Development of X-band High power High efficiency Klystron

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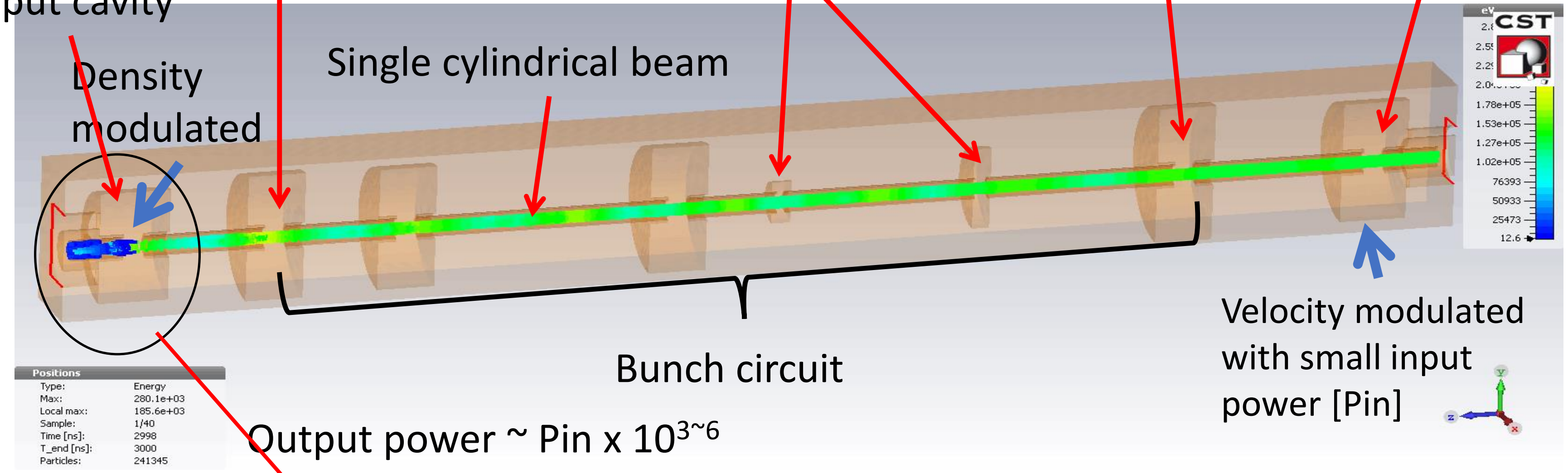
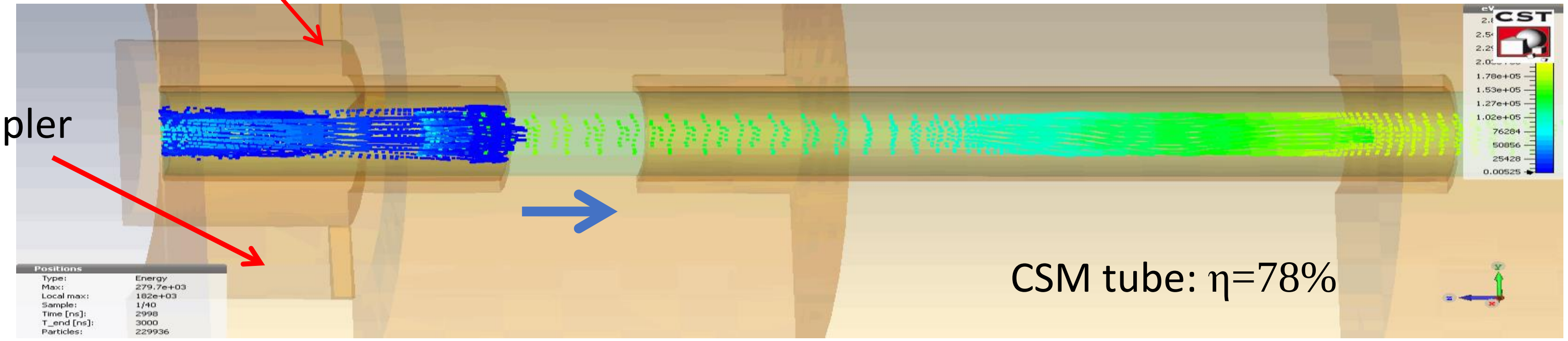
Special thanks: T.Kimura (CPI), T. Anno (Canon)

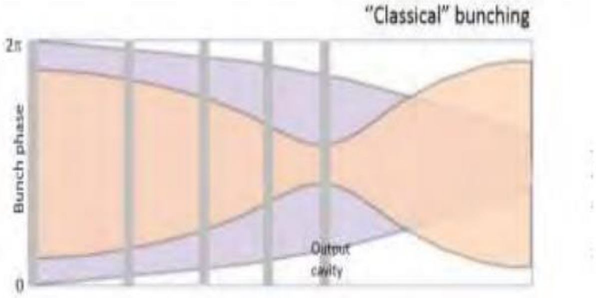
Outline

- Background
- RF circuits design
  - KlyC : code review
  - Multi-cell output cavity, bunch circuit
- Instability issues
  - Monotron oscillation
  - Multipolar modes oscillation
- Beam optics design
  - CGUN: 2D optics code freshly developed
  - GUN, magnet, collector

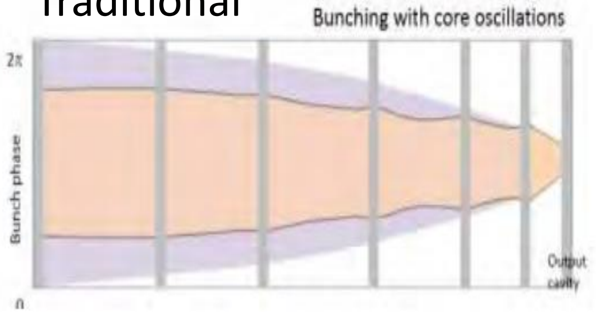
HE klystron: Mechanism and concepts



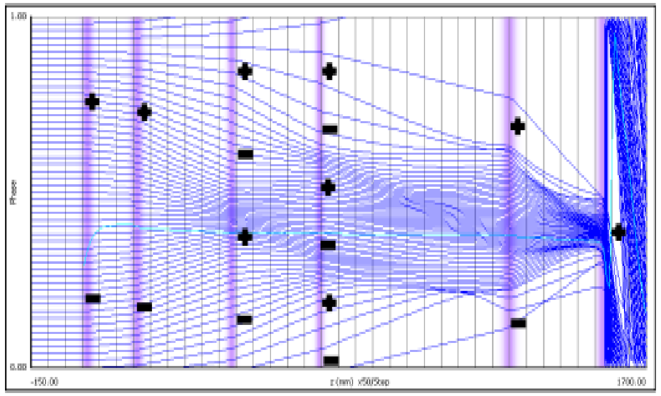




Traditional

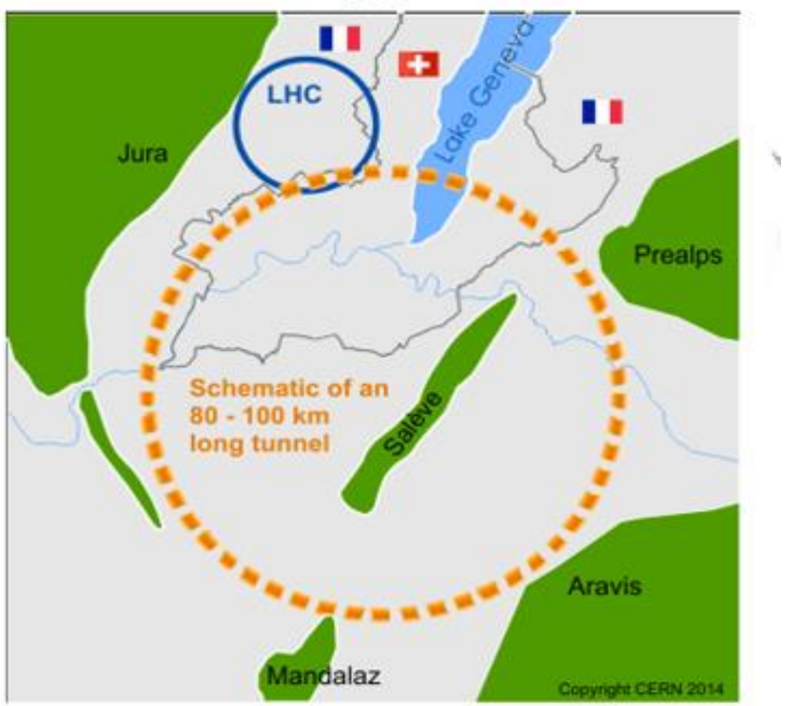


Core oscillation method (COM)

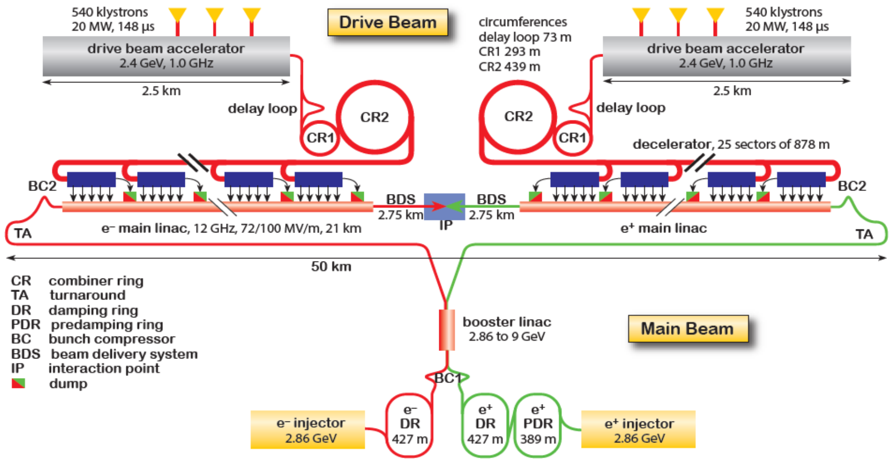


Core stabilization method (CSM)

Glossary: Saturation, velocity congregation, Radial stratification



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**

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

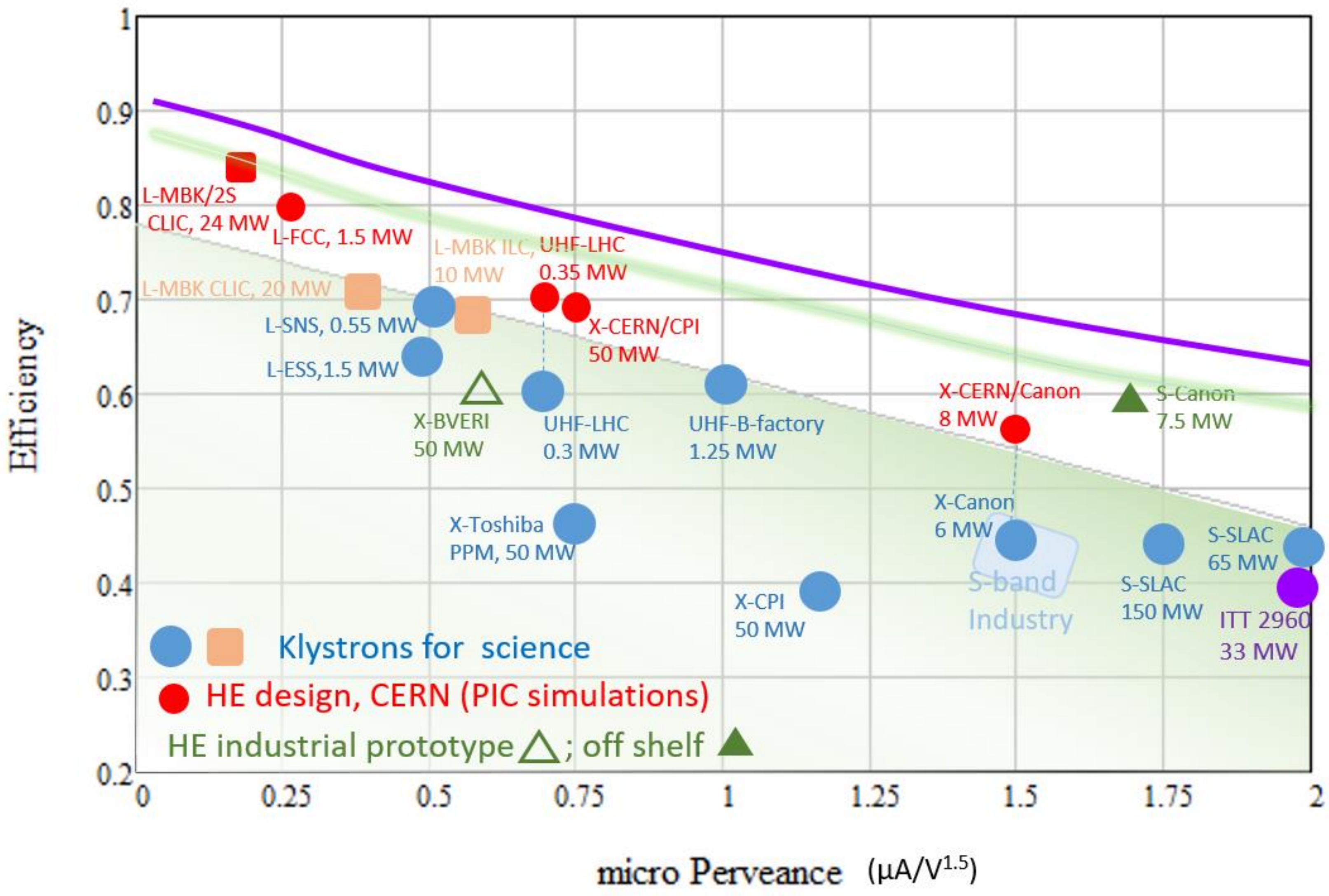
The klystron efficiency impact on the CLIC 3TeV power consumption.
Example of the efficiency upgrade from existing 70% to 85%.

	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!

High efficiency klystron development at CERN



- The new klystron bunching technologies have been established and evaluated.
- The computer code KlyC/2D and special scaling procedures have been developed.
- A number of high efficiency klystrons has been designed.
- Ultimate efficiency by giving the beam perveance is limited by space charge effect (Purple line, idealized bunch).
- Practically, impedance inadequate, ohmmic loss, low bunching quality due to poor design or compactness requirement or bandwidth compromise will further decrease efficiency

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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]).

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.

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.

Bunched beam generator module[5].
Simulation of IOT and output couplers with bunched beam

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

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

Monotron oscillations module [3].
Simulates the threshold of monotron oscillations in the RF cavities (klystron stability issueS)

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]).

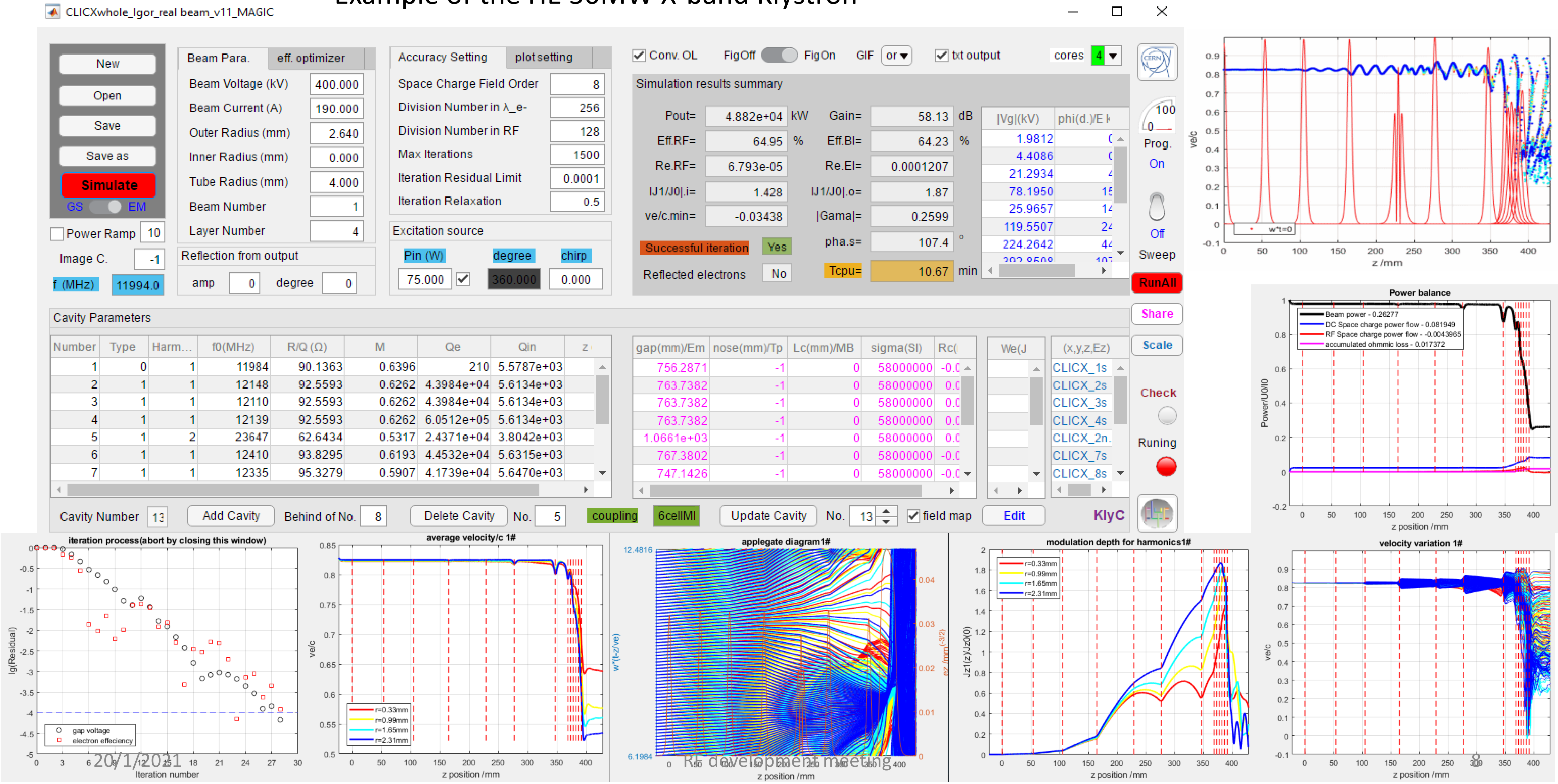
Magnetostatics module.
Simulates DC B-field maps in the 2D system with arbitrary shaped coils and iron shields (saturation etc.)

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)

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

Example of the HE 50MW X-band Klystron

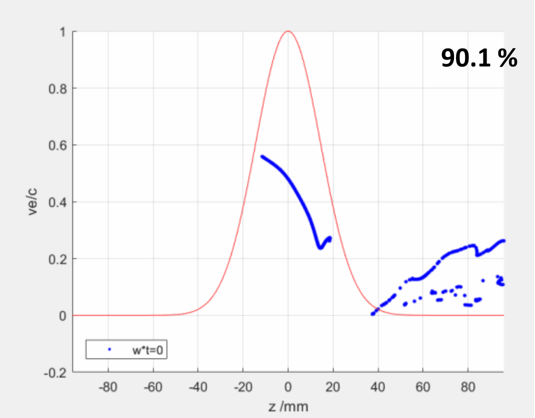


Bunched beam generator module.

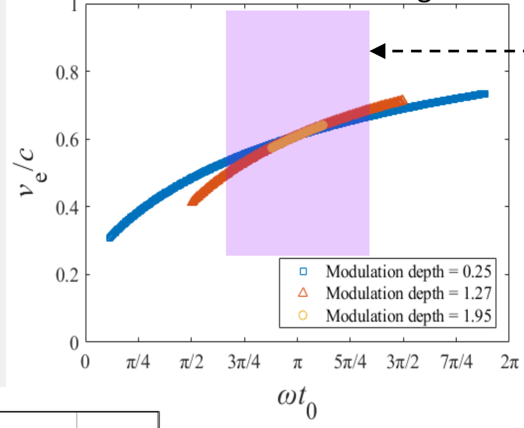
The ultimate power extraction efficiency in the linear beam devices

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

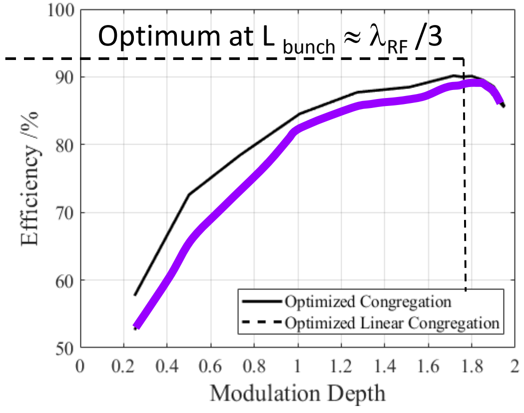
Fully saturated bunch with optimised congregation

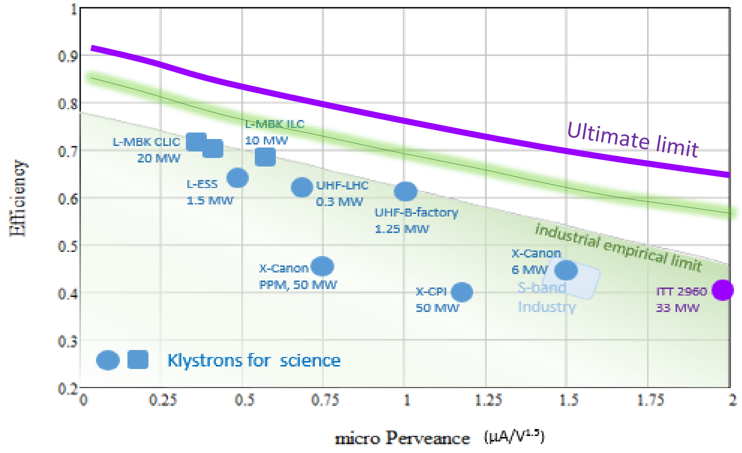


Optimised congregation for the different bunch lengths.



Effect of the bunch length





High efficiency Klystrons design objectives

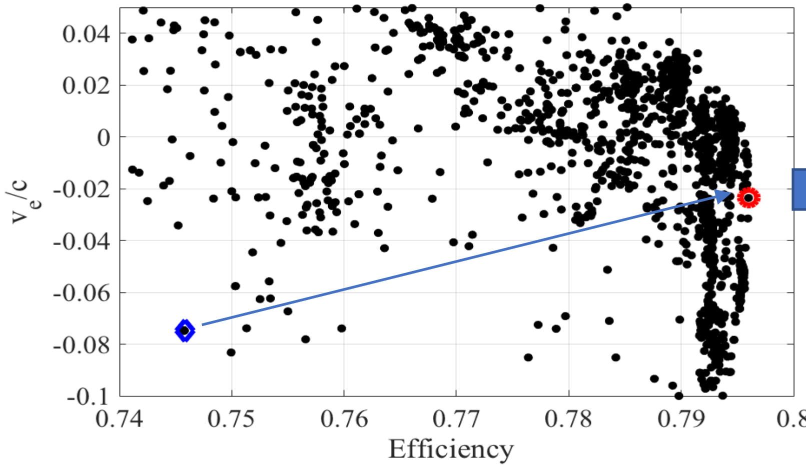
- E field expansion in the drift tubes
- Ohmic Losses
- Space charge depression
- Bunch saturation
- Bunch congregation
- Bunch stratification
- Radial bunch expansion

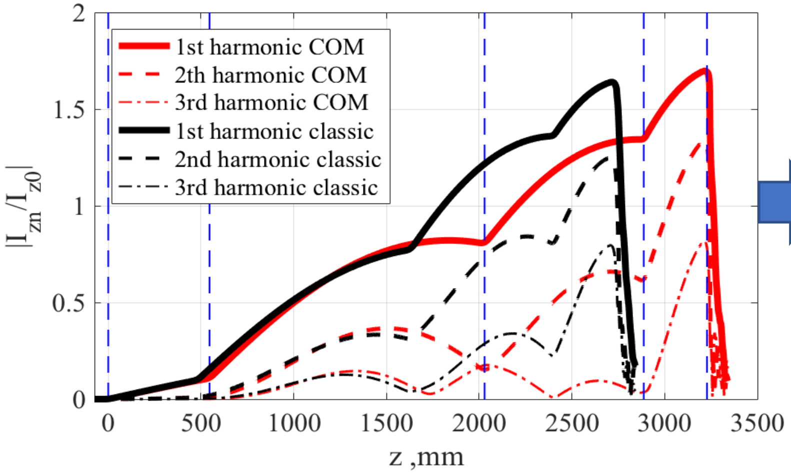
Optimised RF bunching circuit

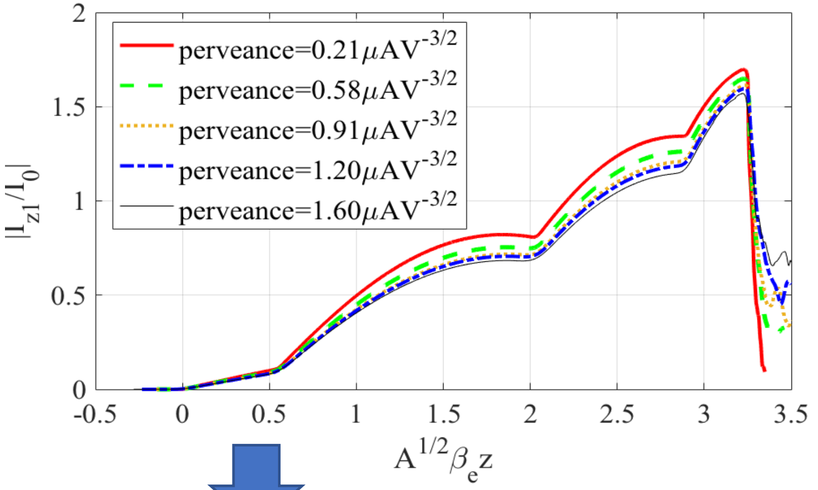
Parameters scaling module @ Klystron optimizer module

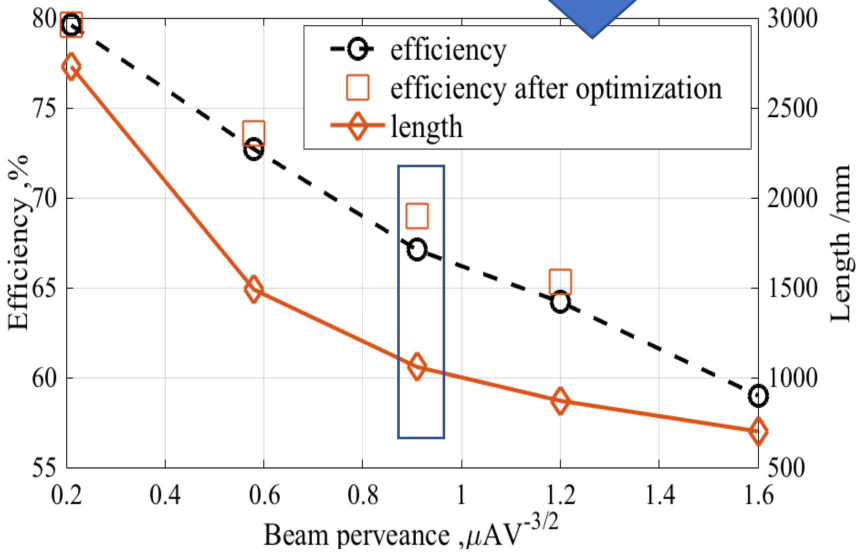
1GHz, 180kV, 16A, r_m=6mm, r_c=10mm

Parametric Scaling Procedures(PSP)

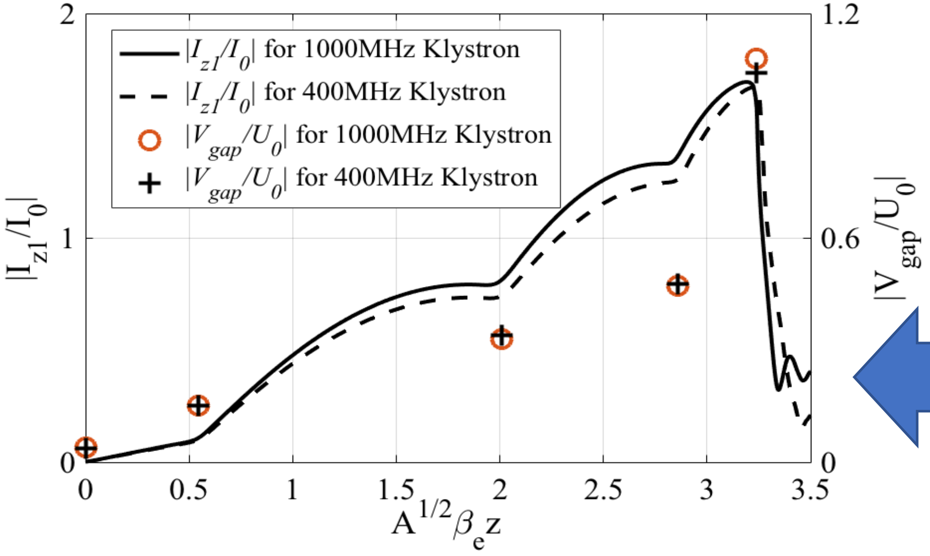






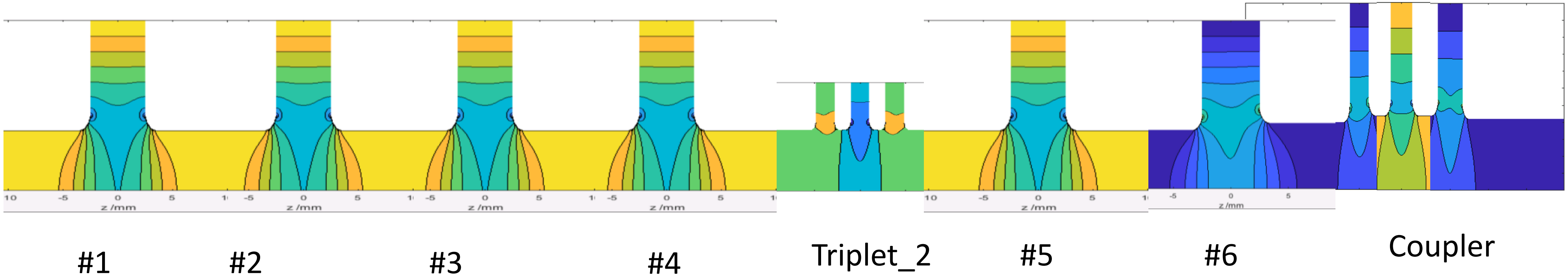


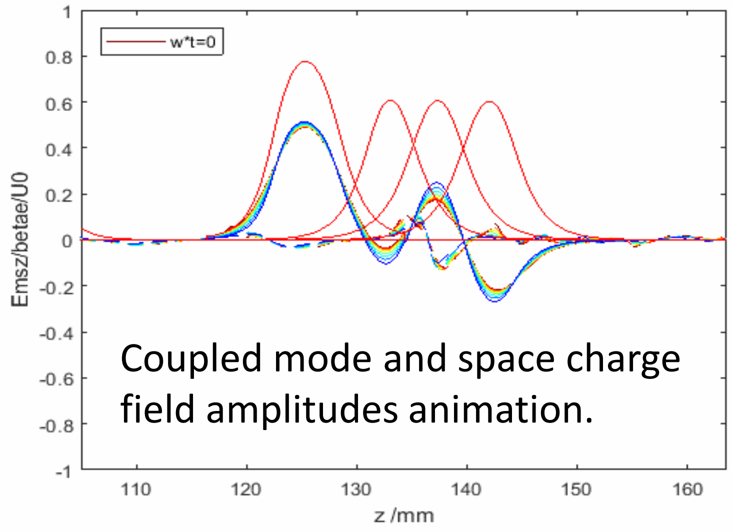
54kV, 9A, 0.4 GHz (LHC tube), 65.5% @1.5D

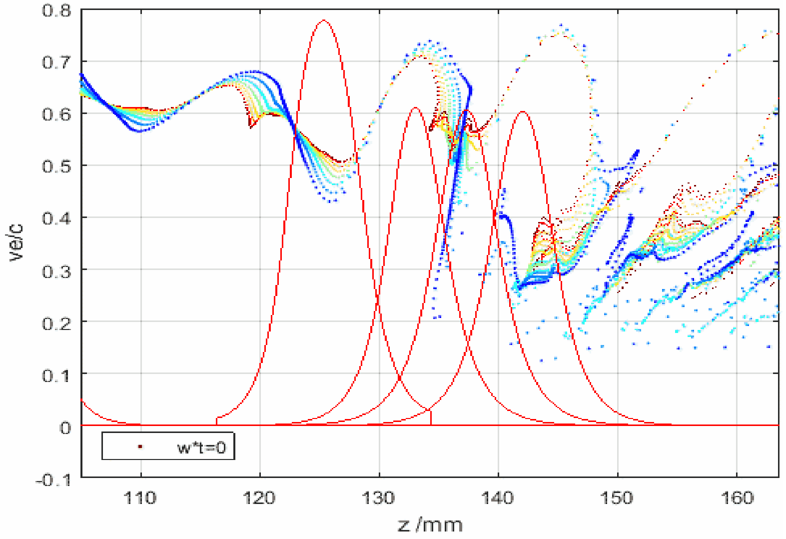


Coupled cavities module @ Electro-Magnetic module

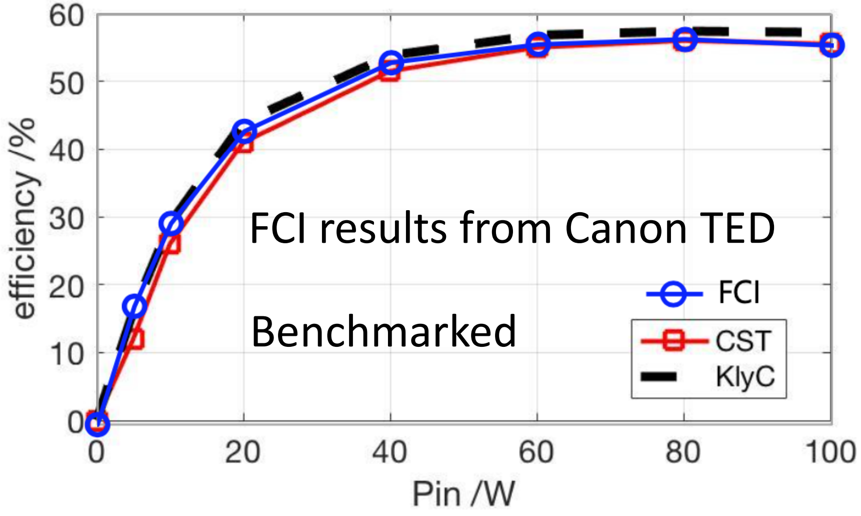
Compact 8MW X-band layout (in collaboration with Canon).







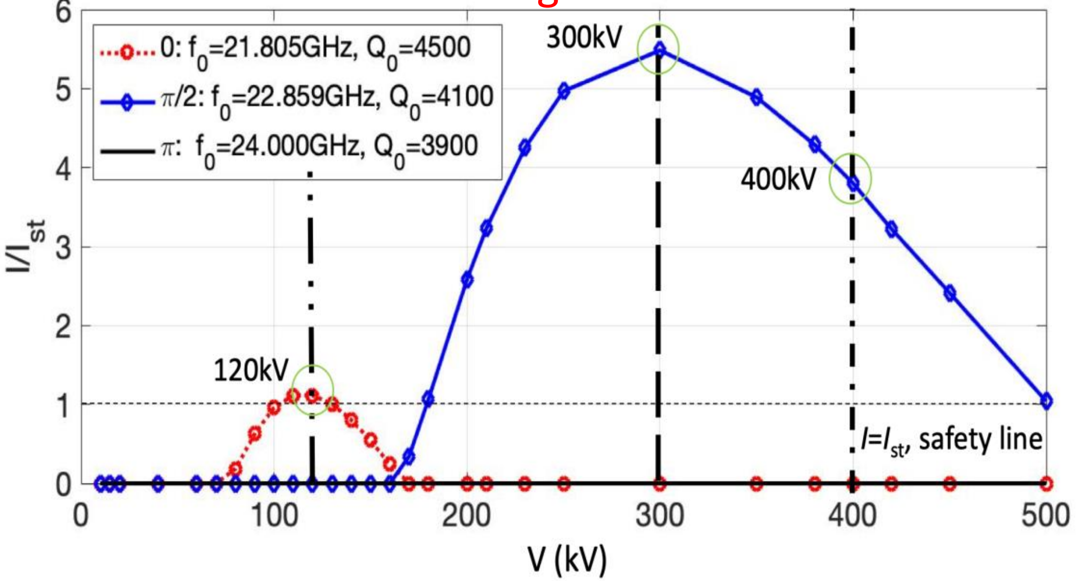
Transfer characteristics



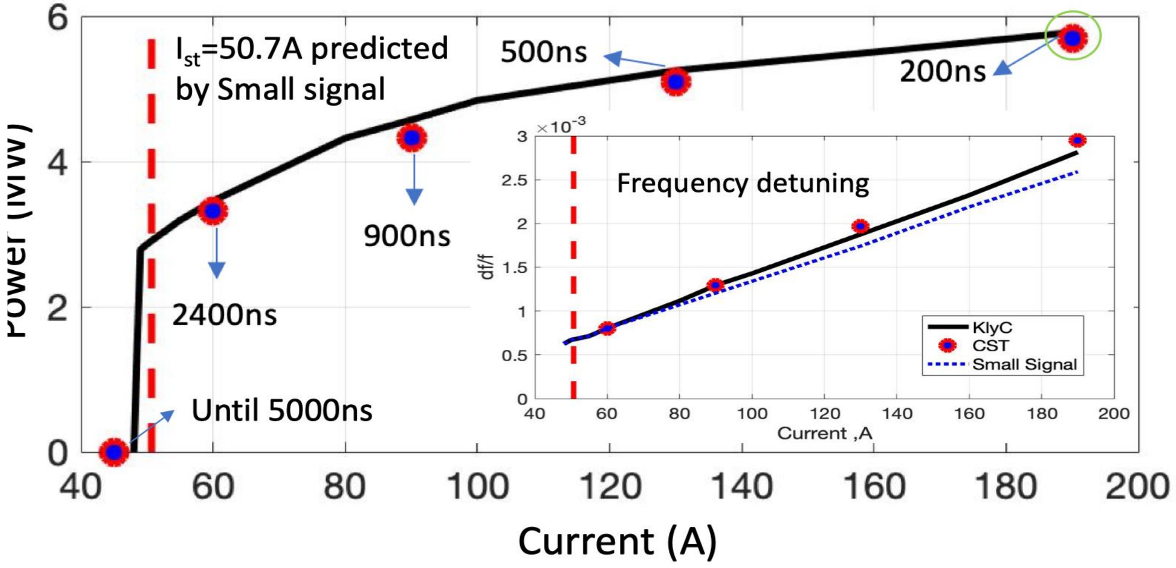
✓ Eff.~57.4%; E_{max}~87kv/mm; -1dBbandwidth~[-20MHz,15MHz]; Pin=80W

Monotron oscillation module

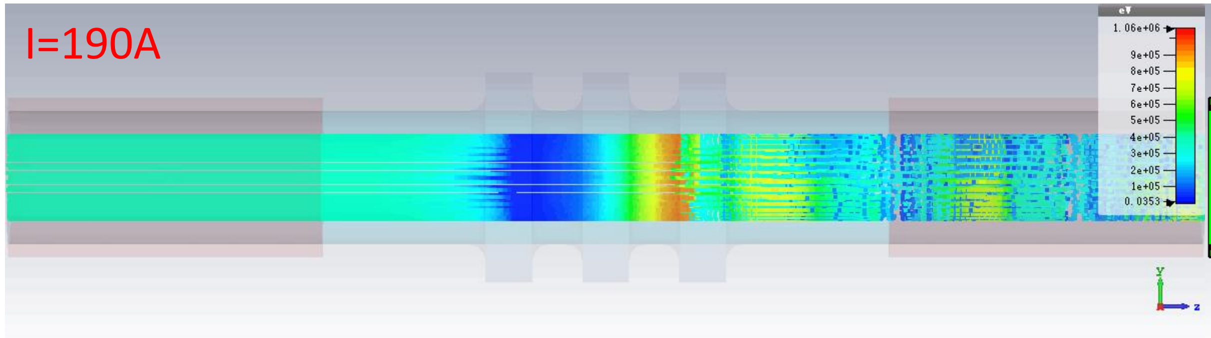
Small signal



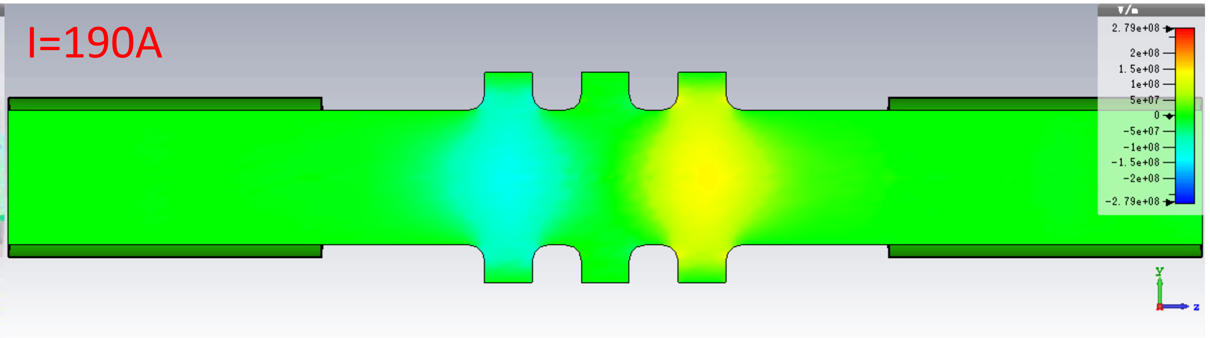
Large signal



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



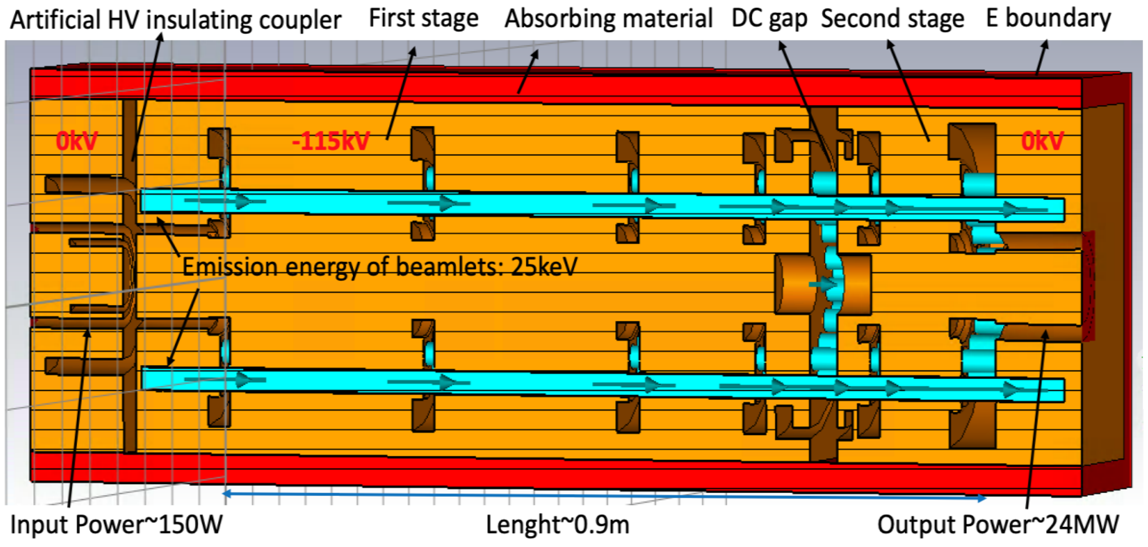
Beam dynamics in CST PIC



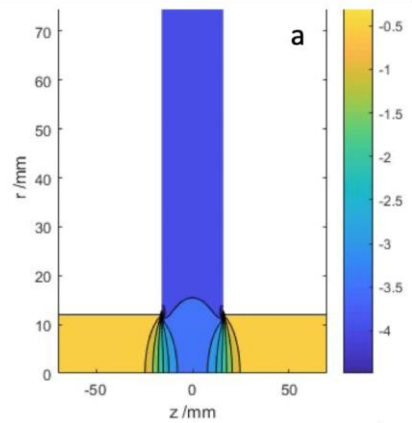
Pi/2 mode oscillated in CST PIC

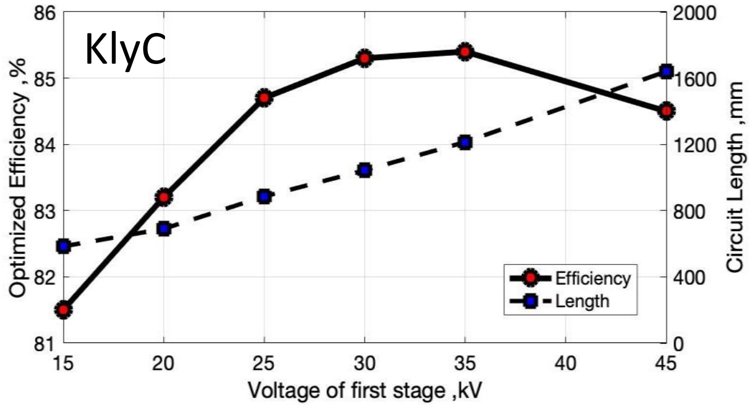
Wave-beam interaction module & Electrostatics module. Two Stages CLIC MBK

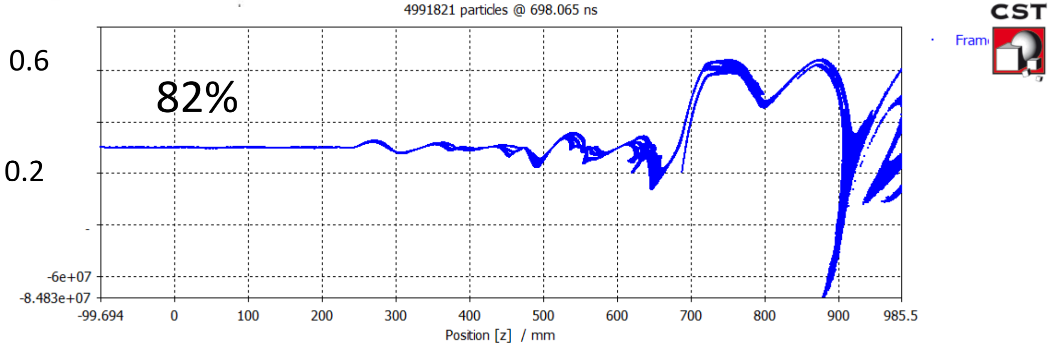
30 beams, 24 MW, 1GHz. CST/3D model.

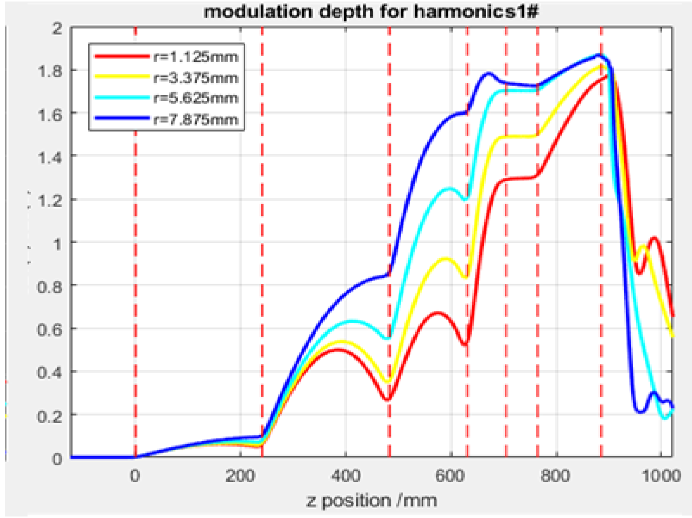


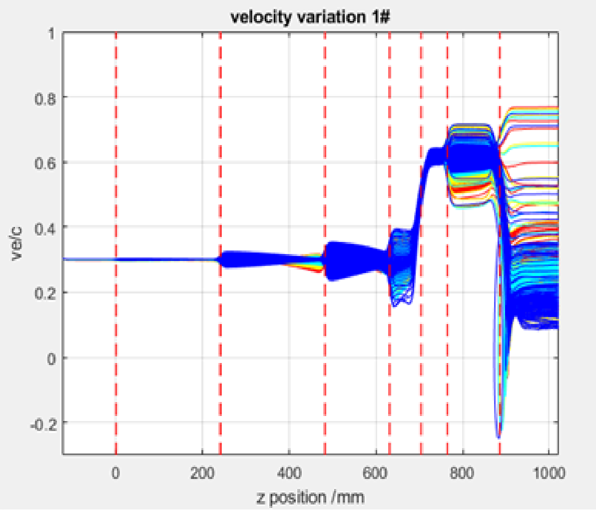
DC gap field

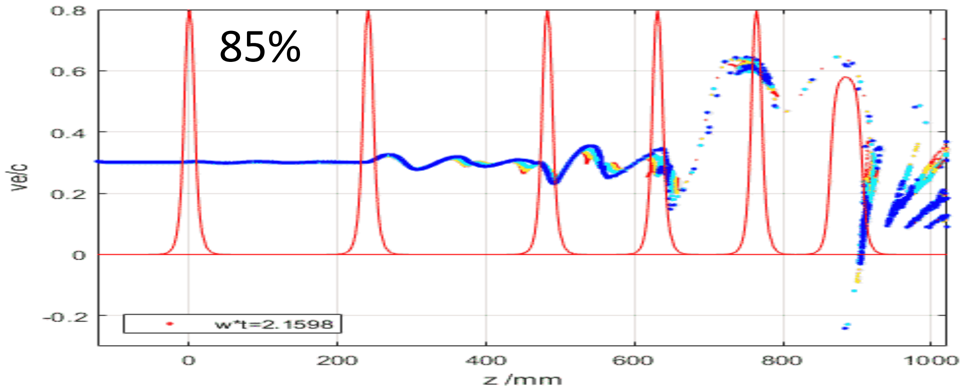












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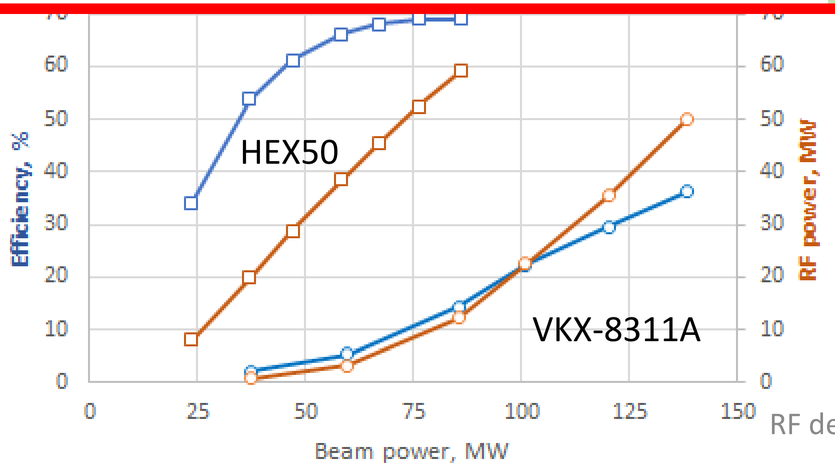
High Efficiency X-band klystrons retrofit upgrades (in collaboration with CPI and Canon).

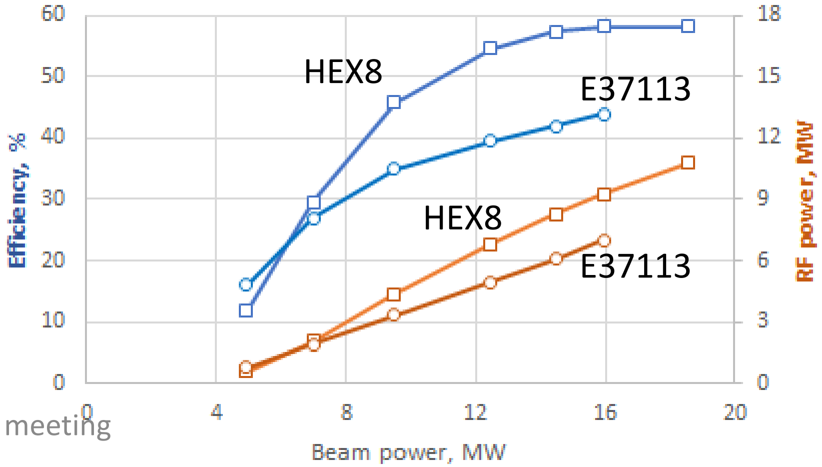
Communications & Power Industries

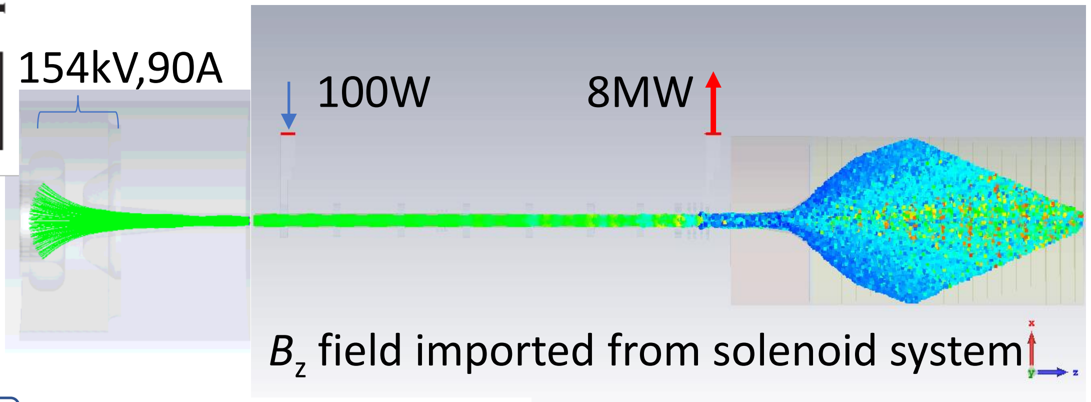
50 MW	VKX-8311A	HEX COM_M (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	58
Efficiency, %	36.2	68 / KlyC
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.35/0.6
RF circuit length, m	**0.32**	**0.32**

8-10 MW	E37113 at factory	HEX COM_M (CERN/Canon)
Voltage, kV	154	154
Current, A	93	90
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.1
Sat. gain, dB	49	58
Efficiency, %	42	57/ FCI
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.4
RF circuit length, m	**0.127**	**0.127**

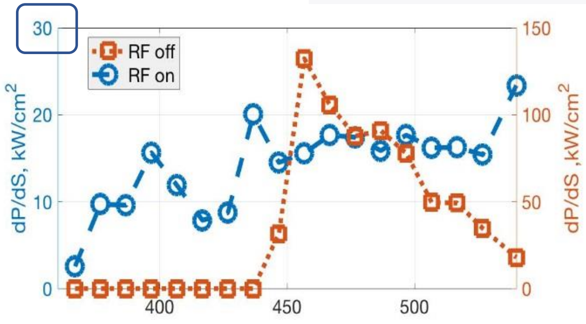
Canon

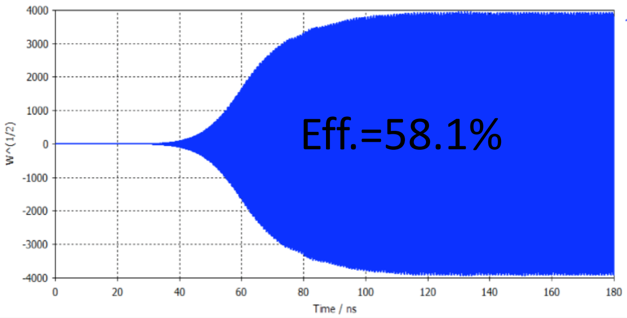


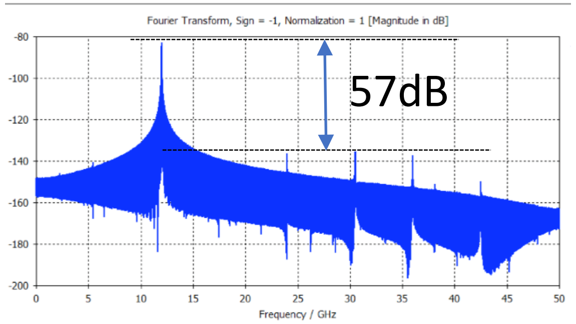


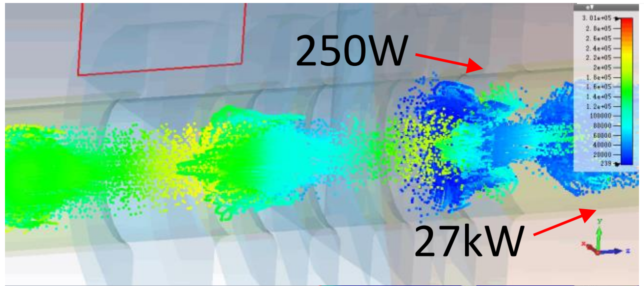


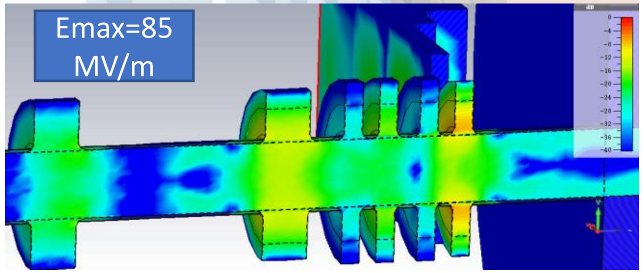
- All in one simulation is done in CST
- 22 million mesh cells
- 2 million particles
- ~ 1 day on 2-cores GPU
- ~1 month on CERN server

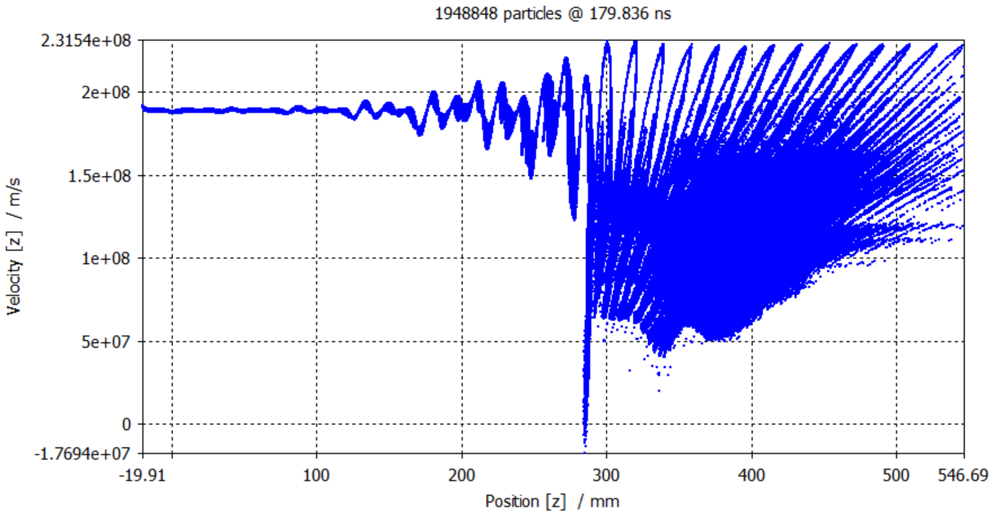










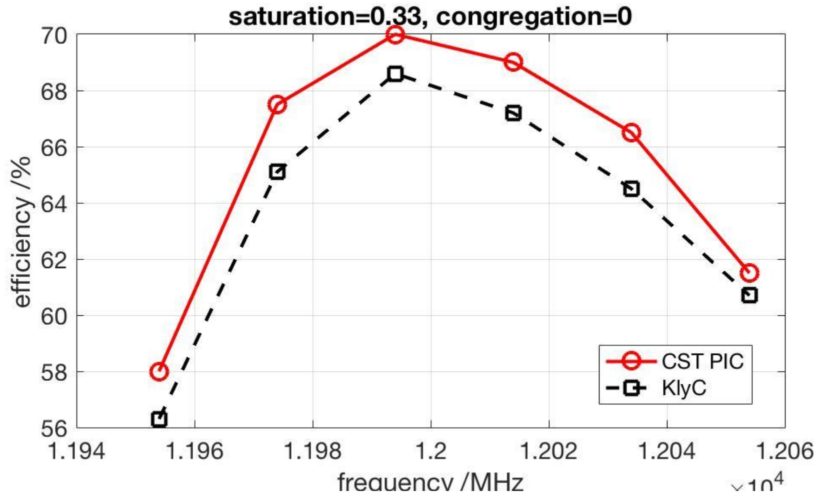


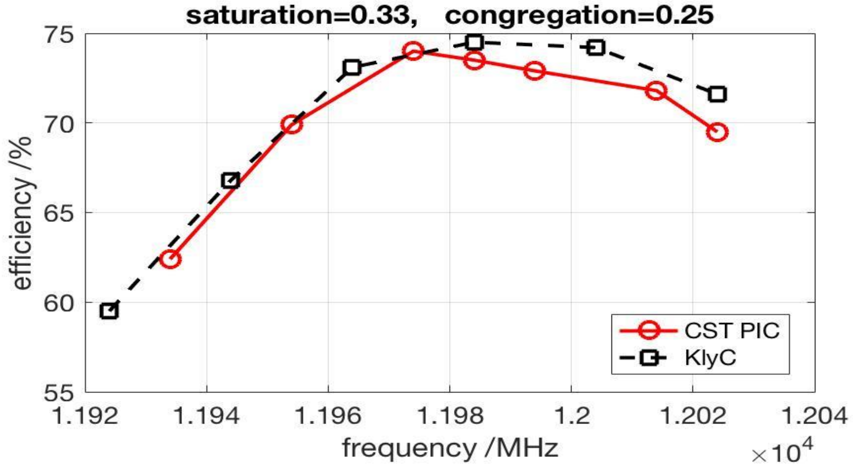
Min(ve/c)=-0.059

Canon

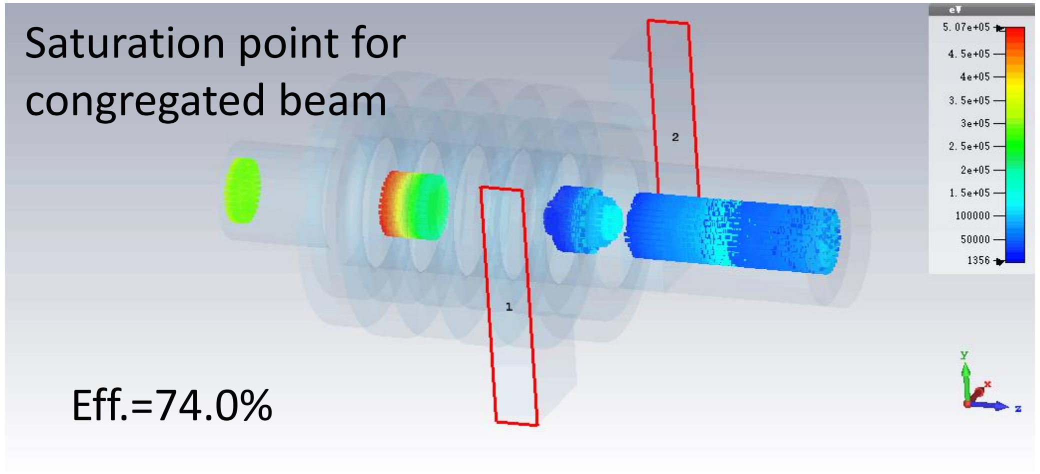
- ✓ Preliminary 8MW X-band Klystron proposed by CERN
- ✓ RF design and optics design included
- ✓ Further optimization are done with cooperation with Canon
- ✓ Coupling cells are tapered to ensure more clearance
- ✓ Circuits are shrink to priorities the compactness
- ✓ Most of the design and optimization process are consistent with 50MW version

6-cell output cavity design for 50MW tube

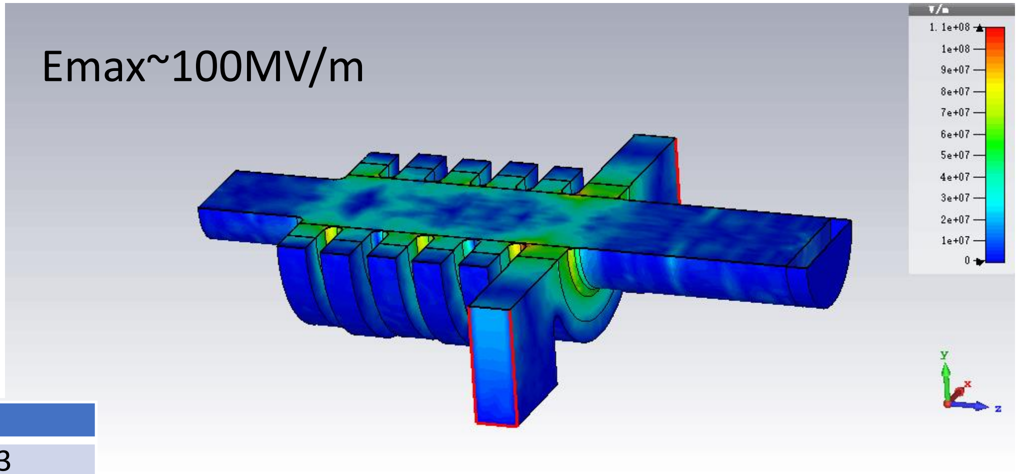




modes	1	2	3	4	5	6
f /KlyC	10.56	11.05	11.60	12.07	12.20	12.43
Qext	214	93.9	40.8	75.0	148	2071
f /CST	10.63	11.02	11.51	12.04	12.21	12.46
Qext	359	114	38.1	76.4	102	1994



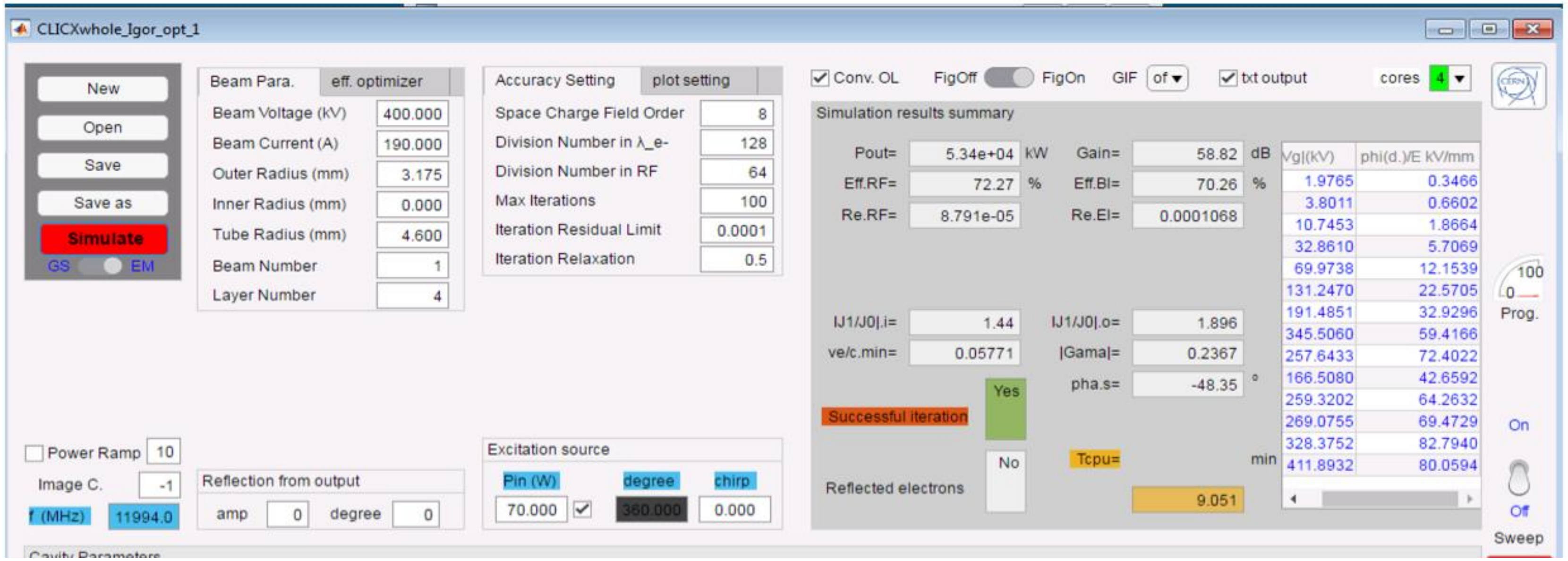
Beam dynamics



Electric Field Distribution

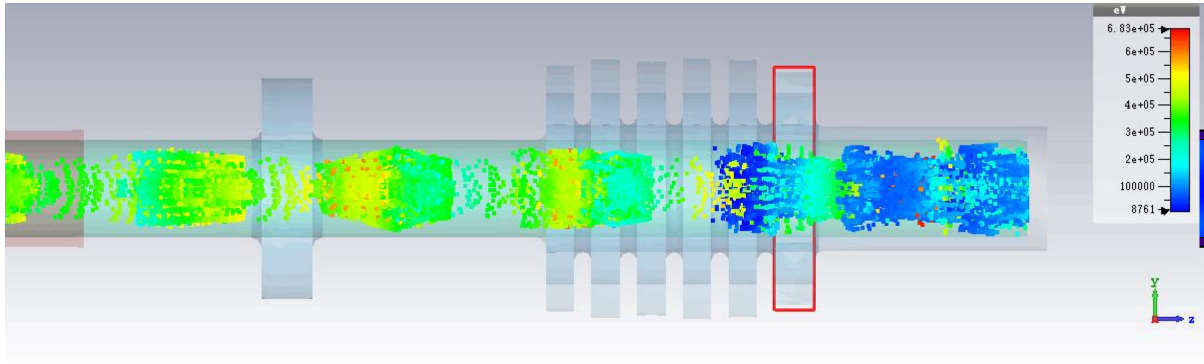
- ✓ If single output waveguide is used to extract the power, the efficiency performance will be more or less the same with slightly offset the center of the cavity from the center of the beam tunnel
- ✓ Previously, SLAC has a TW version of coupling cell design, but slightly less efficient

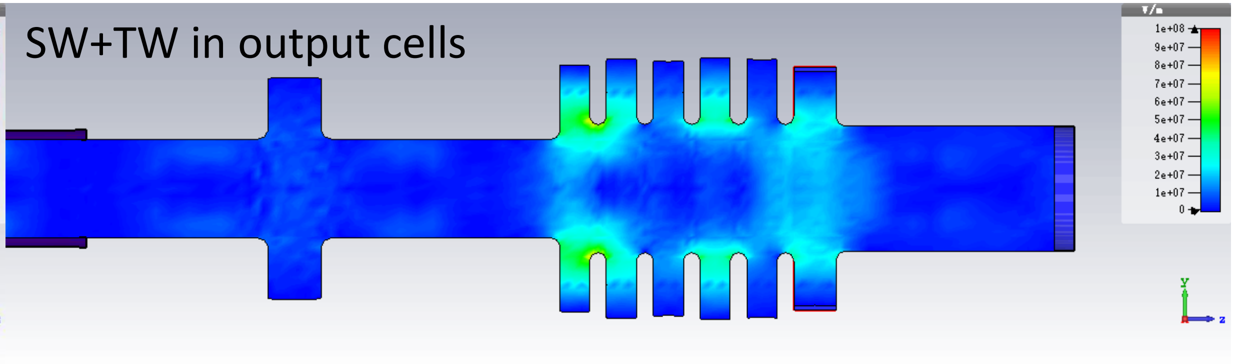
COM bunch circuit scheme (L=865mm)



- ✓ COM bunch circuit are directly scaled from preliminary 8MW X-band Klystron and optimized further by CERN and SLAC
- ✓ For strong coupling and complex beam dynamics, it seems the coupling mode theory is not accurate enough (~4% error).
- ✓ Harmonic cavity to be introduced to shrink tube

<u>CST benchmark for COM design</u>

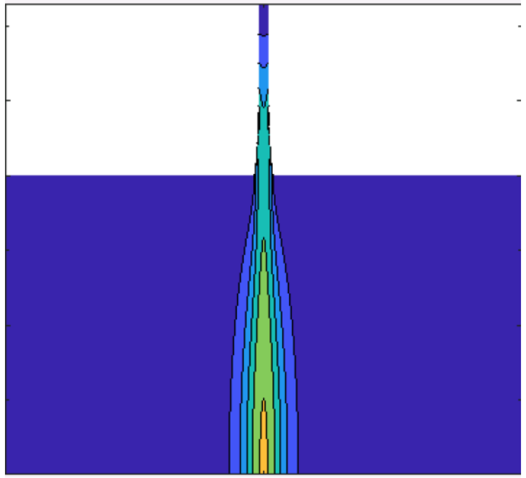




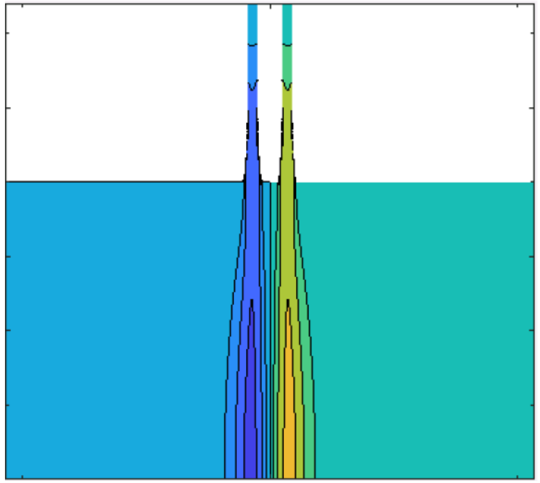
Frozen beam: Eff~66%; Bz=0.35T, Eff~64%

Emax~100kV/mm

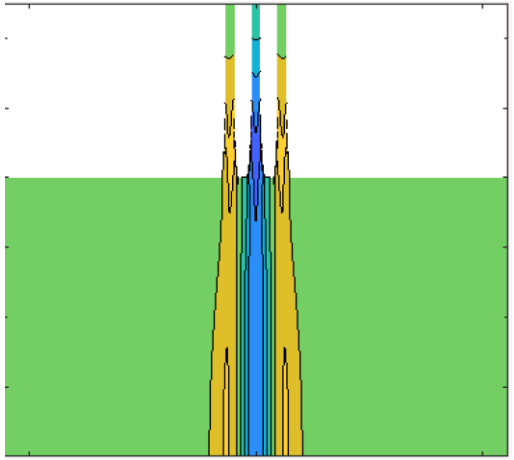
Second harmonic cavity



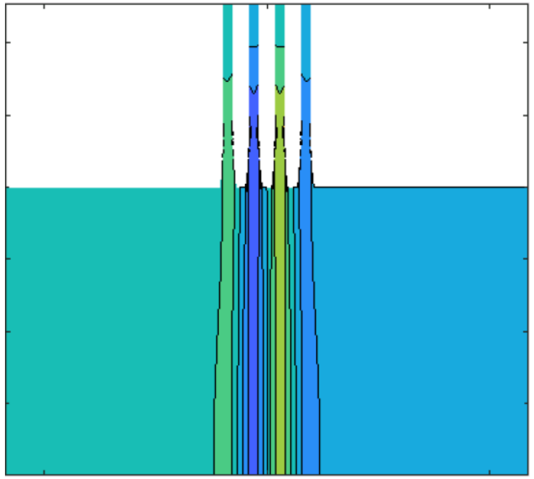
1cell: R/Q=195ohm, M=0.176.



2cell: R/Q=162ohm,M=0.317.



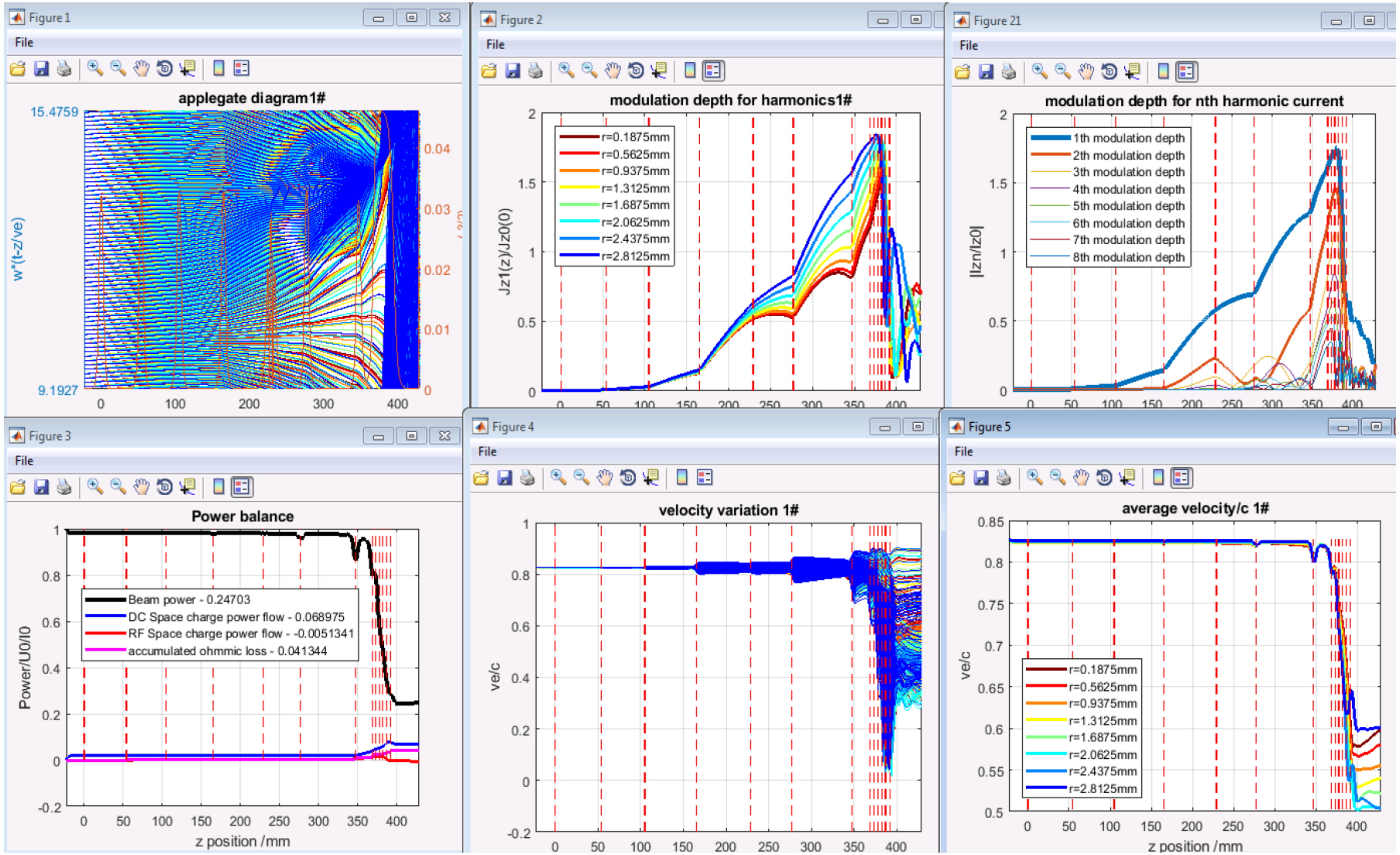
3cell: R/Q=159ohm, M=0.380.

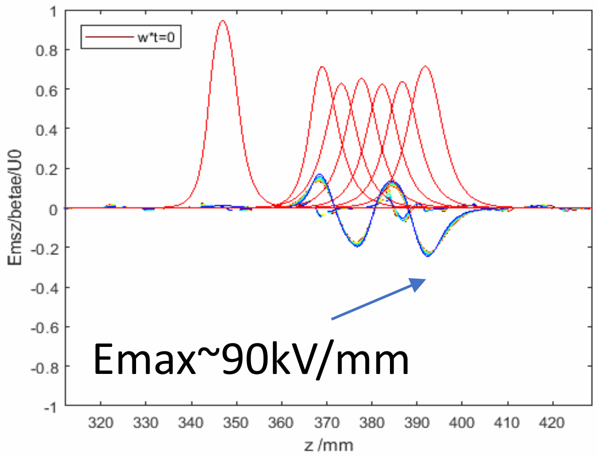


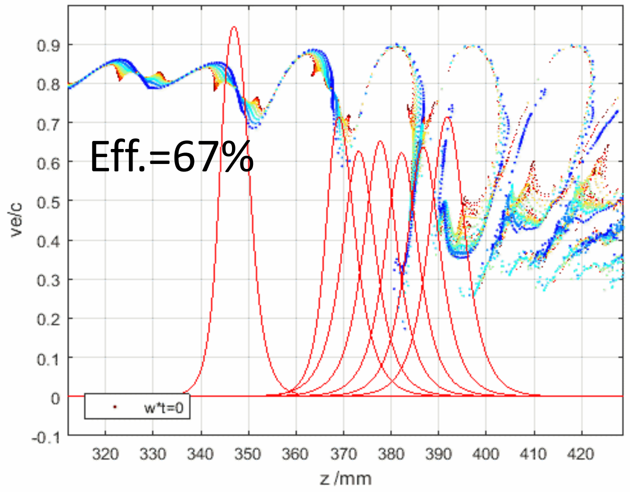
4cell: R/Q=157ohm, M=0.434.

1. Gap length of the cavity is optimized maximize the R/Q*M^2 for single gap.
2. Period is selected as 5.8mm to synchronize pi mode with electron beam.
3. Number of cells are determined as compromise between R/Q*M^2 and mode separation: 720MHz for quadruplet and 1000MHz for triplet.
4. After some optimization efforts, the length of the circuit could be compressed from 865mm to 392mm; Efficiency slightly drops from 70% to 67% in KlyC. (Output cavity untouched)
5. Instabilities issues are addressed later on, the period is adjusted to 3.8mm at last.

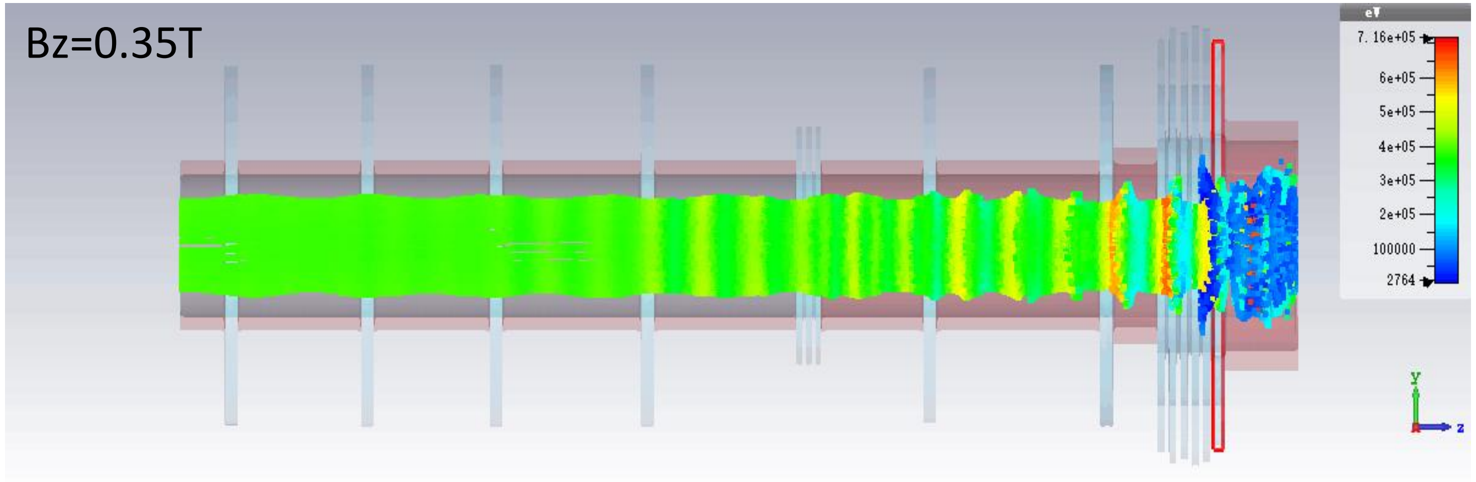
bunch circuit with harmonic cavity scheme (L=392mm)



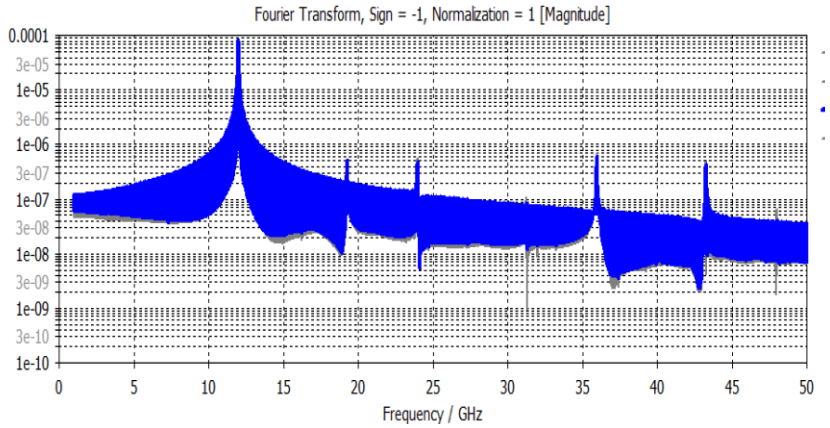


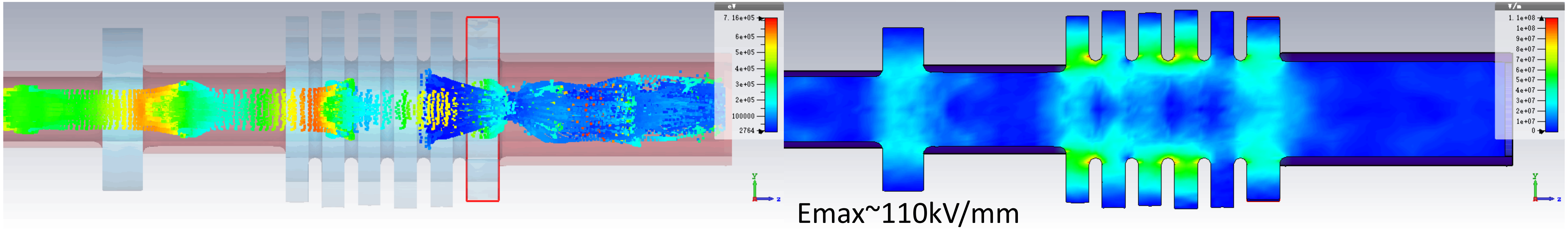


CST PIC benchmark for shorter circuit design (L=392mm)



Spectrum for output signal



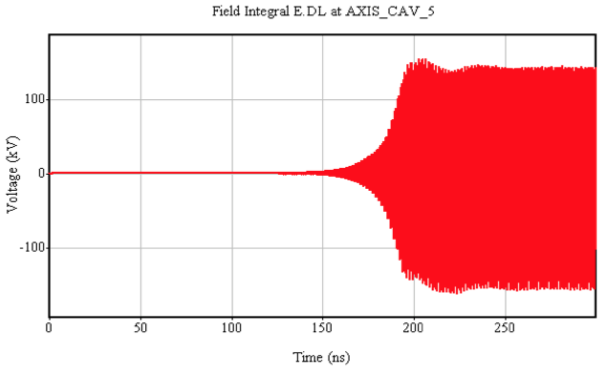


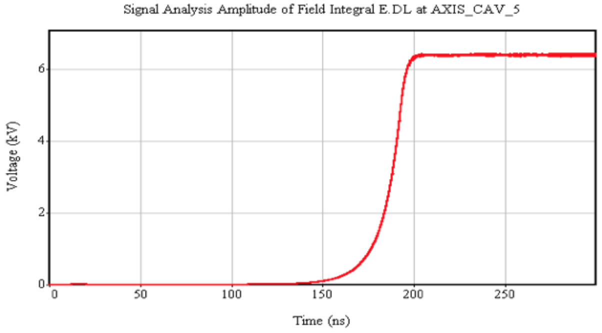
- ✓ For frozen beam, efficiency will be 63% while for Bz=0.35T, efficiency is 62%;
- ✓ In MAGIC 2D PIC simulation, the efficiency is 65%.
- ✓ Takuji (CPI) did some optimization on cell frequencies and Qext in MAGIC, 68% efficiency could be achieved(Bz=0.35T).
- ✓ For the updated parameters, the efficiency is 65.3% in KlyC and 64% in CST (Emax~120kV/mm, Bz=0.35T).

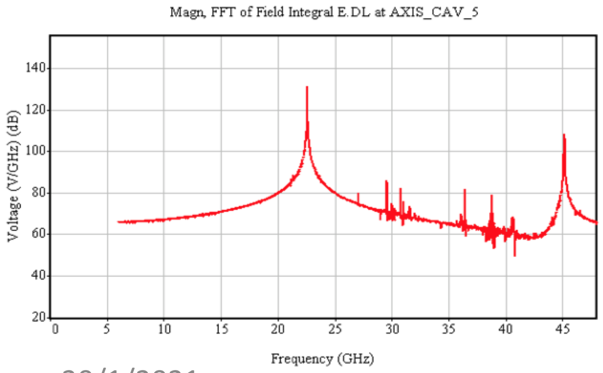
Outline

- Background
- RF circuits design
  - KlyC : code review
  - Multi-cell output cavity, bunch circuit
- Instability issues
  - Monotron oscillation
  - Multipolar modes oscillation
- Beam optics design
  - CGUN: 2D optics code freshly developed
  - GUN, magnet, collector

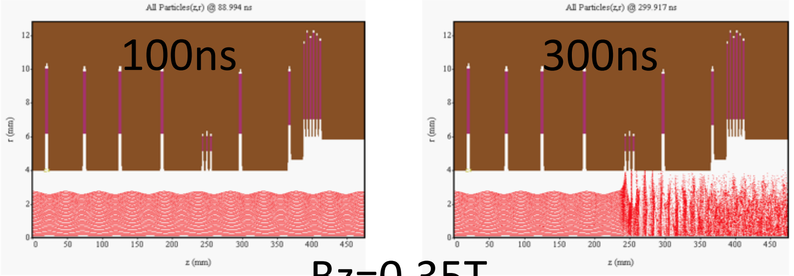
Problem addressed



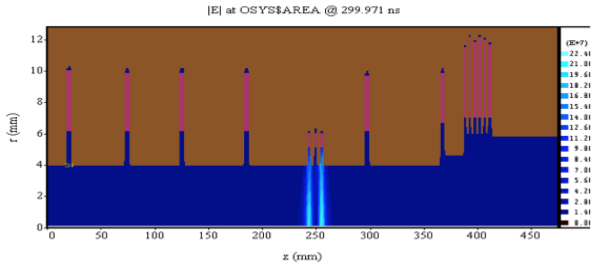




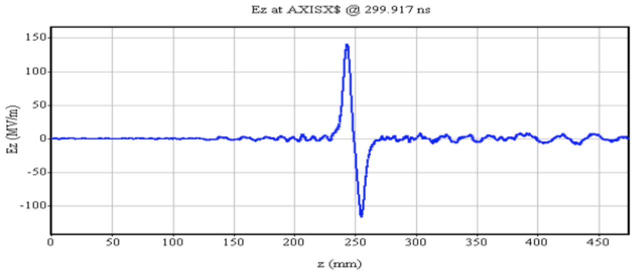
DC beam for 50MW tube (Original triplets design with p=5.8mm)



Bz=0.35T



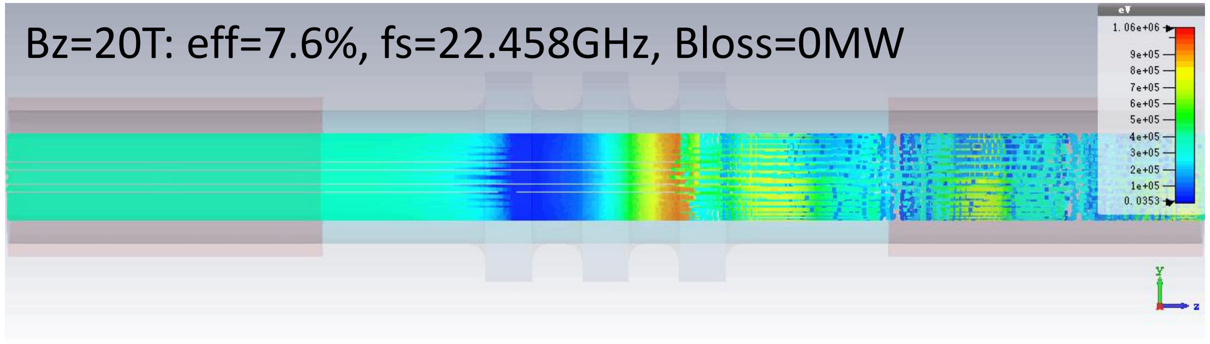
π/2 mode

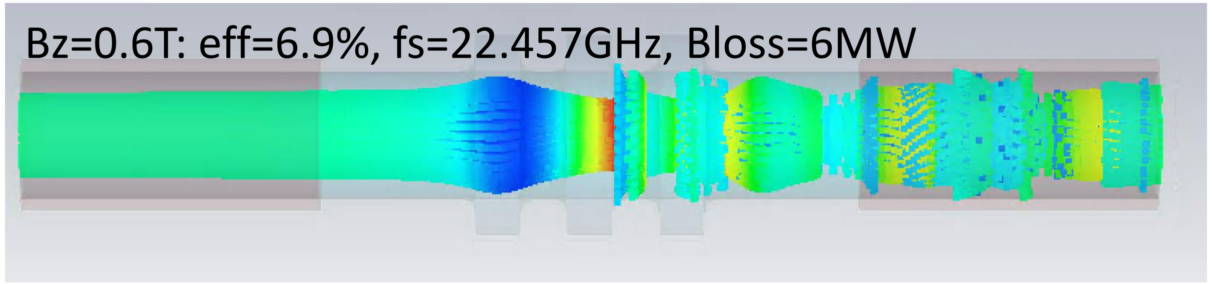


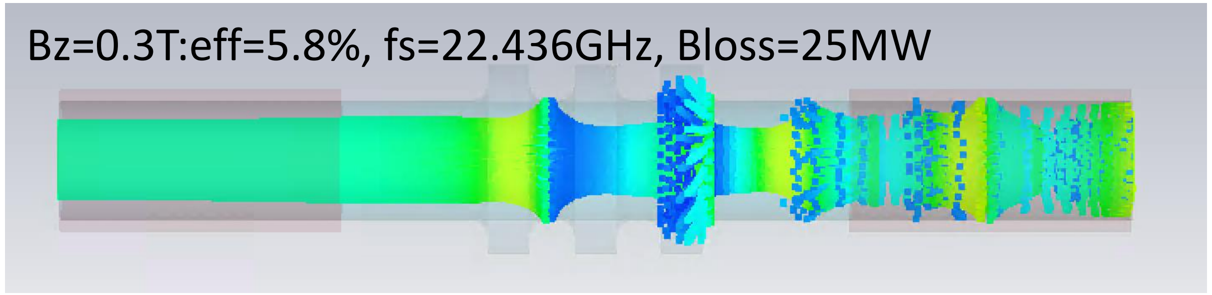
- ✓ 50MW short tube with 2nd harmonic cavity (triplet) is initially optimized in KlyC shown the efficiency is up to 67%
- ✓ Triplet is designed with p=5.8mm to maximize the R/Q*M^2 for the cavity (TM_{010} **π** mode)
- ✓ Benchmark with PIC simulation shows the stable efficiency is up to 62% but heavy damping material is used to suppress the numerical oscillation (Physical oscillation may also be suppressed)
- ✓ Magic simulation (No numerical damping material is added) shows that the monotron oscillation will occur at the triplets, so no stable amplification process can't be achieved
- ✓ New triplets design should be provided to avoid the monotron oscillation

Monotron oscillation confirmed in CST PIC

Frozen beam case will be used to investigate threshold current



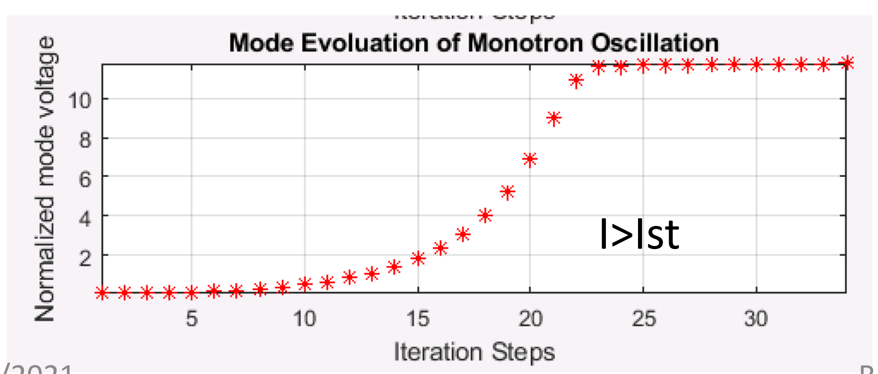


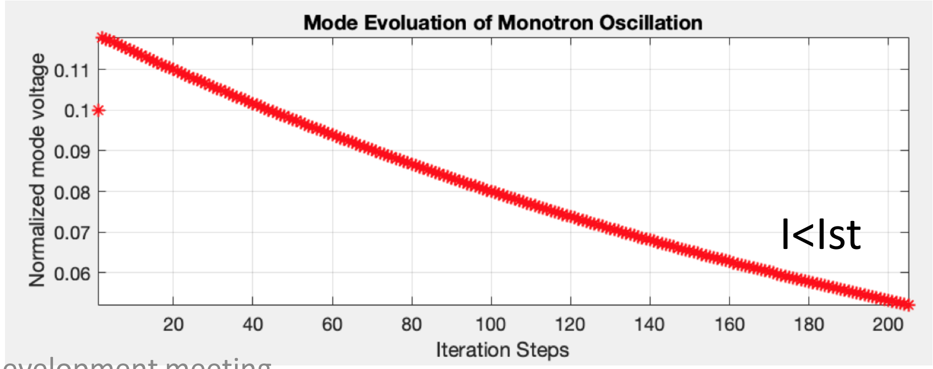


- For single cavity simulation, no damping material added to suppress numerical noise and oscillation
- For different confining Bz, oscillation occurs after 200ns~300ns
- DC beam is emitted from the beginning (V=400kV, I=190A)
- With lower magnetic field, beam expansion together with beam interception exerbated. The power level generated by oscillation slightly decreases
- Threshold current is determined by small signal scenario, thus is dominated by the parameters of DC beam, in which case Bz doesn't affect much (Slightly radially expansion)

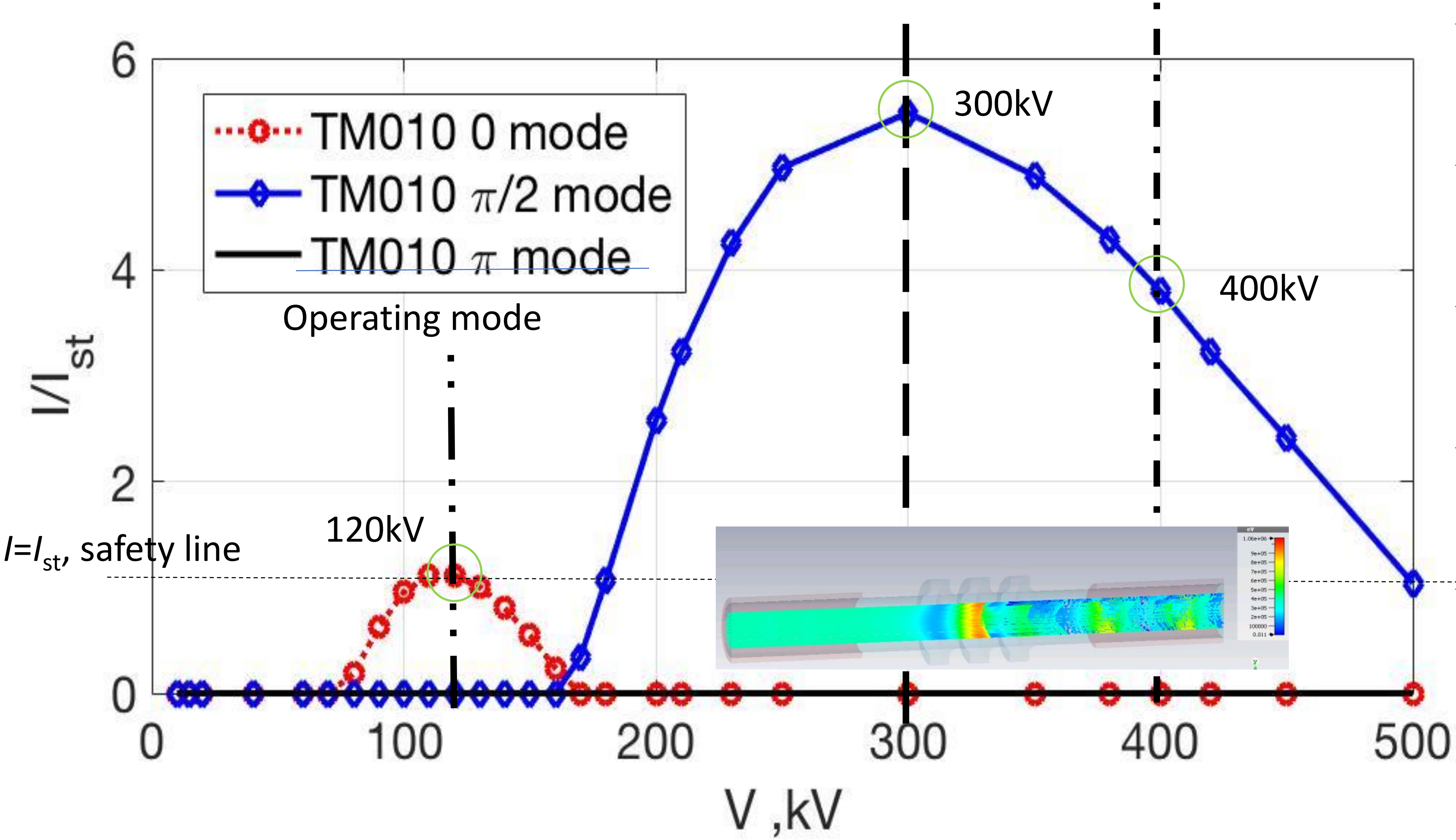
Theoretical model established

- CST PIC simulation is too time consuming, where the start oscillation time may be up to 1000ns (1 days for 100ns in mainstream computer)
- Fast and still accurate theoretical method needs to be put forward to predict the threshold current for a given resonant mode and e-beam
- Small signal theory is derived from large signal theory for KlyC, in which 1D approximation, simplification of SC formalism are adopt.
- Large signal simulation can also be done with the modification of KlyC, which will give oscillation frequency and power level generated when beam current exceeds the threshold by iteration methods

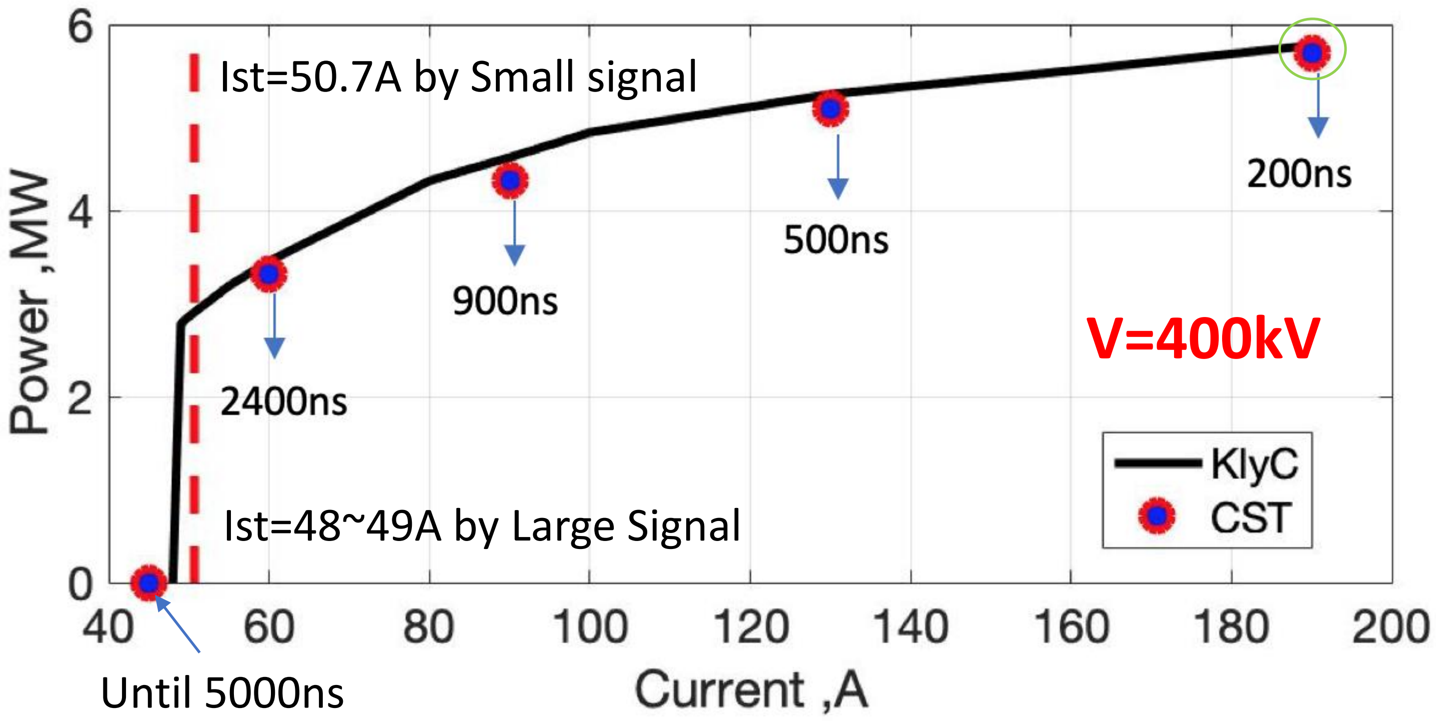


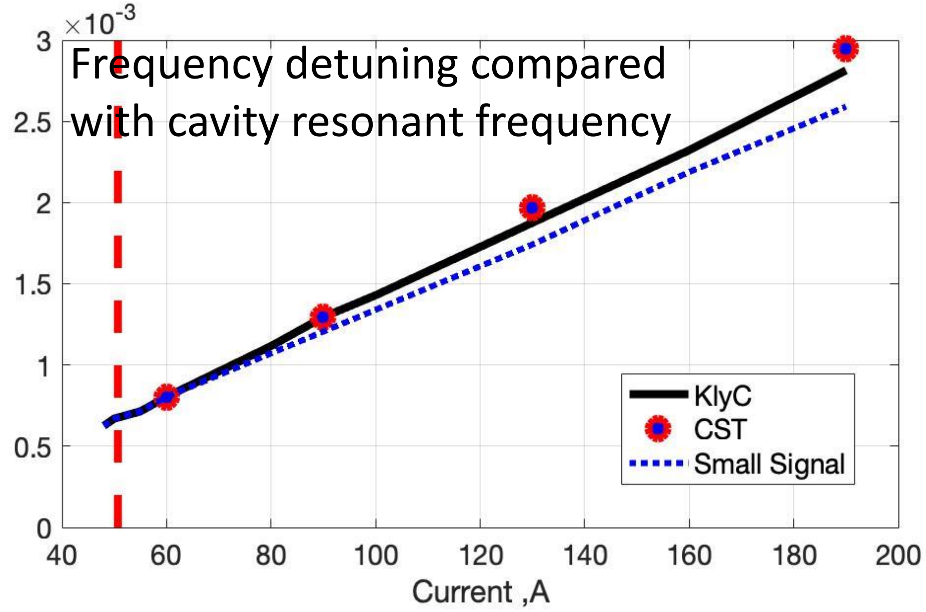


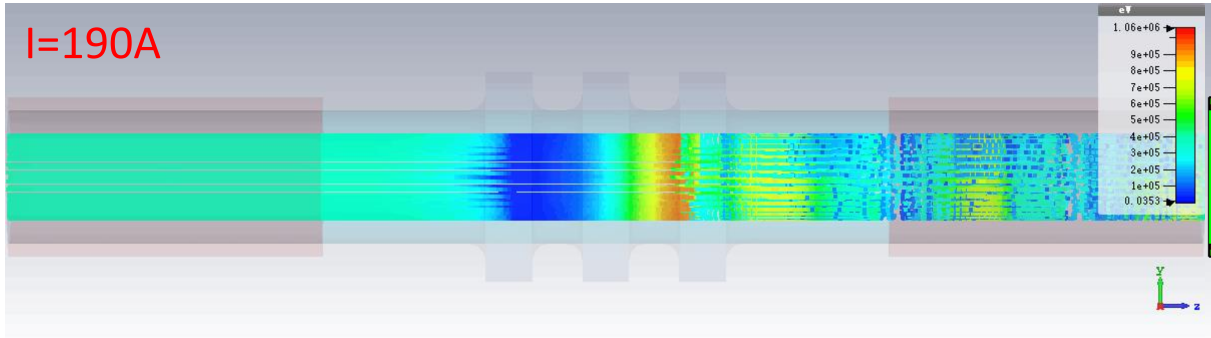
Threshold current analysis for the triplets



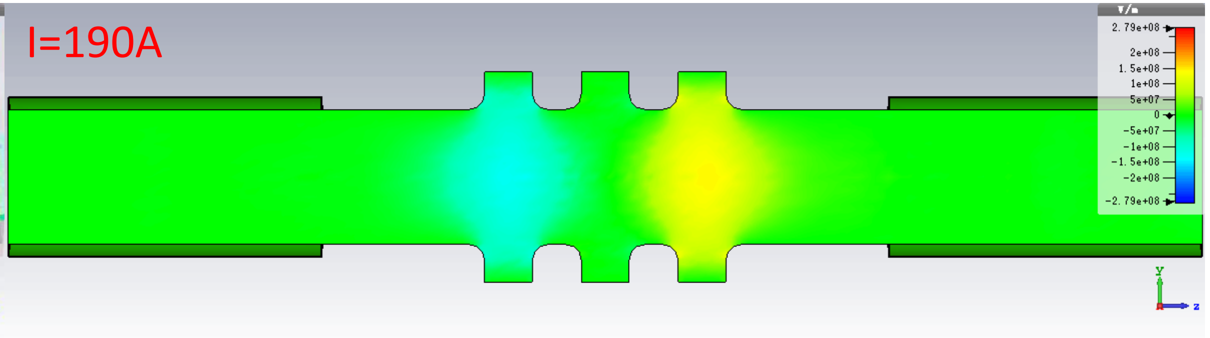
- ✓ Threshold current is calculated by the developed small signal theory
- ✓ Beam Current is calculated by beam voltage with fixing the beam perveance
- ✓ In all possible voltage level (200~450kV), monotron instabilities is unavoidable
- ✓ 0 mode will be excited in low voltage range, while pi/2 in high voltage range
- ✓ Small signal theory needs to be benchmarked (3 cases marked in Fig.)before it is applied for stabilities checks



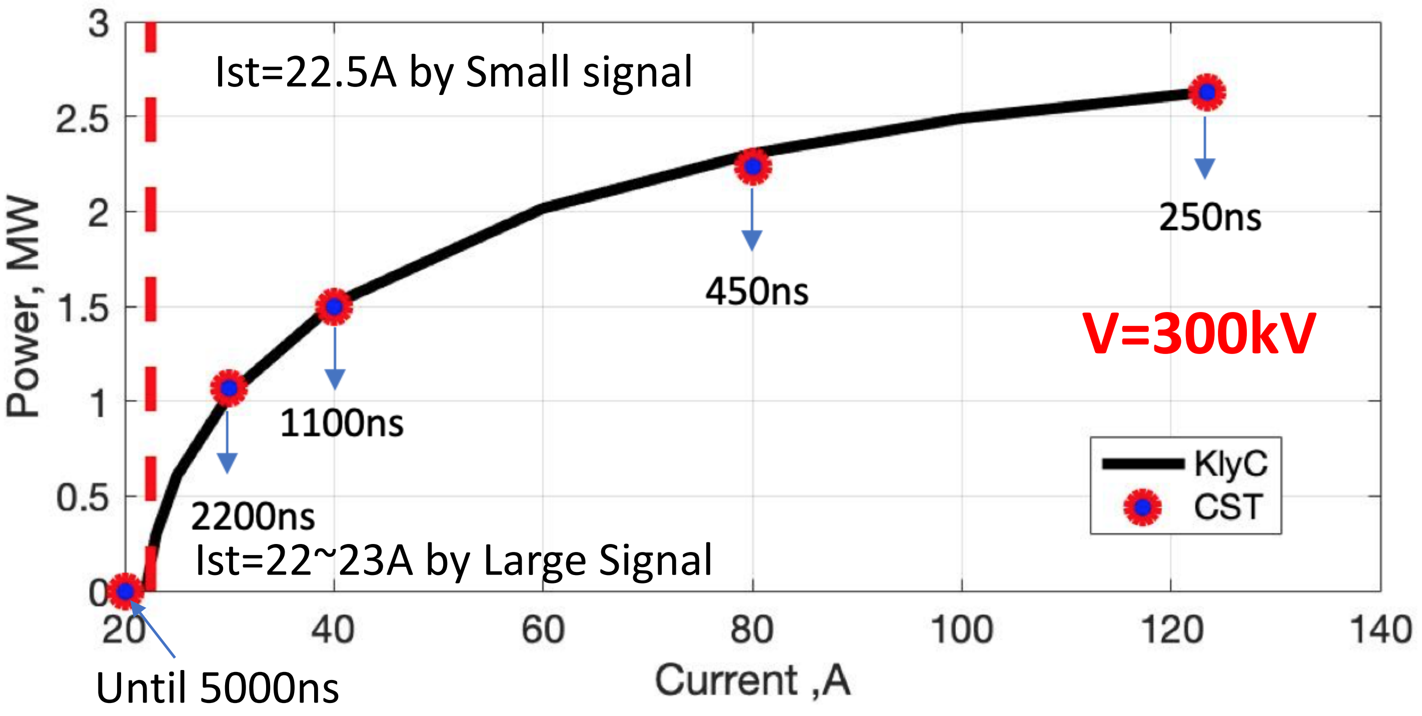


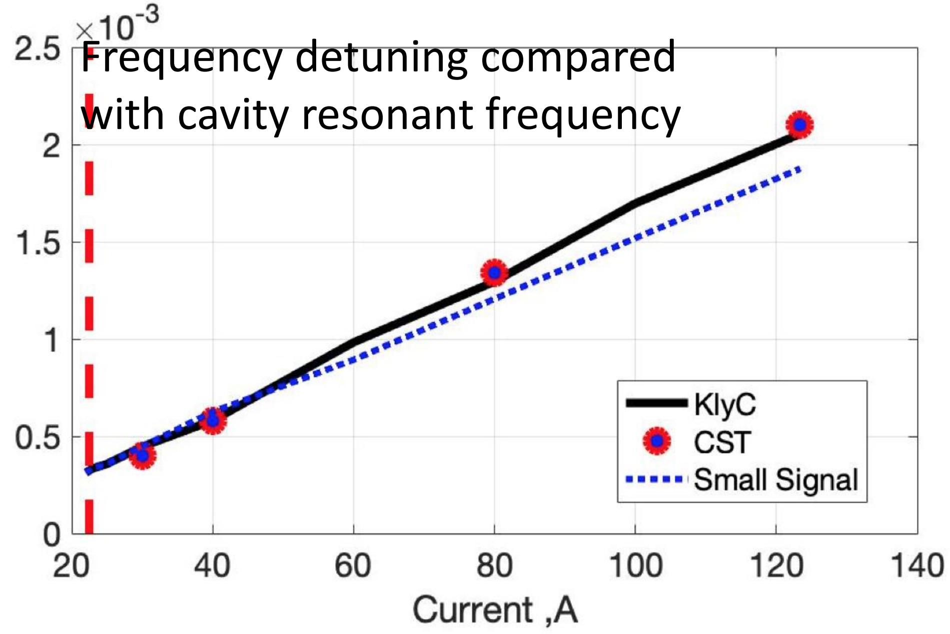


Beam dynamics in CST PIC

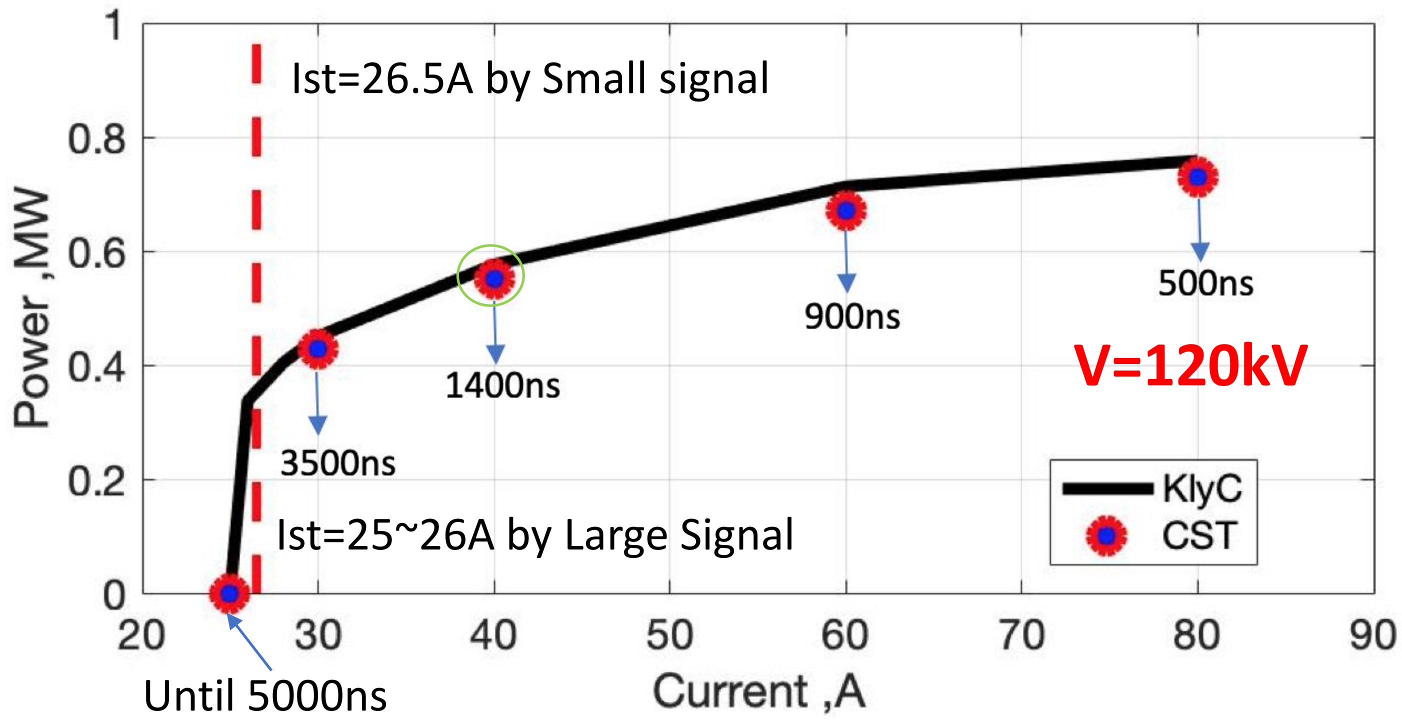


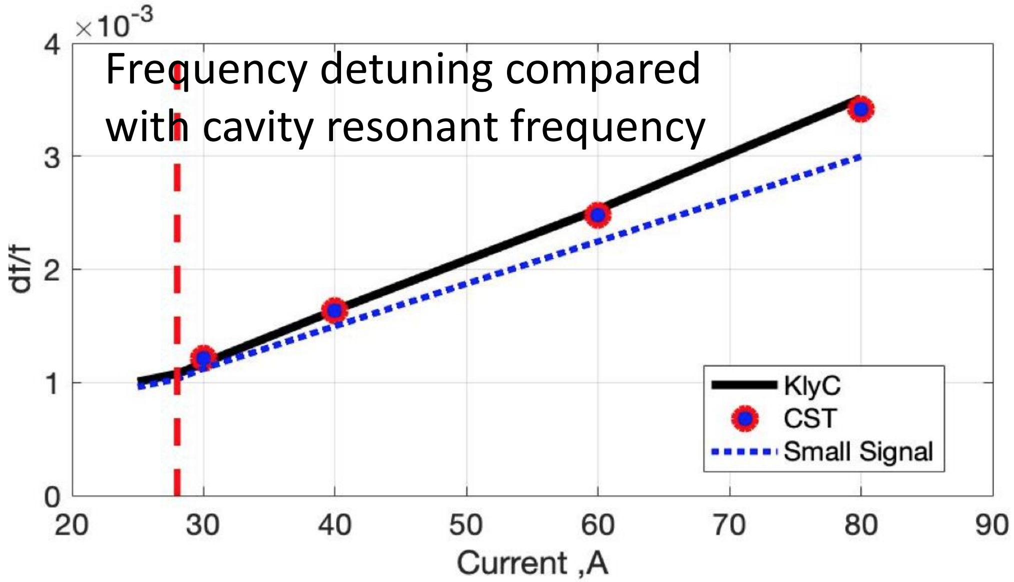
Pi/2 mode oscillated in CST PIC

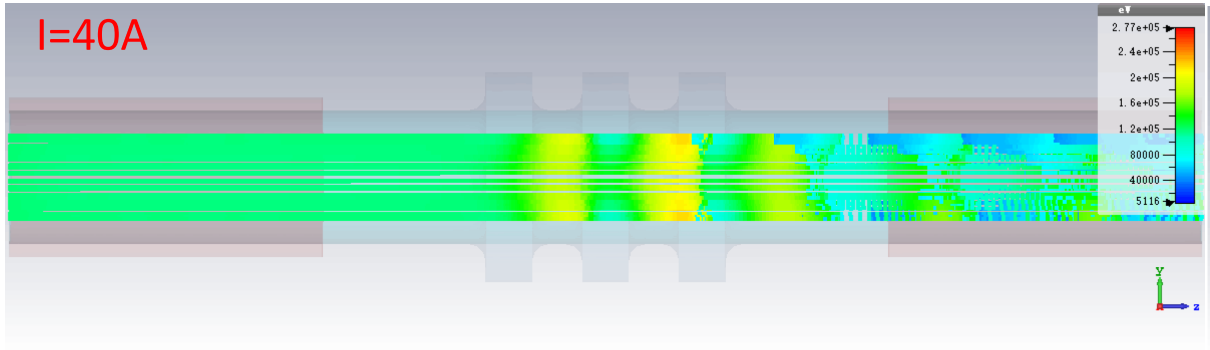




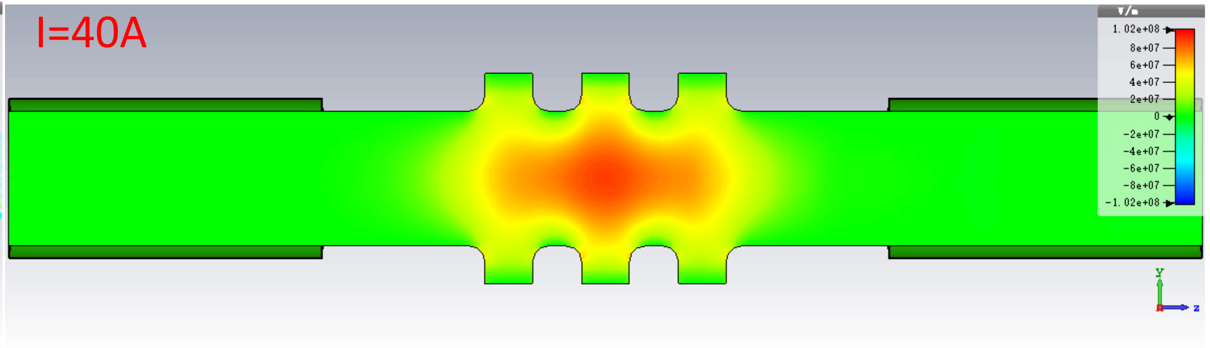
- Large signal theory is benchmarked with CST PIC for V=400kV and V=300kV;
- Small signal theory is benchmarked with Large signal theory in the 2 cases where pi/2 mode is oscillated
- Both small and large signal model works well and can be used for monotron analysis
- More benchmark work will be done for V=120kV with TM010 0 mode oscillated





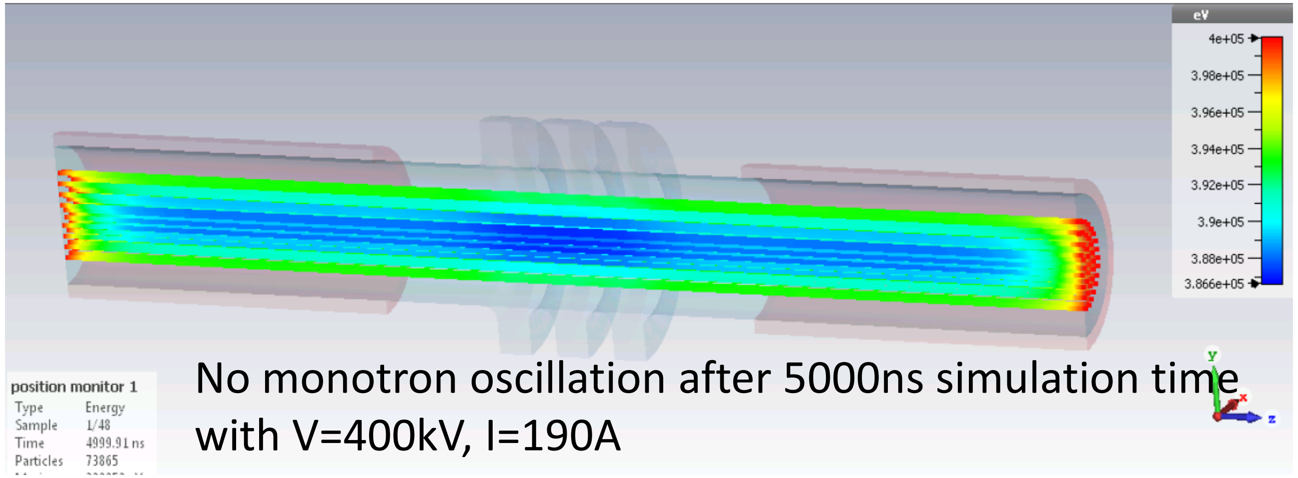


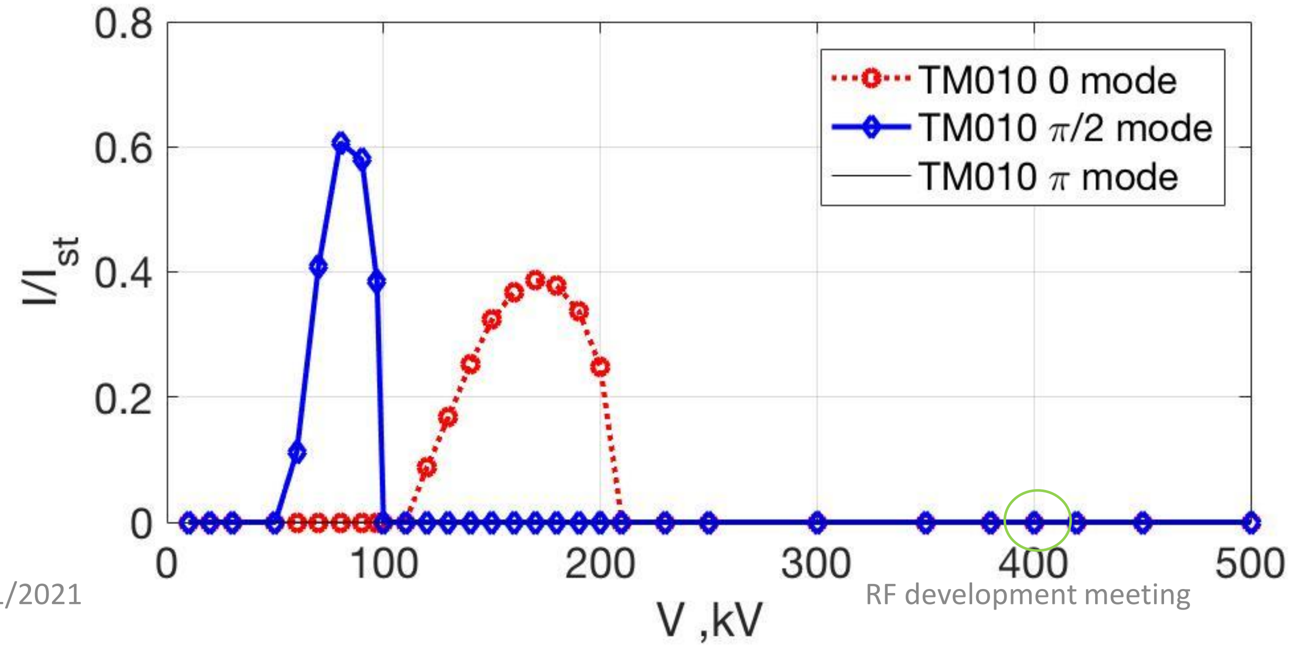
Beam dynamics in CST PIC



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

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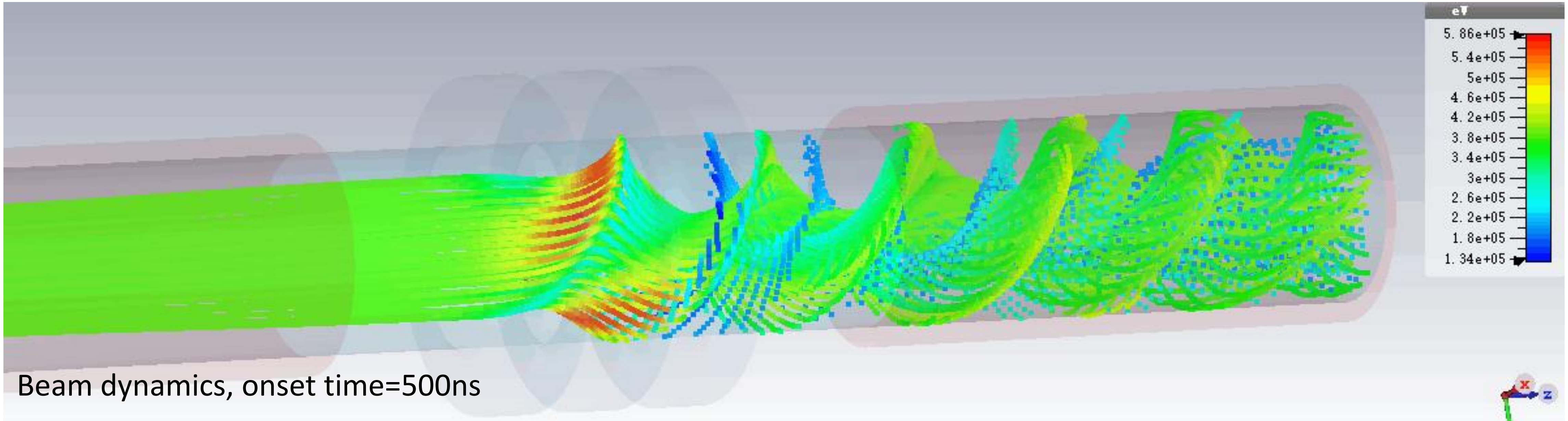
Problem Background

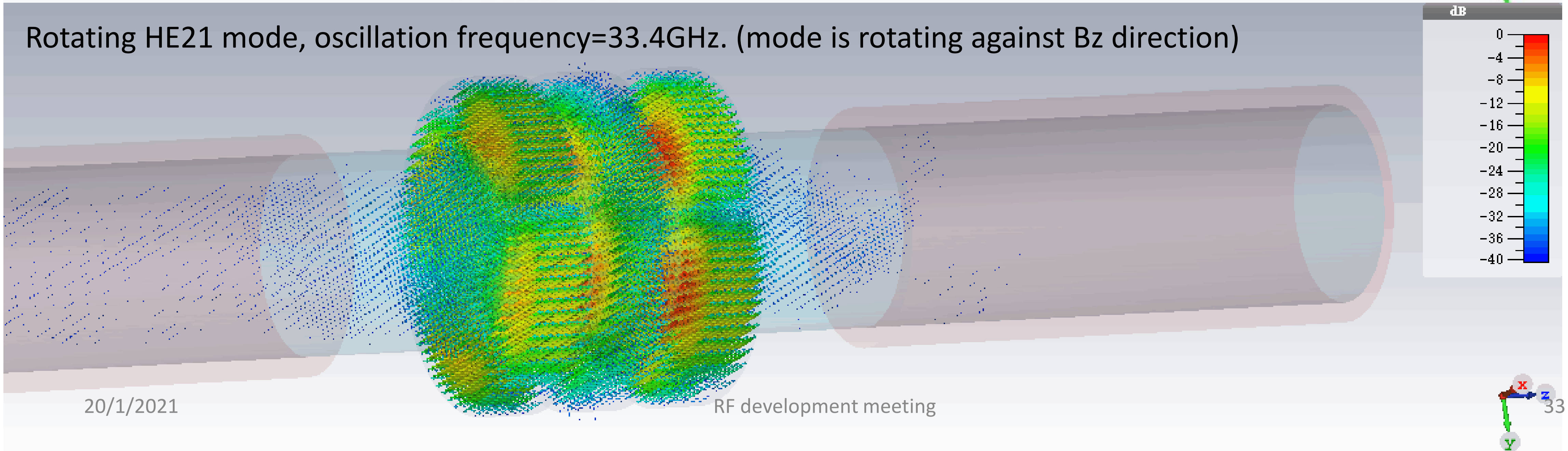
- In X-band 50MW Klystron design, 2nd harmonic cavity is considered to use to boost the efficiency performance (+5%) and reduce the tube length(half of COM)
- As large beam aperture is adopted to accommodate high current, triplet structure is adopted to ensure enough impedance, thus enough bandwidth
- The original design use period of 5.8mm (gap=2.5mm) to optimize the effective impedance, but monotron oscillation is spotted for TM010 pi/2 mode
- Based on monotron theory, new triplet with period of 3.5mm (gap=2.1mm) is used to exclude monotron oscillation. No oscillation is observed during 2us simulation time when Bz=20T; No monotron oscillation is observed when Bz=0.35T as well.
- However, HE type oscillation (HE21) is spotted after 1000ns simulation time when Bz=0.35T. For Bz=0.3T and Bz=0.4T, HE type oscillation (HE31) will still be there.

HE21 oscillation observed, Bz=-0.35T

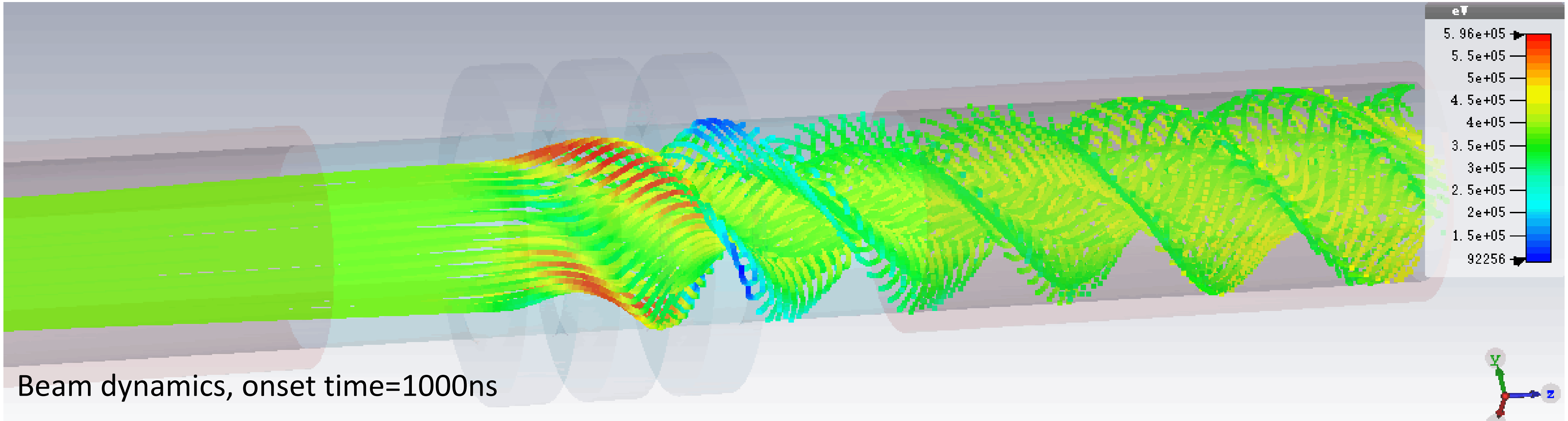


Beam dynamics, onset time=500ns

Rotating HE21 mode, oscillation frequency=33.4GHz. (mode is rotating against Bz direction)

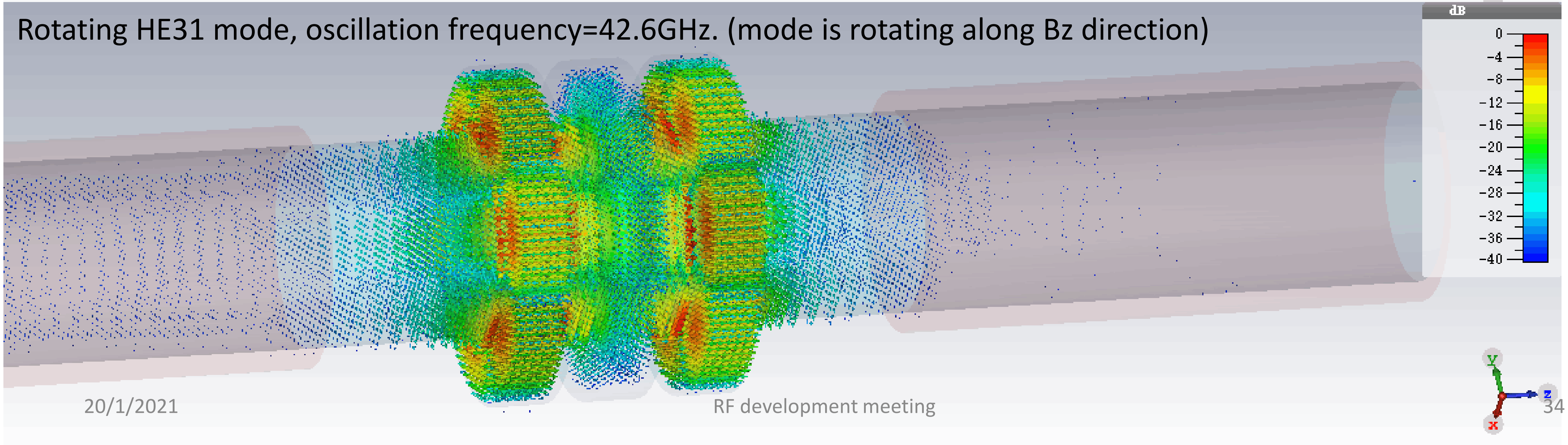


HE31 oscillation observed, Bz=+0.30T



Beam dynamics, onset time=1000ns

Rotating HE31 mode, oscillation frequency=42.6GHz. (mode is rotating along Bz direction)

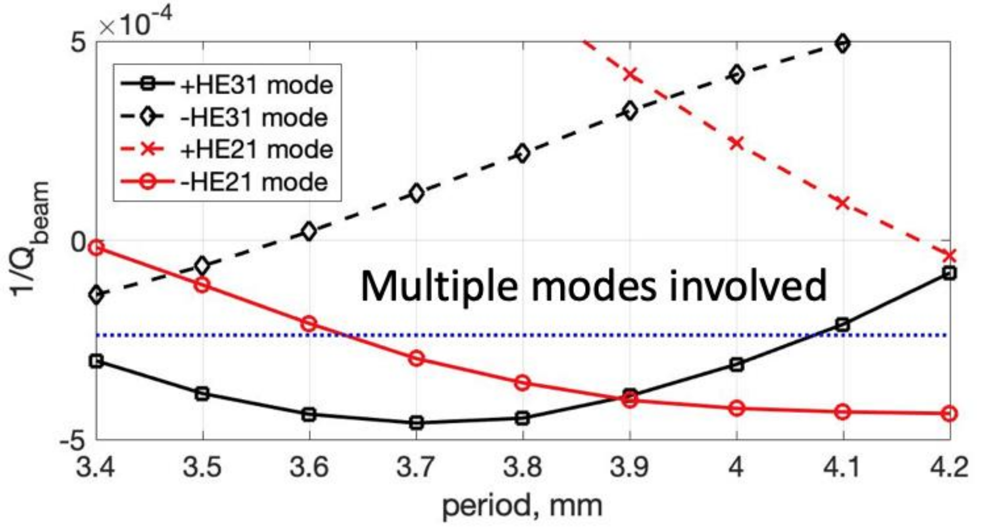


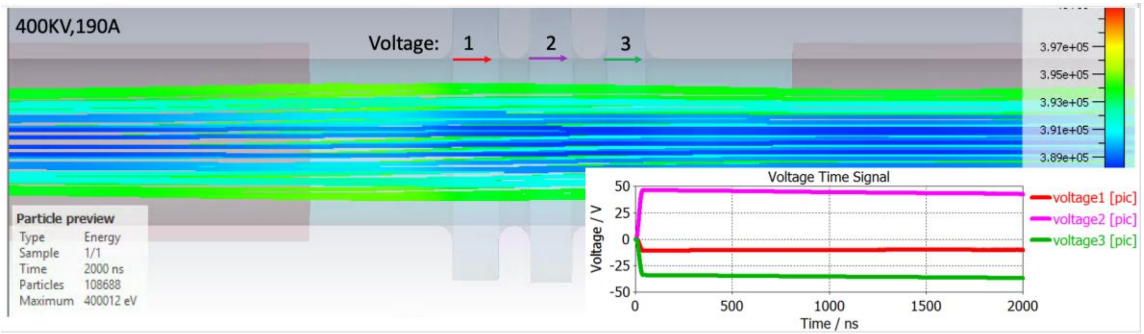
Quick fix for the HE type oscillation

- Sabotage: Hybrid mode oscillation will surely invalidate the nominal amplification. More seriously, the transverse RF field will kick the beam onto the metallic wall, which generates severe beam interception (For example,0.35T, beam interception~20MW) which might destroy the device permanently.
- Fix1: PIC simulation shows that the HE type oscillation will disappear when Bz>0.7T; But enlarge the Bz field seems not a very economical way to suppress HE type oscillation, 0.35T consume 10% power of 50MW. (Fast cure)
- Fix2: Reduce the radius of beam; Interactive impedance will be affected.
- Fix3: PIC simulation shows that the HE type oscillation could be suppressed by using stainless steel wall rather than copper. (Q_0 reduced by 7~8 times). This is a universal approach to suppress all self-oscillated instabilities. (Fast cure)
- Fix4: Adjust the geometry to change the field pattern and frequency of HE mode, which might increase or decrease threshold current depending on how the structure is modified. (Delicate cure)

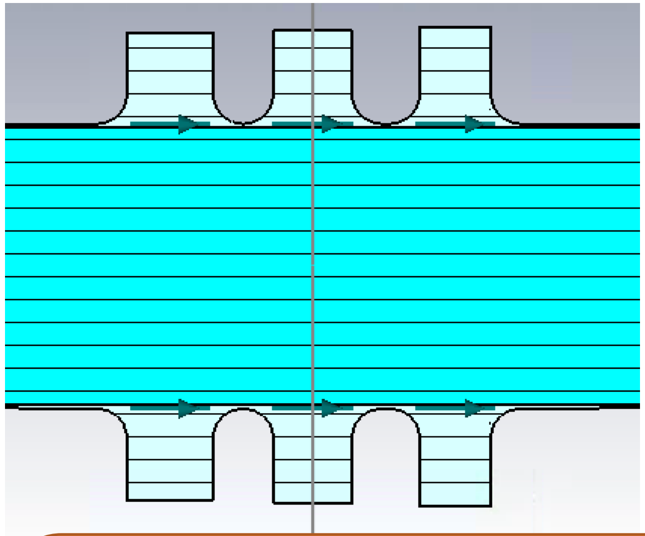
Geometry modification

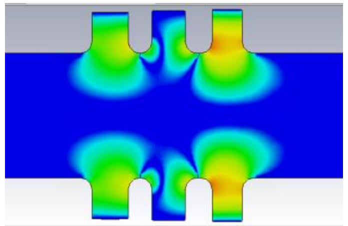
Some numerical methods are developed for fast analysis, work is submitted to peer review; Period sweep is firstly studied.

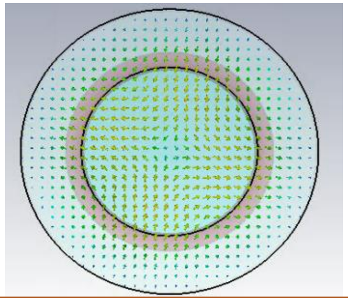




By tapering the gap while making cell frequency of TM010 identical; Effective impedance of operating mode is unvaried; But the mode pattern of HE mode are overhauled.







No oscillations are spotted at Bz=0.35T and copper wall with filling factor up to 85%. In anticipation that with design value of 70% and beam scalloping at 10% level, the tube will be stable. (Stable when voltage range from 150kV to 430kV)

Short summary for instabilities issues

- For high power (50MW), long pulse (1500ns, 1kHz) Klystron, instabilities are likely to occur when triplets are adopted as a second harmonic cavity which is used to boost the efficiency and preserve short circuits length.
- Possible instabilities issues were address and mitigated with proper triplet geometry design.
- As an alternative, CPI suggested the bunching circuit without 2nd harmonic triplet to avoid any doubt about tube stability associated with the triplet. As a drawback the efficiency reduction by about 4% shall be accepted.

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Simulation Tool

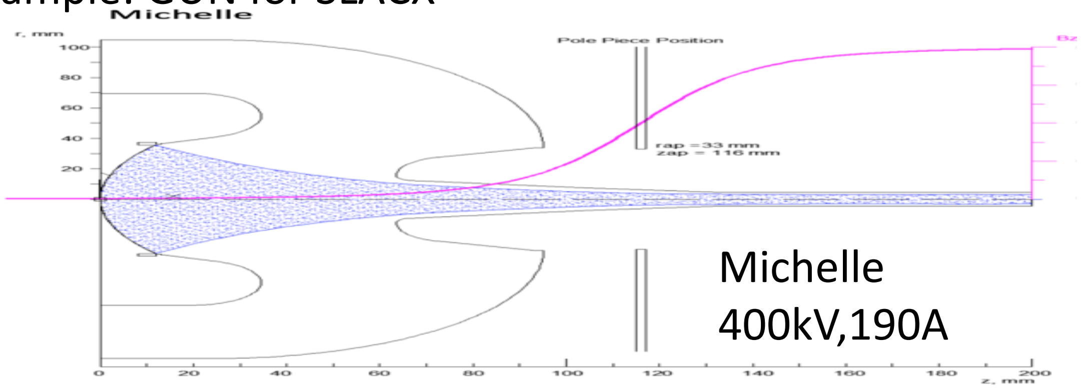
- CST TRK, DGUN, CGUN (home-made 2D code)

Beam optics module

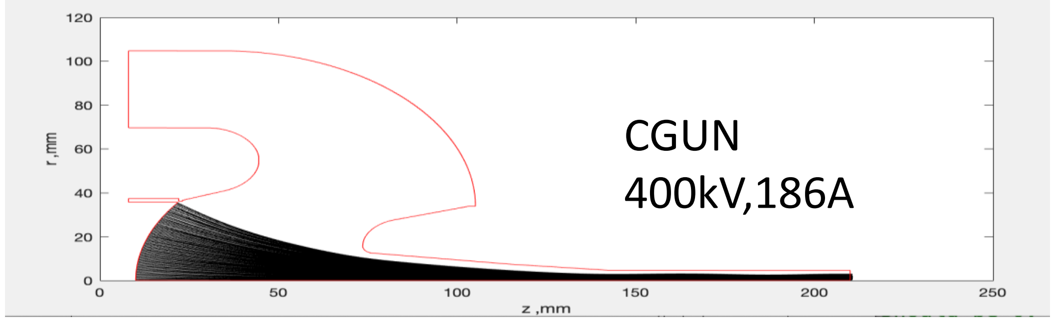
Some benchmark results for complicated cases

Magnetic module

Example: GUN for SLACX

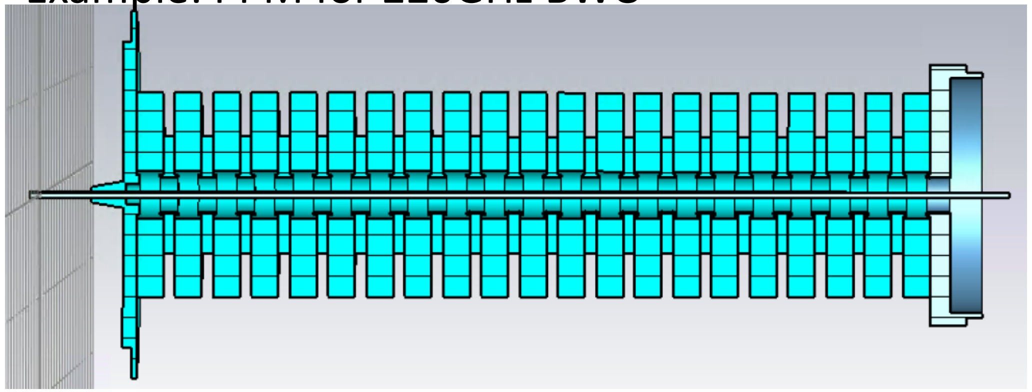


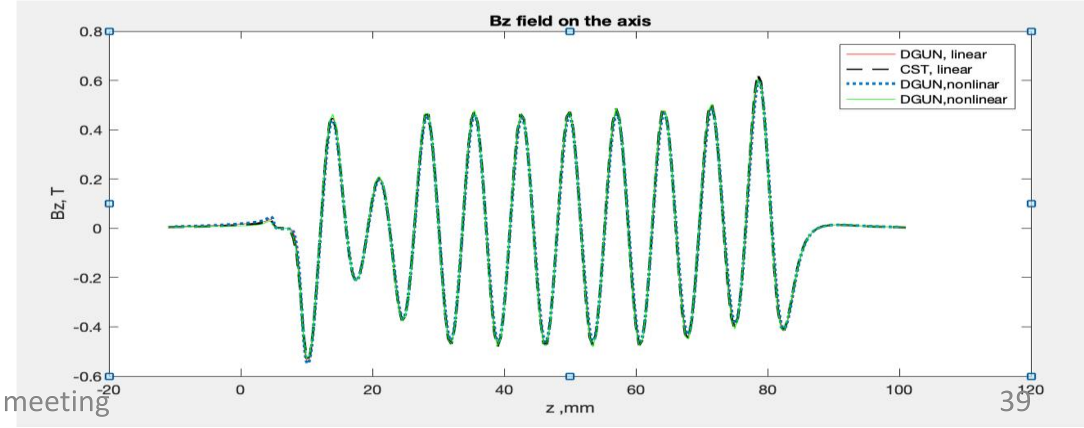
Michelle
400kV,190A



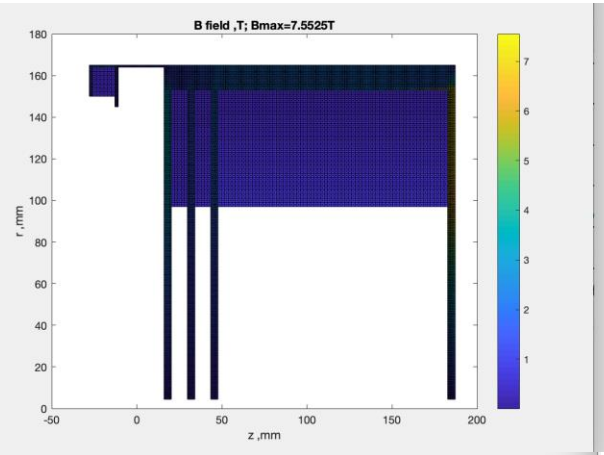
CGUN
400kV,186A

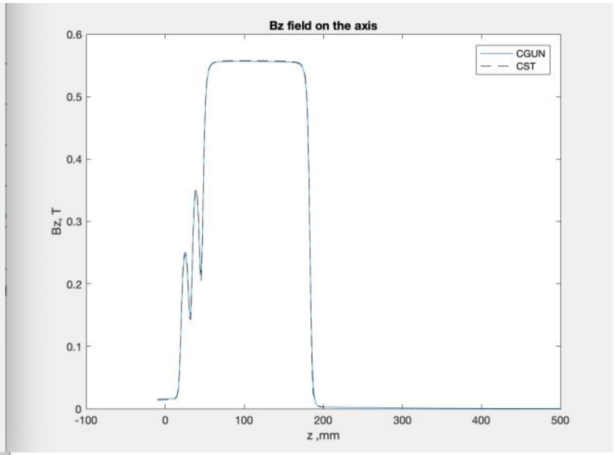
Example: PPM for 220GHz BWO

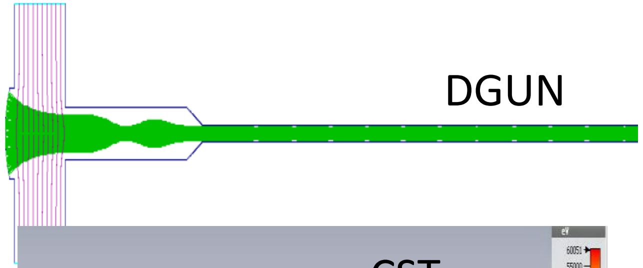


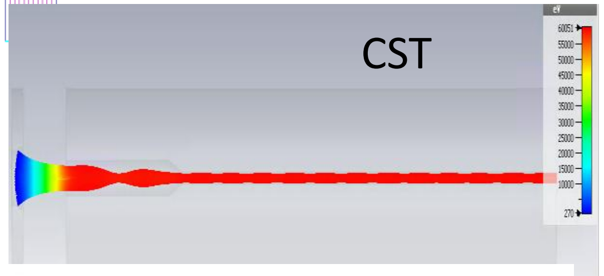


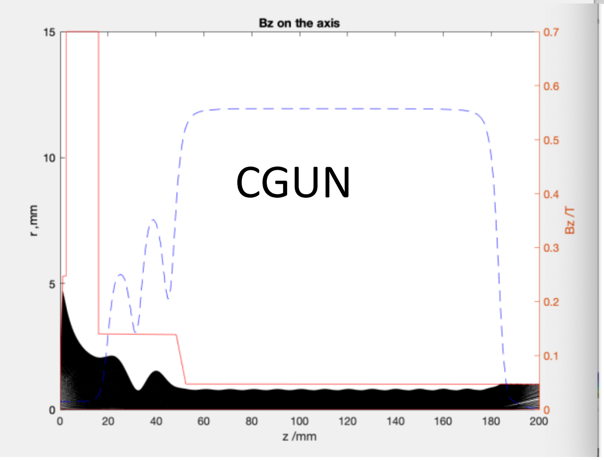
36GHz HOM MBK optics design and benchmark

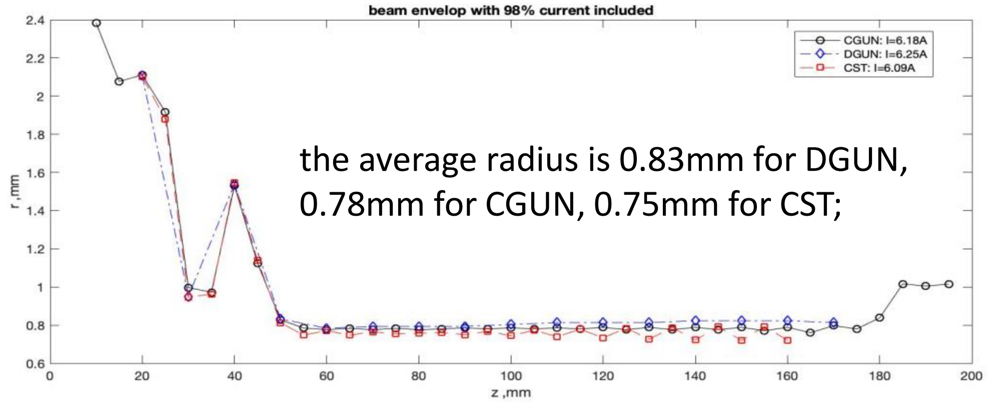












- ✓ CGUN is fast 2D optics code could get very accurate results for axial-symmetric system in fast manner;
- ✓ CGUN is more suitable for analyzing system with GUN section, magnet as an integrity
- ✓ GUI for CGUN will be developed in next few months

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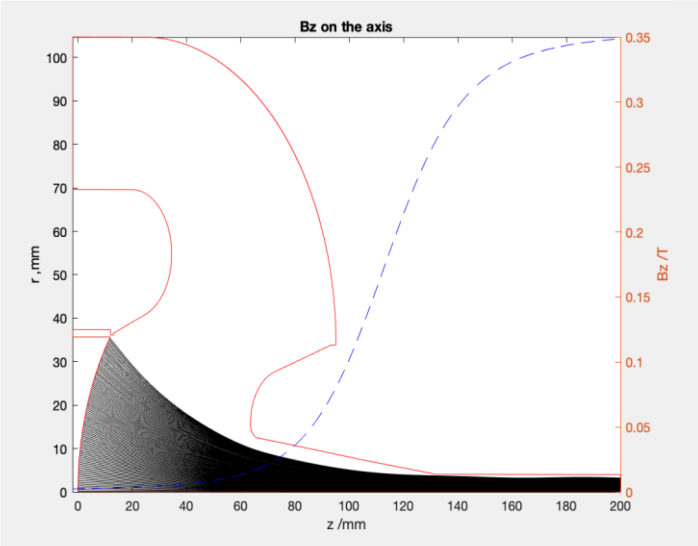
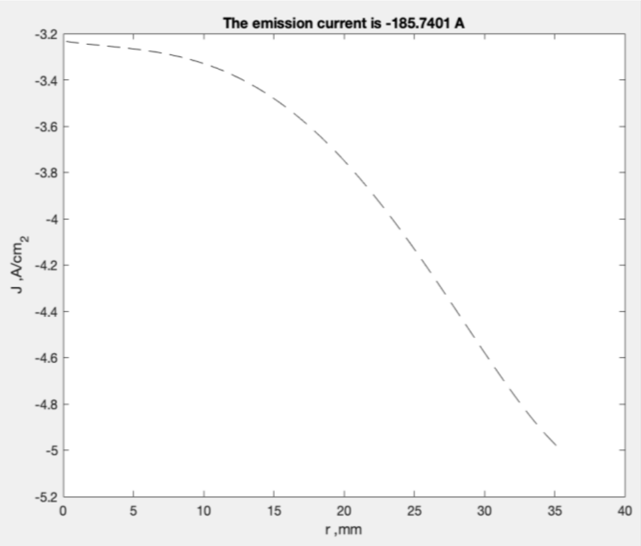
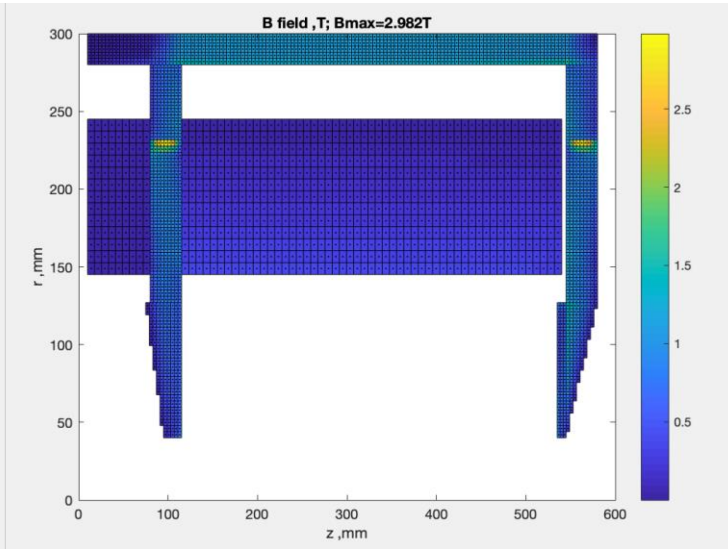
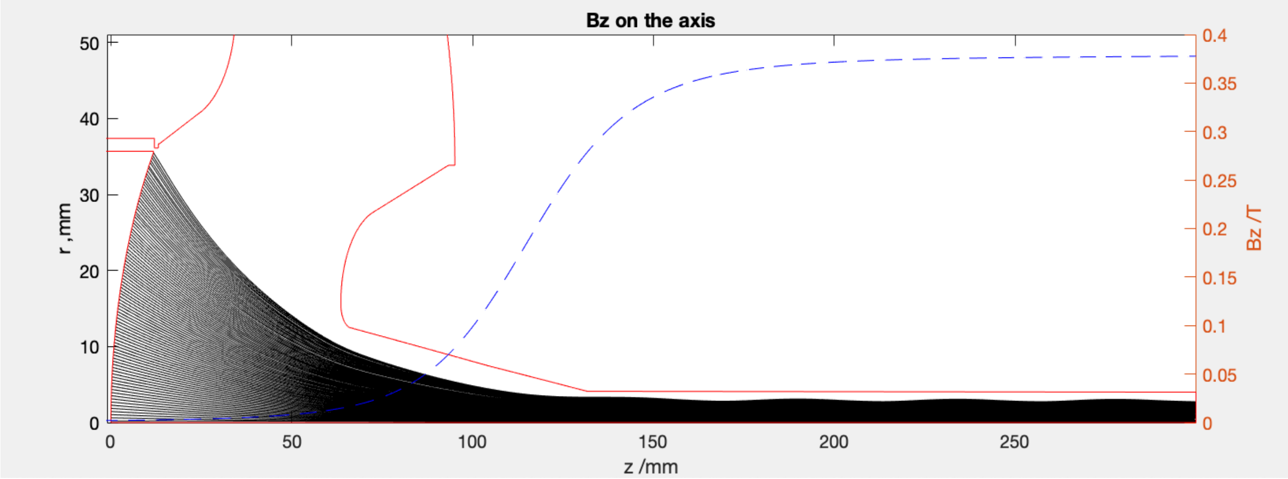
  - GUN, magnet, collector

GUN and magnet for SLACX GUN



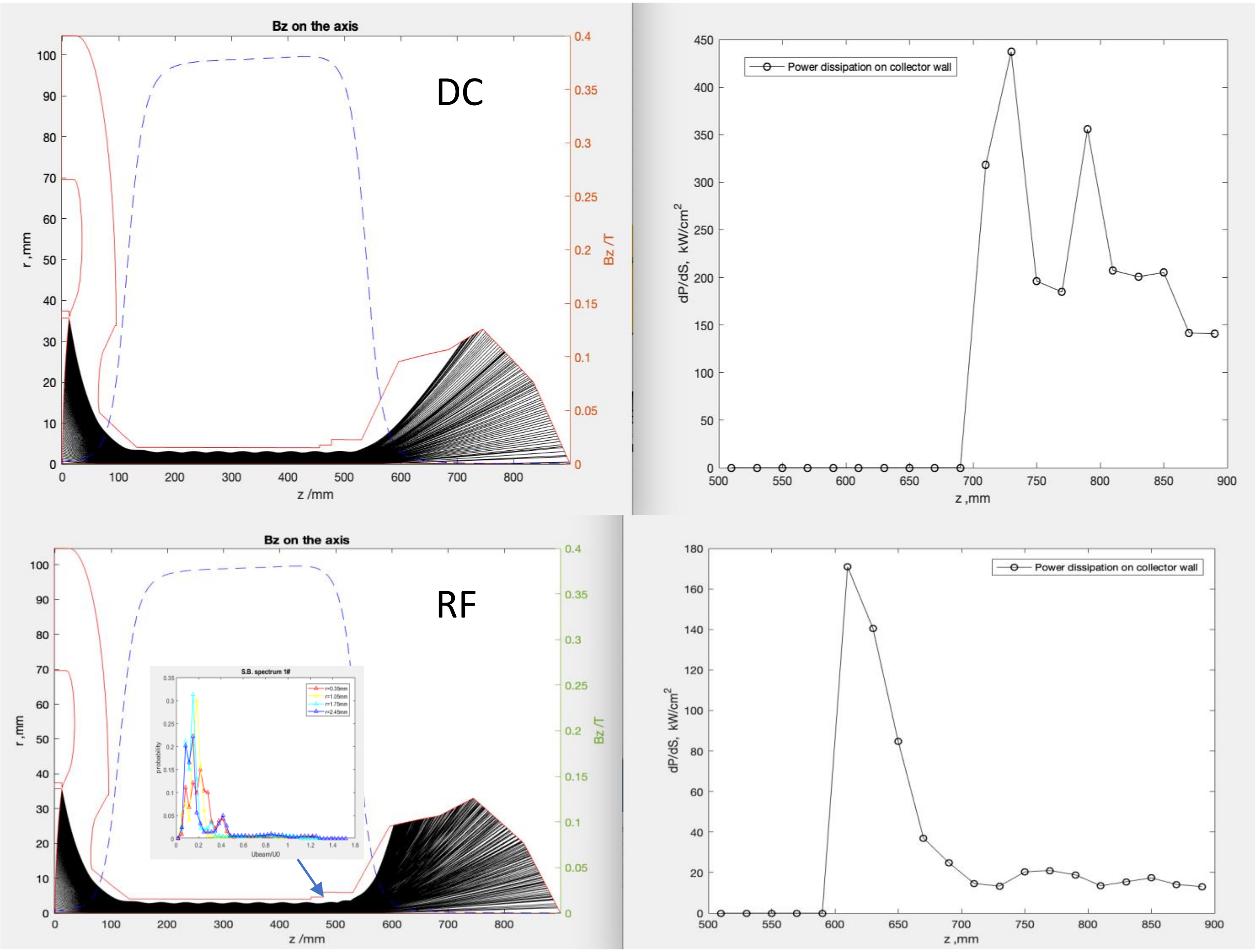






- ✓ GUN geometry and magnet configuration are not changed from original design;
- ✓ Filling factor is a bit high when Bz=0.35T
- ✓ Power consumption~8kW for copper coil
- ✓ Current on coils are adjusted to ensure r_m=[2.8mm,3.0mm]

Optics system with collector



- For Klystron running at 1500ns/1000Hz, peak power density on the collector wall should not exceed 330kW/cm^2 if the maximum average power density is 0.5kW/cm^2 with water cooling.
- CGUN could decelerate the beam with energy spread and radial dependency to simulate the RF case in equivalent way
- Collector profile should be re-optimized due to different spent beam information
- Simulation time for whole optics is about 10min
- For DC, maximum dP/dS=450kW/cm^2
- For RF, maximum dP/dS=180kW/cm^2

Summary

- KlyCv5 will be released on 1 February 2021. It will be available in a public domain.
- CGUN GUI development is underway. The code release for the public is expected in the middle of 2021.
- RF Designs of 50MW and 8MW X-band Klystrons was completed at CERN and communicated to our industrial partners.
- Beam optics design of both Klystrons are re-evaluated and confirmed.
- The X band tubes development was done in close collaboration with our industrial partners. Such a collaboration showed to be very efficient and ensured mitigation of all the technical issues along the design process.

Thanks for your attention!

KlyCv5 and updated User Manual will be released on 1st February 2021. If interested, please contact via email to:

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