Energy efficiency of particle accelerators – a review after 4 years

M.Seidel, PSI

4th EuCARD-2 Annual Meeting, Glasgow, March 29, 2017

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

Workshops

all workshops had good participation and resulted in documentation of relevant themes:

- **February 29 - March 2, 2016** - Workshop on **Efficiency of Proton Driver Accelerators**
  hosted by PSI, Villigen, Switzerland
  More Information: http://indico.psi.ch/event/Proton.Driver.Efficiency.Workshop
- **October 29-30, 2015** - III. Workshop on **Energy for Sustainable Science at large Research Infrastructures**
  hosted by DESY, Hamburg, More Information: http://erf.desy.de/energyworkshop ,
  session storage systems: https://indico.desy.de/conferenceOtherViews.py?view=standard&confId=11870
- **April 21-24, 2015** - **EuCARD² 2nd Annual Meeting**
  Dedicated EnEfficient session: https://indico.cern.ch/event/364085/session/25/?slotId=0#20150423
- **November 26-28, 2014** - Workshop on **Compact and Low Consumption Magnet Design for Future Linear and Circular Colliders**
  hosted on CERN, More Information: https://indico.cern.ch/event/321880/
- **June 3-4, 2014** - Workshop on **EnEfficient RF Sources**, hosted at Cockroft Institute in Daresbury
  More Information: https://indico.cern.ch/conferenceDisplay.py?confId=297025
- **April 28-29, 2014** - Workshop on **heat recovery**, held at MAX IV in Lund, Sweden
  More Information: https://indico.esss.lu.se/indico/conferenceDisplay.py?confId=148
- **February 3, 2014** - Workshop Session **Energy Efficiency Aspects** of the CLIC Project under the frame of activities for EnEfficient/Eucard-2
  More Information: https://indico.cern.ch/sessionDisplay.py?sessionId=9&confId=275412#20140204
- **October 23-25, 2013** - 2nd Workshop on **Energy for Sustainable Science**
  hosted at CERN, Geneva, Switzerland
  More Information: https://indico.cern.ch/event/245432/

Dedicated Studies

- Cooling Related Inventory, Del. Report, J.Torberntsson et al (ESS)
  - https://edms.cern.ch/file/1325126/4/EuCARD2-Del-D3-1-Final.pdf
- Pulsed Quadrupoles, Del. Report, C.Tenholt (GSI)
  - https://edms.cern.ch/file/1325127/4/EuCARD2-Del-D3-2-Final.pdf
- Review of Energy Storage Systems, Del. Report, J.Eckoldt (DESY), R.Gehring (KIT), M.Seidel (PSI)
  - https://edms.cern.ch/file/1325129/2/EuCARD2-Del-D3-4-final.docx
- Comparison of Beam Transport Options, Del. Report, Ph.Gardlowski (GSI)
  - https://edms.cern.ch/file/1325128/3/EuCARD2-Del-D3-3-Final.pdf
- Energy Management, Report, Lab Survey, Electrical Engineering, S.Leis, D.Batorowicz (Uni Darmstadt)
  - https://edms.cern.ch/file/1325135/2/EuCARD2-Mil-MS19-Final.pdf
  - [extended thesis version]
- Virtual Power Plant at Science Facilities, Del. Report, J.Stadlmann (GSI)
  - https://edms.cern.ch/file/1325130/2/EuCARD2-Del-D3-5-Final.docx
- Review of Proton Driver Accelerators, Report, M.Seidel (Editor), pres. F.Gerigk this w.
  - https://www.psi.ch/enefficient/PastEventsList/pdriver-efficiency-summary_compilation_V6.pdf
- Analysis of PSI High Intensity Accelerator, Report, pres. A.Kovach this workshop
  - to be included in database

Use of Waste Heat

produce work → electrical power?
(not recommended)

$$W_{\max} = Q\,(1 - T_0/T)$$

example: T=40°C: efficiency 8%
T=95°C: efficiency 20%

heating: either have high T cooling circuits
→ technical compromises

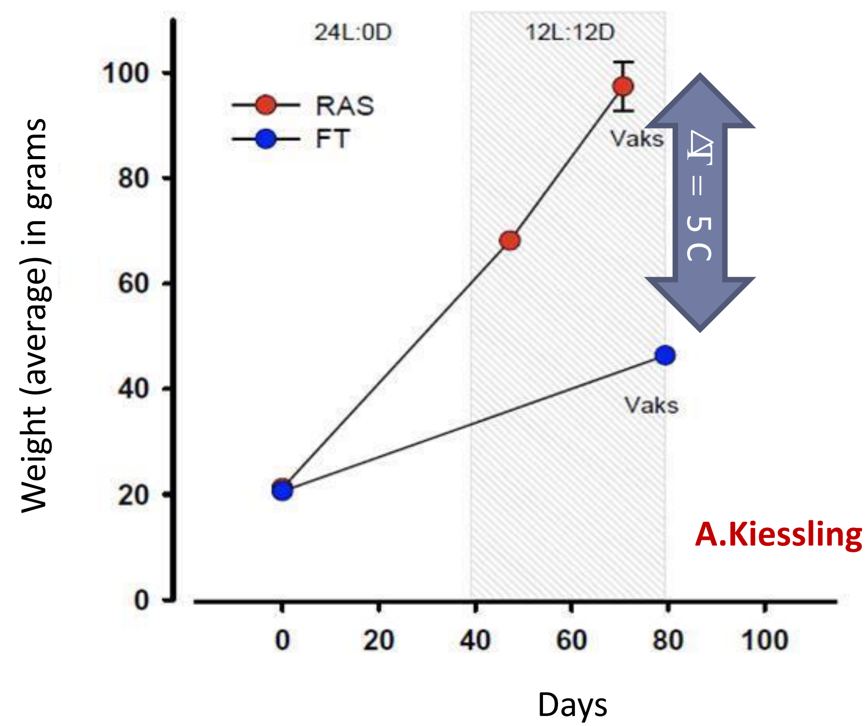
or convert heat to higher T level for heating purposes (recommended)

$$Q_{\mathrm{H}} = W \cdot \mathrm{COP}$$

example: T=40°C, T_{use} =80°C, COP=5: W=10kW,
Q_C=40kW, Q_H=50kW (availabe for heating)

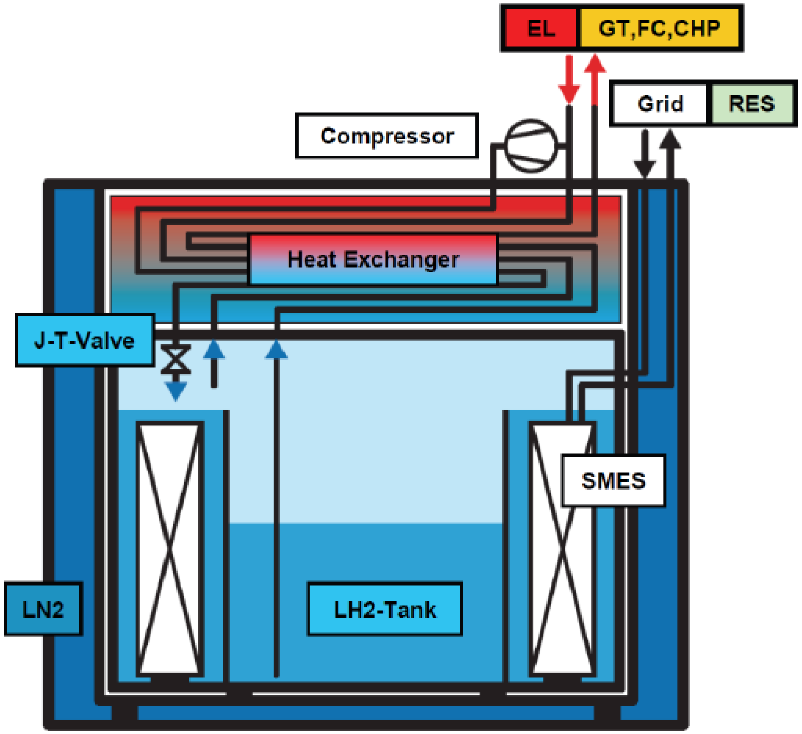
nature is more effective: T from 8.6 to 13.7 °C doubled the growth rate in salmon smolt.

BY B.Fyhn Terjesen, Nofima



Energy Storage Systems

review of energy storage systems for accelerators; **important for pulsed and cycling machines**; in the future possibly also for energy management of large facilities



LIQHYSMES = combination of SMES with liquid hydrogen (chemical energy storage)

→ high power/capacity possible, fast reaction possible

R.Gehring, KIT

Rough cost estimate:
300 MW / 69 GWh with gas turbines:
~1900 €/kW ~8.25 €/kWh

Efficient RF Generation and Beam Acceleration

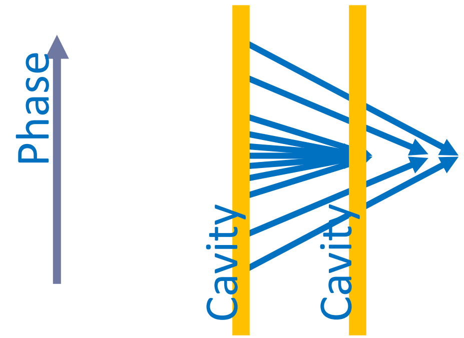
RF generation efficiency is key for many accelerator applications, especially high intensity machines

topics:

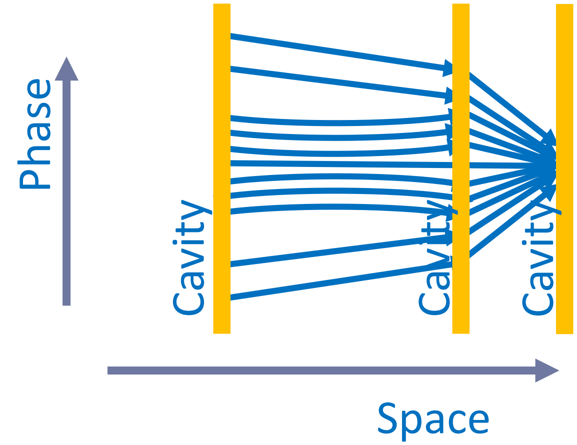
- klystron development
  (new bunching concept leads towards 90%)
- multi beam IOT (e.g. ESS)
- magnetrons (U.Lancaster, Fermilab)
- high Q s.c. cavities (Fermilab, LCLS-II)

workshop EnEfficient RF sources:
https://indico.cern.ch/event/297025/
session at FCC workshop:
http://indico.cern.ch/event/340703/session/76/
session at p-driver workshop:
http://indico.psi.ch/conferenceTimeTable.py?confId=3848#20160301.detailed

Traditional bunching



Core oscillations



low power accelerator magnets

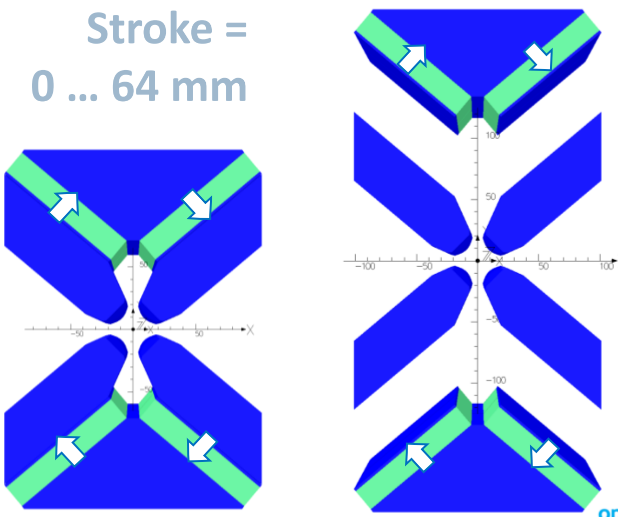
permanent magnets Pro: no power required, reliable, compact	Con: tunability difficult, large aperture magnets limited, radiation damage
optimized electromagnet Pro: low power, less cooling	Con: larger size, cost
pulsed magnet Pro: low avg. power, less cooling, high fields	Con: complexity magnet and circuit,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

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

Stroke = 0 … 64 mm



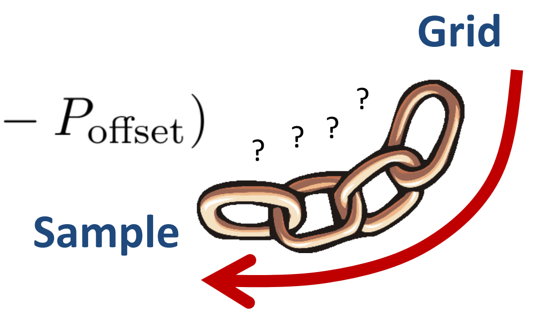
Workshop on Proton Driver Efficiency

idea: **comprehensive approach to cover the entire power chain from Grid to secondary radiation at the user.**

goal: **Assess state of the art and development potential for each stage.**
(comparison of potential of each link in the chain)
R&D recommendations in each field.
Workshop, not Conference.

at each power conversion step:

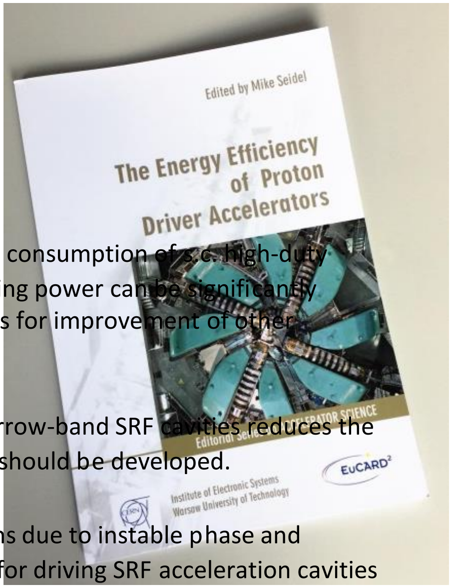
$$P_{\text{out}} = \eta(P_{\text{in}} - P_{\text{offset}})$$



Sessions and Chairs:

Mon, morning	**Applications of proton drivers, physics requests**	J. Grillenberger, PSI
Mon, afternoon	**Targets, conversion to secondary radiation**	Ch. Densham, STFC
Tue, morning	**RF generation, methods and efficiency**	F. Gerigk, CERN
Tue, afternoon	**Accelerator Concepts**	V. Yakovlev, FNAL
Wed, Morning	**Conventional systems and cryogenics**	A. Lundmark, ESS

P-Driver Efficiency:
R&D Recommendations



high Q_0 and high T_c superconducting cavities: Cryogenic cooling power is a major contribution to total consumption of s.c. high-duty factor and CW linacs. By either improving the quality factor, or by raising the operating temperature, the cryogenic cooling power can be significantly reduced. New methods should be developed to treat the Nb surface (N-doping, Nb3Sn coating, etc.) as well as new ideas for improvement of other techniques (e.g., Nb over Cu, etc.).

resonance control of the narrow-band superconducting cavities: resonance control of the narrow-band SRF cavities reduces the RF power consumption. The active (piezo control) and passive (improving of the cavity mechanical properties) methods should be developed.

magnetron: the magnetron is known for high efficiency of ~90%, but it could not be used for accelerator applications due to instable phase and amplitude behavior. New techniques to operate magnetrons in injection-locked mode with amplitude control methods for driving SRF acceleration cavities should be developed.

klystron: New approaches to achieve a radical improvement of klystron efficiency should be investigated. In particular the Bunching-Alignment-Collecting (BAC) technique may allow raising the klystron efficiency beyond 90%.

cryogenic and conventional systems: It is recommended that every lab appoints an energy manager and sets up an energy management plan. This would facilitate comparison of performance between research labs as well as increase focus on energy consumption issues. Also consider behavioural and organizational aspects. Key Performance Indicators should be developed. Energy consumption and flexibility can be improved by choosing state-of-art components and modern controls, e.g. frequency driven pumps. Regarding future s.c. accelerators it is recommended that the cryomodule operation temperature is considered as this can impact energy consumption significantly. E.g. 2 K operation requires much more power compared to 4.5 K and this relates to the development of new s.c. cavities.

targets: The conversion of proton beam power into a rate of secondary particles is an important part of the energy conversion chain. Computer aided simulation tools are the key for optimizing all kinds of targets. In particular for neutron sources good results were achieved for integrated optimizations of spallation target / moderator assemblies. Specific optimizations can be done for certain ranges of neutron energies. In case of muon production targets the optimized arrangement of strong magnetic fields in the vicinity of targets, for example horn magnets or strong superconducting solenoids, can help to achieve a much more enhanced capture efficiency.

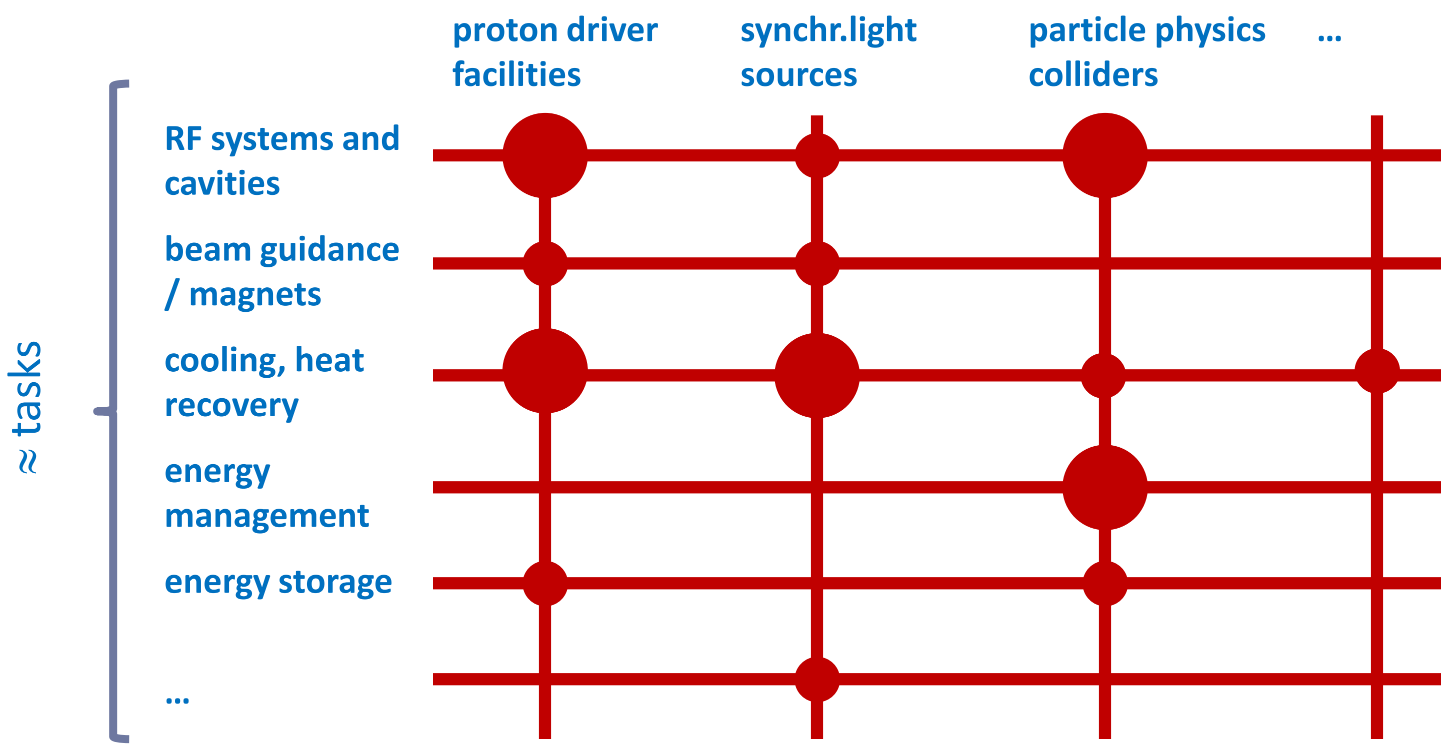
Status EnEfficient WP3,

M.Seidel, PSI

Task	**Workshops / Deliverables**	
heat recovery	Workshop ESS 3/14 Lab Inventory, Master Thesis ESS 3/14	✓ ✓
efficient RF generation	Workshop STFC 7/14 Session FCC week write up / summary 2/17	✓ ✓ ✓ (in prep)
energy storage	Session in DESY workshop 10/15 write up document 9/16	✓ ✓
virtual power plant	Lab survey on volatility, GSI, TUD write up document 12/16	✓ ✓
efficient beam transfer systems	design study pulsed quad 3/14 Workshop CERN 11/14 pulsed magnets work GSI concept comparison, Master Thesis GSI 10/15	✓ ✓ ✓ ✓
others that evolved	Workshop DESY : sustainable energy for large RI’s 10/15 Workshop Proton Driver Efficiency ca 3/16 summary document on p-driver efficiency	✓ ✓ ✓

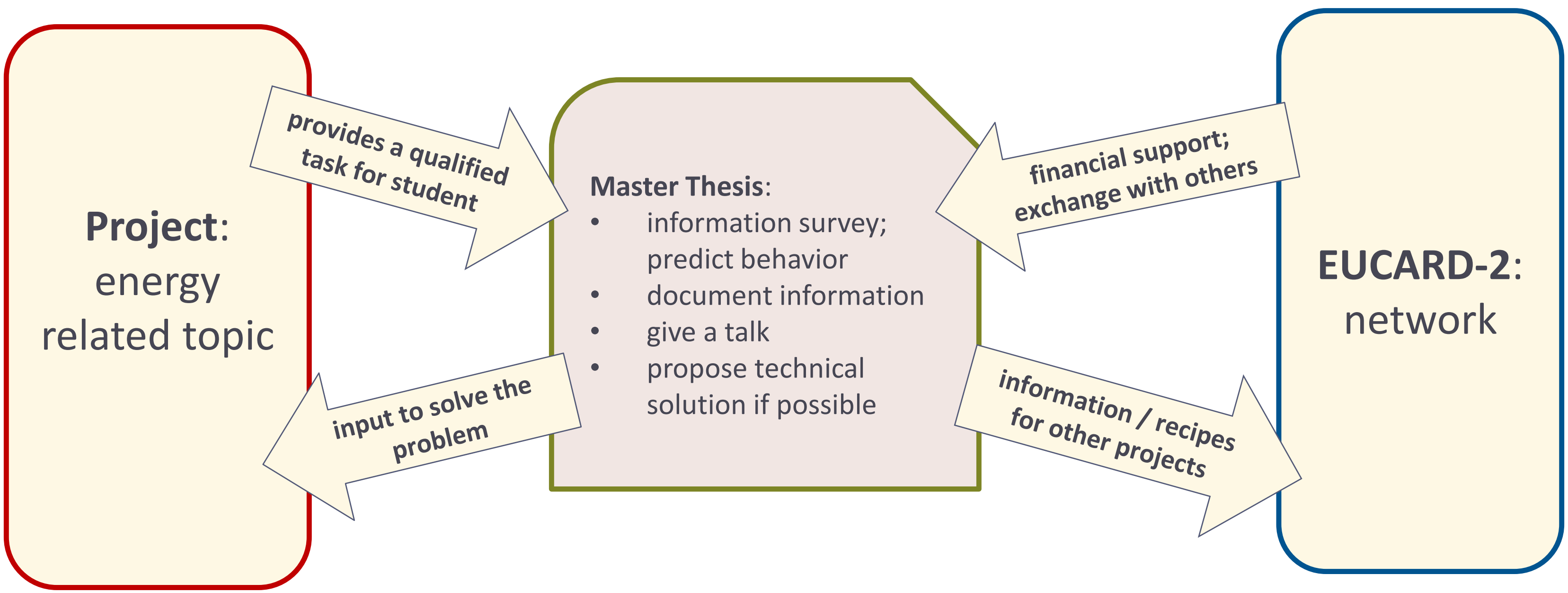
EnEfficient network: topic matrix, projects vs systems

- 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 [e.g. inv. talk at IPAC15, ICFA panel on sustainable accelerators]
- the **right balance** between efficiency, reliability and investment cost must be found for each project (efficiency/sustainability still rated too low)
- important technical developments are ongoing and should be fostered for **heat recovery, RF generation, s.c. cavities, magnets, E management in times of sust.sources;** EnEfficient has contributed by summarizing and documenting status and promising technologies
- will be continued through **ARIES**, but more focused on **specific promising topics**

www.psi.ch/enefficient

Outlook ARIES

→ new ARIES program more focused on specific topics; co-funding of PhD/Postdoc
→ one workshop per topic plus 1..2 general workshops; ongoing: ERF Energy Workshop Nov17 in Magurele/Romania

Task 1.1 Coordination (Mike Seidel, PSI)
(general workshop, contrib. to series on "sustainable research facilities")

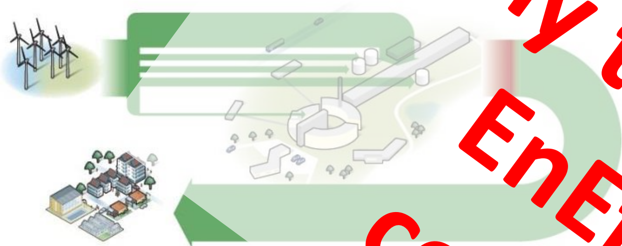
Task 1.2 High Efficiency RF Power Sources (Claude Marchand, CEA Saclay+UppsalaU.)
(development of a very high efficiency klystron with adiabatic bunching)

Task 1.3. Increasing energy efficiency by increasing the efficiency of the spallation target station (M.Wohlmuther, PSI + ESS)
(optimized design of the moderator in a neutron spallation source using extensive Monte Carlo simulations; Realistic design for manufacturing including cooling aspects.)

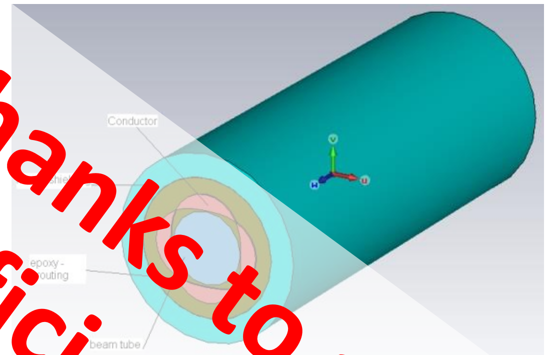
Task 1.4. High Efficiency SRF power conversion (F.Gerigk, CERN)
(reduce cryogenic losses in superconducting cavities; e.g. effective shielding of the residual earth magnetic field, a major cause of Q drop)

Task 1.5. Efficient operation of pulsed magnets (P.Spiller, GSI)
(technical solution including energy recovery feature)

many thanks to all contributers of EnEfficient and the good collaboration since 2013!



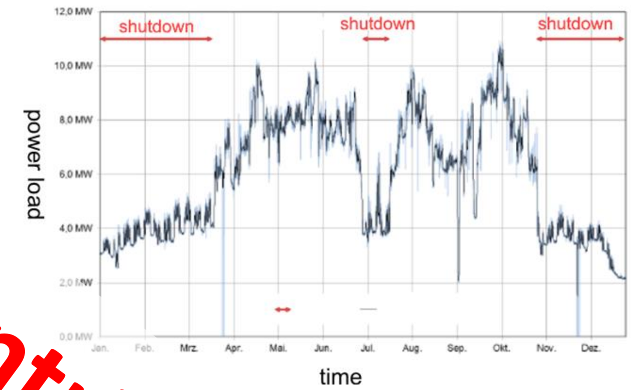
heat recovery at ESS



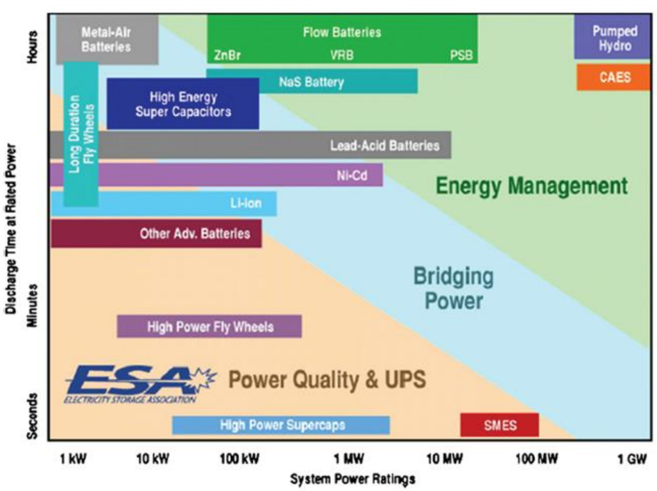
pulsed quads [ESS]

need for energy management

power load curve of GSI 2011



review of energy storage systems



permanent magnet [CLIC]

multi-beam IOT by company CPI