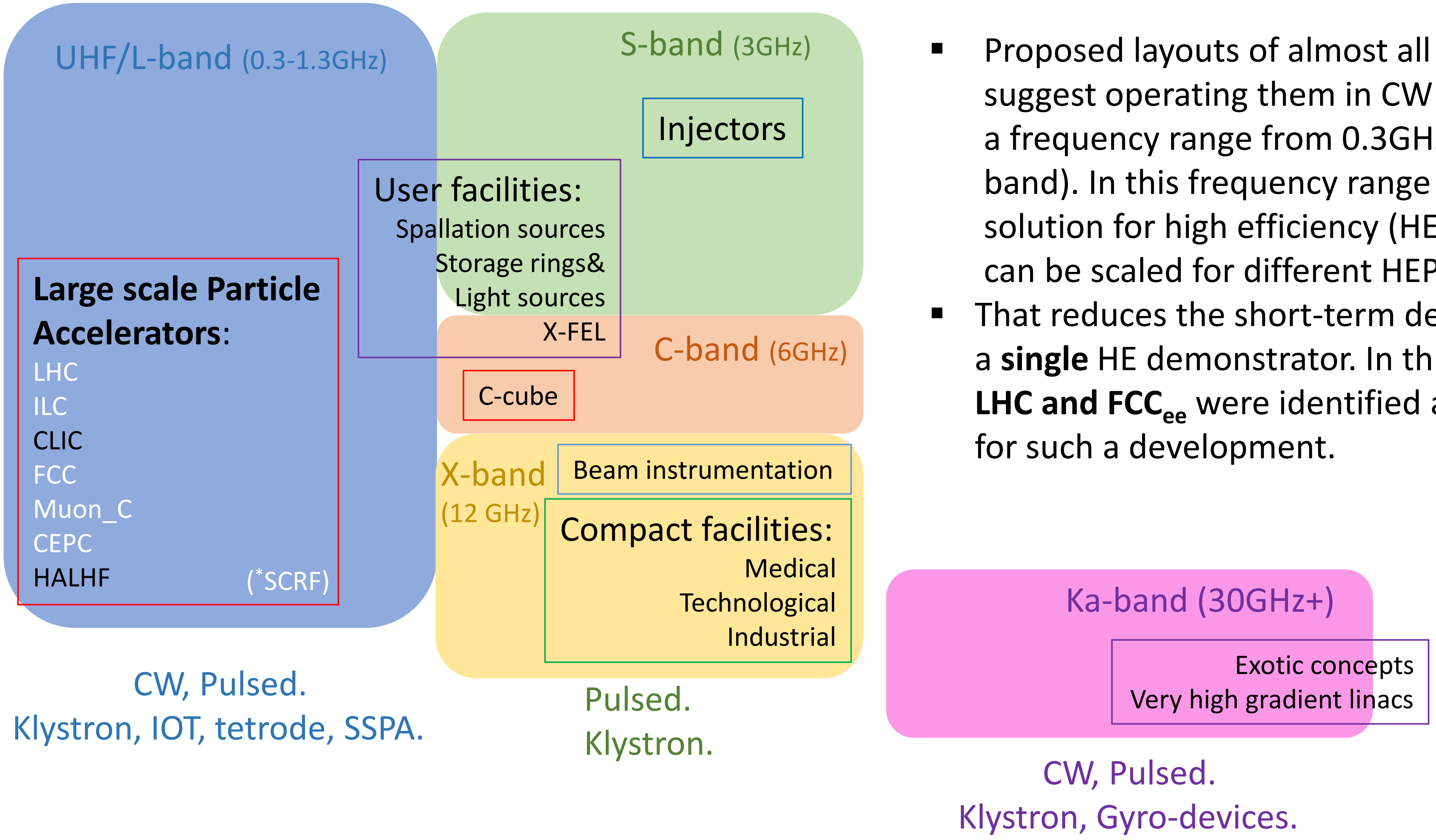
2nd Workshop on efficient RF Sources

23-25 September 2024, Toledo, Spain

Status of FCC$_{ee}$ 400 MHz 1 MW Two-Stage Multibeam Klystron

Zaib Un Nisa for CERN & ULAN HE klystron team

RF power sources for particle accelerators



UHF/L-band (0.3-1.3GHz)

Large scale Particle Accelerators:
LHC
ILC
CLIC
FCC
Muon_C
CEPC
HALHF (*SCRF)

CW, Pulsed.
Klystron, IOT, tetrode, SSPA.

User facilities:
Spallation sources
Storage rings&
Light sources
X-FEL

S-band (3GHz)

Injectors

C-band (6GHz)

C-cube

X-band (12 GHz)

Beam instrumentation

Compact facilities:
Medical
Technological
Industrial

Pulsed.
Klystron.

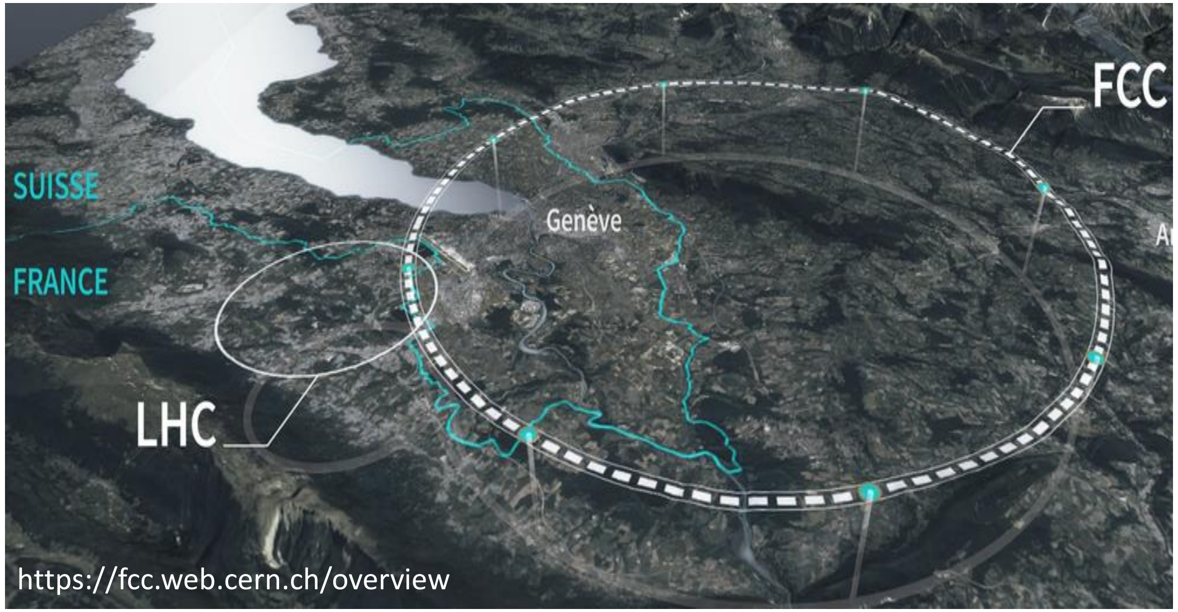
Ka-band (30GHz+)

Exotic concepts
Very high gradient linacs

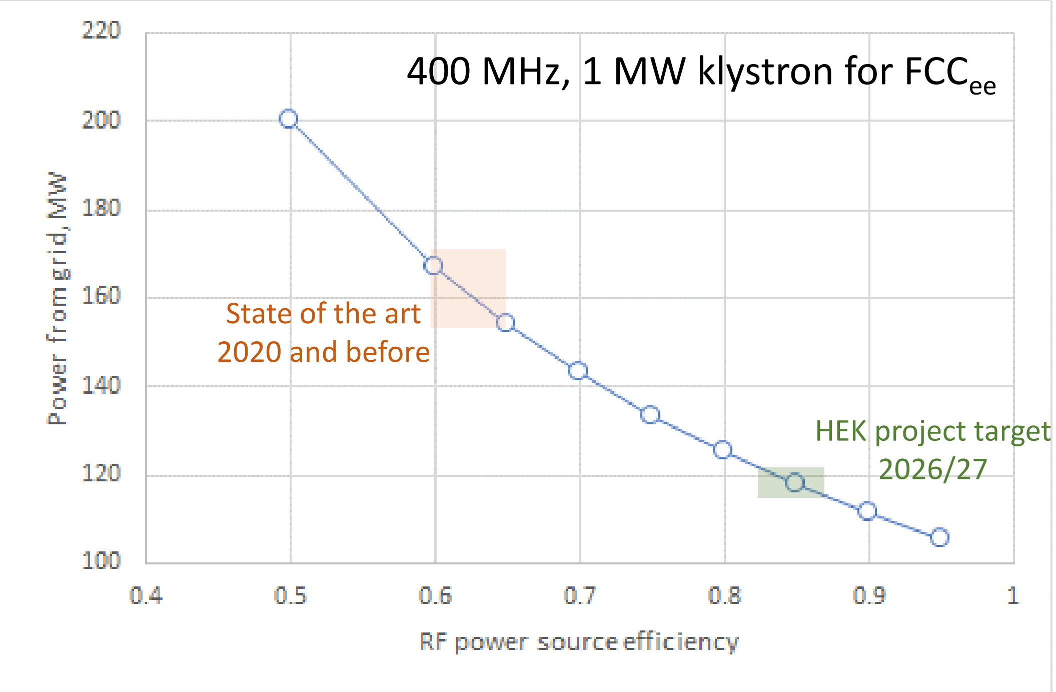
CW, Pulsed.
Klystron, Gyro-devices.

- Proposed layouts of almost all future colliders suggest operating them in CW or Pulsed regimes in a frequency range from 0.3GHz-1.3GHz (UHF/L-band). In this frequency range new technological solution for high efficiency (HE) RF power source can be scaled for different HEP applications.
- That reduces the short-term development scope to a **single** HE demonstrator. In this context High-Lumi **LHC and FCC$_{ee}$** were identified as primary objectives for such a development.

Grid power required for the large-scale HEP Accelerators (FCC_{ee})



https://fcc.web.cern.ch/overview



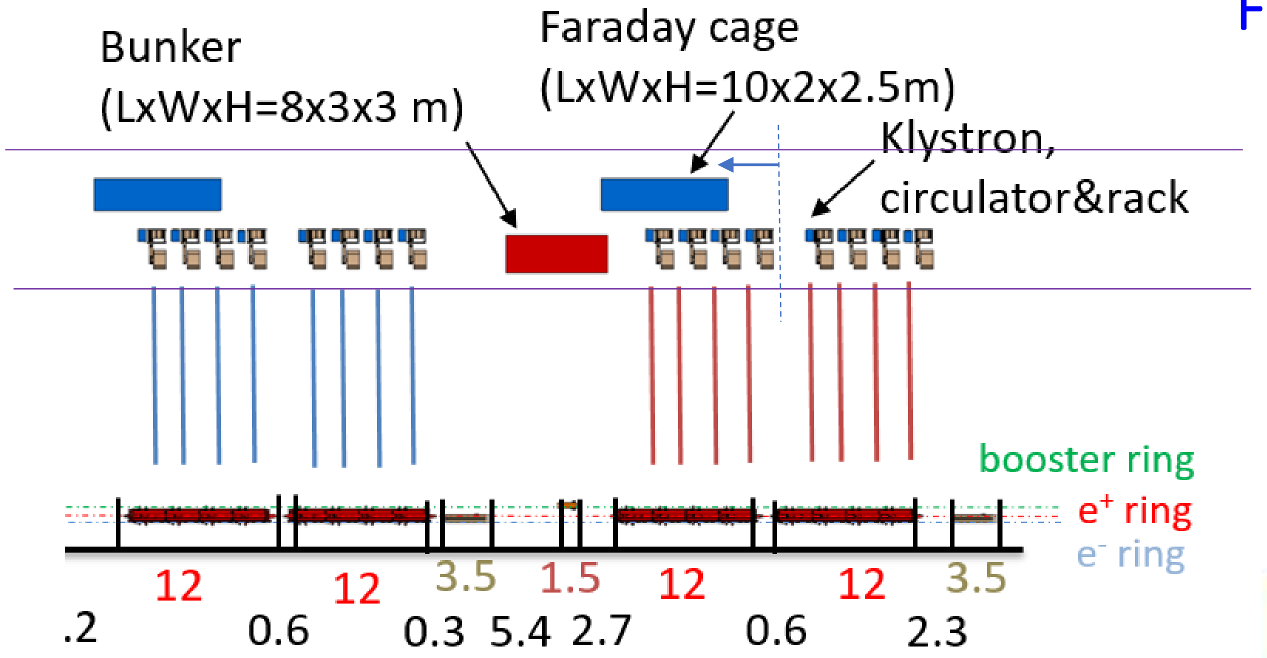
To operate FCC_{ee}, **100 MW** Continues Wave RF power is needed to accelerate particles and to compensate for the energy lost into synchrotron radiation.

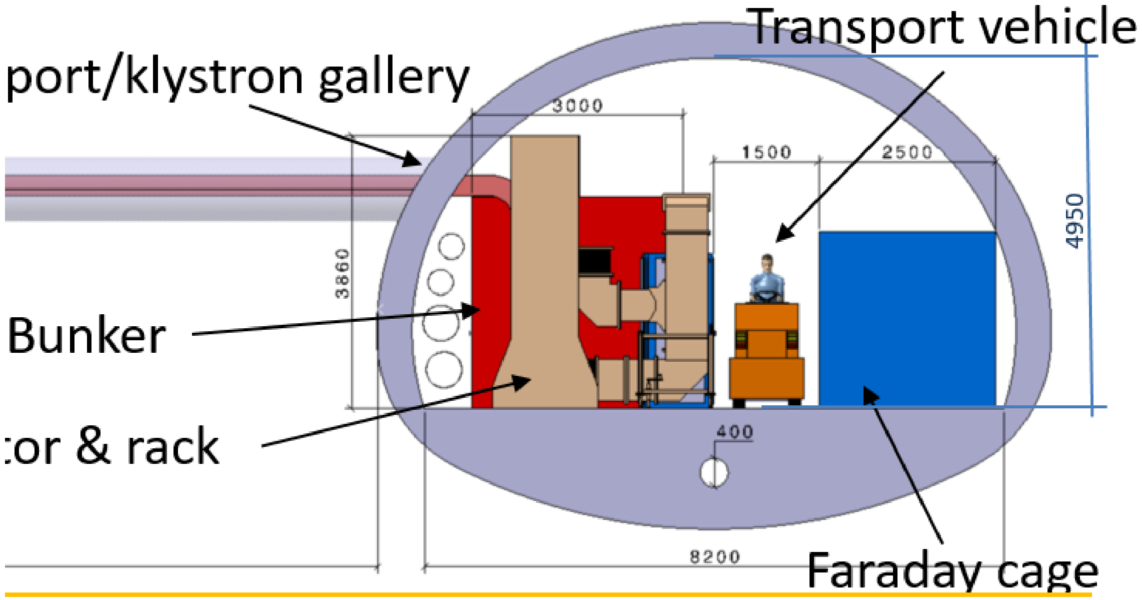
Improving klystron RF efficiency from 65% in the best existing commercial devices to 85% in the new HE tubes will:

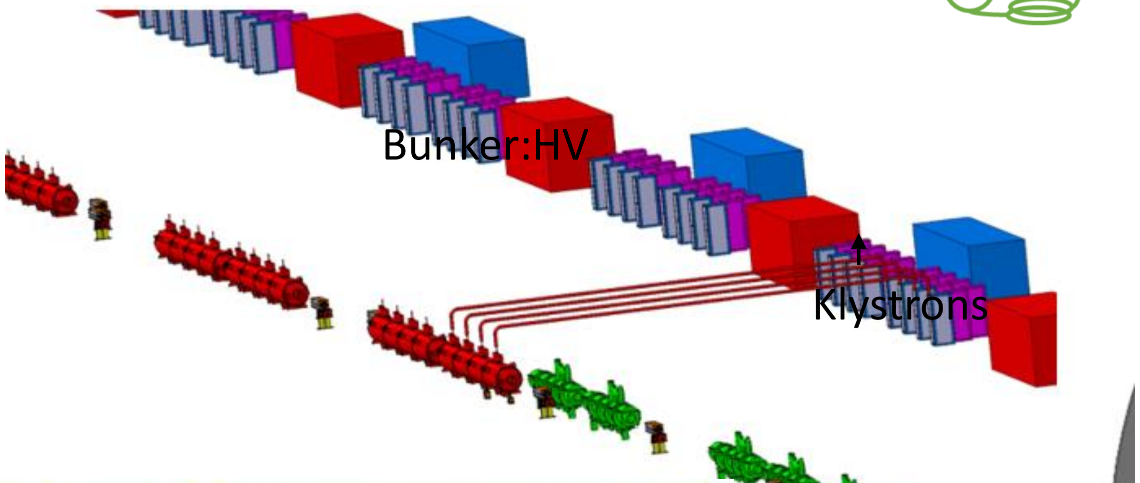
- Save 32.2 MWh -> 253 GWh (7000h/year) -> **2.53TWh over 10Y.**
- Reduce cost and power consumption of power converters and cooling system (environmental impact).

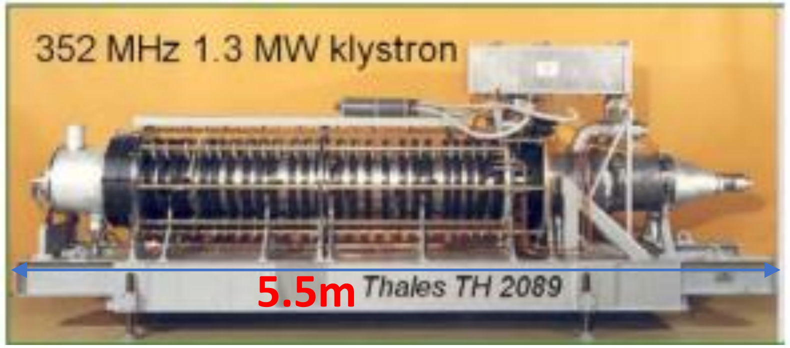
FCC$_{ee}$ (Z) accelerator tunnel integration

High Efficiency Klystrons









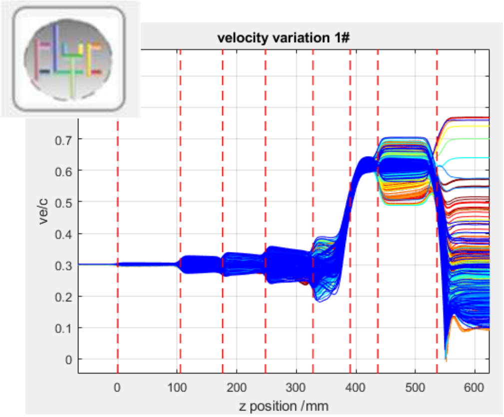
1.3MW CW,
352MW, 100kV,
20A, eff.=63%.

1. Each Klystron should deliver 1MW @ 400MHz.
2. Preferably, klystron should be placed vertically in the tunnel.
3. The total length of Klystron should be about 3m.
4. The efficiency of Klystron is targeted >80%.

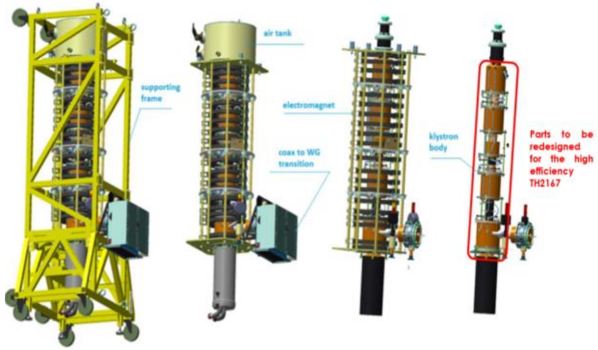
High efficiency klystrons projects at CERN

High Efficiency klystrons activity was initiated at CERN in 2014. In 2021 it was transformed into a CERN's **project.**

Objectives: Development, design, fabrication and testing of the new HE klystrons for application in various particle accelerators.

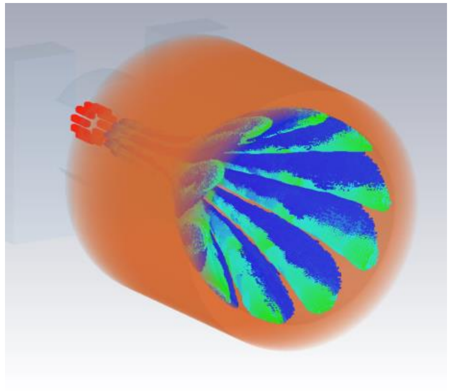


Task 1: Design & simulations
- Maintenance and distribution of the CERN made klystron code KlyC.
- High level expertise in using commercial tools like CST PIC, HFSS etc.



Task 2: HE LHC 400 MHz klystron
- Retrofit upgrade of Thales klystron (60% to 70%) in close collaboration with industry.
- **A base line option for HL-LHC**.

Selected topic



Task 3: Novel two-stage klystron technology with 80%+ RF production efficiency
- Design, fabrication and testing of the 400 MHz 1MW CW klystron for **FCC** in collaboration with industry.
- Promote this new technology towards CLIC, ILC and Muon_C.

First commercial X-band 10 MW HE (56%) klystron.
CERN-Canon collaboration.

Task 4: High efficiency X-band pulsed klystrons in the power range 10-50MW
- Strong Collaboration with industry (Canon, CPI and Thales).
- Important for multiple projects (CompactLight, DEFT, EUPRAXIA etc.).
- Great show case for CERN's technology and **contribution to worldwide society**.

Two-Stage Multi Beam Klystron (TS MBK) technology in UHF/L-band

Specific features

1. Bunching at a low voltage (high perveance). Very **compact RF bunching circuit.**
2. Bunched beam acceleration and cooling (reducing Δp/p) along the short DC voltage post-accelerating gap.
3. Final power extraction from high voltage (low perveance) beam. **High efficiency.**

Additional advantages:

1. For pulsed tubes, the second HV stage can be operated in DC mode. Thus, simplifying the modulator topology. (cost/volume) and increasing the modulator efficiency.
2. Simplified feedback for the first stage pulsed voltage. Improved klystron RF phase and amplitude stability.

Drawbacks:

1. Reflected electrons from the output cavity and collector shall be **avoided at any cost.**
2. RF radiation into DC gap must be sealed.
3. Requires special HV isolated RF feedthrough to inject RF signal into input cavity.
4. Large bore (∅400mm) ceramic insulator on the 2nd stage.

GOOD FOR:

FCC hh ee he

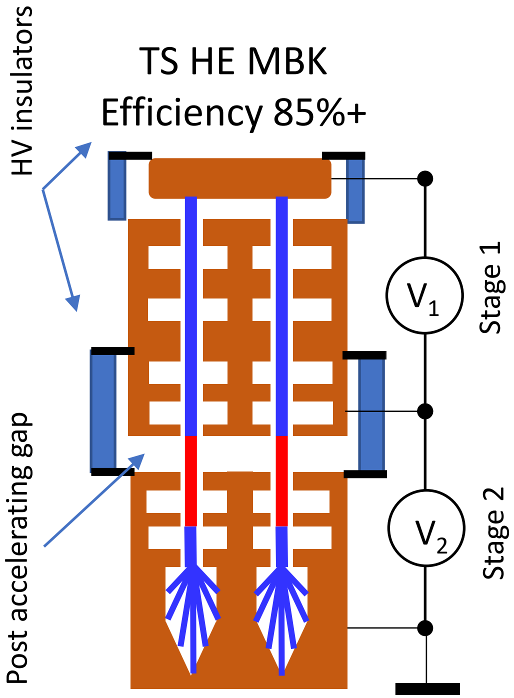
ilc

CLIC

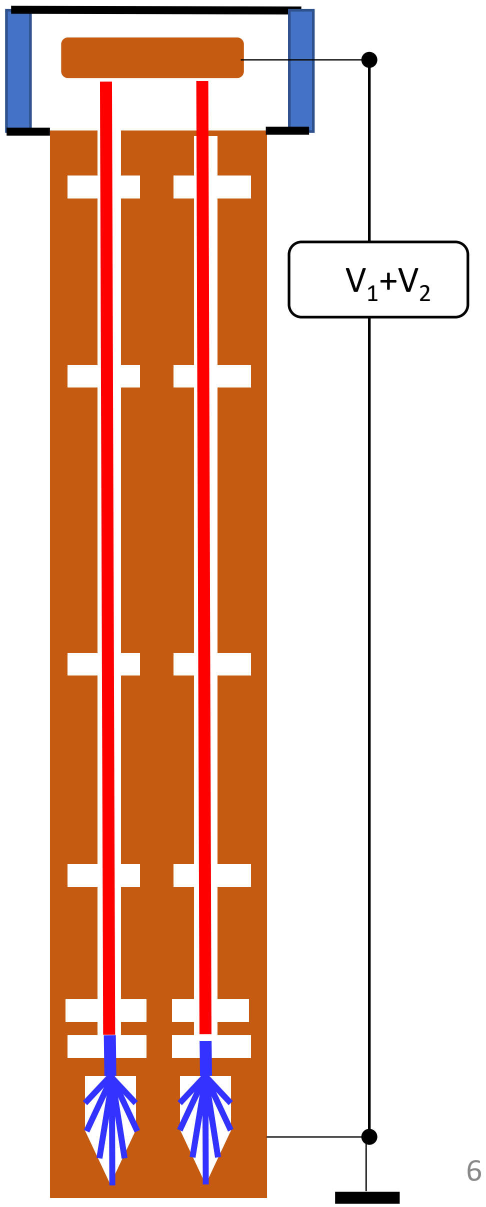
International MUON Collider Collaboration

CEPC

TS HE MBK
Efficiency 85%+



Commercial HE MBK
Efficiency 65%

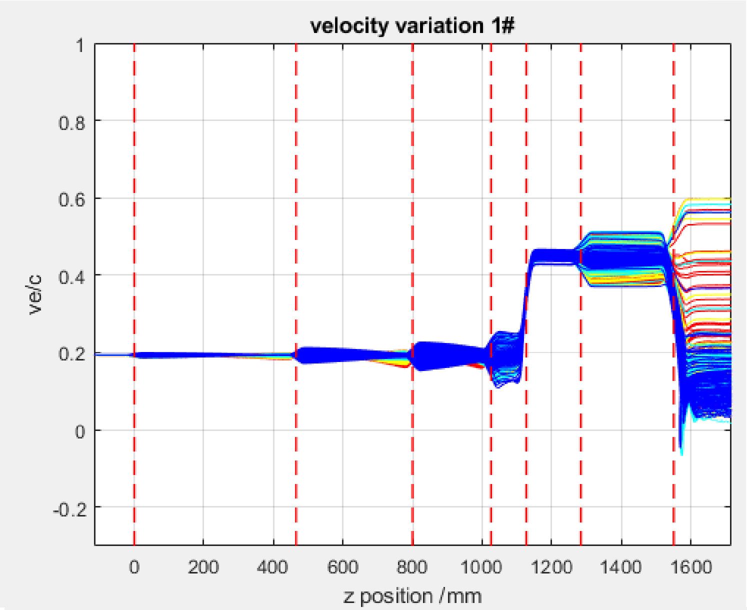


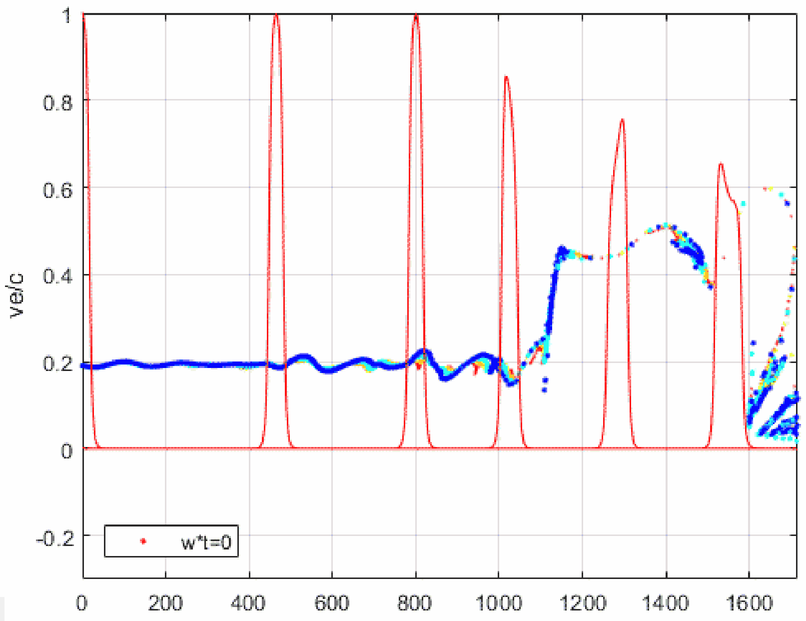
FCC 400 MHz, CW TS MBK klystron design (KlyC)

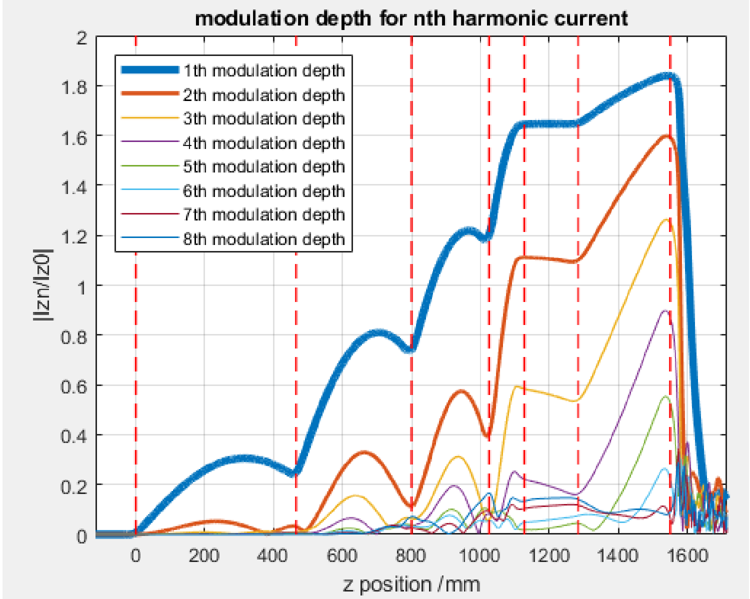
Input parameters:	KlyC
Frequency: 400 MHz	(FCCee **H-pole**)
N beams: 10	
RF power: 0.6-1.2MW	0.845 MW
Perveance total: 0.11	0.108 (1st: 1.5)
Total HV: 55-65 kV	60 (10+50) kV
RF Efficiency: > 80%	**88.1%**
Power gain > 40 dB	41.5
Total length: <3m	1.55m (RF)

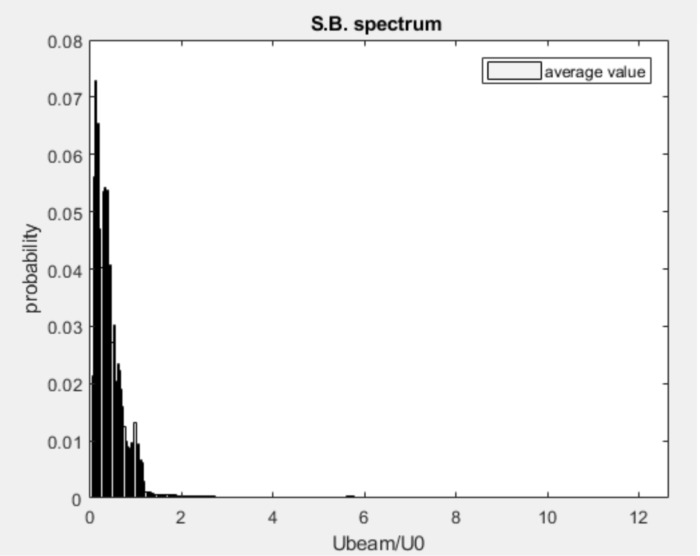
HE featured:

1. 4 cavities COM bunching circuit (1st stage).
2. RF bunching/linearization in DC gap by rotating/compressing bunch in the phase space).
3. Optimized congregation in the penultimate cavity.
4. ‘Long’ gap in the output cavity allows control of the bouncing electrons (no reflected electrons) in a wide RF power/Voltage range/



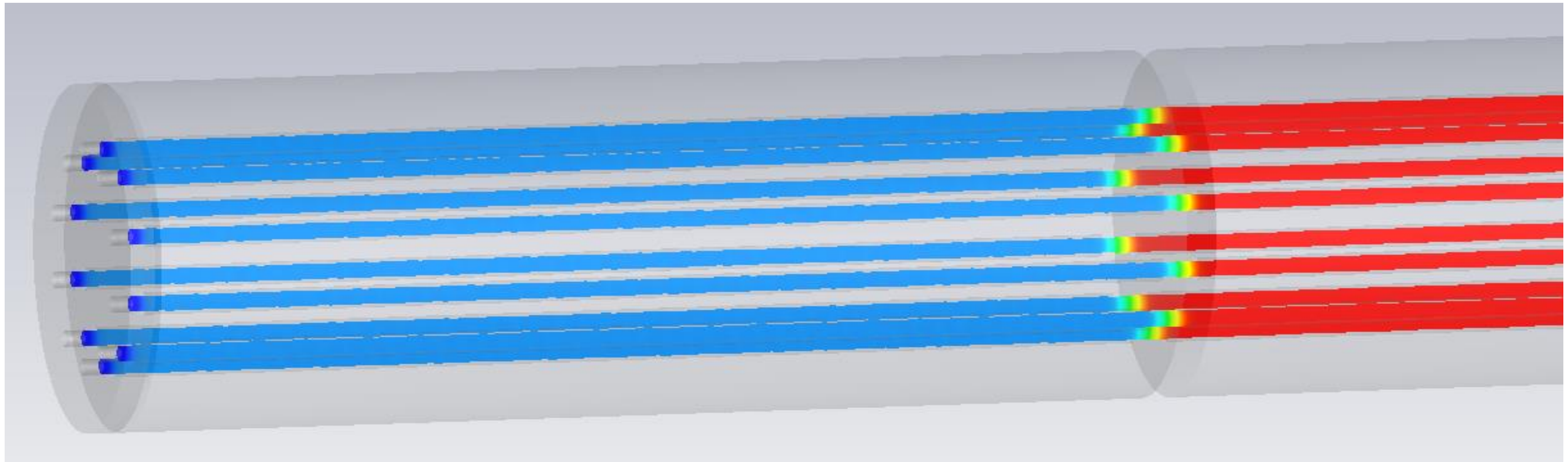




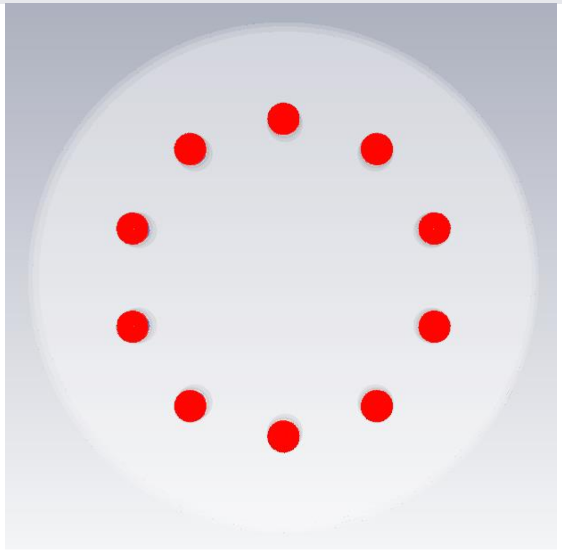


Beam Optics of TS HE MBK Gun in TRK Solver

Current=**17.8 A** ,Perveance= **1.6 µ*A*/*V*$^{3/2}$**, Beam Radius= **7.06 mm**



- ☐ 3D Magnetic field is imported from CST solenoid project.
- ☐ 3D effects brought by the MB topology are fully considered.



Z = 600 mm

Z = 1480 mm (Output cavity gap position)

TRK

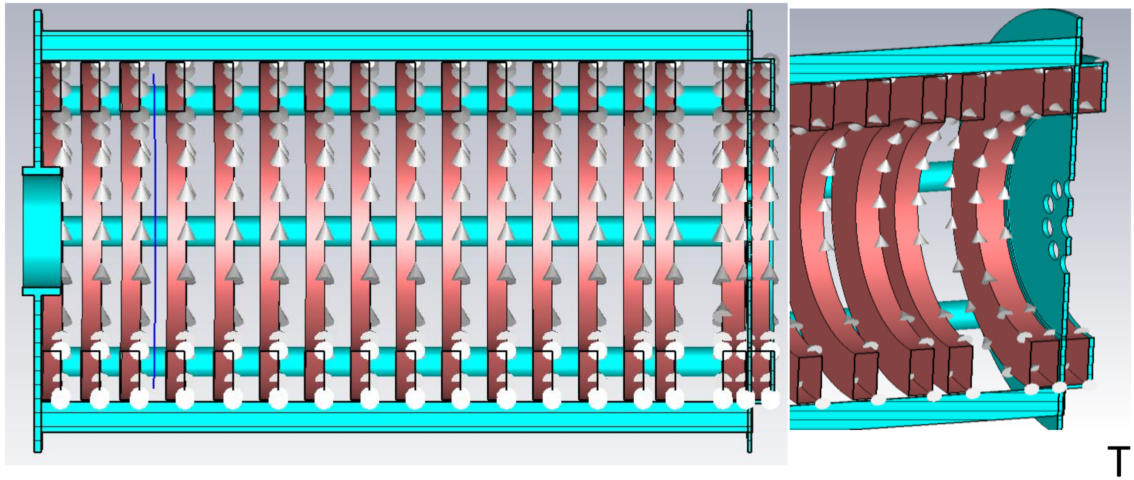
Solenoid Design in CST Software

High Efficiency Klystrons

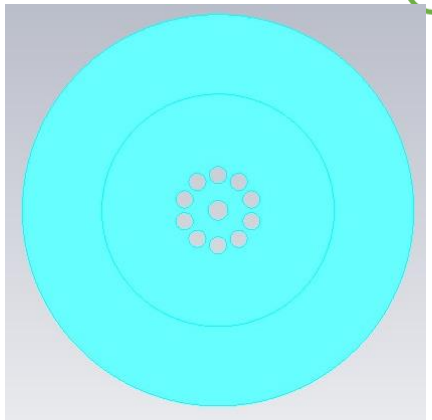
Magnetic Field = **0.095 T**

Power Consumption= **8.08 kW**

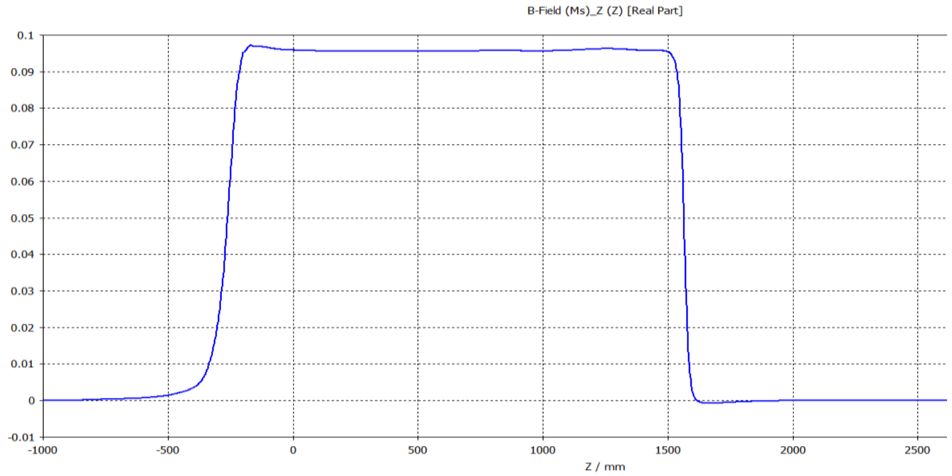
Using **ρ** value for Al (3.05E-08)
Power Consumption= **14.35 kW**



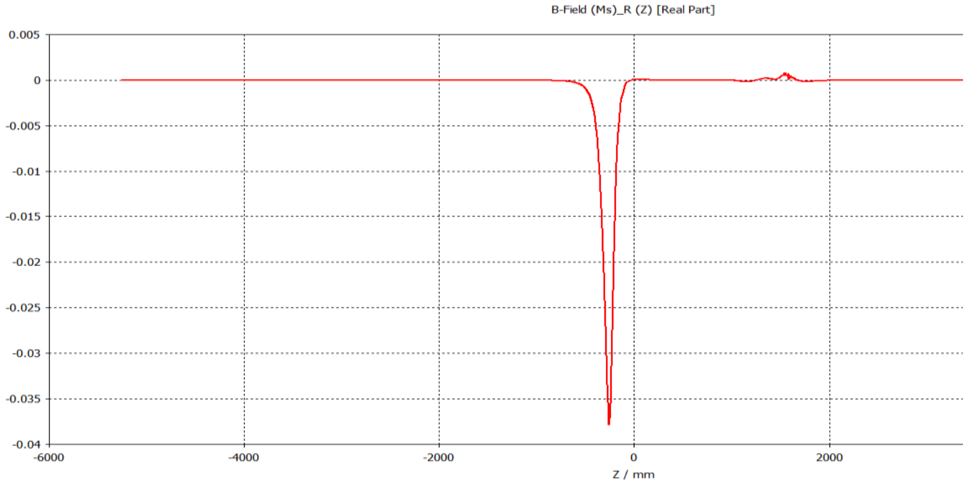
Whole structure of solenoid together with the position of the collector coil



The ending pole-piece with 10 holes and a coaxial at the centre on a rear view of the solenoid



Plot of Bz value along the z-axis generated from solenoid



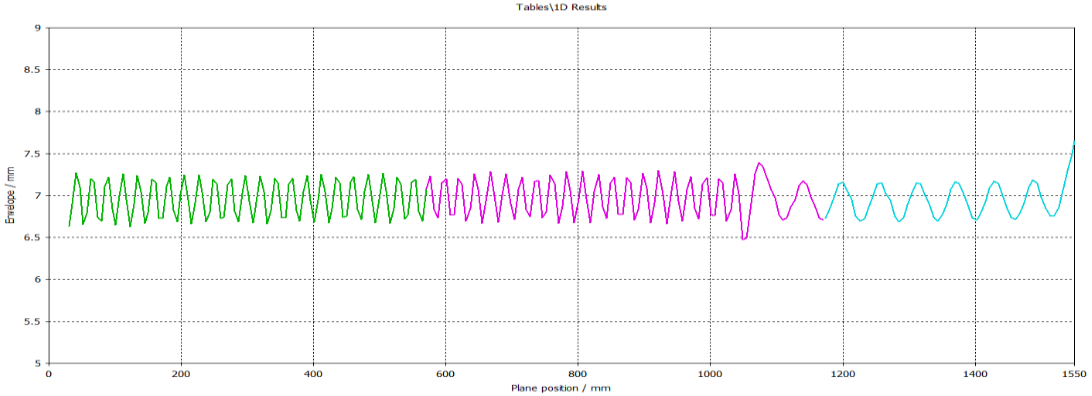
- Plot of transverse magnetic field *B*t along the z-axis
- The *B*t value of the focusing magnetic field is limited under 0.5 Gauss from the cathode to exit of output-cavity.

TRK simulation of TS HE MBK Gun at Different Voltages

TRK simulation of TS HE MBK Gun for Z, WH and ttbar Machines using same Magnetic field **0.095 T**.

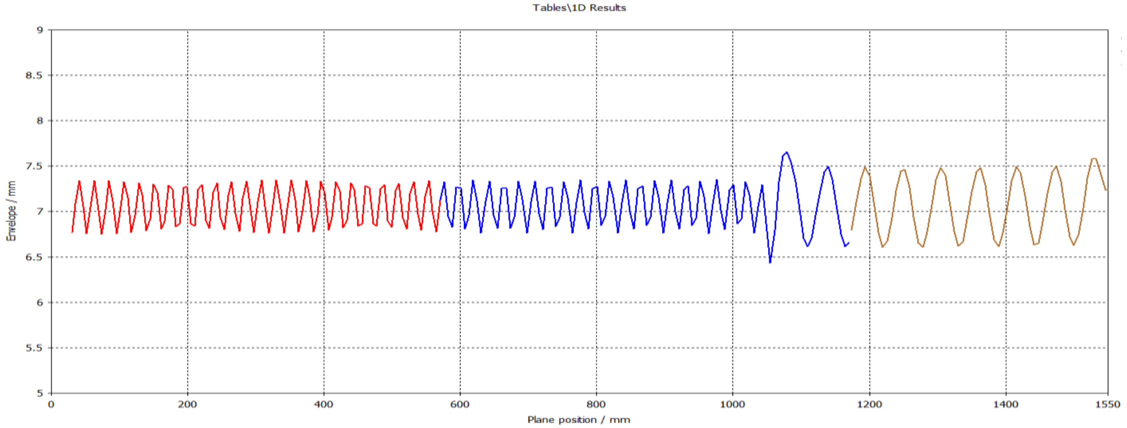
Z

1st Stage Voltage, V1 = 10.75 kV
2nd Stage Voltage, V2= 53.75 kV
Current = 1.78 A
Perveance = 1.6 $\mu A/V^{3/2}$



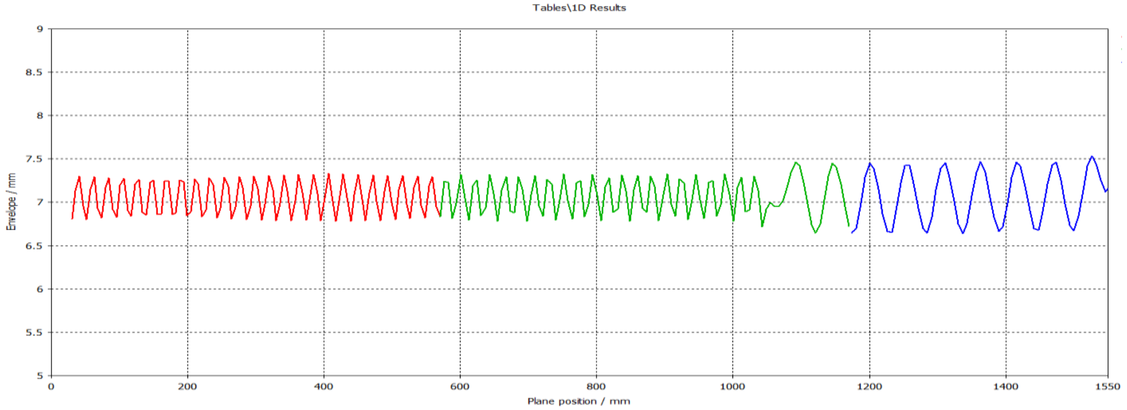
WH

1st Stage Voltage, V1 = 10.0 kV
2nd Stage Voltage, V2= 50.0 kV
Current = 1.6 A
Perveance = 1.6 $\mu A/V^{3/2}$

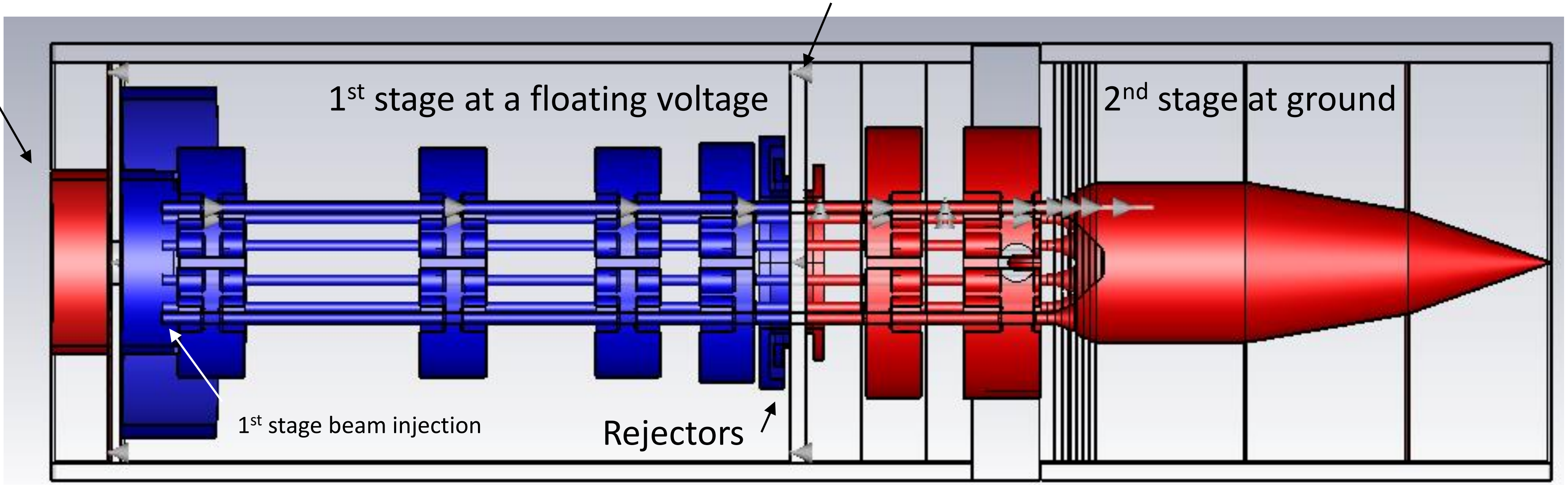


tt bar

1st Stage Voltage, V1 = 9.40 kV
2nd Stage Voltage, V2= 46.20 kV
Current = 1.456 A
Perveance = 1.6 $\mu A/V^{3/2}$



Setting up CST3D PIC simulations



Special coaxial input coupler (at ground)

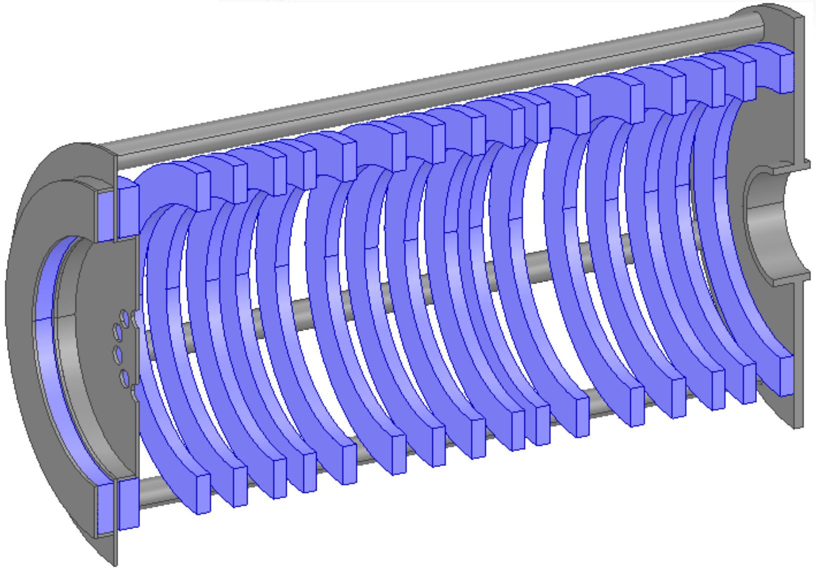
DC gap

1st stage at a floating voltage

2nd stage at ground

1st stage beam injection

Rejectors

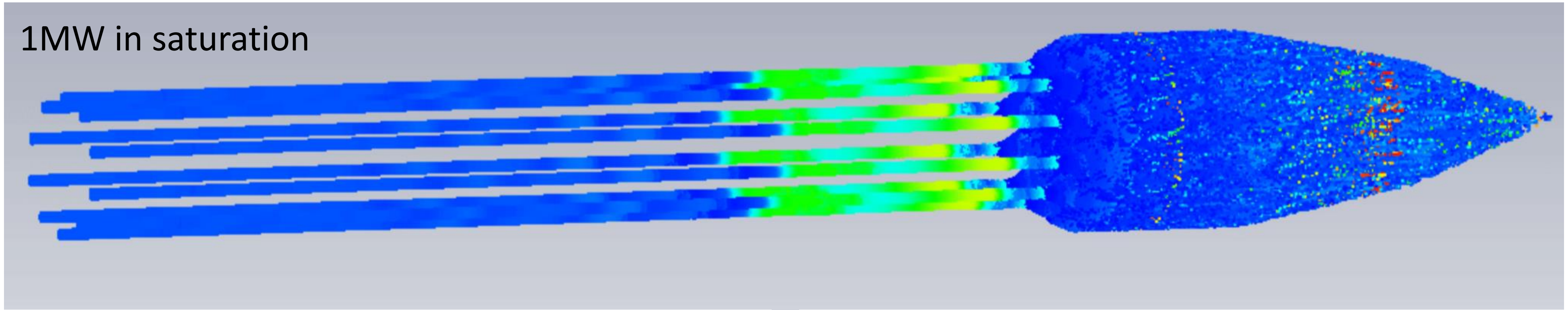


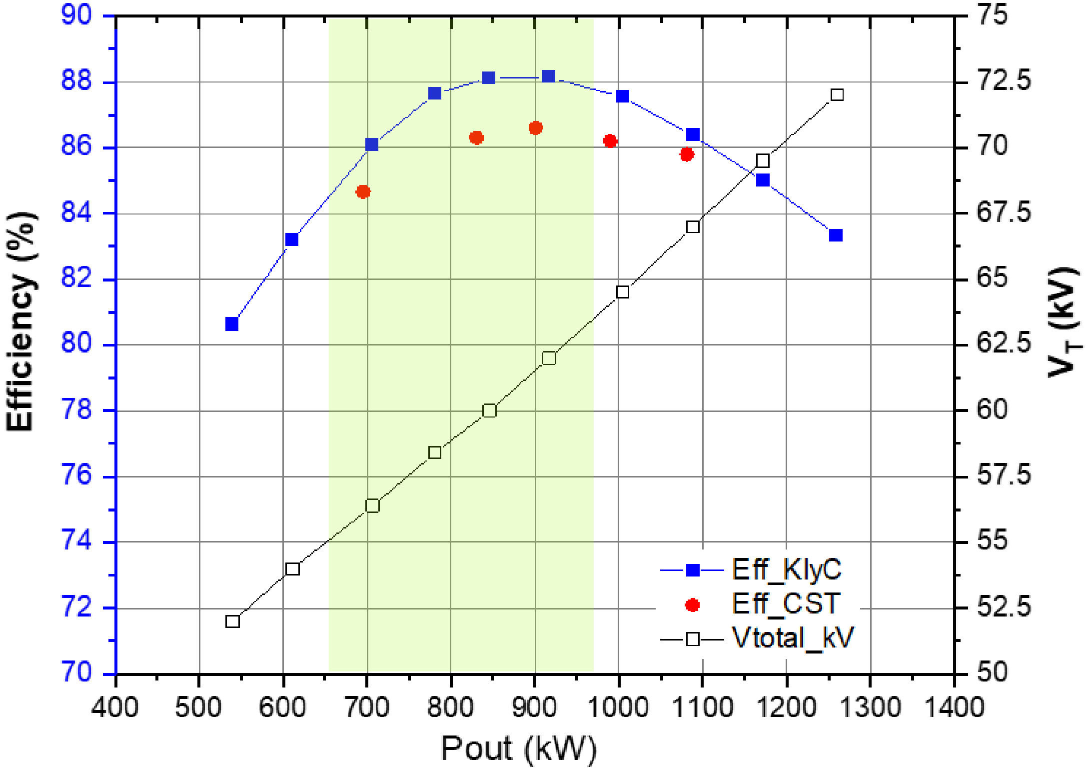
Solenoid is simulated in CST separately and magnetic filed 3D map is imported into PIC simulations directly.

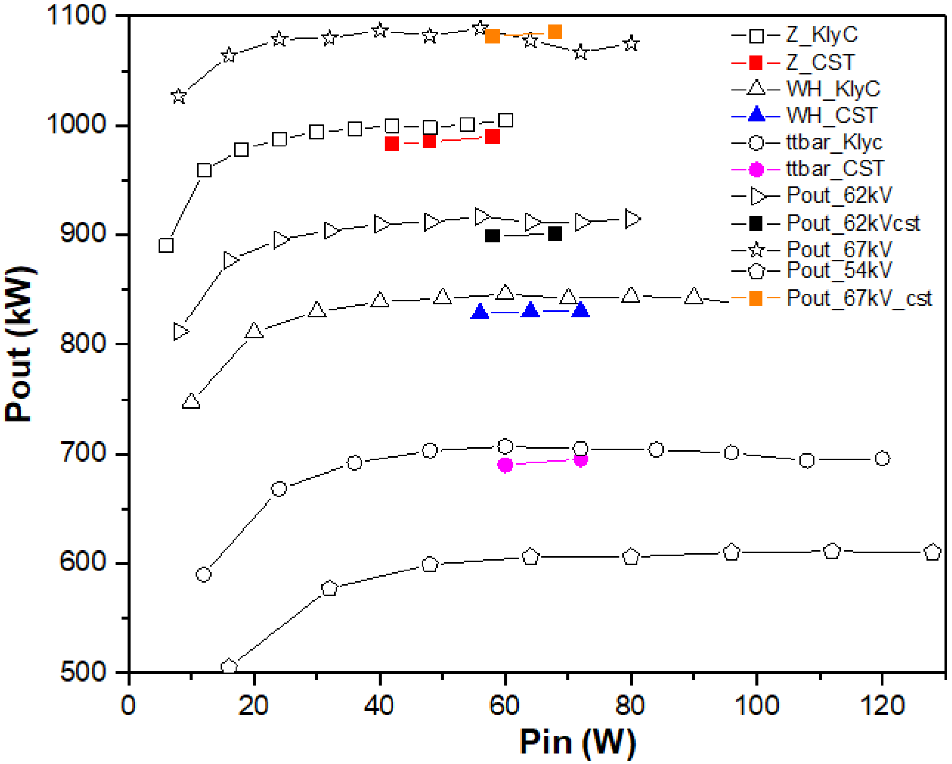
Output ports are used only for monitoring the power envelope and frequency spectrum. Efficiency is calculated by direct integration of the beam power at emission plane, integrated beam losses on the collector part and Ohmic losses in the output cavity:

$$\eta = P_{\text{spent beam}}\,(1-Q_{ext}/Q_0)/(\,I \text{x}\, U)$$

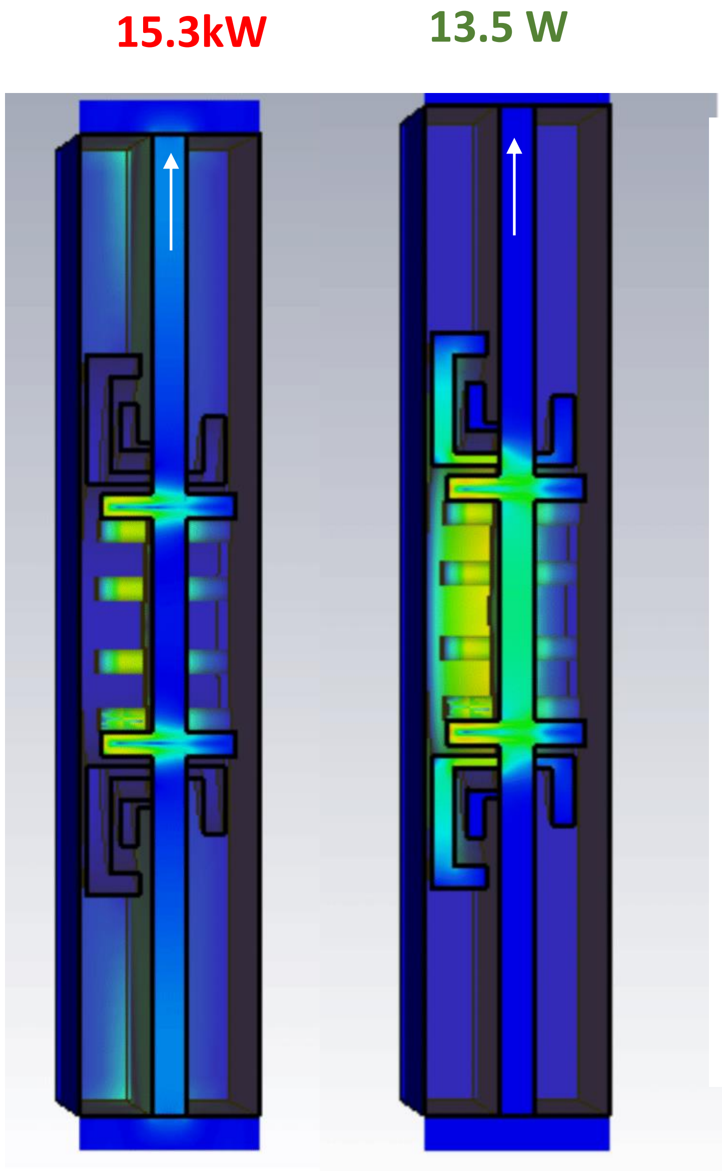
FCC 400 MHz, CW TS MBK RF performance summary (CST3D PIC)



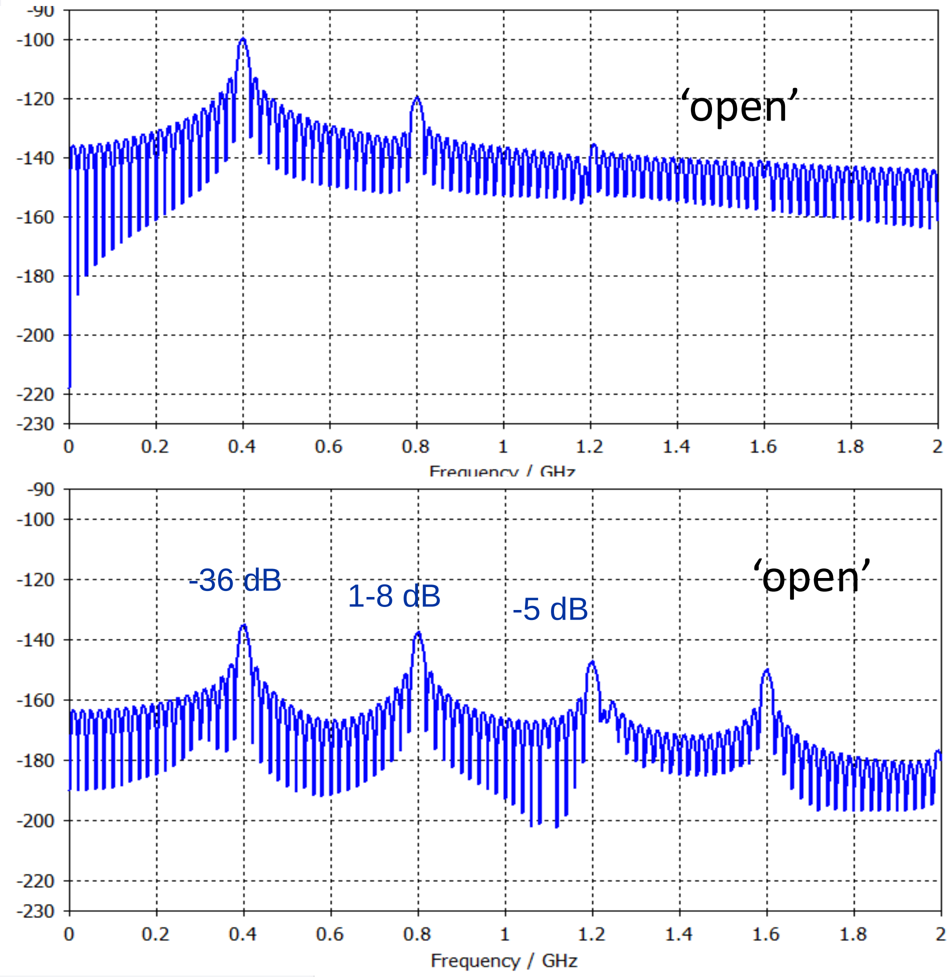




Suppression of RF radiation into DC gap (concept)

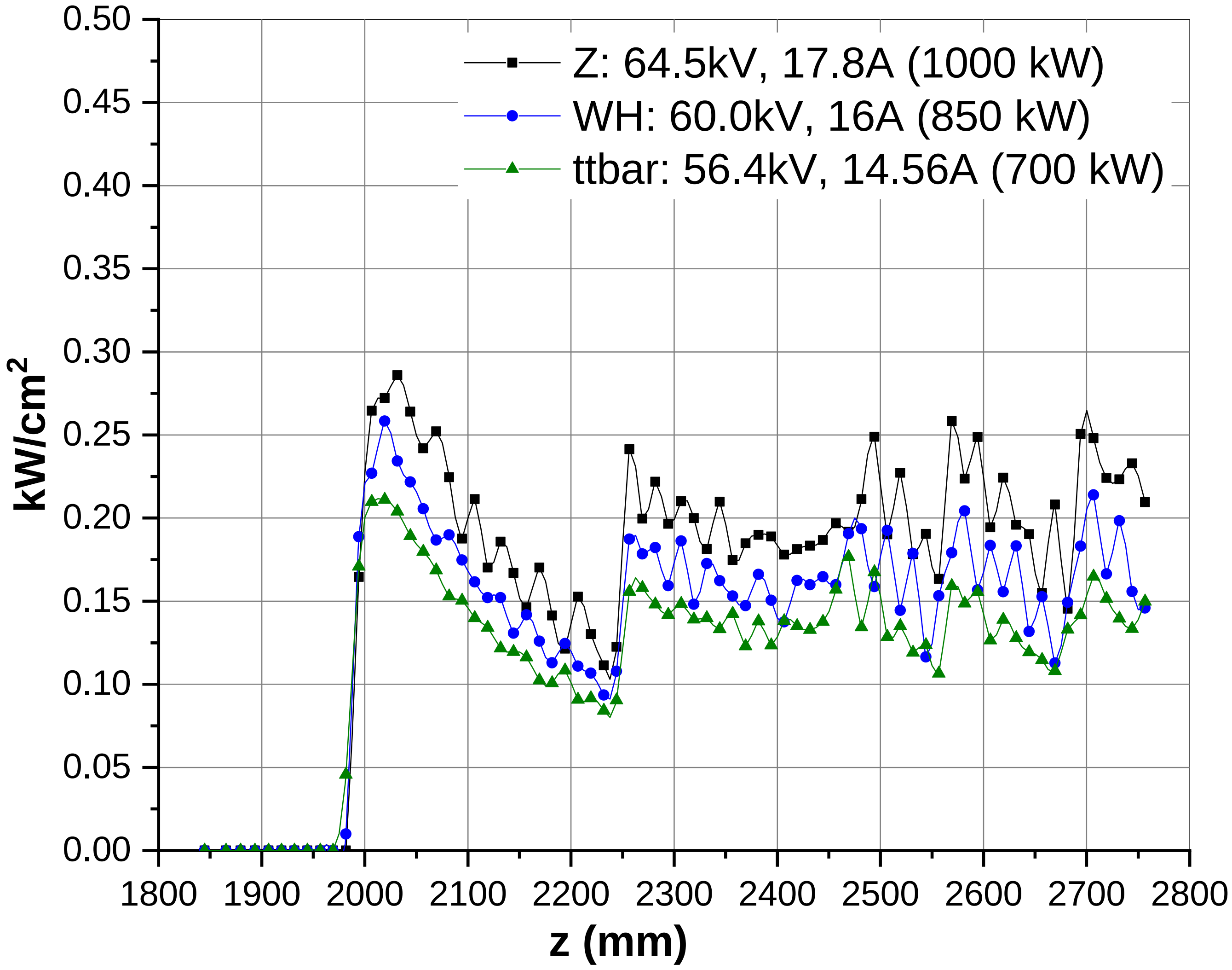


Spectra of RF radiation into DC gap

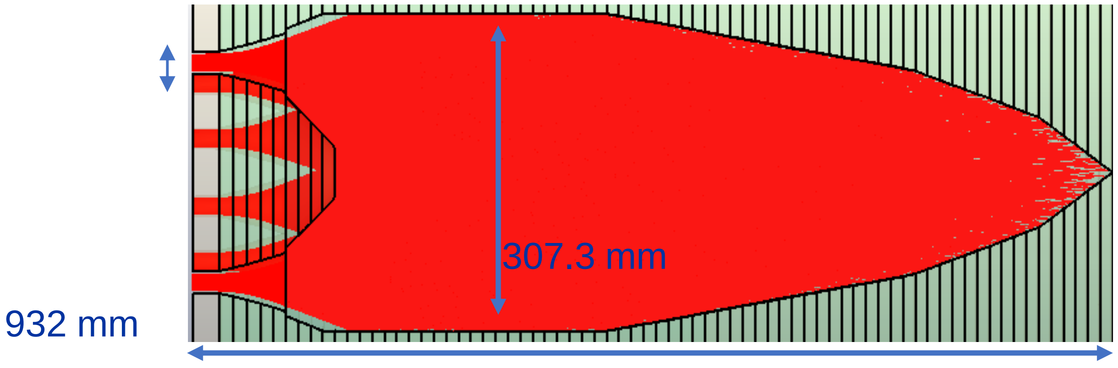


- By using 3 radial resonant choke rejectors, total radiation into DC gap is suppressed by >30dB
- Illustrated case uses bunched beam at 0.96 MW (16Ax60kV)/ H-pole

TS MBK collector baseline design



CST3D TRK simulations

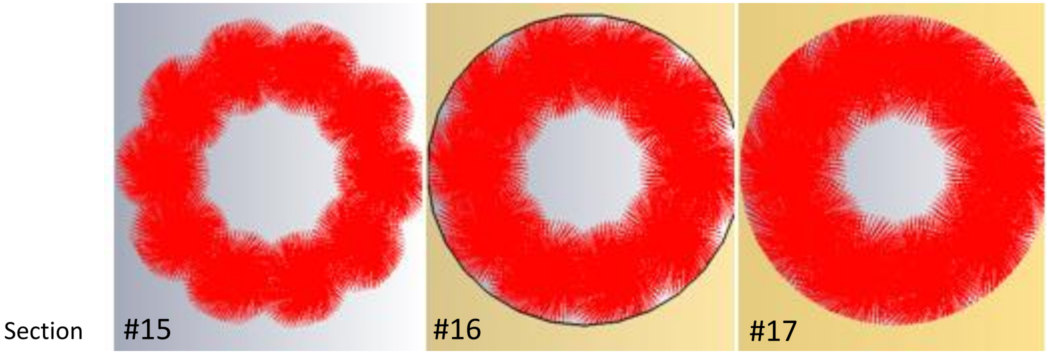


	Voltage	Current	dP/dS (max)
ttbar	56.4 kV	14.56 A	211 W/cm^2
WH	60 kV	16 A	258 W/cm^2
Z	64.5 kV	17.8 A	285 W/cm^2

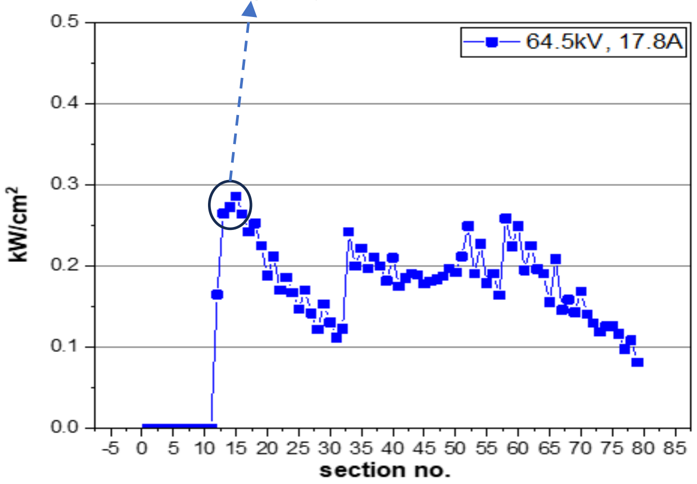
Collector was optimised to maintain power loss density on the surface < 300 W/cm^2 for DC operation

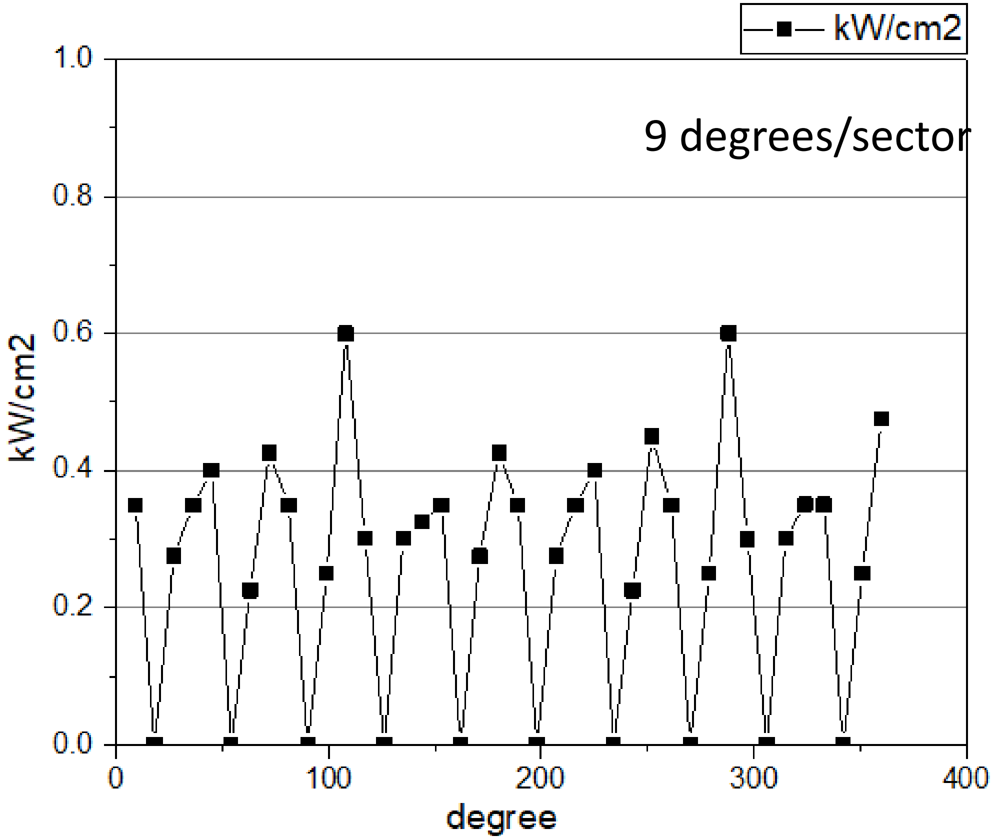
Specifics of MBK collector.

Azimuthal beam losses distribution.



Averaged power over the section





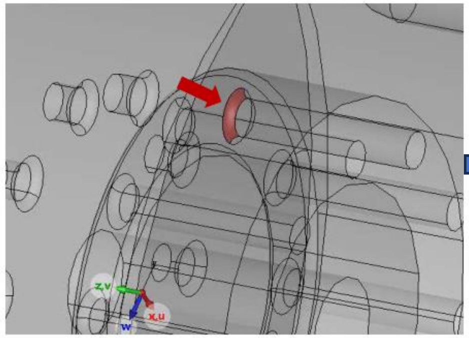
Azimuthal peak power density is about 400W/cm^2 . We will need to:

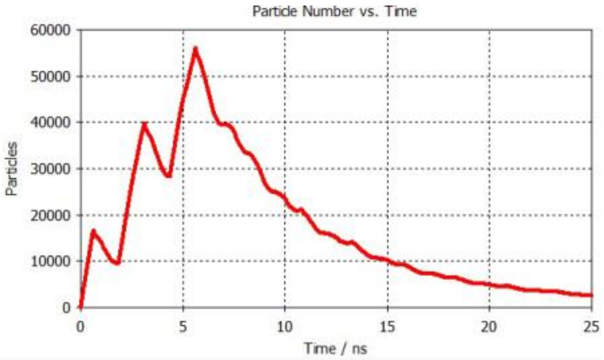
- **Increase collector diameter by 10-20% (307mm -> 340/360mm).**
- **Lengthen the input taper part so that first impact will happen at a grazing angle.**

Multipacting Simulation at 1 MW RF

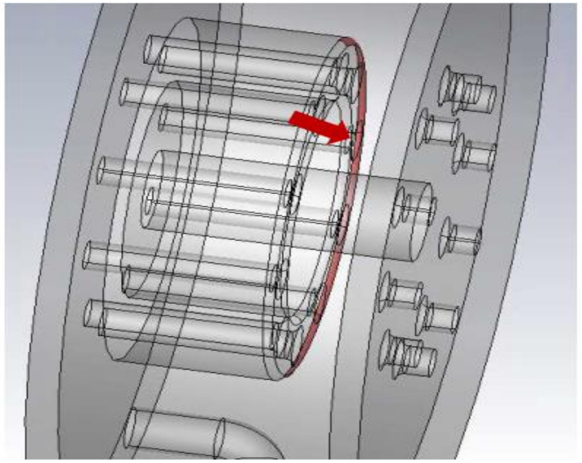
Courtesy: Franck Peauger

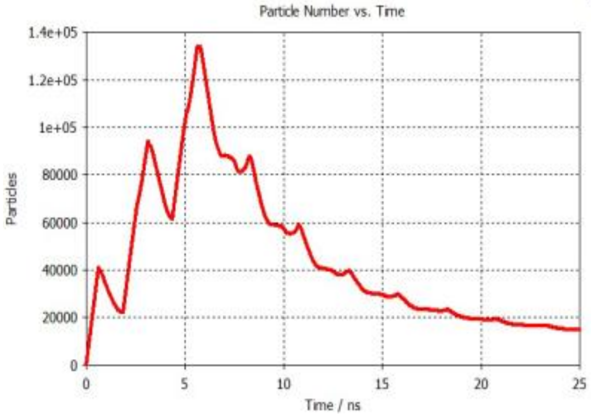
Inner fillet of one beam hole



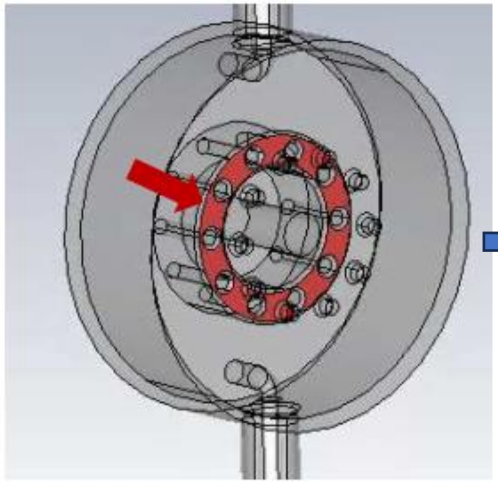


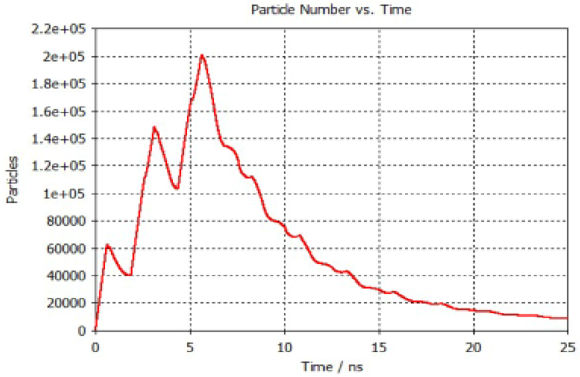
Outer fillet of the cavity nose



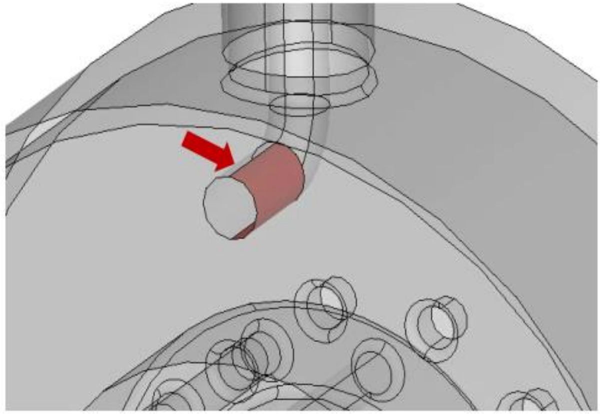


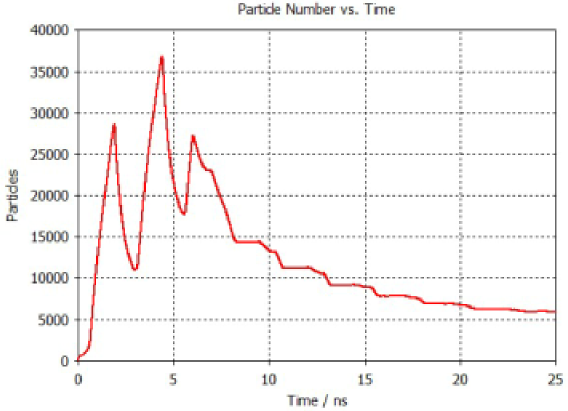
Flat Part of the nose





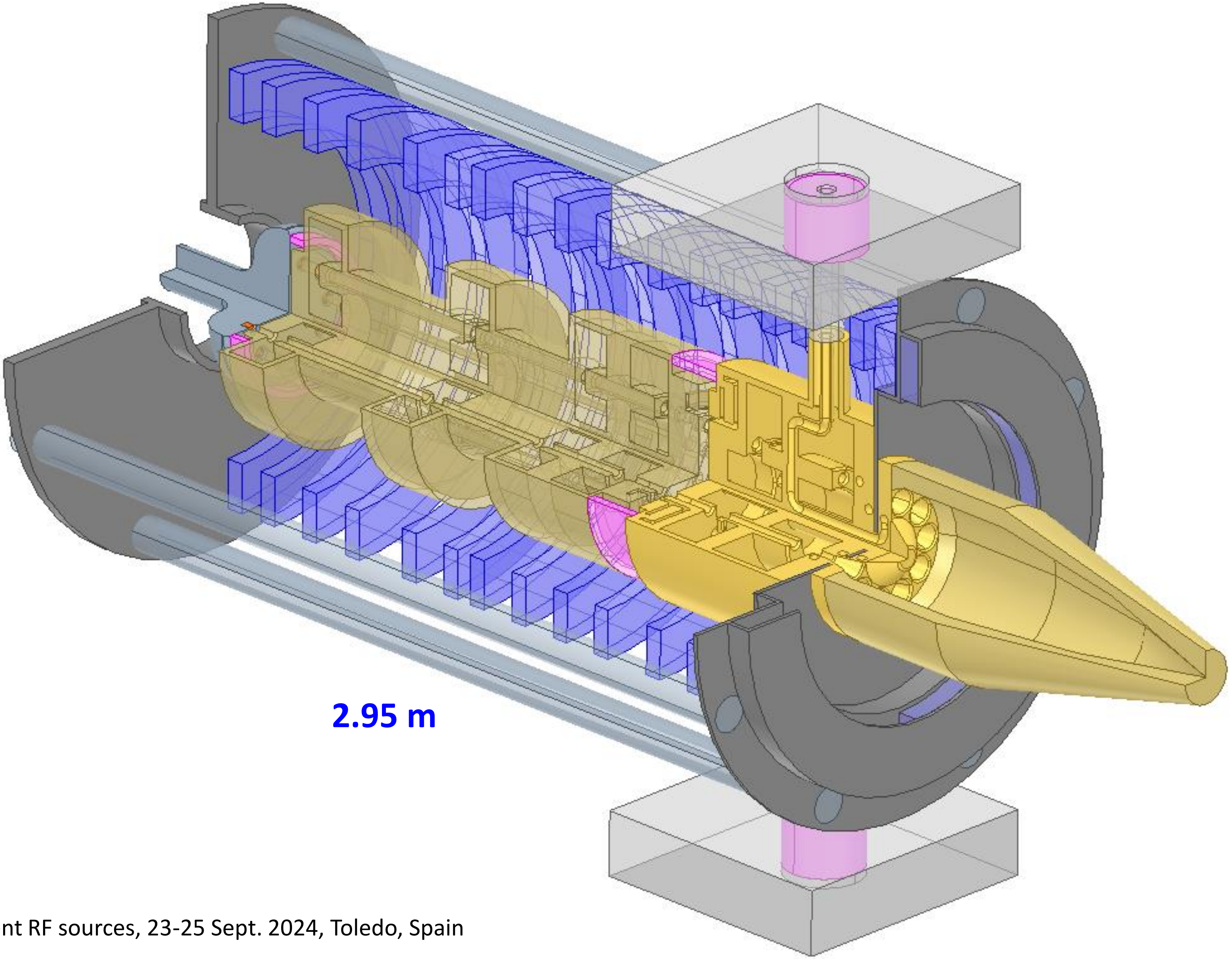
RF Loop





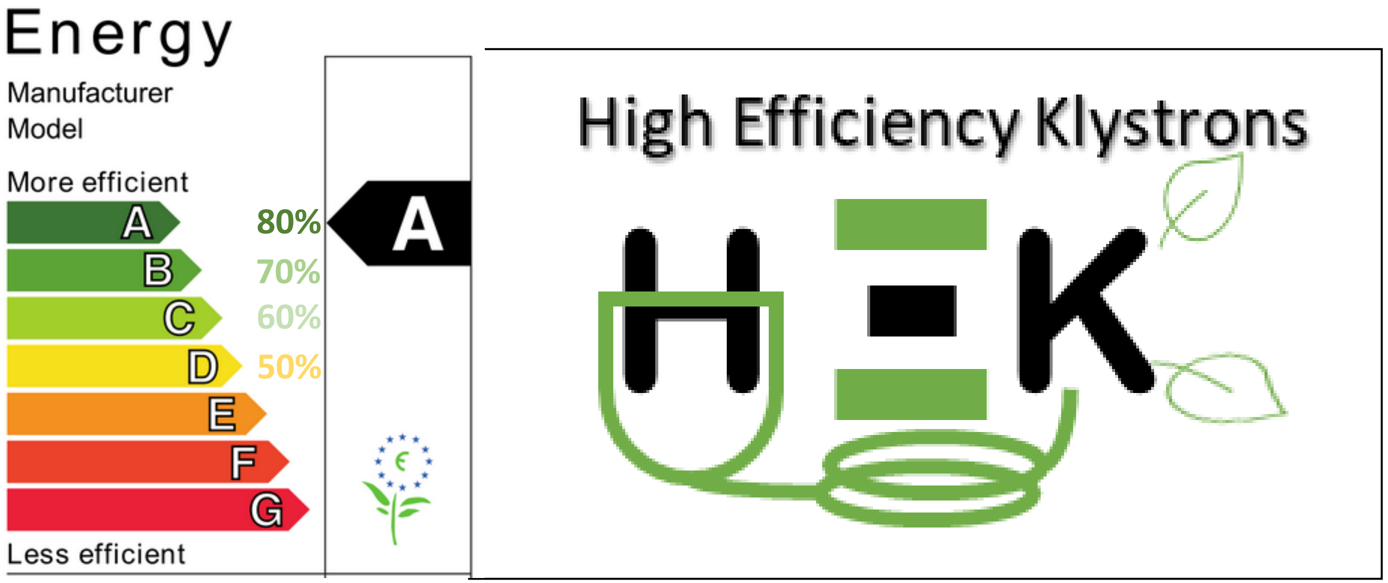
400 MHz HE Two-Stages MBK for FCC$_{ee}$. Integration.

High Efficiency Klystrons



FCC TS MBK Summary and outlook

- The reduction of energy consumption in the future large-scale accelerators, like FCC, is of a great importance.
- Novel two-stage (TS) klystron technology was introduced recently. It enables compact solution in UHF band, with potential to increase the efficiency from 65% in existing commercial tubes up to 80%.
- Such a 400 MHz, 1.0 MW TS MBK klystron for FCC is now under development at CERN as a part of the High Efficiency Klystrons project.
- RF circuit, beam optics and special axillaries, like HVRFT and DC accelerating gap rejector, have been evaluated and confirmed in simulation the tube conceptual feasibility with potential to reach target efficiency of >85%.
- The next step will be integration of beam optics and RF circuit, followed by technological development and prototype fabrication in collaboration with industrial partner.
- Multipacting effect has been checked.



- Project leader: Igor Syratchev
- Project team @CERN: Zaib Un Nisa, Nuria Catalan Lasheras.
- Project team@ Lancaster: Lee Millar, Graem Burt.