SY-FCC workshop

Friday Oct 4, 2024, 8:30 AM → 5:50 PM

High Efficiency Klystrons

Roadmap towards efficient RF system.

Electro-vacuum technologies for FCC_{ee}

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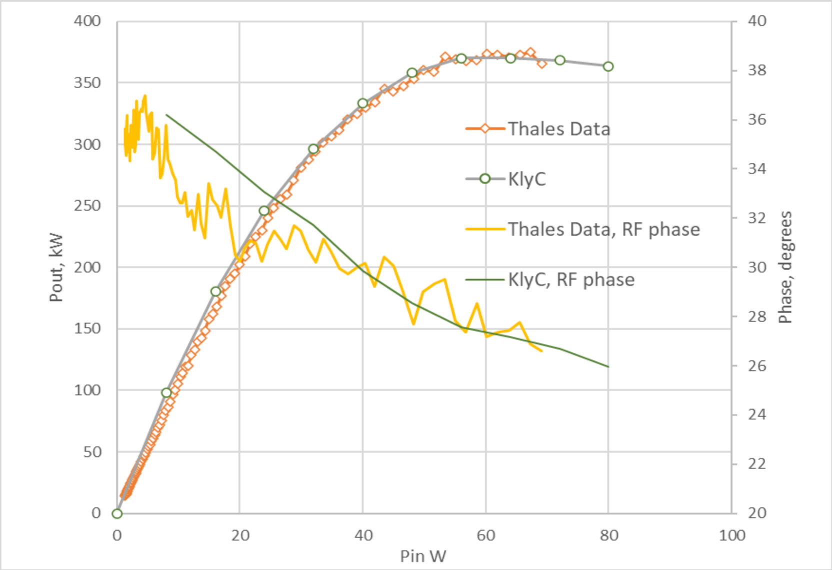
HOT NEWS

TH2167 **HE**

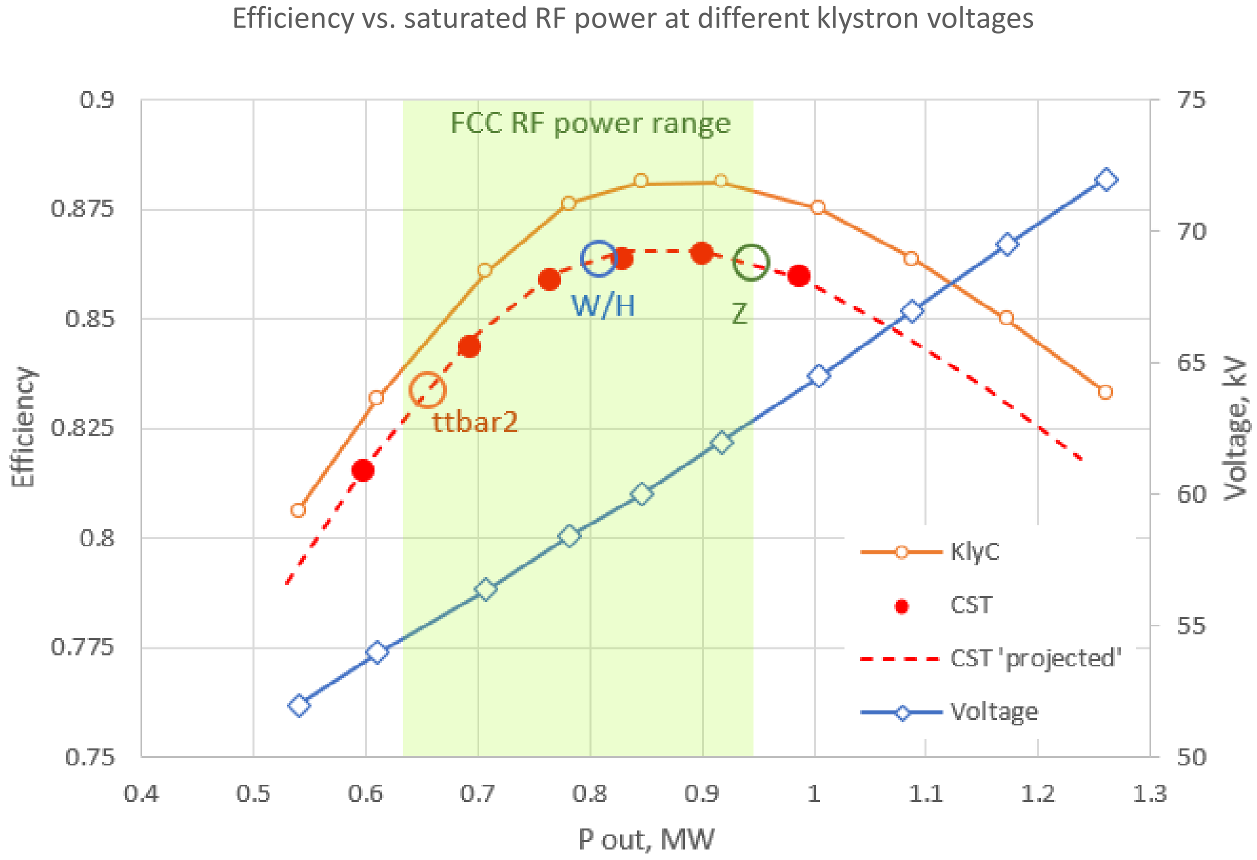
High Efficiency Klystrons

- Retrofit upgrade of existing Thales tube TH2167 to boost RF production efficiency from 60% to 70% and to provide >350kW CW 400MHz power required by HL-LHC.
- Designed at CERN, built by Thales – great example of efficient collaboration between the Lab and Industry.
- Misson completed, 365 kW (eff.=70.2%) has been demonstrated at factory. First tube will arrive at CERN by November 2024.
- Next, Thales will provide series production at a rate of ~4 tubes/year.

THALES
Building a future we can all trust

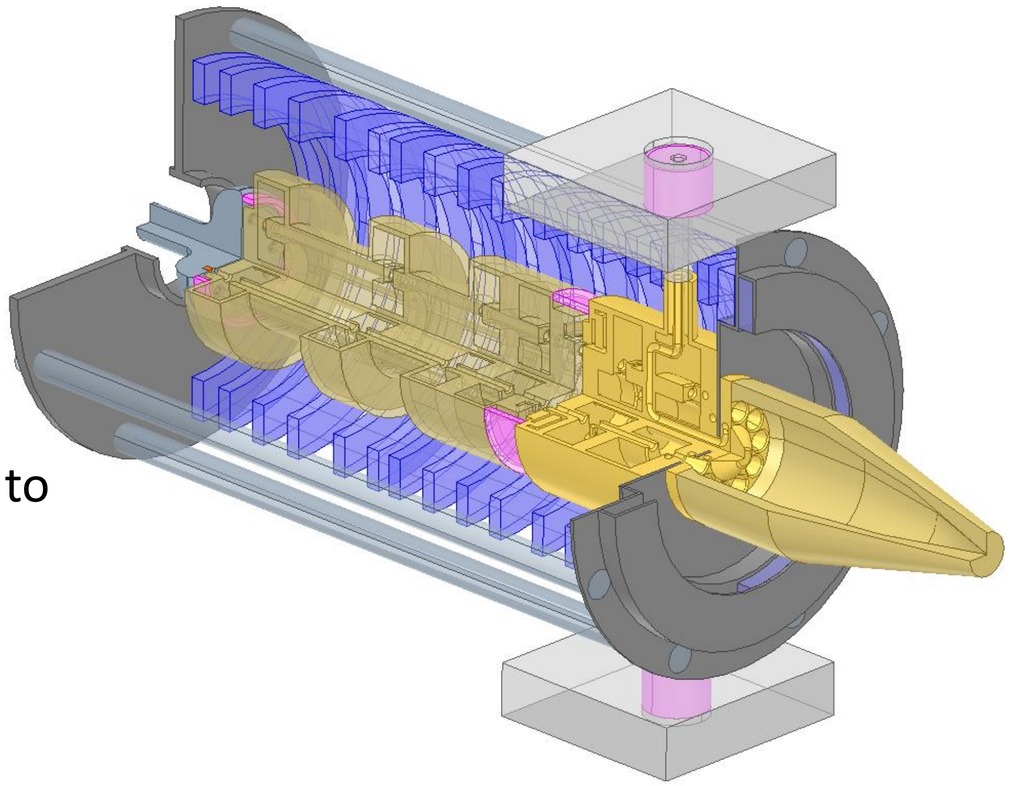


Novel 400 MHz, 1MW HE Two-Stages MBK for FCC_{ee}. Performance summary.



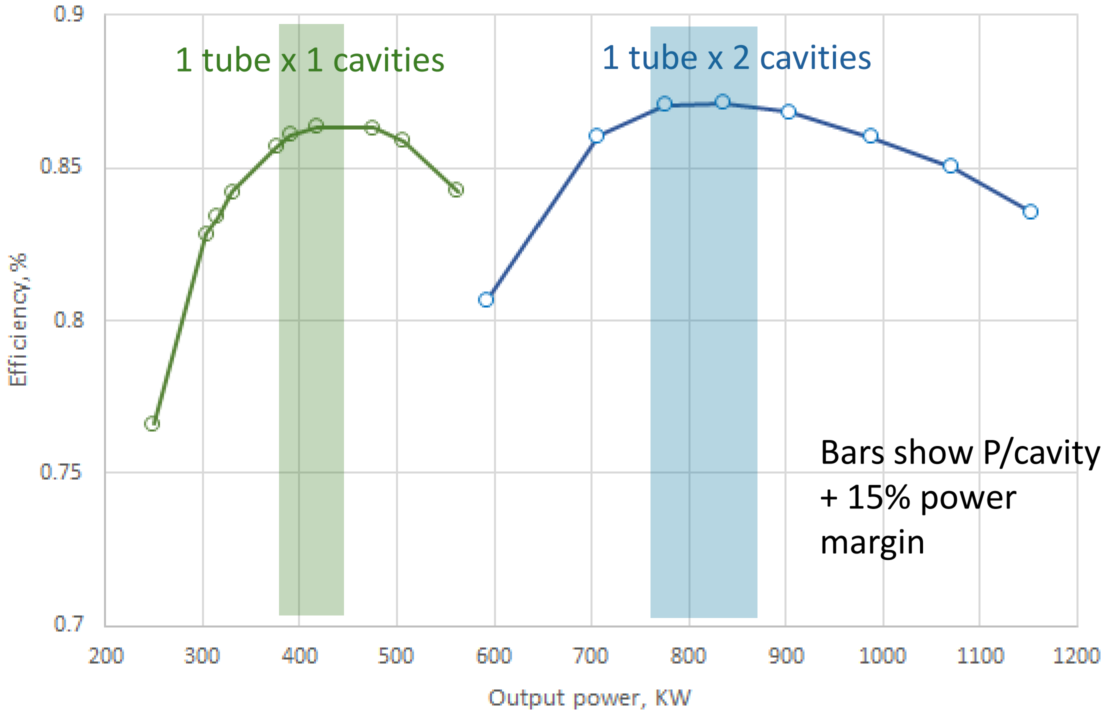
Featured:

- **Very efficient**. 86% @ Z,W,H and 83% @ ttbar2.
- **Compact**. Total length <3m.
- **Low Voltage**. Up to 64kV @ 1 MW.
- **High RF power gain**. 43dB @ 1MW.
- **Broadband**. 3.5 MHz @ -1dB.
- **Robust**. Can handle mismatch up to -15dB.



For FCC_{ee}, such an efficiency improvement from conventional 65% to 85% will allow to save 38MW of the grid electric power. That is compatible to the electric power needed for the entire FCC_{ee} cryogenic system (40MW).

The new layout with one unique two-gaps cavity for Z,W,H poles, opens options of using one power source per single, or two cavities. Performance of the TS klystron is now optimized for both options with almost identical efficiencies.



With reduced power per klystron:

- Reduced by ~50% collector volume.
- Improved beam extraction quality into collector.
- Reduced by 10% RF circuit length.
- Reduced from 62kV to 47 kV operating voltage.
- Reduced power in solenoid
- Improved life- time.
- Single RF output.
- With chosen technology, cost saving will be rather modest – no more than 20% when moving from 1MW tube to 0.5MW tube.
- Will need x2 more klystrons.

High Power Gridded Tubes

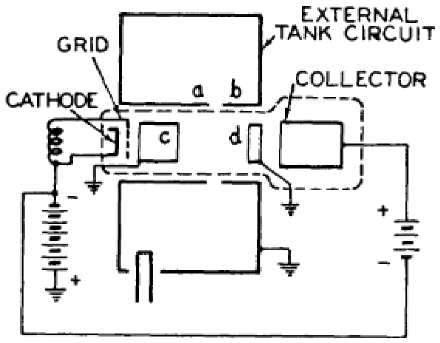
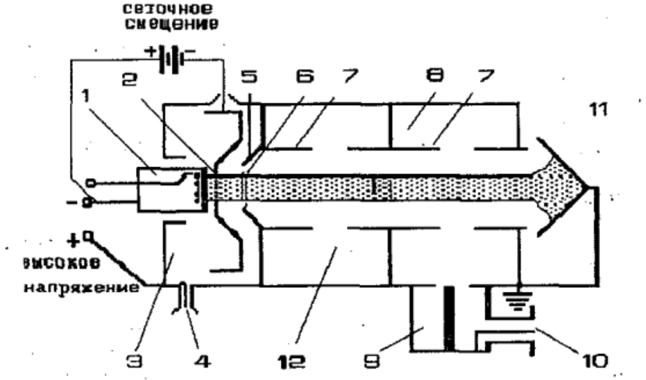


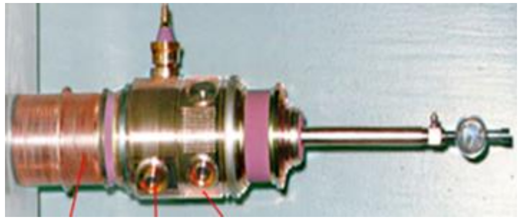
Fig. 2—Diagram of an inductive-output amplifier with an external output circuit.

IOT (A. Haeff, 1939)

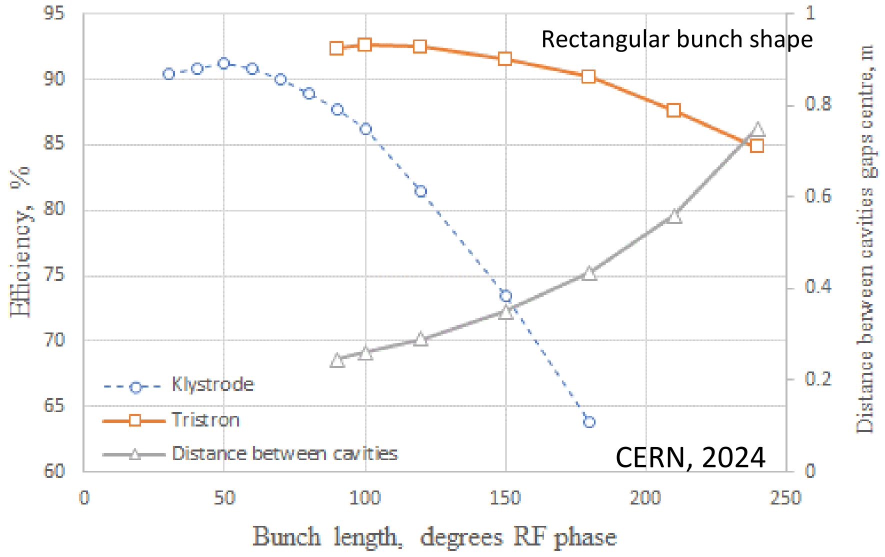
Klystrode
(H. Priest and M.B. Shrader 1982)



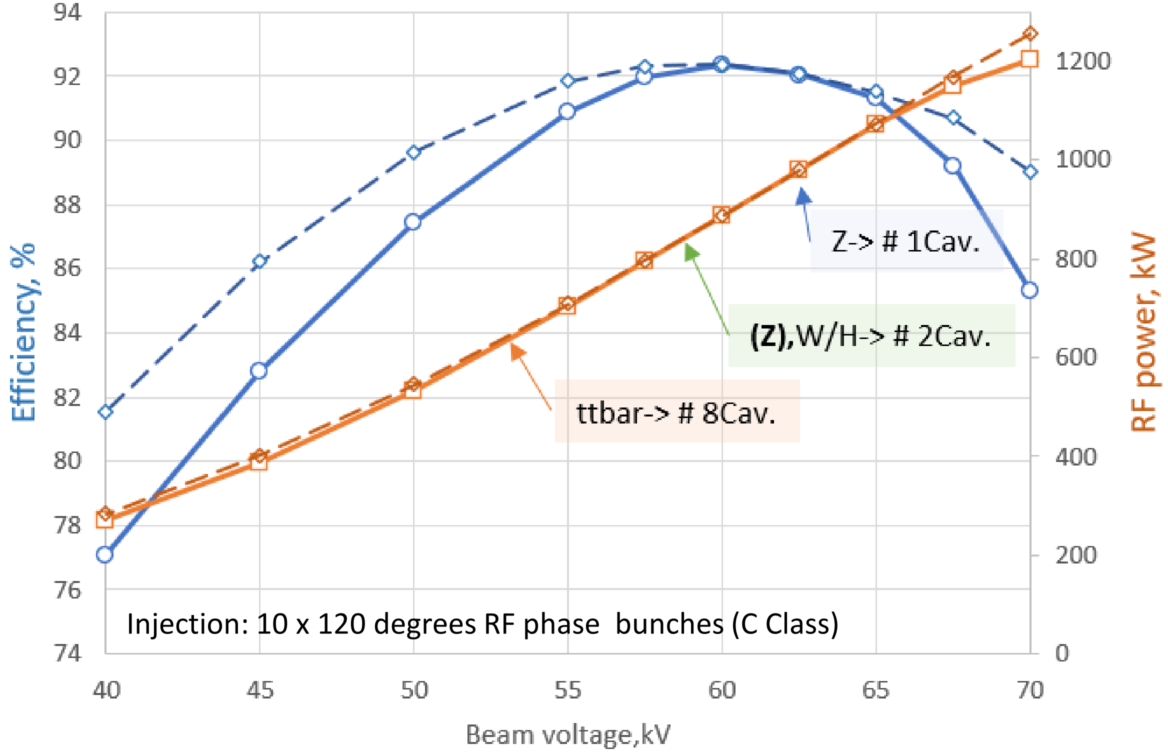
Tristron (A.D. Sushkov et. al. 1967)
MB Prototype tested in 1997, V. Tsarev:



FCC_{ee} 1MW, 400 MHz 10 beams gridded tubes performance (KlyC simulations)



1 MW, MB Tristron power-efficiency capabilities

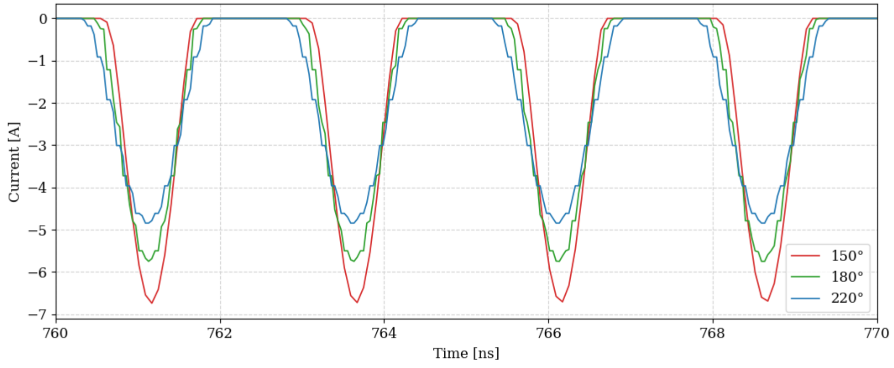


"*Il n'y a de nouveau que ce qui est oublié*« . Marie Antoinette (1785)

Tristron CST 3D PIC simulations

High Efficiency Klystrons

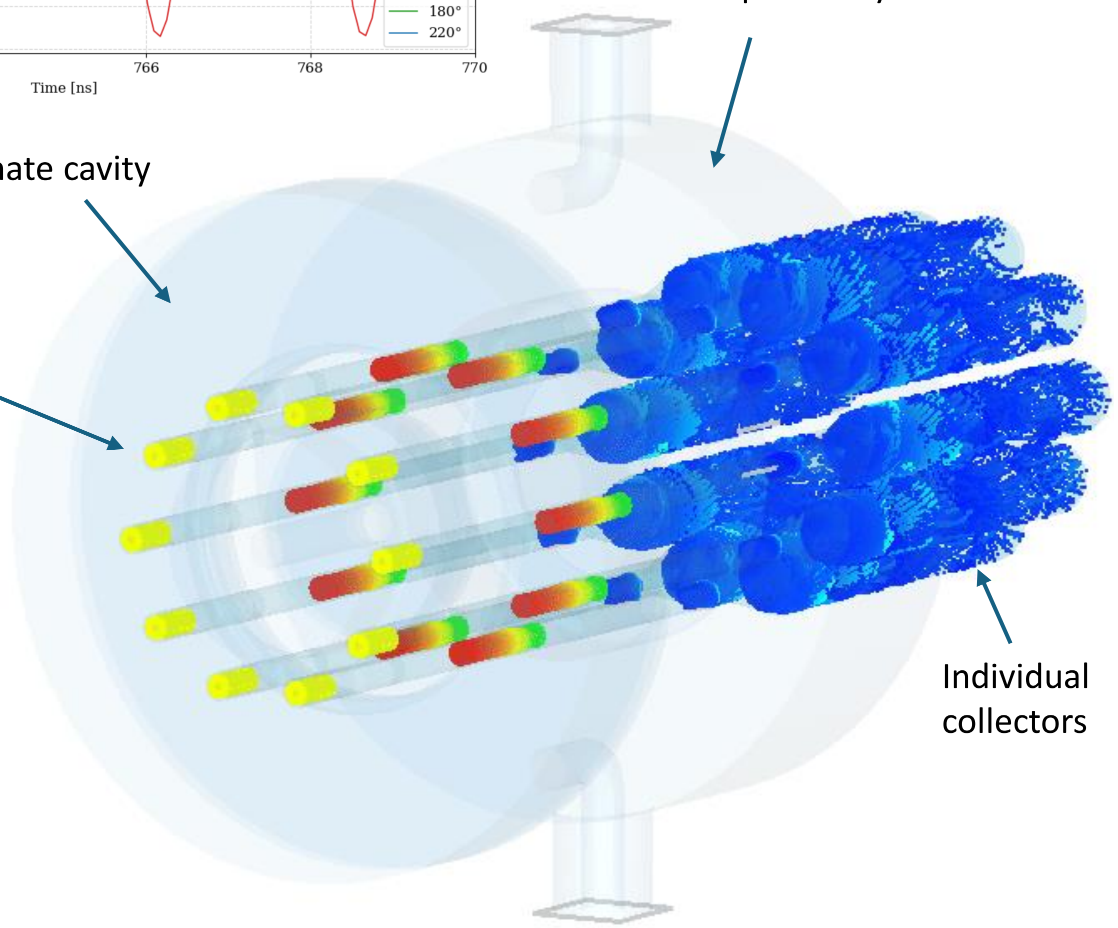
Realistic bunched beam generated in CST



Output cavity

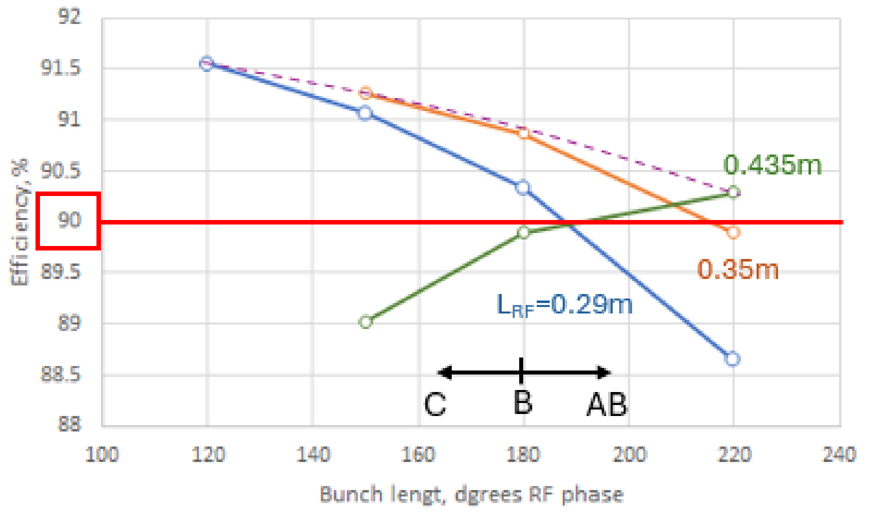
Penultimate cavity

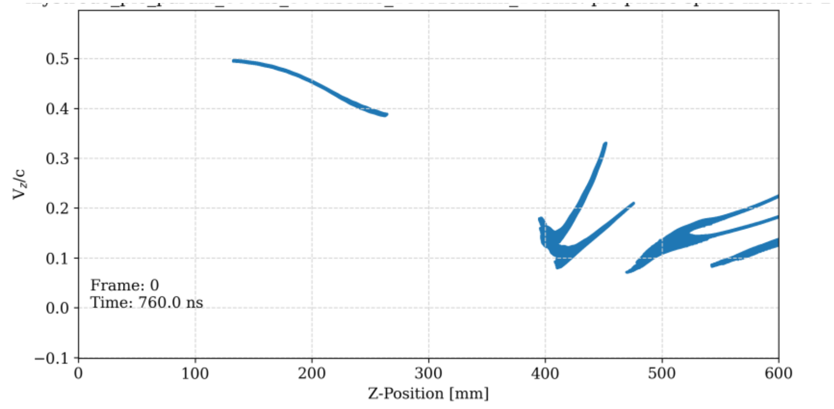
Bunched beams
B Class
10x1.6A
60kV



Individual collectors

1MW, MB Triston efficiency (measured at RF port)



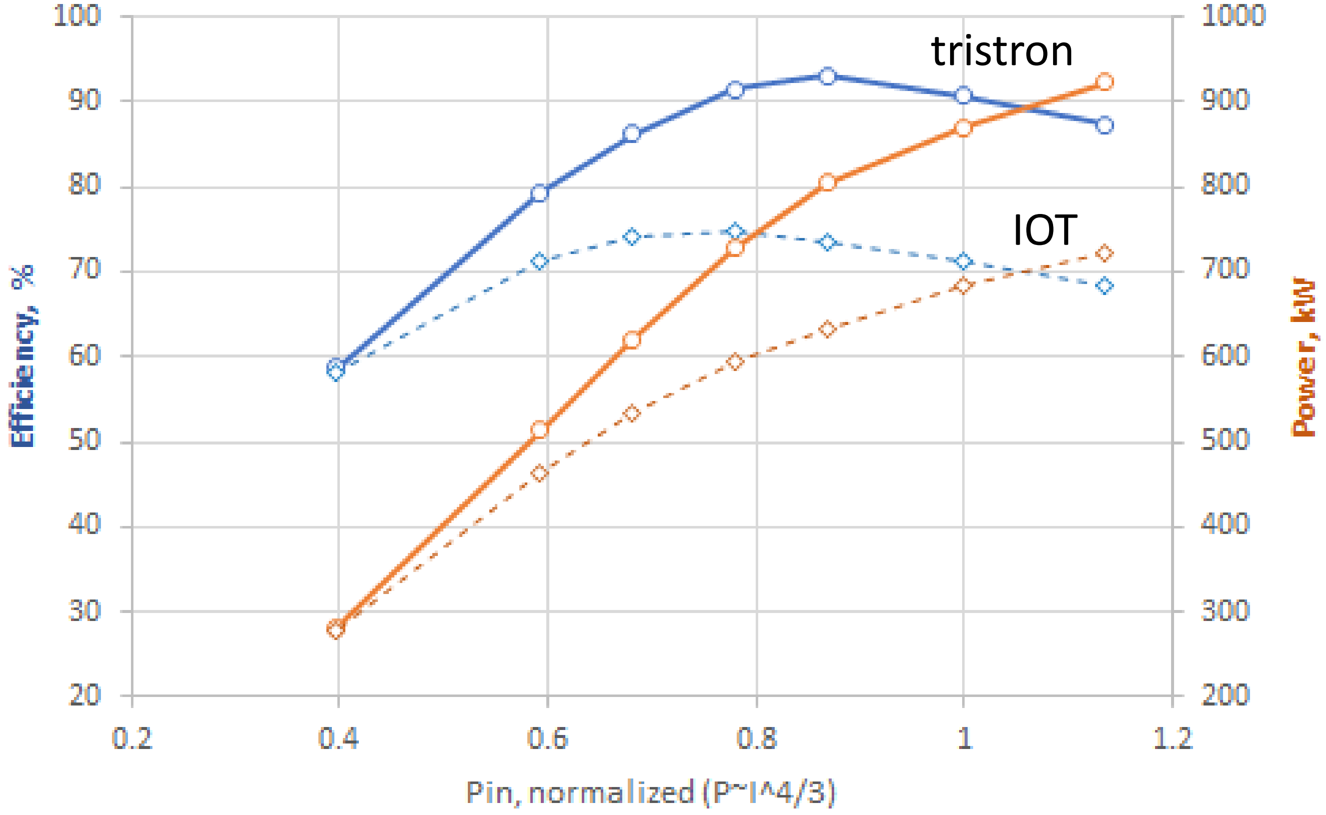


position monitor 1

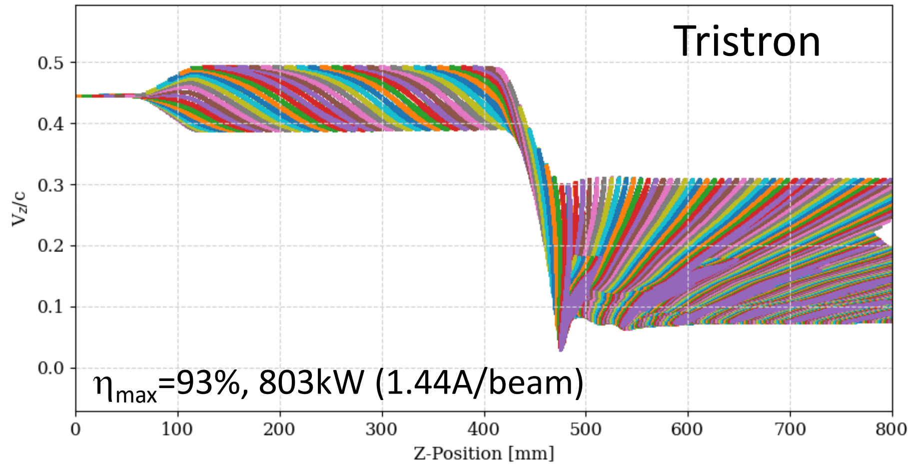
Output	Energy
Sample	1800/1920
Time	790.548 ns
Particles	2343259
Maximum (Sample)	81606 eV
Minimum (Sample)	0.23049 eV
Maximum (Global)	82038.8 eV
Minimum (Global)	0.00185256 eV

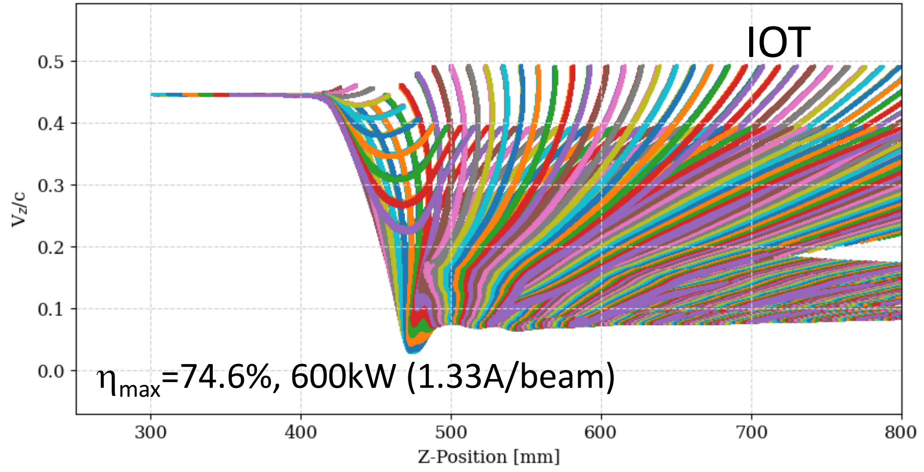
MB Tristron vs. IOT power gain curves

B class (180 degrees bunches)
V beam=60kV



Bunched beam velocity modulation





System efficiency (400MHz). W/H poles.

High Efficiency Klystrons

Sub-System	TH2167 HE	MB TS klystron	MB Tristron
At cavity	378 kW		
WG losses	95% ← 398kW		
Amplifier	70% ← 569kW	86% ← 462 kW	93% ← 427kW
HV converter	95% ← 598kW	95% ← 486kW	95% ← 450kW
Solenoid	5kW	12kW	2.5kW
Driver	0.1kW	0.1kW	5kW
Heater	1kW	1kW	1kW
Power/cavity	604.5 kW / 62.5%	500kW / 75.6%	460kW / 82.1%
Grid Power	160 MW	132 MW	121.5 MW
Installed cooling power	*150MW*	*122MW*	*7.6 MW*

- In worse case (safety), colling system shall enable operation of all the klystron in DC mode.
- Tristron, as a gridded tube, will only have beam in collector with RF on (no DC mode).

The MB Triston has a **remarkable potential as an FCC_{ee} RF power source**, both in terms of power handling and attainable efficiency – above 90%.

Compared to its TS MBK counterpart operated in similar conditions, it has numerous advantages:

- Very compact (shorter by factor 3) – less then 1m long.
- Reduced power in solenoid (factor ~ 10) due to the lower magnetic field and shorter RF circuit
- Very compact and simple collector (factor ~6 in volume).
- Reduce by factor 10 cooling capacity need (Tristron will never be operated in DC diode mode).
- The cost of MB Tristron will be about 0.5 (or less) of those for TS MBK.
- Directly scalable to 200 kW, 800MHz.

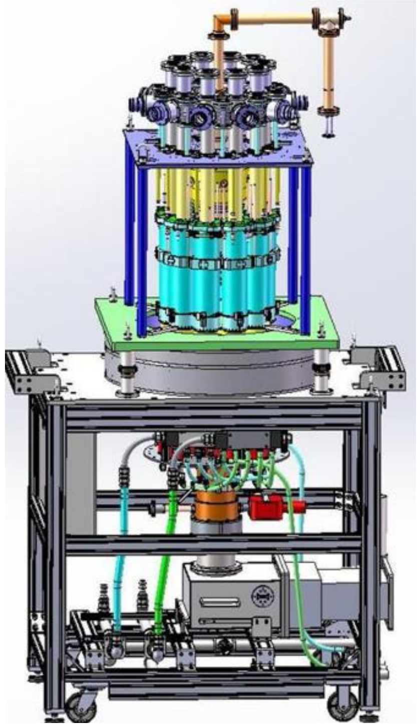
Tristron for FCC_{ee}. Possible implementation scenarios.

Technology demonstrator (low cost at short time): Retrofit upgrade of existing ESS 0.7GHz, 1.5 MW MB IOT, anticipating efficiency increase from 70% to > 85%.

- Full recycling of the exiting components (gridded cavity, output cavity and collector).
- RF circuit and optics design and optimization at CERN.
- Tube refurbishment at Thales – introducing extra cavity and compact external solenoid.
- Testing at ESS using existing facilities.
- Estimated schedule is about **18 month**.

** Potential candidate for the graceful replacement of ESS klystrons along accelerator life-time.*

*** Frequency is close to 800MHz needed for FCC.*



FCC_{ee} Tristron prototype at 400MHz.

- Selection of operating power level (400-500 kW can be recommended).
- RF circuit and optics design and optimization at CERN.
- Common input cavity vs. clustered option design and cost optimization (Thales+ ? + CERN)
- Tube fabrication at Thales+?.
- Estimated schedule is about **36 month**.

Tristron 500kW, 400MHz series production estimations.

- Anticipating that the first cost optimized prototype will be ready by 2027-2028, and expecting at least two vendors to be engaged, the production rate of 40 tubes per year seems to be a practical case. With that, it will take about 7 years to produce and deliver 264 tubes (<2035).
- 200kW, 800 MHz HE power source (Z,W,H booster and ttbar collider) will be a down scaled version of 400MHz tristron. It will be developed in a wake of its 400MHz partner on the same time scale. Albeit much smaller series will be required for Z, W and H.