Status of CLIC operation and machine protection

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Outline

- CLIC beam power and destructive capacity
- Base line CLIC machine protection
- Progress
  - Operational bootstrap scenario identified
  - Fault tolerant powering configurations
- Topics not covered
- TDR Work packages
- Outlook
- Workshop

Beam Power and destructive capacity

Beam Power = BeamCharge ParticleEnergy CyclingRate

Drive Beam: 2 70 MWatt Main Beam: 2 14 MWatt

this makes a sustained disposal of this power a challenging task.

Energy Density = BeamCharge × BeamSize^{-1} × dE/dx (ionisation loss)

Destructive potential: determined by BeamCharge BeamSize^{-1} **not** Beam Power.

	Particle Energy [GeV]	Pulse Charge [μC]	Beam Size [mm^2]	Energy Density in copper [J g^{-1}]	
				Incident Beam	Shower Core
Drive Beam Train (1 of 24)	2.4	25	1	**3.4 10^3**	40
Main Beam @ Damping Ring	2.8	0.20	125 10^{-6}	**1.8 10^5**	0.34
Main Beam @ β collimation	1.5 10^3	0.18	40 10^{-6}	**6.7 10^5**	120

Energy density in shower core is less significant than energy density of the incident beam.

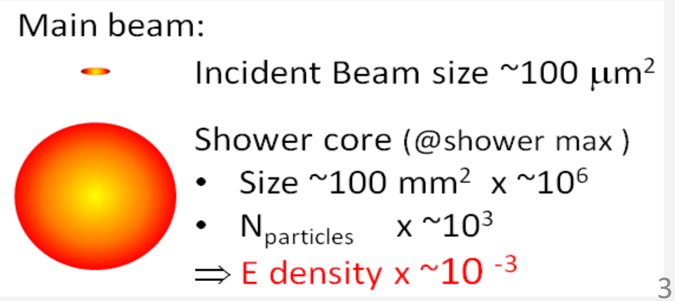
Main beam already **unsafe** in the **damping ring** even with low beam power.

Particle energy is not the primary worry, however, no doubt **at 1.5 TeV you 'drill' deeper holes**.

Safe Beam:: yield limit in copper **(62 J g^{-1})**

Main Beam : 10000 × 'safe beam'

Drive Beam : 100 × 'safe beam'



Failure types and Protection strategies

Slow Failures

Time scale larger than the machine cycle period (10 ~ 20 ms) .

–Temperature drifts

–Alignment drifts

–Beam feedback saturations.

N.B.: Normally, the beam feedback system should keep drifts under control. Any deviation of the expected behaviour is potentially dangerous.

Inter-Cycle Failures

Time scale comparable to machine cycle period (10 ~ 20 ms).

–Power supply failures

–Positioning system failures

–Vacuum system failures

Last moment Equipment Failures

As above but to late for the Interlock system to react (< 2 ms)

Fast Failures

Time scale of beam flight time through the accelerator complex (*in flight < 0.2 ms*).

–RF breakdown: (transversal kicks...)

–Kicker misfiring: (damage to septum magnet).

–RF klystron trip. (disrupt beam, large losses)

N.B. the drive beam linac: 1.5 drive beam train in the pipeline: i.e. two orders above damage level.

Next Cycle Permit

Post Cycle Analysis

BEAM Interlock

Safe by construction

Static Protection

Next Cycle Permit

– Systematically **revoked after every cycle**

– **Re-established** if predefined beam and equipment **quality checks** have passed:

≈10 ~ 20 ms to analyse the previous cycle and to decide if OK for next cycle.

Static Protection

In flight failures:

– Difficult to detect beam failures and dump the misbehaving beam.

– Impossible for the head of the beam (causality, speed of light).

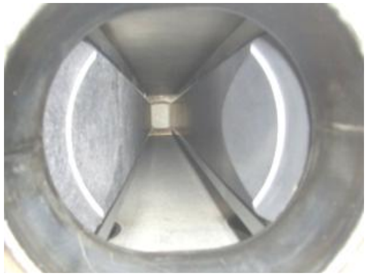
Passive protection: masks and spoilers.

Make passive protection robust enough to provide full protection for the whole pulse.

Many of the systems are already designed along this principle.

Locations (mostly associated with kickers)

- Extraction channels damping ring
- Extraction from combiner rings
- Drive Beam turn around



Protective masks. (Picture of an LHC Collimator)

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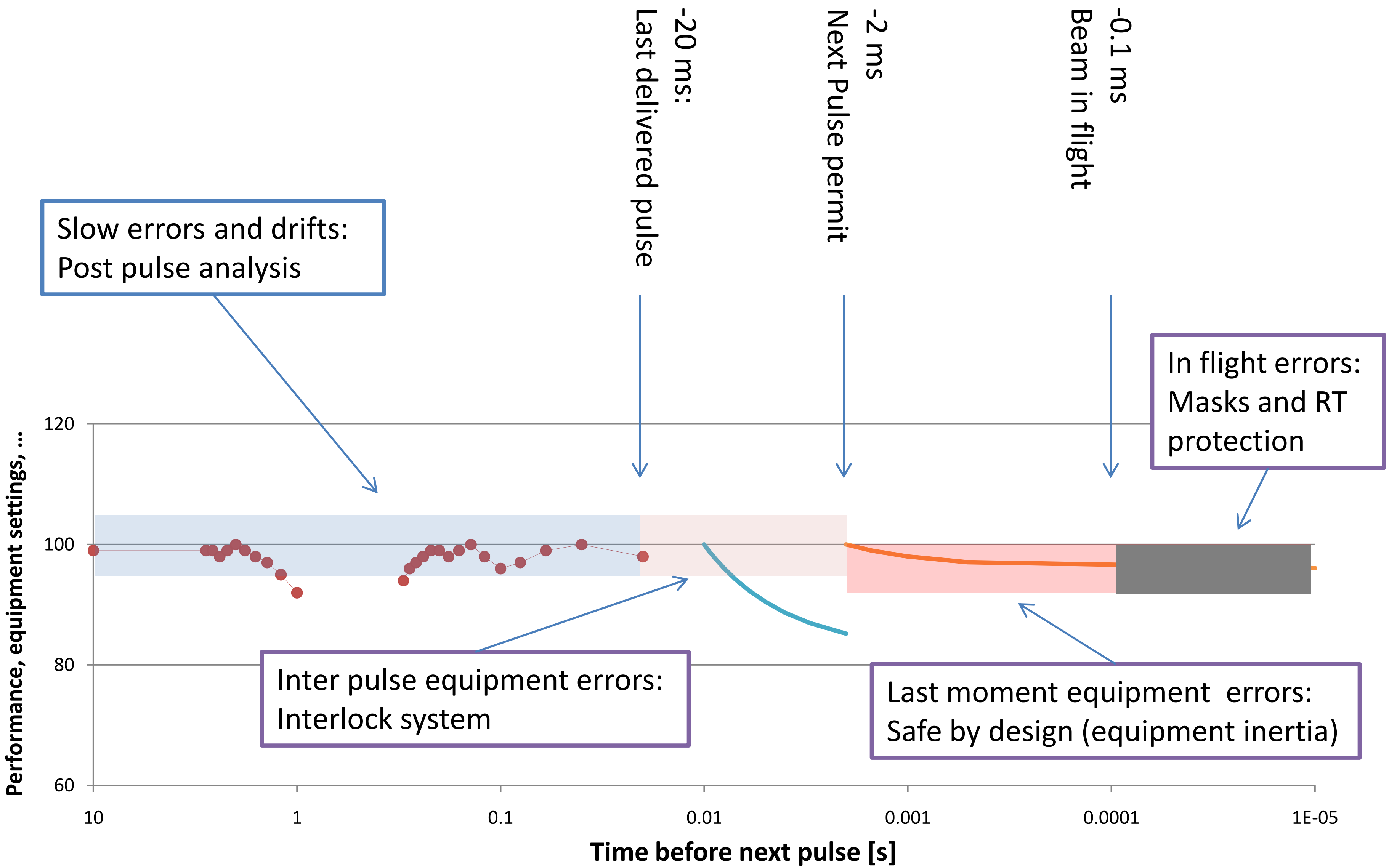
Decision time: 2 ms before next pulse

Machine Protection Timeline



Operational scenario

Post pulse analysis and next cycle permit are key concepts.

How to bootstrap the next cycle permit?

Safe operation: Do not allow potentially harmful beam in the machine

potentially harmful :: current state of the machine & brilliance of the beam

- '*Cold start-up*' (i.e. unknown machine): only beam that cannot cause structural damage to the installation is safe
- Once probed by safe pilot beam: increase charge density of the beam in steps (as long as allowed by the post cycle analysis of every previous step)
- Note:

  No important degrading of beam observation at lower intensities is expected,
  (drive beam position measurements with reduced bunches works even better)

Drive Beam: 100 × Safe Beam

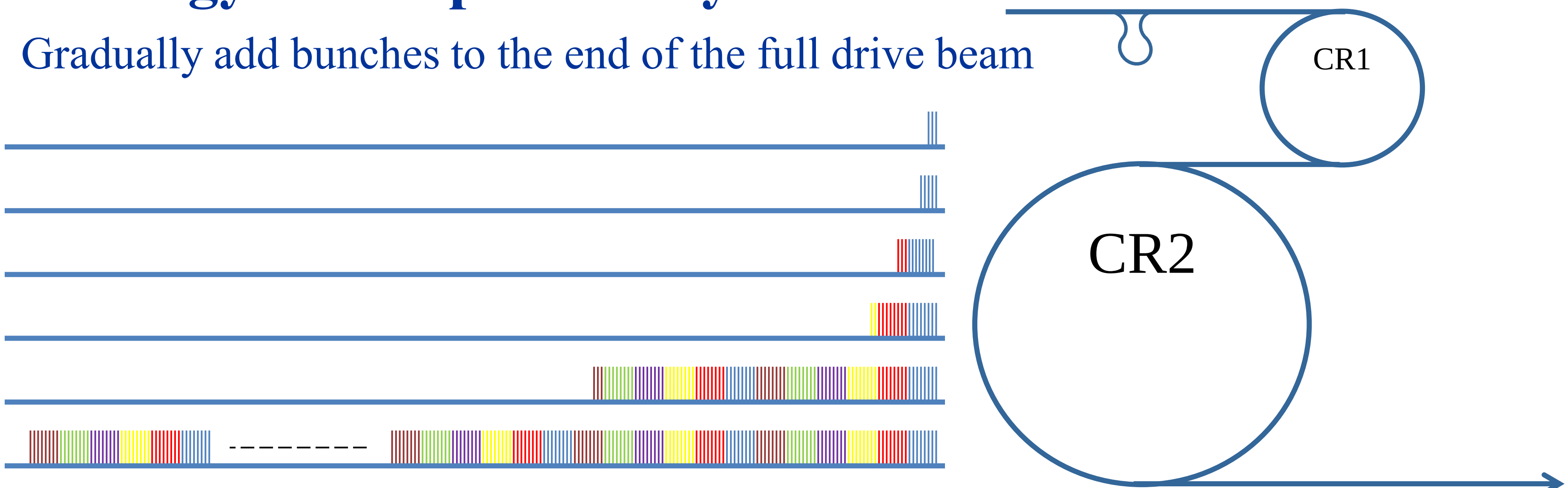
(for a single train out of 24)

One train = 24*121 bunches ⇒ safe beam is 30 Bunches.

Full drive beam: 1+24x24 sub-pulses (1SP = 121b). Header is dumped, remaining 24x24 sub-pulses are arranged in combiner complex in 24 ***"trains"***, of 24x121 bunches @ 12 GHz

Strategy to ramp intensity :

Gradually add bunches to the end of the full drive beam



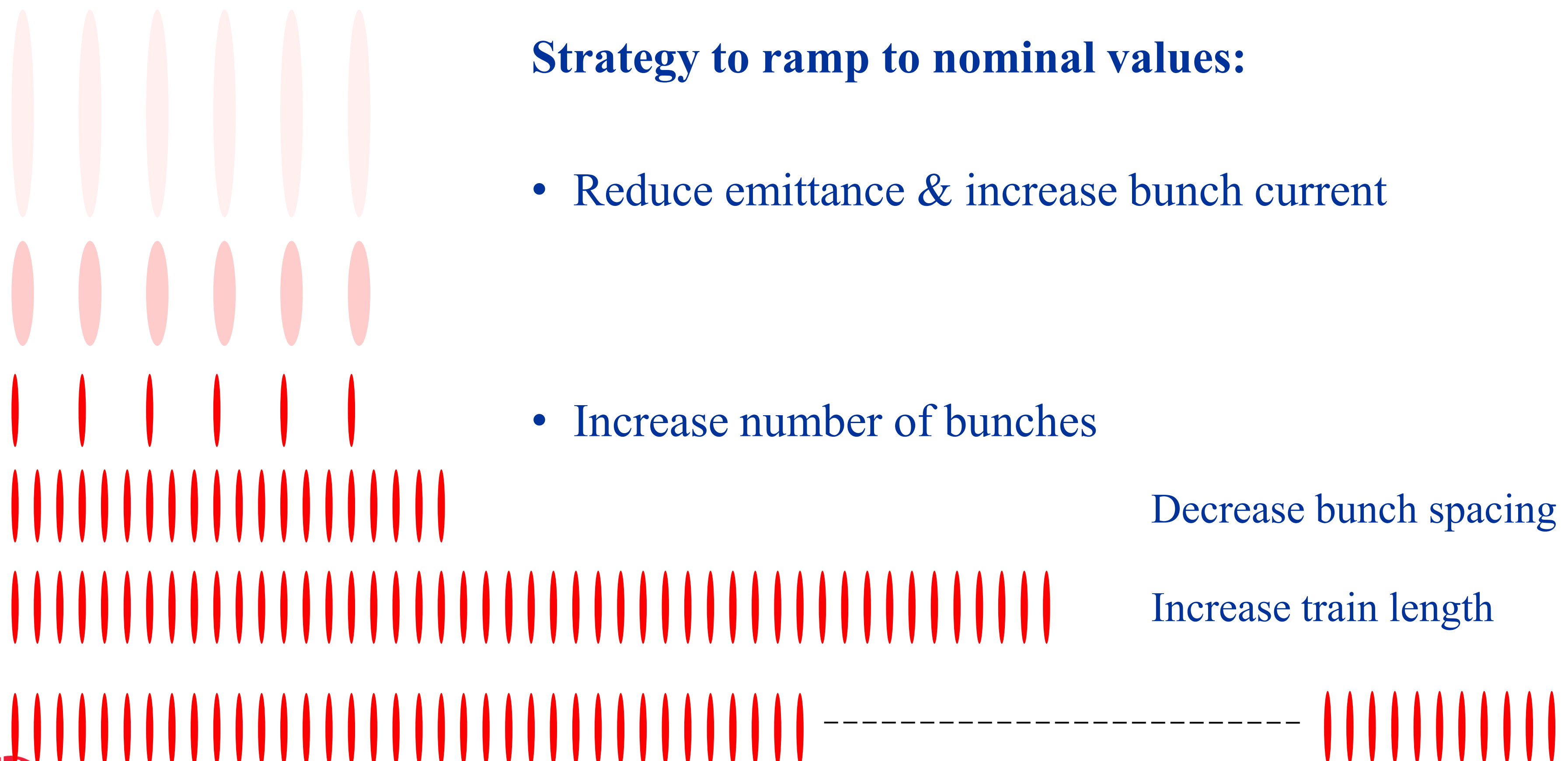
- 30b, 60b, 1SP+30b, 1SP+60b, 2SP+30b, … 24SP ⇒ Recombination complex and decelerator 1 tested
- 1T+30b, 1T+60b, 1T+1SP, 1SP+2SP, 1T+6SP 1T+24SP ⇒ Decelerator 2 tested
- 2T+30b, 2T+60b, 2T+2SP, 2SP+2SP, 2T+6SP 2T+24SP ⇒ Decelerator 3 tested
- etc… 23T+30b, 23T+60b, … 23SP+2SP, 23T+6SP 23T+24SP ⇒ Decelerator 24 tested

Total 48+23*5 =164 pulse combinations to test full circuit

Main Beam: 10000 × Safe Beam

Reduced brilliance by 10^4 with respect to nominal (312 bunches in 152 ns).

- Reduce to 6 bunches in 10 ns (for Beam Position Monitors) ⇒ factor 50
- Reduce intensity / bunch ⇒ factor 3
- Reduce emittance in damping rings (ε_h: 1/3, ε_v: 1/20) ⇒ factor 60



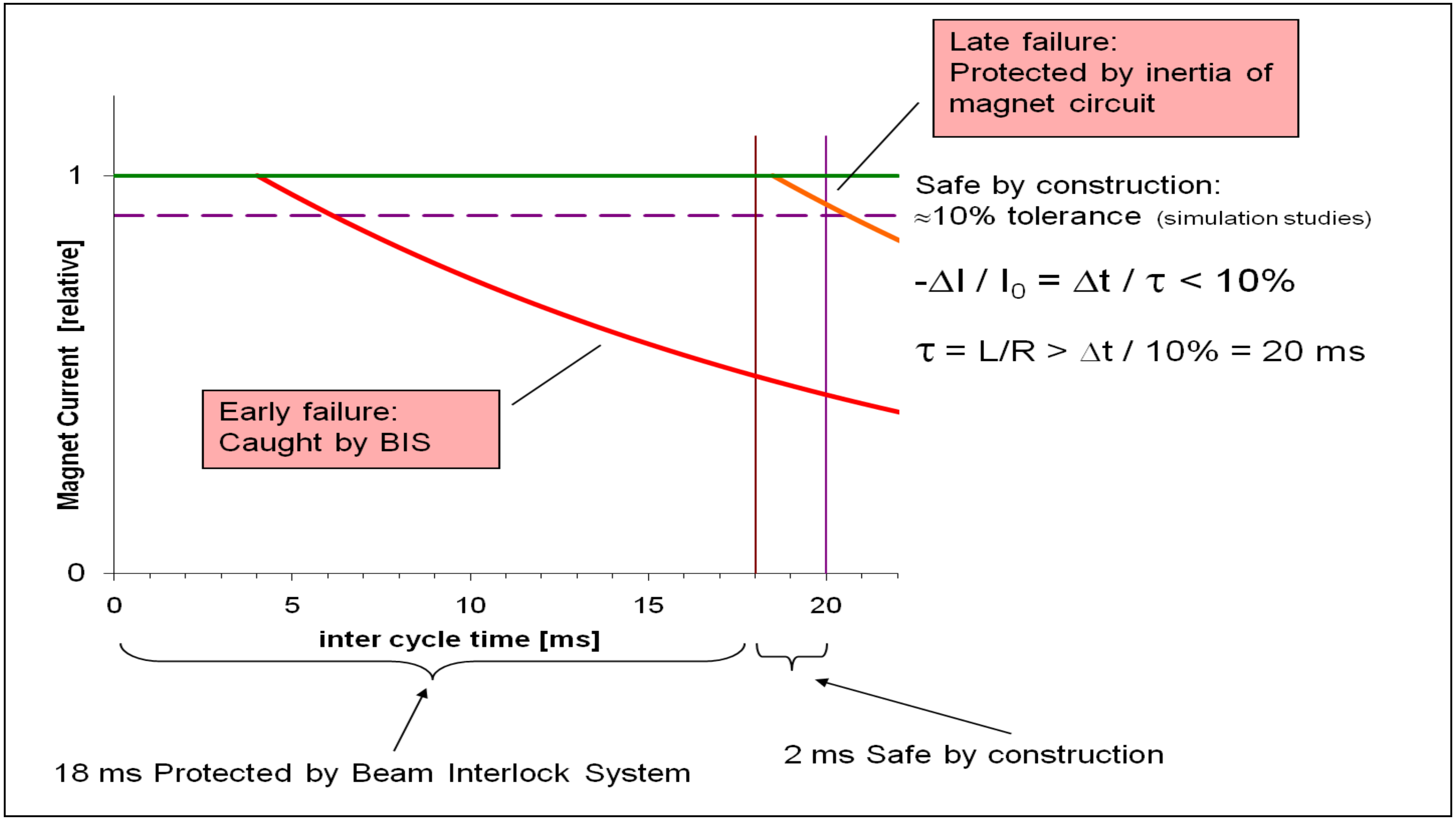
Safe by construction

Cover the 2 ms blind period prior to the each cycle:

Stay within tolerance (for safe beam passage) for 2ms after a power converter fault

Studies: acceptable tolerances ~10% ⇒ need magnet circuits with a $\tau = L/R > 20$ ms.

Same principle for all active equipment (vacuum, positioning systems, RF-HV, kicker-HV etc.)

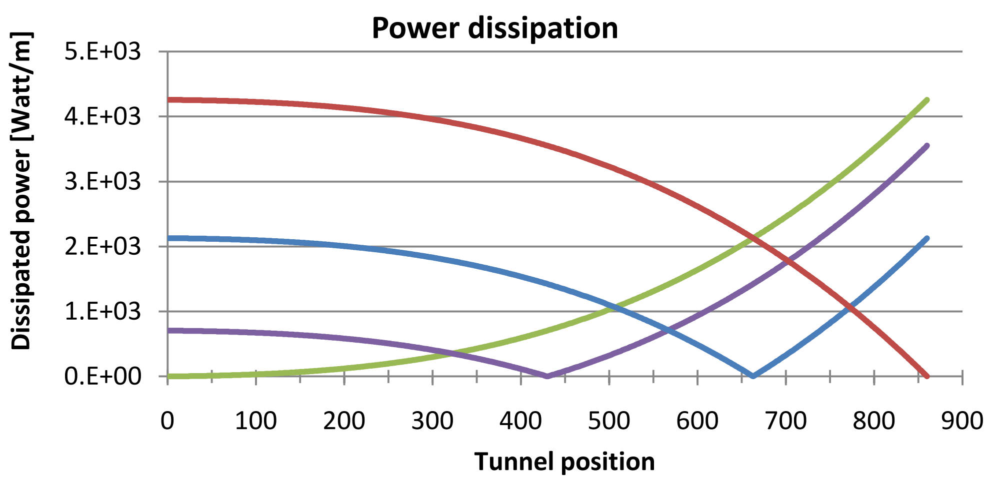


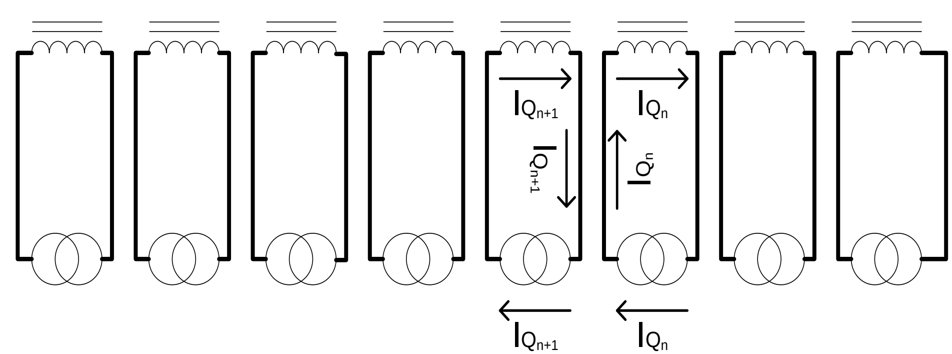
Fault tolerant powering configurations

Investigated powering of quadrupoles in main linac:

Initial motivation

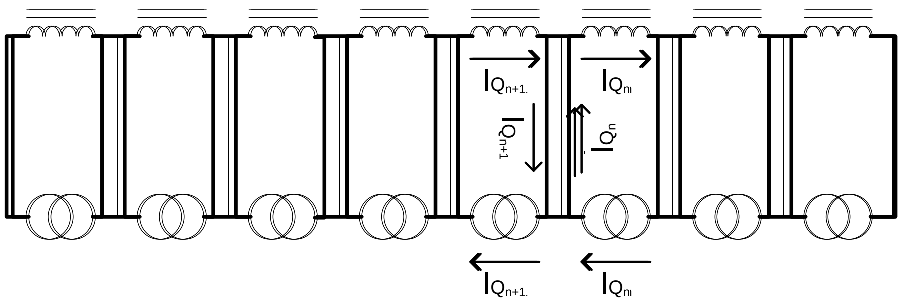
- Solve the unrealistic high cable power dissipation (2KWatt/m , 1.2 MWatt/decelerator), based on allocated cable space and one power converter/magnet.
- Alternative: unrealistic amount of Cu and cable trays.



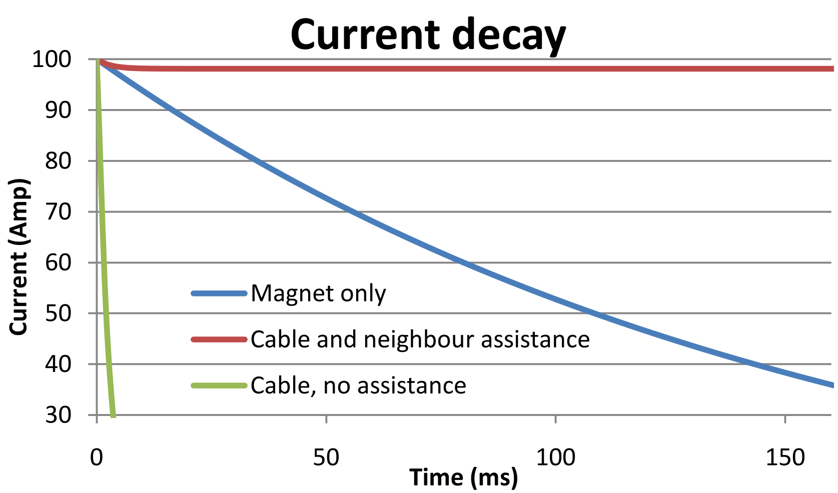


Fault tolerant powering configurations
for main linac quadrupoles

- In case of almost identical currents one can share cables.
- These 'trim' cables carry only the difference currents.



- Various alternative configurations are possible (shown here provides 1:1 control)
- These configurations are beneficial in case of power converter failures: **Neighbour assistance**

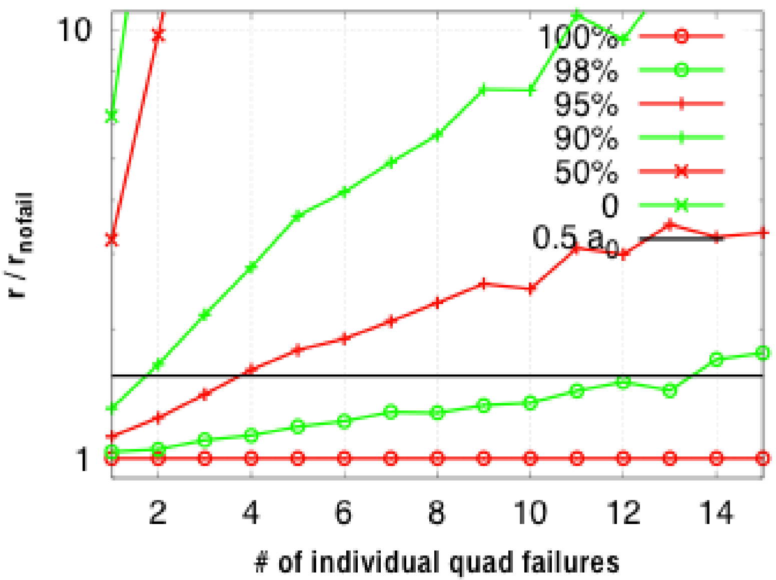


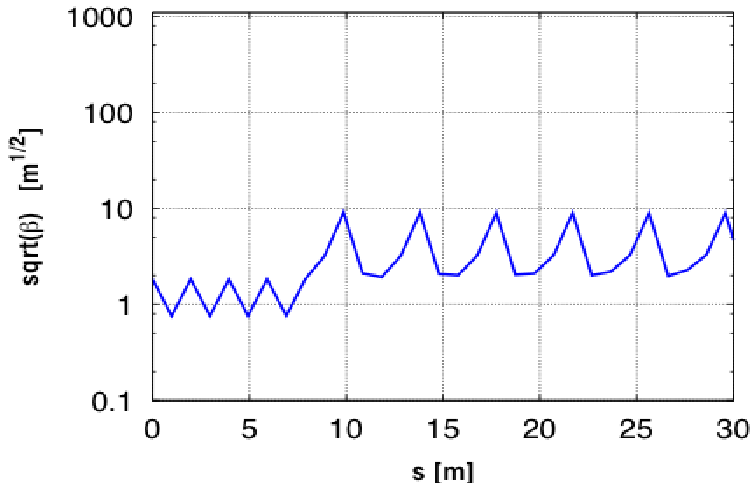
- Note: current decal level depends on resistance of the trim cables in the actual circuit

Failure analysis decelerator quadrupoles

Erik Adli

Impact on beam envelope was studied as a function of the number of quadrupole failures, for different failure types (full failure … partial failure)





Increase in beta function as result of the current in a single magnet set to zero

Single failure tolerance: - 10 %, $\tau > 20$ ms

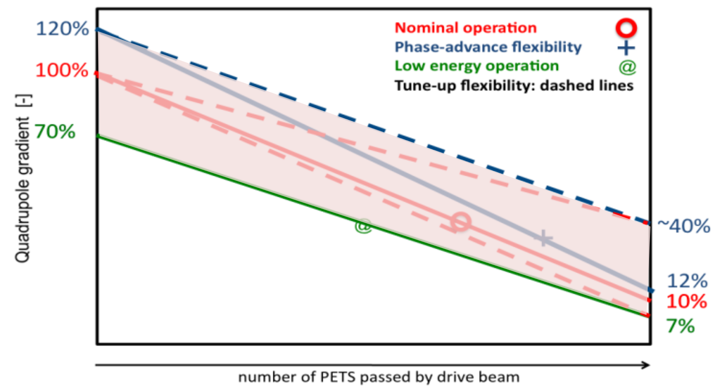
Double failure tolerance : - 5 %

At -2% failure level: decelerator operational with a few failures. Important availability implications

Quadrupole powering configuration

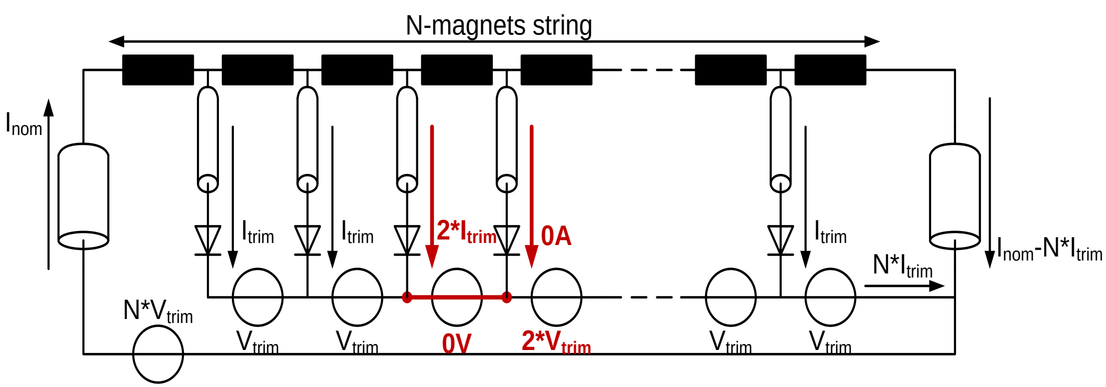
Daniel Siemaszko, Serge Pittet, Erik Adli

Drivebeam quads families are to be powered with a monotonously decreasing current. (line in the shaded area).



Power magnets in series of up to 60 magnets.

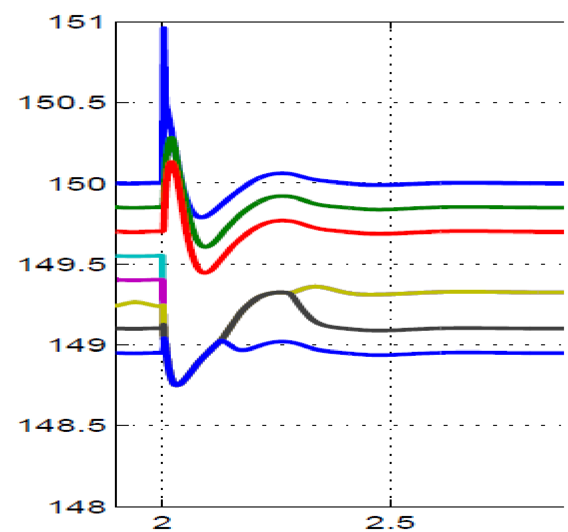
- Powering configuration based on passive trimmers:



serial powering circuit with dissipative trimmers

Simulation result of trimmer failure:

- Small transients (less than 1 %)
- Current stabilizes to an tolerable level



Quadrupole powering configurations

Conclusions

Quadrupole magnets in main linac can be powered in series.

- Applicable for main beam and drive beam.
- Reduction of power dissipation in cables
- **Satisfies the safe by design** criteria $\tau = L/R > 400$ ms >> 20ms
- Cost effective: active supplies for drive beam quadrupoles down by a factor ~ 50
- High failure tolerance for trimmers in decelerators
- Hot spare technologies possible for main converters improves the machine availability.

Without neighbour assistance and hot spare technology and one to one powering

- Number of power supplies: 5 10^4 power supplies
- MTBF 3 10^5 -> MTB-Machine failure 6 h,
- 4 hours / repair => machine availability = 40% is unacceptable

With the failure tolerant system, a proper choice of hot spares, and preventive maintenance campaigns: down time due to power converters only a few percent.

Fault Tolerant Powering

Kicker systems

- Drive beam: Combiner Rings, Turn-around — 10^2 x safe beam (single train)
- Main beam: Damping Ring — 10^4 x safe beam

- Kicker misfiring will lead to substantial damage.
  - Septum magnet, or septum magnet protection mask.
  - Still to be proven: **Do we have the material that can survive a beam impact.**

- Fault occurrence to be minimized

  Based on 1 failure in 10 years:

  - Single kick failures < 1 in $1.5\text{x}10^{12}$ (DB), < 1 in $1.2\text{x}10^{10}$ (MB)

  DB: 2x(4x24x1+24x1+1x24) = 248 kicks in 26 kickers per machine cycle

  4 10^6 pulses per day, 150 days/year, 10 year operation = 1.5 10^{12} kicks/10y

  MB: 2x(1x1) = 2 kicks in 2 kickers per machine cycle

  4 10^6 pulses per day, 150 days/year, 10 year operation = 1.2 10^{10}

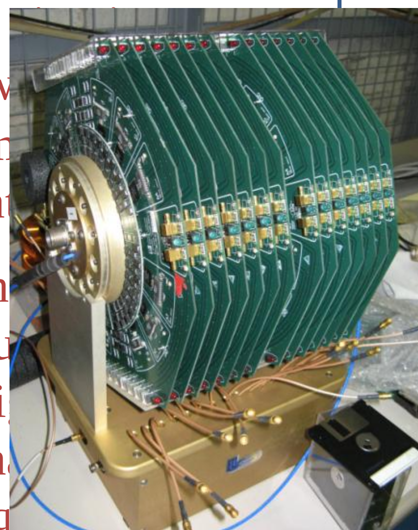
- Solutions? Improved kicker firing circuits …

Mike Barnes
Wednesday session

"n-Cell" Inductive Adder

An **Inductive Adder** [12] is a promising means of compensating for losses in the PFL and transmission cables as well as ripple. The adder consists of:

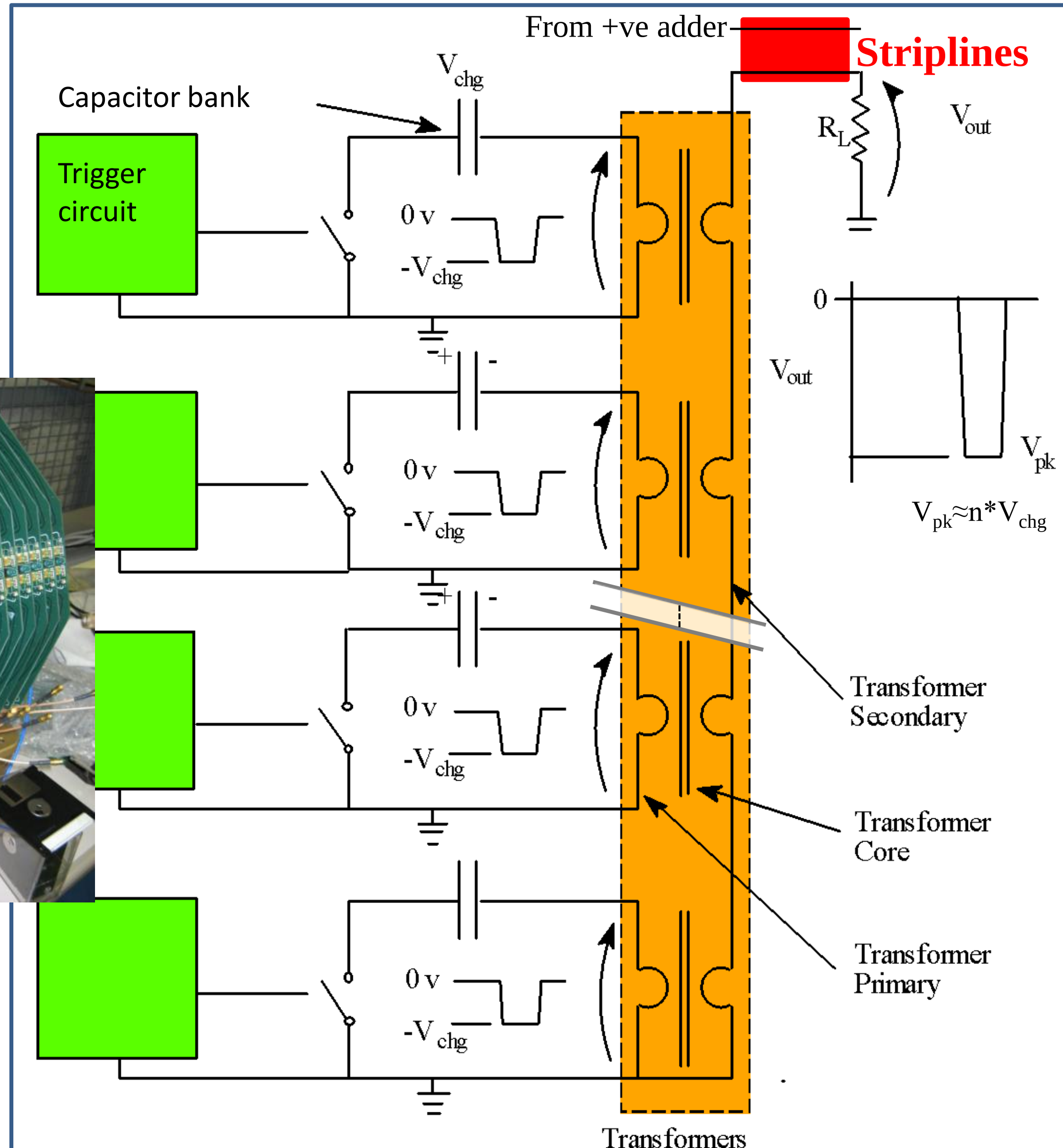
- A multi-cell primary
- A single secondary w
- A fast pulse transforn
adequate voltage isolat



Each primary circuit h
The switches can be tu
independently, via tri
provide some pulse sh
➢ Many cells may be req
fine control over pulse shape (to be studied further).

➢ Good for machine protection & reliability (redundancy) too.

To be studied by Janne Holma, a PhD student, who started August 1, 2010.



n-Cell Inductive Adder: adapted from [12]

Not discussed here

- RT protection and dumps for drive beam linac (24 x 100 x safe beam)
- RT protection and dumps damping rings (and/or fast emittance control)
- Beam loss monitoring specifications (covered in BI session)
- Radiation issues, implication for electronic systems
- CLIC @ 100 Hz
  - Not really a problem, if needed we can do fast post pulse analysis in 8 ms on limited systems and detailed post pulse analysis over a few pulses.

For TDR phase:

- Detailed analysis of fault scenario
- Validation of bootstrap procedure (i.e. beam optimisation procedures at low intensities)
- Detailed operational availability studies
- Protection of extraction channels in case of kicker failures
- Fixed protection masks and protection recovery (spare surface)
- RF breakdown effects

Work packages for TDR phase

Machine protection related work packages

- TE/ABT:
  - specification of masks to protect against kicker failures.
  - Internal emergency dumps
- EN/STI
  - Implementation and materials for protective masks and internal dumps
- TE/MPE
  - Specifications of MP based on simulations of MP subsystems
  - Specification of interlock system
  - Implementation of a scaled down CLIC MPS in CTF3 and validation of general principles
  - Prototyping of CLIC BLMs in CLEX (BE/BI)
  - Prototyping of CLIC BLMs in CLEX (BE/BI)
  - Radiation qualification of components (HES/RP)

Conclusions / Outlook

- Will all be documented in the CDR.
- Work packages defined for the TDR phase for the definition and development of machine protection related issues.
- A fellow will start next month to work on detailed fault simulations.
- A prototype development project was defined to test the machine protection principles in CTF3. A doctoral student will start on this next year.
- MP workshop in 2011 ?

MP Workshop 2011

Machine Protection and Operations workshop

Duration: Three days.
Date: tbd. Possibly linked to the (i.e. before) ILC-CLIC or other workshop?
Objectives: Review issues raised in the CDR and program up to the TDR

Participants from:

- Beam dynamics experts
- Structures experts
- Experts on equipment with impact on beam:
  - Kickers
  - RF
  - Power Converters
  - Vacuum
- Beam transfer experts
- Detector interface experts
- Interlock and controls experts
- Instrumentation
- Collimators and material experts

Institutes: CLIC, ILC, Light sources, LHC

Program

- Parameters of CLIC/ILC
- Protection issues
- Interlock systems
- Operational aspects

Topics:

Fault studies

- Fast failures
- Equipment failures
- Slow drifts

Risk analysis

Requirements for fixed masks (in flight protection)
Interlock systems
Safe by construction

Post Pulse analysis
Beam Loss detection
Fault Detection and instrumentation

Material Damage
Operational procedures
Fast emittance control
MP with beam based feedback
Availability issues