Improving the Energy Efficiency of Accelerator Facilities

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Accelerator Efficiency - Outline

abstract

1) political picture of energy efficiency
   - desire: **sustainable energy**: but insufficient storage; numerical examples of amounts of energy
   - consequences for accelerator facilities
   - work package EnEfficient within the Eucard-2 program
2) power flow in an accelerator
   - major consumers in typical accelerator facilities
   - conversion to secondary radiation: highest potential
3) examples of technical developments towards higher efficiency
   - heat recovery
   - efficient magnets
   - efficient RF generation, s.c. cavities
   - energy management

concrete

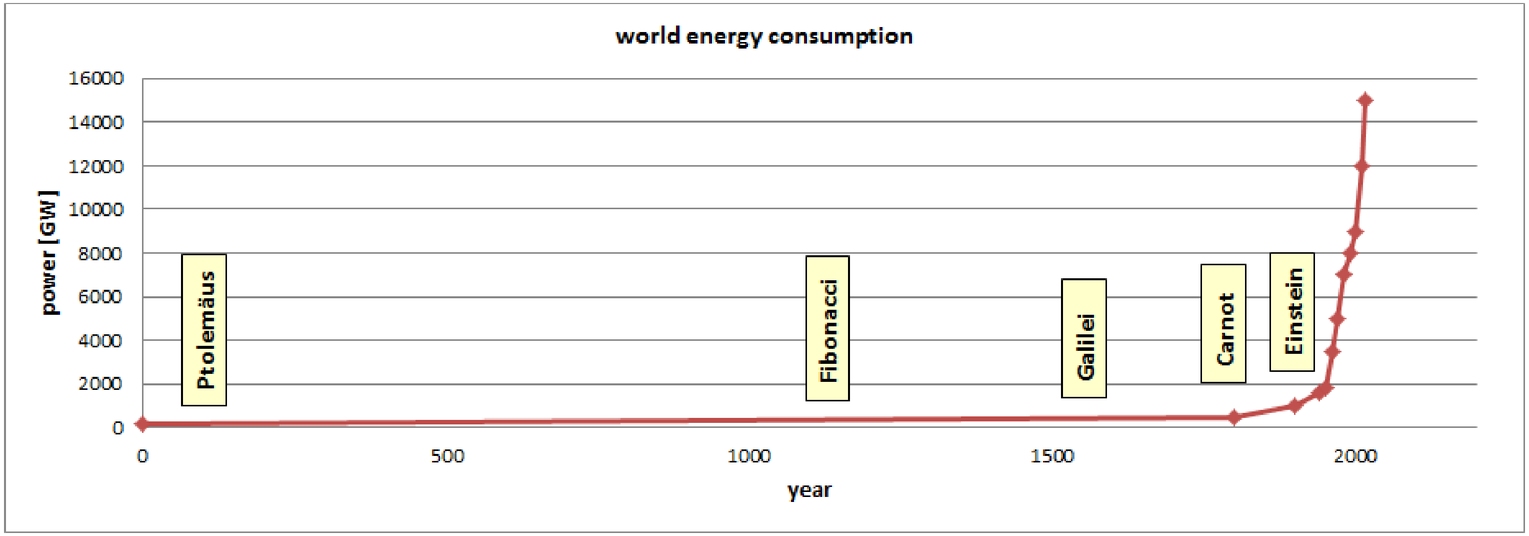
the energy problem

climate change and worldwide scarcity of resources cause critical reflections on the use of fossile energy carriers; nuclear power has other problems and is disputed

energy cost will rise over medium timescales

→ improving efficiency is a strategy in many countries, affects also accelerator projects

→ new accelerator projects and existing facilities must consider efficiency



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

networking EnEfficient, Eucard-2

Eucard: „European Coordination for Accelerator Research", co-funded by European commission, 2013…2017

EnEfficient: WP3, networking activity to stimulate developments, support accelerator projects, thesis studies etc.

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

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

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

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

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

links to all workshops on www.psi.ch/enefficient

Powerflow in Accelerators

public GRID

Accelerator
- Radio Frequency
- Magnets
- Vacuum etc.

Auxiliary systems
- cryogenics
- conv. cooling, AC etc.

Instruments
- e.g. particle detectors

beam

conversion to secondary radiation (beam collisions, targets, undulators ...)

direct beam application:
- p-therapy
- isotope production

secondary radiation
- exotic particles, e.g. Higgs, B-mesons
- synchrotron radiation
- neutrons
- muons

finally all converted to waste heat !

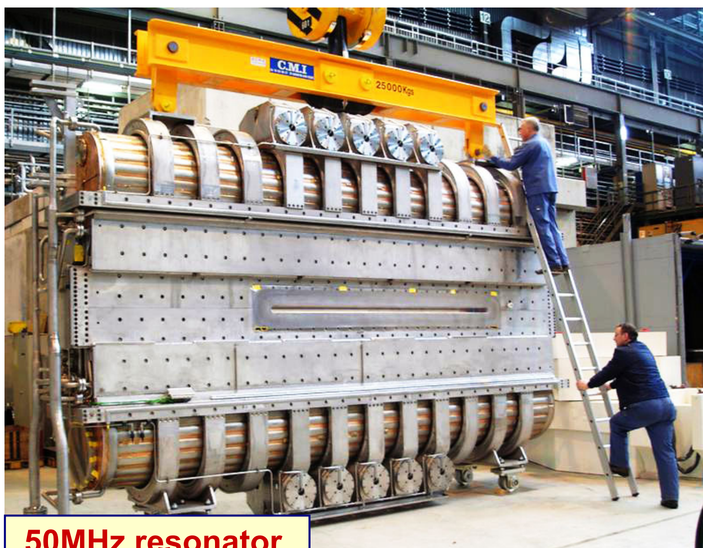
figure of merit:
secondary particles, X-rays on sample per KWh

Example: PSI Facility, 10MW

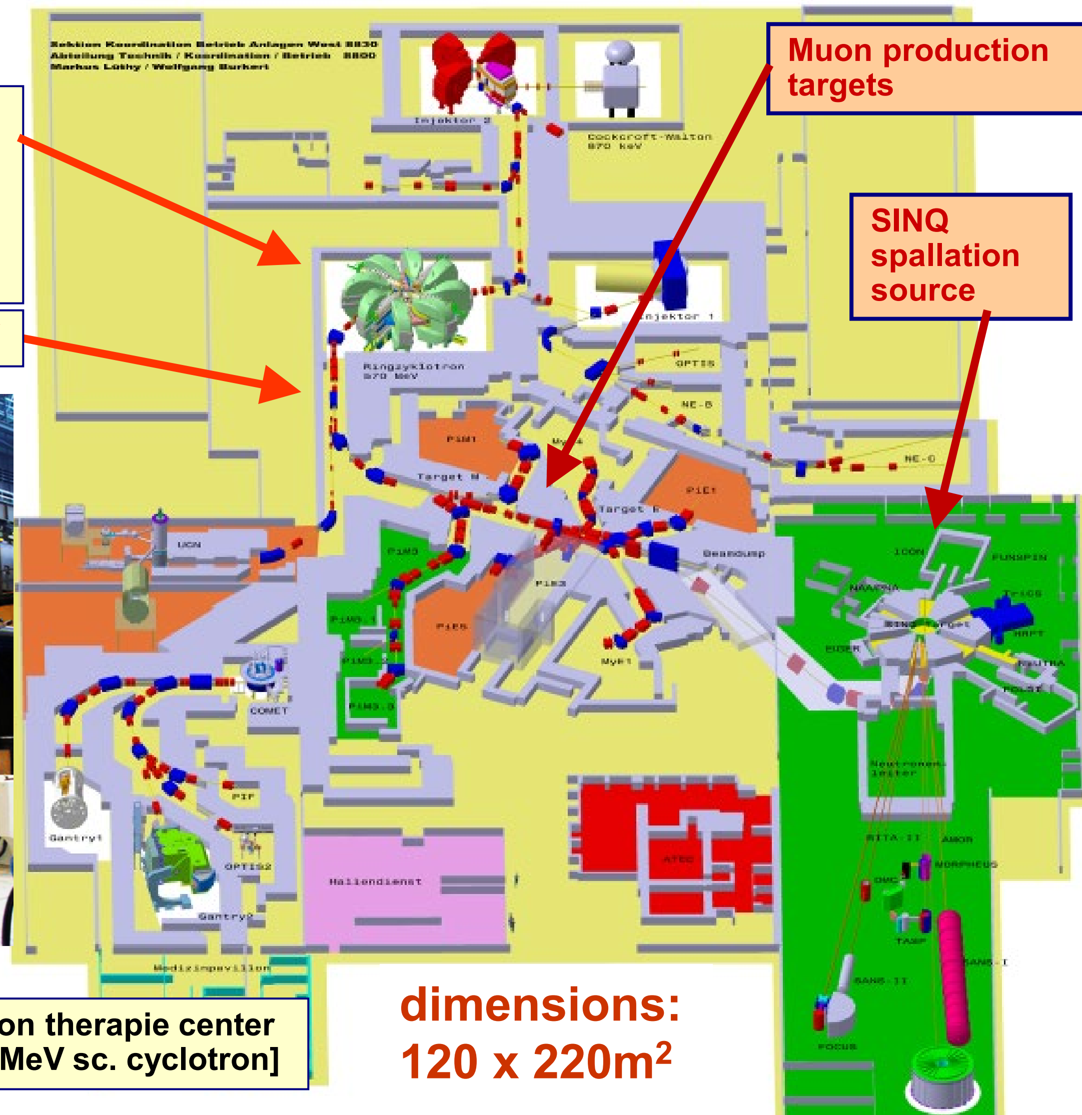
Ring Cyclotron 590 MeV
loss ≈ 10^{-4}

Power transfer through
4 amplifier chains
4 resonators 50MHz

2.2 mA /1.3 MW



50MHz resonator



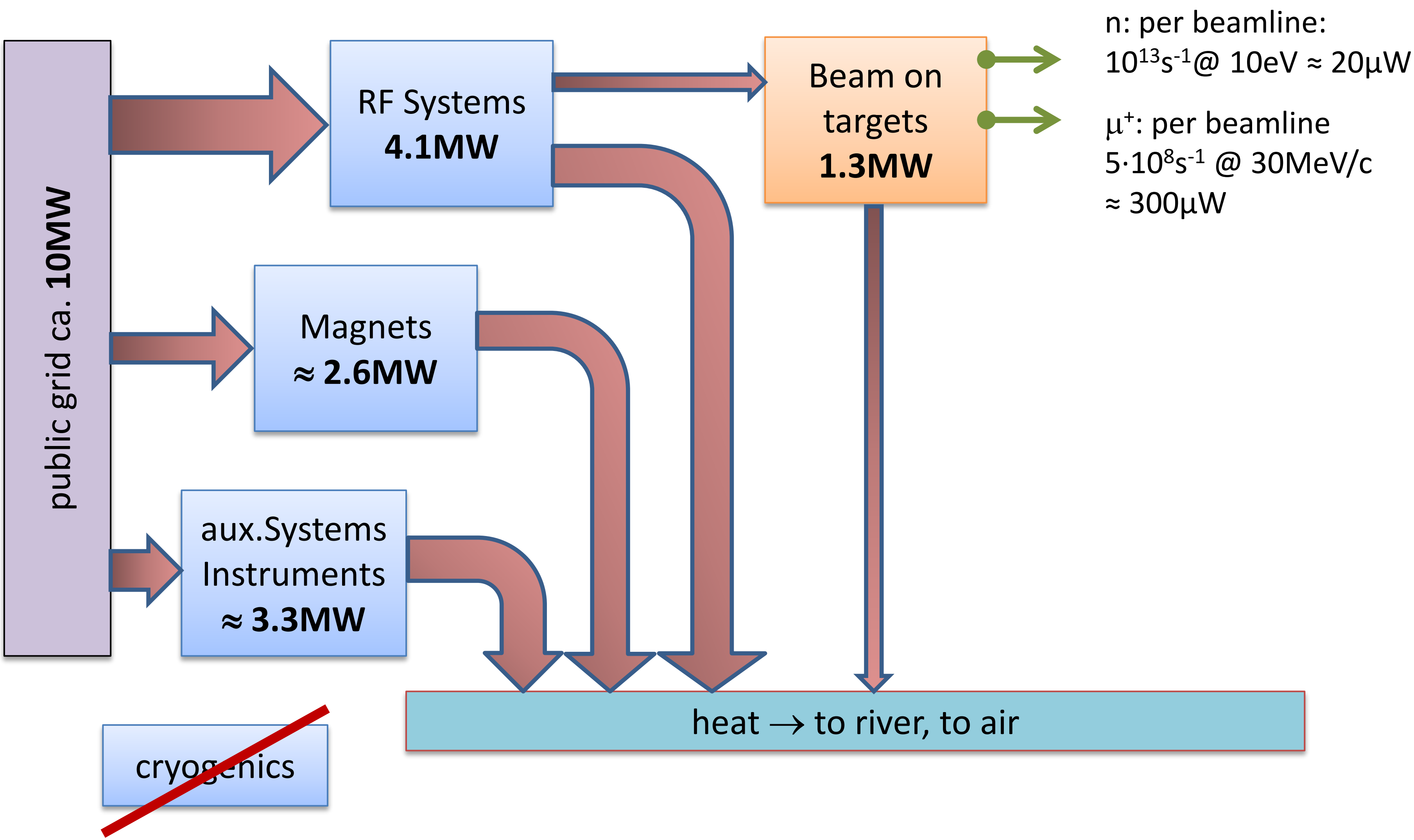
Muon production targets

SINQ spallation source

proton therapie center [250MeV sc. cyclotron]

dimensions: 120 x 220m²

Example: PSI Facility, 10MW



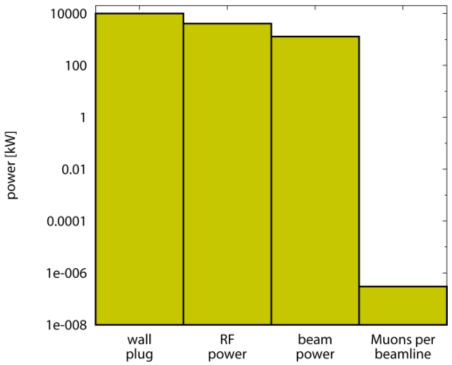
conversion efficiency grid to secondary radiation

conversion to secondary radiation/particles is often required
→ has great potential for the overall efficiency, for example:

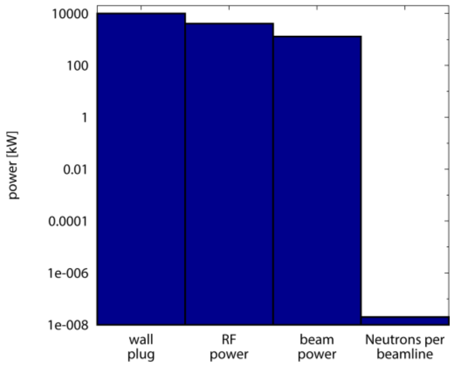
- **Synchrotron Radiation**
  emittance!; optimized undulators; FEL: coherent radiation; energy recovery
- **Colliders**
  low-beta insertion; crab cavities etc.
- **Neutron Sources**
  target; moderators, neutron guides etc.
- **Muon Sources**
  target; capture optics; µ-cooling

linear collider, high energy: $$L \propto \sqrt{\frac{\delta E}{\gamma \varepsilon_y}} \cdot \frac{P_{\mathrm{beam}}}{E_{\mathrm{cm}}}$$

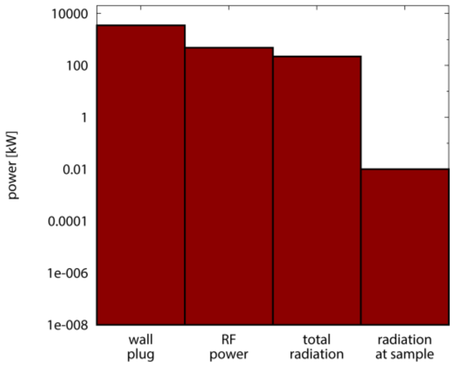
PSI-HIPA: muons



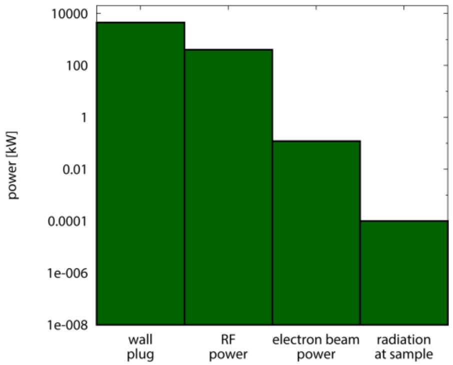
PSI-HIPA: neutrons



SLS: SR

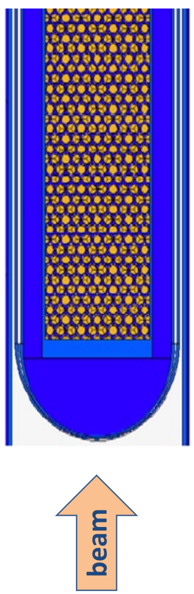


SwissFEL: SR

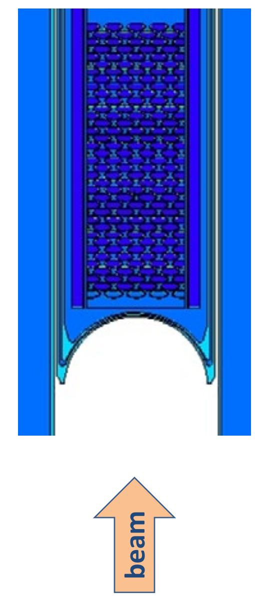


Example: improved conversion efficiency Spallation Target [M.Wohlmuther, PSI]

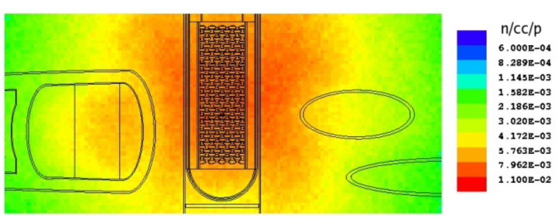
old



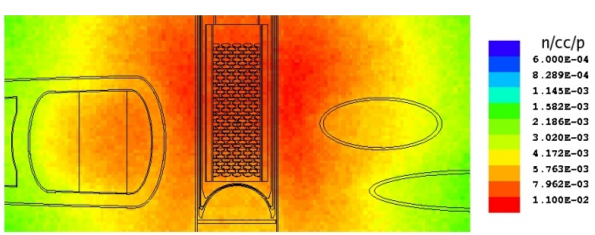
new



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)



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Heat Recovery Workshop, Lund, March 2014

[Th.Parker, E.Lindström, ESS]

Participants (Experts) from
DESY, ALBA, SOLEIL, ESS, MAX-4, PSI, DAFNE, ISIS (institutes)
E.ON, Kraftringen, Lund municipality (industry, local authorities)

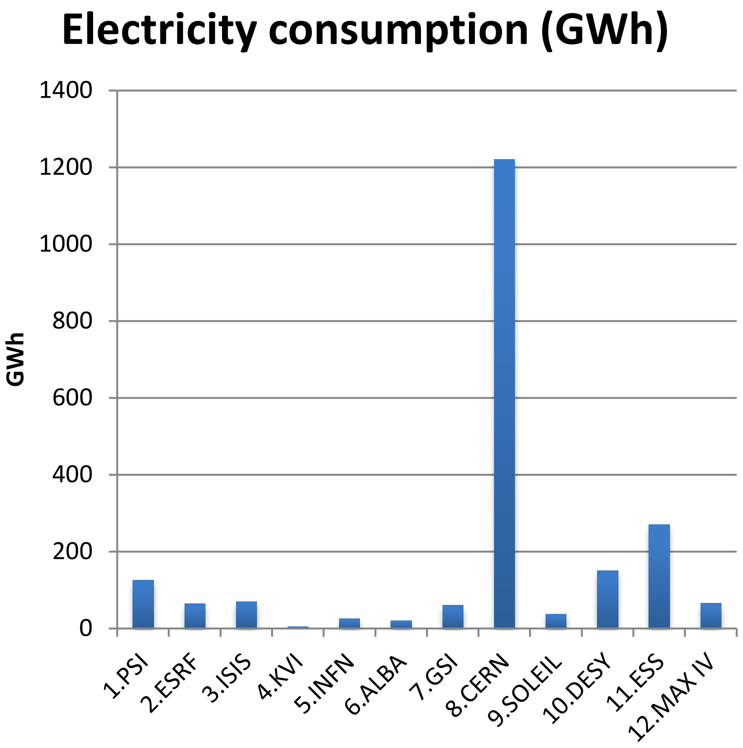
- lab survey on consumption and heat recovery
- heat recovery works for many facilities; high temperatures beneficial; local heat distribution system required
- greenhouses/food production present interesting application (non-linear scaling)
- new facilities MAX-4 and ESS foresee heat recovery on large scale

talks: http://indico.esss.lu.se/indico/event/148/

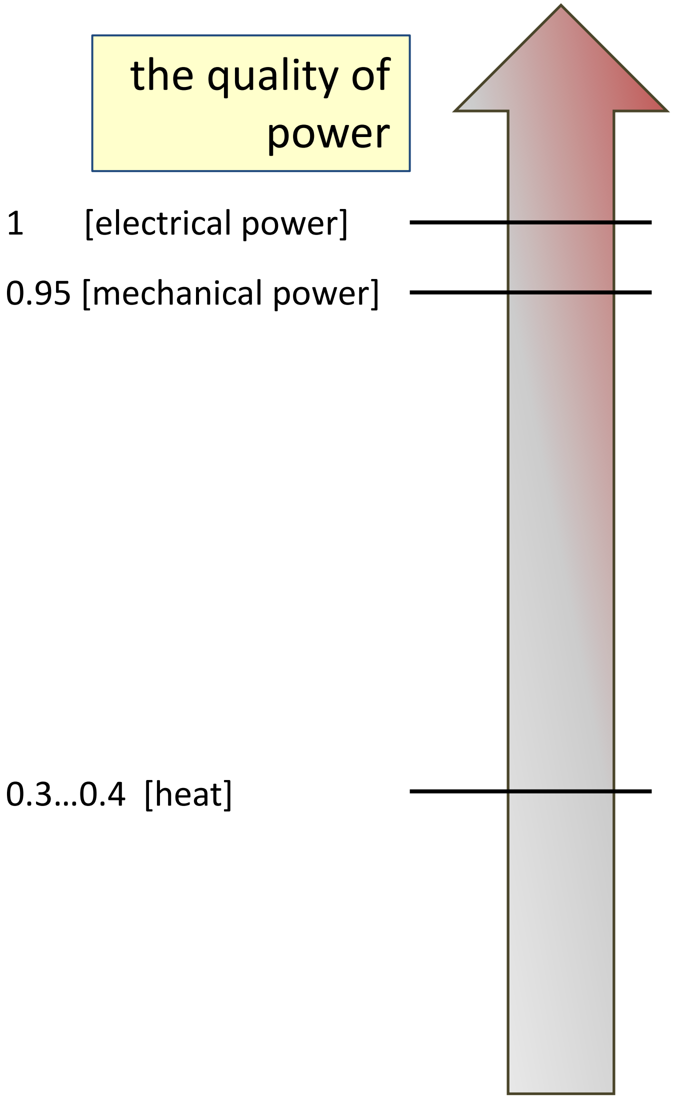
Lab Survey: Energy Consumption & Heat

[Master Thesis, **J.Torberntsson, ESS**]

- **10 in operation**
- **2 under Construction**
- **Energy consumption**
- **Cooling methods**
- **Energy related costs**



Use of Waste Heat



- produce work → electrical power?

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

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

- convert heat to higher T level for heating purposes

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

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

- use heat directly at available temperature

  example: T_{use}=50°C …80°C : heating
  T_{use}=25°C…50°C: green houses, food production

However: strong scaling with T for food production, i.e. fish!

An increase in temperature from 8.6 to 13.7 °C doubled the growth rate in salmon smolt.

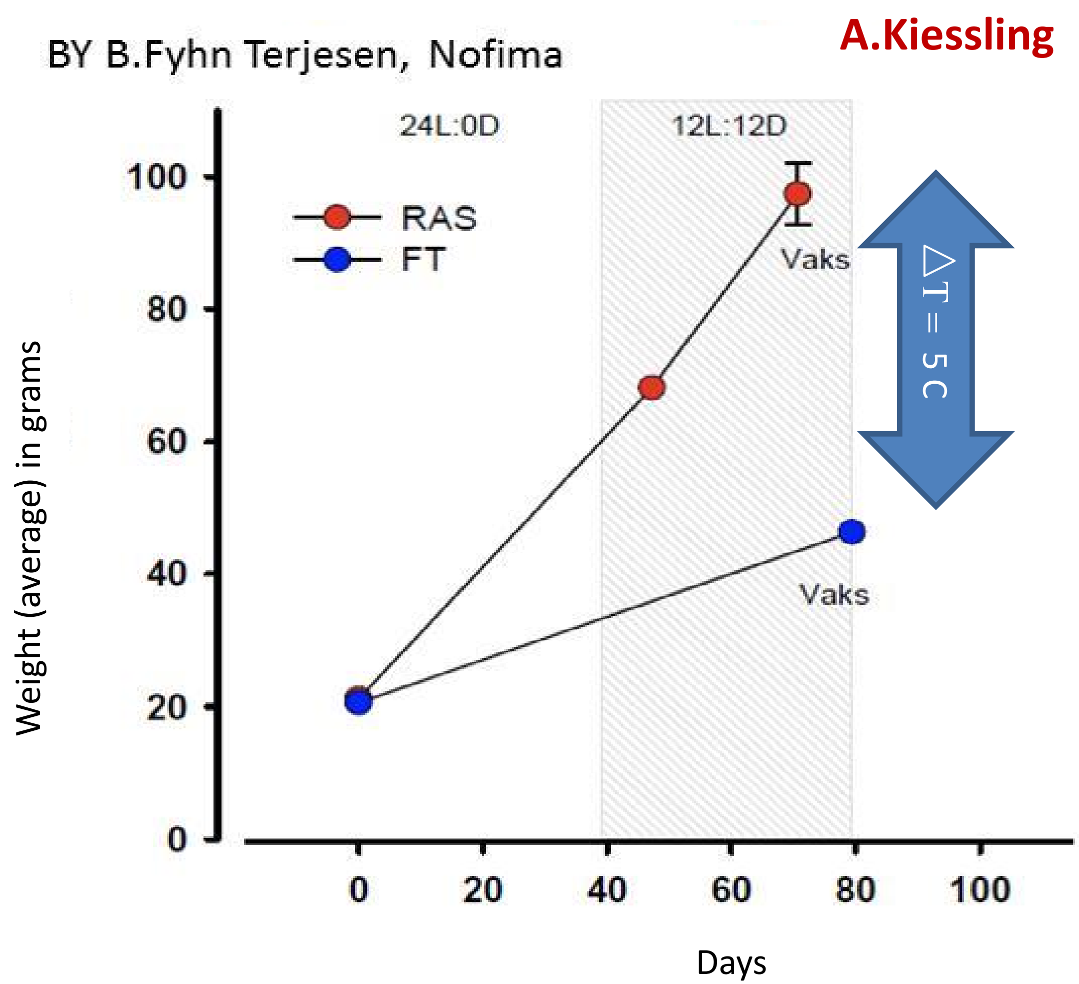


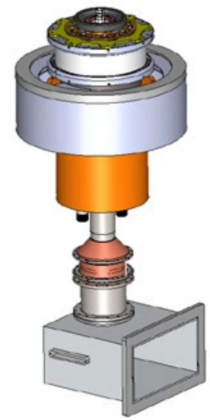

Photo A.Kiessling

Efficient RF Generation and Beam Acceleration

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

topics at workshop:

- klystron development
- multi beam IOT (ESS)
- magnetrons
- high Q s.c. cavities



CPI: multi-beam IOT

E2V: magnetron

THALES: multi-beam klystron

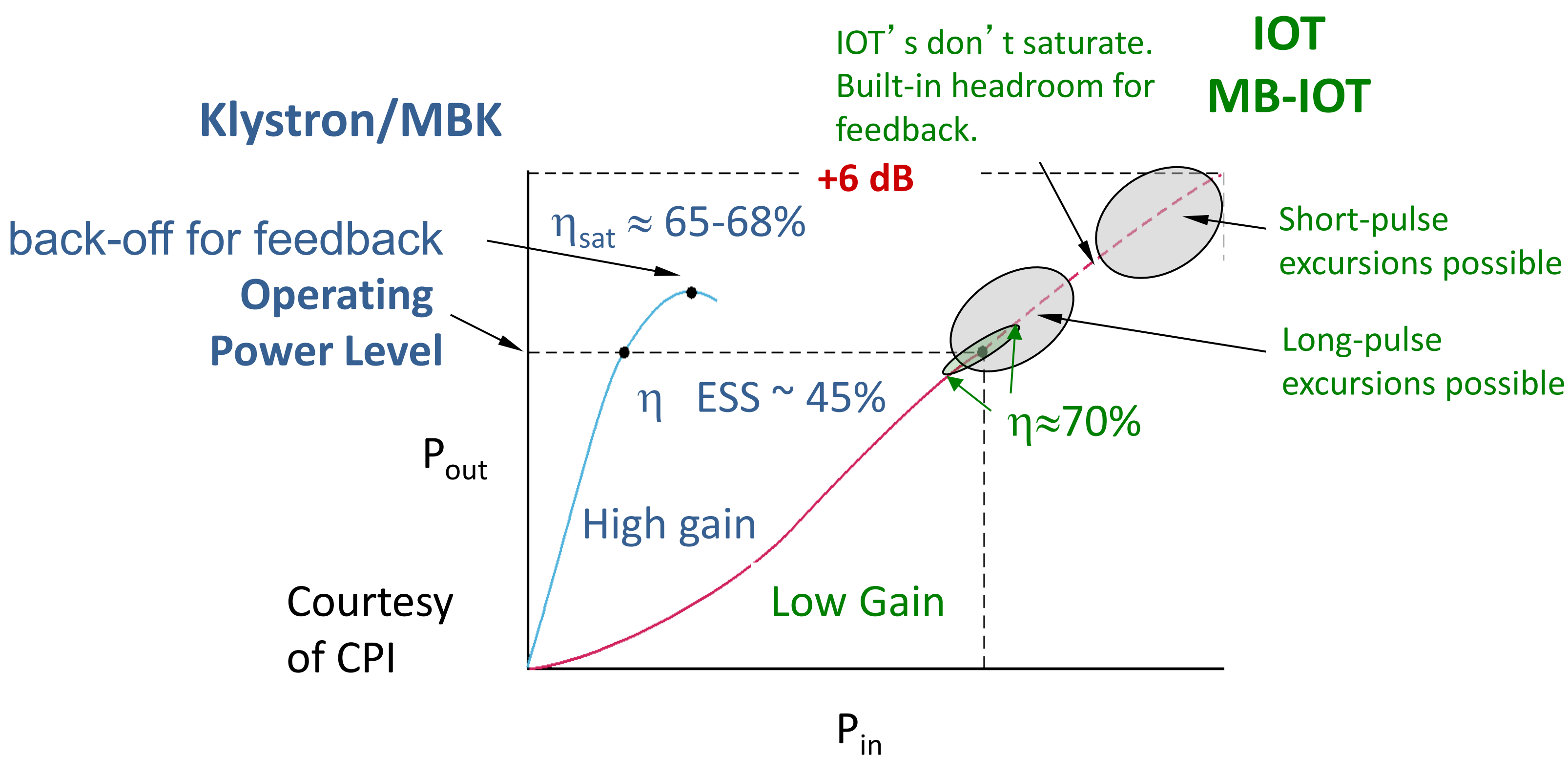
SIEMENS: solid state amplifier

THALES: TETRODE

workshop EnEfficient RF sources:
https://indico.cern.ch/event/297025/

Inductive Output Tubes – considered for ESS

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



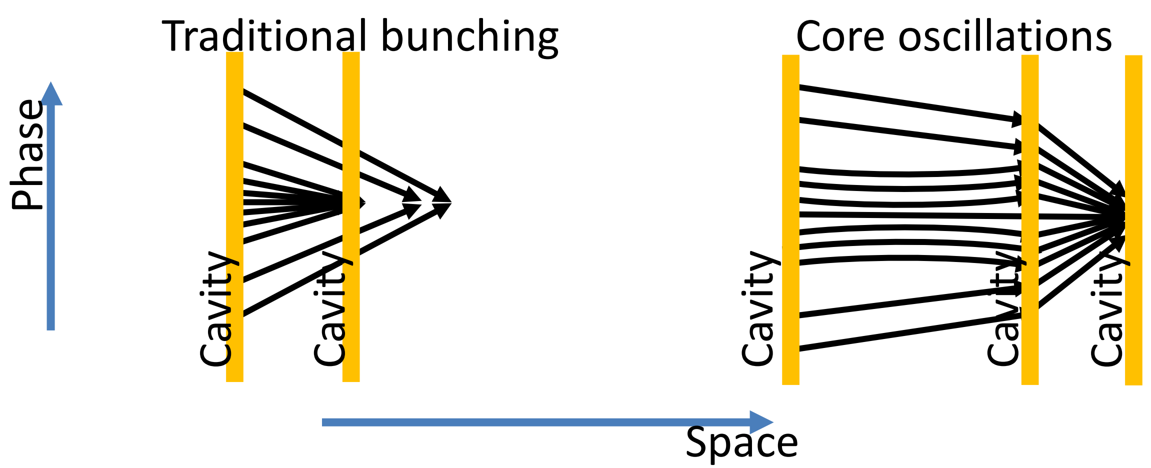
→ **Klystrons:** **Back-off for feedback, cost: 30%**

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

Klystrons: Methods to get high efficiency

[Ch.Lingwood, I.Syratchev et al]

- Bunching split into two distinct regimes:
  - non-monotonic: core of the bunch periodically contract and expand (in time) around center of the bunch
  - outsiders monotonically go to the center of the bunch
- Core experiences higher space charge forces which naturally debunch
- Outsiders have larger phase shift as space charge forces are small
- **long but efficient** tubes result.
- from simulations: 90% efficiency comes into reach



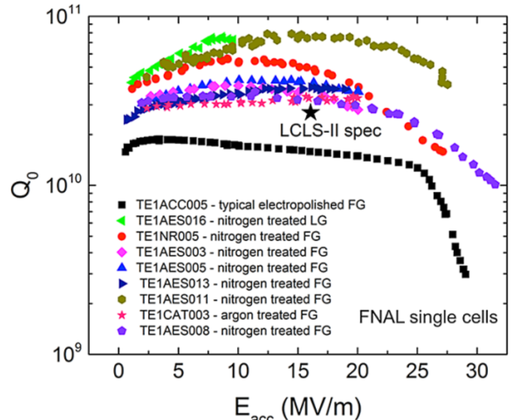
superconducting structures for CW operation

voltage, dissipated power and cryogenic efficiency:

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

new developments:

- N_2 doping, high Q, low P_{dissip}
- possibly Nb_3Sn cavities, high Q at 4.5K, thus better η_c



promising example: FNAL results

related references:

- A.Grasselino, this conference
- 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

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 (+vibrations)	Con: larger size, cost
pulsed magnet Pro: low average 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

Workshop on Special Compact and Low Consumption Magnet Design, November 2014, CERN; **indico.cern.ch/event/321880/**
in prep: Ph.Gardlowski, master thesis, systematic comparision of beam transport

EnEfficient EuCARD² PAUL SCHERRER INSTITUT PSI

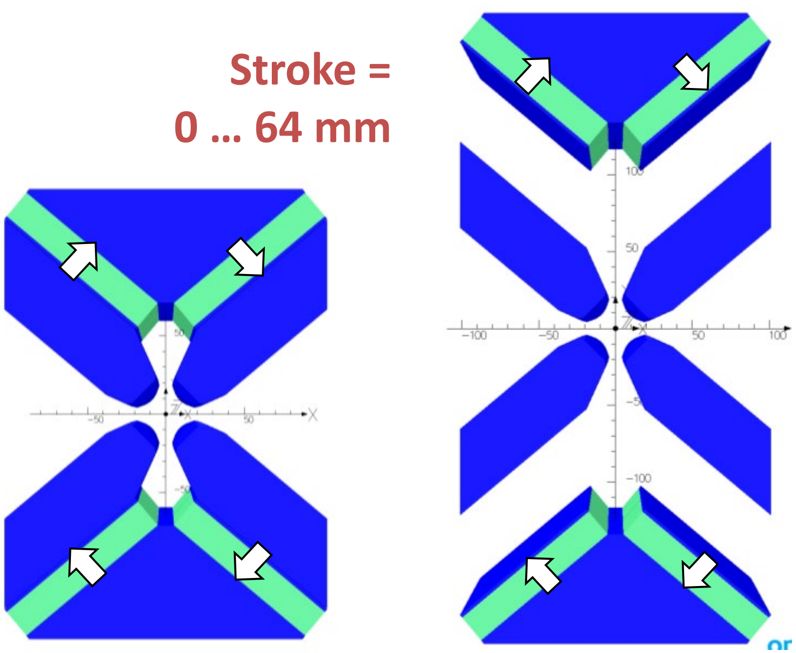
Permanent Magnet Quad Design for CLIC

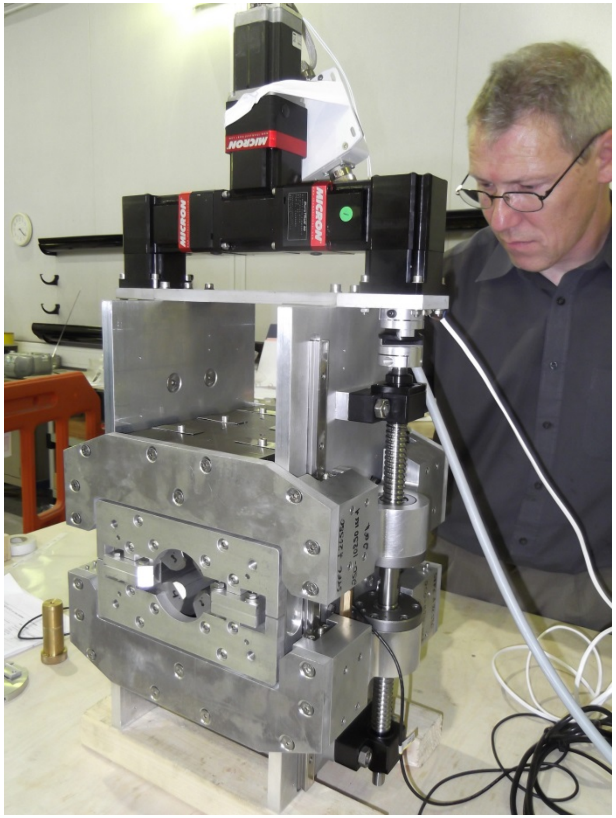
[B.Shepard, STFC Daresbury]

- **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

Stroke = 0 … 64 mm

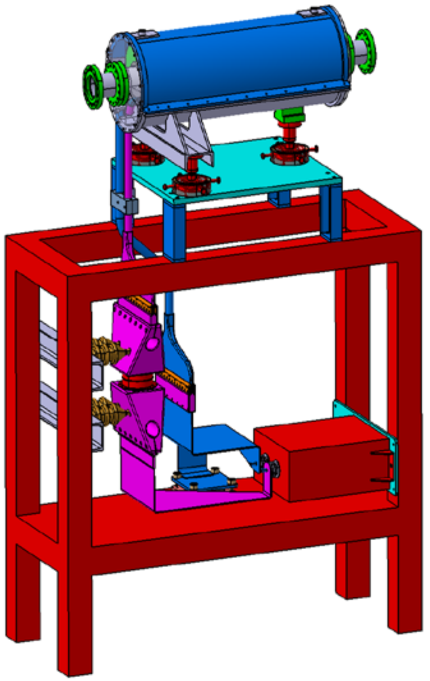




Pulsed Quadrupole Magnet

[P.Spiller et al, GSI]

	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

see U.Bell et al: WEPMA021

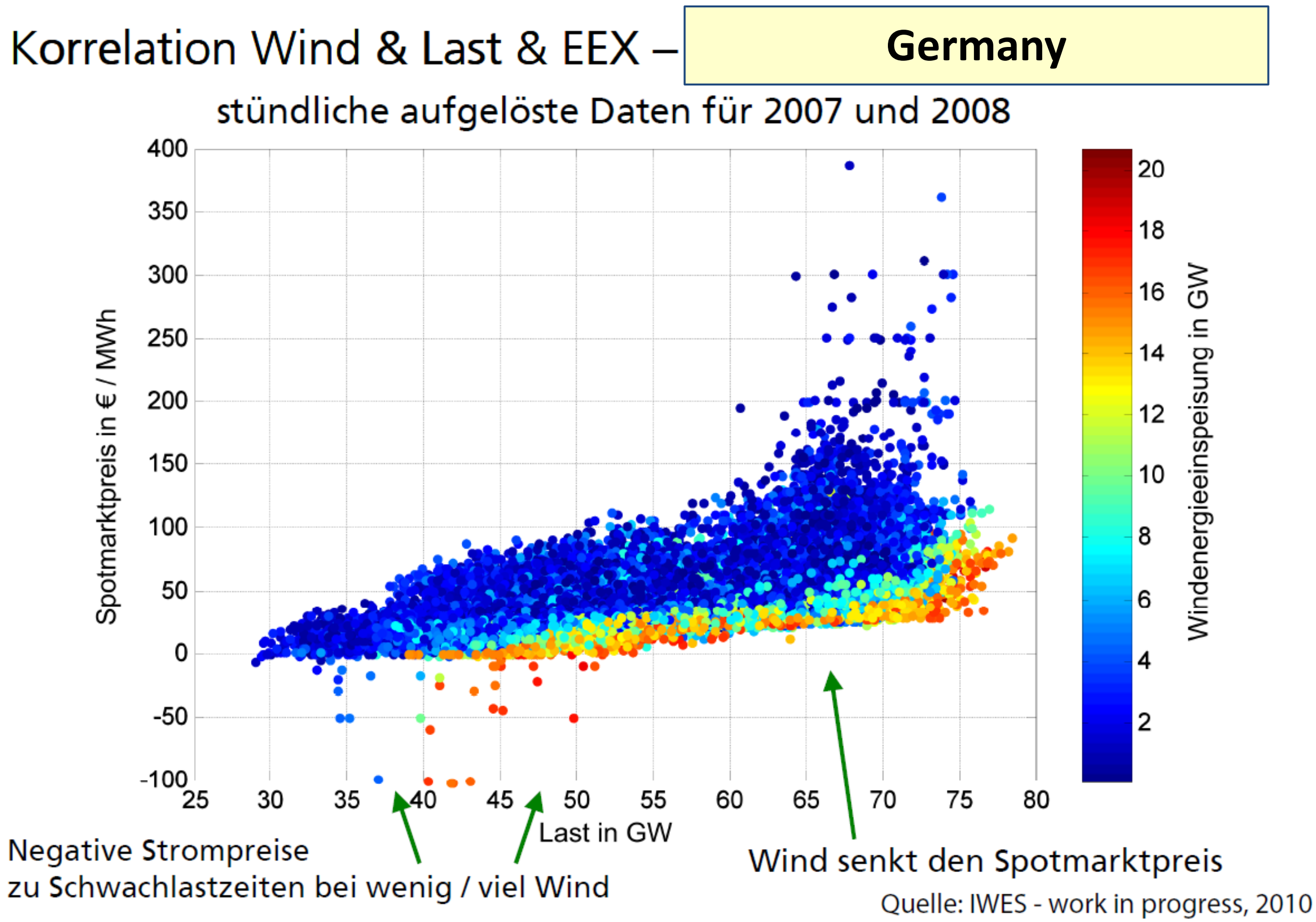
- low average power; energy recovery in capacitive storage possible for periodic operation; high field
- complexity added by pulsing circuit; field precision potentially challanging

E management: impact of solar/wind energy
(taken from internet)

renewables cause strong variations

Impact on accelerators?

energy management, but how?



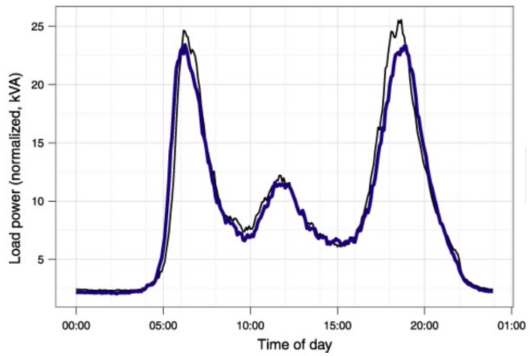
Energy management example: CLIC Study on standby modes

Andrea Latina, CERN

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

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 standbys 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})

Energy Storage for Accelerators

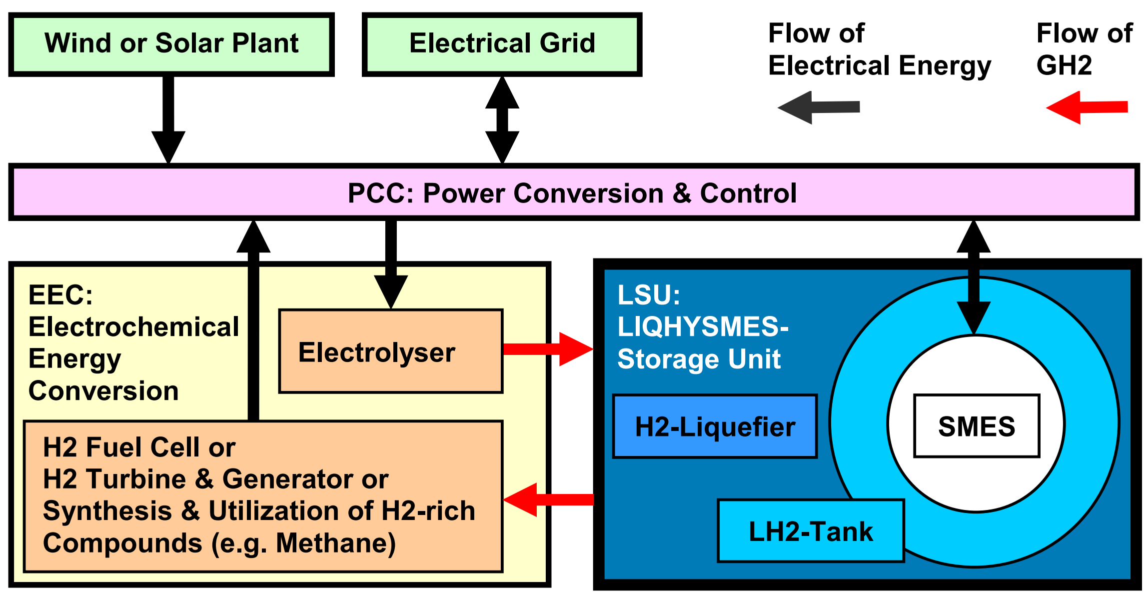
storage systems needed for:

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

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



Summary

- with scarcity of resources and climate change Energy Efficiency becomes important for accelerator projects; Eucard-2 provides networking on this topic
- physics concept to generate radiation for users has large potential for efficiency (SR, exotic particles, μ, n etc.); advancements should be better communicated as efficiency improvements
- many technical efforts are undertaken with heat recovery, RF systems, cavities, magnets, energy management
- next general workshop on Energy for large RI's (Oct 15): http://erf.desy.de/energyworkshop
- planned: proton driver efficiency (Mar 16), Energy management (2016)
- **Eucard-2/EnEfficient stay tuned:** www.psi.ch/enefficient