Density IB @ 0.1 mm^2 [J g^{-1}]	778	719	624	510
Energy Density IB @ 1 mm^2 [J g^{-1}]	78	72	62	51
CLIC Main Pulse (1.5 TeV, 186 nC)				
Energy Density @ shower core [J g^{-1}]	3.41	9.12	122.37	614.43
Energy Density IB @ 5.7 μm^2[J g^{-1}]	5.7 10^6	5.3 10^6	**4.6 10^6**	3.7 10^6
Energy Density EIB @ 0.001 mm^2 [J g^{-1}]	32	30	26000	21
Energy Density EIB @ 1 mm^2 [J g^{-1}]	32	30	26	21
CLIC Main Pulse @DR (2.8 GeV, 204 nC)				
Energy Density @ shower core [J g^{-1}]	0.01	0.03	0.34	1.57
Energy Density IB @ 14 μm^2 [J g^{-1}]	2.6 10^6	2.4 10^6	**2.0 10^6**	1.7 10^6
Energy Density EIB @ 1 mm^2 [J g^{-1}]	36	33	29	23
CLIC Drive Train (2.4 GeV, 24545 nC)				
Energy Density @ shower core [J g^{-1}]	1.34	3.08	40	187
Energy Density IB @ 1 mm^2 [J g^{-1}]	4293	3964	**3444**	2810
Energy Density EIB @ 1 cm^2 [J g^{-1}]	43	40	34	28

Beam induced damage

- Damage to machine structures primarily due to the large charge density.
  - Small beam size for main beam
  - High current for drive beam

- However, total beam power makes proper disposal of the main beam more challenging.

Type of failures

- Failures causing slow onset of losses
  - Magnet system
  - Vacuum system
  - Slow drifts (alignment, temperature, …)
- Failures causing fast losses
  - RF breakdown
  - Kicker misfiring
  - Klystron trips

Protection against slow losses

Avoid slow losses by choosing magnet current circuits with a large time constant:

- A power converter commit to stay within an acceptable tolerance for 2 ms after failure.
- We have time to abort the next pulse in case of failures of a magnet power converter.

If so, magnet failures should not be a major issue

  – But we still have to evaluate the required reliability (SIL level) for the interlock system.

Similar: A 2 ms closure-inhibit time window for fast sector valves of the vacuum system. (Closure speed ~1 mm / ms)

Protection against fast losses

- Oops, we are loosing the main beam, can we still dump it?

CLIC is essentially a continuous beam line.

- Fast loss detection and fast dump may catch the tail of the pulse.
- For the head of the pulse, we must rely on passive protection.

Can the passive protection also be robust enough such that we do not need a fast dump?

Many studies for collimation system already along these lines.

Note: many processes that causes a loss of the main beam will most likely already spoil its brilliance.

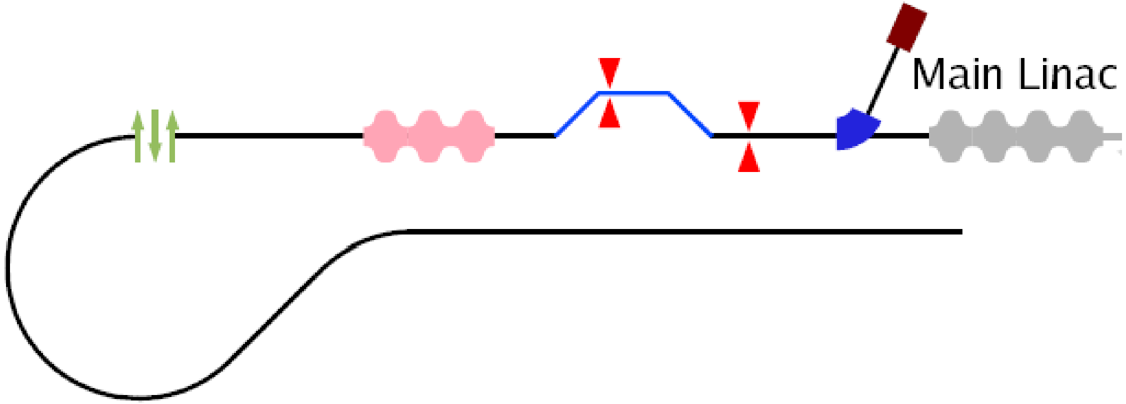
Note: there are some shortcuts to be investigated

Shortcuts:

Options for shortcuts:

- Damping ring (just wait one turn)
  - Important protection against synchrotron radiation causing quenches of superconducting wigglers.

- Turn around loop at entry of main linac (1000 M)
  - Dump in case of, position errors, phase errors, energy errors…

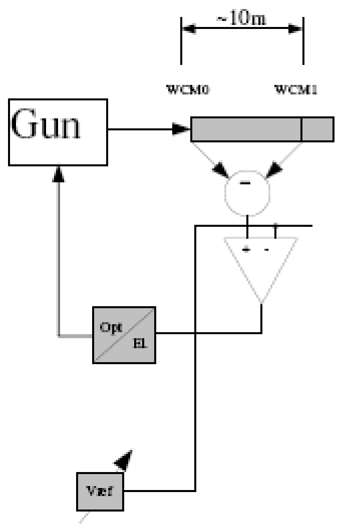


- Otherwise cut the source….

CTF3 MP (David Belohrad)

Principle:

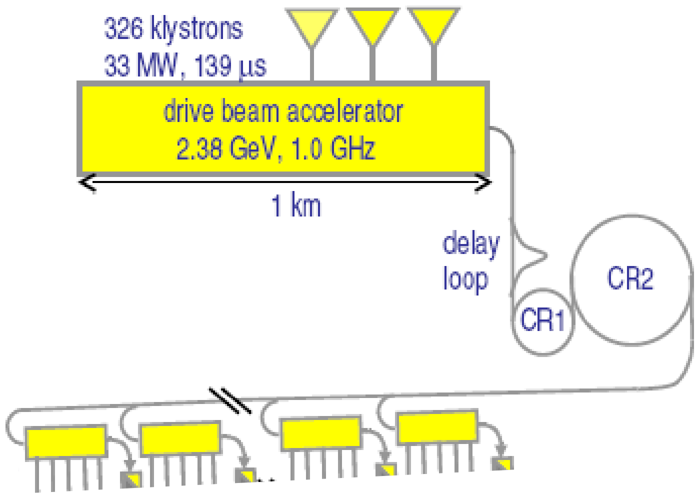
- Beam loss is measured by difference of beam charge measured at two consecutive wall current monitors
- Stops the LINAC source beam production inside the present pulse
- Note: By cutting the source, you do not dispose of what is still in the pipeline!
  (2.5us for CLIC drivebeam linacs, 50% of a train, 12000 nC)



CTF3 Prototype

- Only one stage protection with 2 WCM monitors
- Basic part of the system & infrastructure is built to test the speed of the system
- To be commissioned
- Offline analysis of WCM data to estimate performance of such a system.

Purging a pipeline



If a real-time problem is detected in

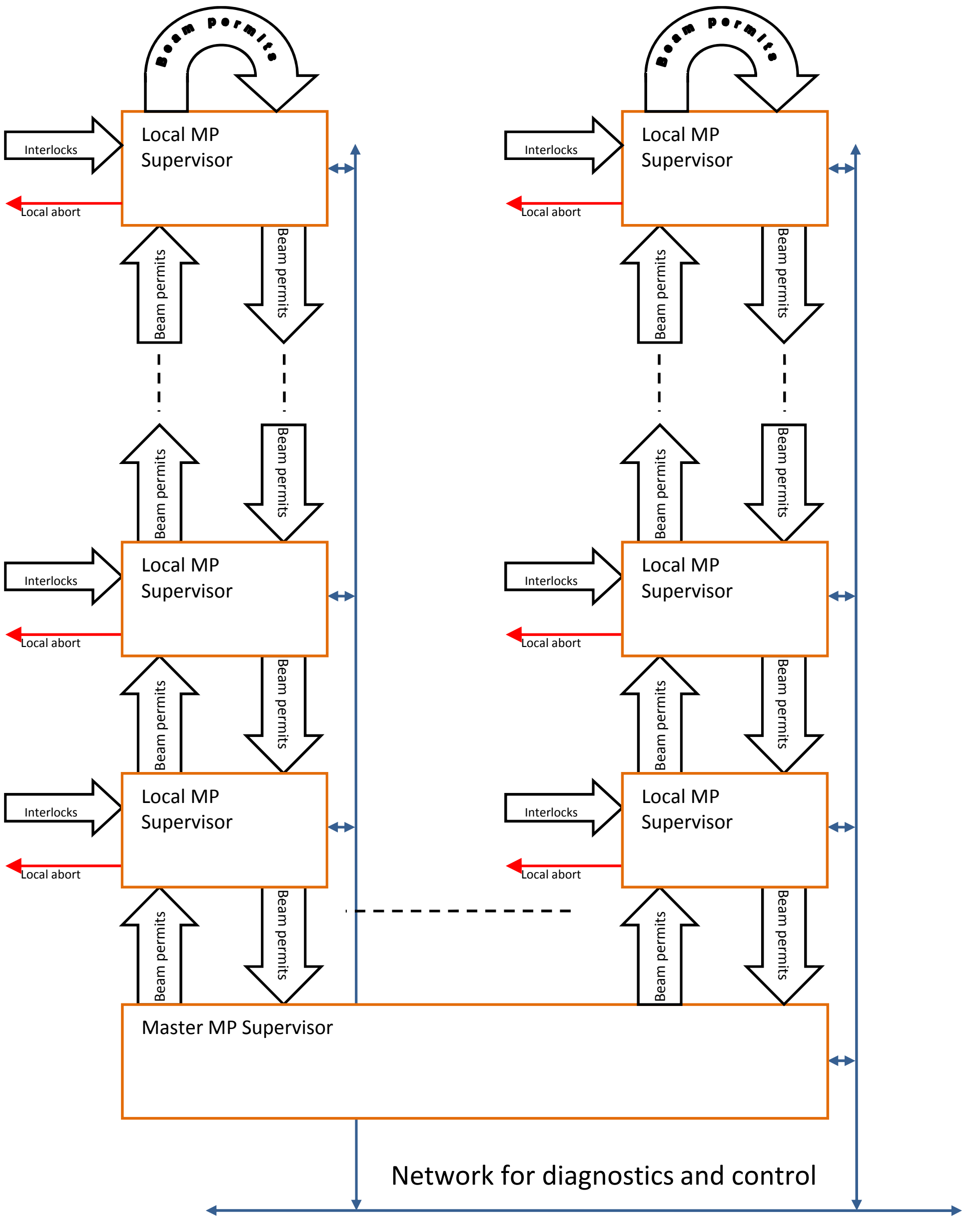
- a decelerator section
  - Option: the extraction in the decelerator and dump the train at the end of the line
- the drive beam transport line

  Note: Stopping the source will not solve the problem: long delay to reach the source (a huge pipeline).

  - However we can clean the pipeline by switching the trains prematurely into decelerator lines.

Not likely to be a realistic fault scenario

HW architecture of CLIC MP logic



- A central MP supervisor controls 4 parallel Beam-Permit-Chains (BPC) for the two drive and two main beams.
- Each Beam permit chain carries the beam permits for different beam types (pilot, tests, nominal).
- A Beam-Permit-Chain contains n local nodes with user permit inputs that can inhibit the beam permit chain (in both directions).
- In case the beam permit chain is interrupted, the local node will also provide signals that can be used by local beam and equipment abort systems.

Next pulse permit:

The next pulse is only allowed in the presence of the next pulse permit. This pulse permit is delivered if:

- a successful pulse have been delivered previously, (confirmed by post pulse analysis of previous pulse)
- no slow equipment failure (power converter, vacuum, trips) was detected up to 2 ms before next pulse.

In case of absence of the next pulse permit:

successive test beams of lower intensity, and emmittance will have to used to re-establish the readiness of the machine.

(i.e. the permit system is also aware of the beam type)

=> Establishment of operational procedures

Working Group

- Mandate
- Composition
- What can be done before the CDR in 2010

Mandate

Machine protection:

- Produce a detailed catalogue of possible equipment failures and their effect on the beam.
- Evaluate within the present design of elements the time constants between equipment failure and the critical impact on the beam.
- Use the above results to determine a strategy of machine protection
- Following the above strategy specify the functionality of specific equipment needed for machine protection
- In collaboration with the beam instrumentation experts produce a concept for beam performance monitoring of the individual beams

Safety:

Review all safety issues which could possibly affect CLIC operation

Plant Commissioning Strategies (staged construction, staged energy)

Elaborate and document

- will commissioning of subsystems be possible during construction, evaluate the impact on security and shielding
- review possible scenario for energy staging

Operational Strategies

Elaborate and document the operational cycle of the fully commissioned CLIC machine

- what type of beams will be needed

Operational Availability

Evaluate the availability for physics for the machine taking into account:

- Preventive maintenance on RF structures/klystrons for drive beams, Sources, Passive alignement, Calibration of BI/alignment/stabilization equipment, re-optimization of the working point of the stabilization system…
  Note: certain technologies used for CLIC are so much pushed to the technological limits that regularly scheduled interventions may be needed to ensure the operational state.
- Down-times due to equipment failures (i.e. specification of the MTBF and MTTR of various equipment)
- Others

Contribution to CLIC cost estimate

Composition of WG:

Permanent members (7) from

- TE/MPE (machine protection group)
- BE/BI (Beam instrumentation)
- BE/OP (Operation)
- TE/BT (Beam transfer)
- SC/RP (Radiation protection)

With help of consulting members

- BE/AP (accelerator physics)
- BE/RF (RF)

External collaborations

Reporting line: to CTC

What can be done before the CDR in 2010

First meeting of wg 2009 05 19

A detailed action plan of the Working Group will be presented to the CTC in July

Highest priority is

- Machine Protection
- Expected unavailability due to machine failures and recovery.
- Estimation radiation levels for electronics in the tunnel

For CDR in 2010

- Full inventory of failure modes (slow onsets, fast RT) with
  - estimate incidence rate
  - simulated impact on the accelerator structures and damage incurred by these faults (financial, operational).

    => Frequency x Impact = RISK
  - protection strategies must limit the incidence rate and/or damage to a level where the reduced risk is acceptable (i.e. a few percent of operational time & budget).
  - (effect of combined failure modes
- Detailed requirements for passive machine protection
- Evaluation of the requirements for beam observation systems to detect the onset of instabilities in drive and the main beam (i.e. beam loss, beam intensity loss, position and emittance).
- Provide a list of test beams and establish the procedure to reach nominal CLIC operation starting from a “cold” machine, based on successive beams of increasing intensity and brilliance.

For CDR in 2010 (cont)

- Required tolerance for all magnet circuits for safe operation with nominal beams.
- Proof of feasibility for magnet power circuits with guaranteed tolerance for 2 ms after the onset of failure.
- Evaluation of radiation levels for electronics in the tunnel
- Evaluate the unavailability of the machine for nominal operation due to various interlock conditions and equipment failures.

R&D

RD effort related to Machine Protection issues

- The two beam test stand: study the effect of RF break down on the two different beams of CLIC and to confirm simulation studies.
- Simulation of failure modes,
- Simulation of beam loss due to failure modes.
- Simulations for optimal placement of beam loss monitors for diagnostics of the accelerators; or as active components in protection chains.
- Study /test material damage in material (Copper RF structures) by dense electron beams (include indirect effects: synchrotron radiation, wakefield heating).
- Study of activation of accelerator component caused by beam loss. A) implications for control electronics, b) implications for personnel safety (i.e. access restrictions due to hot spots).

Conclusion

- Late start
- Many items to review
- No major complications to do the work
  (which does not imply that the machine protection itself is a trivial subject).
  - Lots of studies have been done already
    to be compiled in a MP related document & make sure it is complete.
  - Use experience of ILC (failure analysis, availability analysis)

Conclusion Beam Instrumentation

- Major fraction of Beam Instrumentation for Machine Protection will not need a real-time response. (20 ms to the next pulse permit).
  - Beam Loss, Intensity, Position, Profiles
    (Like xpos analysis @ LHC, but only at 50 Hz)
- Reliability to detect onset of instabilities is the major concern.
- Use of beam instrumentation for fast decisions in damping rings, turn around loops, drive beam linac.