Sustainable RF for future accelerators

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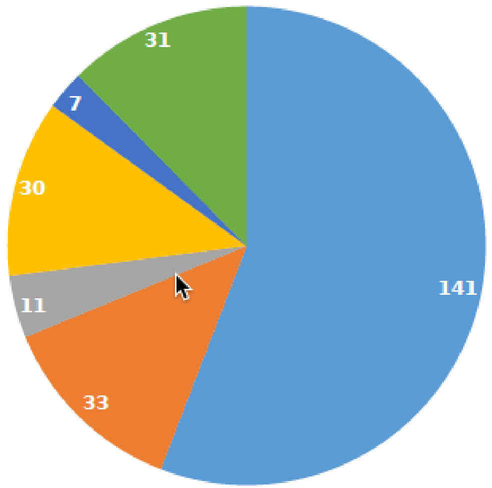
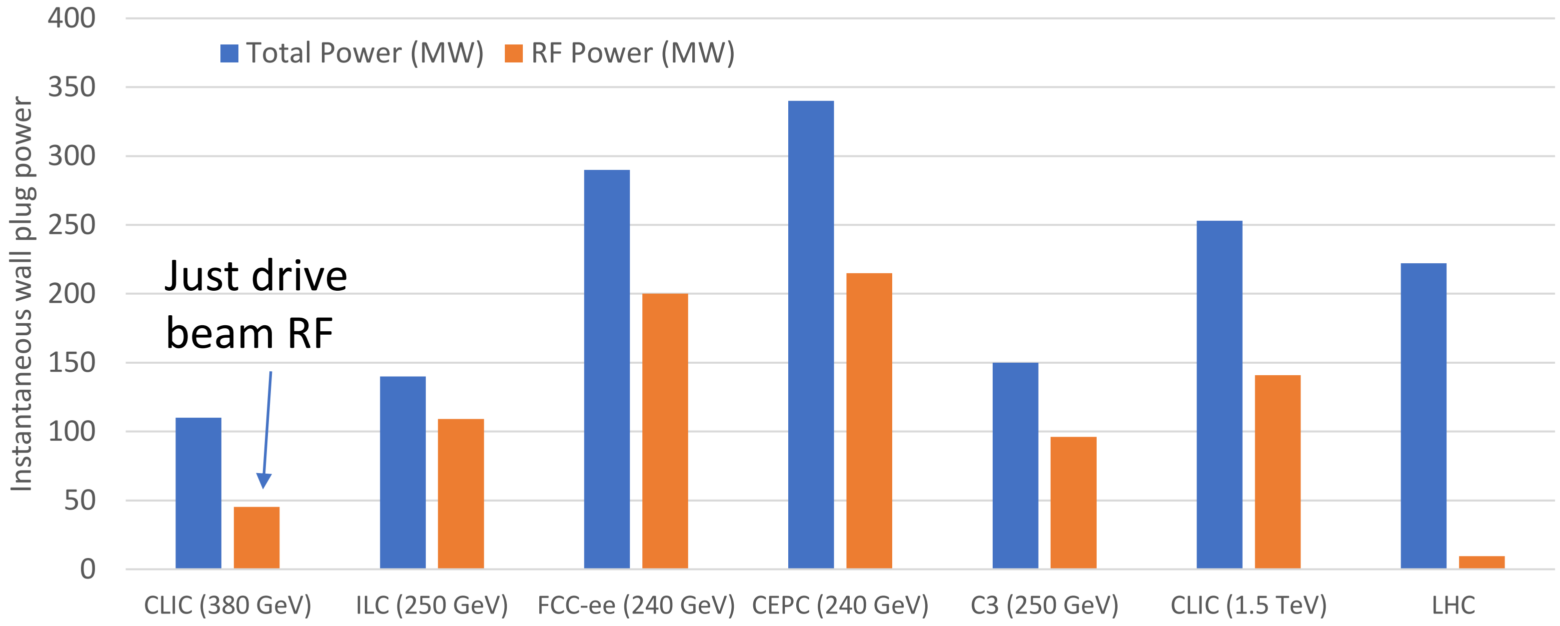
How much of the power budget for future machines is RF?

1.5 TeV CLIC Power MW





- RF power includes all DC power, modulators, chillers, liquifiers and pumps, and magnets required as part of the entire RF system
- Most linacs have between **40-77%** of their total site power going into the RF system.
- Synchrotron need more RF power at higher energy due to frequency scaling of synchrotron radiation

Stapnes CLIC mini workshop 2023

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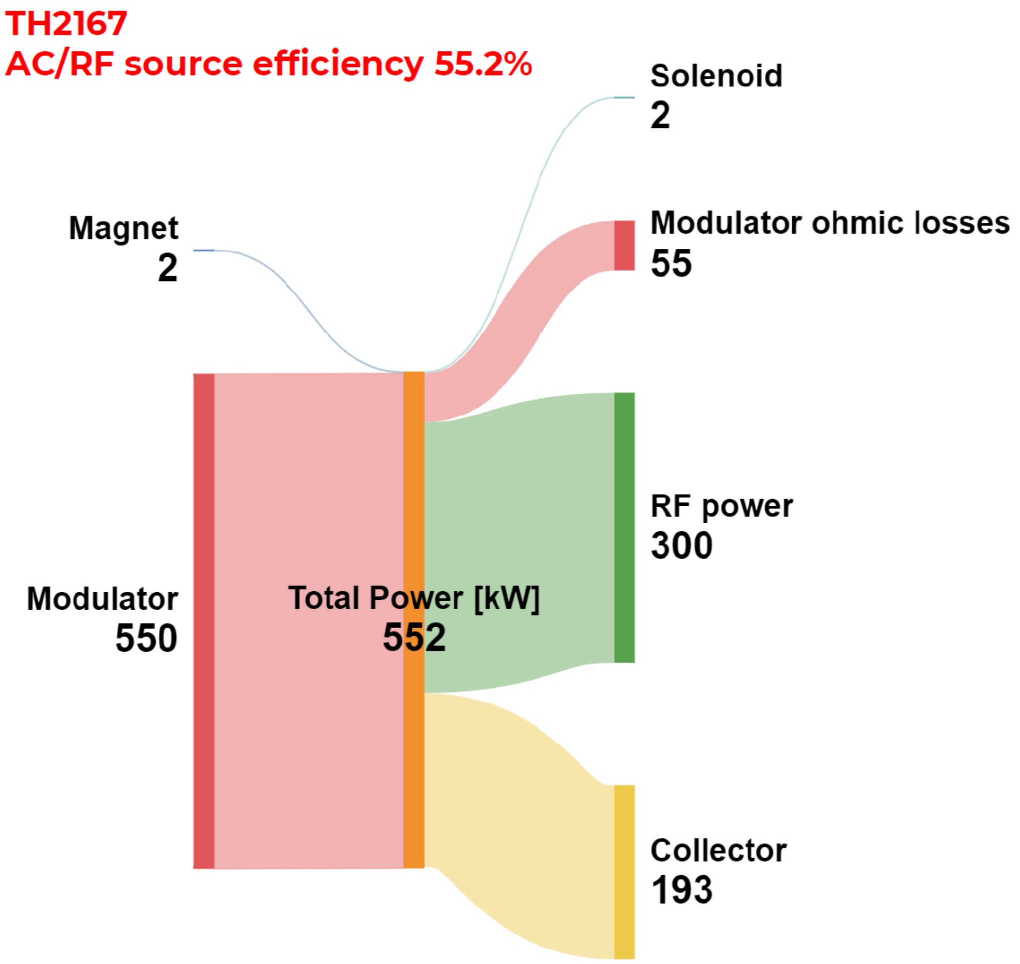
Medical and Industrial linacs

- Modulator is ~10 kW
- Magnetron RF has a duty cycle of 0.1 %, and is 5 MW ~5 kW so around 50% efficiency
- Beam Power is typically 100 μA 6 MeV so 600 W average
- Efficiency is around 6%
- Standby mode is around 50-100 kWh per day which is larger than operational power per day

- There are 11440 medical linacs in the world, which is an installed power demand of 500 GW
- Linacs operate on average 9 hours a day 5 days a week
- 6500 fractions (a round of treatment) are delivered per year per linac with the average fraction 15 min hence around 1625 hours operation per year
- Hence annual power of all radiotherapy machines is **~500 GWh**
- ILC's annual power use is 700 GWh so **1 linear collider uses the same energy annually as the entire worldwide install base of radiotherapy linacs** (11,440)

RF amplifiers

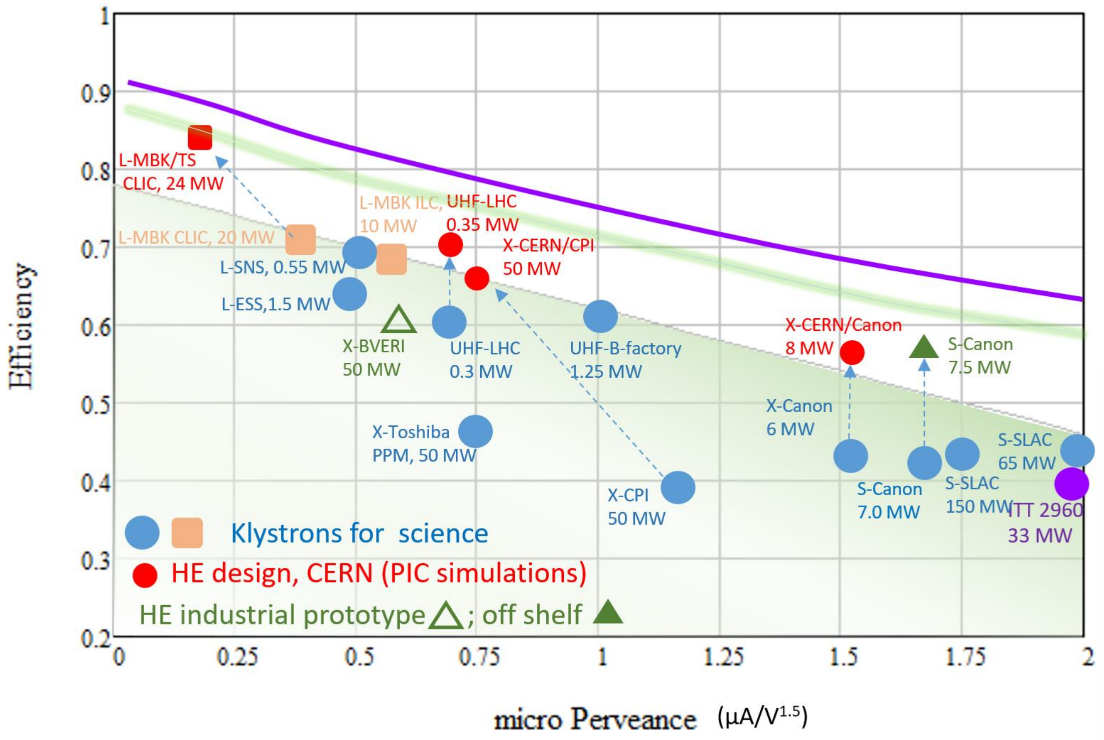
- RF amplifiers are not particularly efficient, the most common type is a klystron
- Typically have a max efficiency **40-70%**
  - 10% of the power goes to modulator losses
  - **35% is heat in the collector from the spent beam**
  - Efficiency limited by extraction of spent beam without reflection and beam energy spread (limited by slowest electrons)
- But only have that efficiency at max power, need LLRF headroom so typically operate backed off (for example ESS uses 25%), **reducing the operational efficiency by around 10%**



Nuria Catalan Lashera, IFAST meeting, 2023

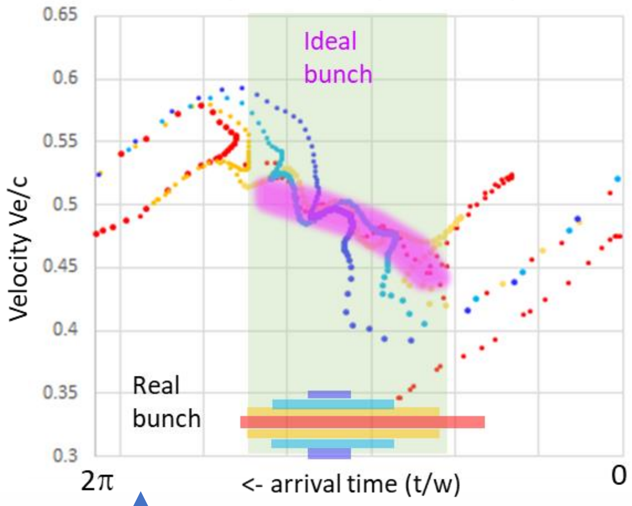
How efficient can RF amplifiers be?

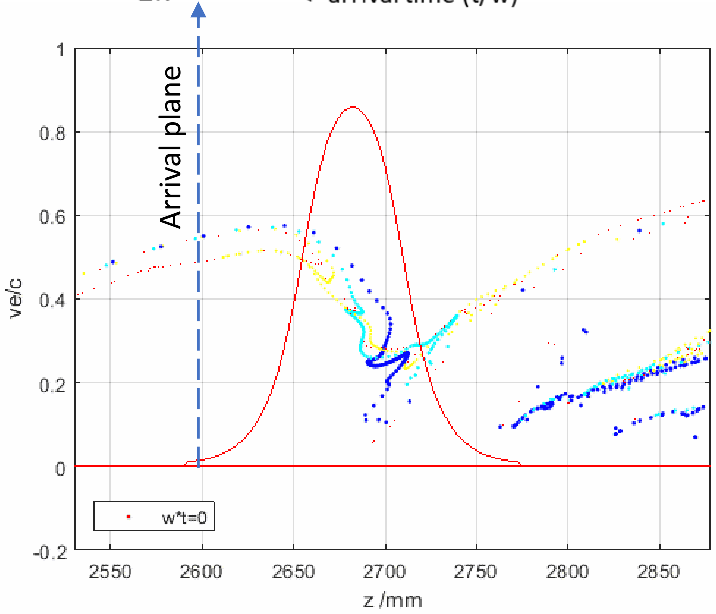
- Perveance is a measure of space charge ($I/V^{3/2}$)
- The higher the perveance the lower the efficiency
- Going to a higher efficiency means a higher voltage which causes other issues
- Recent studies have shown we can **increase efficiency by around 10-15%** from current maximum
- Only a few percent more could be gained before hitting the ultimate limit



The limits are due to energy spread in the extracted beam after the final cavity and the need to avoid reflecting electrons back (which would cause oscillations)

Bunch phase space in the vicinity of the klystron output cavity





High Efficiency Klystrons
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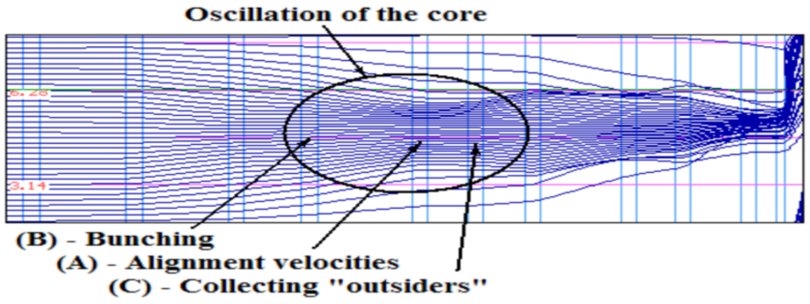
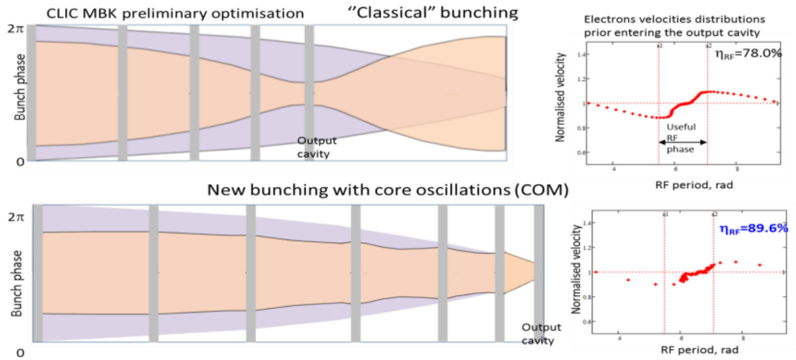
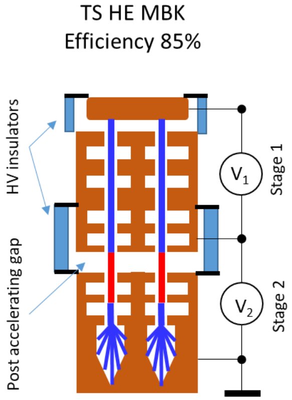
New Klystron Concepts

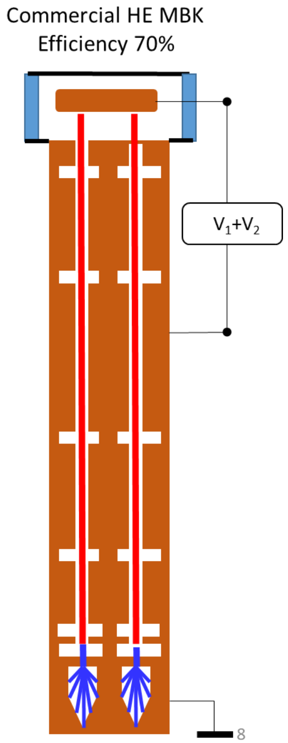
How do we achieve bunch saturation? We cause the core of the bunch to oscillate while focusing the anti-bunch electrons slowly. There ae 4 ways to do this:

- Bunch-Align-Collect (BAC): Using lots of RF cavities closely spaced
- Core oscillation method (COM): Using the beams space charge forces
- Core stabilization method (CSM): Using higher harmonic cavities
- Two stage (TS): Making COM shorter by using a low beam energy and post-accelerating



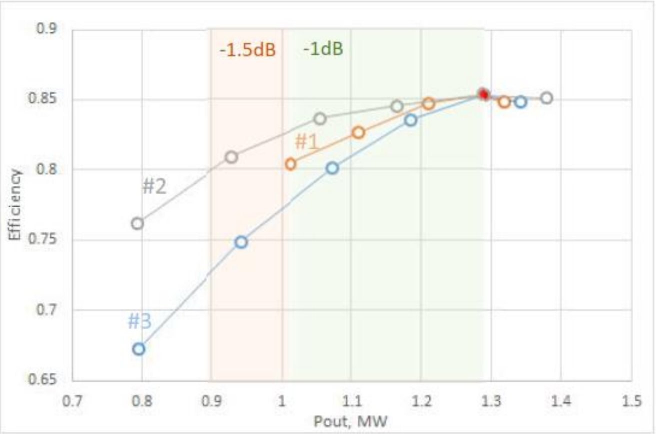


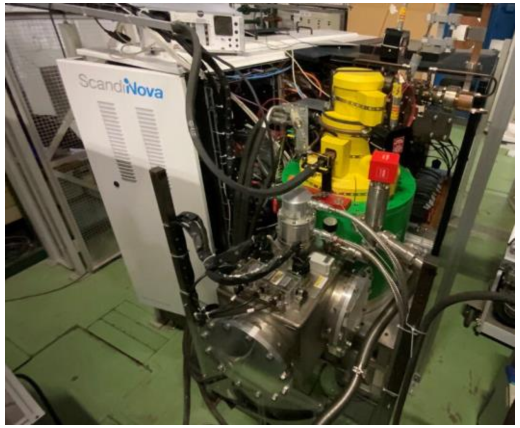




Other Klystron Issues

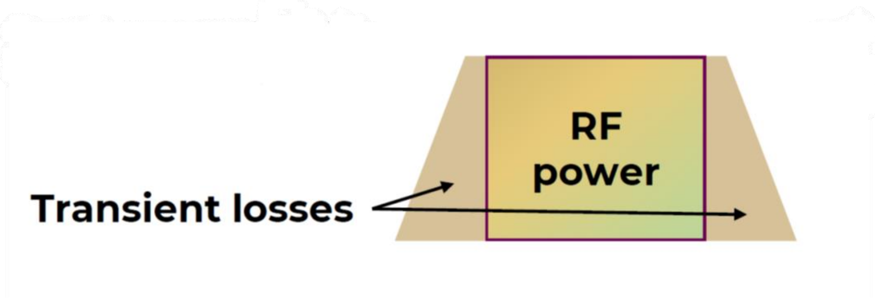
- **Smart Modulators:**
  - ESS have demonstrated power modulation without reducing efficiency by varyingDC voltage
  - 'Smart' Modulator concept that at any required power level, klystron will be **operated at saturation** by adjustment of modulator voltage on a microsecond time scale. This **adds 10% to the operational efficiency**





- Solenoid magnets:
  - A Cu-based solenoid magnet, currently consuming ~20 kW/Klystron, corresponding to ~ 100 MW for ~ 5,000 Klystrons for CLIC-380.
  - This can be significantly reduced by using a superconducting or permanent magnet solenoid

- Transient Losses:
  - At each stage there is a rise time that gets sequentially worse
    - The modulator has a rise time
    - The klystron has a rise time
    - The cavity has a fill and empty time (for SRF this is on the order of ms)
  - The power during the rise and fall is not suitable for acceleration so is lost energy



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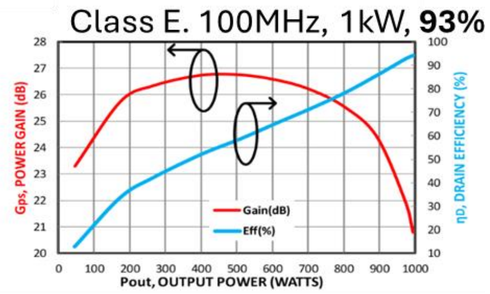
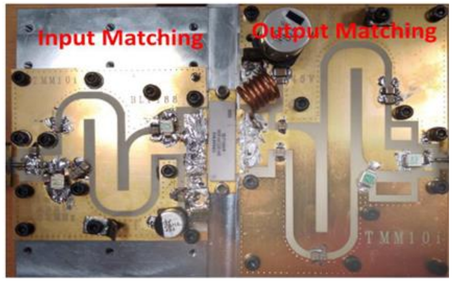
Are SSPA a solution?

- Transistors can achieve very high efficiency below 1 GHz does that mean they could be a solution for sustainable accelerators?



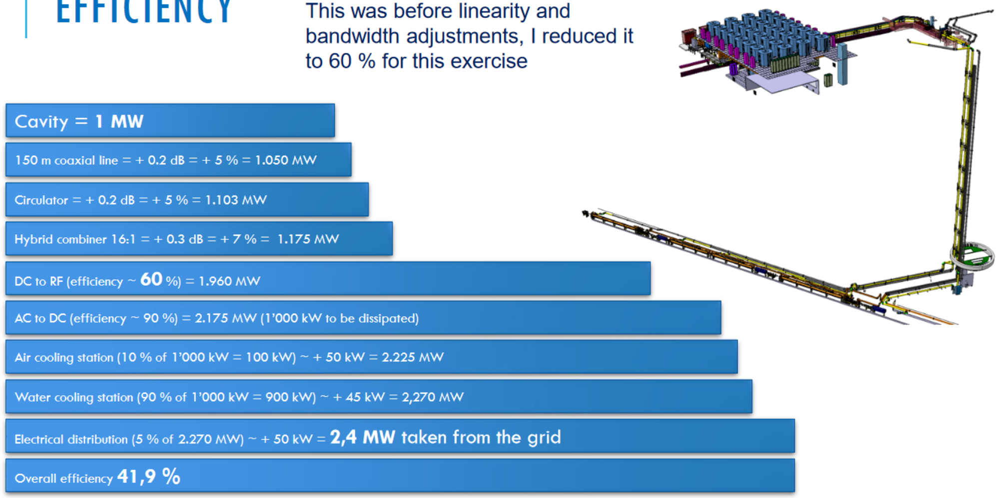


- Transistors are limited to 100-1000 Watts so relevant powers require combining many transistors
- This is a lossy process, for a 200 MHz 1 MW amplifier the efficiency is **only 40%**
- Doesn't scale to higher powers of frequencies well

EFFICIENCY

Thales design report: 'Le rendement des blocs RF avec les MRFE6VP61K25N est de l'ordre de 66 % (valeur conservative)'

This was before linearity and bandwidth adjustments, I reduced it to 60 % for this exercise



Chillers

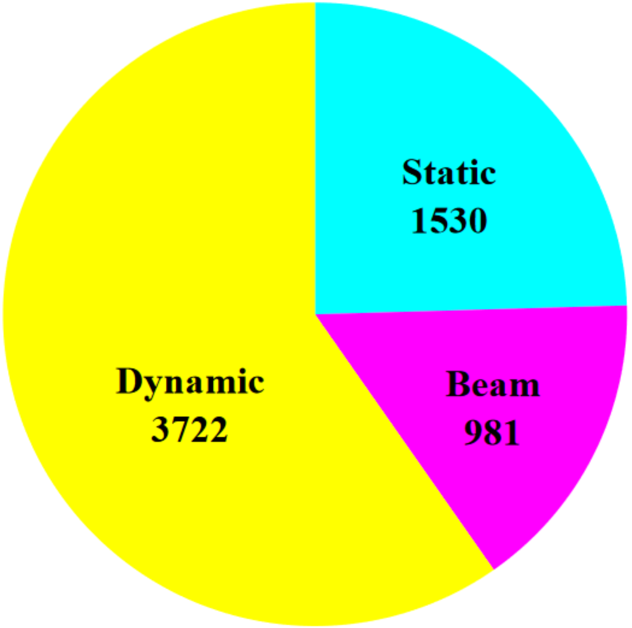
- There is often a desire to lump chillers for RF in with conventional facilities but this hides the true energy consumption of the RF system.
- Improving the efficiency of the RF system also improves the power required from the chillers
- Our Chillers are refrigeration based systems, the efficiency of the whole process is about **60% to 70%.** This means to provide 100 kW cooling, the plug power is around 35kW.
- Also heats up the room (air conditioning costs)
- Including the modulator and chiller **every Watt of RF saved from sustainable tech reduces the wall plug power by 1.5 Watts**

SRF

- By going to SRF we reduce the RF power loses, but we then need cryogenics. How does this change power usage?
  - All refrigerators have a technical efficiency, η_T of 20%-30%
  - The Carnot efficiency is given by

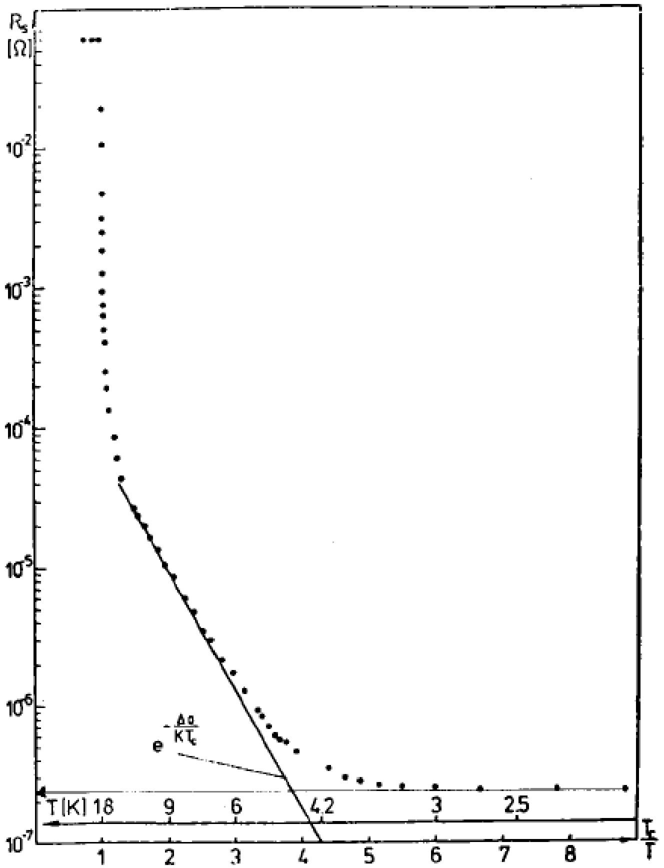
$$\eta_C = \frac{T}{300 - T}$$

  - The dynamic heat load, P_c, is the rf power dissipated in the cavity walls.
  - A static heat load, P_s, adds an additional heating (~5-10 W)
  - Liquid helium transfer lines require 0.1-1W per metre, so total loss is length L (More efficient lines can be used)
  - It is standard to fill to an overcapacity, O (~50%)
  - Overall efficiency of a refrigerator at 2 K temperature is around **0.1 %** to improve this we need to run at a higher temperature to improve Carnot efficiency

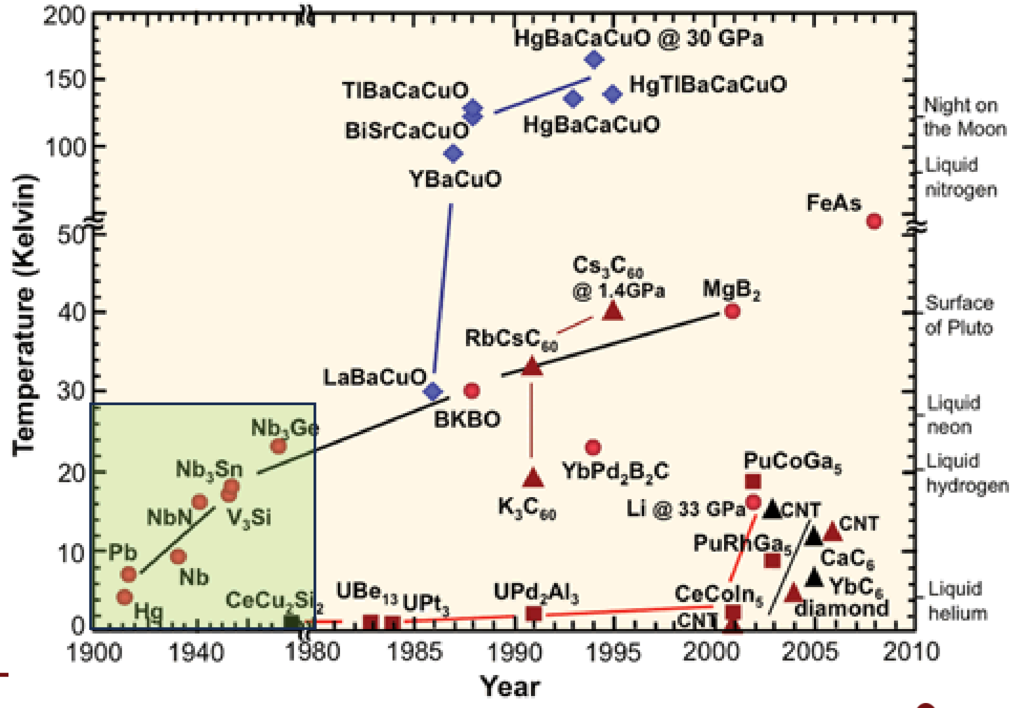


ESS cryo loads

RF Superconductivity Transition Temperatures



- SRF losses increase exponentially with temperature reaching normal conducting values at a transition temperature T_c
- For **Nb** T_c is **9.3 K** so operation temperature is 2-4 K
- To operate at higher temperatures we need materials with higher T_c



- Unfortunately most of these have high RF losses. The green box shows those suitable for RF
- The best candidates are the A15's like **Nb$_3$Sn** which has a T_c of **18.3 K**
- It is however brittle so depositing as a thin film may be the best approach

$$R_{BCS} = A\frac{1}{T}\omega^2 \exp\left(-\frac{\Delta(T)}{kT}\right)$$

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Potential Impact of Thin Film SRF Cavities

- **Using UK XFEL as an example:**
- The cryogenic system required to operate the UK XFEL linear accelerator at **2 K** will consume **~8 MW** of electrical power.
- If we can successfully develop an equivalent thin film coated cavity that can operate at **4.2 K** then the power requirement will reduce to **~2.7 MW.**
- The power consumption for the cryoplant per year will fall from **58 GWhr to 19 GWhr**. At current prices this equates to **£11.5m per year or 3000 tCO2e/yr**, assuming 2030-40 grid intensity of 77.4 gCO2e/kWh.
- Currently **STFC is investing <£1m/yr** into this R&D. If we want to reap the benefit of this technology on our pipeline projects **this investment needs to radically increase.**

From ISAS presentation P Williams STFC

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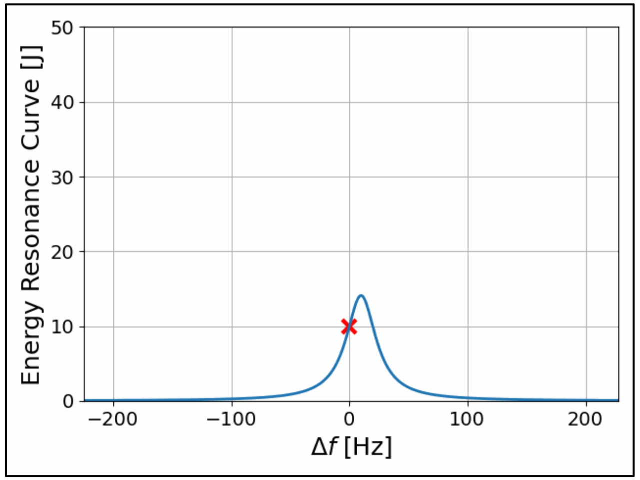
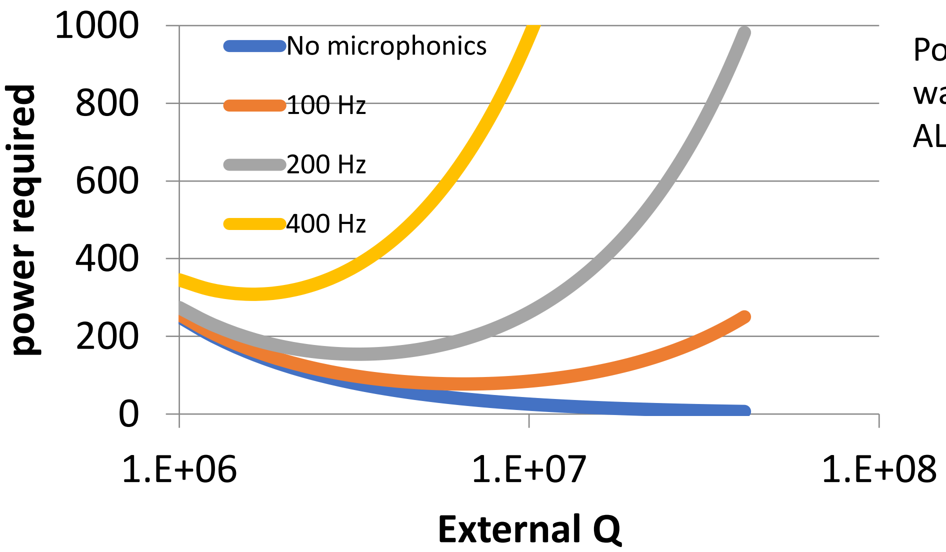
Microphonics

- Microphonics cause the cavity resonant frequency to vary in time by anywhere from 10 Hz to 1 kHz.
- As we have seen before the **reflections are dependent on the difference** between the drive and natural frequencies.





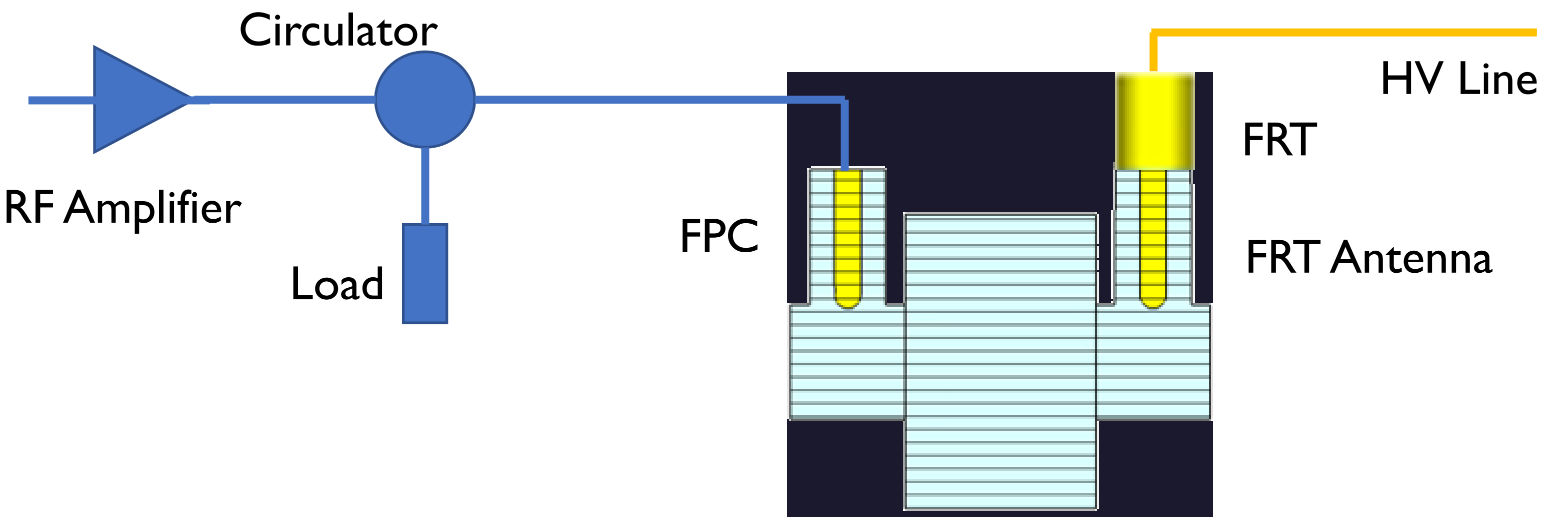
Power demand for 1 watt ohmic heating in ALICE

$$S_{11} = \frac{V_-}{V_+} = \frac{\beta - 1 - i\delta}{\beta + 1 + i\delta}$$

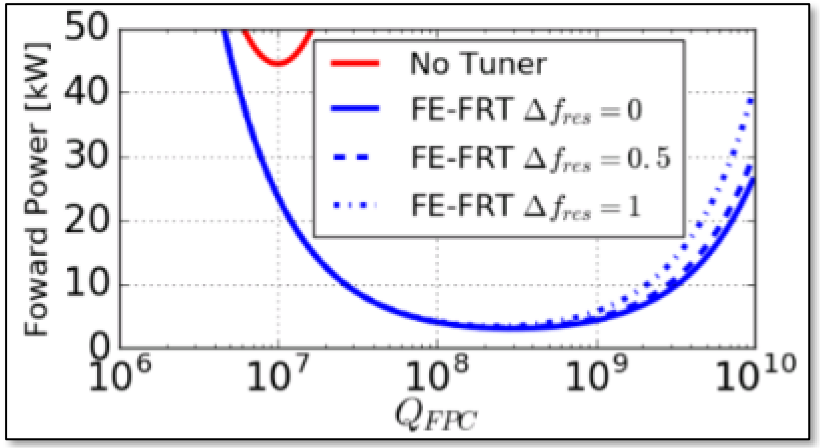
- As the detuning angle is proportional to the Q factor it leads to an **poor coupling** for SRF cavities, which have **high Q's**.
- To avoid this a **lower external Q** is chosen than the ohmic Q, ie the coupler is not matched.

$$P_+ = \frac{V_c^2 (1+\beta)^2}{8R\beta}\left(1 + 4Q_L^2 \frac{\Delta\omega^2}{\omega^2}\right)$$

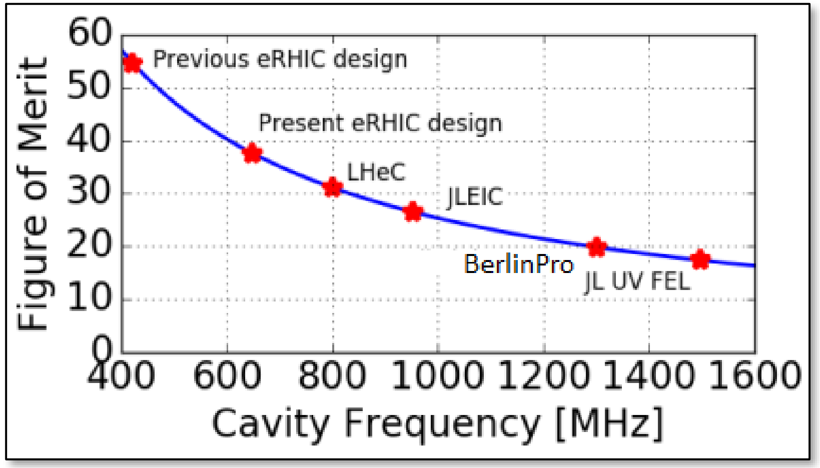
FRT Concept



- An Fast reactive Tuner (FRT) is a shorted co-axial structure containing a ferro-electric element
- RF power flows into the FRT and is reflected back to the cavity
- Voltage applied to the ferro-electric changes its permittivity
- Permittivity change → Phase change of the reflected power → Cavity frequency change
- Tuning speed measured at less than 600ns, limited by HV circuit

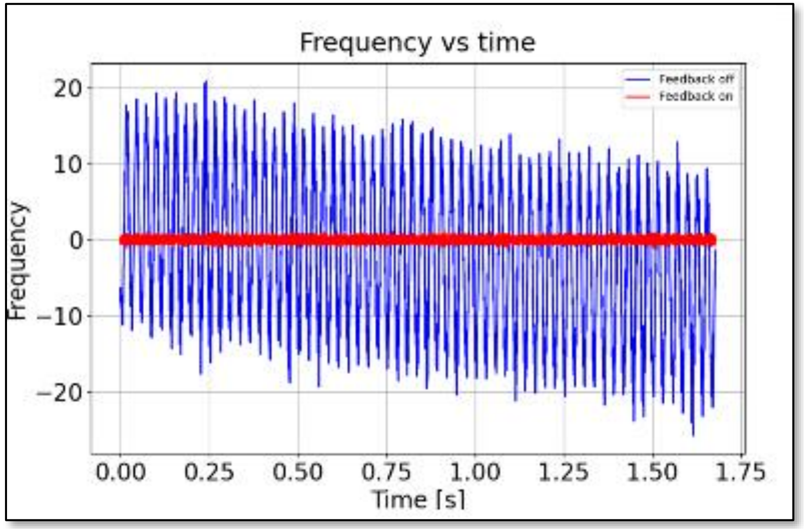


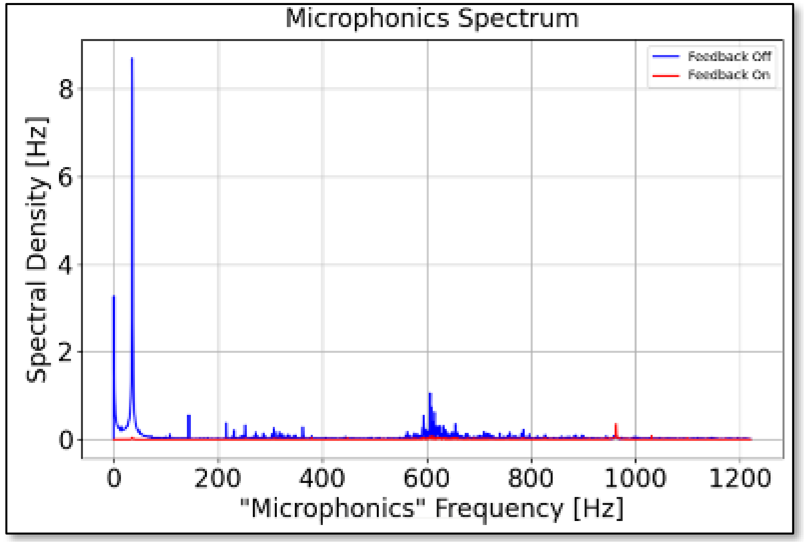
Case study: RF power for PERLE vs QL with and without FRT

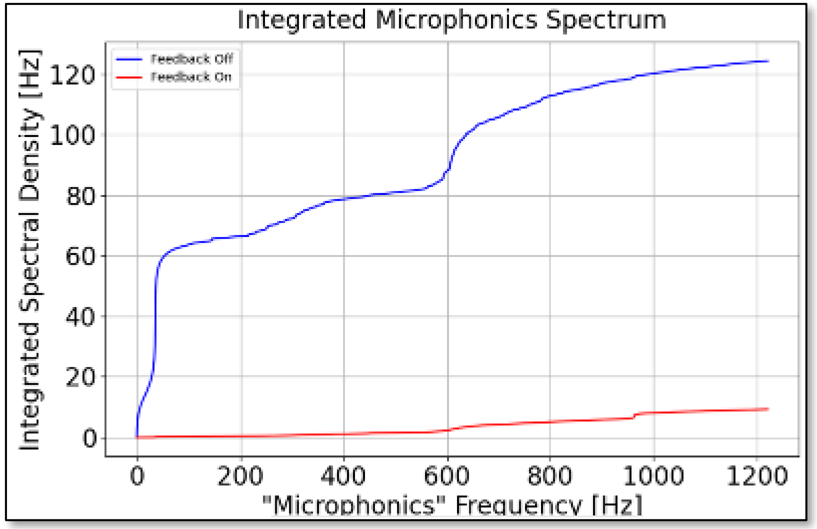


Estimated FRT FoM vs RF frequency

Microphonics suppression results







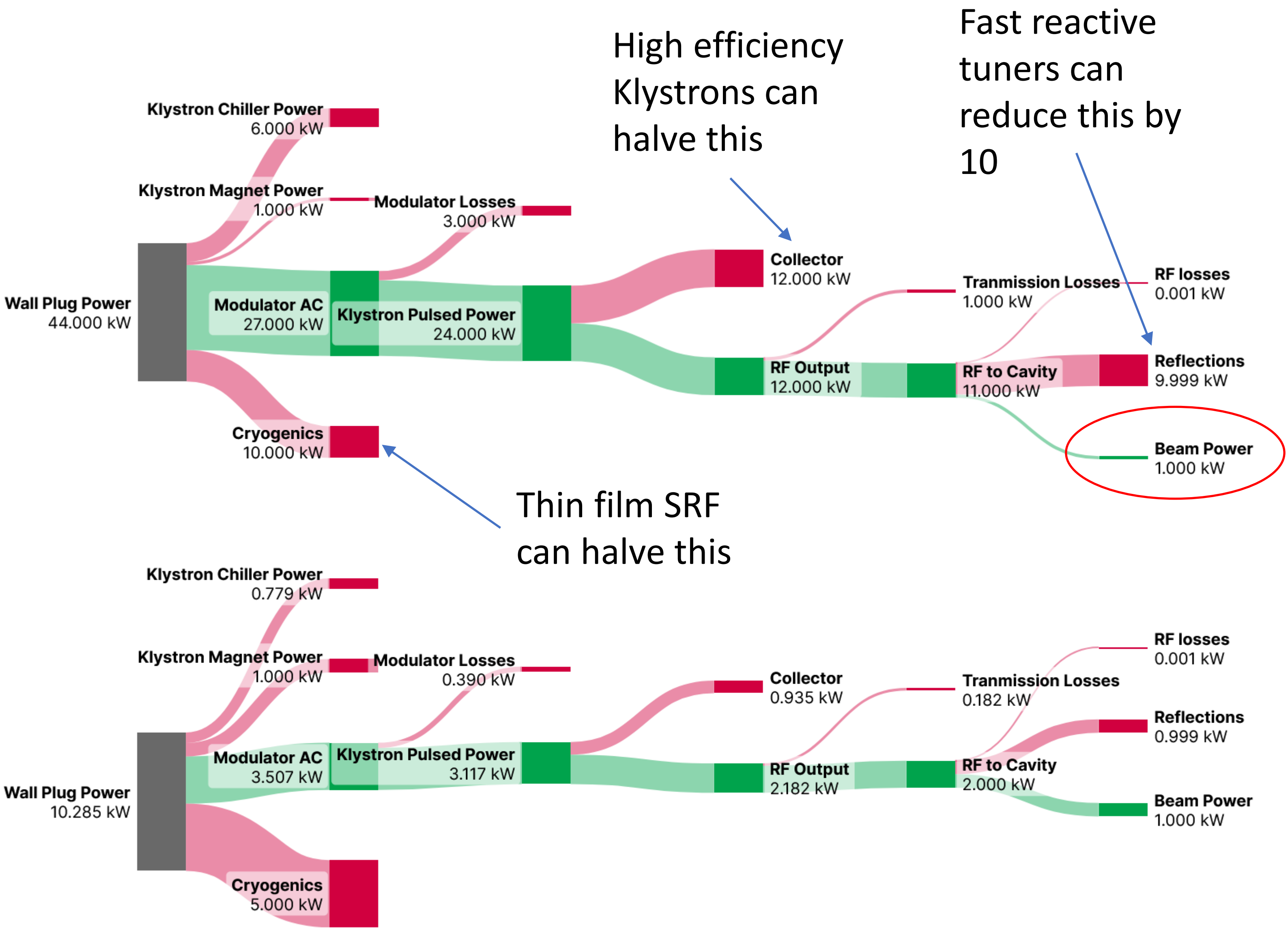
- Vibration generator set to 37Hz
- Spectral density also shows good suppression at higher frequencies e.g. ~600Hz
- Peak deviation with correction 1.2Hz
- N.B. long transmission line, lossy brazing
  - Low FoM
  - Little to no RF power reduction

No correction

With correction

Putting it together (SCRF)

- By going superconducting we reduce the RF power losses but we now have cryogenic losses and RF reflections
- Klystrons are still a big issue.
- Microphonics makes it difficult to transfer power to the cavity
- Carnot efficiency makes cryogenics inefficient
- Typically, only 2-10% of the wall plug power ends up in the beam but there is scope to improve this.



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Conclusions

- The next generation of accelerators are likely to be linacs and hence the vast majority of energy use is the RF system
- Typical wall-plug to beam efficiency is **5-20%**
- The largest wastes of energy are the RF amplifiers, refrigerators and RF reflections and there is current R&D aiming to reduce these
  - **High efficiency klystrons** to reduce power dumped in collectors as heat (**can increase RF system operational efficiency by 10-20%**)
  - **Fast reactive tuners** to reduce the effect of microphonics (**reduces reflections by an order of mag**)
  - **Thin film SRF** to operate at higher temperatures (**doubles cryo efficiency**)
- Even with all these improvements the efficiency of the RF system **will not exceed 50%.**