Energy Recovery & Sustainability

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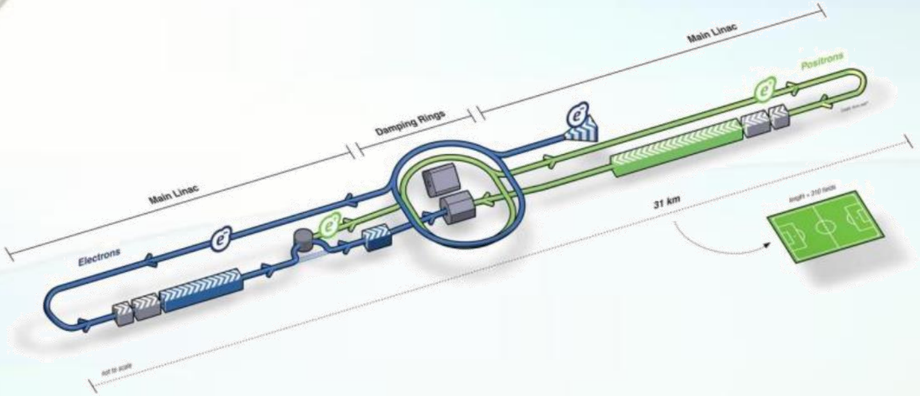
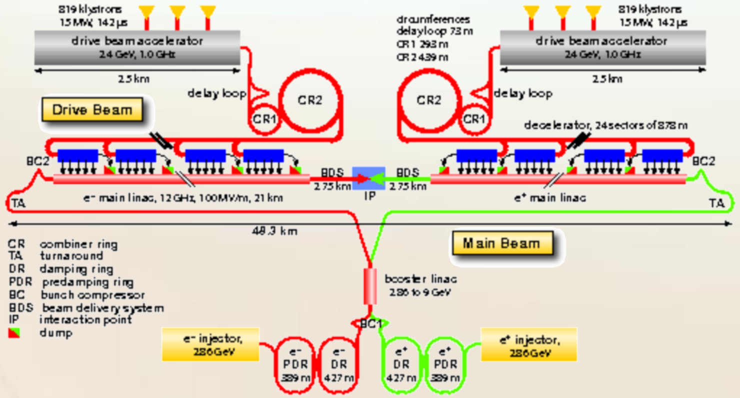
CERN

Symposium on Energy Recovery Linacs

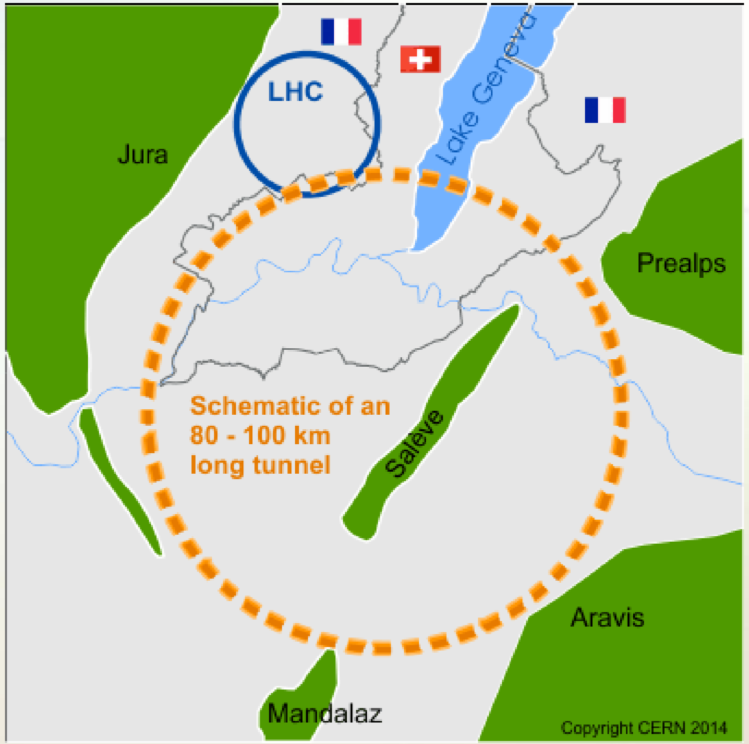
Average power needs for future HEP projects



ILC 0.25 TeV: Pulsed, 1.3 GHz, $P_{\text{RF,total}} =$ **88 MW + cryo!**



CLIC 3 TeV: Pulsed, 1 GHz, $P_{\text{RF,total}} =$ **180 MW**



FCC-ee: CW, (0.4 & 0.8) GHz, $P_{\text{RF,total}} =$ **105 MW + cryo!**

Total energy need: $\mathcal{O}(1 \ldots 3\ \text{TWh/y})$!

Obligation and Opportunity

- The size of these HEP facilities is $\mathcal{O}(200 \ldots 600\ \mathrm{MW})$ or $\mathcal{O}(1 \ldots 3\ \mathrm{TWh/y})$, comparable to the energy need of a small town!
- For facilities like these, we have the obligation to significantly improve energy efficiency – otherwise society will just not approve them. It is a must!
- Obligations:
  - Be aware and make aware of efficient energy use and energy conversion
  - Make good design choices to minimize "waste"!
  - Design and use energy-efficient equipment
  - Monitor and plan energy use (Energy Management)
  - Recover otherwise "wasted" energy!

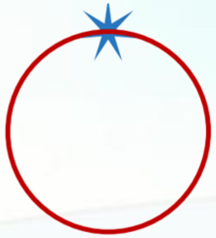
On the other hand, the size of HEP facilities enables & encourages dedicated R&D.

- Benefits:
  - Concepts and designs developed to improve energy efficiency in accelerators will be relevant for society at large.
  - Significant savings in operational cost.

Ongoing concerted effort to improve energy efficiency

- EuCARD² ("*European Coordination for Accelerator R&D*"), 2013 – 2017, co-funded by EC (FP7), Grant Agreement 312453.
  - Work Package 3 of EuCARD² was the networking activity "***EnEfficient***", www.psi.ch/enefficient, which stimulated developments, supports accelerator projects, thesis studies etc., in different areas of energy efficiency of accelerators.
- ARIES ("*Accelerator Research and Innovation for European Science and Society*"), 2017 – 2021, cofounded by EC (Horizon2020), Grant Agreement 730871.
  - In continuation of EnEfficient, Work Package 4 of ARIES is the networking activity "Efficient Energy Management (EEM)", www.psi.ch/eem, which coordinates efforts on energy efficiency.
- iFAST ("*Innovation Fostering in Accelerator Science and Technology*"), started in 2021, co-funded by EC (Horizon2020), Grant Agreement 101004730.
  - Work Package 11 of I.FAST is "Sustainable concepts and Technologies" is studying sustainable concepts for research infrastructures, combined with the realization of high-efficiency klystrons jointly with industry
- Workshop Energy for Sustainable Science … along with a series of "*Energy for Sustainable Science*" workshops (the most recent, 5th workshop: https://indico.psi.ch/event/6754/)

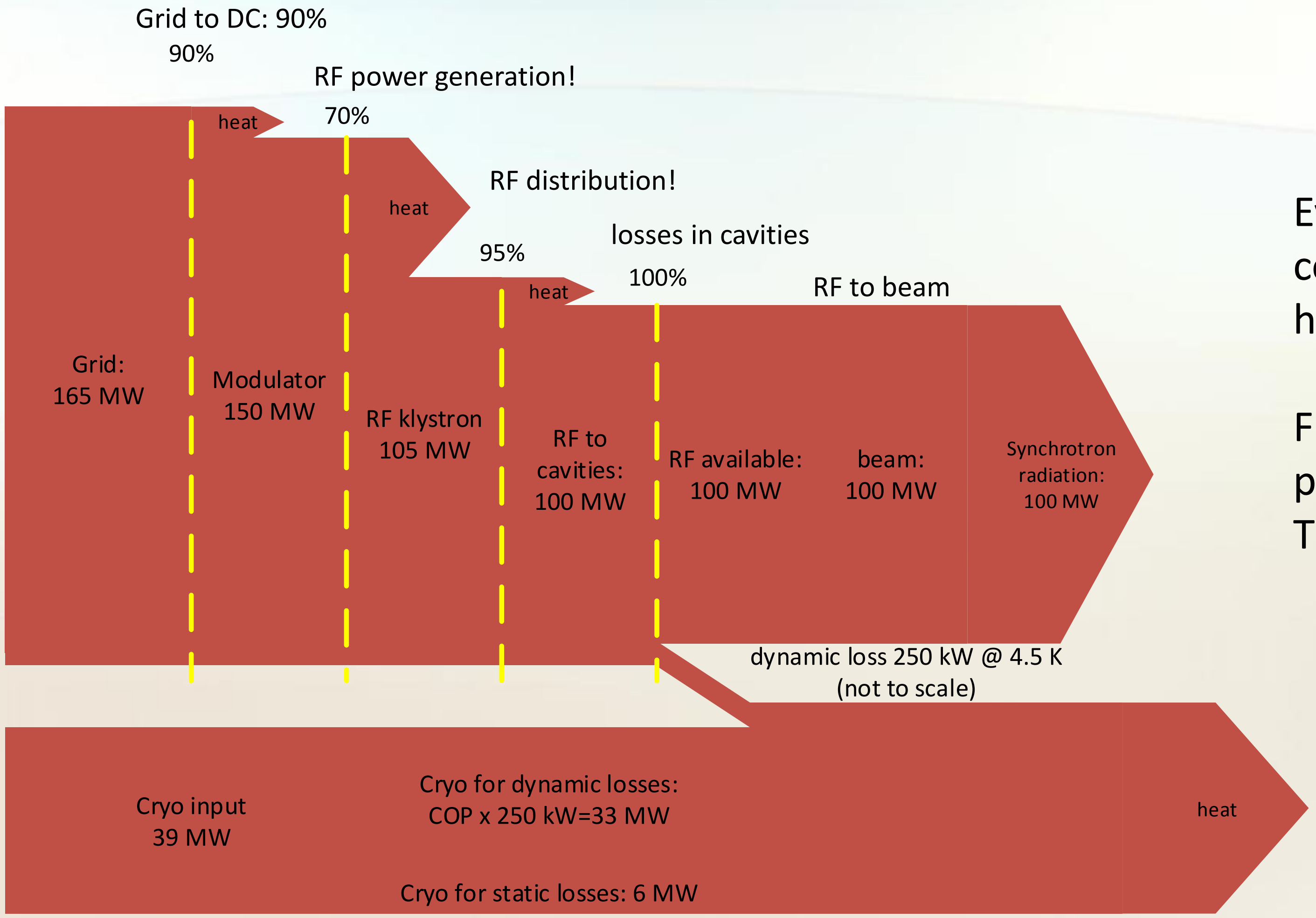
Storage ring collider vs. Linear collider



- Pros:
  - Perpetual recirculation after initial fill
  - Beam energy is stored (attention SR!)
  - Virtual beam power can be very large (e.g. LHC: beam power 0.5 A × 7 TV = **3.5 GW!**
  - Can have >1 interaction region.
- Cons:
  - Synchrotron radiation $\propto E^4$ - a steep limitation! Requires large power to compensate SR losses.
  - Beam-beam effects limit bunch intensity (luminosity)

- Pros:
  - Beam is used only once and can be of high quality (tiny emittance and size)
  - No systematic limitation by SR
- Cons:
  - Beam disposed of at full energy (large dump)
  - Energy efficiency!
  - Only 1 IR

Example FCC-ee ($t\bar{t}$): Sankey diagram

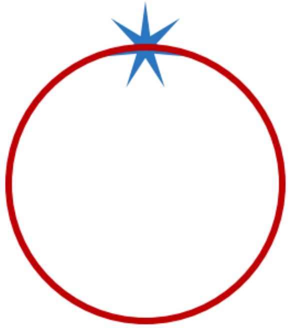


Eventually, all is converted to waste heat!

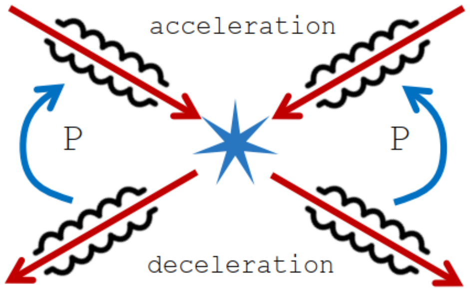
Figure of merit: physics results per TWh!

Collider concepts in comparison

Ring Collider
beams circulate



ERL
power re-cirulated



Linear Collider
beams collide once

- beam used once
- but power recirculated
- ambitious collision parameters lead to low beam intensity

→ **overall low energy consumption, but higher initial investments**

attainable collision parameters (design reports)

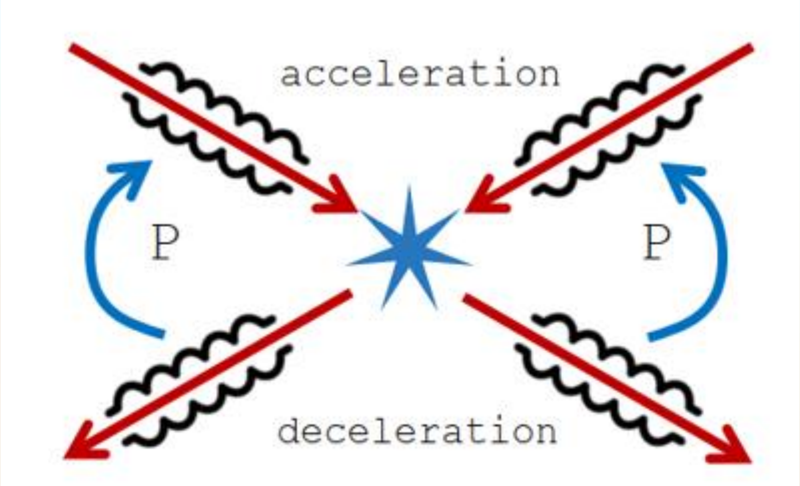
	$FCC\text{-}ee_{365GeV}$	$CLIC_{380GeV}$
σ_x [nm]	38‘000	150
σ_y [nm]	68	3
σ_z [µm]	2‘500	70
N [10^9]	230	5,2
f_b [kHz]	17,6	147
P_b [MW]	985	2.8

iFAST

M. Seidel @ I.FAST Kick-off meeting, May 2021: https://indico.cern.ch/event/1024993/contributions/4312541/

ERL: the best of both worlds

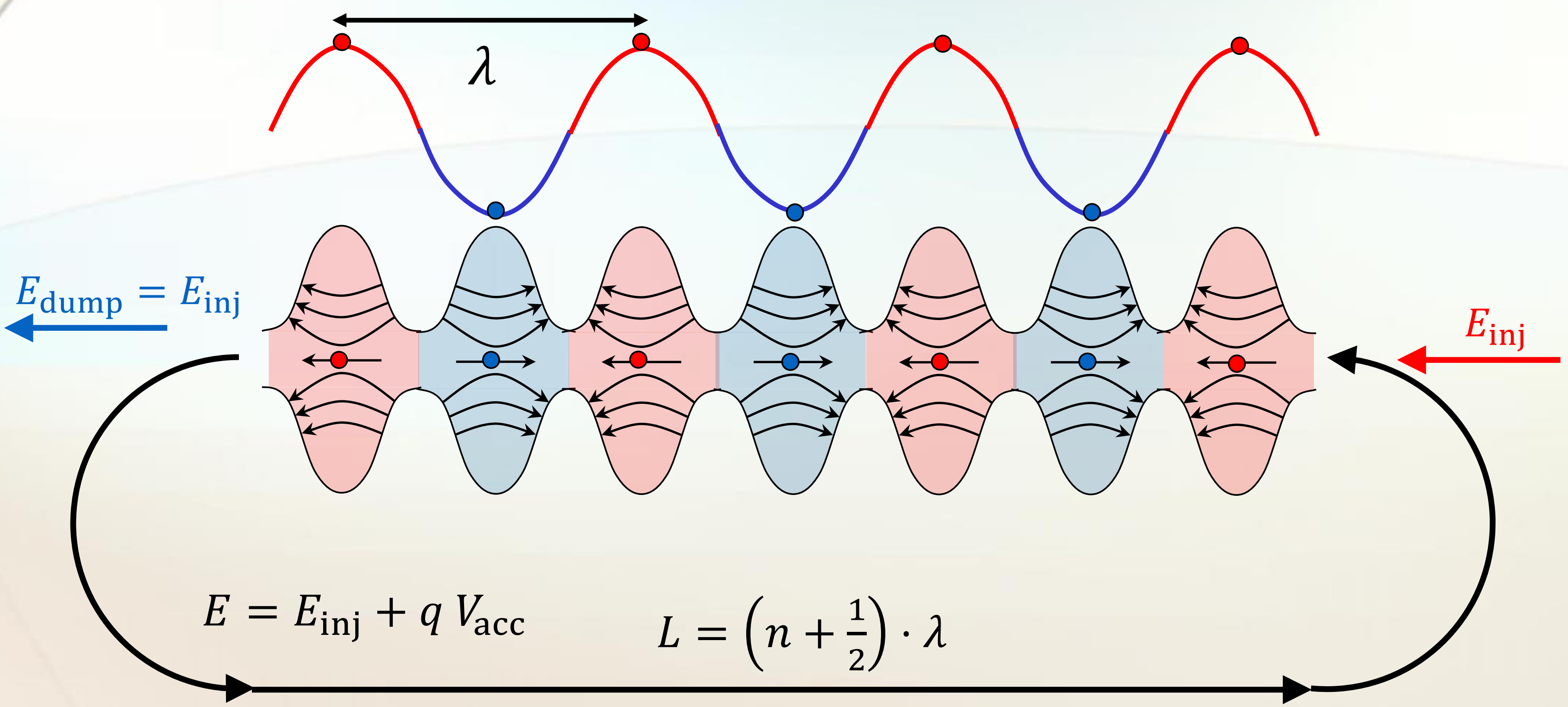
- This is the hope: Beam quality like in a linac, but full recovery of beam energy.



… stolen from Oliver's presentation

How does energy recovery work ?

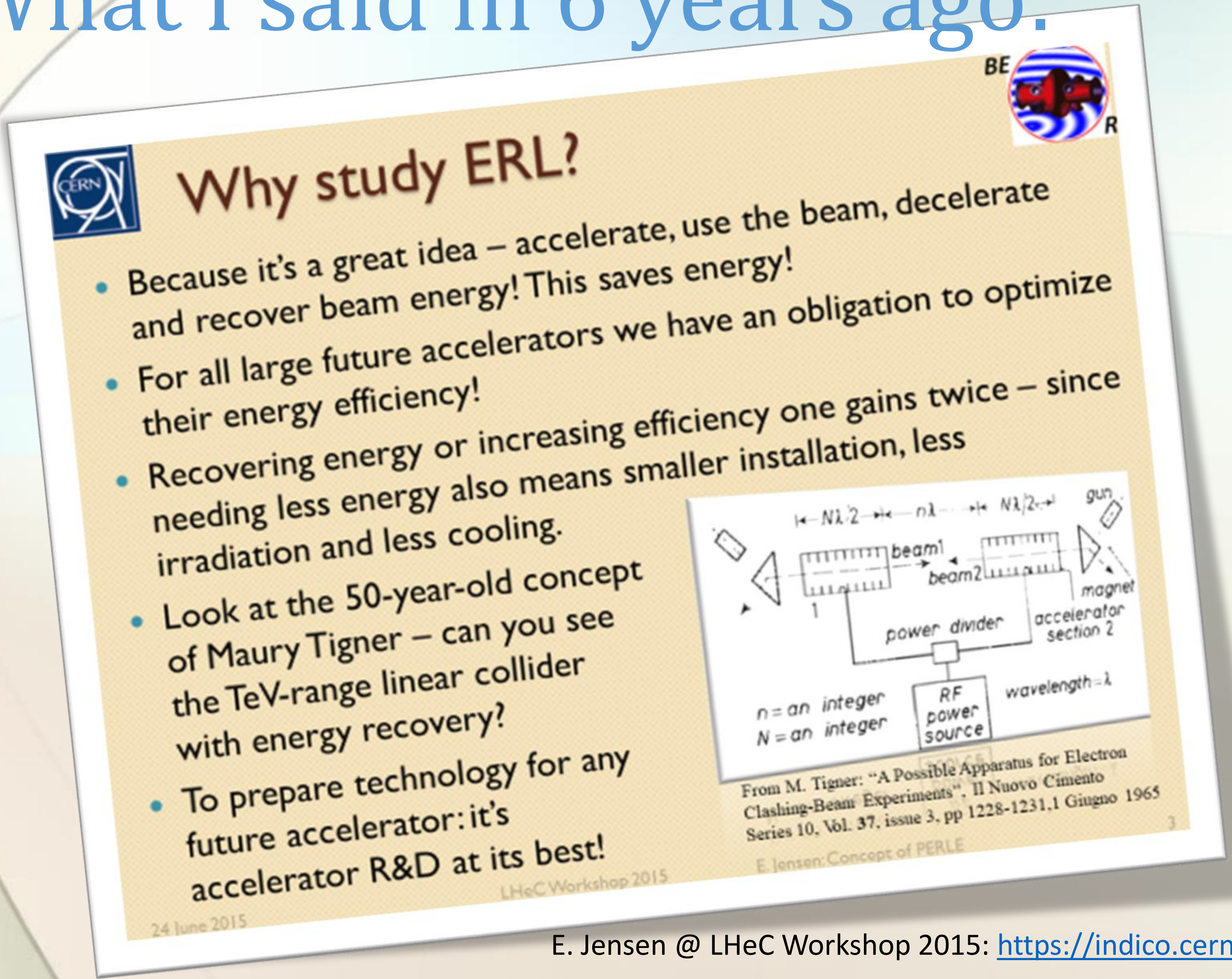
… sorry – I know this is a repetition, but with the title I was given I can't skip this!



Energy supply = acceleration → „loss free“ energy storage (in the beam) → Energy recovery = deceleration

A. Jankowiak in "CAS on FELs and ERLs", 2016: https://indico.cern.ch/event/441441/contributions/1931923/ 4312541/

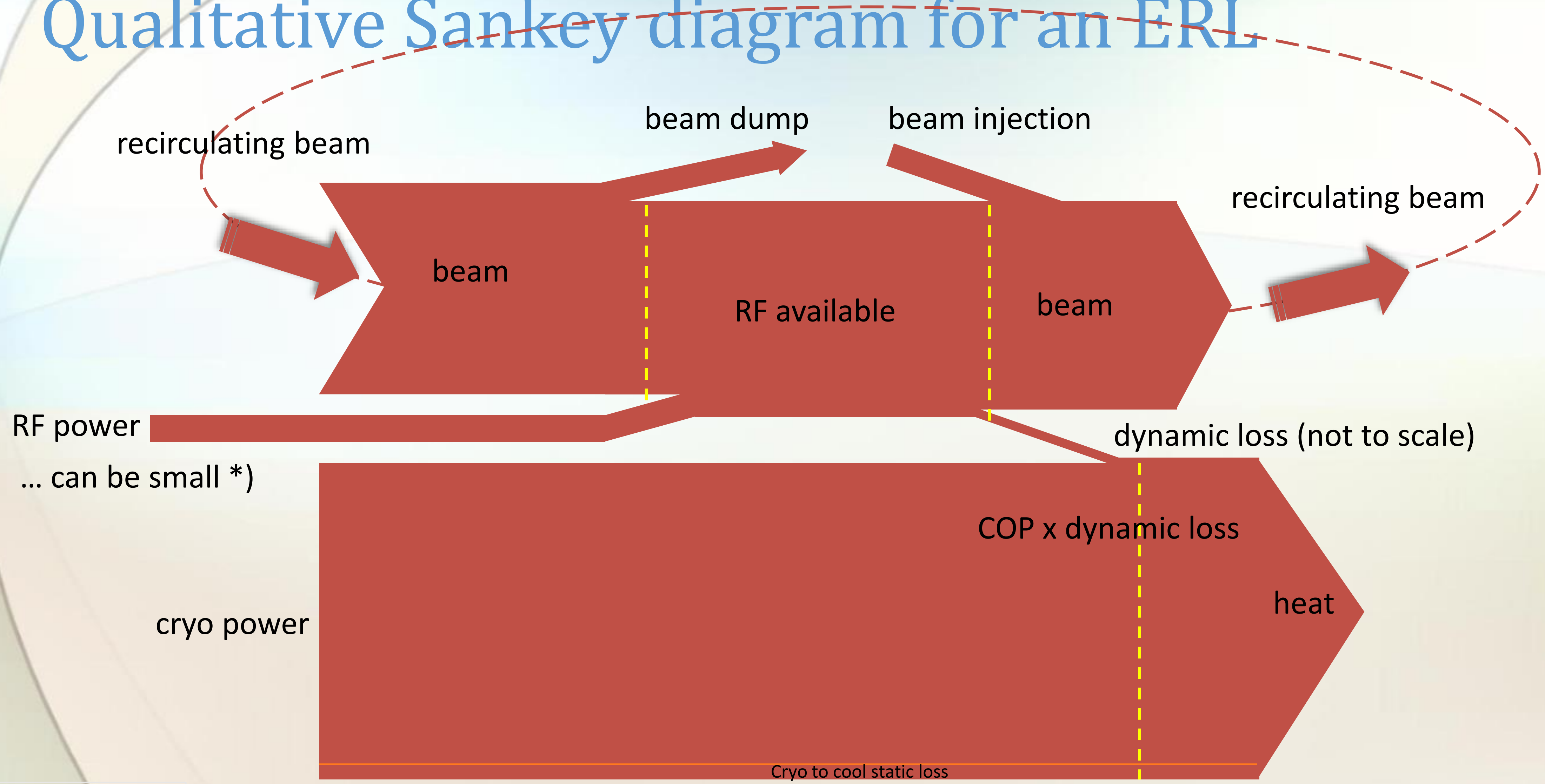
What I said in 6 years ago:



These statements are all still valid.

E. Jensen @ LHeC Workshop 2015: https://indico.cern.ch/event/356714/contributions/844995/

Qualitative Sankey diagram for an ERL



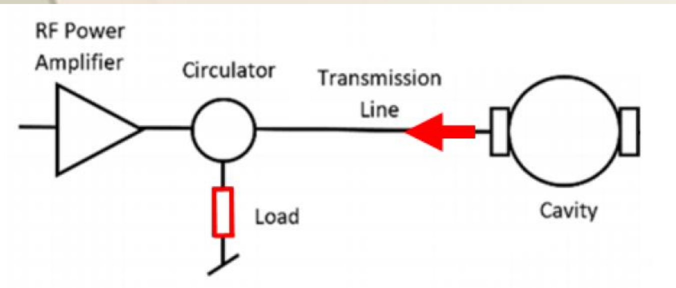
*) see next page

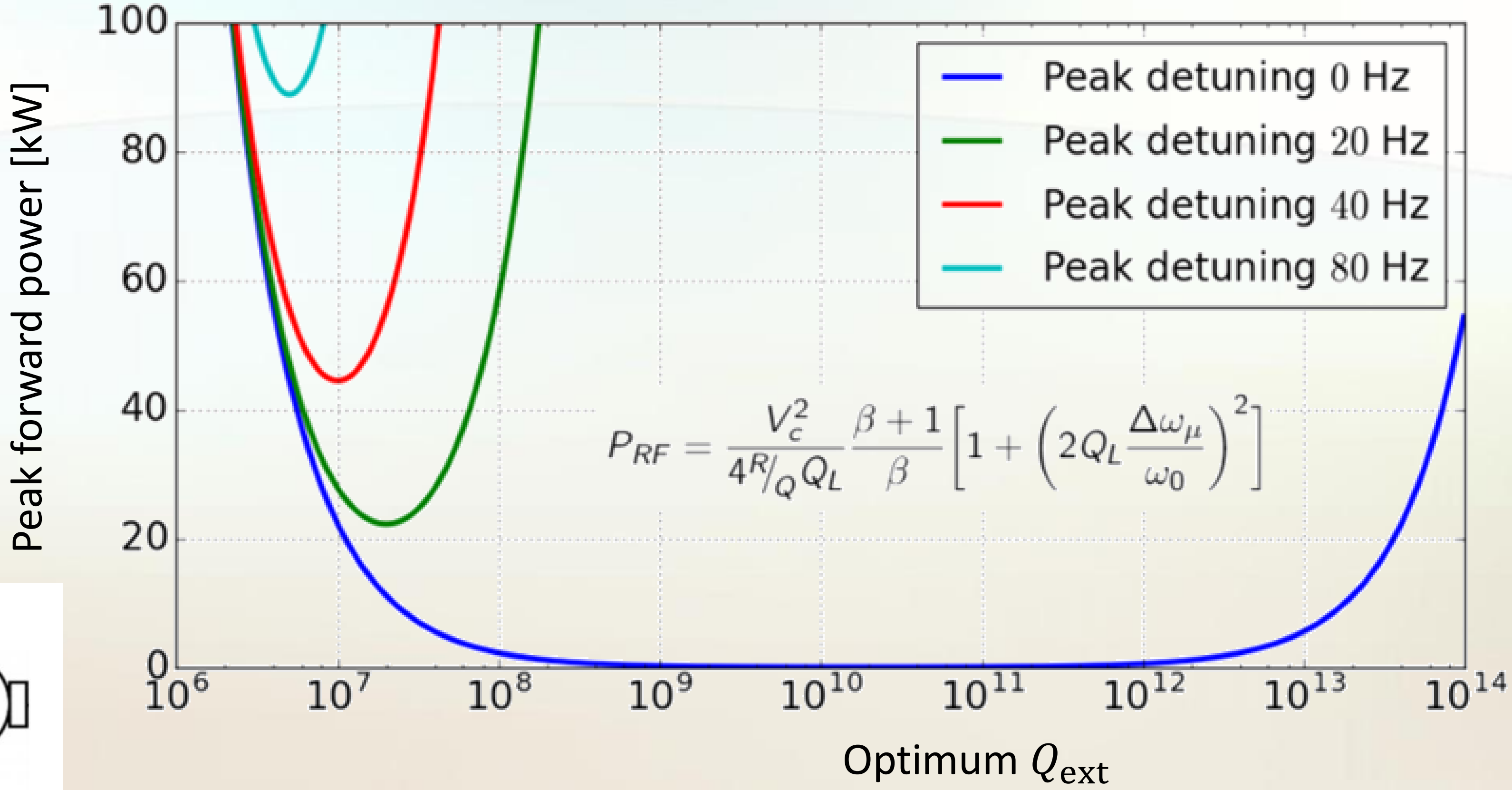
ERL RF power requirement

- Since there is no fundamental beam loading in a CW ERL, RF power is required to keep the beams stable and under control in the presence of microphonics.
- Equally, RF power has to be fed into the beam to compensate for transients (e.g. unequal currents in accelerated and decelerated beams, ramp-up and ramp-down).
- Microphonics inside the cavities force you to very strongly over-couple, meaning that you have to provide much more RF power than the beam needs. This is characterized by the external Q of the cavity.

ERL RF power requirement – e.g. PERLE

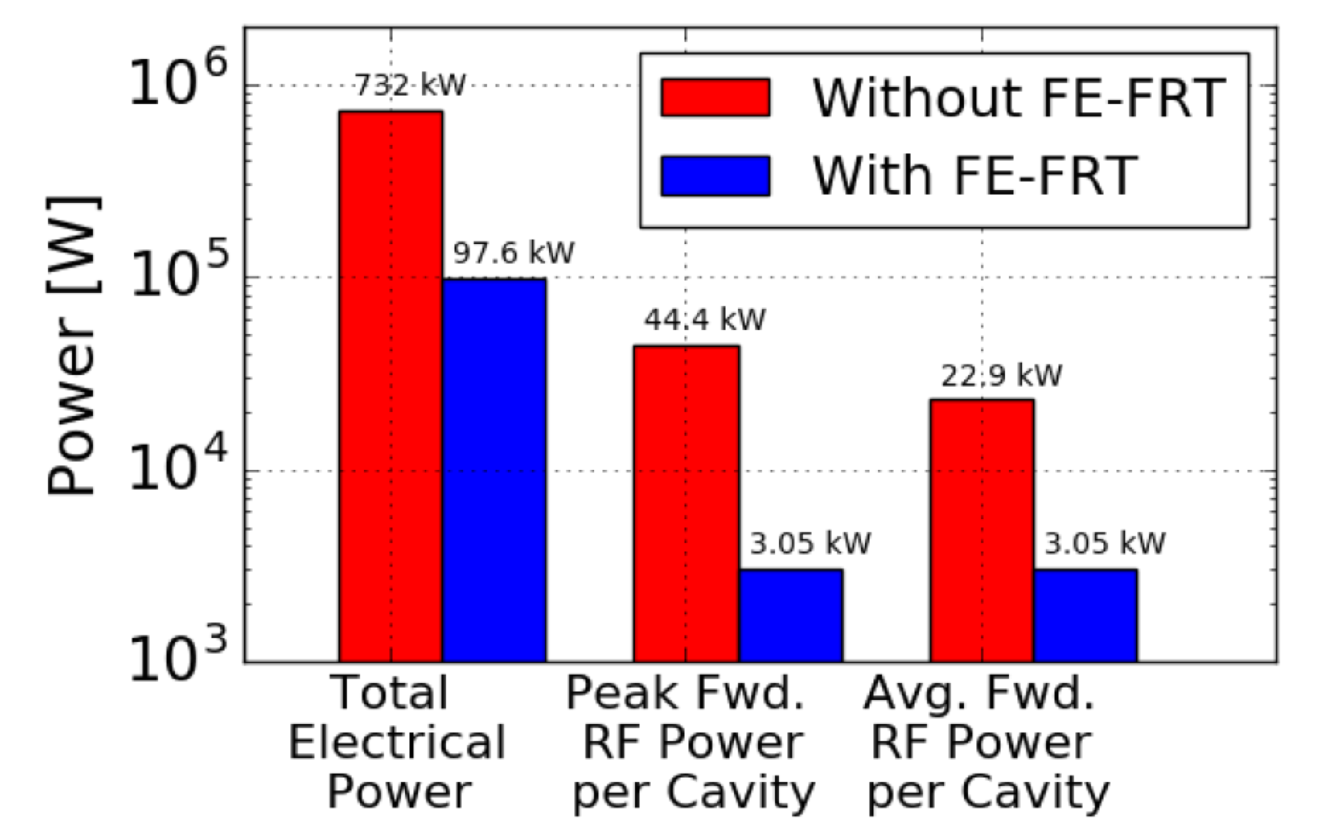
Power loss: **44 W**
Power installed: **45 kW**



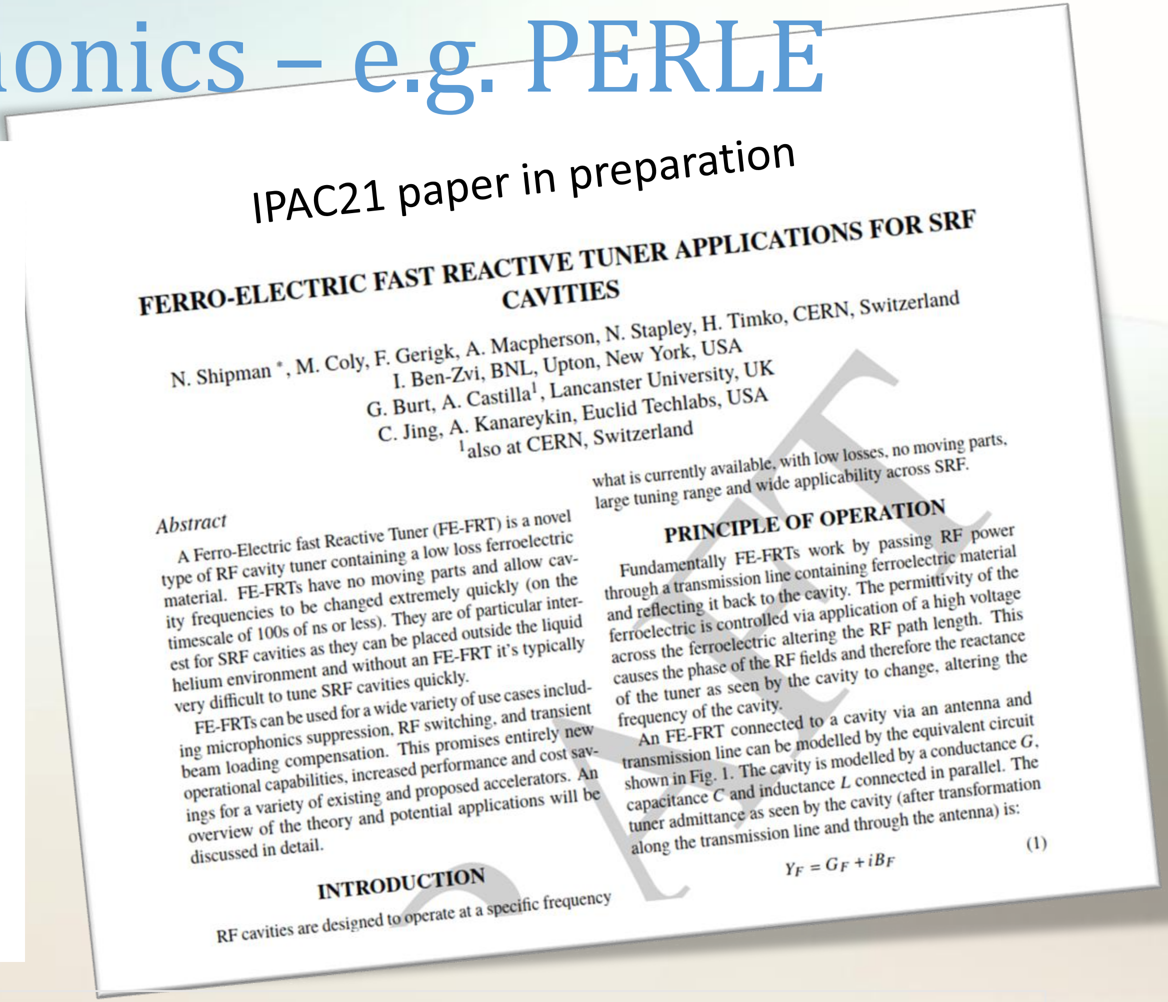


N. Shipman @ "Electrons in the LHC", Chavannes 2019, https://indico.cern.ch/event/835947/contributions/3609044

RF power can be reduced with active compensation of microphonics – e.g. PERLE



IPAC21 paper in preparation



FERRO-ELECTRIC FAST REACTIVE TUNER APPLICATIONS FOR SRF CAVITIES

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I. Ben-Zvi, BNL, Upton, New York, USA
G. Burt, A. Castilla[1], Lancanster University, UK
C. Jing, A. Kanareykin, Euclid Techlabs, USA
[1]also at CERN, Switzerland

Abstract

A Ferro-Electric fast Reactive Tuner (FE-FRT) is a novel type of RF cavity tuner containing a low loss ferroelectric material. FE-FRTs have no moving parts and allow cavity frequencies to be changed extremely quickly (on the timescale of 100s of ns or less). They are of particular interest for SRF cavities as they can be placed outside the liquid helium environment and without an FE-FRT it's typically very difficult to tune SRF cavities quickly.

FE-FRTs can be used for a wide variety of use cases including microphonics suppression, RF switching, and transient beam loading compensation. This promises entirely new operational capabilities, increased performance and cost savings for a variety of existing and proposed accelerators. An overview of the theory and potential applications will be discussed in detail.

INTRODUCTION

RF cavities are designed to operate at a specific frequency

what is currently available, with low losses, no moving parts, large tuning range and wide applicability across SRF.

PRINCIPLE OF OPERATION

Fundamentally FE-FRTs work by passing RF power through a transmission line containing ferroelectric material and reflecting it back to the cavity. The permittivity of the ferroelectric is controlled via application of a high voltage across the ferroelectric altering the RF path length. This causes the phase of the RF fields and therefore the reactance of the tuner as seen by the cavity to change, altering the frequency of the cavity.

An FE-FRT connected to a cavity via an antenna and transmission line can be modelled by the equivalent circuit shown in Fig. 1. The cavity is modelled by a conductance G, capacitance C and inductance L connected in parallel. The tuner admittance as seen by the cavity (after transformation along the transmission line and through the antenna) is:

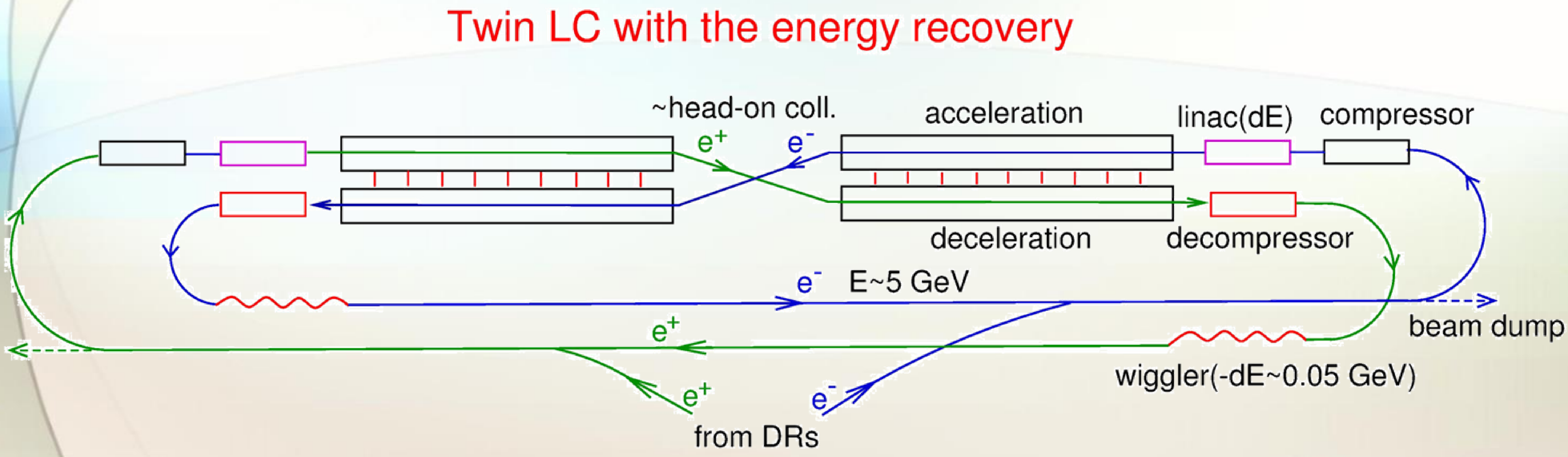
$$Y_F = G_F + iB_F \quad (1)$$

N. Shipman et al. ERL2019, Berlin, http://accelconf.web.cern.ch/erl2019/papers/tucozbs02.pdf

… here starts the less established…

to trigger discussion (this is a symposium!)

Telnov's proposal ("ERLC")



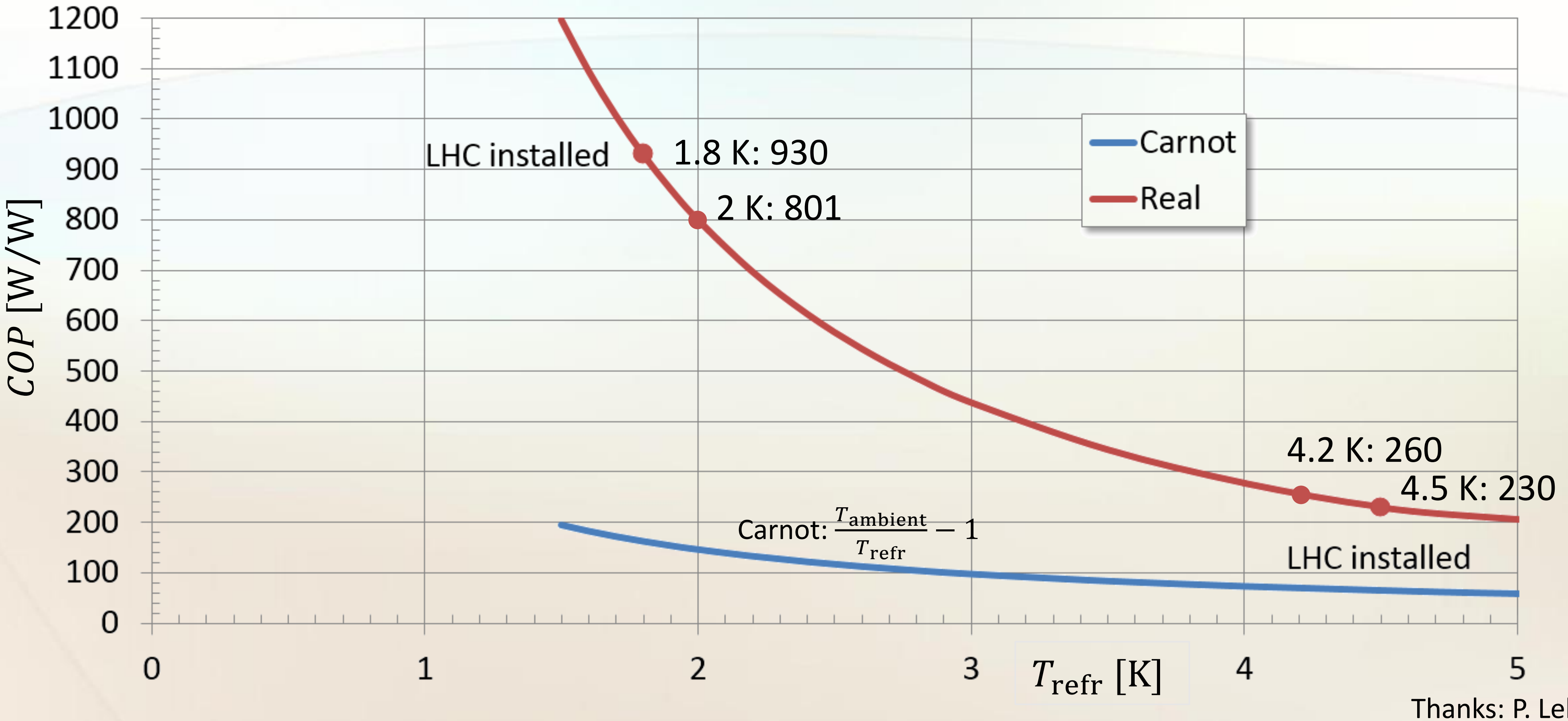
V. Telnov/BINP, LCWS2021, https://indico.cern.ch/event/995633/contributions/4275159/
…and preprint paper https://arxiv.org/pdf/2105.11015.pdf

Personal comments on the ERLC

- While TeV-scale linear colliders require very high power to produce multi-MW beams, …
- … and large **circular** electron-positrons colliders require very high power to compensate for SR losses:
- … the ERLC is a **very exciting proposal**.
- However: The cryogenics power need is $\propto E_{\mathrm{acc}}^2$. It is $\mathcal{O}(1\,\mathrm{MW/GeV})$, which Telnov eased by using a duty factor of 1/3.
- I personally believe that the ERL scheme very much favours CW – can this be made possible?
- Another potential issue is HOM power – can this be eased? … by going to CW and reducing the current? – just food for thought!

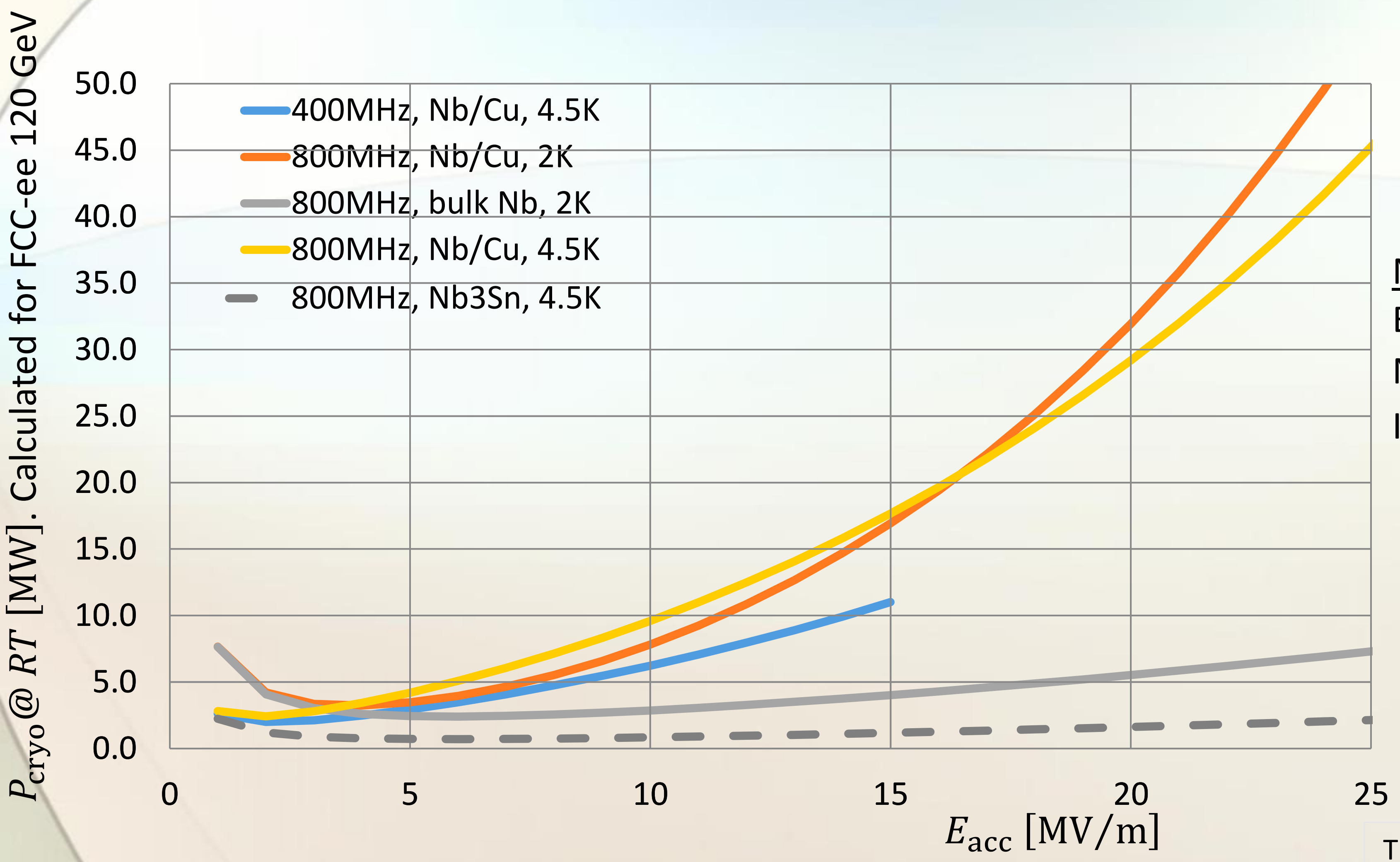
Real COP of cryogenic He refrigeration

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



Thanks: P. Lebrun/CERN

Cryogenic needs in CW operation

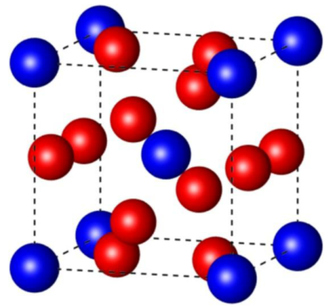


Note: @ 25 MV/m , 800 MHz:
Bulk Nb @ 2 K: $P_{cryo} = 7.3$ MW
NB_3Sn @ 4.5 K: $P_{cryo} = 2.1$ MW
Improvement factor **3.5!**

Thanks to Sarah Aull & Olivier Brunner

Nb vs. Nb_3Sn

Higher critical temperature
→ Operation at 4.2 K
Higher superheating field
→ Double the limit of niobium

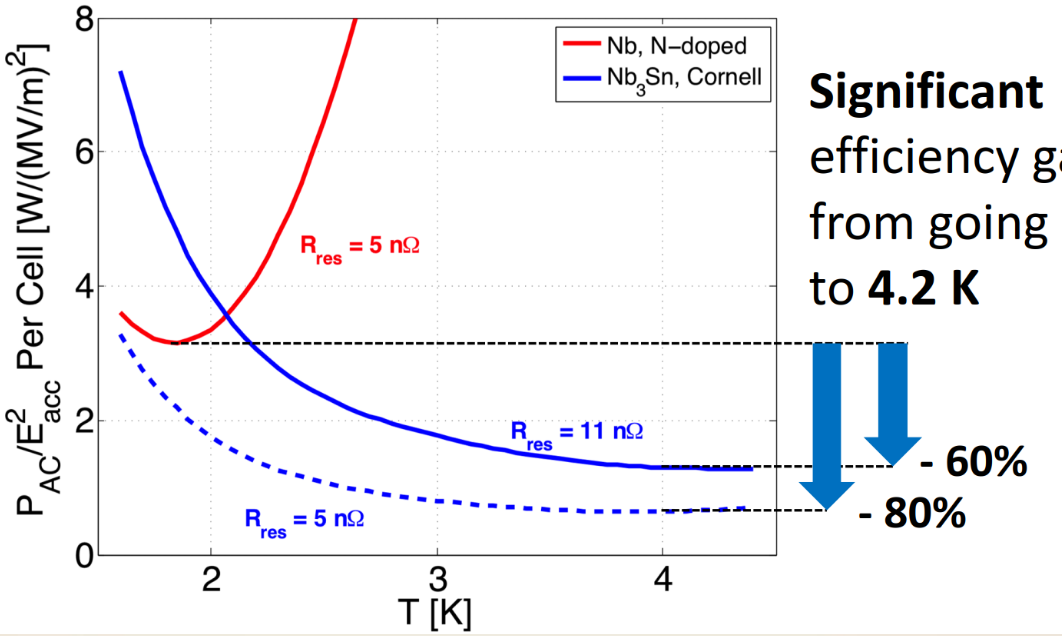


Blue: tin
Red: niobium

Parameter	Niobium	Nb_3Sn
Transition temperature	**9.2 K**	**18 K**
Superheating field	**219 mT**	**425 mT**
Energy gap Δ/k_bT_c	1.8	2.2
λ at T = 0 K	50 nm	111 nm
ξ at T = 0 K	22 nm	4.2 nm
GL parameter κ	2.3	26

Transition temperature → **Lower losses**
Superheating field → **Higher gradients**

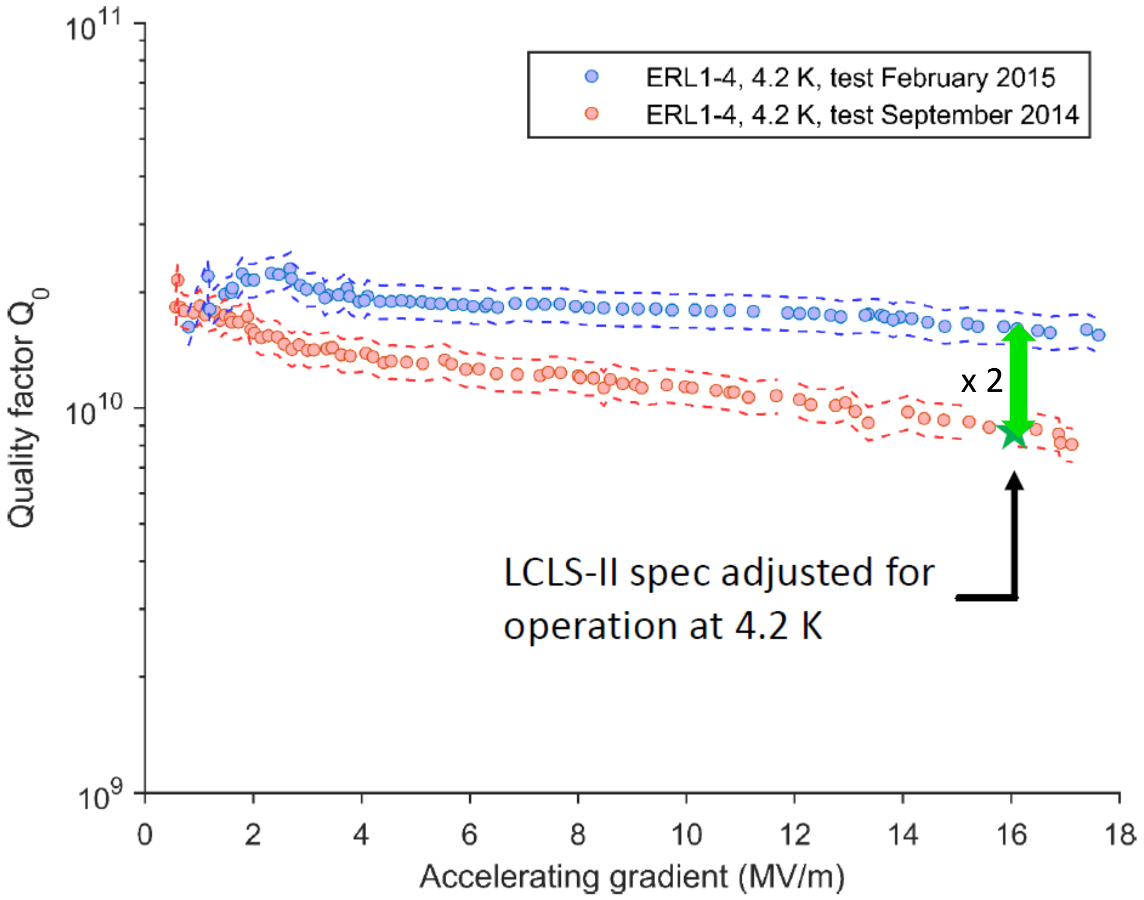
Niobium → 45 MV/m
Nb_3Sn → 90 MV/m



Significant efficiency gain from going to **4.2 K**

Thanks: S. Posen, D. Hall, M. Liepe, R. Porter, see e.g. https://indico.desy.de/event/21337/contributions/42597/

Results with Nb_3Sn coated cavities

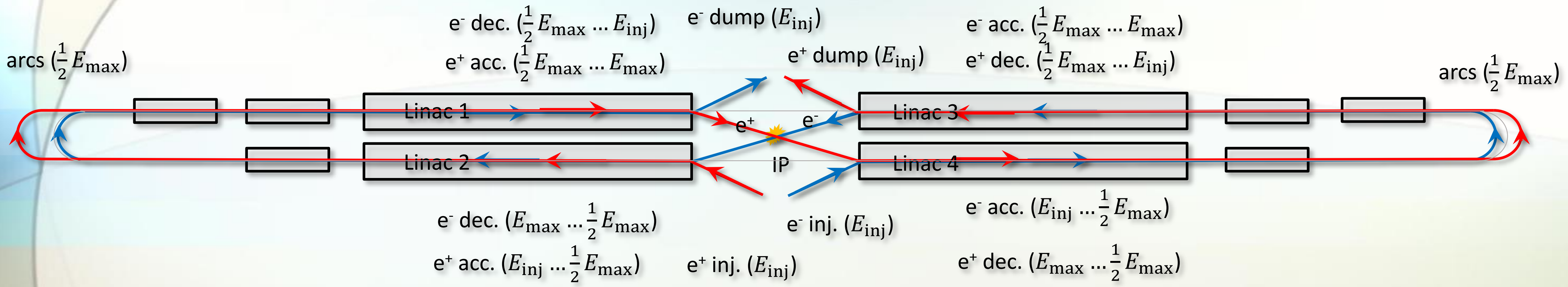


Small thermal gradients give better performance

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

Daniel Hall, SRF 2015, Whistler, CDN

Modified ERLC proposal … for discussion



Practically the same as Telnov's proposal, except:

- Each of the four linacs is used for both acceleration and deceleration – maybe one could ease on the coupling. For minimum static losses, one would possibly still put the two adjacent linacs in one cryostat.
- For the same E_{max}, the accelerating gradient is halved – thus the dynamic losses reduced by a factor 4. This would probably allow to run in CW!
- This comes at the expense of SR losses in the outer arcs at $\frac{1}{2}E_{max}$ (which is still large, but only 1/16 of the SR power at E_{max}).

  The arcs could be dog-bone type to reduce curvature; they could be at a smaller energy than $\frac{1}{2}E_{max}$.
- I omitted the wigglers at E_{inj} only not to overload the sketch – they can be redone exactly as in Telnov's original proposal.