2nd Workshop on efficient RF Sources

23-25 September 2024, Toledo, Spain

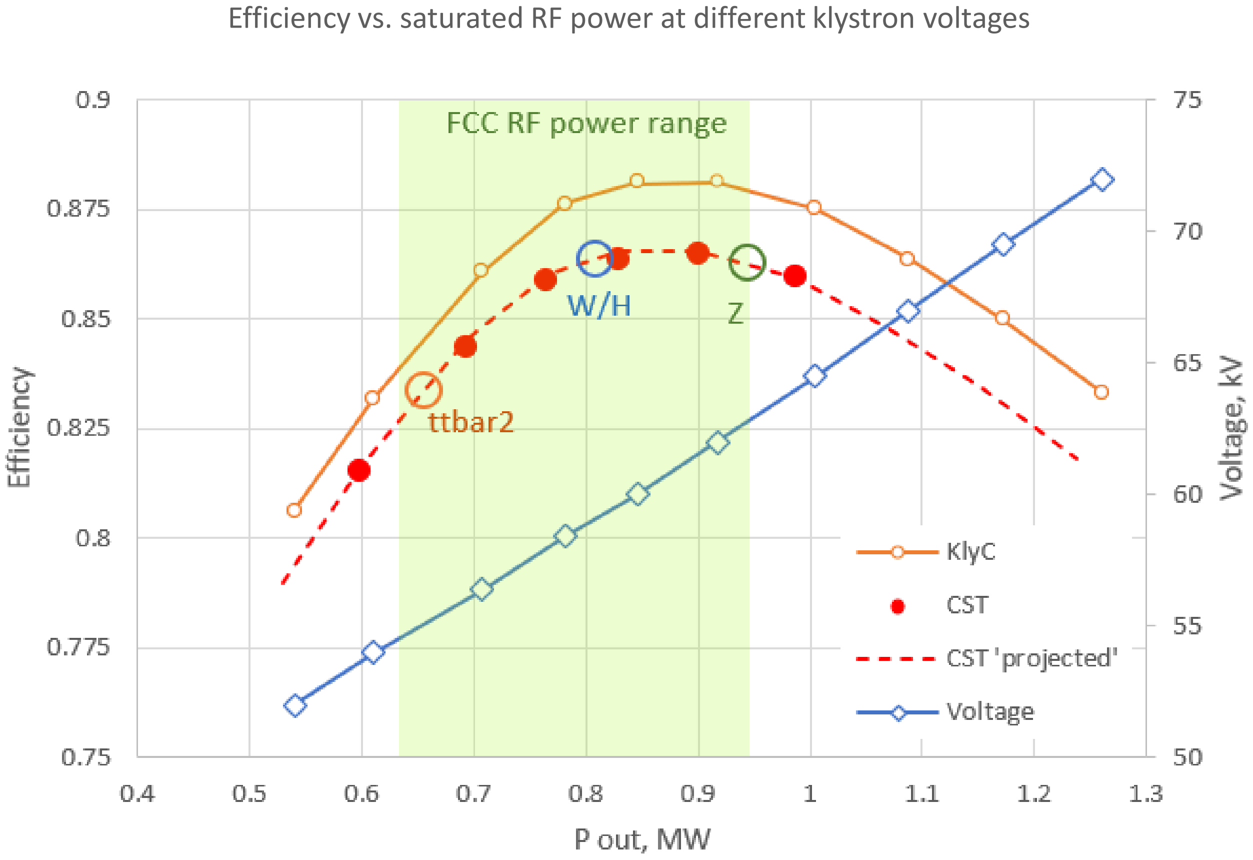
Ultimate efficiency in linear beam devices.

Electro-vacuum technologies for FCC$_{ee}$

I. Syratchev, CERN

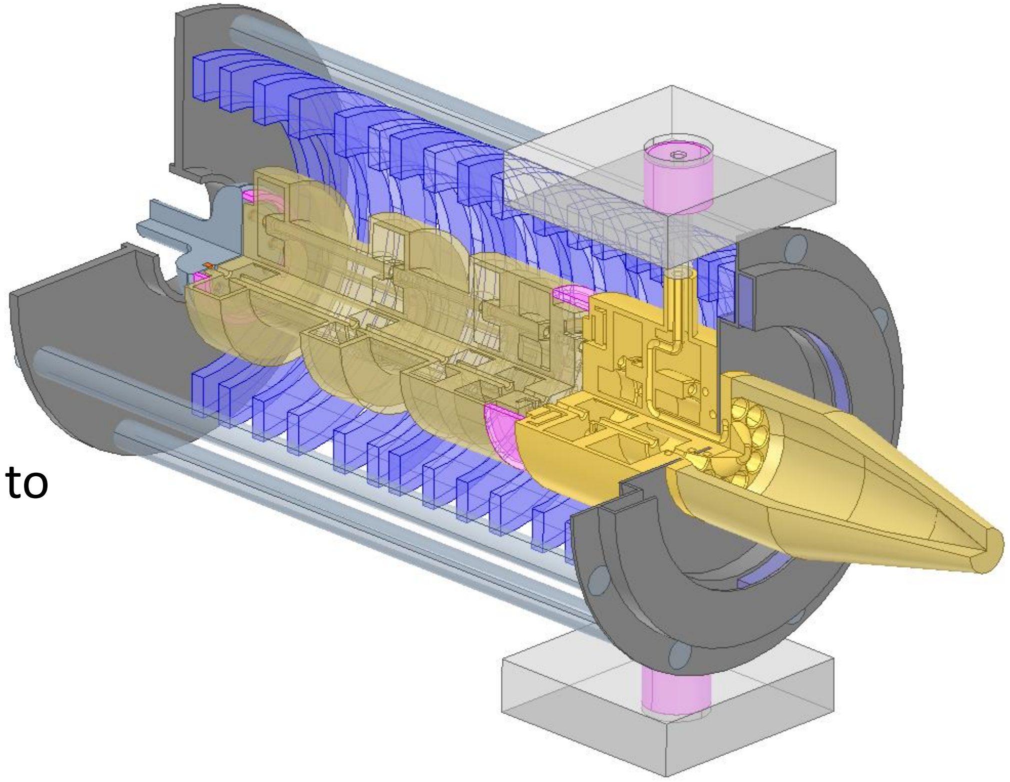
Novel 400 MHz, 1MW HE Two-Stages MBK for FCC$_{ee}$. Performance summary.

High Efficiency Klystrons



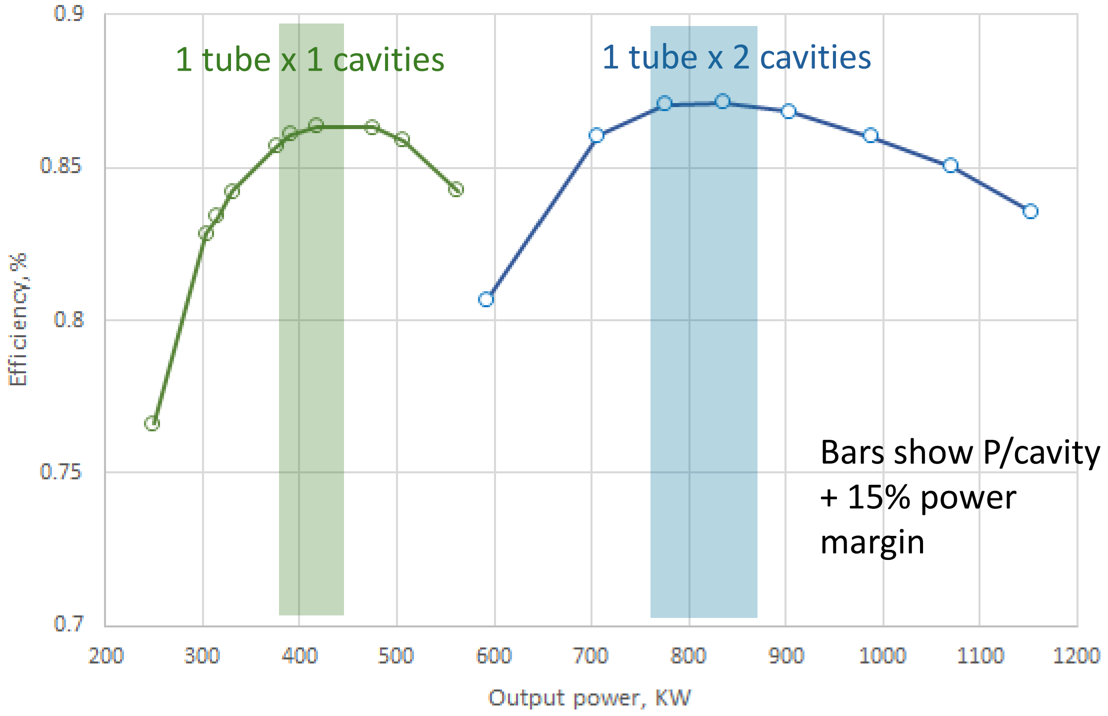
Featured:

- **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 efficiency.



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 x2 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

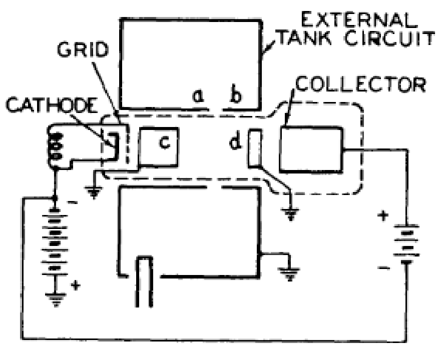
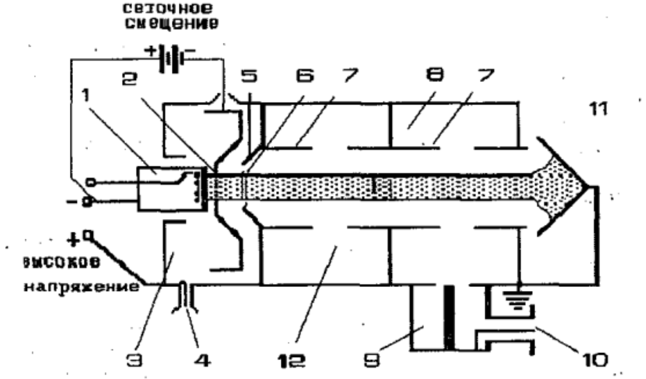


Fig. 2—Diagram of an inductive-output amplifier with an external output circuit.

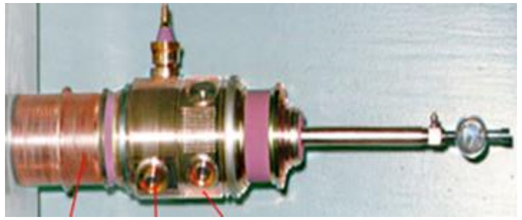
IOT (A. Haeff, 1939)

Klystrode

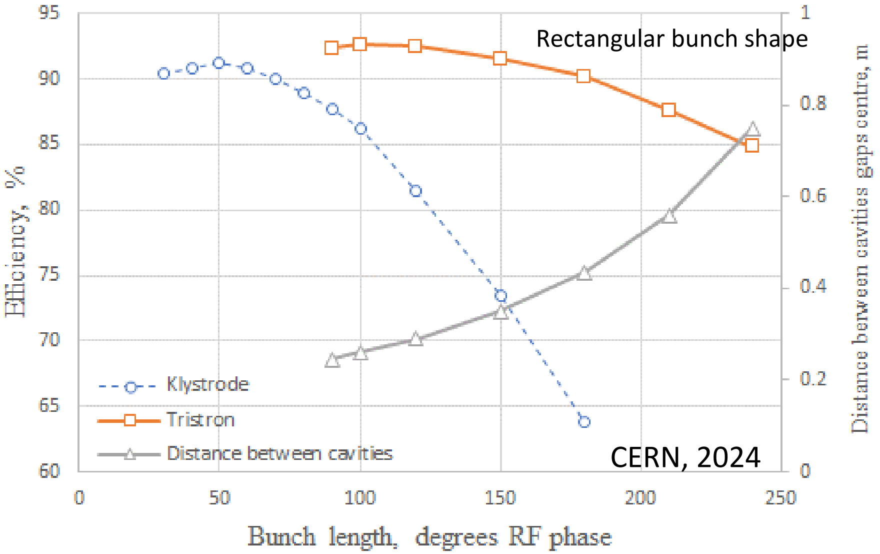
(H. Priest and M.B. Shrader 1982)



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



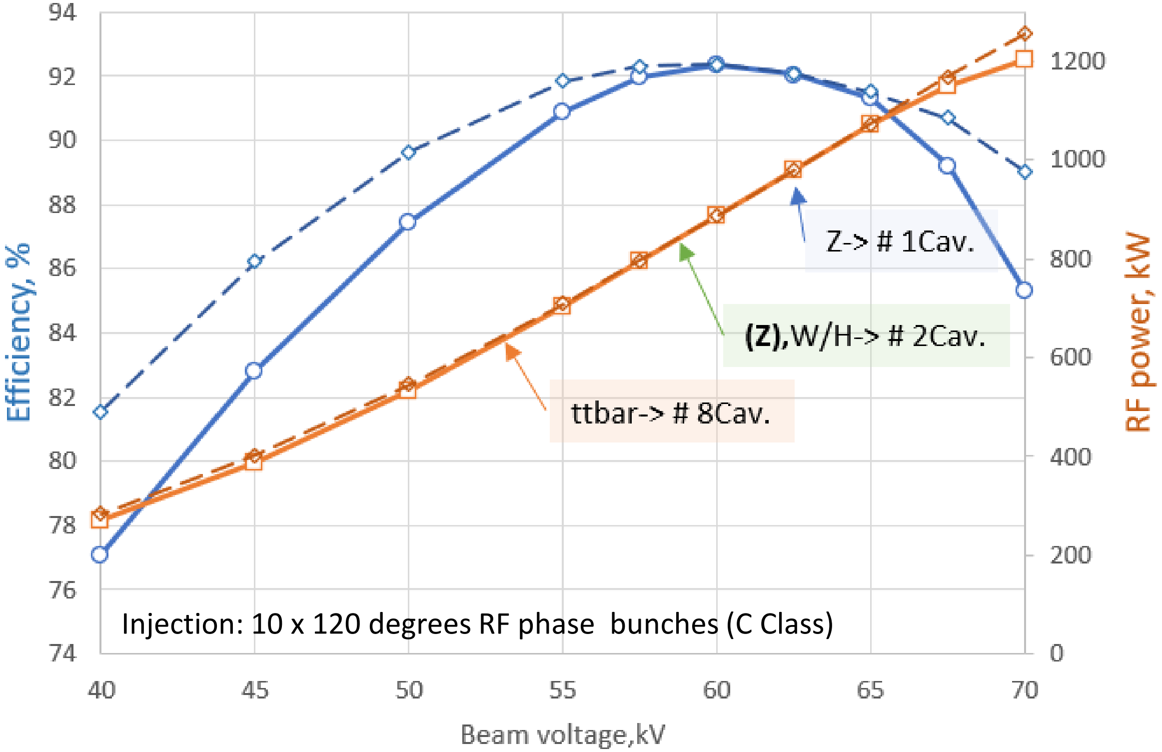
FCC$_{ee}$ 1MW, 400 MHz 10 beams gridded tubes performance (KlyC simulations)



Rectangular bunch shape

CERN, 2024

1 MW, MB Tristron power-efficiency capabilities



Z-> # 1Cav.

(Z),W/H-> # 2Cav.

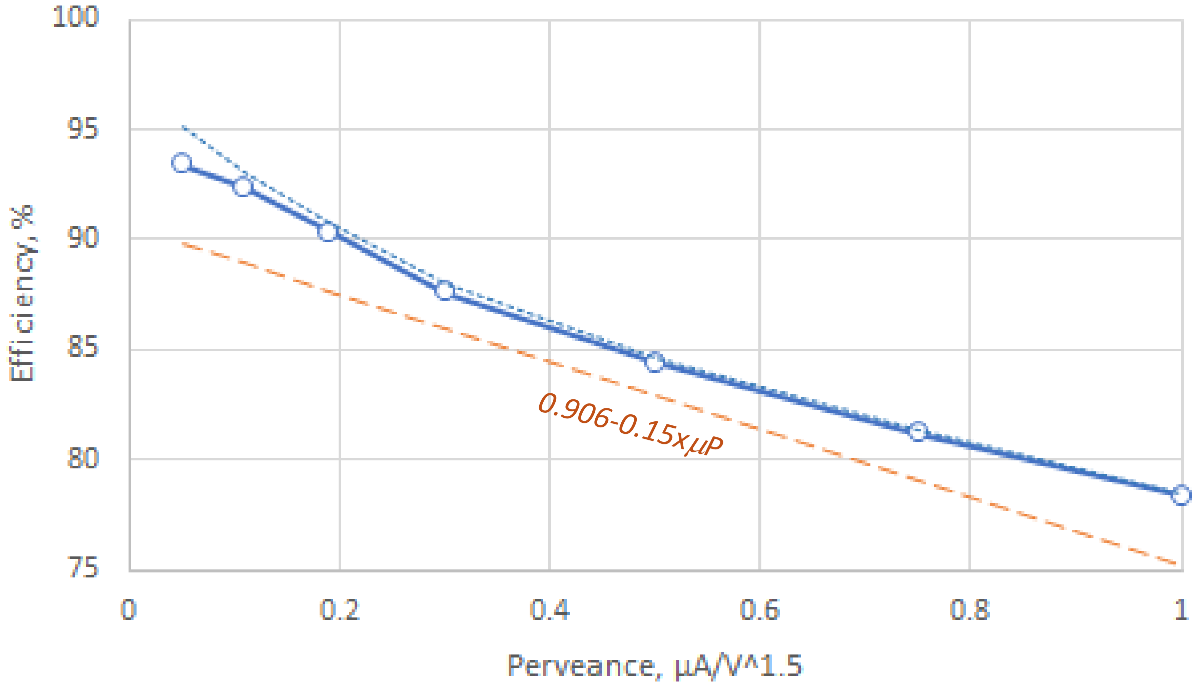
ttbar-> # 8Cav.

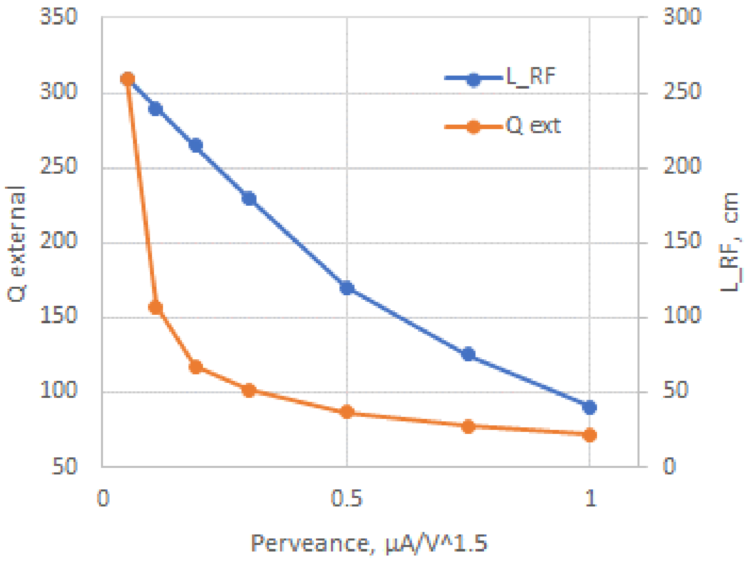
Injection: 10 x 120 degrees RF phase bunches (C Class)

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

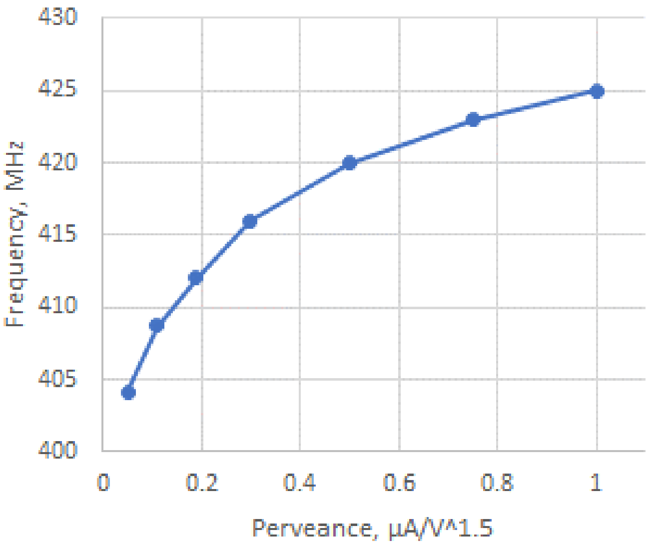
Tristron efficiency vs. beam perveance

Optimized for bunch length of **120** degrees RF phase and fixed beam power (960 KW)





Penultimate cavity tuning

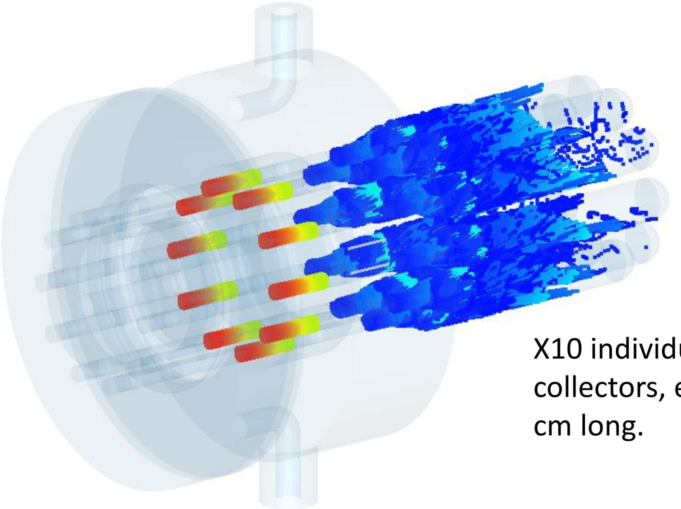


Overall, tristron demonstrated excellent performance in terms of the ultimate efficiency in a wide range of operating perveance.

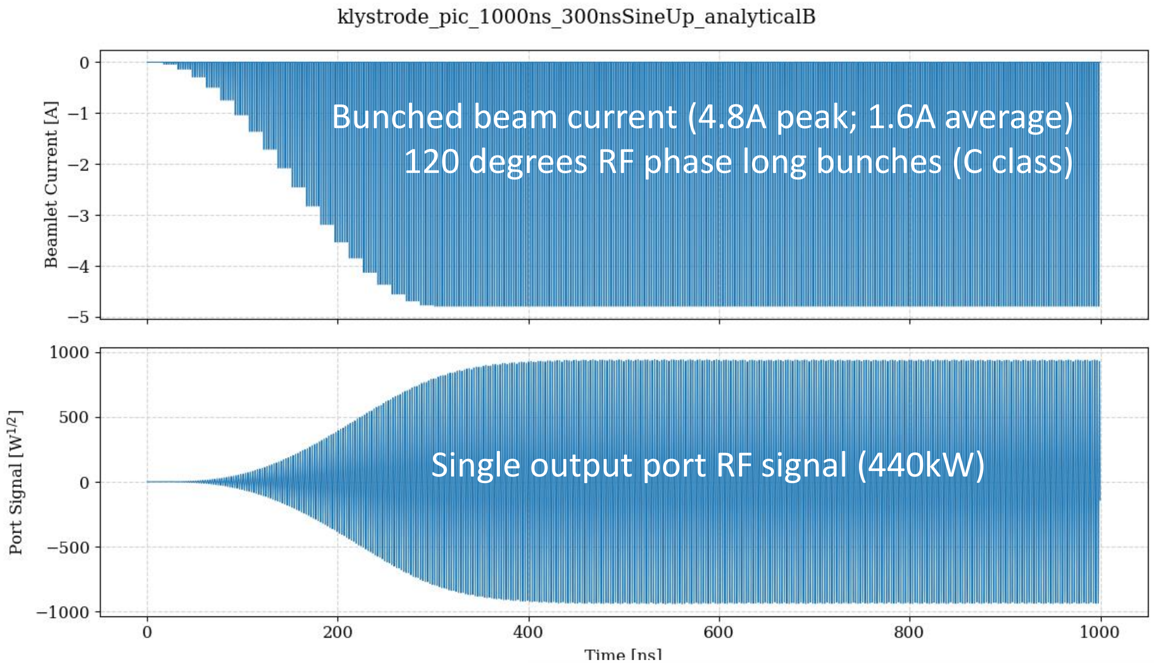
10 beams (1.6A, 60kV each)
Bz: 0.032T
Beam power 960kW
RF power: 880kW
Efficiency: 91.4%

Tristron 3D CST PIC simulations.

Direct benchmarking with CERN made fast 1.5D computer code KlyC

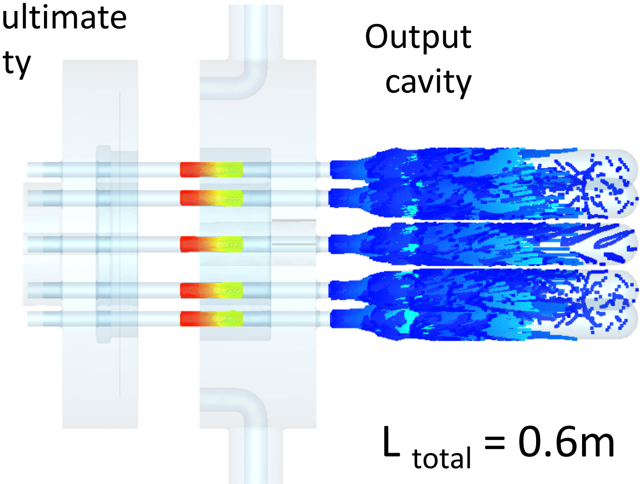


X10 individual collectors, each 30 cm long.



Bunched beam current (4.8A peak; 1.6A average)
120 degrees RF phase long bunches (C class)

Single output port RF signal (440kW)

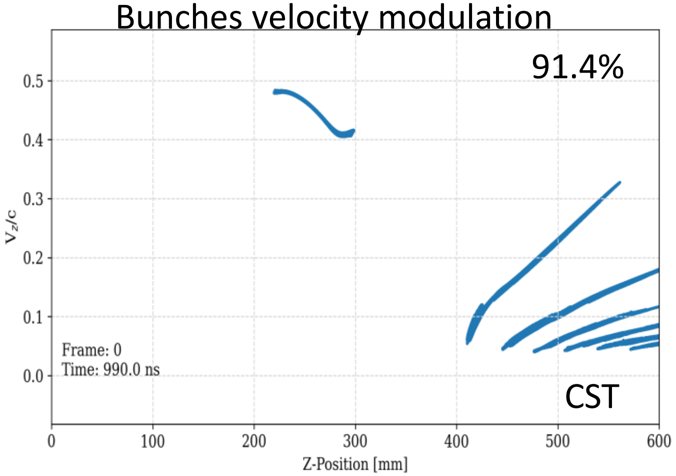


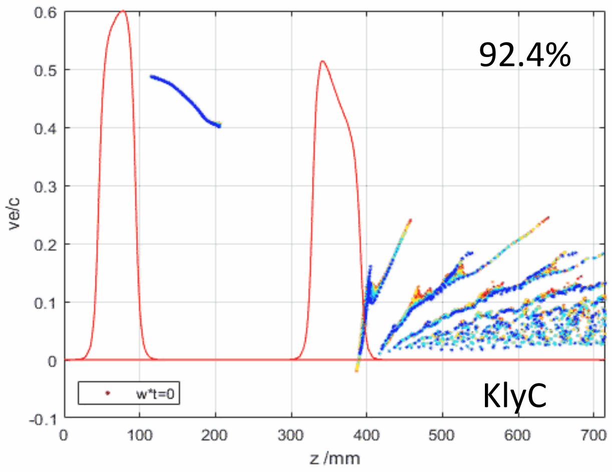
Penultimate cavity

Output cavity

L total = 0.6m

Bunches velocity modulation

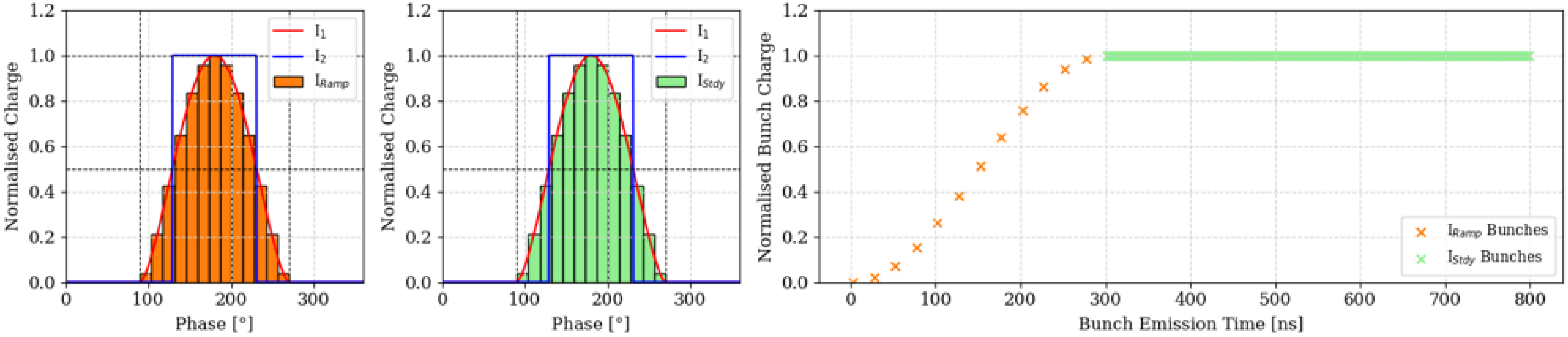




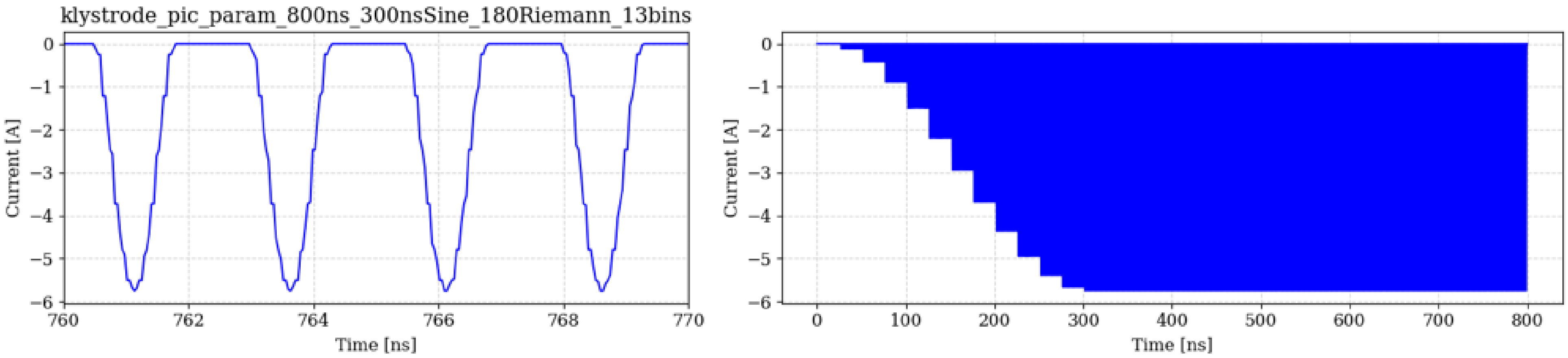
Emission Current – 180° Bunch

$$I(t) = I_0 \times \left(U_{bias} + U_{RF} \times sin(\omega t)\right)^{1.5}$$

Emission Programme

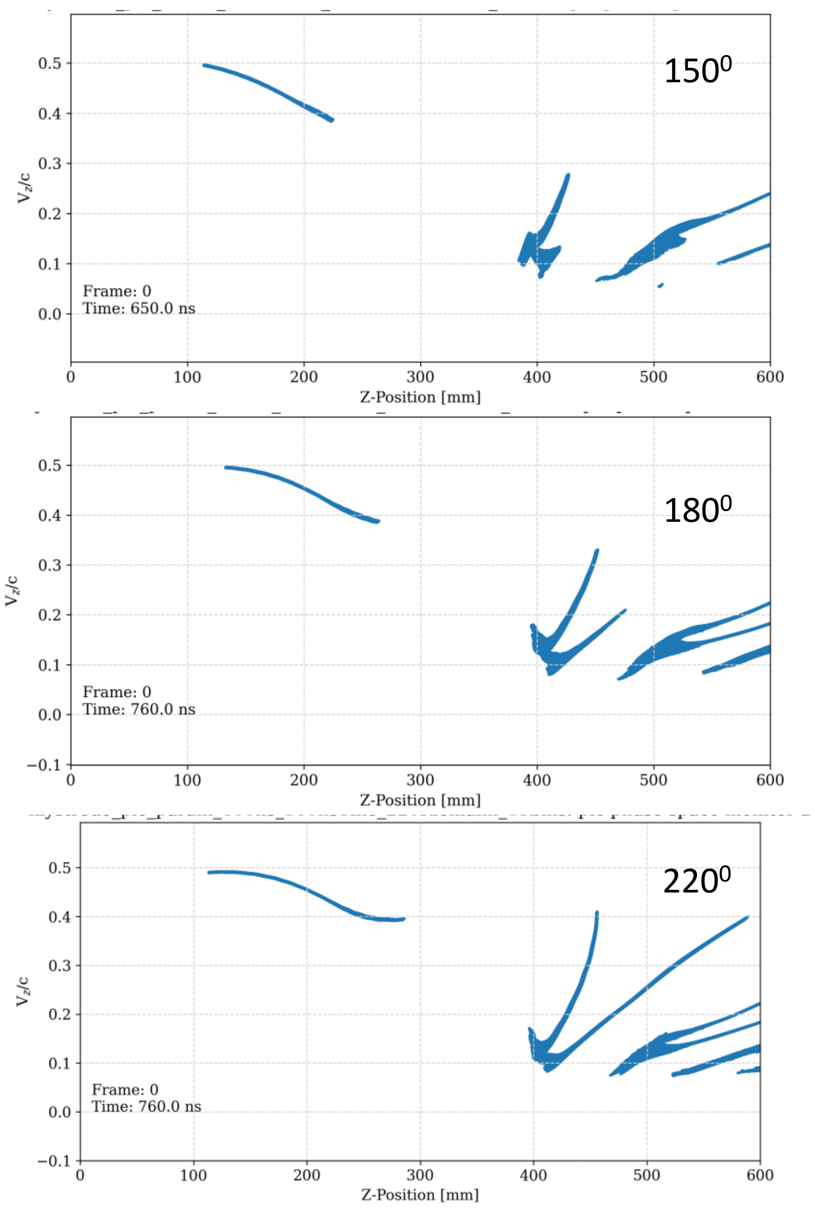


CST monitors

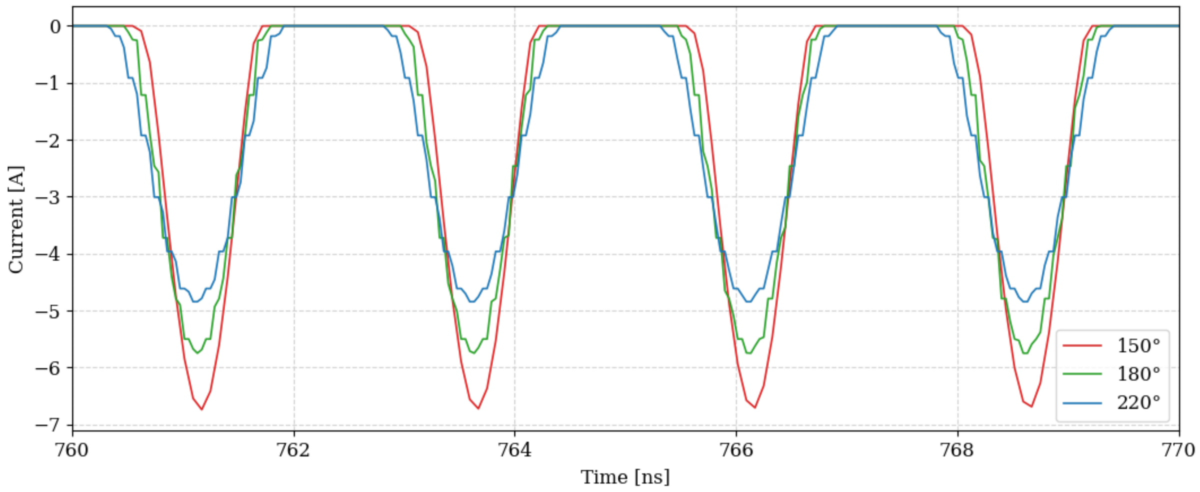


Realistic bunches in gridded tubes

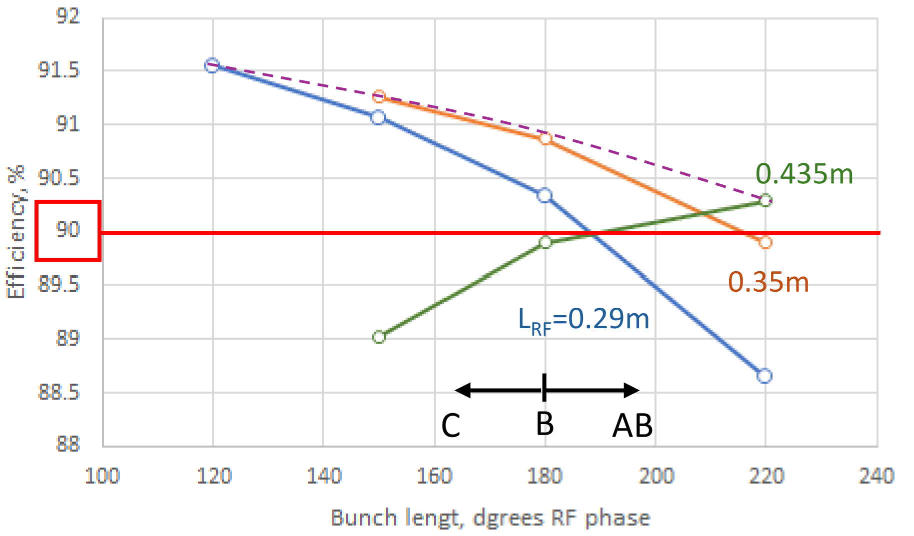
Particles velocity modulation (**L_{RF}=0.29m**)



Average current 1.6A/beam



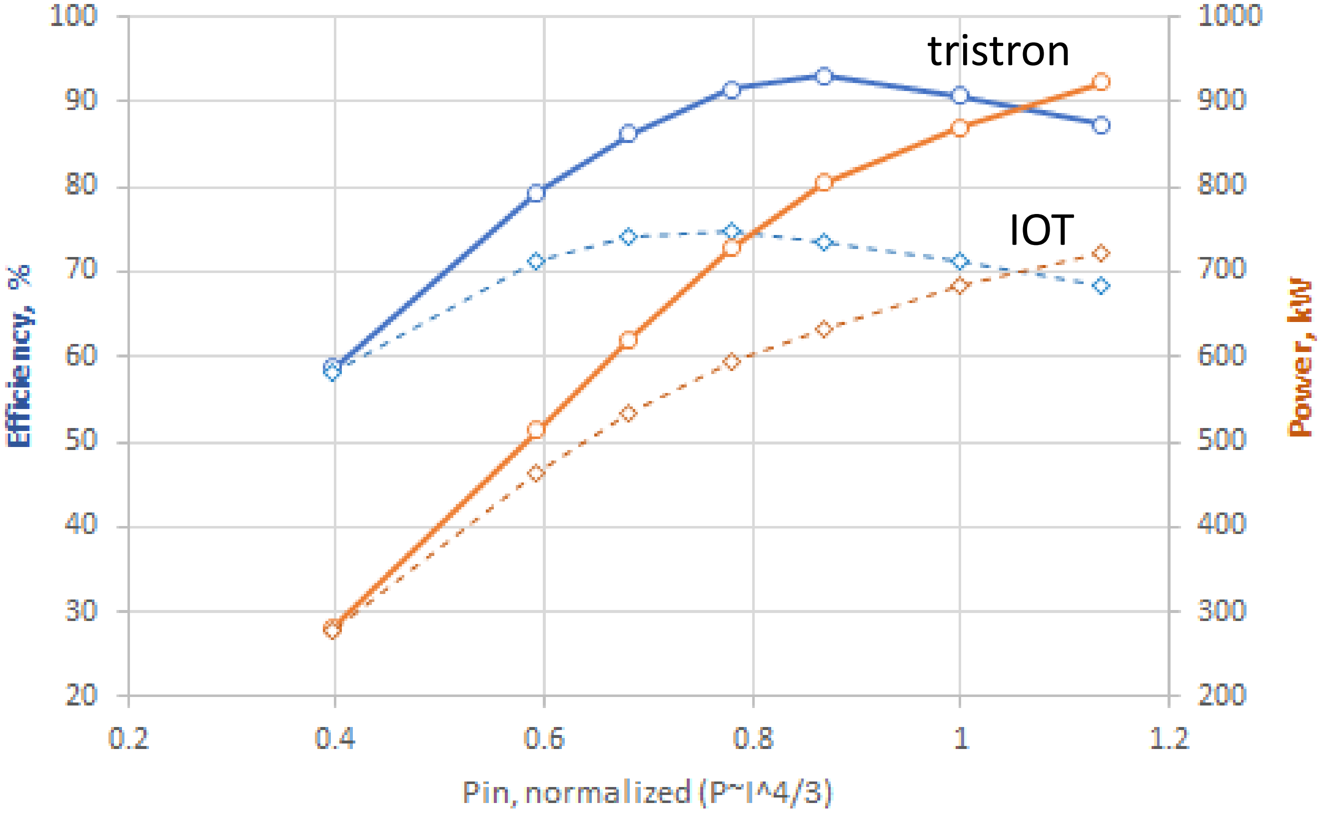
1MW, MB **Triston** efficiency (measured at RF port)

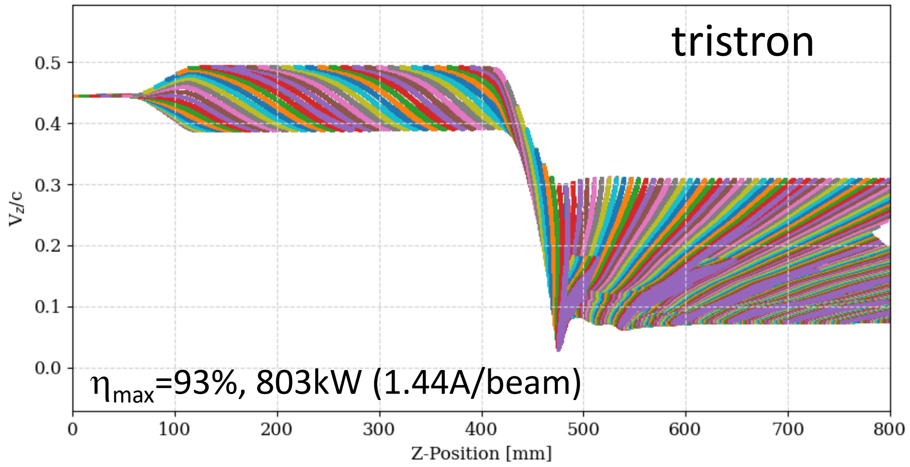


Distance between the cavities (L_{RF}) and penultimate cavity tunings were taken from the ones optimized in KlyC for rectangular bunch shape (see page 4). *The is some space left for post-optimization*

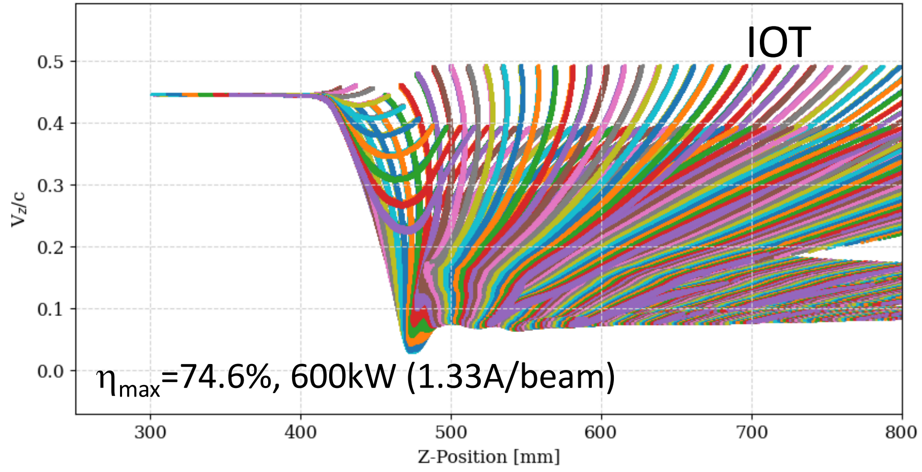
MB tristron vs. IOT power gain curves

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





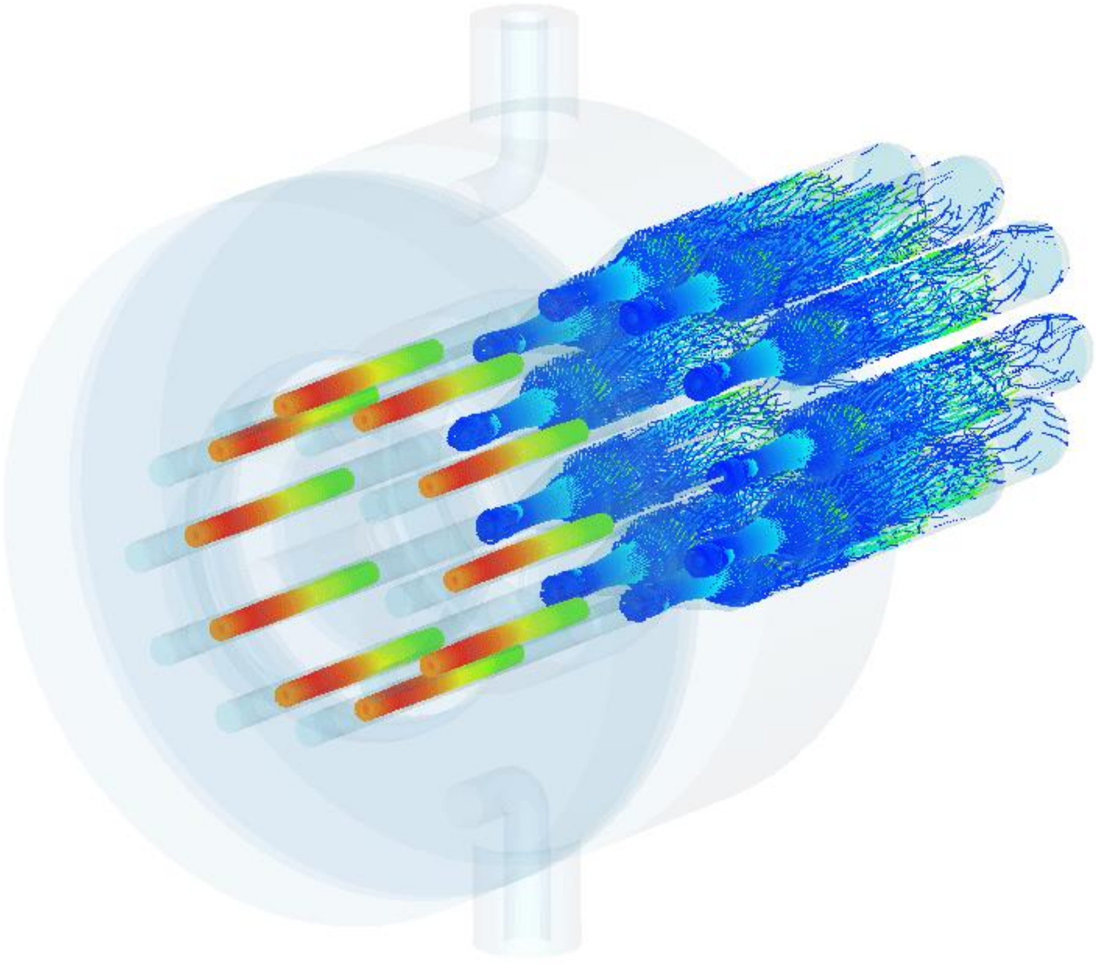
η_{max}=93%, 803kW (1.44A/beam)

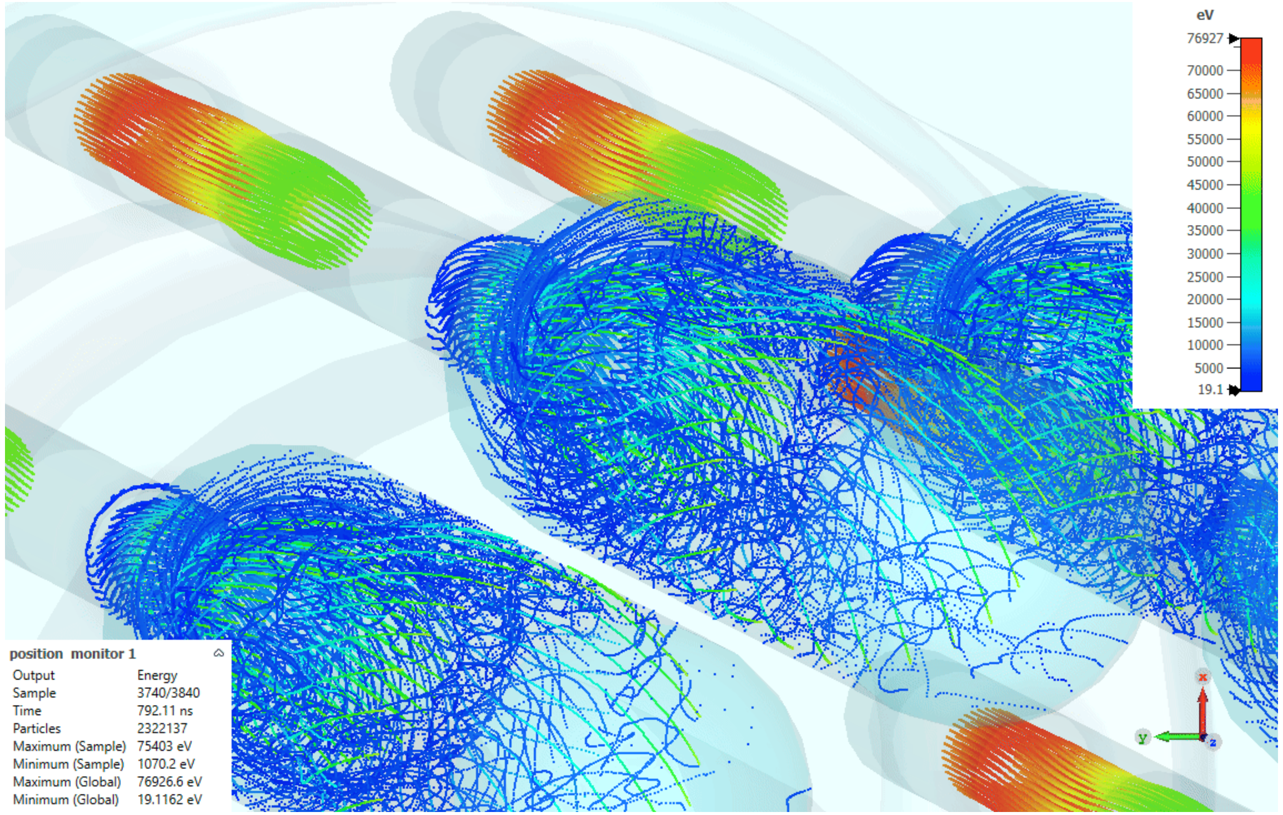


η_{max}=74.6%, 600kW (1.33A/beam)

More particles animations (AB Class)

High Efficiency Klystrons





position monitor 1

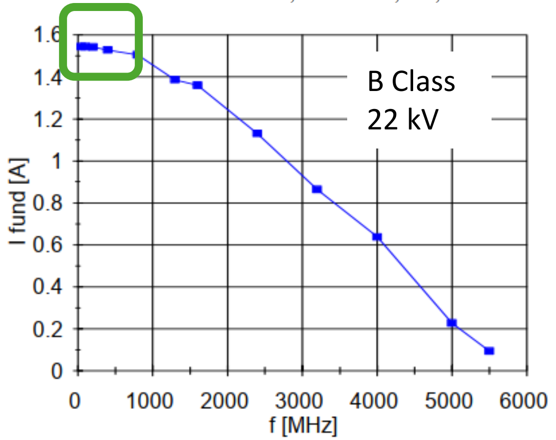
Output	Energy
Sample	3740/3840
Time	792.11 ns
Particles	2322137
Maximum (Sample)	75403 eV
Minimum (Sample)	1070.2 eV
Maximum (Global)	76926.6 eV
Minimum (Global)	19.1162 eV

RF power limit in **CW** UHF/L-band gridded tubes

Proceedings of LINAC 2004, Lübeck, Germany

IOT RF POWER SOURCES FOR PULSED AND CW LINACS

H. Bohlen, Y. Li, R. Tornoe,
CPI Eimac Division, San Carlos, CA, USA



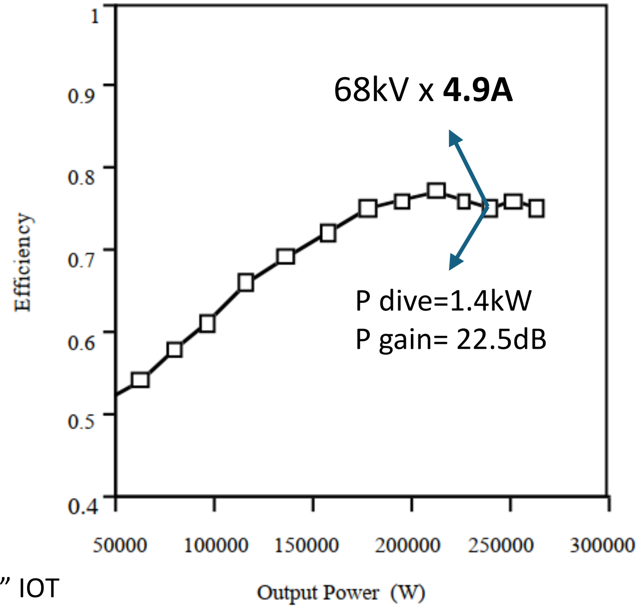
30 kW CW L-Band (1.3GHz) IOT by CPI / Eimac

Voltage(kV)	Current(A)	Drive(W)	Output(kW)	Gain(dB)	Eff(%)
24	0.79	208	10.0	17	52.7
25	1.10	203	15.1	19	54.9
26	1.46	183	20.6	21	54.3
32	1.35	192	25.7	21	59.5
34	1.39	253	30.2	21	63.8

CHARACTERIZATION OF A KLYSTRODE AS A RF SOURCE FOR HIGH-AVERAGE-POWER ACCELERATORS*

D. Rees, D. Keffeler, W. Roybal, and P. J. Tallerico
Los Alamos National Laboratory, Los Alamos, NM 87545 USA

250kW, 267 MHz CW “Chalk River” IOT



68kV x **4.9A**

P dive=1.4kW
P gain= 22.5dB

“…We have approximately 664 high-voltage hours on the 250-kW CW klystrode at Los Alamos, and we have had to process the grid at least three times to remove material deposited on the grid by the cathode. We are afraid that the cathode is being overheated
by the RF drive power and that the result will be a reduced tube life…”

In the gridded tubes CW RF power level will be limited by:

- ➢ The average beam current (current interception on the grid - direct heating).
- ➢ Cathode overheating by the dive power (material deposition on the grid).
- ➢ More?

In MB tubes, the current and drive power per beam can be controlled/adjusted by beams number. In the FCC_{ee} MB tristron designs:

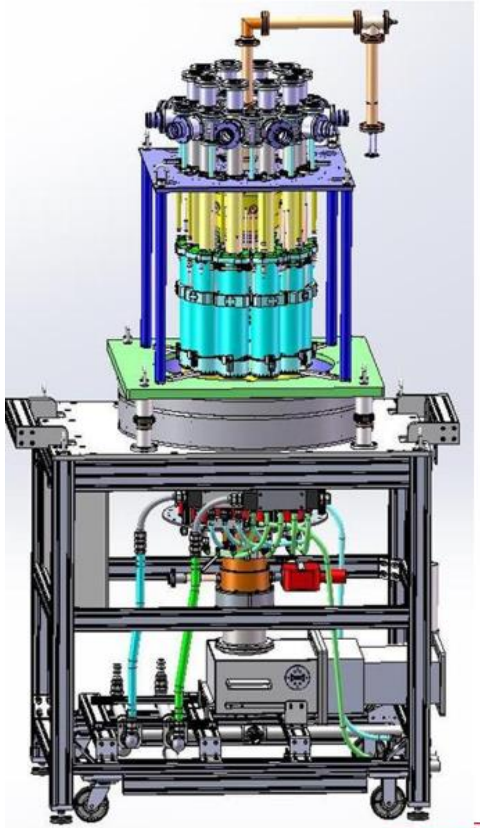
- 10 beams, 60kV, Pout 880kW; beam current is 1.6 A, P dive/beam = 440W (P gain=23 dB)
- 10 beams, 47kV, Pout 440kW; beam current is 1.0 A, P drive/beam = 220W (P gain=23dB).

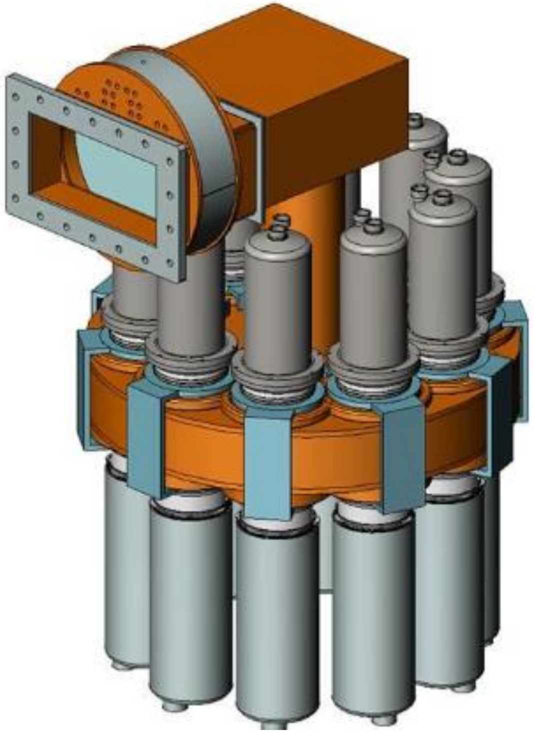
Both cases look like a feasible options.

MB input gridded cavity

High Efficiency Klystrons

ESS MB IOT prototypes





THALES

CPI
Communications & Power Industries
microwave power products division

L3

COMPREHENSIVE DESIGN AND WHOLE-CAVITY SIMULATION OF A MULTI-BEAM INDUCTIVE OUTPUT TUBE USING A 3rd HARMONIC DRIVE ON THE GRID

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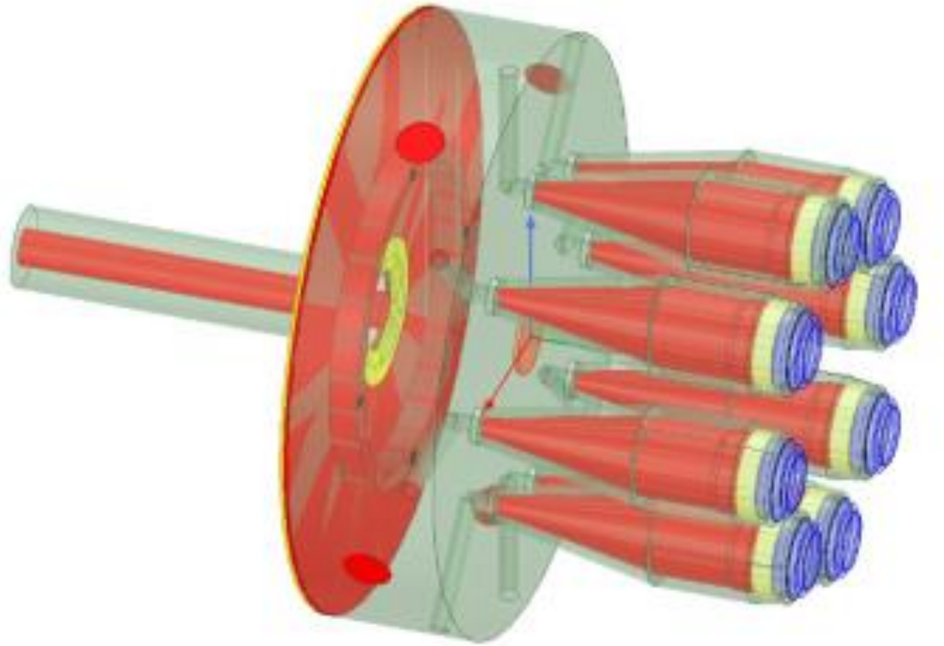


From ESS MB IOT experience, input cavity can be rather expensive and complicated if composed of many individual cavities (coupled or not). It will be useful to investigate more compact and reliable solution with a ‘common’ volume (one of the concepts is shown above on the right).

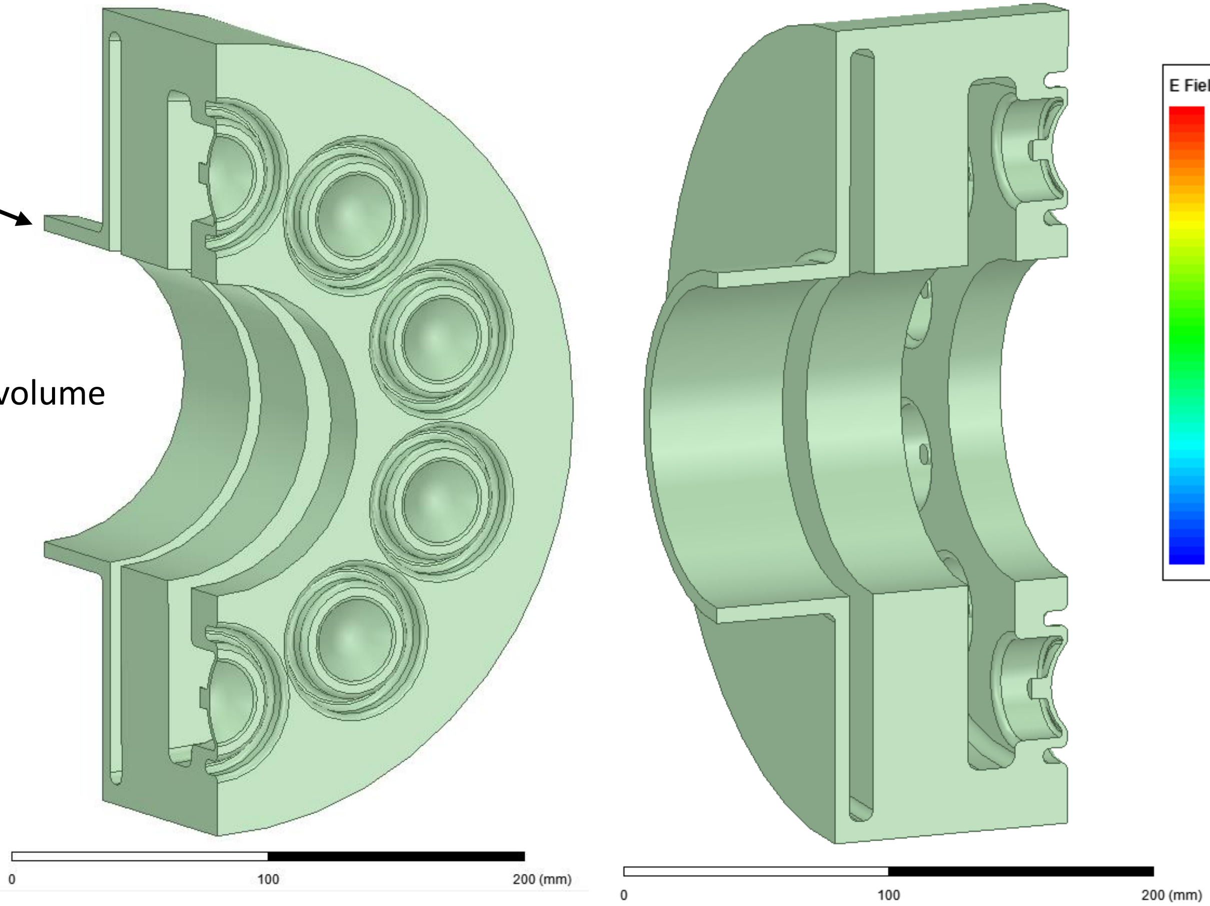
400MHz Double-gap coaxial compact cavity **concept** (CERN).

High Efficiency Klystrons

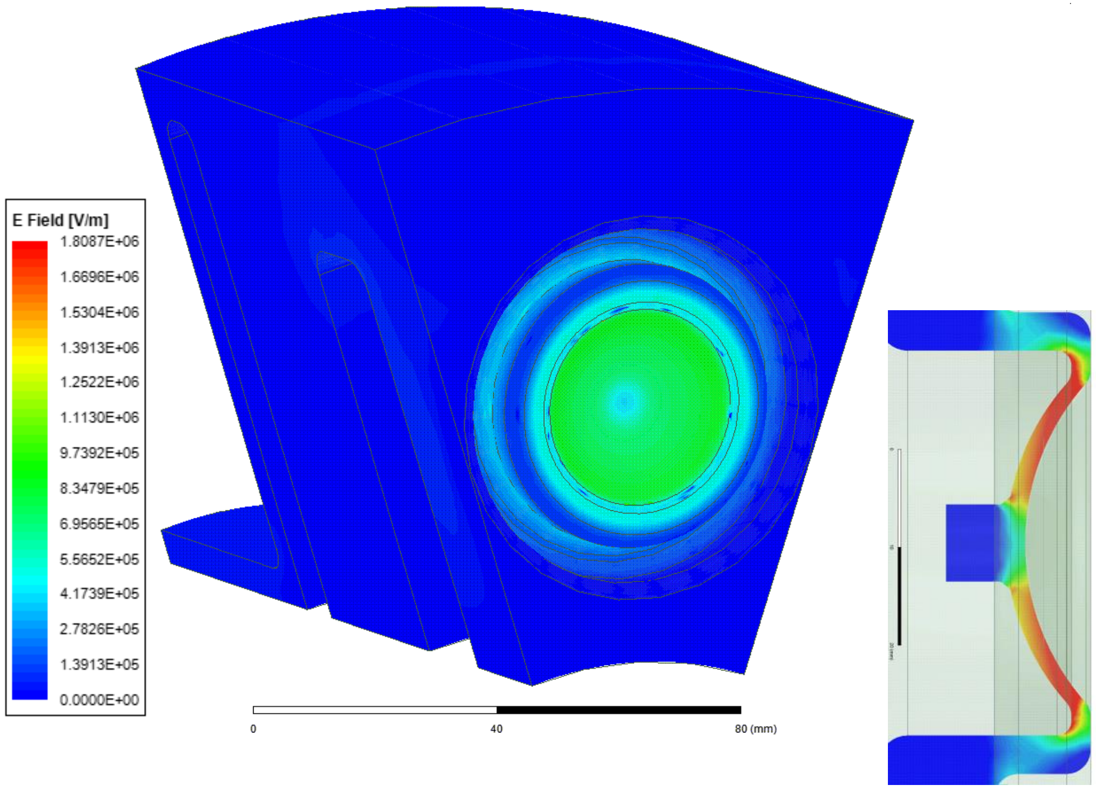
grid-cathode distance = 2mm

Pin

Vacuum volume is shown



Q0=3080, Qext=61.5 (Ohmic losses ~2%)



With P_{RF}=880kW, assuming 23 dB power gain (Pin=4.4kW) and Qext=61.5, average gap field is ~0.7MV/m. With 2mm gap distance, the gap RF voltage is about 1.4 kV.

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 development is already planned as a part of the future CERN-Thales collaboration.