Energy efficiency and power consumption of ERLs

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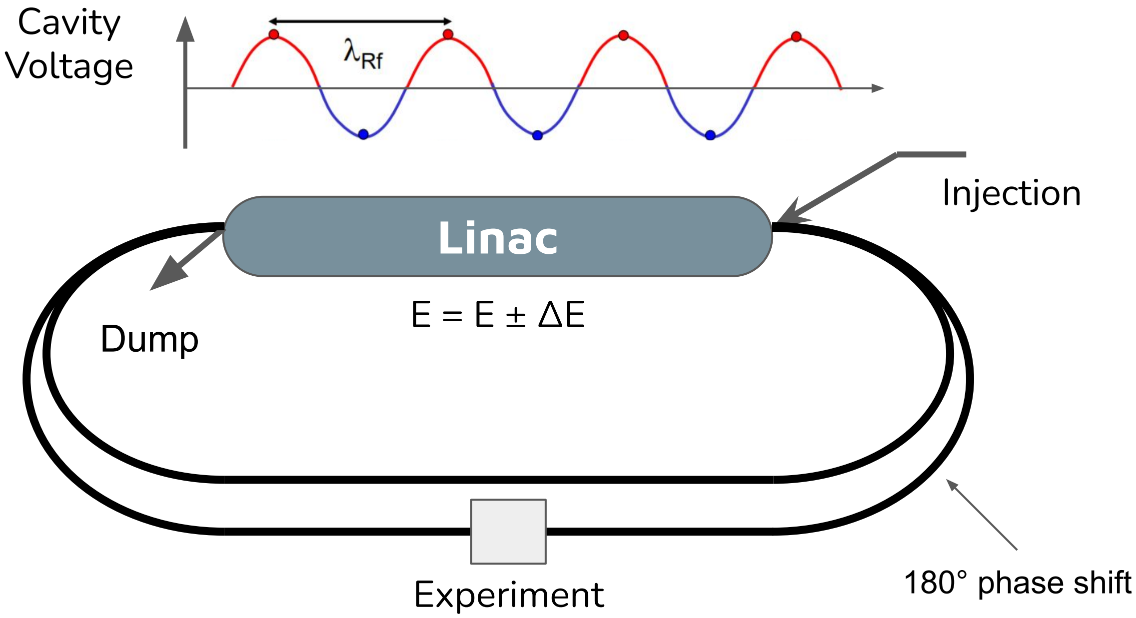
The Energy Recovery technology

The energy recovery technology allows to recycle the power given to the beam.

$$\tilde{P_{RF}} = P_{RF}(1 - \eta_{recovery})$$



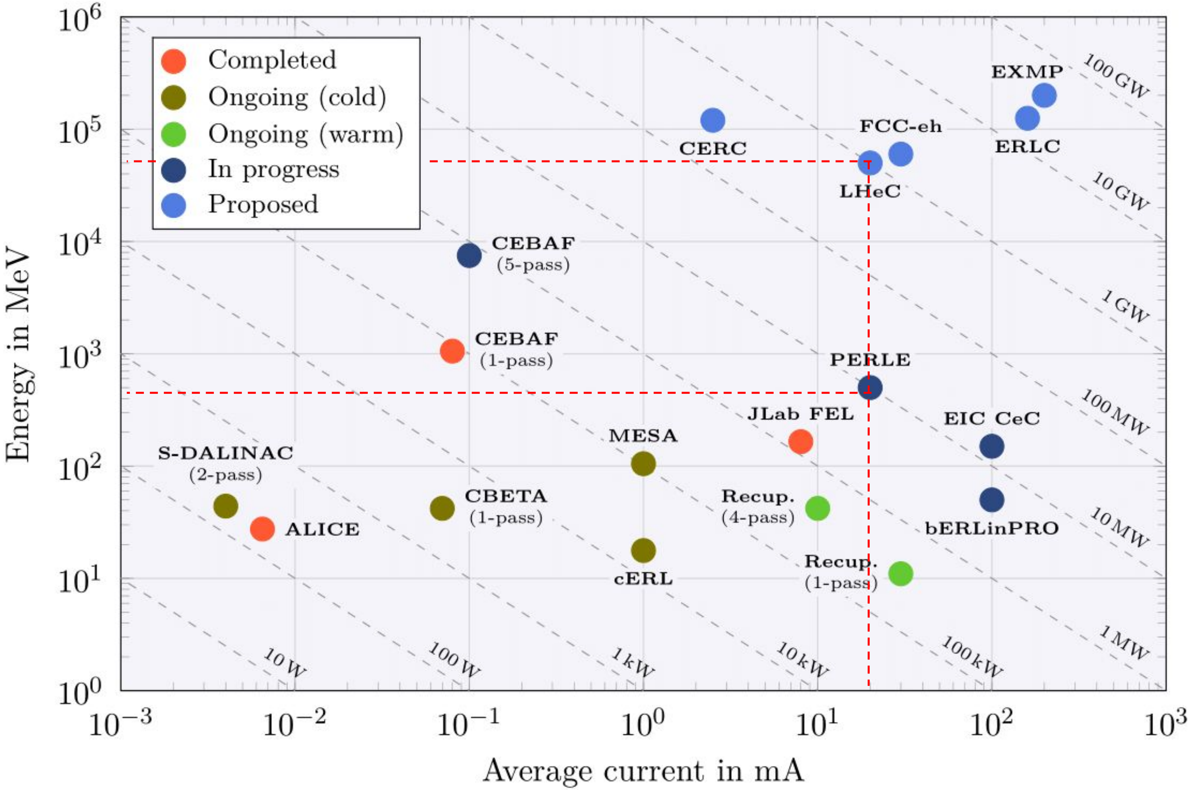
The Energy Recovery landscape

Up to now, low energy physics application and proof-of-principle.

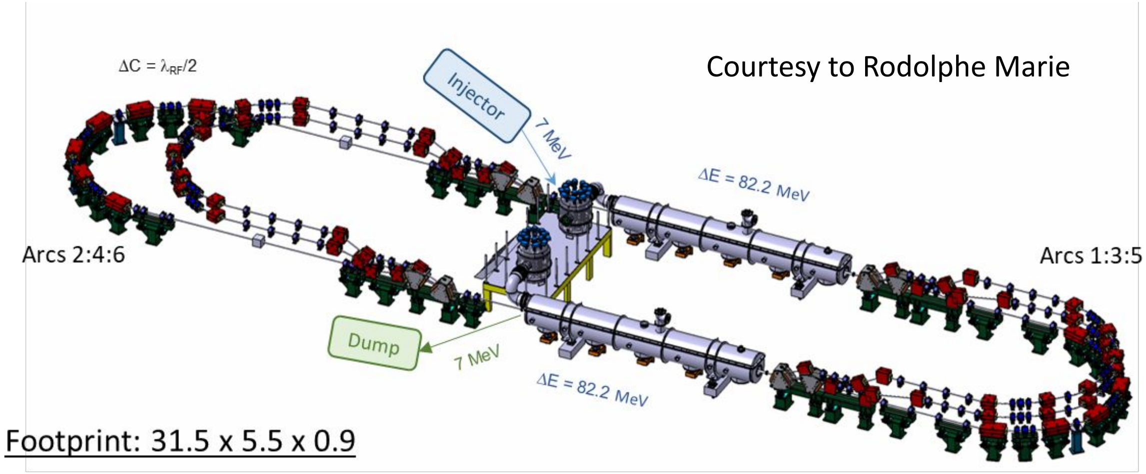
Now, aiming at ~10MW beam power in the next decade,

paving the way to high energy physics application such as colliders LHeC, FCC-ee (CERC), ILC (ERLC) utilizing energy recovery technology.

ERL R&D Roadmap



ERL description - PERLE @ Orsay



Courtesy to Rodolphe Marie

Footprint: 31.5 x 5.5 x 0.9

Parameter	Unit	Electron
Injection energy	MeV	7.0
Top energy	MeV	500.0
Beam current	mA	20.0
Bunch population	$10^9 e^-$	3.1
Bunch charge	pC	500
Bunch spacing	ns	25
Normalised emittance	mm.mrad	6.0
RMS bunch length	mm	3.0
Longitudinal emittance	keV.mm	25.0
RF frequency	MHz	801.6

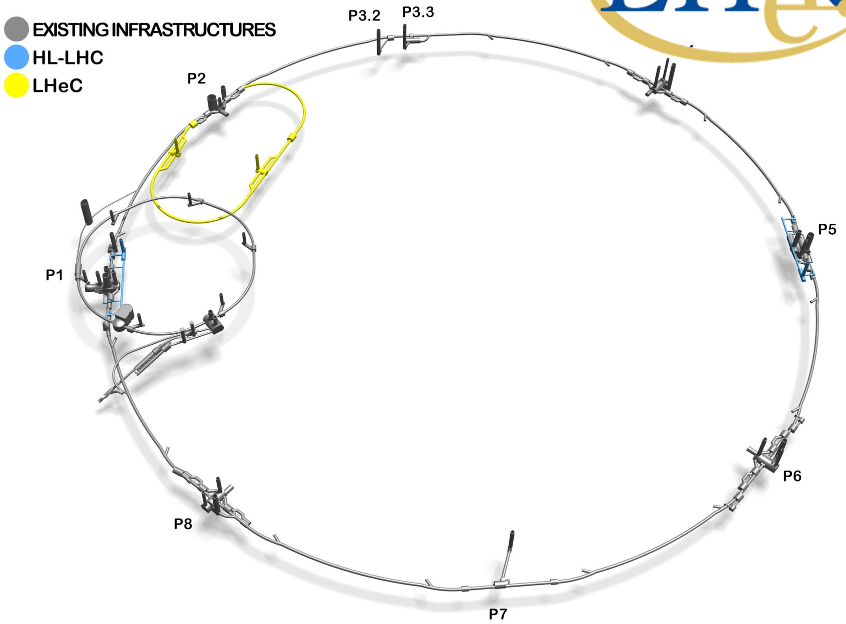
Two insertions for experiments.

PERLE demonstrator facility for the LHeC at Orsay to be commissioned in this decade,

with 3-turn, 20mA, 802 MHz SRF cavities

ERL description - LHeC

		LHeC	
Parameter	Unit	Electron	Proton
Beam energy	GeV	50.0	7000.0
Beam current	mA	20.0	1400
Bunches per beam		1188	2808
Bunch population	10^{10}	0.3	22.0
Bunch charge	nC	0.50	35.24
Normalised emittance at IP	mm.mrad	30.0	2.5
Betatron function at IP	cm	10.0	10.0
RMS bunch length	cm	0.06	7.55
Installed RF voltage	GV	17.2*	0.016
Beam-beam disruption		14.3	1×10^{-5}
Luminosity	$cm^{-2}.s^{-1}$	6.5×10^{33}	



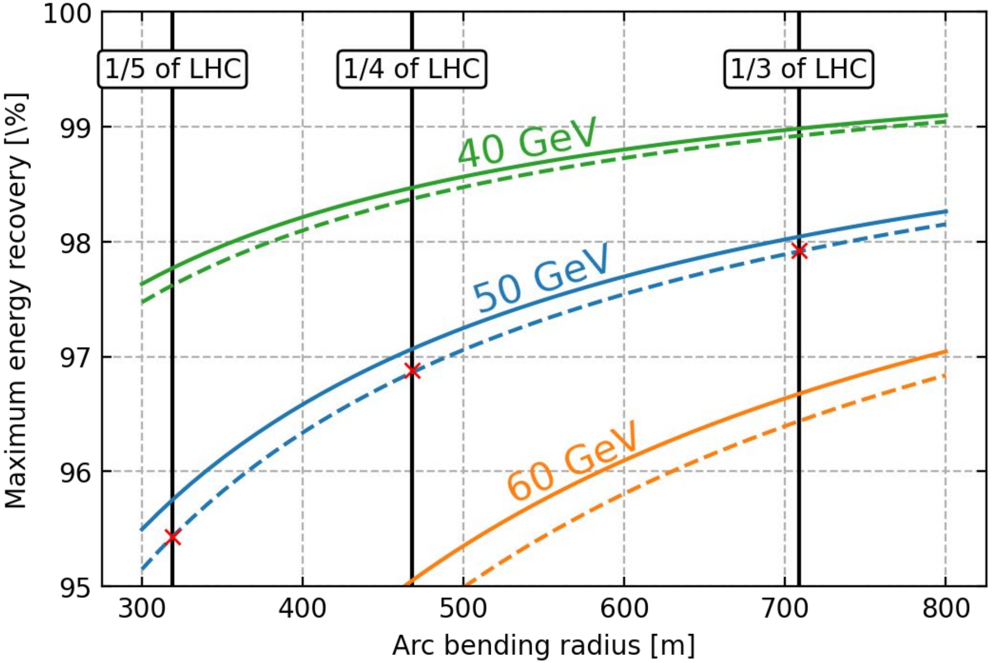
High power electron beam based on **three-turn** ERL racetrack utilising **100 MW electrical power** consumption as a result of the high energy recovery efficiency. The ERL circumference is equivalent to one-third of the LHC. The ERL could be realised in staged phases.

Energy recovery efficiency for LHeC

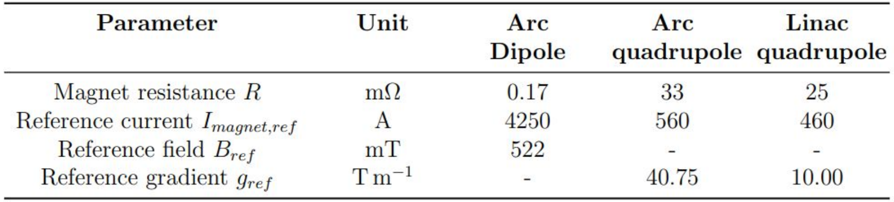
On-crest operation of the RF cavities leads to:

- **97.9%** max energy recovery for ⅓ of C_{LHC}
- **96.9%** max energy recovery for ¼ of C_{LHC}
- **95.4%** max energy recovery for ⅕ of C_{LHC}

Off-crest operation could allow to optimise the energy loss in each arc still reaching 50 GeV at the IP.
→ more margin for the RF cavity voltage.

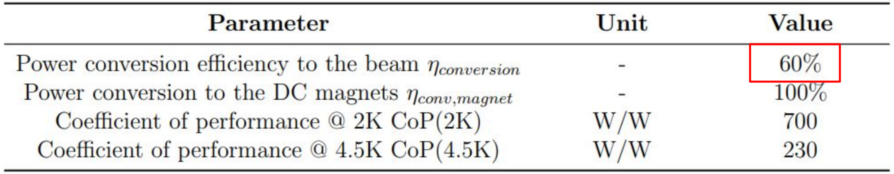


Hardware and other assumptions



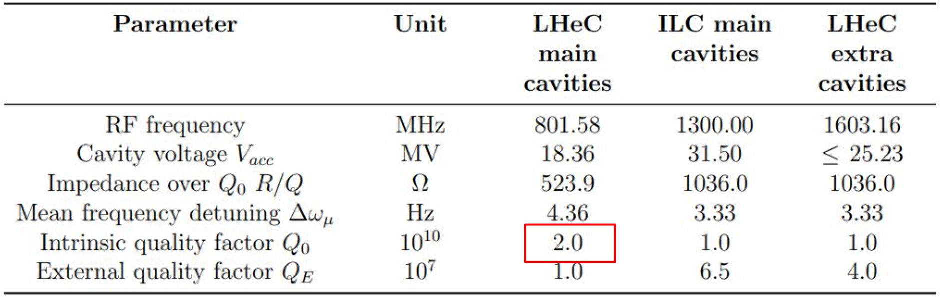
Parameter	Unit	Arc Dipole	Arc quadrupole	Linac quadrupole
Magnet resistance R	mΩ	0.17	33	25
Reference current $I_{magnet,ref}$	A	4250	560	460
Reference field B_{ref}	mT	522	-	-
Reference gradient g_{ref}	$\mathrm{T\,m^{-1}}$	-	40.75	10.00

Table D.1: Summary of magnet parameters involved in the magnet power consumption.



Parameter	Unit	Value
Power conversion efficiency to the beam $\eta_{conversion}$	-	60%
Power conversion to the DC magnets $\eta_{conv,magnet}$	-	100%
Coefficient of performance @ 2K CoP(2K)	W/W	700
Coefficient of performance @ 4.5K CoP(4.5K)	W/W	230

Table D.2: Summary of the parameters regarding cryogenics and power conversion.



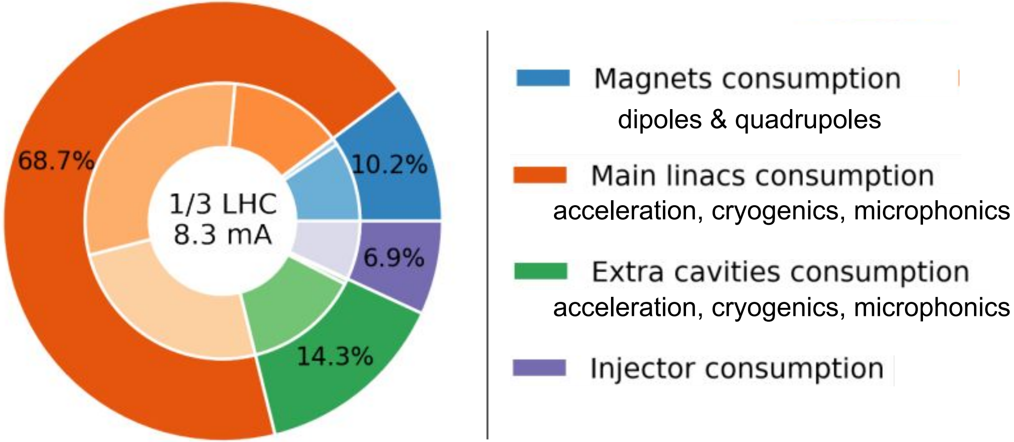
Parameter	Unit	LHeC main cavities	ILC main cavities	LHeC extra cavities
RF frequency	MHz	801.58	1300.00	1603.16
Cavity voltage V_{acc}	MV	18.36	31.50	$\leq$ 25.23
Impedance over Q_0 R/Q	Ω	523.9	1036.0	1036.0
Mean frequency detuning $\Delta\omega_\mu$	Hz	4.36	3.33	3.33
Intrinsic quality factor Q_0	10^{10}	2.0	1.0	1.0
External quality factor Q_E	10^7	1.0	6.5	4.0

- The magnet consumption is driven by the arc quadrupoles trade-off low emittance vs. aperture
  - Permanent magnets as in CBETA
- The RF power consumption depends on Q_0, and the operation temperature.
  - N doping of the Nobium and undergoing studies of Nb_3Sn.
- Power conversion to the beam
  - high-voltage power supply → klystron → waveguide → RF cavity → beam

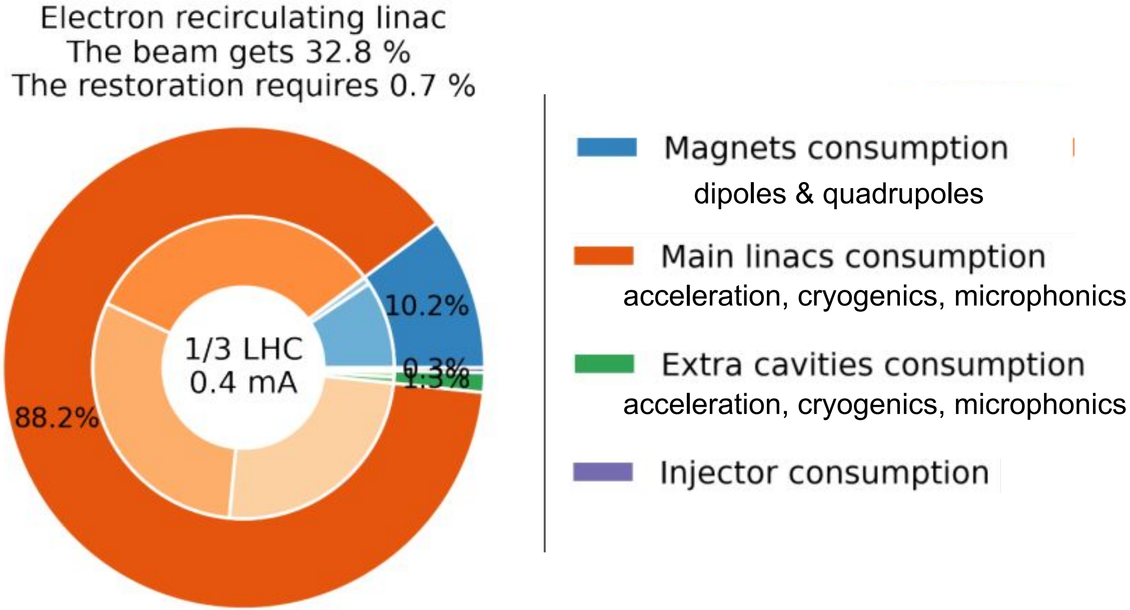
Energy consumption

- RF cavity: power to accelerate the beam, for the cryogenics (50% margin assumed), for the microphonics
- Extra RF cavities to compensate the synchrotron radiation energy loss
- Magnet power consumption
- Injector power consumption

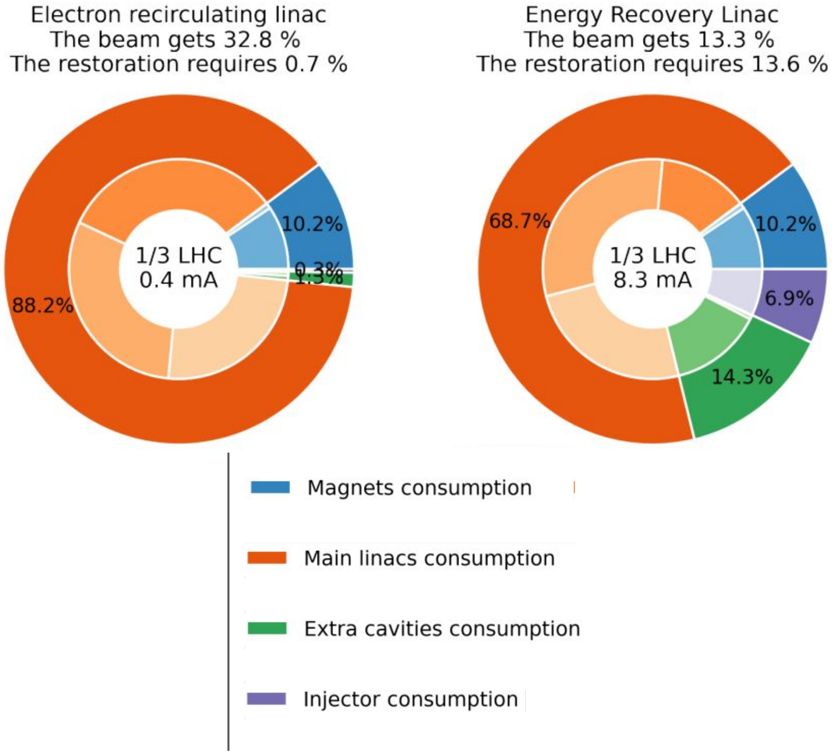
Limit of **100 MW** electrical power consumption to obtain the maximum beam current for luminosity.
Depends on the ERL circumference, the RF cavity hardware, the beam energy



Electron recirculating linac



Energy recovery linac



Without energy recovery the beam current would be low for a constrained power consumption.

The **magnet consumption** only varies with the beam energy E_{beam} and the ERL circumference.

One observes the reduction in RF power delivered to the beam w.r.t. cryogenics and microphonics.

The **extra cavities** kick in as more beam power must be replenished to reach 50 GeV at the IP.

Similarly, **the injector** power consumption increases with the beam current.

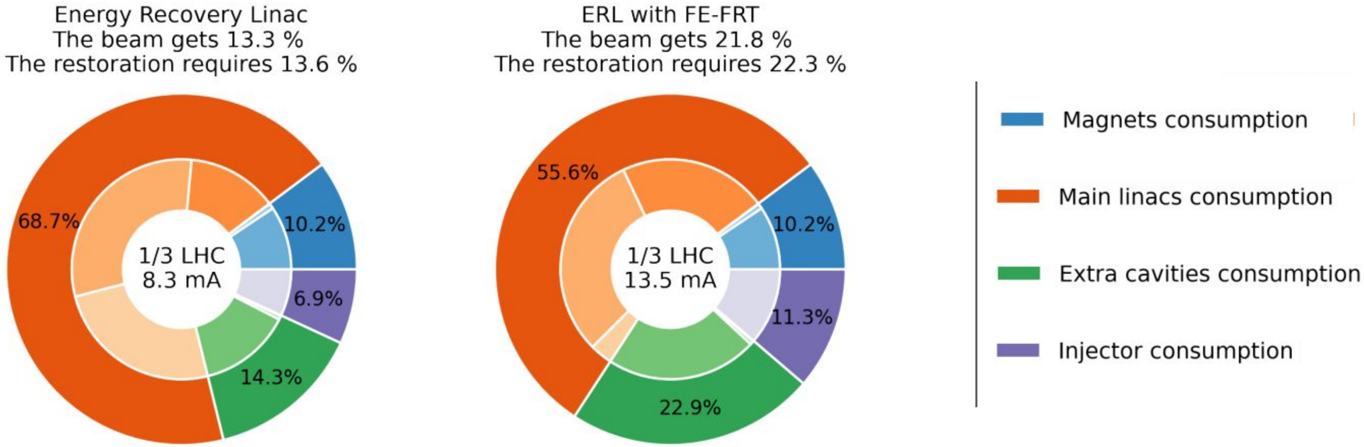
About ⅔ of the power consumption remains devoted to the main linacs, with **only** 13% delivered to the beam from the main RF cavities (incl. energy recovery) and 14% delivered from the extra cavities (w/o energy recovery).

Energy recovery linac

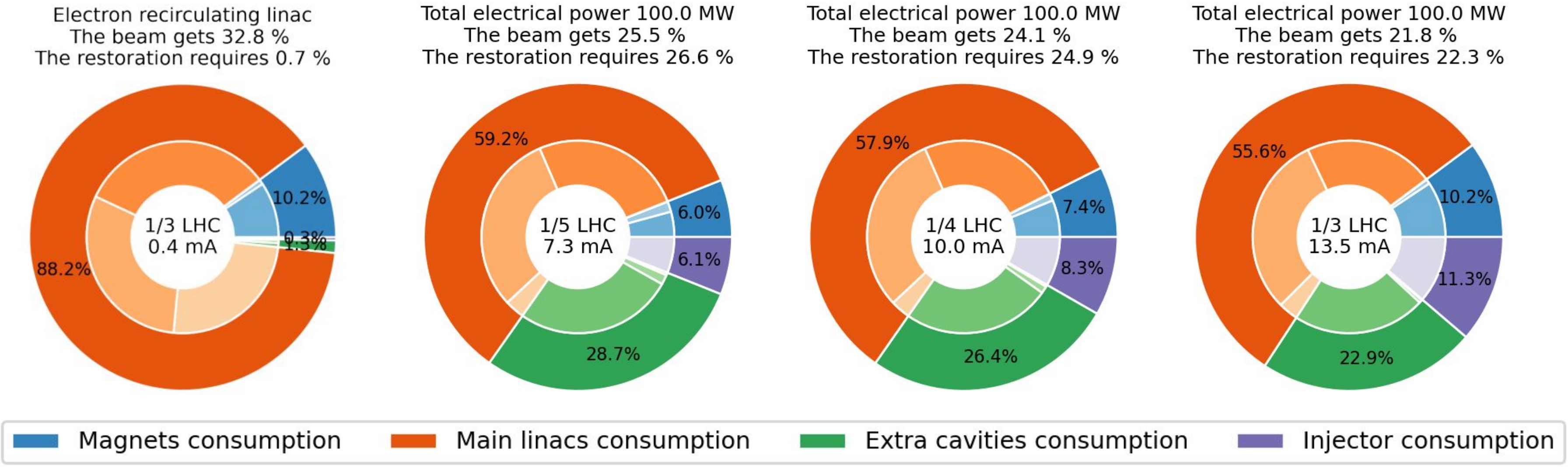
The share of the main linacs consumption decrease with the implementation of FerroElectric Fast Reactive Tuner (FE-FRT).

The **extra cavities** must replenish more energy as the circumference decreases.

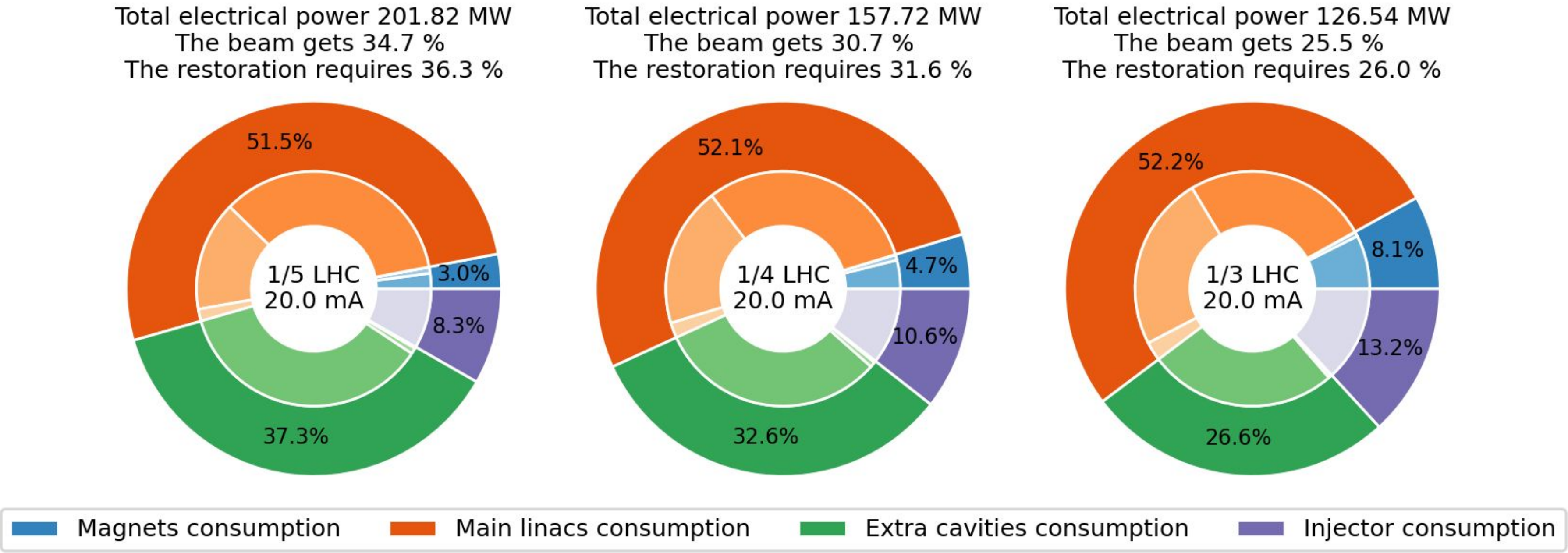
About 60% of the power consumption remains devoted to the main linacs, with 22% delivered to the beam from the main RF cavities (incl. energy recovery) and 22% delivered from the extra cavities (w/o energy recovery).



Power consumption evolution with circumference

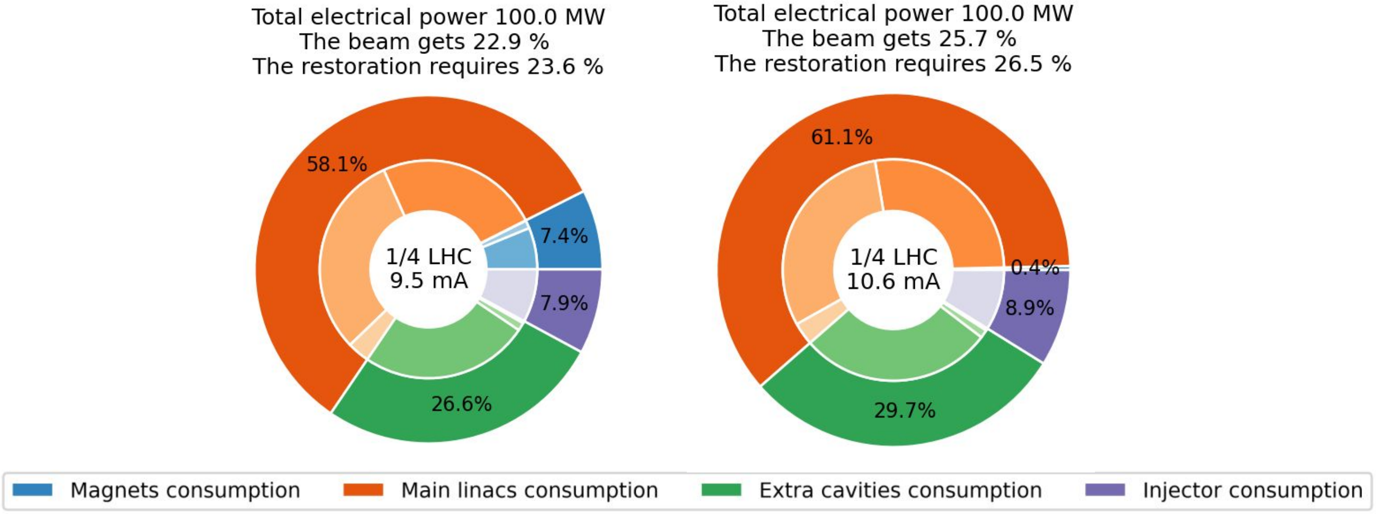


Power consumption to reach nominal beam current



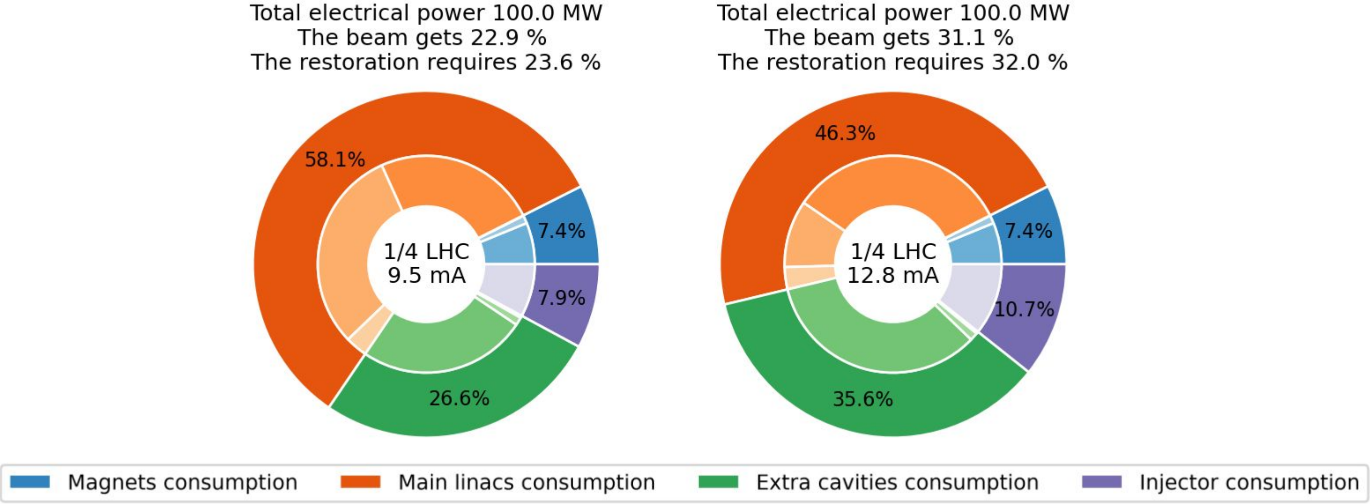
Possible improvements

- Permanent magnets, no ramping, magnet consumption decreases (~1.1mA)
- Higher temperature RF cavities operation 1.9K to 4.2K at constant Q_0
- Better grid to beam conversion (60-70%), RF cavities consumption decreases
- Reduced the injection energy, small gain between 300 & 500 MeV
- Improved energy replenishment scheme, off-crest acceleration



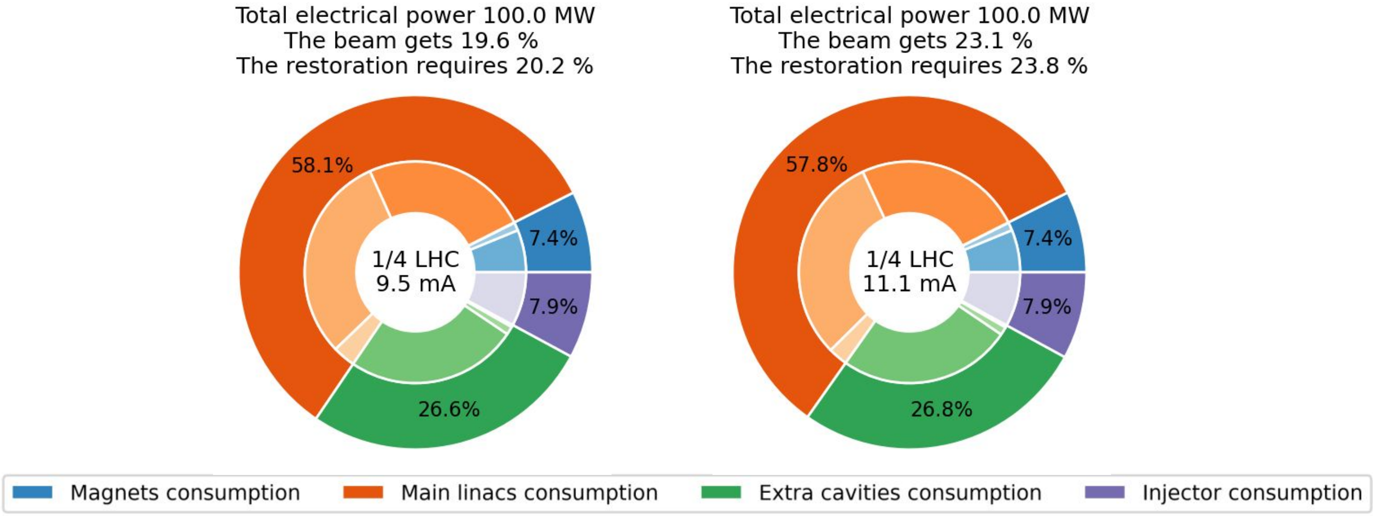
Possible improvements

- ➢ Permanent magnets, no ramping, magnet consumption decreases (~1.1mA)
- ➢ Higher temperature RF cavities operation 1.9K to 4.2K at **constant** Q_0 (~3.3mA)
- ➢ Better grid to beam conversion (60-70%), RF cavities consumption decreases
- ➢ Reduced the injection energy, small gain between 300 & 500 MeV
- ➢ Improved energy replenishment scheme, off-crest acceleration



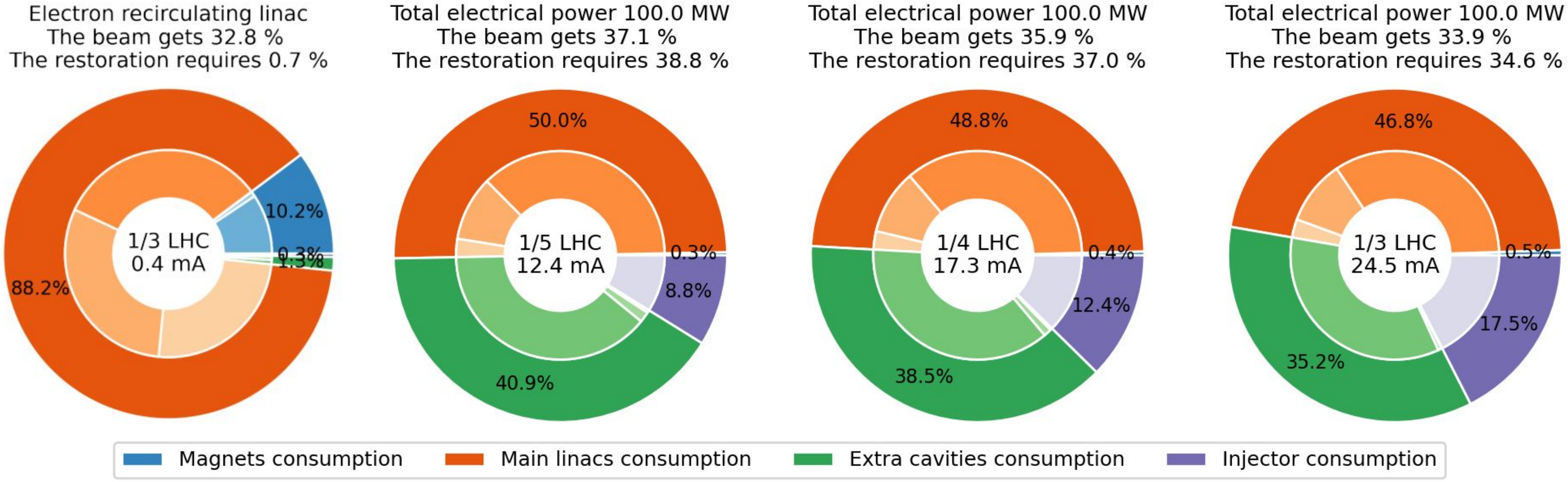
Possible improvements

- Permanent magnets, no ramping, magnet consumption decreases (~1.1mA)
- Higher temperature RF cavities operation 1.9K to 4.2K at constant Q_0 (~3.3mA)
- Better grid to beam conversion (60-70%), RF cavities consumption decreases (~1.6mA)
- Reduced the injection energy, small gain between 300 & 500 MeV
- Improved energy replenishment scheme, off-crest acceleration



Possible improvements

- ➢ Permanent magnets, no ramping, magnet consumption decreases (~1.1mA)
- ➢ Higher temperature RF cavities operation 1.9K to 4.2K at constant Q_0 (~3.3mA)
- ➢ Better grid to beam conversion (60-70%), RF cavities consumption decreases (~1.6mA)
- ➢ Reduced the injection energy, small gain between 300 & 500 MeV (~0.8mA)
- ➢ Improved energy replenishment scheme, off-crest acceleration



Electron recirculating linac
The beam gets 32.8 %
The restoration requires 0.7 %

Total electrical power 100.0 MW
The beam gets 37.1 %
The restoration requires 38.8 %

Total electrical power 100.0 MW
The beam gets 35.9 %
The restoration requires 37.0 %

Total electrical power 100.0 MW
The beam gets 33.9 %
The restoration requires 34.6 %

Summary

- The energy recovery technology represents a great alternative to achieve **high beam brilliance** with limited **facility footprint and electrical power consumption**.

- On going R&D effort for the **development of superconducting RF cavities** with **high quality factor** and **high accelerating gradient** with in the near future the same performance at **higher cryogenic temperature 2K → 4.2K**.

- The use of **permanent magnets** has the potential to reduce the power consumption of an ERL facility.

- The footprint of the ERL has a large influence on the power consumption there is a **trade-off between synchrotron radiation / highest luminosity performance**.

Energy consumption context and energy efficiency

- Worldwide: Historical trends show a rapid increase in global energy demand; whereas future projections advocate an urgent need for sustainable solutions to address environmental concerns.
    - Renewable and nuclear energy production to replace fossil fuel.
- Accelerator-wise: Rising concerns about cost of electricity (long-term price stability) and climate change necessitate improved energy efficiency. Accelerators are rather inefficient and heat-up cooling fluids.
    - Figure of merit: Luminosity per MWh, collision product per MWh.
- Emphasis on energy efficiency and reduced carbon footprint and technologies such as Energy Recovery Linacs could play a crucial role.
    - Recovery and re-use of the power delivered to the beam through RF cavities.