Power Converters for Energy Savings

East Area and North Area Consolidation

CERN & J-PARC/KEK high power beam workshop

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edms. 3170427

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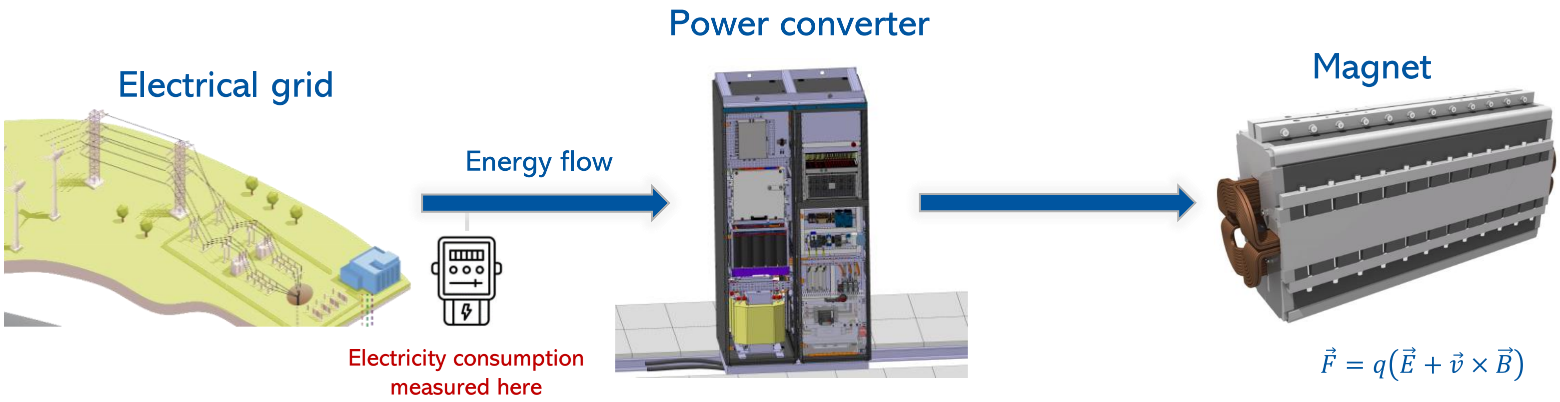
Outline

- ✓ Introduction to Power Converters
- ✓ Power Converters: Concepts for Energy Savings
- ✓ Past work: East Area Consolidation
- ✓ Ongoing work: North Area Consolidation
- ✓ Conclusions

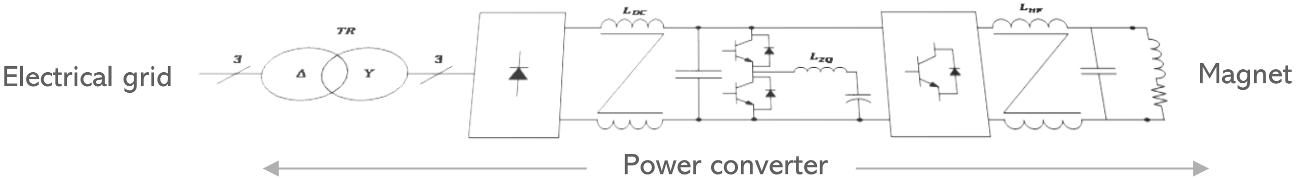
1. Introduction to Power Converters

Introduction to Power Converters

- ✓ Power converters transformer grid energy and supply it to magnet to control current.
- ✓ Energy consumption (typical)
  - ➢ 90% of energy is consumed by magnet.
  - ➢ 10% of energy is lost in power converters for energy conditioning.



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

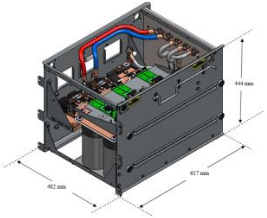


Introduction to Power Converters

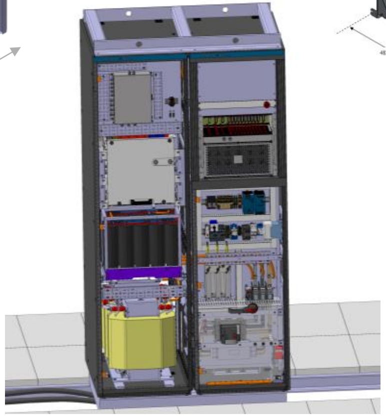
Power converters consists of many components which define its precision, controllability (DC vs Cycling), energy efficiency, magnetic energy recoverability etc.

Electrolytic Capacitors
Energy Recovery

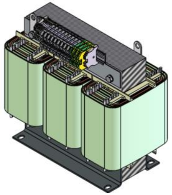
Power
semiconductors stack



DCCT
high-precision

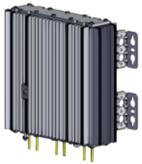


Transformer



Control
electronics

Resistors



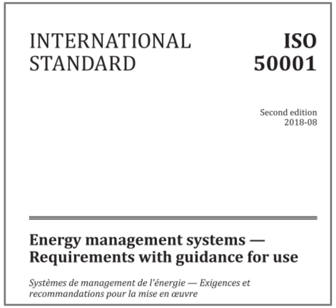
2. Power Converters: Concepts for Energy Savings

CERN Energy Management Panel

brings all main energy consumers and stakeholders at CERN together (edms. 2788210)

CERNs Energy Management Panel (EMP) Mandate:

- Estimates of CERN's projected energy consumption
- Rising awareness by virtual invoices…
- ISO 50001 Certification (awarded since 2023)
  - Setting improvement goals and monitoring,
  - Selecting energy efficient designs and materials…


INTERNATIONAL STANDARD

ISO 50001

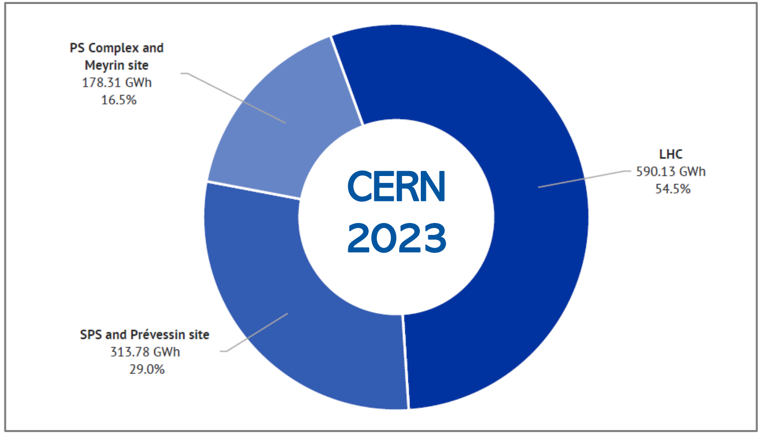
Second edition
2018-08

Energy management systems — Requirements with guidance for use

Systèmes de management de l'énergie — Exigences et recommandations pour la mise en œuvre

EMP recommendations

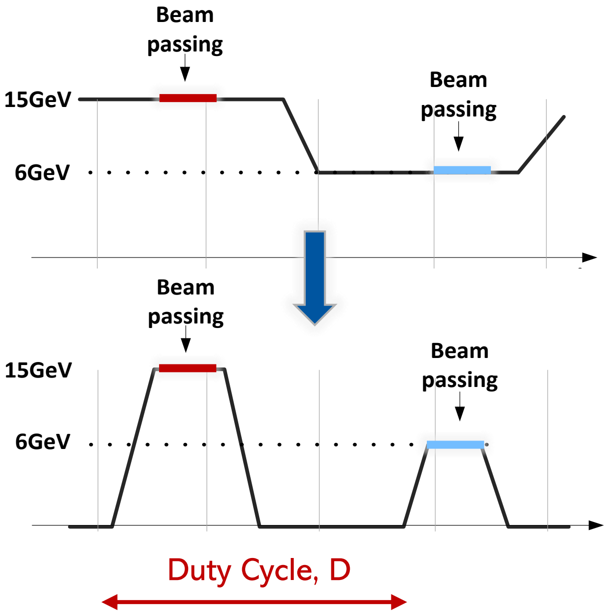
- ✓ Consume less
- ✓ Improve efficiency
- ✓ Recover energy where possible
- ✓ Consider Total Ownership Cost (TOC) including Capital + Operational Expenditure (CAPEX + OPEX)



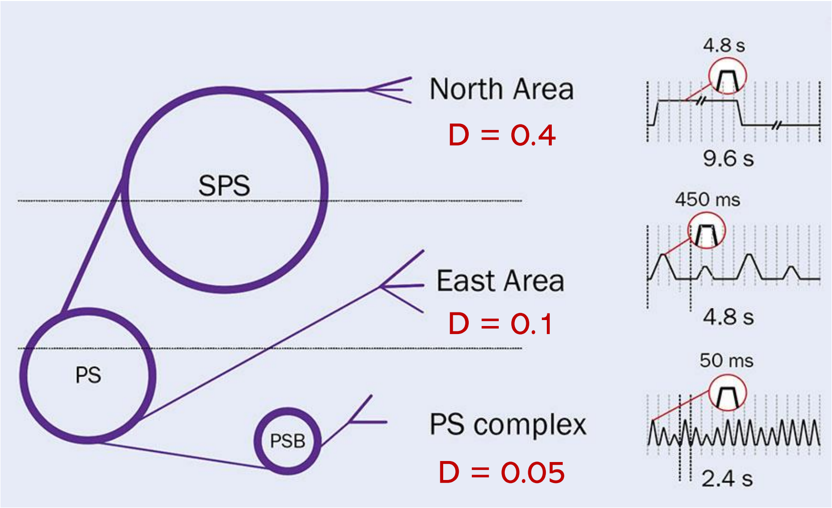
Courtesy: T. Zickler, M. Wolf, E. Freddy EN-EL, Virtual Invoice 2023: EDMS 2599454

Powering for Energy Savings: Consume Less

- Power magnets only when beam passing
  - Cycled operation instead of DC → Magnets compatibility for cycling
  - Economy modes – min RMS for current → enabled by new FGC electronics / software
- Potential savings dependent on "Duty Cycle (D)" of accelerator



Magnet Duty cycle in different Accelerators

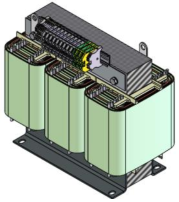


Powering for Energy Savings: Improve Efficiency

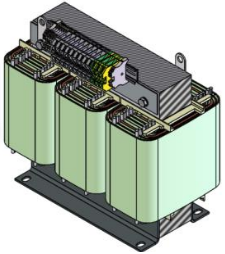
- Power converter efficiency depends on the performance of its sub-systems / components.
- Efficient powering means higher CAPEX and lower OPEX.

Power transformers

Efficiency: 97 %



Efficiency: 99 %

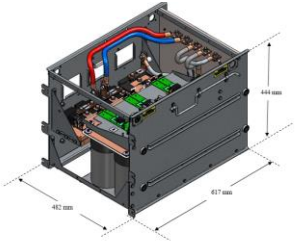


Efficiency increase

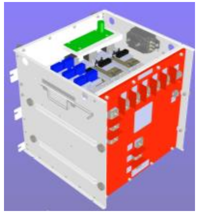
- ✓ More winding, core material
- ✓ Better materials (Cu vs Al, iron vs amorphous)
- ✓ Often limited by space constraints and available CAPEX.

Semiconductors power stack

Si IGBTs, Efficiency: 95 %



SiC MOSFETs, Efficiency: 98 %



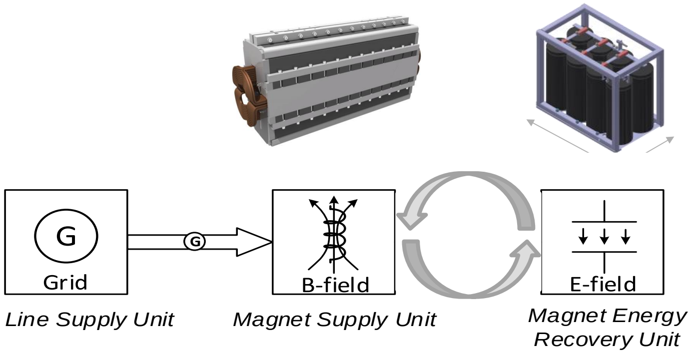
Efficiency increase

- ✓ Soft-switching techniques
- ✓ SiC and GaN (wide band-gap) semic.
- ✓ Use of wide band-gap often limited by reliability concerns when cycling and available CAPEX.

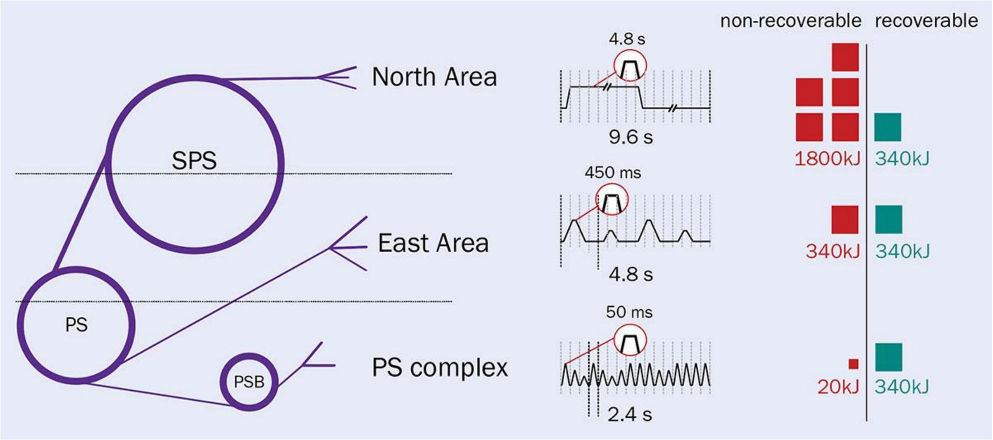
Powering for Energy Savings: Recover Energy

- Resistive losses → non-recoverable energy from grid
- Magnetic energy → recoverable, exchanged with energy storage in converter

Magnetic energy recoverable when cycling



Recoverable vs non-recoverable energy

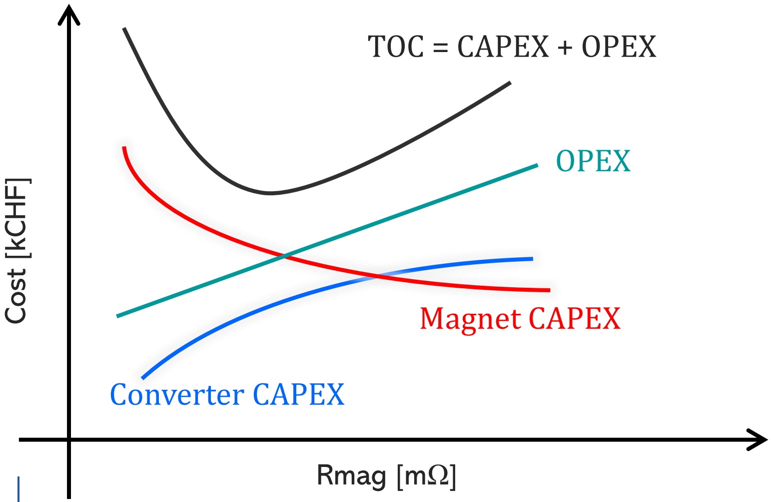


Courtesy: K. Papaestergiou: https://cerncourier.com/a/powering-for-a-sustainable-future/

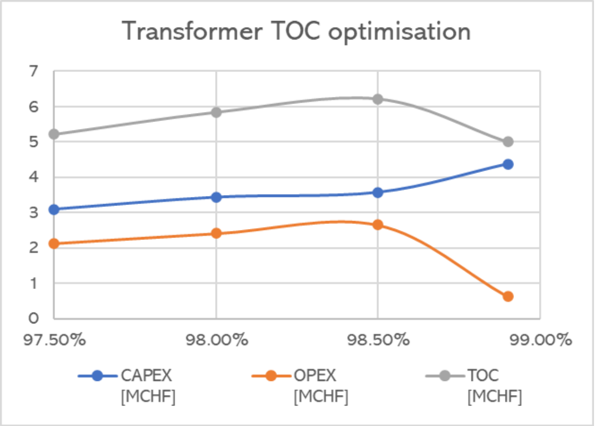
Powering for Energy Savings: TOC = CAPEX + OPEX

- Optimization of Total Ownership Cost (TOC):
  - CAPEX: CAPital EXpenditures: Expenses for initial purchasing and/or for extending lifetime of the asset
  - OPEX: OPerating EXpenses: Ongoing expenses inherent to the operation of the asset
- System level optimization: converters + magnets (+ cooling…e.g. indico1407783)
- Components level optimization: consider TOC and not only CAPEX in Tendering?

System level TOC Optimization



Component Level – Transformer TOC



Benefits of TOC optimization vs Risk of amplified CAPEX

3. East Area Consolidation

East Area Consolidation

East Area: Slow extraction physics

- Physics during 0.45 s / every 4.8 s

CONS motivation: aged converters

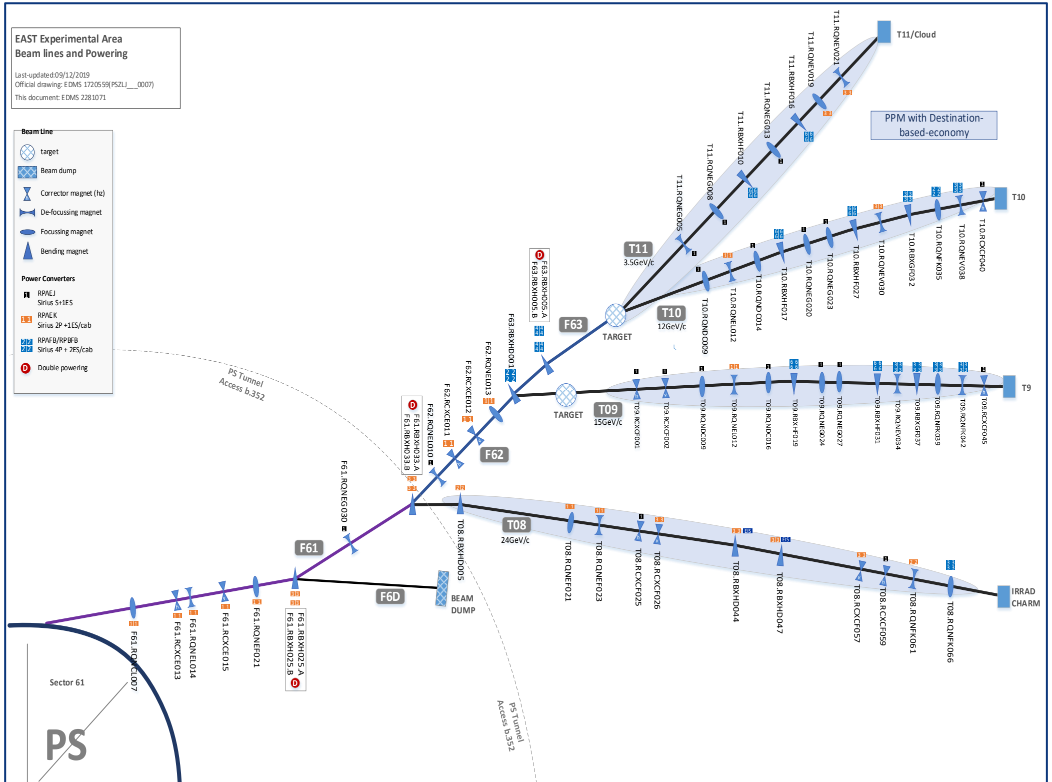
Consumed energy continuously:

- 9.1 GWh / year
- Operated in DC while used for ~10% of time (PS Super-Cycle)

Consolidation for Energy Sustainability:

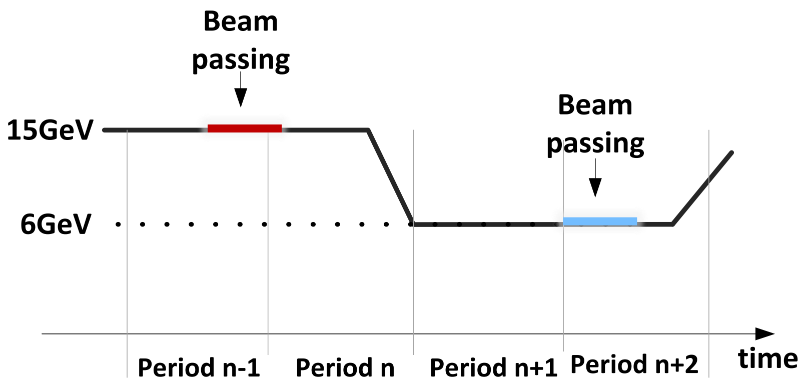
- TOC = CAPEX + OPEX
- Consolidation completed in 2020.

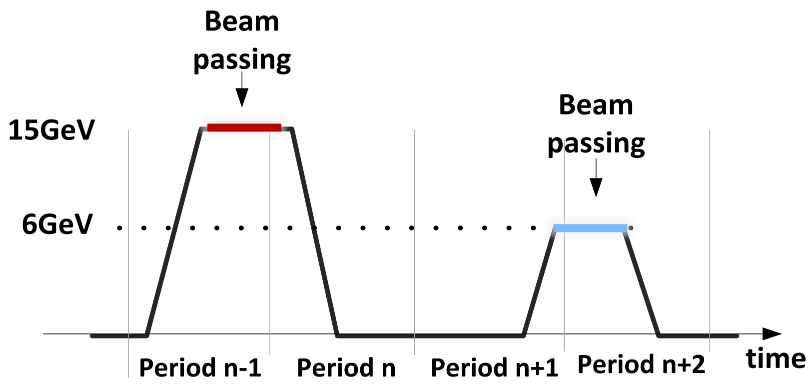
East Area Beamlines



Courtesy: K. Papaestergiou: edms. 2461130

East Area Consolidation: Consume Less, DC to Cycling



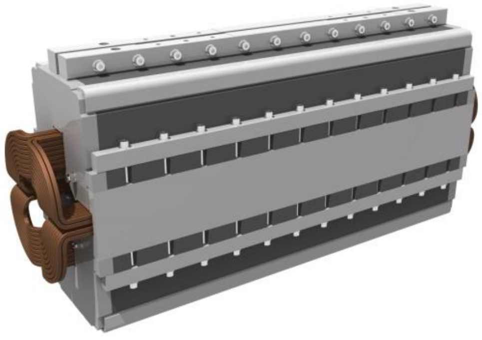


Cycling operation (D =0.1!) would have leaded to large energy savings

Cycling operation required magnets consolidation

- 23/55 magnets were with solid yokes - do not support cycling
- Eddy currents would heat up the yoke material

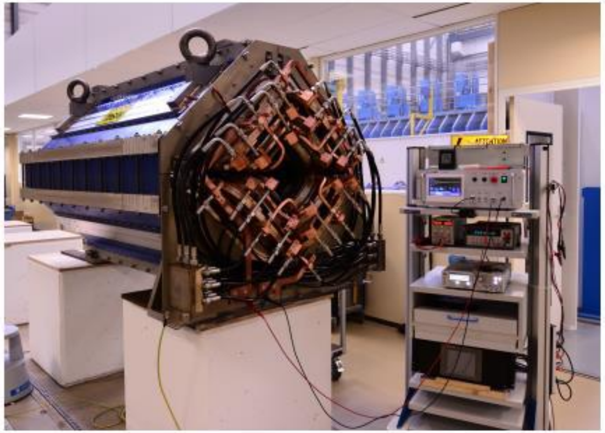
Recoverable energy was significant due to short-cycling period (4.8 s)



Courtesy: K. Papaestergiou: edms. 1770489

East Area Consolidation: CAPEX + OPEX Results

Magnets with laminated yokes



Capacitors for energy recovery

SIRIUS converters

Measured in 2012: 9.10 GWh (before CONS)

Measured in 2021: 0.51 GWh (after CONS)

Energy Savings: 8.50 GWh / year

OPEX savings: 510 kCHF / year (@ 60 CHF / MWh)

CAPEX SIRIUS + Energy Storage: 1.5 MCHF

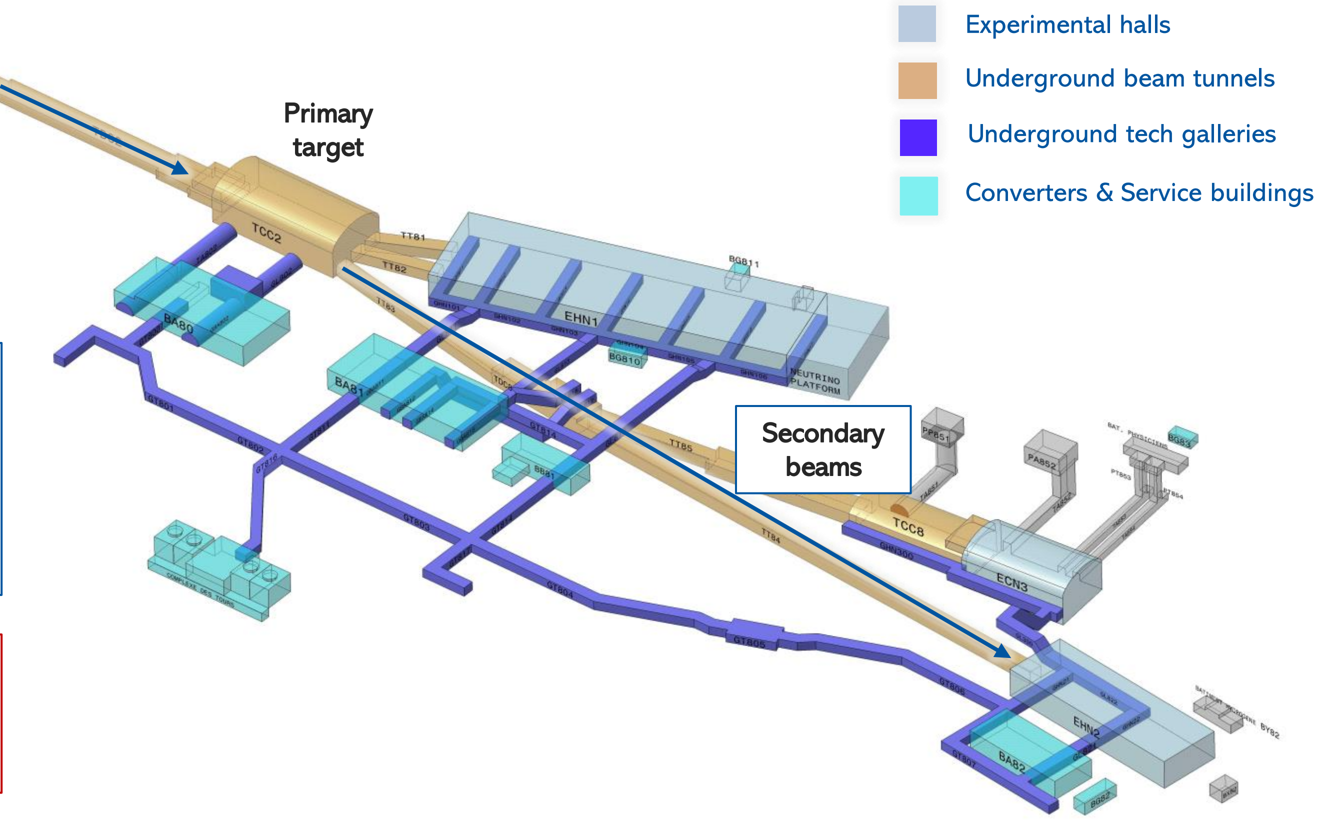
CAPEX magnet yokes: 1.3 MCHF

Total CAPEX: 2.8 MCHF

Total CAPEX can be amortized through lower OPEX in ~5 years.

4. North Area Consolidation

North Area Consolidation



In Scope

Power converters (~380)

Electrical & Cooling infrastructure

Beam instrumentation, Safety

Building renovation…

Out of Scope

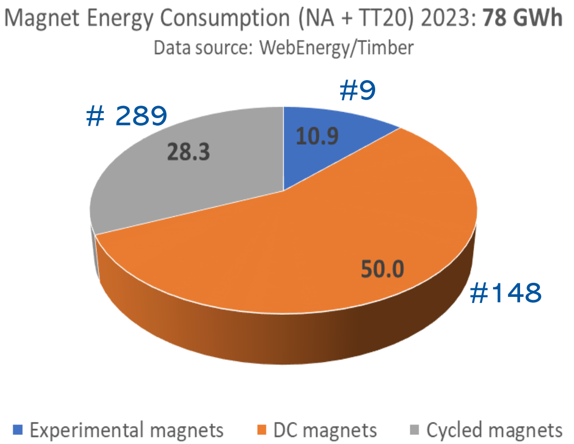
Magnets consolidation

(Only critical spare strategy)

Magnets consolidation: Consume Less?

Energy Consumption in 2018 (study from 2019)

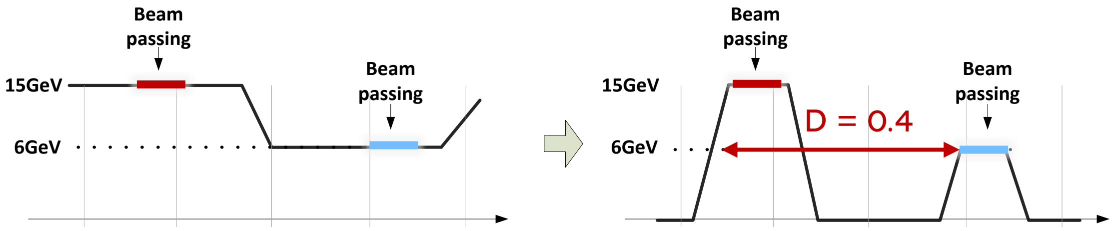
- DC magnets (1/3 of total) consume ~2x more than the cycled



Courtesy: T. Zickler, https://indico.cern.ch/event/1350982/

Consume Less going from DC to Cycling Mode?

- Duty Cycle of NA is D = 0.4 → the savings potential are not the same as in East Area (D = 0.1)
- CAPEX for laminated yokes ~ 9 MCHF (2019)
- Return on CAPEX (yokes) through energy savings: > 20 years



CAPEX amortization for Magnets Yokes through Electricity Savings was > 20 years.

Future Converters shall be compatible with Cycling Mode for potential Magnets CONS in future.

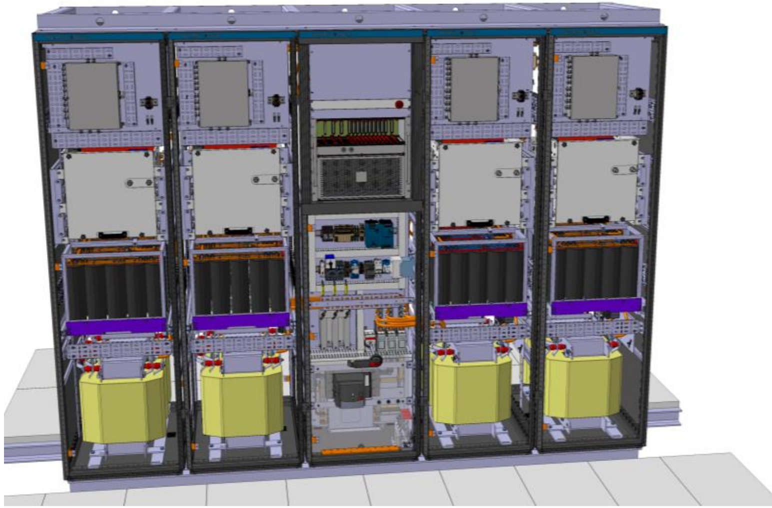
POLARIS Converter for North Area

- Consolidation with POLARIS converter family (for 95% of all magnets)
- Modularity for current / voltage / power upgrade
- Compatible with DC & Cycling mode of operation – integrated energy storage

POLARIS S
360 V / 400 A / 50 kW

POLARIS 2P
360 V / 800 A / 100 kW

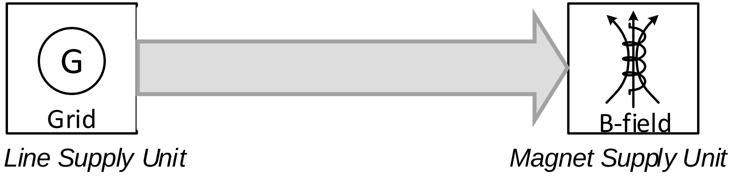
POLARIS 4P
360 V / 1600 A / 200 kW



POLARIS Converter: Consume Less & Recover Energy

- Magnets which are already cycling consume ~33 GWh / year (~3.3 MCHF / year)
- Consume less by ramping up/down faster
- Recover energy from large (high-energy) magnets

Old converters w/o Energy Recovery

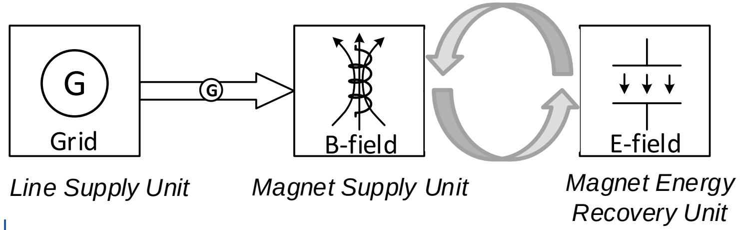


Old converters

1Q converter operation

- Slow current ramp rates
- No energy recovery

New POLARIS converter with Energy Recovery



New POLARIS converters

4Q-converter operation

- Fast current ramp rates
- With energy recovery!

POLARIS Converter: Consume Less & Recover Energy

Old Converters Operation

Old controls (ramp @ t=0) & No Energy Recovery

OPEX: 507 GWh → 50.7 MCHF (*)

POLARIS Converters Operation

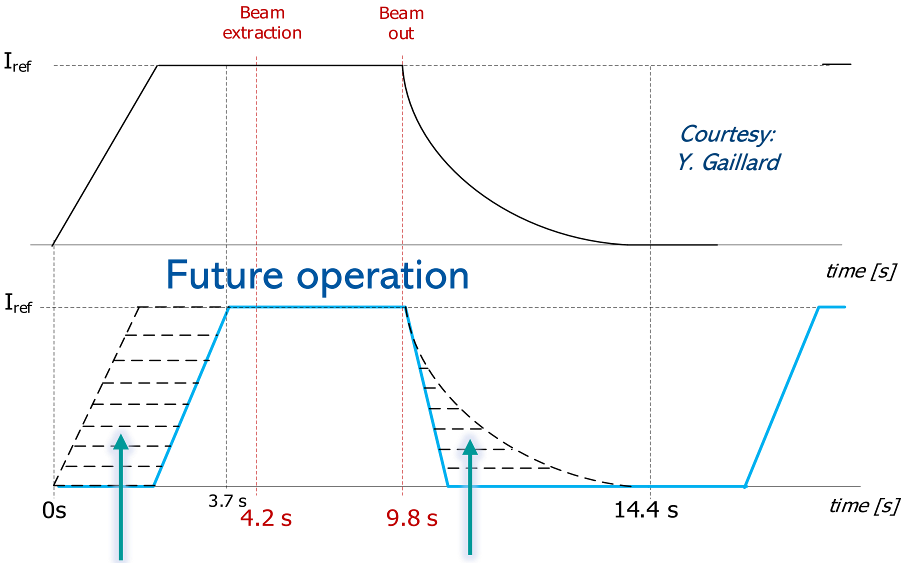
FGC controls (delayed ramp) & Energy Recovery

OPEX: 329 GWh → 33 MCHF (*)

OPEX Savings: 17.7 MCHF

- Ramp-up: - 14.4 MCHF (optimized ramp-up)
- Ramp-down: -3.3 MCHF (energy recovery)

Operation today



Ramp-up savings enabled by FGC Controls

Ramp-down savings enabled by Energy Recovery

50% of converter CAPEX (Phase I + II) can be amortized by lower OPEX after 15 years.

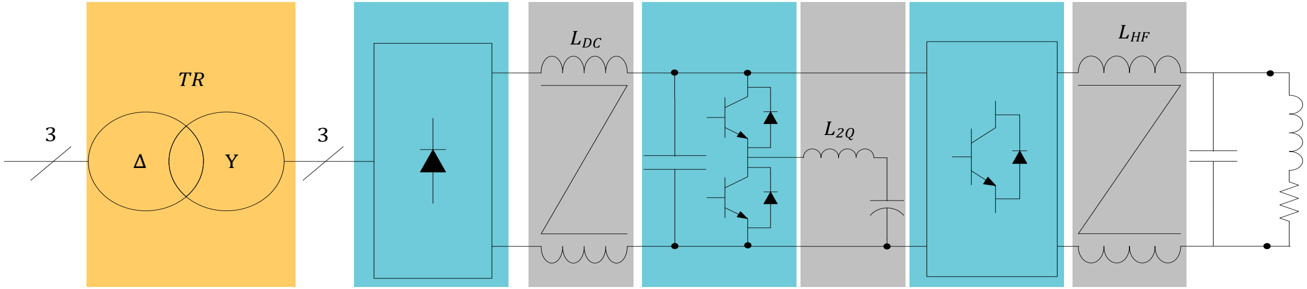
(*) Operation hypothesis:
Average operation at 0.7xIref (0.49 x Pref), 5500 hours / year, Stabilization time = 0.5 s,
Electricity cost = 100 CHF / MWh, The same energy efficiency of old and new converters

POLARIS Converter: Improve Efficiency

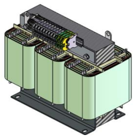
- Target converter efficiency: > 92% at full load

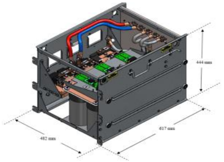
POLARIS power brick

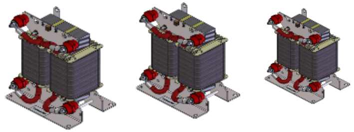
Energy efficiency > 92% @ nominal power (P = 50 kW)



Transformer	Power stack semiconductors	Set of three chokes
1050 W (98.5%)	2500 W (95.2%)	~700 W (99.5% per choke)



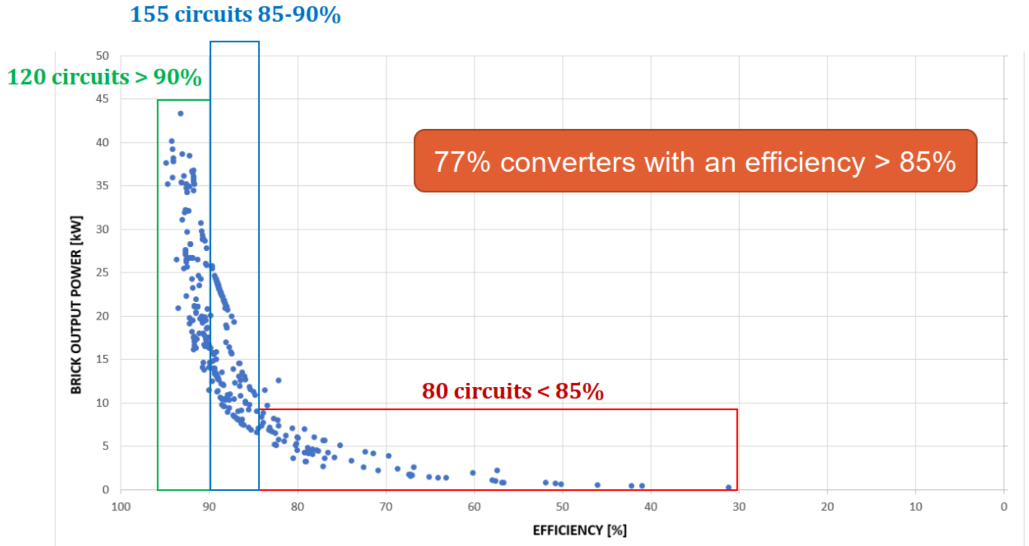




POLARIS Converter: Efficiency vs Standardisation

Efficiency vs Load

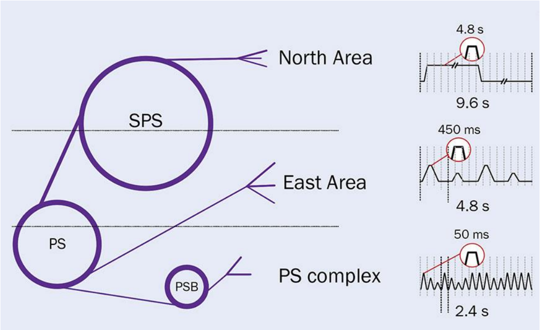
- ➢ Circuits operated at higher power have high-efficiencies
- ➢ Circuits operated at low power have lower efficiencies → acceptable for standardization reasons



Semiconductors Power Stack: Improve Efficiency?

Improve efficiency by deploying SiC semiconductors?

- Technology not yet suitable for power cycling applications
- Lifetime estimation: 5 million magnet current cycles
  - 4 years in North Area (1 year in East Area, 6 months in PS)
  - Power stack needs to be replaced 3 times in a lifetime (15 y)



North Area Case: SiC vs Si

CAPEX increase: +28 kCHF unit → **+23.8 MCHF / 850 units!**

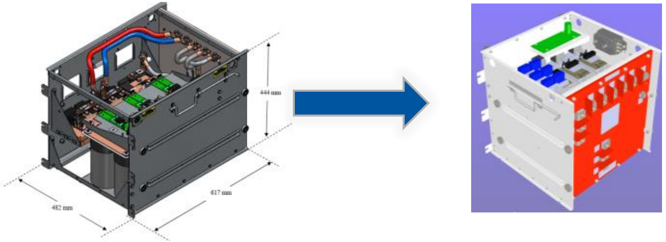
- SiC Power Stacks CAPEX: + 5.95 MCHF / 850 units
- Spare power stacks CAPEX: +17.85 MCHF / 850 units

OPEX reduction: -3.5 MCHF / 850 units / 15 years

- Power stacks not used at full power
- 3% gain in efficiency → savings 35 GWh / 15 years

Semiconductors power stack

Si IGBTs, Efficiency: 95 % SiC MOSFETs, Efficiency: 98 %



Courtesy: G. Le Godec, D. Xystras

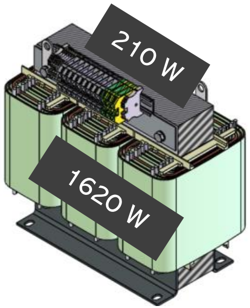
Moving towards SiC would explode CAPEX which cannot be compensated through gains in energy efficiency and lower energy bills.

(*) Operation hypothesis:
Average magnet operation at 0.7xIref (0.49 x Pref), 5500 hours / year, 850 transformers, Electricity cost = 100 CHF / MWh

Transformer: TOC (CAPEX + OPEX) Considerations

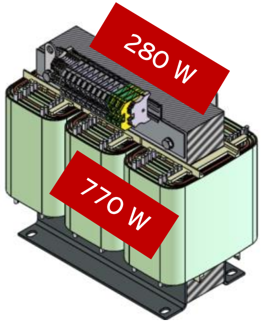
- Contract adjudication based on TOC not followed due to high risk for large CAPEX increase
- Contract adjudication: minimum CAPEX + Compliance to Maximum allowed Power Loss
- Power losses: total loss + distribution between core and windings
- Power loss distribution matters! Loss in core consumed constantly even when Imag = 0 A.

Eco-design Requirements



Ecodesign Directive 2009/125/EC sets requirements for energy-related products to ensure energy efficiency and environmental protection. Regulation No 548/2014 specifies Ecodesign criteria for power transformers with a minimum rating of 1 kVA.

Initial design (1050 W)

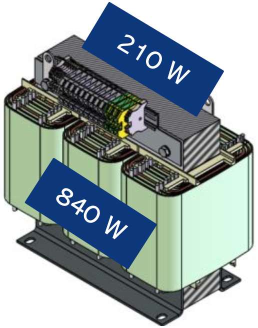


CAPEX = CONST MCHF

22.3 GWh (*)

OPEX = 2.2 MCHF

Final design (1050 W)



CAPEX = CONST CHF

17.5 GWh (*)

OPEX = 1.7 MCHF (-480 kCHF)

(*) Operation hypothesis:
Average magnet operation at 0.7xIref (0.49 x Pref), 5500 hours / year, 850 transformers, Electricity cost = 100 CHF / MWh

Conclusions

- Magnets will remain the largest energy consumers (90% in magnets, 10% in converters).
- Large energy savings can be made by moving from DC to Cycling Operation (example East Area).
- Considerable energy savings can be made by optimized current cycling (delayed ramp-up) in combination with energy recovery (example North Area).
- Energy recovery is sustainable approach and return on capital investment can be achieved over a lifetime of the equipment (example North Area).
- The energy efficiency of new generation power converters remains high (92%). Improving efficiency of converter's components is possible but with highly increased (often non justified) Capital Investments.
- The optimization of Total Ownership Cost (CAPEX+OPEX) on the component level can be possible without increase of capital investments (example POLARIS transformer).