High Efficiency Klystron Development at CERN

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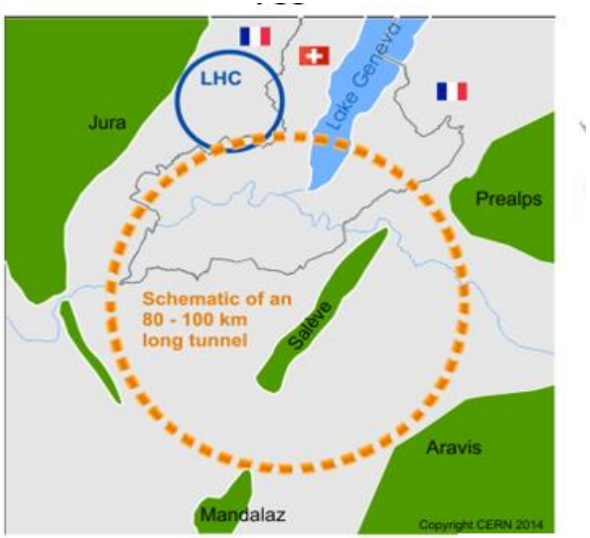
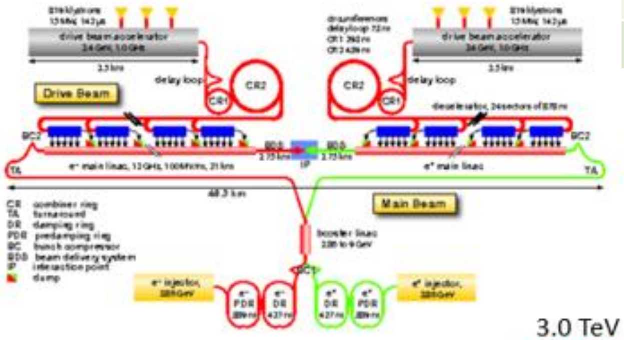


FCC ^{ee}: CW, 0.4/0.8 GHz, P_{RF} total= 105 MW



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 Projects

The klystron efficiency impact on the FCC power consumption.
Example of the efficiency upgrade from 60% to 80%.

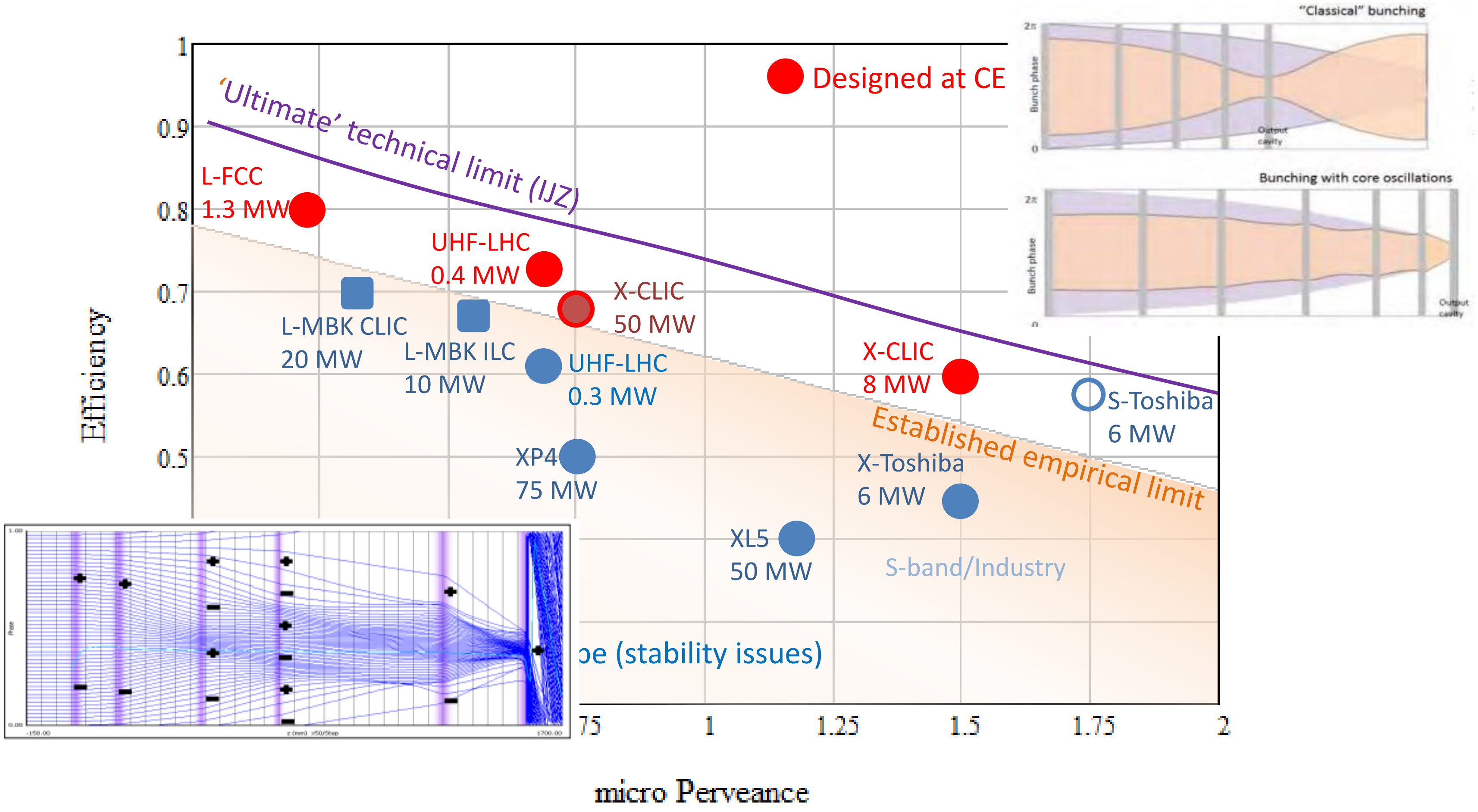
	Klystron eff. 60%	Klystron eff. 80%	Difference
RF power needed for 3TeV CLIC	105 MW		
DC input power	150 MW	123 MW	-27MW
Waste heat	45 MW	18 MW	-27MW
Annual consumption (5500 h assumed)	825 GWh	676 GWh	-149 GWh
Annual cost (60 CHF/MWh assumed)	49.5 MCHF	40.5 MCHF	-9 MCHF

- Potential saving are 1.49 TWh in 10 years (**90 MCHF in 10 years**).
- Reduced environmental impact (cooling and ventilation)
- Reduced installation cost (stored energy in modulators).
- Reduced maintenance cost (factor 2 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 and few completed designs have



KlyC v4

- Disk model: AJDISK,Klys4.5,Dev5,Klypwin
- Discrete model: Tesla, **KlyC**
- PIC:FCI,MAFIA,CST PIC, Magic, GDFIDL, Vorpal (+?)

Of all of them only AJDisk is a non-commercial product.

Klyc1D/2D potentials:

1. Free access for the klystron community.
2. Efficiency, much faster (~1/1000) simulation than PIC
3. Precision, 2D simulation are supported ('frozen' beam)
4. Diversity, possible extension to other Klystron's topologies (Multi-gap, Multi-beam, Traveling wave structure etc…)
5. Flexibility, full adapted for special needs (partitioning, bunched beam generation etc.) and versatile output data interface.

Outline

- L-band Klystron for FCC
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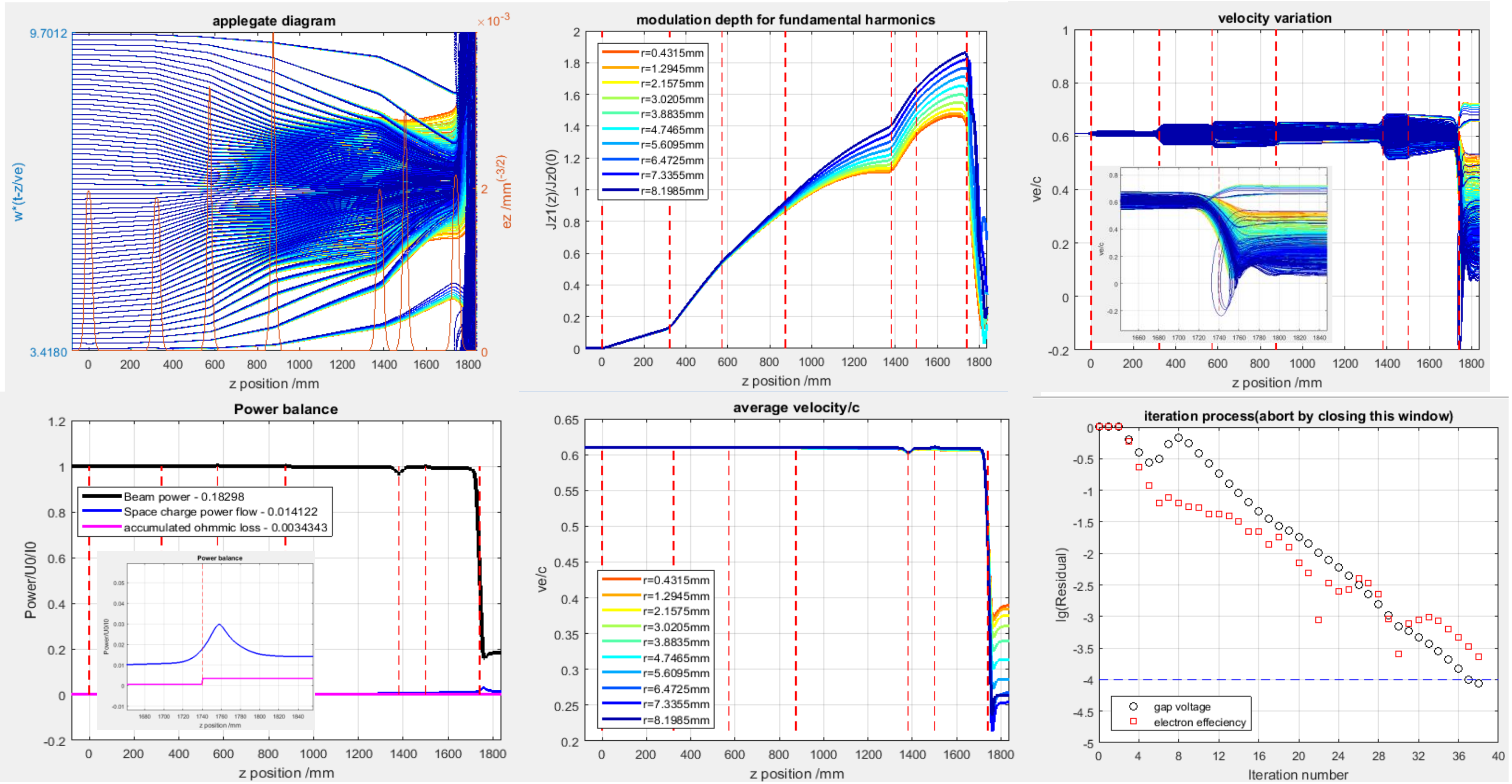
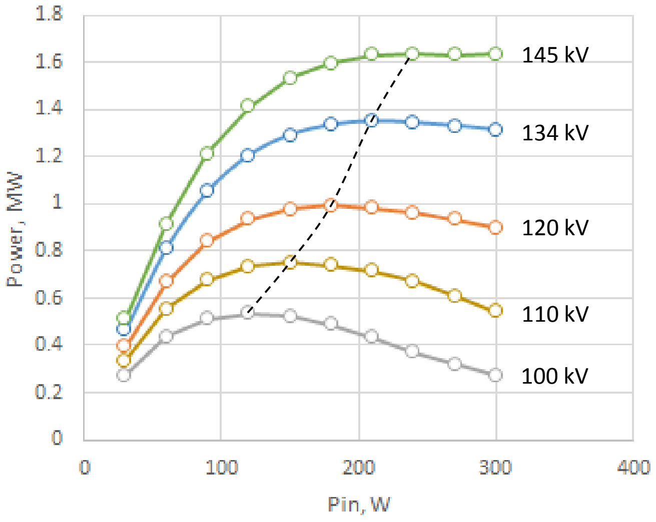
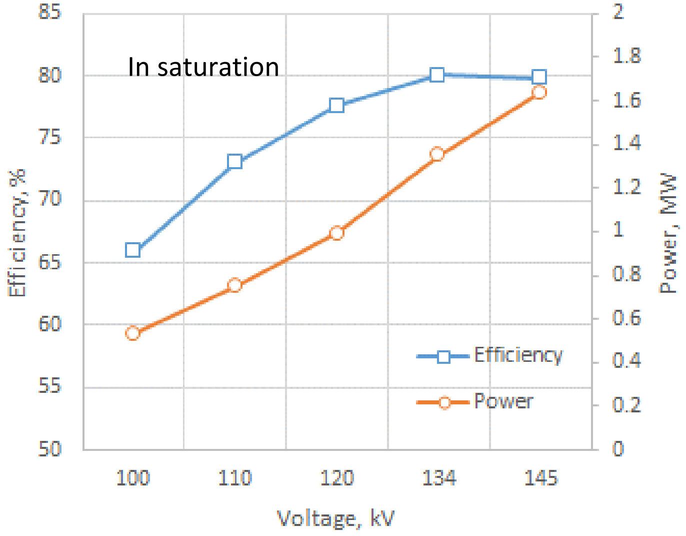
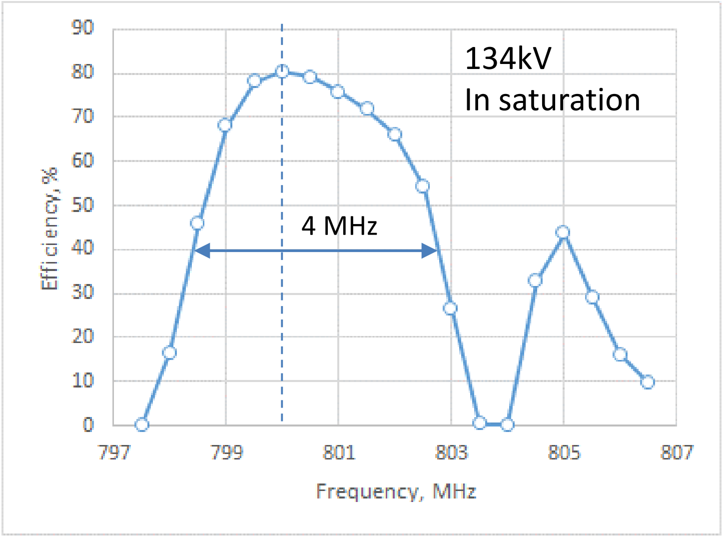
FCC e^+e^-:
0.8GHz,133.9kV×12.5A×**80%**>1.3MW

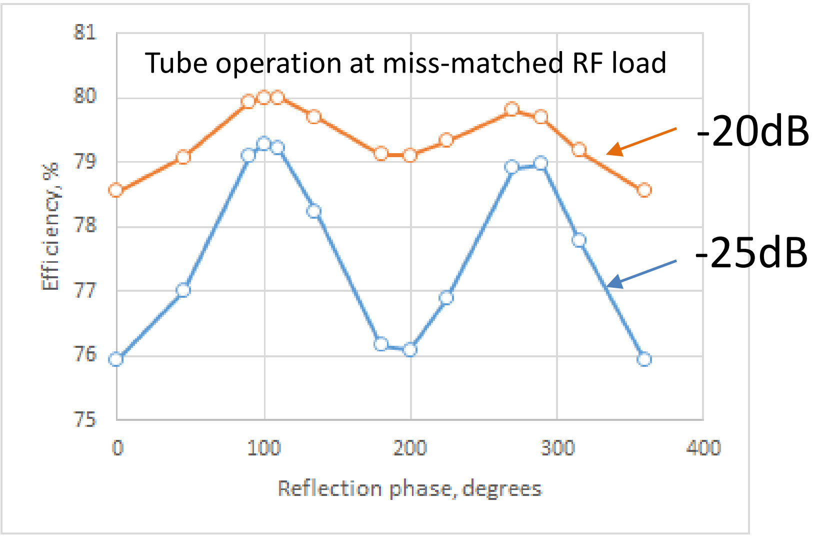


Klystron's Power gain curves and bandwidth (KlyC).

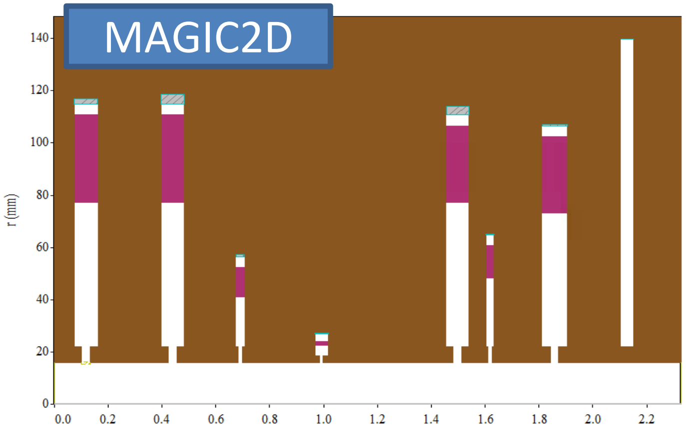




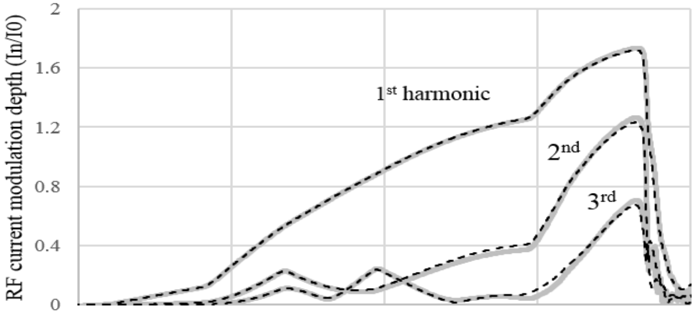


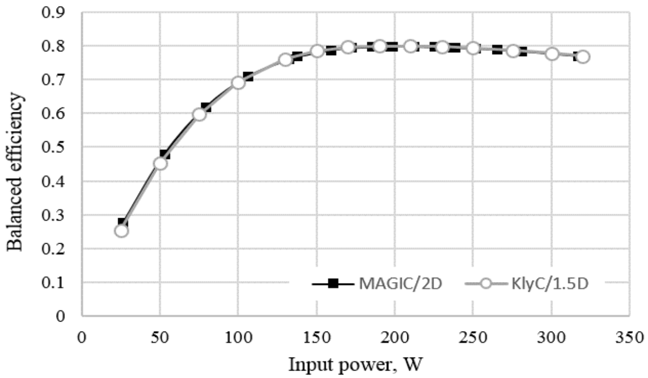


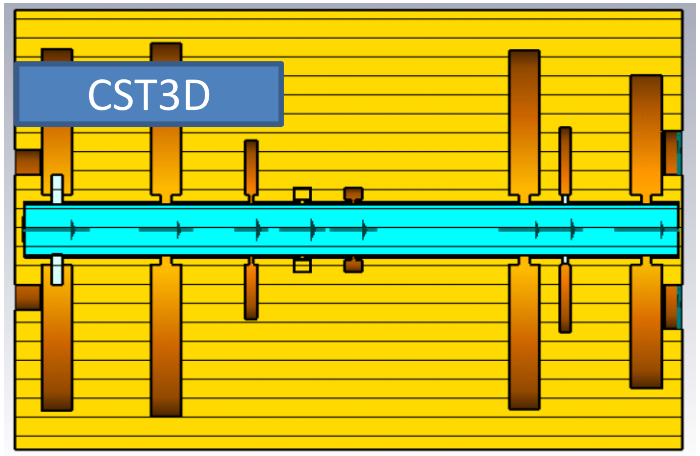
Benchmark with PIC code



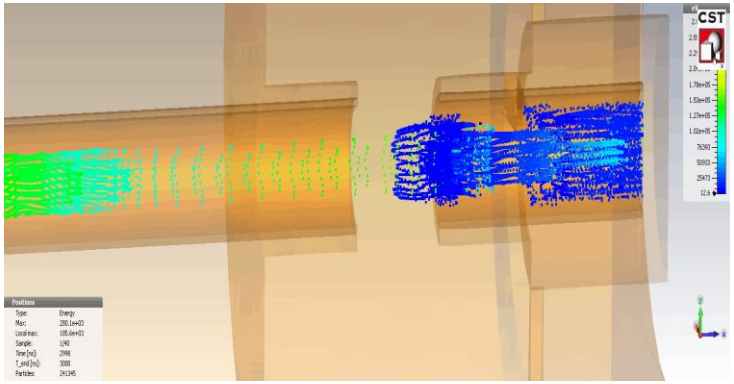
Efficiency=**80%**, Time cost=12h







Efficiency=**79%**, Time cost=50h



B_z=0.07T (5xBr). **Efficiency 79%**

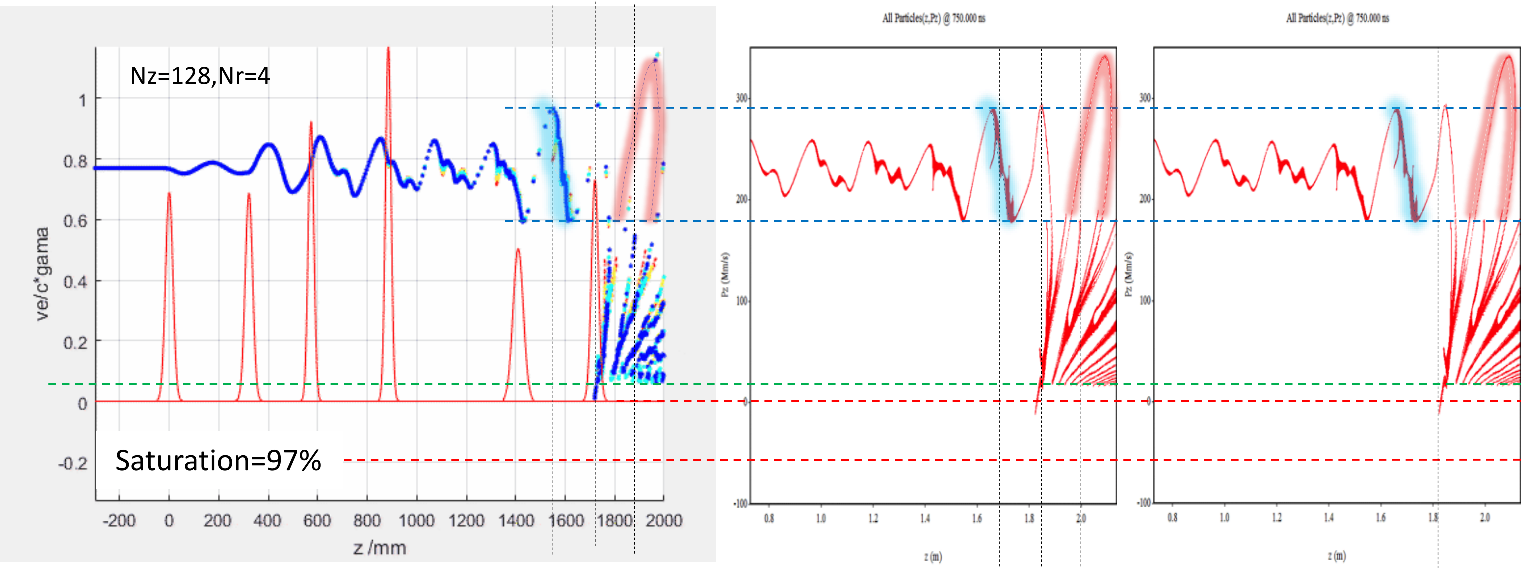
FCC#6. KlyC2D vs MAGIC

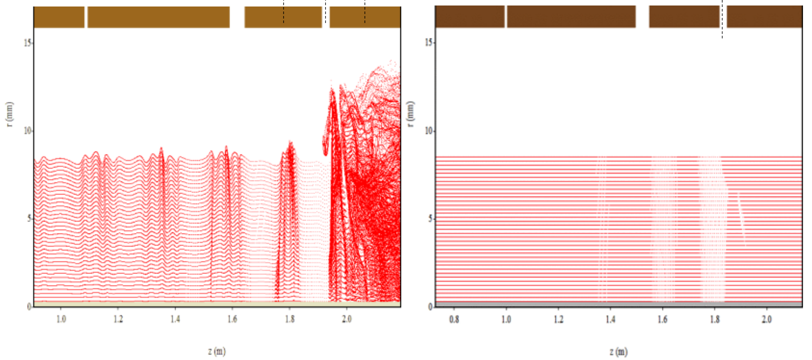
Beam settings:

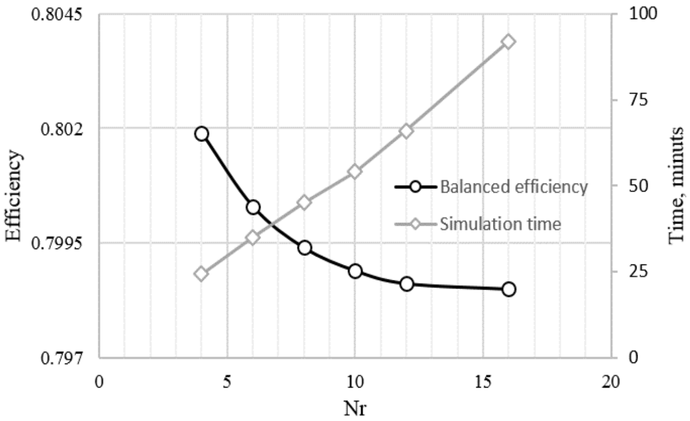
Nz=256,Nr=4, η=79.9%,Tcpu= 20 min

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.

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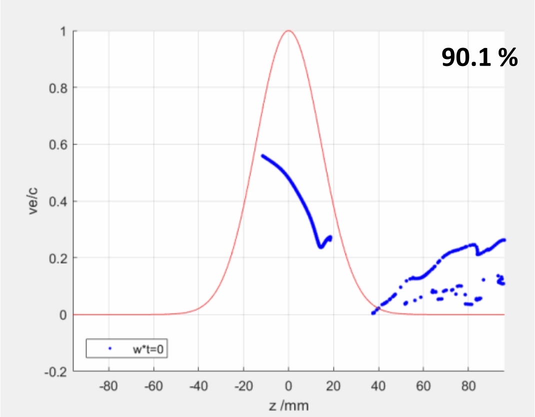
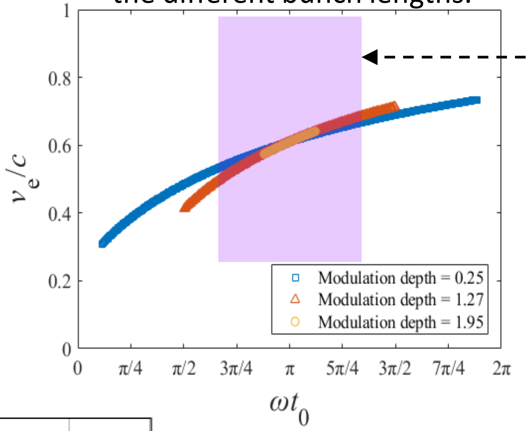
The ultimate power extraction efficiency in the linear beam devices

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

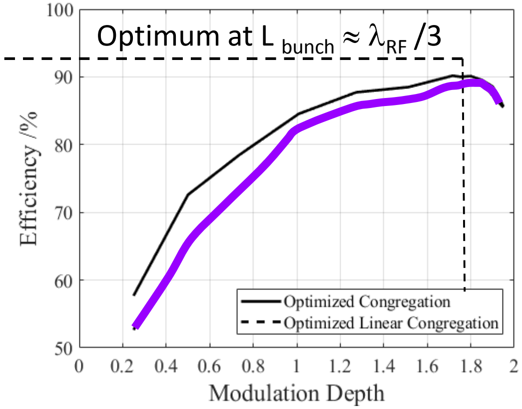
Fully saturated bunch with optimised congregation

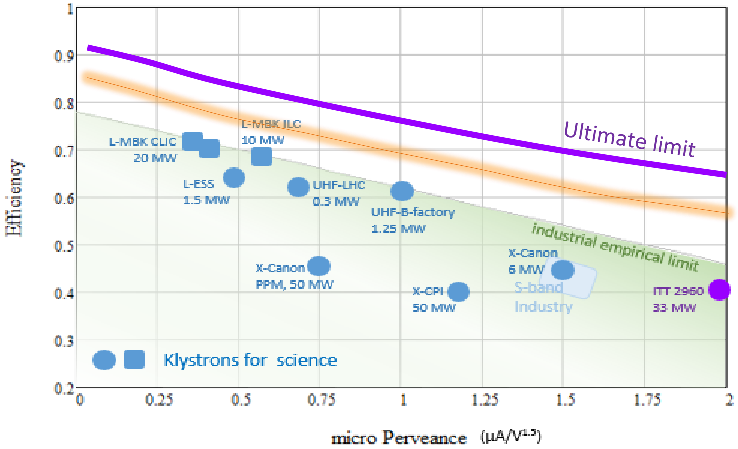


Optimised congregation for the different bunch lengths.



Effect of the bunch length





High efficiency Klystrons design objectives

- E field expansion in the drift tubes
- Ohmic Losses
- Space charge depression

Optimised RF bunching circuit

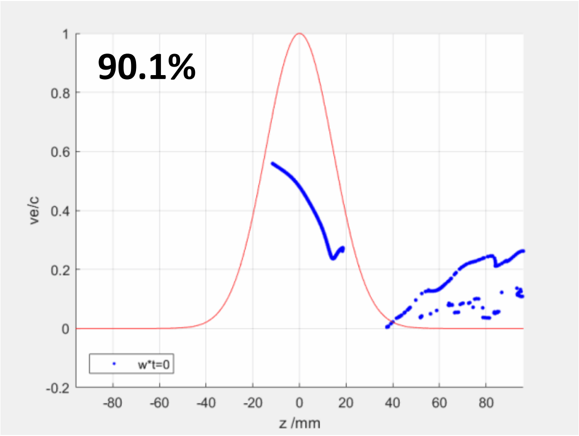
- Bunch saturation
- Bunch congregation
- Bunch stratification

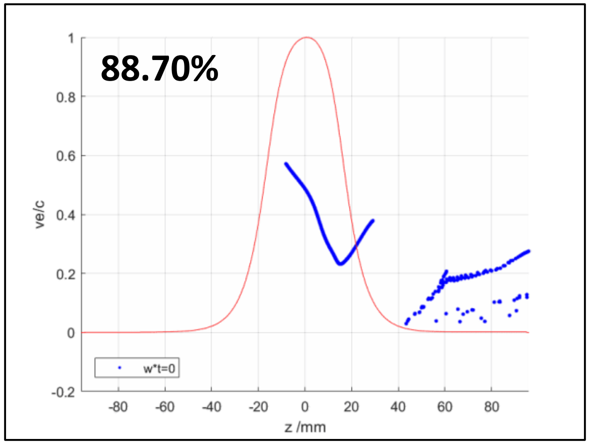
- Radial bunch expansion

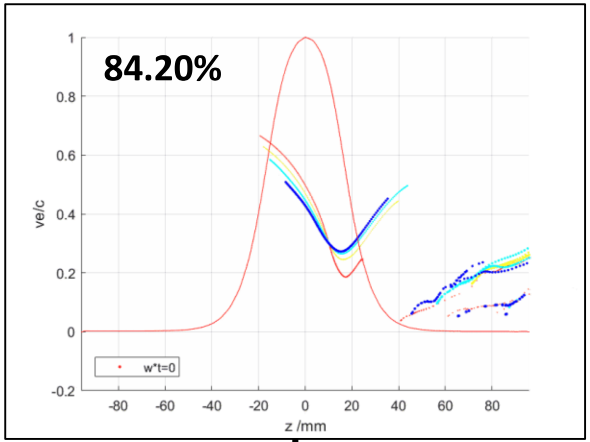
Power conversion efficiency. Limiting factors.

Fully saturated bunch

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

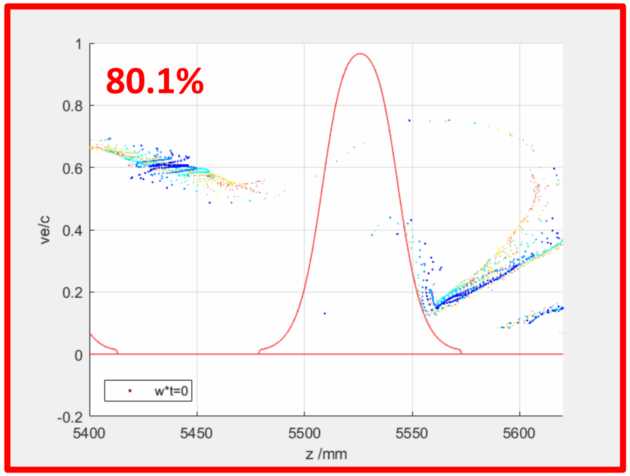


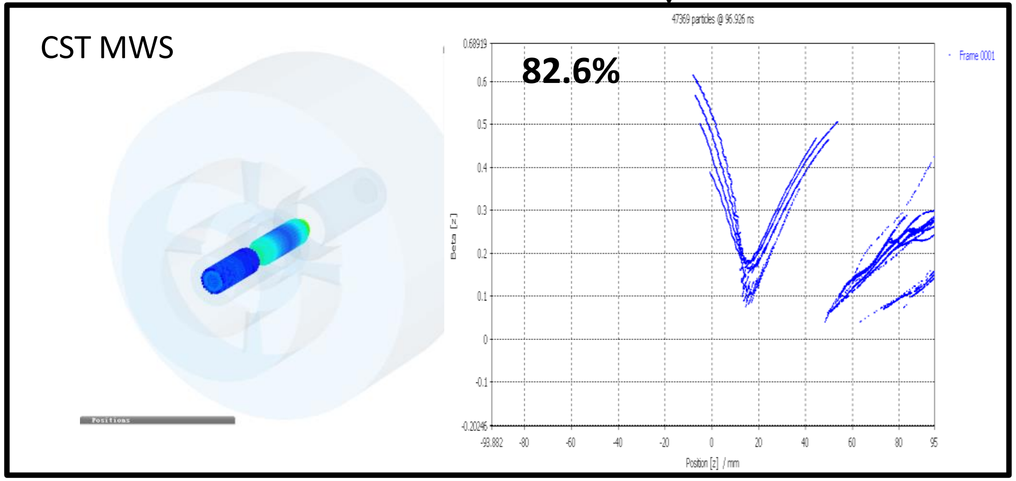




FCC CSM tube ← **Sabre** effect and Ohmic ←

Benchmark with CST for the same bunch quality





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Scaling: Why we do that

- The new HE klystron design is a very time consuming process (Global optimization).
- Scaling allows to obtain a new Klystron design using the existing one without dedicated design efforts (Local optimization).
- Scaling can be used as a sophisticated tool for the new klystron performance & cost evaluation.

Parametric Scaling Procedures

- The beam power, perveance and frequency can be modified

General scaling procedure

$$|\mathrm{M}(\beta_{e0})| \approx constant, \sqrt{A}\beta_e L_{drift} = constant$$

$$\frac{A^{0.4}\gamma(\gamma+1)}{\rho|\mathrm{M}(\beta_{e0})|^2\mathrm{Q}}\frac{U_0}{N_b I_0} = constant$$

$$\frac{n\omega-\omega_0}{\rho|\mathrm{M}(\beta_{e0})|^2\omega_0}\frac{U_0}{N_b I_0}A^{0.4}\gamma(\gamma+1) = constant$$

$$\frac{1}{\rho \mathrm{Q}_{Loaded}}\frac{1}{|\mathrm{M}(\beta_{e0})|^2}\frac{U_0}{N_b I_0}\gamma(\gamma+1) = constant$$

$$\frac{n\omega-\omega_0}{\rho\omega_0}\frac{1}{|\mathrm{M}(\beta_{e0})|^2}\frac{U_0}{N_b I_0}\gamma(\gamma+1) = constant$$

$$\frac{P_{in}}{U_0\cdot N_b I_0}\frac{1}{|\mathrm{M}(\beta_{e0})|^2 A^{0.4}}\frac{1}{\gamma(1+\gamma)} = constant$$

$$\frac{f\times r_c}{v_e} \approx constant$$

Bunch circuit

Simplified Extraction theory

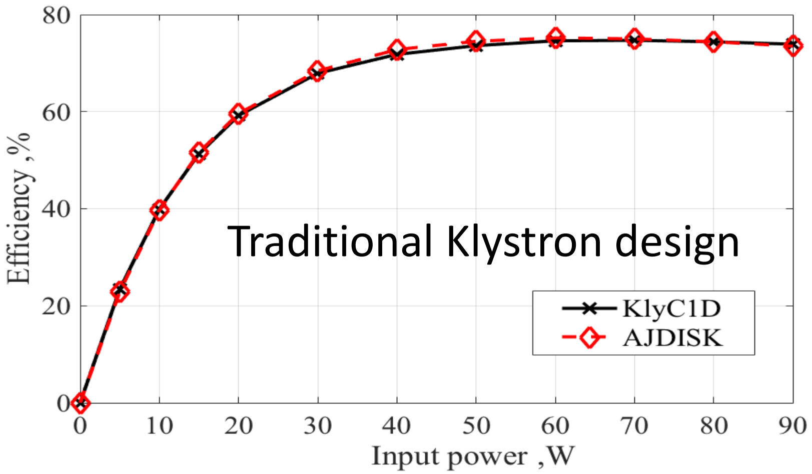
Preserve $U_{gap}|\mathrm{M}(2\beta_{e0})|/U_0$

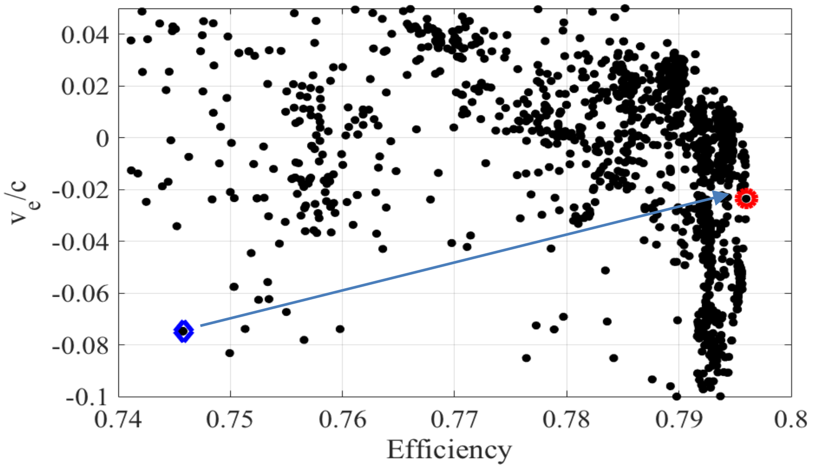
Output cavity

Input power

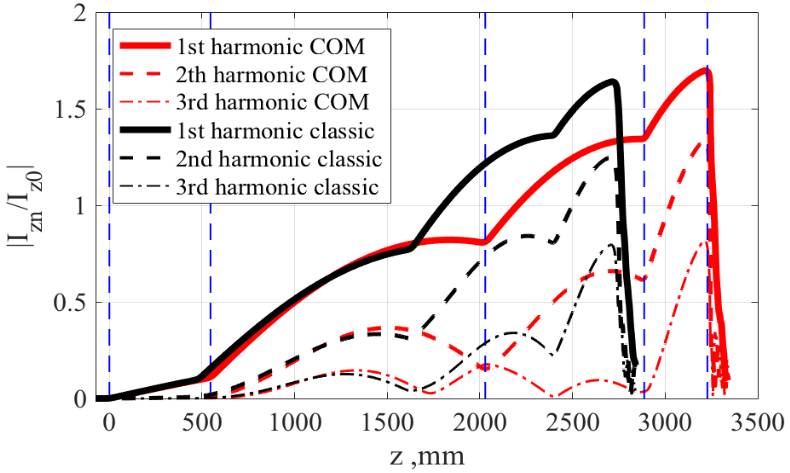
5 cavity L-band Klystron example

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

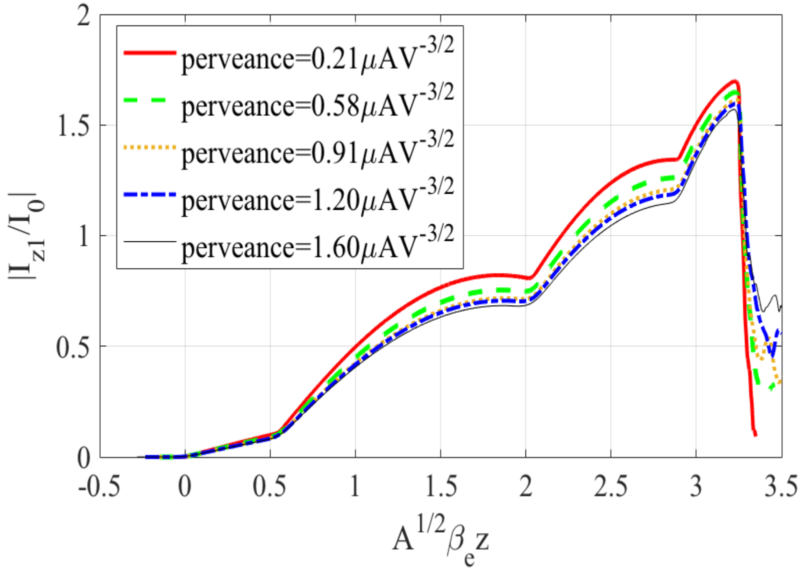


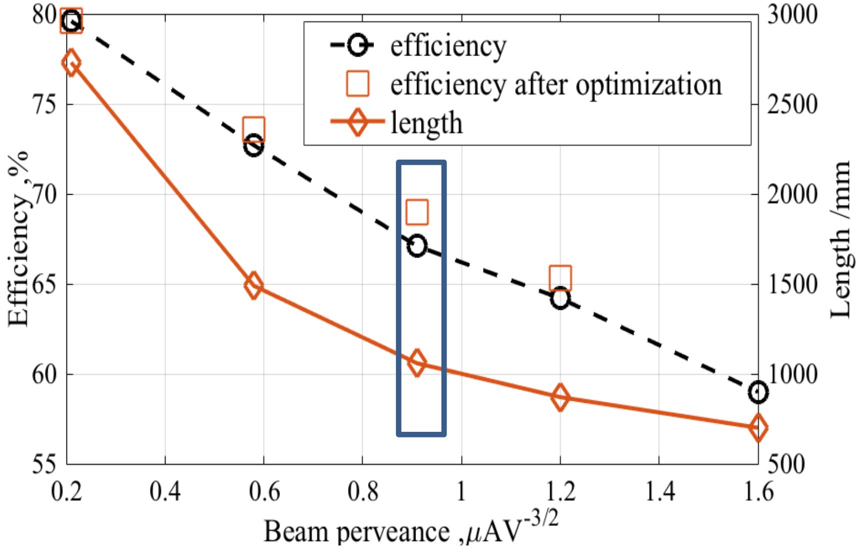


- KlyC1D is benchmarked with AJDISK1D
- Classic design optimized to COM design
- COM design (eff.~80%) tube will be demonstrated as methodology of scaling and post optimization procedure



Scaled to different perveances

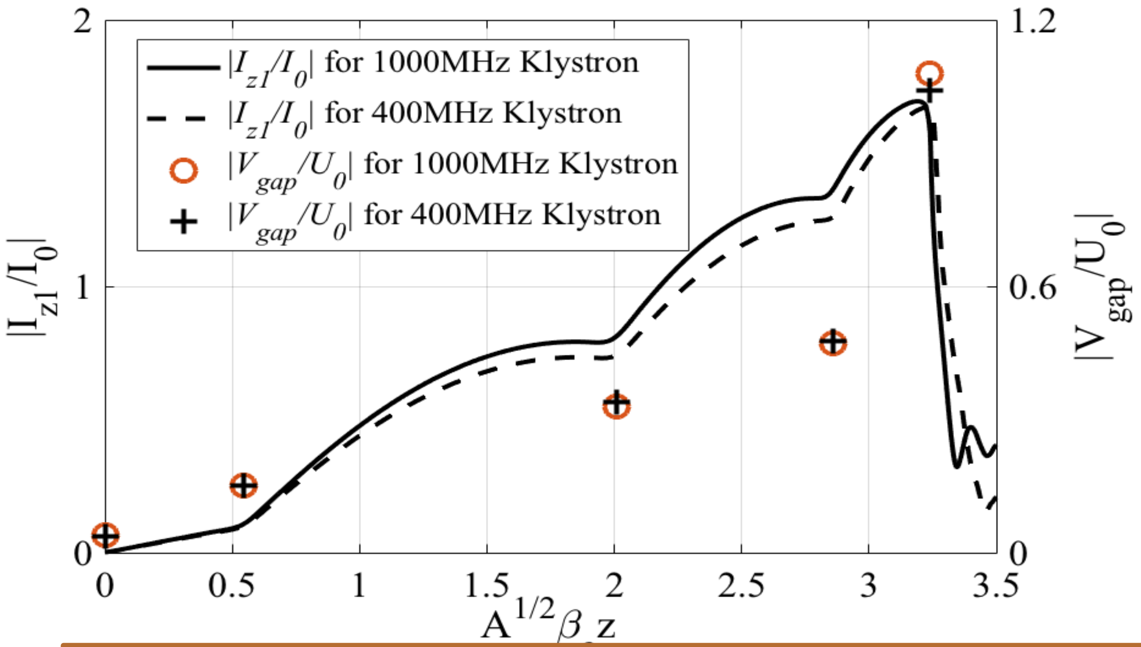




- Scaling preserves the current modulation process (slightly changed)
- Scaling tries to preserve the eff. (but follows the eff. vs perveance law)
- Larger beam perveance means larger SC effects, therefore low efficiency
- Larger beam perveance also shrinks the device length
- Gap voltage changes little (not shown here) with beam power unchanged
- Post-optimization increases the efficiency slightly, means scaling works
- 0.9 uP post-optimized case will be selected for the following analysis

Scaled to different power level

54kV, 9A (LHC parameters), relativistic perveance almost unchanged



- ✓ PSP scaling is done
- ✓ Current modulation not changed
- ✓ Normalized gap voltage barely changed
- ✓ Eff=69.3% which is almost not changed
- ✓ M and R/Q coming from real cavity EM simulation
- ✓ Post optimization can bring the efficiency to 71.0% in KlyC 1D simulation

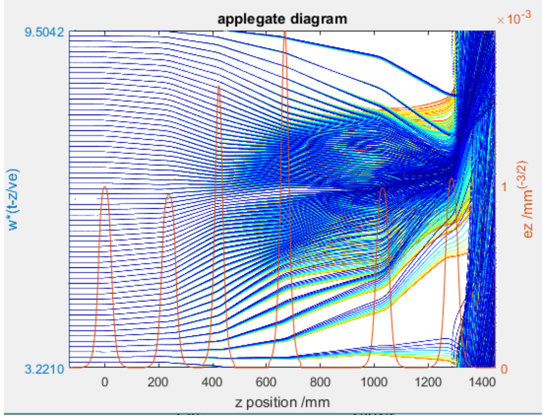
KlyC1.5D shows the saturation efficiency as 65.5% which is not further optimized

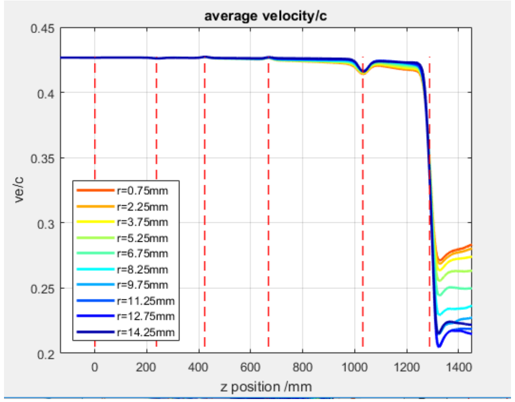
This case is benchmarked in CST PIC simulation

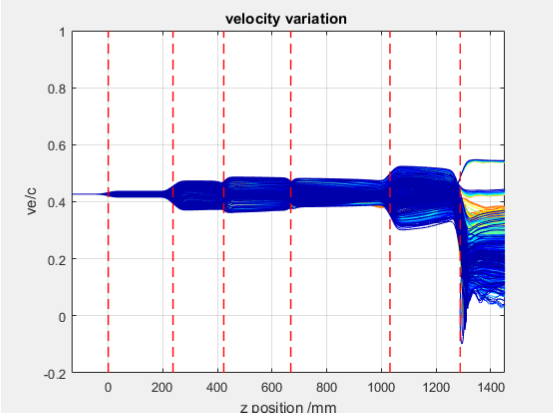
Constrained by the existed modulator

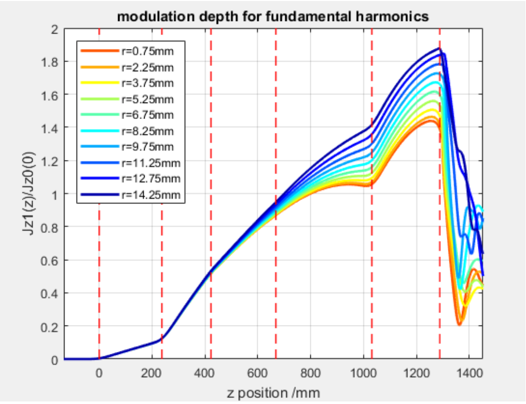
FCC h$^+$h$^-$ /LHC: 0.4GHz,54kV×9A×**70%**~0.35MW (Pin=80W)

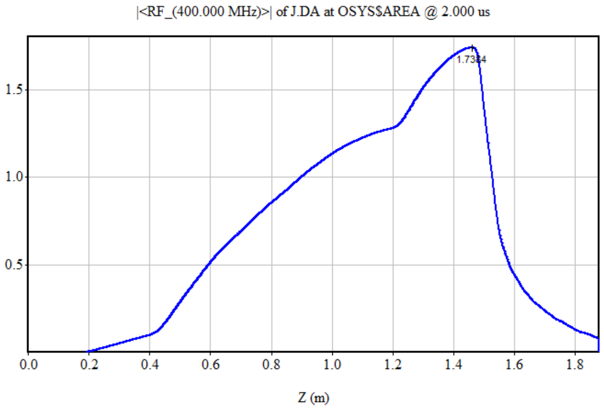
Scaled from FCC 6 cavity design

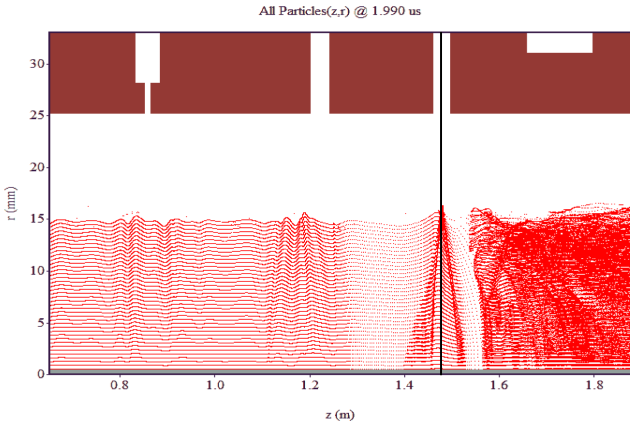












Magic Efficiency = 69.46%

KlyC Efficiency = 70.06%

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- Design and study of the High efficiency Klystrons relies on the massive computer simulations. The computer code KlyC developed at CERN provides the capabilities and reliability of such optimization campaign.
- FCC Klystron design is finished with efficiency~80%.
- Efficiency limit is carefully investigated, which can be taken as the reference for future HE Klystron design.
- Scaling procedure is developed for providing the preliminary design of new Klystron from existed one.

Thanks for your attention!

MAGIC PIC