Safe by Design CLIC Powering

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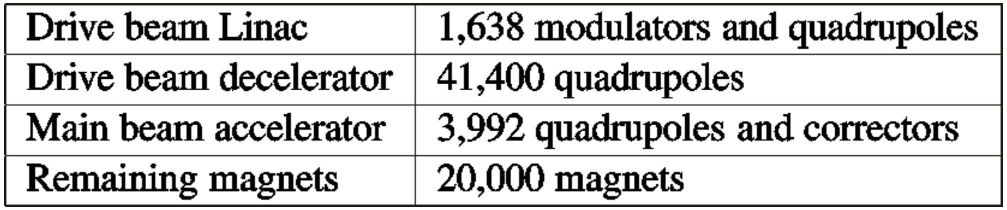
OUTLINE

- CLIC magnet powering requirements
- Technical solutions for the Drive Beam Decelerator
- Powering CLIC and machine availability

CLIC Powering

- CLIC is a huge machine that will contain some **75’000 power converters**, including modulators, correctors, trimmers and converters for feeding the magnets.

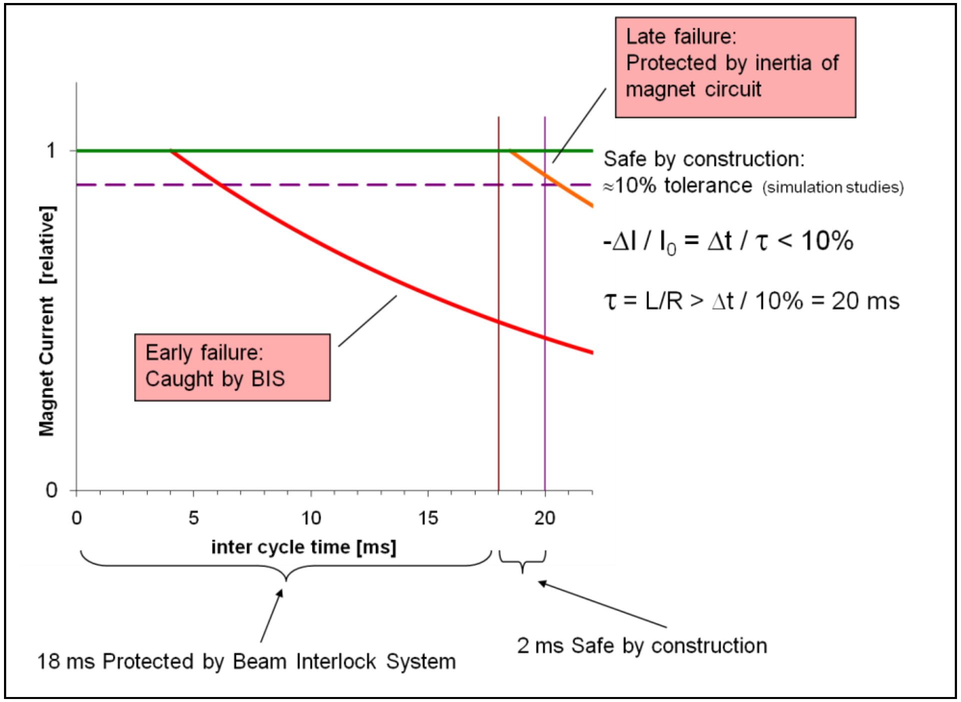


Drive beam Linac	1,638 modulators and quadrupoles
Drive beam decelerator	41,400 quadrupoles
Main beam accelerator	3,992 quadrupoles and correctors
Remaining magnets	20,000 magnets

- If every single magnet is **powered individually** and is **mandatory for operation**, global mean time between failures is ~4 hours due only to the power converters, meaning a **machine availability close to zero**.
- The specification and design of CLIC Powering must consider machine availability and reliability and the close relationship with machine protection

CLIC powering failure tolerance

- Inter-cycle failures are caught by the BIS
- Stay within tolerance (for safe beam passage) for 2ms after a power converter fault
  - Acceptable tolerances ~10% -> need magnet circuits with a $\tau = L/R > 20$ ms.



Late failure:
Protected by inertia of magnet circuit

Safe by construction:
≈10% tolerance (simulation studies)

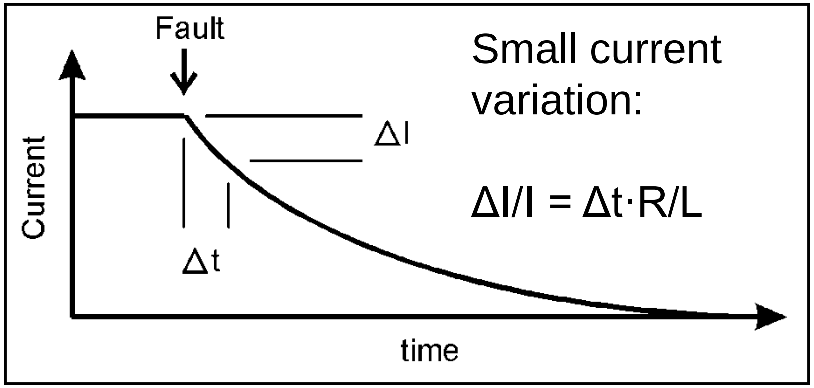
$-\Delta I / I_0 = \Delta t / \tau < 10\%$

$\tau = L/R > \Delta t / 10\% = 20$ ms

Early failure:
Caught by BIS

18 ms Protected by Beam Interlock System

2 ms Safe by construction

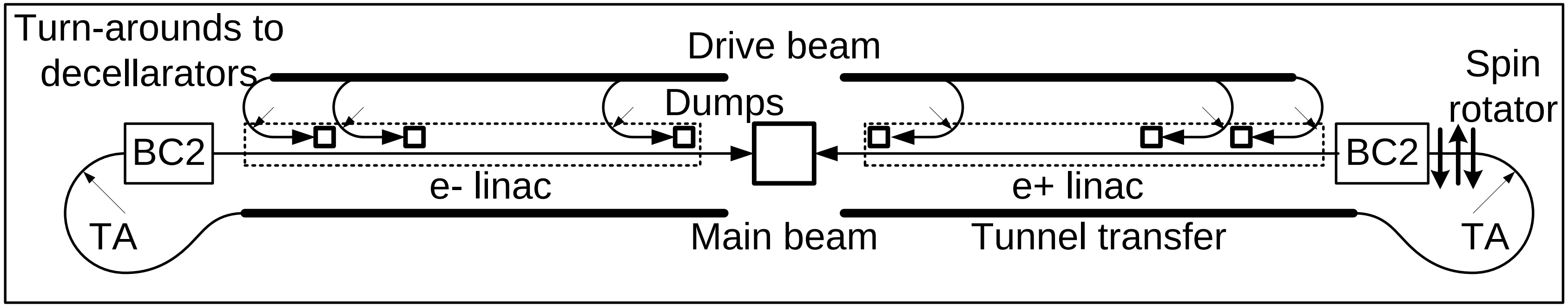


Small current variation:

$\Delta I/I = \Delta t \cdot R/L$

- Magnet inductance and resistance determine decay characteristics
- Type 4 main beam quadrupoles (125A/0.26Ω/43mH) would keep magnet current in a 1.2% window for 2ms

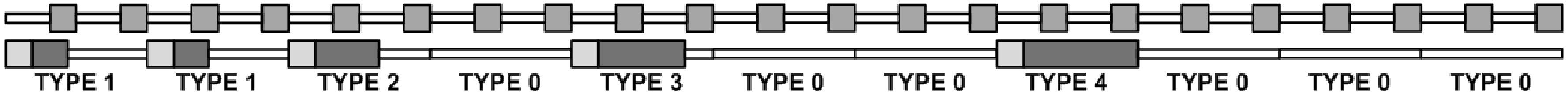
Main linac (two-beam accelerator)



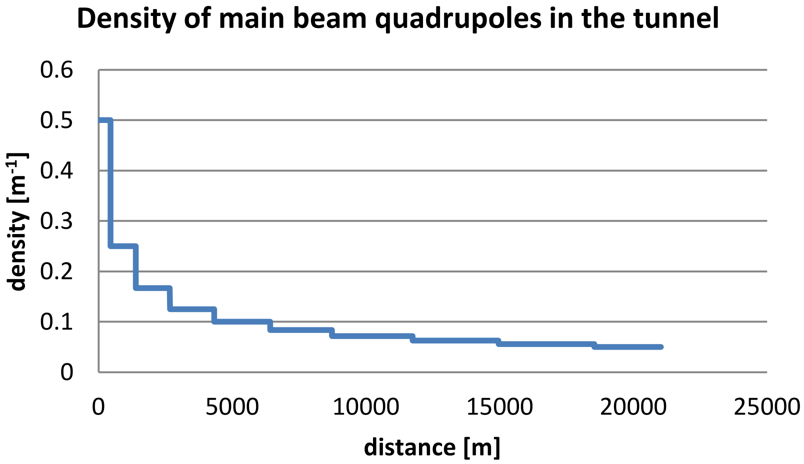
- The main beam is accelerated by RF energy exchanger linking the drive beam which is sequentially decelerated.
- For reaching 3TeV, the 50km long tunnel contains 48 accelerating sectors and need the powering of about **45’000 quadrupoles** and **4’000 dipole correctors**.
- The power converters are located in a **confined area**, meaning strong restrictions on power dissipation and accessibility.
- High radiations lead to the use of dedicated caverns along the tunnel.
- Cabling aspects (number and power dissipation) does not allow individual powering.

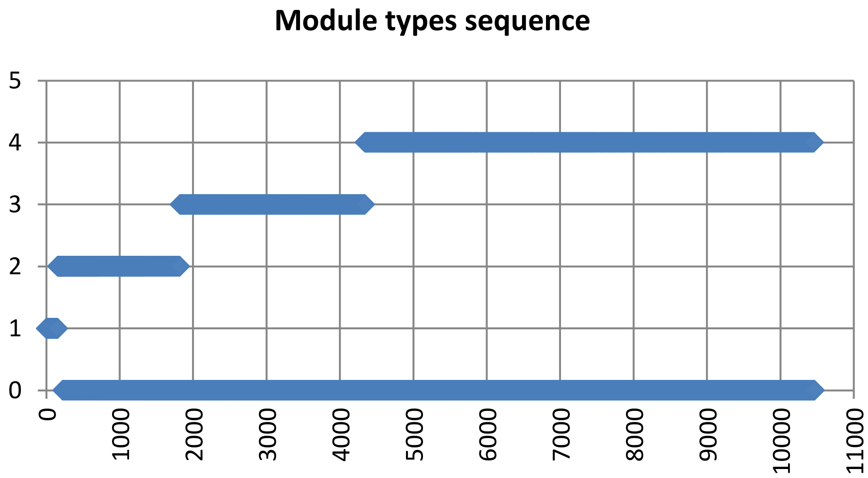
Sequence of modules

- The module sequence along the tunnel is a composition of modules of type 1,2,3 or 4 each containing a quadrupole and module of type 0 without quadrupoles.
- Two powering strategies, one for each beam is presented.



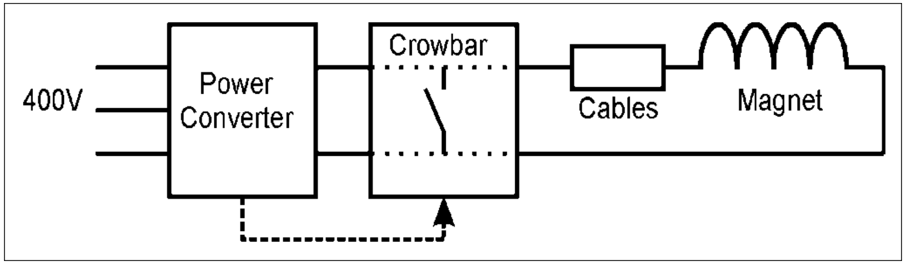
- **High density of quadrupoles in the first section**, then the number of them decreases along the tunnel. Impact on the number of power converters with a factor 3.

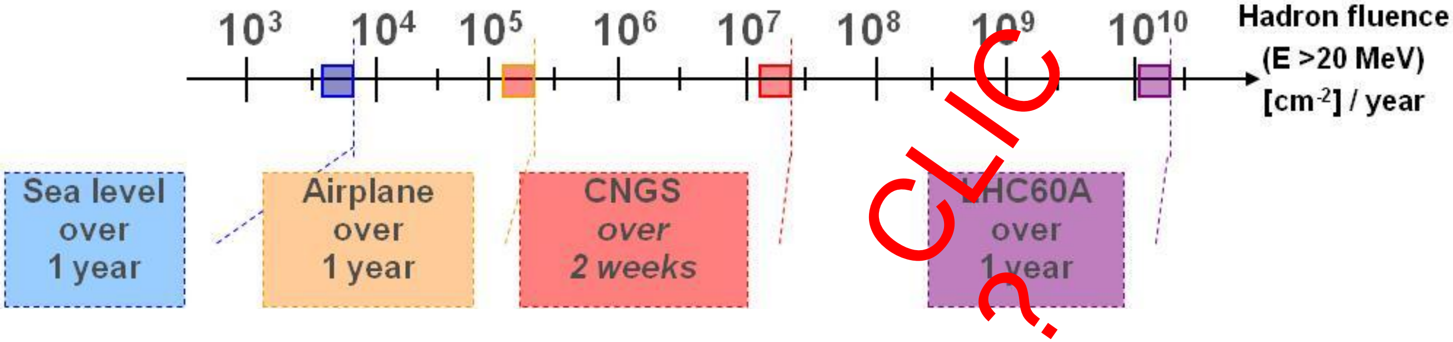




Power converter failure modes

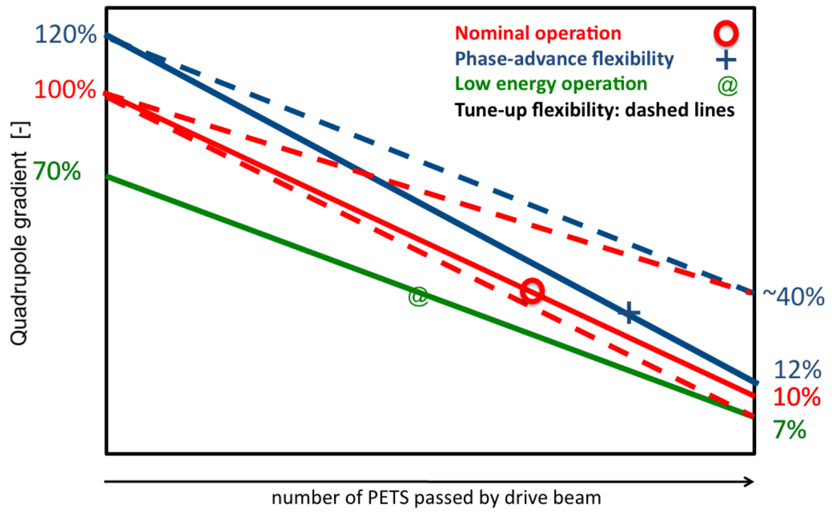
- Any power device may fail open or shorted. The converter usually fails
  - Open in case of internal control failure
  - Shorted in case of a power semi-conductor failure
- An additional external passive crowbar is then needed to ensure a failure in shorted mode.
- SEU or SEL will contribute to failures.



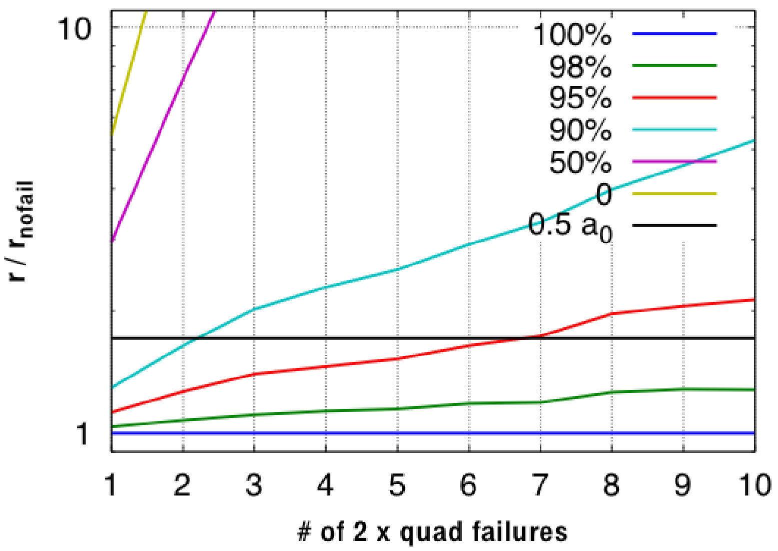


CLIC powering failure tolerance

- Field profile in nominal operation in the range of 69 to 6.9 T/m linearly distributed along each sector within the 860 quadrupole (meaning 120A-12A).



100% corresponds to a quadrupole gradient of 81.2 T/m (assuming a magnet active length of 0.15 m)

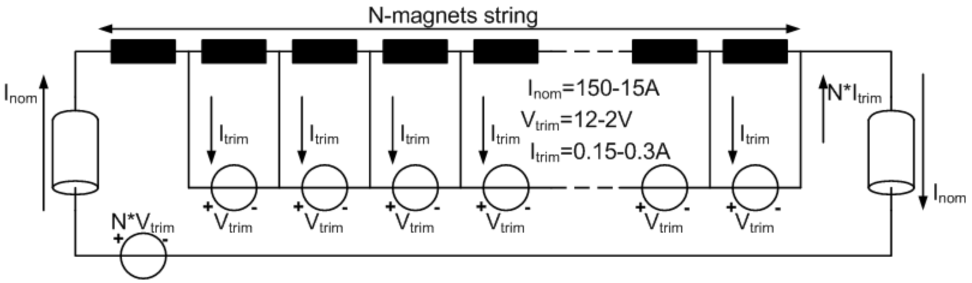


- **Failure tolerant** powering strategy required.
  - More than 20 failures can be tolerated in each accelerating sector if the current in failed magnets does not drop under 98% (**ref. Adli**).

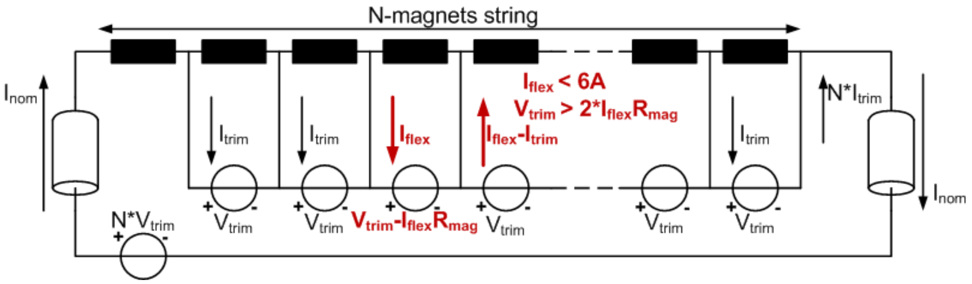
Example of Drive Beam Quadrupoles

Drive beam quads powering

- One big converter with serial connection of active trimmers approach. The main converter ratings depend on the number N of trimmers in series.
- N=[10-60], depending on the position in the lattice.
- Solution allows a serious reduction on cabling costs and power consumption.
- **Flexibility in magnet currents profile** is guaranteed and a negative slope in current profile is reachable with only **dissipative trimmers**.

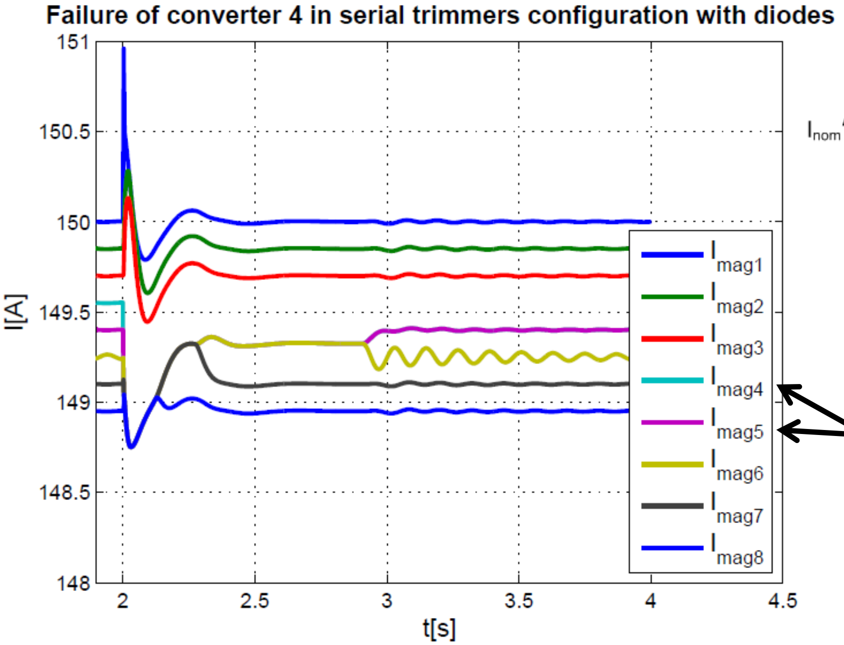


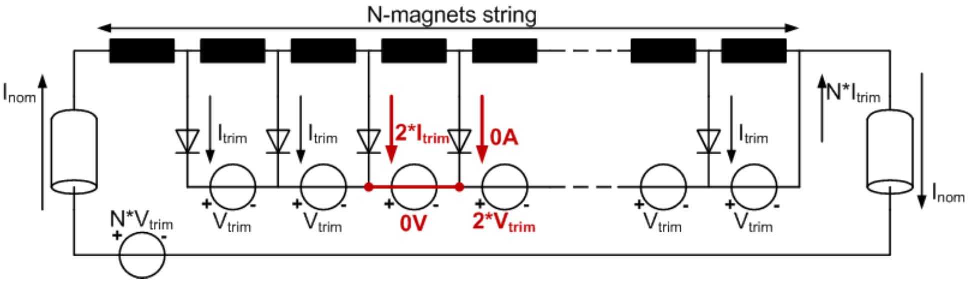
- **Flexibility on one magnet current** guaranteed for calibration purpose.



Failure tolerant operation

- Trimming cables are implemented with serial diodes (only dissipative trimming).
- When a **failed trimmer is short-circuited**, the diode does not allow the current magnet to fall lower than the following one.
- Open circuit case affects all previous magnets.
- Few seconds are needed for stabilising the currents in the remaining magnets.

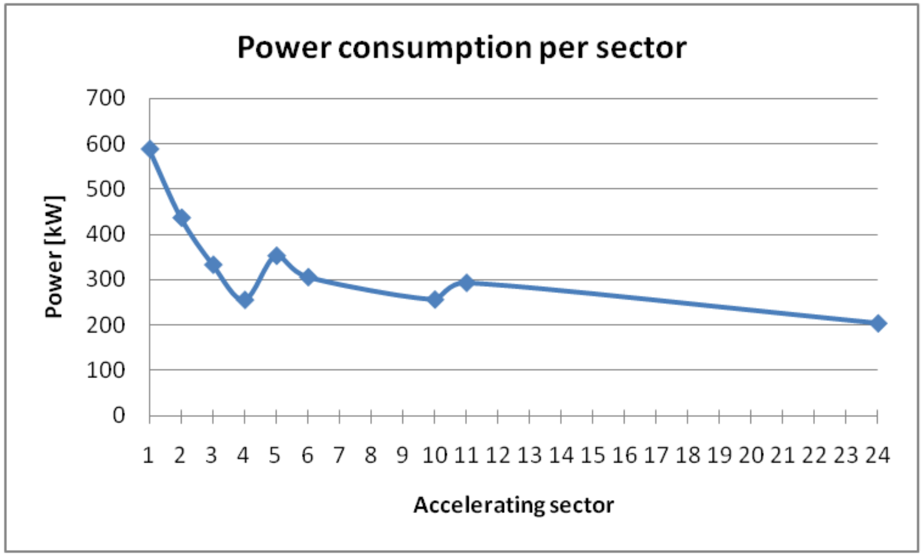


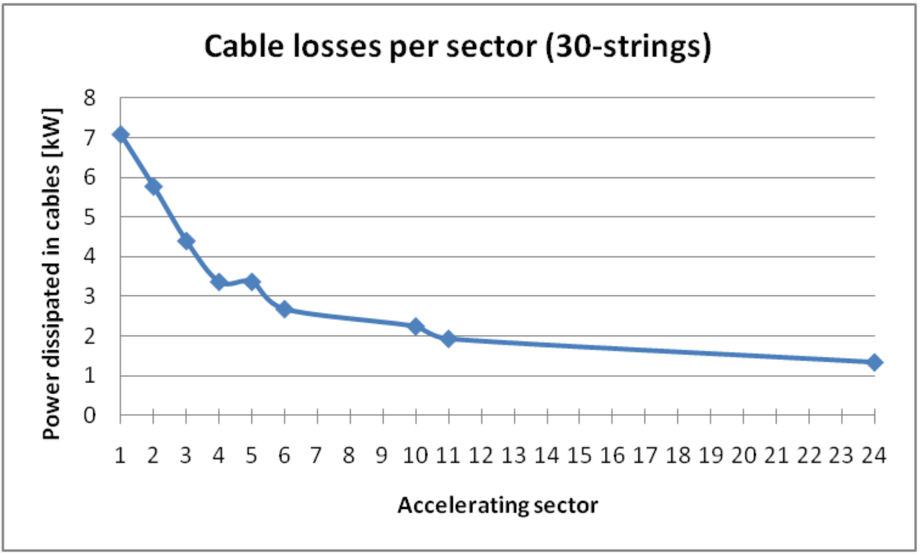


$I_{mag4} = I_{mag5}$ after trimmer 4 failure

Power consumption

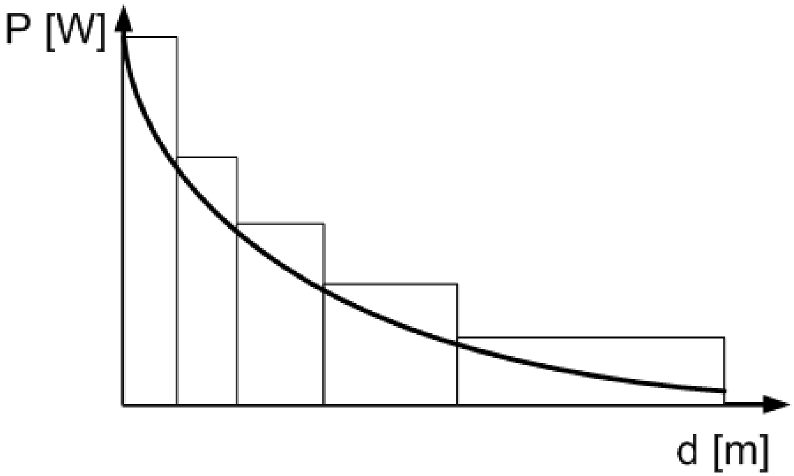
- The power consumption of the whole linac is not distributed linearly. There is a factor of three between the first accelerating sector and the last.
- **Total power consumption per linac: 7 MW.**
- The losses in the cables, meaning the dissipation to air reach 7 KW in the first sector (7.95W/m mean value along the tunnel, 19W/m maximal value).

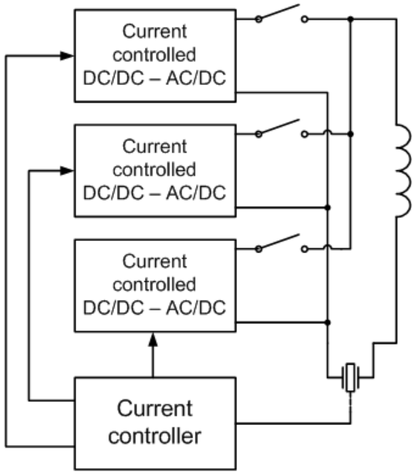




Reliability of the decelerator

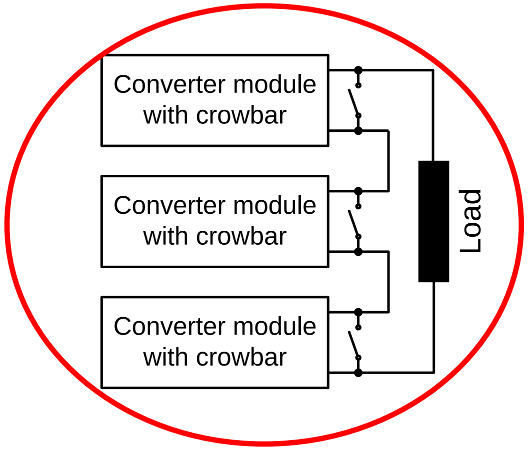
- Reliability of solutions using trimmers depends on **the reliability of the main converter**.
- (N+1) redundancy is achieved using a modular solution. The number of modules depends on current need for the magnets.
- The whole lattice can be assembled with one type of modules only.
- Power profile along the tunnel is divided into powering regions defining converter families.

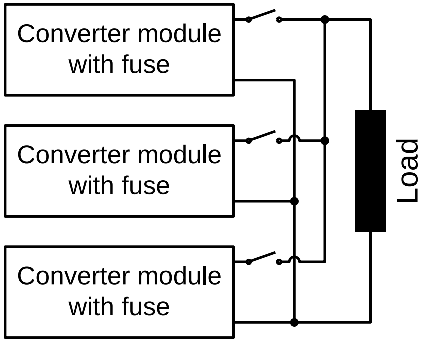


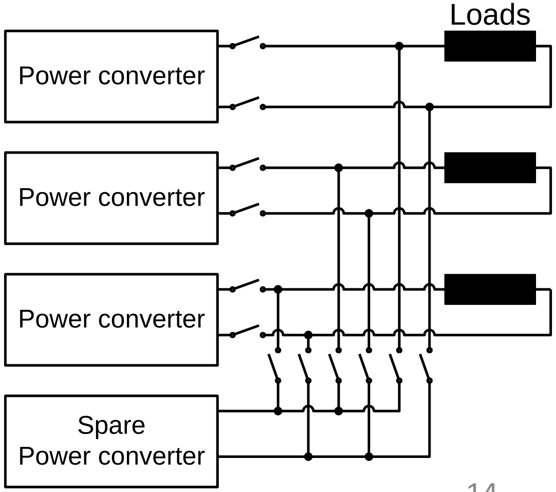


Modular/Redundant systems

- To increase the reliability of a power converter, use modularity and redundancy.
- However, adding modules has an opposite effect on reliability and proper bypass systems need to be carefully designed.
- Parallel configurations need typically a fuse or a breaker.
- Serial configuration need typically a crowbar (quite reliable).
- Hot swap approach need a complicated switching circuit (manual or semiconductors).
- Parameter κ, standing for the probability of saving a failure, needs to be assessed for each configuration as a factor of technology, design and operation.
- Belief that κ is maximal in a serial configuration.

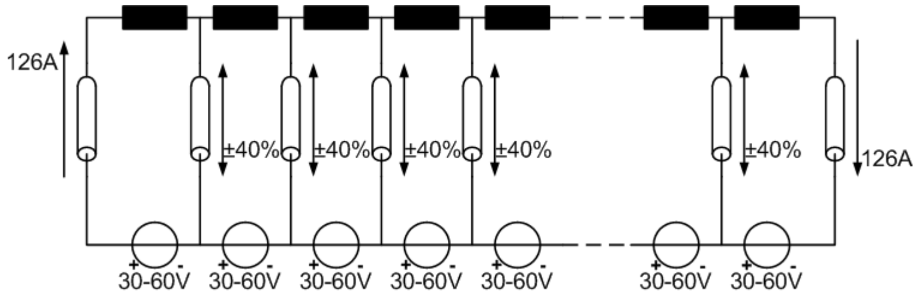




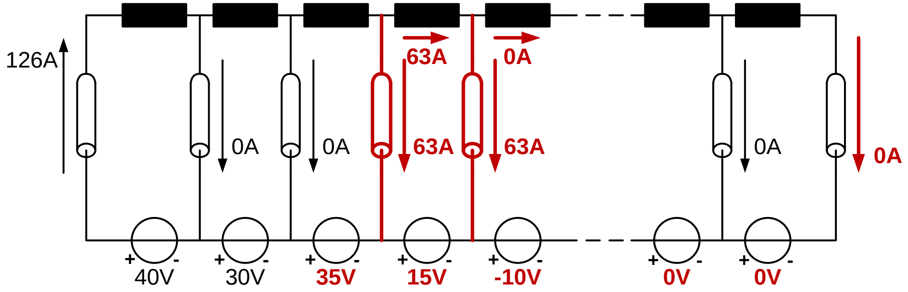


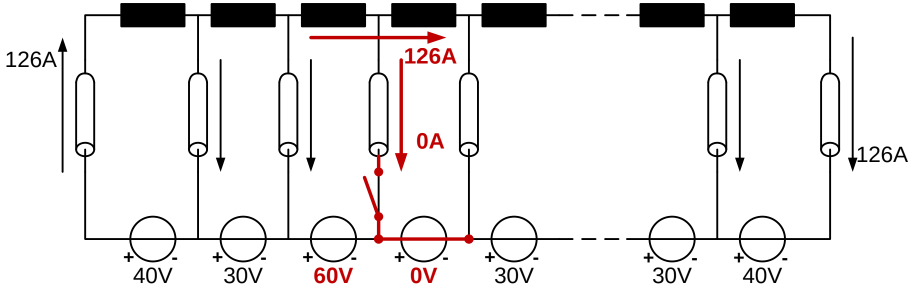
Main beam quads powering

- **Serial connection of converters** approach, voltage sources with regulated output currents. (Converters ratings : 126A, 30V for types 1-2, 60V for types 3-4).
- **Failure tolerant operation** if two consecutive magnets can share the same current.
- Around nominal operation**, flexibility in magnet currents** is guaranteed**.**



- **Flexibility in magnet sequence** requirement also guaranteed.
- The second quadrant in the converters can be implemented with only dissipative components to dump the inductive energy during transients.





Machine Availability

Composite MTBF model

- Failure rates $\mu = MTBF^{-1}$ combined with the same association rules as impedances.
- Reliability calculated as a function of failure rate and mean time between preventive maintenance.
- Expected down time has a linear relationship to the energy to be reached.

$$R(t) = e^{-t\mu}$$

$$R_{LINAC} = R_{CTRL} R_{PC} R_{STRING}$$

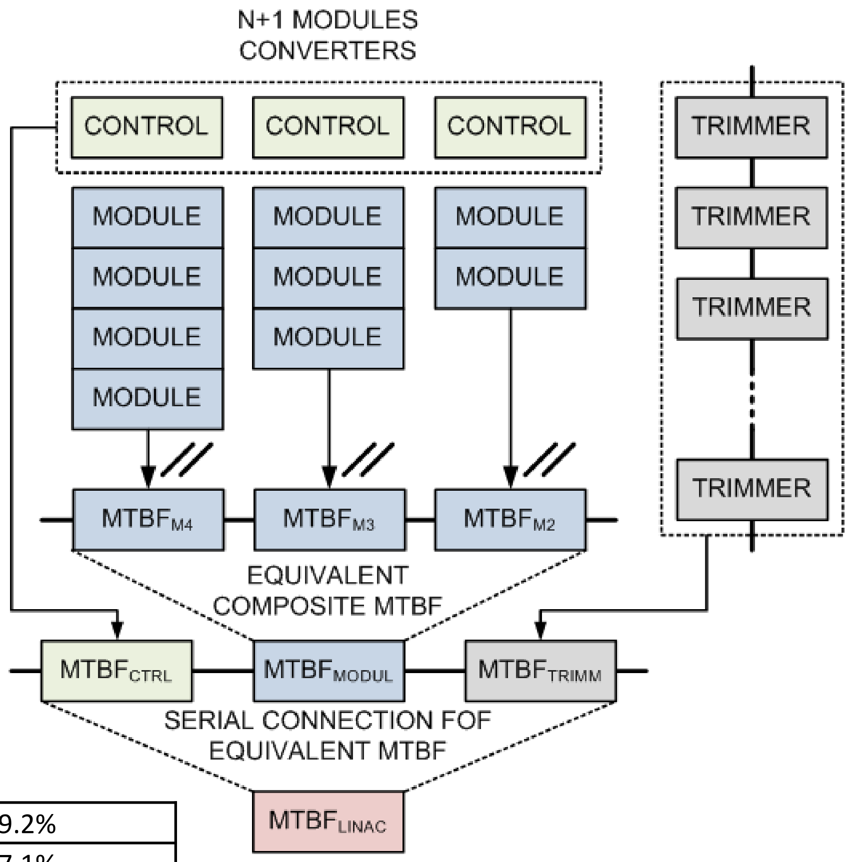
$$R_{CTRL} = R_{CONTROLLER}^{nb\_conv}$$

$$R_{PC} = \prod R_{Mi}$$

$$R_{Mi} = \sum_{i=0}^{1} \binom{N+1}{i} \left[R_{MODUL}\right]^{N+1-i} \left[1 - R_{MODUL}\right]^{i}$$

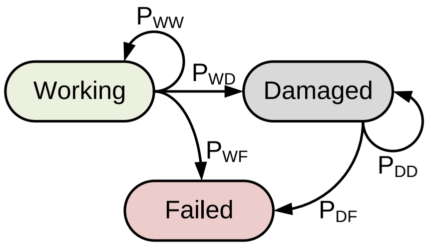
$$R_{STRING} = \sum_{i=0}^{\Phi_{TRIMM}} \binom{N_{TRIMM}}{i} R_{TRIMM}^{N_{TRIMM}-i} \left(1 - R_{TRIMM}\right)^{i}$$

Reliability of Power converters **with** redundancy (t=100days)	99.2%
Reliability of Power converters **without** redundancy (t=100days)	57.1%
Reliability of trimmers **with** failure tolerance (t=100days)	71.8%
Expected down time (3TeV)	**8.5%**
Expected downtime (500GeV)	1.5%



Markov chains (Drive Beam)

- Each converter defined as a set of states with probability transitions after each time step R.
- Failure probabilities defined as a function of failure rate and time step.
- The failure probability of the whole system is a combination of all components probabilities.



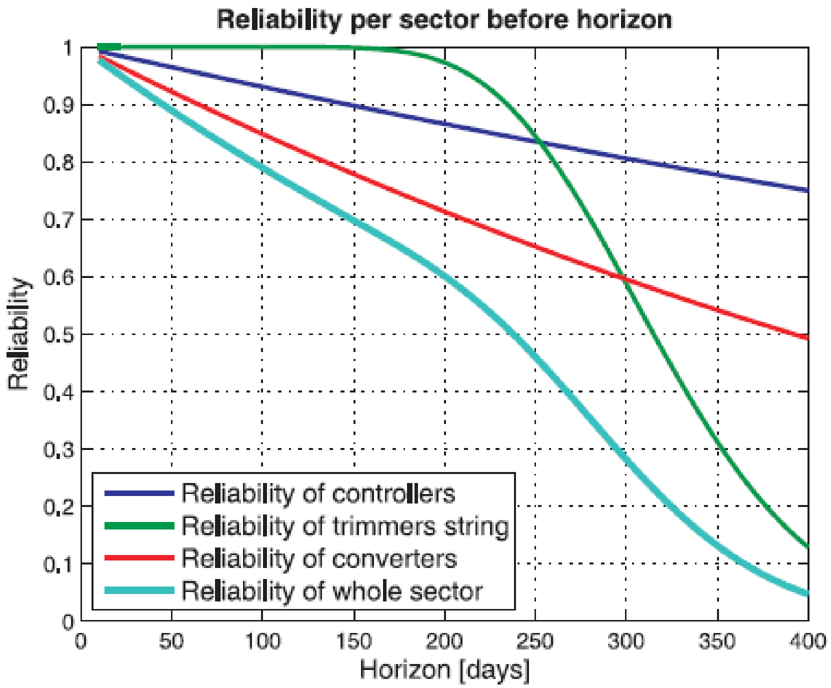
$$P_m = \begin{pmatrix} P_{WW} & P_{WD} & P_{WF} \\ 0 & P_{DD} & P_{DF} \\ 0 & 0 & 1 \end{pmatrix}$$

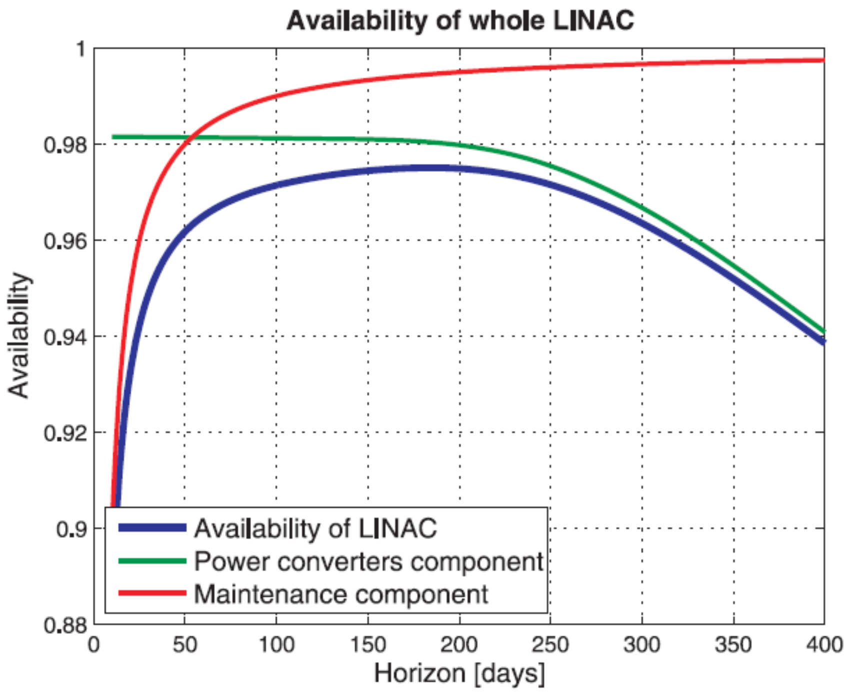
$$\begin{aligned} P_{WD} &= 1 - e^{-m\mu_{MODUL}(1-\kappa)R} \\ P_{WF} &= 1 - e^{-m\mu_{MODUL}\kappa R} \\ P_{WW} &= 1 - P_{WD} - P_{WF} \\ P_{DF} &= 1 - e^{-(m\text{-}1)\mu_{MODUL}R} \\ P_{DD} &= 1 - P_{DF} \end{aligned}$$

Individual m-modules-PC failure	$f_m=[P_m^{h/R}]_{1,3}$	$f_2=0.18\%, f_3=0.29\%, f_4=0.44\%$
At least one m-module-PC fails	$F_m=1-(1-f_m)^{Nm}$	$F_2=0.36\%, F_3=4.65\%, F_4=5.13\%$
At least one PC fails	$F_{PC}=1-P(1-F_m)$	$F_{PC}=22.4\%$
Individual controller failure	$f_{ctrl}=1-(e\text{-}^{mctrl})^h$	$f_{ctrl}=0.49\%$
At least one controller fails	$F_{ctrl}=1-(1-f_{ctrl})^{Npc}$	$F_{ctrl}=13.9\%$
More than F_{TRIMM} out of N_{TRIMM} fail	$F_{TRIM}=\text{Poisson}(hT_F)$	$F_{TRIM}=2.49\%$
Individual accelerating sector failure	$F_{SECTOR}=1-(1-F_{PC})(1-F_{ctrl})(1-F_{TRIM})$	$F_{SECTOR}=24.3\%$

Applying the Markov technique

- The expected number of failures is given as a function of horizon time (namely days between preventive maintenance).
- Down time is a function of number of failures and MTTR (Mean time to repair) and considered the down time of the maintenance days.


Reliability per sector before horizon


Availability of whole LINAC

CLIC Powering availability

- Comparison of ‘doing nothing’ with ‘appropriate redundant solutions’ (ie hot swap and N+1 where appropriate)

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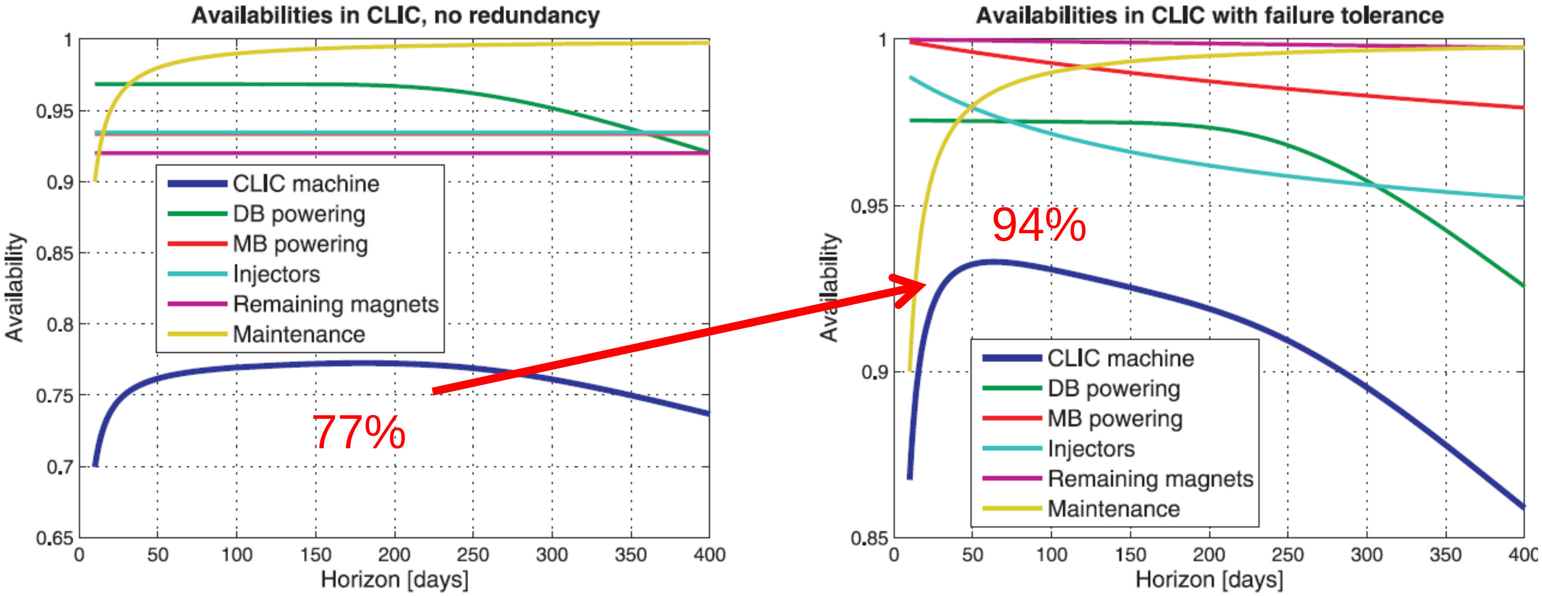

Conclusion

- Magnet powering satisfies the **safe by design** criteria of $\tau >> 2\text{ms}$

- By evaluating the powering needs with machine optics and machine protection constraints, an optimised powering architecture can be found
- As an example, a possible solution for the quadrupole powering of the drive beams has been shown and a fault tolerant powering scheme has been proposed
- Use of the proposed availability and reliability analysis tools can be extended across other areas of the machine powering to validate technical decisions for machine protection and machine availability needs

- With the failure tolerant system, a proper choice of hot spares, and preventive maintenance campaigns, machine down time due to power converters is a few %.

References:

•*Powering the main linac implications,* Daniel Siemaszko, Serge Pittet - EDMS 1075533
•*Main beam magnets powering strategy* Daniel Siemaszko, Serge Pittet - EDMS 1060595
•*Powering strategy for the main beam quadrupoles in the main linac*, Daniel Siemaszko, Serge Pittet - EDMS 1095022
•*Drive beam magnets powering strategy* Daniel Siemaszko, Serge Pittet - EDMS 1064316
•*Failure tolerant operation and powering strategy for the drive beam quadrupoles*, Eric Adli, Daniel Siemaszko - EDMS 1095023
•*Reliability requirements for* powering CLIC, Daniel Siemaszko - EDMS 1095024
•*Drive beam RF injector*, Daniel Siemaszko, David Nisbet - EDMS 1083575
•*Existing pulsed power modulator topologies*, Carlos De Almeida Martins – INDICO 87528