Improving the Energy Efficiency of Accelerator Facilities

M.Seidel (PSI)

Energy Efficiency - Outline

- Context and Motivation
  - Climate & Politics, Order of Magnitude Examples, European Programs, Workshop Series Sustainable RI´s
- Accelerator Concepts – Trends & Assessment
  - Powerflow in Acc., High Intensity Proton Acc., HEP Facility Proposals
- Technological Developments towards Higher Efficiency
  - RF sources, magnets, s.c. resonators, heat recovery, energy management

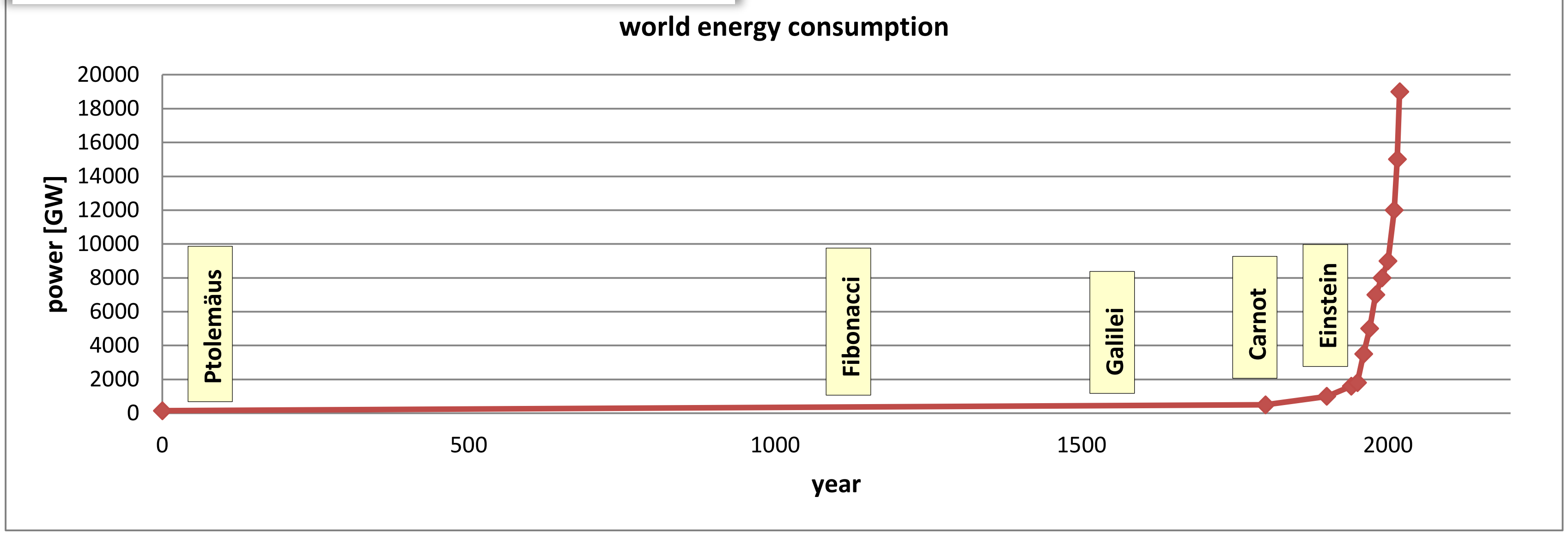
The Energy Problem

climate change causes critical reflections on fossile energy carriers; nuclear power has other problems and is disputed; renewable energy sources are on the rise but suffer from fluctuations

→ **legitimate but often emotional discussions; impacts politics**

→ **improving efficiency is a strategy in many countries,**
affects also research facilities

includes all carriers, today ≈ 19TW



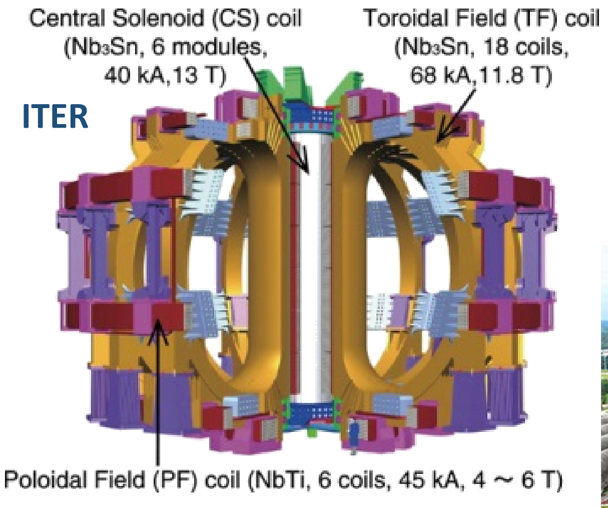
„school strike for climate“
source: Wikipedia

Energy – Orders of Magnitude

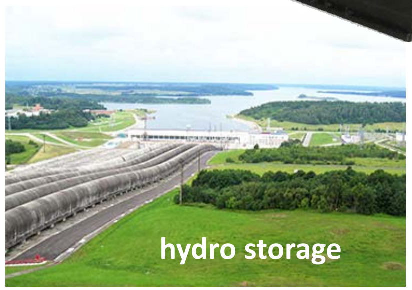
generation	consumption	storage
1d cyclist „Tour de France“ (4h x 300W): **1.2 kWh**	1 run of cloth washing machine: **0.9 kWh**	Car battery (60 Ah): **0.72 kWh**
1d Wind Power Station (avg): **12 MWh**	1d SwissLightSource 2.4 GeV, 0.4 A: **82 MWh**	ITER superconducting coil: **12.5 MWh**
1d nucl. Pow. Plant (e.g. Leibstadt, CH): **30 GWh**	1d CLIC Linear Collider @ 3 TeV c.m. **14 GWh**	All German storage hydropower: **40 GWh**
1d Earth/Moon System E-loss: **77 TWh**	1d electrical consumption mankind: **73 TWh**	World storage hydropower: ***O*(1 TWh)**


cyclist, 300 W


nucl. plant 1.3 GW



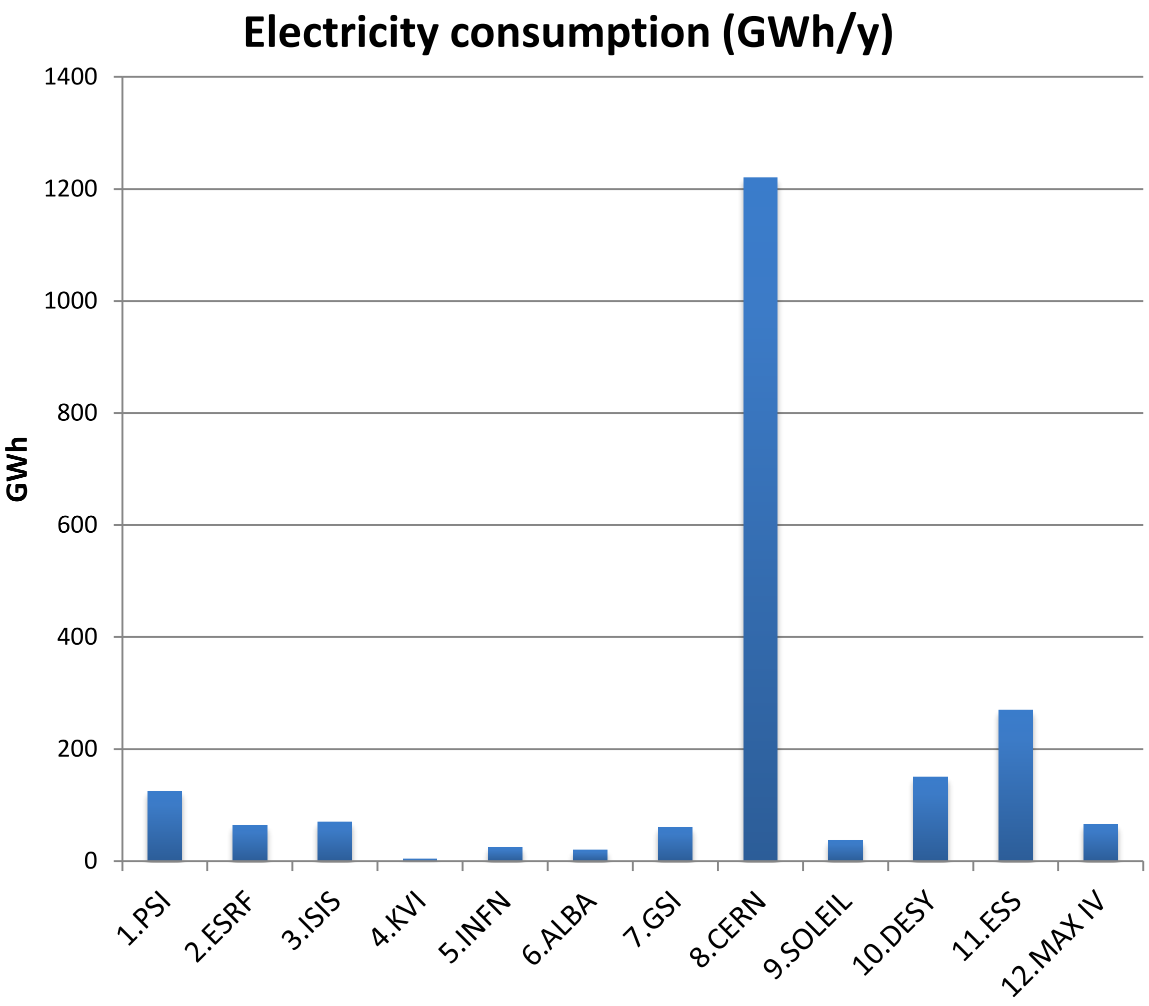
car battery



Lab Survey: Energy Consumption & Heat

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

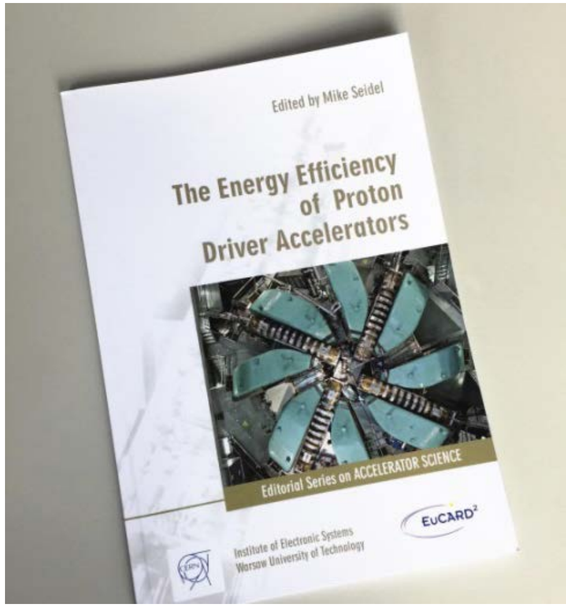
- 10 in operation
- 2 under Construction
- Energy consumption
- Cooling methods
- Energy related costs



European co-funded programs

EUCARD-2 and ARIES Programs, 2013 - 2021

- organisation and co-organisation of **≈ 15 workshops on efficient concepts & technologies 2013-2020**
- topics: heat recovery, s.c. cavities, efficient magnets, efficient RF systems, proton driver accelerators, energy storage, high brightness neutron production
- **≈10 selected development & survey projects,** master, PhDs, Postdocs (e.g. klystron, pulsed quad, s.c. cav. flux expulsion, energy consumption survey)
- deliverables: reports on recommended technology choices, workshop documentation
- networking between intl. labs, also: ICFA panel on sustainable accelerators



Energy for Sustainable Science

Series of workshops

Workshop Energy for Sustainable Science

Initiated 2011 by CERN, ESS and ERF

(European Association of National Research Facilities)

- Past workshops:
  - 2011: ESS, Lund, Sweden
  - 2013: CERN, Geneva, Switzerland https://indico.cern.ch/event/245432/
  - 2015: DESY, Hamburg, Germany https://indico.desy.de/indico/event/11870
  - 2017, ELI-NP, Magurele, Romania https://indico.eli-np.ro/event/1
- upcoming:
  - 2019, Nov 28-29, PSI, Switzerland https://indico.psi.ch/event/6754

Power Flow in Accelerators

Electricity grid

Accelerator
- Radio Frequency
- Magnets
- Vacuum etc.

Auxiliary systems
- Cryogenics
- Conv. cooling, AC etc.

Instruments
- E.g. particle detectors
- Computing

beam

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

direct beam application:
- p-therapy
- Isotope production

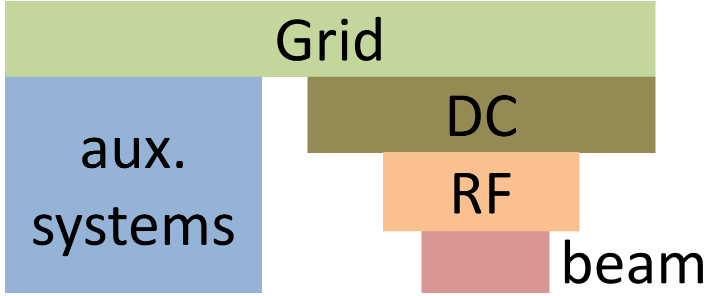
secondary radiation
- Exotic particles, e.g. Higgs, B-mesons
- Photons (synchrotron radiation)
- Neutrons
- Muons

Eventually all converted to waste heat !

Possible figures of merit:
Number of physics events, secondary particles, X-rays on sample … per kWh consumed

beam power dominated vs. auxiliary systems dominated

high avg. beam power is of central importance

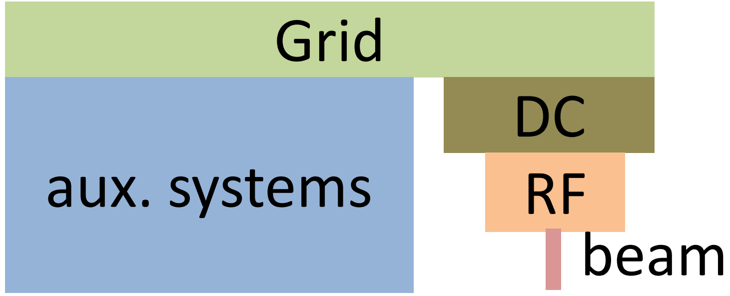


wall plug efficiency is a good measure:

$$\eta = P_{\text{beam}} / P_{\text{wall}}$$

- neutron-, myon- or neutrino sources (high intensity p-beam)
- linear collider (s.c. and n.c.)

power is dominated by other systems (cryo, magnets, SR…)



e.g. LHC (1 run/day):
$\eta \approx$ 20kW/100MW = 2×10^{-4}

wall plug eff. useless for assessment!
other parameters: **Luminosity per power, brightness per power etc.**

- ring light sources
- most FELs
- proton therapy
- ring colliders: hadron and e^+/e^-

High Intensity Proton Accelerators

for neutron, muon or neutrino production high proton beampower is essential → energy efficiency is particularly relevant for those machines

concept	Pro's	Con's
cyclotron	cost efficient, naturally CW, no cycling, good η	difficult tuning for low losses, bulky magnets
s.c. linac	naturally low losses, in CW high η possible	expensive, long building/facility
rapid cycling synchrotron	cost efficient for high energy	inherent inefficiency from cycling, challenging magnets

review of facilities in operation:

	PSI cyclotron	SNS linac	J-PARC linac and RCS
Beam energy	0.59 GeV	1 GeV	3 GeV
Beam Power	1.4 MW	1.4 MW	1 MW
Power consumption	4.5 (RF) in total 10 MW	16.3 MW	32.6 MW
Fraction of grid power converted to beam power	~18-19%	~9%	~3%

V.Yakovlev et al, IPAC´17, The Energy Efficiency of High Intensity Proton Driver Concepts

Fermilab

38 5/19/2017 V.Yakovlev | IPAC 2017

future perspective:

- CW s.c. linac has potential for $\eta \geq 50\%$ (high Q, high beampower, $P_{cryo} \propto E_k$)
- s.c. cyclotron (RF + magnets) is thinkable, but no studies

Proposed HEP Projects and Grid Power

	ECM [TeV]	L / IP [10^{34}cm^{-2}s^{-1}]	P_{Grid} [MW]	power driving effects
FCC-ee (Z)	0.091	230	**259**	SR Power: 50MW/beam
FCC-ee (t)	0.365	1.5	**359**	SR power: 50MW/beam
FCC-hh	100	30	**580**	SR power: 2.4MW/beam @ 50K, cryogenics
ILC	1	4.9	**300**	beam power: 13.6 MW/beam, cryogenics
CLIC	3	5.9	**582**	beam power: 14 MW/beam
muon coll.	6	12	**270**	mu decay, 1.6MW/drive beam, cycling magnets, but scaling advantages, least developed

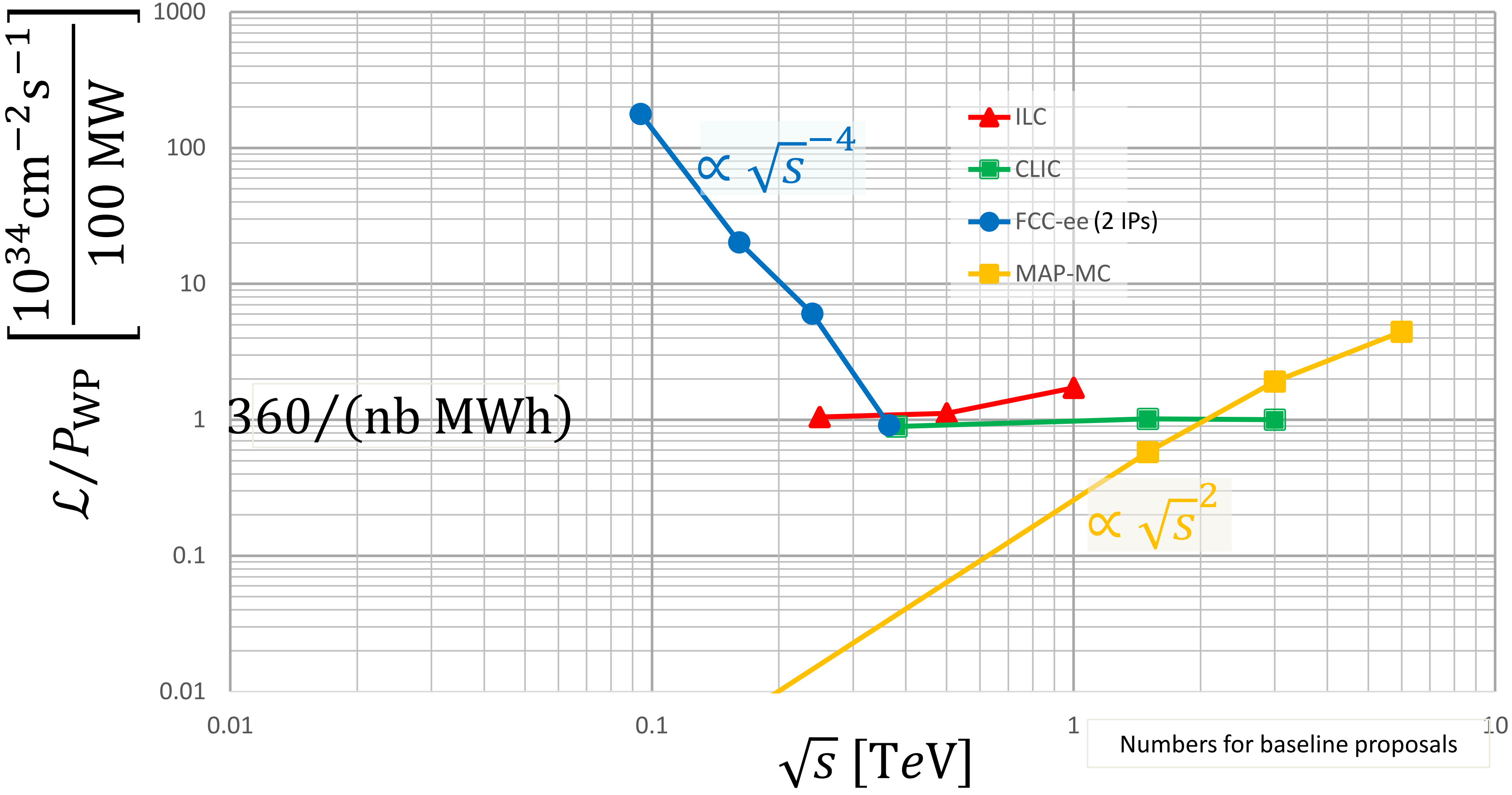
$$P_{\rm SR} \propto \left(\frac{E}{E_0}\right)^4 \frac{1}{R}$$

$$L_{\rm lin.col.} \propto H_D \sqrt{\frac{\delta_E}{\varepsilon_{x,n}}} P_{\rm beam}$$

$$L_{\rm mu.col.} \propto B \frac{N_0}{\varepsilon_{xy,n}} \gamma P_{\rm beam}$$

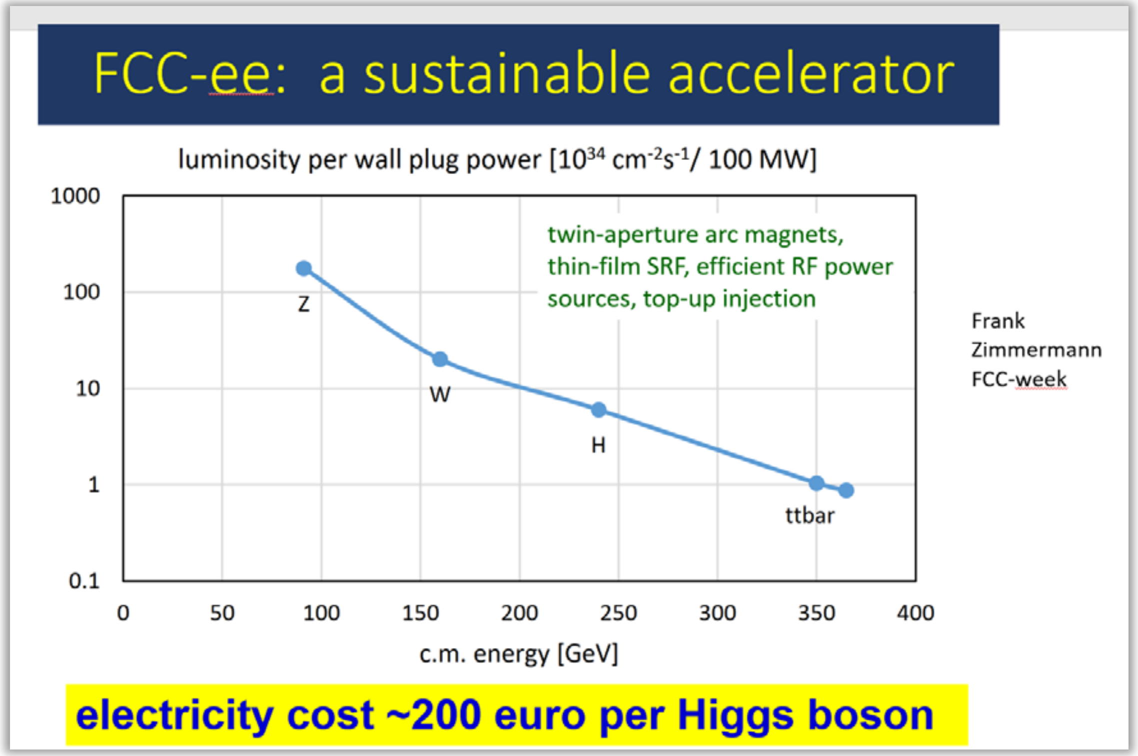
Significant energy cost: 4TWh ~ 200M€
+ Sustainability is a high ranking topic in politics and public discussion.
$\rightarrow$ need more R&D towards efficient concepts & technology, energy management

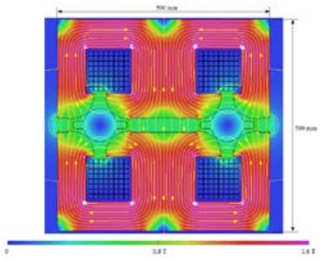
Collider Proposals: Luminosity per Grid Power

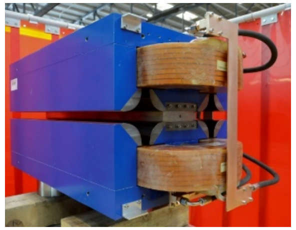


[E.Jensen, Granada]

Example: Luminosity (Higgs) per Grid Energy?







twin aperture magnets: factor 2 power savings

comparison - Higgs at LHC:
70 fb^{-1} / year, 1 TWh / year, σ_H = 50pb →
cost: **300kWh, 15€ / Higgs**

but: e+/e- much cleaner reaction (H + Z)
with ≈ 100% detection efficiency
in LHC efficiency of Higgs detection ≤ 0.3%!
(communication P.Janot, F.Zimmermann)

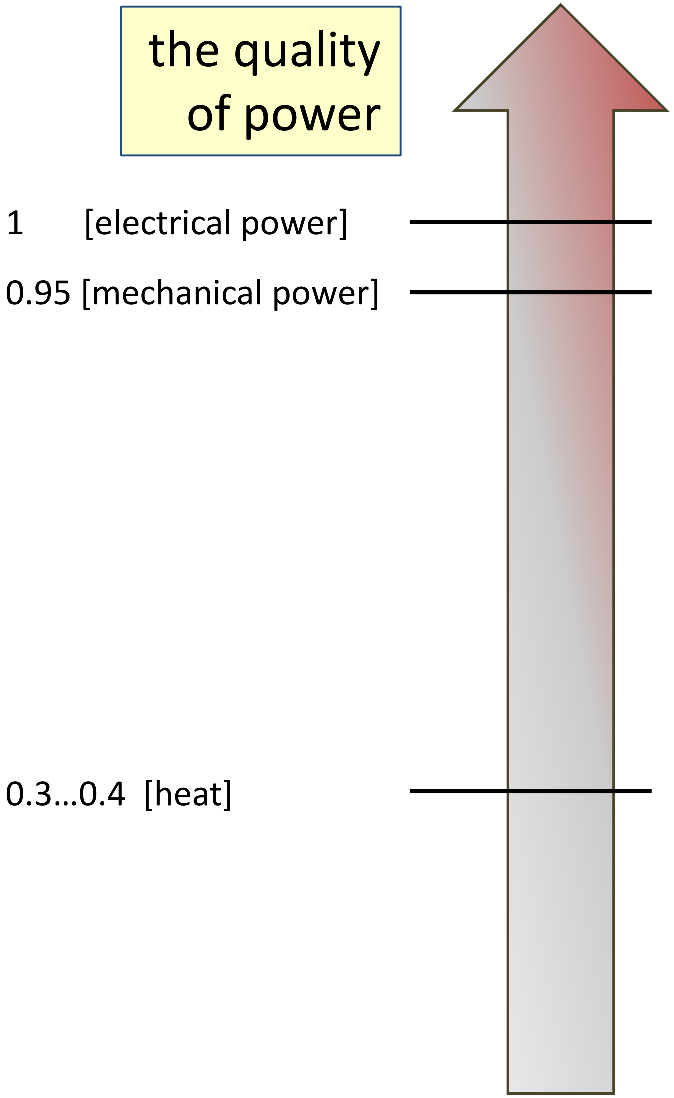
→ example shows complexity of assessing efficiency with a single number.

PAUL SCHERRER INSTITUT

next:

Efficient Technologies for Accelerators

Recover High Quality Power from Heat?



- produce work → electrical power?

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

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

- use heat directly at available temperature

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

- convert heat to higher T level for heating purposes

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

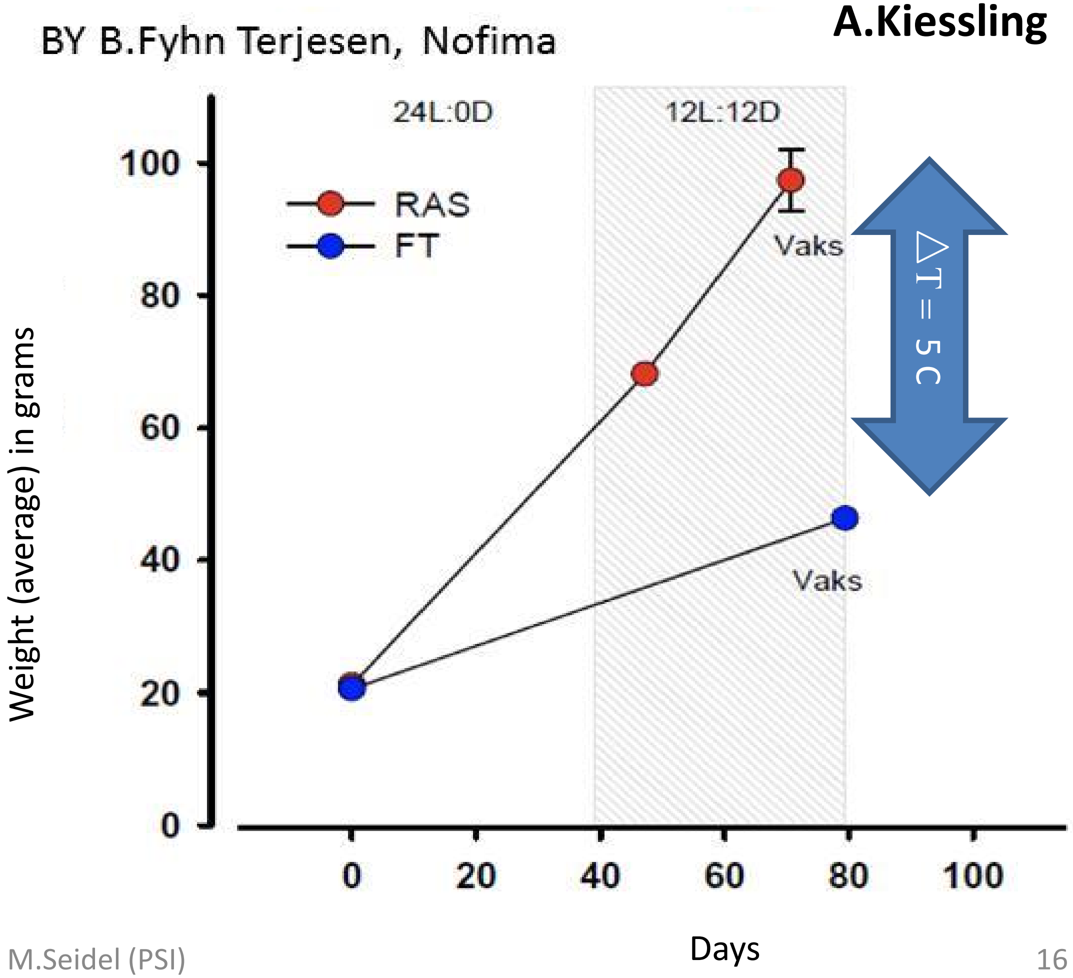
  example: T=40°C, T_{use} =80°C, COP=5:
  W=10kW, Q_C=40kW, Q_H=50kW
  (availabe for heating)

heat pumps at MAX-4
[Björn Eldvall / E.ON, Martin Gierow / Kraftringen]

Biology/Nature is more efficient …

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

A.Kiessling

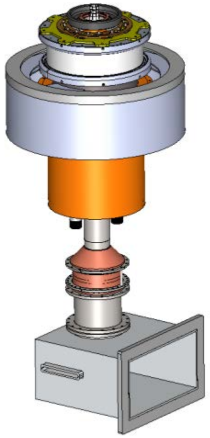


Efficient RF Sources

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

topics:

- klystron development (major focus)
- multi beam IOT (option ESS)
- phase stable magnetrons (e.g. JLAB)



CPI: multi-beam IOT

E2V: magnetron

THALES: multi-beam klystron

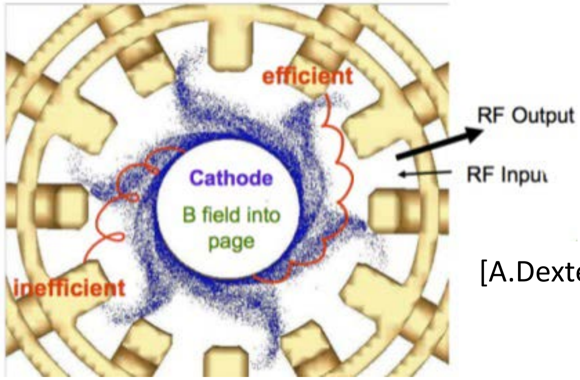
SIEMENS: solid state amplifier

workshop EnEfficient RF sources:

2014: https://indico.cern.ch/event/297025/

2019: https://indico.uu.se/event/515/

e.g. magnetron/CFA:
>80% efficient but poor phase stability
→ understand EM design, towards high Q
→ phase locking, LLRF controls



[A.Dexter]

Klystron Studies in ARIES/CEA-Saclay

- Objectives:

  Provide a 3D RF design of a high efficiency klystron

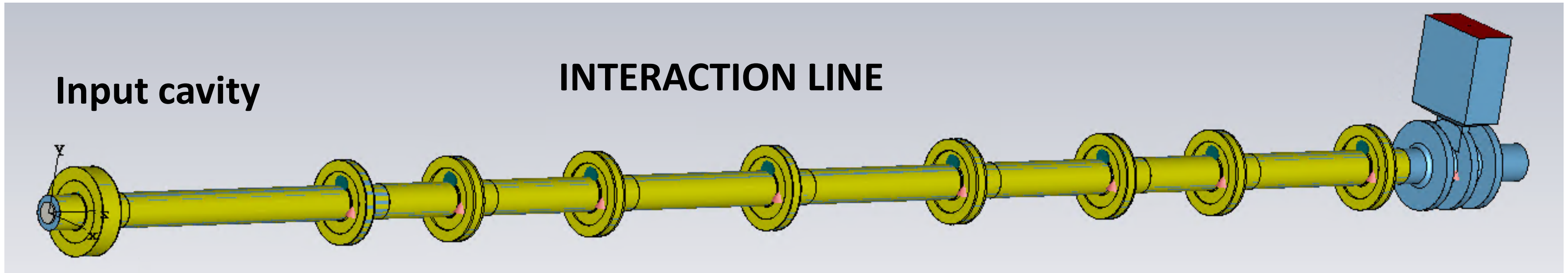
- Progress:

  Study has been focused on klystrons operating in the X band (12 GHz) (XFEL and CLIC RF-sources)

  Preliminary design has been optimized, based on a genetic algorithm. Efficiency of 70% has been reached so far.

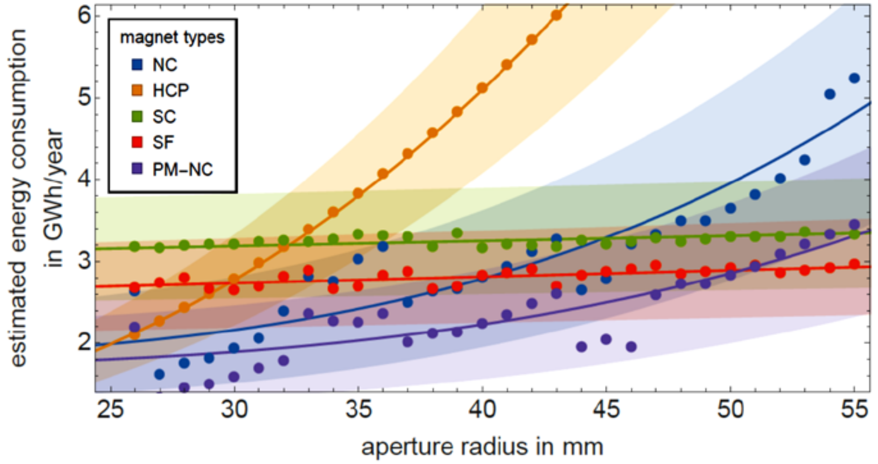
  Results are presented at IVEC 2019.

<u>CEA-Saclay</u>
P.Hamel
J.Plouin
C.Marchand



Energy Efficient Accelerator Magnets

Magnet type	Advantage	Disadvantage
permanent magnet	No power required, reliable, compact	Tuneability difficult, aperture size limited, radiation damage
Optimized electromagnet	Low power, less cooling (and less vibration)	Larger size, cost
Pulsed magnet	Low average power, less cooling, high fields	Complexity of magnet and circuit, field errors
Superconducting magnet	No ohmic losses, higher field	Cost, complexity, cryo installation
High saturation materials	Lower power, compactness and weight	Cost, limited gain



example study: yearly energy consumption vs. aperture

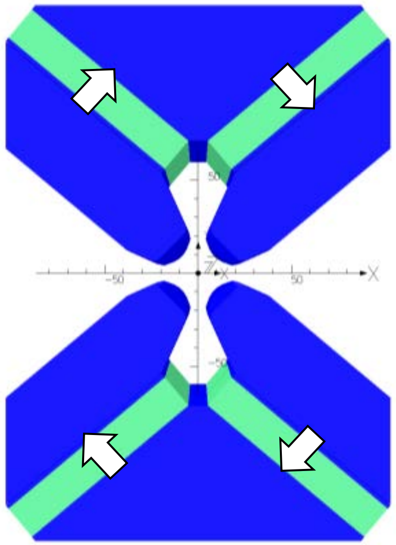
considered:
NC = normal conducting
HCP = high power pulsed
SC = superconducting
SF = superferric
PM = permanent

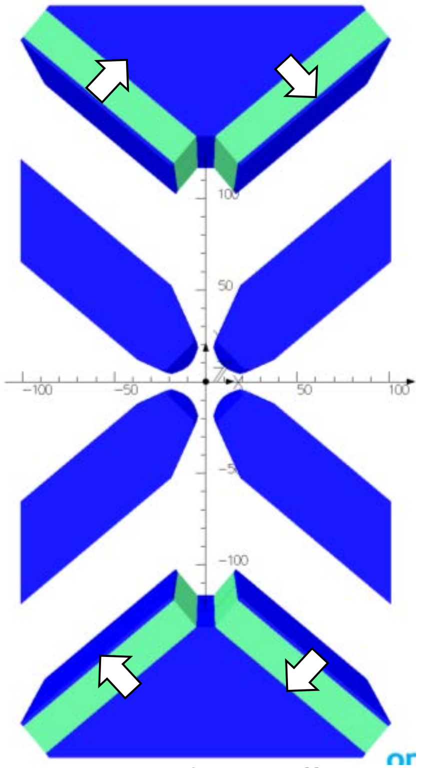
Master Thesis
Ph.Gardlowski (GSI, EUCARD-2): systematic efficiency and economy comparison of accelerator magnets

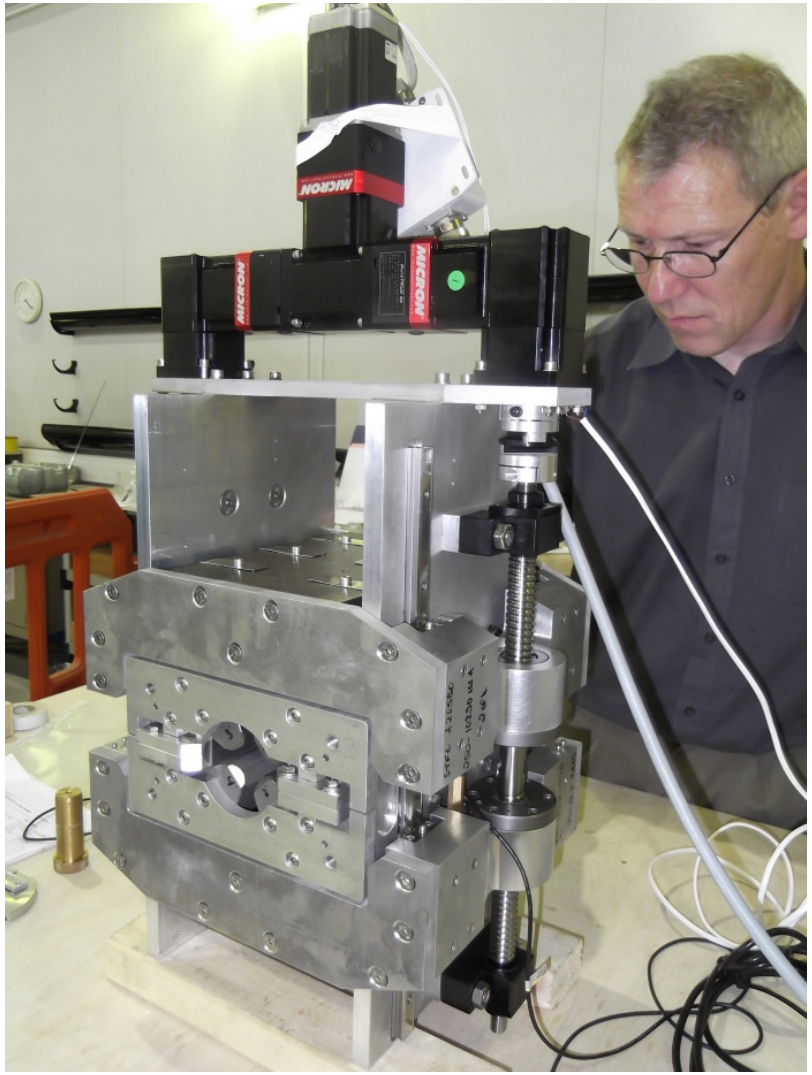
Example: Tunable Permanent Magnet for CLIC

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

Stroke = 0 … 64 mm







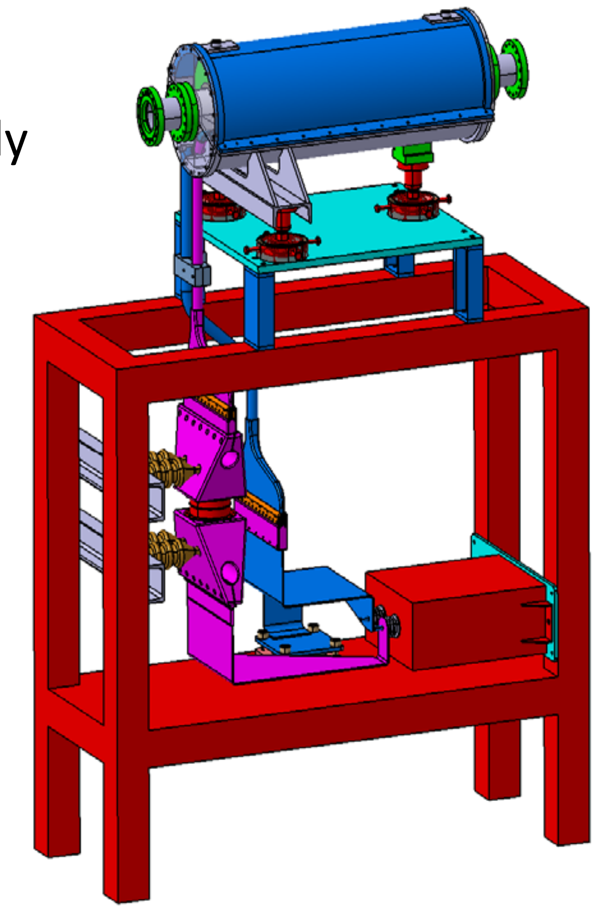
Tunable high-gradient permanent magnet quadrupoles, B.J.A. Shepherd *et al* 2014 *JINST* 9 T11006

Pulsed Magnets for beam Transfer Channels

(GSI, P.Spiller et al)

- low average power; high field; compact; energy recovery in capacitive storage **(ongoing ARIES study)**
- complexity added by pulsing circuit; field precision potentially challanging

	Prototype Quadrupole
Gradient	80 T/m
Length	0.65 m
Pulse length	90 ms (beam 1 ms)
Peak current	400 kA
Peak voltage	17 kV
Energy @17 kV	65 kJ
Inductivity	535 nH
Capacitor	450 mF
Forces	200 kN



Engineering model of the prototype quadrupole magnet incl. support

Superconducting Accelerator Structures

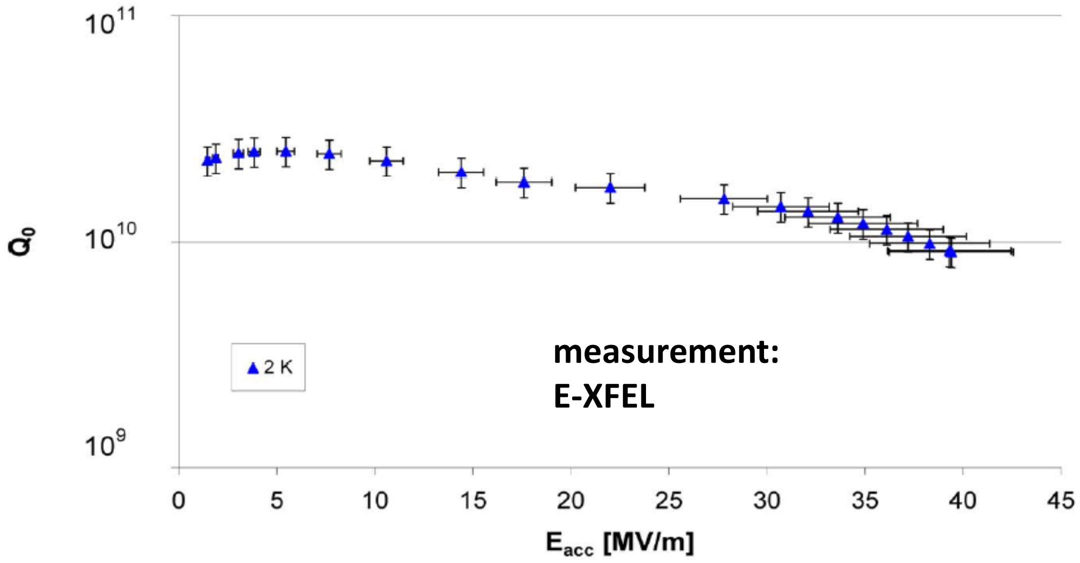
contrary to s.c. coils, s.c. resonators are not loss free, although nearly all RF power is transferred to beam

s.c. resonators have extremely high Q, e.g. 2×10^{10}@1.3GHz (E-XFEL)

at this Q a church bell would ring for 2 years(!)

the relation between dissipated power and voltage is given through (R/Q):

$$\left(\frac{R}{Q}\right) = \frac{U_a^2}{P_{\text{dissip}} Q}$$

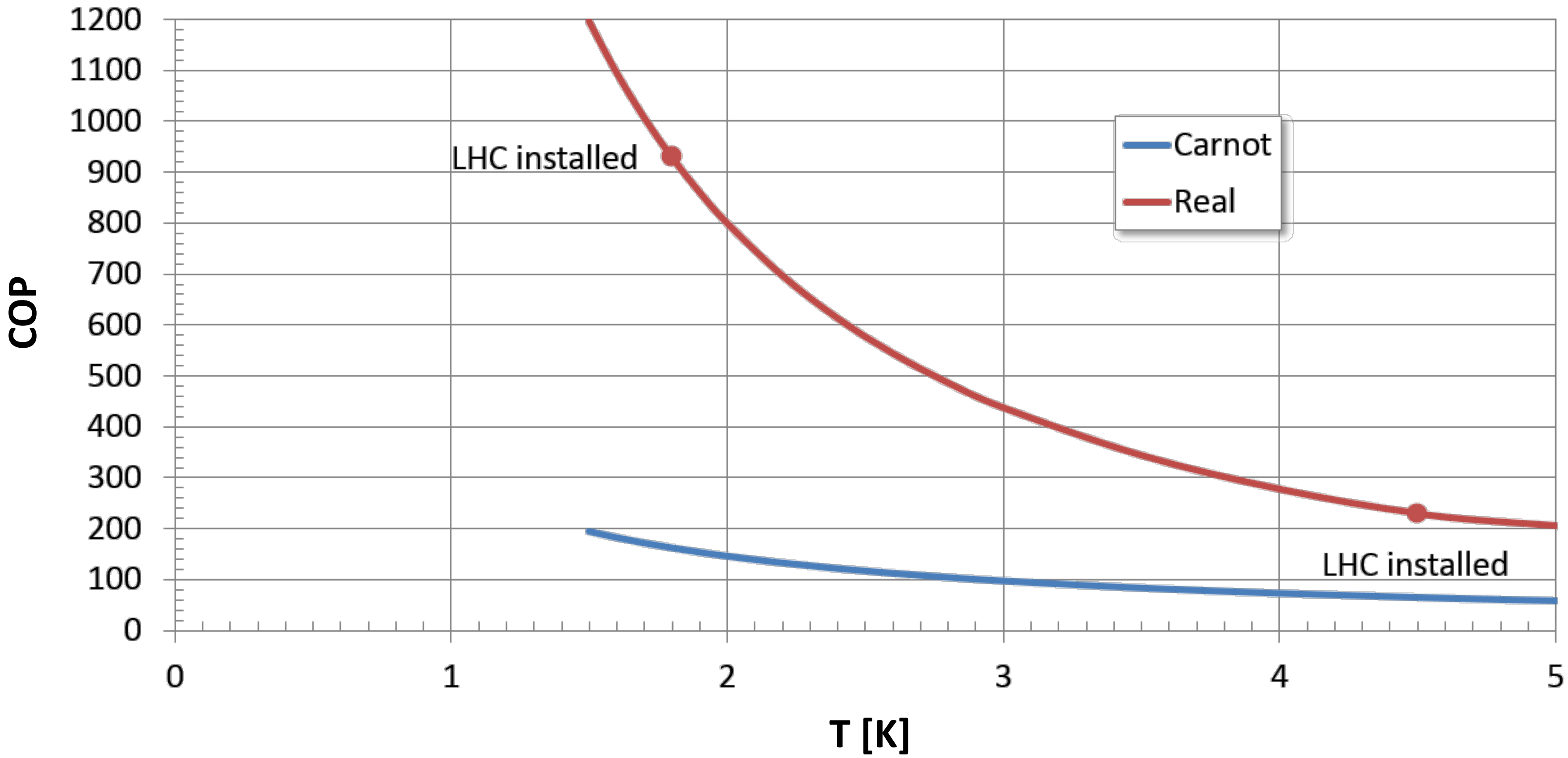


however, cooling efficiency is much reduced due to Carnot efficiency at low T:

$$P_{\text{cryo}} = \frac{P_{\text{cold}}}{\eta_c \eta_p} \approx 700 P_{\text{dissip}} \text{@2K}$$

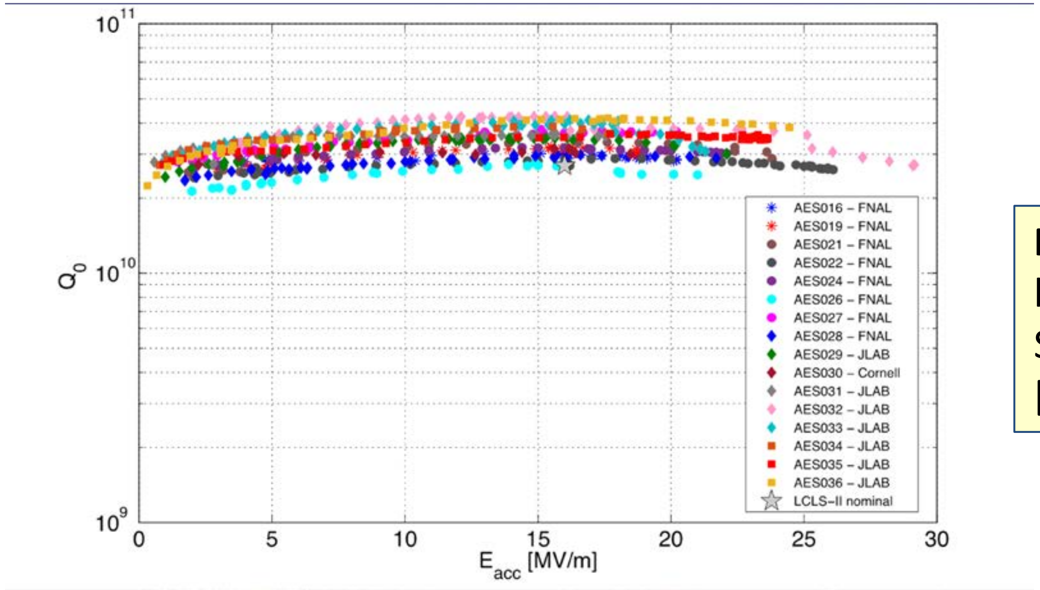
Cooling efficiency at low temperature

COP = Coefficient of performance:
To extract P at T_{refr}, one needs $COP \cdot P$ at T_{ambient}.

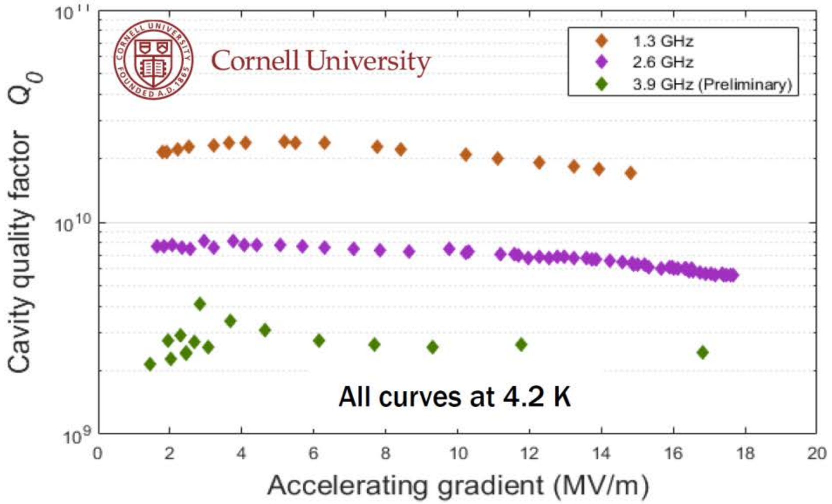


Ph. Lebrun
E.Jensen
CERN

Recent Developments wrt. s.c. Cavities



Results of N_2 doping
lots of activity in US: Fermilab, Cornell, Jlab, SLAC→LCLS-II
[A. Grasselino, SRF2013 & M. Liepe SRF2015]



- **Promising R&D: Nb_3Sn coated cavities at Cornell**
- **4.2 vs. 2.0K → thermodynamic efficiency, simplicity**

[M.Liepe, Cornell, IPAC'19]

ARIES activity: flux expulsion in s.c. cavities

earth magnetic field B≈40μT already leads to $Q<10^{10}$

→ flux trapping must be minimized through
- Magnetic shielding
- Controlled cooldown (thermoelectric currents)

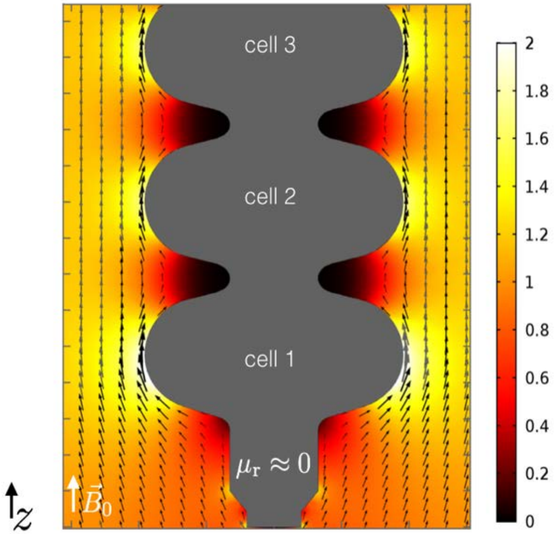
Workshop on Flux Trapping and Magnetic Shielding, Nov 8-9, 2018, CERN

64 participants from the North America, Asia & Europe.

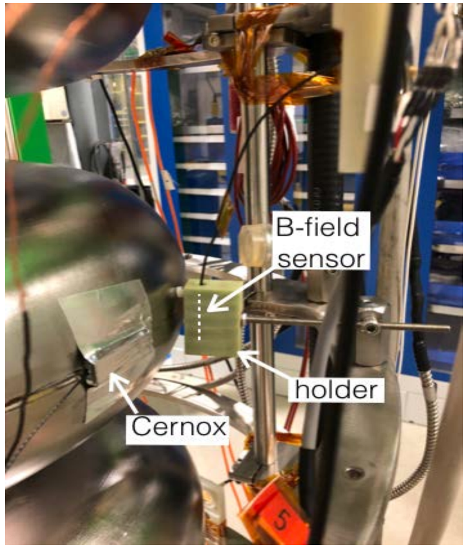
Supported by ARIES. Milestone: MS18, report

https://indico.cern.ch/event/741615/overview

A.Ivanov
F.Gerigk
CERN



Simulation of flux expulsion on multicell bulk Nb cavity



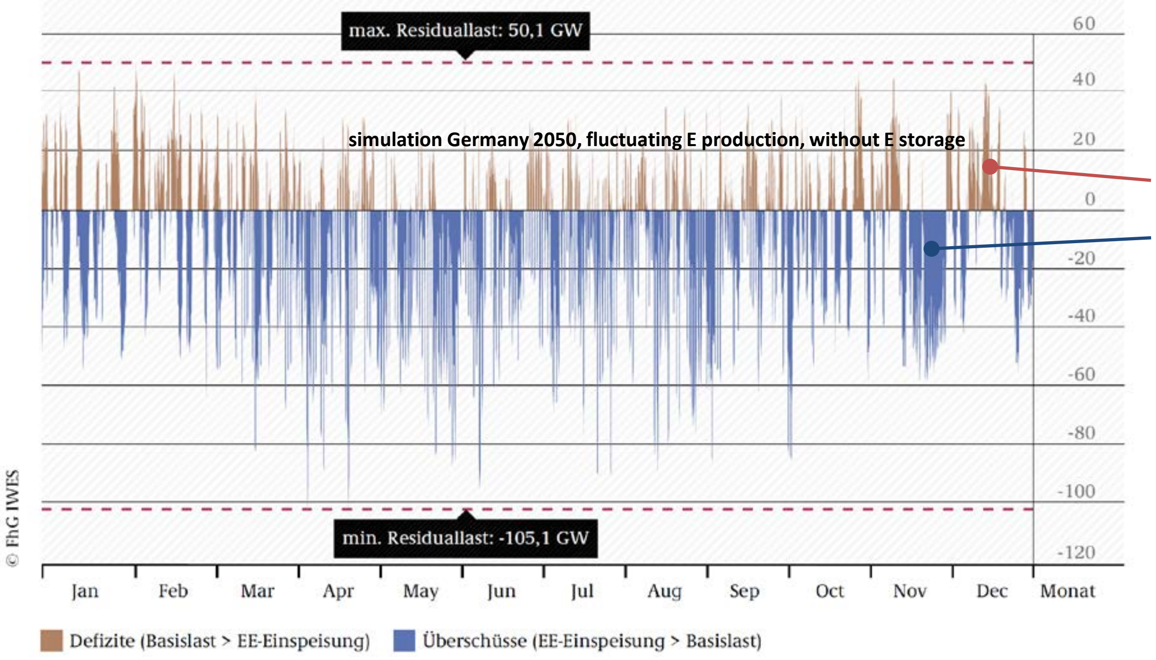
Experimental set-up to measure flux expulsion during cool-down.

sustainable sources – need for energy management

smart energy management: avoid consumption during times of high load

- study dynamic operation concepts
- study capacity energy storage
- e.g. KIT design: LH_2+SMES, up to 60GWh, n x 100MW

simulation Germany 2050, fluctuating E production, without E storage



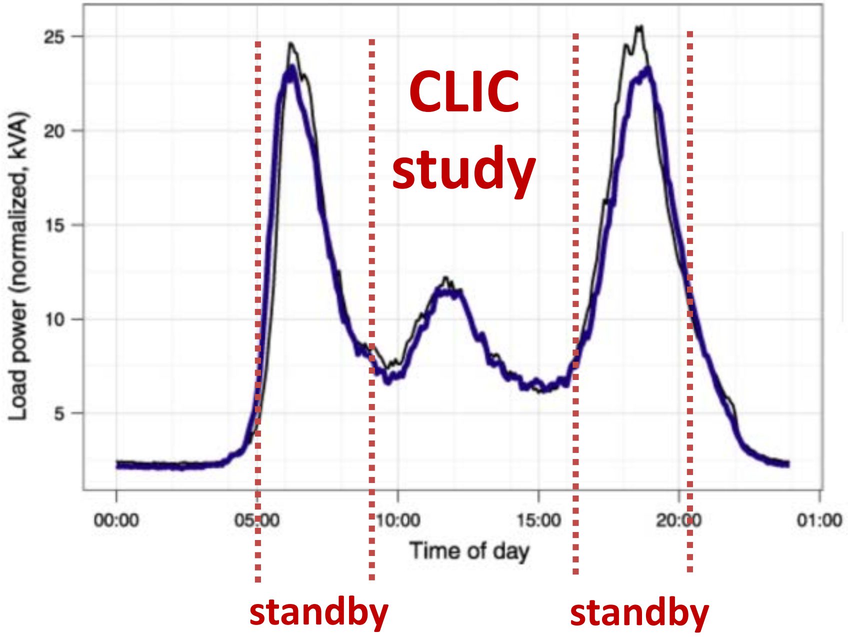
deficit: 53 TWh/y

surplus: 154 TWh/y

FCC-hh: 4 TWh/y

[courtesy : Fraunhofer Gesellschaft]

Energy consumption per day - France -



CLIC dynamic operation Study @ 3TeV (A.Latina et al):

Energy consumed is reduced by 18%(-2.826 GWh)

Luminosity delivered is reduced by 37%(-0.648 fb^{-1})

https://indico.cern.ch/event/275412/contributions/1617775/attachments/498907/689219/Energy.pdf

Energy Storage for Accelerators

storage systems needed for:

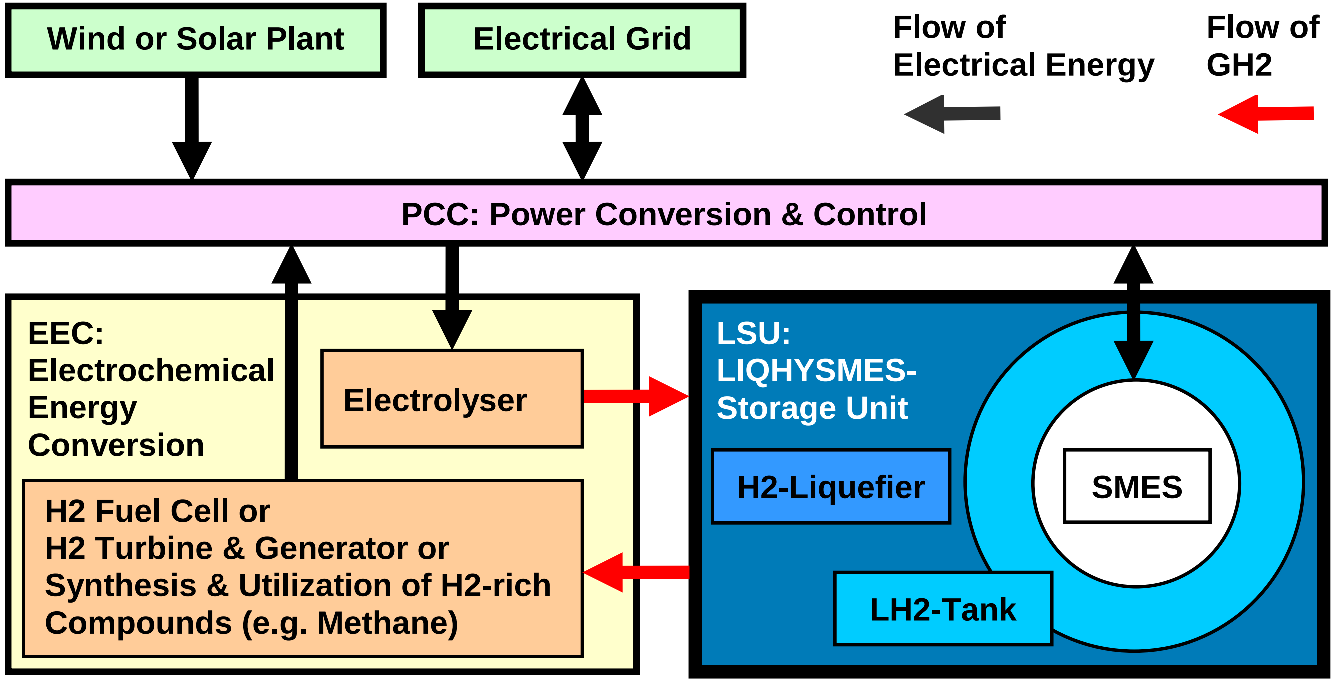
- pulsed RF systems
- cycling synchrotrons
- pulsed magnets
- uninterrupted power
- strategic energy management

Large capacity technology:

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



Accelerator Efficiency - Summary

Energy efficiency and sustainability is a must for future projects!

Energy efficient concepts to be followed up:

- energy management: dynamic operation & local energy storage
- energy recovery linac vs. storage ring; muon collider

Energy efficient technologies:

- RF sources (klystron, magnetron); permanent magnets, pulsed magnets
- s.c. technology: high Q RF; HTS magnets
- heat recovery (low T applications and heat pumps)

Other sustainability aspects:

- water consumption
- sustainable materials and components; sustainable lifecycle management
- Carbon Footprint Analysis helpful?