High Efficiency Work in Context

Erk Jensen, CERN
The raison d’etre

• Our mandate: Prepare technology for the post-LHC era!

From council/en/EuropeanStrategy/esc-e-106.pdf:
To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update [...] CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.
Our mandate: Prepare technology for the post-LHC era!

Economic use of energy resources mandatory!

B. Vierkorn-Rudolph at Workshop Energy for Sustainable Science, ESS 2011: All future (large) accelerators must consider energy efficiency!
If we don’t conceive them for sustainable energy consumption, these projects will not be approved!
Larger overall efficiency means less consumption and less waste heat production (smaller carbon footprint)!
The context

- Our mandate: Prepare technology for the post-LHC era!
- Economic use of energy resources mandatory!
- Societal benefits

From the Executive Summary of the 1st ESS workshop:
Large Scale research infrastructures are able to generate very innovative solutions that can be used profitably elsewhere and be at the base of win/win partnerships with industries through a smart specialization approach.
The challenge of energy efficiency and its impact on the environment have been clearly assessed as well as the increase of efficiency as a major contributor in limiting CO2 emissions. Moreover, new ways of renewable energy supply schemes for existing or future planned RIs should be explored as technologies become more and more competitive. Several main action lines of development have been identified:

- Reduction of primary electricity consumption through increased efficiency,
- [...] Better usage of waste heat by recovery and valorisation schemes,
- Exploiting RIs as test bed for novel developments and technological demonstrators,
- Exploring renewable energy solutions for existing and future RIs,

http://europeanspallationsource.se/energyworkshop

EnEfficient RF Sources, The Cockcroft Institute, 3-4 June 2014
Present CERN consumption

To get a feel for the scale...

Scaling for FCC-hh (or ee) will depend on multi-100eMW power machines AND their duty cycles, but will be a major design issue!
## EuCARD²

### Synergies between projects

<table>
<thead>
<tr>
<th>R&amp;D/Projects</th>
<th>Test Facilities</th>
<th>Protons</th>
<th>Ions</th>
<th>Electron-Hadrons</th>
<th>B Factories</th>
<th>Linear Colliders</th>
<th>Muons &amp; Neutrinos</th>
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<tbody>
<tr>
<td></td>
<td>Coordination</td>
<td>HL-LHC</td>
<td>HE-LHC</td>
<td>LHIC</td>
<td>NICA</td>
<td>RHIC II</td>
<td>FAIR</td>
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<tr>
<td>Electron cloud</td>
<td>Cornell?</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>KEK</td>
<td>X</td>
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<tr>
<td>SC magnets (High Field, Fast Cycling, Super-Ferric, Wigglers)</td>
<td>Magnet R&amp;D network?</td>
<td>CERN</td>
<td>FNAL</td>
<td>GSI</td>
<td>X</td>
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<td>Super-Conducting RF</td>
<td>ELSA Tech coll</td>
<td>FLASH</td>
<td>NML</td>
<td>STF, XFEL</td>
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<td>High field NC Structures</td>
<td>CLIC/ILC WG?</td>
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<td>Low emittance generation</td>
<td>CLIC/ILC WG?</td>
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<td>Nanometer beam focusing</td>
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<td>RF power source high efficiency</td>
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<td>Collimation &amp; targets high power beams</td>
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<td>Cooling (Electron, Coherent, Stochastic)</td>
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<td>crab cavities</td>
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<td>Plasmas</td>
<td>LBL, SLAC</td>
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<td>Drive beam generation</td>
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<td>Beam dynamics simulations</td>
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<td>Beam based feedbacks</td>
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<td>Energy recovery linacs</td>
<td>CERN, FNAL, GSI</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>Nanobeam scheme (LPA &amp; Crab waist)</td>
<td>CERN, FNAL, GSI</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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*Taken from: J.-P. Delahaye, “New Accelerator Projects”, ICHEP10, 22.-28, July 2010, Paris*
Based on Linacs ...  

<table>
<thead>
<tr>
<th></th>
<th>IFMIF</th>
<th>ESS</th>
<th>SPL II</th>
<th>ILC .5 TeV</th>
<th>CLIC 3 TeV</th>
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<tr>
<td>Frequency</td>
<td>175 MHz</td>
<td>704 MHz</td>
<td>704 MHz</td>
<td>1300 MHz</td>
<td>1000 MHz</td>
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<tr>
<td>Technology</td>
<td>Grid tubes</td>
<td>klystrons</td>
<td>klystrons</td>
<td>MBK</td>
<td>MBK</td>
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<tr>
<td>Total AC power</td>
<td>38 MW</td>
<td>40 MW</td>
<td>230 MW</td>
<td>415 MW</td>
<td>255 MW</td>
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<tr>
<td>Modulator output</td>
<td>60 MW</td>
<td>17.8 MW</td>
<td>26.5 MW</td>
<td>135 MW</td>
<td>255 MW</td>
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<tr>
<td>Power source output</td>
<td>25 MW</td>
<td>8.9 MW</td>
<td>10.7 MW</td>
<td>88 MW</td>
<td>180 MW</td>
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<tr>
<td>Drive beam power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>140 MW</td>
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<tr>
<td>Acc. structure input</td>
<td>15 MW</td>
<td>6.5 MW</td>
<td>7.8 MW</td>
<td>67 MW</td>
<td>101 MW</td>
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<tr>
<td>Total beam(s) power</td>
<td>10 MW</td>
<td>5 MW</td>
<td>4 MW</td>
<td>21.6 MW</td>
<td>28 MW</td>
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<tr>
<td>Efficiency</td>
<td>13.5 %</td>
<td>10 %</td>
<td>9.4 %</td>
<td>6.7 %</td>
<td></td>
</tr>
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</table>
**... and Synchrotrons**

<table>
<thead>
<tr>
<th></th>
<th>FCC-hh</th>
<th>FCC-ee*)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td>400 MHz</td>
<td>800 MHz</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>klystrons</td>
<td>klystrons</td>
</tr>
<tr>
<td><strong>Total AC power</strong></td>
<td>$\mathcal{O}(300\text{ MW})$</td>
<td>$(300 \div 400)\text{ MW}$</td>
</tr>
<tr>
<td><strong>Cryogenic power (magnets)</strong></td>
<td>200 MW</td>
<td>0</td>
</tr>
<tr>
<td><strong>Cryogenic power (RF)</strong></td>
<td>$&lt;10\text{ MW}$</td>
<td>45 MW</td>
</tr>
<tr>
<td><strong>Power source output</strong></td>
<td>Design for max reliability! (cf. E. Montesinos’ talk)</td>
<td>110 MW</td>
</tr>
<tr>
<td><strong>Acc. structure input</strong></td>
<td></td>
<td>100 MW</td>
</tr>
<tr>
<td><strong>Total power to beam</strong></td>
<td></td>
<td>100 MW</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td></td>
<td>33%</td>
</tr>
</tbody>
</table>

*) preliminary estimates from [http://cds.cern.ch/record/1588120](http://cds.cern.ch/record/1588120)

EnEfficient RF Sources, The Cockcroft Institute, 3-4 June 2014
CLIC in a nutshell

- **Drive Beam Accelerator**: 2.38 GeV, 1.0 GHz
- **Delay Loop**: 1 km
- **Circumferences Delay Loop**: 73.0 m
  - CR1 146.1 m
  - CR2 438.3 m
- **Decelerator**: 24 sectors of 876 m
- **Main Linac**:
  - 12 GHz, 100 MV/m, 21.02 km
  - Booster Linac: 6.14 GeV
- **injector**: 2.86 GeV

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FCC in a nutshell

Forming an international collaboration to study:

- **pp-collider (FCC-hh)** → defining infrastructure requirements
  - ~16 T ⇒ 100 TeV pp in 100 km
  - ~20 T ⇒ 100 TeV pp in 80 km

- **e^+e^- collider (FCC-ee)** as potential intermediate step

- **p-e (FCC-he)** option

- **80-100 km infrastructure in Geneva area**
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Example: CLIC @ 3 TeV

\[ \eta_{K} = 0.75 \]

Power supplies klystrons

Drive beam acceleration

\[ F(\sigma) = 0.97 \cdot 0.96 \]
\[ \eta_D = 0.84 \]

\[ \eta_{klys\rightarrow struct\rightarrow beam} = 0.86 \]
\[ \cos \varphi_s = 0.94 \]

Drive beam power extr.

140 MW

\[ \eta_{trs} = 0.98 \]
\[ \eta_T = 0.96 \]

PETS

102 MW

(2 \times 101 \text{ kJ} \times 50 \text{ Hz})

Main linac

\[ \eta_{RF\rightarrow beam} = 0.277 \]

28 MW

Main beam

\[ \eta_{Mod} = 0.9 \]
\[ \eta_{rise} = 0.875 \]

Modulator

337 MW

293 MW

594 MW

549 MW

(45 MW less!)

MB+DB production & transport, services, infrastructure and detector

‘wall plug’

Wall plug

<table>
<thead>
<tr>
<th></th>
<th>100%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>To DB-RF</td>
<td>57%</td>
<td>57%</td>
</tr>
<tr>
<td>To DECEL</td>
<td>41%</td>
<td>48%</td>
</tr>
<tr>
<td>To PETSout</td>
<td>73%</td>
<td>73%</td>
</tr>
<tr>
<td>To Main Beam</td>
<td>28%</td>
<td>28%</td>
</tr>
<tr>
<td>Overall ( \eta )</td>
<td>4.7%</td>
<td>5.1%</td>
</tr>
</tbody>
</table>
This example ($\eta_K = 0.65 \rightarrow 0.75$) demonstrates that the R&D is worth the effort:

Possible saving per year (assuming 5500 h operation and $40$/MWh):

$$45 \text{ MW} \times 5500 \text{ h} = 250 \text{ GWh} = 900 \text{ TJ} \text{ or }$ 10 Million!
This workshop concentrates on methods to increase the efficiency of RF power sources ... so I skip this.

... but this is not the only area that affects the overall efficiency

... other areas of R&D affecting the overall efficiency:
SC-RF R&D: larger $Q_0$!

- Minimize residual resistance $R_{res}$, maximize $Q_0$ → surface physics, technology, materials, fabrication techniques, shape optimisation, operating $T$ optimisation.
- Today's investment in R&D may pay off significantly!

Example: 800 MHz 5-cell cavity for 18 MV, $P_a$ is the cryogenic power at ambient temperature. Thanks: R. Calaga, S. Claudet, P. Lebrun!

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- Superconducting RF – technology (example)
  - Push coating techniques – on Cu substrate – performance reach?
  - Coating with Nb$_3$Sn on Nb looks promising – note potential at 4.2 K!

The $Q_0$ is only a factor 0.7 worse at 4.2 K compared to 2 K, the COP is about a factor 3 better! The impact on total power consumption is significant!

Sam Posen et al. (Cornell): “RF Test Results of the first Nb3Sn Cavities coated at Cornell”, SRF 2013

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Use the spent beam: ERL

E.g.: the LHeC ERL (left) accelerates 6.4 mA of (continuous) electrons to 60 GeV. The “beam power” at collision is 384 MW – but the power consumption is <100 MW.
Recover non-used RF power: Smart RF loads

Idea 1) – reconver to DC power!

- WR-1150 waveguide
- Pressurized air at ambient temp.
- Metal enclosure at high temp. (800 °C)
- Thermal insulation

Idea 2) – use high-T loads!

- Air tight RF window
- Perforation serves as RF tight air inlet
- Tapering for low RF-reflections
- Ceramic foam
- Perforation serves as RF tight air outlet

1) http://accelconf.web.cern.ch/AccelConf/IPAC10/papers/wepd090.pdf

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Now have a interesting and constructive Workshop!

Thank you very much!