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ARIES

Energy Efficiency of Accelerators in the European Programs Eucard2 and ARIES

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E.Jensen, F.Gerigk (CERN), R.Gehring (KIT), C.Marchand (CEA), A.Lundmark (ESS), J.Stadlmann, P.Spiller (GSI), M.Wohlmuther (PSI)

Accelerator Efficiency - Outline

1) Motivation, concept of energy efficiency for accelerators
   - World energy consumption
   - Energy: order of magnitude examples
   - Example of power flow in PSI-HIPA

2) Workshop Highlights in EUCARD-2 and Projects in ARIES
   - Heat Recovery
   - Magnets
   - RF Generation
   - Cavities
   - Energy Storage
   - Target Systems

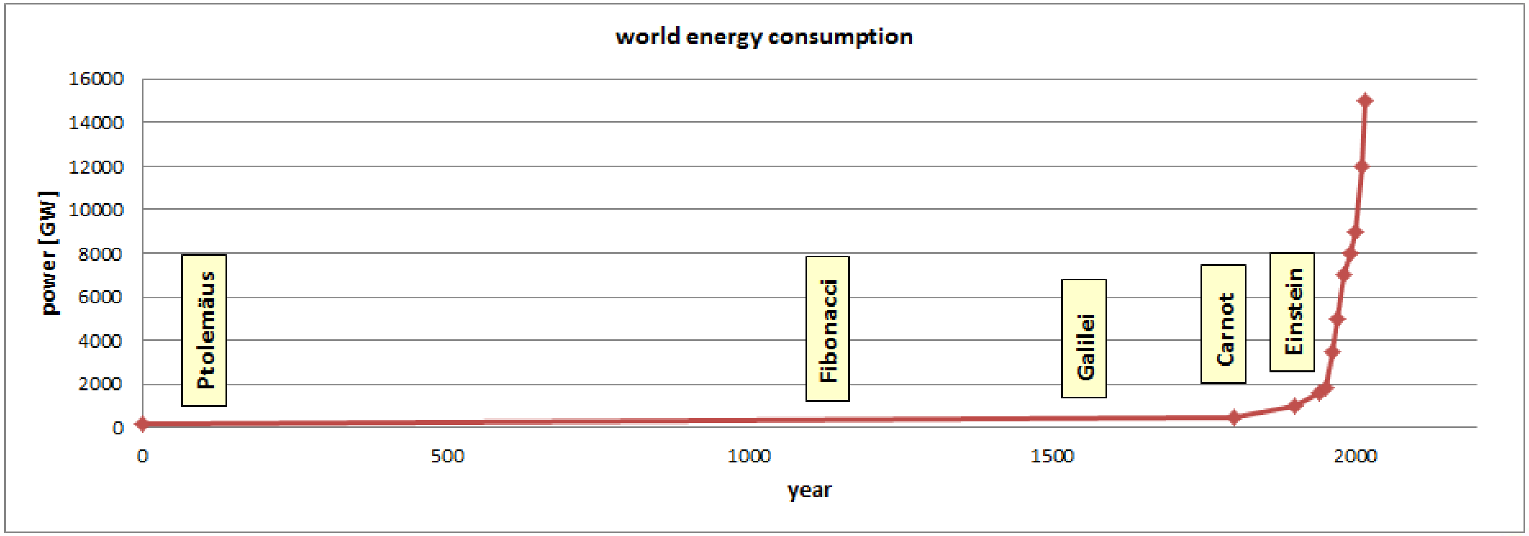
the energy problem

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

renewable energy sources are on the rise but have problems due to fluctuations

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

→ new accelerator projects and existing facilities must consider efficiency



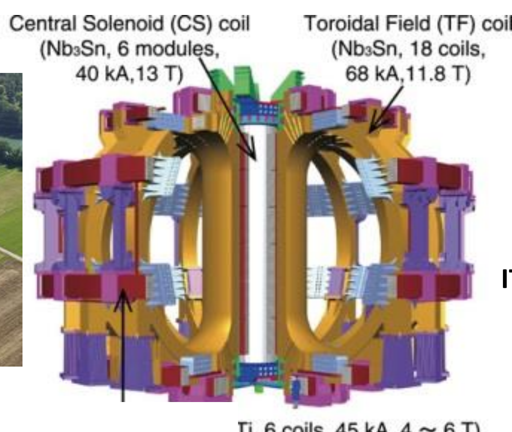
Energy: Order of Magnitude Examples

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 SwissLightSource 2.4GeV,0.4A: **82MWh**	ITER superconducting coil: **12,5MWh**
1d nucl. Pow. Plant Leibstadt (CH): **30GWh**	1d CLIC Linear Collider @3TeV: **14GWh**	all German storage hydropower: **40GWh**

cyclist, 300W

wind-power, 3MW peak

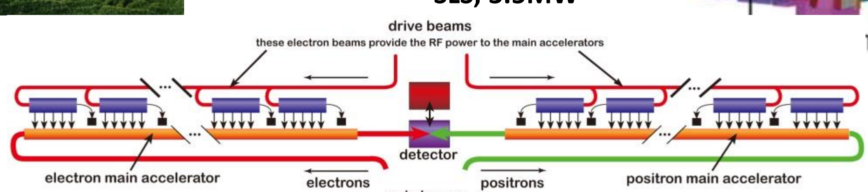
SLS, 3.5MW



ITER

car battery

nucl. plant 1.3GW



CLIC, 580MW

hydro storage

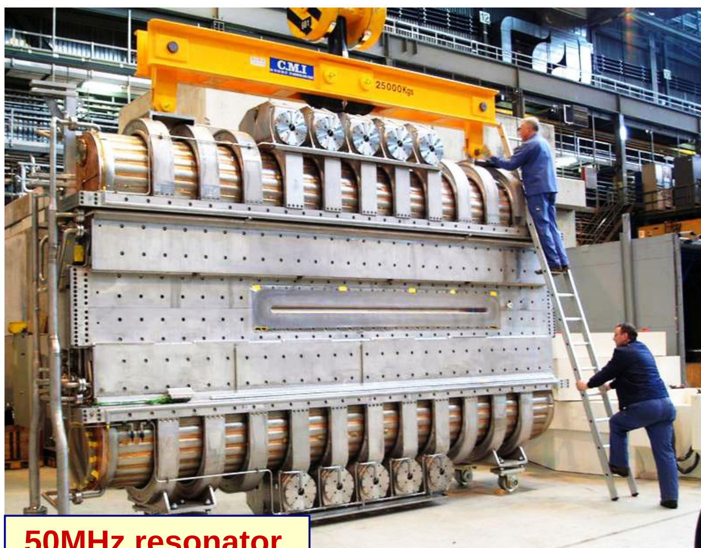
Example: PSI Facility, 10MW

Ring Cyclotron 590 MeV
loss ≈ 10^{-4}

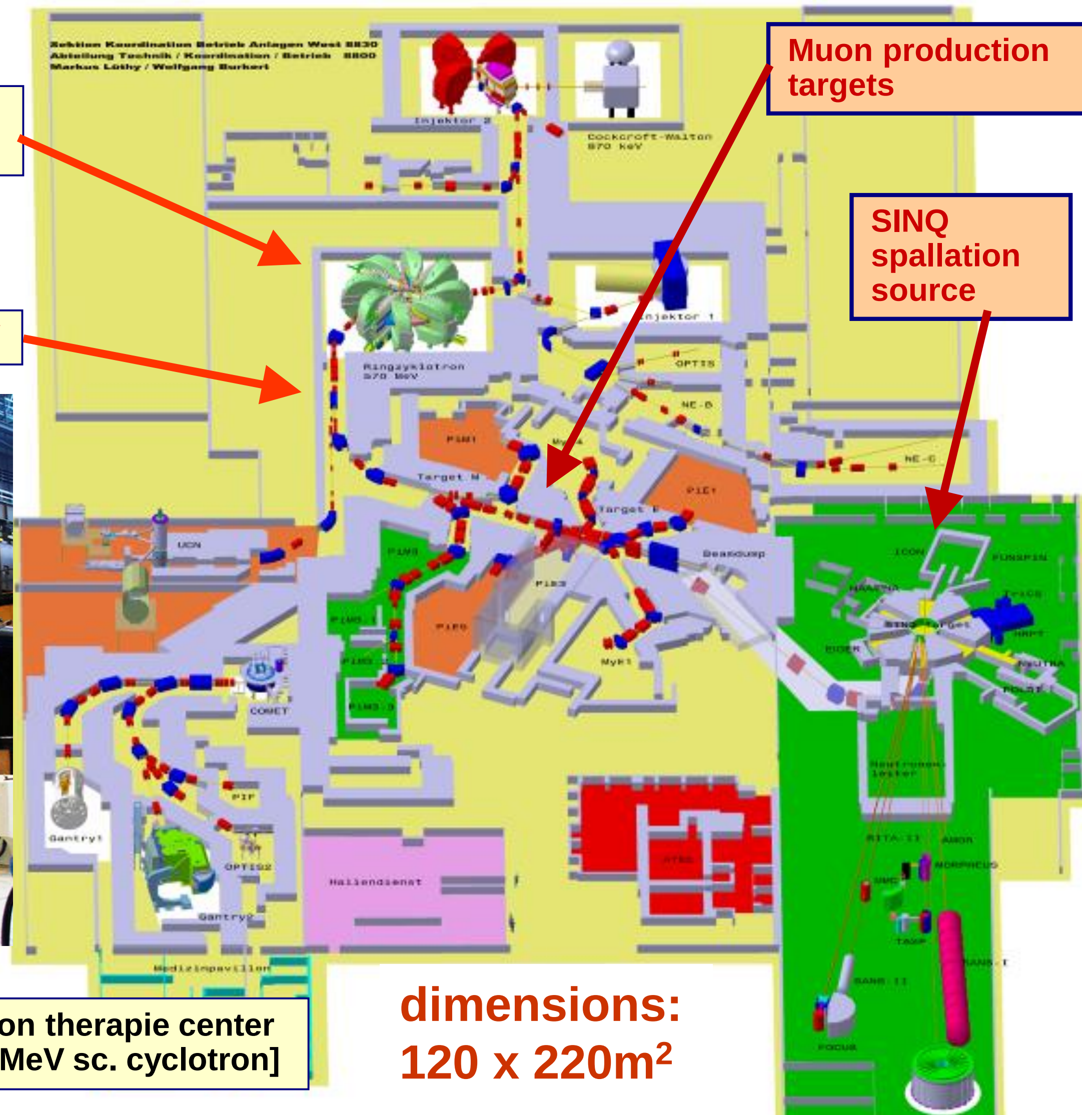
2.4 mA /1.4 MW

Muon production targets

SINQ spallation source



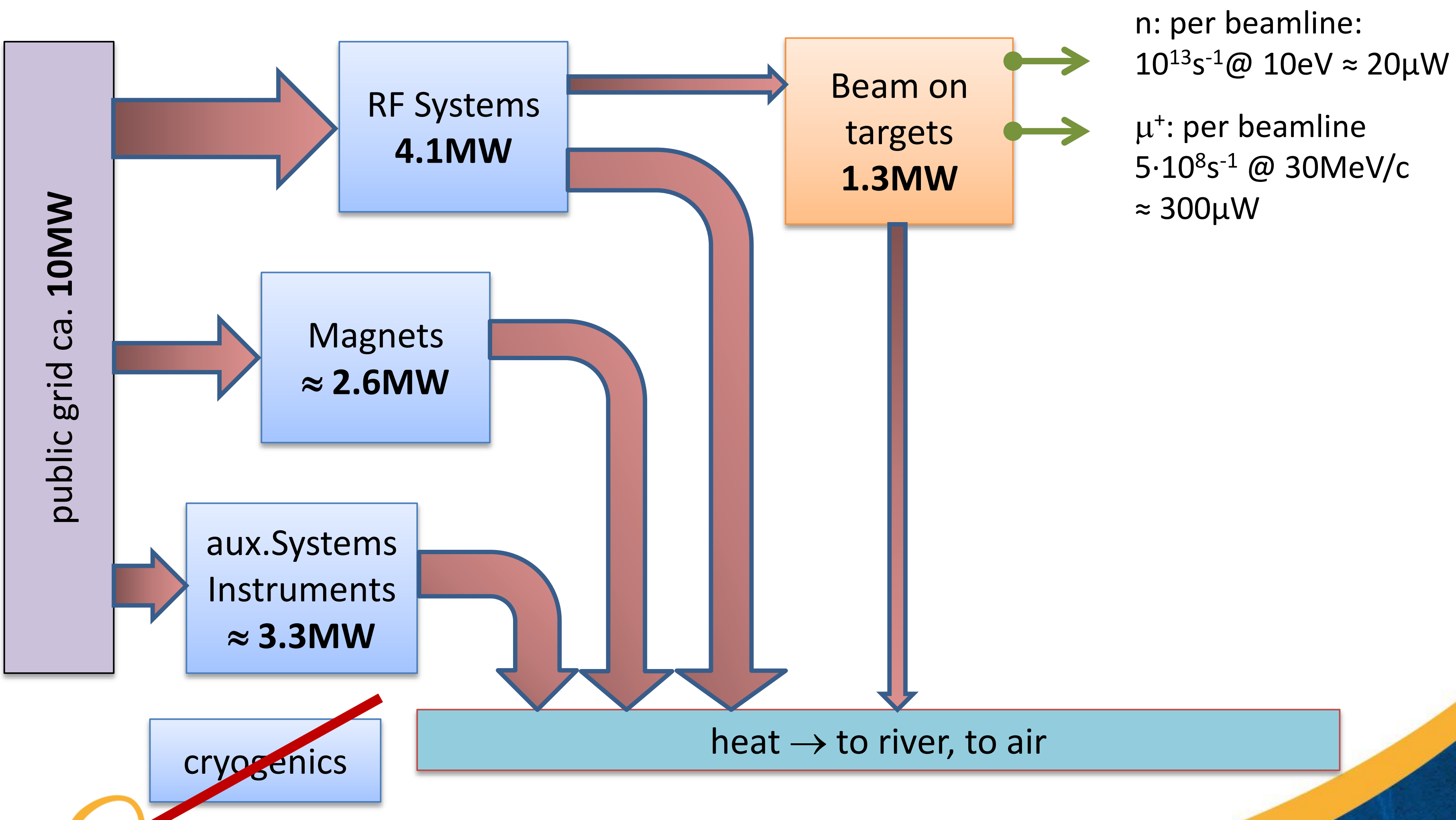
50MHz resonator



proton therapie center
[250MeV sc. cyclotron]

dimensions:
120 x 220m^2

example: PSI Facility, 10MW



Projects Eucard-2 and ARIES, co-funded by EC

Eucard-2: European Coordination for Accelerator Research, 2013…2017

www.psi.ch/enefficient:

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)

ARIES: Accelerator Research and Innovation for European Science and Industry, 2017…2021

Efficient Energy Management: www.psi.ch/eem

task 1: High Efficiency RF Power Sources (C.Marchand / CEA, R.Ruber / Univ.Uppsala)

task 2: Increasing energy efficiency by increasing the efficiency of the spallation target station (M.Wohlmuther / PSI, L.Zanini / ESS)

task 3: High Efficiency SRF power conversion (F.Gerigk / CERN)

task 4: Efficient operation of pulsed magnets (P.Spiller, S.Haberer / GSI)

ARIES Kickoff Meeting 2017

Examples of Technical Systems

- **Heat Recovery**
- **Magnets**
- **RF Generation**
- **Cavities**
- **Energy Storage**
- **Target Systems**

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)

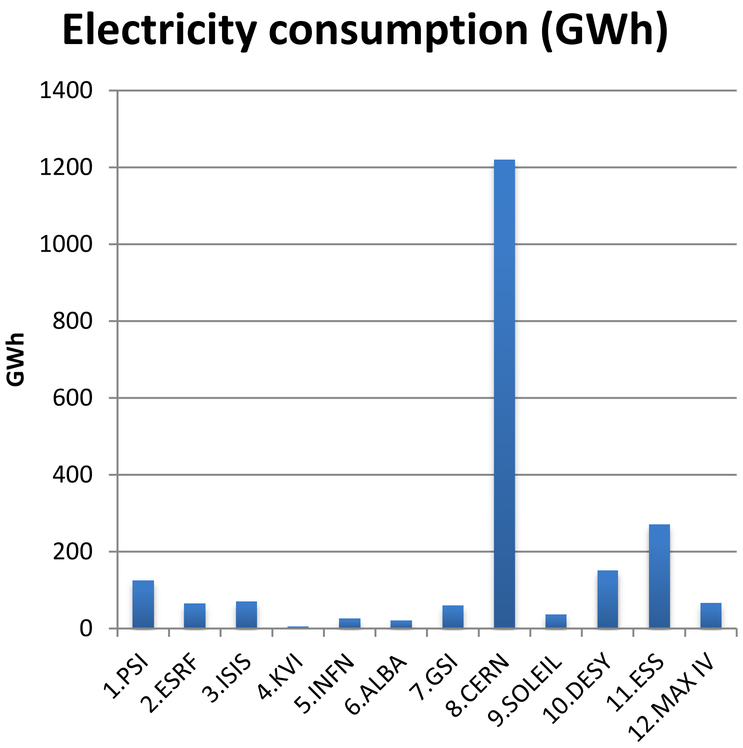
- lab survey on consumption and heat recovery
- heat recovery works for many facilities; high temperatures beneficial; local heat distribution system required
- Heat pumps can be used to convert power to higher temperature level
- new facilities MAX-4 and ESS foresee heat recovery on large scale

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

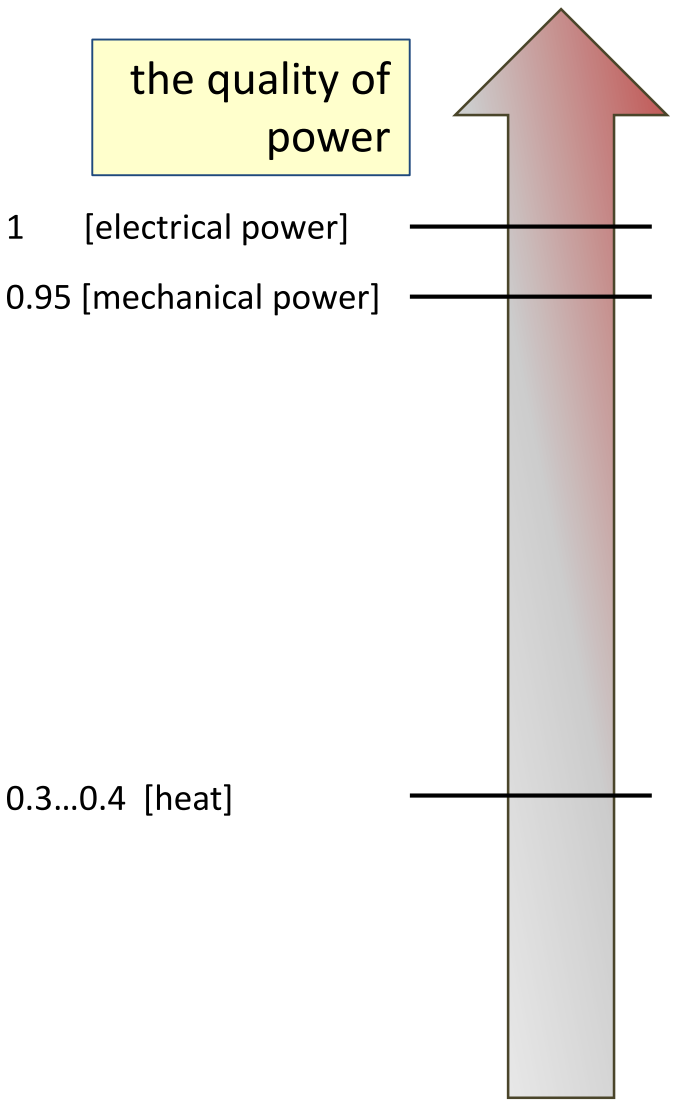
Lab Survey: Energy Consumption & Heat

[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%

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

- 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

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

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

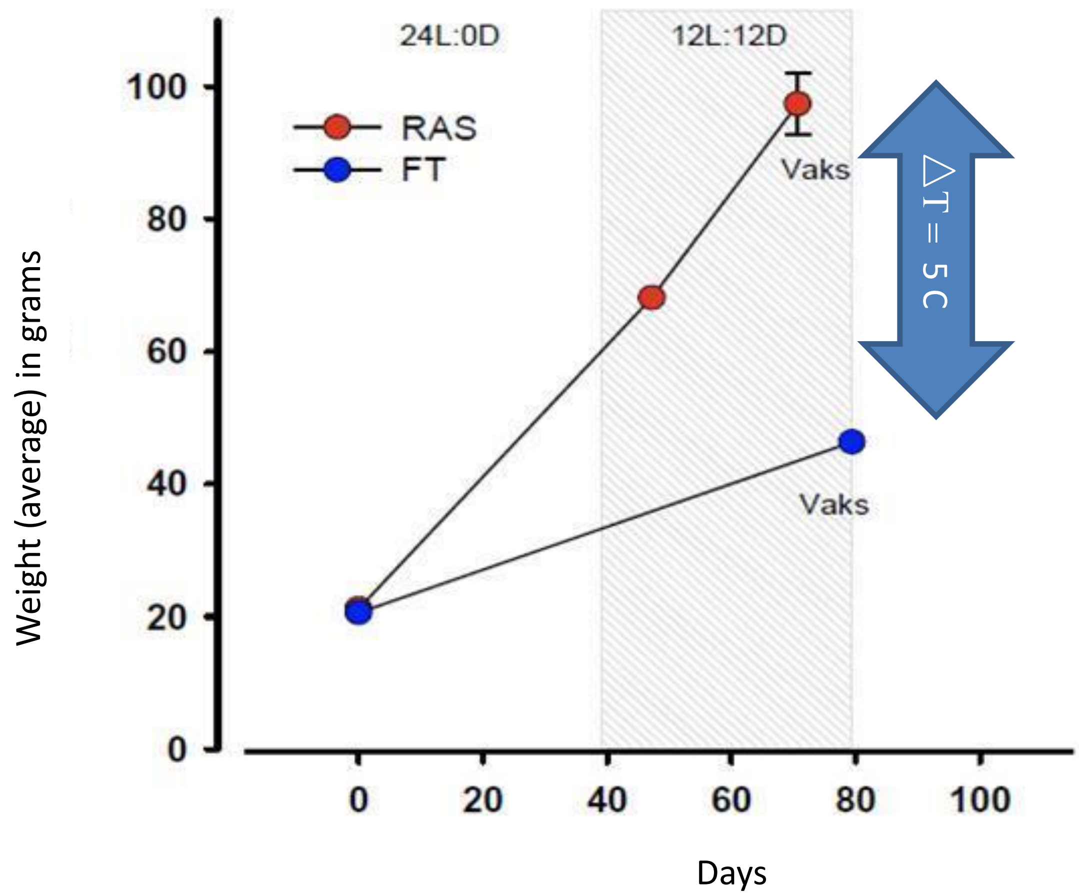
However: strong scaling with T for food production, i.e. fish!

Photo A.Kiessling

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

A.Kiessling

BY B.Fyhn Terjesen, Nofima



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 power, less cooling, high fields	Con: complexity, field errors
s.c. magnet Pro: no ohmic losses, higher fields	Con: cost, complexity, cryo installation
high saturation materials Pro: lower power, compactness, weight	Con: cost, gain is limited

Workshop on Special Compact and Low Consumption Magnet Design,
CERN: indico.cern.ch/event/321880/
study: Ph.Gardlowski (GSI), systematic comparision of beam transport options

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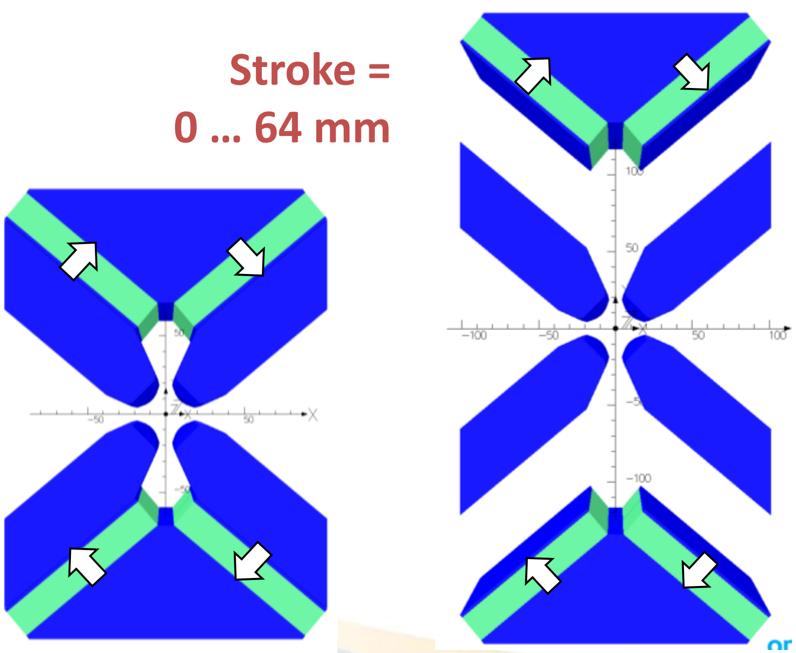
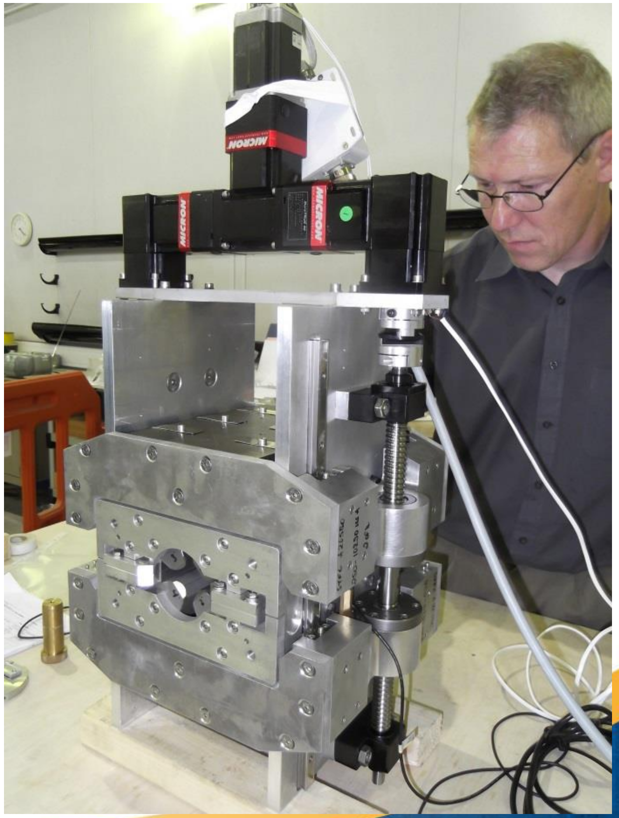
Permanent Magnet Quad Design for CLIC

[B.Shepherd, STFC Daresbury, this workshop]

- **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

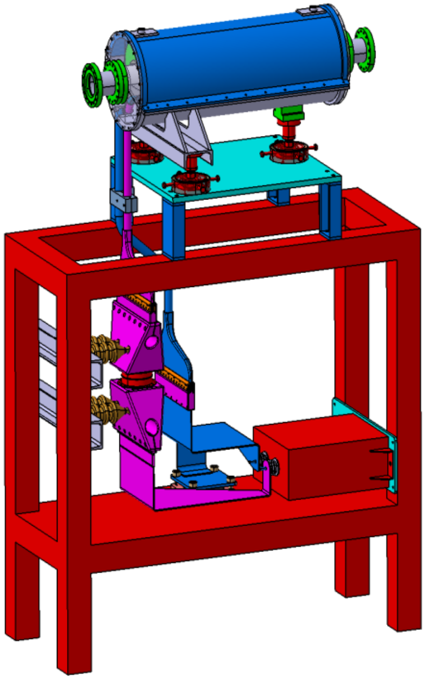
Tunable high-gradient permanent magnet quadrupoles, B.J.A. Shepherd *et al* 2014 *JINST* 9 T11006





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

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

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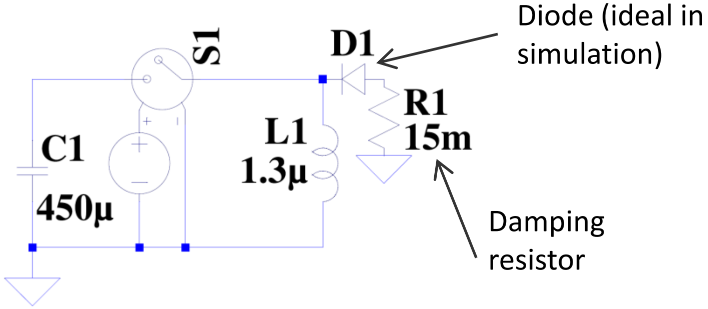
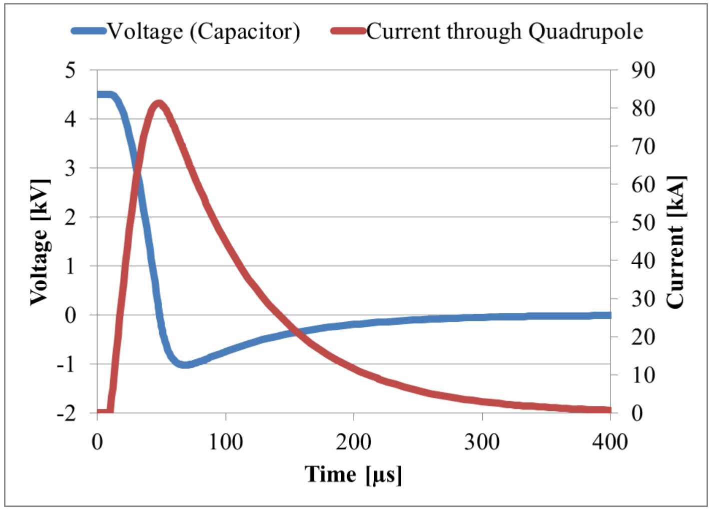
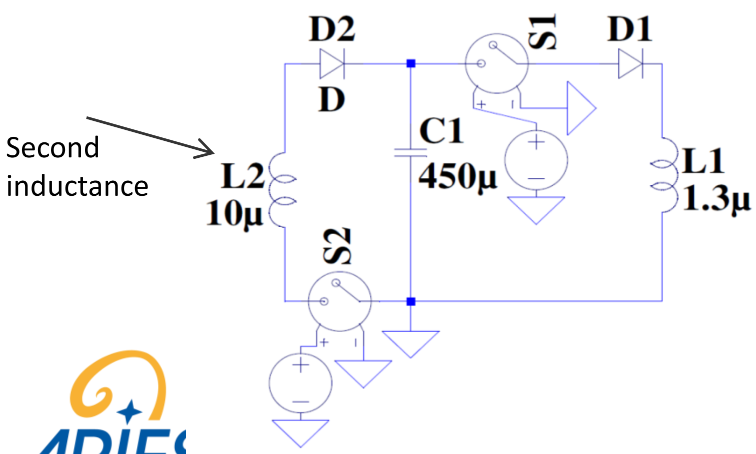
ARIES task: Circuit Layout for Energy Recovery

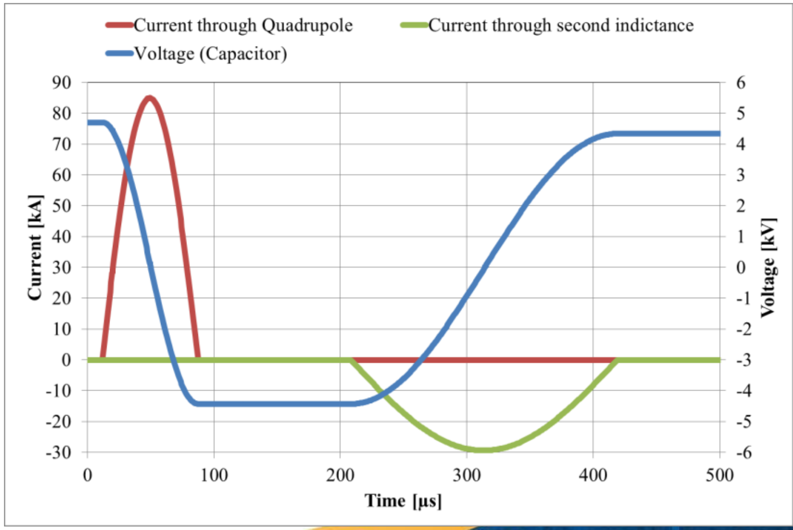
- 1. Improved circuit: Damping resistor not in main circuit
  → significantly higher current and gradient
  - Voltage reversal avoided with diode





- 2. Energy recovery achieved with second inductance
  - Components are exposed to full reverse voltage





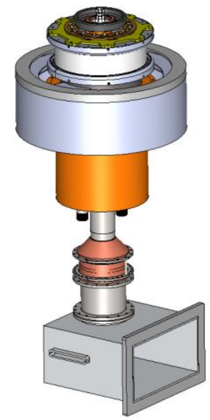
Efficient RF Generation and Beam Acceleration

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

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


CPI: multi-beam IOT


E2V: magnetron


THALES: multi-beam klystron

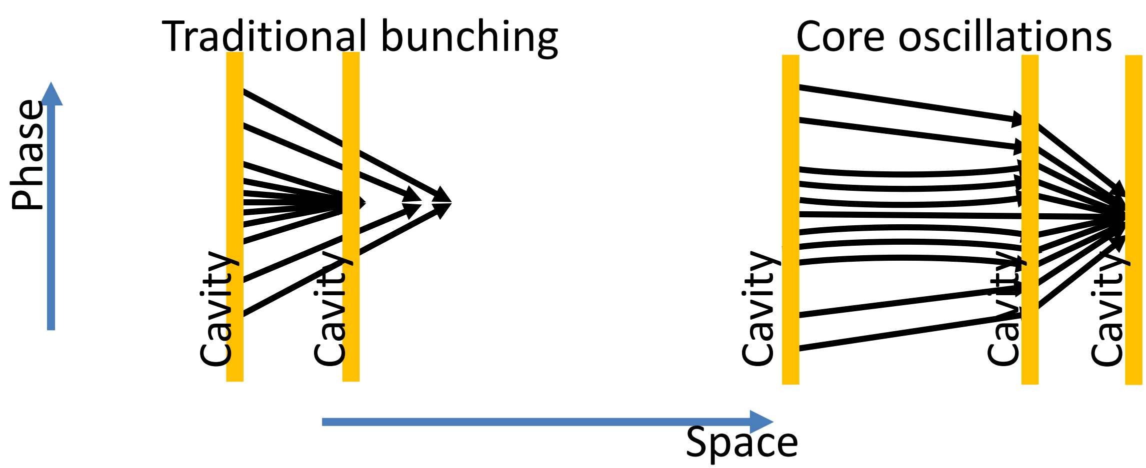

SIEMENS: solid state amplifier


THALES: TETRODE

Klystrons: Methods to get high efficiency

[I.Syratchev (CERN) et al, C.Marchand (CEA), ongoing ARIES study, this workshop]

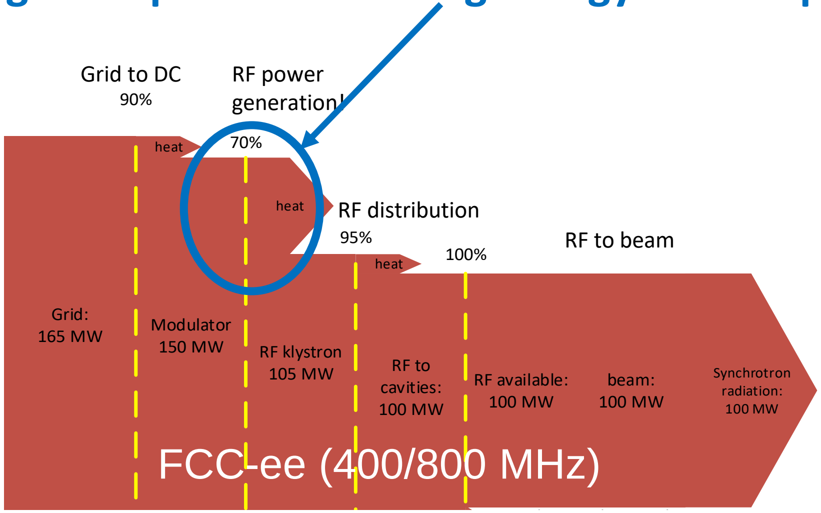
- Bunching split into two distinct regimes:
  - non-monotonic: core of the bunch periodically contract and expand (in time) around center of the bunch
  - outsiders monotonically go to the center of the bunch
- Core experiences higher space charge forces which naturally debunch
- Outsiders have larger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



IMPROVE EFFICIENCY OF RF POWER SOURCES

C.Marchand, CEA Saclay

Largest impact for reducing energy consumption of accelerators by RF power generation



Increase of 5% efficiency for RF generation
- ➔10 MW less electricity consumed
- ➔gain 50 GWh/year (2M€/year)

Increase of 5% efficiency of 12 GHz klystrons
- ➔10% less electricity consumed
- ➔gain 100 GWh (4 M€)

Photo: CLIC Xbox 12 GHz facility for cavities conditioning

superconducting structures for CW operation

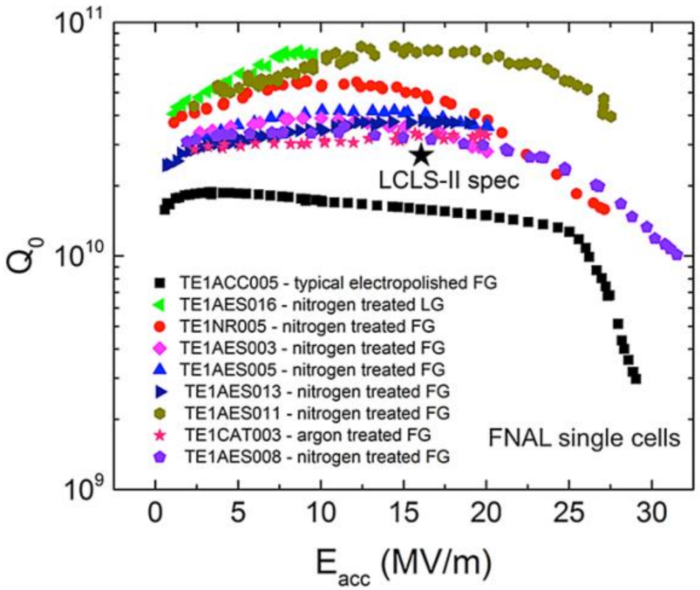
[V.Yakovlev, FNAL, this workshop]

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

The planned ARIES work [F.Gerigk, CERN]

- Optimize the **magnetic shielding scenario** for a 4-cavity 704 MHz cryo-module. (CERN PhD Student, co-funded by ARIES)
- **simplified mock-ups** that can be measured on a test stand
- Study a appropriate **cool-down strategy** and assess how active magnetic compensation can help.
- Assess and compare operational scenarios to minimise energy consumption (e.g. beam pulse structure in linacs, minimisation of cavity failures in circular colliders, power consumption due to off-axis beams, power needs for microphonics compensation, ...)

704 MHz cavity under EP

Vacuum vessel for 704 MHz cryo module

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Energy Storage for Accelerators

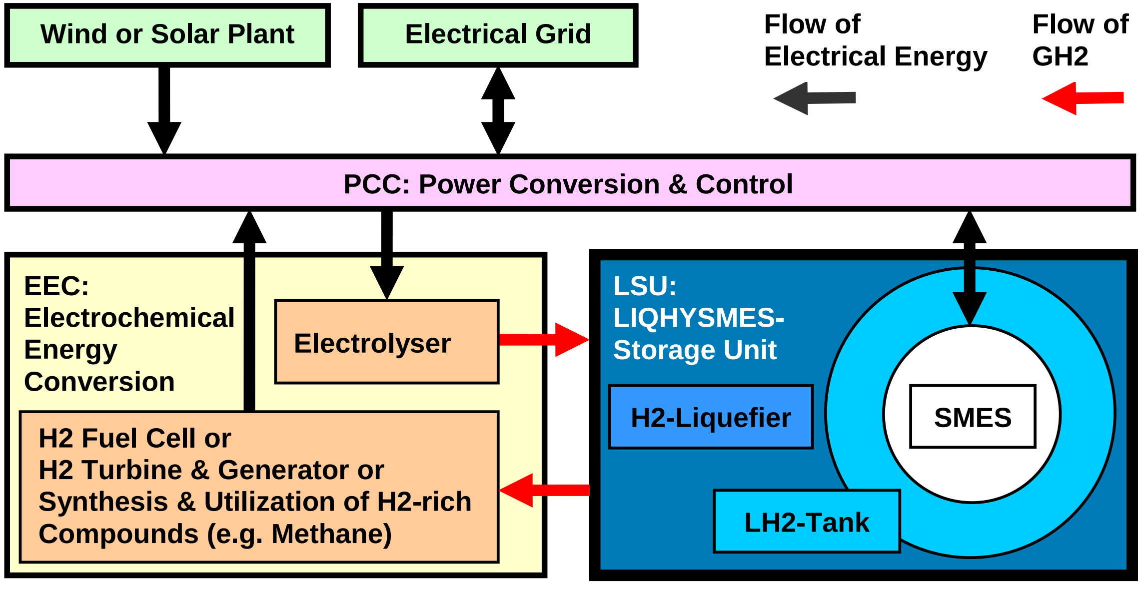
storage systems needed for:
- pulsed RF systems
- cycling synchrotrons
- pulsed magnets
- uninterrupted power
- strategic energy management(?)

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

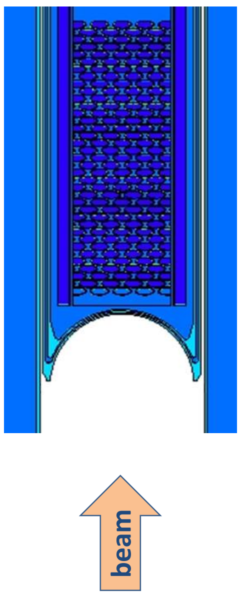


Targets, or **Conversion to Secondary Radiation**

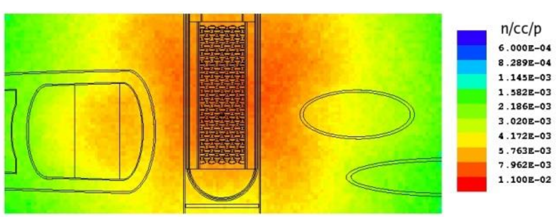
Example: neutron production target at PSI

old

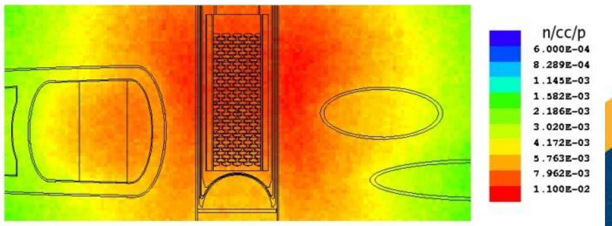
new



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



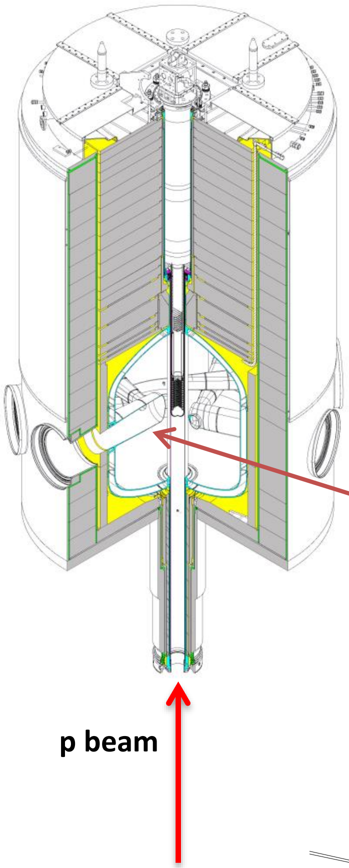
color code: neutron density on same scale (MCNPX)

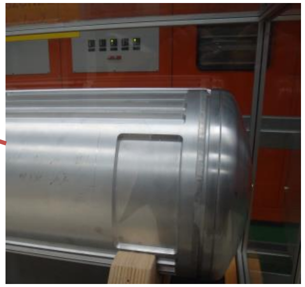


ARIES task: improving neutron flux per beam power

M.Wohlmuther, PSI; L.Zanini, ESS

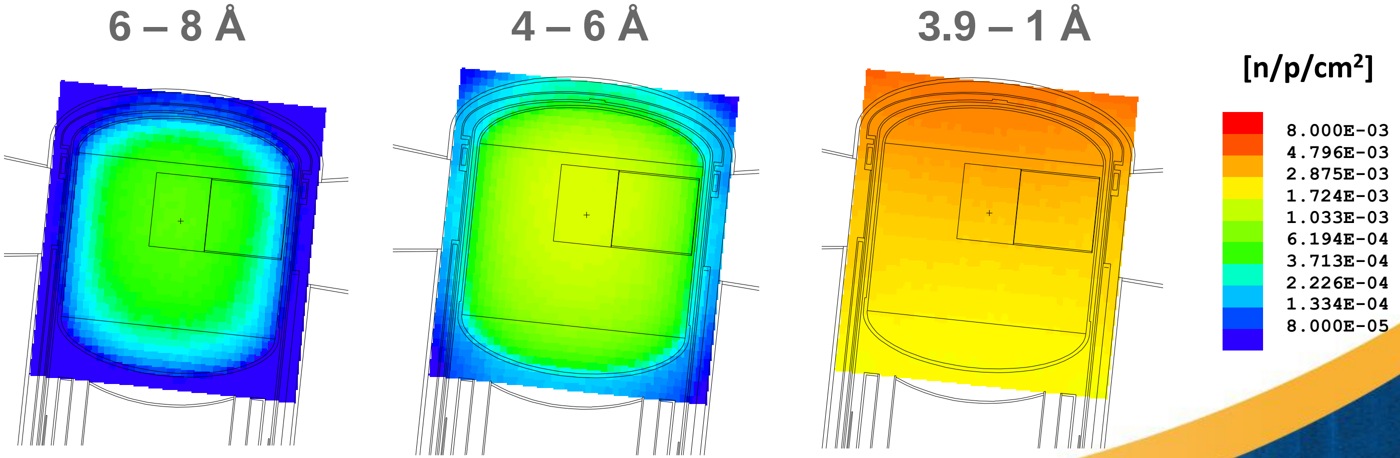
D_2 Cold Source





- **Neutrons are produced by a 1MW p-beam impinging on a Pb-Target**
- **Neutrons must be moderated to low energies (eV) using deuterium with low capture cross-section**

Simulation of Spatial Neutron Flux Distribution in D_2 cold source with MCNP



Enefficient Workshops

- **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** - **EuCARD^2 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/

EnEfficient: 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)
  - https://www.psi.ch/enefficient/PastEventsList/pdriver-efficiency-summary_compilation_V6.pdf
- Analysis of PSI High Intensity Accelerator, A.Kovach (PSI)
  - https://www.psi.ch/enefficient/DocumentationEN/Analysis_and_Optimisation_of_HIPA_Power_Consumption-20161214.pdf

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Summary

- with scarcity of resources and climate change Energy Efficiency (sustainability) becomes important for accelerator projects; Programs Eucard-2 and ARIES provide networking, R&D on this topic
- many technical efforts for better sustainability are undertaken with heat recovery, RF generation, low loss s.c. cavities, low power magnets, energy management
- 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
- **Documentation past workshops:** www.psi.ch/enefficient
- **Ongoing program:** www.psi.ch/aries-eem