Energy Efficiency

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CERN

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Outline

• Introduction
  • Orders of magnitude – energy use – setting the scene – definition “efficiency” – EnEfficient network

• Power flow in an accelerator
  • Example PSI (special thanks to M. Seidel/PSI!)

• Is everything lost?
  • Can we recover (make good use of) the heat?

• Optimizing magnets
  • Why do they need power at all?

• RF power generation
  • The power to accelerate

• Conversion RF power → beam
  • A trade-off between accelerating gradient and efficiency

• Cryogenic system
  • How much power do you need to save power?

• Recovering the beam energy
  • The “master class” of better energy efficiency
Introduction

Orders of magnitude – energy use – setting the scene – definition “efficiency”
Why does energy efficiency matter?

• Scarcity of fossil energy – problematic nuclear power
• Volatile & unpredictable energy costs
• Increasing environmental concerns (global warming, El Niño, CO₂ emission)
• Awareness for 50 years (Club of Rome 1968, Oil crisis 1973)
• Political – societal imperative: must go towards sustainable energy!
• Also particle accelerator facilities must be conceived/built/operated with this in mind! ... in fact – they should give a good example and incite R&D!
Orders of magnitude – e.g. USA

A large fraction is wasted!

The world: $135 \text{ PWh} = 486000 \text{ PJ} = 15.4 \text{ TW} \cdot \text{a}$

https://flowcharts.llnl.gov/commodities/energy
More orders of magnitude

<table>
<thead>
<tr>
<th>generation</th>
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<tr>
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<td>1d nucl. Pow. Plant (e.g. Leibstadt, CH): 30 GWh</td>
<td>1d CLIC Linear Collider @ 3 TeV c.m. 14 GWh</td>
<td>all German storage hydropower: 40 GWh</td>
</tr>
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</table>

- wind-power, 3 MW peak
- SLS, 3.5 MW
- ITER
- CLIC, 580 MW
- car battery
- hydro storage

M. Seidel/PSI
More orders of magnitude

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<td>all German storage hydropower: 40 GWh</td>
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<tr>
<td>1d Earth/Moon System E-loss: <strong>77 TWh</strong></td>
<td>1d electrical consumption mankind: 53 TWh</td>
<td>World storage hydropower: <strong>O(1 TWh)</strong></td>
</tr>
<tr>
<td>1d sunshine absorbed on Earth: <strong>3,000,000 TWh = 3 EWh (Exa = 10^{18})</strong></td>
<td>1d total consumption humankind: 360 TWh</td>
<td>Energy storage seems not to scale up!</td>
</tr>
</tbody>
</table>

- Accelerators are in the range where they become relevant for society and public discussion.
- Desired turn to renewables is an enormous task; storage is the problem, not production!
- Fluctuations of energy availability, depending on time and weather, will be large!
**Efficiency $\eta$, definition**

- **Larger efficiency**
  - Useful energy $= \eta \cdot \text{consumed energy}$
  - Rejected energy (normally heat)

- **Smaller efficiency**
  - Useful energy $= \eta \cdot \text{consumed energy}$
  - Rejected energy (normally heat)

**Note:**
larger $\eta$ means less energy consumed, less energy wasted and smaller installation!

- Definition makes sense only for an energy-converting sub-system.
- For an accelerator facility, we need other figures of merit!
Acknowledging EuCARD² Network *EnEfficient*

EuCARD² ("European Coordination for Accelerator R&D") is co-funded by its partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453, and runs from 2013 to 2017.

- Work Package 3 of EuCARD² is the networking activity "EnEfficient", which stimulates developments, supports accelerator projects, thesis studies and similar in the areas of:
  - Energy recovery from cooling circuits,
  - Higher electronic efficiency RF power generation,
  - Short term energy storage systems,
  - Virtual power plant,
  - Beam transfer channels with low power consumption.

- More details under [www.psi.ch/enefficient](http://www.psi.ch/enefficient)
- Partners: PSI, CERN, KIT, ESS, GSI
Power flow in an accelerator

Example PSI (special thanks to M. Seidel/PSI!)
Power flow in Accelerators

**Electricity grid**
- Accelerator
  - Radio Frequency
  - Magnets
  - Vacuum etc.
- Auxiliary systems
  - Cryogenics
  - Conv. cooling, AC etc.
- Instruments
  - E.g. particle detectors

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

M. Seidel/PSI
Example: PSI – 10 MW

Ring Cyclotron 590 MeV loss \(\approx 10^{-4}\)

Power transfer through 4 amplifier chains
4 cavities 50 MHz

2.2 mA / 1.3 MW

Muon production targets

SINQ spallation source

50 MHz cavity

proton therapy centre
[250 MeV sc. cyclotron]

dimensions:
120 x 220m²
Example: PSI – 10 MW

- RF Systems: 4.1 MW
- Magnets: ≈ 2.6 MW
- aux. Systems Instruments: ≈ 3.3 MW
- Beam on targets: 1.3 MW
- Cryogenics
- Reject heat → to river, to air

Neutrons (per beam line): $10^{13}\, \text{s}^{-1} @ 10\, \text{eV} \rightarrow 20\, \mu\text{W}$
Muons ($\mu^+$ per beam line): $5 \cdot 10^8\, \text{s}^{-1} @ 30\, \text{MeV/c} \rightarrow 300\, \mu\text{W}$

M. Seidel/PSI
Often great potential for possible $\eta$ improvement:

- Light sources/synchrotrons: emittance control! – optimized undulators!
- Light sources/FEL: coherent radiation – beam energy recovery (ERL)!
- HEP colliders: low-beta insertion; crab cavities etc.
- Neutron Sources: target optimization; moderators, neutron guides etc.
- Muon Sources: target optimization; capture optics; $\mu$-cooling

**Linear collider:** $L \propto \sqrt{\frac{\delta E}{\gamma \varepsilon_y}} \cdot \frac{P_{\text{beam}}}{1E_{\text{c.m.}}}$
Example: measures to improve conversion $\eta$ of a spallation target

- **Old target design**

- **New target design**

<table>
<thead>
<tr>
<th>Implemented measure</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr cladding (instead of steel)</td>
<td>12%</td>
</tr>
<tr>
<td>More compact rod bundle</td>
<td>5%</td>
</tr>
<tr>
<td>Pb reflector</td>
<td>10%</td>
</tr>
<tr>
<td>inverted entrance window</td>
<td>10%</td>
</tr>
<tr>
<td><strong>total gain in conversion</strong></td>
<td><strong>42.3%</strong></td>
</tr>
</tbody>
</table>

Colour code: neutron density, same scale
Is everything lost?

Since all the consumed energy seems to be converted to heat:
Can we recover (make good use of) the heat?
It the heat wasted? The **Carnot** cycle

- **Heat engine ("steam engine")**
  - Heat $Q_H$ at $T_H$
  - Wasted heat $Q_C$ at $T_C$
  - Mechanical work
    $$W = \eta \cdot Q_H$$
  - Carnot: $\eta \leq 1 - \frac{T_C}{T_H}$
  - Limit when converting heat to work; large $\eta$ requires large $T_H$!

- **Reversed: refrigeration system (or heat pump)**
  - Cooling, $Q_C$ at $T_C = T_{\text{refr}}$
  - Work done
    $$W = COP \cdot Q_C$$
  - $Q_H$ heat at $T_H = T_{\text{ambient}}$
  - COP: Coefficient of performance
    $$COP \geq \frac{T_H}{T_C} - 1 \text{ (Carnot limit)}$$
  - $$Q_C = \frac{T_C P}{T_H \eta} = \frac{W}{COP}$$
In principle, heat engine could be used to produce work.

- Limit: Carnot efficiency! With $T_C = T_{ambient} = 20^\circ C$:
  - $T_H = 40^\circ C$: Carnot efficiency 6.8%
  - $T_H = 200^\circ C$: Carnot efficiency 38%
- It is more interesting to recover heat at high $T$!

Heat could be converted to higher $T$ heat with a heat pump:

- E.g.: 10 kW heat pump could pump 40 kW of heat from 40°C to 50 kW at 80°C (for heating at 80°C). $COP = 5 \leq 7.8 = \frac{T_C}{\Delta T}$

Heat could be used directly for heating:

- recovered at 50°C to 80°C: district heating
- recovered at 25°C to 50°C: green houses, food production
An increase in water temperature from 8.6°C to 13.7°C doubled the growth rate in salmon smolt.

A Kiessling, Institute of Marine Research, Matredal, NO
Optimizing magnets

Why do they need power at all?
## Low-power accelerator magnets

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

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2014 workshop on Special Compact and Low Consumption Magnet Design: indico.cern.ch/event/321880/
Example: Permanent Magnet Quadrupole Design 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.
- Pole gap = 27.2 mm
- Field quality = ±0.1% over 23 mm

Stroke = (0 ... 64) mm

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

B. Shepard/STFC
Pulsed Quadrupole Magnet

<table>
<thead>
<tr>
<th></th>
<th>Prototype Quadrupole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>80 T/m</td>
</tr>
<tr>
<td>Length</td>
<td>0.65 m</td>
</tr>
<tr>
<td>Pulse length</td>
<td>90 µs (beam 1 µs)</td>
</tr>
<tr>
<td>Peak current</td>
<td>400 kA (35 kA)</td>
</tr>
<tr>
<td>Peak voltage</td>
<td>17 kV (5 kV)</td>
</tr>
<tr>
<td>Energy @17 kV</td>
<td>65 kJ (5.6 kJ)</td>
</tr>
<tr>
<td>Inductivity</td>
<td>535 nH</td>
</tr>
<tr>
<td>Capacitor</td>
<td>450 µF</td>
</tr>
<tr>
<td>Forces</td>
<td>200 kN</td>
</tr>
</tbody>
</table>

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

The power to accelerate
Average RF power needs

**Future large scale accelerators**

- **FCC-ee:** CW, 400 MHz/0.8 GHz, $P_{RF, total} = 110$ MW
- **CLIC:** Pulsed, 1 GHz, $P_{RF, total} = 180$ MW

Pulsed, 0.7 GHz, 92 MW
Note: largest impact by RF power generation

Eventually, all is converted to waste heat!

Figure of merit: physics results per kWh!
69% instead of 70% - what does this mean?

- I had assumed above: 70% efficiency for RF power generation.
- With 105 MW RF output and at 70% efficiency, this means that 1 percentage point less means
  - Input power up from 150 MW to 152.2 MW, waste heat up from 45 MW to 47.2 MW.
  - 2.2 MW more electricity consumed (assuming 5000 h and 40 €/MWh: 10 GWh/year or 400 k€/year)
  - 2.2 MW more heat produced and wasted in the environment.
  - The electrical installation has to be larger by 1.45%!
  - The cooling and ventilation has to be larger by 4.8%!
- All the above are significant!
- Work on increasing the useable efficiency is worth every penny/cent invested!
How does a klystron work?

- A continuous electron beam is accelerated by a DC voltage and guided by magnets,
- A small power RF input causes an RF voltage in the input gap, where the velocity of the electrons will be modulated with the RF.
- Passing through a subsequent drift tube, this velocity modulation will lead to density modulation (bunching).
- The density modulation causes an RF component of the current which will excite large power in the output gap.
- With just input cavity and output cavity, the maximum possible efficiency of a klystron is 58%.
- Additional cavities (near the operation $f$ and possibly at harmonics) will help the bunching process.
- The best efficiency reached this way is around 70%.
- Space charge effects limit the efficiency – they can be reduced using many small beams rather than one big (Multi-beam klystron – MBK)

From A.S. Gilmour, Jr. “Microwave Tubes”, Artech House 1986, who took this from Microwave Tube Manual by Varian Associates, Air Force Publication Number T.0.00-25-251, 1979
MBK developments for CLIC

- Frequency: 1 GHz
- Peak power: 20 MW
- Pulse length: 150 µsec
- Rep. rate: 50 Hz
- Efficiency: >67%

Simulated klystron efficiency vs. perveance

Optimised at CERN
Recommended by industry

I Syratchev/CERN
A promising new concept (2013)

http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7194781

"Classical" bunching

New bunching with core oscillations (COM)

Output cavity

RF period, rad

Normalised velocity

Bunch phase

η<sub>RF</sub>=78.0%

Output cavity

RF period, rad

Normalised velocity

Bunch phase

η<sub>RF</sub>=89.6%

I Syratchev/CERN
Comparison of the two bunching methods

RF extraction efficiency: 86.6%;

N beams = 8
V = 180 kV
I total = 128 A

## RF power generators - efficiencies

<table>
<thead>
<tr>
<th></th>
<th>Tetrodes</th>
<th>IOTs (Inductive Output Tubes)</th>
<th>Conventional klystrons</th>
<th>Solid State PA</th>
<th>Magnetrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$ range:</td>
<td>DC – 400 MHz</td>
<td>(200 – 1500) MHz</td>
<td>300 MHz – 1 GHz</td>
<td>DC – 20 GHz</td>
<td>GHz range</td>
</tr>
<tr>
<td>$P$ class (CW):</td>
<td>1 MW</td>
<td>1.2 MW</td>
<td>1.5 MW</td>
<td>1 kW @ low $f$</td>
<td>&lt; 1MW</td>
</tr>
<tr>
<td>typical $\eta$:</td>
<td>85% - 90% (class C)</td>
<td>70%</td>
<td>50%</td>
<td>60%</td>
<td>90%</td>
</tr>
<tr>
<td>Remark</td>
<td>Broadcast technology, widely discontinued</td>
<td>new idea promises significant increase</td>
<td>Requires $P$ combination of thousands!</td>
<td>Oscillator, not amplifier!</td>
<td></td>
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**Remarks:**
- Broadcast technology, widely discontinued
- Requires $P$ combination of thousands!

**Thales RS 1084 CJ**
- $< 30$ MHz, 75 kW
- $\eta < 78\%$ (class B)

**CTF3 klystron**
- 3 GHz, 45 MW, 4.5 $\mu$s, 50 Hz, $\eta \approx 45\%$

**M. Jensen: EnEfficient RF Sources, 2014, Daresbury**

**Klystron/MBK**
- back-off for feedback
- Operating Power Level
- Courtesy of CPI

**IOT’s don’t saturate. Built-in headroom for feedback.**

**MB-IOT**
- Short-pulse excursions possible
- Long-pulse excursions possible

**CF3 klystron**
- 3 GHz, 45 MW, 4.5 $\mu$s, 50 Hz, $\eta \approx 45\%$
Conversion RF power $\rightarrow$ beam

A trade-off between accelerating gradient and efficiency
Cavity parameters: Wall losses & $Q_0$

- The losses $P_{loss}$ are proportional to the stored energy $W$.

- The tangential $\vec{H}$ on the surface is linked to a surface current $\vec{J}_A = \vec{n} \times \vec{H}$ (flowing in the skin depth $\delta$).

- This surface current $\vec{J}_A$ sees a surface resistance $R_s$, resulting in a local power density $R_s|H_t|^2$ flowing into the wall.

- $R_s$ is related to skin depth $\delta$ as $\delta \sigma R_s = 1$.
  - Cu at 300 K has $\sigma \approx 5.8 \cdot 10^7$ S/m, leading to $R_s \approx 8$ m$\Omega$ at 1 GHz, scaling with $\sqrt{\omega}$.
  - Nb at 2 K has a typical $R_s \approx 10$ n$\Omega$ at 1 GHz, scaling with $\omega^2$.

- The total wall losses result from $P_{loss} = \iint_{wall} R_s |H_t|^2 dA$.

- The cavity $Q_0$ (caused by wall losses) is defined as $Q_0 = \frac{\omega_0 W}{P_{loss}}$.

- Typical $Q_0$ values:
  - Cu at 300 K (normal-conducting): $O(10^3 ... 10^5)$, improves at cryogenic $T$ by roughly a factor 10.
  - Nb at 2 K (superconducting): $O(10^9 ... 10^{11})$
Shunt impedance

• The square of the acceleration voltage is proportional to the power loss $P_{\text{loss}}$.
• The proportionality constant defines the “shunt impedance”

$$R = \frac{|V_{\text{acc}}|^2}{2P_{\text{loss}}}.$$  

• **Attention, also here different definitions are used!**  
  (Rama Calaga used a different definition yesterday!)
• Traditionally, the shunt impedance is the quantity to optimize in order to minimize the power required for a given gap voltage.
Cavity Resonator – equivalent circuit

\[ V_{acc} \]

\[ I_G \quad I_B \]

\[ \frac{R}{\beta} \quad C \quad L \quad R \]

\[ P \]

\[ \beta: \text{coupling factor} \]
\[ R: \text{shunt impedance} \]
\[ \sqrt{\frac{L}{C}} = \frac{R}{Q}: \text{R-upon-Q} \]
Matching a source to a load

- An ideal voltage source with $V_0$ in series with an inner resistance $R_i$ is equivalent to an ideal current source with $I_0 = V_0 / R_i$ in parallel to an inner resistance $R_i$.

- The available power from this equivalent source is

$$P_{\text{avail}} = \frac{V_0^2}{4R_i} = \frac{I_0^2 R_i}{4}.$$

- When connecting this equivalent source to a real load $R = r \cdot R_i$, the power transferred to the load varies as function of $r$ as

$$P = \frac{4r}{(1 + r)^2} P_{\text{avail}}.$$

- All available power is transferred for $R = R_i$; this is called “matching”. Less power will be transferred for a mismatch.

- In RF, this is equivalent to a reflected wave; the mismatch is described with a reflection coefficient.
• Note that the generator inner impedance also loads the cavity – for very large $Q_0$ more than the cavity wall losses.

• To calculate the loaded $Q$ ($Q_L$), losses have to be added:

$$\frac{1}{Q_L} = \frac{P_{\text{loss}} + P_{\text{ext}} + \cdots}{\omega_0 W} = \frac{1}{Q_0} + \frac{1}{Q_{\text{ext}}} + \cdots.$$ 

• The coupling factor $\beta$ is the ratio $P_{\text{ext}}/P_{\text{loss}}$.

• With $\beta$, the loaded $Q$ can be written

$$Q_L = \frac{Q_0}{1 + \beta}.$$ 

• For NC cavities, often $\beta = 1$ is chosen (power amplifier matched to empty cavity); for SC cavities, $\beta = O(10^4 \ldots 10^6)$.
• While a high $Q_0$ results in small wall losses, so less power is needed for the same voltage.
• On the other hand the bandwidth becomes very narrow.
• Note: a 1 GHz cavity with a $Q_0$ of $10^{10}$ has a natural bandwidth of 0.1 Hz!
• ... to make this manageable, $Q_{ext}$ is chosen much smaller!
Beam loading

- The beam current "loads" the cavity, in the equivalent circuit this appears as an impedance in parallel to the shunt impedance.
- If the generator is matched to the unloaded cavity ($\beta = 1$), beam loading will (normally) cause the accelerating voltage to decrease.
- The power absorbed by the beam is $-\frac{1}{2} \Re\{V_{\text{acc}} I_B^*\}$.
- For high power transfer efficiency RF $\rightarrow$ beam, beam loading must be high!
- For SC cavities (very large $\beta$), the generator is typically matched to the beam impedance!
- Variation in the beam current leads to transient beam loading, which requires special care!
- Often the "impedance" the beam presents is strongly reactive – this leads to a detuning of the cavity.
3 GHz Accelerating structure (CTF3)
Travelling wave structure

shown: $\Re \{ \vec{E} \times \vec{B} \}$ (power density)

Input coupler

Output coupler

Travelling wave structure
(CTF3 drive beam, 3 GHz)

$\frac{1}{4}$ geometry shown
Full beam loading in CTF3 drive beam

Beam current 4.50 A
Acceleration 6.3 MV
Input power 30 MW
Beam power gain 28.5 MW
Output power 0 MW
Ohmic loss 1.17 MW

\[ \eta = 94.94\% \]

Remember: power to the beam is
\[ -\frac{1}{2} \Re\{V_{acc}I_B^*\} \]
Compromise: high $\eta$ vs. high gradient

- Choice for CLIC main beam
- Full beam loading – optimum efficiency
Cryogenic system

How much power do you need to save power?
What about a cryogenic system?

- Heat engine ("steam engine")
  - Heat $Q_H$ at $T_H$
  - Wasted heat $Q_C$ at $T_C$
  - Carnot: $\eta \leq 1 - \frac{T_C}{T_H}$
  - Mechanical work $W = \eta \cdot Q_H$

- Reversed: refrigeration system (or heat pump)
  - Cooling, $Q_C$ at $T_C = T_{refr}$
  - Work done $W = COP \cdot Q_C$
  - $Q_H$ heat at $T_H (= T_{ambient})$
  - COP: Coefficient of performance: the smaller the better!
  - $COP \geq \frac{T_H}{T_C} - 1$ (Carnot limit)
  - $Q_C = \frac{T_C}{T_H} \frac{P}{\eta} = \frac{W}{COP}$

This is the limit when cooling. Small $T_C$ requires large $COP$, i.e. large $W$!
Real \(\textit{COP}\) of cryogenic He refrigeration

Operating at 1.8 K, the cryoplant requires \(4 \times\) the energy as at 4.5 K.
According to BCS theory (Bardeen-Cooper-Schrieffer, 1957), $Q_0$ increases with decreasing $T$ (left plot, Nb $T_C = 9.3$ K: BCS: blue, with “residual resistance”: red).

On the other hand, even though the RF losses in SC cavities are very small, they are difficult to extract at low temperature – this is described by the COP (right plot).
The optimum operating $T$

- Combining these two curves results in an optimum operating $T$. This is why it is very interesting to investigate materials with higher $T_C$! ... and to optimize the technology in order to shift the optimum towards higher $T$.

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!
Example FCC-\(t\bar{t}\): orders of magnitude

Now we’re looking at cryogenic power
Cryogenic system optimization (1/2)

• In the example above (FCC-tt), 20% of the total power for the RF system is used to cool the cavities – this was already a result of an initial optimization.

These results allowed to converge to baseline parameters! They also indicate:

• With present day technology, to contain cryogenic losses, fields should remain moderate.
• 4.5 K or 2 K operation – no significant difference at 800 MHz, 10 MV/m.

S. Aull, O. Brunner, A. Butterworth, R. Calaga, N. Schwerg, M. Therasse et al.
Cryogenic system optimization (2/2)

- But this also indicates what significant improvement could be obtained when $\text{Nb}_3\text{Sn}$-like (A15) materials can be successfully used!!!
State of the art: High $Q_0$, $N_2$ doping

A. Grasselino, SRF2013 & M. Liepe SRF2015
Recent results with Nb$_3$Sn coated cavities

Small thermal gradients give better performance

This cavity exceeds LCLS-II spec by a factor of 2

Daniel Hall, SRF 2015, Whistler, CDN
Recovering the beam energy

The “master class” of better energy efficiency
Recovering the energy from the beam: The concept

One could use a waveguide and reuse the RF power!
In the CLIC scheme, 90% of the drive beam power is recovered (to produce the RF power for the main beam)
The CLIC power source idea

Long RF Pulses

- $P_0$, $f_0$, $\tau_0$
- to accelerate the drive beam

98% RF $\rightarrow$ beam

beam manipulation

- long bunch train, moderate current, 1 GHz

Short RF Pulses

- $P_A = P_0 \times N$
- $\tau_A = \tau_0 / N$
- $f_A = f_0 \times N$
- extracted from recombined drive beam

90% beam $\rightarrow$ RF

next step from here: the ERL

short bunch train with 12 x current, 12 GHz
Natural next step: The Energy Recovery Linac

... stay tuned for A. Jankowiak’s lecture tomorrow morning
Thank you for your interest!