RF efficiency and sustainability

NURIA CATALAN LAHERAS

COMMUNITY REPORT ON ACCELERATORS ROADMAP

INFN FRASCATI 12-13 JULY 2023

Outlook

- The impact of RF in accelerators
- Power sources
- Cavity technology
  - Normal conducting structures
  - SC cavities
- LLRF and operation
- ERL

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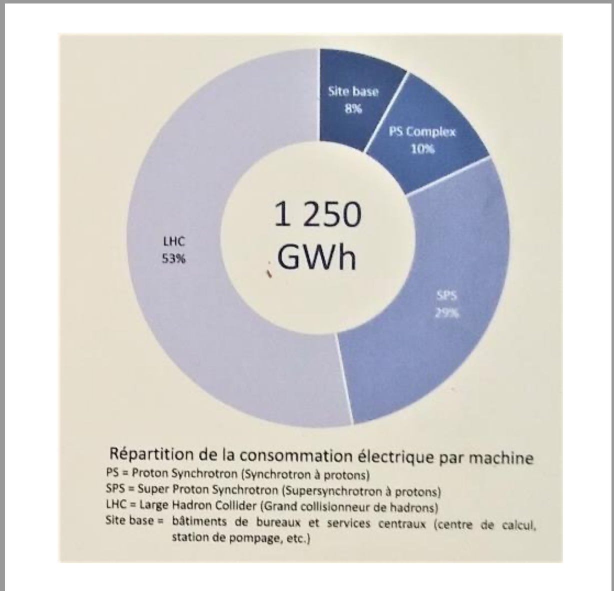
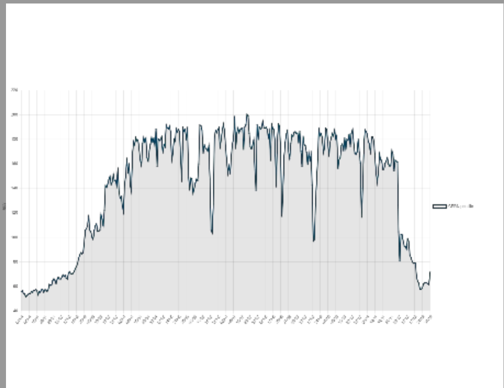
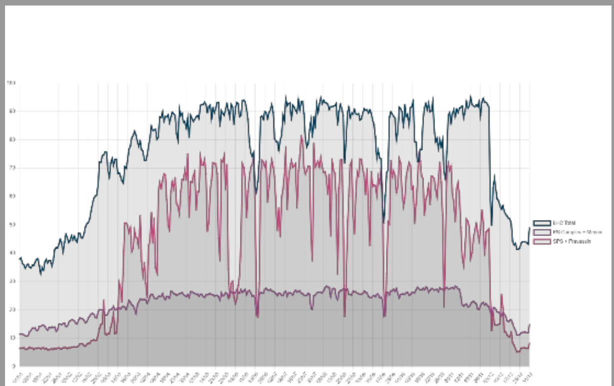
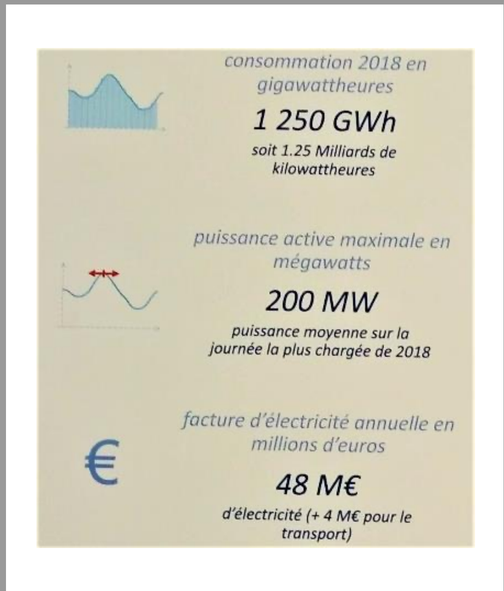


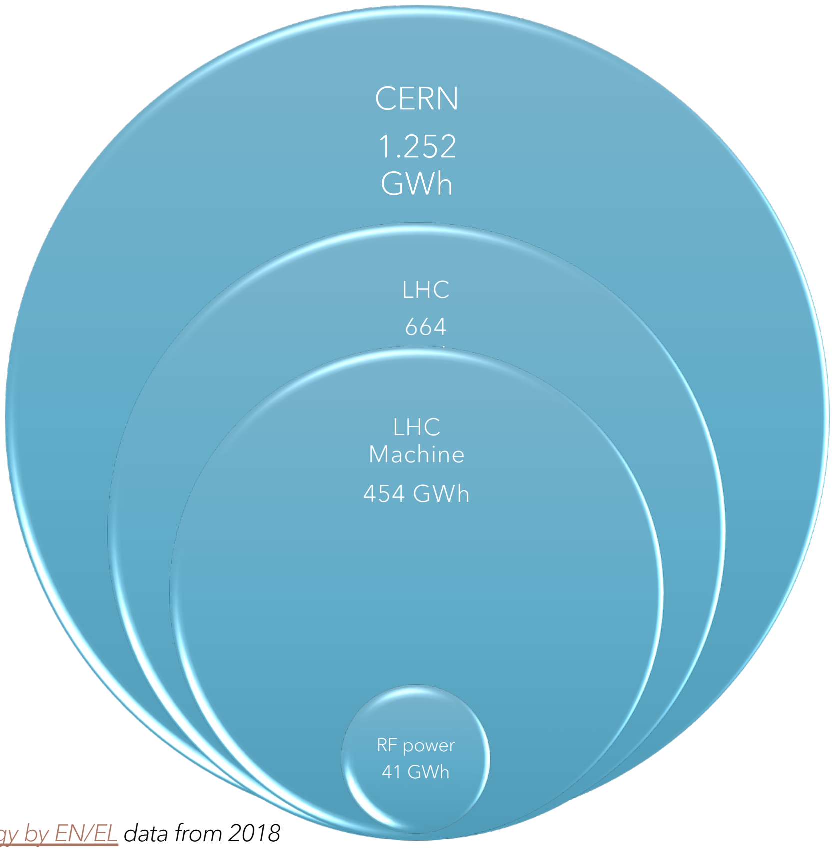




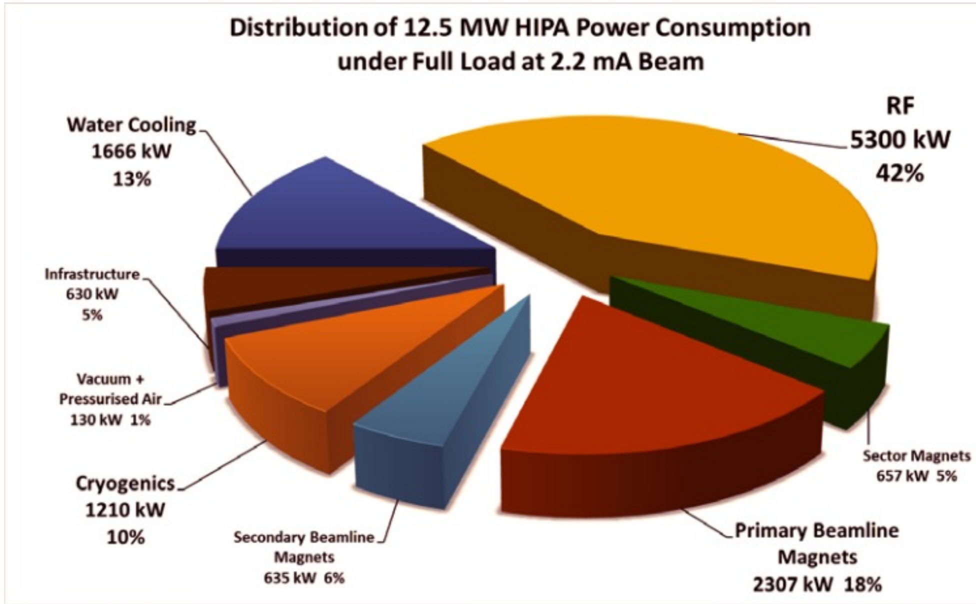


- *The consumption of the LHC represents more than half of the CERN energy bill*
- https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.energy_consumption
- *But how much is the contribution of the RF system?*

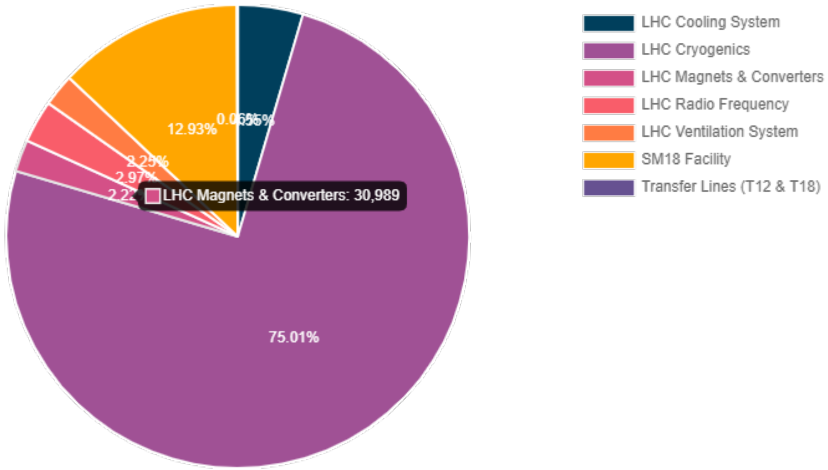
What data says



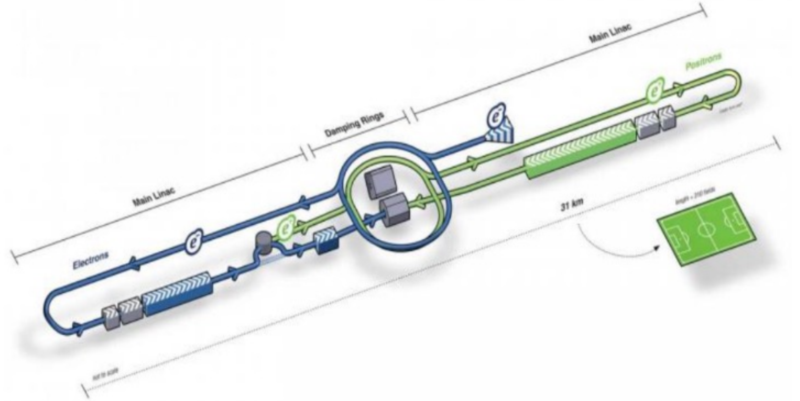
WEB Energy by EN/EL data from 2018



Energy Efficiency Analysis and Optimisation of HIPA Power Consumption. Andras Kovach, Angelina Parfenova

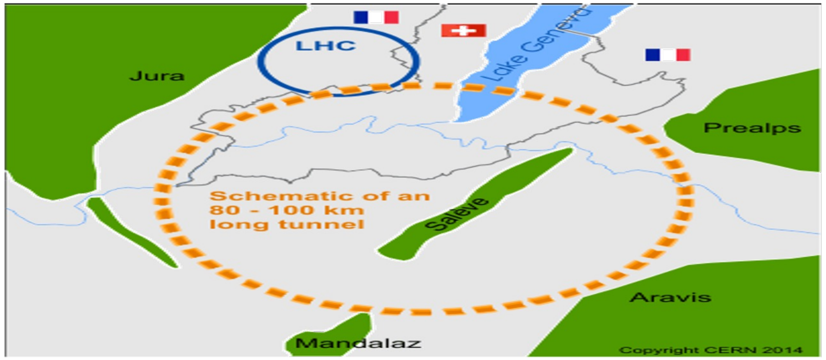


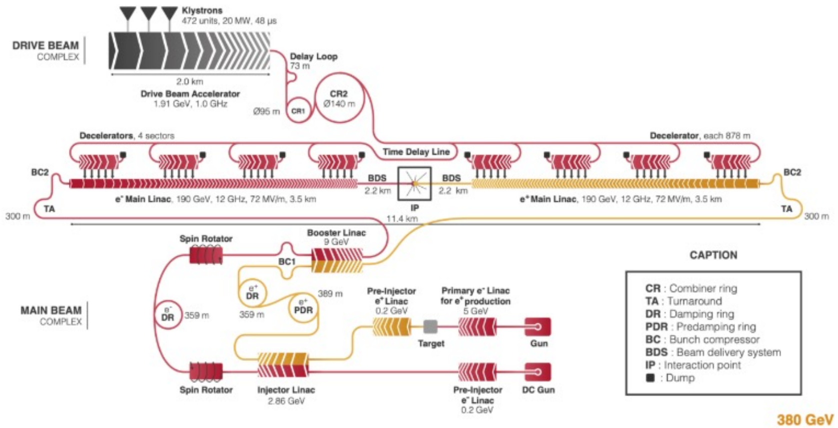
Average RF power needs of the next Higgs factory



ILC 0.5 TeV: Pulsed, 1.3 GHz, $P_{\mathrm{RF,total}}$ **60 plus cryo out of 134 MW**

B. List ILC Power Consumption and Performance Risks, https://agenda.infn.it/event/21199/



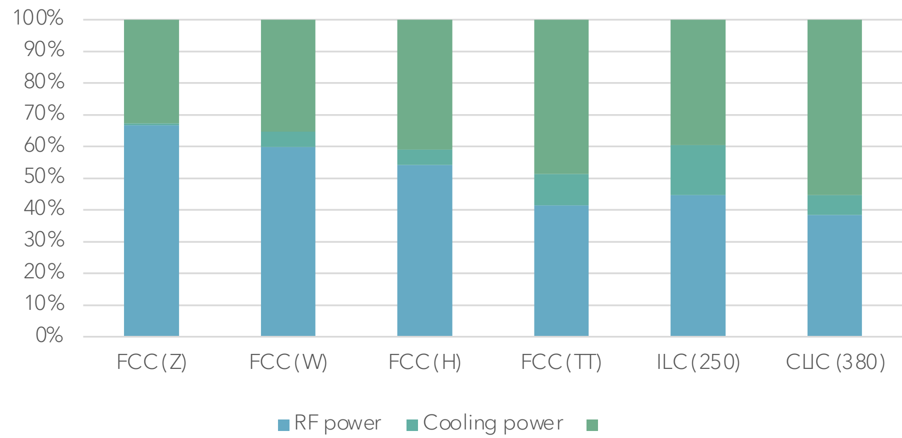


CLIC 380 GeV: Pulsed $P_{\mathrm{RF,total}}$ = **41 out of 107 MW**

The CLIC project. arXiv 2203.09186

FCC-ee: CW, (0.4 & 0.8) GHz, $P_{\mathrm{RF,total}}$ = **146 MW** plus cryo

Update of the power demand and energy consumption, gird connection,



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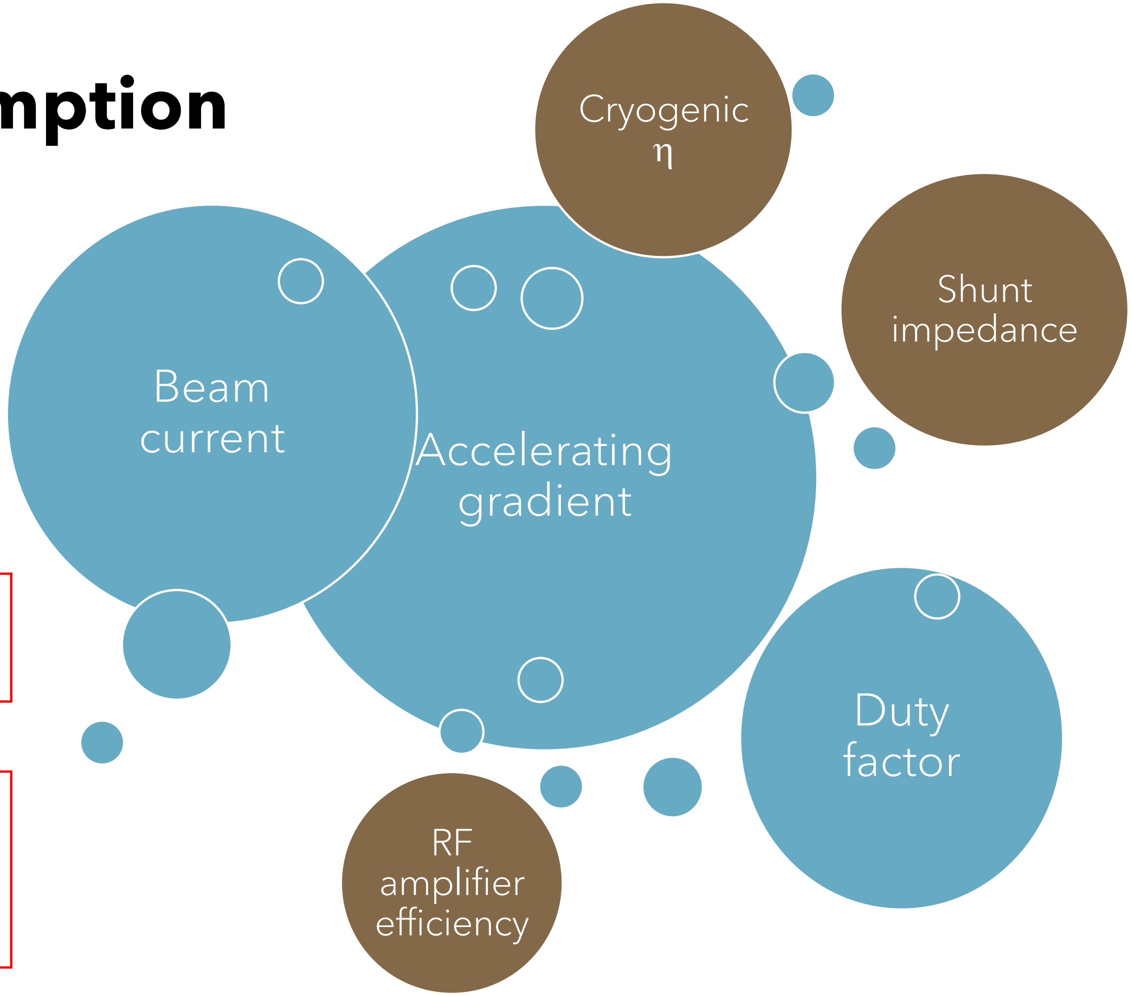
Plug-power consumption

- Some of this factors have a direct impact on physics (and cost) through:
  - Beam Energy
  - Luminosity
- Some margin for efficiency improvement
  - RF amplifier
  - Cryogenics
- Optimization
  - Geometry
  - Choice of NC/SC, material, frequency, temperature, pulse length, etc.



Superconducting versus normal conducting cavities - Podlech, Holger - arXiv:1303.6552

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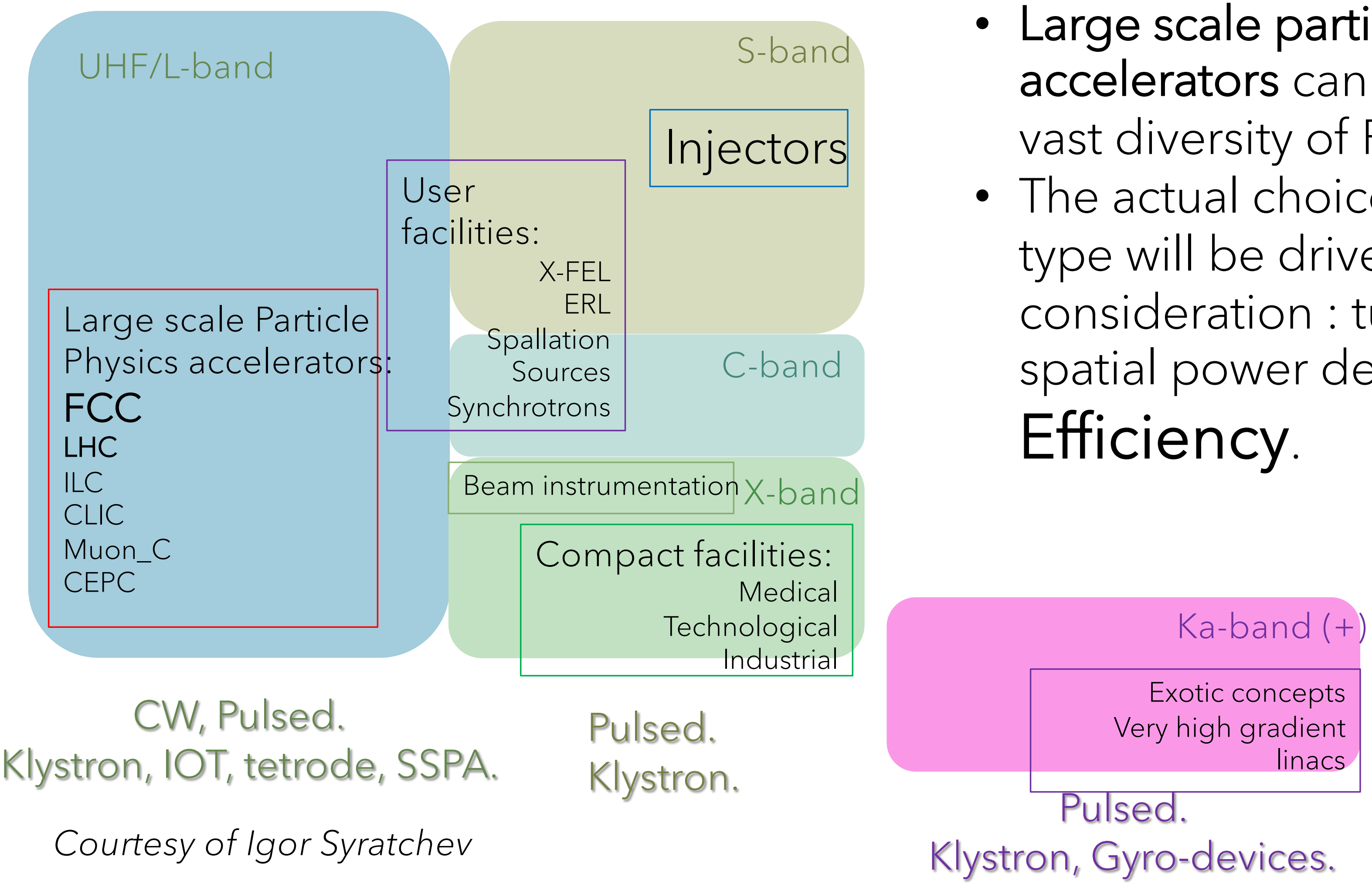
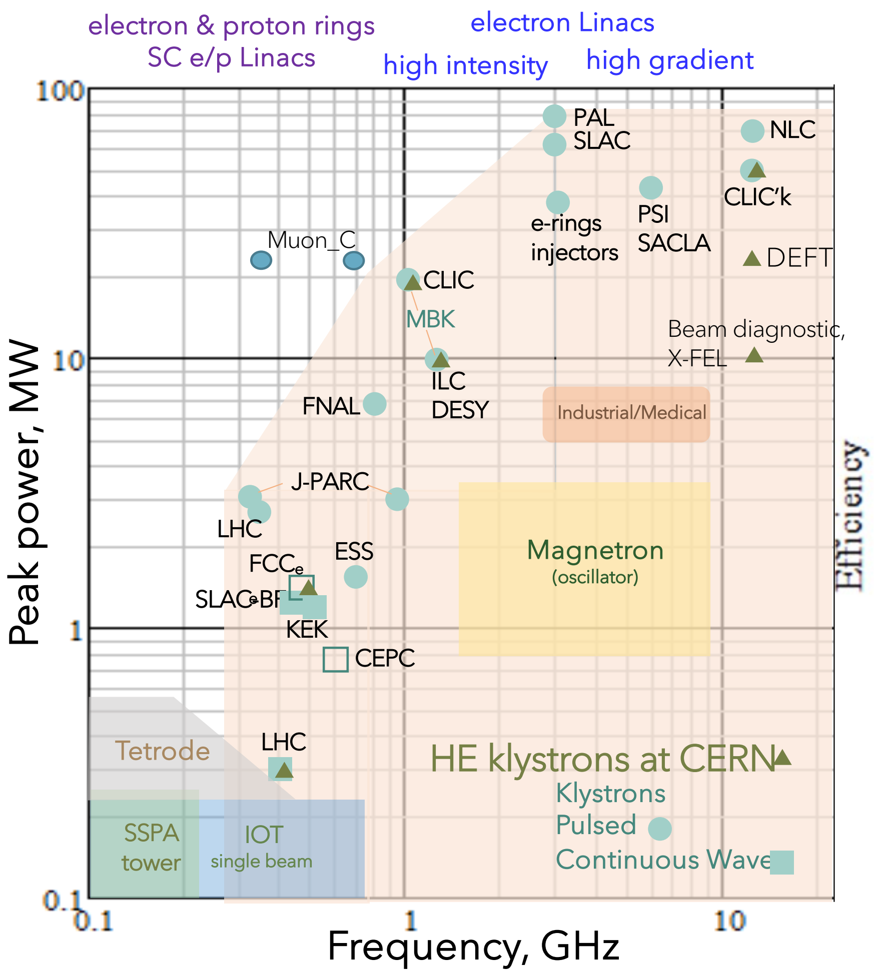
RF sources for science



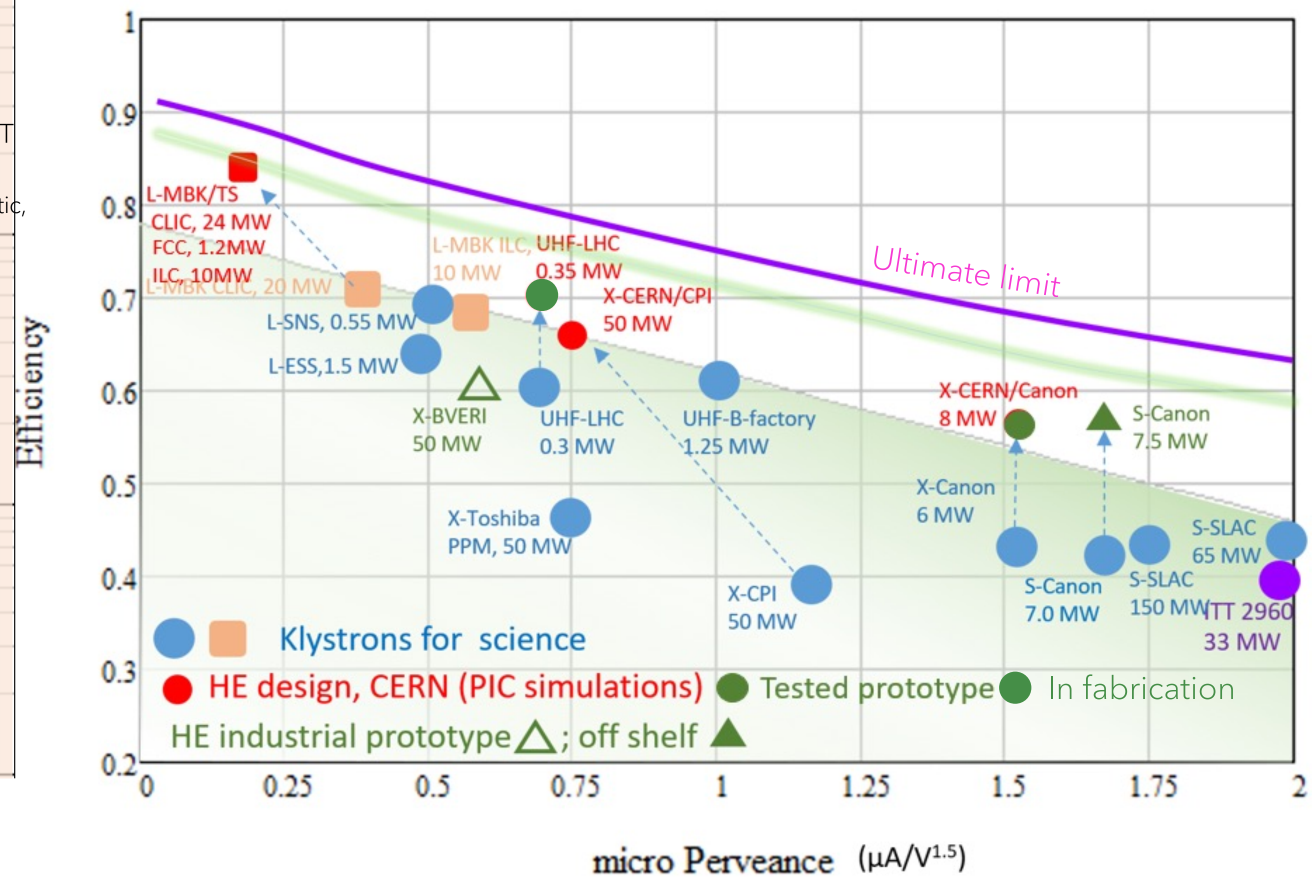
Courtesy of Igor Syratchev

- **Large scale particle physics accelerators** can be operated with vast diversity of RF power sources.
- The actual choice of the RF source type will be driven by the practical consideration : tunnel integration, spatial power density, cost/W and **Efficiency**.

The klystron is a key element of almost all particle accelerators.

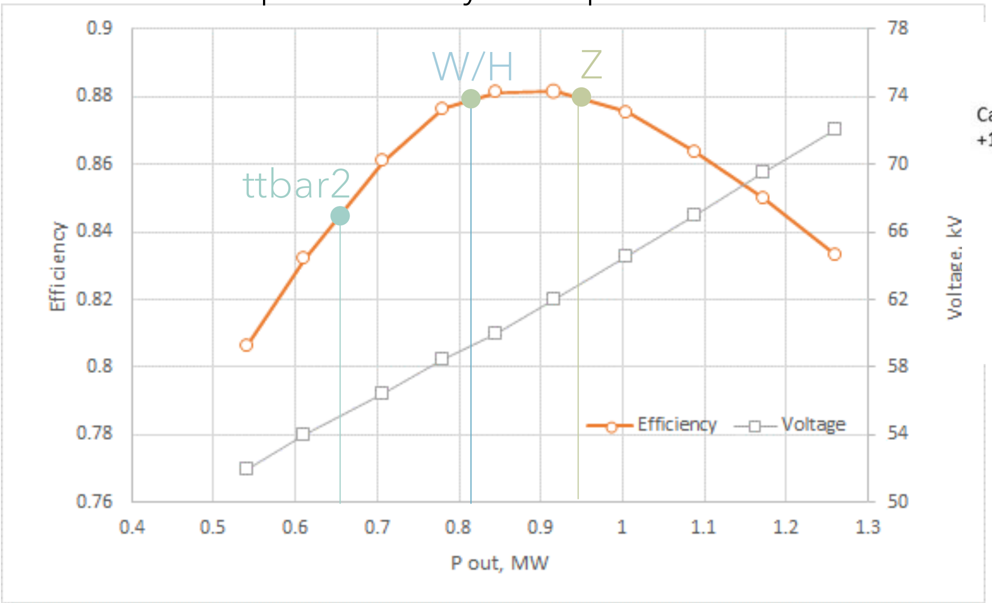


High Efficiency klystrons project at CERN is targeted to improve efficiency and performance of these devices for various applications.

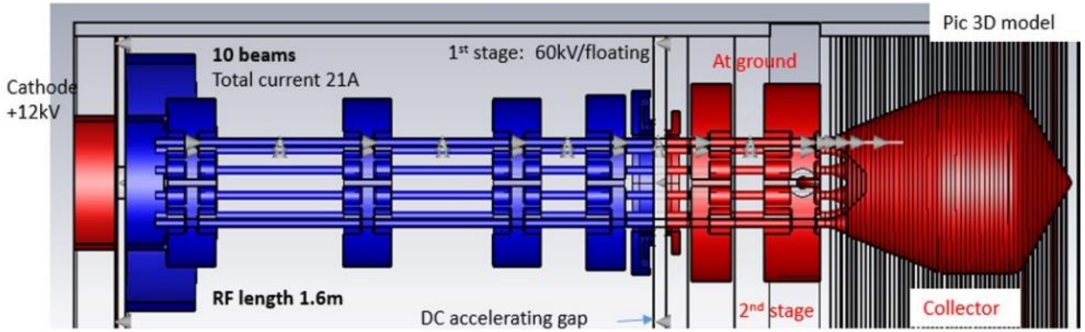


400 MHz KLYSTRON for FCC

Optimized klystron performance.



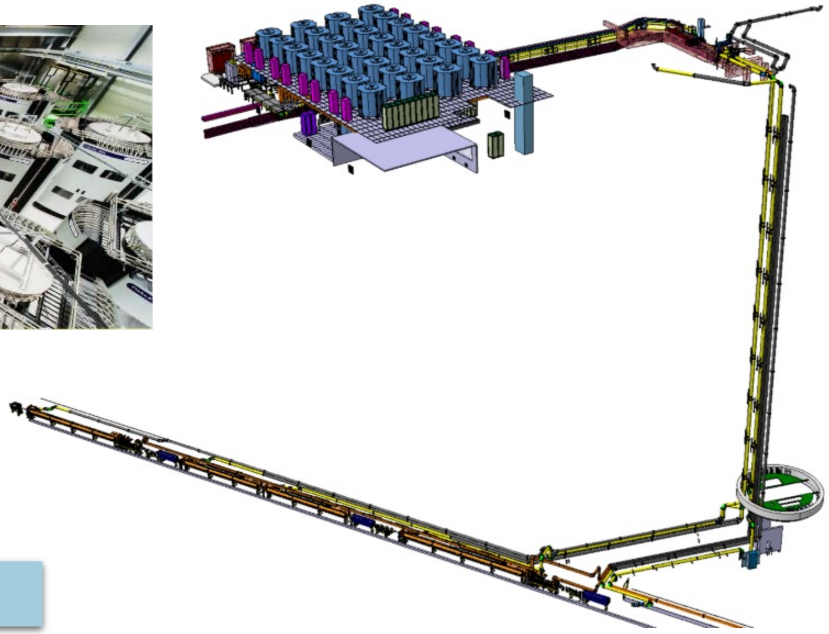
Two stage MBK topology



- Large dynamic range: 0.5MW -> 1.3 MW MW, CW
- Very Efficient: up to 88% (yet in simulations)
- Compact: ~2.5m length in total
- Low voltage: 50-70kV
- High saturated power gain: >40dB

- High efficiency Klystron project at CERN and ULAN develops HE **FCC 0.4GHz, 1MW** MBK klystron as a highest priority item.
- Selected Two-Stage klystron topology provides compact and efficient solution.
- The project time-line suggests that FAT will be performed in **2026**. Strong collaboration with industry is mandatory from the very beginning of the project .
- Within L-band, such a topology can be scaled and used for different high energy large accelerator (**FCC, CLIC, ILC, CEPC, Muon_C**).

SSAA Efficiency



Cavity = **1 MW**

150 m coaxial line = + 0.2 dB = + 5 % = 1.050 MW

Circulator = + 0.2 dB = + 5 % = 1.103 MW

Hybrid combiner 16:1 = + 0.3 dB = + 7 % = 1.175 MW

DC to RF (efficiency ~ **60** %) = 1.960 MW

AC to DC (efficiency ~ 90 %) = 2.175 MW (1'000 kW to be dissipated)

Air cooling station (10 % of 1'000 kW = 100 kW) ~ + 50 kW = 2.225 MW

Water cooling station (90 % of 1'000 kW = 900 kW) ~ + 45 kW = 2,270 MW

Electrical distribution (5 % of 2.270 MW) ~ + 50 kW = **2,4 MW** taken from the grid

Overall efficiency **41,9 %**

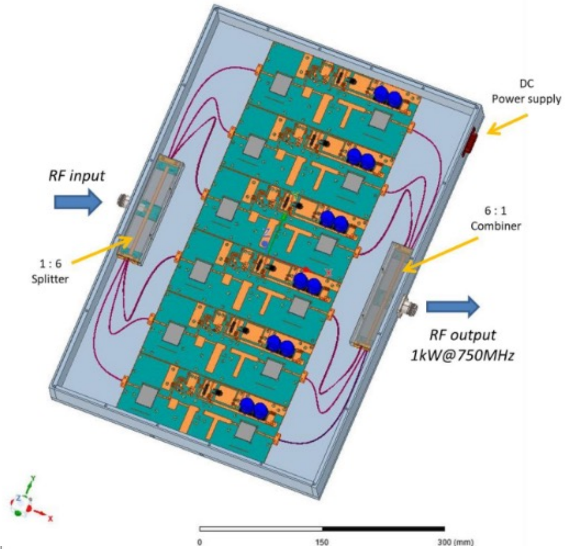
2nd Annual Meeting

iFAST

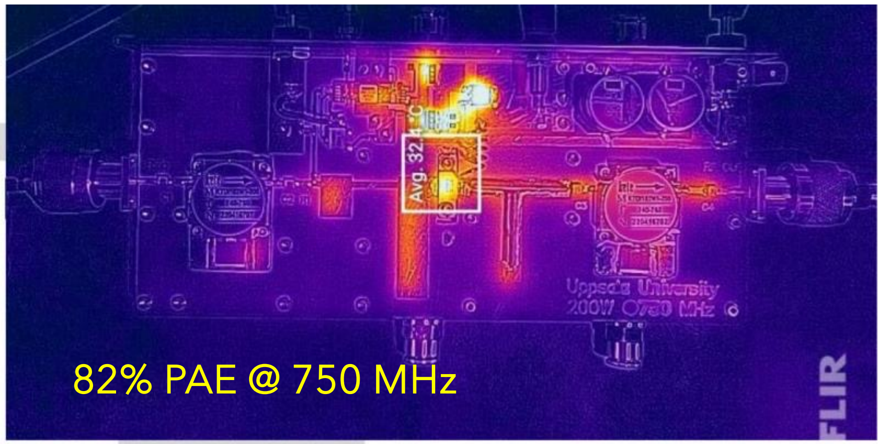
17–21 Apr 2023
NH Hotel, Trieste, Italy
Europe/Zurich timezone

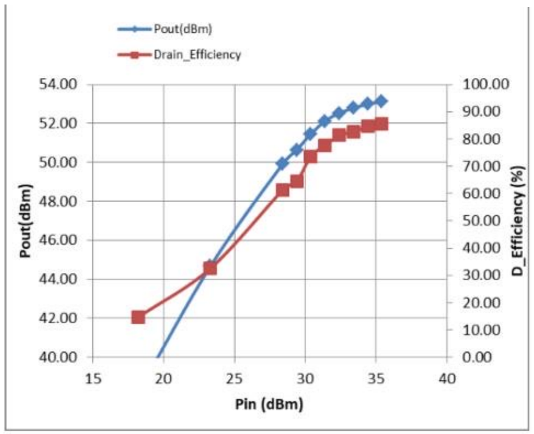
New RF amplifiers based on GaN semiconductors M1 – M24

D. Dancila and A. Mohadeskasaei
(Uppsala University - FREIA)



73.5% PAE @ 750 MHz





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Where does the power supplied to the RF device go?

Power to the beam

- Increases with accelerating gradient
- Increases with beam current

Power dissipated in the device

- Normal vs. super conducting
- Proportional to the pulse length

HOM/Wakefields

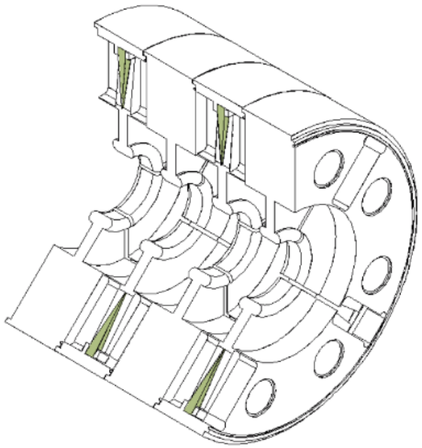
- Lost by the beam and dissipated in the device
- Geometry and aperture dependent
- Increases with beam current
- Negligible power
- Still a considerable load for the cooling system!!

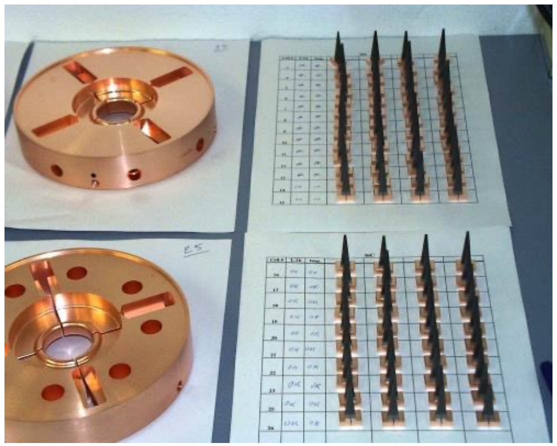
Power extracted

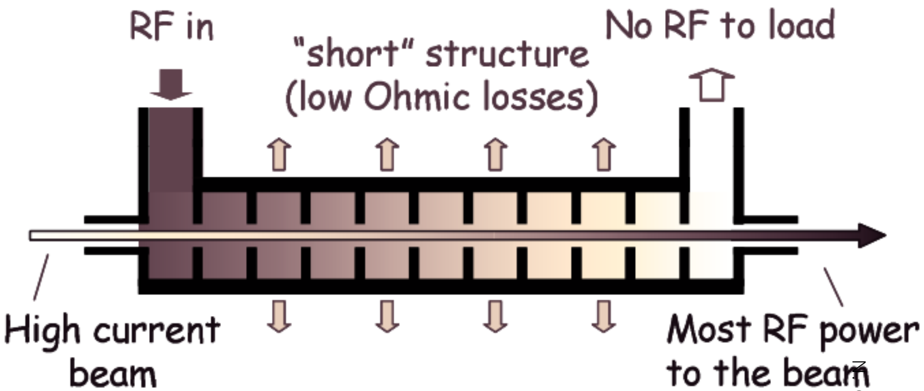
- Energy extracted to a power load
- Only for travelling wave structures

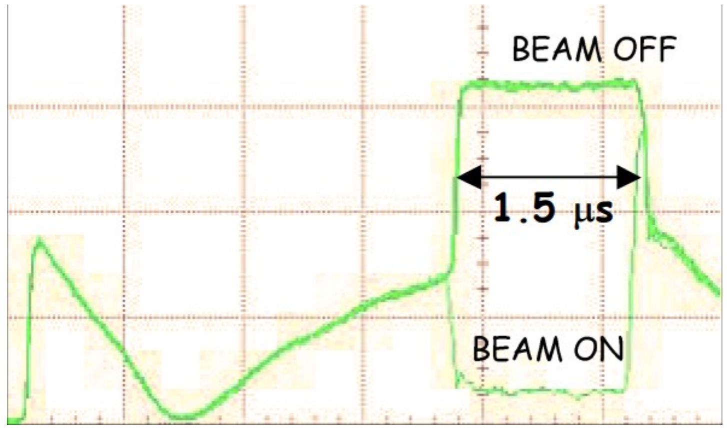
Normal conducting for high efficiency

- Use of travelling wave structures
- Very high beam loading:
  - Large current and high gradient in a very short pulse
- Management of wakefields by low Q plus local extraction/absorption
- SICA 94% RF to beam demonstrated in CTF3









M. Bernard et al. EPAC 2004 Lucerne

SC cavities: cryogenics and static losses

The Carnot limit:

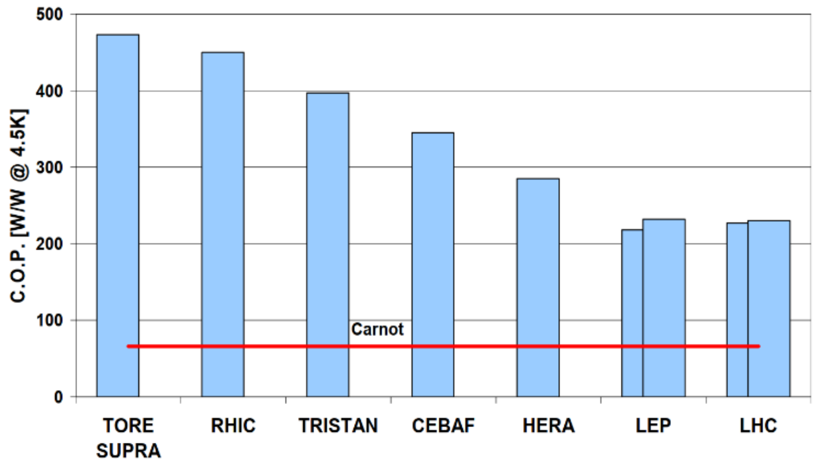
$$W_{min} = Q_i \cdot \left(\frac{T_0}{T_i} - 1 \right) = 1 \cdot \left(\frac{300}{4.5} - 1 \right) = 65.7 \ \ W$$

At 2K 3 x times more power is needed!

Clear advantage to go to materials with high Tc like Nb3Sn, A15 or multilayers

Important to optimized cryostat against thermal leaks

C.O.P. of large cryogenic helium refrigerators



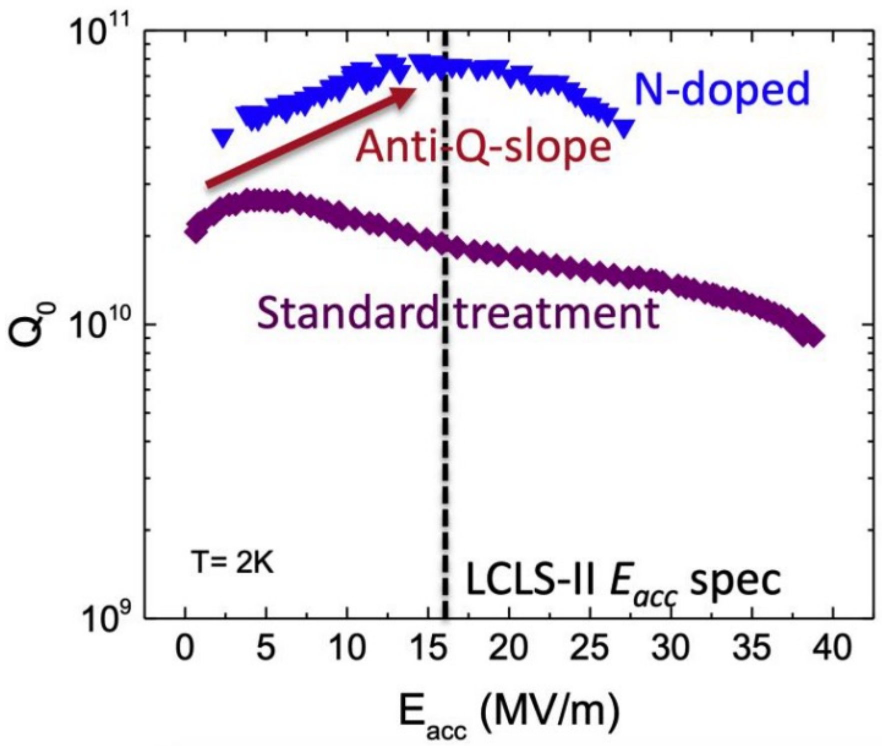
SC cavities dynamic losses

$$Ps = \frac{V_{acc}^2}{\left(\frac{R}{Q}\right) Q}$$

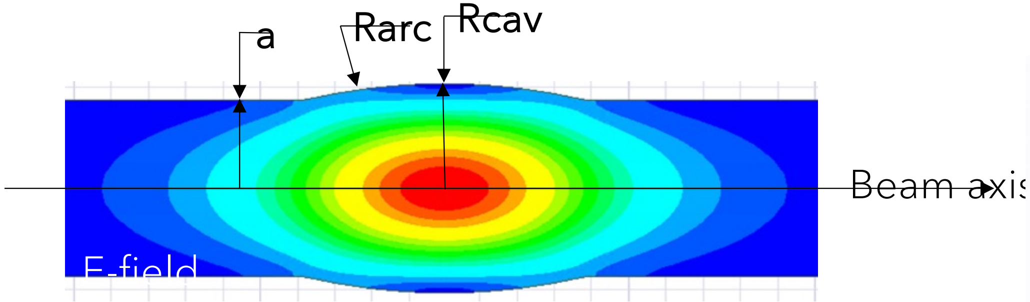
$$\frac{1}{Q} \propto R_S = R_{BCS}(T) + R_{res} = \left(\frac{A\omega^2}{T}\right) e^{-\frac{\Delta}{kT}} + R_{fl} + R_r$$

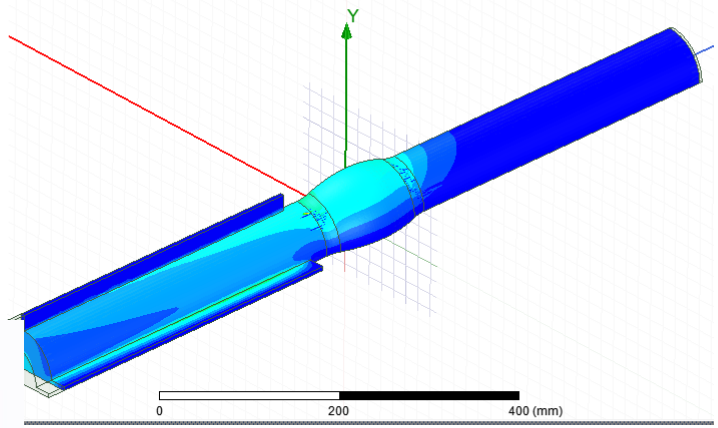
1/Q0

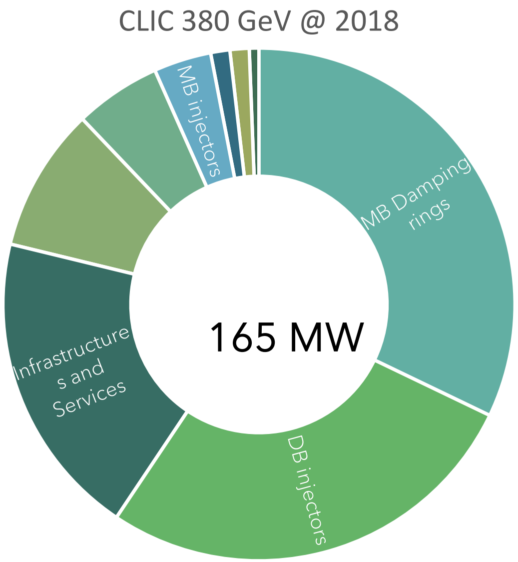
- Cooling procedures
- Material purity
- Manufacturing procedure
- Trapped magnetic flux

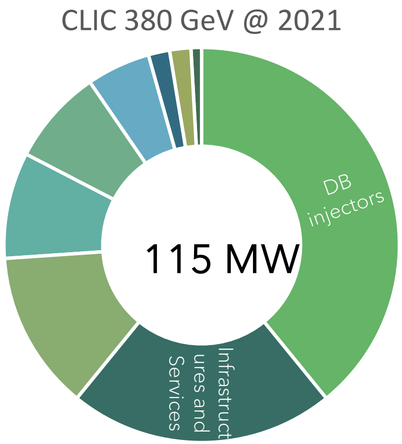


SC cavities. Shape optimization









- Large aperture => low R/Q
- Long cell: ~**λ** **=> low transit time factor**
- **Low field on the cavity wall**

A. Grudiev. 2021 Update of the 380 GeV CLIC power consumption

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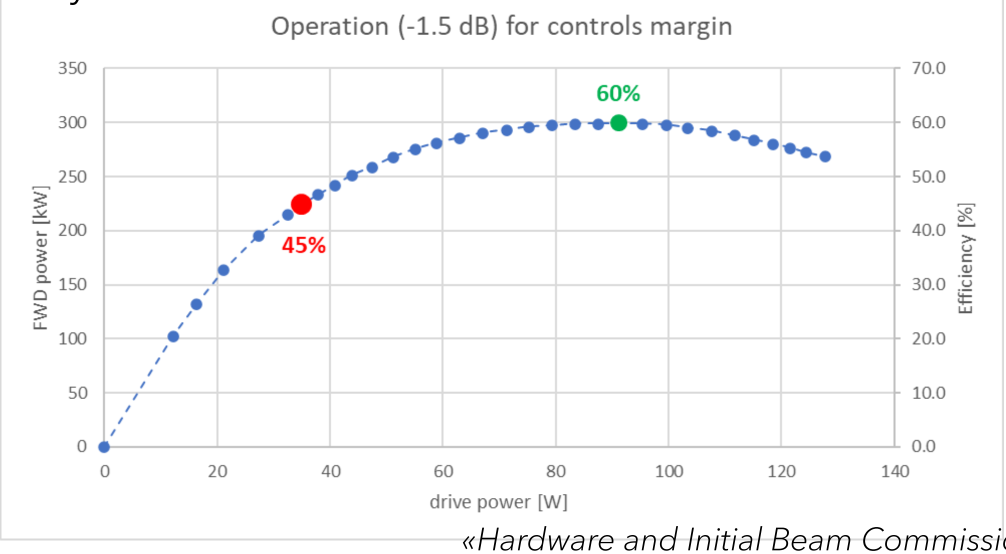
Operational efficiency. Controls margin

- Today's klystrons are rated for 300 kW CW in saturation. Regular operation for klystrons is typically 1.5 dB below saturation
- Polar loop to linearize the klystron gain
- The trip Level prevents from overdriving the klystron



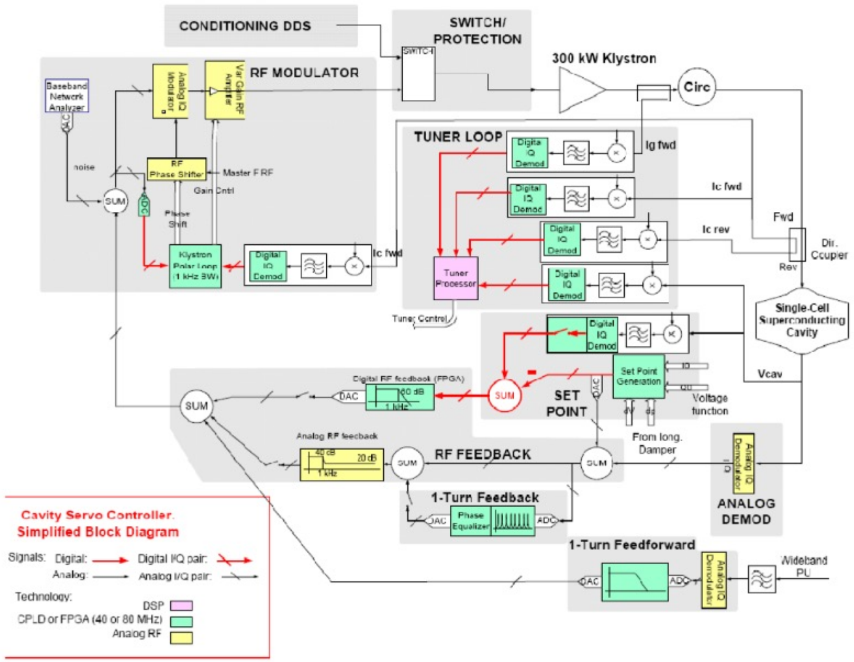
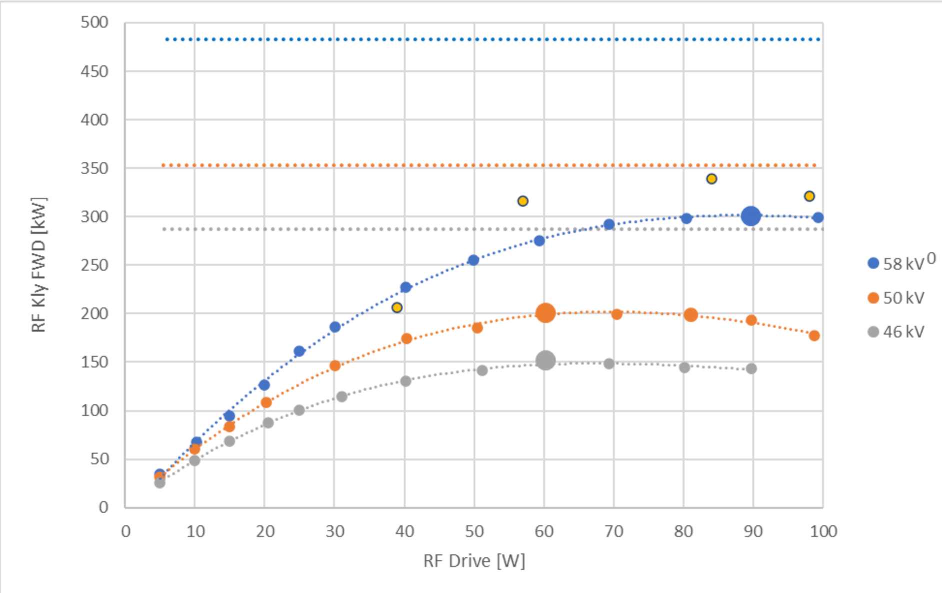
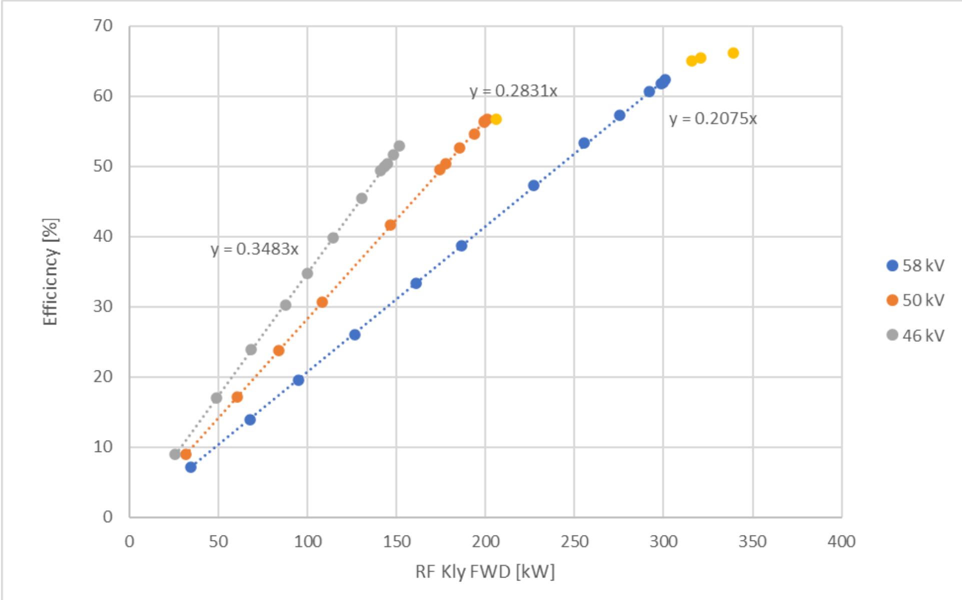


Fig.3: Block diagram of the Cavity Controller

«Hardware and Initial Beam Commissioning of the LHC RF Systems». M.E. Angoletta et al. LHC project report 1172

Operational efficiency. The example of LHC





- Ìn collision, efficiency of the klystron is about 20% (hadrons).
- Looking into reducing the voltage during the ramp

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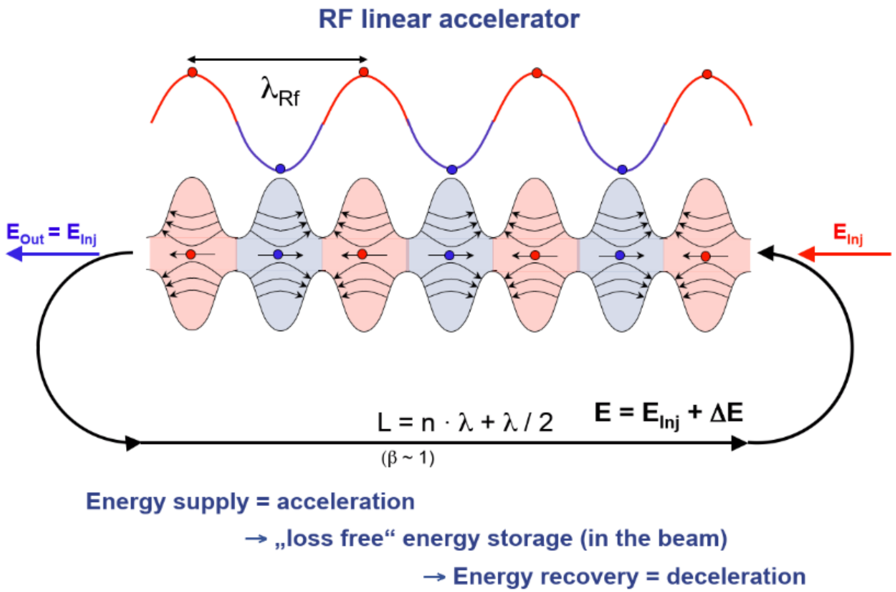
Energy efficiency on ERLs?



- Only a small portion of the power lays in the beam
- Beam power in circular machines is virtual
- Recovery is limited to a small number of turns
- Still, any energy recovery is comparable to all other mentioned improvements
- Practical problems with power couplers

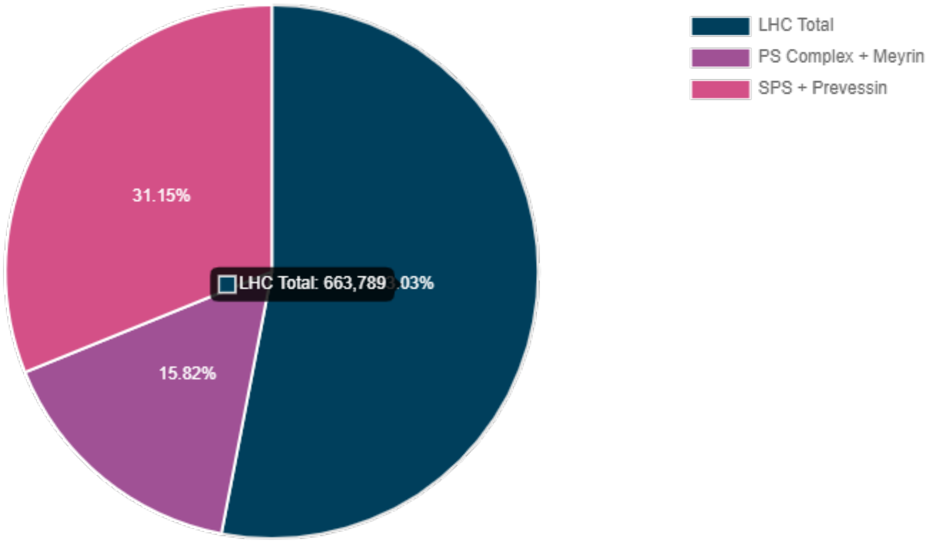
Some thoughts on sustainability

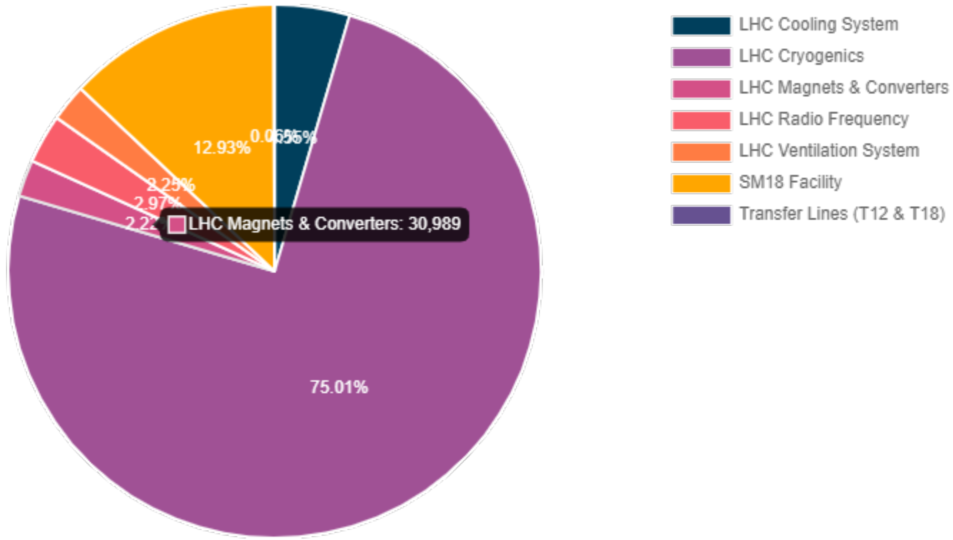
- Air and water cooling are not included in most calculations, and it is extremely inefficient
- Solid state industry rapid change forces updates every 5-10 years with a considerable number of "old technology" spares. Is that sustainable?
- Measuring and estimating power consumption is mandatory
- CO_2 footprint calculations are even more rare.
- Many initiatives but all different
- Welcome all initiatives to agree on a set of rules for evaluation of CO_2 and sustainability in general

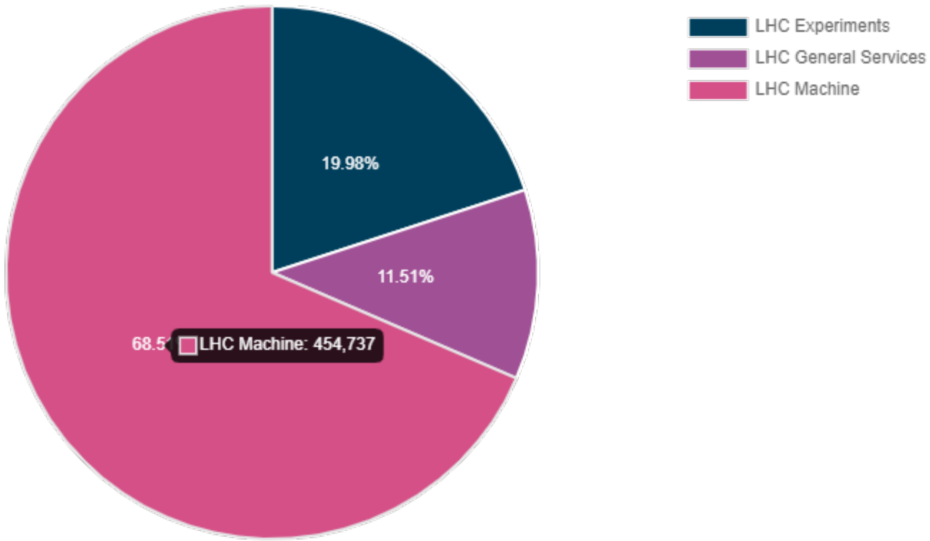
Summary

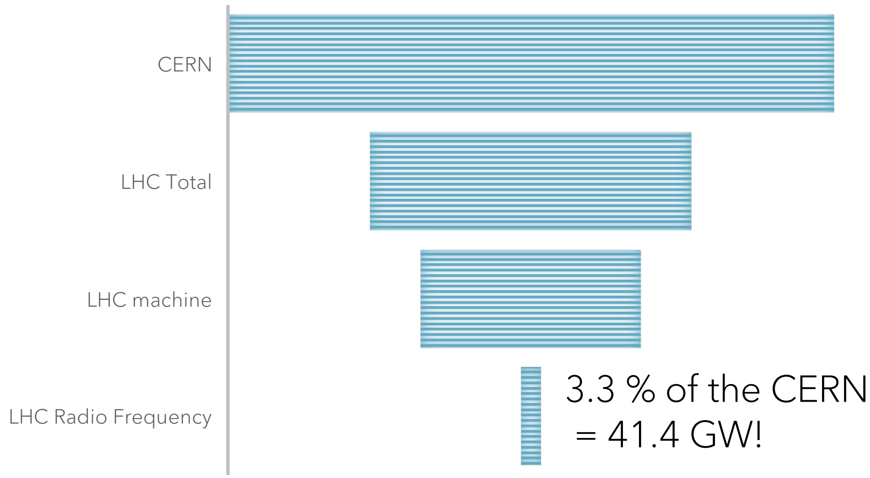
- Data from operating machines is paramount to improve our current and future systems
- RF will be the main contributor to the energy spent by the next pp collider
- The main factors are being investigated and improved as we speak
  - Power sources: klystrons and solid state
  - SC Cavities: material, process, operation
  - NC structures:
  - <u>However, this is not a one size fits all!!!</u>
- Operation is not optimized for energy efficiency but for reliability
- The ERL case is promising but needs further development

THANKS


LHC Total
PS Complex + Meyrin
SPS + Prevessin
31.15%
15.82%
LHC Total: 663,789


LHC Cooling System
LHC Cryogenics
LHC Magnets & Converters
LHC Radio Frequency
LHC Ventilation System
SM18 Facility
Transfer Lines (T12 & T18)
12.93%
75.01%
LHC Magnets & Converters: 30,989


LHC Experiments
LHC General Services
LHC Machine
19.98%
11.51%
LHC Machine: 454,737


CERN
LHC Total
LHC machine
LHC Radio Frequency
3.3 % of the CERN
= 41.4 GW!