THE TRISTRON, A NEW PARADIGM IN HIGH-EFFICIENCY RF POWER GENERATION

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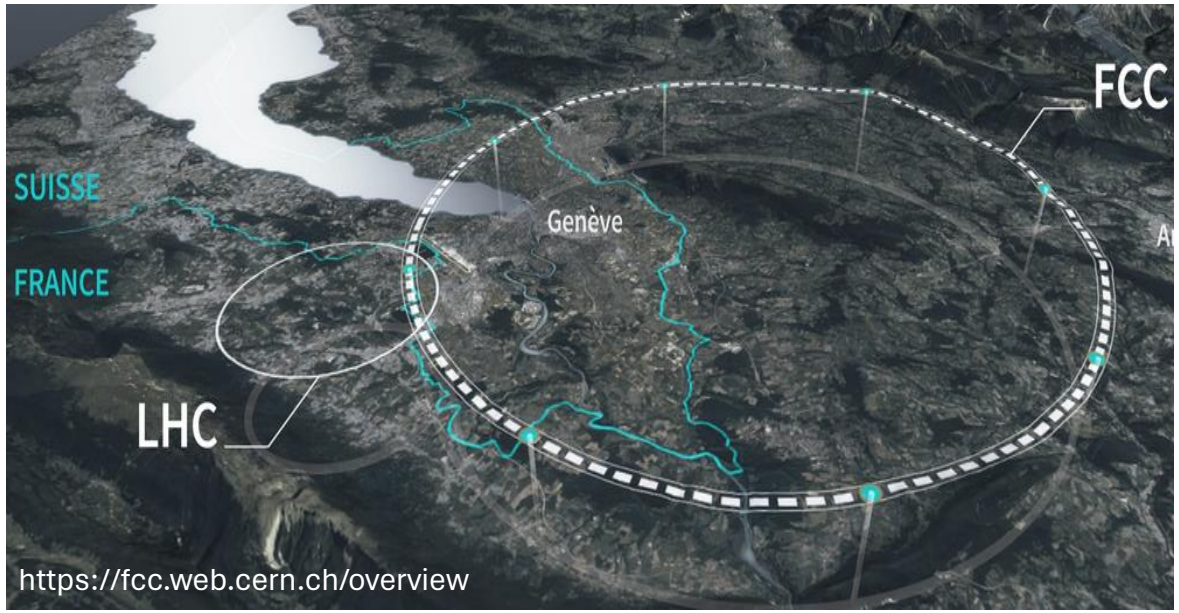
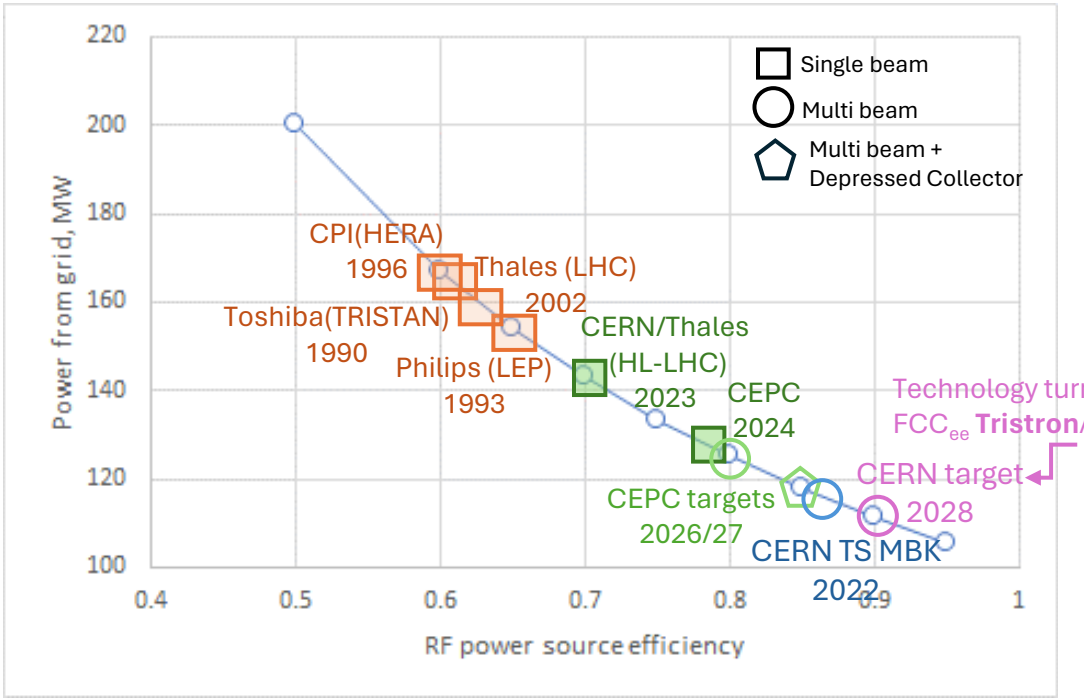
RF power generation in FCC_{ee}.



UHF, 0.3-1MW range, CW klystrons.



FCC_{ee} RF power sources must compensate for the beam synchrotron radiation losses in the collider ring:

	Z	W	H	ttbar2	booster
400MHz	**100MW**	**100MW**	**100MW**	**21MW**	
800MHz				**79MW**	**~1 MW/all poles**

Improving RF power sources efficiency will not only reduce considerably electricity power consumption but also will reduce installation and operation cost of power converters and cooling system (environmental impact).

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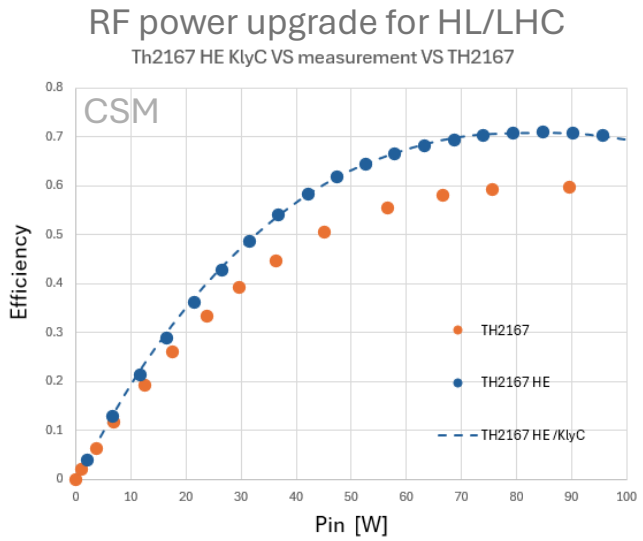
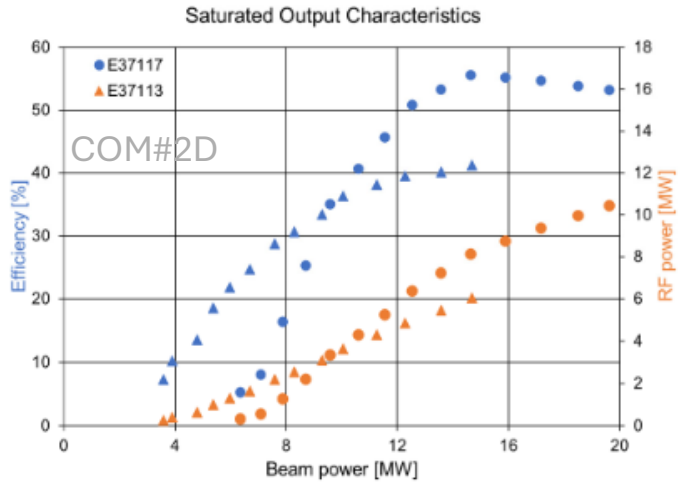
High efficiency RF power sources development at CERN.

Canon ETD





High Efficiency International Klystron Activity (HEIKA) was initiated at CERN in 2014 (9 experts worldwide from Europe, Asia and USA). 15 publications over 3 years.

- New electrons bunching methods like COM, COM#2D, BAC and CSM (η> 80%)
- CERN home made code KlyC. A fast and accurate tool to simulate linear beam, devices.

HEIKA was converted into CERN HE klystron project in 2021.

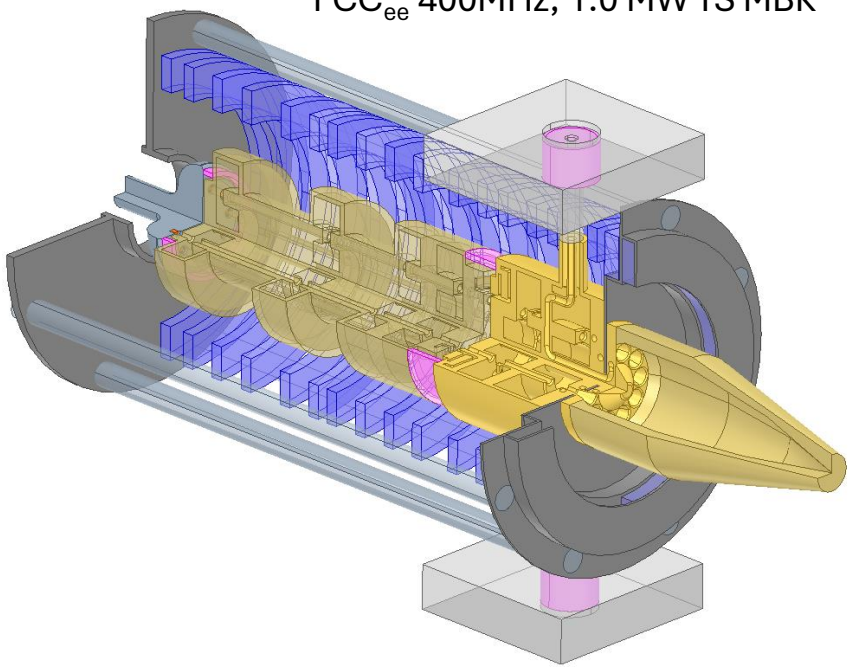
- Retro-fit efficiency upgrade of existing commercial klystrons:

1. X-band Canon 6MW, pulsed tube (41%-> 56%) 2022.
2. X-band CPI 50MW, pulsed tube (39%-> 65%). To be tested at MPP (former CPI) in 2026.
3. UHF Thales 0.3MW, CW tube (60%->70%) 2024.

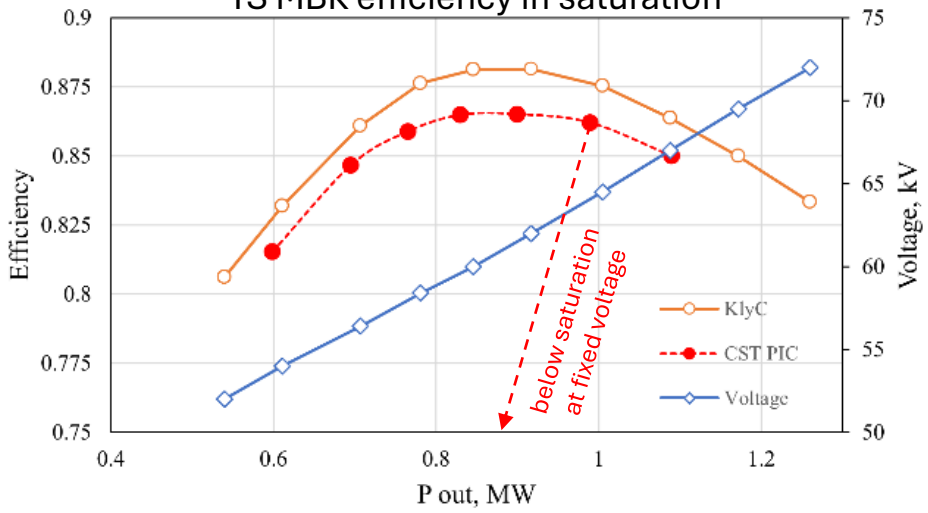
- New Two-stage Multi-Beam klystron technology (η>85%) 2020. A potential technology of choice for large colliders like CLIC, ILC, FCC_{ee} , MuCol…

High efficiency RF power source for FCC_{ee}. Challenges.

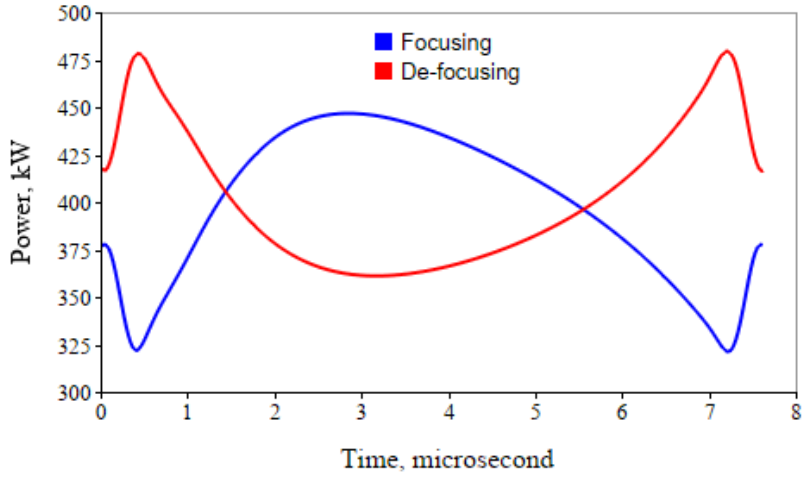
FCC_{ee} 400MHz, 1.0 MW TS MBK



TS MBK efficiency in saturation



- In the last 5 years the novel concept of the very efficient 1.0MW multi-beam (MB) Two-Stage (TS) klystron was developed at CERN, and it was ready for the industrialization.
- Recent (2024) evolution of the FCC_{ee} collider layout **reduces the maximum needs RF power from 1MW to below 0.5 MW** and suggests operating collider in Reverse Phase Operation regime (RPO) for Z pole.
- RPO requires **~25% of RF power transient modulation** to compensate for the effect of the beam abort gap in the two families of accelerating cavities:



- With such RF power modulation, most of the time klystron will be operated below saturation. Thus, klystron's operational efficiency will be reduced from 86 % (in saturation) to 67 %.

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State of the art

ESS 0.7GHz, 1.2MW Mult-Beam IOT

- Gridded tubes, like **Inductive Output Tubes** (IOT), are another class of electrovacuum devices that are renowned for their ability for efficient operation in a wide range of the output power levels when regulated by the input RF signals.
- The practical efficiency in industrial prototypes was limited to ~70%.

TESTING OF THE ESS MB-IOT PROTOTYPES

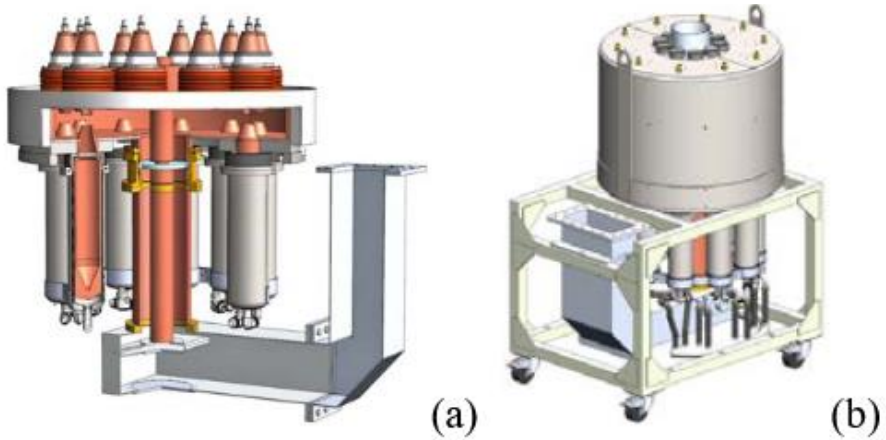


Figure 1: L3 MB-IOT: (a) Section view showing the configuration of the guns, combining cavity and coaxial output cavity. (b) Main assembly.

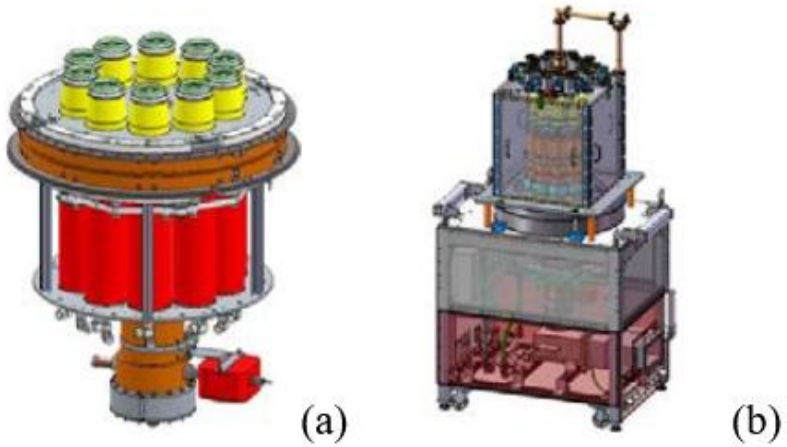


Figure 2: TED/CPI MB-IOT: (a) 3D models of sealed tube. (b) Main assembly.

https://proceedings.jacow.org/ipac2018/papers/wexgbf1.pdf

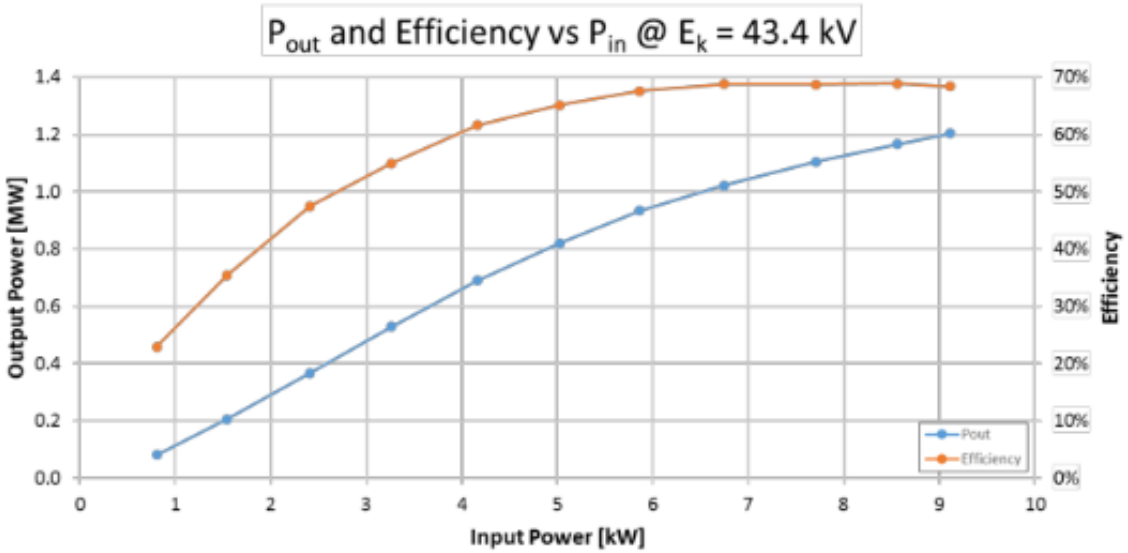
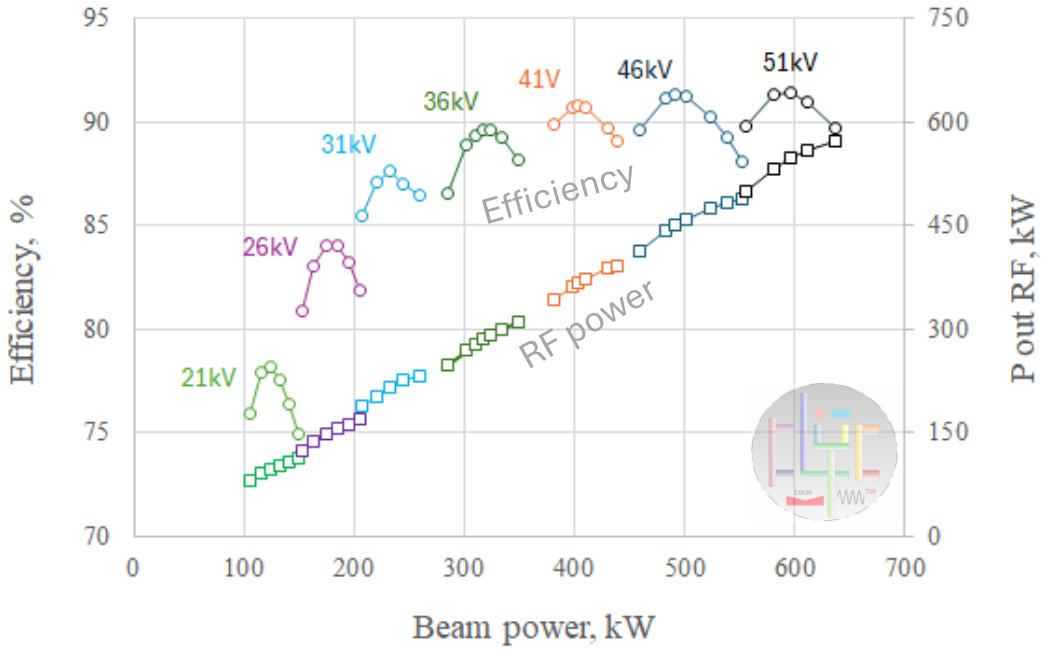
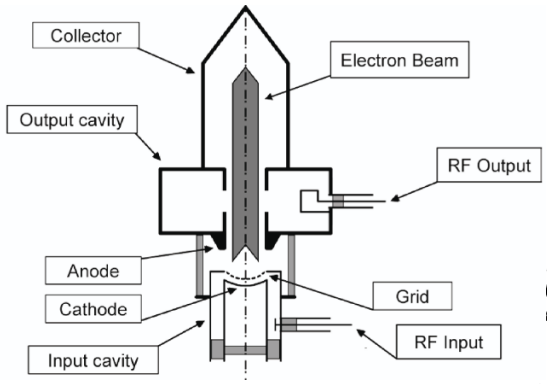


Figure 3: L3 MB-IOT: Plot of output power and efficiency recorded in the factory test.

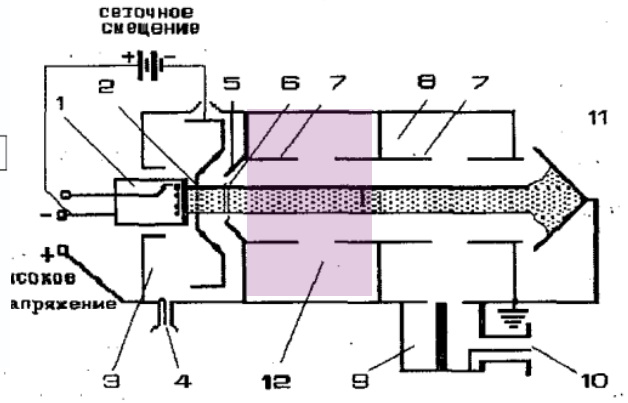
MB Tristron RF circuit with beam

400 MHz FCC_{ee} tristron power/efficiency performance simulated by CERN's home-made code KlyC.

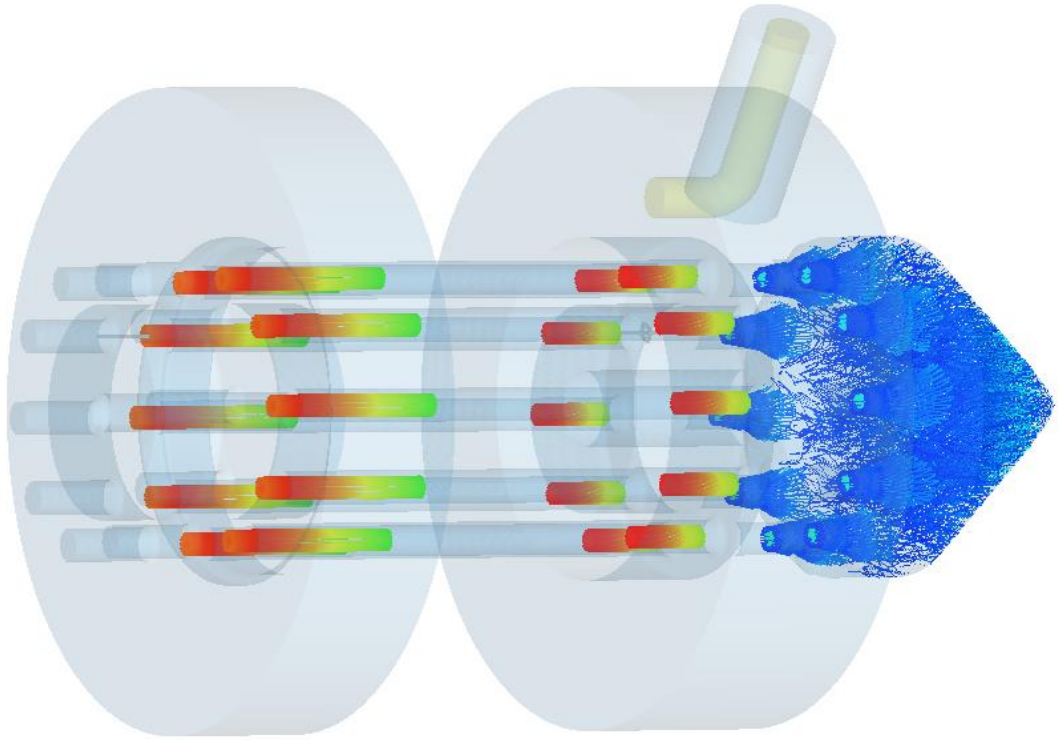




IOT (A. Haeff, 1939)



Tristron (A.D. Sushkov *et. al.*, 1967)

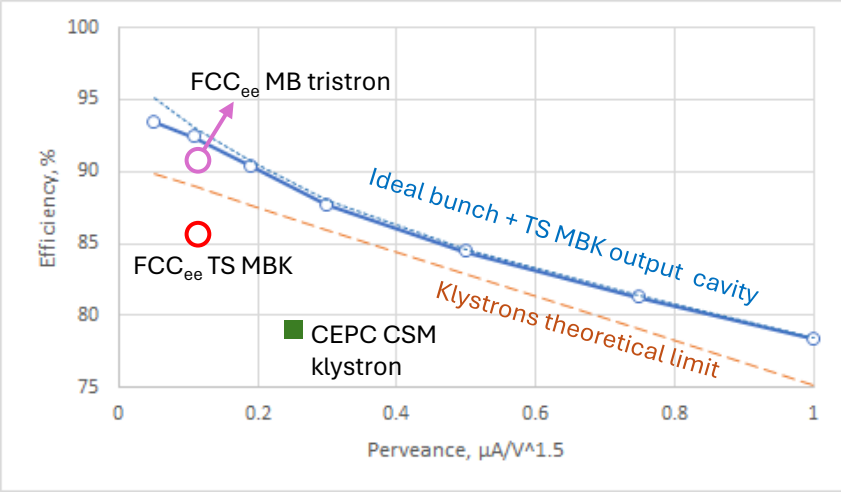


- Alike IOT, Tristron (a hybrid between **tri**ode and kly**stron**) is a gridded tube with additional penultimate cavity that can boost the RF power production efficiency from 70% to above 90%.
- Tristron concept is almost 60 years old, but it was never commercialized.

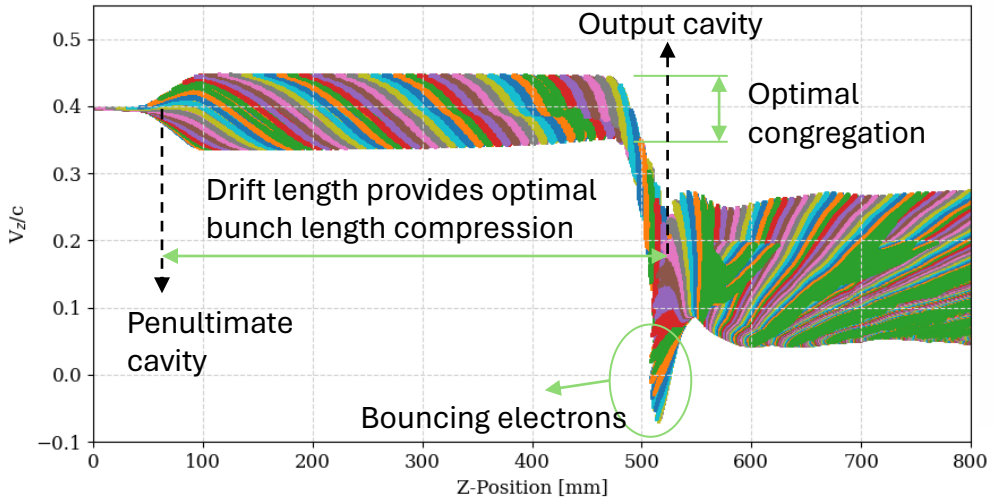
How Tristron can be so efficient?

1. Multi-beam technology -> low perveance (K=I/V$^{1.5}$) per beam: $\eta \approx 0.94 - 0.16 \times \mu K$.
2. Gridded gun provides fully saturated bunches -> **75%** (best IOT performance; B class)
3. Penultimate cavity controls optimal velocity spread (congregation) within the bunch, followed by bunch length compression in the drift -> **85%** (basic of the Tristron concept).
4. Long gap in the output cavity with negative detuning allows electrons bouncing -> **90%.**
5. Hollow beam configuration reduces radial bunch stratification -> **93%**.

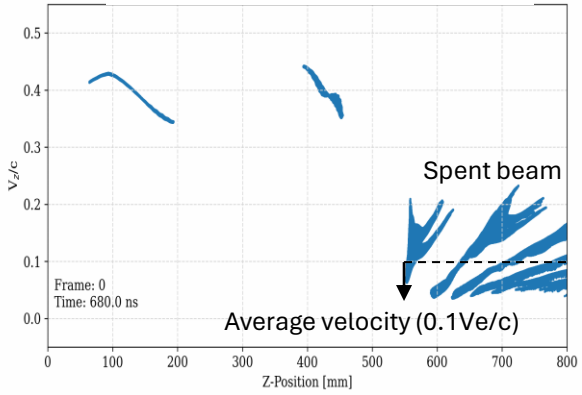
Tubes efficiency vs. perveance



Electron bunches velocity modulation in tristron



Phase space animation



$$\eta = 1 - (V_e/V_0)^2 = 1 - \left(\frac{0.1}{0.4}\right)^2 = 0.93$$

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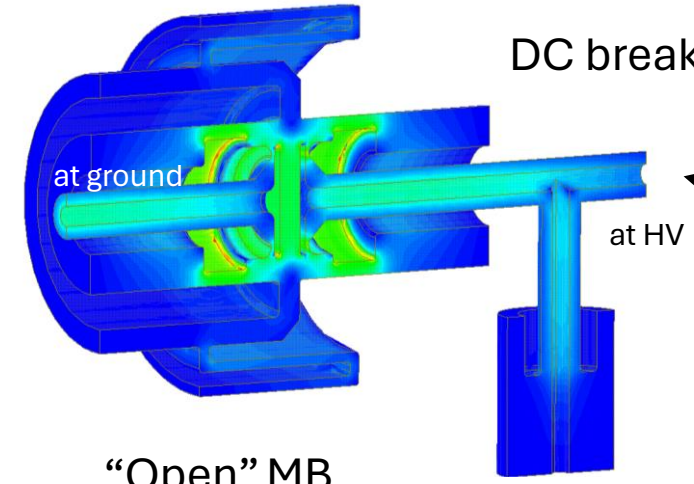
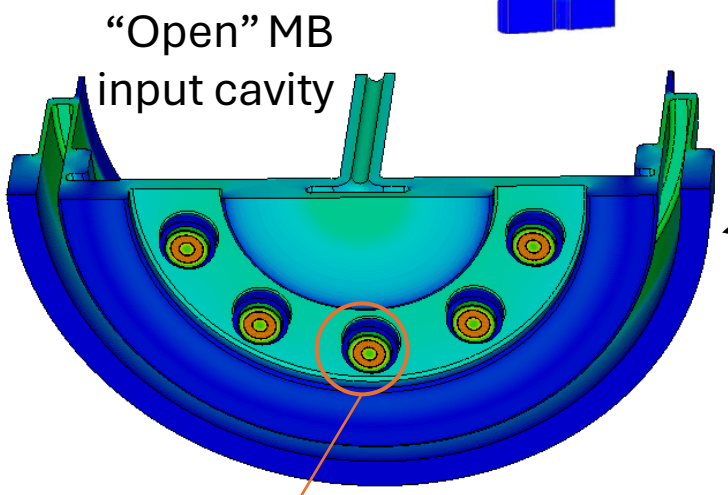
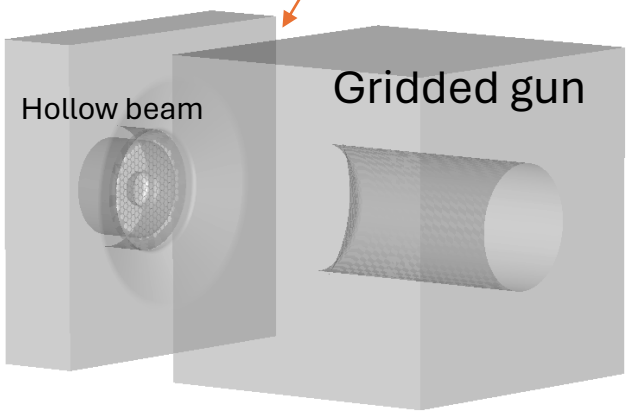
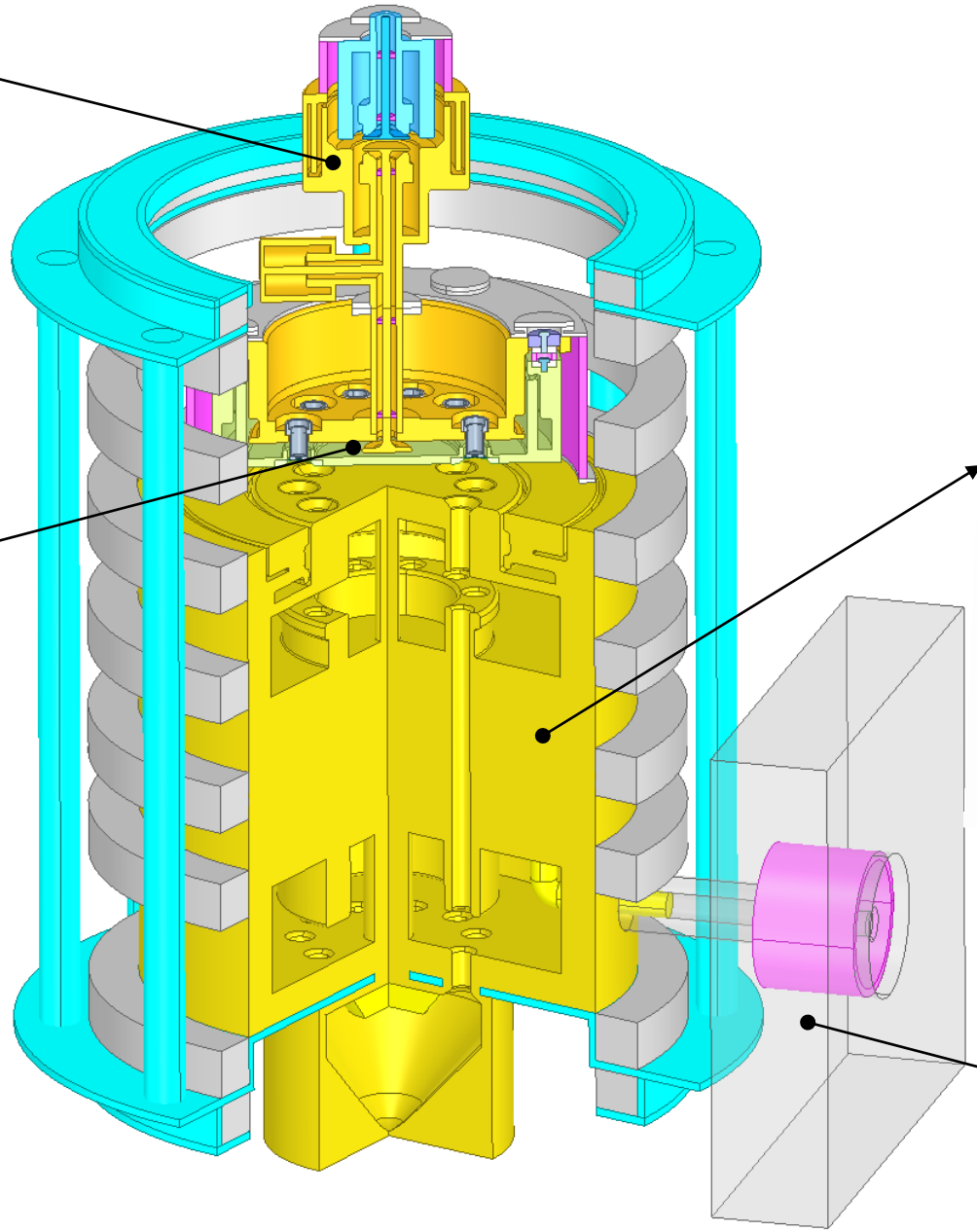
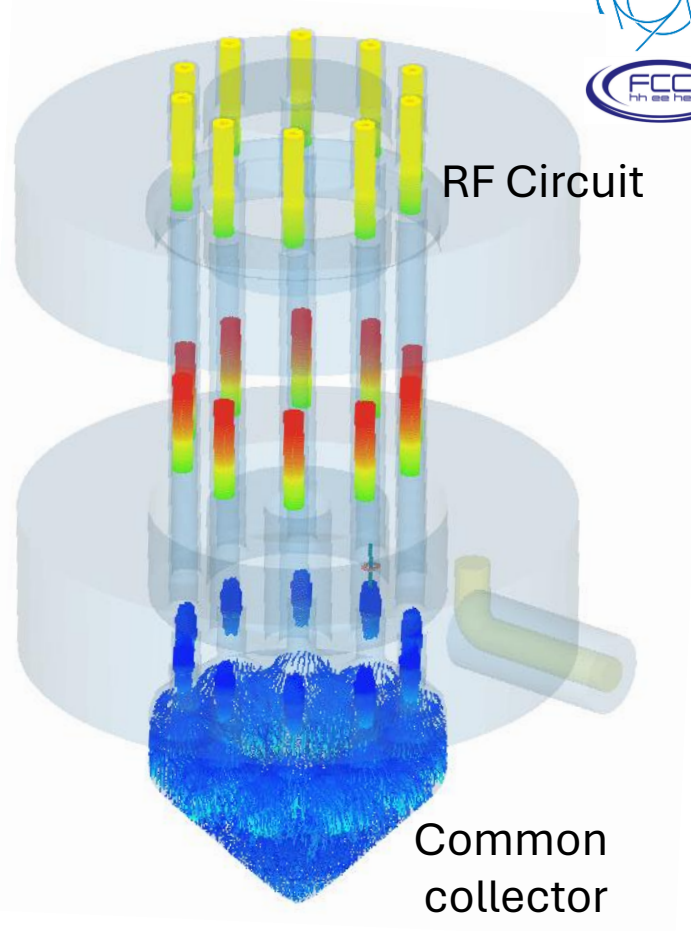
FCC$_{ee}$ 400MHz MB Tristron on one slide

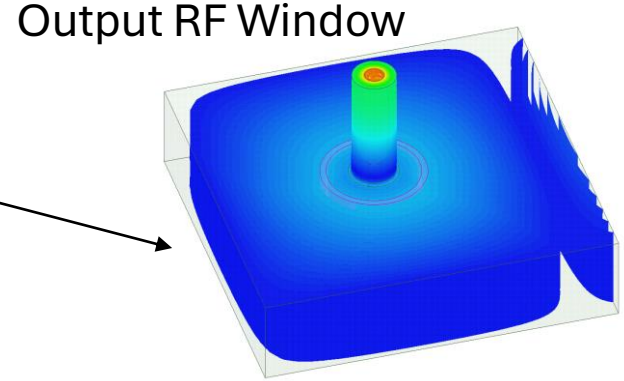












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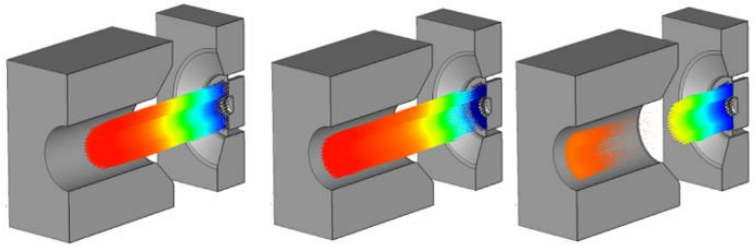
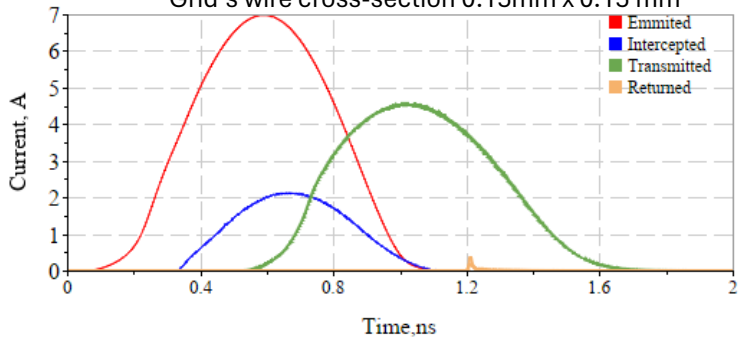
Gridded gun for tristron

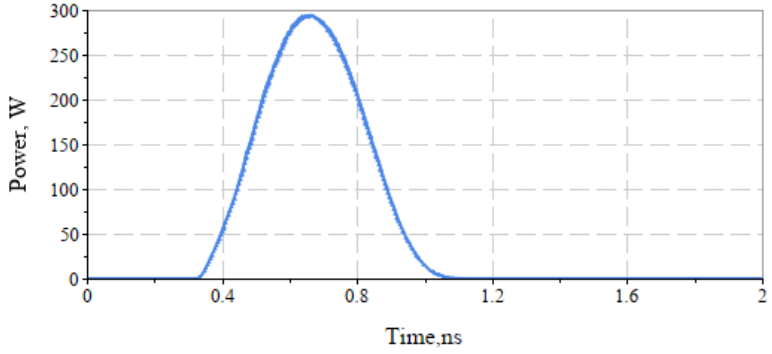
Bunch generation in the gridded gun (CST 3D PIC)



Cathode – grid gap is 0.3mm.
Grid's wire cross-section 0.15mm x 0.15 mm

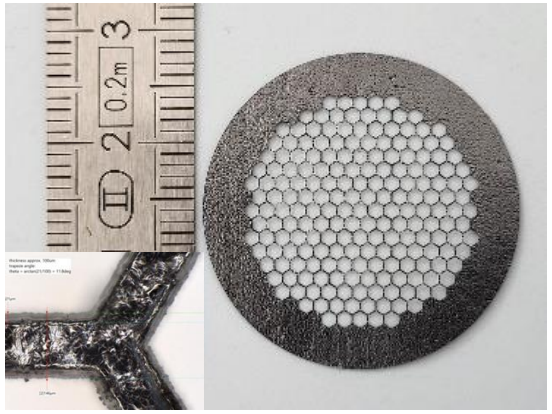


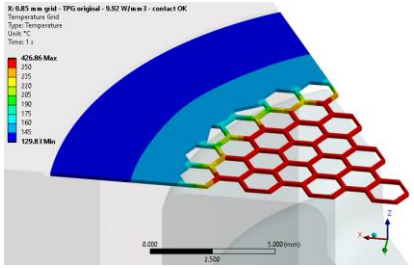
Beam power intercepted on the grid



A.S. Thakur poster session MOP7192

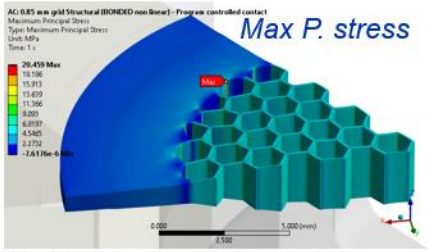
Flat HEX grid fabricated at CERN using Laser-cut technology on Pyrolytic Graphite wafer sample with 150 microns thickness.

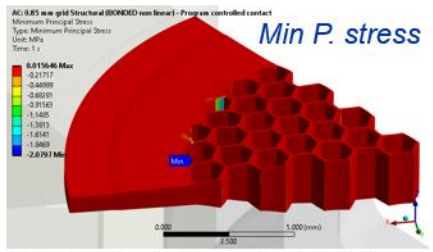


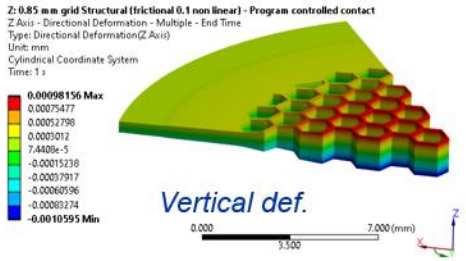


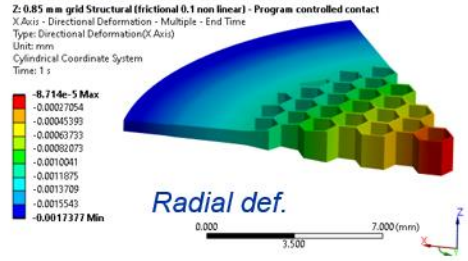
For the design point of 450kW output RF power:

- Maximal temperature reaches 426 C^0 ($T_{cathode}$ = 1000 C^0; $T_{ambient}$ =100 C^0; beam intercepted power 58W).
- Grid deformation in 'Z' direction is +/-1 micron.

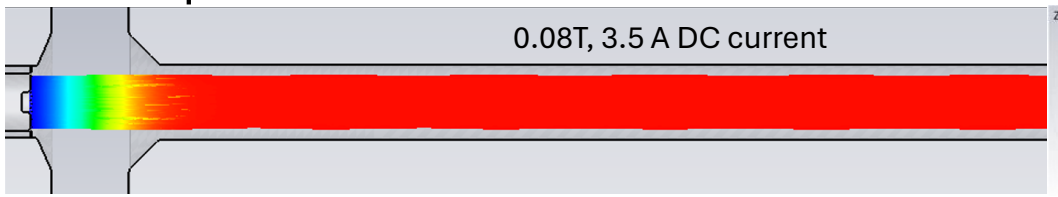


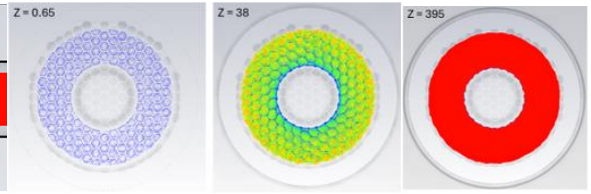


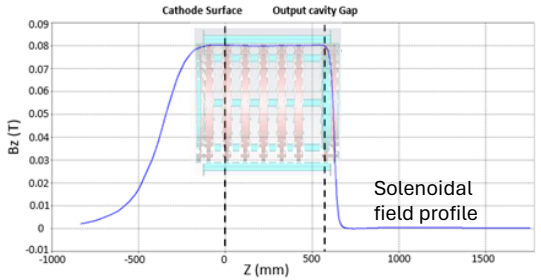


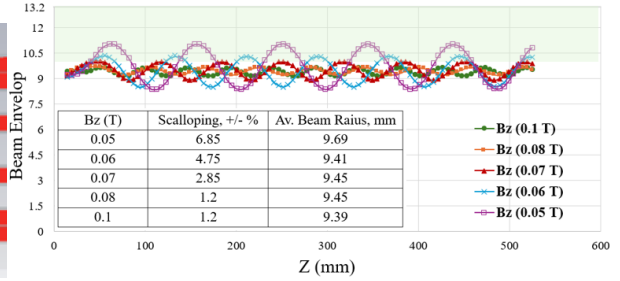


Beam optics









Bz (T)	Scalloping, +/- %	Av. Beam Raius, mm
0.05	6.85	9.69
0.06	4.75	9.41
0.07	2.85	9.45
0.08	1.2	9.45
0.1	1.2	9.39

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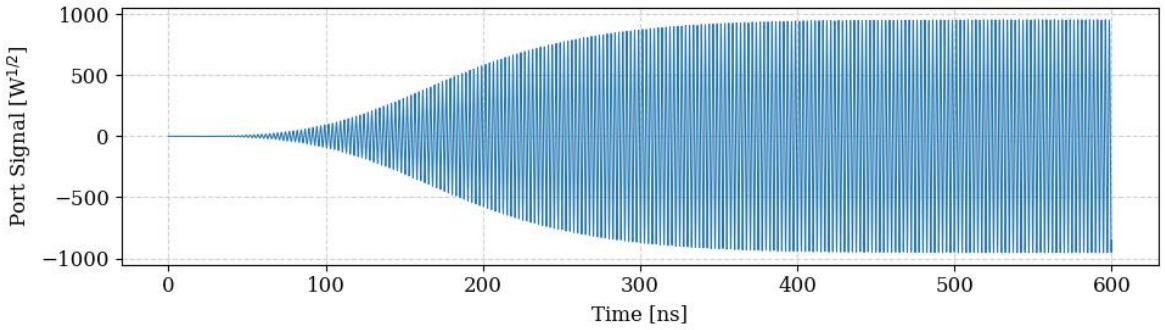
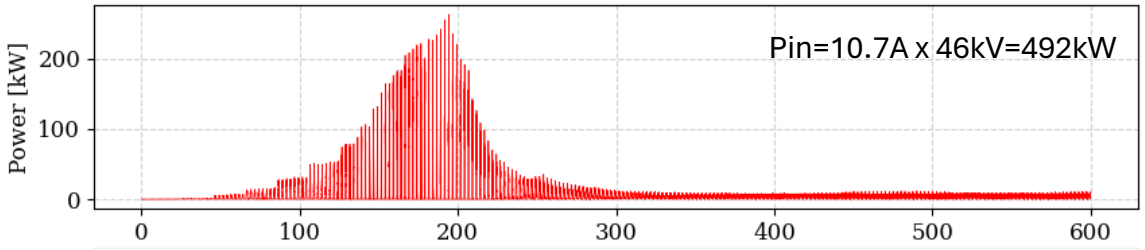
FCC_{ee} 400MHz MB Tristron performance simulated in CST 3D PIC

Calculating efficiency in CST 3D PIC#1 (RF efficiency).
RF power measured at the output coupler port.



Calculating efficiency in CST 3D PIC#2 (Balanced efficiency).
Spent beam power measured in the collector

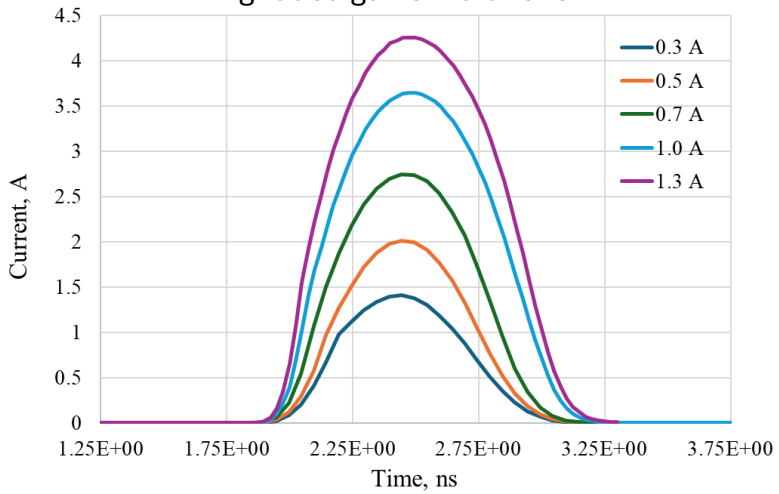


	KlyC	CST
$\eta_{RF} = \frac{P_{RF}}{I \times V}$	92.66%	93.52%
$\eta_{balanced} = \frac{I \times V - P_{collector}}{I \times V} \times \left(1 - {}^{Q_{ext}}/_{Q_0}\right)$	91.75%	90.5%

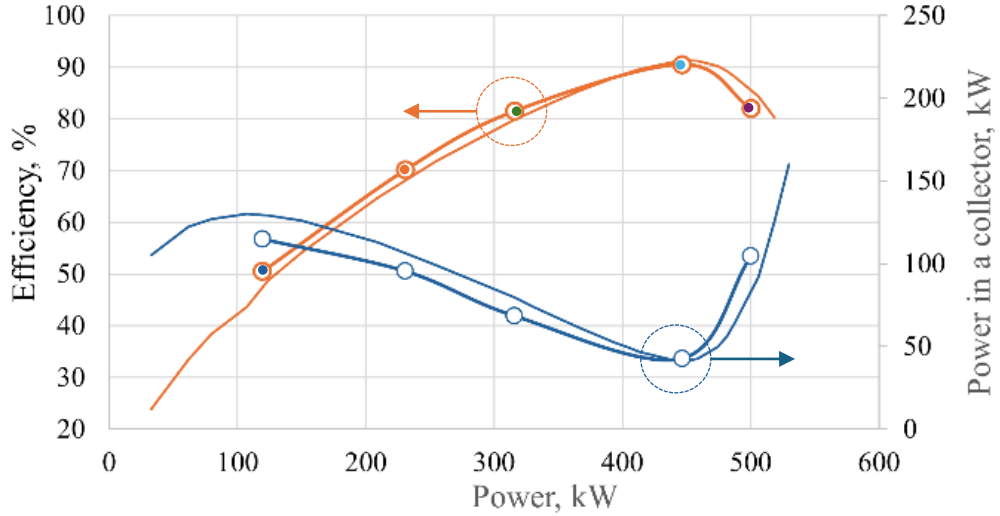
Electronic eff. Ohmic eff.

"Public" value

Bunches profiles generated in CST 3D PIC gridded gun simulations.



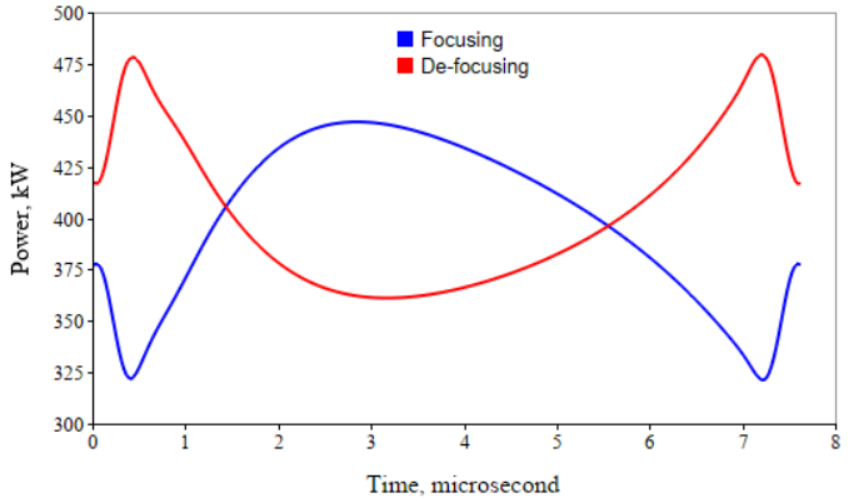
MB tristron efficiency and collector beam power vs. output RF power. CST (circles) and KlyC (thin lines) results.



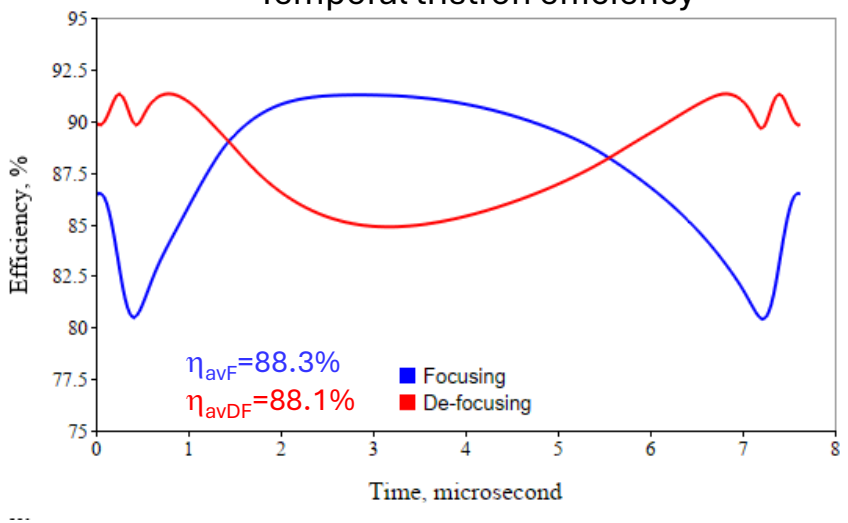
MB tristron operational efficiency. FCC_{ee} Z-pole (RPO).

#1 Nominal operation (46kV)

Accelerating cavities RF power modulation

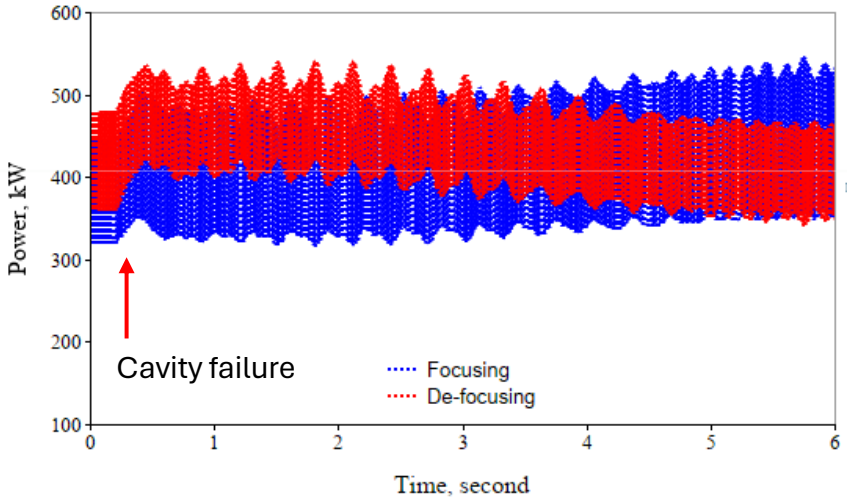


Temporal tristron efficiency

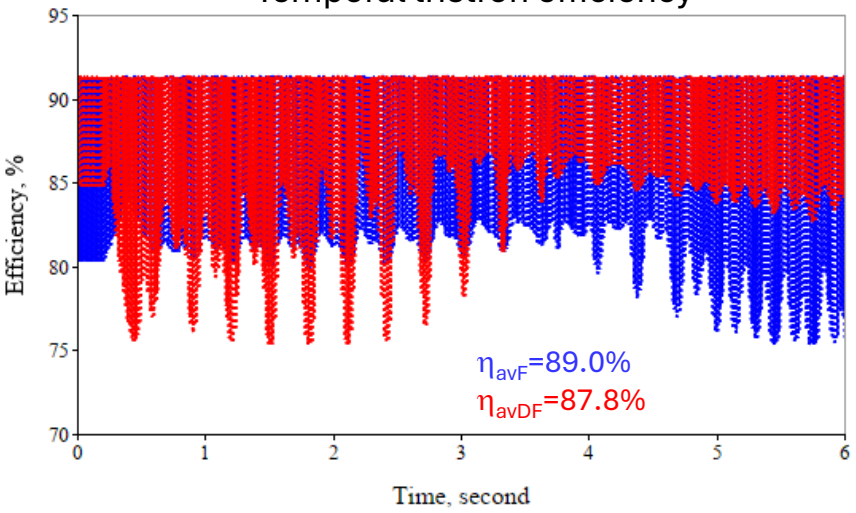


#2 Single cavity failure mode (46kV)

Accelerating cavities RF power modulation



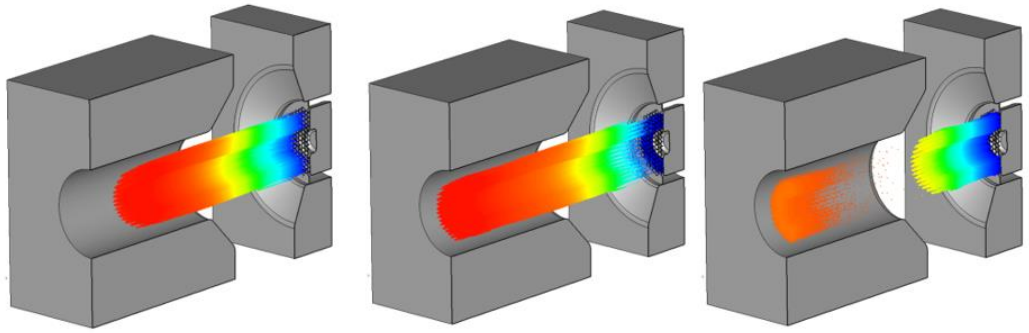
Temporal tristron efficiency



*By putting two tristrons on a single DC HV power supply, it will see almost constant in time power load.

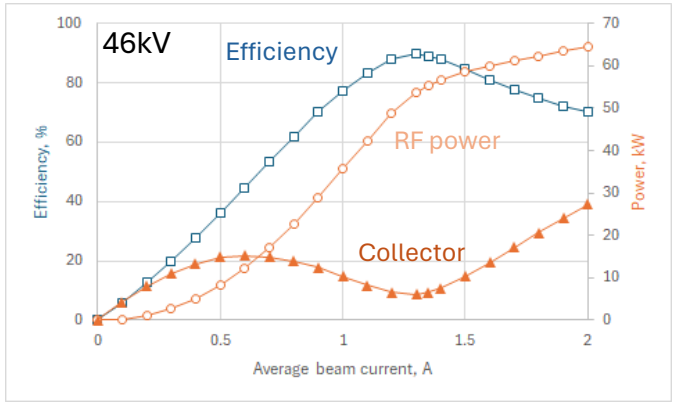
Tristron technology for FCC_{ee} 800MHz RF power sources

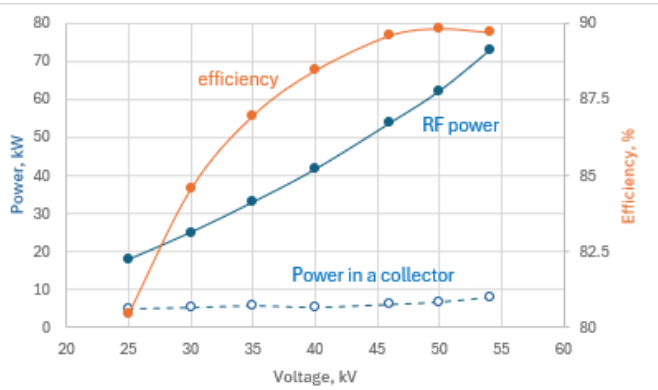
400MHz gridded gun operated at 800MHz.



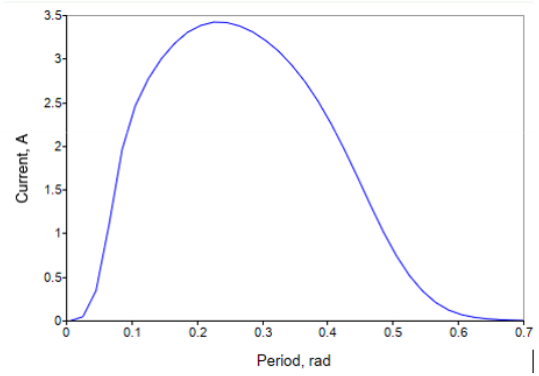
- FCC_{ee} booster (Z,W,H) : **800MHz, 50kW**
- FCC_{ee} ttbar collider: 800MHz, 220 kW

Peak efficiency/RF power vs. HV

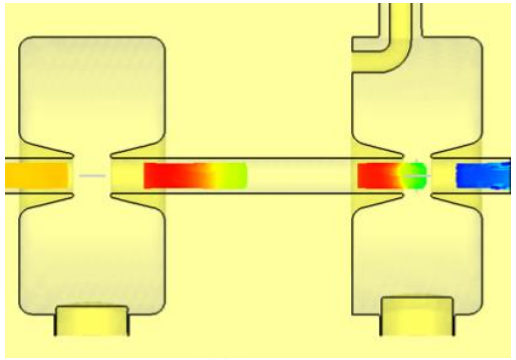




800MHz pulses, 1.3A average current. CST 3D PIC results.

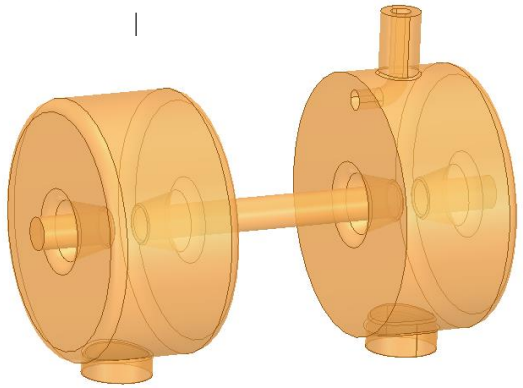


88.2%, 56kW (46kV, 1.3A)



- 400 MHz gridded gun can be used effectively in the higher frequency devices (up to 1.5 GHz).
- For the **single beam** devices, the gridded gun and input cavity particular layouts are not constrained. Thus, IOT vendors can procced with a retro-fit upgrade of the existing devices to boost the efficiency and RF power.
- Due to the high bunch quality, tristron can be designed as an efficient frequency multiplier (x3), brining gridded tubes into S-band with an option of the continues wave operation.

800 MHz, 50kW tristron's **Single Beam** RF circuit (0.35m long).



Summary

- The MB tristron is selected now as a baseline for 400MHz 0.5MW, CW RF power source for the FCC_{ee}. It provides a high operational efficiency (almost 90%), compact (1.4m high and 1m in diameter) and cost-efficient solution.
- Currently the MB tristron is under progressive development as CERN's internal project, anticipating that the first prototype will be built and tested at CERN in 2028.
- FCC_{ee} MB tristron is fully compatible/interchangeable with current LHC klystrons with minor modifications of HV circuit.
- Tristron could be a technology of choice to improve overall efficiency of the high intensity and high-power proton SRF Linacs like ESS, MYRRHA and various Energy Recovery Linacs.