# Energy efficiency of particle accelerators – a network in the European program EUCARD-2

M.Seidel, PSI

2nd EuCARD-2 Annual Meeting, Barcelona, April 22, 2015

EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

# Outline

## Energy Efficiency in Particle Accelerators

- Power and Energy – Order of magnitude examples.
- Workshops and Examples
  - RF workshop Daresbury
  - Magnet Workshop CERN
- Outlook
  - Sustainable Energy for large RI`s DESY
  - Energy Management GSI
  - Proton Driver Efficiency PSI
- Summary and Comments on Networking Experience

# Energy: Order of Magnitude Examples

| generation | consumption | storage |
|---|---|---|
| 1d cyclist „Tour de France“ (4hx300W): **1.2kWh** | 1 run of cloth washing machine: **0.8…1kWh** | car battery (60Ah): **0.72kWh** |
| 1d Wind Power Station (avg): **12MWh** | 1d Swiss Light Source (2.4GeV, 400mA): **82MWh** | ITER superconducting coil: **12,5MWh** |
| 1d nucl. Pow. Stati. Leibstadt (CH): **30GWh** | 1d CLIC Linear Collider @3TeV: **14GWh** | all German storage hydropower: **40GWh** |
| 1d Earth/Moon System E-loss: **77.000GWh** | 1d electrical consumpt. mankind: **53.000GWh** | World storage hydropower: ***O*( 1.000GWh )** |
| 1d sunshine absorbed on Earth: **3.000.000.000GWh** | 1d total mankind (inc.fuels): **360.000GWh** | |

**1.) accelerators are in the range were they become relevant for society and public discussion**
**2.) desired turn to renewables is an enormous task; storage is the problem, not production**
**3.) fluctuations of energy availability, depending on time and weather, will be large**

# tasks within EnEfficient

**task 1**: energy recovery from cooling circuits, Th.Parker→ A.Lundmark (ESS)

**[workshop April 14, survey of European Labs, applications of heat, T-levels etc.]**

**task 2**: higher electronic efficiency RF power generation, E.Jensen (CERN)

**[workshop Daresbury in June 14, e.g. Multi Beam IOT's]**

**task 3**: short term energy storage systems, R.Gehring (KIT)

**[non-interruptable power, short term storage, session in Hamburg workshop]**

**task 4**: virtual power plant, J.Stadlmann (GSI)

**[adaptation of operation to grid situation – context renewables..., possibly backup power generator ...]**

**task 5**: beam transfer channels with low power consumption, P.Spiller (GSI)

**[pulsed magnets, low power conventional magnets, permanent magnets, parameter comparison etc.]**

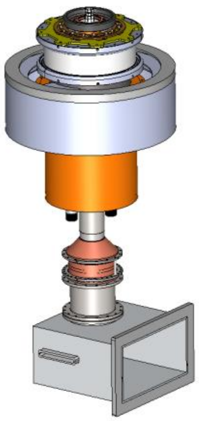
# Efficient RF Generation and Beam Acceleration

RF generation efficiency is key for many accelerator applications, especially high intensity machines

topics:

- klystron development
  (new bunching concept leads towards 90%)
- multi beam IOT (ESS)
- magnetrons
- high Q s.c. cavities

→ **see also I.Syratchev's talk**



CPI: multi-beam IOT

E2V: magnetron

THALES: multi-beam klystron

SIEMENS: solid state amplifier

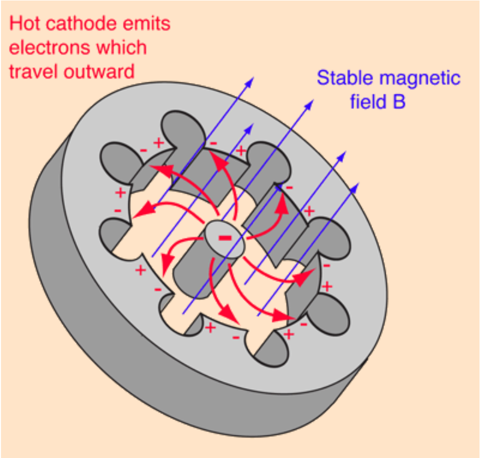
THALES: TETRODE

workshop EnEfficient RF sources:
https://indico.cern.ch/event/297025/
session at FCC workshop:
http://indico.cern.ch/event/340703/session/76/

# Example: Magnetron

**[Amos Dexter, RF workshop Daresbury (2014)]**

| | | 800W Cooker | 1200W Cooker | SPL 704MHz |
|---|---|---|---|---|
| Radius Cathode | rc (mm) | 1.93 | 2.96 | 17.74 |
| Radius Anode | ra (mm) | 4.35 | 5.80 | 24.01 |
| Anode voltage | V | 4000 | 4000 | 41876 |
| ~Electric field | E (V/m) | 1.65E+06 | 1.41E+06 | 6.68E+06 |
| Magnetic field | B (T) | 0.185 | 0.135 | 0.413 |
| Nominal Efficiency | η | 77.3% | 69.1% | 92.9% |

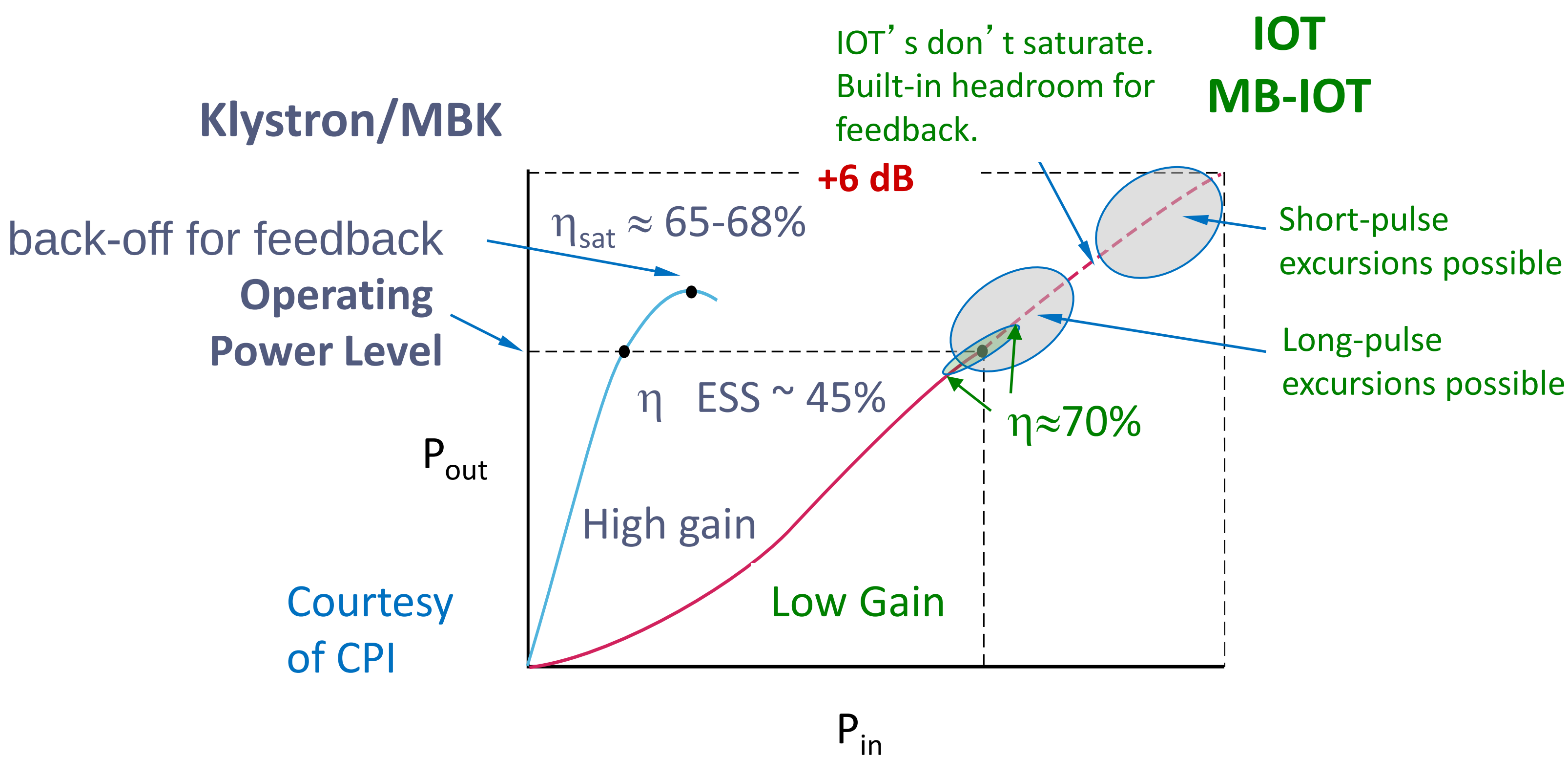



- magnetron concept has very high efficiency and is simplistic
- however: phase control difficult; needs injection-locked driver; hard to drive high Q resonators as s.c. cavities; research ongoing

High-power magnetron transmitter as an RF source for superconducting linear accelerators, FERMILAB-PUB-13-315-AD-TD

# Inductive Output Tubes – considered for ESS

**[Morten Jensen (ESS) @ EnEfficient RF sources, 2014]**



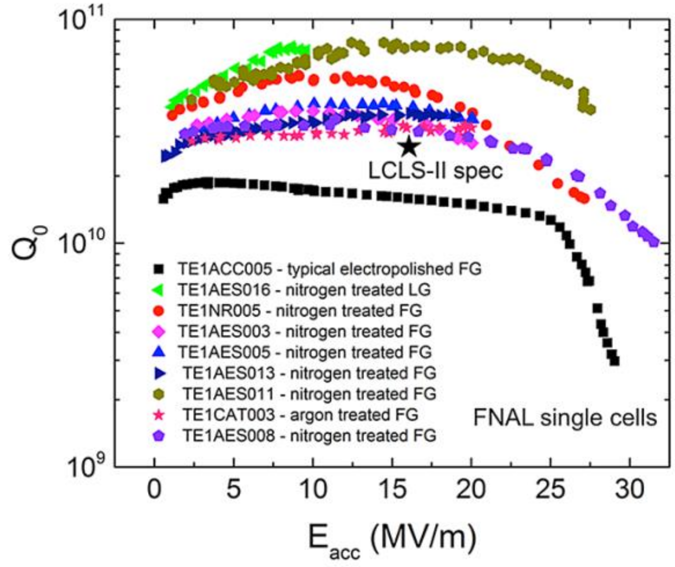

→ **Klystrons:** **Back-off for feedback, cost: 30%**

→ **IOTs:** **Operate close to max efficiency**

# superconducting structures for CW operation

**voltage, dissipated power and cryogenic efficiency:**

$$\left(\frac{R}{Q}\right) = \frac{U_a^2}{P_{\text{dissip}} Q} \qquad P_{\text{cryo}} = \frac{P_{\text{cold}}}{\eta_c \eta_p} \approx 700 \cdot P_{\text{dissip}}@2\text{K}$$




example: FNAL results

**new developments:**

- $N_2$ doping, high Q, low $P_{dissip}$; best benefit for low frequencies
- possibly $Nb_3Sn$ cavities, high Q at 4.5K, better $\eta_c$

related references:

- THE JOINT HIGH Q0 R&D PROGRAM FOR LCLS-II, A. Crawford et al, CLASSE/FNAL/SLAC/TJNAF, IPAC 2014
- Nb3Sn – PRESENT STATUS AND POTENTIAL AS AN ALTERNATIVE SRF MATERIAL, S. Posen, M. Liepe, LINAC 2014
- Ultraefficient superconducting RF cavities for FCC, A.Romanenko, FCC workshop, Washington, 2015

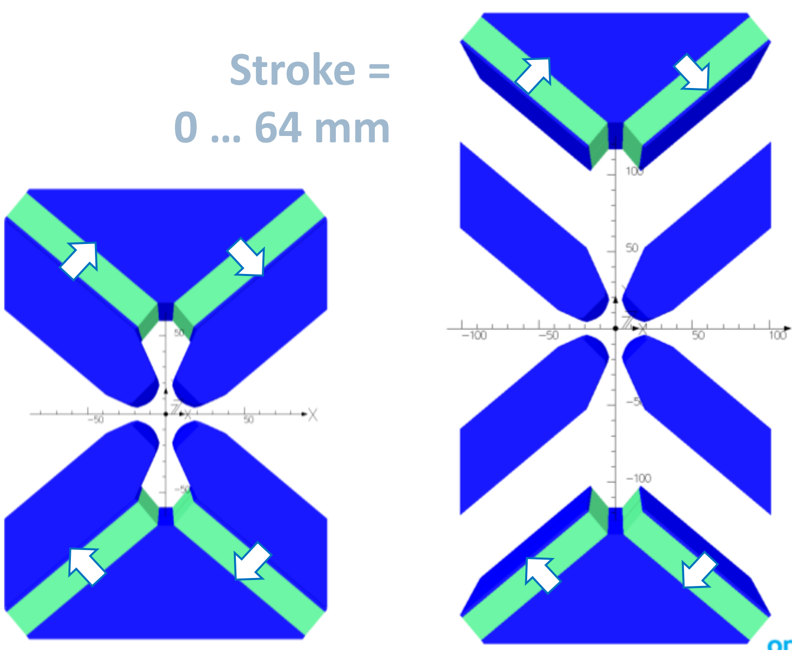
# low power accelerator magnets

| | |
|---|---|
| **permanent magnets**<br>Pro: no power required, reliable, compact | Con: tunability difficult, large aperture magnets limited, radiation damage |
| **optimized electromagnet**<br>Pro: low power, less cooling | Con: larger size, cost |
| **pulsed magnet**<br>Pro: low average power, less cooling, high fields | Con: complexity magnet and circuit, field errors |
| **s.c. magnet**<br>Pro: no ohmic losses, higher fields | Con: cost, complexity, cryo installation |
| **high saturation materials**<br>Pro: lower power, compactness and weight | Con: cost, gain is limited |

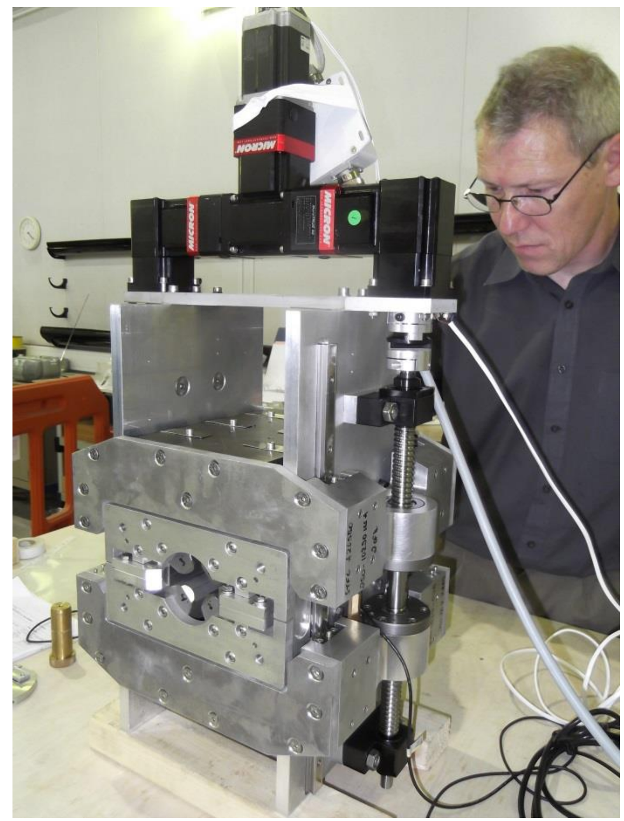
**Workshop on Special Compact and Low Consumption Magnet Design,** November 2014, CERN; **indico.cern.ch/event/321880/**

# Permanent Magnet Quad Design for CLIC [B.Shepard et al, STFC Daresbury]

- **NdFeB** magnets with $\mathbf{B_r = 1.37\ T}$
- 4 permanent magnet blocks
- gradient = **15.0…60.4 T/m,** stroke = 0..64 mm
- Pole gap = 27.2 mm
- Field quality = ±0.1% over 23 mm




Tunable high-gradient permanent magnet quadrupoles, B.J.A. Shepherd *et al* 2014 *JINST* 9 T11006



# Permanent Magnet Quad for Light Sources [P. N'gotta, J.Chavanne, G. Le Bec, ESRF]

**H-type Hybrid structure :**

- Possible structure for future light source
- Strong gradient & compactness
- Simple field correction
- Easy assembly
- Possibility to implement tuning coils
- No power consumption

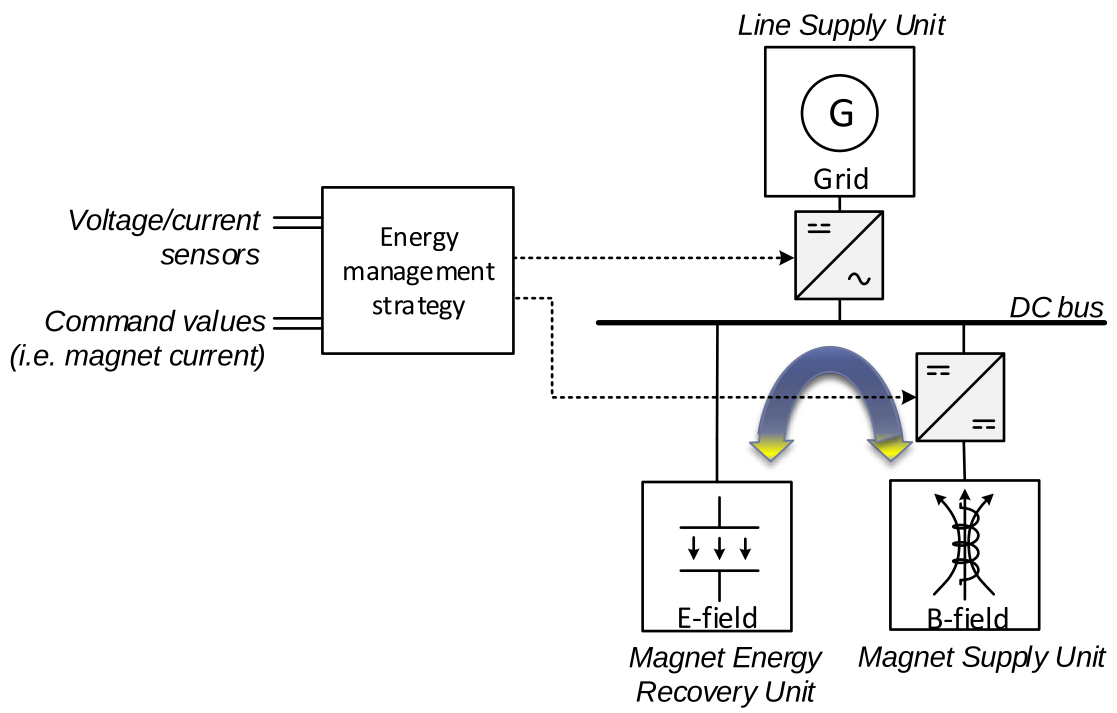
**Prospects :**

- Mechanical improvement
- Field tuning
- Temperature compensation
- Correction tools improvement

# Pulsed Magnets – Energy Recovery

**[Konstantinos Papastergiou, CERN]**

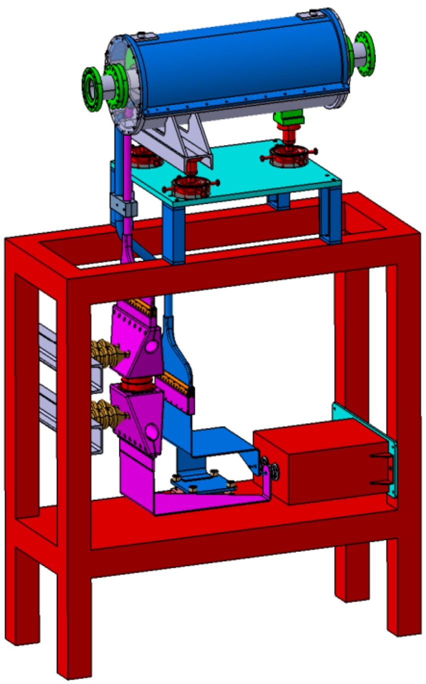
- **Magnet Energy Recovery is a specific variant of power cycling in which energy is stored locally in the power converter instead of returning it to the grid**



# Pulsed Quadrupole Magnet

**[P.Spiller, C.Tenholt GSI → also presentation Thursday]**

| | Prototype Quadrupole |
|---|---|
| Gradient | 80 T/m |
| Length | 0.65 m |
| Pulse length | 90 μs (beam 1 μs) |
| Peak current | 400 kA (35 kA) |
| Peak voltage | 17 kV (5 kV) |
| Energy @17 kV | 65 kJ (5.6 kJ) |
| Inductivity | 535 nH |
| Capacitor | 450 μF |
| Forces | 200 kN |



Engineering model of the prototype quadrupole magnet incl. support

- low average power; energy recovery in capacitive storage possible for periodic operation
- complexity added by pulsing circuit; field precision potentially difficult

**next**:

- future activities:
  energy management; survey on volatile consumption; sustainable energies for RI`s; proton driver efficiency
- experience from networking:
  master thesis work; topic matrix

# Energy Management

**[virtual power plant]**

- motivation: strong variations of supply by wind and sun energy
- even today strong variation of energy cost by order of magnitude (!)

→ consider „dynamic operation“ of accelerators, depending on supply situation (challenging, loss of efficiency)

→ consider options to store energy on site (expensive)

→ **economy depends on supply volatility and cost of energy**

## Questionnaire

### on Accelerator Electric Power Consumption and Efficiency

| Contact | | |
|---|---|---|
| **Helmholtzzentrum für Schwerionenforschung** | Dr. Jens Stadlmann | j.stadlmann@gsi.de |
| **Paul Scherrer Institut** | Dr. Mike Seidel | mike.seidel@psi.ch |
| **Technische Universität Darmstadt**<br>Elektrische Energieversorgung unter Einsatz Erneuerbarer Energien (E5) | Damian Batorowicz<br>Christina Mahler<br>Stanislav Leis | damian.batorowicz@e5.tu-darmstadt.de<br>christina.mahler@e5.tu-darmstadt.de<br>leis@stud.tu-darmstadt.de |

**Part 1: Description of the nature of your facility**

| | | A | B |
|---|---|---|---|
| 1. | **Description of facility** | | |

**survey by J.Stadlmann & TU Darmstadt: D.Batorowicz, C.Mahler**

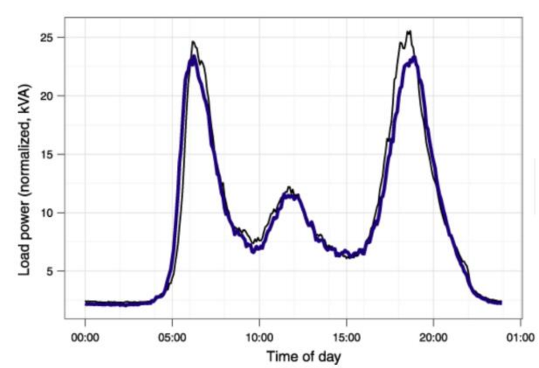
# Energy management example: CLIC study on standby modes

**CLIC project predicts large power for 3TeV case: 580MW**
**idea:**

- prepare standby modes for high consumption times during day; relatively fast luminosity recovery from standby (challenging)
- model calculation includes standby power, startup times

**Andrea Latina et al, CERN**

Energy consumption per day




We could go to stand-by mode during the most critical (i.e. expensive) hours of the day...

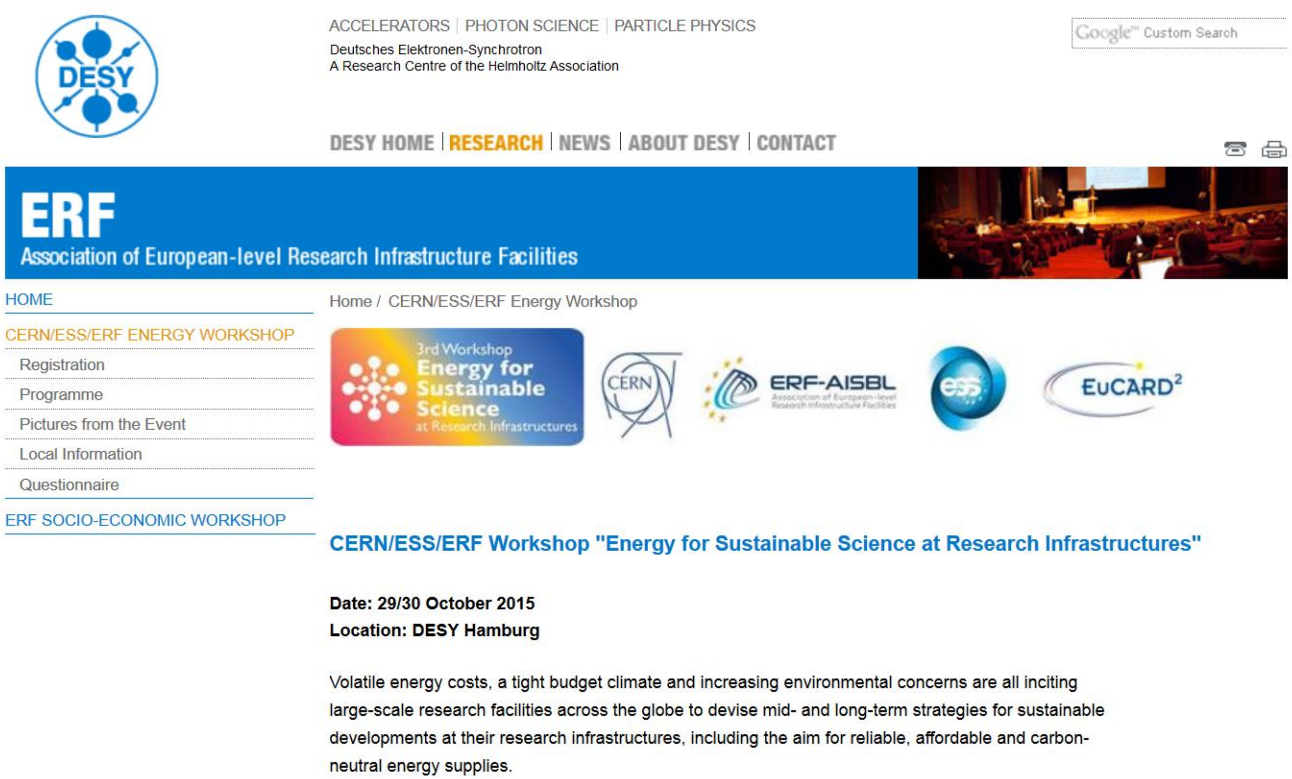
**result of model with 2 standby periods during day:**

- 1 day with 2 × standbys:
  $E_{standby}$ = 582 MW × 14 hours + 2 × (4 × 268 MWh + 1 × 425 MWh) = 11.14 GWh
  $L_{standby}t = 2.0\times10^{34}\ cm^{-2}s^{-1} \times (14 + 2 \times ½)$ hours = $1.08\ fb^{-1}$

**Energy consumed is reduced by 18% ( -2.826 GWh )**
**Luminosity delivered is reduced by 37% ( $-0.648\ fb^{-1}$ )**

# workshop on sustainable science at research infrastructures (DESY, Oct/2015)

- covers all aspects of efficient technical systems, energy politics, energy management; special session on energy storage systems for accelerators
- focus not only accelerators but generally large RI‘s
- 2 days, plenaries plus three parallel sessions



ACCELERATORS | PHOTON SCIENCE | PARTICLE PHYSICS

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

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ERF
Association of European-level Research Infrastructure Facilities

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3rd Workshop Energy for Sustainable Science at Research Infrastructures

CERN/ESS/ERF Workshop "Energy for Sustainable Science at Research Infrastructures"

**Date: 29/30 October 2015**
**Location: DESY Hamburg**

Volatile energy costs, a tight budget climate and increasing environmental concerns are all inciting large-scale research facilities across the globe to devise mid- and long-term strategies for sustainable developments at their research infrastructures, including the aim for reliable, affordable and carbon-neutral energy supplies.

# Energy Storage for Accelerators

**[session at Hamburg Workshop]**

**storage systems needed for:**

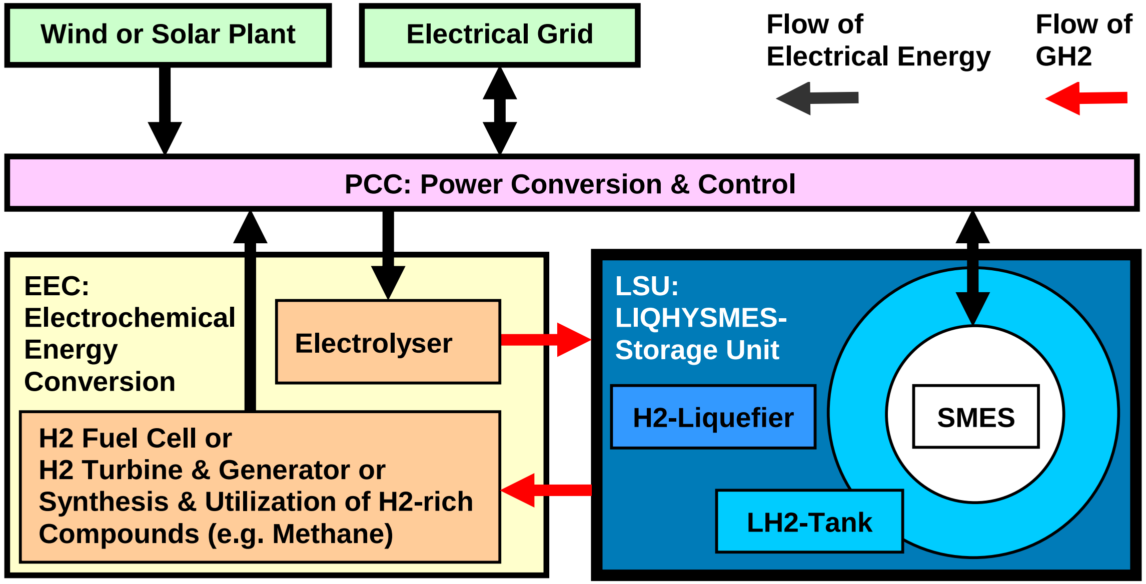
- pulsed RF systems
- cycling synchrotrons
- pulsed magnets
- uninterrupted power
- strategic energy management

**exmple: LIQuid HYdrogen & SMES**

development by KIT for general purpose: hybrid SMES/LH2

**[M.Sander, R.Gehring, KIT]**

- large power 10..100 MW
- capacity to ~70 GWh
- SMES to ~10 GJ
- synergy with existing cryogenics



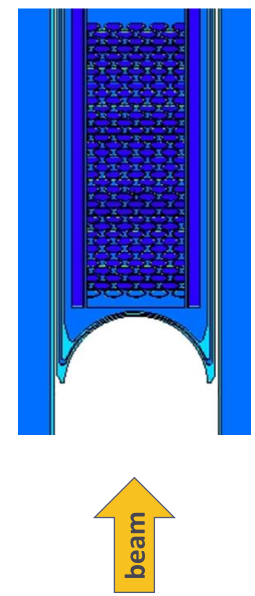
# Planned Workshop: Proton Driver Efficiency

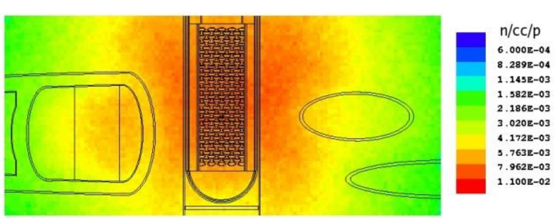
- proton drivers needed for several high intensity applications: accelerator driven systems (ADS), neutron sources, Muon sources, neutrino sources
- common workshop with WP4 Accelerator Applications
- will consider all aspects of proton drivers, such as:
  - accelerator concepts (cyclotron, s.c. linac, n.c. linac, RCS)
  - efficient RF generation; cavities, especially s.c. and CW
  - aux. systems: cryogenics, conv. cool.; energy management
  - conversion to secondary radiation

# Example: Efficiency of Spallation Target [M.Wohlmuther, PSI]

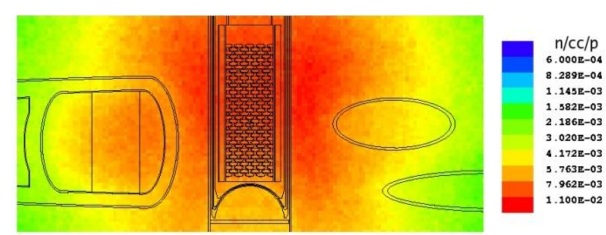
| old | new |
|---|---|


| measure | gain |
|---|---|
| Zr cladding instead steel | 12% |
| more compact rod bundle | 5% |
| Pb reflector | 10% |
| inverted entrance window | 10% |
| total gain factor | 1.42 |



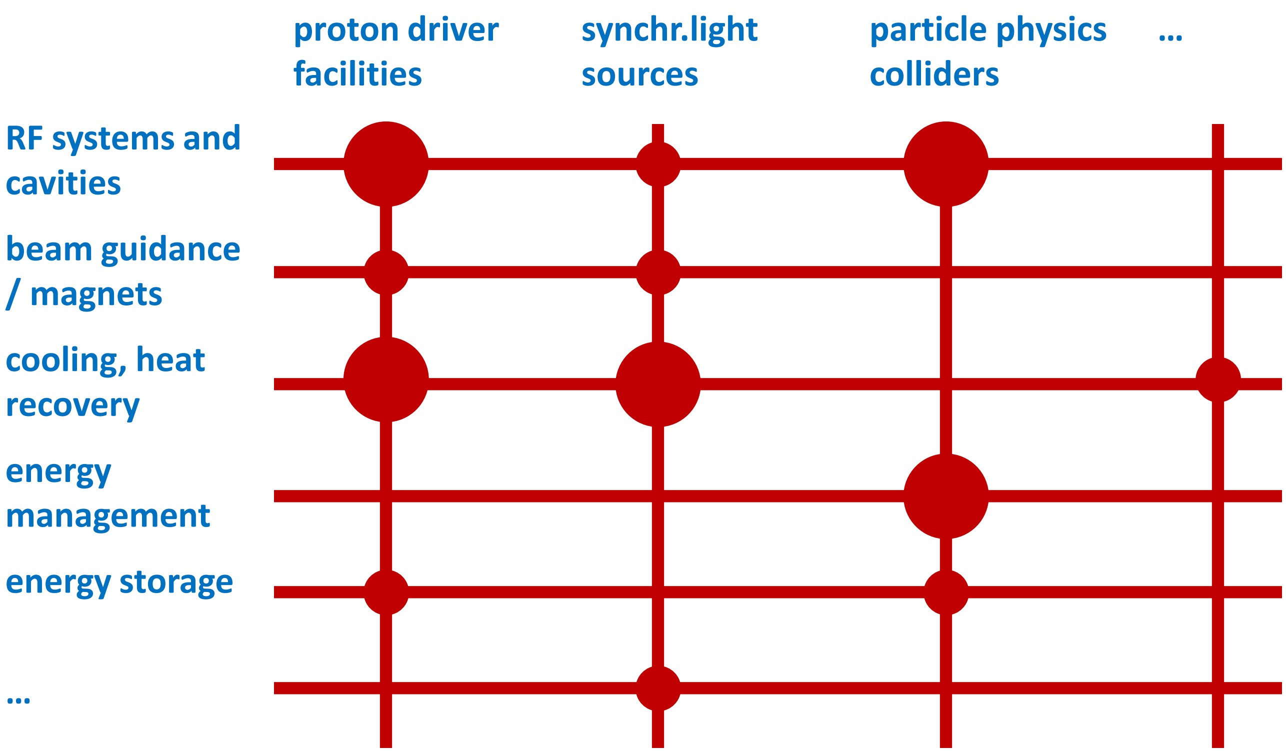




color code: neutron density on same scale (MCNPX)



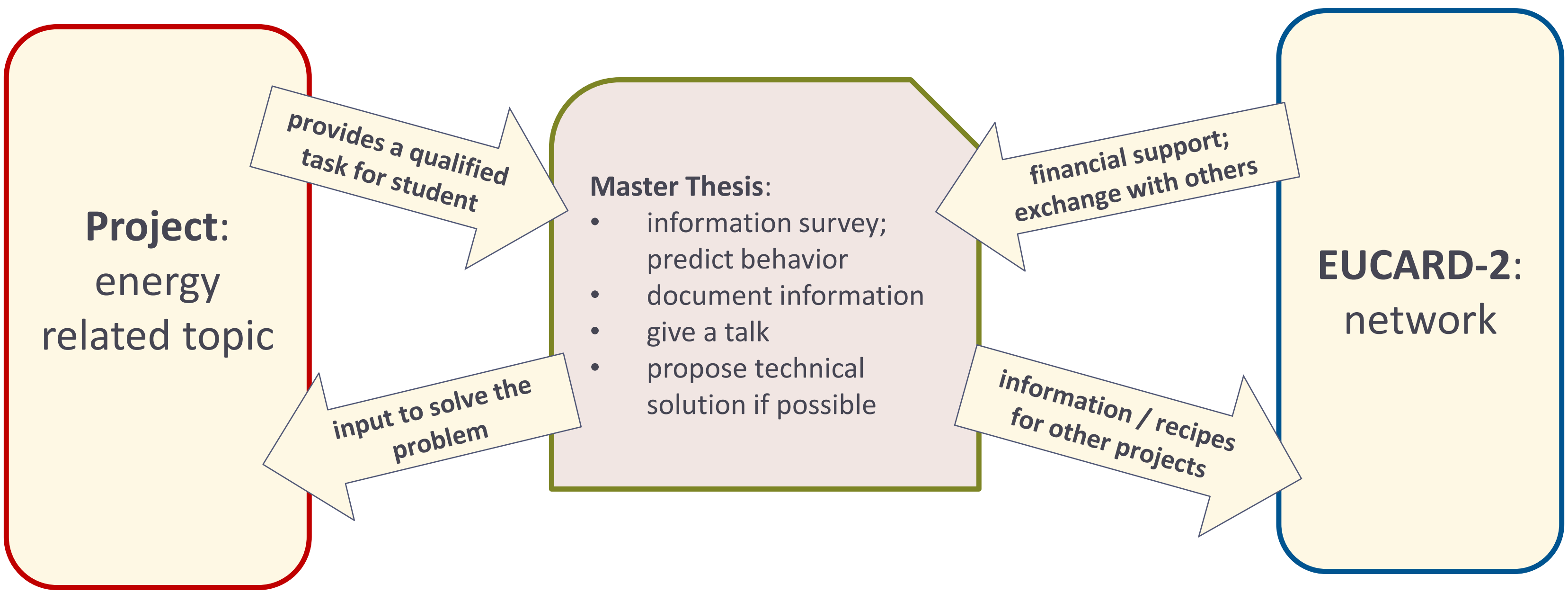
# EnEfficient network: topic matrix, projects vs systems

- tasks in EnEfficient are technology related, and so where the workshops
- another way to look at energy efficiency is to consider all aspects for a class of facilities → example: „Proton Driver Efficiency“
- this can better **support synergies with concrete projects** due to focusing on a concrete application



# EnEfficient Network: synergies with projects and students

our practical experience: Master or PhD. students could be financed by network, have time to focus on a technical problem, provide excellent documentation




**win-win for student, project, Eucard !**

# Summary WP3

- **energy efficiency** is accepted as an **important aspect** of accelerator projects [inv. talk at IPAC15]
- the **right balance** between efficiency, reliability and investment cost must be found for each project
- important developments take place on **heat recovery, RF systems, cavities, magnets, E management**

- synergies with real projects are important; **thesis work, topical workshop**

- specific workshops that took place:
  - heat recovery, efficient RF generation, efficient magnets
- still to come:
  - virtual power plant (energy management); storage systems
- additional (unplanned): sustainable energy for RI's (Hamburg Oct 15); proton driver efficiency (early 2016)

www.psi.ch/enefficient

# Status EnEfficient WP3,

M.Seidel, PSI

| **Task** | **Workshops / Deliverables** | |
|---|---|---|
| heat recovery | Workshop ESS 3/14<br>Lab Inventory, Master Thesis ESS 3/14 | ✓<br>✓ |
| efficient RF generation | Workshop STFC 7/14<br>Session FCC week<br>write up / summary 2/17 | ✓<br>✓<br>o |
| energy storage | Session in DESY workshop 10/15<br>write up document (?) | o<br>o |
| virtual power plant | Workshop 2015 (in prep)<br>Lab survey on volatility, GSI, TUD (ongoing)<br>write up document (12/16) | o<br>o<br>o |
| efficient beam transfer systems | design study pulsed quad (3/14)<br>Workshop CERN 11/14<br>pulsed magnets work GSI (ongoing)<br>concept comparison, Master Thesis GSI (10/15 ongoing) | ✓<br>✓<br>o<br>o |
| others that evolved | Workshop DESY : sustainable energy for large RI’s 10/15<br>Workshop Proton Driver Efficiency ca 3/16<br>summary publication in journal, under discussion | o<br>o<br>o |