Two Stage High Efficiency Klystron for FCC-ee

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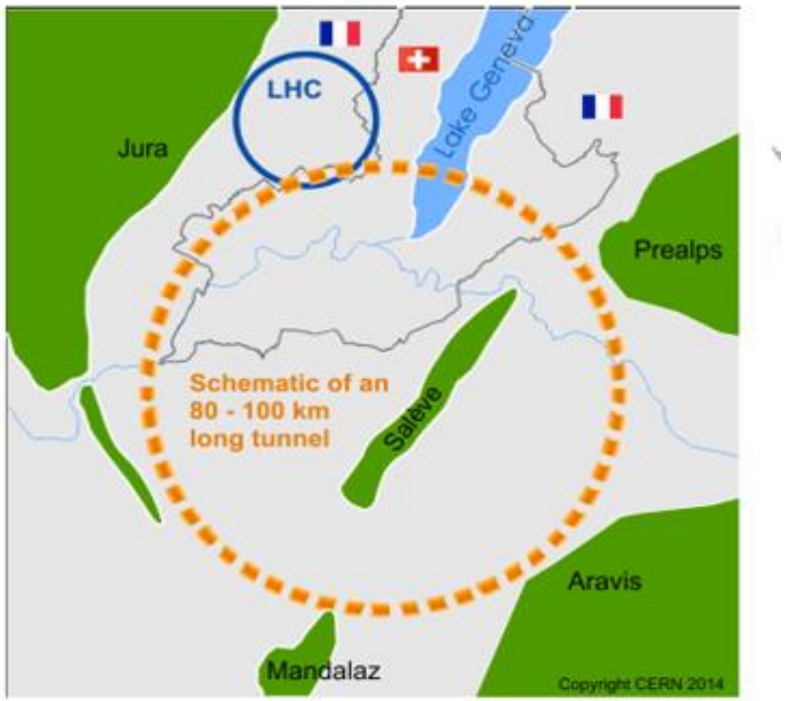
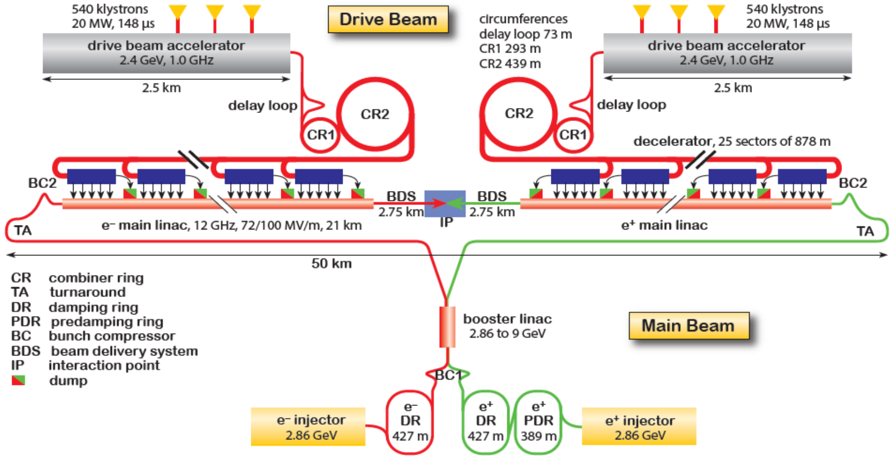
2021/6/30

Average RF power needs of the large-scale HEP Accelerators Studies.



FCC ee: CW, 0.4/0.8 GHz, P_{RF} total= 105 MW



3.0 TeV CLIC^{e+e-} ; pulsed, 1.0 GHz, P_{RF} total = **180 MW**

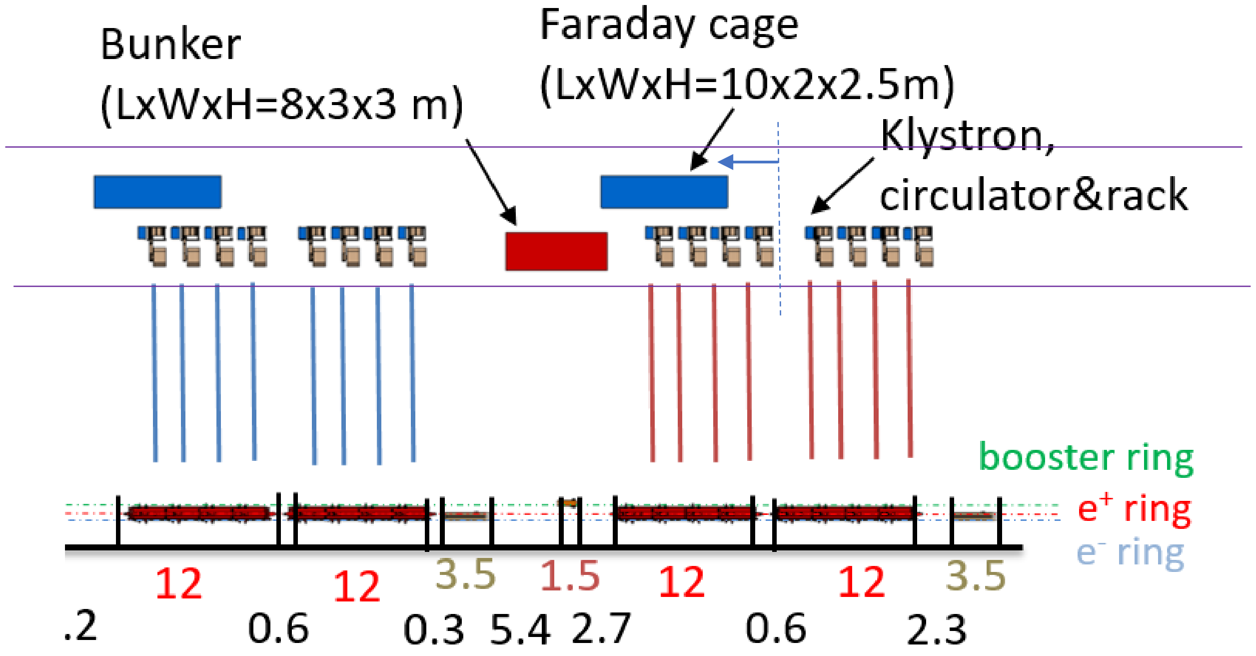
The klystron efficiency impact on the FCC power consumption.
Example of the efficiency upgrade from existing 70% to 85%.

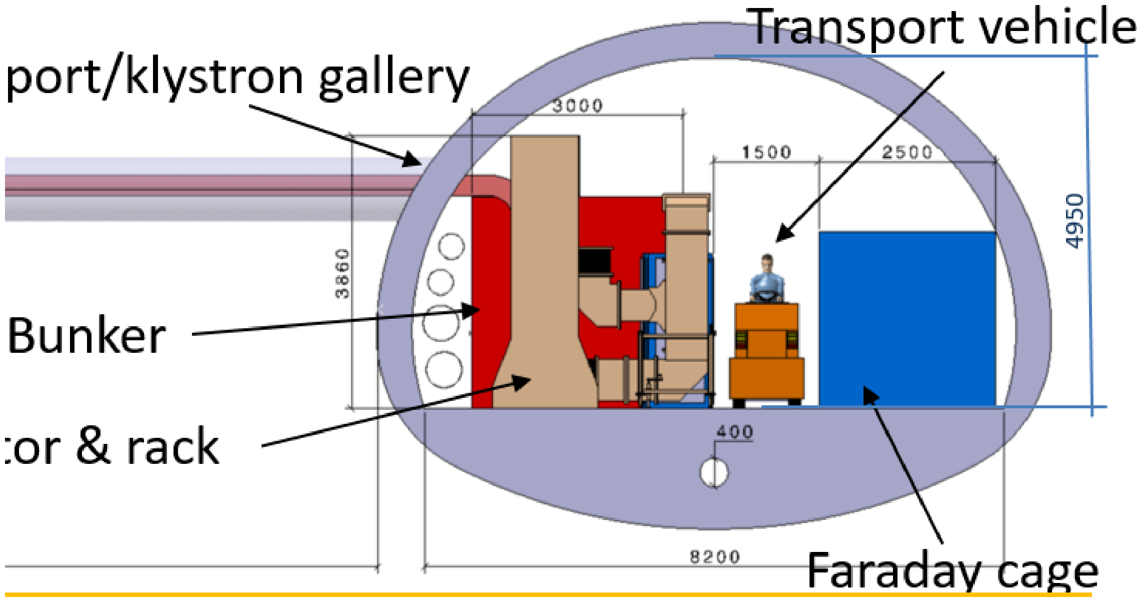
	Klystron eff. 70%	Klystron eff. 85%	Difference
RF power needed for 3TeV CLIC	105 MW		
DC input power	150MW	131MW	-19MW
Waste heat	45MW	26MW	-19MW
Annual consumption (5500 h assumed)	825 GWh	720.5GWh	-104.5 GWh
Annual cost (60 CHF/MWh assumed)	49.5 MCHF	43.2 MCHF	-6.3 MCHF
Electricity installation dimensioned for	150MW	131 MW	-13%
CV installation dimensioned for	45 MW	26 MW	-42%

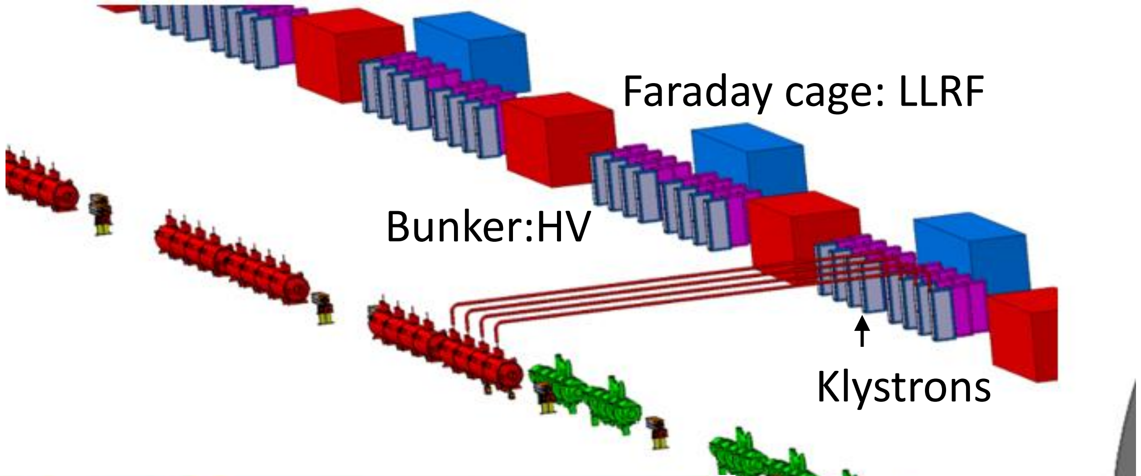
From Erk Jensen

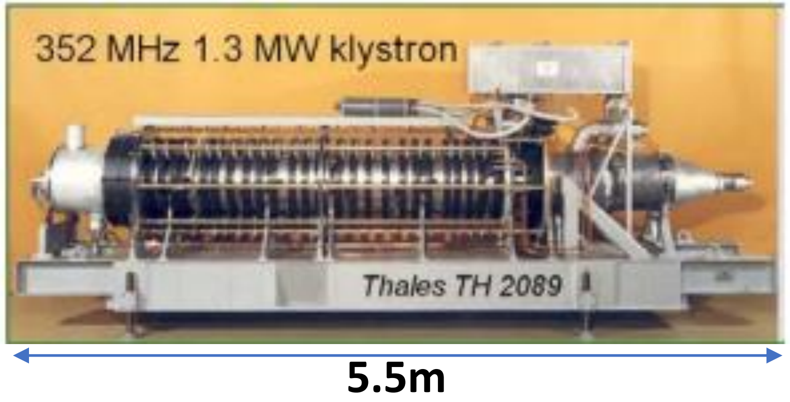
- Potential saving are 1.04 TWh in 10 years (**63 MCHF in 10 years**).
- Reduced environmental impact (cooling and ventilation)
- Reduced installation cost (stored energy in modulators).
- Reduced maintenance cost (klystron life time).

R&D on increasing the useable efficiency is worth every penny/cent invested!









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

1. Each Klystron should deliver at least 1MW @ 400MHz.
2. Klystron should be placed vertically in the tunnel.
3. The total length of Klystron should be less than 3m.
4. The efficiency of Klystron is targeted at 80%.
5. The referred Klystron with similar specs will be too big!
6. New technology should be used for the compact design.

Two-Stage Multi Beam Klystron (TS MBK) technology.

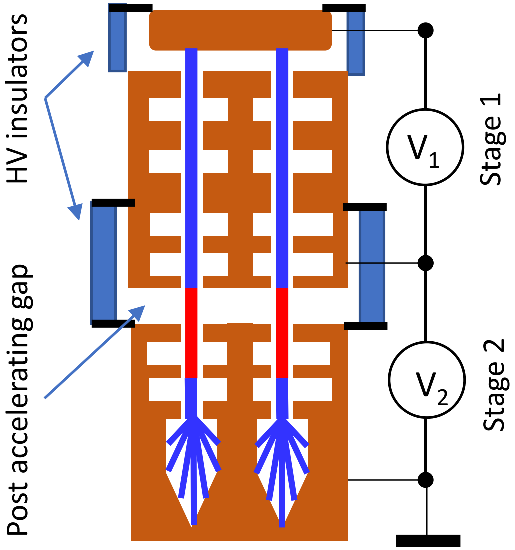
Specific features

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.**

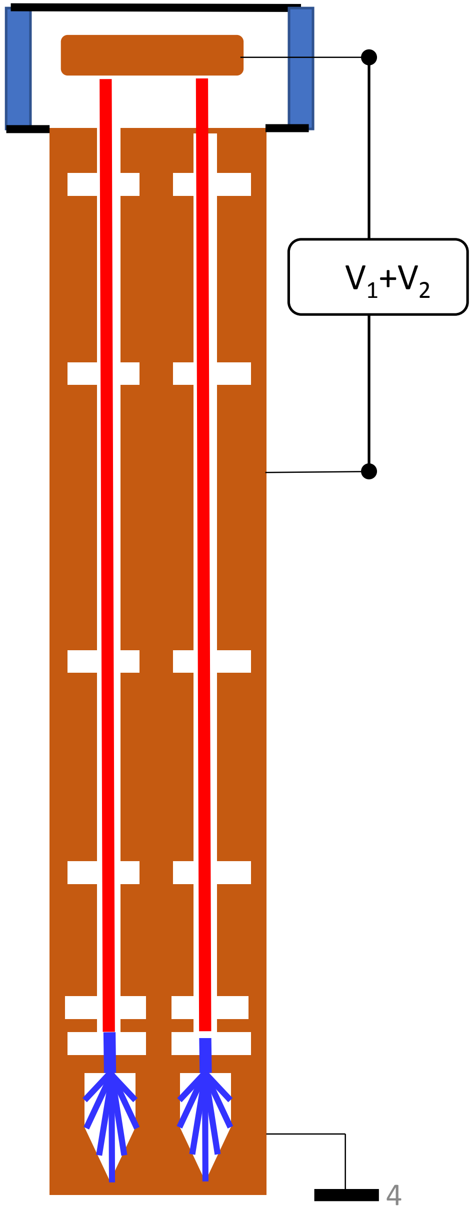
Additional advantages:

1. The second HV stage can be operated in DC mode. Thus simplifying the modulator topology (cost/volume) and increasing the modulator efficiency (in pulsed mode).
2. Simplified feedback for the first stage pulsed voltage. Improved klystron RF phase and amplitude stability.
3. Gap's accelerating DC voltage is a natural barrier for reflected electrons. Improved tube stability.

TS HE MBK
Efficiency 85%



Commercial HE MBK
Efficiency 70%



Home-made codes for HE Klystron development

KlyC (v5): Large signal 1/1.5D klystron simulator.

1/1.5D Beam-wave interaction module[1].

Beam dynamic simulation (single beam and MBK [7]).

Electro-Magnetic module [1].

RF eigenmode and eigenfield solver in the arbitrary axisymmetric RF cavities. 2D field maps. Enables E-field maps import from HFSS and CST.

Coupled cavities module [2].

Special EM simulator of the coupled cavities with or without external loading. Coupled eigen frequencies and 2D field maps.

Monotron oscillations module [3].

Simulates the threshold of monotron oscillations in the RF cavities (klystron stability issueS)

Klystron optimizer module [1].

Allows versatile optimization of the klystrons within specified condition.

Parameters scaling module [4].

Allows internal scaling with changing the frequency, beam power and perveance.

Bunched beam generator module[5].

Simulation of IOT and output couplers with bunched beam

Design report module.

Generates various tables, graphs and animations to analyze the device performance.

Service functions. Automatic simulation of the power gain and bandwidth curves, arrival functions, reflected electrons absorber, batch mode and more…

CGUN: electron beam tracking

Electrostatics module.

Simulates DC E-field maps and potentials in the 2D system with arbitrary shaped electrodes. Can be used in KlyC (***TS MBK for example*** [6]).

Magnetostatics module.

Simulates DC B-field maps in the 2D system with arbitrary shaped coils and iron shields (saturation etc.)

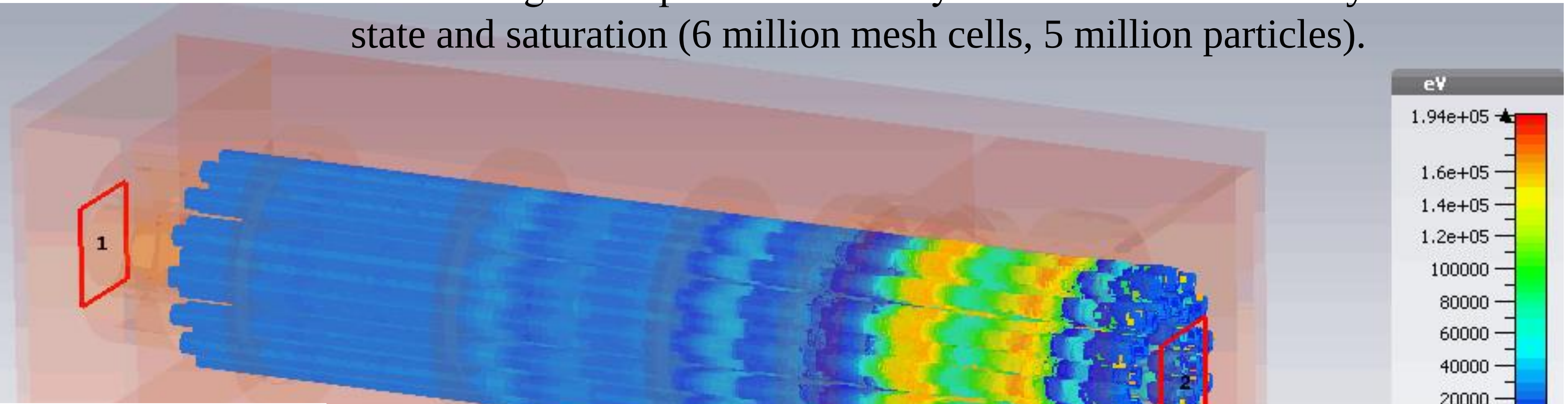
Electron beam tracking module [7].

- Simulates the cathodes with space charge limit.
- Electrons tracking (trajectories) in the calculated B field (beam scalloping etc).
- Simulates collector in DC mode and RF mode using the spent beam energy spectra simulated in KlyC.
- Ultimately, A-Z beam tracking in entire device.

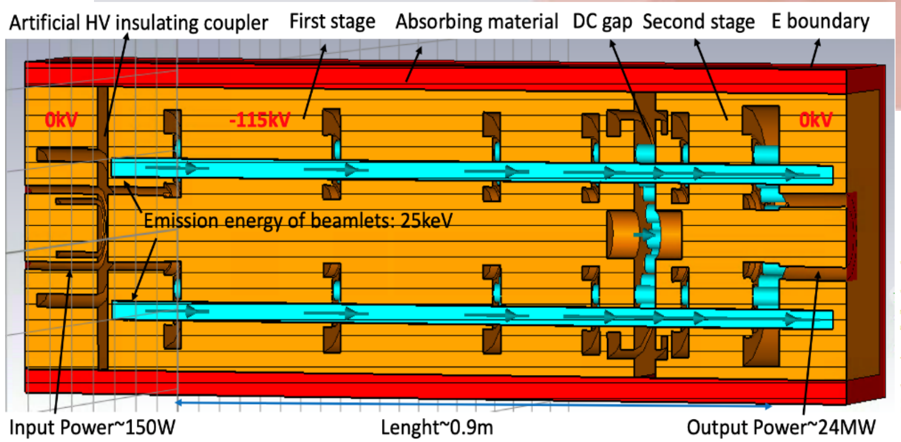
[1] J. Cai, I. Syratchev, 'KlyC: 1.5-D Large-Signal Simulation Code for Klystrons', IEEE Transactions on Plasma Science (Volume: 47 , Issue: 4 , April 2019)
[2] J. Cai, I. Syratchev 'Modelling of Coupled Cell Output Structures for the Klystrons', IEEE Transactions on Electron Devices (Volume: 66 , Issue: 11 , Nov. 2019)
[3] J. Cai, I. Syratchev, G. Burt 'Accurate Modeling of Monotron Oscillations in Small- and Large-Signal Regimes', IEEE Transactions on Electron Devices (Volume: 67 , Issue: 4 , April 2020))
[4] J. Cai, I. Syratchev, 'Scaling Procedures and Post-Optimization for the Design of High-Efficiency Klystrons', IEEE Transactions on Electron Devices (Volume: 66 , Issue: 2 , Feb. 2019)
[5] Z. Liu, et al, 'Study on the efficiency of Klystrons', IEEE Transactions on Plasma Science(Volume: 67 , Issue: 7 , April. 2020)
[6] J. Cai, I. Syratchev 'Modelling and technical design study of Two-stage Multibeam Klystron for CLIC', IEEE Transactions on Electron Devices (Volume: 64 , Issue: 8 , August 2020)
[7] J. Cai, I. Syratchev, G. Burt 'Design study of a High-Power Ka-band HOM Multibeam Klystron', IEEE Transactions on Electron Devices (Volume: 67 , Issue: 12 , December 2020)

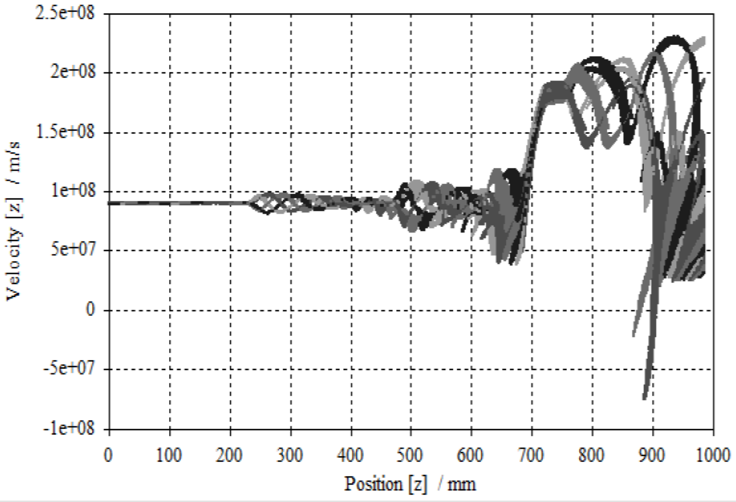
Example I.

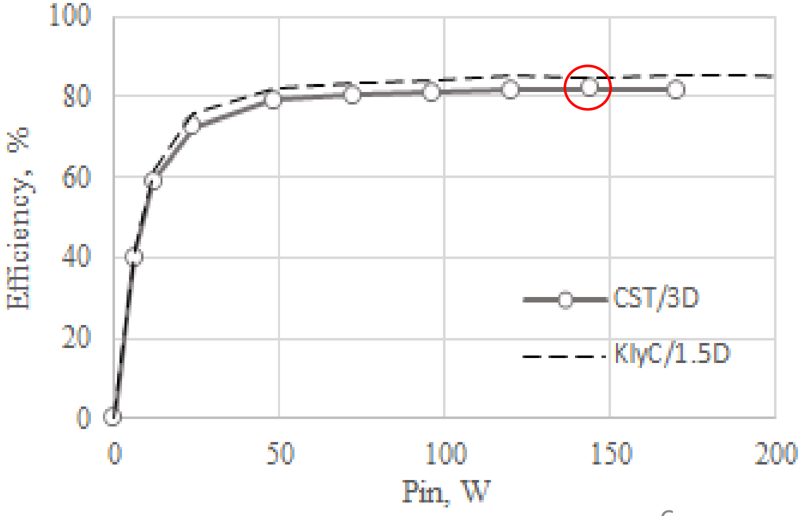
High Efficiency 24 MW, 1 GHz, CLIC TS MBK. Full PIC CST/3D simulations



Rendering of the particles' velocity modulation in the steady state and saturation (6 million mesh cells, 5 million particles).







The record high efficiency of 82% is achieved in 3D PIC without post optimisation (~3% (+) still in reserve).

Example I.

High Efficiency 24 MW, 1 GHz, CLIC TS MBK performance summary (PIC CTS/3D)

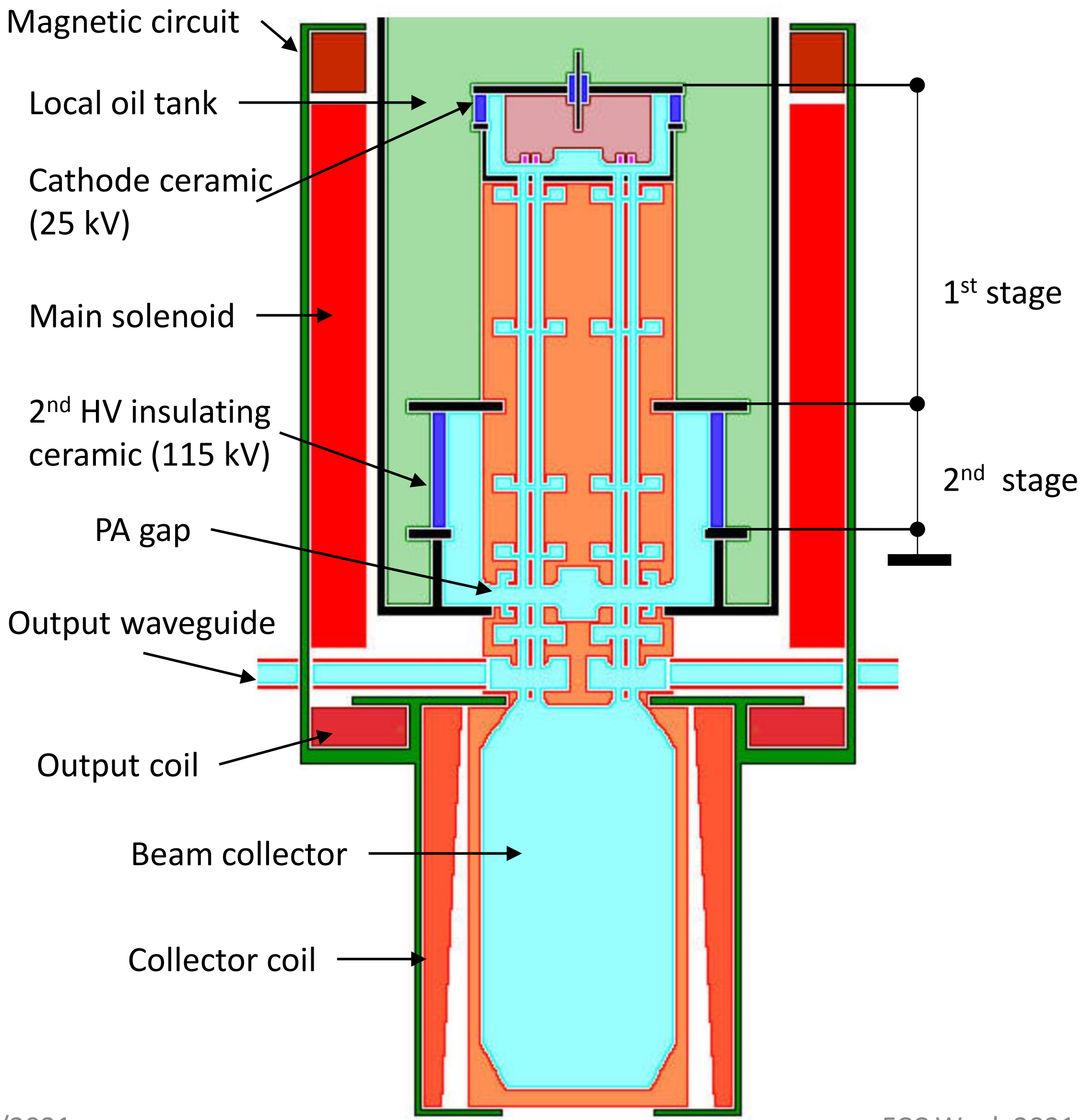
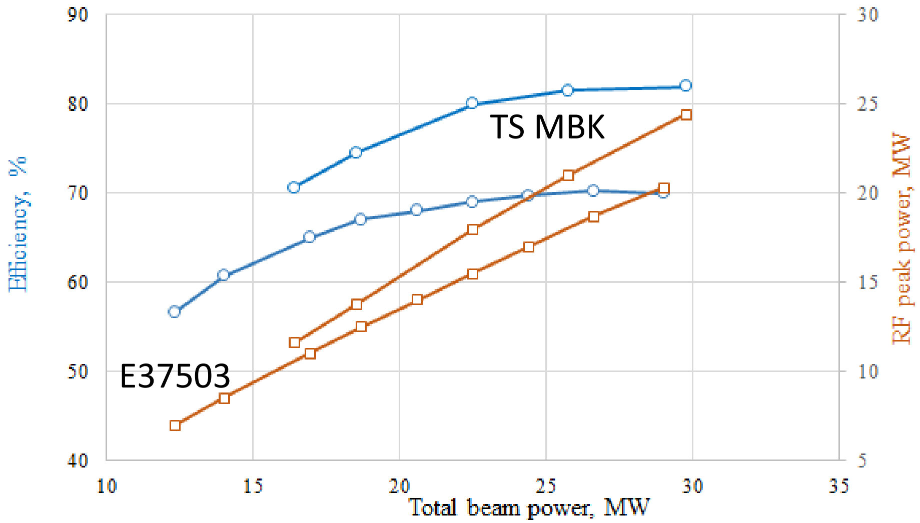


TABLE I. DESIGN AND SIMULATED PARAMETERS (CST/3D) OF THE CLIC TS MBK AND CANON MBK E3750 CATALOGUE DATA

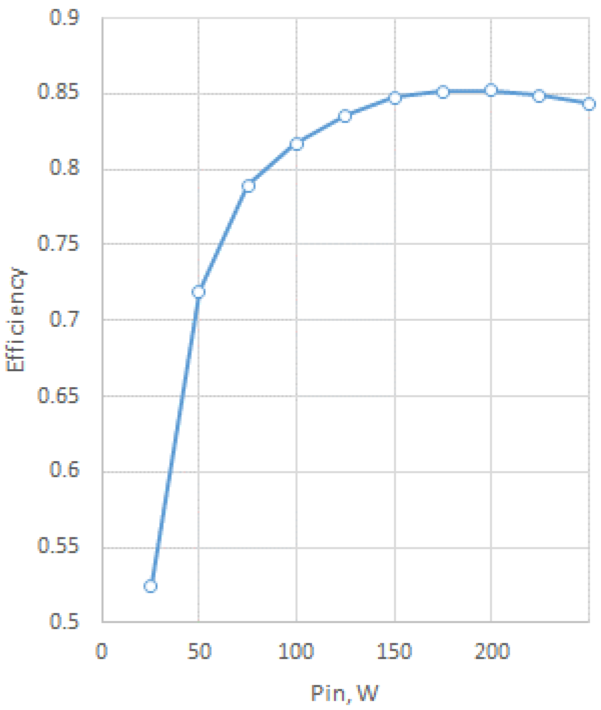
Parameter	TS MBK	E37503	Unit
Operating frequency	1000	1000	MHz
Voltage at the 1st stage	25	160	kV
Voltage at the 2nd stage	140		
Total beam current	212	180	A
Number of beamlets	30	6	
Number of cavities	6	6	
Perveance at the 1st stage	1.77	0.47	µA/V$^{3/2}$
Perveance at the 2nd stage	0.133		
Output RF power	24.1	20	MW
Saturated power gain	52	54	dB
Saturated efficiency	82	70	%
Length of RF circuit	900	1500	mm

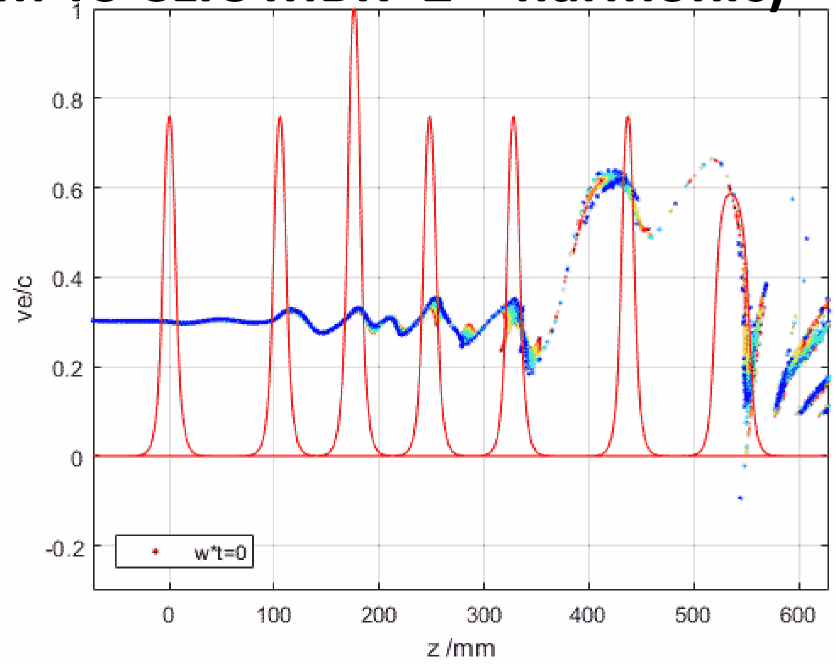


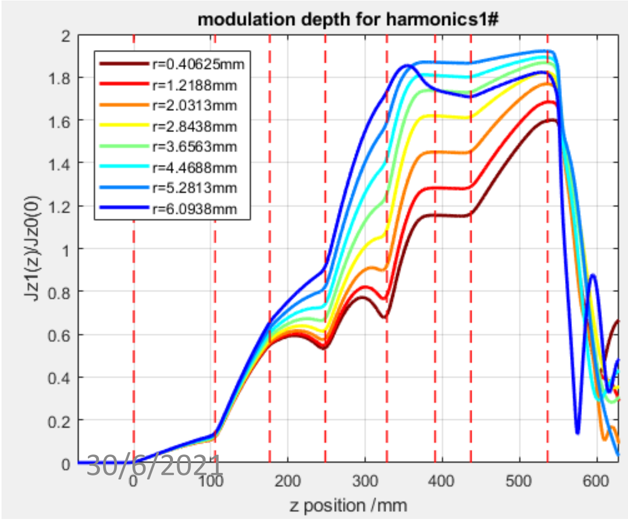
Example II.

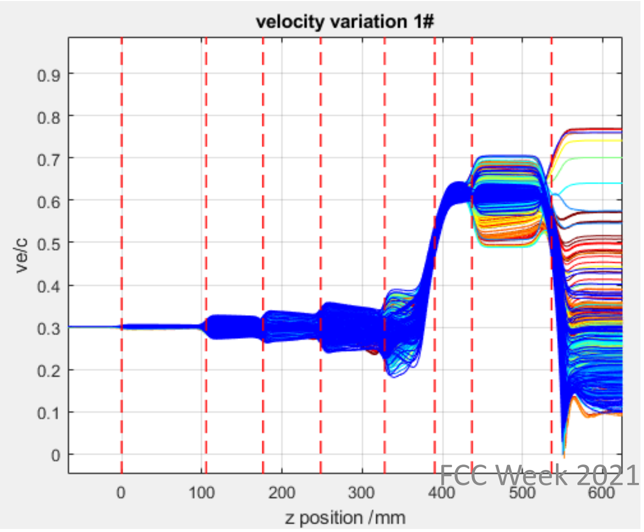
High Efficiency 10 MW, 1.3 GHz, ILC TS MBK (scaled from TS CLIC MBK+2nd harmonic)

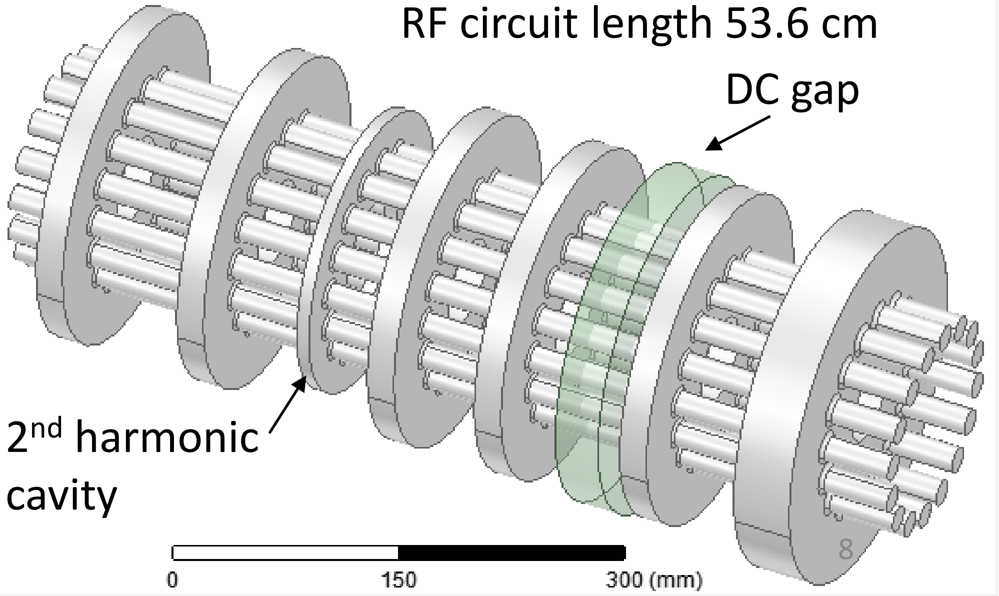
Parameter	TS MBK	E37536	Unit
Operating frequency	1300	1300	MHz
Voltage at the 1st stage	25	118.8	kV
Voltage at the 2nd stage	140		
Total beam current	88	129.5	A
Number of beamlets	16	6	
Number of cavities	7	6	
Perveance at the 1st stage	1.68	0.53	μA/V$^{3/2}$
Perveance at the 2nd stage	0.105		
Output RF power	**10.5**	**10**	MW
Saturated power gain	47.2	48.2	dB
Saturated efficiency	**85**	**65**	%
Length of RF circuit	536	---	mm









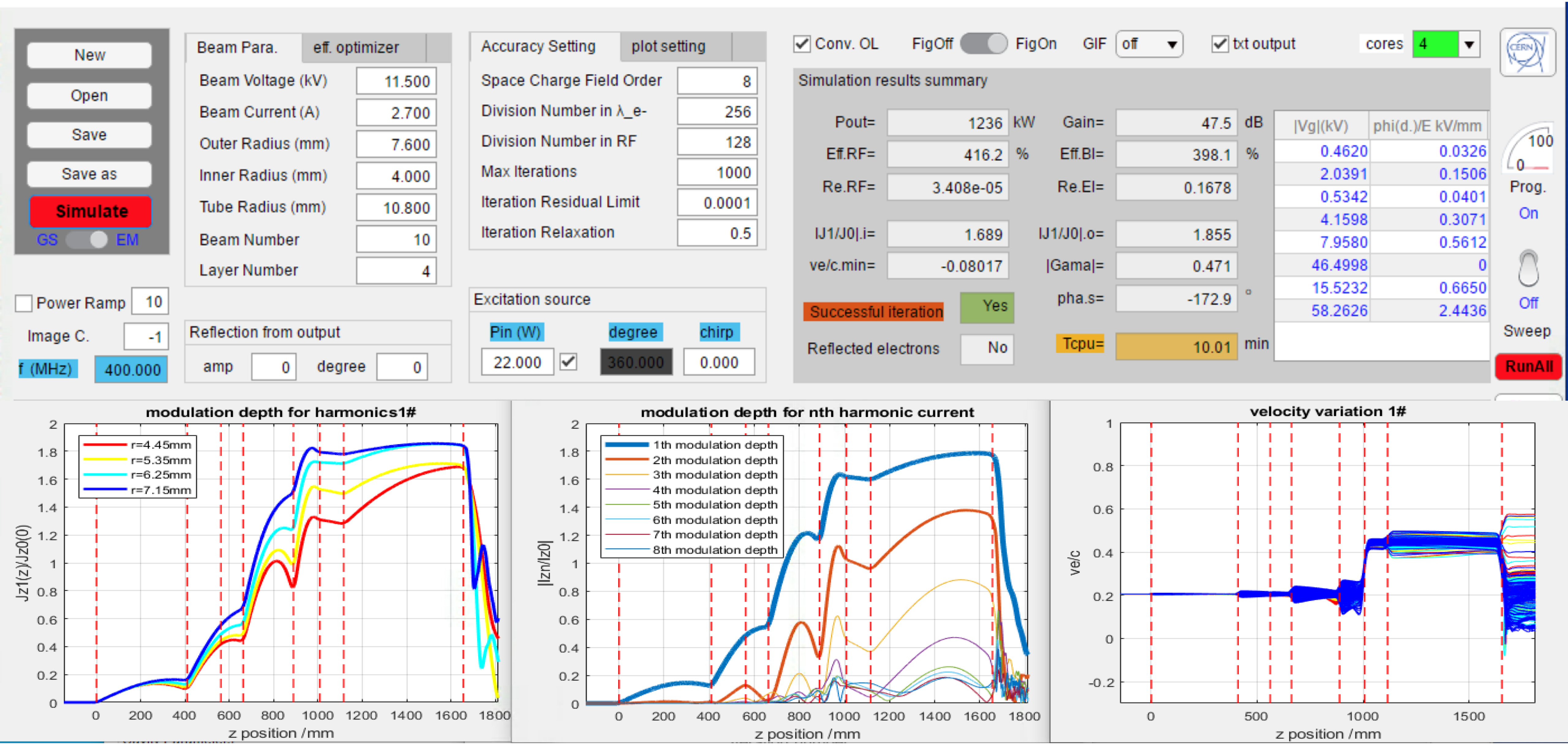


RF circuit length 53.6 cm

DC gap

2nd harmonic cavity

FCC TS 400MHz, 1.2MW MBK KlyC design



Beam Voltage (kV) 11.500
Beam Current (A) 2.700
Outer Radius (mm) 7.600
Inner Radius (mm) 4.000
Tube Radius (mm) 10.800
Beam Number 10
Layer Number 4

Space Charge Field Order 8
Division Number in λ_e- 256
Division Number in RF 128
Max Iterations 1000
Iteration Residual Limit 0.0001
Iteration Relaxation 0.5

☐ Power Ramp 10
Image C. -1
f (MHz) 400.000

Reflection from output
amp 0 degree 0

Excitation source
Pin (W) 22.000 ☑
degree 360.000
chirp 0.000

☑ Conv. OL
GIF off
☑ txt output
cores 4

Simulation results summary

Pout= 1236 kW
Gain= 47.5 dB
Eff.RF= 416.2 %
Eff.Bl= 398.1 %
Re.RF= 3.408e-05
Re.El= 0.1678
lJ1/J0|.i= 1.689
lJ1/J0|.o= 1.855
ve/c.min= -0.08017
|Gama|= 0.471
pha.s= -172.9 °
Successful iteration Yes
Reflected electrons No
Tcpu= 10.01 min

|Vg|(kV)	phi(d.)/E kV/mm
0.4620	0.0326
2.0391	0.1506
0.5342	0.0401
4.1598	0.3071
7.9580	0.5612
46.4998	0
15.5232	0.6650
58.2626	2.4436

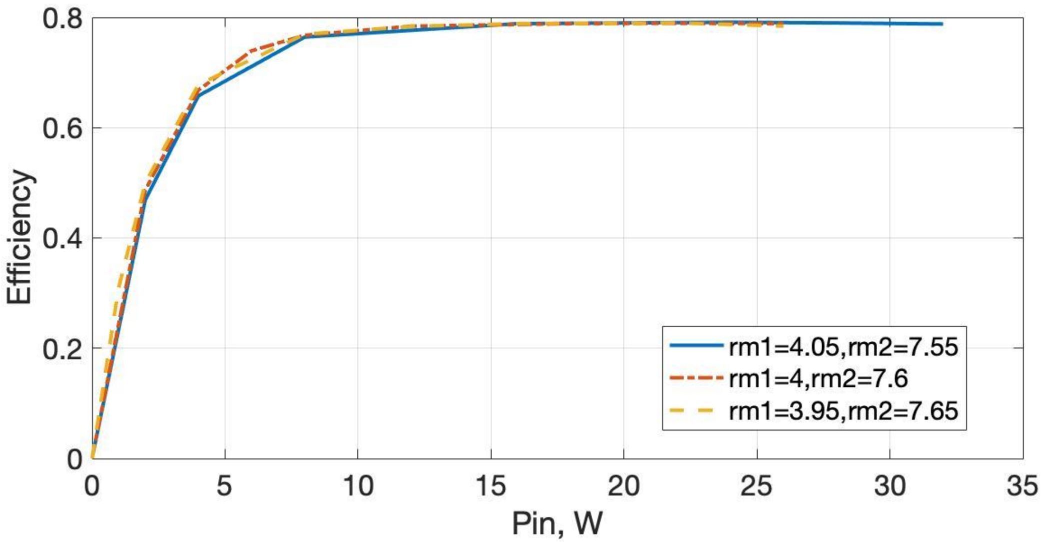
Prog. On
Sweep Off

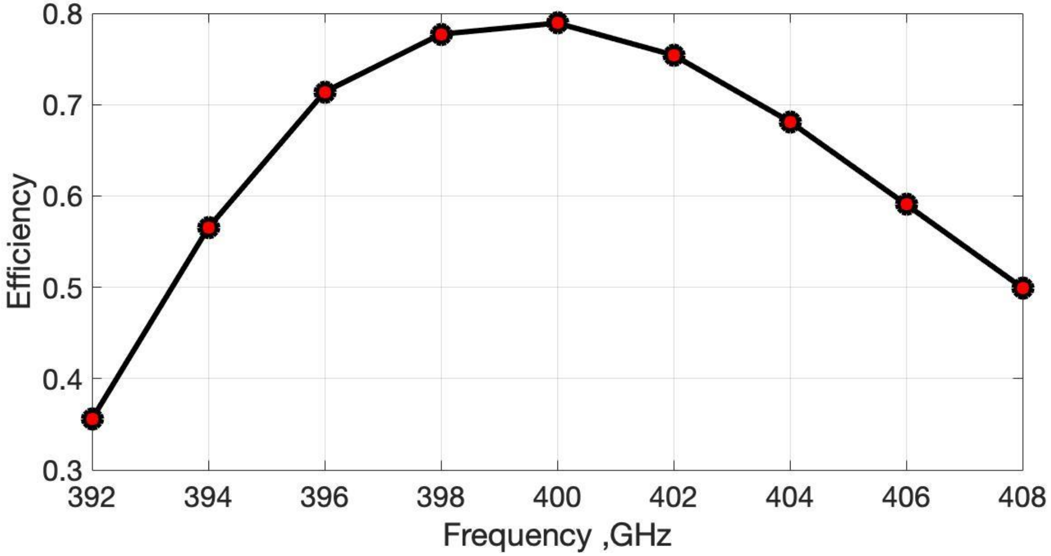
modulation depth for harmonics1#

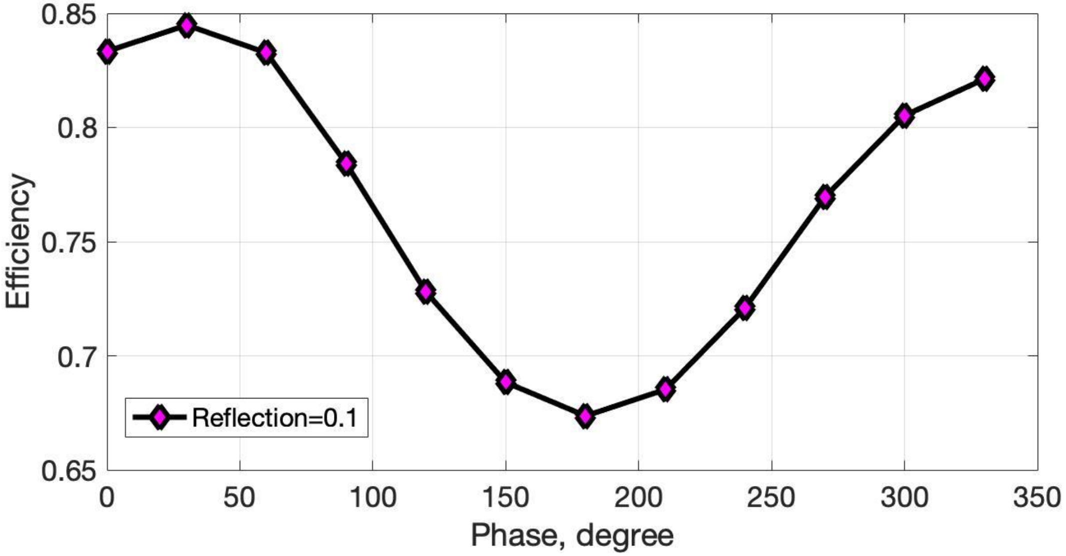
modulation depth for nth harmonic current

velocity variation 1#

Sensitivity analysis

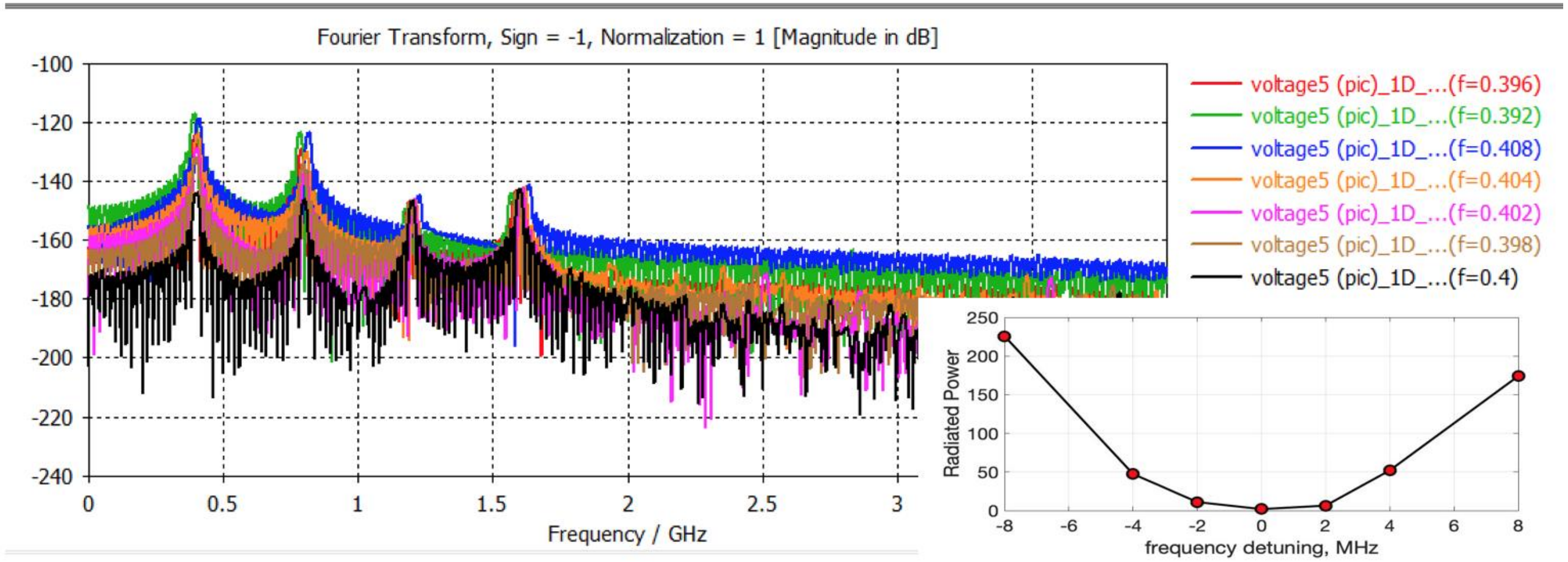


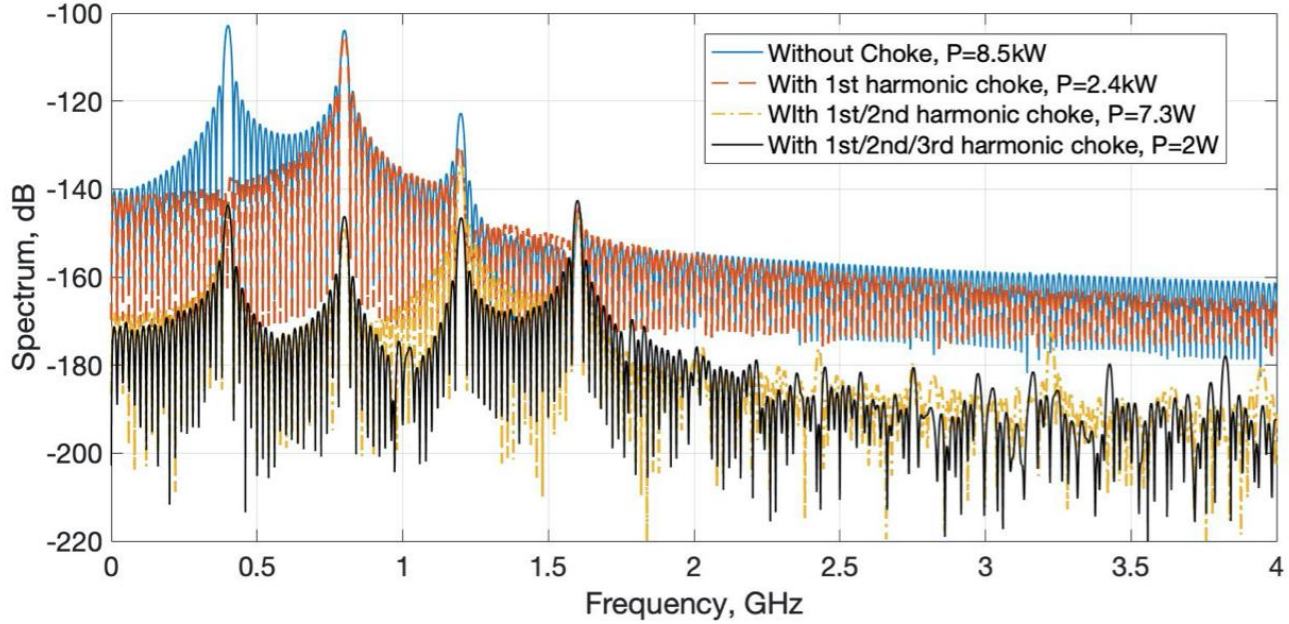


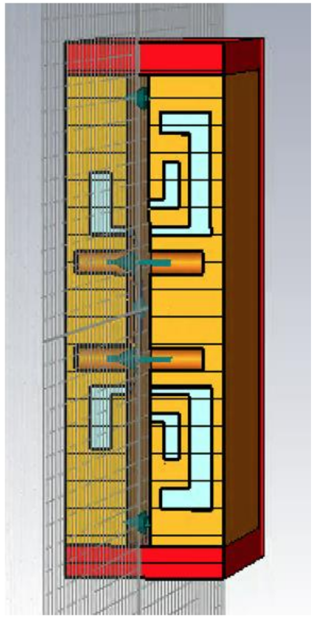


1. Hollow beam design makes tube less sensitive to beam parameter.
2. 11.5kV for the first stage, 58kV for the second stage, oil tank is not necessary for HV insulation.
3. -3dB bandwidth is over 16MHz.
4. Qext is deliberately dropping down to make sure there is no reflection electron issues with port signal reflection.
5. Klystron could deliver 1.23MW output power at 400MHz, with circuit length of 1.8m. No instability issues are found so far.
6. 80% as the operation point to avoid reflected electrons when error presents. Efficiency could be tuned higher according to load.

Choke design for Post acceleration DC gap







- ✓ RF Power radiation will be 8.5kW (~0.6% of DC beam power) when idealized bunched beam passing through DC gap without choke structures.
- ✓ Hazard: Ceramic & metal over heating; EM environmental leaking; Feedback into input leading to oscillation.
- ✓ Presumably, 200W is defined as the limit of power radiation from DC gap and further damping mechanism is considered to be added.
- ✓ The power radiation could be less than 10W with optimization of choke structure when the gap length is between 20mm and 30mm.

GUN Simulation Tool-CGUN benchmark

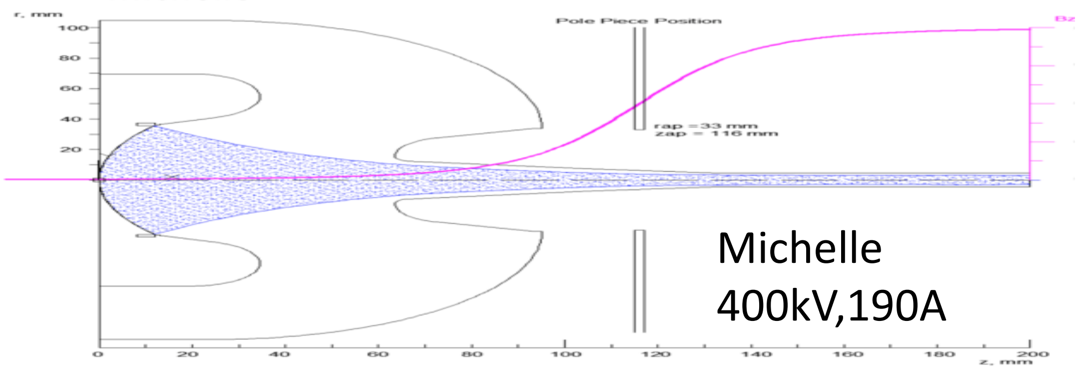
- CST TRK, DGUN, CGUN (home-made 2D code)

Beam optics module

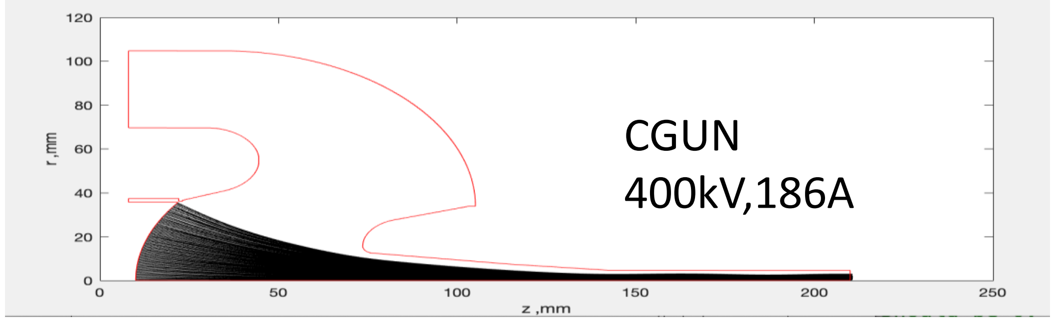
Some benchmark results for complicated cases

Magnetic module

Example: GUN for SLACX

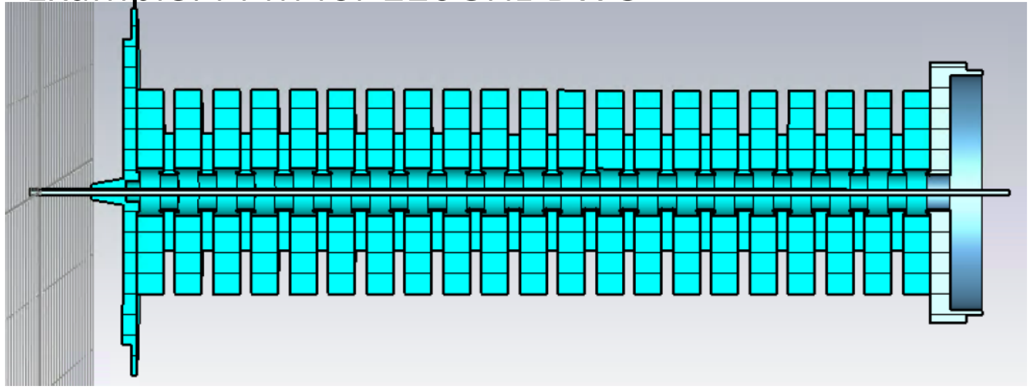


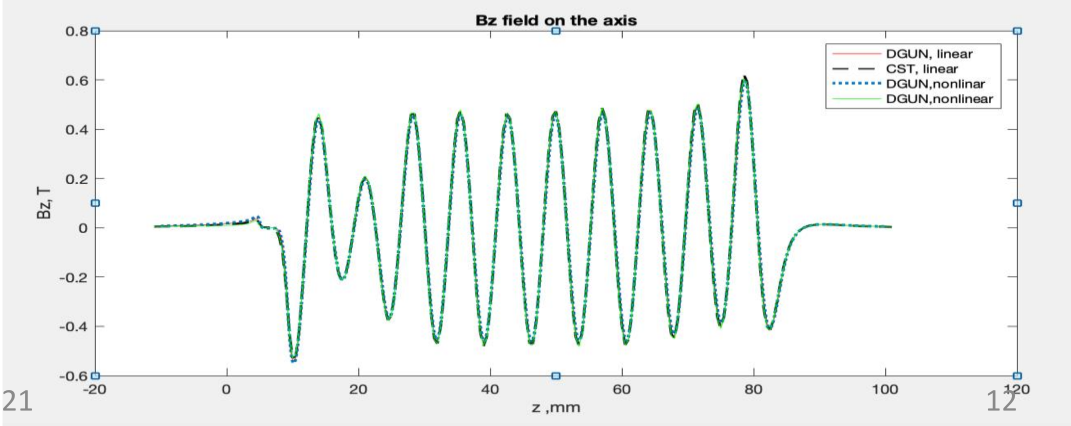
Michelle
400kV,190A



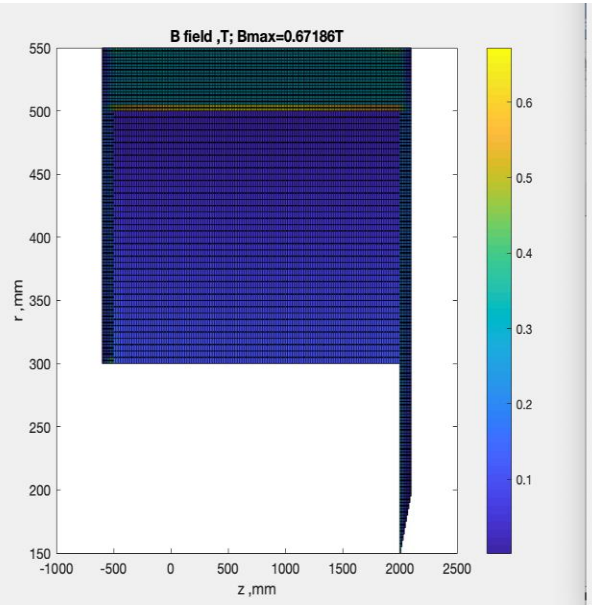
CGUN
400kV,186A

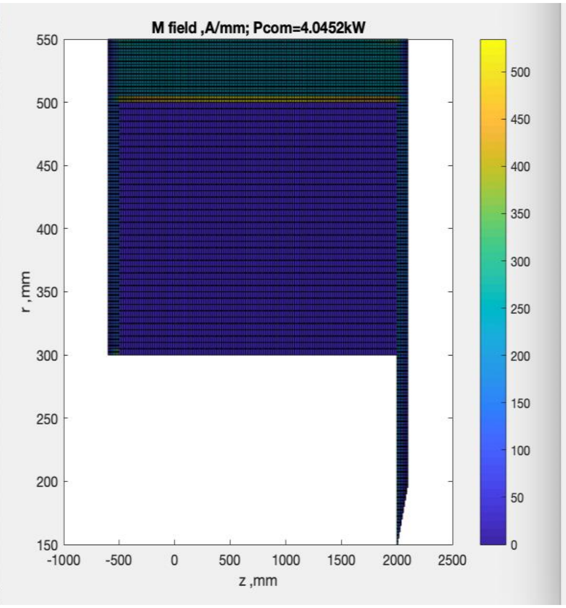
Example: PPM for 220GHz BWO

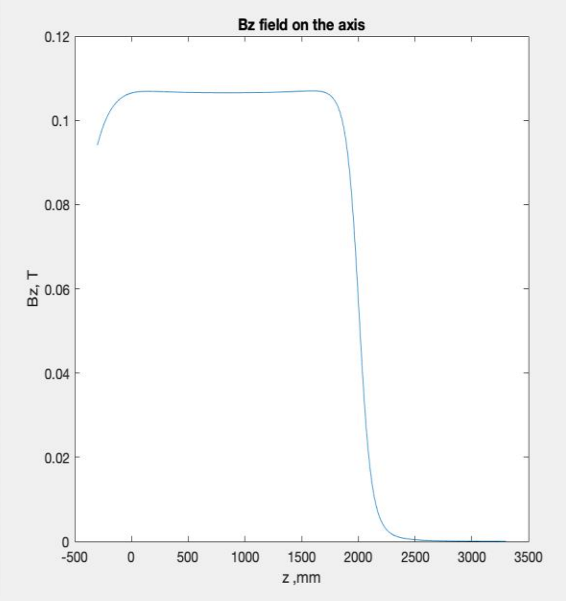


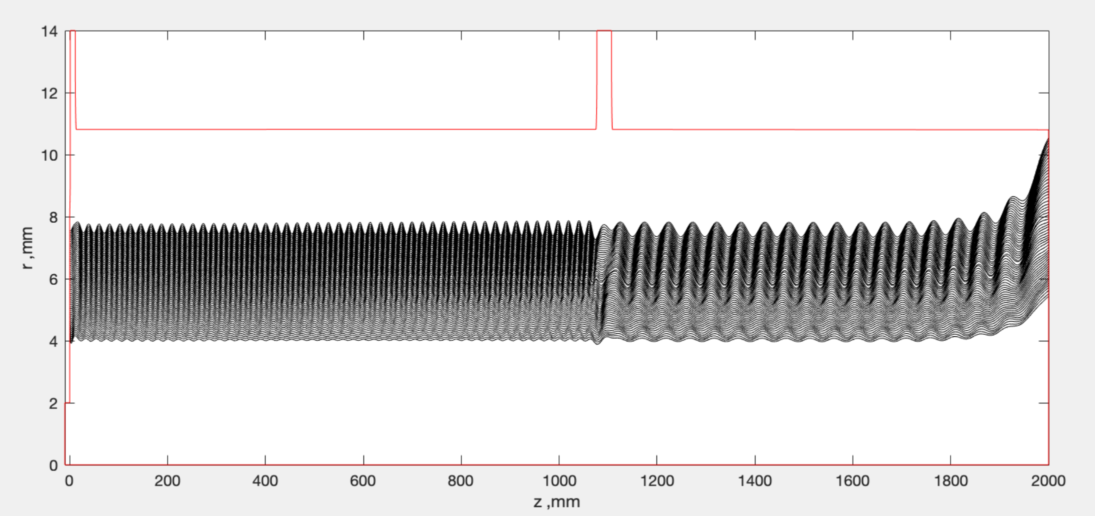


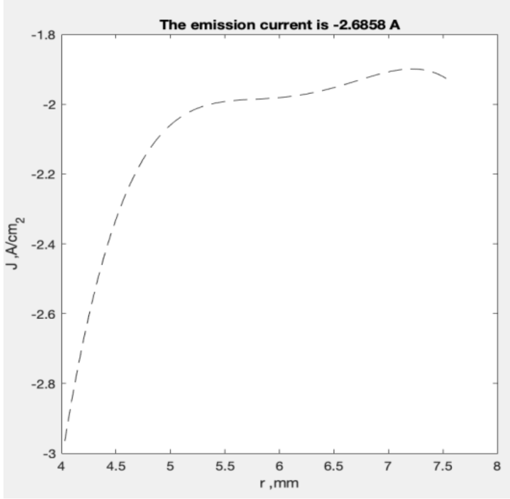
FCC TS MBK Optics design CGUN results (Electron GUN & magnet)





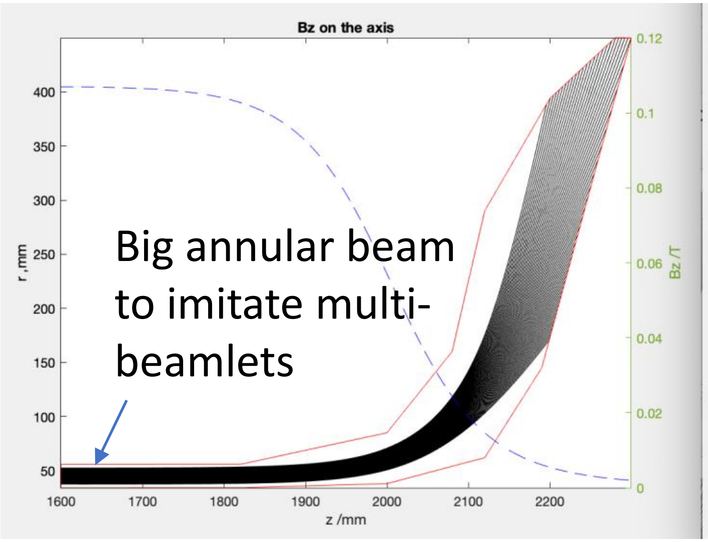




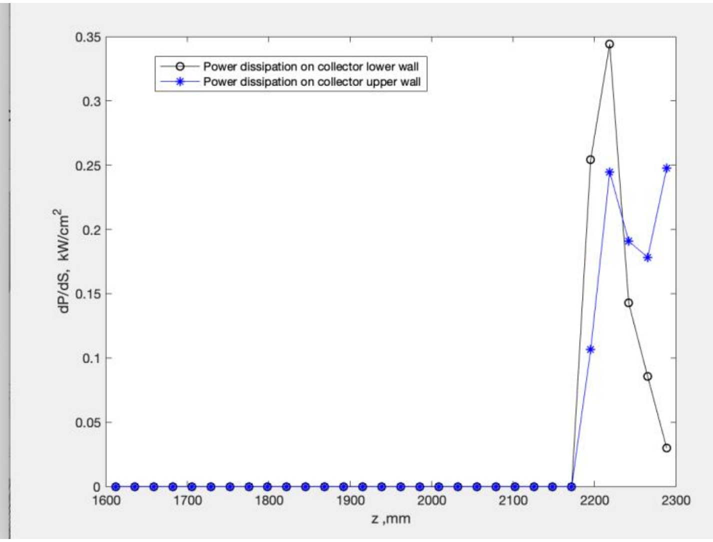


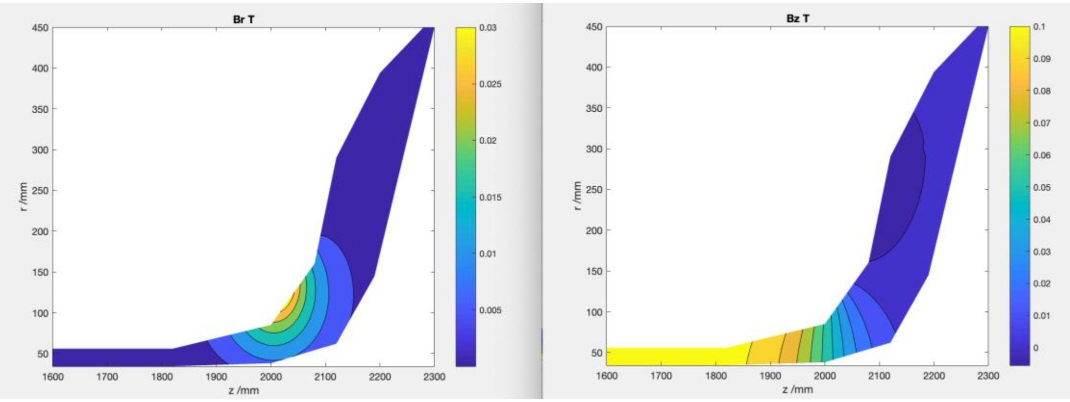
- ✓ Non-convergence GUN design, 0.1T uniform magnetic field is used.
- ✓ Current density on cathode is less than 3A/cm^2, long life operation.
- ✓ Gap length is optimized to ensure transverse electric field kick is small to ensure smooth beam envelop after DC gap.
- ✓ Magnetic system is optimized to ensure 0.1T in the RF circuit and proper ramping down for beam collection
- ✓ 2D simulation will be accurate enough for uniform magnetic system since every beamlet is identical (no transverse B)
- ✓ 3D track simulation in CST will be done to benchmark the 2D CGUN design

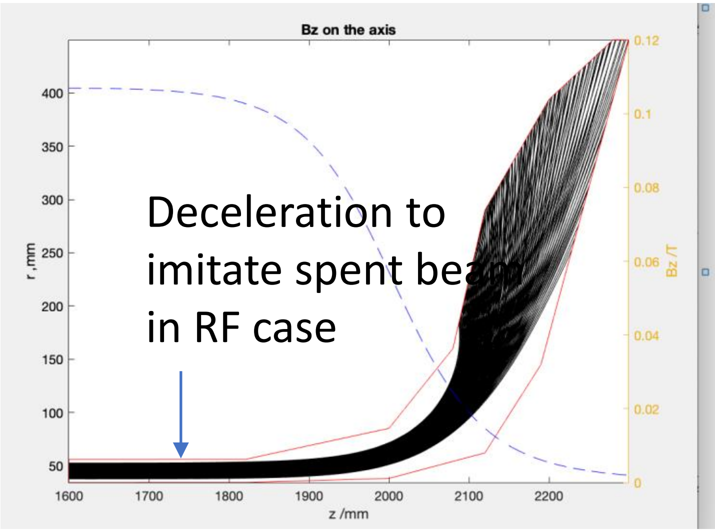
Optics design CGUN results (Collector & magnet)



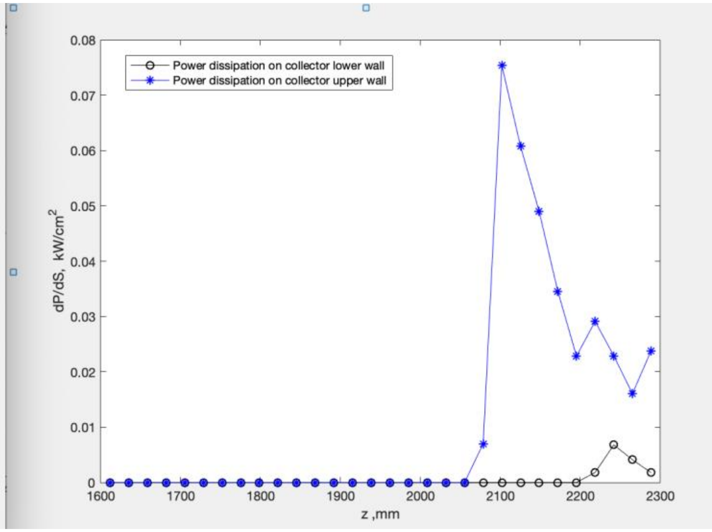
Big annular beam to imitate multi-beamlets





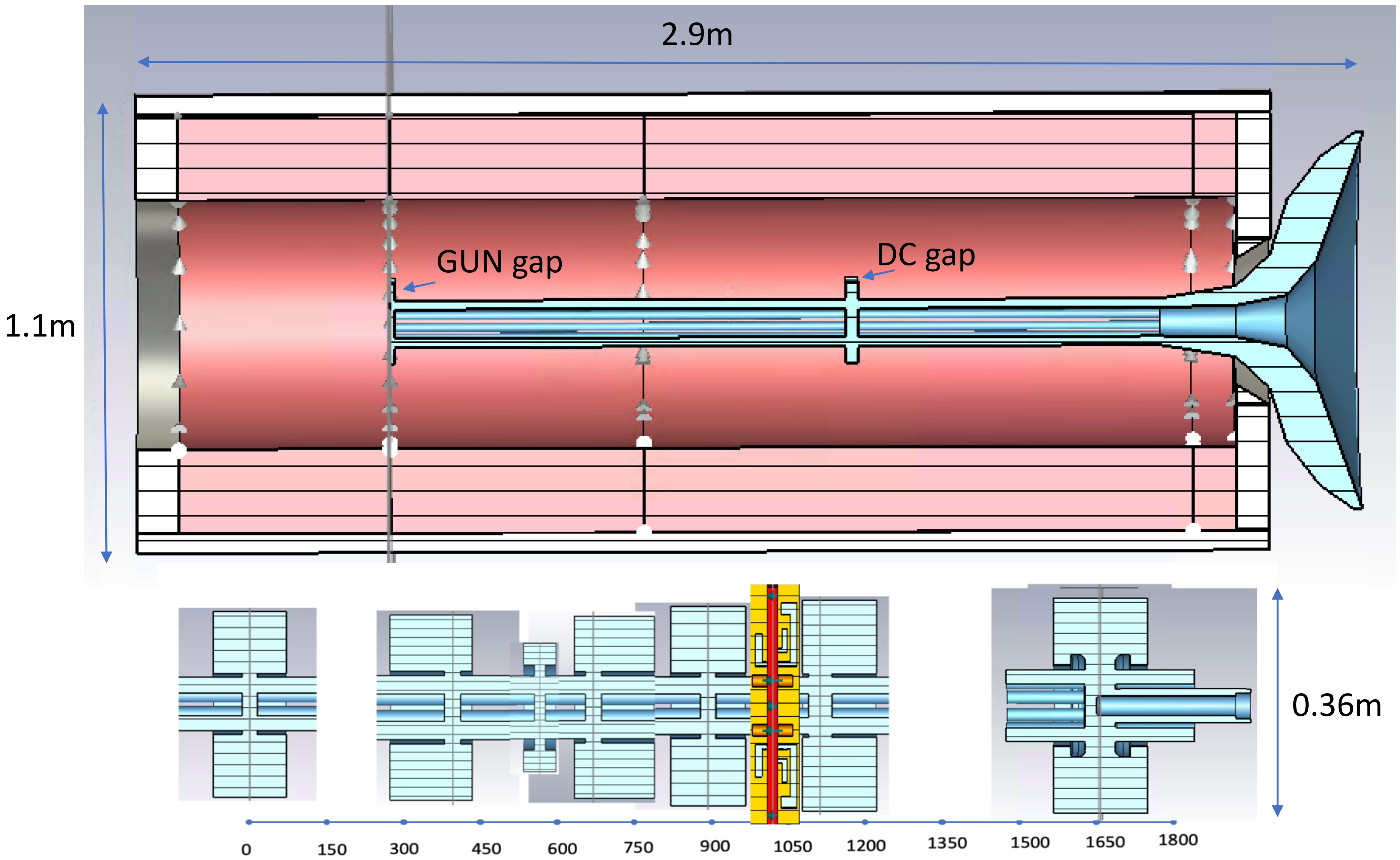


Deceleration to imitate spent beam in RF case



- ✓ Innovative collector design using radial plane to collect spent beam to save longitudinal space
- ✓ Transverse size of collector is still smaller than magnet, but this is not paraxial system any more
- ✓ Bz(z,r),Br(z,r) is imported from magnetic module directly, instead of using expansion series of Bz(z,0) and its high order derivatives.
- ✓ Power dissipation density is less than 0.35kW/cm^2 for DC and 0.1kW/cm^2 for RF, which is safe for water cooling (limit~0.5kW//cm^2)

Schematic layout of TS MBK for FCCee



FCC TS MBK Summary and outlook

- The high efficiency (~85%) TS MBK is most practical when the generation of low frequency (UHF and L-band) and high power (Multi Mega Watts) microwave signals is required. This technology could be considered as an appropriate choice for **CLIC, ILC, FCC and CEPC large-scale electron accelerators and high power proton Linacs (ESS, MYRRHA, etc.)** in which compact Klystron layout is essential for underground tunnel environment.
- FCC TS MBK is optimized and designed in updated KlyC(v5) and newly developed optics code CGUN, which shows that such Klystron could deliver 1.2MW output power with efficiency of 80%, within a dimension of D1m*L3m.
- Further 3D PIC simulation has to be done to analysis full 2D/3D effects in beam-wave interactions; Further 3D TRK simulation will be done for verification and study for 3D effects brought by multi-beam (DC case).
- All in one simulation will be done with optics imported and PIC is launched (RF scenario).

Thanks for your attention!

Version 5

KlyCv5 and updated User Manual has been released since 1st February 2021. If interested, please contact via email to:

jinchi.cai@cern.ch
Please put in Cc…:
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g.burt1@lancaster.ac.uk