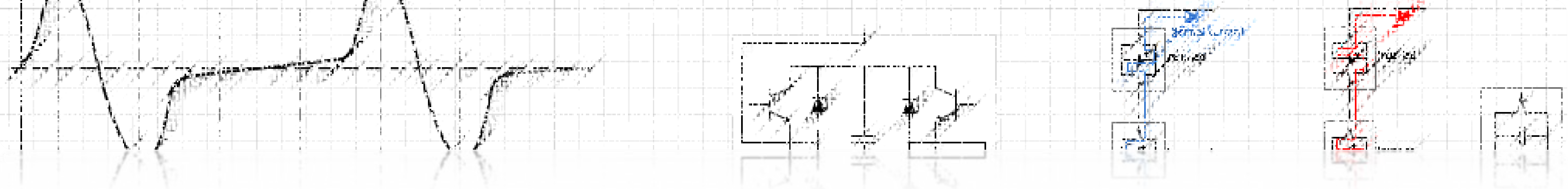

# Magnet Energy Recovery

***towards more compact and efficient systems***

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Workshop on Special Compact and Low Consumption Magnet Design
CERN November 2014

# Presentation Outline

**Key message:** operating mode (dc, cycling, energy recovery) impacts the magnet design as well as system sizing**.**

- **Current Cycling Warm Magnets**
  - Illustration of how magnet current cycling vs dc operation can help fund system upgrades using the East Area study. System level gains.
- **Magnet Energy Recovery**
  - Definition and benefits across the power supply chain
- **Magnet and system design intersection**
  - An example of how ISR-era magnets hinder the standardisation process and a proposal for collaborative system design.

# Current Cycling of Warm Magnets

# The East Experimental Area


- Houses **five beam lines**
- Protons derived **from the PS**
- Momentum **3.5 to 24GeV/c**
- **Slow** extraction

**Targets**

- Beam T7 can be operated as :
  - a secondary test beam (<10 GeV/c) or
  - as an Irradiation facility with primary proton beam
- T8 is a primary proton beam for DIRAC exp. (up to $2\ 10^{11}$ p+/cycle)
- T9 is secondary test beam (<15 GeV/c at 0 mrad production angle)
- T10 secondary test beam (<7 GeV/c at 60mrad production angle)
- T11 can be used as
  - test beam (<3.6 GeV/c at 210 mrad) or
  - as a very large spot (almost 2x2 m2) hadron beam (CLOUD experiment)

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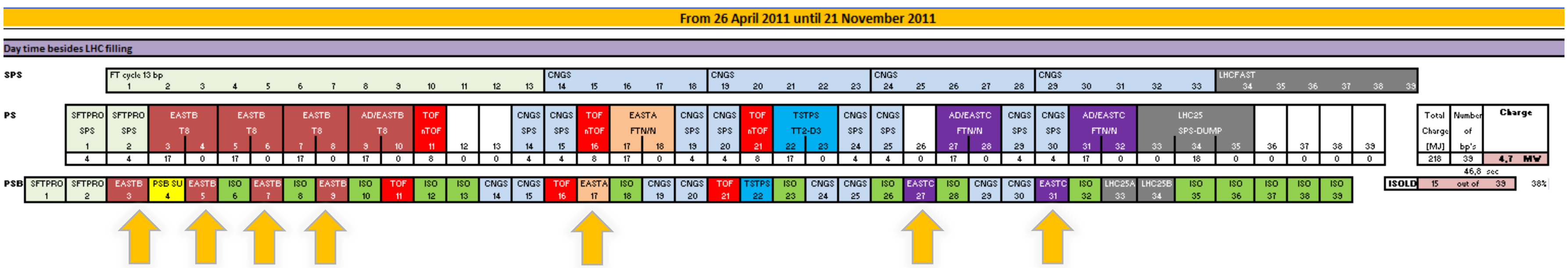
# Duty cycle of East Area installations

**A typical Super-cycle at CERN**

46.8s (39 cycles of 1.2s)

| Zone | Time in PS Supercycle |
|---|---|
| EASTA | 4301 h |
| EASTB | 4044 h |
| EASTC | 3274 h |




- Number of “EAST” area cycles: 7
- Beam takes 400ms to 700ms to pass through the beam line
- Particles in East Area beam lines: **3.5s** over **46.8s** of the super-cycle!
- “duty cycle” is only **7.5 %**

# Future Energy Consumption

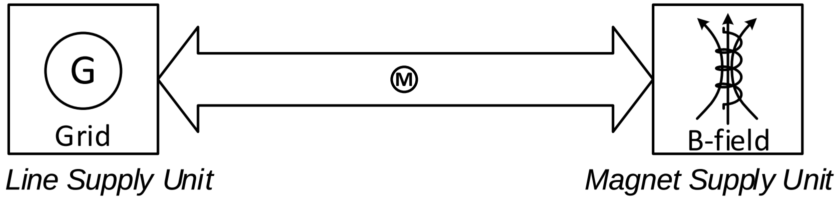
- **Assuming future operation in continuous mode**
  - The total energy cost will rise by more than 25%
  - The cooling fluid (mainly water) costs will rise by 25%
- **Despite fewer users the operating cost is higher**

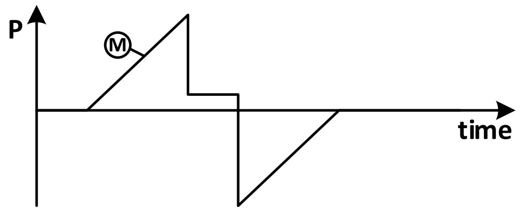
| | Future (3 beam lines) | | Present (5 beam lines) | |
|---|---|---|---|---|
| | Energy in GWh | Price in kCHF | Energy in GWh | Price in kCHF |
| Electrical energy | 10.9 | **552** | 9.0 | **406** |
| Total cooling fluid | | **102** | | **75** |
| **TOTAL energy cost** | | **653 kCHF** | | **480 kCHF** |

- Unless operation is changed to “cycling mode”…

**Cycling operating mode:** Magnet current is reduced to zero while no beam is present in its vacuum chamber (as opposed to the continuous operating mode)

# Direct versus Cycling operation

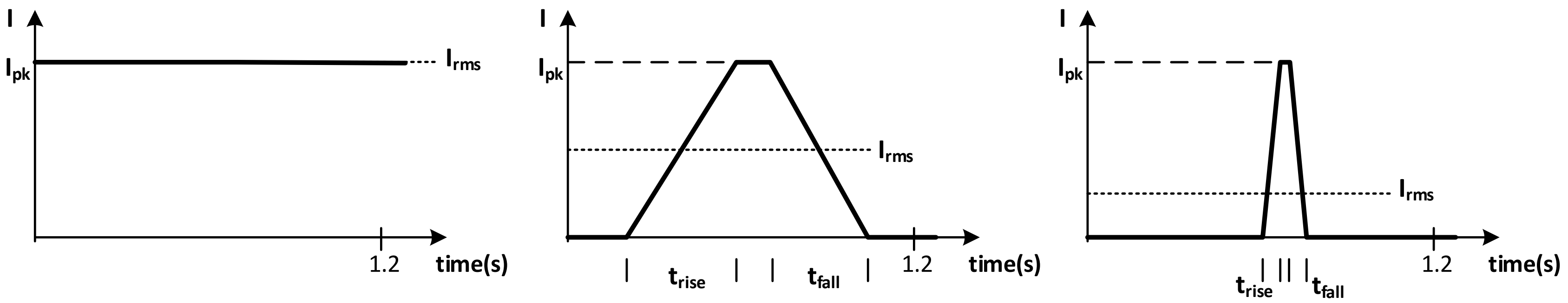



| Magnet type | Total (1.2sec) | Recoverable | Thermal loss (1.2sec) |
|---|---|---|---|
| Quadrupole (26Gev) | 11kJ | 6kJ | 5kJ |
| Small Dipole (26Gev) | 31.5kJ | 25kJ | 6.5kJ |
| Large Dipole (26Gev) | 101kJ | 82kJ | 19kJ |

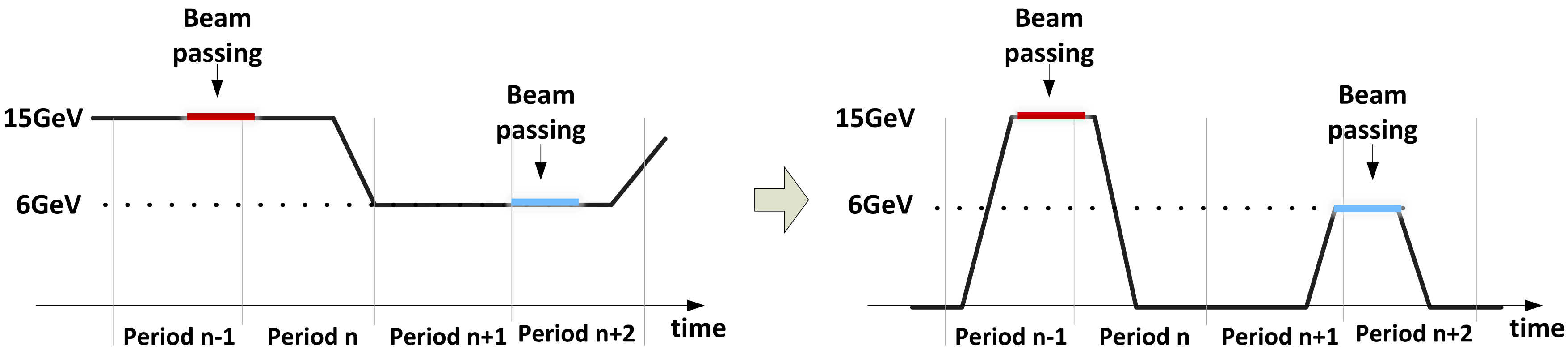
**Annual cost of electricity for 1kJ: 270-350 Swiss francs***

*(Non-recoverable/consumed every 1.2seconds)*

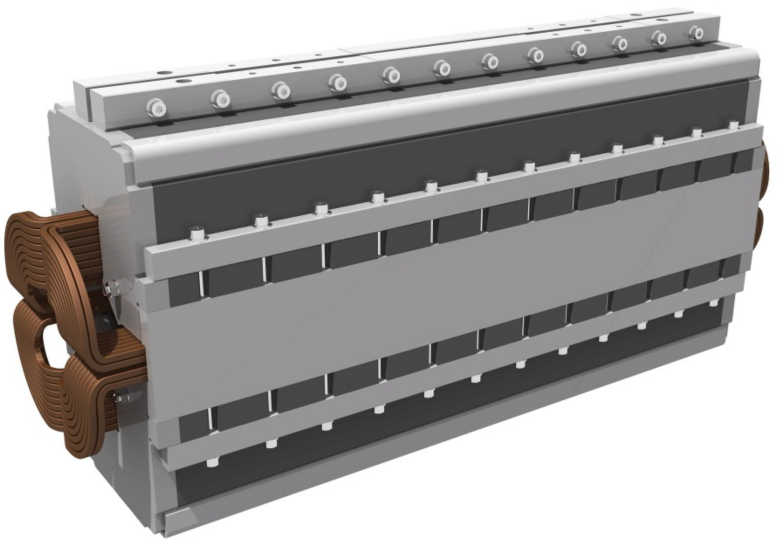



* Assuming cost of electricity between 0.05 and 0.065CHF/kWh. 1kJ of energy over a 1.2sec cycle corresponds to 1kJ/1.2sec=0.83kW of average power. Assuming this 1.2sec (PS) cycle repeats for 24hours over 270 working days the total energy required from the power network (for each 1kJ) is 5378kWh/annum. If this energy is not recovered in capacitor banks after every magnet cycle it is returned to the power network and is not remunerated by the provider.

# Cycling operation




- **Cycling operation requires a di/dt through the magnet**
  - 23/55 magnets do not support cycling due to a solid steel yoke
  - Eddy currents would heat up the yoke material



# Cycling Operation: consumption

| FUTURE OPERATION (HYPOTHESIS) | | | |
|---|---|---|---|
| **Zone** | **number of cycle per Supercycle** | **duration in 2011 (in hr)** | **duty cycle** |
| **Total - East** | **6** | **4301** | **15%** |
| **EASTA** | **2** | **4301** | **5%** |
| EASTA on T9 | 1 | 4301 | 2.5% |
| EASTA on T10 | 1 | 4301 | 2.5% |
| **EASTB** | **4** | **4044** | **10%** |

| CALCULATION RESULTS: ENERGY-WATER CONSUMPTION | | | | |
|---|---|---|---|---|
| | **Pulsed Mode** | | **Continuous Mode** | |
| | **Energy in MWh** | **Price in kCHF** | **Energy in MWh** | **Price in kCHF** |
| Total magnet electrical consumption | 557 | 28.3 | 9 128 | 464 |
| Water cooling electrical consumption | 79 | 4.0 | 1 294 | 66 |
| Air cooling electrical consumption | 26 | 1.3 | 431 | 22 |
| **Total electricity consumption** | **662** | **33.7** | **10 853** | **551.8** |
| **Total cooling fluid cost** | | **6.2** | | **101.5** |
| **TOTAL energy cost** | | **40 kCHF** ● | | **653 kCHF** ● |

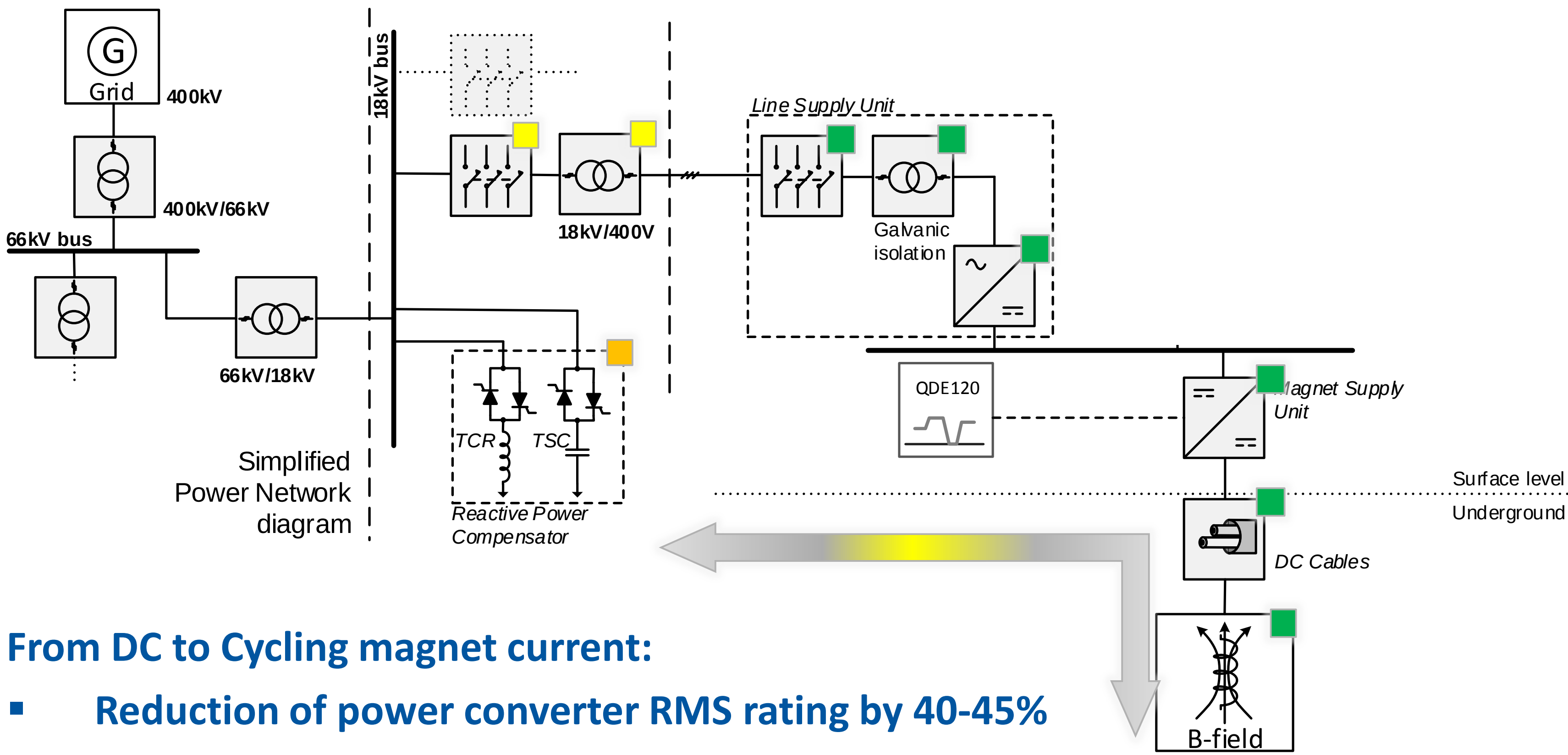
# Cycling Operation: Impact

- **Cycling operation will raise the project costs:**
  - Magnet consolidation of solid steel yokes: 1.3MCHF
  - Power Converter replacement costs will increase by: 1.5MCHF
    - ⇨ Power converter consolidation was already scheduled
  - Electrical distribution costs will be lower
    - ⇨ 2x2MVA transformers are sufficient to power the EAST Area (currently 8 transformers)

- **BUT pulsed operation will result recurring savings:**
  - 10GWh/year
  - 600kCHF/year
- **…and a much smaller carbon**  **from the East Experimental Area**

**AND pay back of the project costs will occur in 5 years**

# The System View



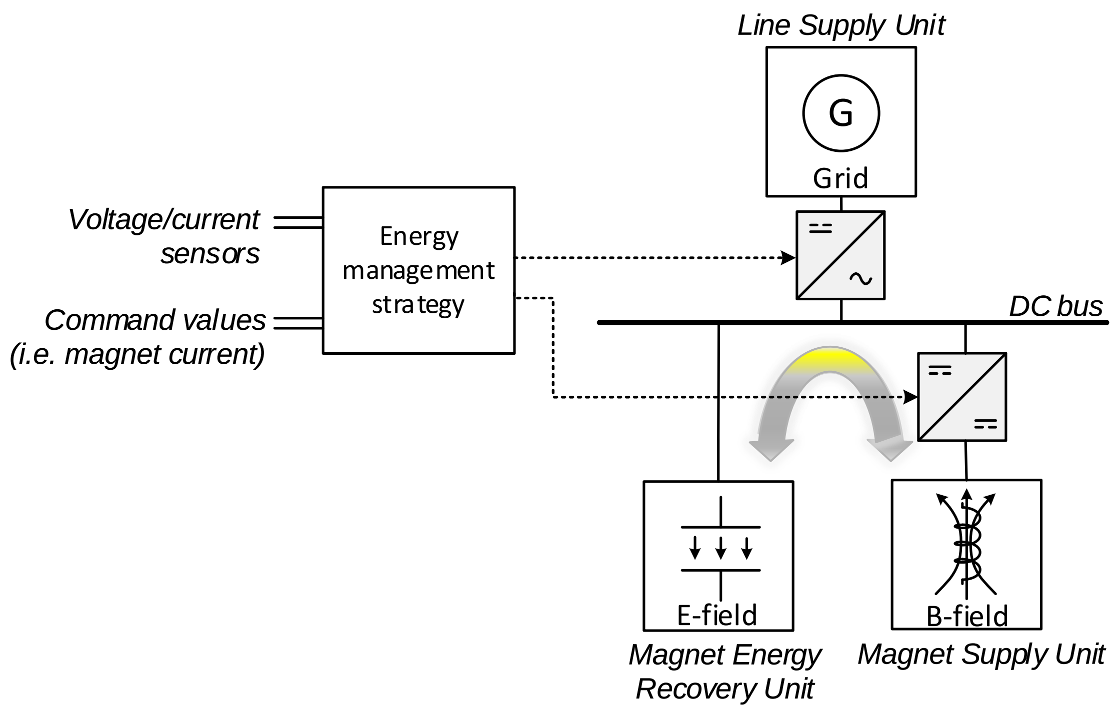

**From DC to Cycling magnet current:**

- **Reduction of power converter RMS rating by 40-45%**
- **Reduction of power losses in magnets**
- **Reduction of cooling requirements**

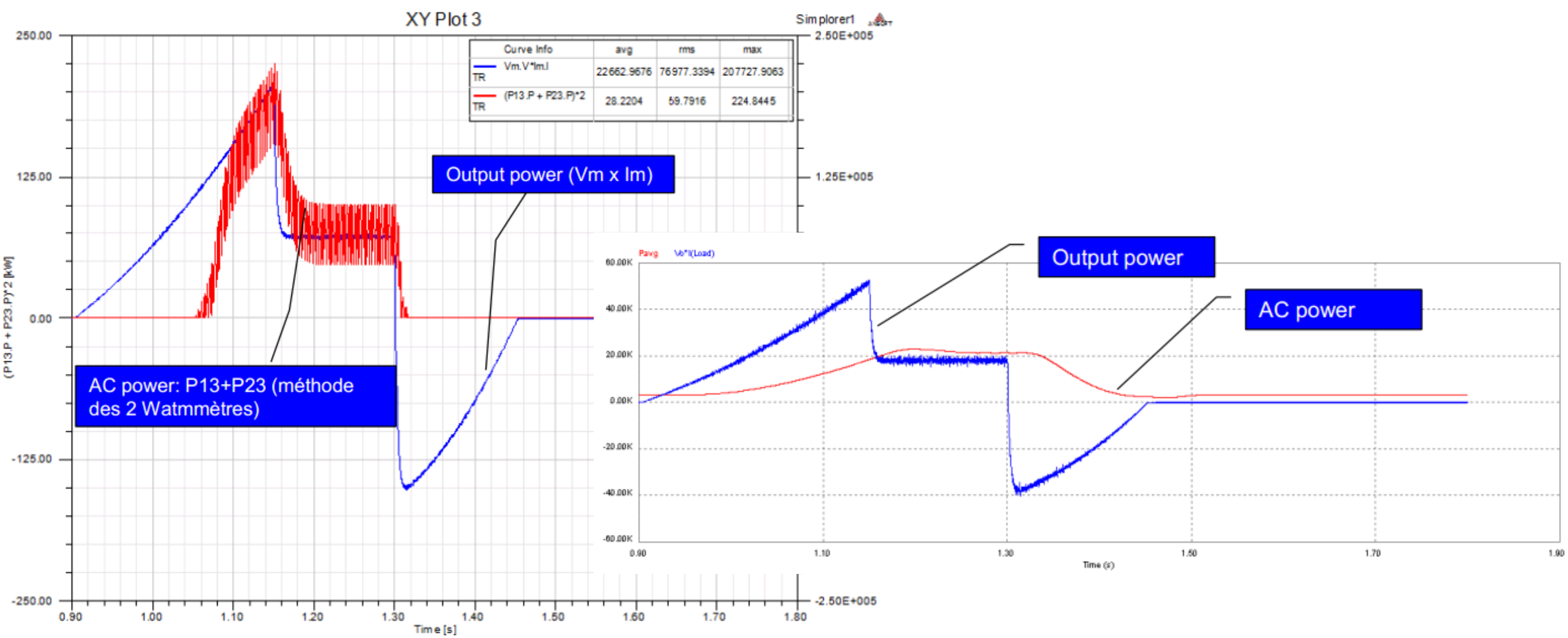
# Magnet Energy Recovery

# Definition

- **Magnet Energy Recovery is a specific variant of power cycling in which energy is stored locally in the power converter instead of returning it to the grid**



# Magnet Energy Recovery



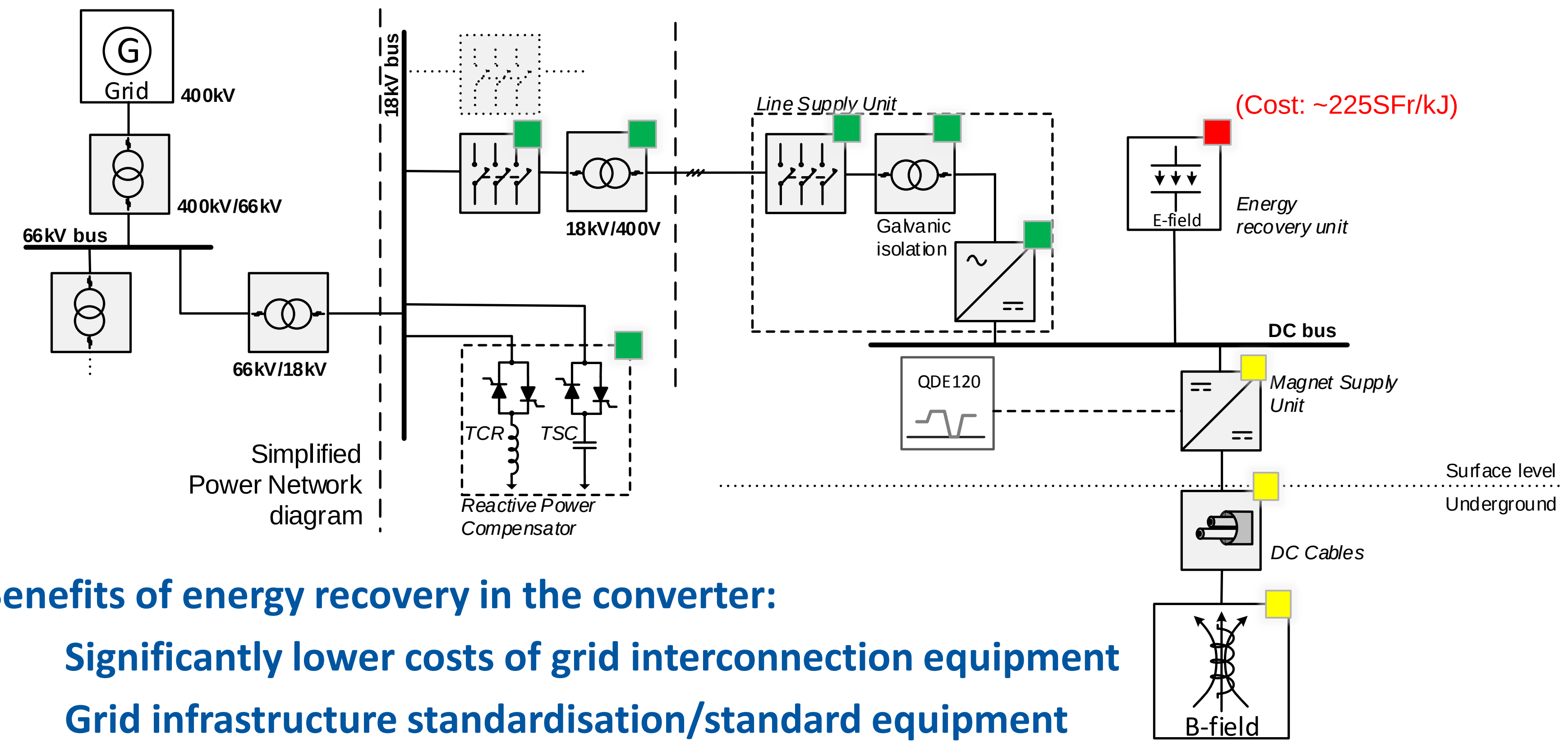

**Uncontrolled power from grid:**

- **Average AC power: 28kW**
- **Peak AC power: 210kW**

**Controlled power from grid:**

- **AC input power bound to nearly magnet flat-top power level**

# System Level Gains




**Benefits of energy recovery in the converter:**

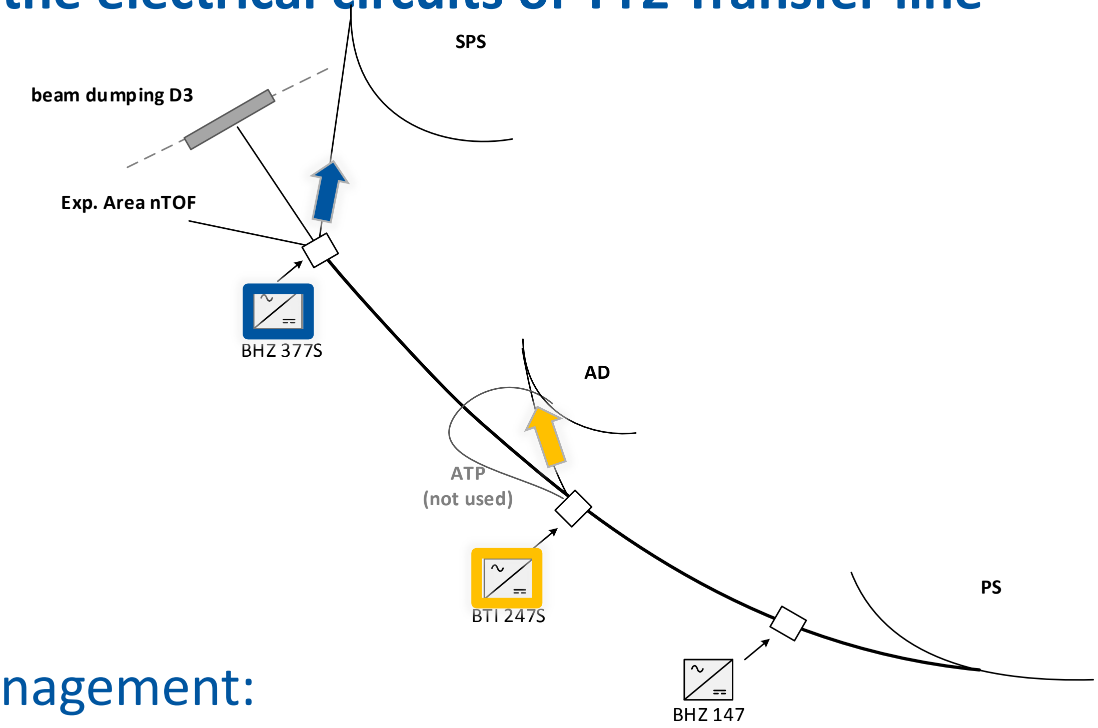
- **Significantly lower costs of grid interconnection equipment**
- **Grid infrastructure standardisation/standard equipment**
- **Lower capacity of reactive power compensation**
- **Fault ride-through capability of power converters**

# Magnet and System design intersection

# A real example

- **We are consolidating the electrical circuits of TT2 Transfer line**

- **BTI247+BTI248**
- **BHZ377+BHZ378**




The message from the management:

*« Benefit of this opportunity to generalise the process of building families of power converters for new projects ». One design per circuit is not an option.*

# A real example

- BHZ377 (type HB2/MCB)
  - 2.5m long
  - Aperture: 320mm(W) × 80mm(H)
  - 639mH/160mΩ, 490A
- BTI247 (type HB1/MCA)
  - 2.5m long
  - Aperture: 320mm(W) × 80mm(H)
  - 62.9mH/15mΩ, 1500A

(c) Rey Hori / KEK

- they have the same aperture, length and integrated field and so,
- they store the same amount of B-field energy!

$E_{BHZ377}$=76.7kJ $E_{BTI247}$ = 70.7kJ

- However, **they have different L,R** -> standardisation is a challenge!

# System Design: where to start?

## The eternal question:

*"should we design a magnet to match with*
*a powering system or design a powering system*
*for the magnet in hand?"*

**The Accelerator Engineer:**

- a certain magnetic cycle shape
- the particle beam characteristics
- a required bending angle *α*
- field quality etc

**The Magnet/Power Engineers:**

- $t_{rise}$, $t_{fall}$, $t_{flat\text{-}top}$
- Beam rigidity *B.ρ*
- Ampere turns *N.I*
- Mechanical layout

$$\vec{B} \cdot \rho = \frac{m_r \cdot \vec{v}}{q} = \frac{\vec{p}}{e}$$

$$m_r = \gamma \cdot m_0$$

$$\int \vec{B} \cdot ds = \alpha \cdot B \cdot \rho = \mu_0 \cdot N \cdot \mathrm{I}$$

α: bending angle
ρ: radius

I: electrical current
N: winding number of turns

# A collaborative approach

## Accelerator Designer

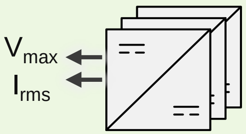
- **Bend proton beam by α rad/meter within certain vacuum chamber dimensions**
- **Magnetic cycle duration (e.g.1.2sec), minimum time extraction-to-extraction (e.g.0.9sec so rise and fall time could be 0.3sec each)**

## Magnet Designer

- **Calculate beam rigidity, estimate integrated field/magnet length. At this point the energy *E* in the magnet is known.**
- **Final windings design (number of turns, wire type/cross-section)**
- **Iterate**

## Converter Designer

- **Magnet energy known. Use current rise time to calculate peak and RMS power needed. *and Prms is typically* $P_{rms}=0.6 \times P_{pk}$**
- **Propose a family of power converters**




- **Finalise system design**

# Conclusions

- **We anticipate system level improvements in cost and size**
  - By implementing magnet **current cycling** where possible.
    - ⇨ Economic gains in energy costs can often finance the upgrade of dc magnets
  - By implementing **magnet energy recovery** inside power converter
    - ⇨ Reduction of grid interconnection costs
    - ⇨ Better power quality at the PCC of the power converter
    - ⇨ Longer lifetime of upstream transformers and
    - ⇨ major saving in reactive power compensation capacity

- **To achieve a compact and cost effective system design**
  - **Standardisation** of equipment is needed such as standard distribution equipment and power converter bricks that can be modularised
  - Reduction of **magnet consumption** offers benefits in the entire power supply chain RMS ratings

- **A collaborative system design is instrumental in system-wide optimisation**

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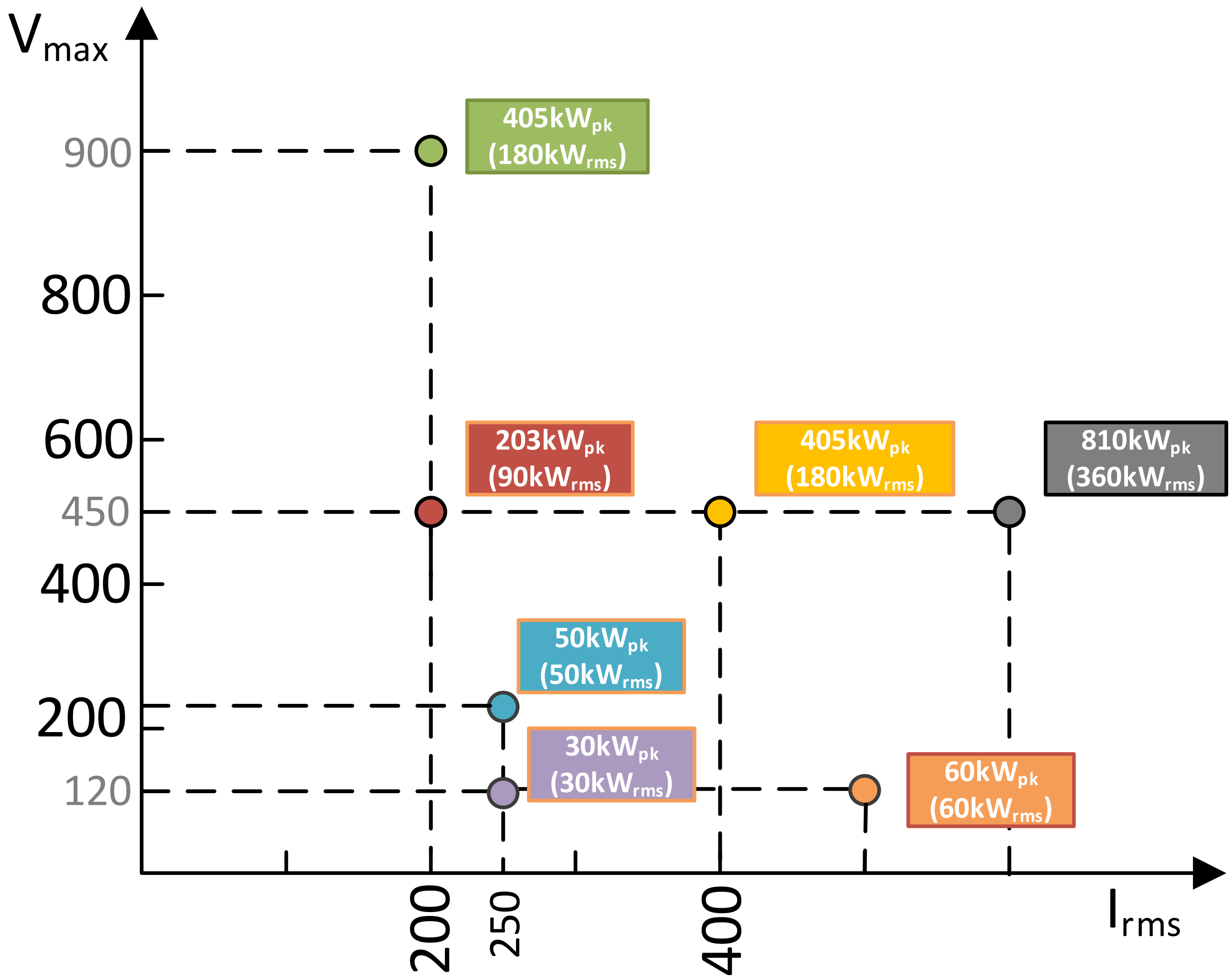
# Examples of converter standard bricks



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