ERLs and Sustainability

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For the ERL European Roadmap Panel

What is Sustainability?

- Sustainability has been defined in various ways:

  "The quest for sustainability involves connecting what is known through scientific study to applications in pursuit of what people want for the future" [1]

  "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2]

  "The property of being environmentally sustainable; the degree to which a process or enterprise is able to be maintained or continued while avoiding the long-term depletion of natural resources" [3]

- But my favorite quote is from a climate activists who wanted a more positive word

  "If you asked a couple about their marriage and they replied that it was 'sustainable', that wouldn't be very positive!"

  "Transformative" would be better

[1] Harrington, Lisa M. Butler (2016). *Papers in Applied Geography*. **2** (4): 365–382
[2] United Nations General Assembly (1987) *Report of the World Commission on Environment and Development: Our Common Future*. Transmitted to the General Assembly as an Annex to document A/42/427 – Development and International Co-operation: Environment
[3] Oxford Dictionary

Accelerators

- By their very nature, accelerators alone are not sustainable
- Sustainability for accelerators has three axes:
  - Offset the power usage by building an associated green power station
    - ESS is the leader with its own wind farm planned in the Baltic Sea, on-site solar systems, and a biomass conversion facility that also produces fertilizer
  - Reuse waste heat and water
    - Again, ESS is the leader with hot water supplied for commercial and residential heating, and the production of biogas
  - Minimize the power and water required by improving efficiency in every way possible
    - Minimizing the power required is being addressed in all new accelerator projects
    - Component efficiencies are being adopted by everyone
- ERLs have an additional advantage by recovering the energy in the beam after use
  - This will be the subject of my talk ("The Good") but I will also point out problems that still need to be solved ("The Bad") and those that may have no solution ("The Ugly")

ERL HISTORY AND ACHIEVEMENTS

1965 M. Tigner
"A possible apparatus for electron
cl
be

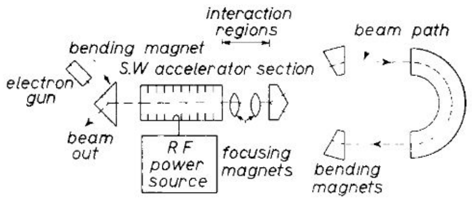


Fig. 3.

1987 High Energy Physics Lab
Stanford University
SRF cavities, pro principal experiment

1987 Los Alamos
FEL-operation, nC, coupled acc/dec cavities

2000
Jefferson Lab
"Front End Test"
SRF, first CW recovery

2002
Jefferson Lab
"IR-Demo"
SRF, 5mA, 48MeV, 2.1kW beam power IR
2003
CEBAF, 1 GeV, single turn
2007 Upgrade:
9mA, 150MeV
1.1MW beam power with ~300kW RF power

2002 JEARI, Japan
FEL, SRF, 700kW beam power

2004 BINP, Russia
FEL-operation
normal conducting RF,
30 mA
2007: 4-passes

2005 Daresbury Lab, GB
"Alice", SRF, 26MeV, versatile 10-year u program

2013 KEK, Japan
"cERL", prototype ERL light source

2020, Cornell
CBETA, FFAG-arc
4-pass ERL
(80mA injector, ε = 0.3mm mrad)

under construction:
MESA, Germany
particle physics application

PERLE, France
Test facility (FCC-ee)

bERLinPro, Germany
SRF/ERL technology test facility

The Good, the Bad and the Ugly

- The Good
  - Beam energy recovered
- The Bad
  - HOMs (beam energies cancel, HOMs add)
  - Return arcs (synchrotron radiation loss)
  - RF mismatching
- The Ugly
  - Cryogenic Power
- For ERLs to be widely adopted, enhance “The Good” and reduce “The Bad” and “The Ugly”

Where ERLs are Beneficial

- The beam quality in an ERL is defined by the Injector
  - Extremely small emittances are possible, optimum for FELs
- Electron cooling of proton beams requires high currents – energetically unacceptable without energy recovery
  - Example: EIC electron cooling requires 100 mA @ 150 MeV = 15 MW without energy recovery
- Next generation Electron-Ion Colliders (LHeC, FCC-eh) also require high electron currents – energetically impossible without energy recovery
  - Example: LHeC requires 20 mA @ 50 GeV = 1 GW without energy recovery

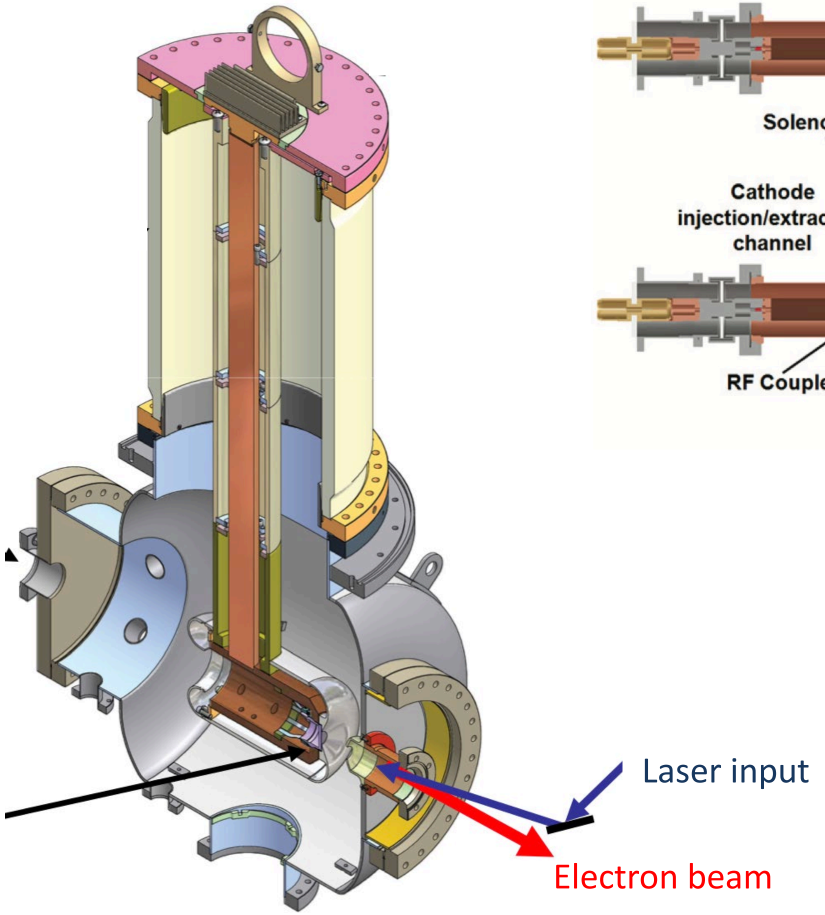
Advantages of ERLs

- Accelerating an electron beam using the energy of the spent beam with practically no losses is a unique feature of ERLs
- Overall efficiency of the process is extremely high
- Advantages
  - Reduction in the RF power needed for acceleration
  - Smaller RF sources and their associated power transformers
  - Less electric power and water cooling required
  - Reduced operating costs as well as a reduced carbon footprint
- Requirements
  - SRF cavities which maintain the accelerating gradient with very low losses
  - Careful control of the high beam power
    - Design, diagnostics, algorithms

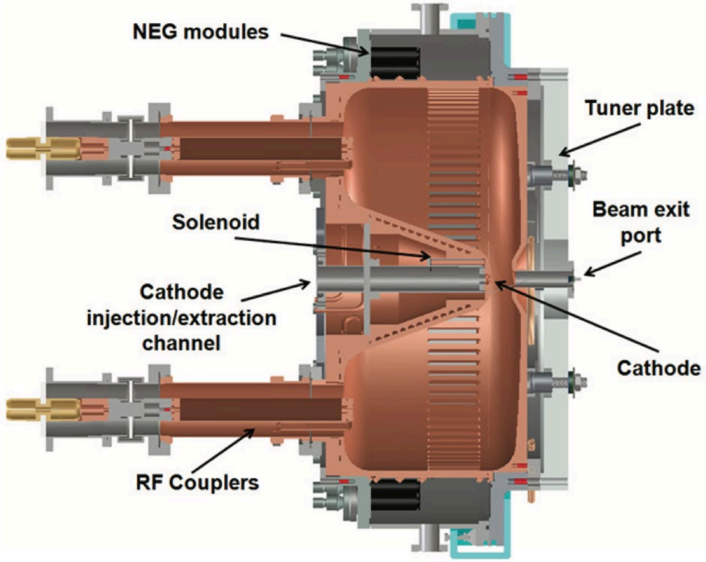
Gun

- Gun technology is improving regularly
- DC guns are inherently efficient, but high-current beams still pose problems
- Room temperature RF guns are less efficient as RF losses are unavoidable
- SRF guns have low RF losses, but at cryogenic temperature, so will be relatively inefficient
  - Likely to have the best emittance characteristics
- Since the gun is a small part of the power load, most effort is directed to high bunch charge and small emittance

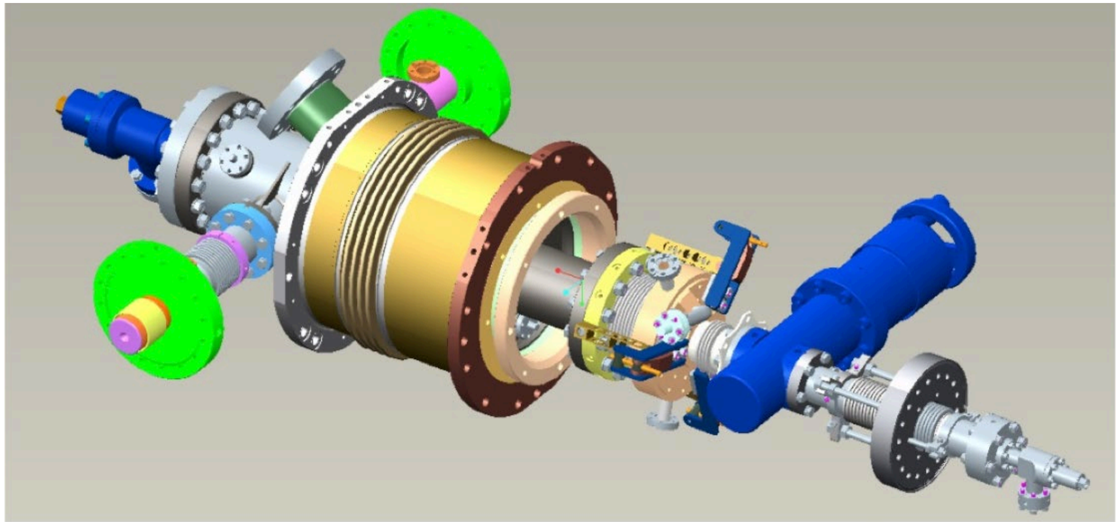
Electron Guns



Cornell DC Gun



LBNL RF Gun



bERLinPro SRF Gun

Injector

- The injector operates in a regime where the velocity changes with energy for longitudinal bunching
- The beam energy from the injector cannot be recovered and ends up in a dump
  - The injector should have as low an energy as possible, consistent with the beam quality required
- The RF sources in an ERL injector require significantly higher power than in the ERL itself
- Example of an ERL light source
  - Injector beam energy = 5 MeV
  - Injector current = 1 Amp
  - Injector beam power = 5 MW
- High energy colliders require cascaded ERLs to keep the energy ratio reasonable

- The spent beam at the dump has an energy equal to the injector
- The energy is usually below the neutron production threshold (~ 8 MeV)
  - Significant reduction in the shielding needed

Higher Order Modes (HOMs)

- Recovering the energy of the beam is the hallmark of ERLs
- But HOMs from the accelerating and decelerating beams are additive
- ERLs are most efficient with high-power beams
  - HOM power dissipation must be minimized by cavity design
  - Heat must be brought out of the cavity to a higher temperature
    - Thermal isolation should be maintained

- Only possible solution is intra-bucket energy recovery*
  - Brings other problems!

*Erk Jensen:
https://indico.cern.ch/event/1040671/contributions/4371231/attachments/2258316/3834412/Energy%20Recovery%20%26%20Sustainability.pptx

ERLS Require Precise RF Matching

- To minimize RF losses, it is important to properly match the cavity to the power source under all the different operating conditions
- Variable fundamental power couplers are needed
  - Power must be delivered to the cavity during start-up, which requires a large coupling coefficient
  - Power required by the cavity drops to a small value during steady-state operation, so a small coupling constant is preferred
- Variable couplers are used to avoid large reflected (and, therefore, wasted) power
- Traditionally, tuners that squeeze the cavity are used to match the frequency of superconducting cavities to the power source
  - These are relatively slow (seconds)
- Piezo-electric tuners have been used to make faster adjustments (up to 3 kHz)

Fast Reactive Tuners

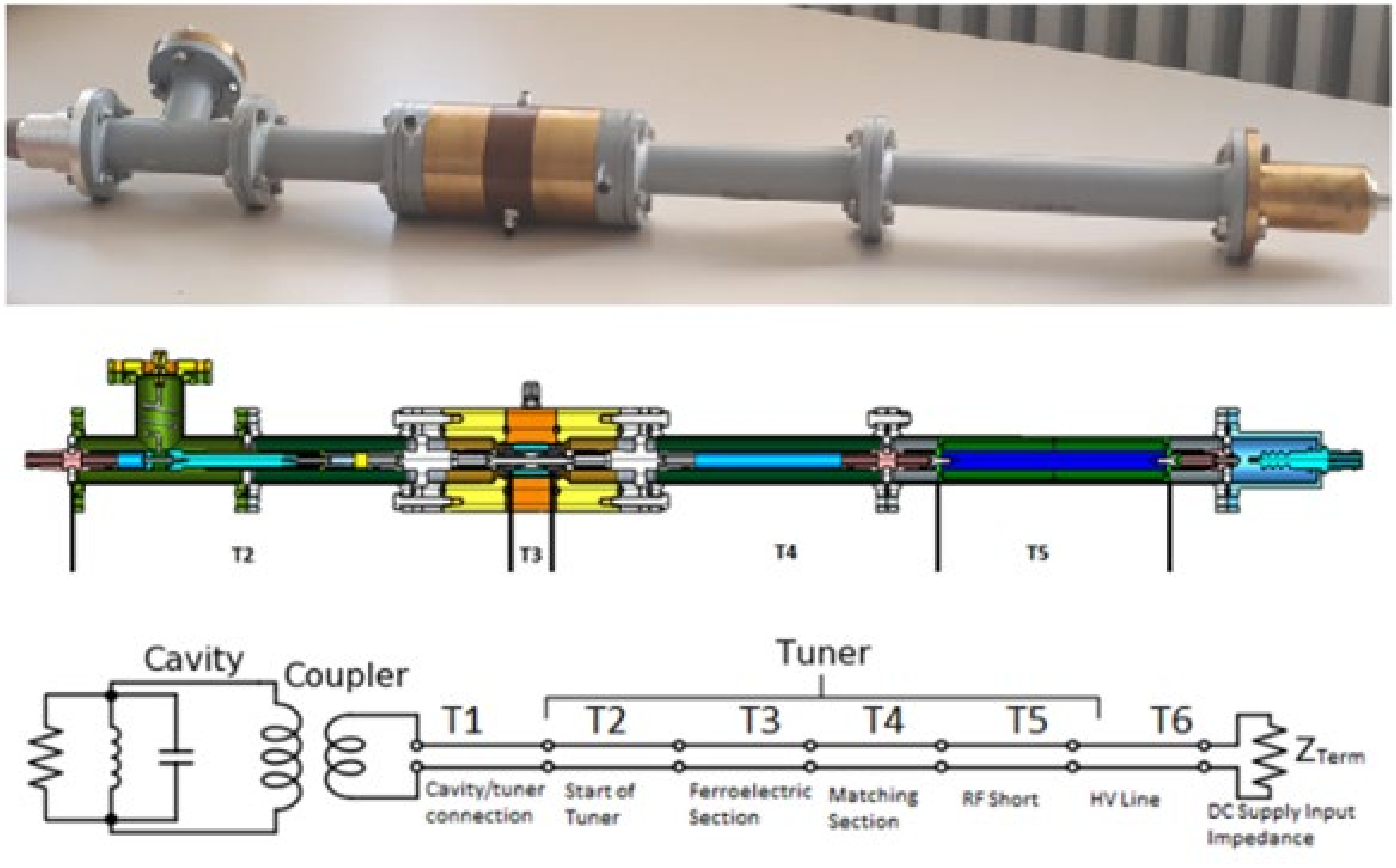
- The recent development of Fast Reactive Tuners (FRTs) is a big step forward for ERLs
- The change in tuning is achieved using an external magnetic field to change the permittivity of a special ceramic
- No moving parts so the FRT can respond to fast transients (up to 10MHz)
- Simulations show that the reflected RF power can be reduced almost to zero
- This will be tested in a cryomodule at bERLinPro

- For ERLs, this capability is a game-changer!

- Shout-out to Nick Shipman who has spearheaded this development*

* https://indico.cern.ch/event/835947/contributions/3609044/attachments/1932966/3202118/Shipman_Electrons_For_the_LHC.pdf

Prototype Fast Reactive Tuner

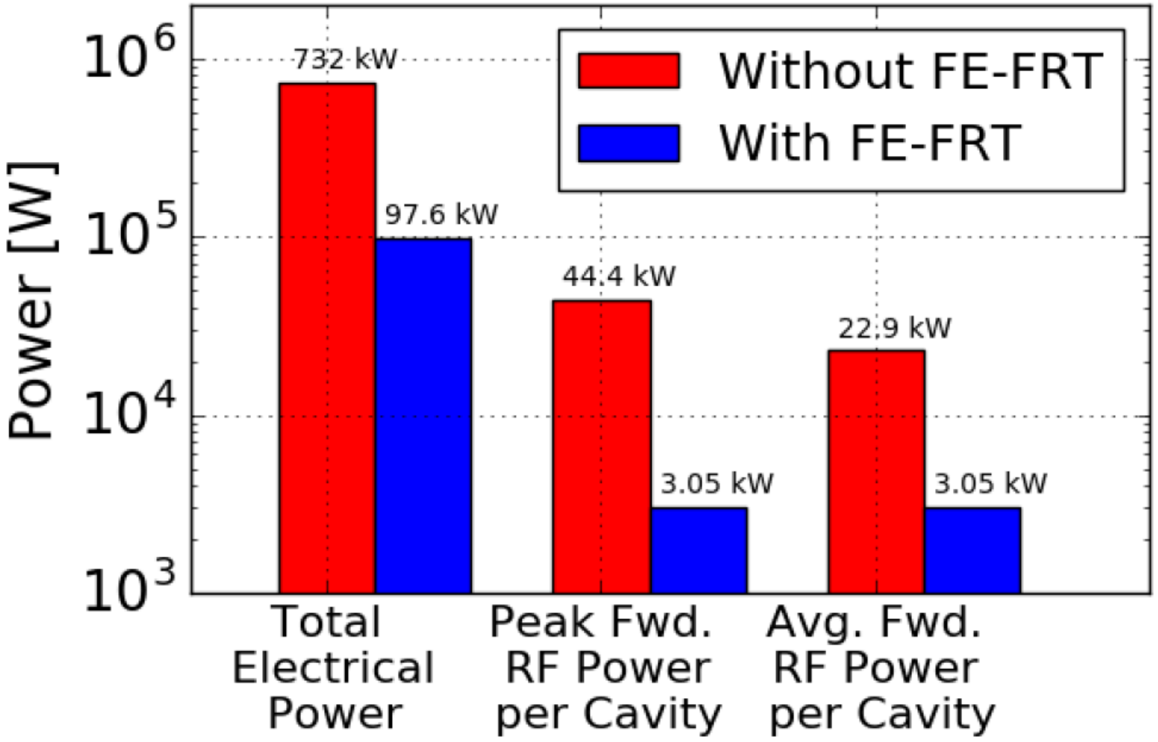


Prototype Tuner, 3D model and transmission line model.

- No moving parts
- Outside cryomodule
- Continuous tuning range
- No need to generate a large magnetic field
- Intrinsic speed < 10 ns
- Low losses/small increased bandwidth

Case Study - PERLE

$$P_{RF} = \frac{V_c^2}{4 R/_Q Q_L} \frac{\beta + 1}{\beta} \left[1 + \left(2 Q_L \frac{\Delta\omega_\mu}{\omega_0} \right)^2 \right]$$



- Peak power per cavity 44.4 kW → 3.05 kW
- Total Electrical Power 732 kW → 97.6 kW

- Calculated results of the application of Fast Reactive Tuners to PERLE
  - Reduction of total RF power by a factor of 7.5 from 732 kW to 97.6 kW

Note log scale!

- https://indico.cern.ch/event/835947/contributions/3609044/attachments/1932966/3202118/Shipman_Electrons_For_the_LHC.pdf

FRTs - Why Now?

- Suitable material only recently developed*
  - $BaTiO_3$ - $SrTiO_3$ solid solution (BST)
- Added linear (non-tunable) Mg-based ceramic component**
- Enhanced tunability with low losses

- Sustained R&D program at CERN, and commercial support from Euclid Techlabs

- This is what it takes to solve the various R&D challenges!

* E. Nenasheva et al., Journal of European Ceramic Society, vol. 30, pp.395–400, Jan. 2010.

** A. Kozyrev et al., Appl.Phys. Lett., vol. 95, pp. 1–5, Jul. 2009

Power dissipation in an SRF Cavity

- The dynamic heat produced in an SRF cavity is usually written as:

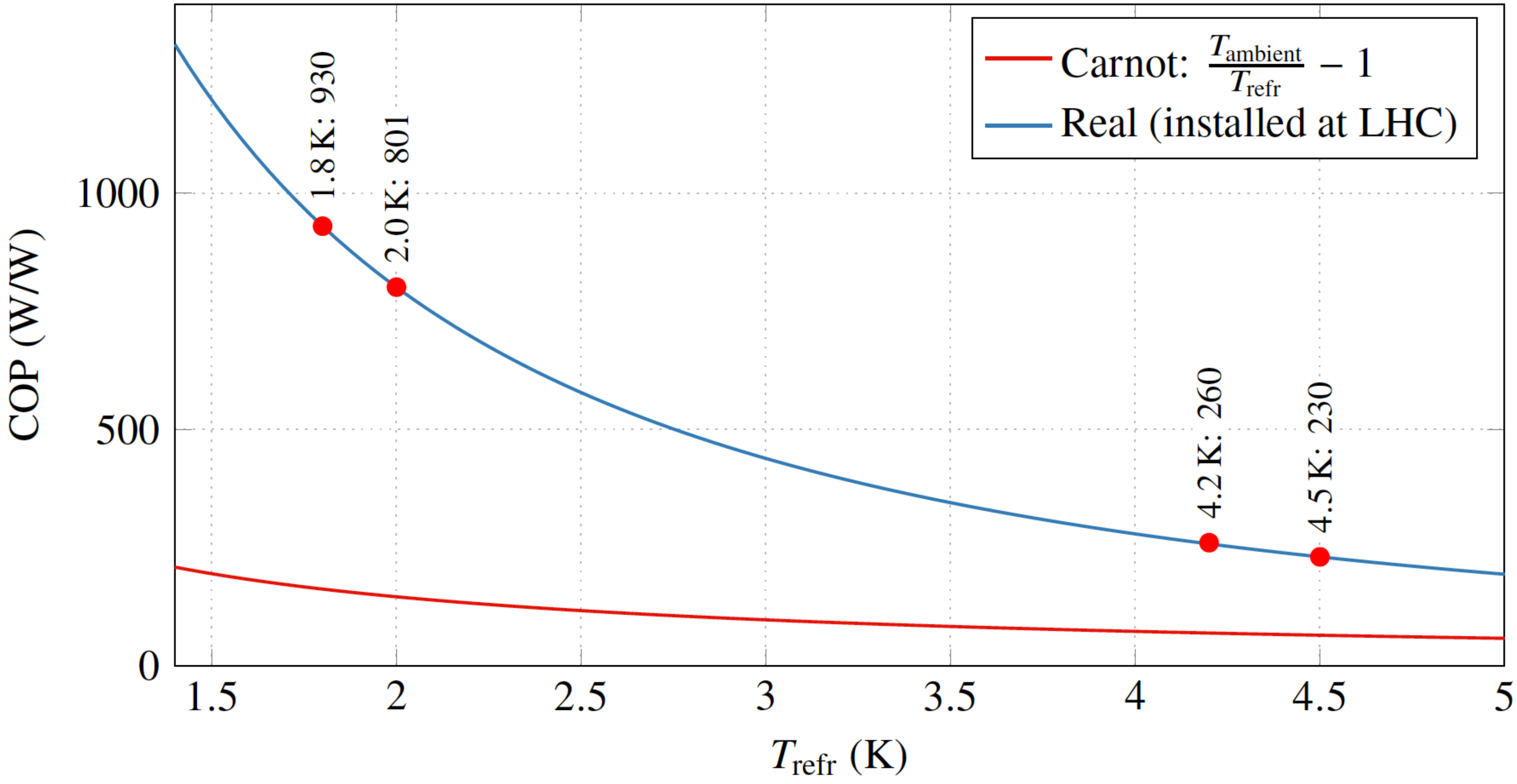
$$P_{cryo} = V^2 * D \,/\, [(R/Q) * Q_0]$$

- Where:
  - P_{cryo} is the power deposited at cryogenic temperature in the cavity
  - V is the accelerating voltage across the cavity
  - *D* is the duty factor (=1 for CW)
  - (R/Q) is a geometrical constant of the cavity, usually 100 – 1,000 for SRF cavities
  - Q_0 is the quality factor of the cavity

- The power is dissipated at cryogenic temperature so we need to examine the whole cryogenic system, not just the cavities

Coefficient of Performance

- Coefficient of performance (COP) as a function of temperature of a cryogenic system for the LHC [thanks to P. Lebrun]



Efficiency improved by factor 3.5 between 2K and 4.5K

Electrical Power to Cool an SRF Cavity

- COP is the ratio of the electrical power input to the cryoplant to the cooling at cryogenic temperature
  - ~ 800 @ 2K
  - ~ 230 @ 4.5K
  - In a typical plant, additional power is required for the cryo-support systems (e.g., guard vacuum, purifier), cryo-controls, and conventional utilities (e.g., cooling water, instrument air)
  - These items are not included in the COP
    - Let ε be the fraction of the cryoplant cooling that is delivered to the SRF cavities
- The power required from the grid P_{rt} to cool an SRF cavity is then

$$P_{rt} = (COP/\varepsilon)*V^2*D \,/\, [(R/Q)*Q_0]$$

A Useful SRF Energy Metric for SRF

- Instead of considering the cavity and cryoplant separately, we should optimize the system
  - Need a metric that includes all of the factors
- Define an SRF Energy Metric Ξ (nΩ)

$$\Xi = [(R/Q)*Q_0] \times 10^{-9} \,/\, (COP/\varepsilon)$$

- The electrical power (P_{rt}) at room temperature needed to sustain an accelerating voltage V is then

$$P_{rt}\ (kW) = V(MeV)^2 * D \,/\, \Xi$$

- So Ξ acts like the resistance in Ohms Law

Ξ (Xi)

- Ξ is the 14th letter of the Greek alphabet
- It is not pronounced like the Chinese Xi
- Nor is it related to Tai Chi
- It is pronounced like Banksy

Why Have an SRF Energy Metric?

- Gigi Ciovati explained it well:
- "How many solar panels would be required to operate a cavity at the required accelerating gradient in a given accelerator?
- Example: a C100 cavity at nominal 18 MV/m, $Q_0=8x10^9$, Energy Metric ➔ 58 solar panels"
  - Requires sunlight 24 hours per day

- Compare my house with two air conditioning units
- 24 solar panels provide ~95% of electricity
  - Averaged over night, rain, cloud, etc

How can we improve Ξ?

$$\Xi = [(R/Q)^*Q_0] \times 10^{-9} / (COP/\varepsilon)$$

- R/Q can be improved with low loss cavities
  - Cavity shapes have been carefully optimized already, and further significant progress is unlikely
- Q_0 has seen enormous progress recently, there may be more to come
- COP has been improved about as far is is possible
  - But COP only measures the output of the cryoplant compared to the input power
- ε covers a long list of things which are often ignored
  - ε includes the power required to remove the heat
    - Worst - cooling towers
    - Better – cooling ponds as at Fermilab
    - Best – re-use the heat as at ESS

Cryogenic Distribution Improvements

- ε also includes the losses in the transfer lines, cooling of the shields
- Possible improvements:
  - Increase the cryogenic efficiency by placing the heat exchangers in the tunnel instead of in the cryoplant
    - This results in a 7% improvement in cryogenic efficiency as measured at SNS
  - Increase the cryogenic efficiency by bringing the high pressure stream of the sub-cooler heat exchanger out to the JT valve and then back into the heat exchanger
    - This increases the cryogenic efficiency by an additional 7% as at FRIB

- There is another hidden inefficiency
  - The cryoplant is usually over-dimensioned to cover possible low Q_0 or future expansion
  - Most cryoplants lose efficiency when operated below the design point
  - Solution – use the Ganni cycle where the efficiency stays constant down to ~30% of the design point

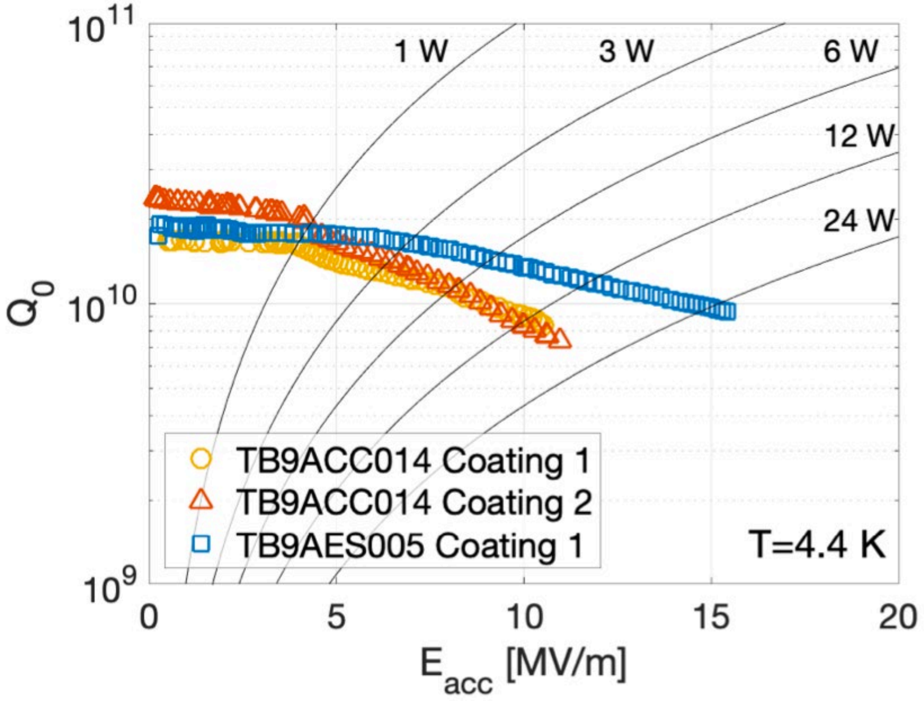
Comparison of 4.5K and 2K Operation

- Compare identical cavity shapes (R/Q is the same)
- Assume that ε is the same for both cases
- Then to be beneficial

$$(Q_0)_{4.5} \text{ must be} > COP_{2.0}/COP_{4.5} * (Q_0)_{2.0}$$

$$(Q_0)_{4.5} \text{ must be} > (Q_0)_{2.0} / 3.5$$

- Example for CW 1300 MHz 9-cell cavities
  - Best Q_0 at 2K is 2.7 x 10^{10} at gradient 16 MeV/m * (in cryostat)
  - Best Q_0 at 4.4K is 1 x 10^{10} at gradient 15 MeV/m ** not in cryostat
- Nb_3Sn cavities are approaching useful Q_0



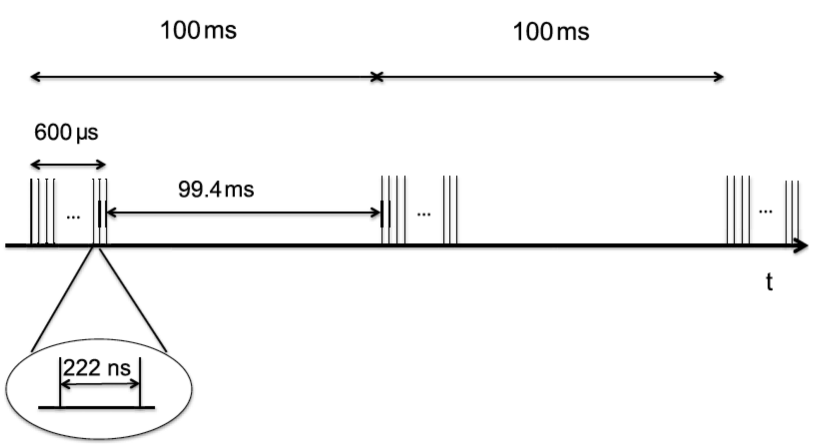
Vertical test performance of Nb3Sn coated 9-cell cavities TB9ACC014 and TB9AES005 at 4.4 K**

* D. Gonella et al, https://indico.desy.de/event/32219/contributions/116543/attachments /71215/90891/Gonnella%20HE%20R%26D%20Presentation.pdf

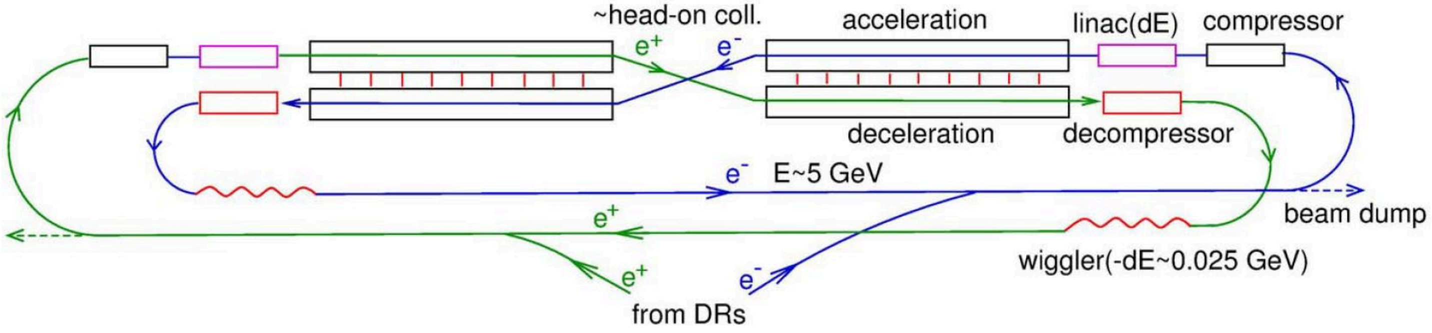
** Sam Posen et al https://arxiv.org/pdf/2008.00599.pdf

Duty Factor *D*

- There are three regimes:
- CW is used for the majority of ERLs
- Pulsed is used for high gradient cavities
  - Example: RF pulse rep rate of the XFEL is 10 Hz
  - Static losses tend to outweigh dynamic losses
- “Gated” RF
  - CERL* proposes 2 seconds RF on, 4 seconds RF off
  - This has never been tried
  - Cornell is seeking funding to test the concept on the CBETA Injector module

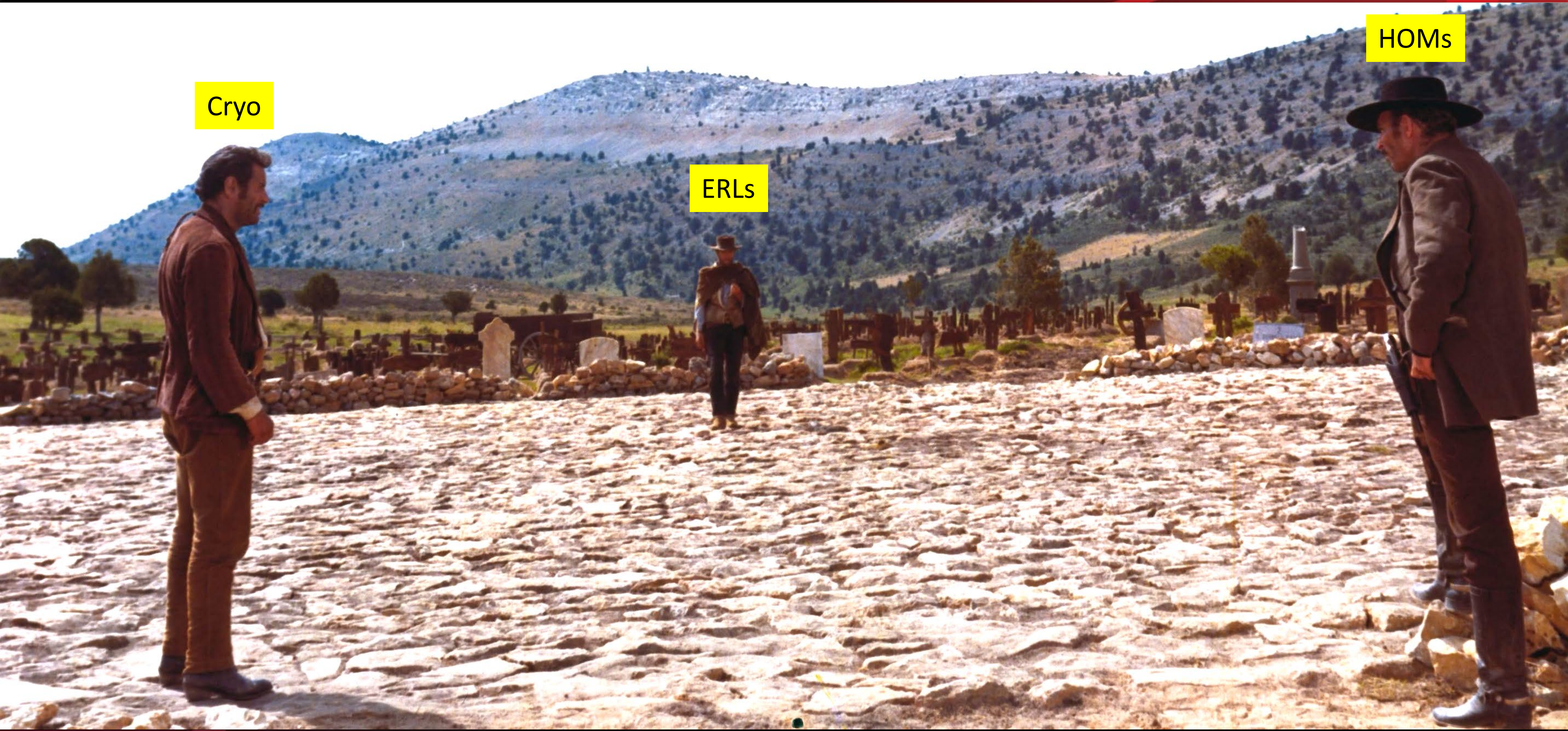


Twin LC with the energy recovery



* V. Telnov, A high-luminosity superconducting twin e+e- linear collider with energy recovery, Journal of Instrumentation 16 (2021) P12025

Thankyou



Back-Up

Floating Pressure

- The “Ganni Cycle” is an improvement in cryogenic plant efficiency
- A cryogenic plant operates using many stages of: compression of the gas; removal of the heat; and decompression of the gas, which lowers the temperature
- Each of these intermediate stages has an input pressure and an output pressure
- The conventional wisdom was that these input and output pressures should be fixed and the compressors/ decompressors should be optimized for these fixed pressures
- In the “floating pressure” scheme, invented by Rao Ganni, the pressures at the interfaces between the different stages of the cooldown are allowed to float
- This increases the plant efficiency, because optimizing each stage is less efficient than optimizing the overall system
- What was initially surprising was that the intermediate pressures would naturally stabilize at the optimum values; this is the so-called “floating pressure” principle
- Note that this is only valid for cooling down to 4.2K

The Ganni Cycle

- The full Ganni Cycle incorporates other efficiency improvements
- Together, the cycle allows the efficiency of the plant to remain at the same high level from 100% down to 30% load
- Since a large cryoplant must be sized for the maximum load plus a safety margin, most existing plants are operated with reduced efficiency; this is not the case for the Ganni Cycle
- At this time, the Ganni cycle is patented and licensed to Linde, one of the two European Cryoplant constructors; the other, Air Liquide, declined