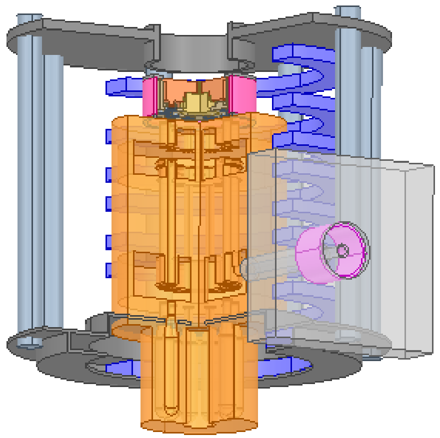
FCC_{ee} RF power sources and powering schemes

I. Syratchev, CERN

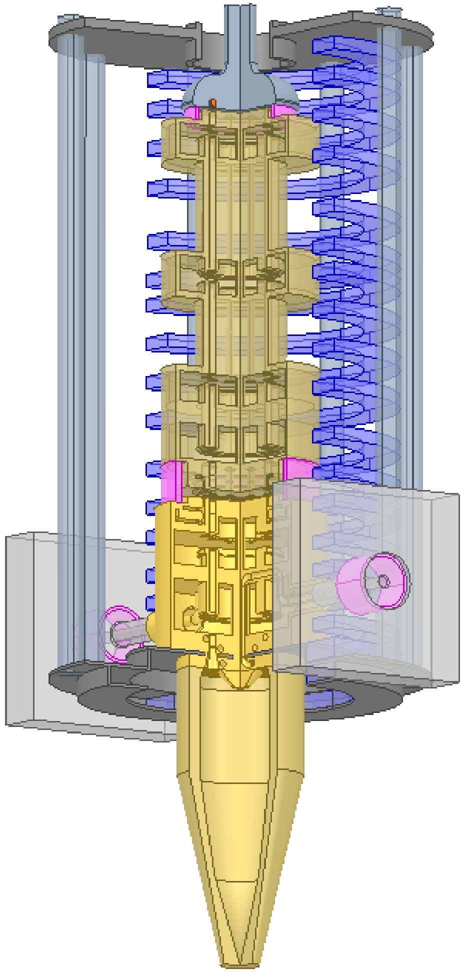
System efficiency (400MHz). Z/W/H poles.

Sub-System	TH2167 HE	MB TS klystron	MB Tristron
At cavity	378 kW		
WG efficiency	95% ← 398kW		
Amplifier	70% ← 569kW	86% ← 462 kW	93% ← 427kW
HV converter	98.5% ← 574.7kW	98.5% ← 466.7kW	98.5% ← 431kW
Solenoid	5kW	12kW	2.5kW
Driver	0.1kW	0.1kW	5kW
Heater	1kW	1kW	1kW
Power/cavity	580.8kW / 65%	479.8kW / 78.8%	439.8kW / 85.9%
Grid Power	153.3 MW	126.7 MW	116.6 MW
Grid power cost/ year • *5000 hours* • *80 Euro/MWh*	*61.3ME*	*50.7ME*	*46.7ME*

MB Tristron (concept)



MB TS Klystron (design)

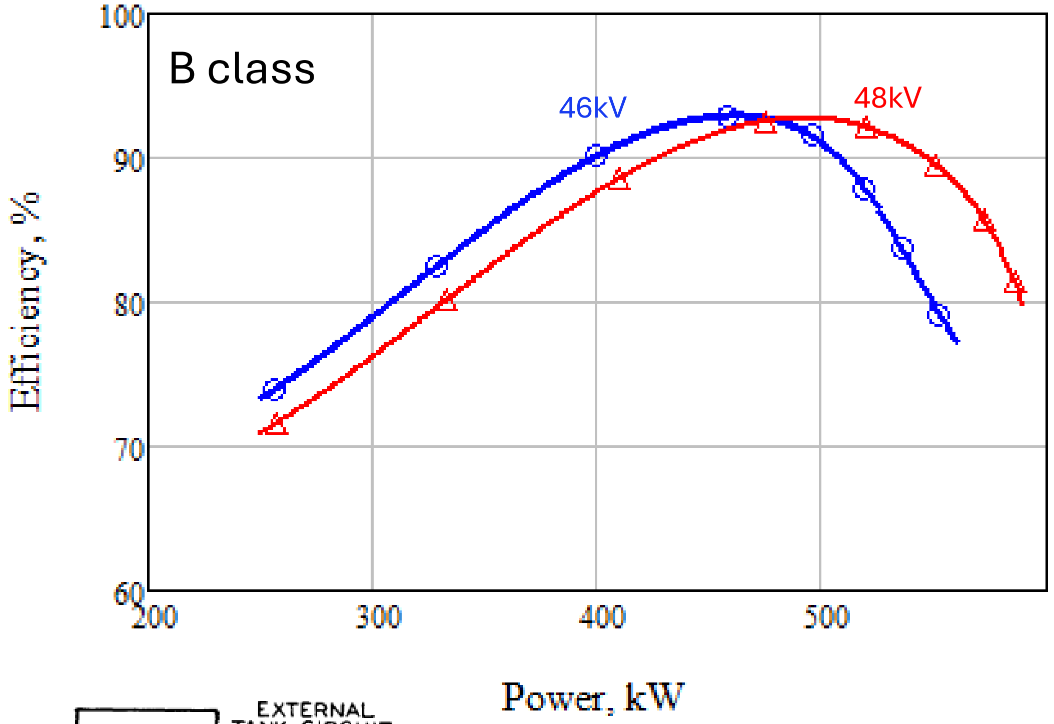


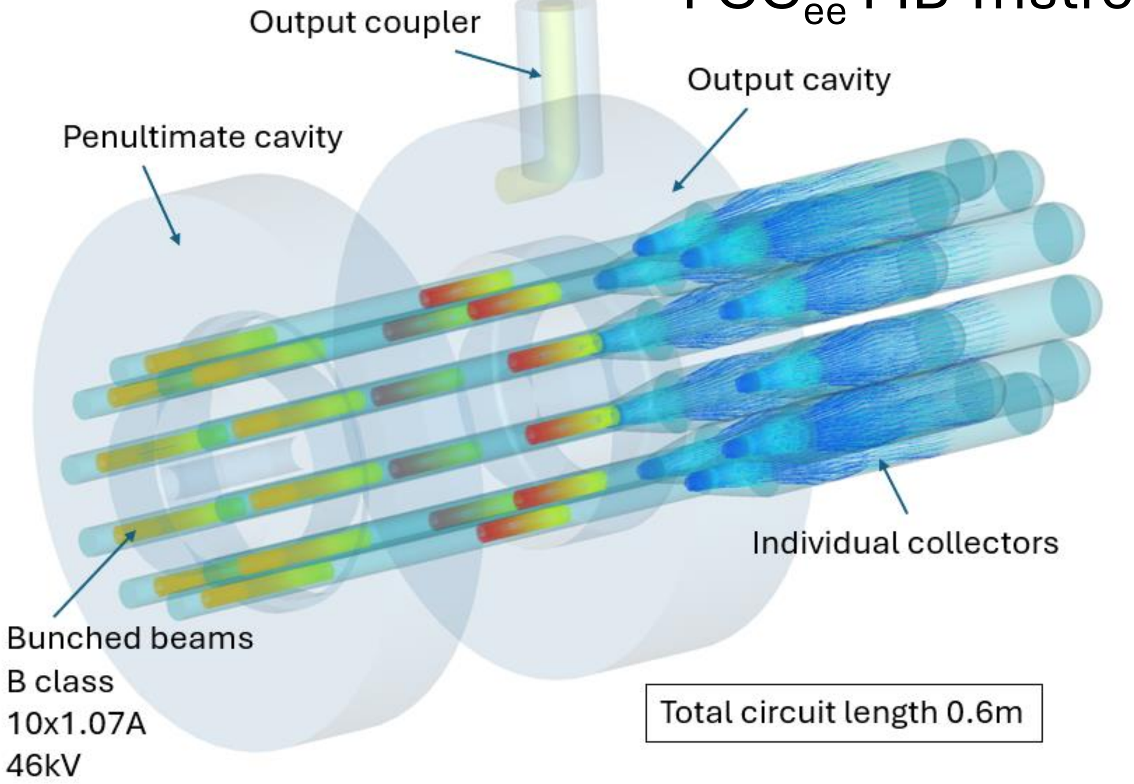
TH2167 HE klystron (HL-LHC)

- Electro-vacuum tubes technologies for FCC_{ee} developed at CERN.
- Fully compatible with HL-LHC power needs and infrastructure.

FCC$_{ee}$ MB Tristron.

400 MHz FCC tristron power /efficiency performance





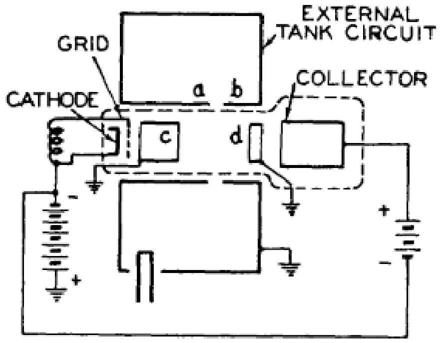
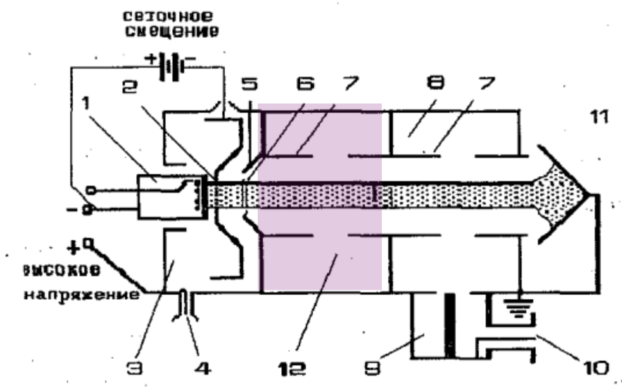


Fig. 2—Diagram of an inductive-output amplifier with an external output circuit.

IOT (A. Haeff, 1939)



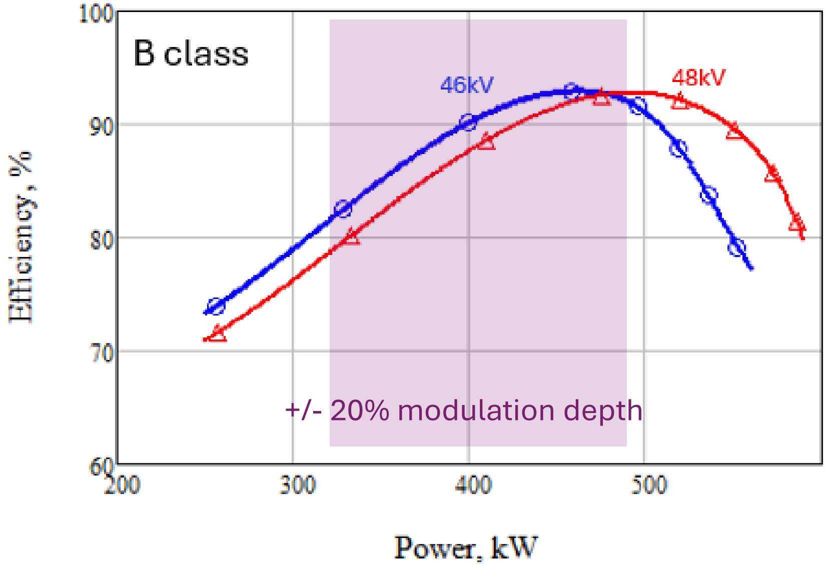
Tristron **(A.D. Sushkov et. al. 1967)**

MB Prototype tested in 1997, V. Tsarev:

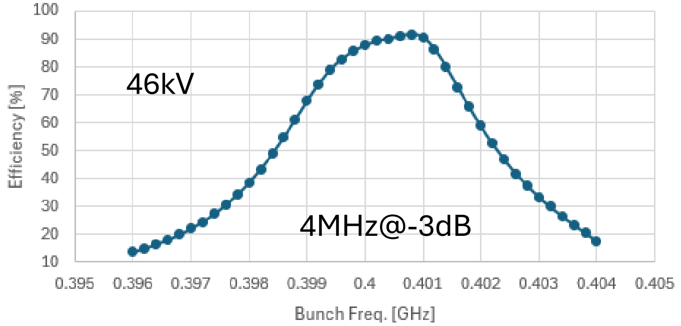
- Alike IOT, Tristron (a hybrid between **tri**ode and kly**stron**) is a gridded tube with additional penultimate cavity that boosts the RF power production efficiency from 75% (IOT) to above 90%.
- Tristron concept is almost 60 years old, but it never been fully commercialized before.

MB Tristron operational efficiency for FCC: Z-pole/RPO.

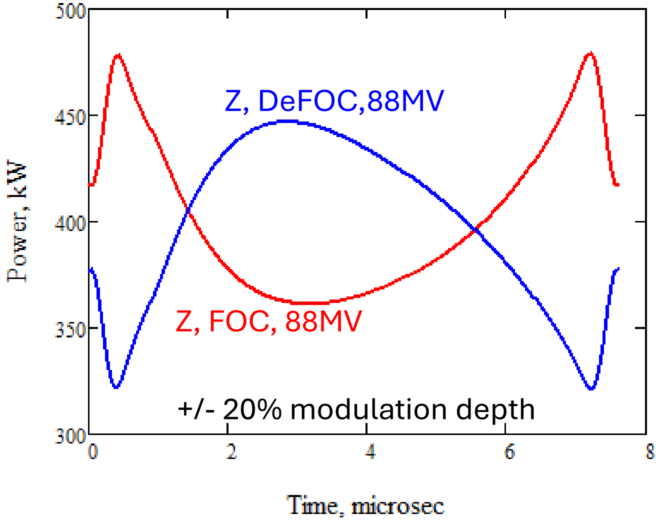
400 MHz FCC tristron power /efficiency performance



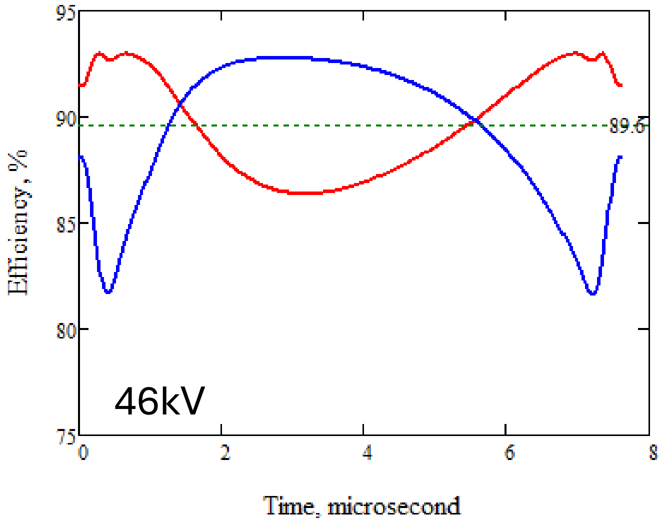
Tristron bandwidth



Cavities RF power modulation, 4 MHz filtered; 88MV



Tristron transient efficiency

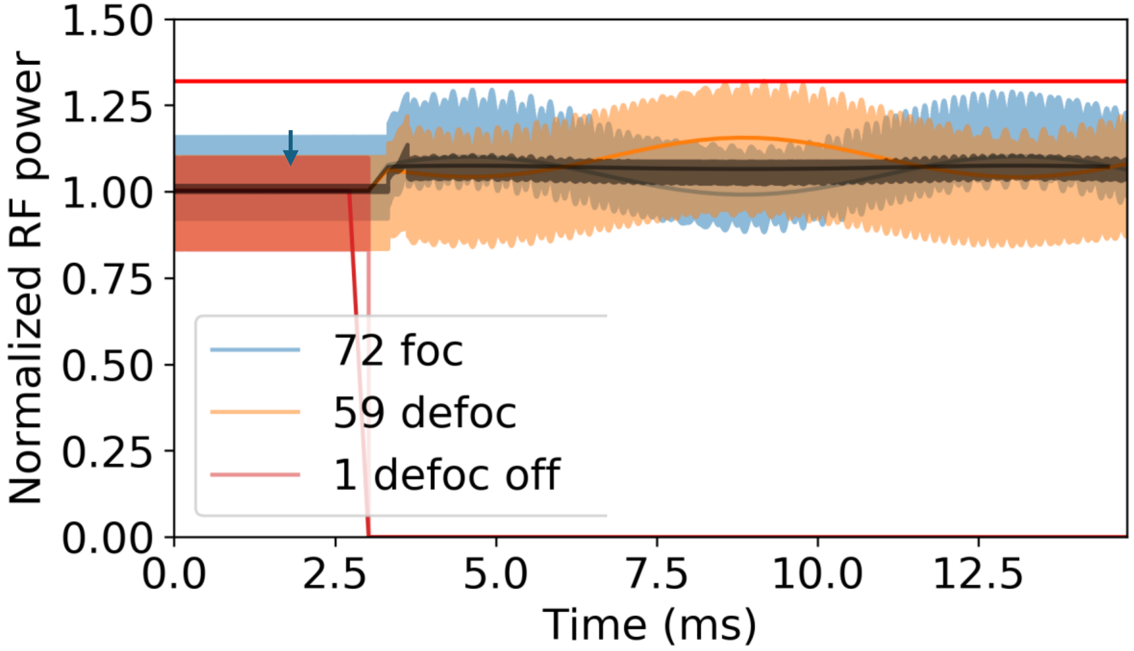


For the required RF power modulation (by LLRF only), the HV set point can be selected (46kV is an example) so that average efficiency will stay ultimately high: 89.6% . With TS MBK klystron average operational efficiency will be dropped from 86% (tube in saturation) down to 67%.

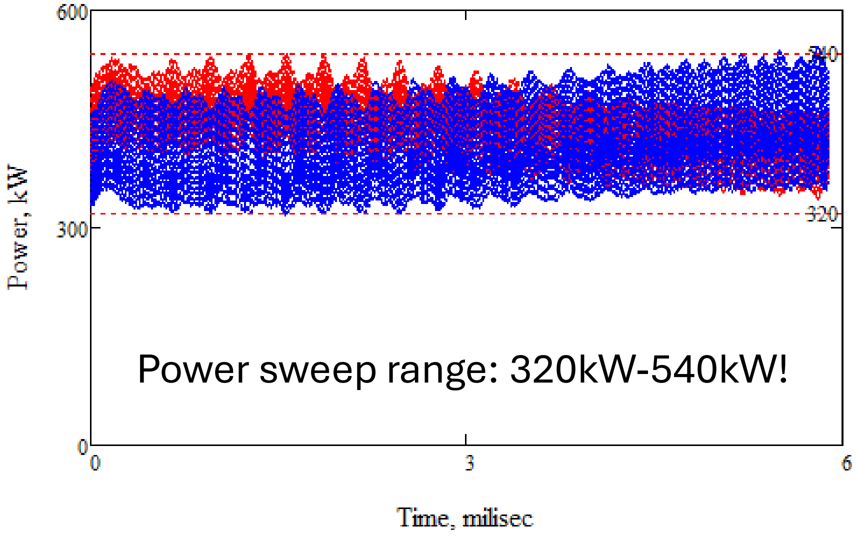
- **MB tristron is** now select as **a baseline option** for 400MHz (500kW) and 800MHz (250kW) FCC_{ee} RF powers sources.
- Transient RF power modulation will impose certain requirement on the HV supply bandwidth, for details see the talk by D. Aguglia.

Failure mitigation mode

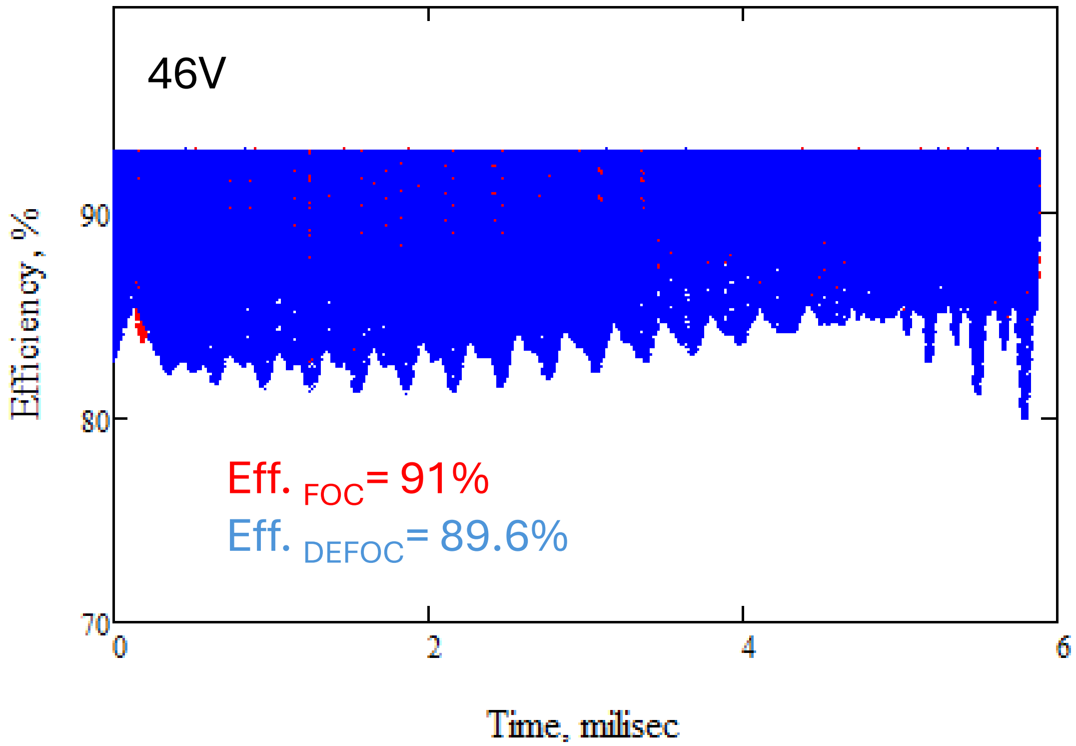
One cavity out of operation;88MV



Required RF power modulation; 88MV



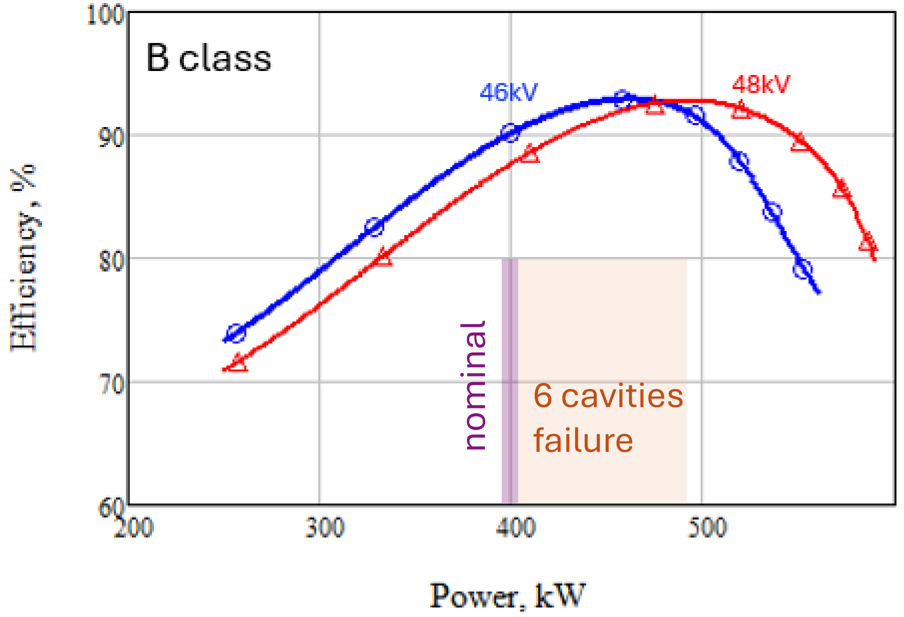
Tristron transient efficiency



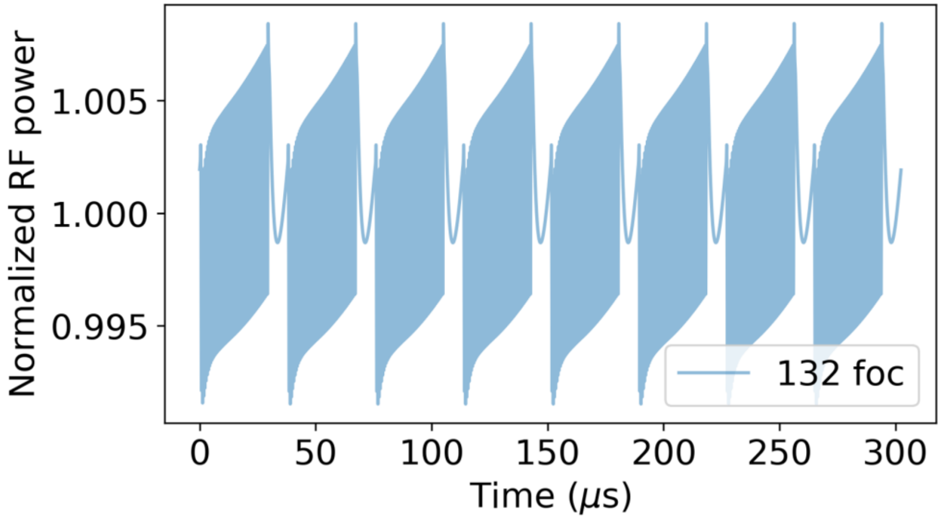
With a single cavity failure, required power modulation will be provided by LLRF system and tristrons will preserve overall very high operating efficiency.

MB Tristron operational efficiency for FCC: W,H-poles.

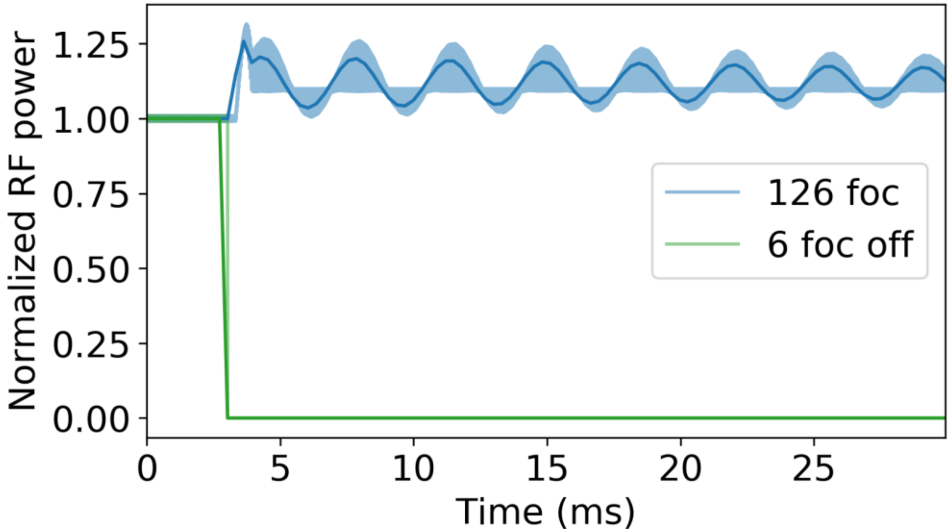
400 MHz FCC tristron power /efficiency performance



Nominal operation



Failure mode: 6 cavities off

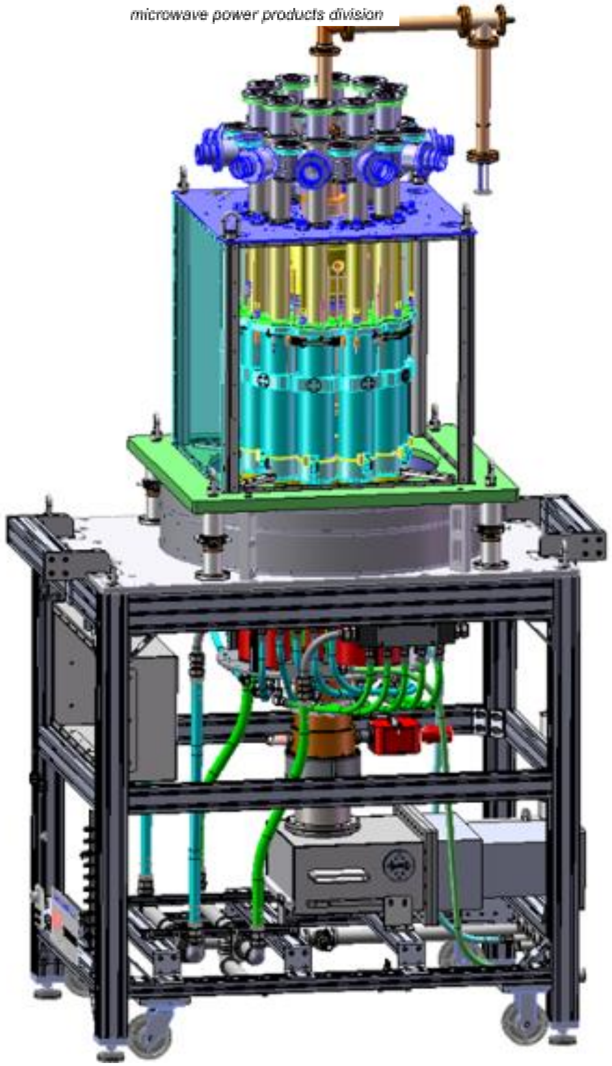


With nominal operation tristron will be set to its optimal voltage/efficiency point. In case of failure LLRF will be able to compensate the effect providing operational efficiency above 90% (6 cavities failure case is shown as an example).

EUROPEAN SPALLATION SOURCE

THALES

CPI
Communications & Power Industries
microwave power products division



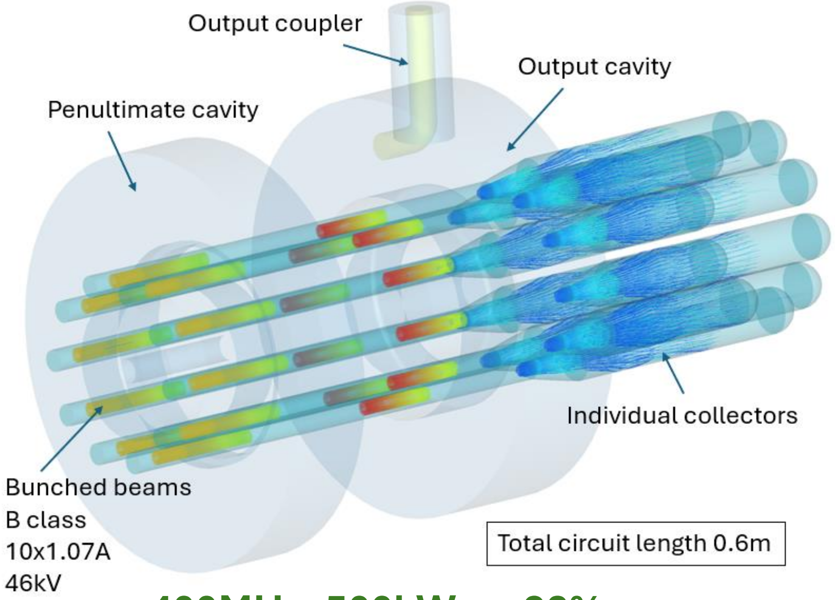
Technology readiness. State of the art.

- Multibeam gridded tubes technology is well established in industry. Two MB IOT (**1.2 MW, 0.7GHz, 10% duty**) prototypes were built and successfully tested about 10 years ago.
- MB tristron has similar topology as an MB IOT with an additional cavity located before the output cavity.
- The major cost/complexity of existing MB IOT is driven by an array of 10 separate input cavities (one per beam) that must be tuned to be almost identical.

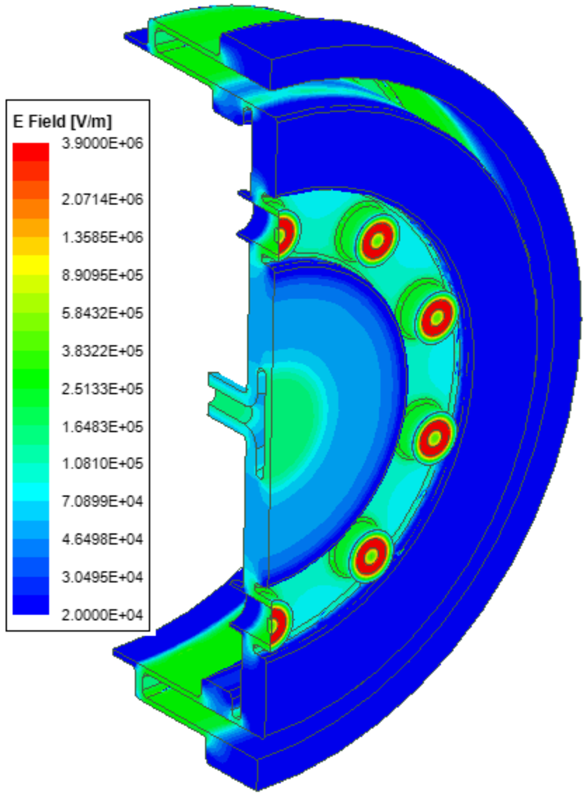
FCC$_{ee}$ 400MHz, 0.5MW MB Tristron design with a common input cavity (CERN).

Completed:

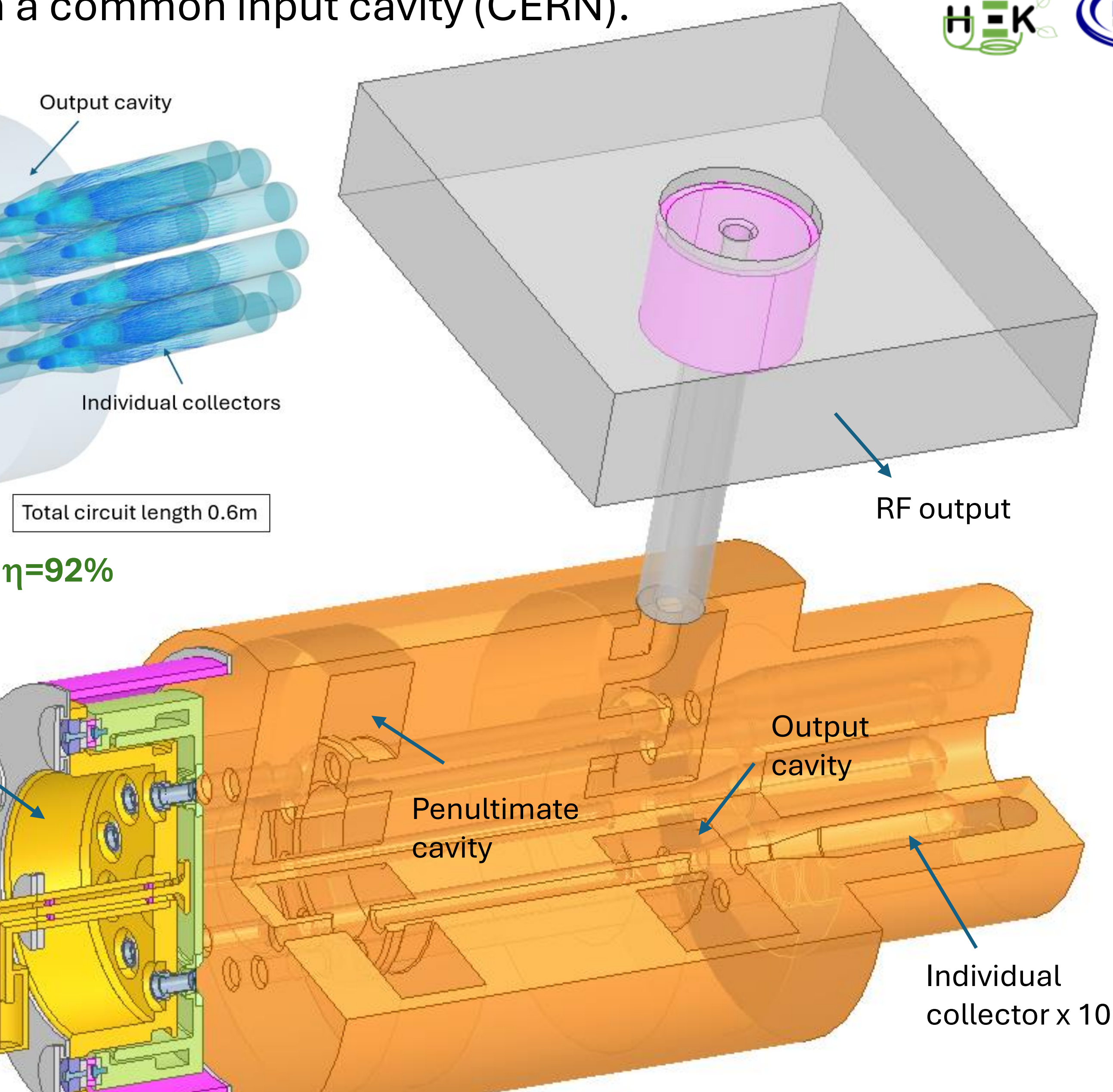
- RF design
- Systems integration
- Tolerances analysis
- With-beam simulations



400MHz, 500kW, η=92%

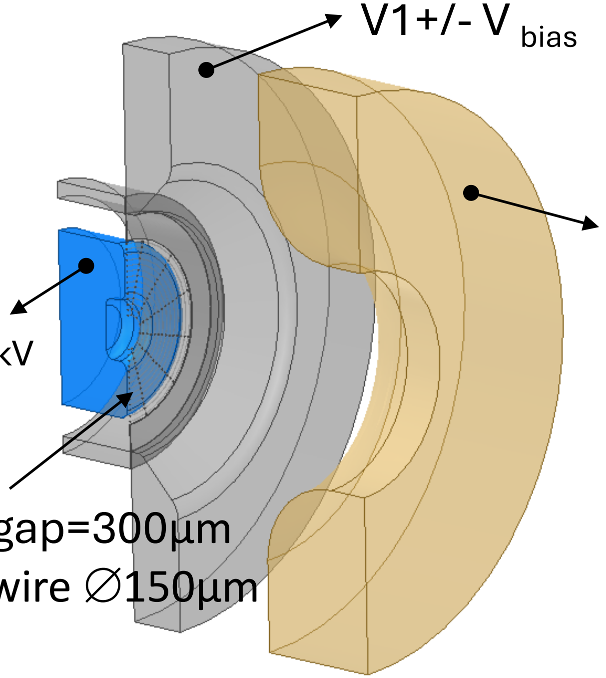


RF E-field in the input cavity



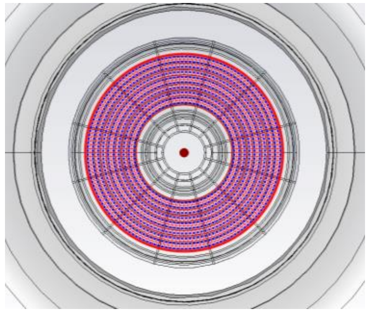
Total length 1.49m. External solenoid is not shown

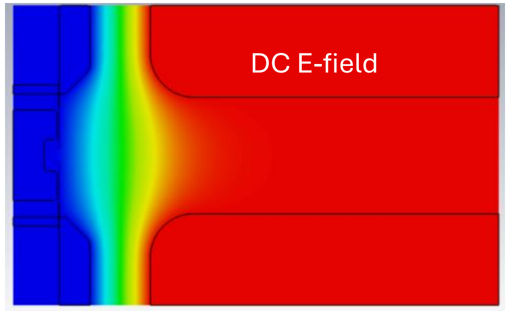
Tristron's gridded cathode optics simulations in CST TRK (DC)



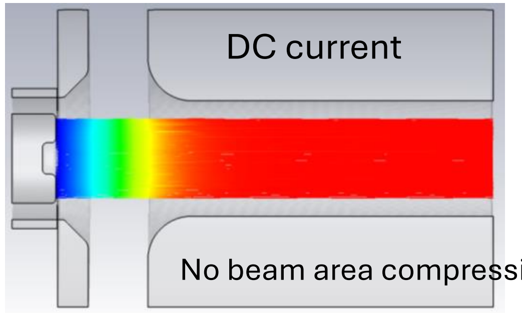
This topology is used now for **thermal stresses and mechanical deformation simulations.**

Current emission sites

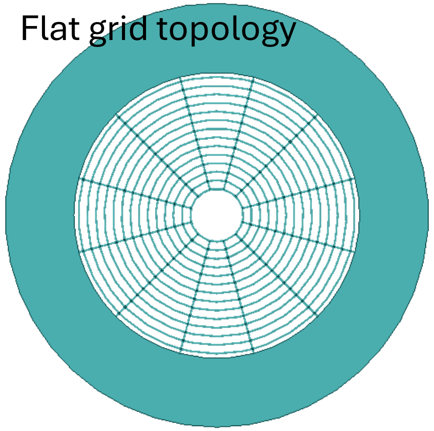


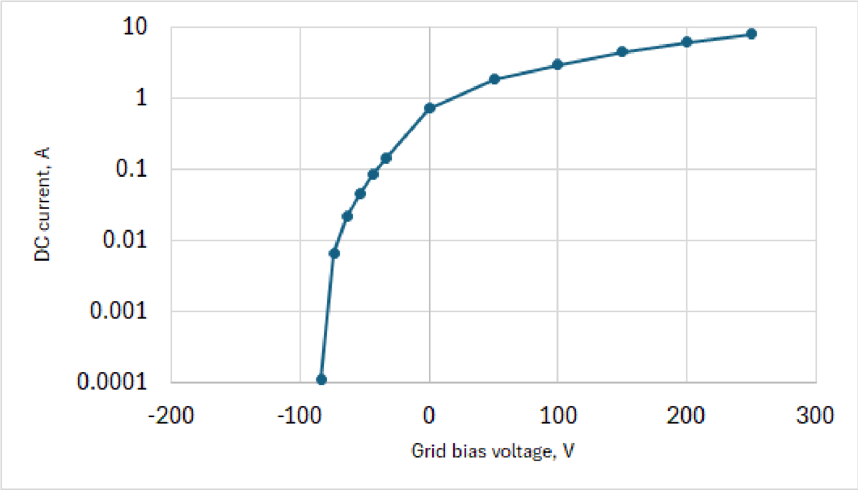


0.026T external B_z -field



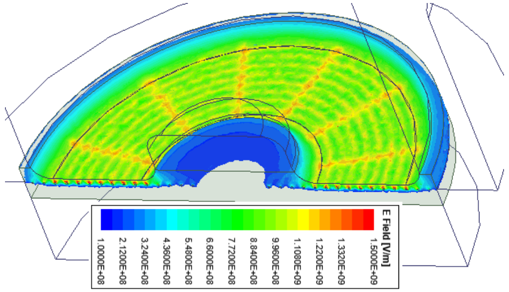
Flat grid topology





- Next step will be import of RF fields and full PIC simulation of the bunching processes.

RF E-filed in the gap area of the input cavity →



- External solenoid and collector designs are in progress.

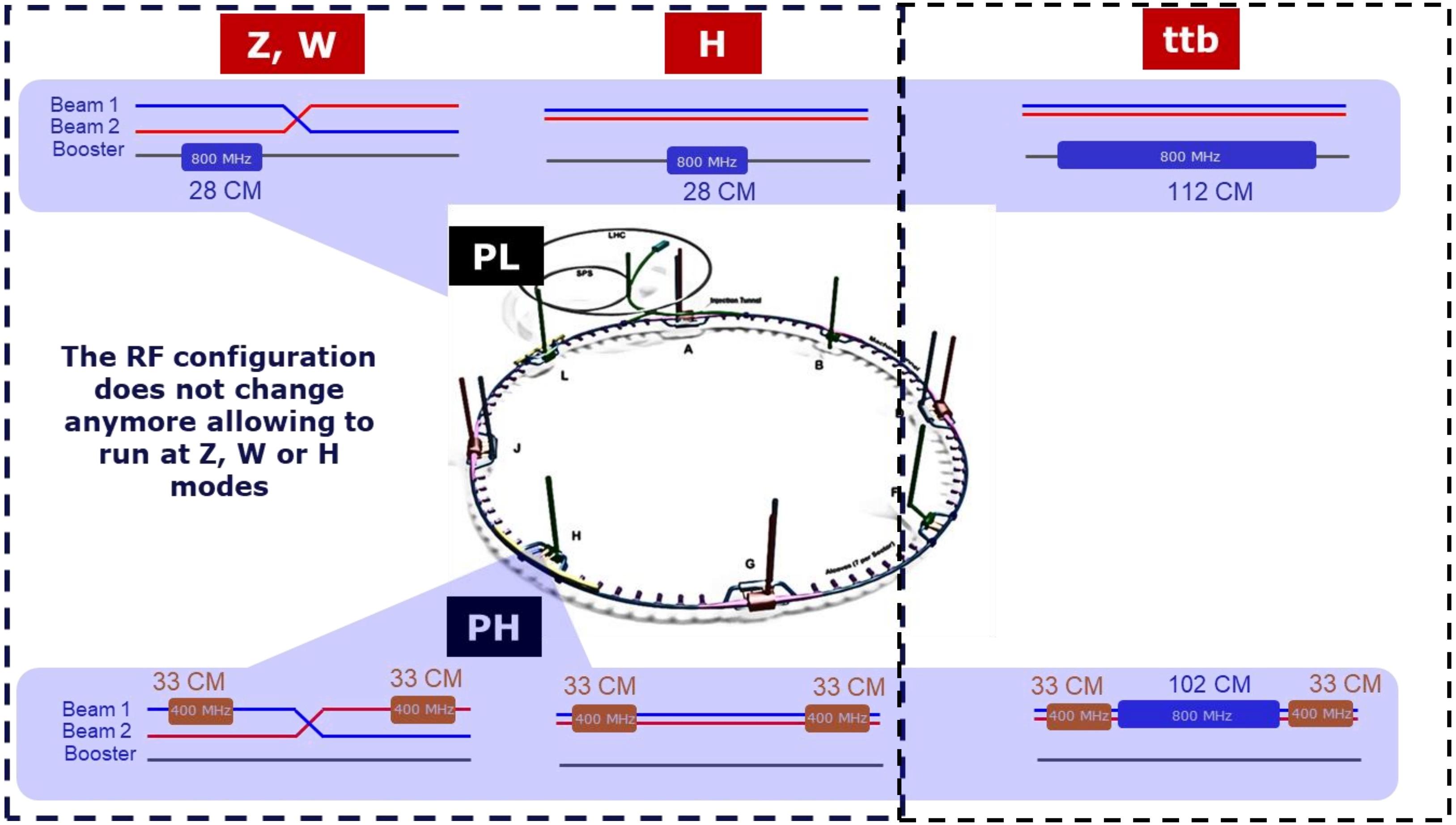
Layout of the FCC_{ee} SRF system

Start operation in March 2047

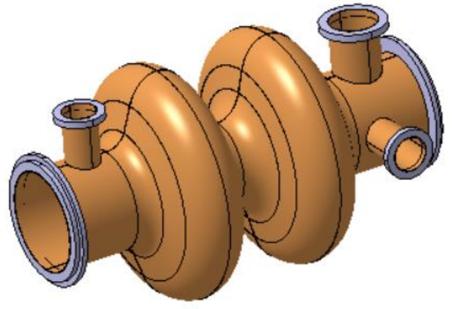
Duration: 10 years

Start operation in March 2058

Duration: 5 years



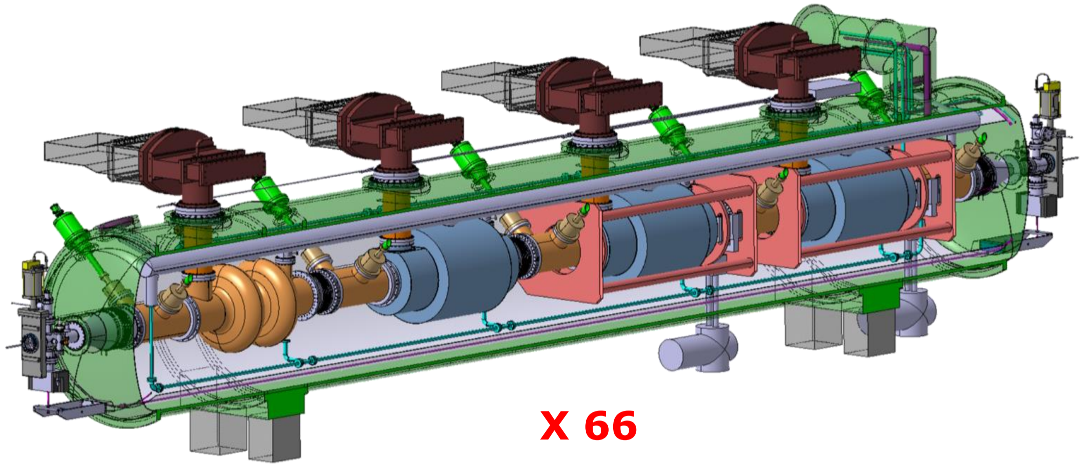
400 MHz system – collider Z, W, ZH



X 264

Superconducting elliptical cavity

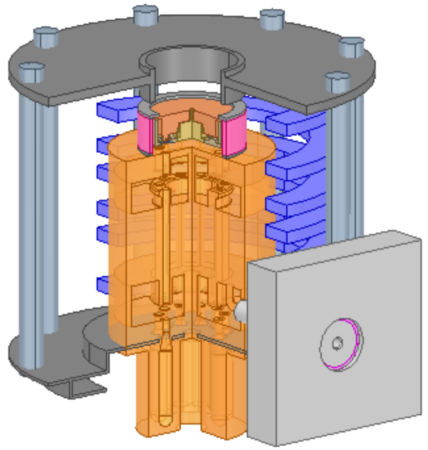
- 400 MHz, 2-cell
- 1.5 m. long
- Electropolished and seamless RF surface
- Niobium thin film with HiPIMS



X 66

Cryomodule

- Segmented design, 4 cavities
- Vertical FPC, HOM damping and extraction
- Frequency tuning system
- Thermal and magnetic shielding

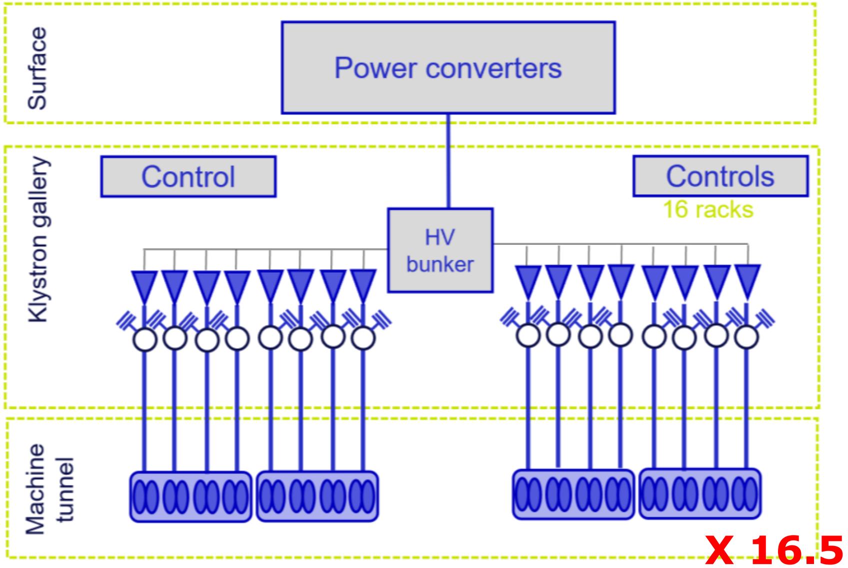


Multibeam Tristron

- **400 MHz**
- 46 kV
- 500 kW, CW

X 264

Collider	Z	W	ZH
	1 beam RPO	1 beam	2 beams
Total RF voltage [MV]	89	1049	2098
Beam current [mA]	1292	135	2 x 26.8
RF Frequency [MHz]	400.79		
Operating temp. [K]	4.5		
Cavity voltage [MV]	7.95		
# cell/cavity	2		
Eacc [MV/m]	10.6		
Q0	2.70E+09		
RF power [kW]	380		
Optimum coupling QL	9.2E+05		
# CM (with 4 cav/CM)	66		
# cavities	264		



X 16.5

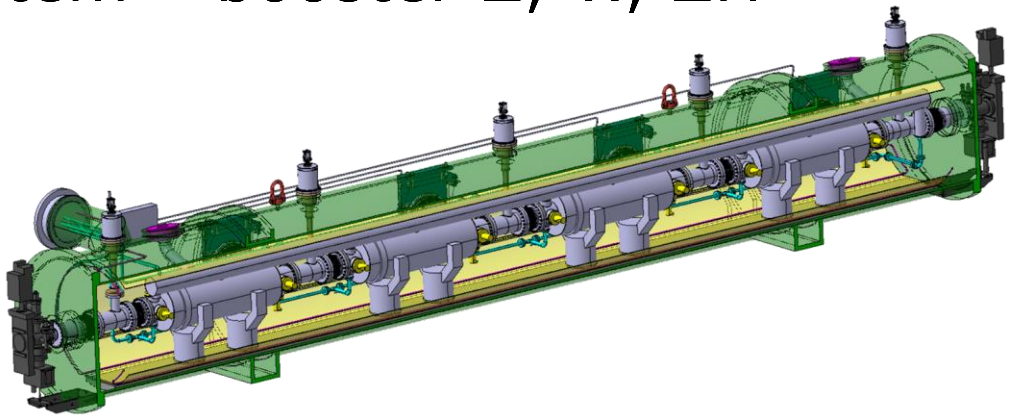
RF Unit

- RPO at Z
- 2 beams at ZH
- 500 kW per cavity with overhead
- 500 kW MB Tristrons
- 1 cavity + 1 circulator per RF source
- 16 cavities (4 CM) per RF unit
- WR2300 WG

800 MHz system – booster Z, W, ZH

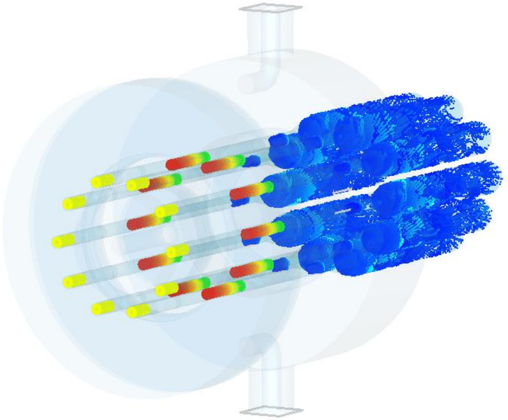
X 112

Superconducting elliptical cavity
- 800 MHz, 6-cell
- 1.5 m. long
- Bulk Niobium with electropolished and doped RF surface (mid T baked)



X 28

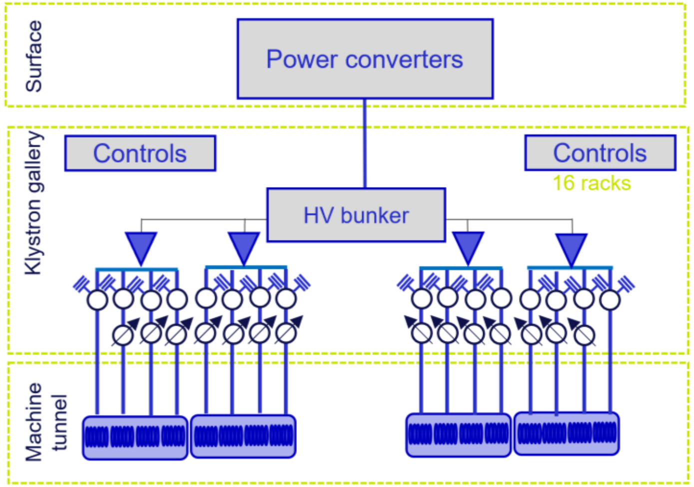
Cryomodule
- Segmented design, 4 cavities
- FPC on side, HOM damping and extraction
- Frequency tuning system
- Thermal and magnetic shielding



Multibeam Tristron **X 28**
- 800 MHz
- 250 kW, pulsed (high duty cycle)

Could be replaced by SSPA (1/cav) if RF efficiency is good and solution is economically feasible and reliable.

Booster	Z	W	ZH
	RPO	RPO	
Total RF voltage [MV]	80	401.9	1961
Beam current [mA]	16.2	6.2	2
RF Frequency [MHz]	801.58		
Operating temp. [K]	2		
Cavity voltage at extraction [MV]	5.6	13.5	17.5
# cell/cavity	6		
Eacc [MV/m]	4.9	12	15.6
Q0	3E+10		
Max RF power [kW]	42		
Coupling QL	1E+07		
# CM (with 4 cav/CM)	28		
# cavities	112		



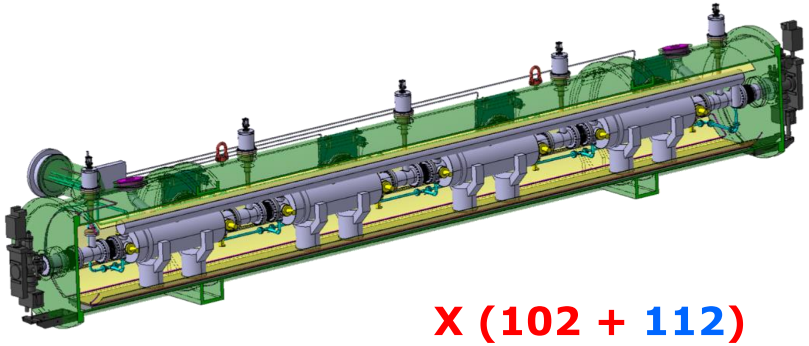
X 7

RF Unit
- RPO at Z&W booster
- 50 kW per cavity
- 200 kW MB tristrons
- 4 cavities per tristron
- 16 cavities (4 CM) per RF unit
- WR 1150 WG

800 MHz system – ttb (collider and booster)

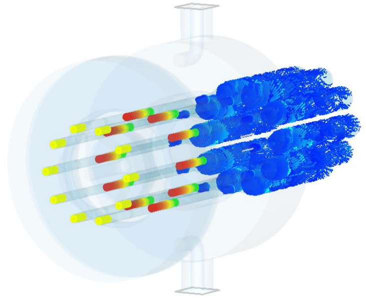
X (408 + 448)

Superconducting elliptical cavity
- 800 MHz, 6-cell
- Nb3Sn if R&D is successful



X (102 + 112)

Cryomodule
- Segmented design, 4 cavities, 2 K
- Operation at 4.5 K is R&D successful



Multibeam Tristron
- 800 MHz
- 250 kW, CW

X 408

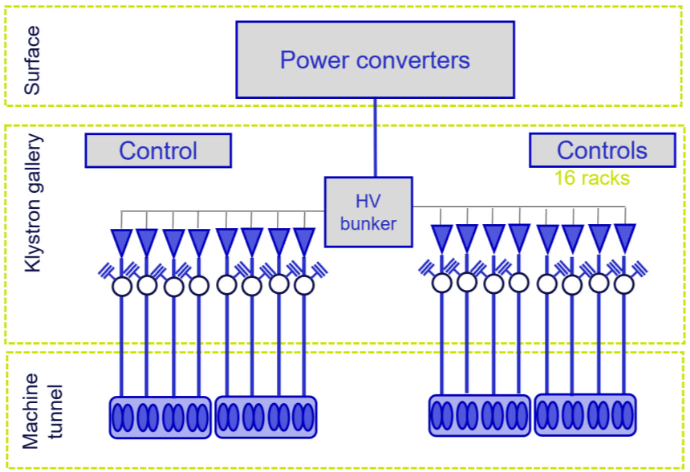
Solid State Amplifier (SSA)
- 800 MHz
- 10-15 kW pulsed

X 448

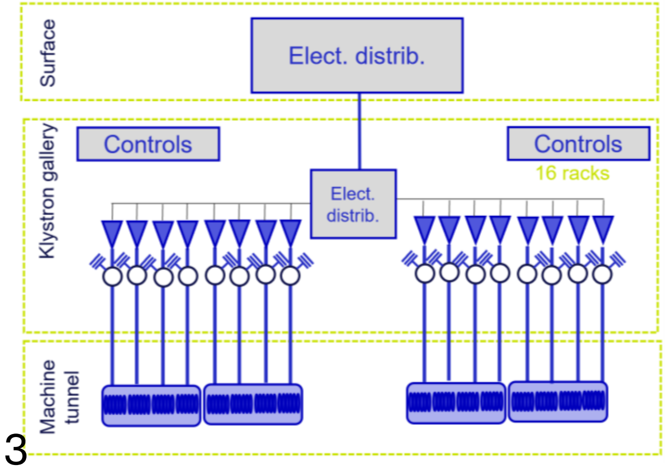
	ttb collider		ttb booster
	2 beams		1 beam
Total RF voltage [MV]	2098	9202	10180
Beam current [mA]	10		0.4
RF Frequency [MHz]	400.79	800.58	
Operating temp. [K]	4.5	2	
Cavity voltage [MV]	7.95	22.5	22.8
# cell/cavity	2	6	
Eacc [MV/m]	10.6	20.1	20.3
Q0	2.7E+9	3E+10	
RF power [kW]	78	195	8.9/12.7
Optimum coupling QL	4.5E+06	4.1E+06	9.2E+07/2.7E+07
# CM (with 4 cav/CM)	66	102	112
# cavities	264	408	448

RF Units

Collider (800 MHz tristrons) X 26



Booster (SSA) X 28

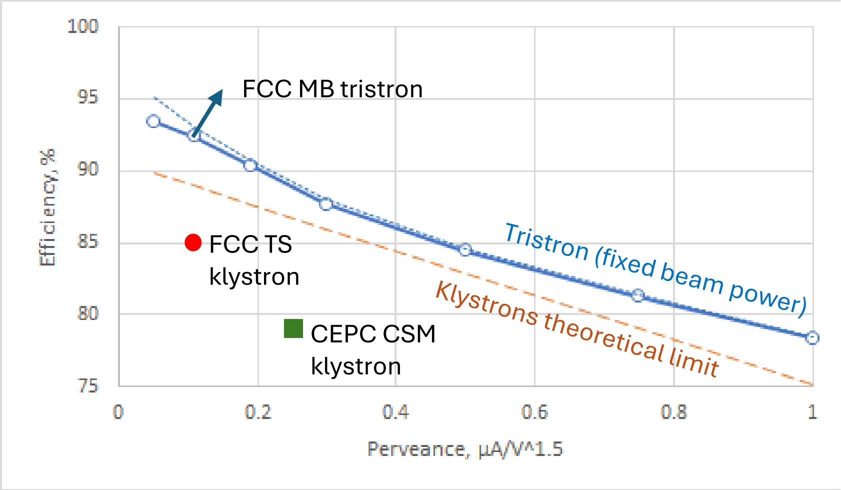


Spare slides

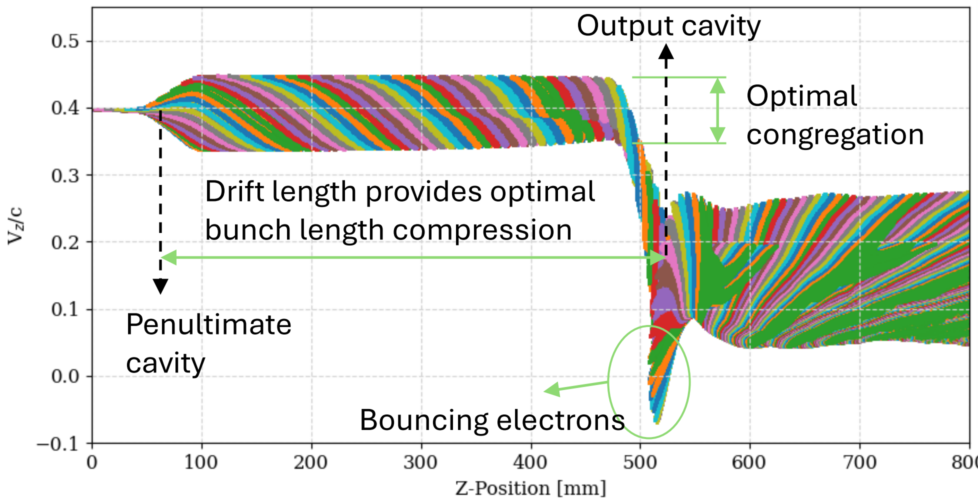
Why MB Tristron can be so efficient?

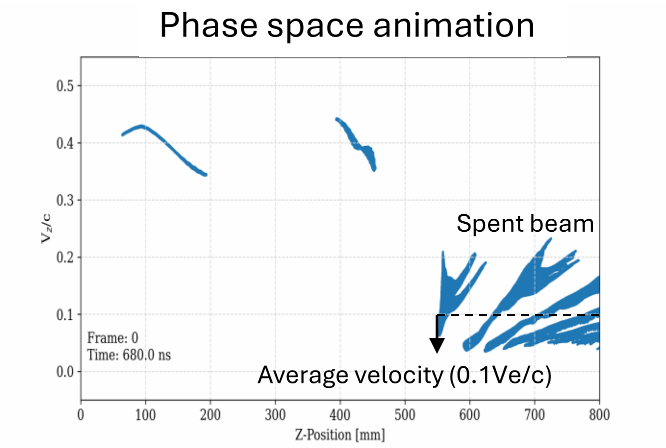
1. Multi-beam technology -> low perveance per beam
2. Gridded cathode provides fully saturated bunches -> **75%** (best IOT performance)
3. Penultimate cavity controls optimal velocity spread (congregation) within the bunch, followed by bunch length compression in the drift -> **85%** (basic of the Tristron concept).
4. ‘Very’ long gap in the output cavity with negative detuning allows partial electrons bouncing -> **91%** (discovered in our studies of the HE klystrons at CERN).
5. Hollow beam configuration reduces radial bunch stratification -> **93%**.

Optimized MB Tristron efficiency vs. perveance



Electron bunches velocity modulation in tristron



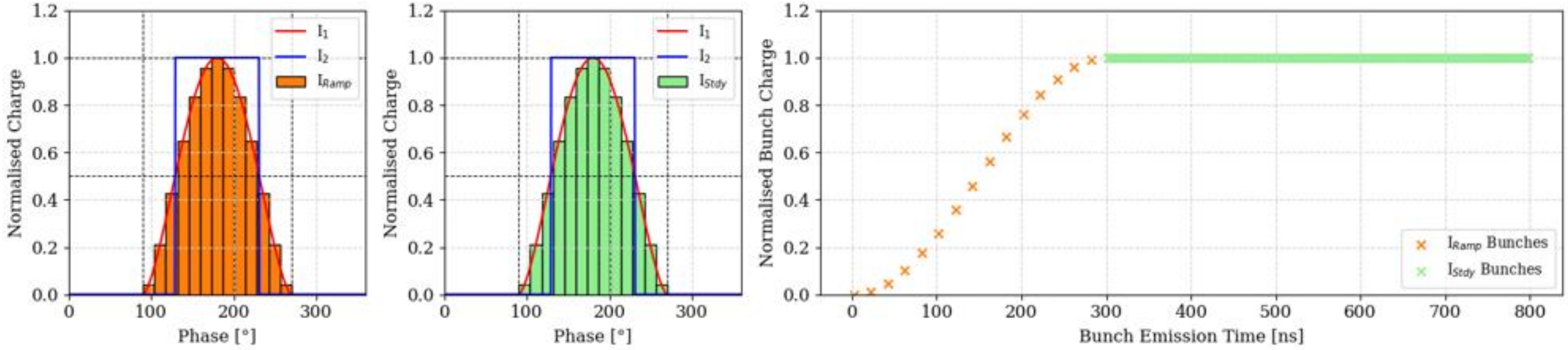


$$\eta = 1 - (V_e/V_0)^2 = 1 - \left(\frac{0.1}{0.4}\right)^2 = 0.93$$

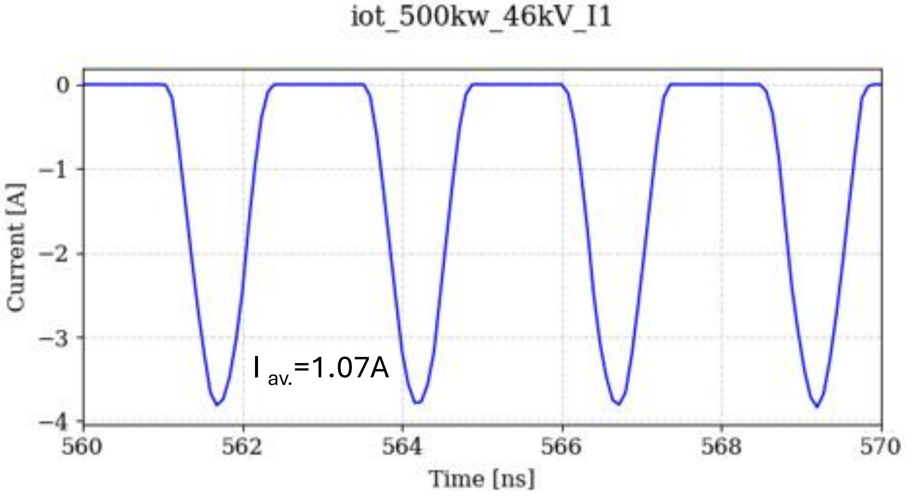
Gridded tube bunch current generation **B CLASS** in CST PIC, design point 46kV, 1.07A/beam

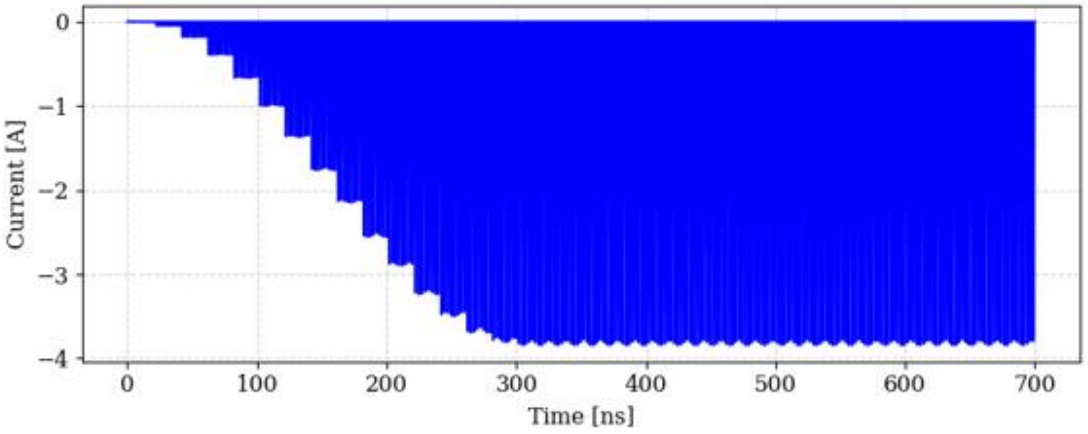
$$I(t) = I_0 \times (U_{bias} + U_{RF} \times \sin(\omega t))^{1.5}; = 0\ if\ I(t) < 0$$

Emission Programme

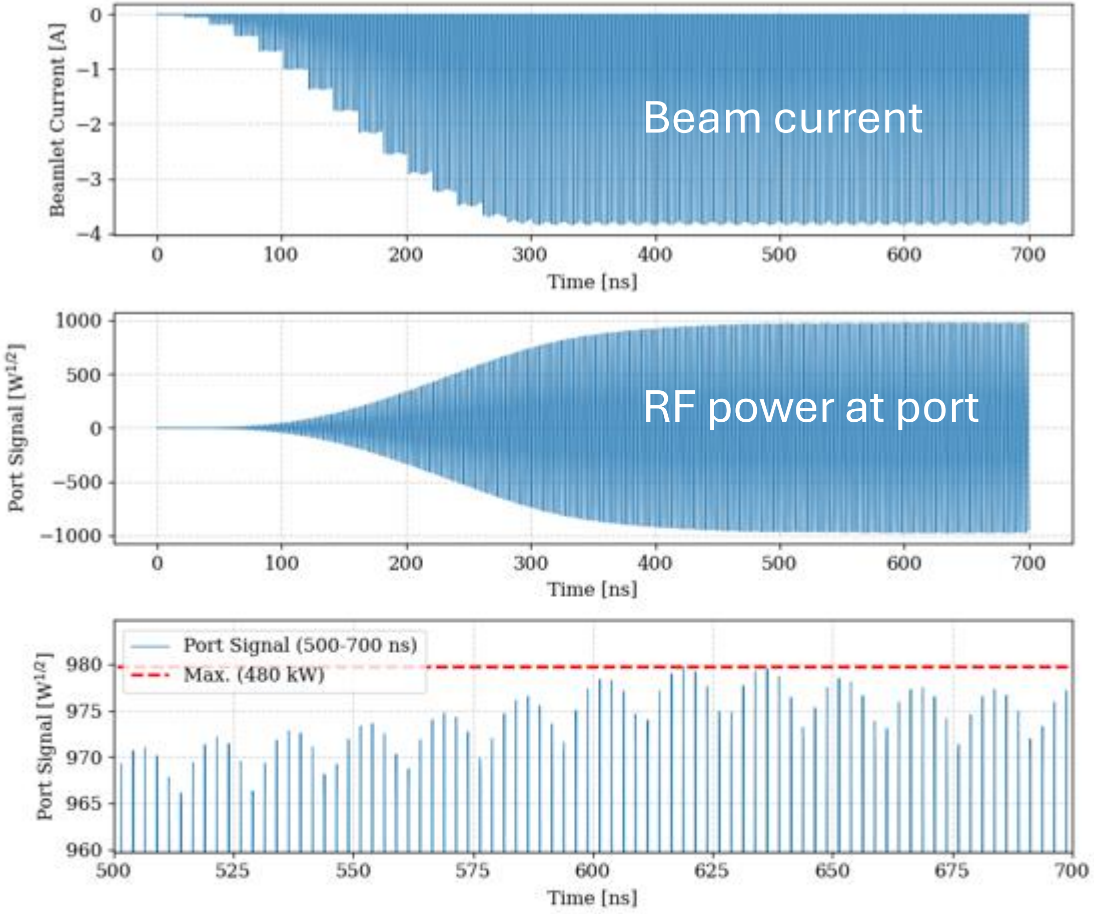


CST monitors

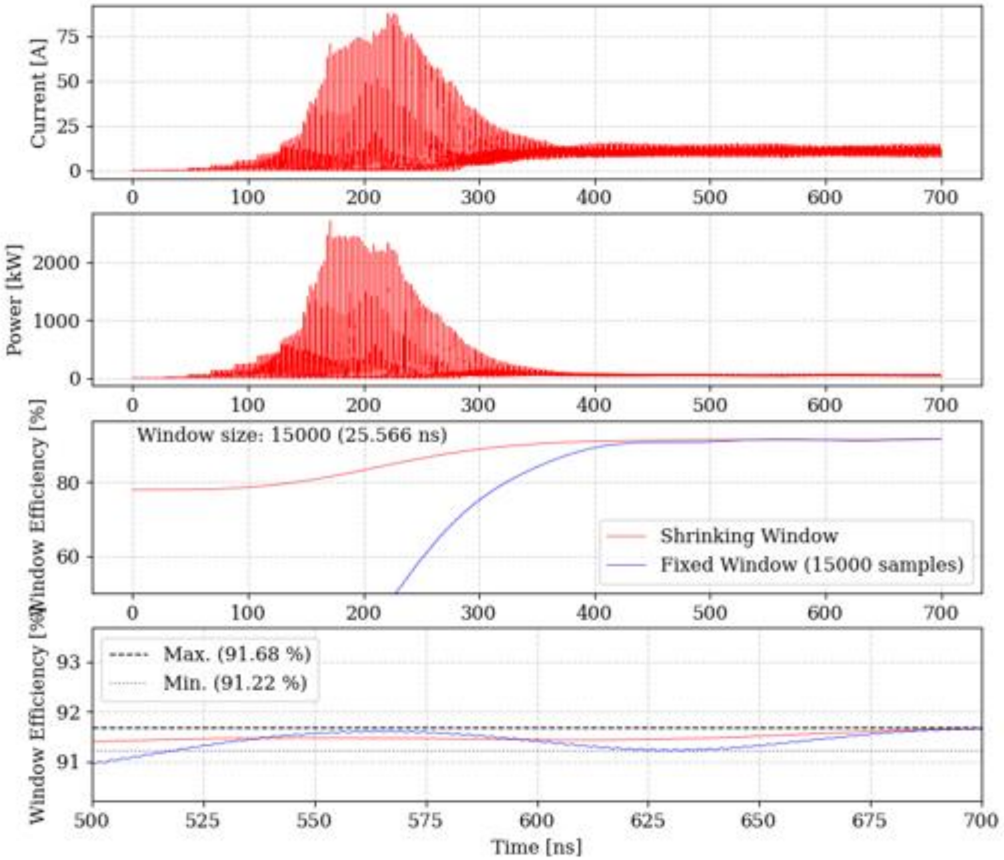




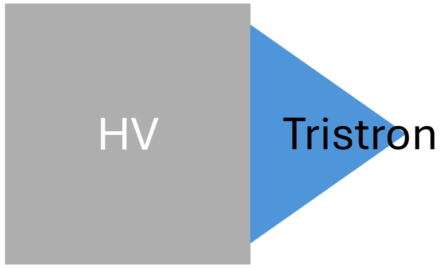
RF power / efficiency measurement in CST

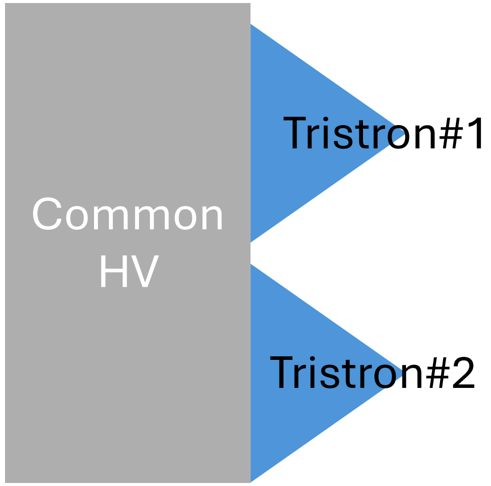


Balanced efficiency calibration (beam in a collector)

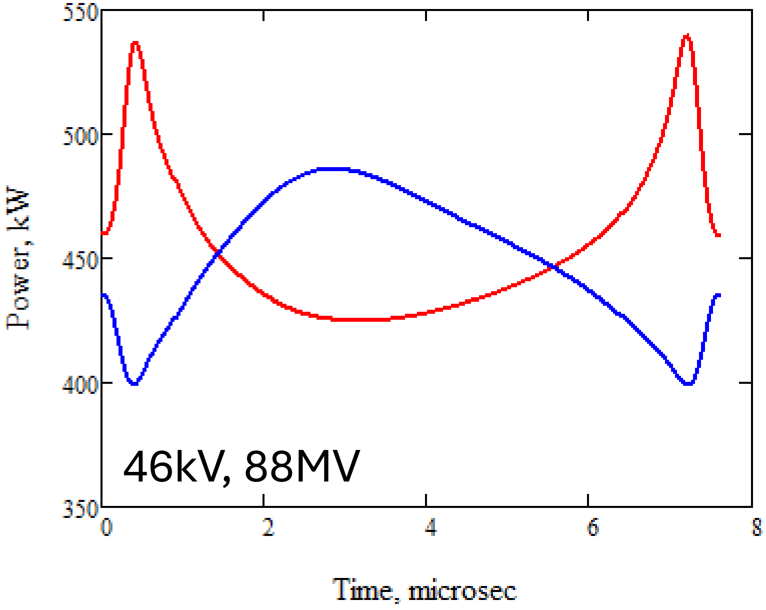


Issues with transient loading of the HV power supply (Z pole)





Transient power drain from HV power supply



Transient power drain from common HV power supply