Reliability and Component Ageing with highlight on Electrolytic capacitors and Batteries

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EDMS 2899178

7th Workshop on Power Converters for Particle Accelerators – 31st May/2nd June 2023 – MedAustron

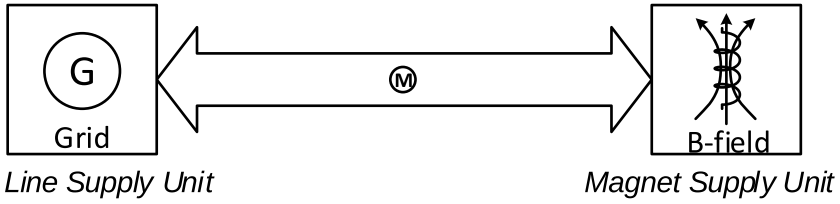
On the Menu

- Why Energy Storage @CERN?
- SIRIUS family case: Electrolytic capacitors
- HL-LHC 18 kA case: Lithium Titanate (LTO) batteries
- A possible outlook on the future

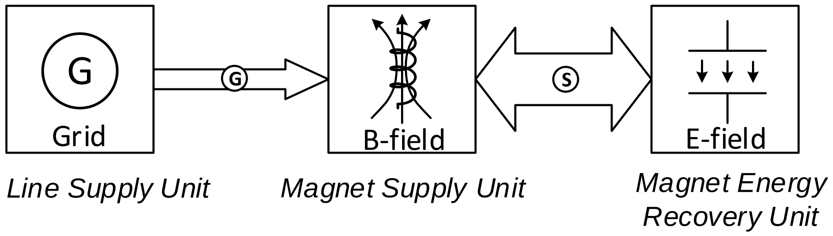
Why Energy Storage?

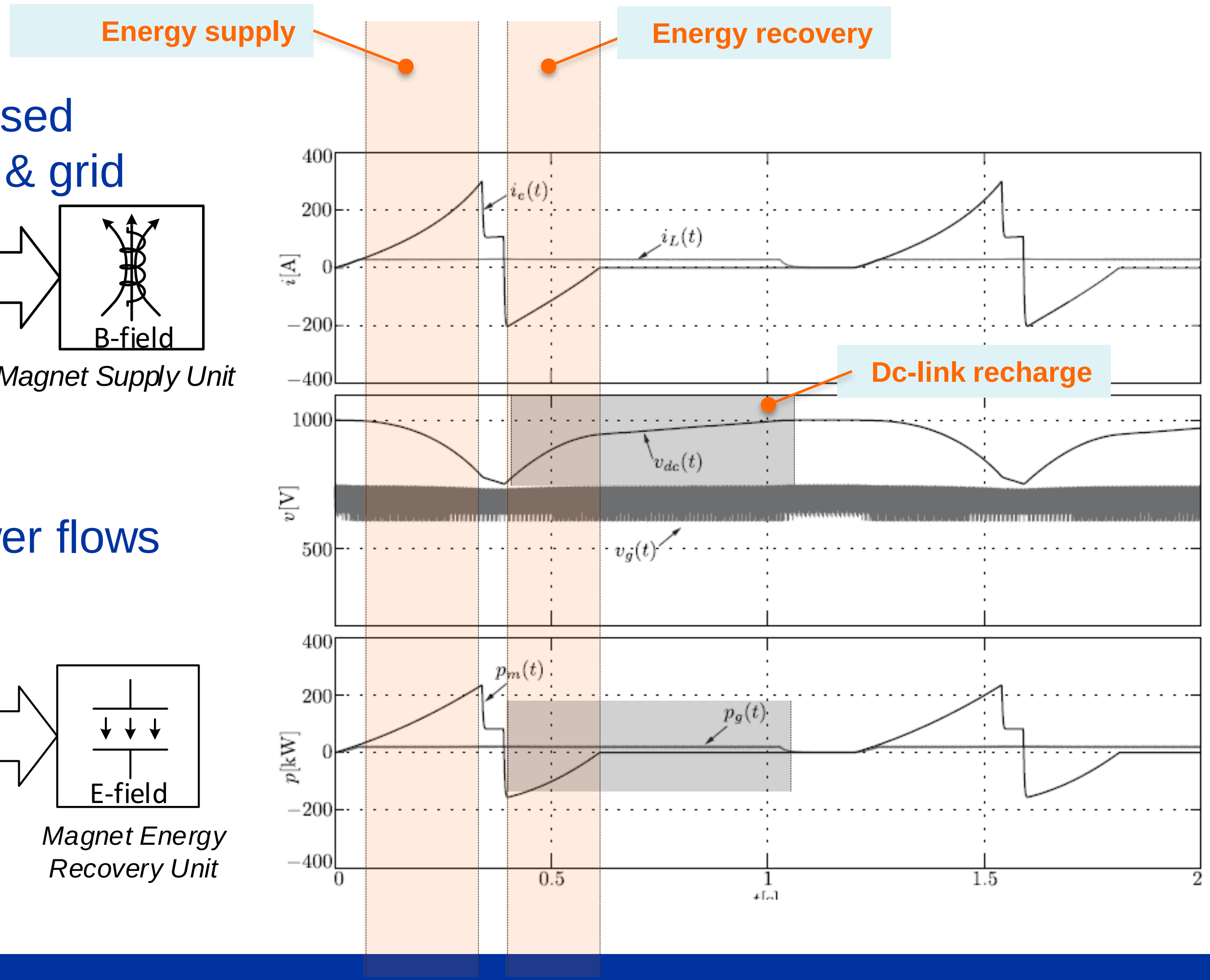
Adding an Energy Storage System (ESS)

"Before" with no ESS – imposed power flow between magnet & grid



With ESS – flexibility on power flows and ESS dimensioning

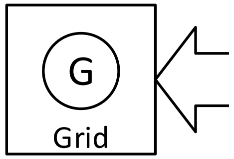




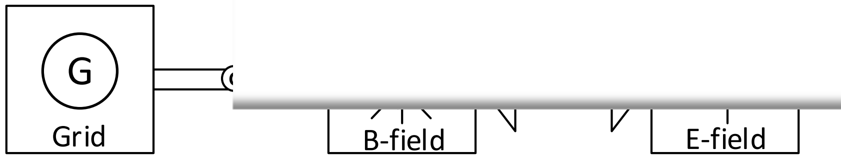
Why Energy Storage?

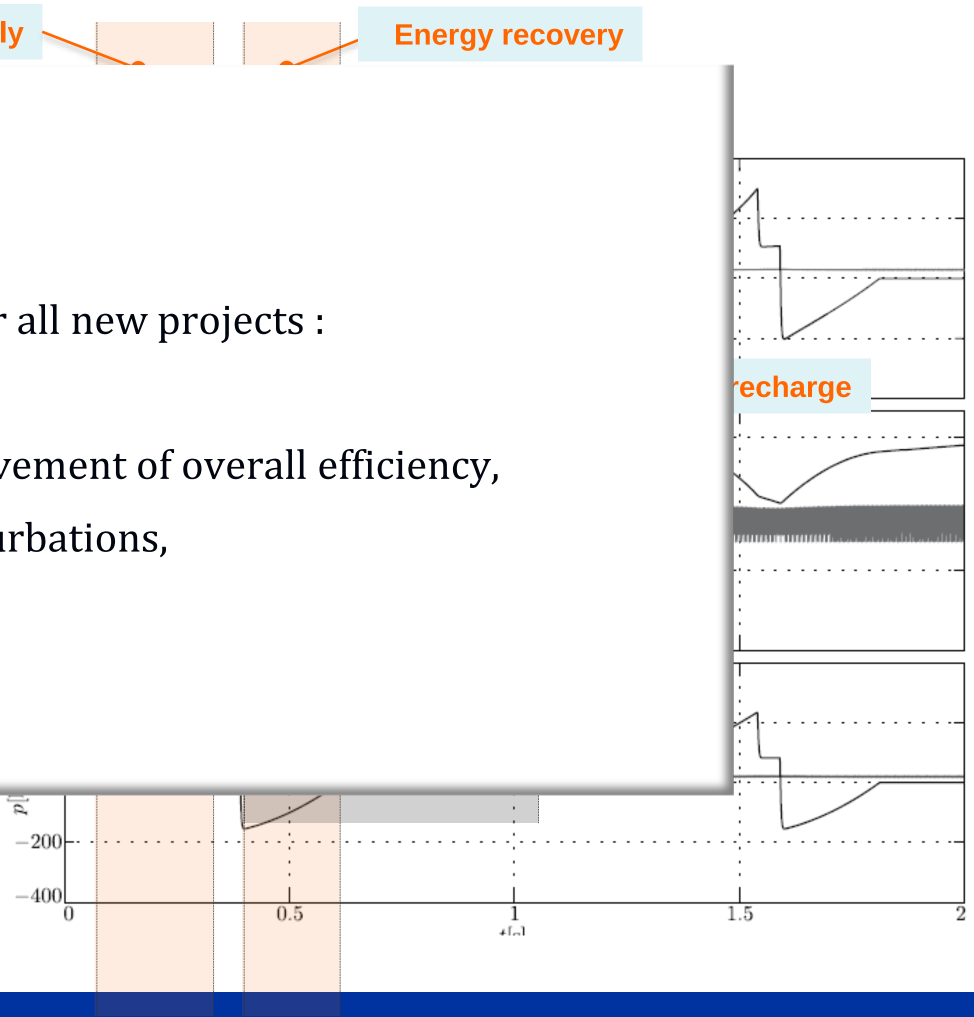
Adding an Energy Storage System (ESS)

Today with
flow betwee



With ESS –
and ESS di





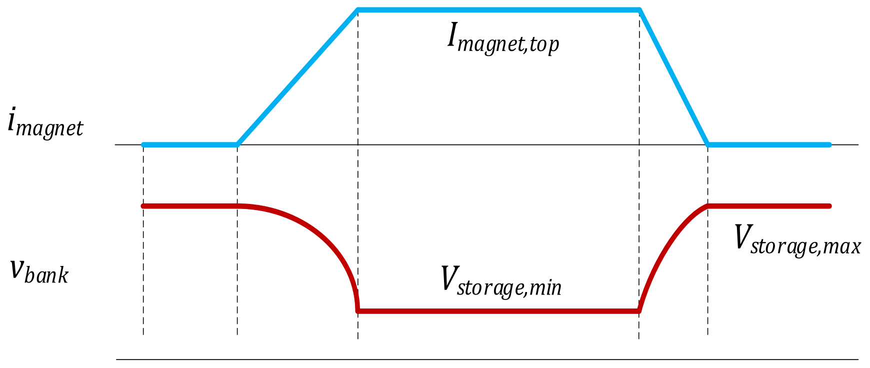
Philosophy considered @CERN for all new projects :

- Local Energy recycling,
- Peak Power shaving and improvement of overall efficiency,
- Increase immunity to grid perturbations,

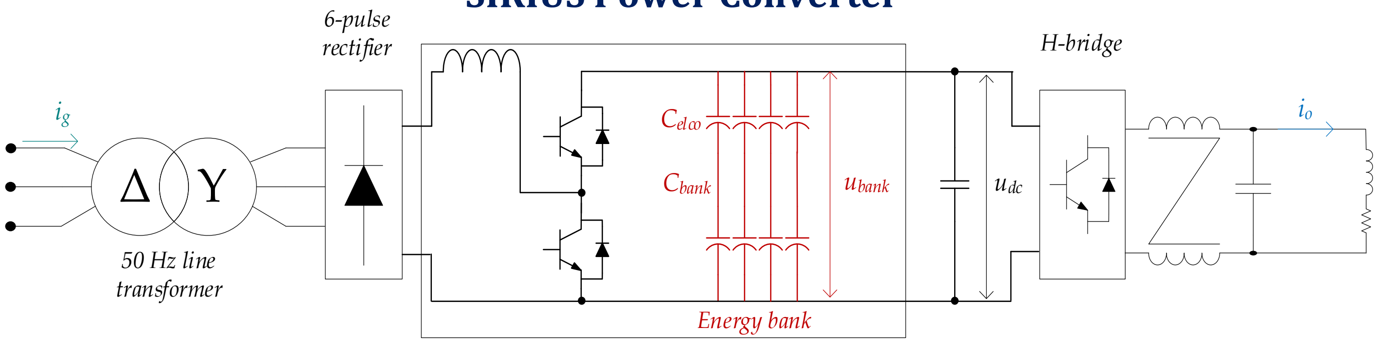
SIRIUS family [200…800 kW] for warm magnets

SIRIUS Converters at CERN

- For Proton Synchrotron Complex
  - 200 SIRIUS in operation since 2020
  - 550 power racks
  - 60 MW of peak power available for users
  - 6 MVA of grid Power
- SIRIUS converter with Boost Charger in DC-link
  - Peak power limitation from Electrical Grid
  - Energy Recovery in DC link / Energy Storage Banks
  - Modularity: possible connections of up to 4 interleaved bricks in series or parallel configuration



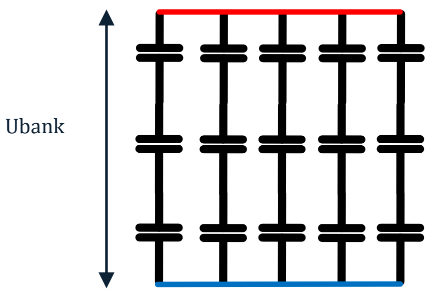
SIRIUS Power Converter

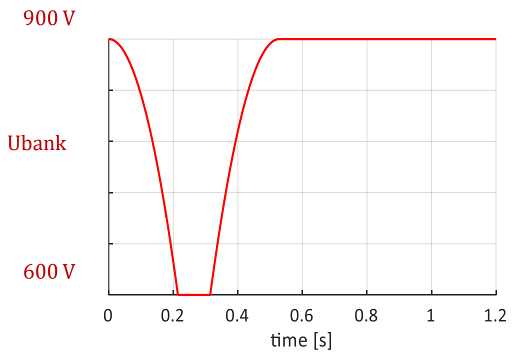


SIRIUS Industrialisation

Energy Storage Banks with Electrolytic Capacitors

- Energy bank = (3 x 5) x C_{elco}
  - C_{elco} = 29 mF (+- 20%) / 400 V
- 300 million cycles over 15-y lifetime
  - Charge / discharge every 1.2 s
- DOD of 100V per capacitor ($V_{max,op}$ = 300V)
- 800 energy storage banks
- 12 000 electrolytic capacitors
- 24 MJ of energy stored





Capacitors integration in Energy Bank

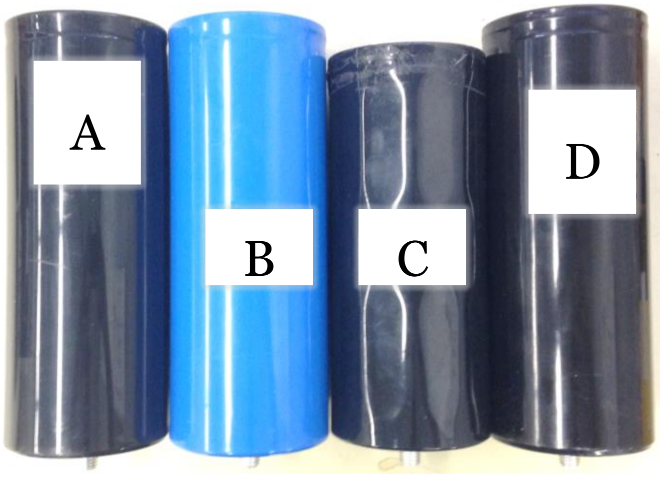
Energy Banks integration in SIRIUS

Market status for 29 mF / 400 V in 2018: Single off-the-shelf, catalog capacitor!

Electrolytic Capacitors Tests in 2018

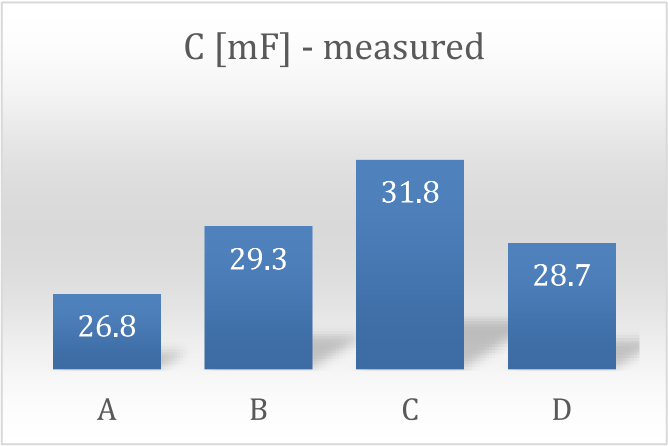
One catalogue capacitor

Three custom-design capacitors

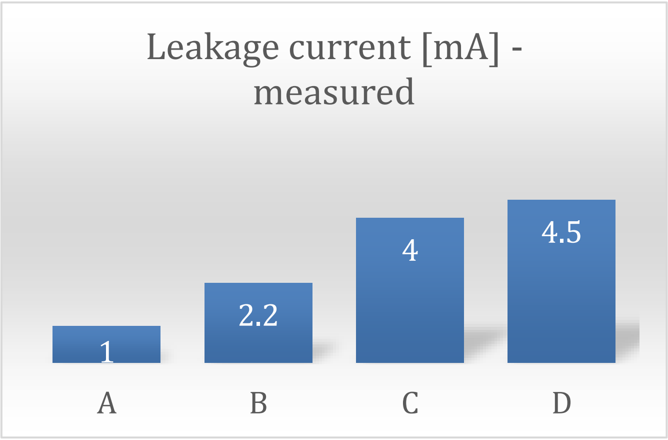


Accelerated aging protocol?

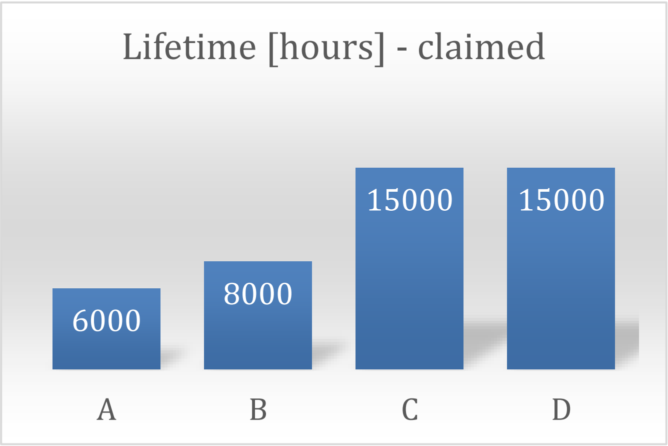
Failure modes in cycling app?



Capacitance – the more the better?



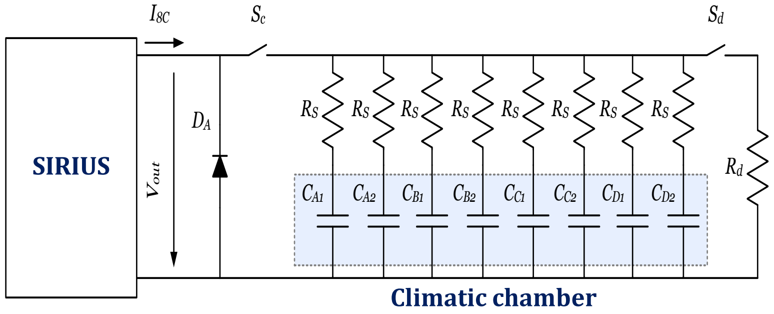
Leakage current – the smaller the better?



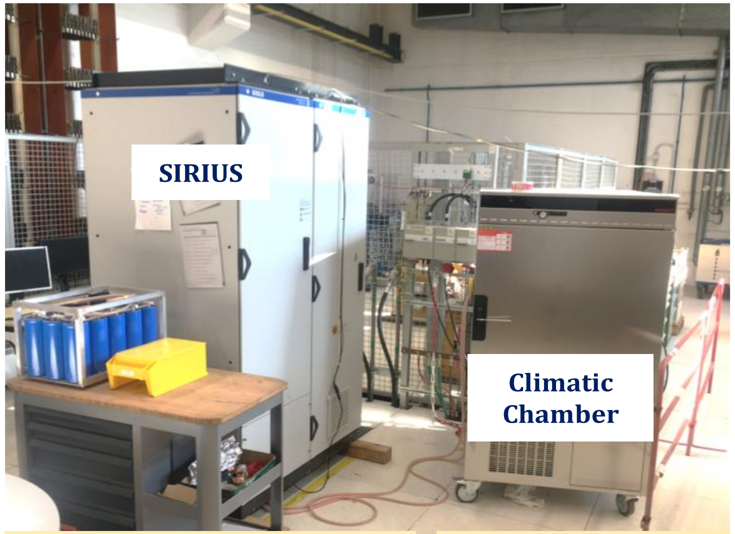
Lifetime – the more the better?

Test set-up and Capacitors Characterisation

Set-up diagram



Test set-up



SIRIUS as a voltage source | Capacitor as a load

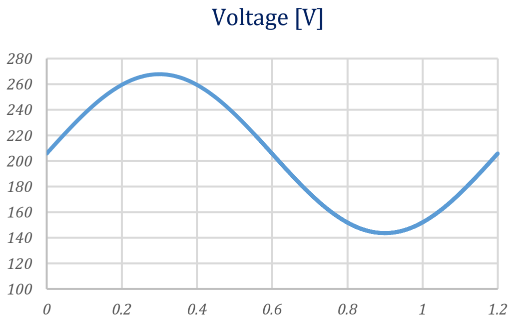
Thermal chamber for ambient temp control

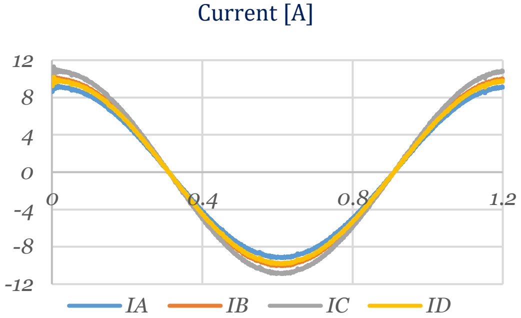
Capacitors samples

2 samples / supplier

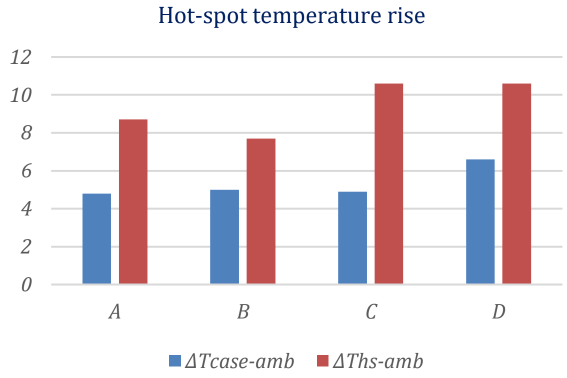
1 with TC in hot-spot

Low-frequency characterisation waveforms with SIRIUS

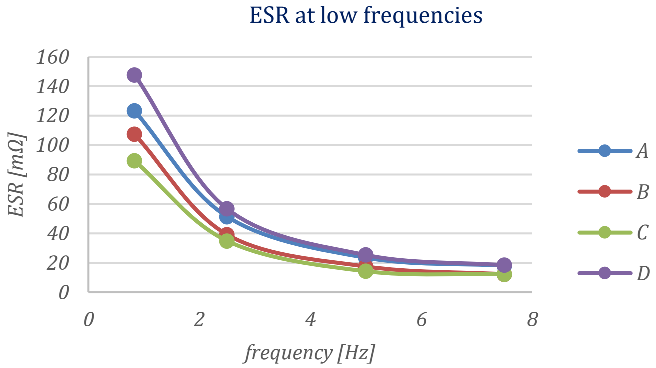




Characterisation results



Internal temperature rise < 15 °C



ESR increases sharply at low frequencies

→ behavior of Al_2O_3 dielectric!

Accelerated Aging – How to Accelerate?

- Use real excitation waveform (1.2 s)
- Push the voltage to the max: 400 Vdc
- Push the current to the max: I_{test}= 16 Arms (I_{op} = 6 A_{rms})
- Push the temperature to the max:
  - $T_{amb,test}$ = 70 °C ($T_{amb,op}$ = 40 °C)
  - $T_{hs,test}$= 85 °C ($T_{hs,op}$ = 45 °C)
- End-off life criteria:
  - ESR > 2 x $ESR_{initial}$
  - C < 0.8 x $C_{initial}$
  - IL > 1.5 x $Il_{initial}$ (too much constraining?)
  - Destruction of capacitor

Arrhenius equation for lifetime

$$L = L_0 \times 2^{\frac{T_{hs\_rated} - (T_{amb} + \Delta T_{hs-amb})}{10}} \times \left(\frac{V_{rated}}{V_{op}}\right)^{2.5}$$

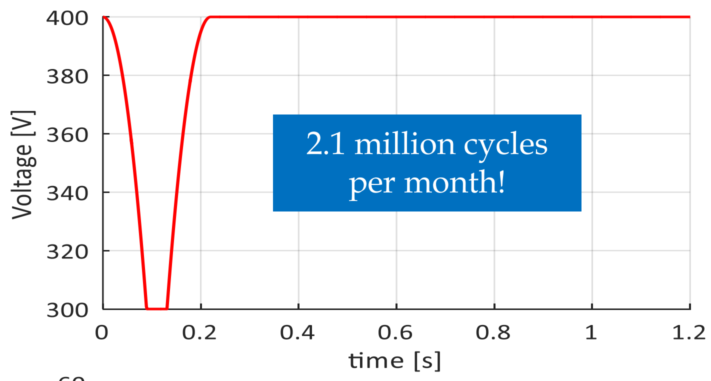
T_{hs_rated} = [90 – 95] °C

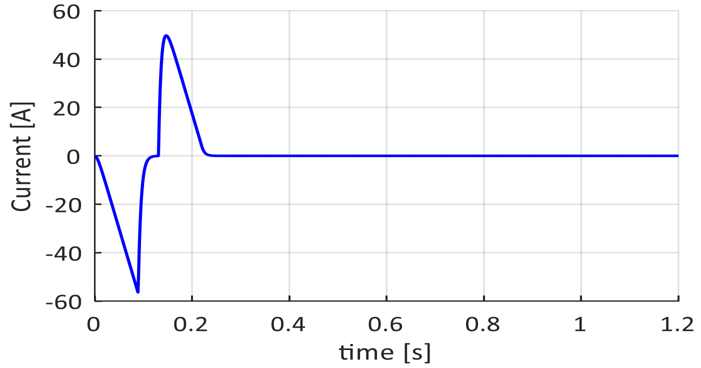
T_{amb} – ambient operating temperature

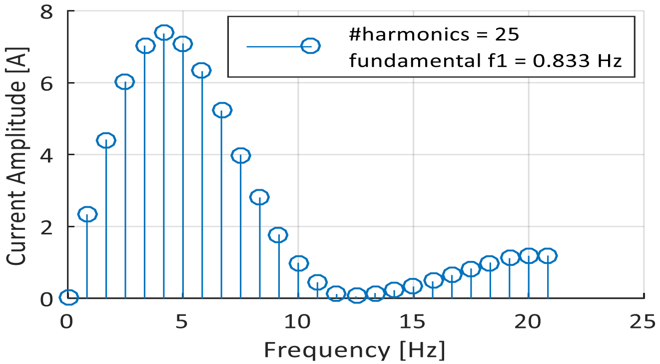
$\Delta T_{hs\text{-}amb}$ – ambient to hot-spot (core) temperature rise

V_{op} – operating DC voltage

V_{rated} – rated DC voltage





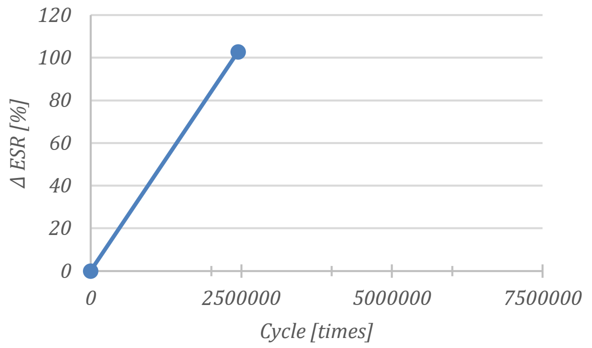


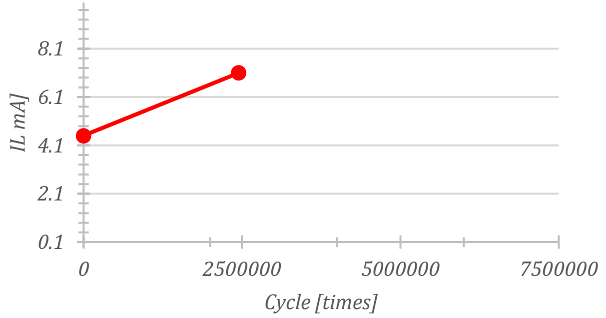
CERN application : Stressing of capacitor at low frequency means stress of Al_2O_3 dielectric!

Accelerated Aging – Test Results

Capacitor D

End of life after 2.4 million cycles
End-of life for 2 samples: ESR and IL

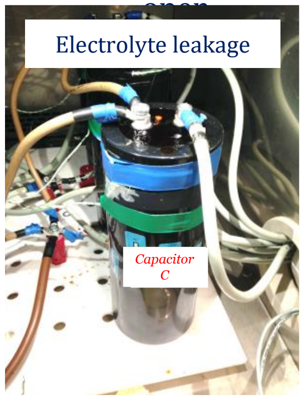




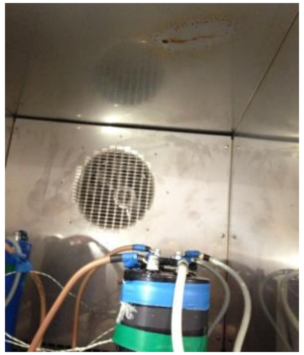
Failed

Capacitor C

End of life after 5.2 million cycles
End-of life, 2 samples: safety vent



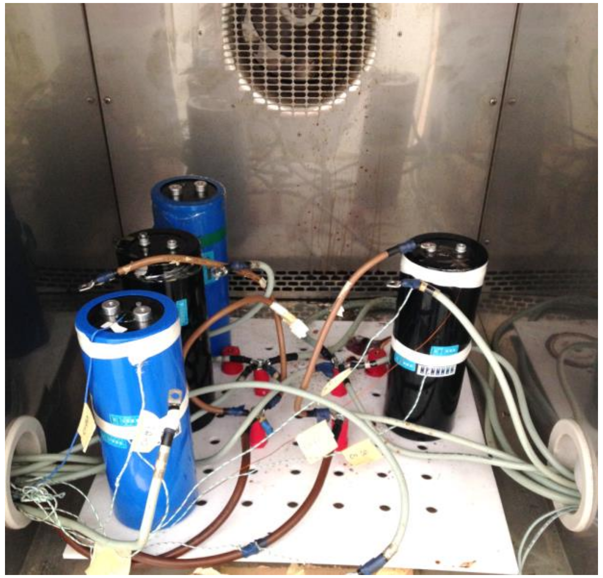
Electrolyte projection

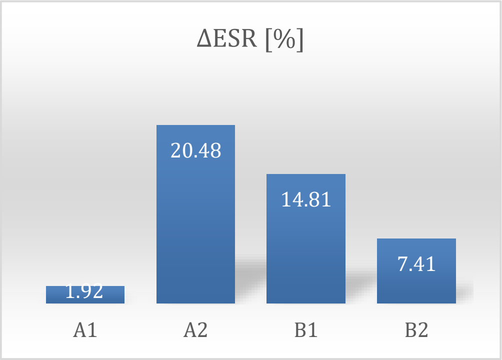


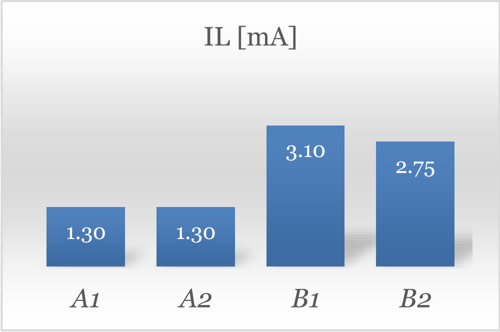
Failed

Capacitor A & B

No end-of-life after 7.5 million cycles



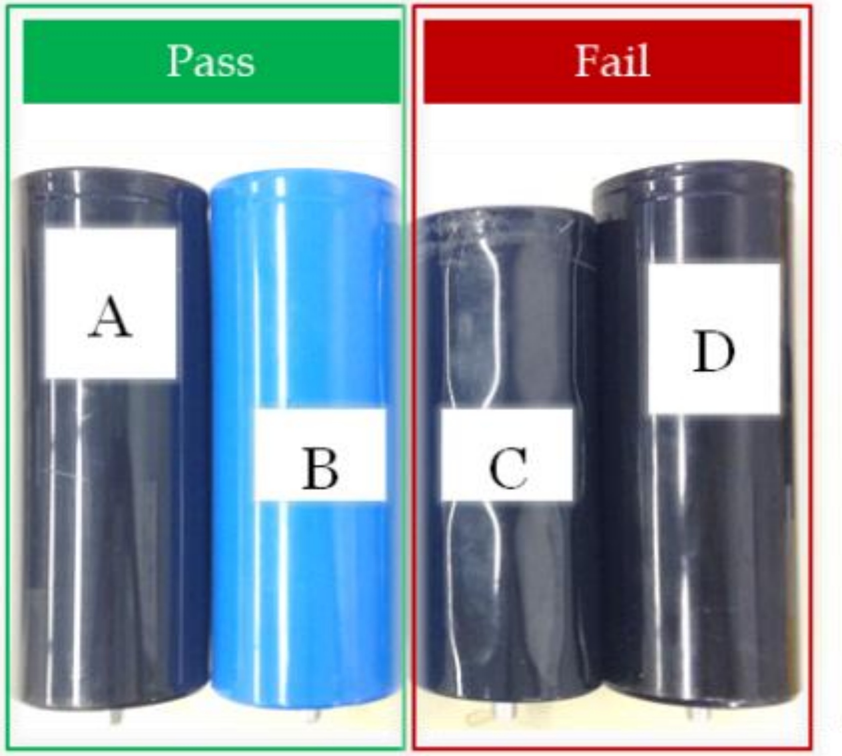




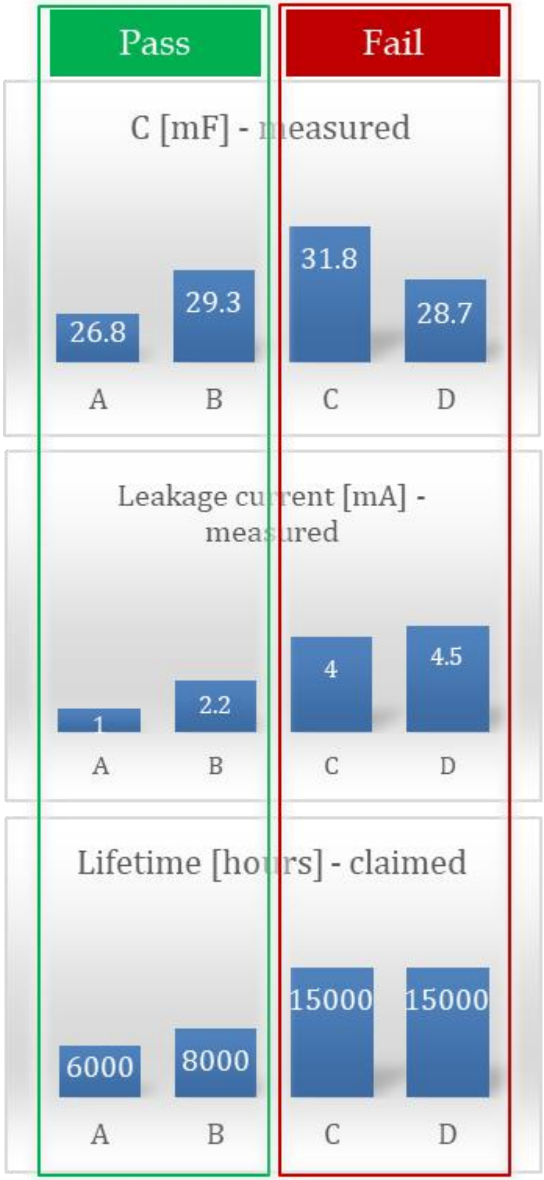
$IL_{A\text{-}initial}$ = 1 mA $IL_{B\text{-}initial}$ = 2.2 mA

Passed: 1x Catalog Capacitor + 1x Custom-design Capacitor

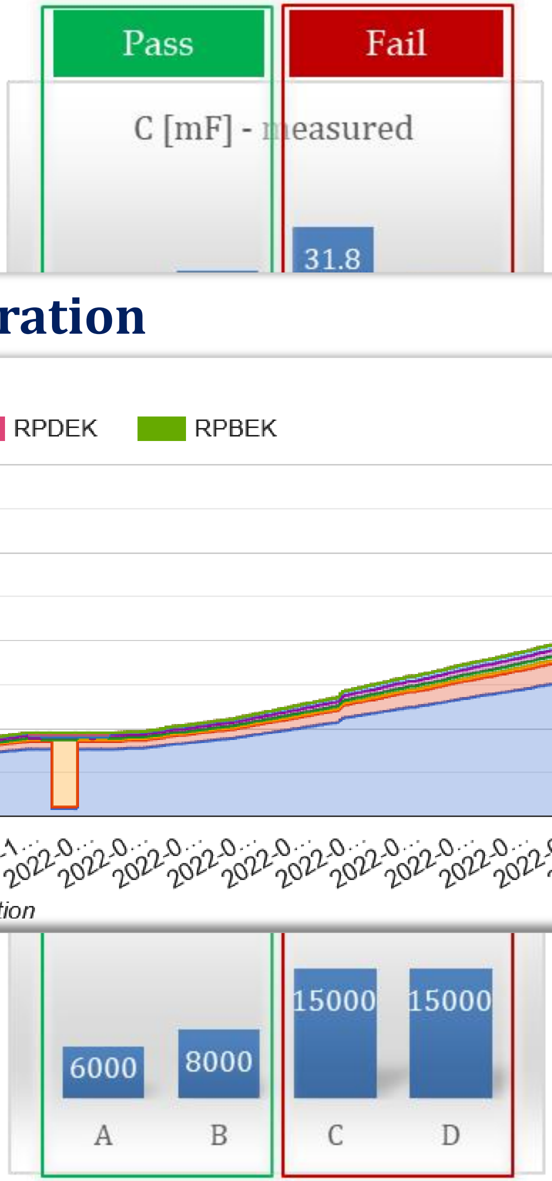
Results summary



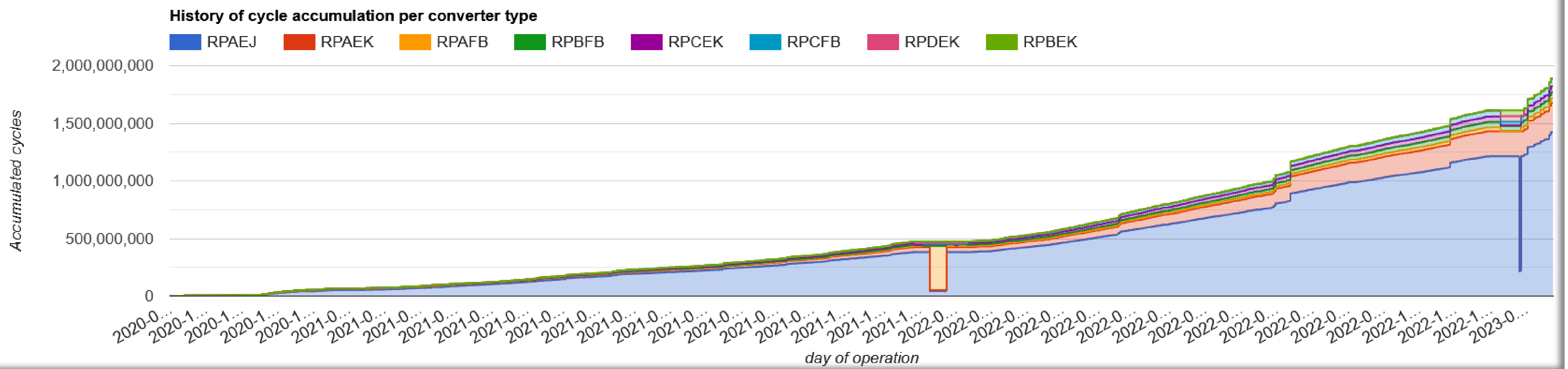
The datasheet lifetime estimation is no meaningful.



Results summary



SIRIUS family in operation



The datasheet lifetime estimation is no meaningful.

What's next? POLARIS: Energy recovery with 2Q-converter

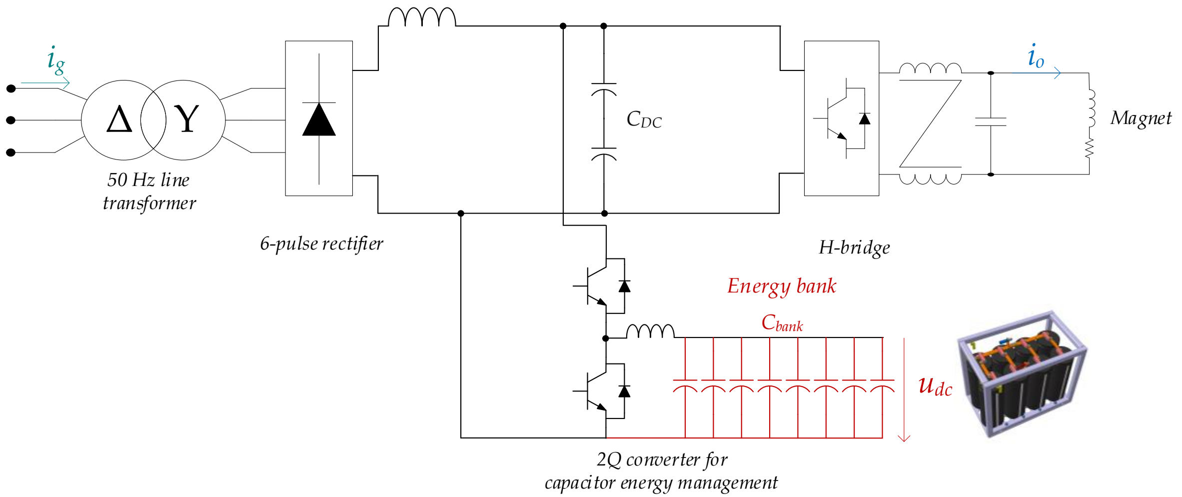
SPS and North Area Consolidation

- Phase I: 2026
- Phase II: 2032
- 450 POLARIS converters
- 1400 converter cabinets

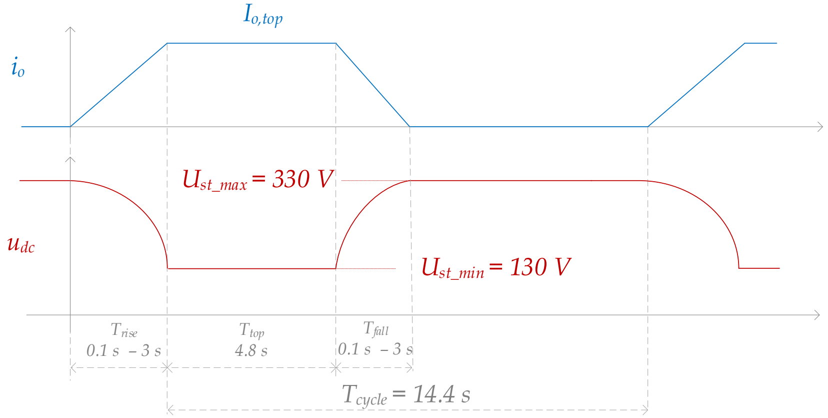
Energy bank

- C_{bank} = 10 x C_{elco}
- C_{elco} = 25 mF (-0 % / + 20%) / 400 V
- DOD of 200V per capacitor
- **34 million cycles** over 15-y lifetime
- 2 500 energy storage banks
- 25 000 electrolytic capacitors

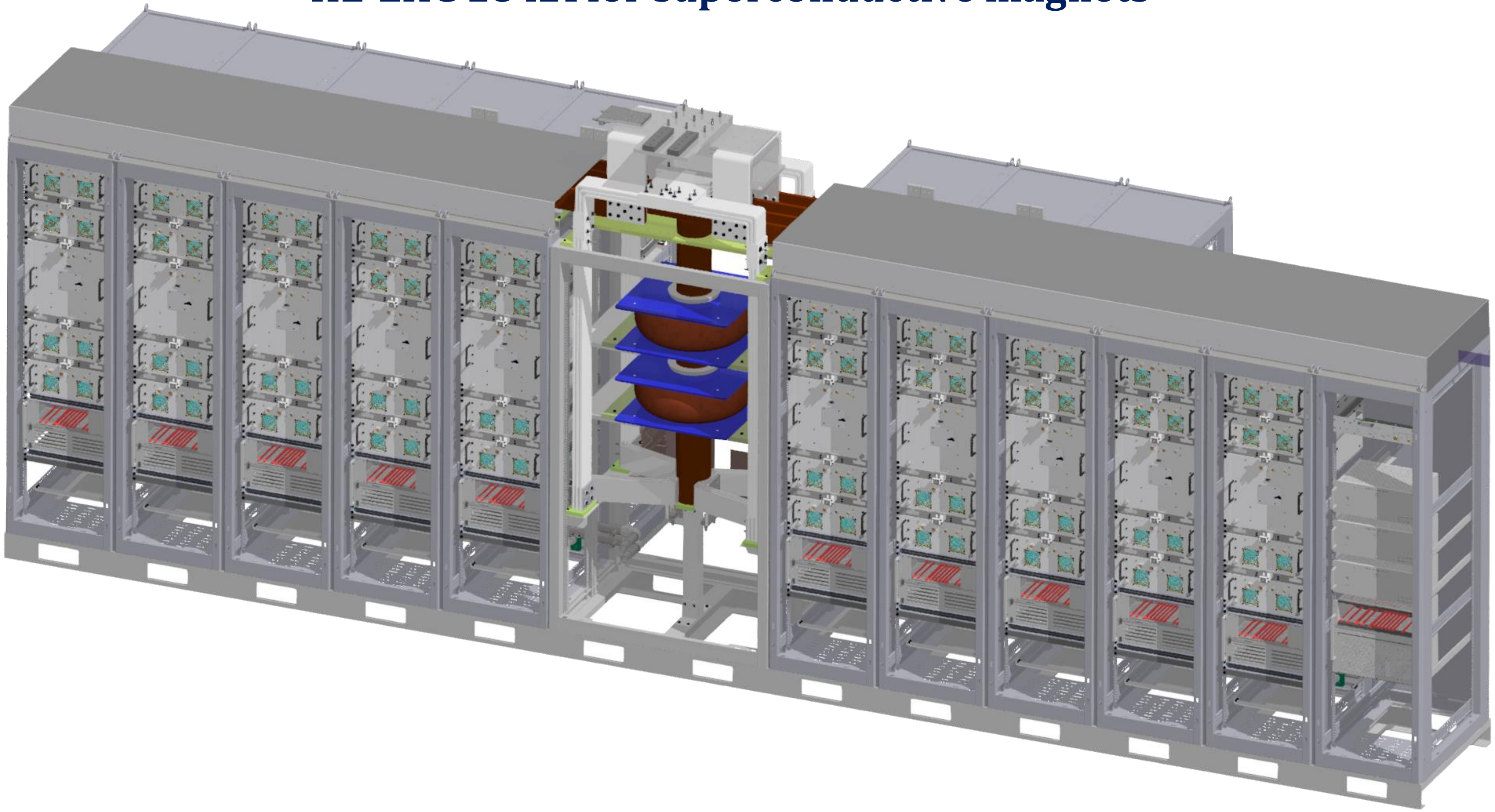
POLARIS with 2Q-converter for Energy Management



Long cycles (14.4 s)



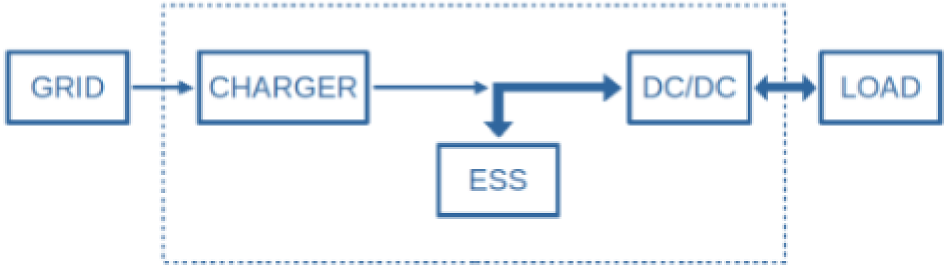
HL-LHC 18 kA for superconductive magnets



HL-LHC18kA-10V POWER CONVERTER TOPOLOGY

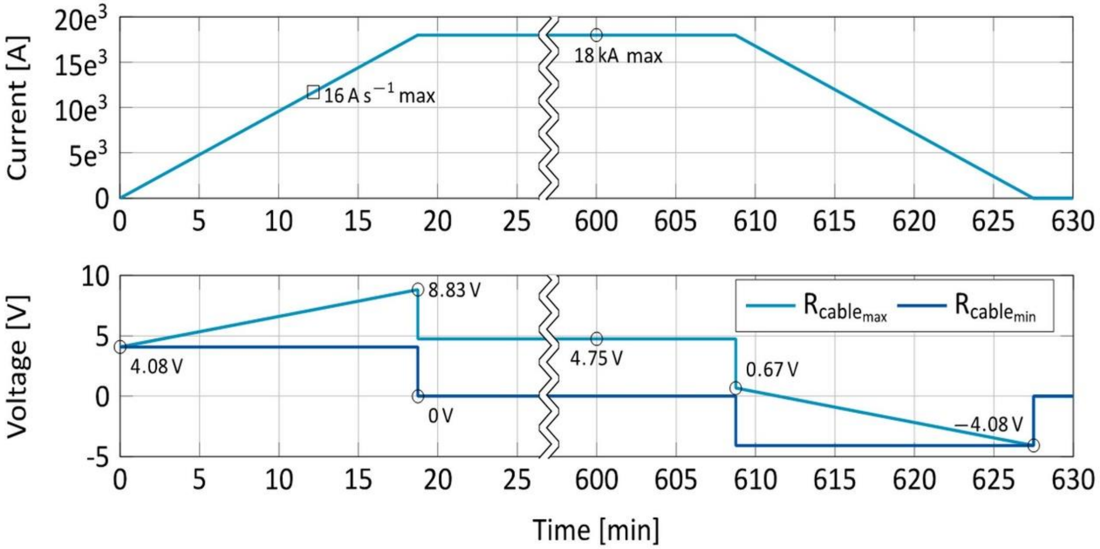
18 kA converter

- 10 x sub-converters of 2kA each (N+1 redundancy)
- Energy Storage System (ESS)
- 4Q DC-DC output stage
- Crowbar for energy extraction



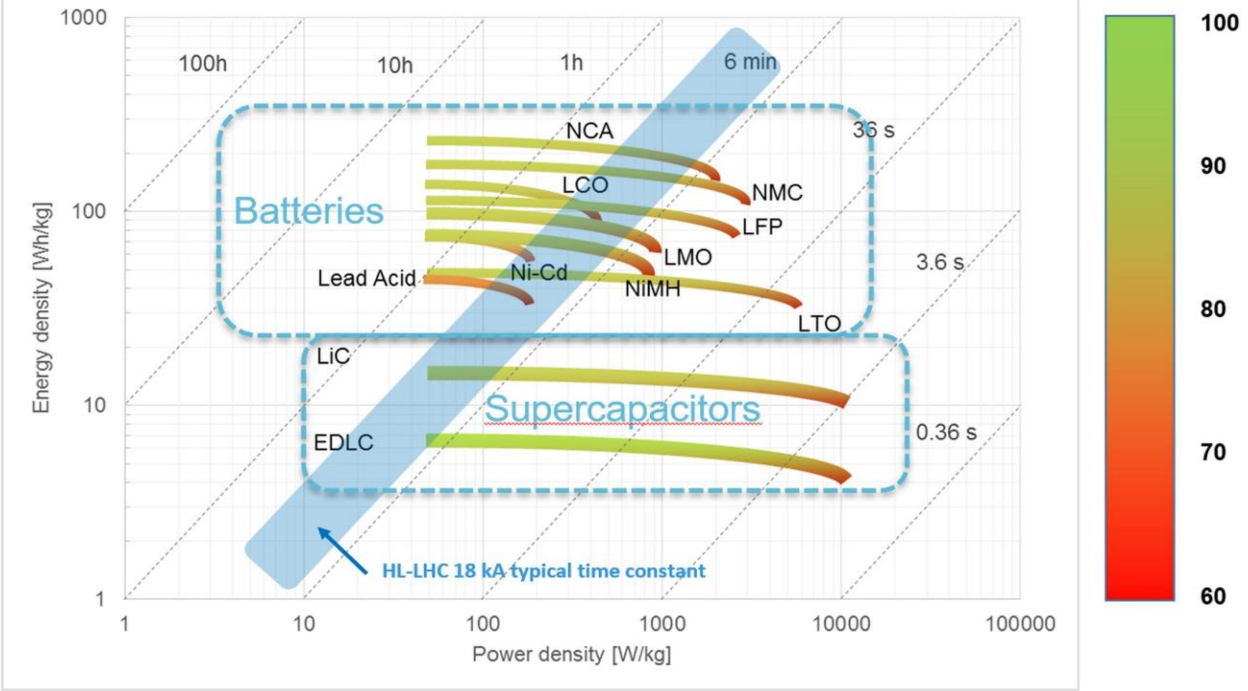
4 Q DC-DC output stage

- 8x H-bridges in parallel per sub-converters -> interleaving
- 960 MOSFETs with TO-220 package for the whole converter
- Simple topology, good efficiency.

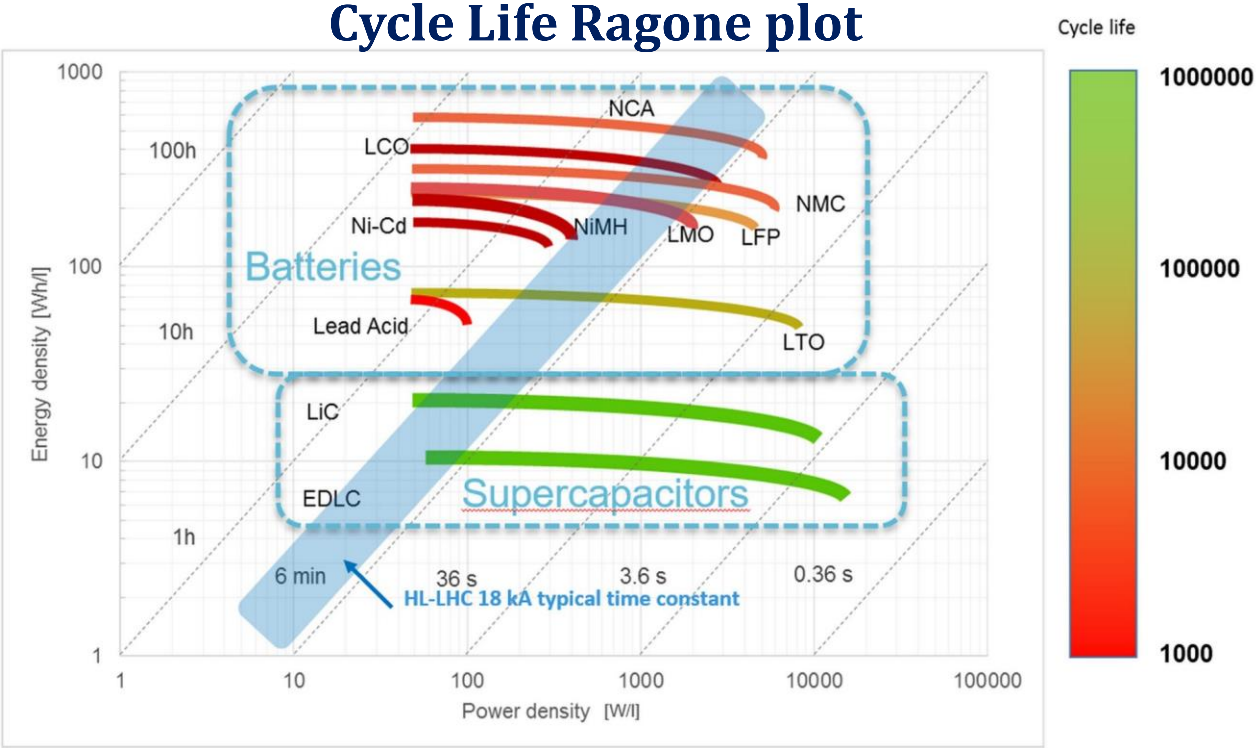


ENERGY STORAGE SYSTEM TECHNOLOGIES

Efficiency Ragone plot



Cycle Life Ragone plot



Tens of thousands of cycles required

ENERGY STORAGE SYSTEM TECHNOLOGIES

Technologies selection

11 kWh example	EDLC Supercaps	LiC Supercaps	LTO Batteries
Weight [kg]	2500	1390	900
Volume [l]	2550	1200	700
Number of racks	5	2-3	2
Total cells price [€]	250k	216k	40k + BMS
Cycle life	1M	>200k	>75k

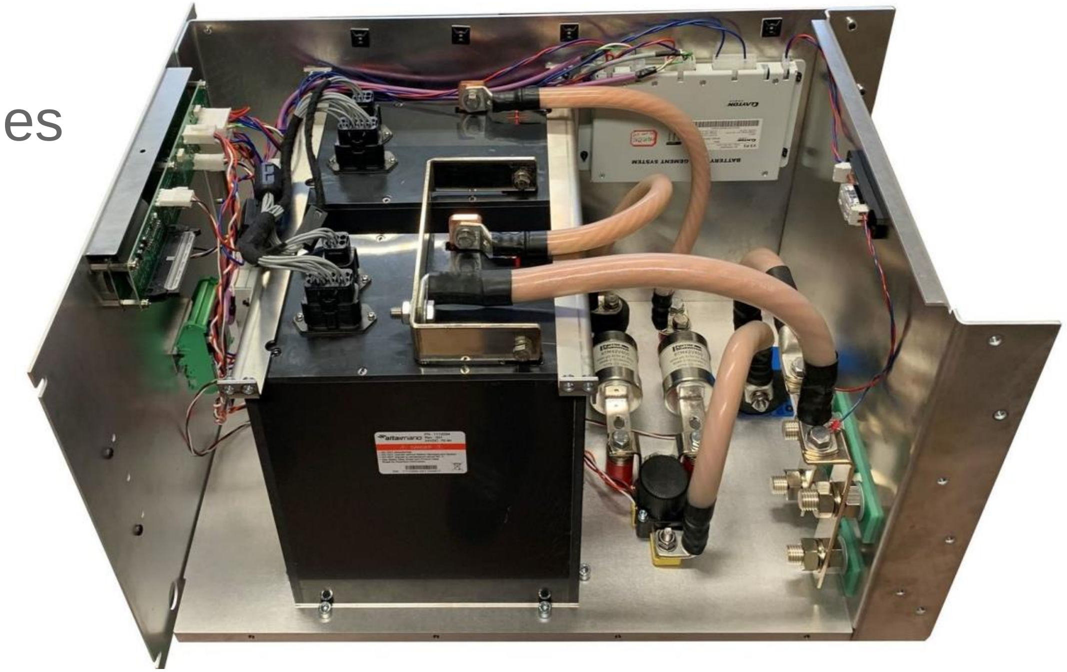
LTO is the most cost and size effective technology for this application

ALTAIR NANO TOSHIBA EiG Energy Innovation Group Leclanché

ENERGY STORAGE SYSTEM TECHNOLOGIES

Reasons to choose Lithium Titanate Oxide (LTO) batteries compared to other battery technologies:

- **Safety first!** Lowest hydrogen emissions, best thermal stability, ...
- Widest operating temperature range
- High current (C-rate) charge/discharge capabilities
- Very low internal resistance
- Very low self-discharge

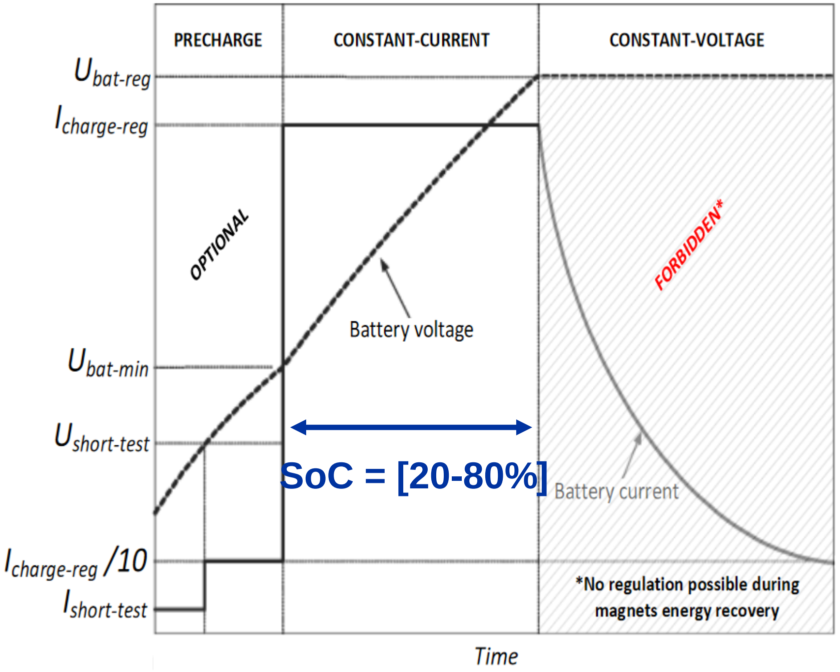


2 batteries in parallel in an ESS module

ENERGY STORAGE SYSTEM SIZING

Oversizing required for several reasons:

- Reduce the State of Charge (SoC) operating range within [20; 80] %
  - Ease the charging process
  - Increase battery cycle life



Cycle Life Table for Altairnano Gen 4 cells and modules

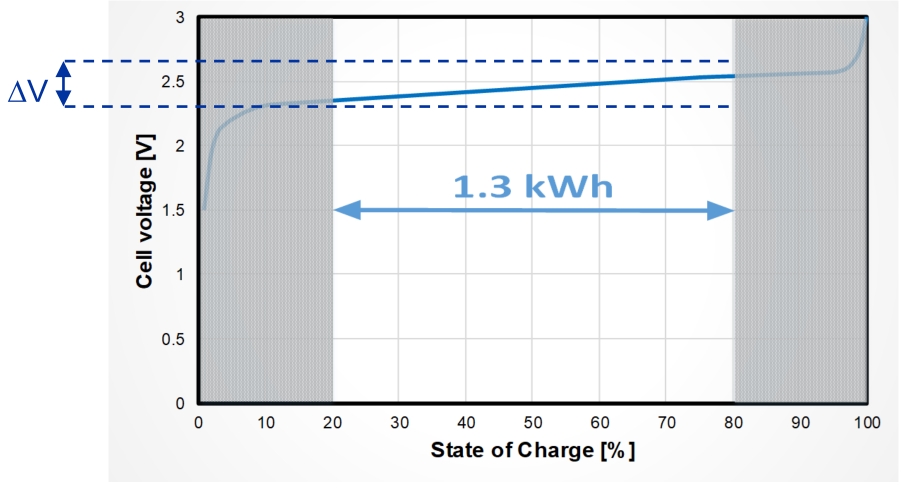
	Average Cell Temperature (°C)						
	25	30	35	40	45	50	55
DOD (%)	Cycle Life (cycles to 80% of original charge capacity)						
100	25,000	19,847	15,753	12,504	9,925	7,878	6,253
90	30,864	24,503	19,449	15,437	12,253	9,726	7,720
80	39,063	31,011	24,615	19,538	15,508	12,309	9,770
70	51,020	40,504	32,150	25,519	20,255	16,077	12,761
60	69,444	55,131	43,760	34,734	27,569	21,883	17,369
50	100,000	79,388	63,014	50,016	39,700	31,512	25,012
40	156,250	124,044	98,459	78,151	62,031	49,237	39,081
30	277,778	220,523	175,038	138,935	110,278	87,532	69,478
20	625,000	496,178	393,836	312,603	248,125	196,947	156,325
10	2,500,000	1,984,711	1,575,344	1,250,412	992,502	787,788	625,298

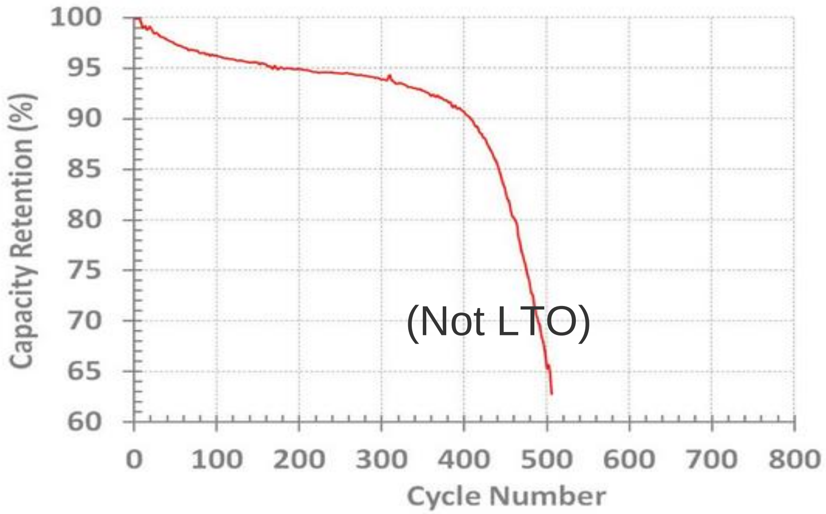
ENERGY STORAGE SYSTEM SIZING

Oversizing required for several reasons:

- Reduce the State of Charge (SoC) operating range within [20; 80] %
  - Ease the charging process
  - Increase battery cycle life
  - Stabilize the battery voltage

- Take into account the ageing of the battery, reducing the capacity of the battery
  - Battery is considered “dead” when charging only up to 80 % of its initial capacity





QUALIFICATION TESTS

Tolerance to thermal and mechanical tests

- Crush
- Vibration
- Impact
- Drop
- Immersion
- Thermal cycling
- Fire propagation


Photograph 5: ALT_08 Crush Setup


Photograph 6: ALT_09 Crush Setup


Photograph 7: ALT_10 Crush Setup


Photograph 8: General Thermal Cycle Setup


Photograph 11: Propagation Setup

QUALIFICATION TESTS

Tolerance to electrical abuse tests:

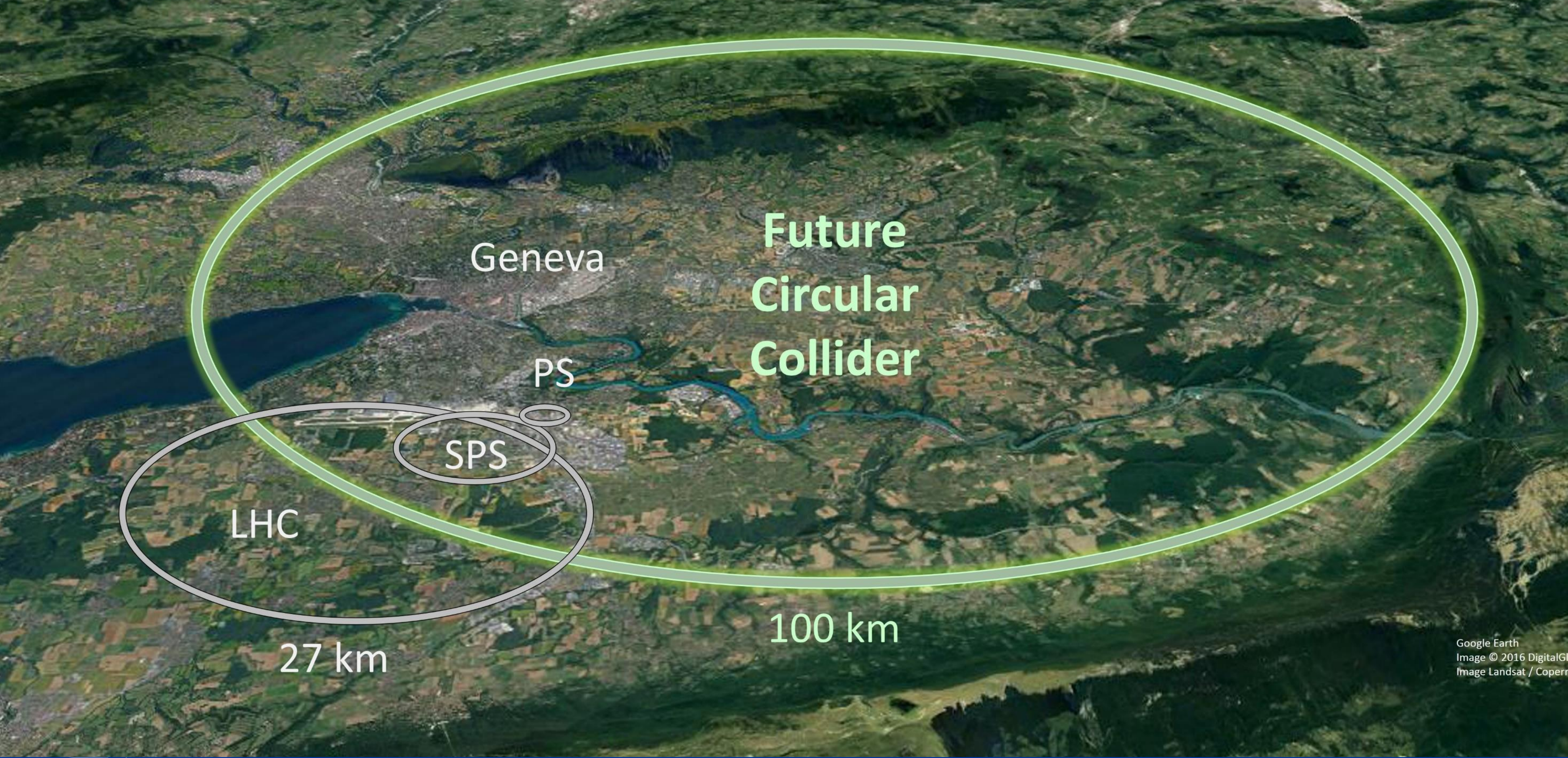
- Forced discharge
- Over-charge
- External short-circuit
- Internal short-circuit
- Overcharge control of voltage (BMS-oriented)
- Overcharge control of current (BMS-oriented)
- Overheating control (BMS-oriented)

Photograph 12: Module Short Circuit Setup

Photograph 13: Short Circuit Load Setup

Photograph 15: Module Overcharge Setup

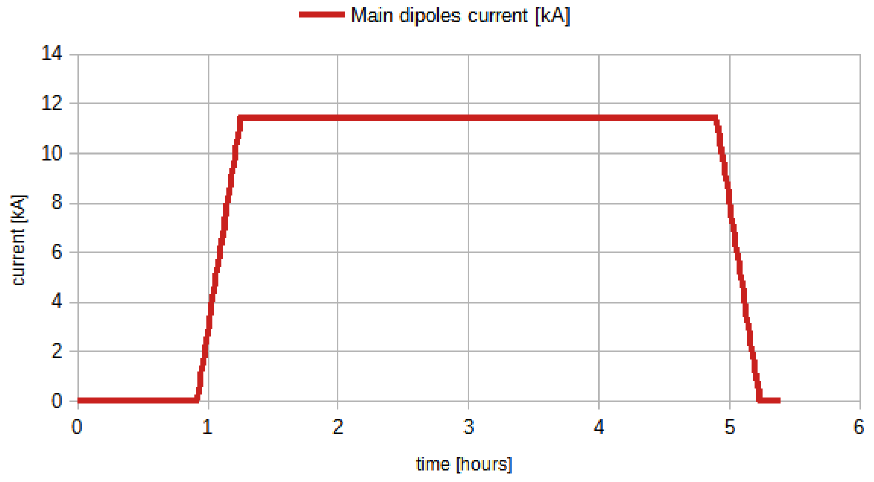
OUTLOOK ON A POSSIBLE FUTURE

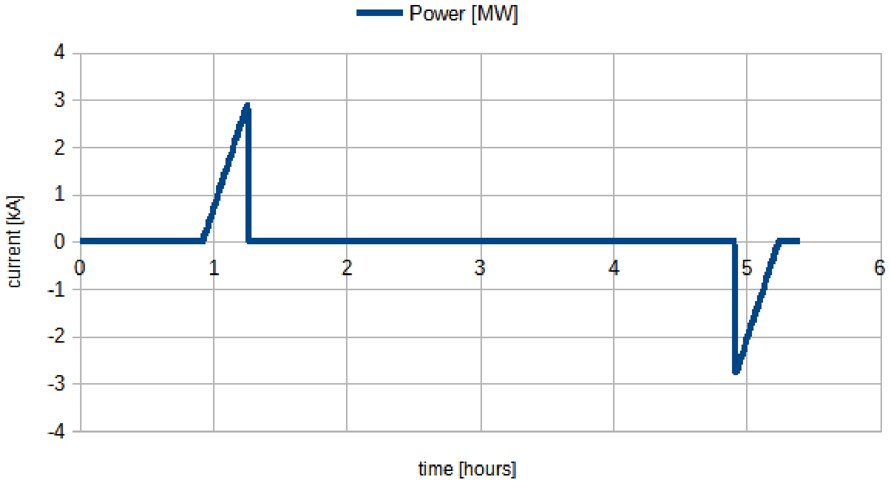


A few numbers for FCC-HH

	Main dipoles	Main quadrupoles
Number of units	4668	744
Operating current	11.4 kA	22.5 kA
Inductance	570 mH	14.4 mH
Total stored energy	174 GJ	2.7 GJ
Peak power	315 MW	20.7 MW

Similar ramp-up/down time than LHC





Storage with LTO batteries

- Total volume: 760 m^3
- Total weight: 1450 Tons
- Expected lifetime with 1600 cycles / year: 22 years
- Total cost over lifetime: 176 MCHF
- Annual cost: 8 MCHF

- Annual savings (0.1 CHF/kWh, 80% efficiency): 6.2 MCHF
  + reduction of infrastructure costs

24 V / 70 Ah
(3.4 MJ from 20% to 80%)
LTO module

	Average Cell Temperature (°C)						
	25	30	35	40	45	50	55
DOD (%)	Cycle Life (cycles to 80% of original charge capacity)						
100	25,000	19,847	15,753	12,504	9,925	7,878	6,253
90	30,864	24,503	19,449	15,437	12,253	9,726	7,720
80	39,063	31,011	24,615	19,538	15,508	12,309	9,770
70	51,020	40,504	32,150	25,519	20,255	16,077	12,761
60	69,444	55,131	43,760	34,734	27,569	21,883	17,369
50	100,000	79,388	63,014	50,016	39,700	31,512	25,012
40	156,250	124,044	98,459	78,151	62,031	49,237	39,081
30	277,778	220,523	175,038	138,935	110,278	87,532	69,478
20	625,000	496,178	393,836	312,603	248,125	196,947	156,325
10	2,500,000	1,984,711	1,575,344	1,250,412	992,502	787,788	625,298

Thanks for your attention…Questions?

home.cern

BACK-UP SLIDES

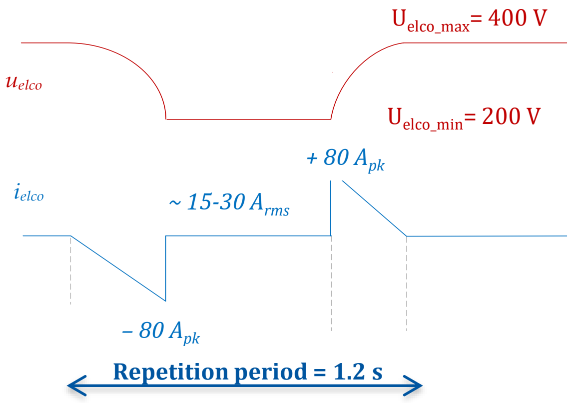
Electrolytic Capacitors Qualification

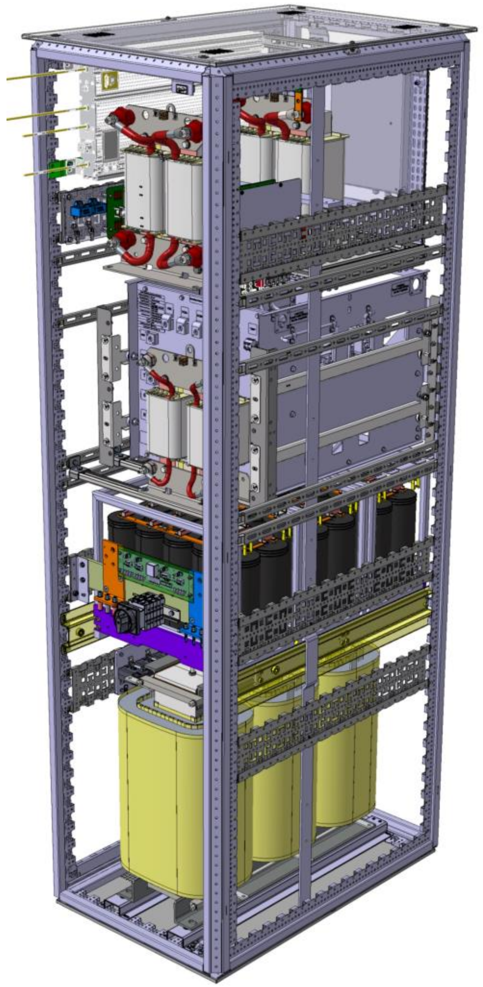
Procurement Strategy:

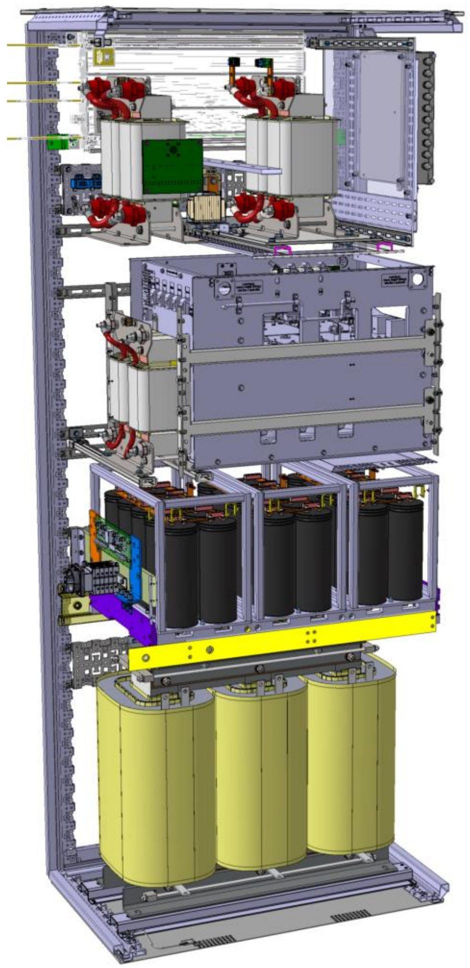
Off-the-shelf or Custom-Design Capacitors

- **Market Survey** – 5 relevant suppliers
- **Procure samples for aging tests** – 5 samples / supplier
- **Qualification tests** – Endurance, accelerated aging
- **Invitation to Tender** – To suppler which passed the tests
- **Product Qualification** – Mechanical shock, vibration tests…
- **Pre-series** – Tests in converter

Endurance Tests



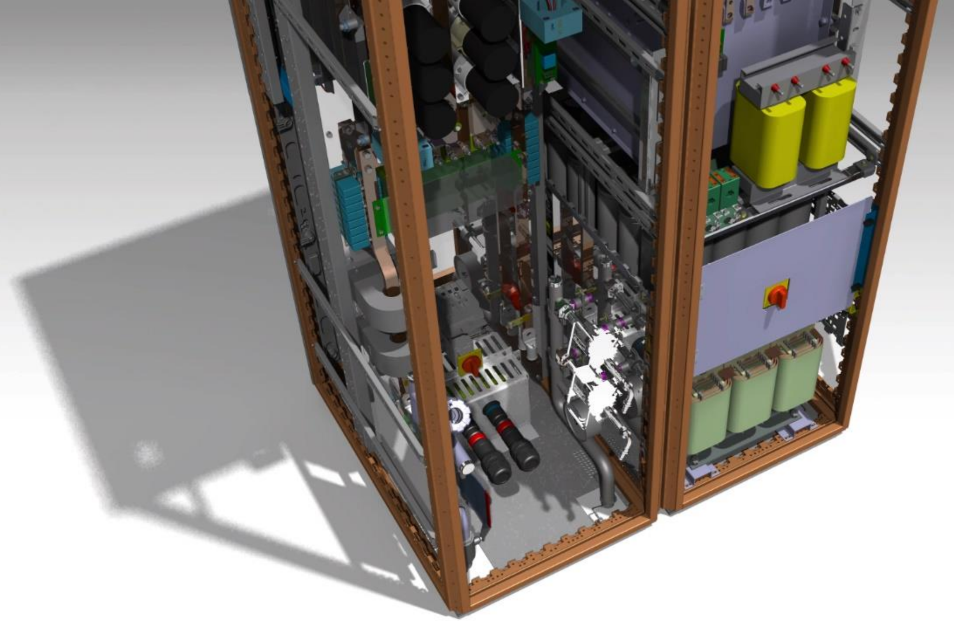




End-of-life: Destruction / ΔC = -20% / ΔESR = +100% / Δ IL = +50%.

Minimum requested number of cycles at T_{amb} = 70 °C = 8 million cycles

Electrolytic capacitors: Safety aspects



Electrolytic Capacitor Tests

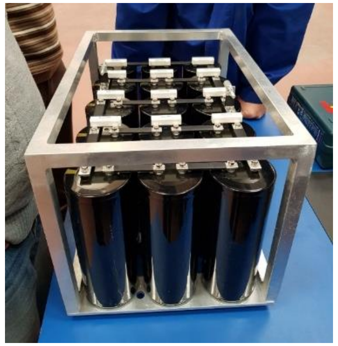
Konstantinos Papastergiou

TE-EPC

25 May 2018

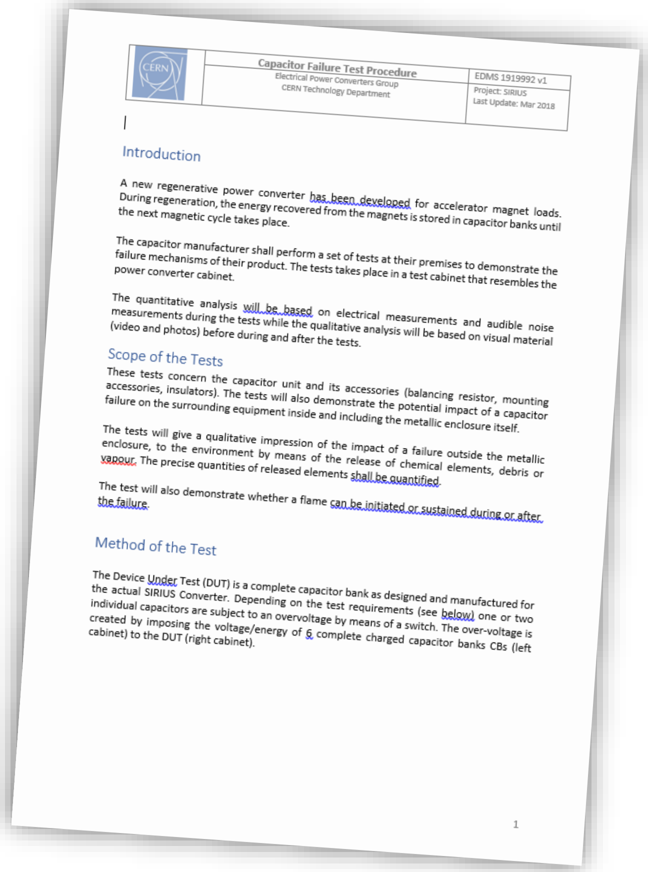
Objectives

- Qualitative assessment of the impact of a capacitor failure
- Verify Sirius metallic enclosure withstand to a destructive failure
- Qualitative assessment of the impact on surrounding equipment
  - From heat and fire
  - From debris and flying parts
  - From the electrolyte evaporation
- Identify the audible magnitude of a failure



Test Protocol

- Test 1: Continuous rated peak voltage across a capacitor
  - Single point of failure will result in this condition
  - Withstand over long time to be determined
  - Repeat on three different samples
- Test 2: Continuous over-voltage (x2) across a capacitor
  - A double failure will result in this condition
  - Worst case if energy source not disconnected
  - Repeat on three different samples
- Test 3: Reverse polarisation
  - Reverse polarisation of a capacitor
  - May occur as a result of manufacturing error
  - Repeat on three different samples



CERN	Capacitor Failure Test Procedure Electrical Power Converters Group CERN Technology Department	EDMS 1919992 v1 Project: SIRIUS Last Update: Mar 2018

Introduction

A new regenerative power converter has been developed for accelerator magnet loads. During regeneration, the energy recovered from the magnets is stored in capacitor banks until the next magnetic cycle takes place.

The capacitor manufacturer shall perform a set of tests at their premises to demonstrate the failure mechanisms of their product. The tests takes place in a test cabinet that resembles the power converter cabinet.

The quantitative analysis will be based on electrical measurements and audible noise measurements during the tests while the qualitative analysis will be based on visual material (video and photos) before during and after the tests.

Scope of the Tests

These tests concern the capacitor unit and its accessories (balancing resistor, mounting accessories, insulators). The tests will also demonstrate the potential impact of a capacitor failure on the surrounding equipment inside and including the metallic enclosure itself.

The tests will give a qualitative impression of the impact of a failure outside the metallic enclosure, to the environment by means of the release of chemical elements, debris or vapour. The precise quantities of released elements shall be quantified.

The test will also demonstrate whether a flame can be initiated or sustained during or after the failure.

Method of the Test

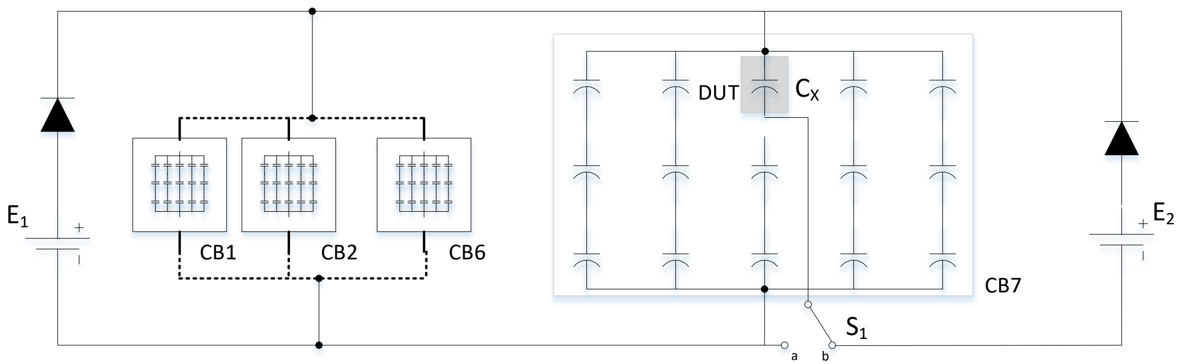
The Device Under Test (DUT) is a complete capacitor bank as designed and manufactured for the actual SIRIUS Converter. Depending on the test requirements (see below) one or two individual capacitors are subject to an overvoltage by means of a switch. The over-voltage is created by imposing the voltage/energy of 6 complete charged capacitor banks CBs (left cabinet) to the DUT (right cabinet).

1

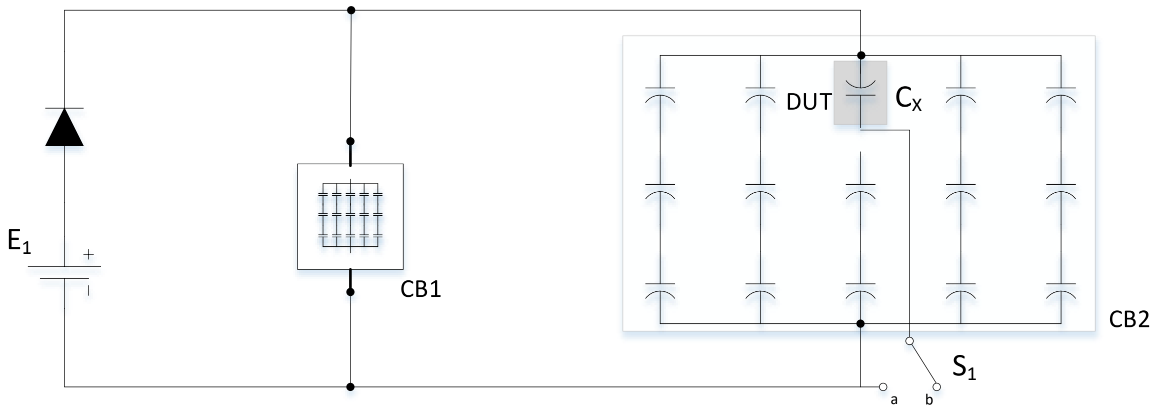
EDMS 1919992

Test setup description

- **Test 1 & 2**
  - Overvoltage on DUT
  - With and without external source



- **Test 3**
  - Reverse polarisation of DUT
  - Gradual increment of source voltage



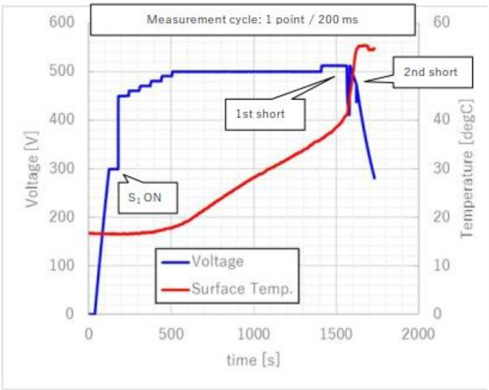
Test 1 Results: continuous peak voltage

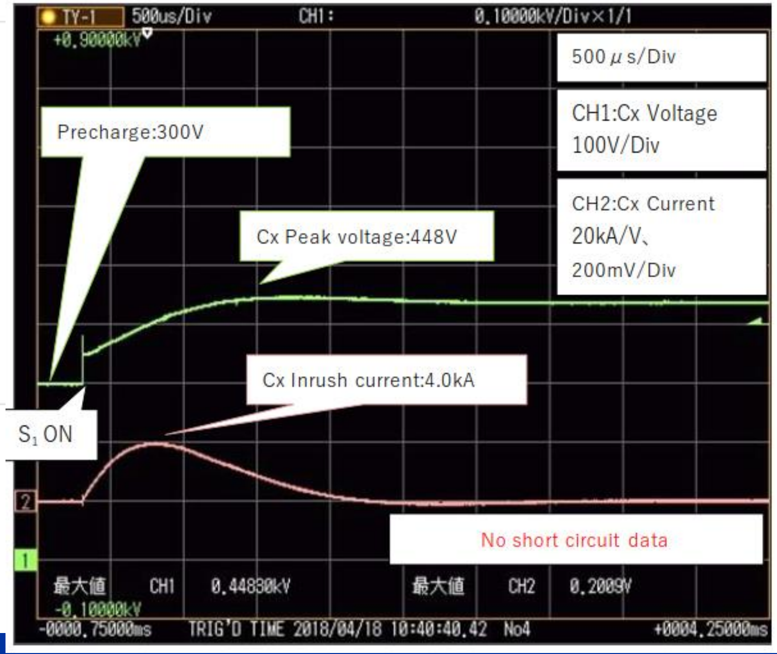
Shot 1: 450V on DUT -> no failure during 1h

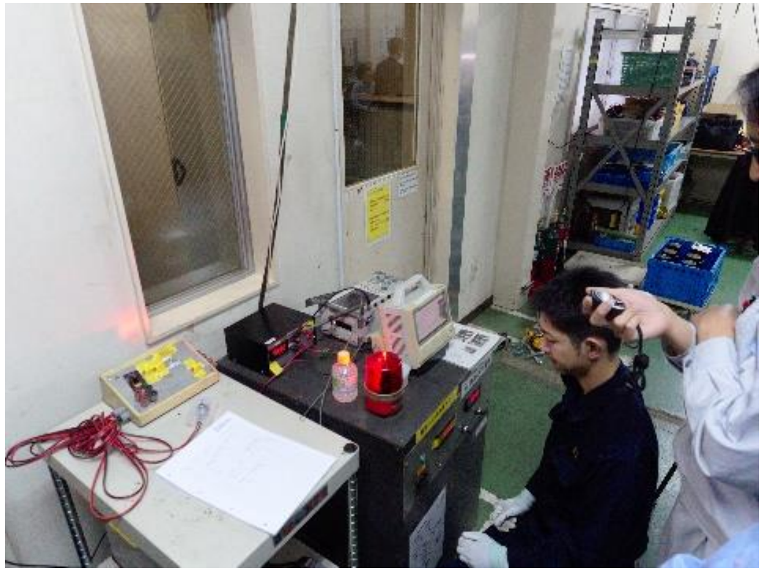
Shot 2: 550V on DUT -> instant destructive failure

Shot 3: gradual increase 450V to 520V on DUT:

- Failure at 520V after 1320sec







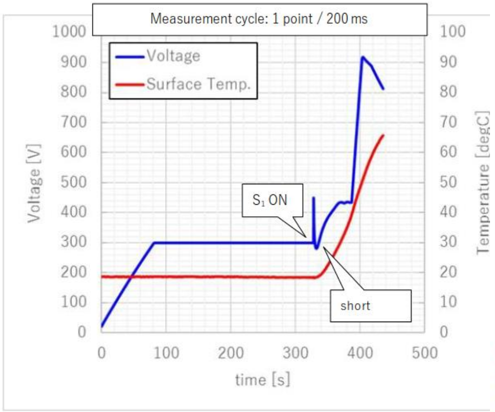
Test 2 Results: over-voltage (x2)

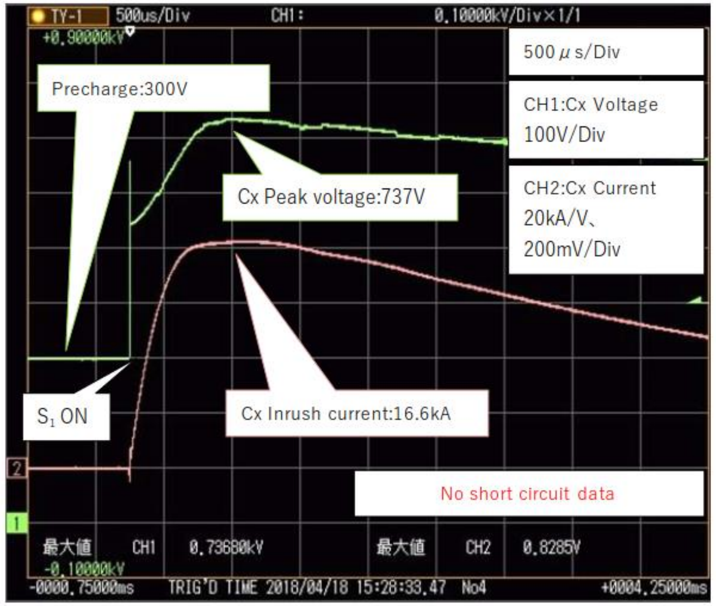
Shot 1: 900V on DUT with external source -> failure after 73s

Shot 2: 900V on DUT, external source disconnected -> no failure, DUT operational after test

Shot 3: 900V on DUT, external source disconnected -> no failure, DUT operational after test

Shot 4: 900V on DUT with external source -> destructive failure

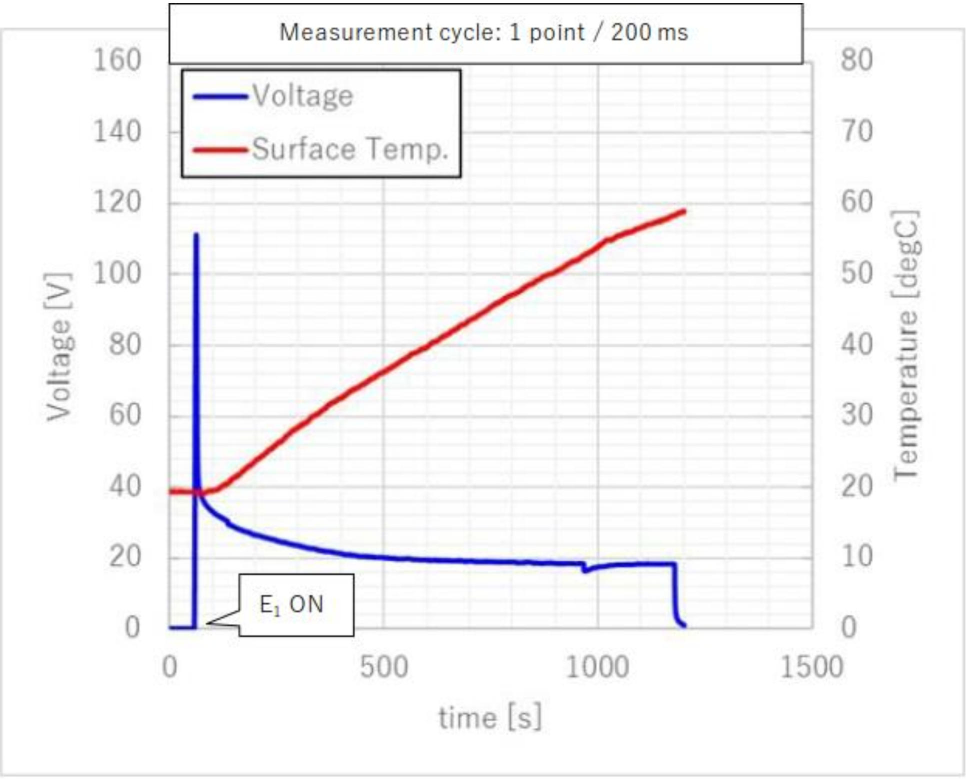


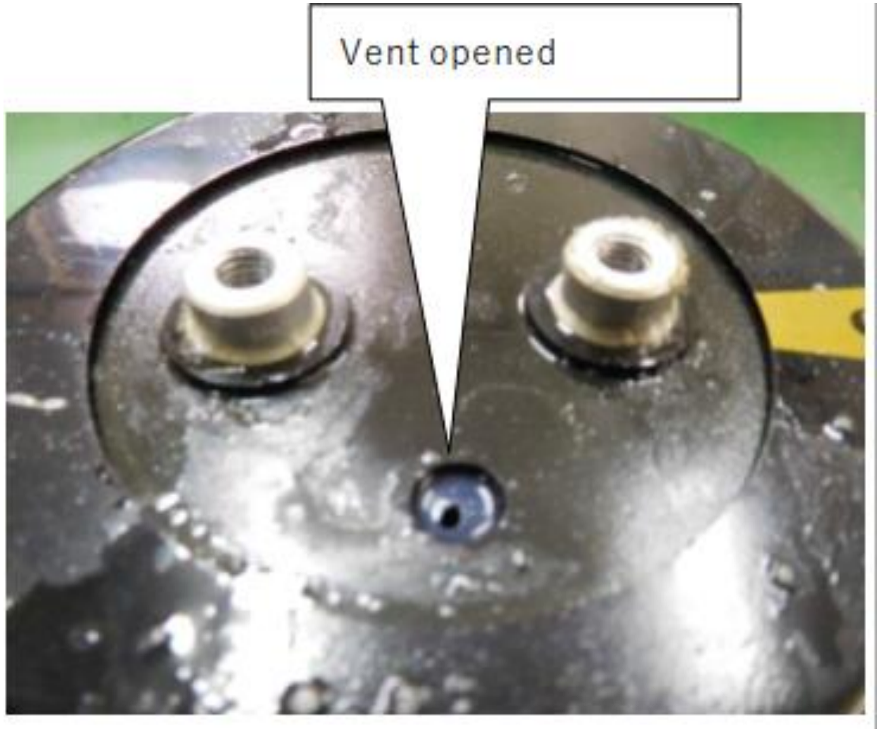


Test 2 ▶ ▶

Test 3 Results: reverse polarisation

Shot 1: Reverse polarisation of DUT with external source -> failure, open vent





Summary of test results

- Test 1 & 2: single point of failure
  - Over-voltage <37%** : No failure after 1 hour of exposure
  - Over-voltage >37% with Sirius capacitor banks energy: Failure mode is uncertain
  - Over-voltage >37% with Sirius capacitor bank energy **and** external energy source: Destructive failure mode after some time

- Test 3: polarity reversal
  - Failure with open-vent after 900sec if source remains energised.

** Over-voltage with respect to the application operating voltage

Sirius Capacitor Failure Tests - Conclusions

- Electrolytic capacitors are prone to failure if exposed to over-voltage.
- There is no evidence that energy stored in a Sirius brick can cause by itself destructive failure or fire.
- A failure may become destructive in case an energy source remains energised after the event.

- **Key findings:**
  - Destructive failure of capacitors (fumes, debris) is contained by the enclosure
  - Destructive failure of capacitors has no structural impact on the Sirius metallic enclosure
  - Destructive failure has limited impact on the equipment directly above
  - The peak observed sound level was 135.5db at 0.5 meter from the cabinet

A report is circulated internally for approval and will be placed under CERN-0000189820

*Destructive is a failure that results on visible damage to the capacitor can or its surroundings

*Reports and media in EDMS folder CERN-0000189820