High Efficiency Klystrons

Status of 400MHz 1MW FCCee Two-Stages 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)

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

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

Pulsed.
Klystron.

- **Large scale particle accelerators** can be operated with vast diversity of RF power sources.
- The actual choice of the RF source type will be driven by practical consideration : tunnel integration, spatial and peak power density, cost/W and efficiency.

Ka-band (30GHz+)
Exotic concepts
Very high gradient linacs

CW, Pulsed.
Klystron, Gyro-devices.

The accelerators technology is very diverse and could require the RF signals in a wide range of the frequencies (few 100 MHz – 12 GHz), peak power levels (few 100 kW – 100 MW) and pulse lengths (CW -100ns). The **klystron** amplifiers technology is the one that covers almost all RF frequency/power demands of the modern accelerators.

0.352 GHz, 2.8MW/LHC

Electro vacuum devices for science

CPI — USA

THALES — France

Canon — Japan

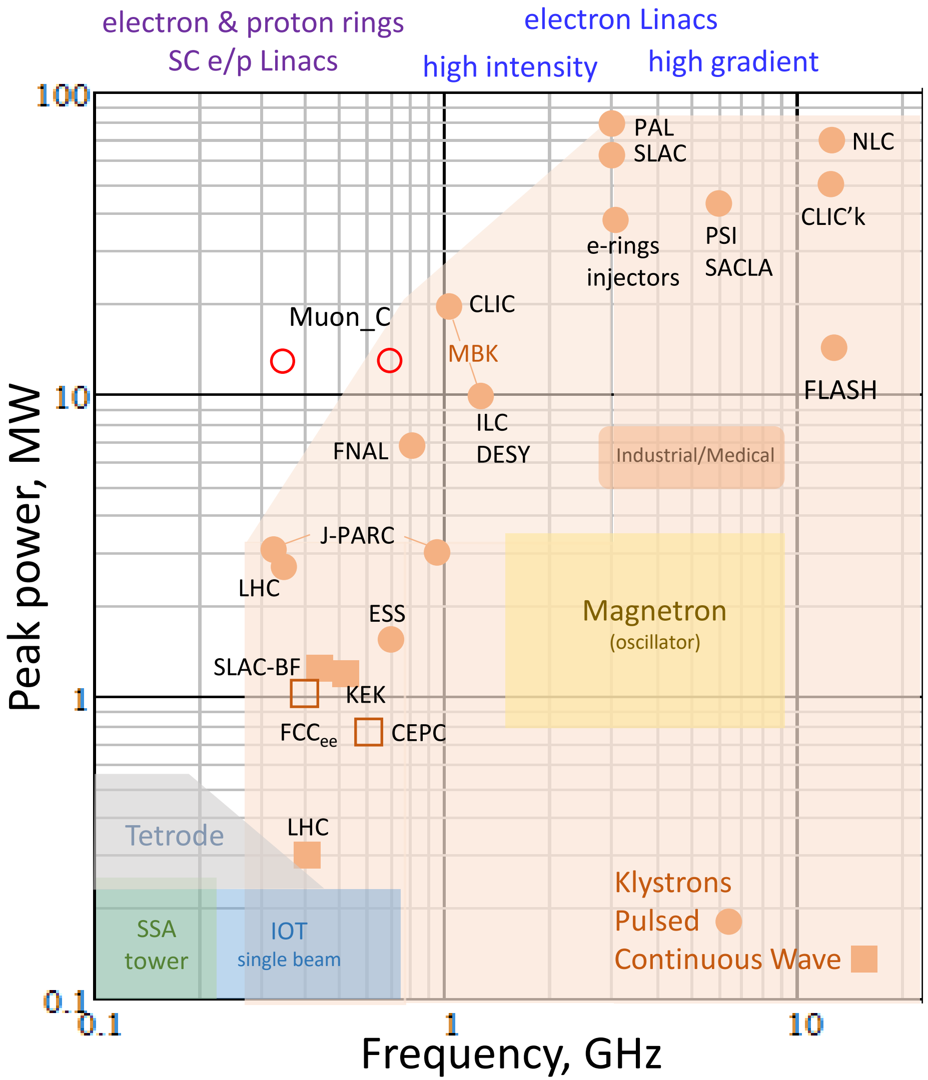
0.7 GHz, 1.5MW/ESS

1.3 GHz, 10MW/DESY

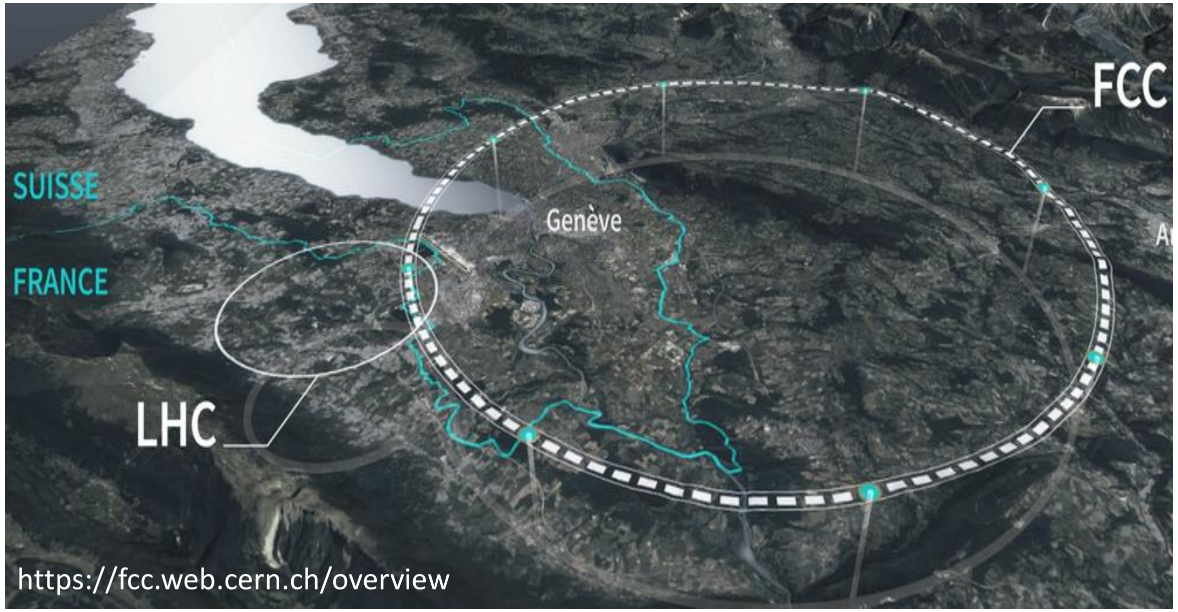
3 GHz, 60MW/SLAC

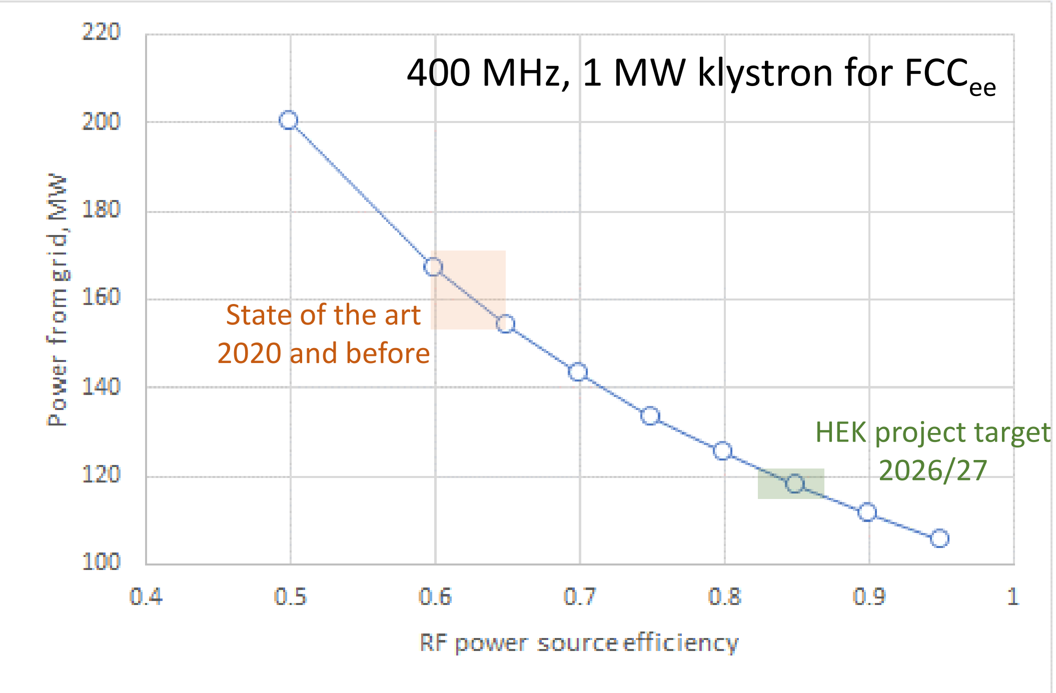
6 GHz, 50MW/PSI

12 GHz, 10MW/CERN



Grid power required for the large-scale HEP Accelerators





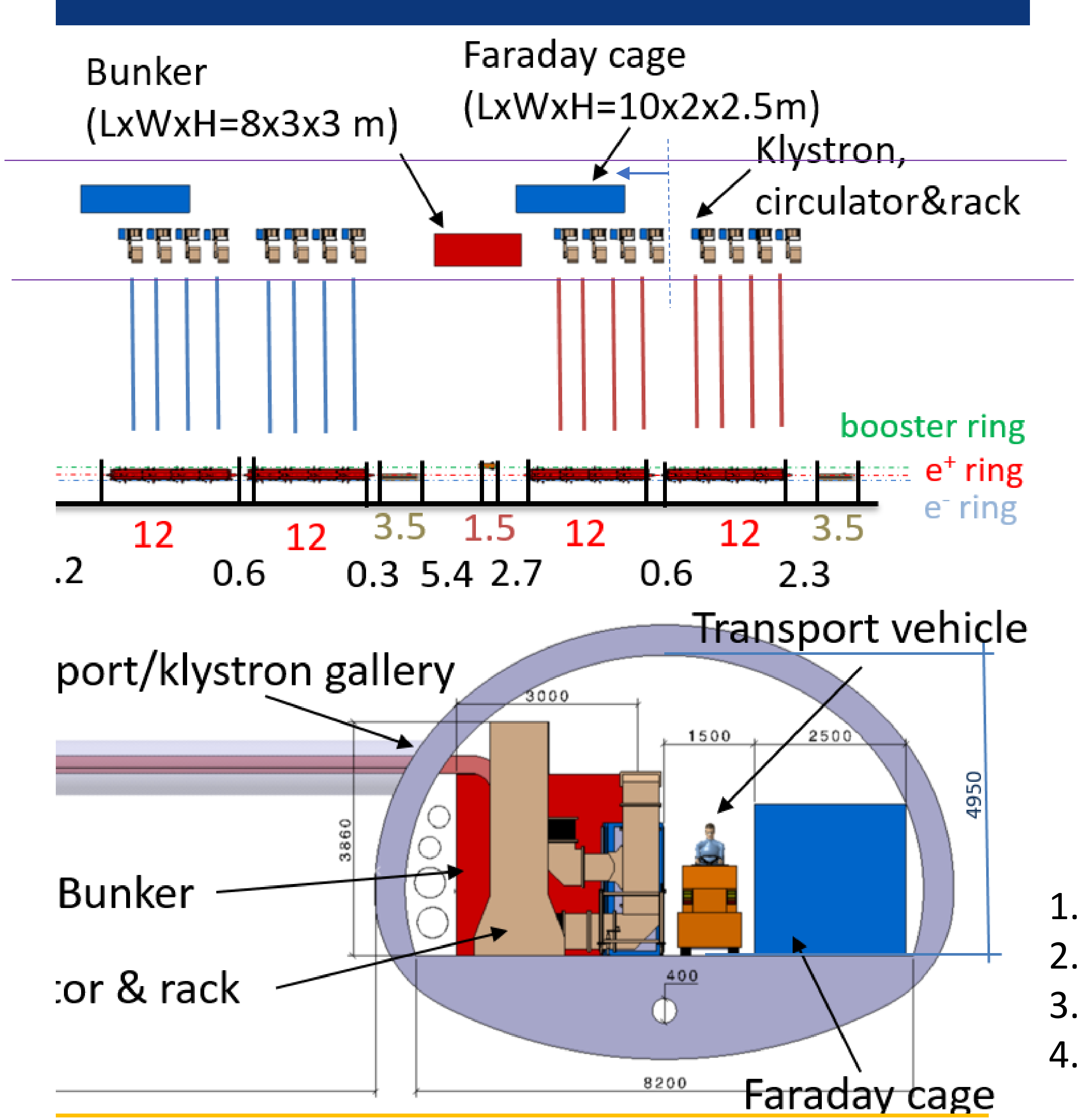
To operate FCC$_{ee}$, **100 MW** Continues Wave RF power is needed to accelerate particles and to compensate for the energy lost into synchrotron radiation.

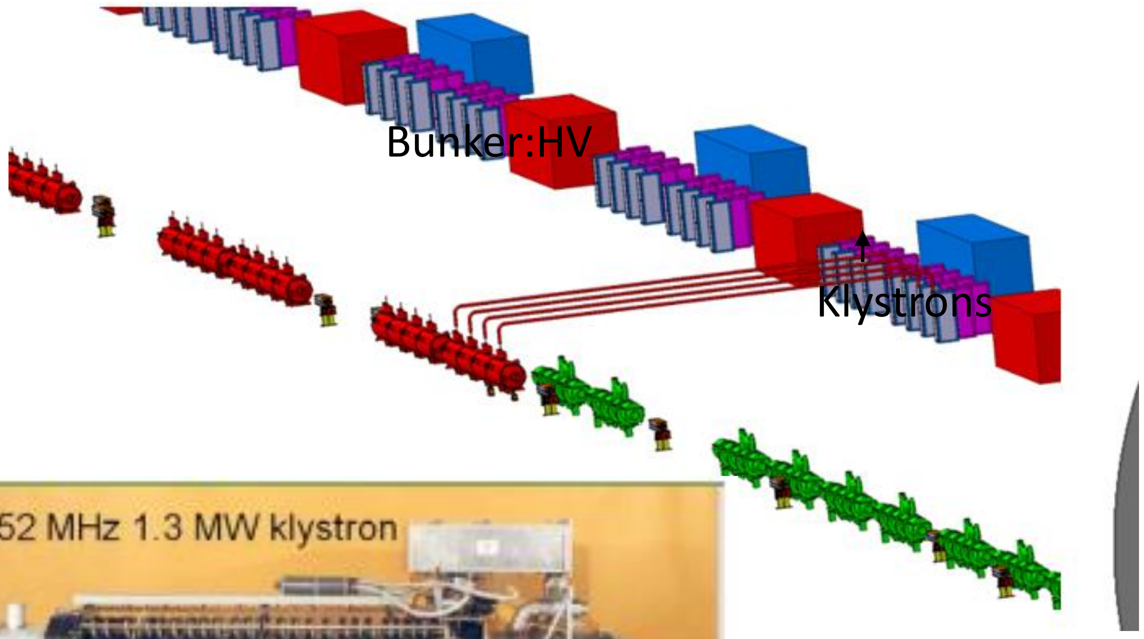
Improving klystron RF efficiency from 65% in the best existing commercial devices to 85% in the new HE tubes will:

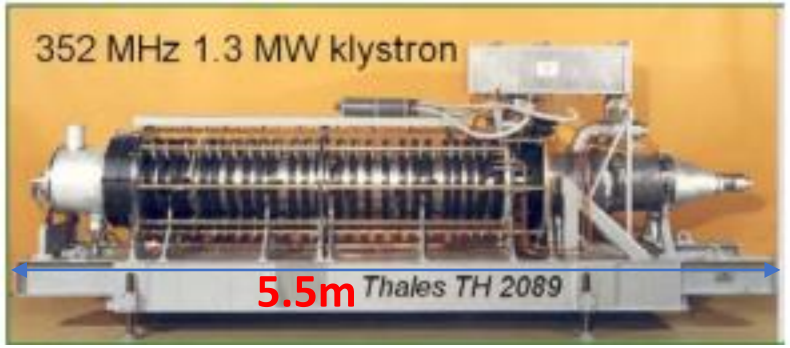
- Save 32.2 MWh -> 253 GWh (7000h/year) -> **2.53TWh over 10Y.**
- Reduce maintenance cost and power consumption of power converters and cooling system (environmental impact).

**100 MW, CW ~100 000 Microwave ovens running 24/7.*

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







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

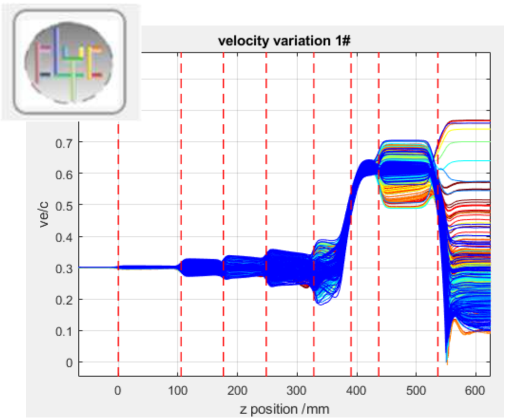
1. Each Klystron should deliver 1MW @ 400MHz.
2. Preferably, klystron should be placed vertically in the tunnel.
3. The total length of Klystron should be about 3m.
4. The efficiency of Klystron is targeted at 80%.

High efficiency klystrons projects at CERN

High Efficiency Klystrons

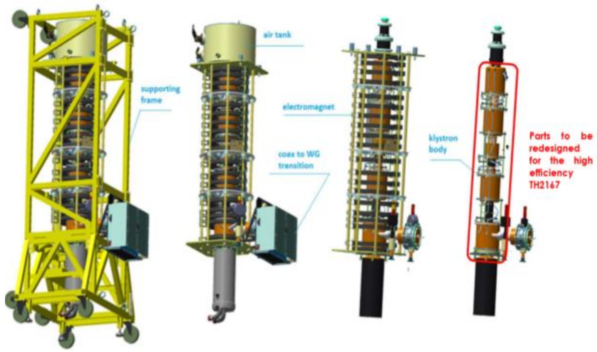
High Efficiency klystrons activity was initiated at CERN in 2014. In 2021 it was transformed into a CERN's **project.**

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



Task 1: Design & simulations

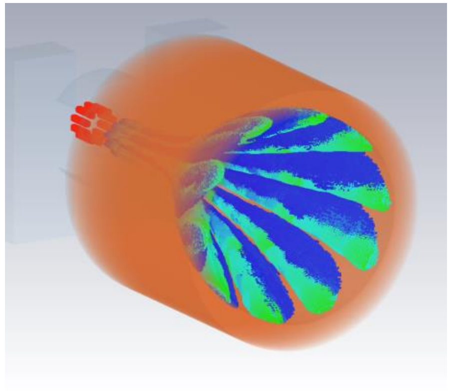
- Maintenance and distribution of the CERN made klystron code KlyC.
- High level expertise in using commercial tools like CST PIC, HFSS etc.



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.

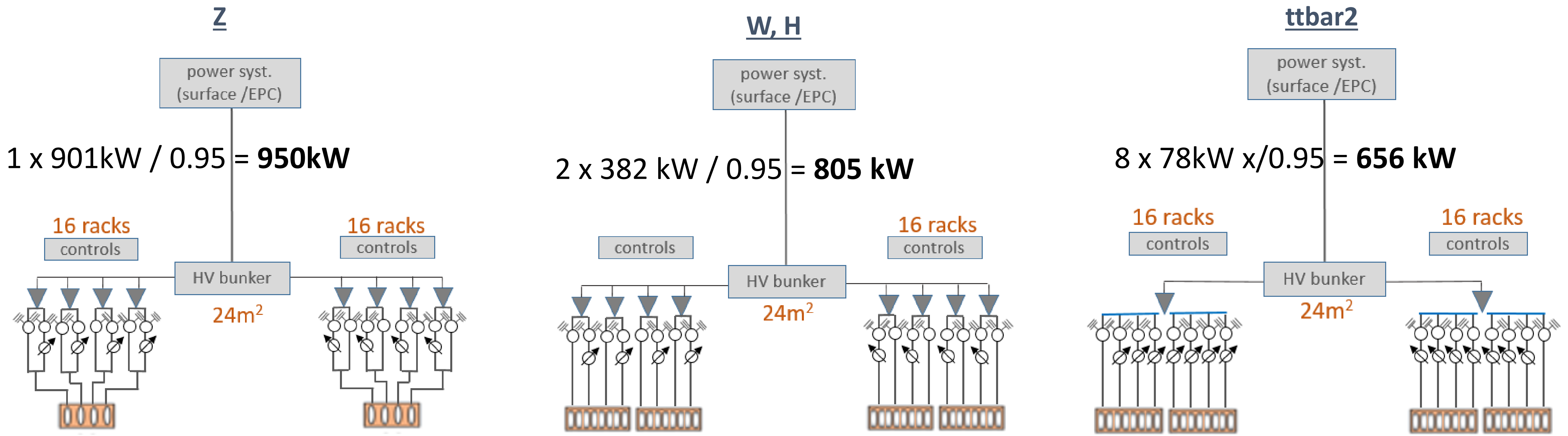
First commercial X-band 10 MW HE (56%) klystron.
CERN-Canon collaboration.

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**.

400 MHz accelerator units for different poles of FCC_{ee} operation stages

High Efficiency Klystrons



14-Jun-23	Z		W		H		ttbar2		
	collider	booster	collider	booster	collider	booster	collider	collider	booster
RF source type	400 MHz - 1 MW klystron	800 MHz - 500 kW klystron	400 MHz - 1 MW klystron	800 MHz - 500 kW klystron	400 MHz - 1 MW klystron	800 MHz - 500 kW klystron	400 MHz - 1 MW klystron	800 MHz - 500 kW klystron	800 MHz - 10 kW solid state amplifier
Frequency [MHz]	400	800	400	800	400	800	400	800	800
Pcav [kW]	901	210	378	89	382	45	78	163	8
Prf no beam [kW]	225	53	95	22	96	11	19	41	2
# cavities / RF sources	1	2	2	4	2	8	8	2	1
# RF sources	112	12	132	14	132	14	33	244	600
RF power overhead [%]	11	19	32	40	31	39	60	54	19

- Up to 132 klystrons (H-pole) will be operated, providing total RF power of **105 MW**.
- To reduce investment cost , the individual/unique tube shall be **efficient** in a wide RF power range from **600 kW to 1 MW**

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 $\Delta p/p$) along the short DC voltage post-accelerating gap.
3. Final power extraction from high voltage (low perveance) beam. **High efficiency.**

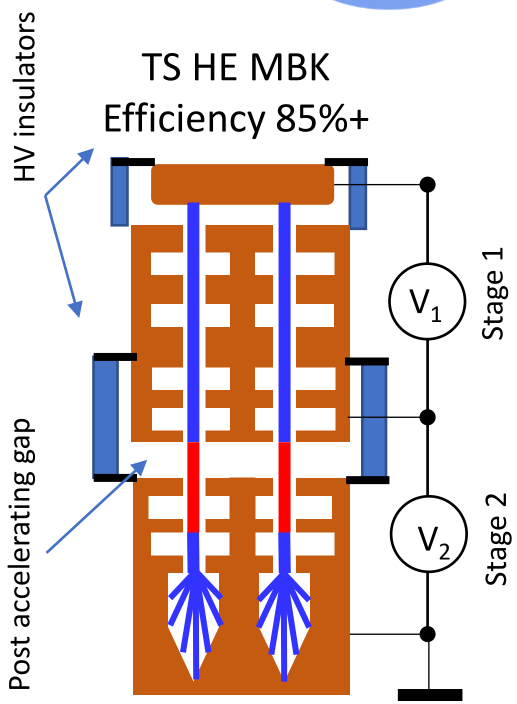
Additional advantages:

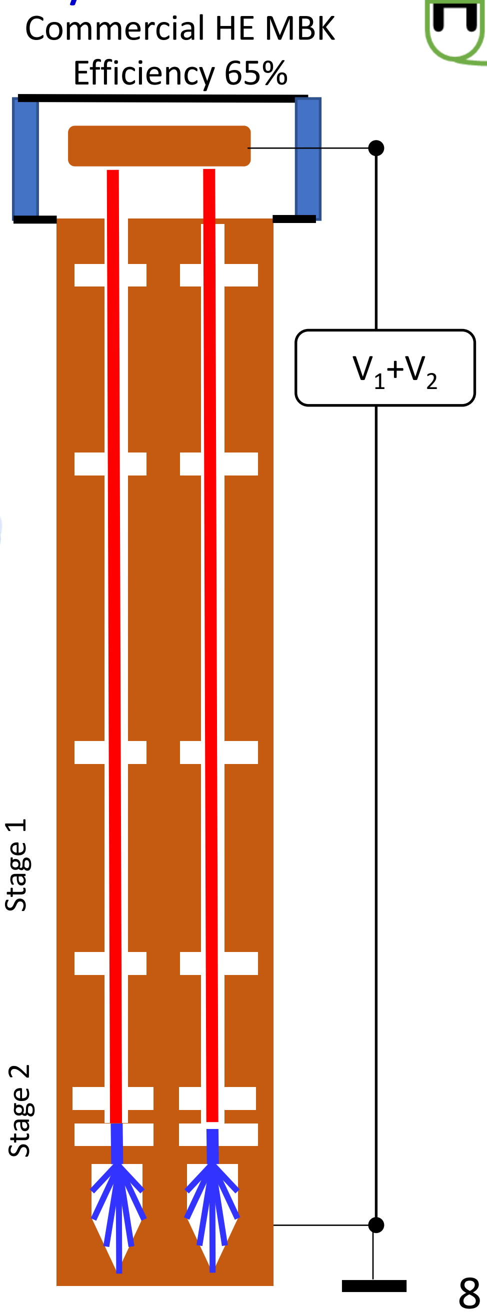
1. For pulsed tubes, the second HV stage can be operated in DC mode. Thus, simplifying the modulator topology. (cost/volume) and increasing the modulator efficiency.
2. Simplified feedback for the first stage pulsed voltage. Improved klystron RF phase and amplitude stability.

Drawbacks:

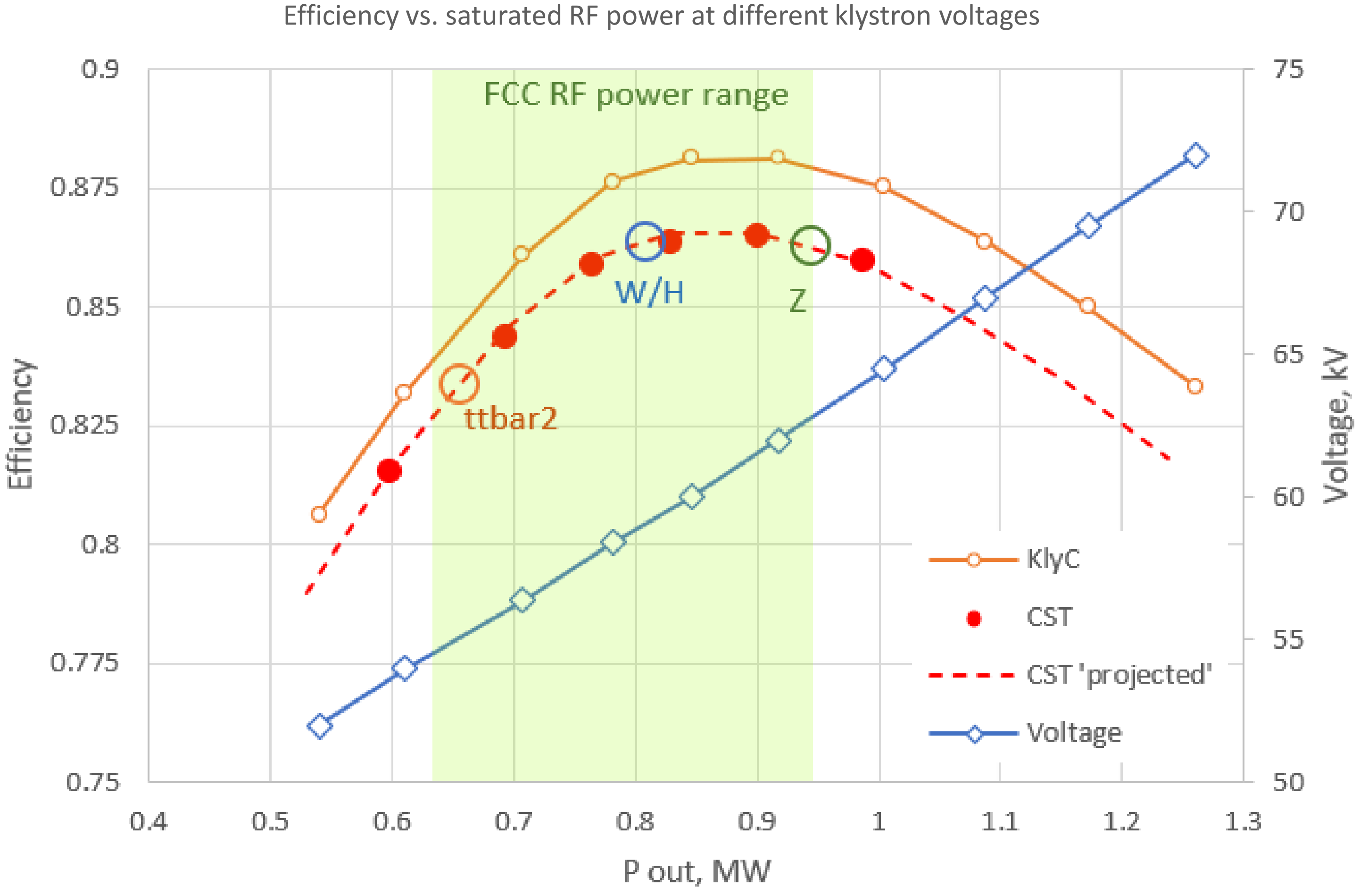
1. Reflected electrons from the output cavity and collector shall be **avoided at any cost.**
2. RF radiation into DC gap must be sealed.
3. Requires special HV isolated RF feedthrough to inject RF signal into input cavity.
4. Large bore (∅400mm) ceramic insulator on the 2nd stage.

GOOD FOR:





400 MHz 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.

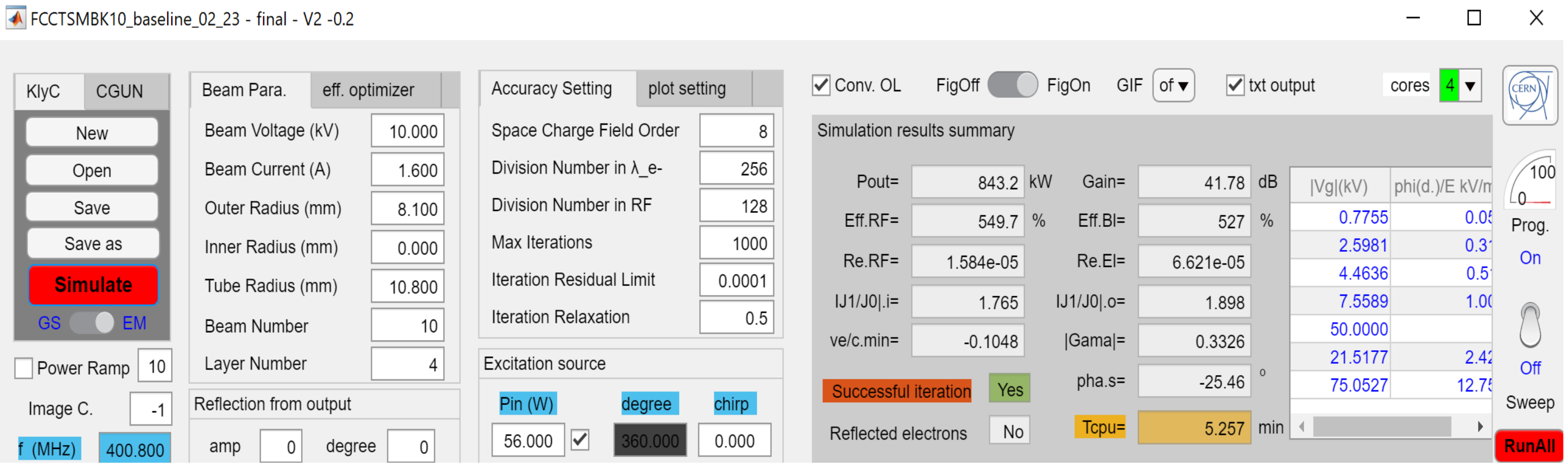
Project status @ CERN

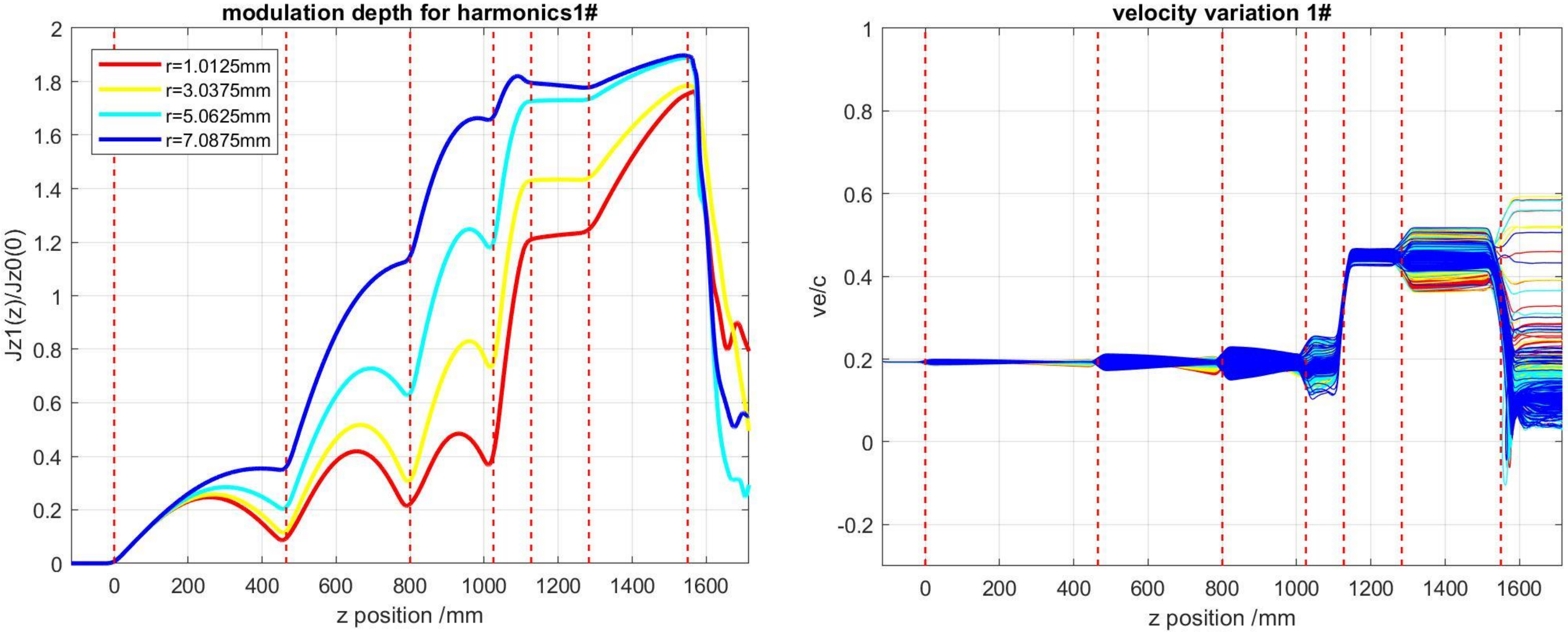
- ✓ RF circuit
- ✓ Collector
- ✓ Cathode
- ✓ Solenoid
- ✓ Special High Voltage isolated RF feedthrough (prototype).
- ❑ Integration
- ❑ Thermal/mechanical analysis

FCC TS 400MHz, 1 MW MBK KlyC design

High Efficiency Klystrons

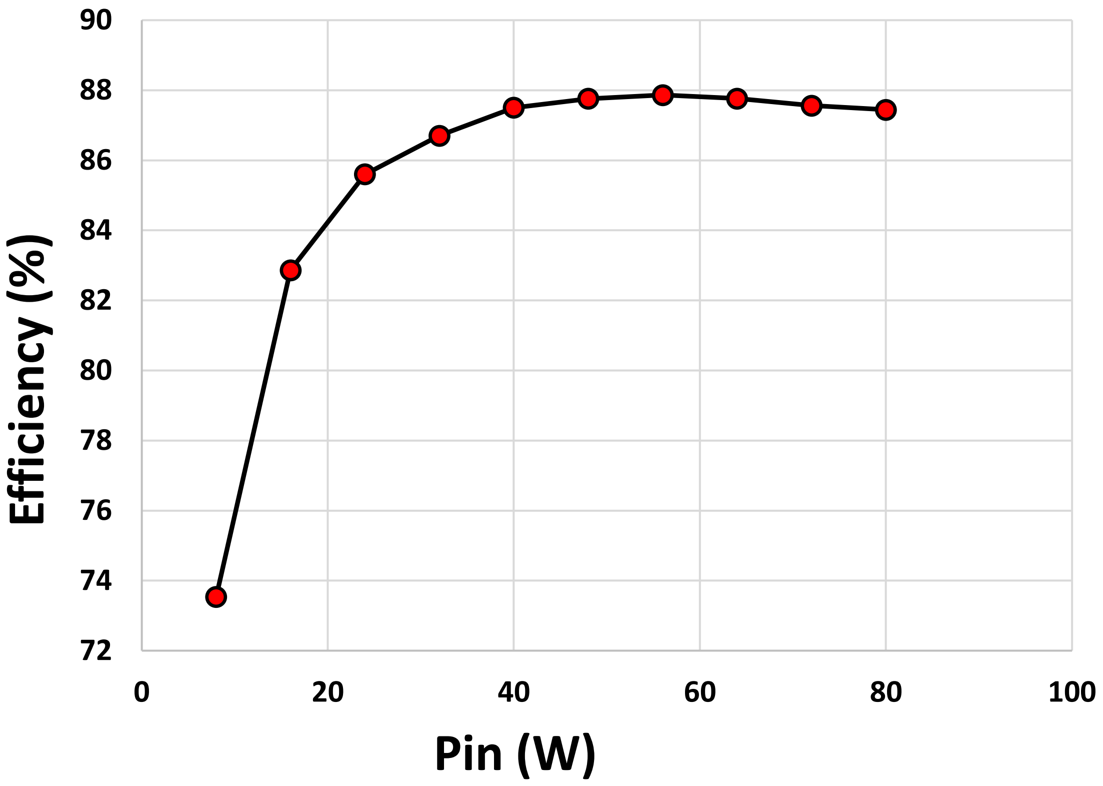
Efficiency = 87.83%



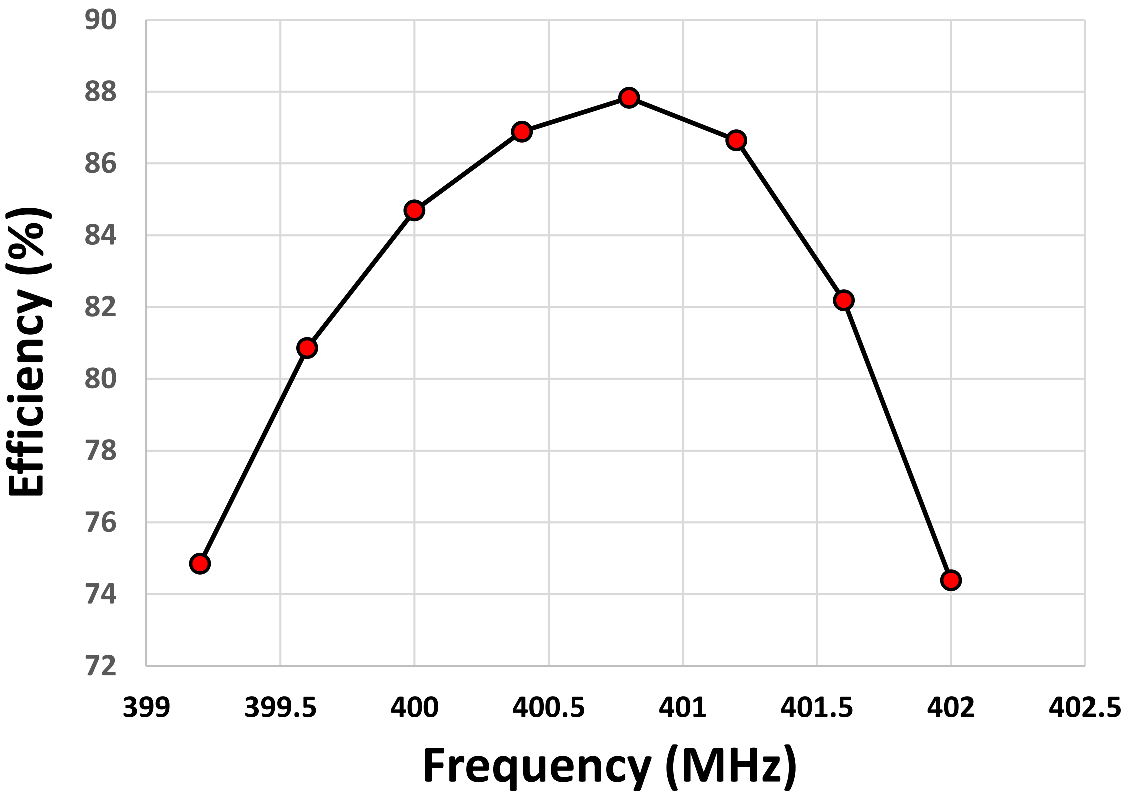


10

Power Gain Curve

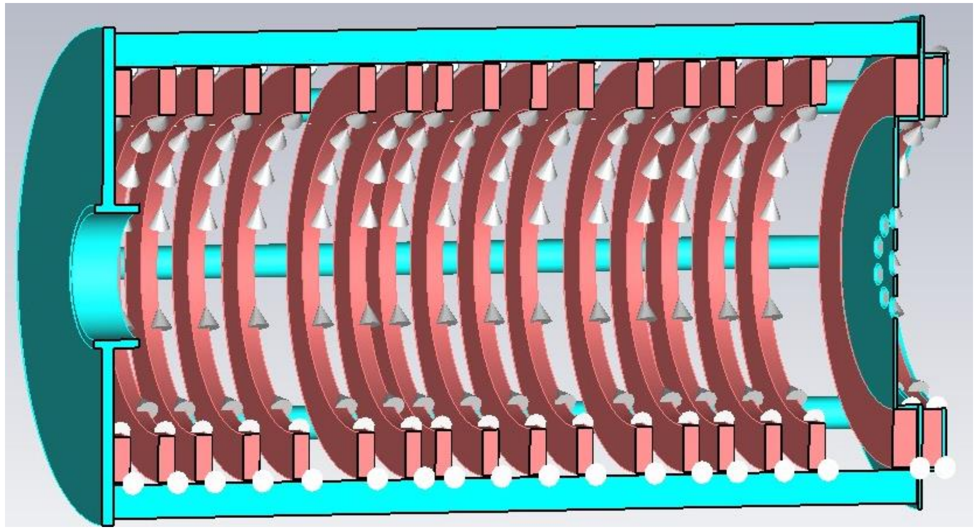


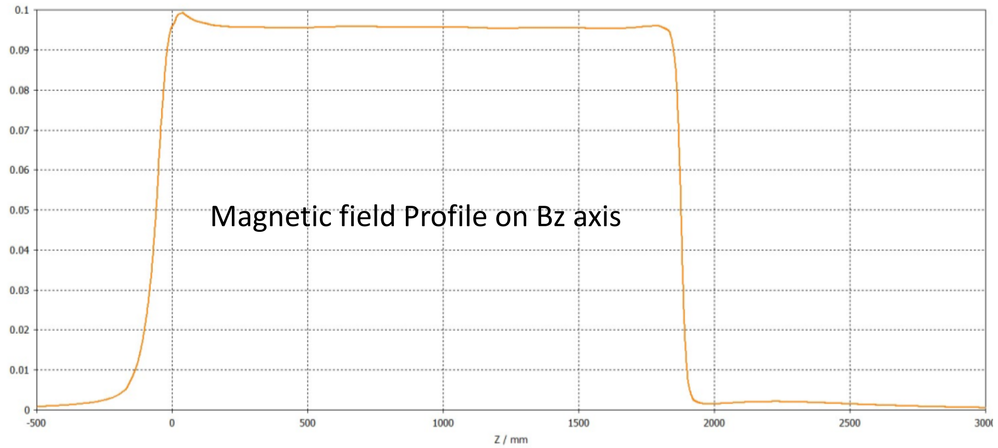
Bandwidth Curve

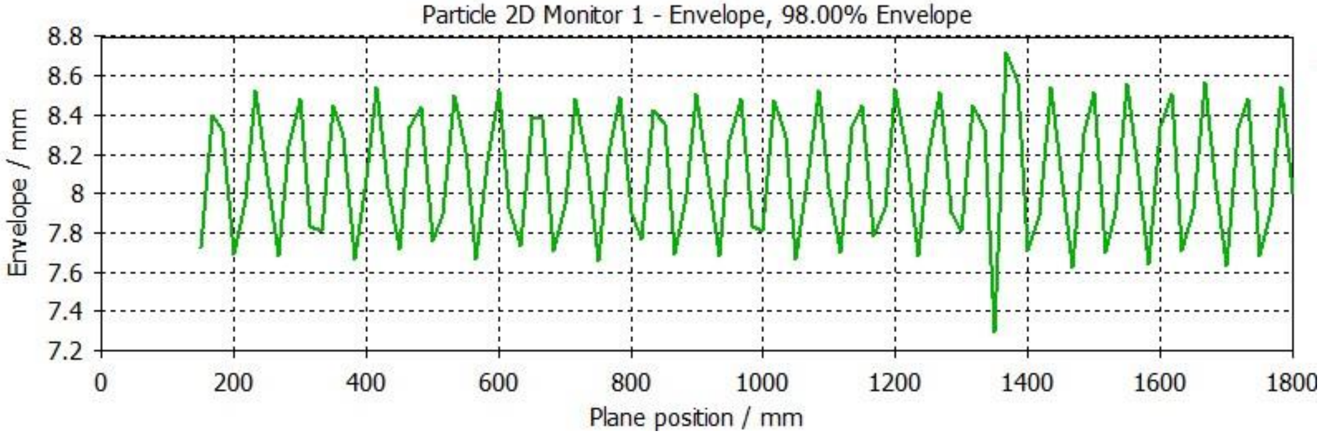


1. 10.75 kV for the first stage, 64.5 kV for the second stage, oil tank is not necessary for HV insulation.
2. -1dB bandwidth is over 3.5MHz.
3. Klystron could deliver 1.0 MW output power at 400MHz, with circuit length of 1.575 m. No instability in RF circuit were found.

TS MBK Solenoid Design



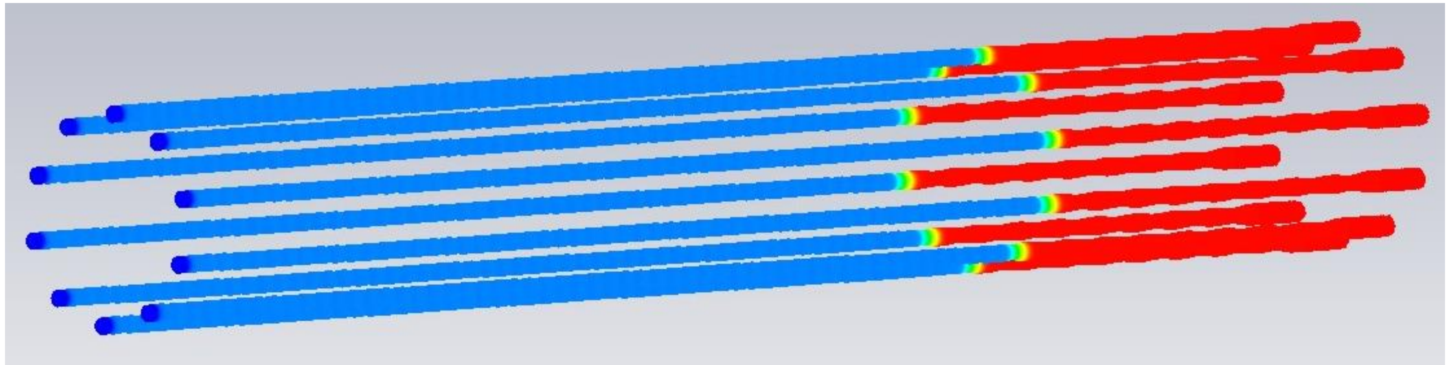


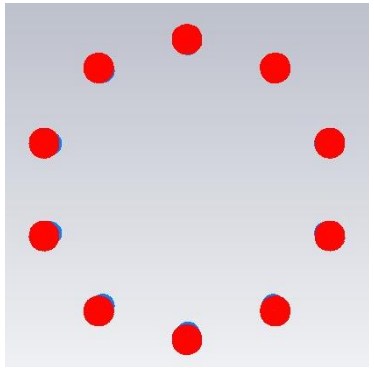


Magnetic field: Bz=5.5XBrillouin (0.095 T) for non-convergent beam optic system.

Beam envelop along the beam tunnel. Gap length is optimized to minimize the beam scalloping before and after DC accelerating gap.

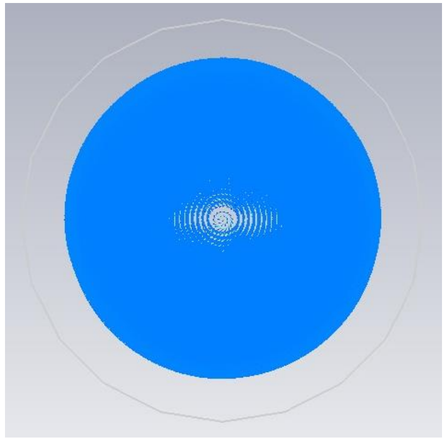
3D TRK & PIC (CST) beam optic simulations



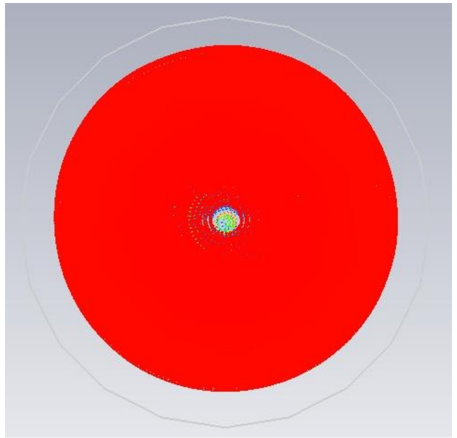


- 3D Magnetic field is imported;
- 3D effects brought by the MB topology is fully considered
- Tube is stabilized during 2000ns simulation time in PIC.
- Peak surface power losses of 500W/cm^2 were set as a target following industrial data.

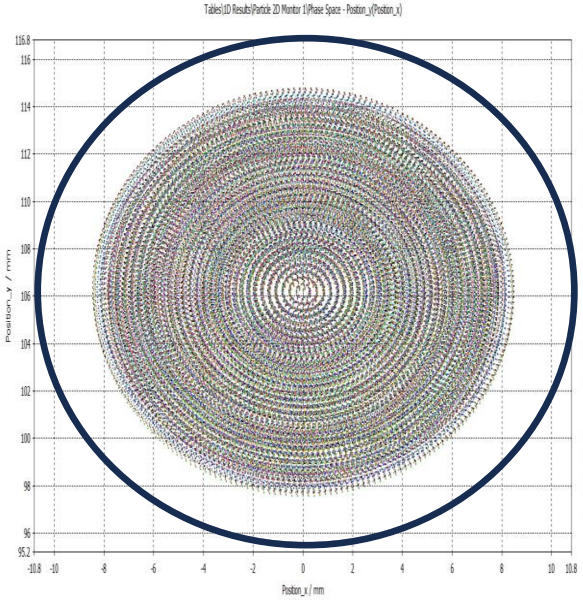
TRK

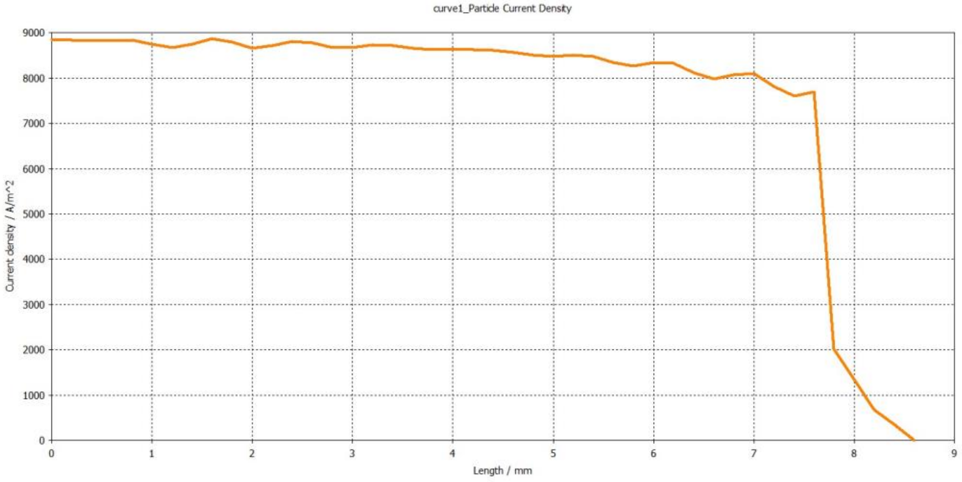


Z=600 mm



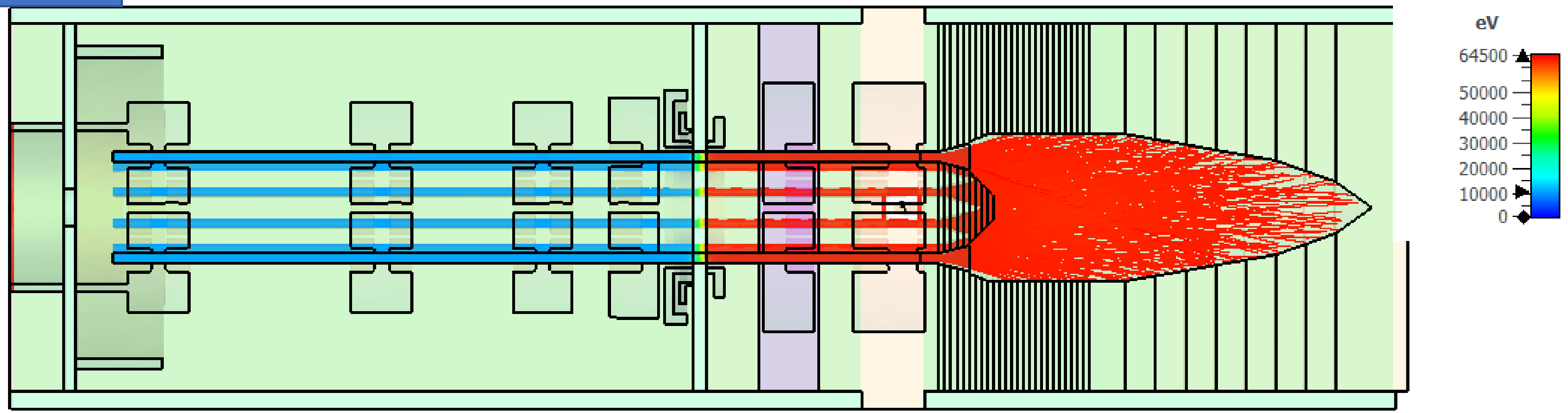
Z= 1800 mm



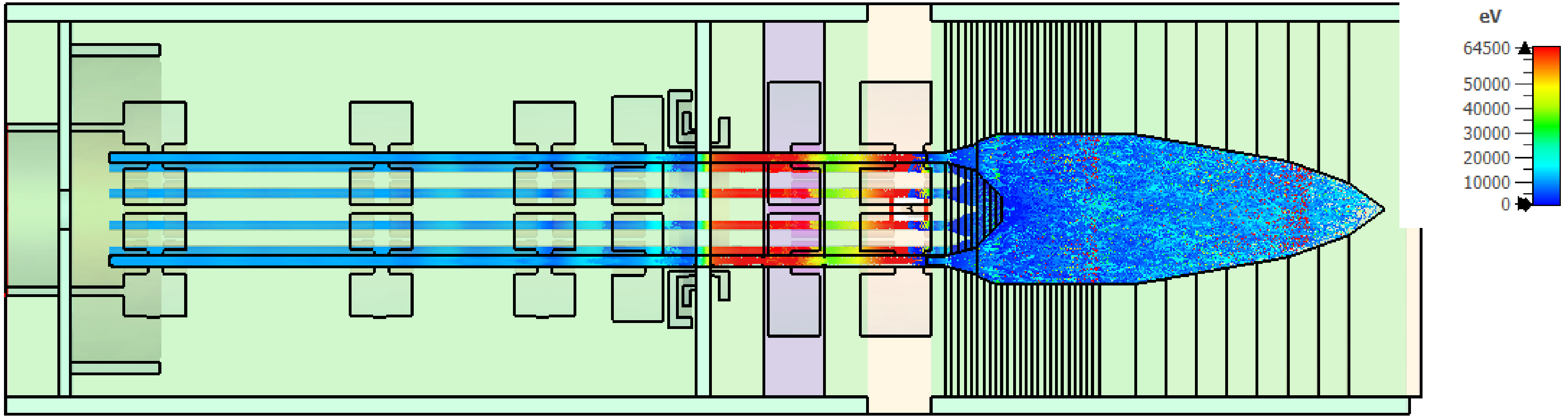


Current density at cathode 0.89 A/cm2

Without RF

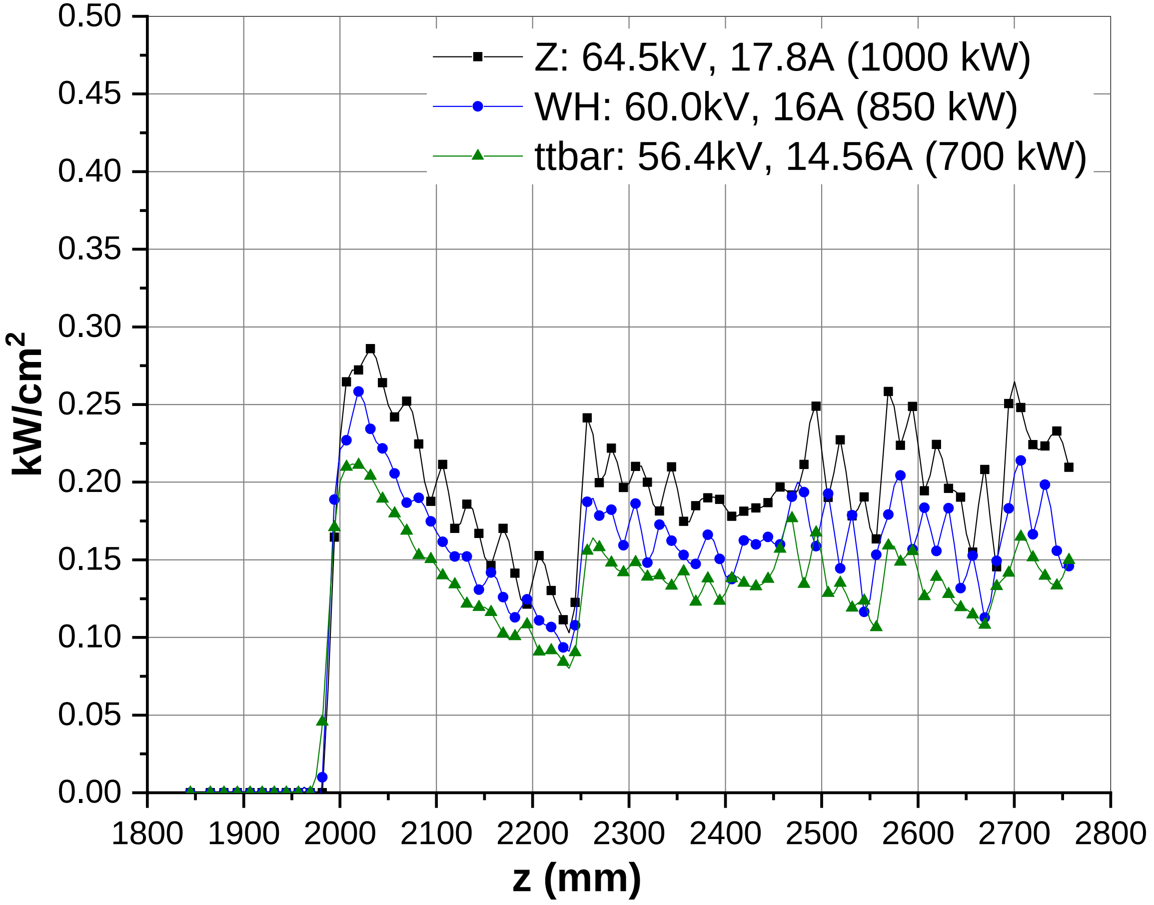


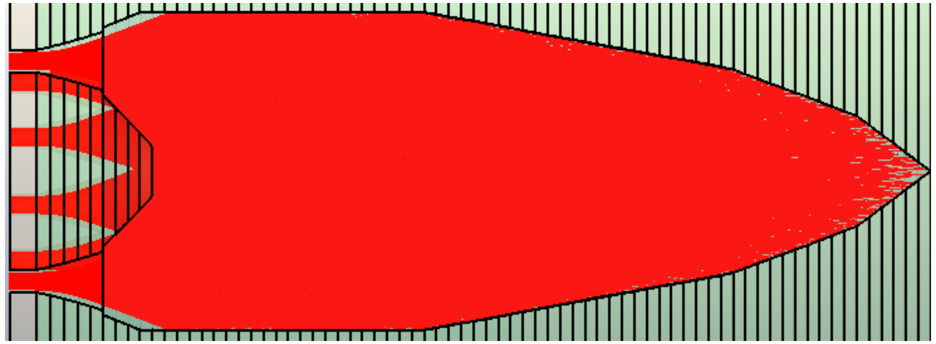
With RF



TS-Collector design for Z (1000kW), WH (850kW), ttbar (700 kW)

High Efficiency Klystrons



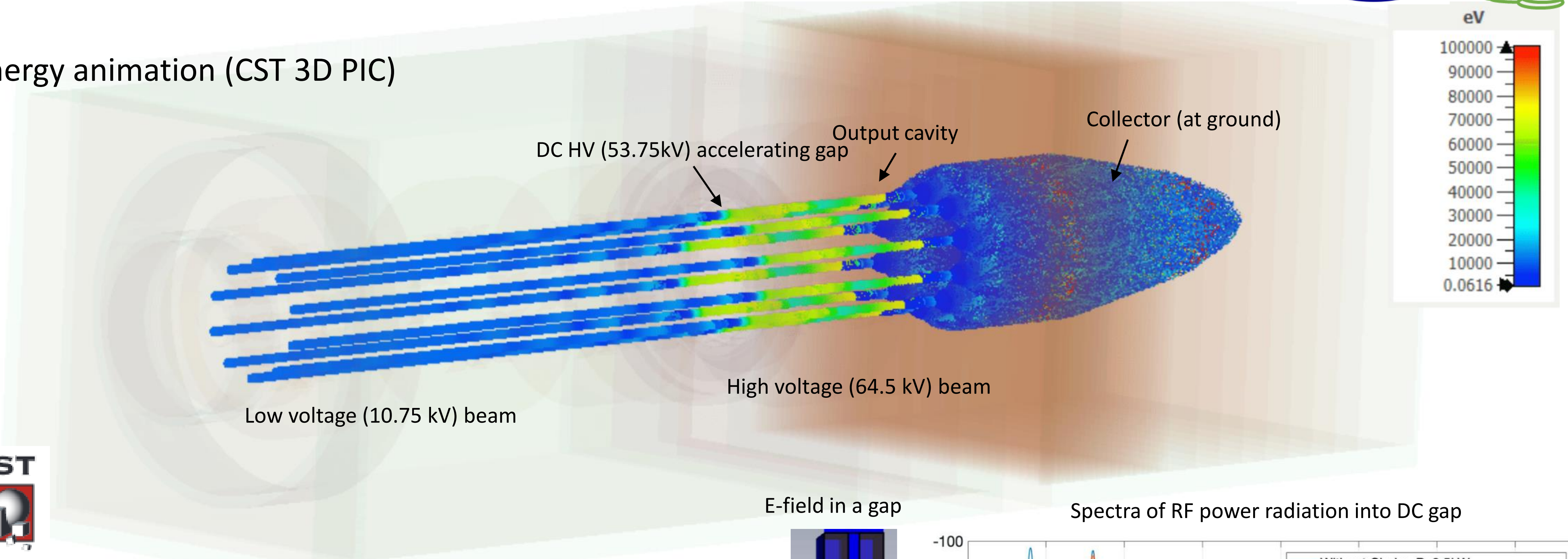


	Voltage	Current	dP/dS (max)
ttbar	56.4 kV	14.56 A	**211 W/cm²**
WH	60 kV	16 A	**258 W/cm²**
Z	64.5 kV	17.8 A	**285 W/cm²**

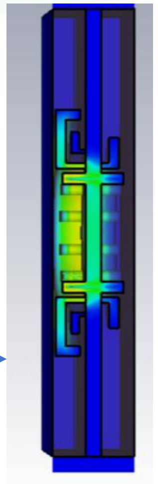
- The collector has been designed to contain power loss density < 300 W/cm² for DC operation
- The interface taper section has been designed keeping in view the pole piece location and margin for cooling channels

Full 3D PIC simulation of FCC 400 MHz, CW, 10 beams TS MBK (@1MW, 86% efficiency)

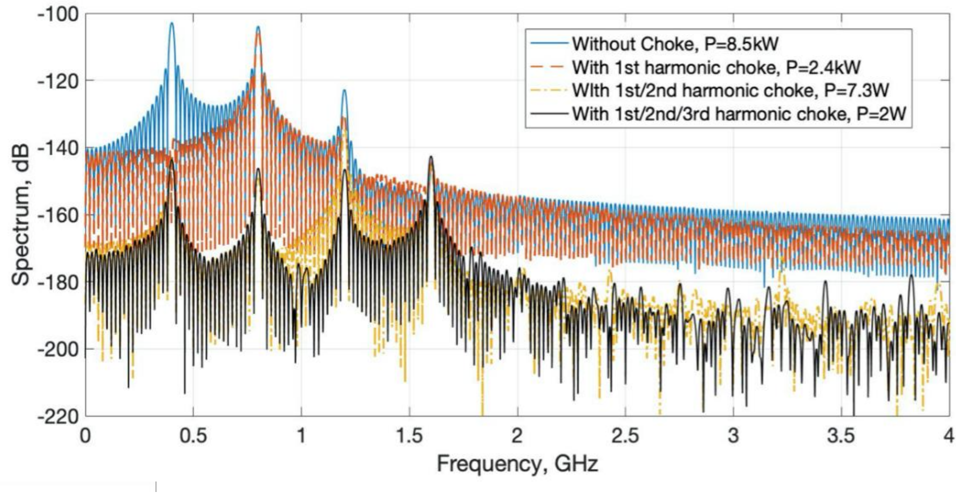
Particles energy animation (CST 3D PIC)



E-field in a gap

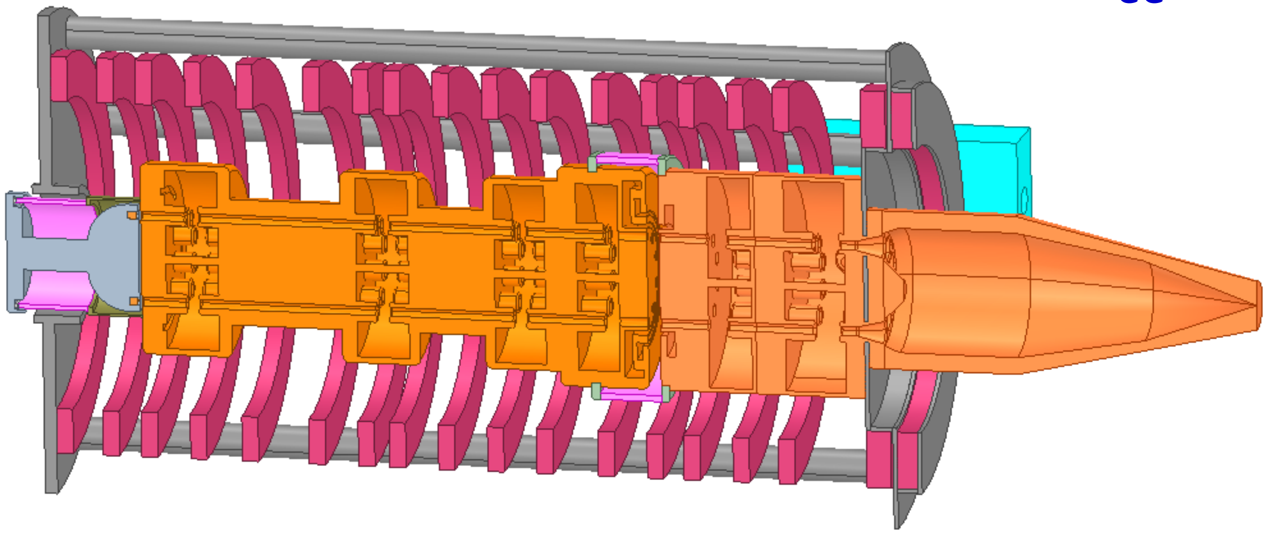


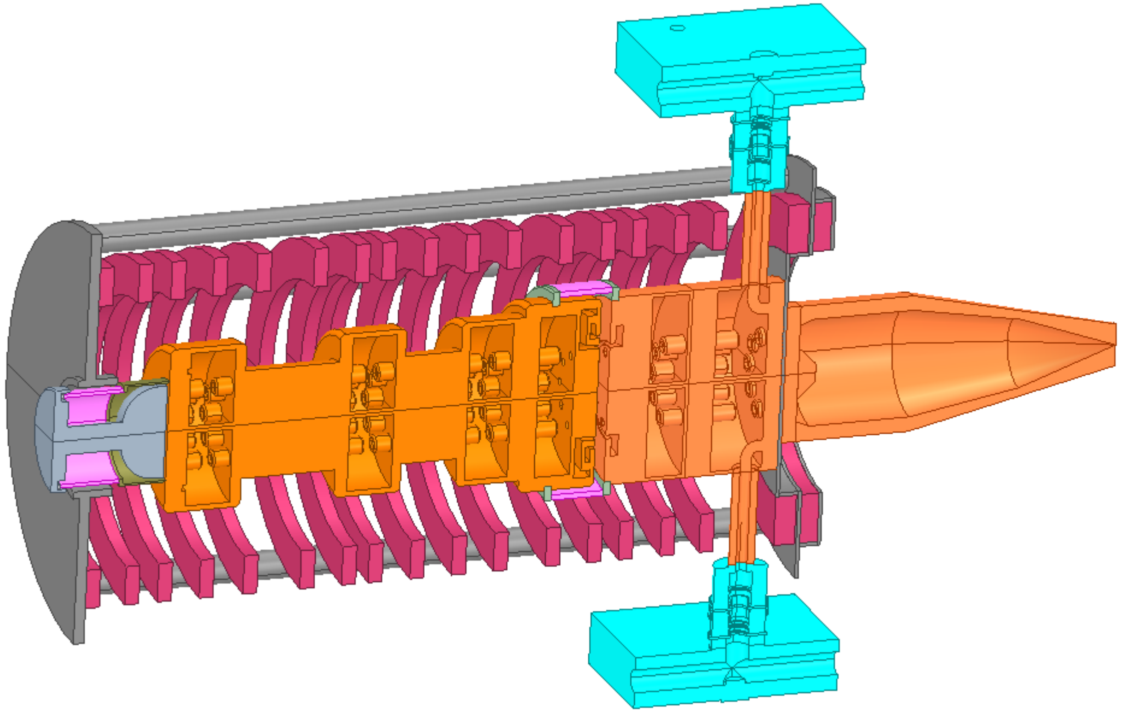
Spectra of RF power radiation into DC gap

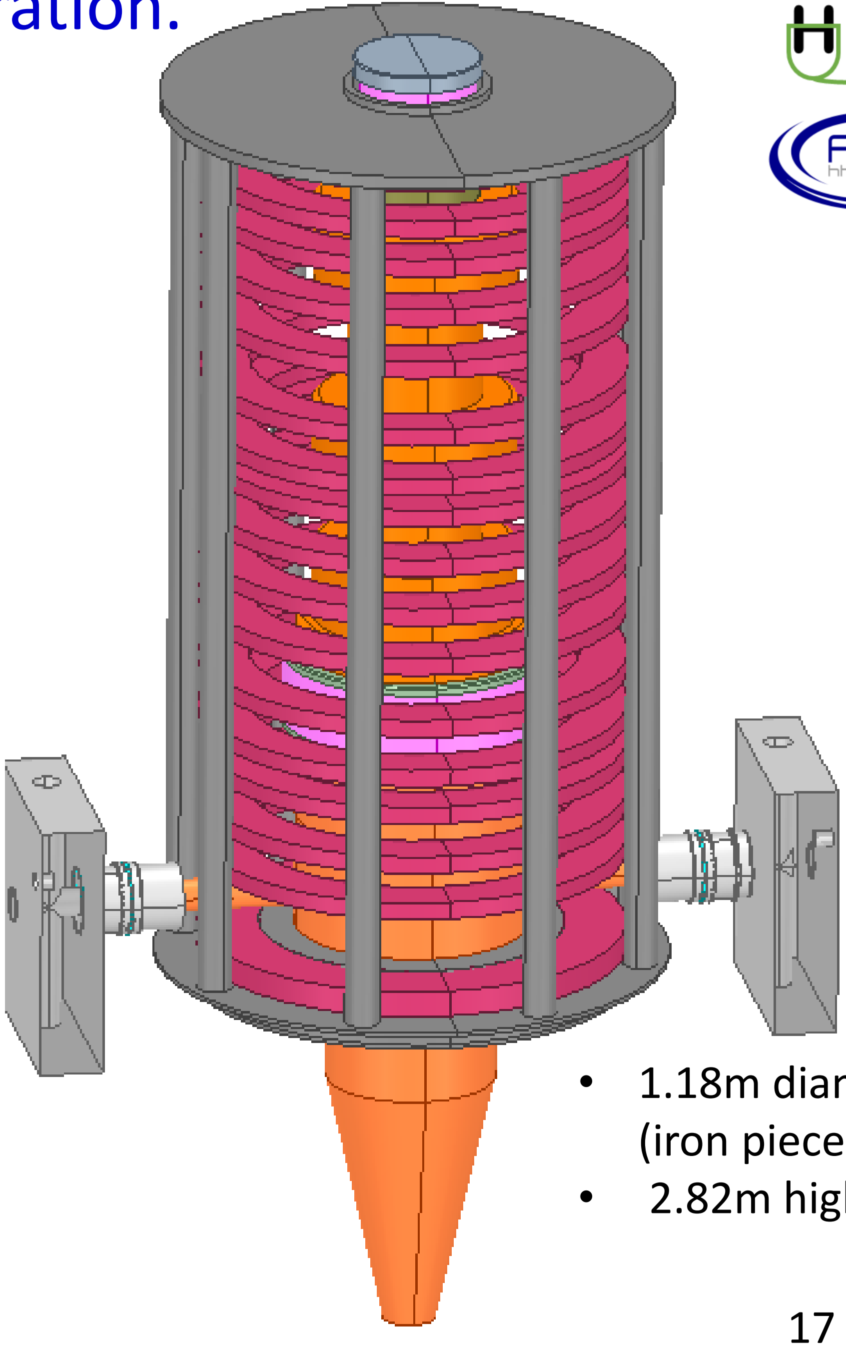


- No reflected electrons were observed at any operating voltage and/or RF power.
- Special collector design concept with low energy electrons filtering.
- RF radiation into DC gap is suppressed using set of 3 harmonic resonant rejectors (from 8.5 kW down to 2W).
- Cathode current density is 0.9 A/cm^2 @1 MW -> life-time > 100 000 hours.

400 MHz HE Two-Stages MBK for FCC_{ee}. Integration.



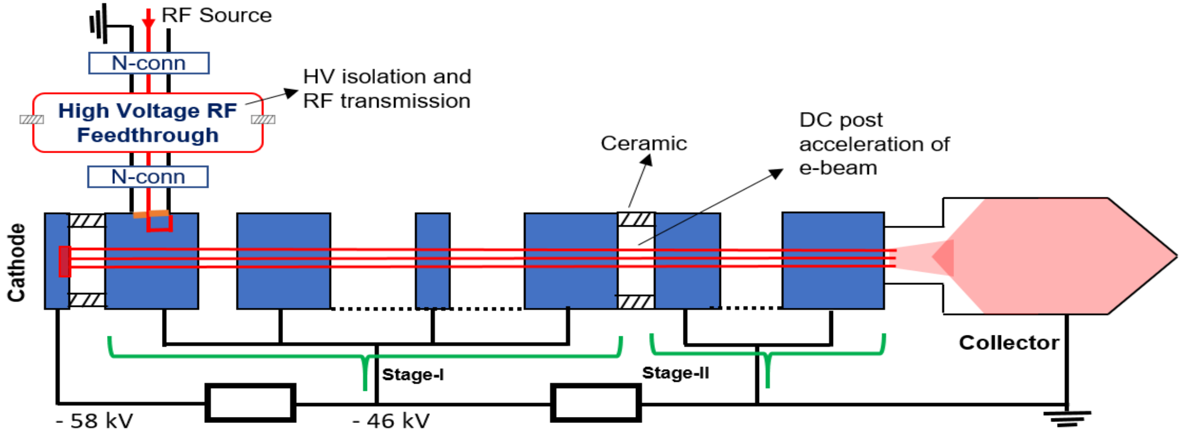


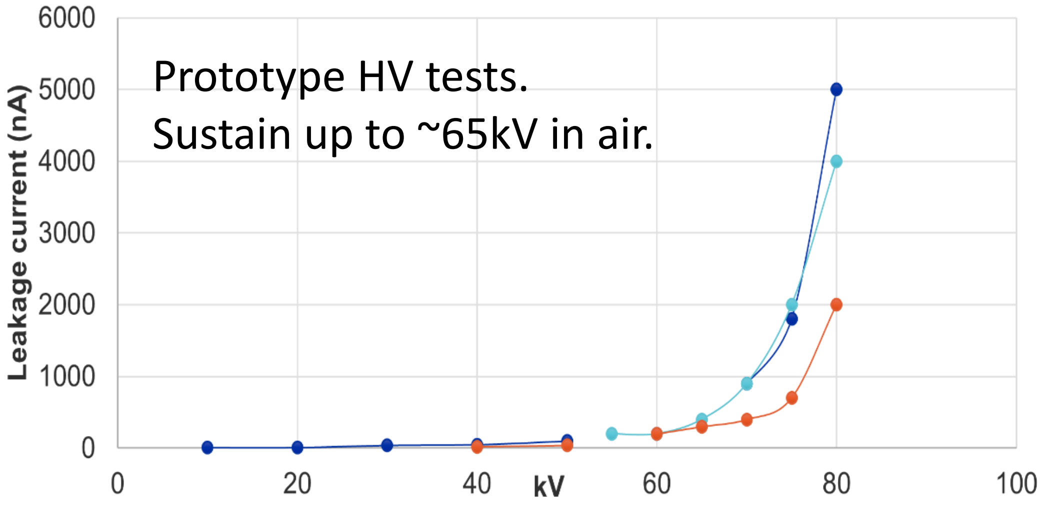


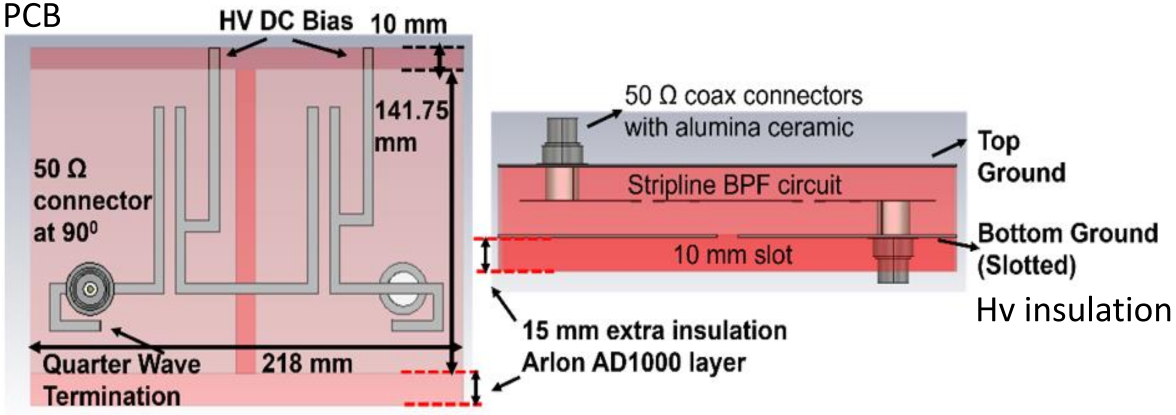
- 1.18m diameter (iron piece pole)
- 2.82m high

HV isolated RF feed-through with strip-line topology

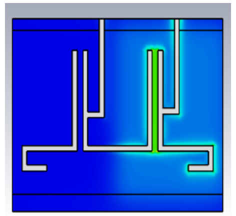
HVRFT is a special device which has to protect the klystron's RF driver from the biasing voltage of the first stage (~50kV) and to enable efficient RF transmission of the driving RF signal (~100W) into the input cavity.

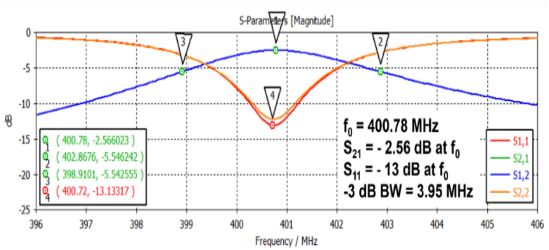




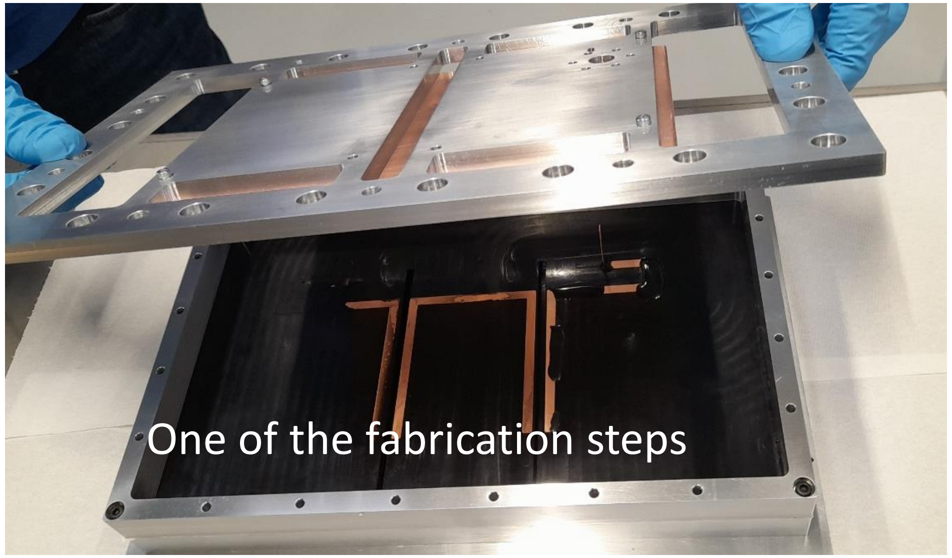


(HV)

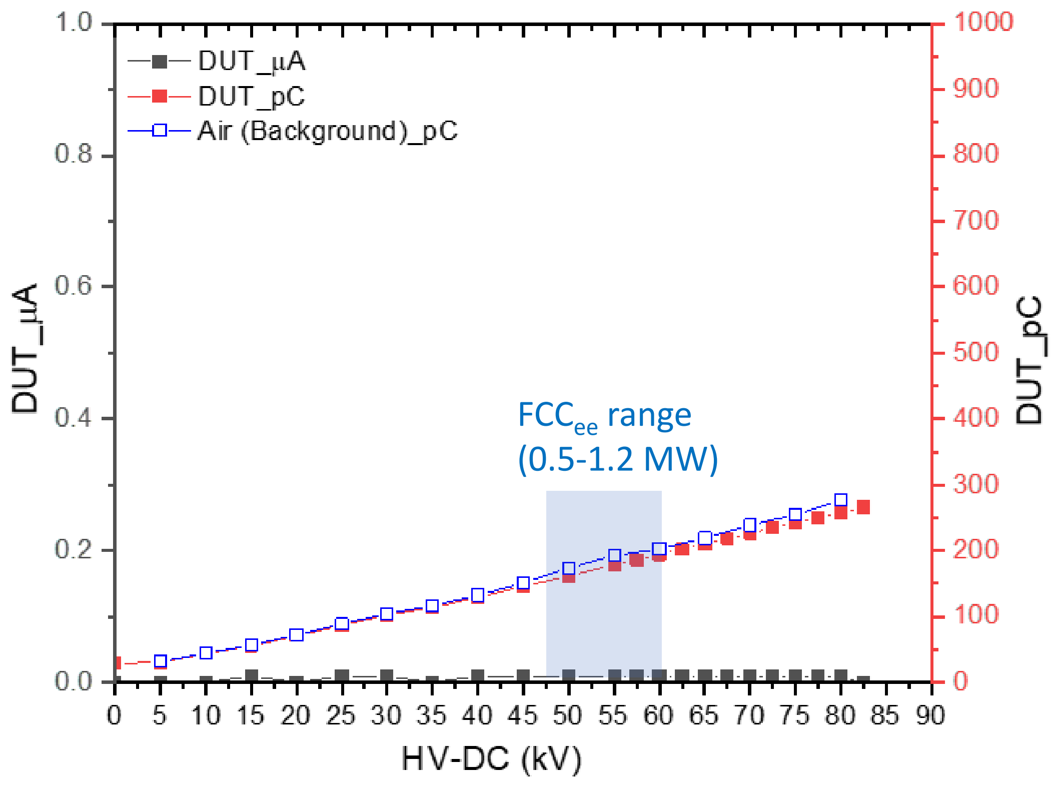


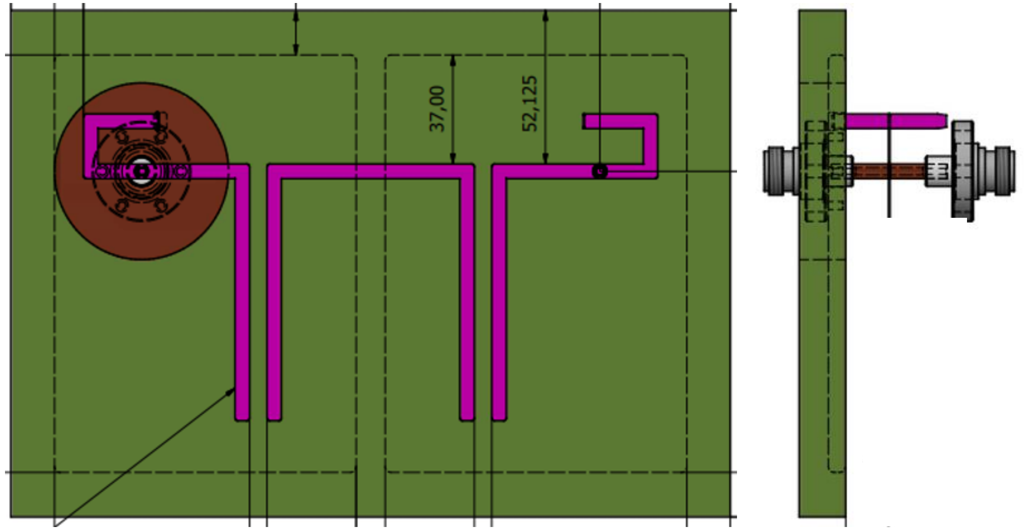


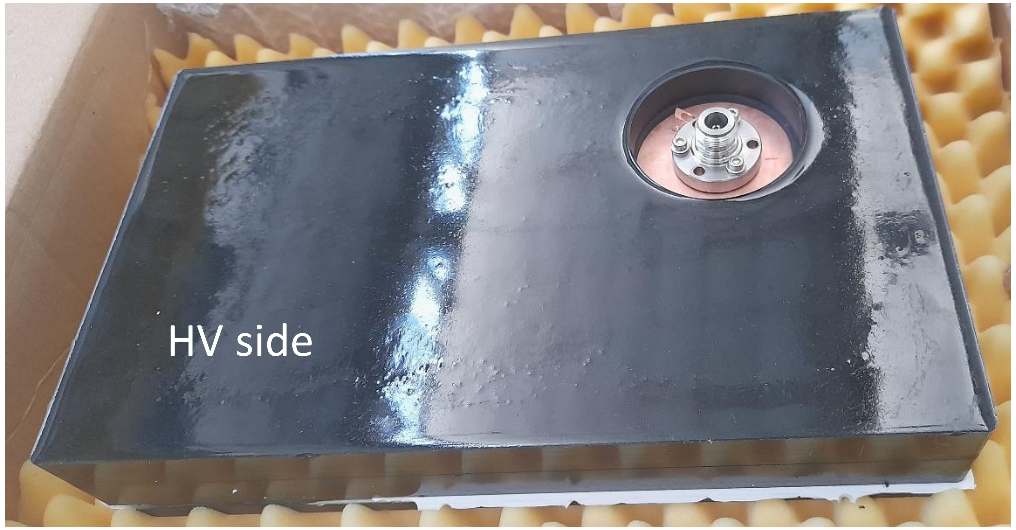
(RF)



High Voltage **isolated** RF feedthrough (HVRFT) prototype. Original CERN's strip-line based concept.



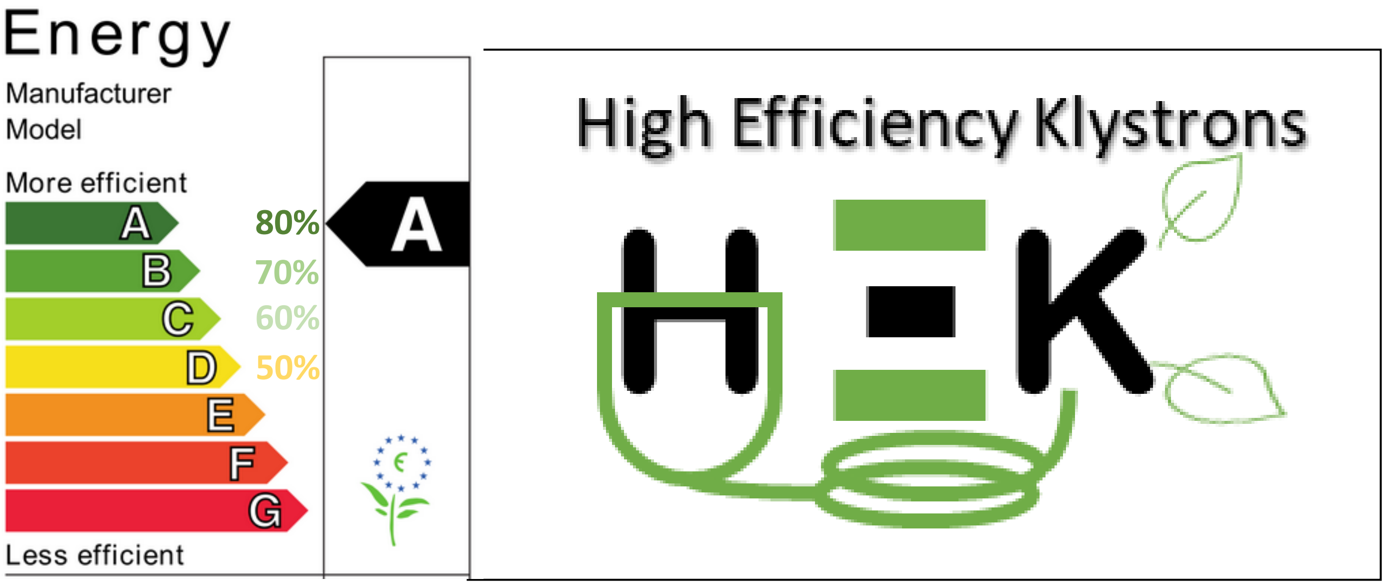




HVRFT is a specialized RF circuit that allows to isolate RF pre-amplifier from the biased voltage of the klystron's 1st stage, whilst maintaining good RF transmission.

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.
- Thermal Analysis will be done in future.



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