1) 2) 3)

Review of computer codes developed for the Klystron design

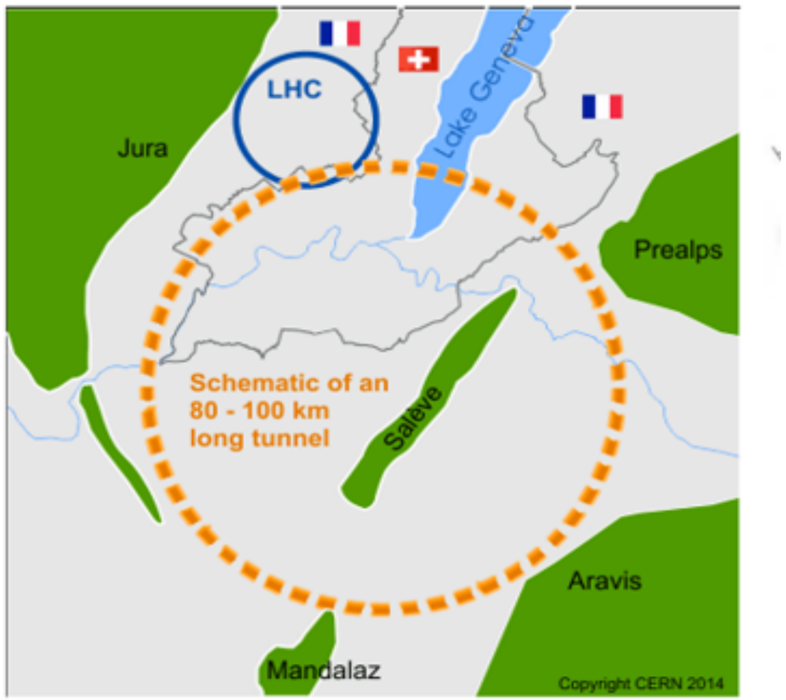
Jinchi Cai[1,2,3], Igor Syratchev[2], Graeme Burt[3]

5/7/2022

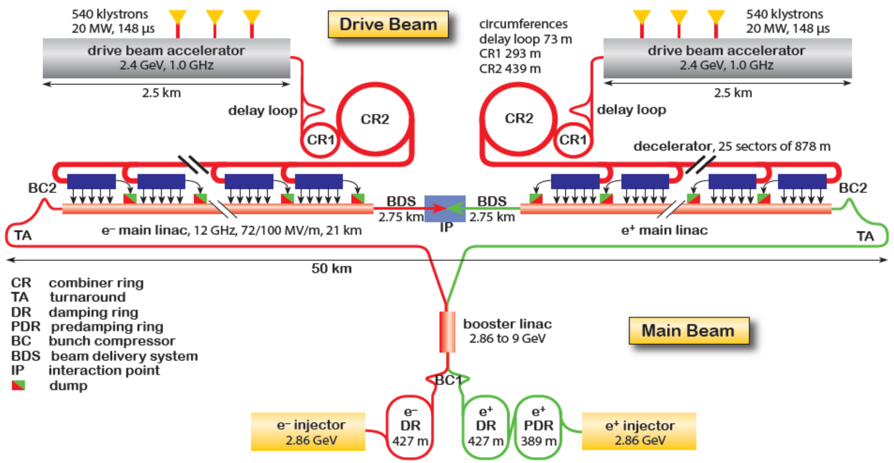
Outline

- Background
- Home-made codes:
  - KlyC : 1.5D large signal Klystron simulation code
  - CGUN: 2D beam optics code
- Summary & updates

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**

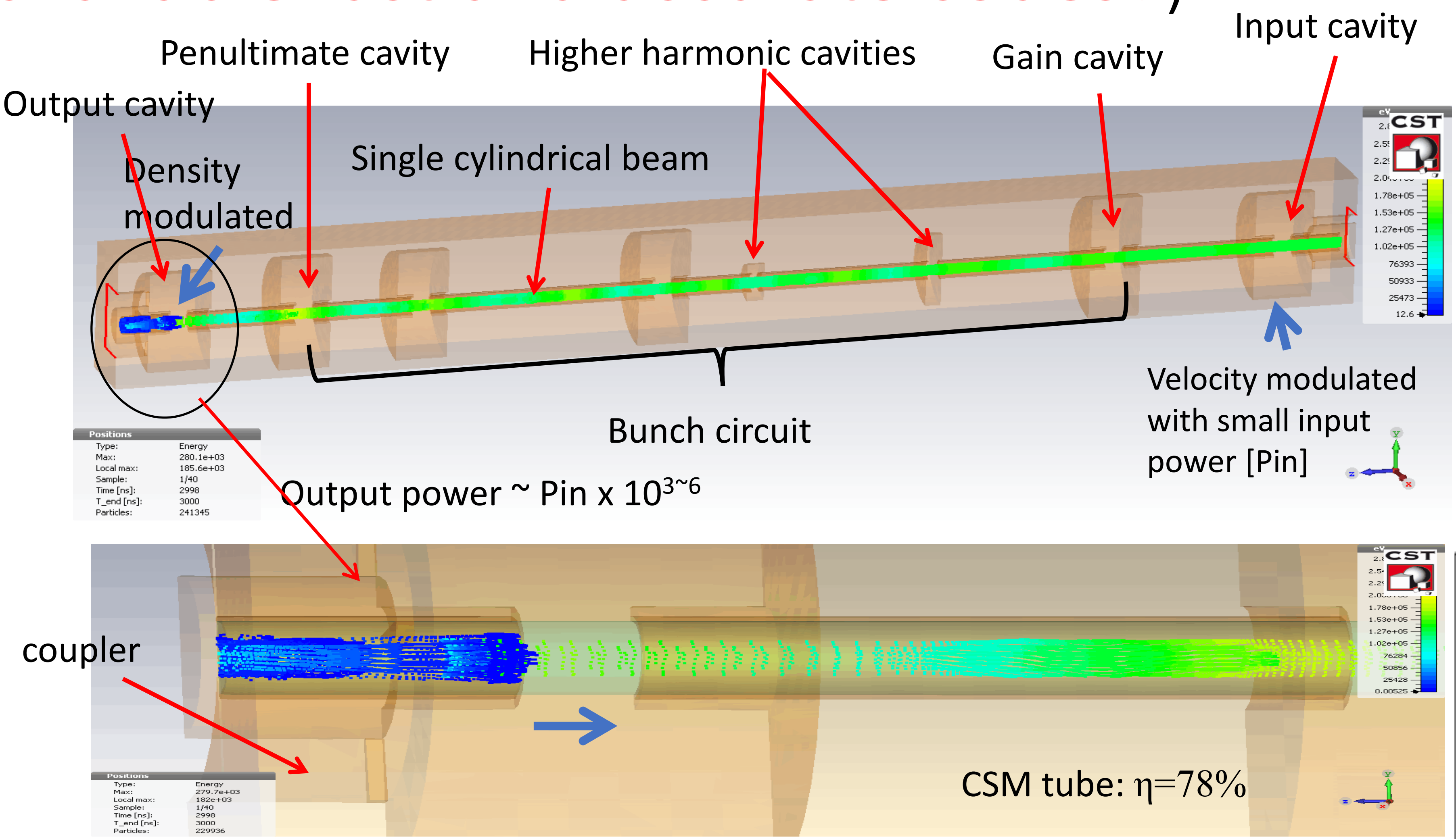
The klystron efficiency impact on the CLIC 3TeV power consumption.
Example of the efficiency upgrade from existing 70% to 85%.

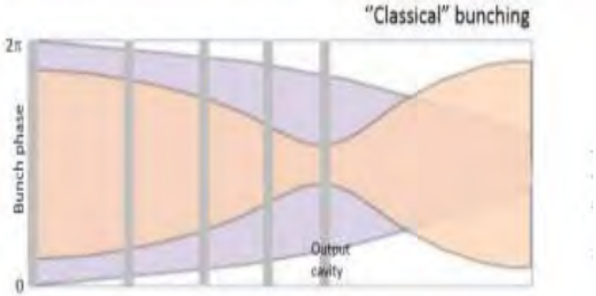
	Klystron eff. 70%	Klystron eff. 85%	Difference
RF power needed for 3TeV CLIC	180 MW		
DC input power	257 MW	211 MW	-46MW
Waste heat	77 MW	31 MW	-46MW
Annual consumption (5500 h assumed)	1413 GWh	1160 GWh	-253 GWh
Annual cost (60 CHF/MWh assumed)	84.8 MCHF	69.6 MCHF	-15.2 MCHF
Electricity installation dimensioned for	257 MW	211 MW	-18%
CV installation dimensioned for	77 MW	31 MW	-60%

- Potential saving are 2.53 TWh in 10 years (**152 MCHF in 10 years**).
- Reduced environmental impact (cooling and ventilation)
- Reduced installation cost (stored energy in modulators).
- Reduced maintenance cost (klystron life time).

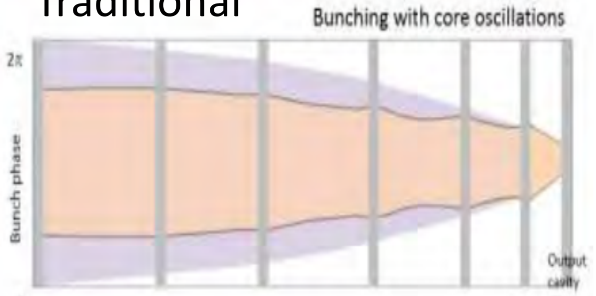
R&D on increasing the useable efficiency is worth every penny/cent invested!

HE klystron: Mechanism and concepts (complex, available fast and accurate codes?)

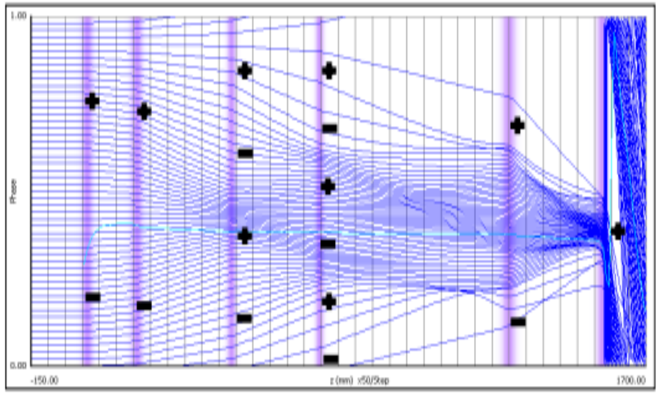




Traditional



Core oscillation method (COM)



Core stabilization method (CSM)

Glossary: Saturation, velocity congregation, Radial stratification

Home-made codes for HE Klystron development (2016-2022)

KlyC (v6): 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[8]

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)
[8] J. Cai, Z.U. Nisa, I. Syratchev, G. Burt 'Beam optics study on a Two-Stage Multibeam Klystron for the future circular collider', IEEE Transactions on Electron Devices (Early Access)

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- Background
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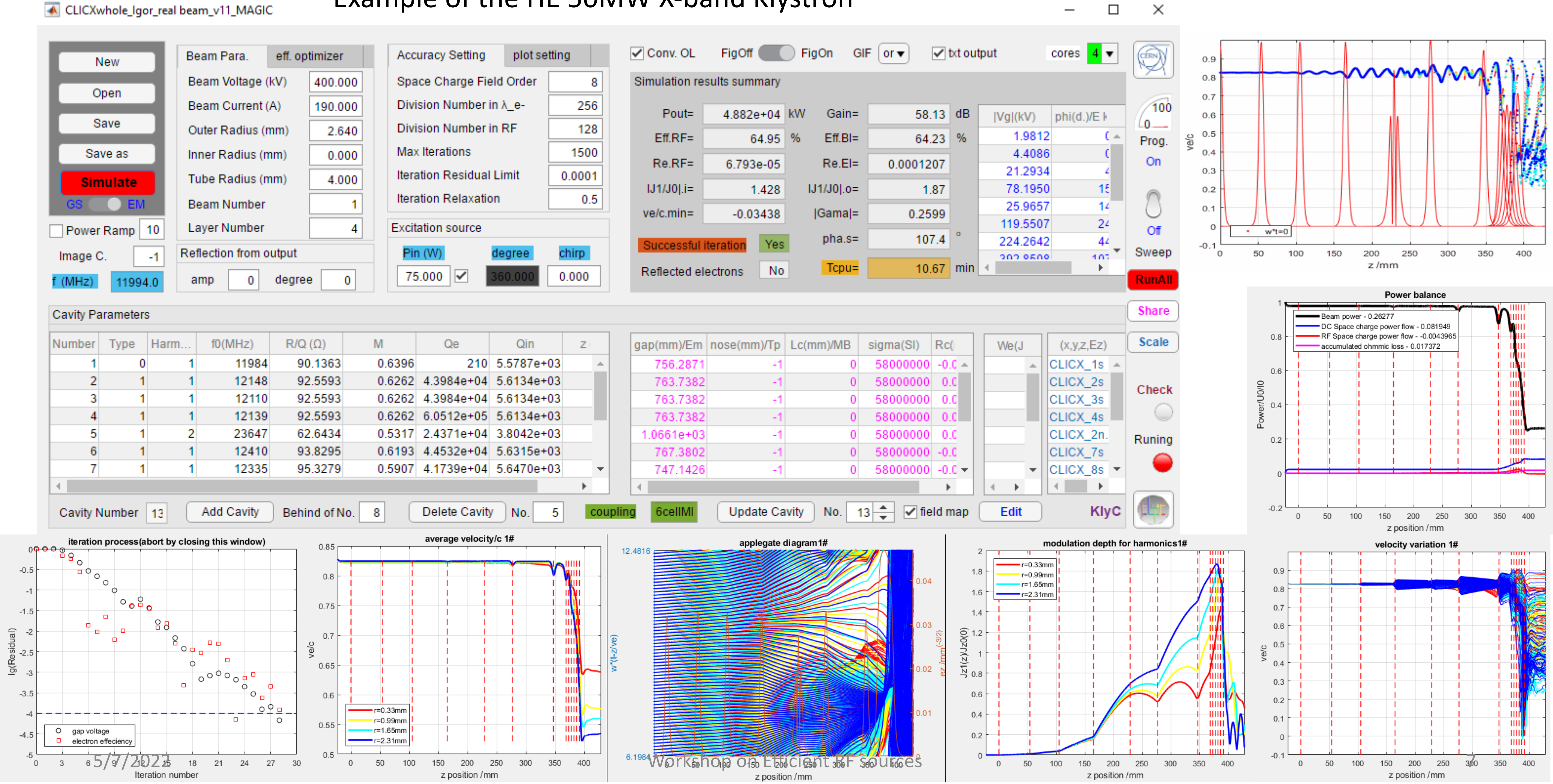
Wave-beam interaction module (KlyC GUI and Design report module)

Example of the HE 50MW X-band Klystron



FCC#6. KlyC2D vs MAGIC

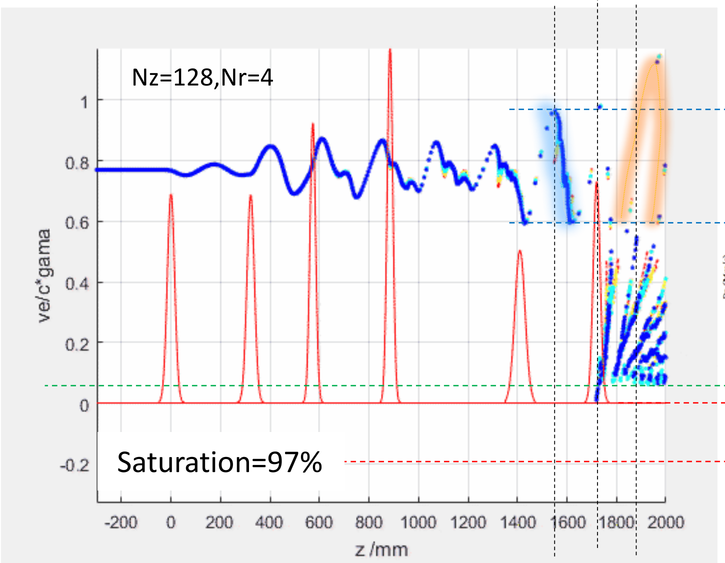
Benchmark: Fast and accurate

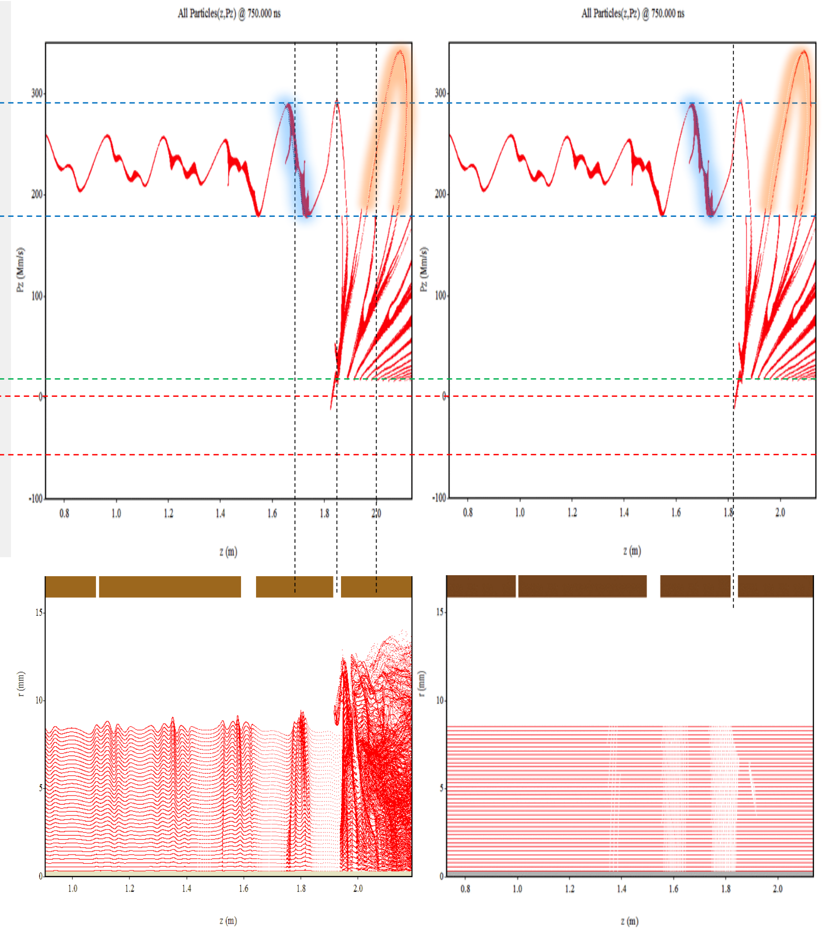
Beam settings:

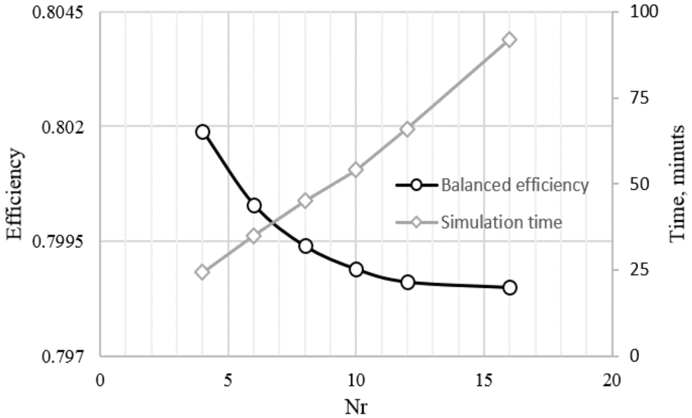
Nz=256,Nr=4, η=79.9%,Tcpu= 10 min

MAGIC (0.07T) **2D**, 79.4% MAGIC (20T) **2D**, 79.6%

Tcpu = 4000 min (~1ooo ns)







Convergent analysis

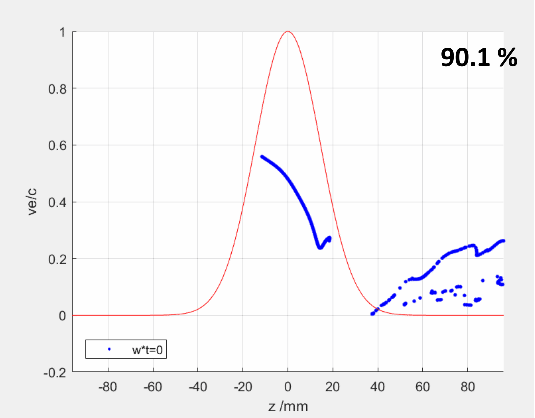
The radial bunch 'expansion' in output cavity (MAGIC2D) practically does not affect efficiency. This validates KlyC2D as an attractive (and fast) tool.

Bunched beam generator module.

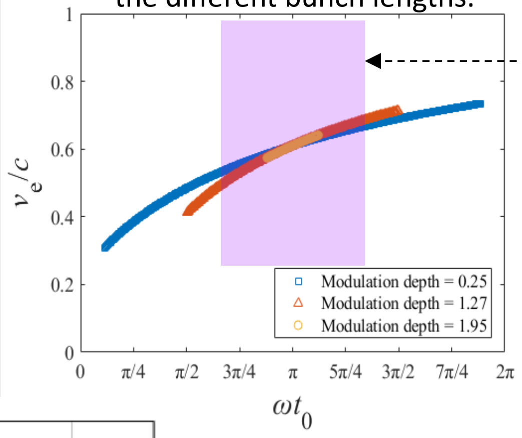
The ultimate power extraction efficiency in the linear beam devices

Example of **0.8 GHz FCC$_{ee}$ klystron**. Voltage 133 kV, Current 12.6 A (μP=0.26 μA/V$^{3/2}$)

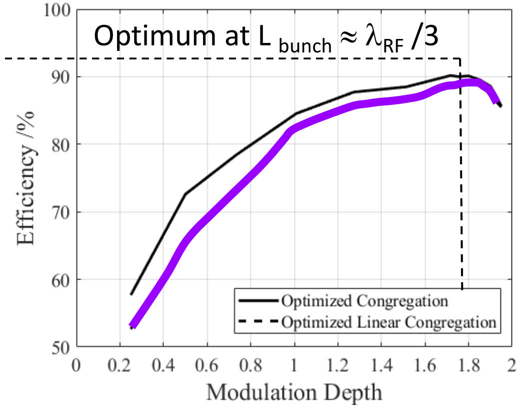
Fully saturated bunch with optimised congregation

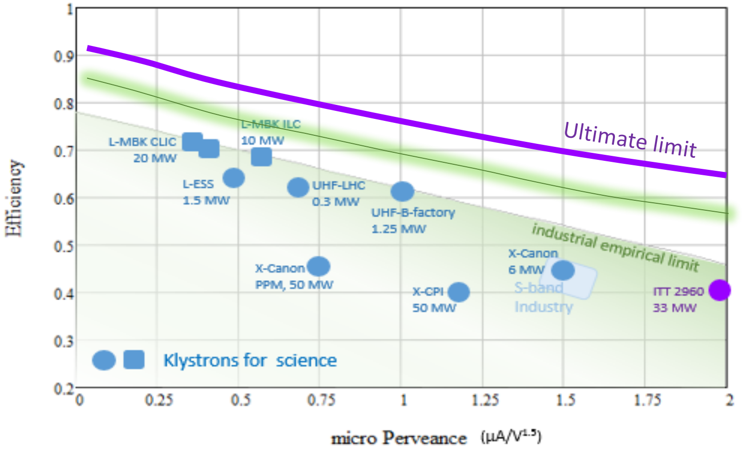


Optimised congregation for the different bunch lengths.



Effect of the bunch length





High efficiency Klystrons design objectives

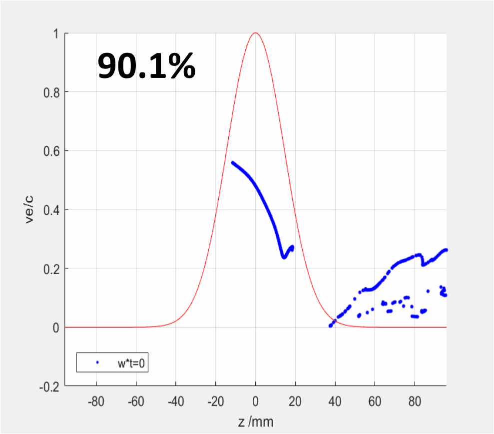
- E field expansion in the drift tubes
- Ohmic Losses
- Space charge depression
- Bunch saturation
- Bunch congregation
- Bunch stratification
- Radial bunch expansion

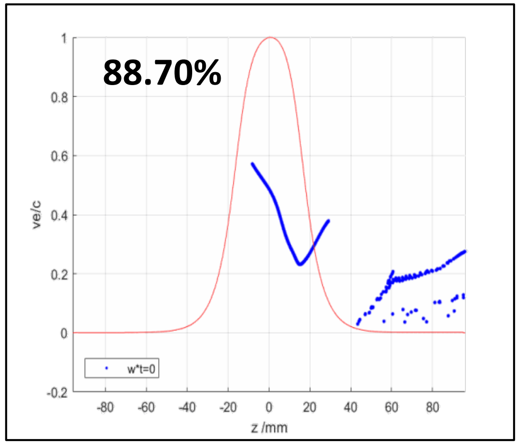
Optimised RF bunching circuit

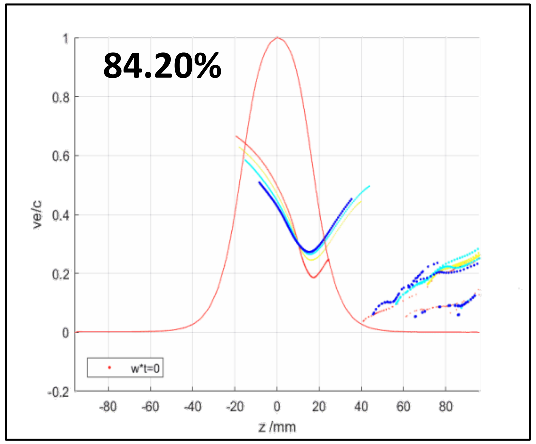
Power conversion efficiency. Limiting factors.

Fully saturated bunch

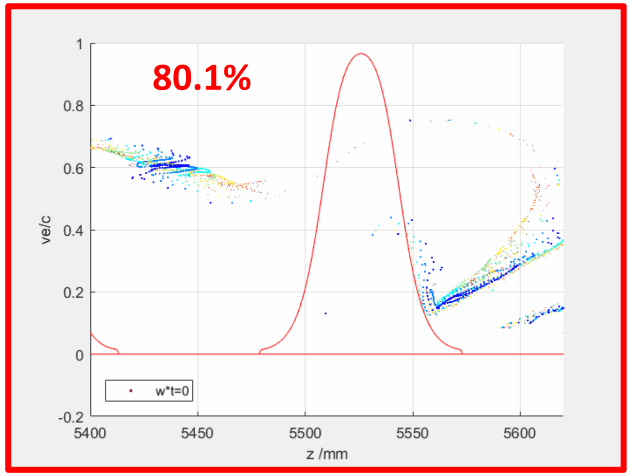
Optimised congregation → **Linear** congregation → **Stratified** bunch with linear congregation

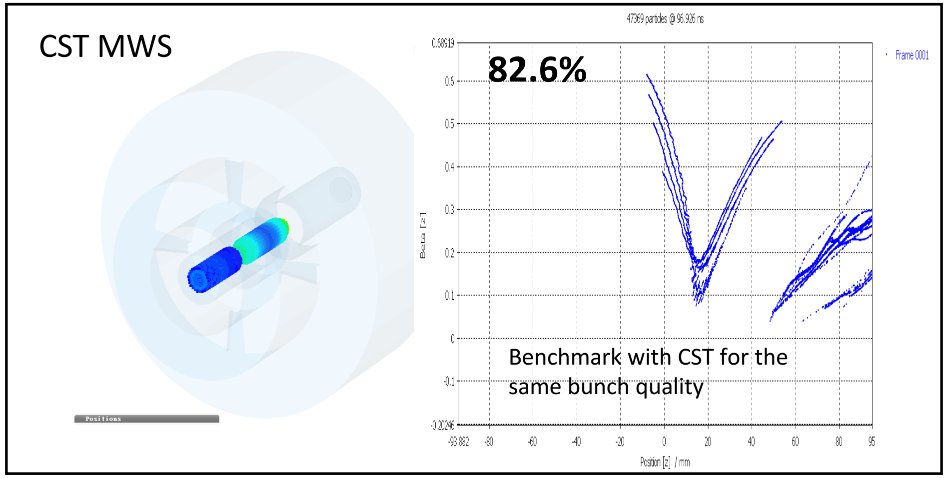






FCC CSM tube ← **Sabre** effect and Ohmic ←





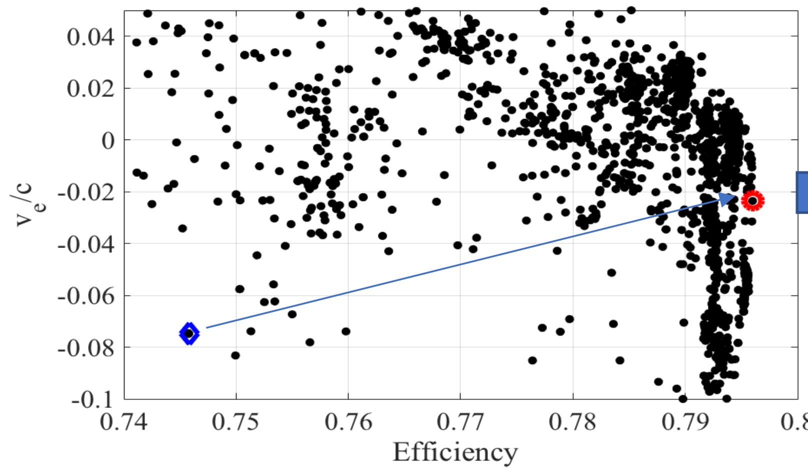
- E field expansion in the drift tubes causes beam reacceleration when it leaves the output cavity.
- Ohmic loses are proportional to the operating frequency.
- Space charge depression is a partial conversion of the beam kinetic energy into the potential DC energy of beam traveling in the drift tube.
- Bunch saturation is optimal, when all the elections populate only the useful RF phase bucket leaving the anti-bunch empty.
- Bunch congregation is a normalized elections velocity spread along the bunch. It has an optimal value for every given bunch length.
- Bunch stratification is a radial dependence of the bunch length and congregation. The ideal bunch should not have such a dependency.
- Radial bunch expansion happens during beam deceleration in the output cavity in the presence of external solenoidal magnetic field.
- Reflected electrons **could be** generated if some of the above effects are not balanced.

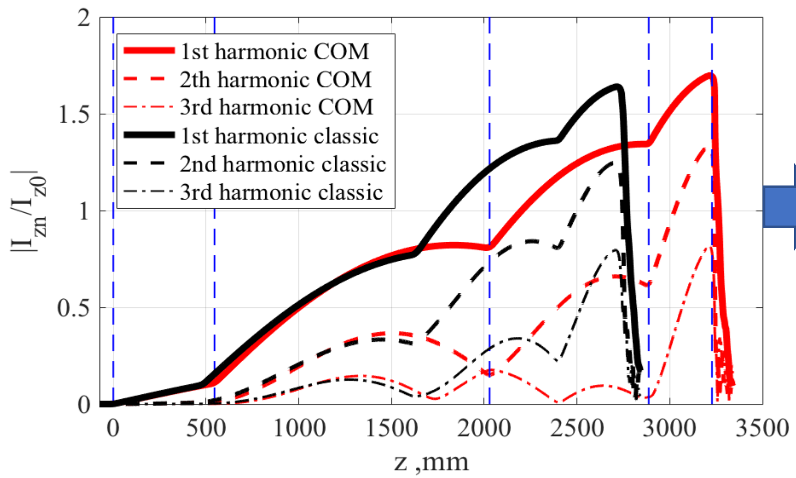
Driven by klystron general parameters.	Driven by RF design and space charge effects.

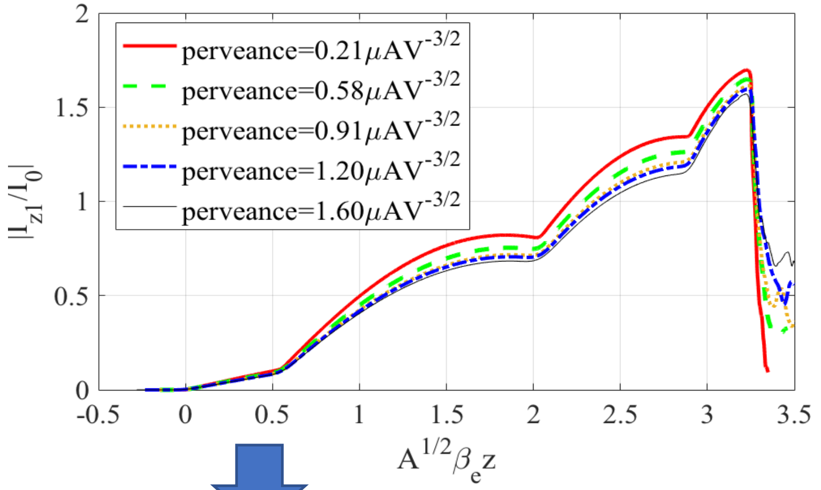
Parameters scaling module @ Klystron optimizer module

1GHz, 180kV, 16A, r_m=6mm, r_c=10mm

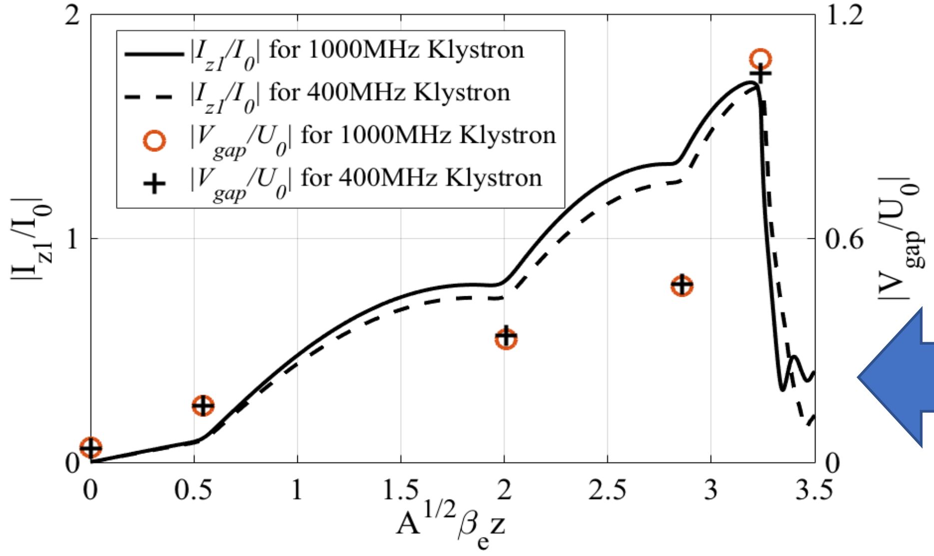
Parametric Scaling Procedures(PSP)

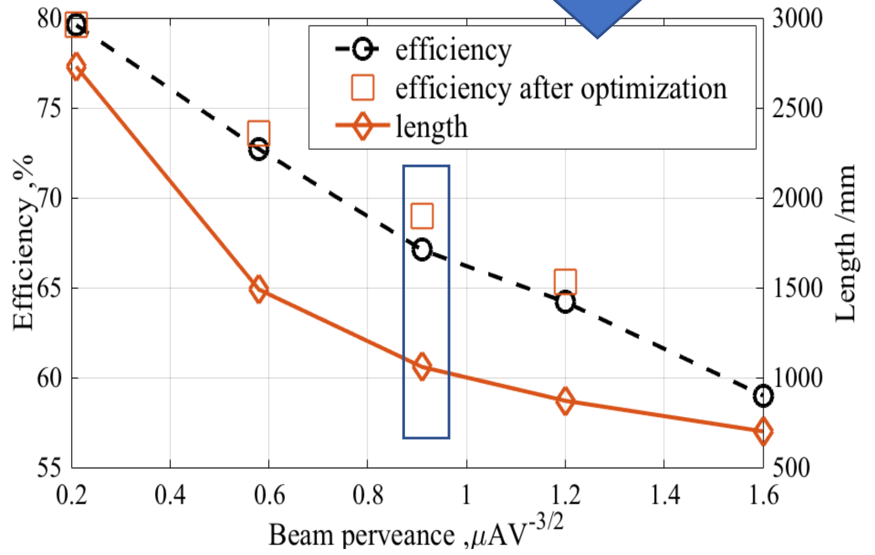




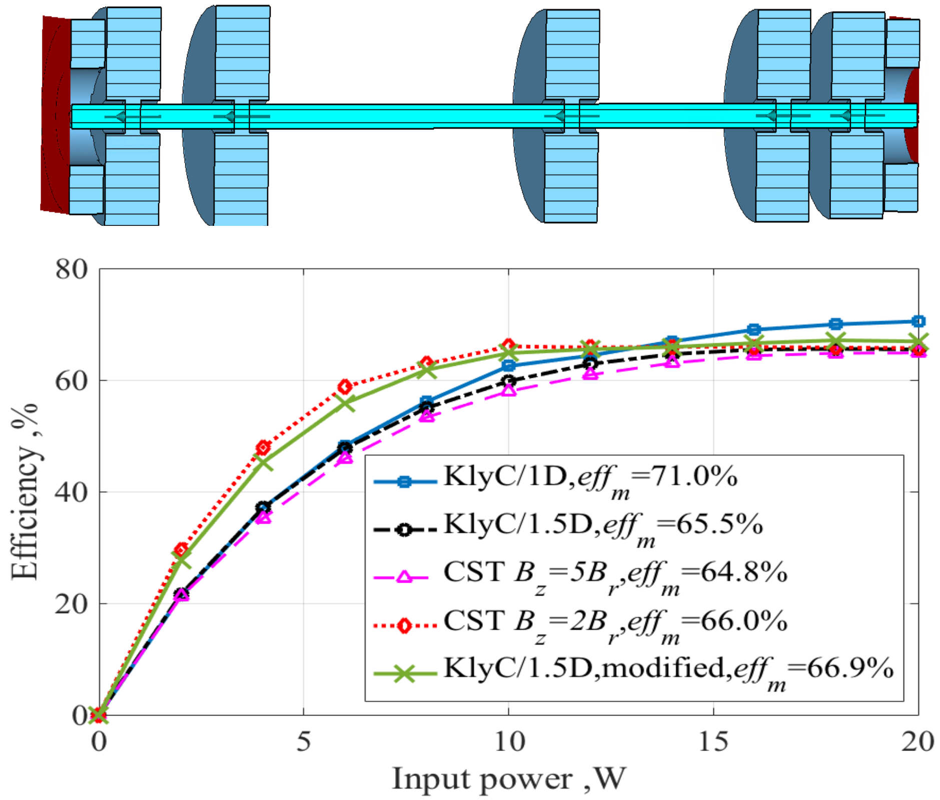


54kV, 9A, 0.4 GHz (LHC tube), 65.5% @1.5D





LHC tube tested in CST PIC

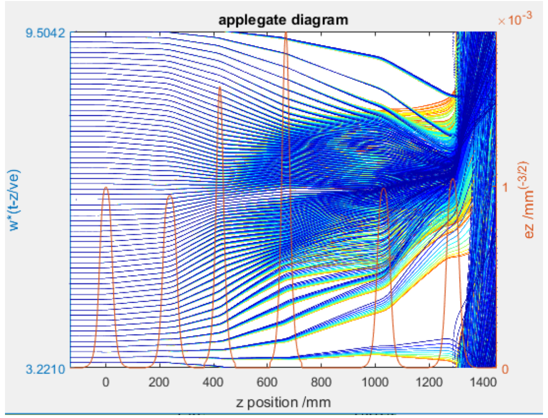


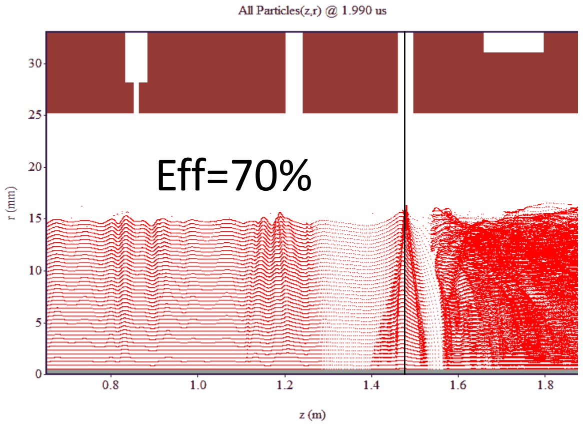
- The saturation efficiency in CST PIC is consistent with KlyC 2D simulation
- Different guiding B_z will lead to different power transfer curves
- KlyC can get similar power transfer curve if radius is modified as the average radius in CST PIC

$$\frac{r_{mod}}{r_b} \sim 1 + (4\frac{B^2}{B_{BR}^2} + 1)^{-1}$$

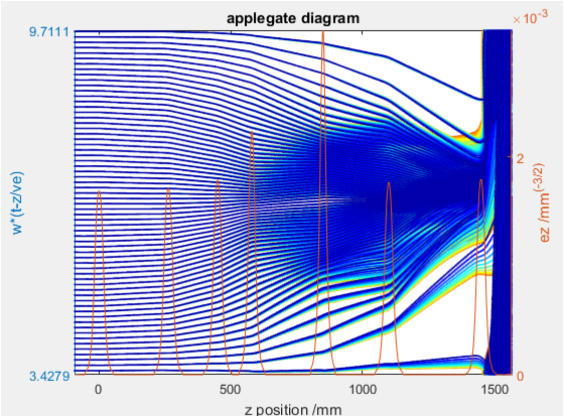
This example is not LHC tube final design, just for demonstration

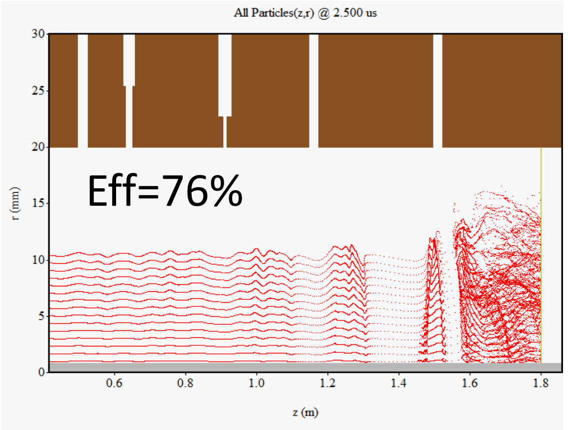
Other examples for the procedure



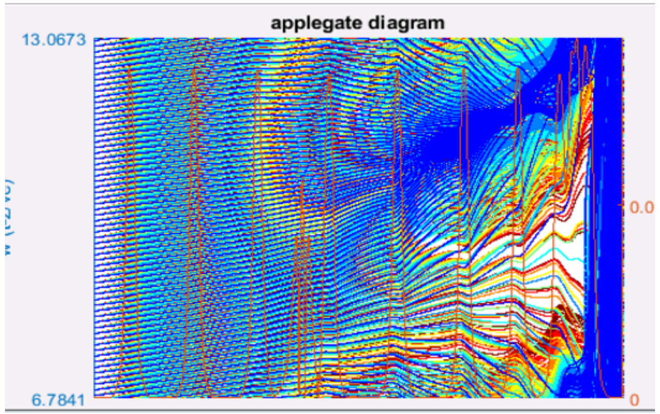


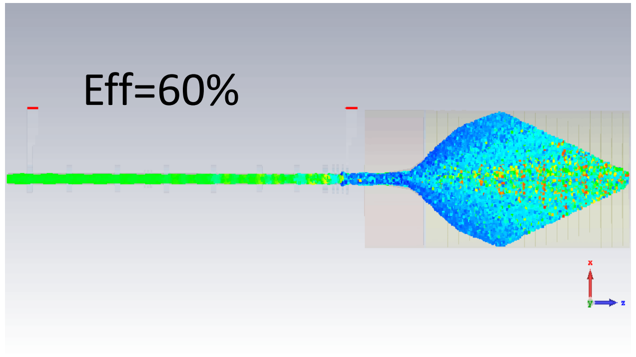
LHC tube scaled from FCC 6 cavity design





ESS tube (by C.Marrelli) scaled from FCC 7 cavity design

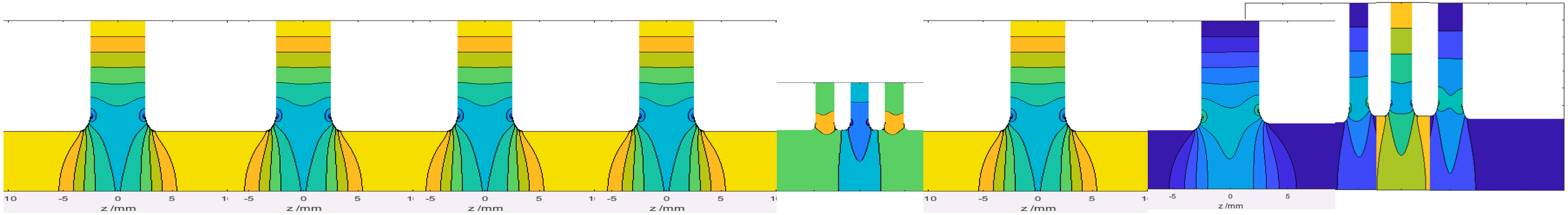




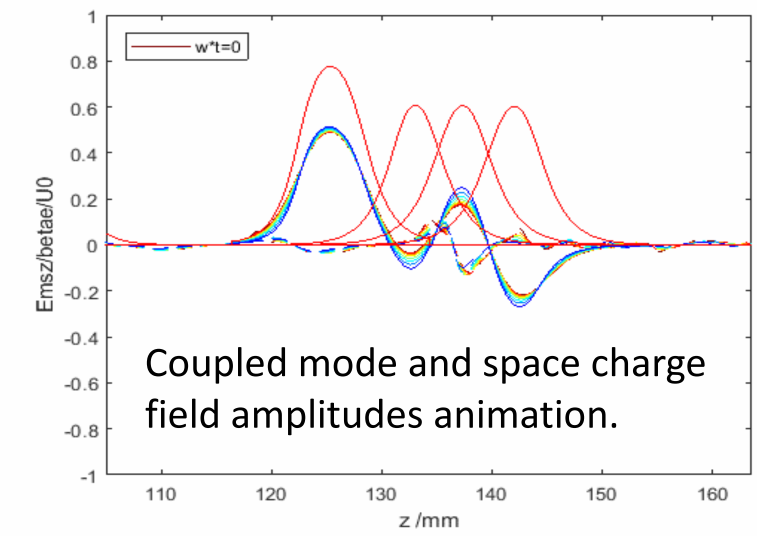
Xbox tube scaled from SLAC X50MW preliminary design

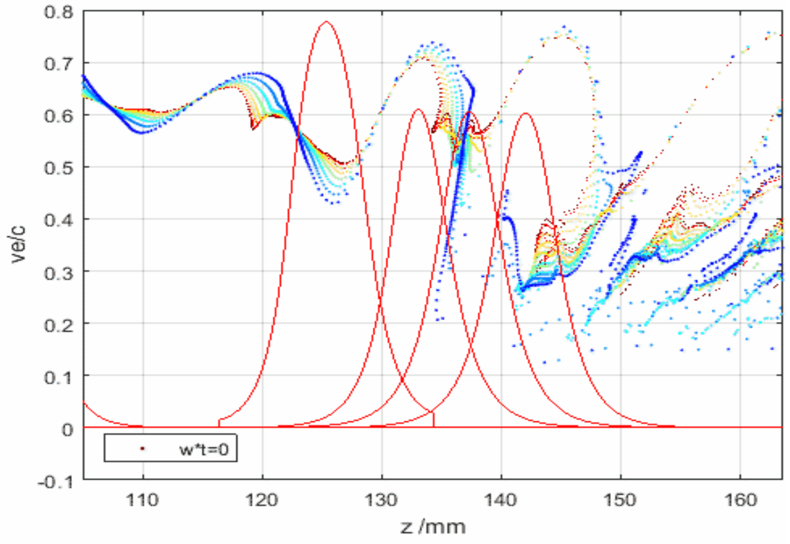
Coupled cavities module @ Electro-Magnetic module

Compact 8MW X-band layout (in collaboration with Canon).

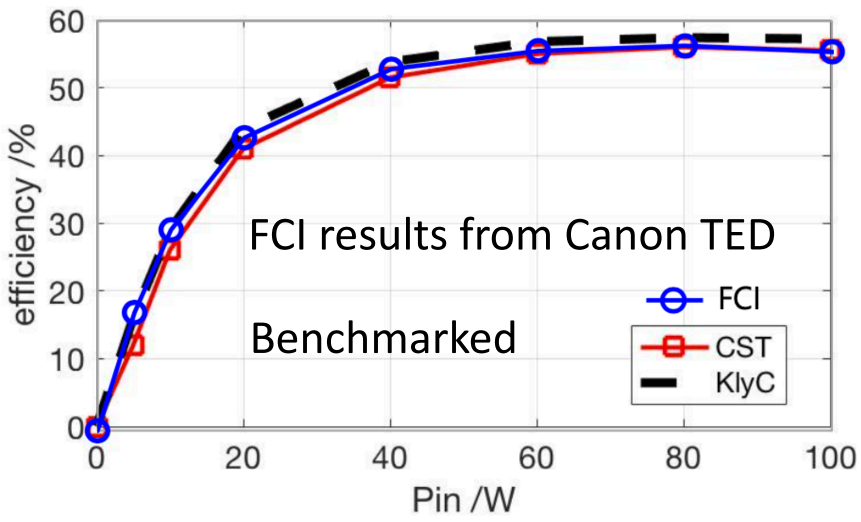


Individual field is generated by eigen-mode module



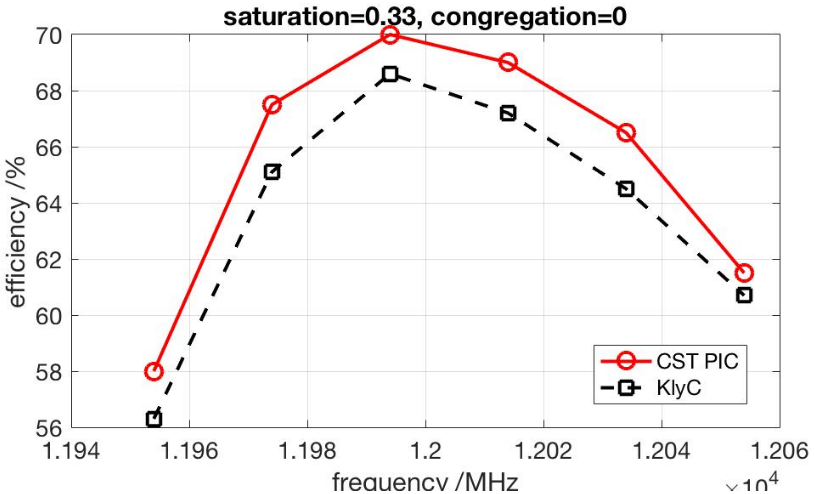


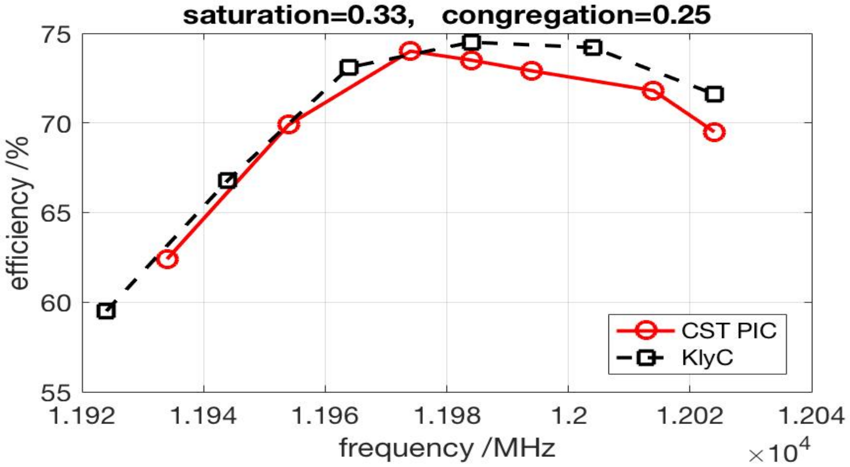
Transfer characteristics



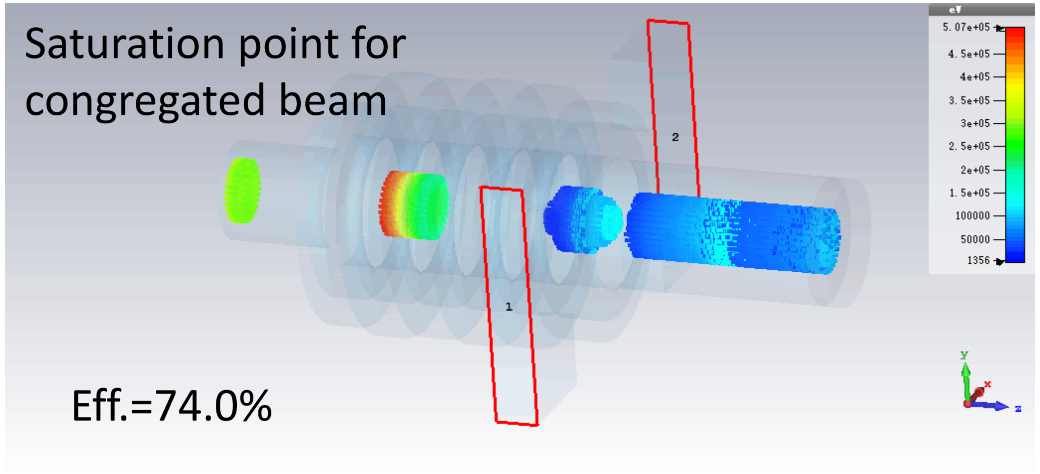
✓ Eff.~57.4%; E_{max}~87kv/mm; -1dBbandwidth~[-20MHz,15MHz]; Pin=80W

6-cell output cavity design for 50MW tube

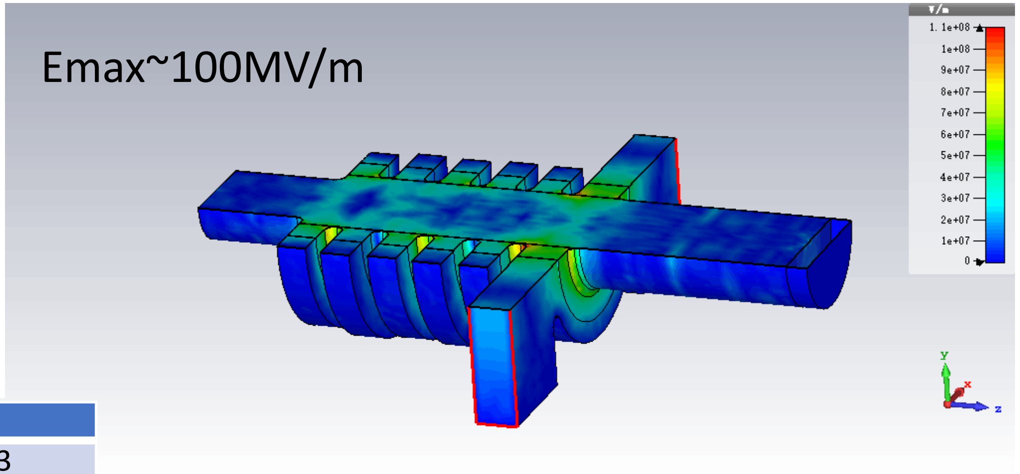




modes	1	2	3	4	5	6
f /KlyC	10.56	11.05	11.60	12.07	12.20	12.43
Qext	214	93.9	40.8	75.0	148	2071
f /CST	10.63	11.02	11.51	12.04	12.21	12.46
Qext	359	114	38.1	76.4	102	1994



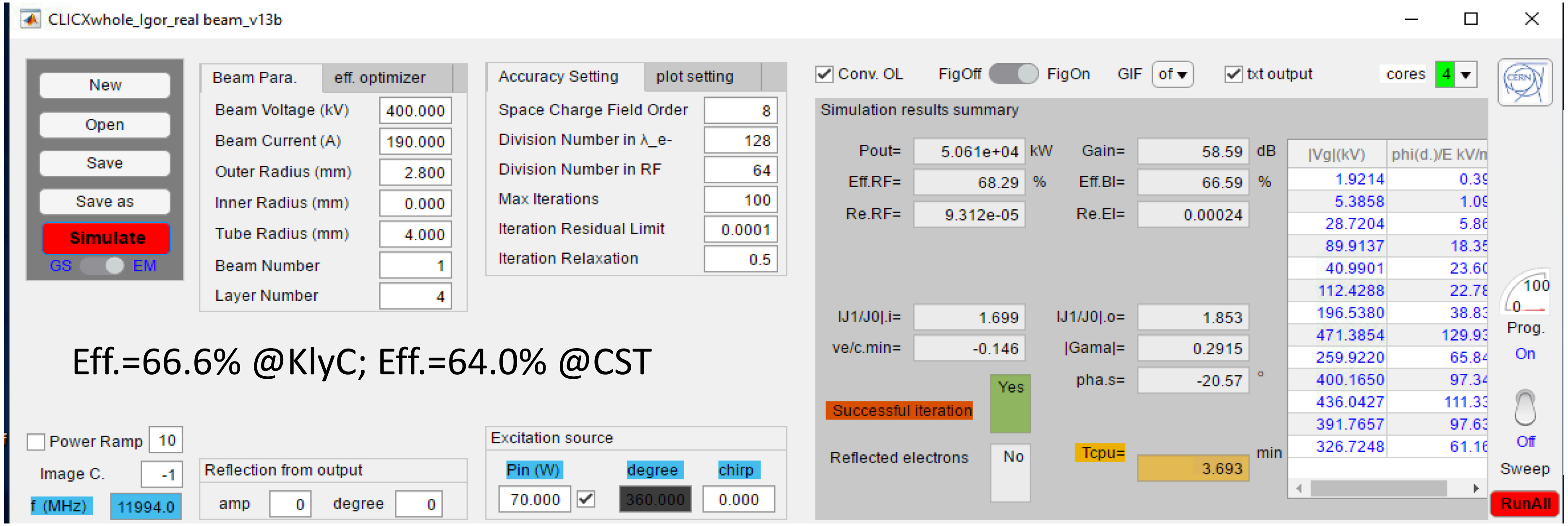
Beam dynamics



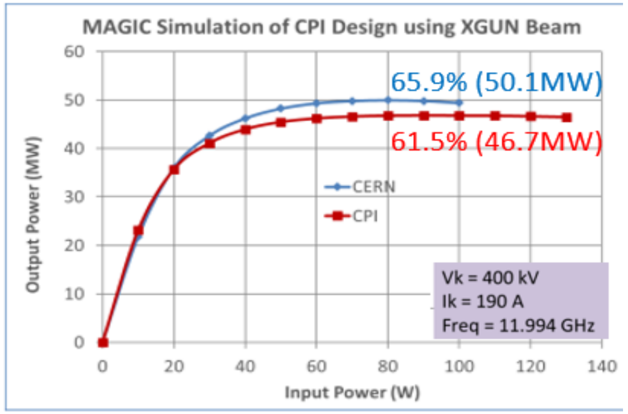
Electric Field Distribution

- ✓ If single output waveguide is used to extract the power, the efficiency performance will be more or less the same with slightly offset the center of the cavity from the center of the beam tunnel
- ✓ Previously, SLAC has a TW version of coupling cell design, but slightly less efficient

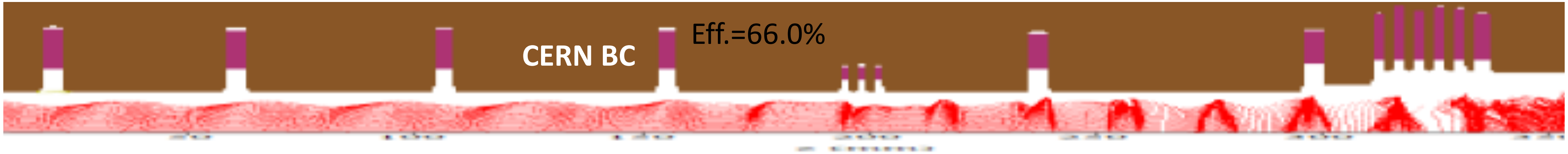
Final shortest version (L=316mm, baseline for final version)

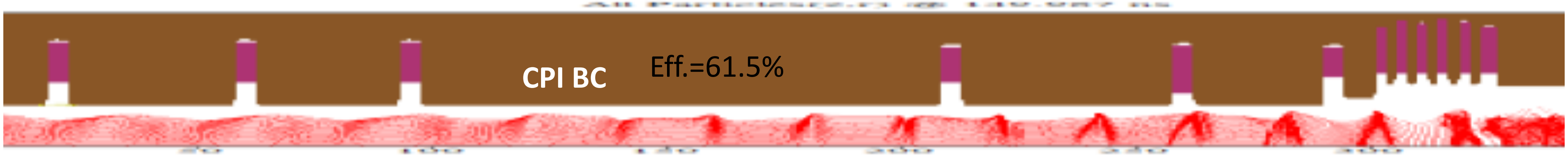


Eff.=66.6% @KlyC; Eff.=64.0% @CST



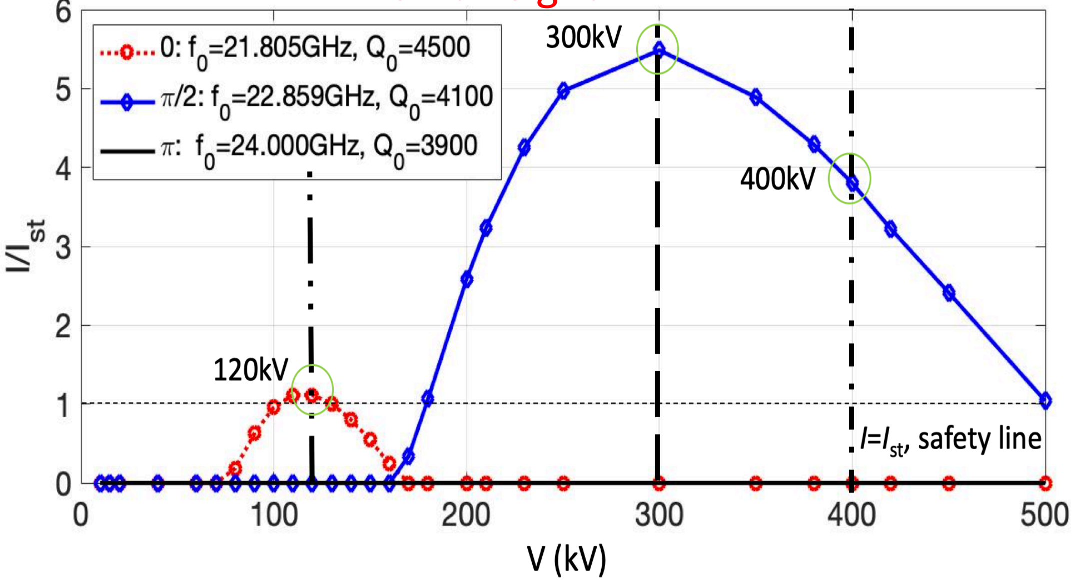
XGUN beam 0.35T Length is compatible with existed beam optics system



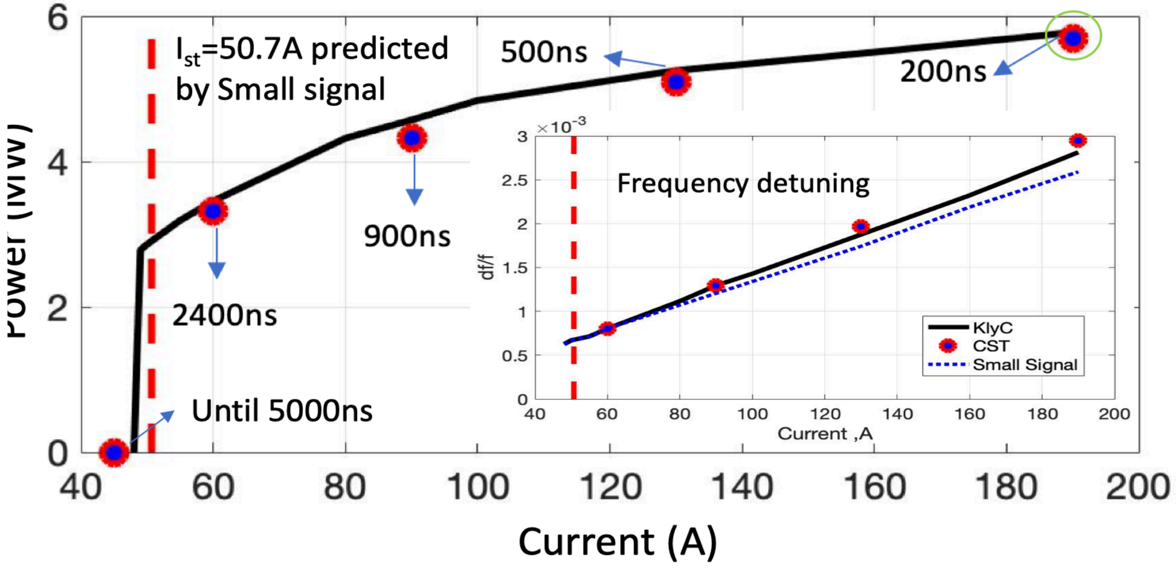


Monotron oscillation module

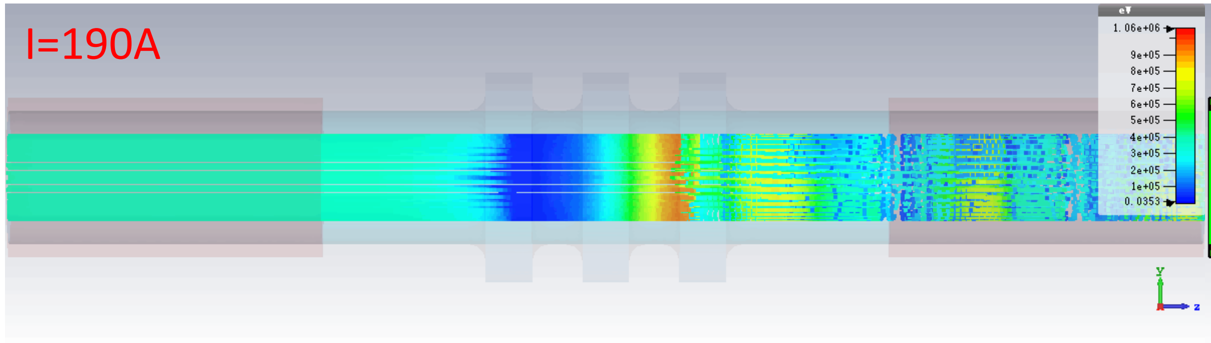
Small signal



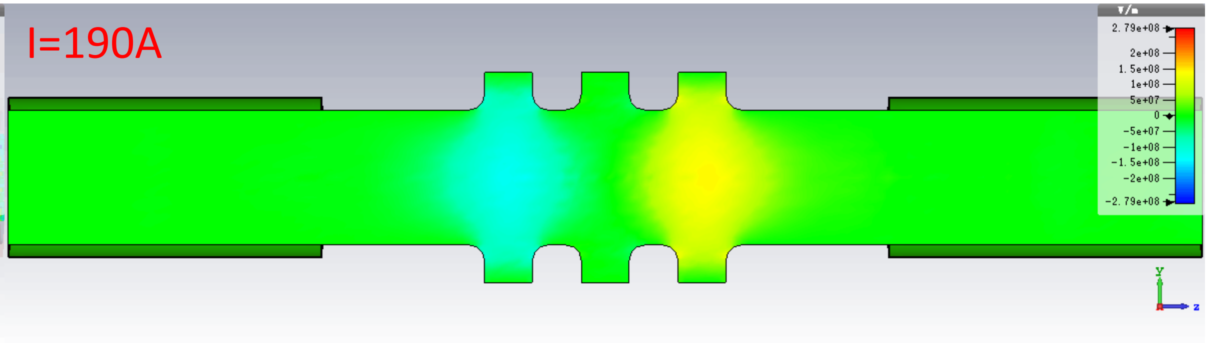
Large signal



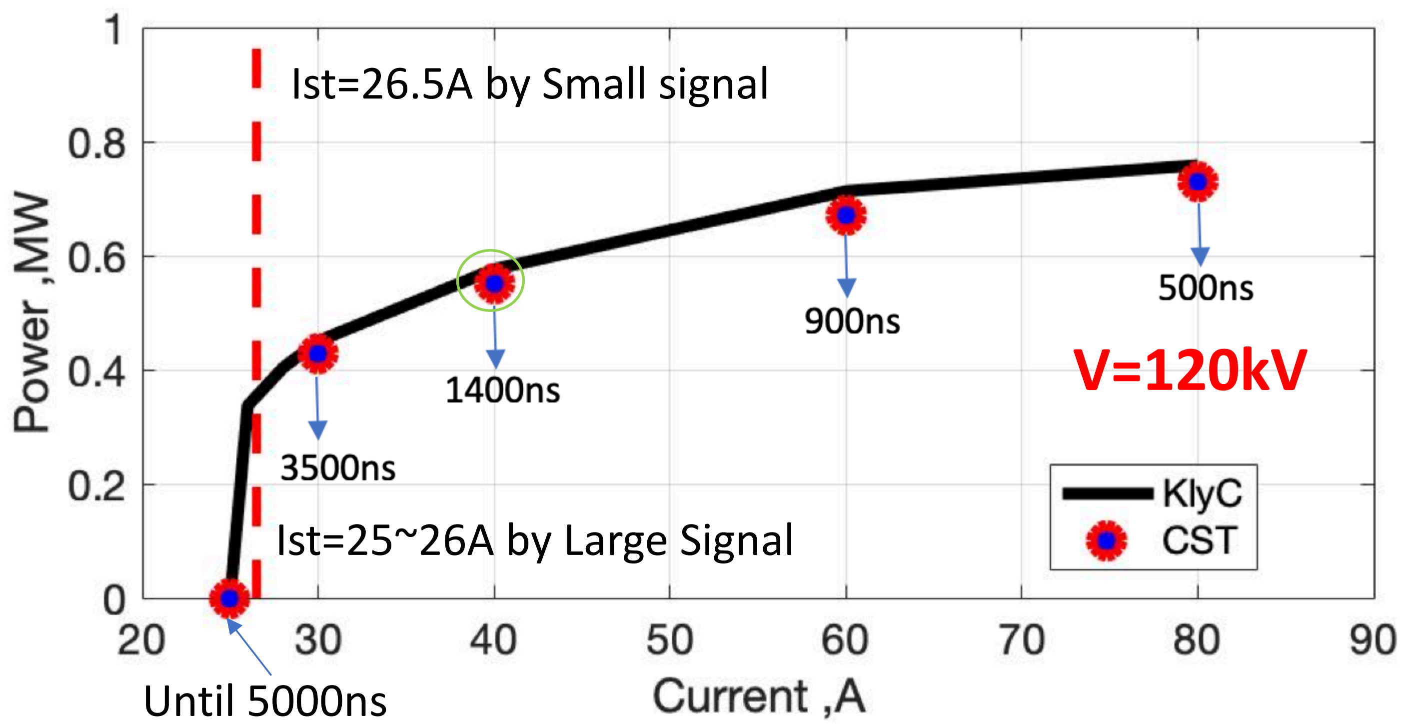
I_{st} is simulated by KlyC, I is calculated by voltage using fixed beam perveance (190A/400kV)

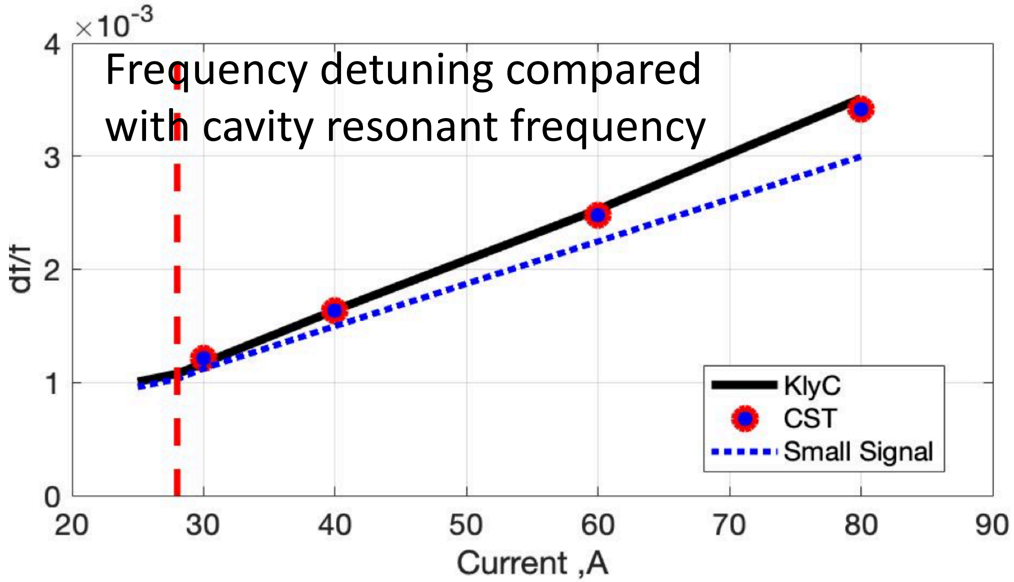


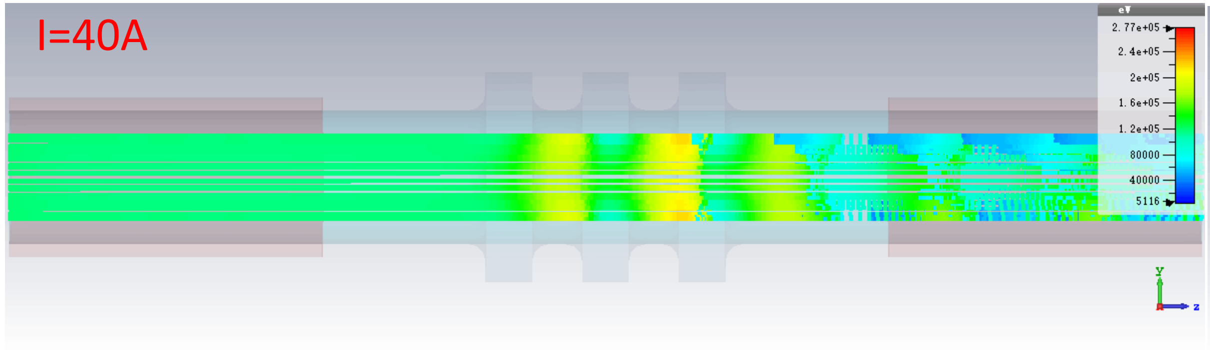
Beam dynamics in CST PIC



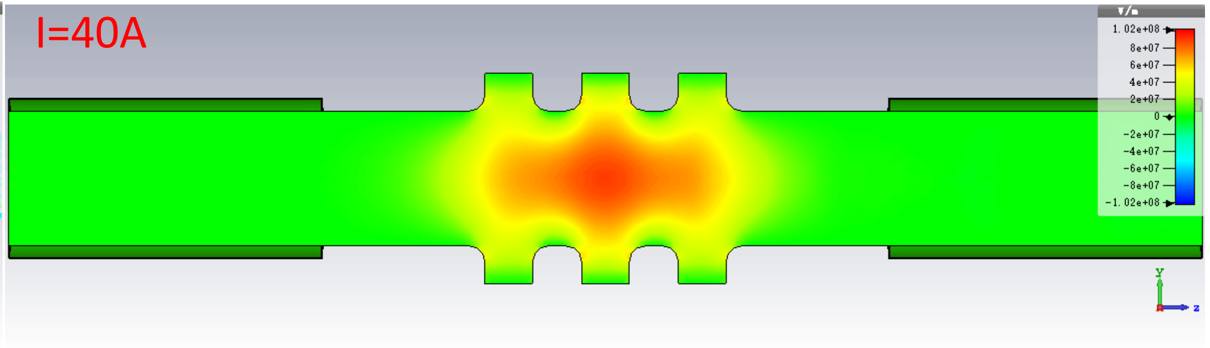
Pi/2 mode oscillated in CST PIC





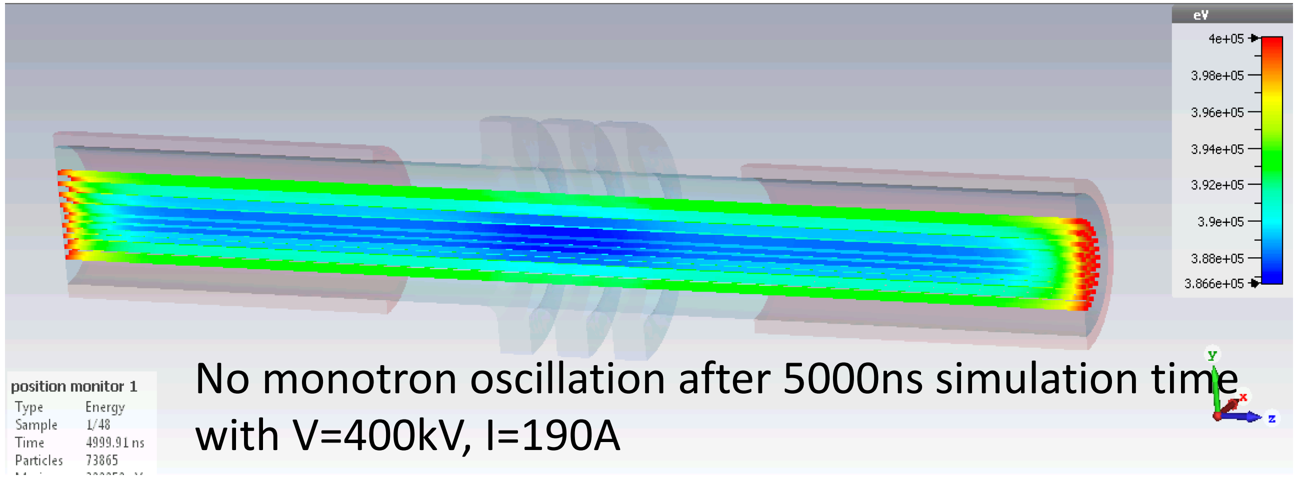


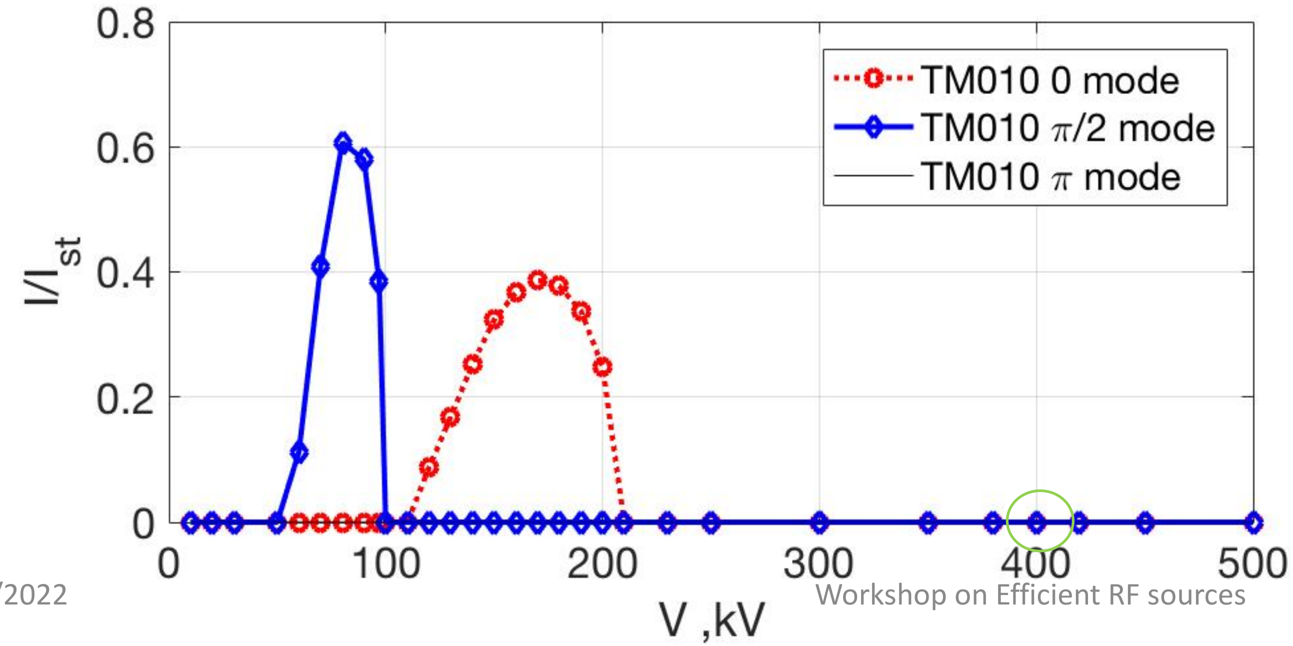
Beam dynamics in CST PIC



0 mode oscillated in CST PIC

Updated triplet with shorter period

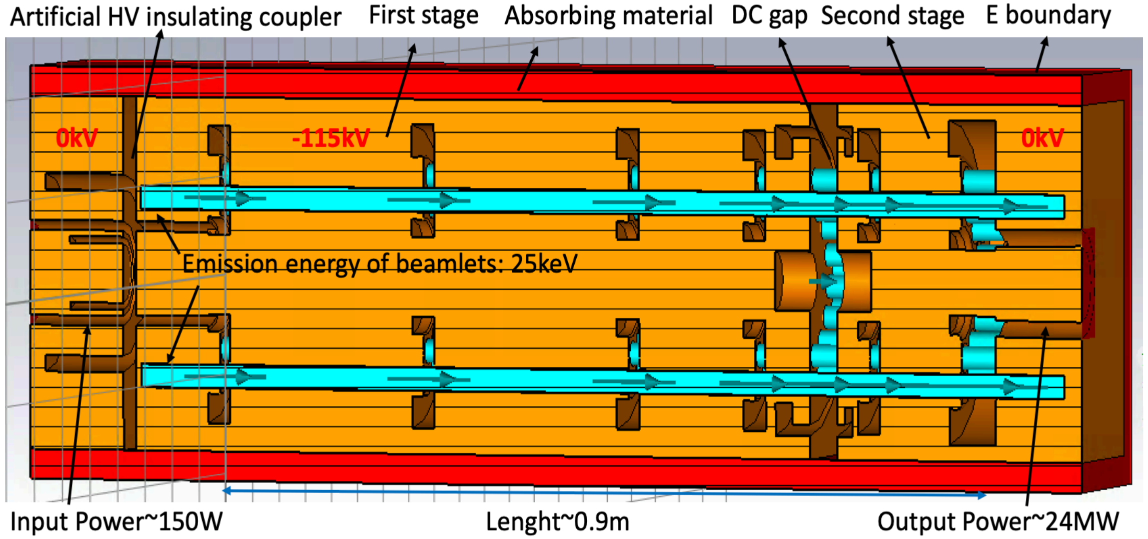




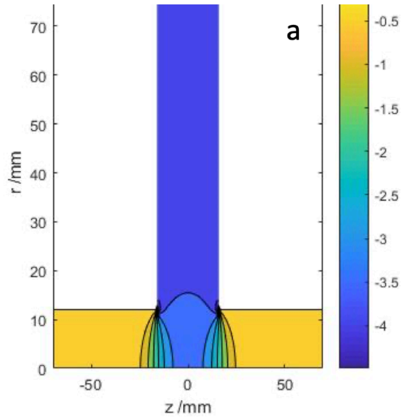
- ✓ Based on small signal theory analysis, updated triplets design (p=3.8mm) shows no monotron instability in all frequency ranges;
- ✓ It is confirmed in CST PIC that the operating point is stable in 5us simulation time; The real pulse length is around 2ms.
- ✓ New triplets replaces the original one in 50MW X band Klystron; Slightly frequency tuning to compensate the impedance degradation of TM010 pi mode.
- ✓ KlyC optimization for updated 50MW tube is done which shows 67% saturation efficiency, while CST shows 62% efficiency as verifications.
- ✓ Magic PIC simulation has also been done in CPI to further confirms tube can yield 65% saturation efficiency without any instabilities

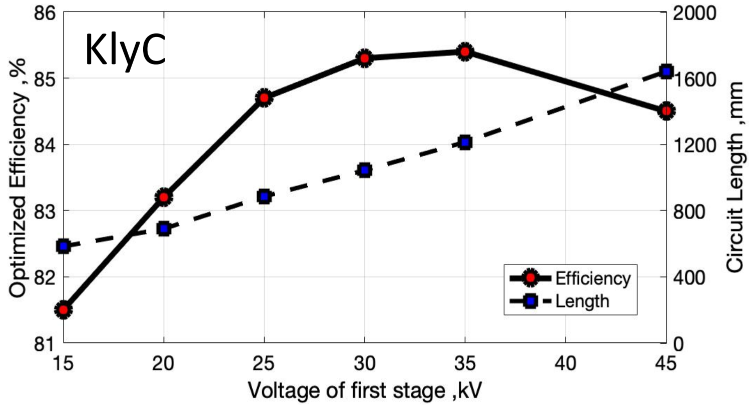
Wave-beam interaction module & Electrostatics module. Two Stages CLIC MBK

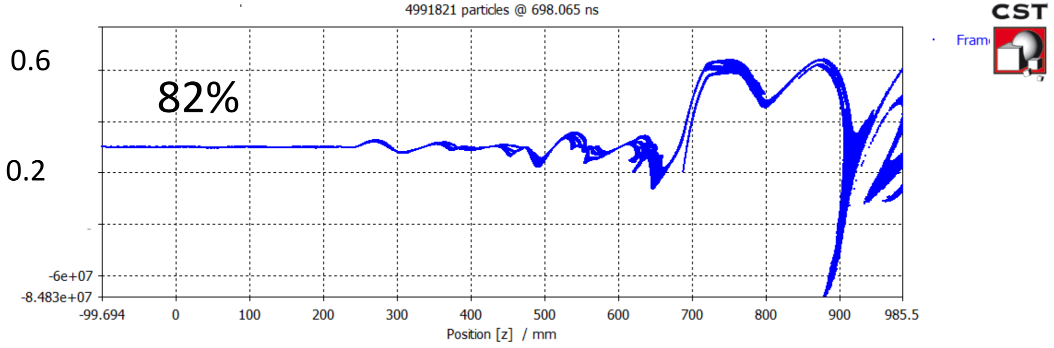
30 beams, 24 MW, 1GHz. CST/3D model.

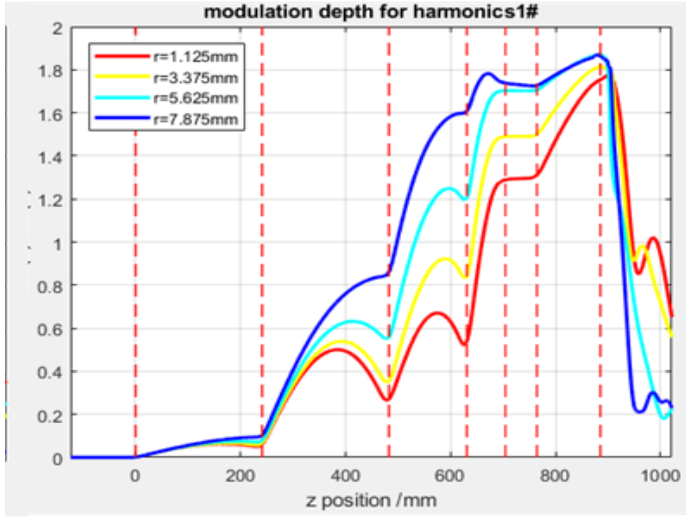


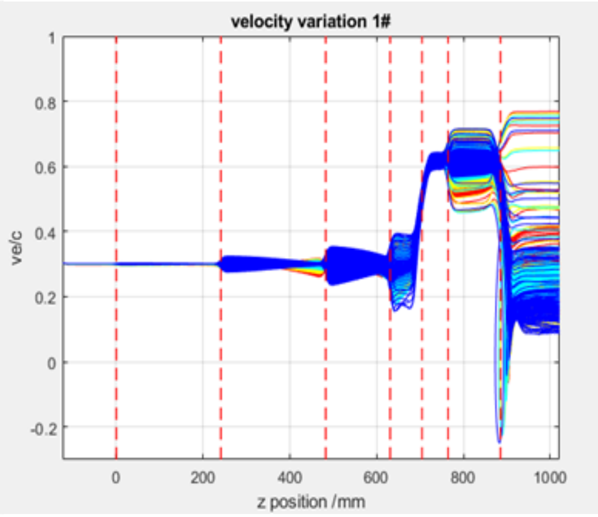
DC gap field

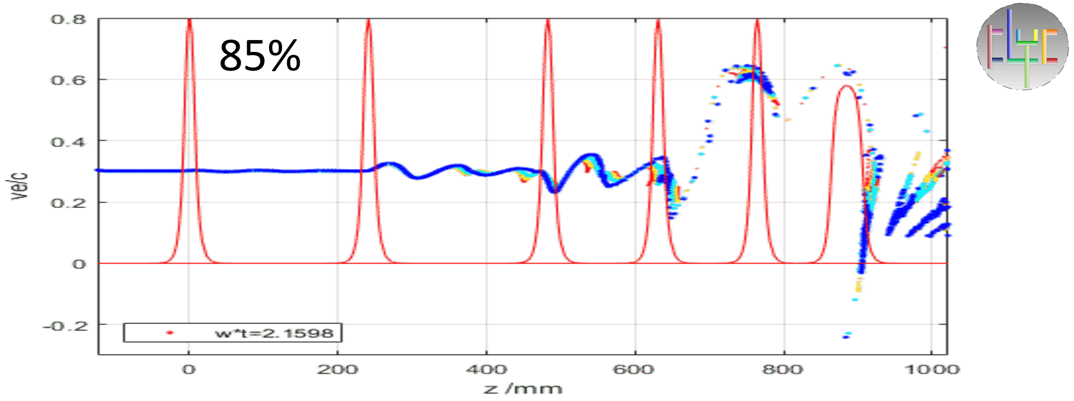






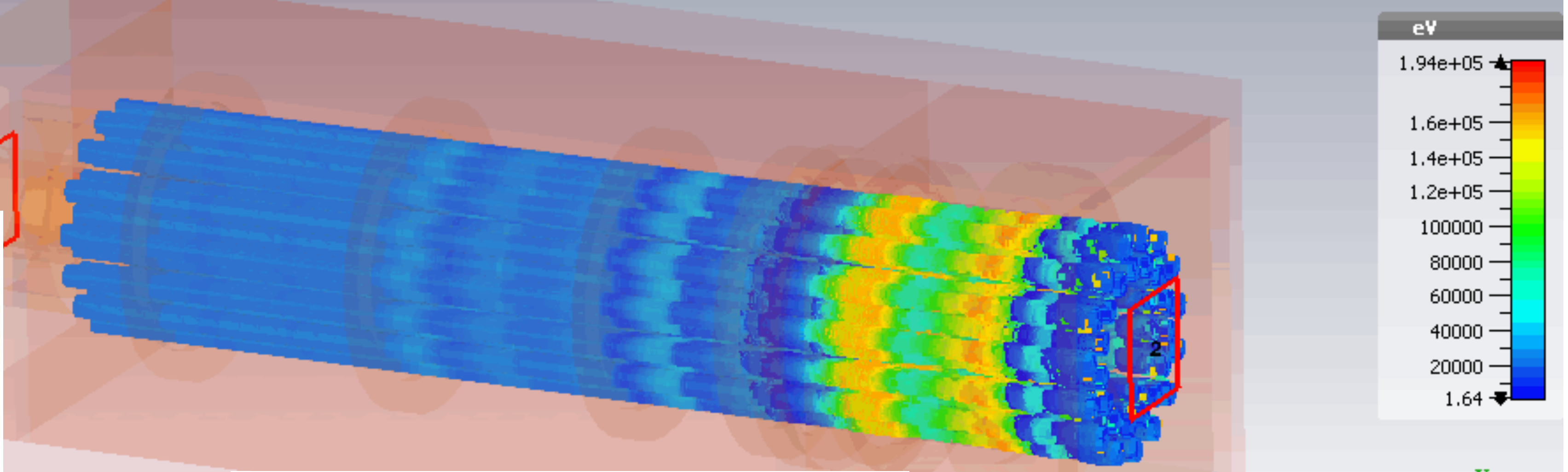


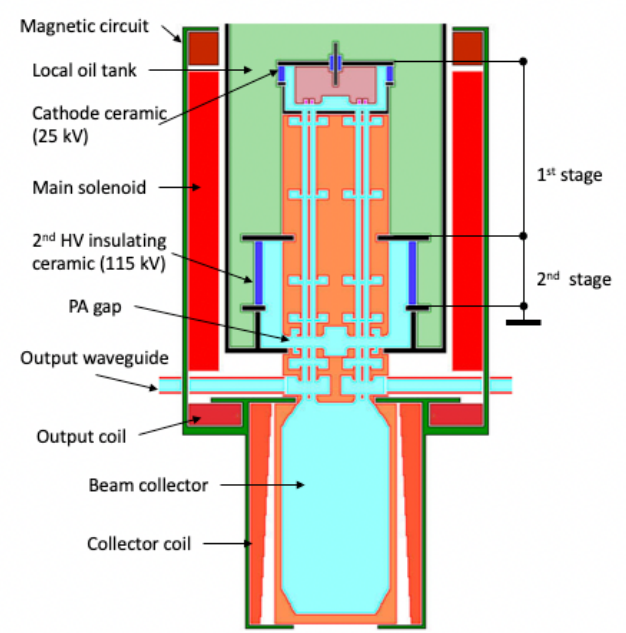


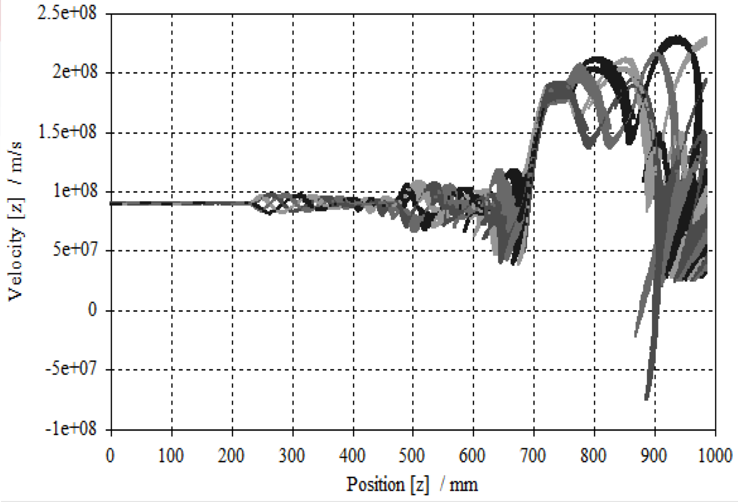


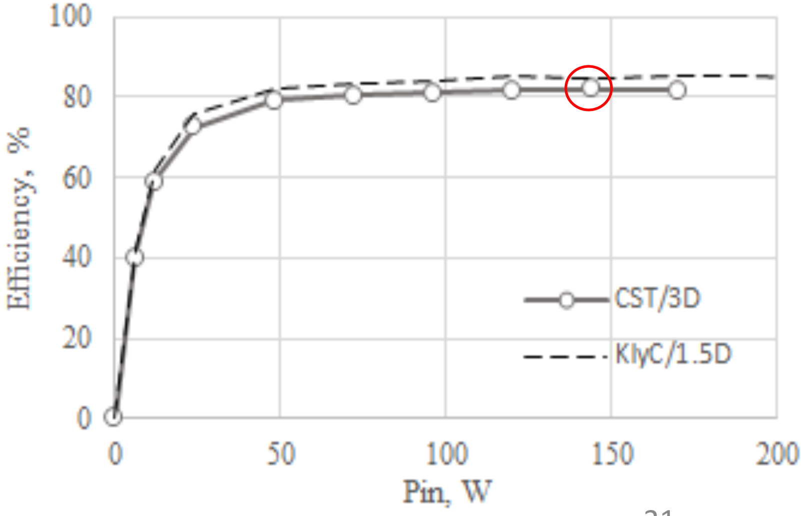
High Efficiency 24 MW, 1 GHz, CLIC TS MBK. Full PIC CST/3D simulations

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).

Outline

- Background
- Home-made codes:
  - KlyC : 1.5D large signal Klystron simulation code
  - CGUN: 2D beam optics code
- Summary & updates

Simulation Tool

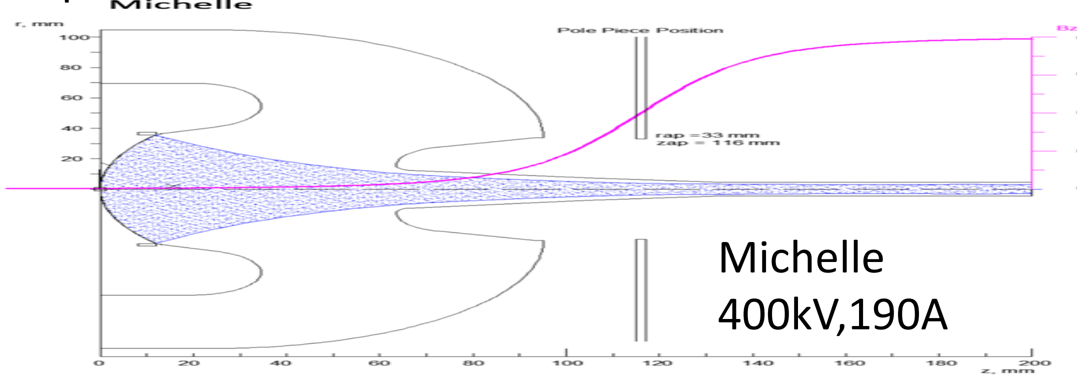
- CST TRK, DGUN, CGUN (home-made 2D code)

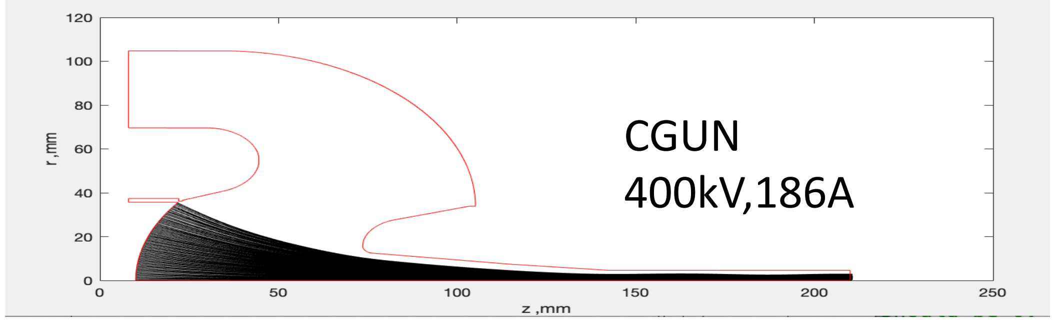
Beam optics module

Some benchmark results for complicated cases

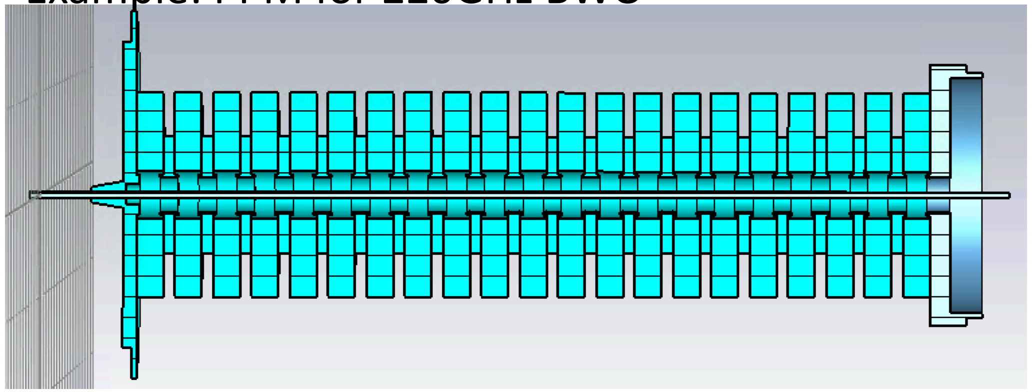
Magnetic module

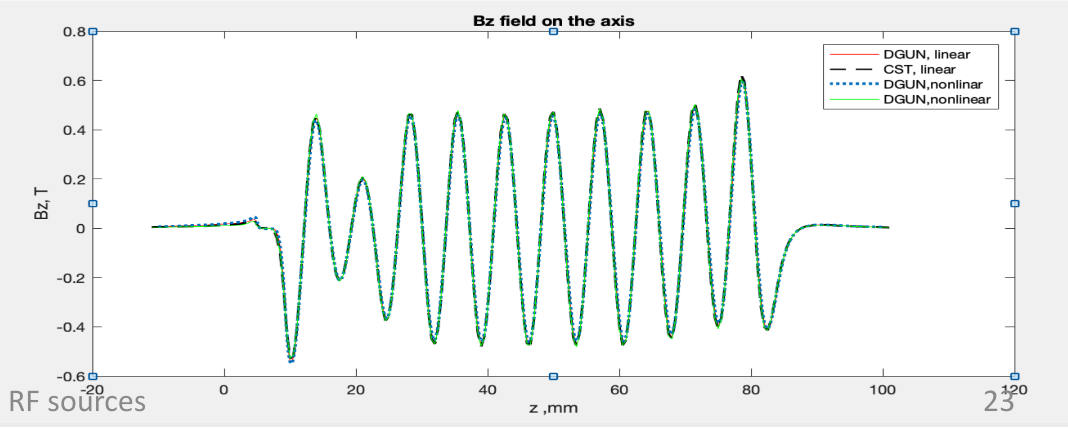
Example: GUN for SLACX



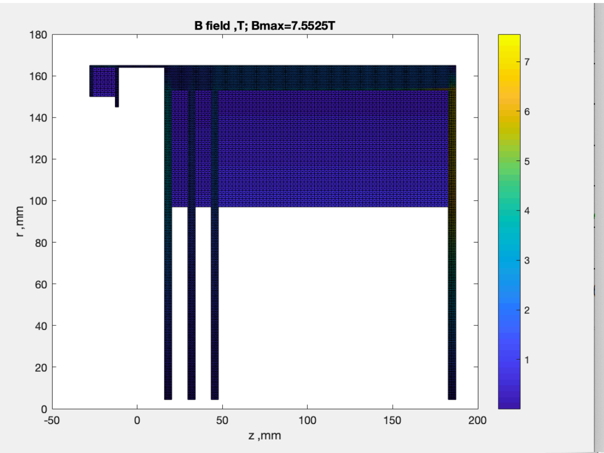


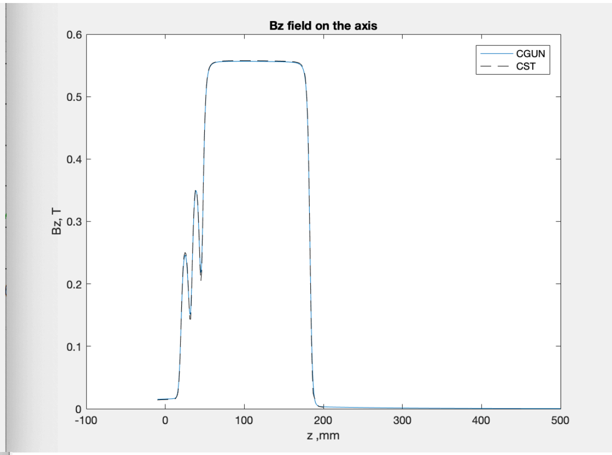
Example: PPM for 220GHz BWO

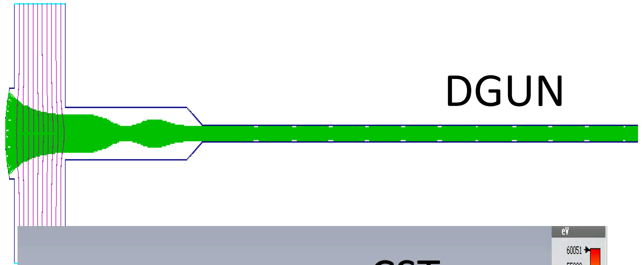


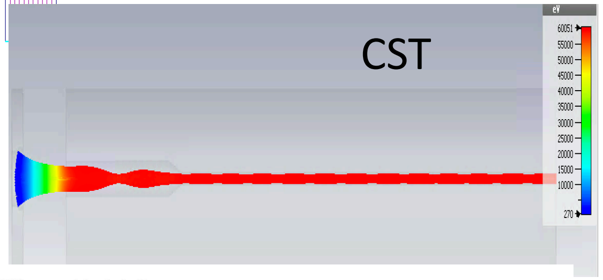


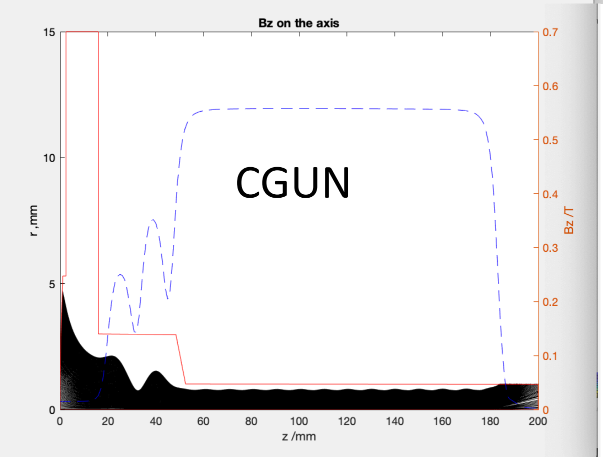
36GHz HOM MBK optics design and benchmark

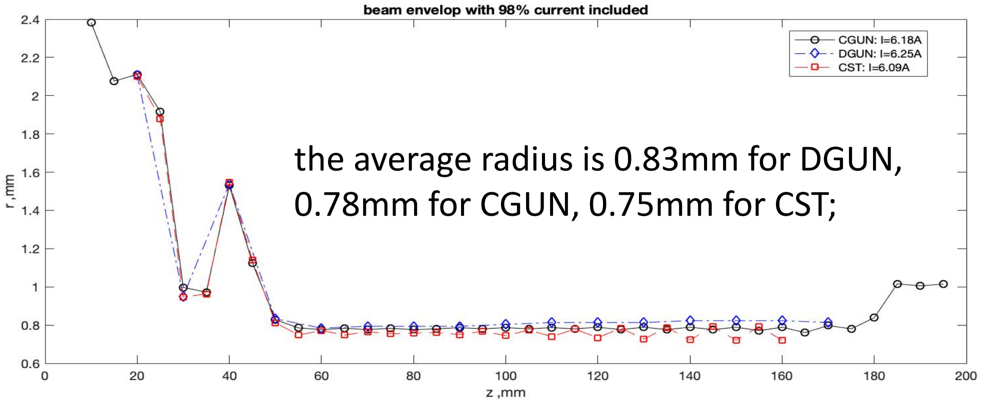






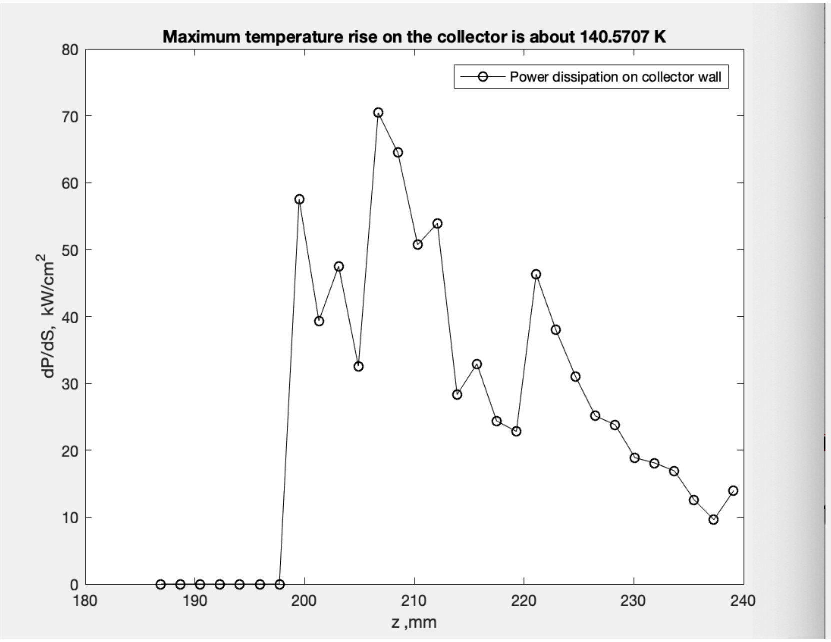


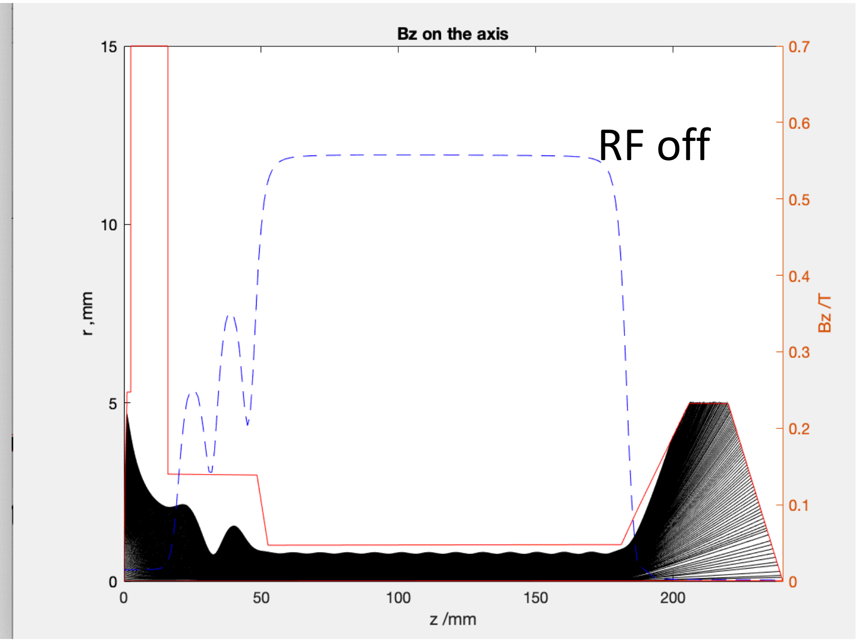




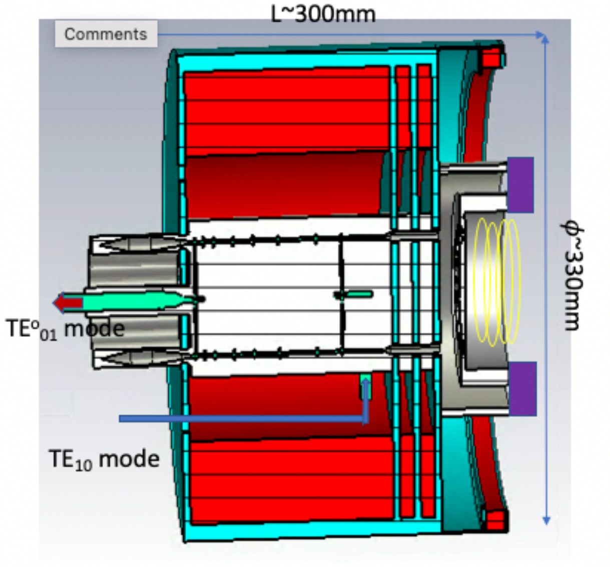
- ✓ CGUN is fast 2D optics code could get very accurate results for axial-symmetric system in fast manner;
- ✓ CGUN is more suitable for analyzing system with GUN section, magnet as an integrity
- ✓ CGUN has been developed and integrated into KlyCv6

Collector design by CGUN

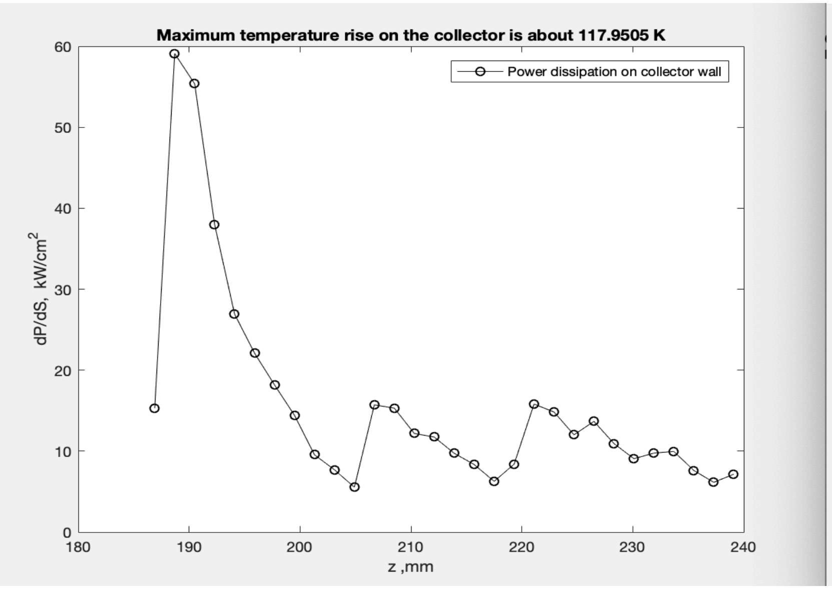


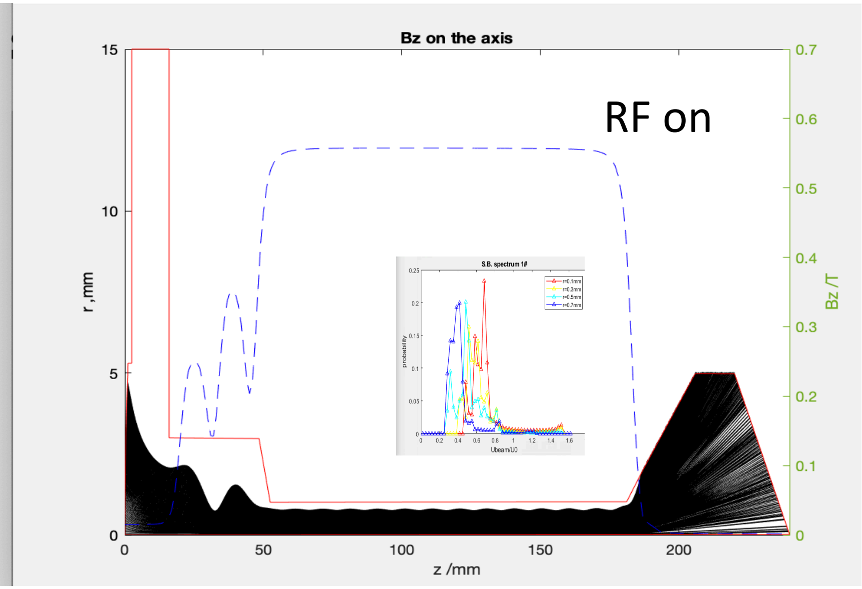


Considering the duty circle is 1/1000, the average power dissipation denstiy for DC and RF case is below 0.07kW/cm^2 and 0.06kW/cm^2.



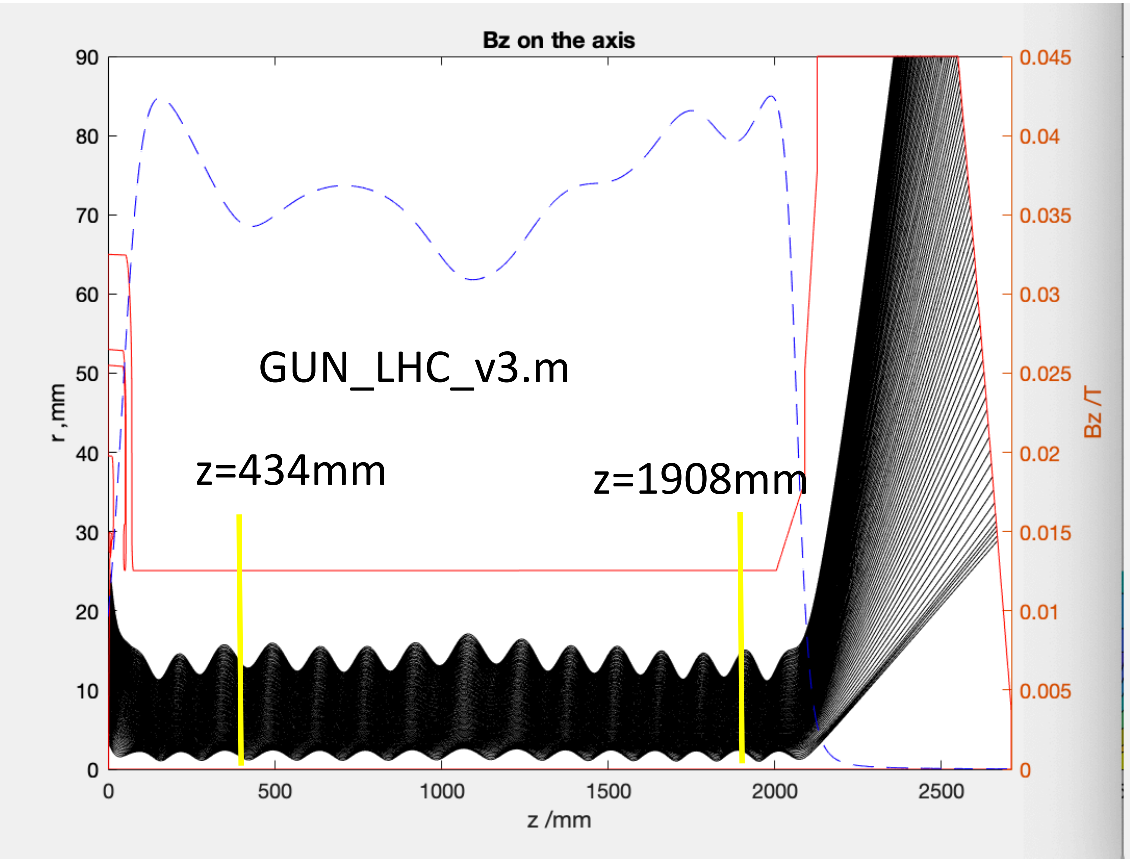
36GHz HOM Klystron configuration

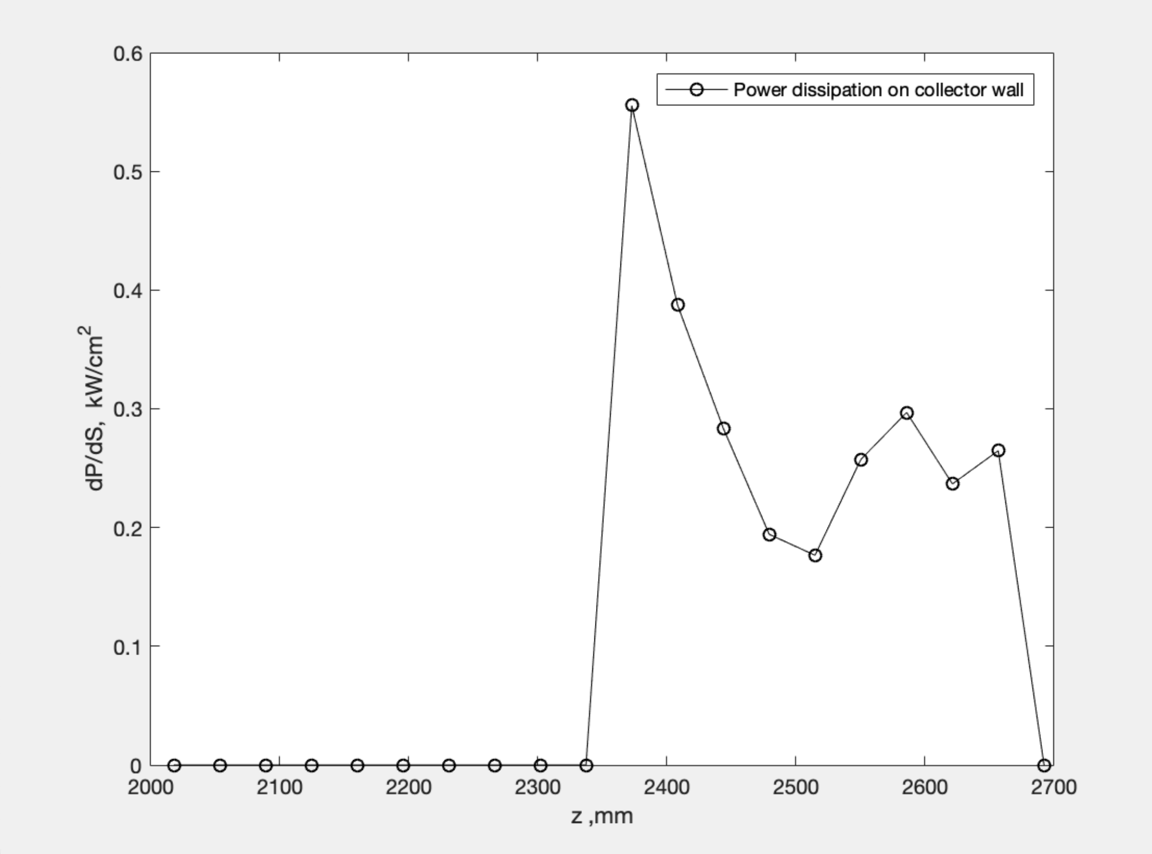




60kV, 6A*20, P=2.3MW

Vc=-54kV, Va=-23.2kV, I=9A (HE LHC design)

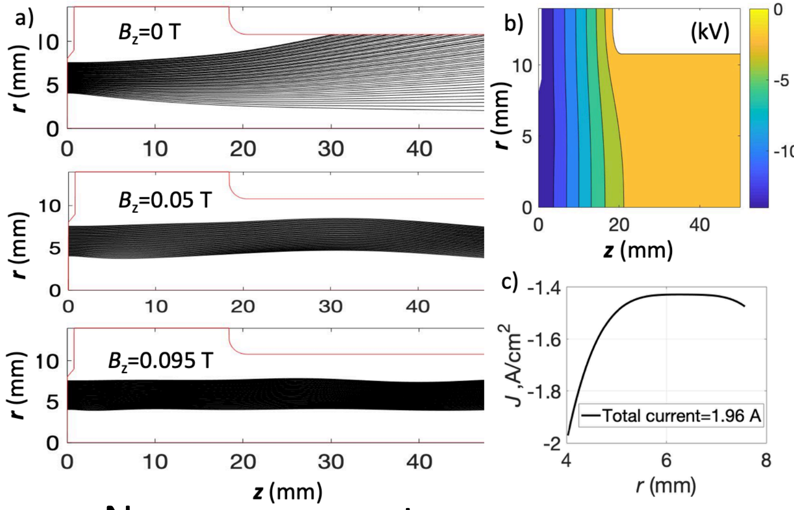




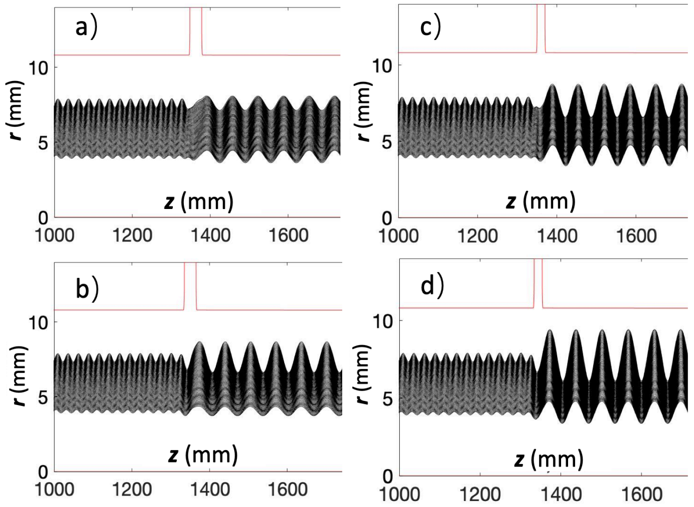
We could roughly say that the maximum dissipated power density on the collector wall is 0.55kW/cm^2, so it is suitable for CW operating even in DC mode (The conventional limit for water cooling is 0.5KW/cm^2).

Collector profile is not modified since DC & RF dissipation are acceptable

0.4GHz TS MBK 80kV version optics study

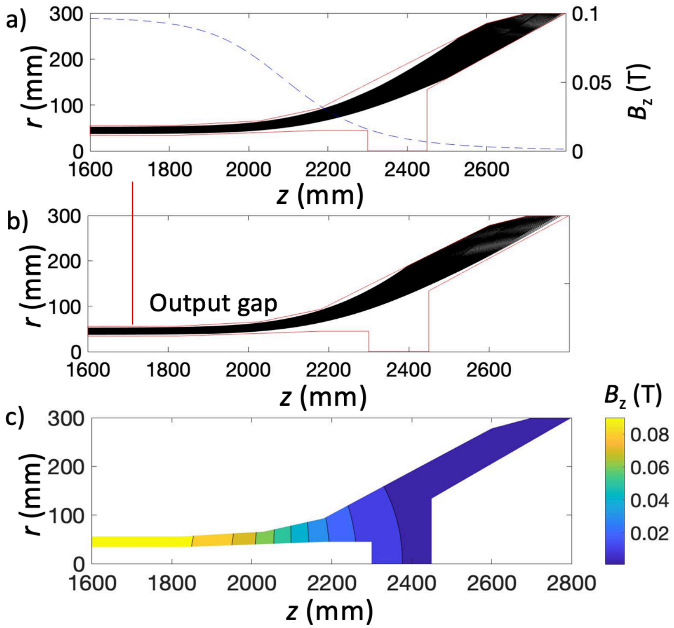


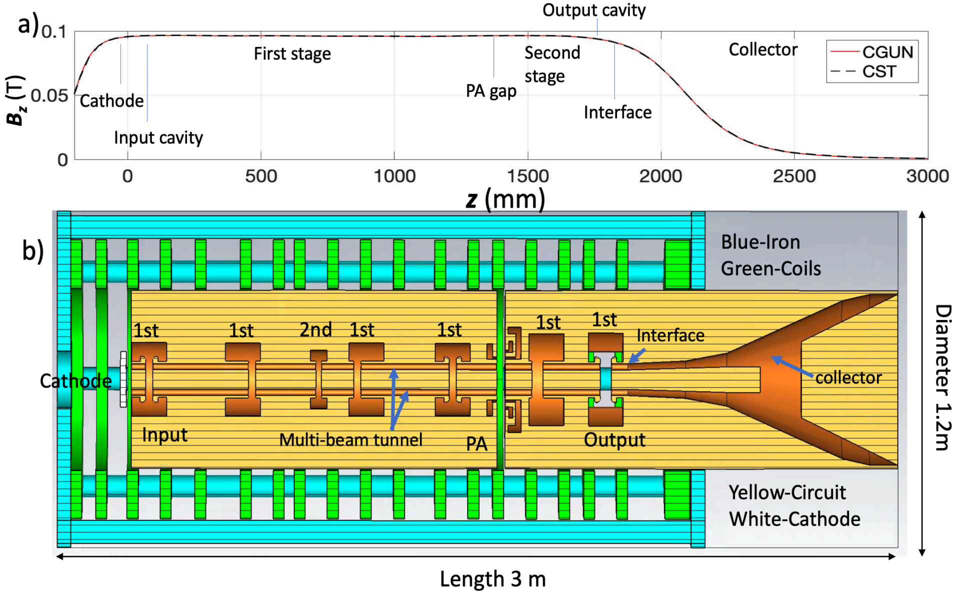
Non-convergent gun

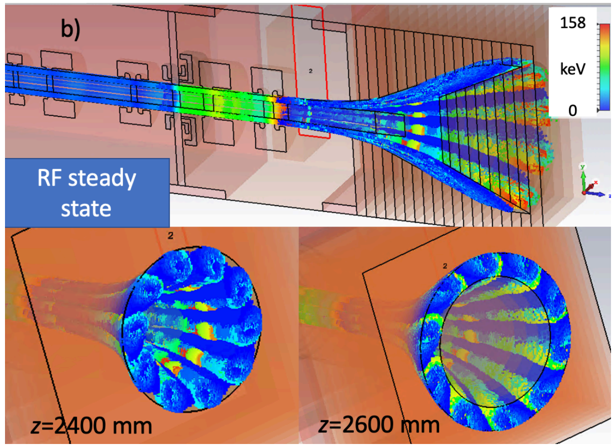


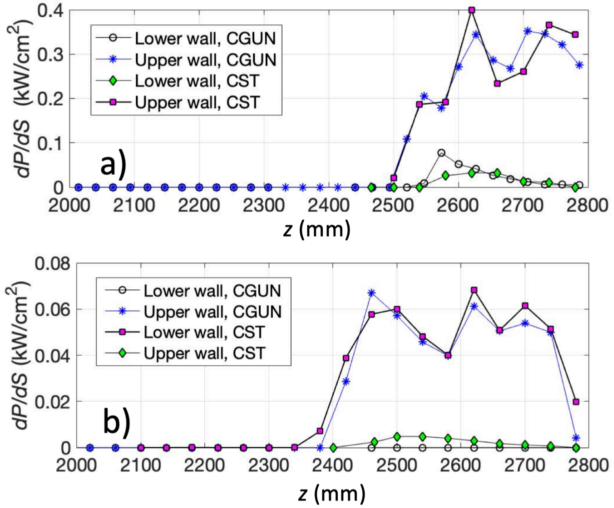
PA gap (Bz, gap length)

Collector & 2D B-field









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Summary & Updates

- KlyC is a fast and accurate simulation tool for mainstream Klystrons (single beamlets, MBK, EIK).
- KlyC has been used on many HE Klystron design and benchmarked with 2D/3D PIC code. Some of the tubes are to be fabricated and tested.
- CGUN is beam optics simulation tool as a complementary module to KlyC. Most of the Klystron design/optimization work could be done in KlyC & CGUN package.
- KlyC has been redistributed to lots of CERN partners and collaborators since the software was released from 2017 and has been upgraded every year for better performance and more useful functions.
- Updates…

Thanks for your attention!