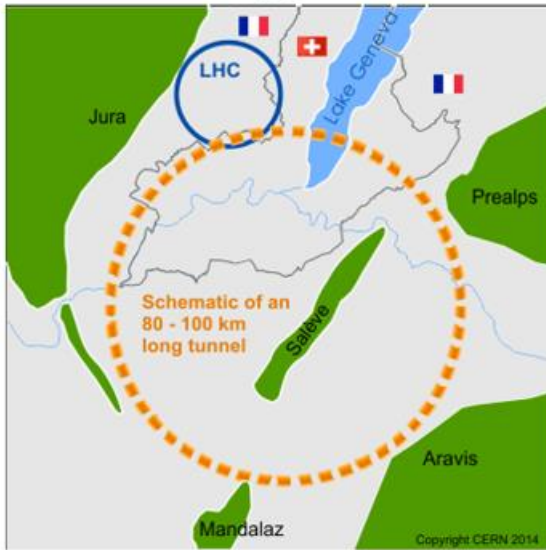


# Advanced techniques for high efficiency klystron simulation

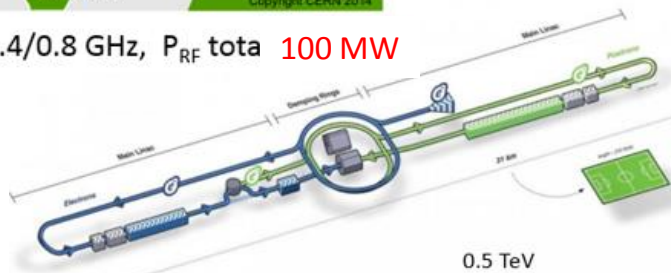
Jinchi Cai, Igor Syratchev  
On behalf of HEIKA team



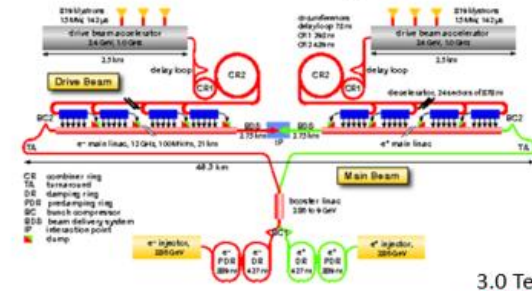
# High efficiency! How high it could/should be!?



FCC  $e^+e^-$ : CW, 0.4/0.8 GHz,  $P_{RF}$  tota **100 MW**



ILC  $e^+e^-$ : Pulsed, 1.3 GHz,  $P_{RF}$  total= **88 MW**



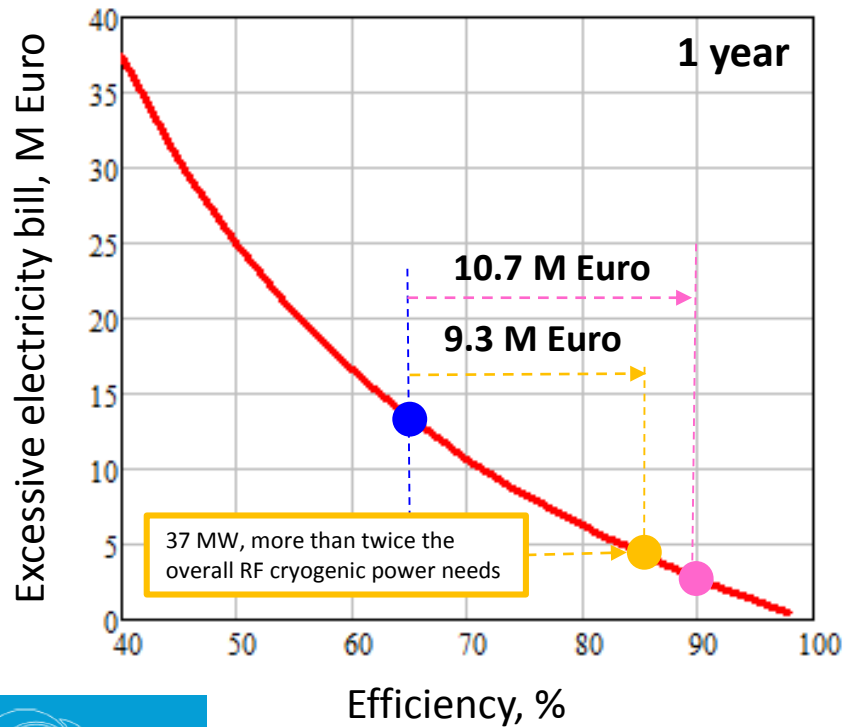
CLIC  $e^+e^-$ : Pulsed, 1.0 GHz,  $P_{RF}$  total= **180 MW**



Pulsed, 0.7 GHz, **92 MW**

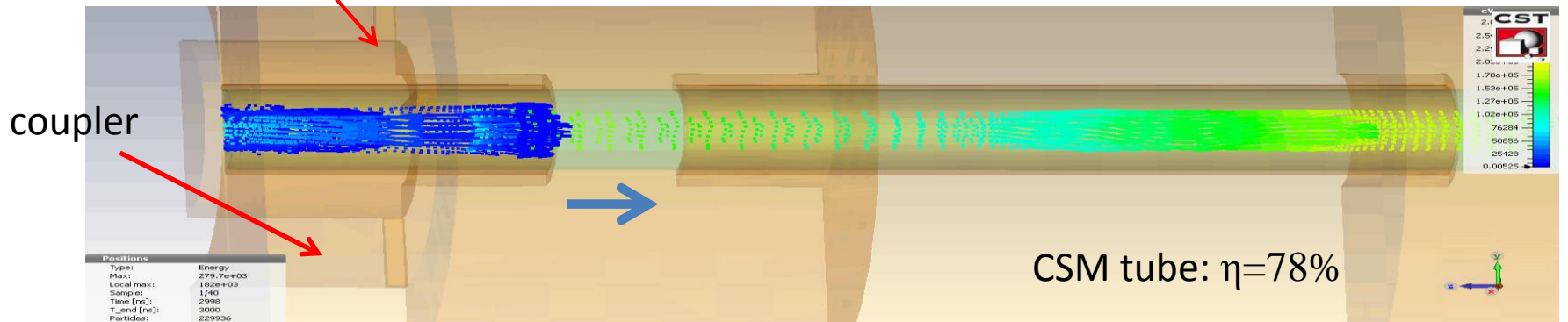
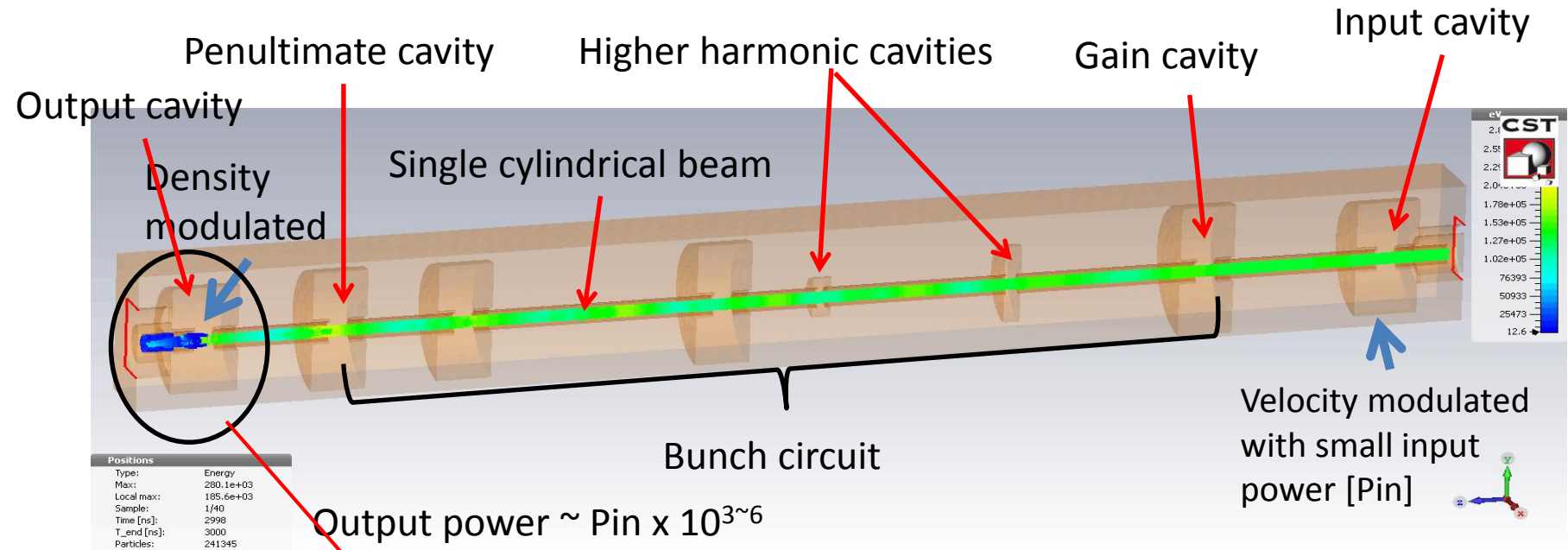
## Efficiency impact on operation cost

FCC  $e^+e^-$  at 50 Euro/MWh and 5000 hours/year:



Efficiency, %

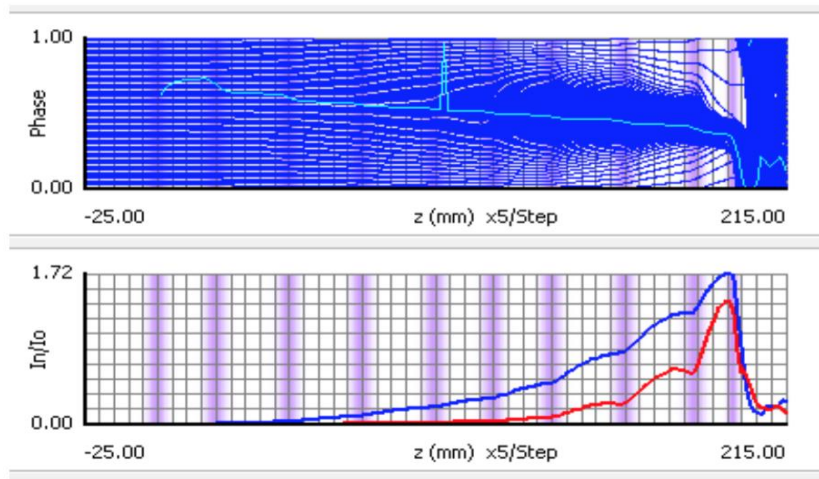
# Mechanism and concepts



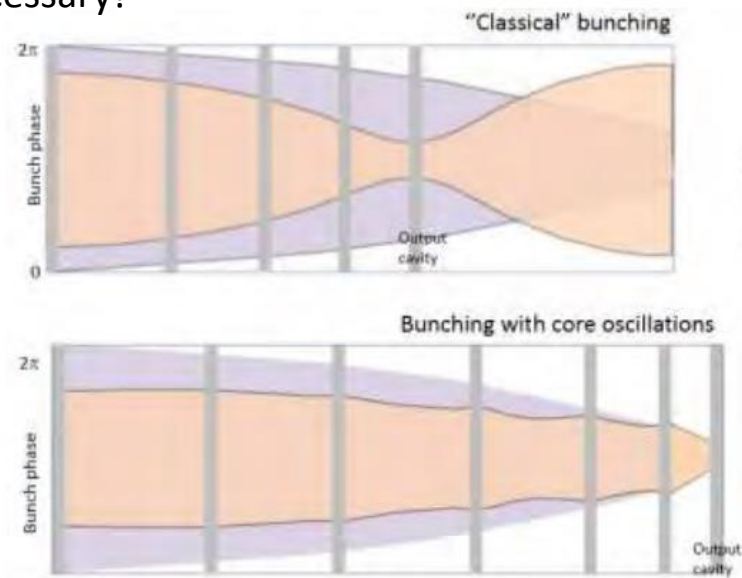
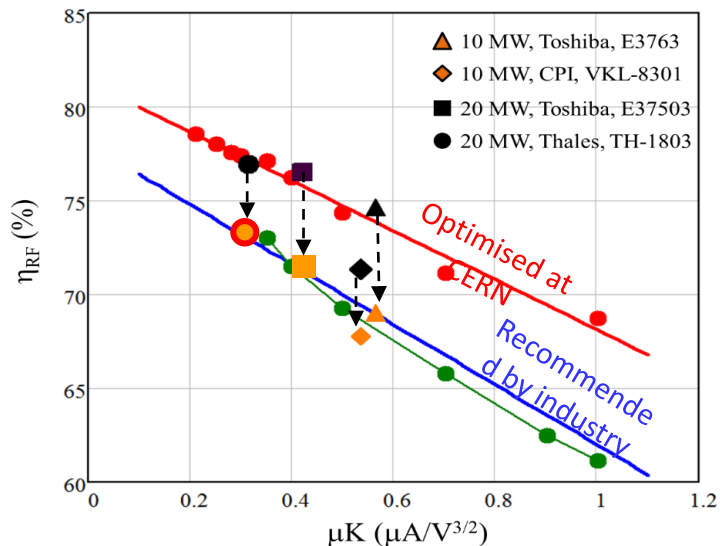
Glossary: Saturation, velocity congregation, Radial stratification

# High Efficiency International Klystron Activity lead by CERN

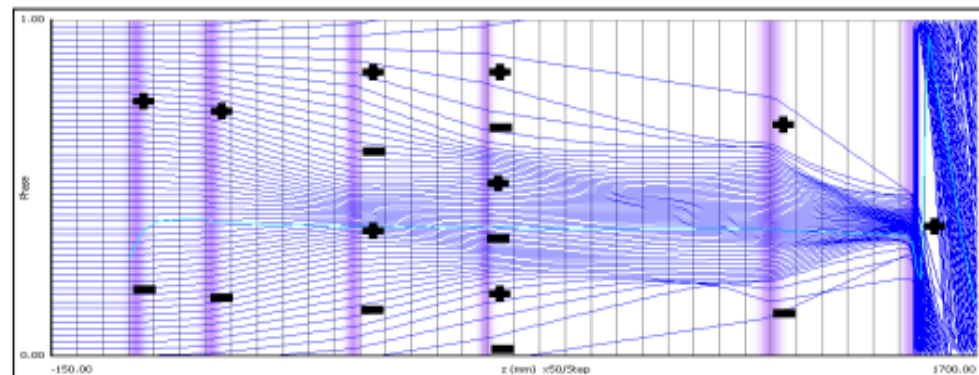
Partitioning analysis and massive optimizations are necessary!



Kladistron



COM method



CSM method

# Available Simulation tools

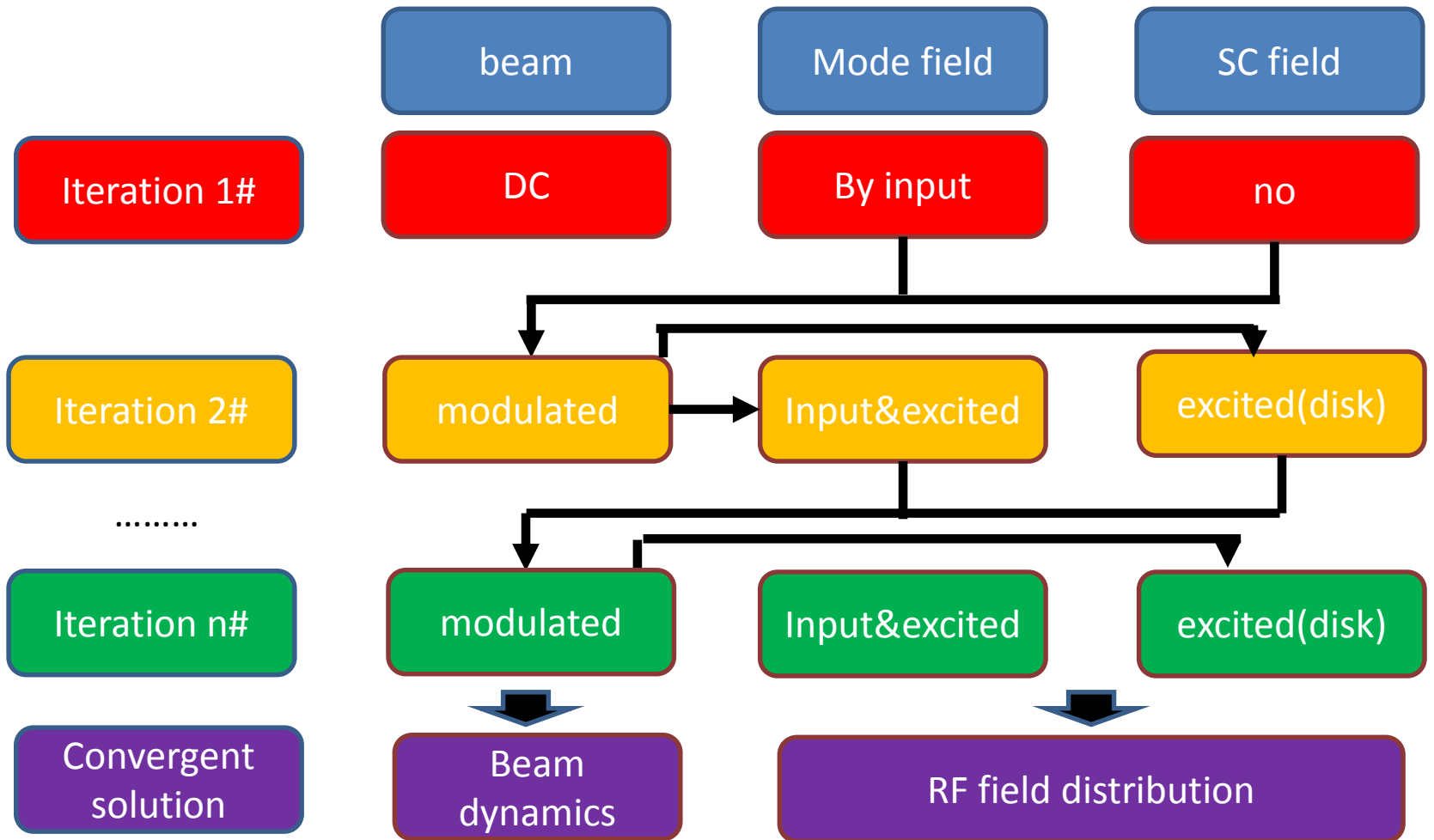
- Disk model: AJDISK, Klys4.5, Dev5, Klypwin
- Discrete model: Tesla, **KlyC**
- PIC: FCI, MAFIA, CST PIC, Magic, GDFIDL, Vorpil (+?)

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 ( $\sim 1/1000$ ) 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.

# Simplified Algorithm for code “KlyC”



Coulomb methods are adopted to calculate the space charge field

Arbitrary mode field distribution is supported

# KlyC Graphical User Interface

New

Open

Save

Save as

Simulate

GS  EM

H.R. accelerate

SC Effect

Considered

Neglected

Beam Para. eff. optimizer

Beam Voltage (kV)

Beam Current (A)

Outer Radius (mm)

Inner Radius (mm)

Tube Radius (mm)

Beam Number

Layer Number

Accuracy Setting plot setting

Space Charge Field Order

Division Number in  $\lambda_e$

Division Number in RF

Max Iterations

Iteration Residential Limit

Iteration Relaxation

Conv. OL   FigOff  FigOn  GIF     txt output   cores

Simulation results summary

Pout=	2161 kW	Gain=	45.94 dB	Vg (kV)	phi(d.)
Eff.RF=	75.04 %	Eff.El=	73.2 %	4.0528	168.0424
Re.RF=	6.738e-05	Re.El=	1.557e-05	13.6916	26.3085
IJ1/J0.i=	1.127	IJ1/J0.o=	1.763	31.7571	130.7212
ve/c.min=	-0.1844	Gama =	0.6239	42.1502	-166.8149
		pha.s=	45.62 °	206.7961	-134.3819

Successful iteration: Yes

Cavity Param

Number	Har	M
1		0.92
2		0.89
3		0.81
4		0.95
5		0.93

Gaussian profile

EM 2D

Reflection for output

amp  degree

(x,y,z,Ez)

default

default

default

default

default

default

check

Import

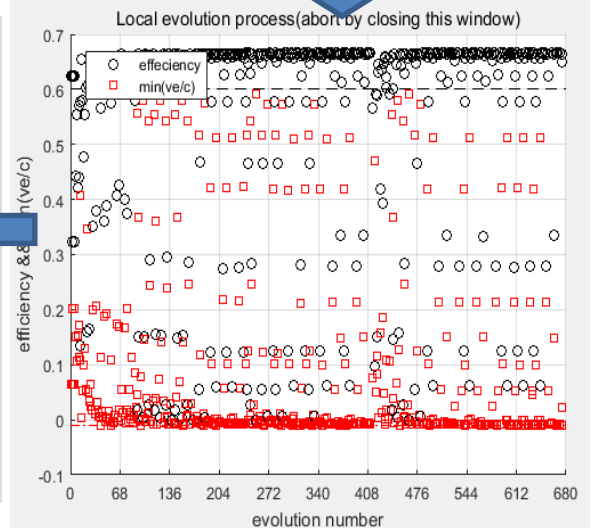
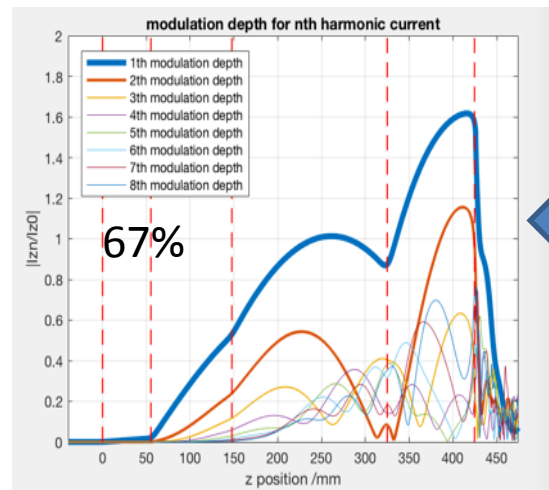
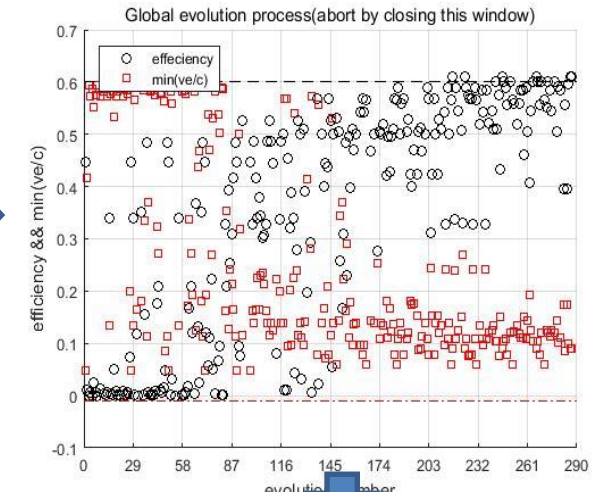
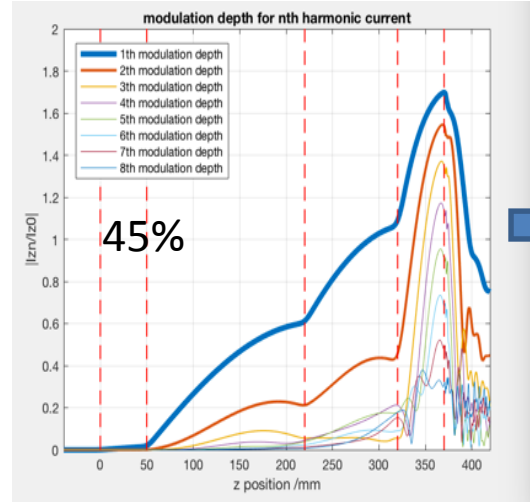
Cavity Number   Behind of No.   No.

No.

field map   Running ● KlyCv3

# Eff. Optimizer in KlyC

Beam Para.		eff. optimizer	
deltaf/f		<input type="text" value="0.01"/>	
delta z /mm		<input type="text" value="20"/>	
seperation /mm		<input type="text" value="30"/>	
-dQe/Qe	<input type="text" value="0.2"/>	+dQe/Qe	<input type="text" value="0.2"/>
eff. LB	<input type="text" value="0.3"/>	ve/c. LB	<input type="text" value="0.1"/>
Max Ev.	<input type="text" value="50"/>	Individual	<input type="text" value="30"/>
<b>start opt.</b>		Global ▼	



- Global: genetic algorithm
- Local: pattern search
- S band, perv.=1.9μP
- 3 days for optimization

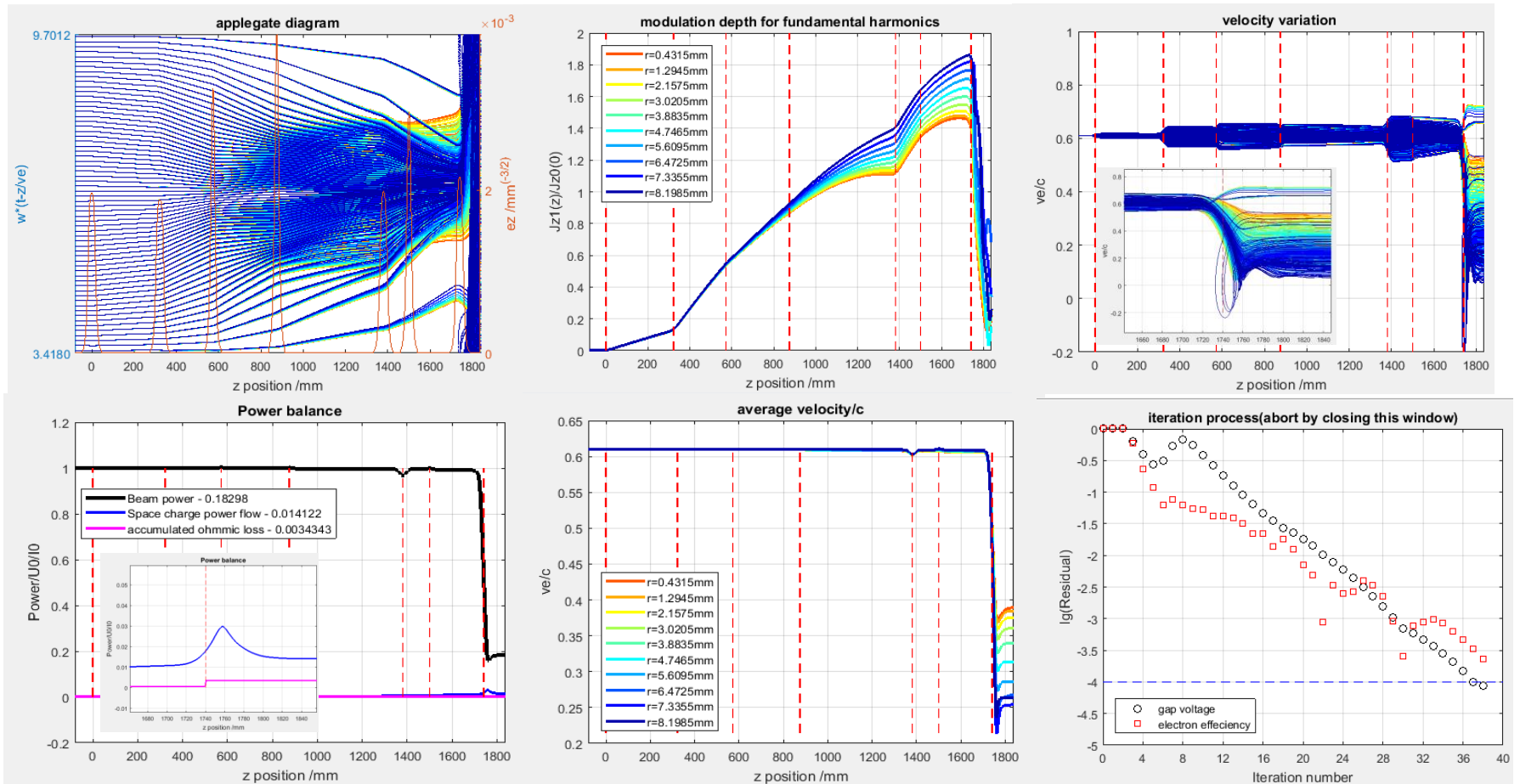


# FCC Klystron design

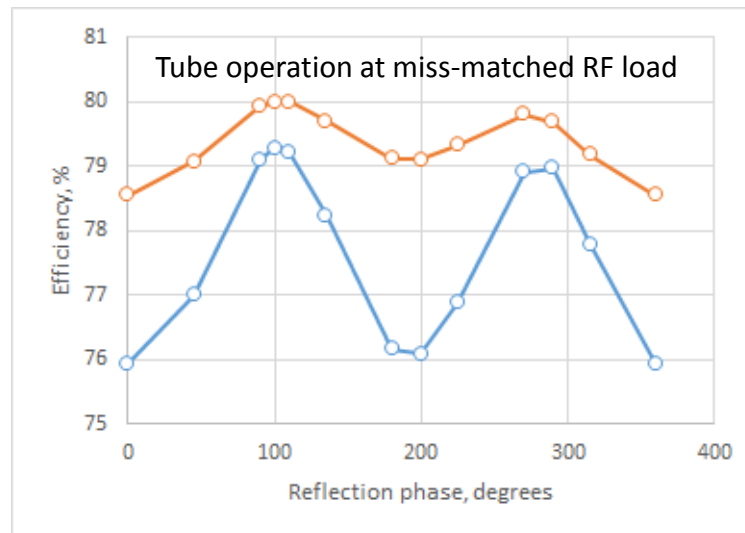
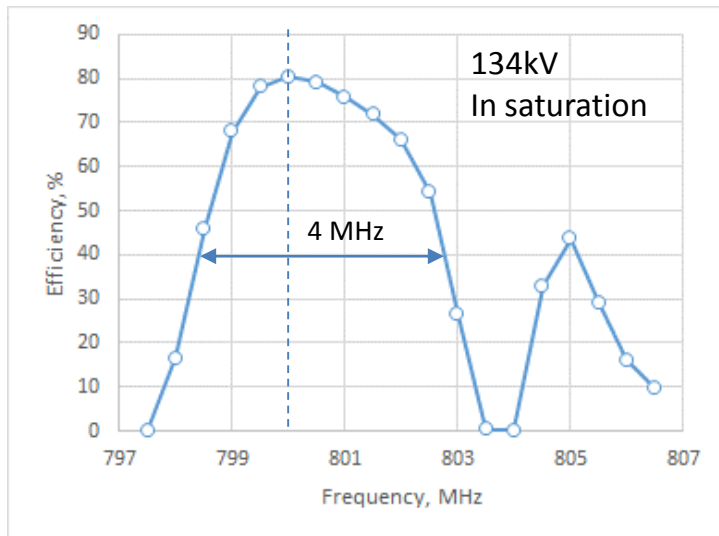
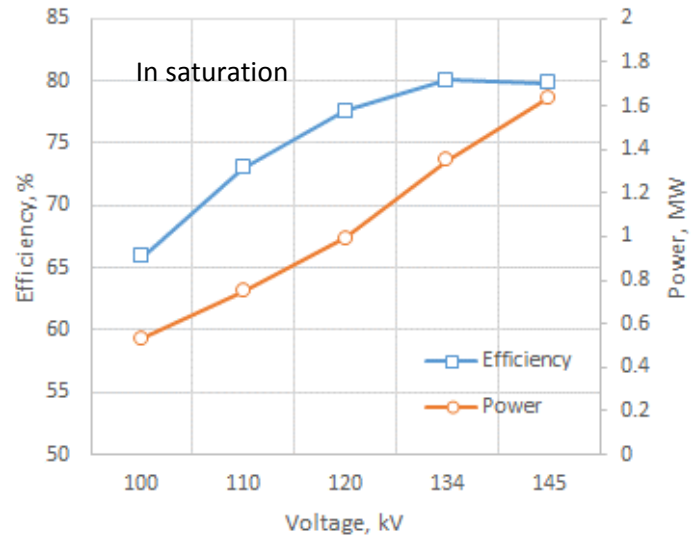
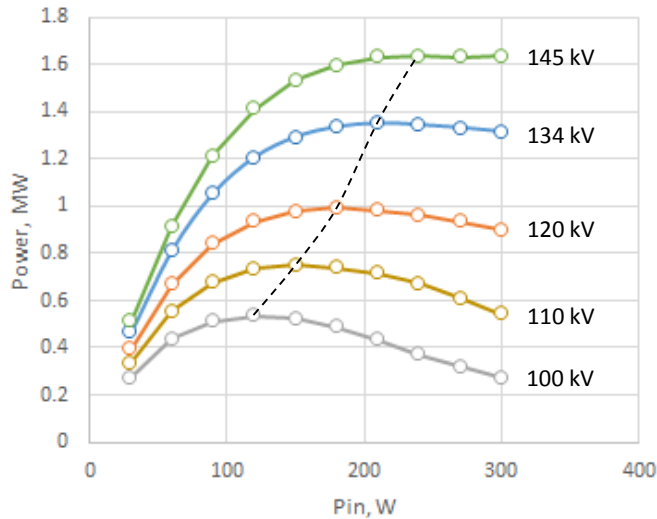
- Scaling method to get the initial CSM design
- Optimized in KlyC1D(~2min per case)
- Polished in KlyC2D(~20min per case)
- Performance summary and Sensitivity analysis in KlyC2D
- Verified by Magic 2D(12h per case) and CST 3D(50h per case)

# FCC $e^+e^-$ :

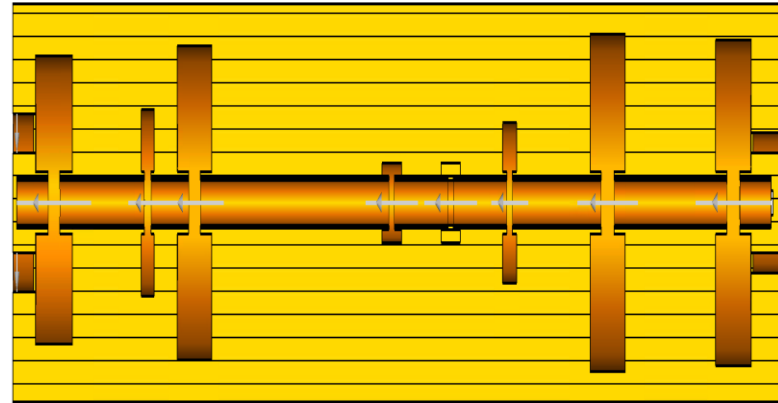
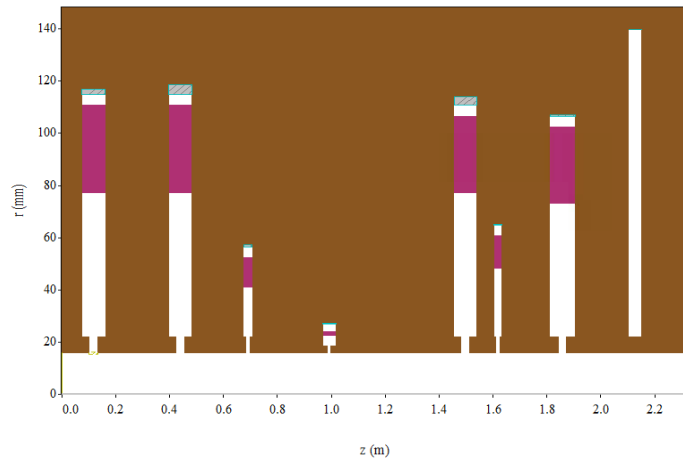
0.8GHz, 133.9kV  $\times$  12.5A  $\times$  **80%** > 1.3MW



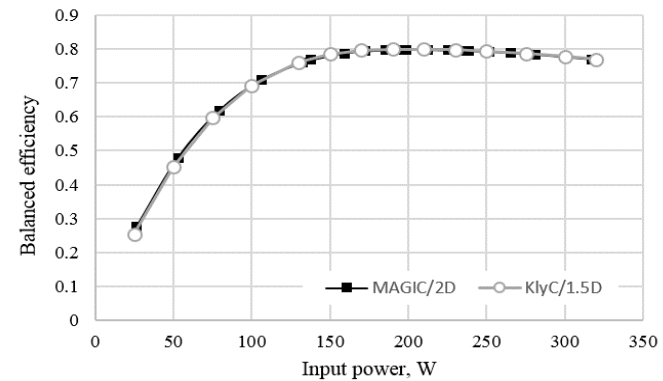
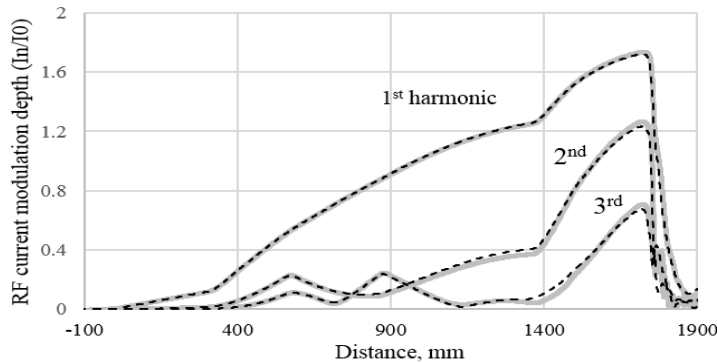
# Klystron's Power gain curves and bandwidth (KlyC).



# Benchmark with PIC code



Efficiency=**80%** @Magic 2D and **79%** @CST 3D  
Time cost=**12 h** @Magic 2D and **50h** @CST 3D





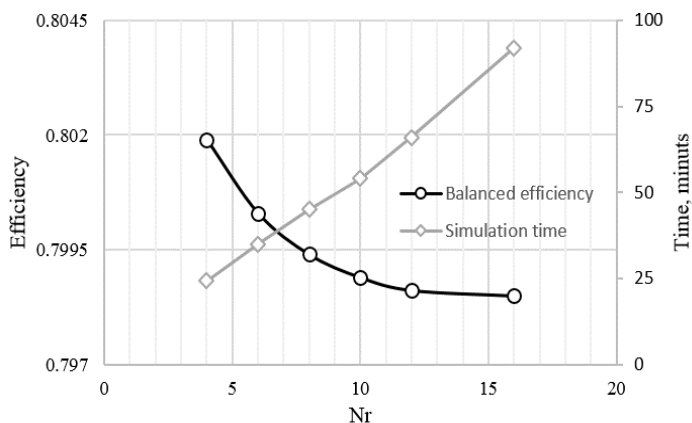
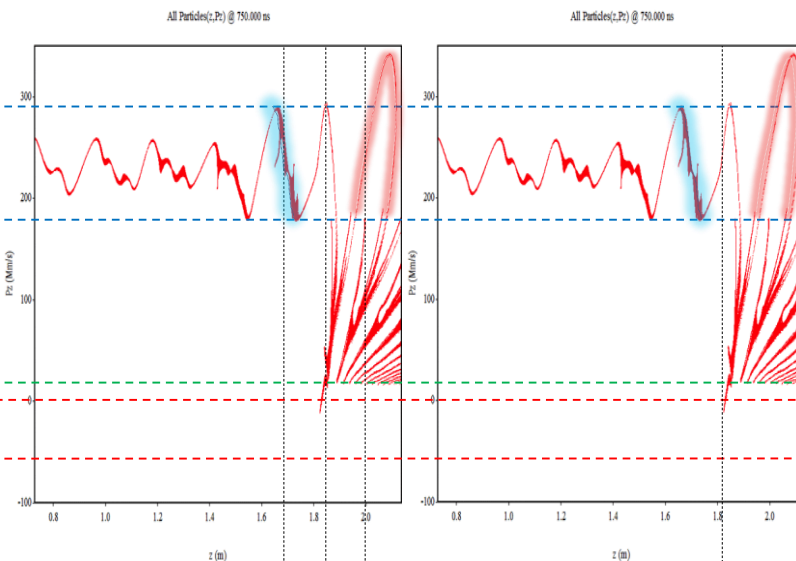
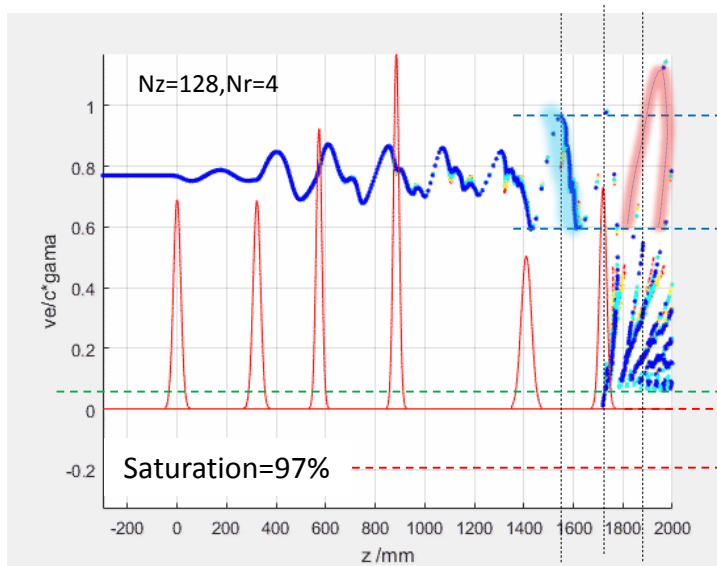
# FCC#6. KlyC2D vs MAGIC

Beam settings

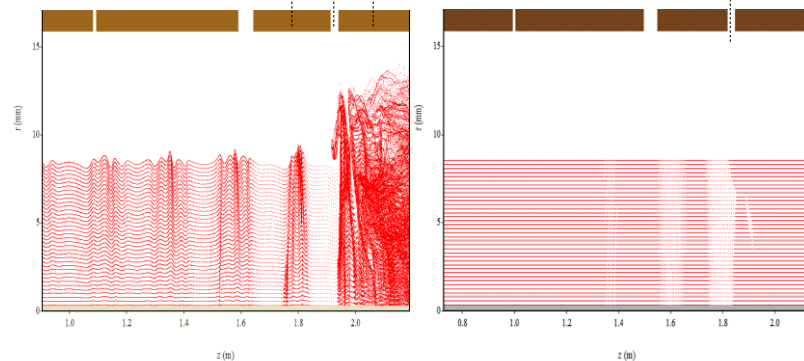
$N_z=256, N_r=4, \eta=79.9\%, T_{cpu}=20 \text{ min}$

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

$T_{cpu} = 4000 \text{ min} (\sim 1000 \text{ ns})$



### Convergent analysis



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

# Power conversion efficiency. **Limiting factors.**

Fully saturated bunch

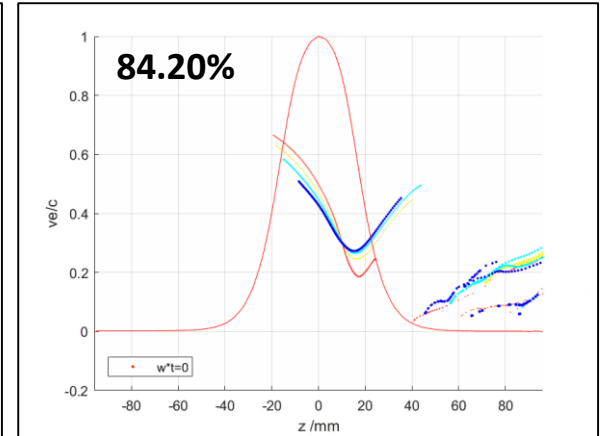
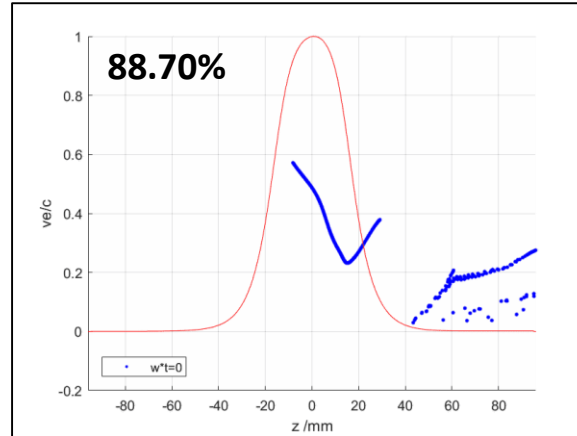
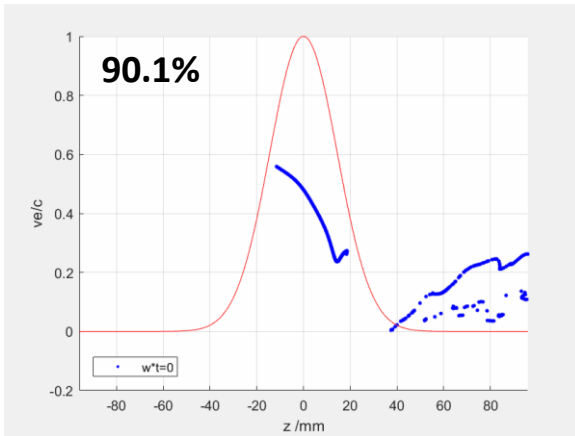
Optimised congregation



Linear congregation



Stratified bunch with linear congregation



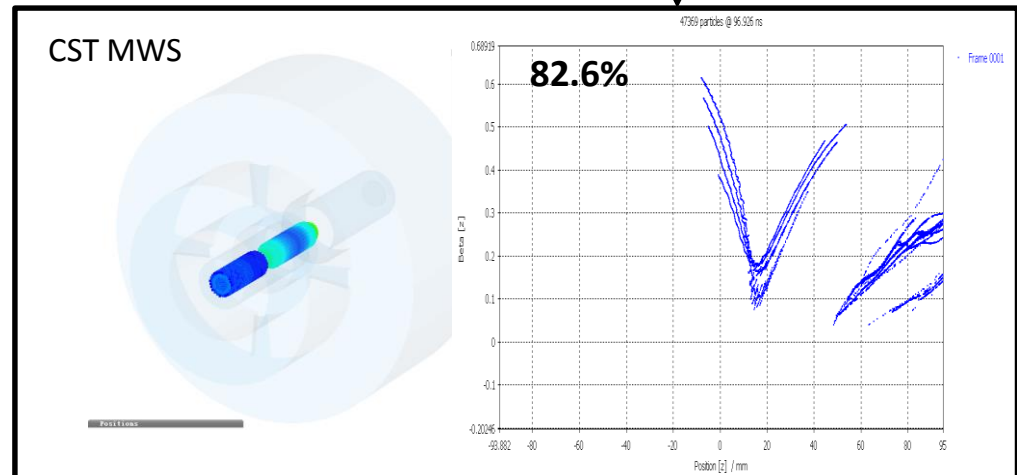
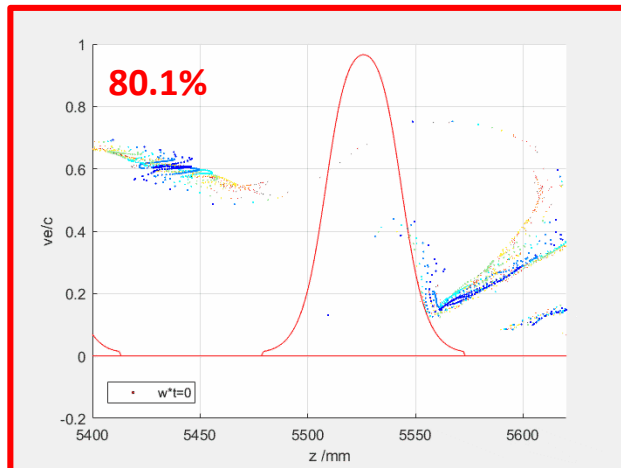
FCC CSM tube



Sabre effect and Ohmic

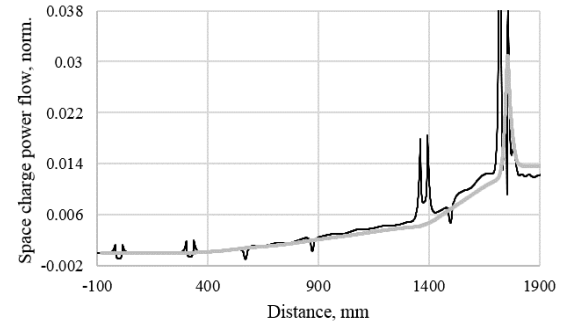
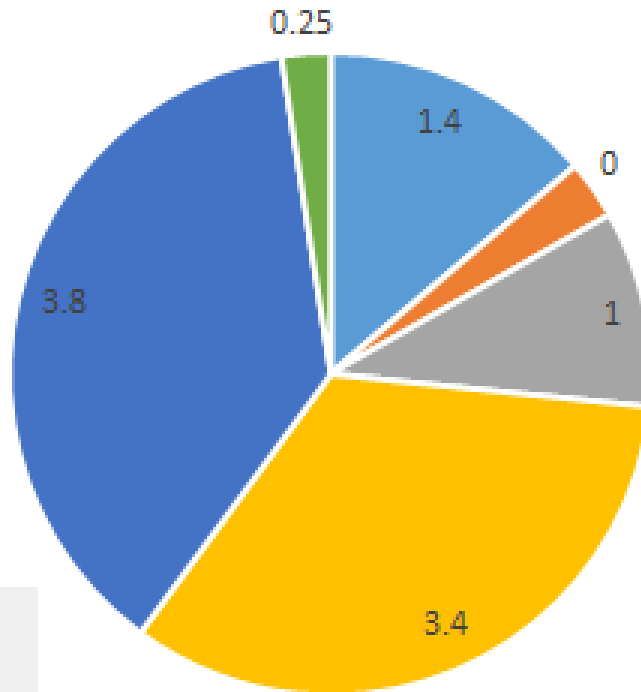
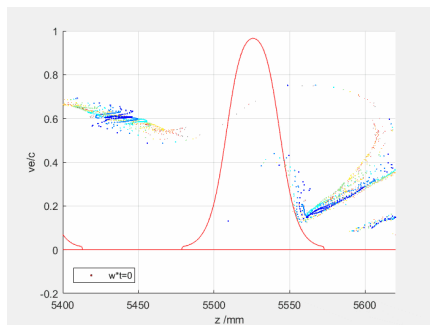
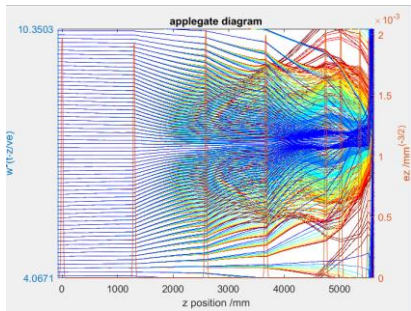
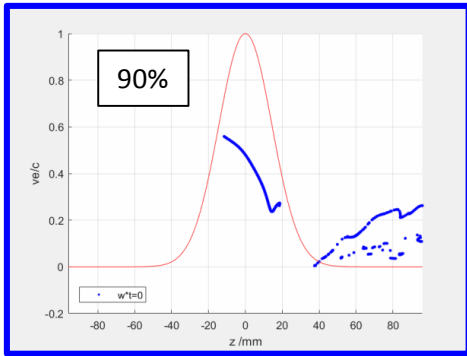


Benchmark with CST for the same bunch quality

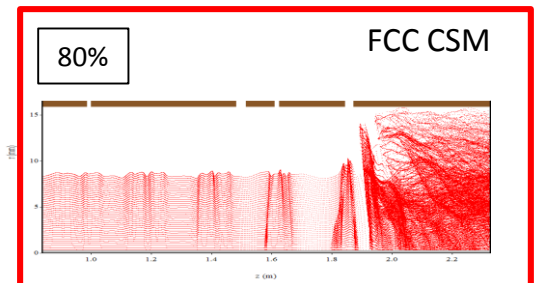


# Power conversion efficiency. Limiting factors. Summary.

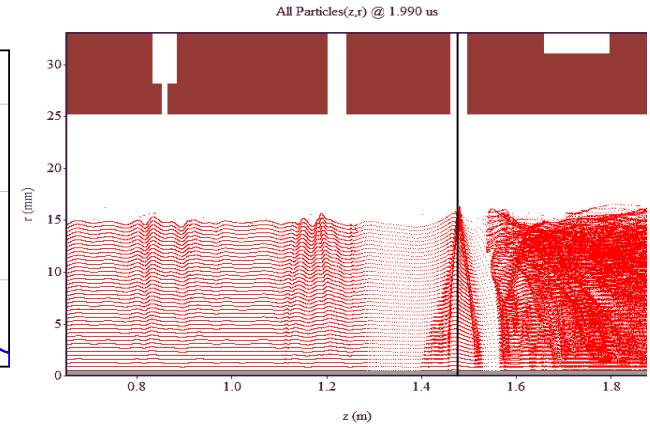
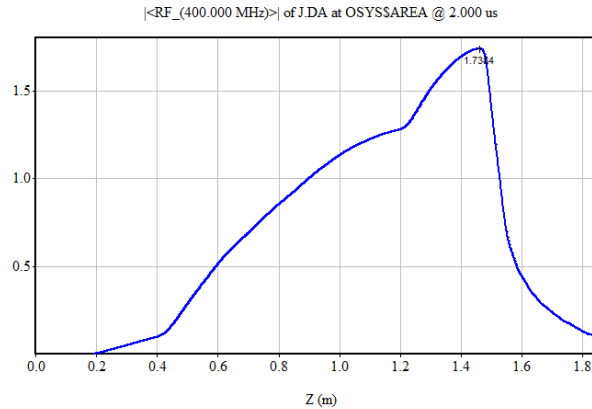
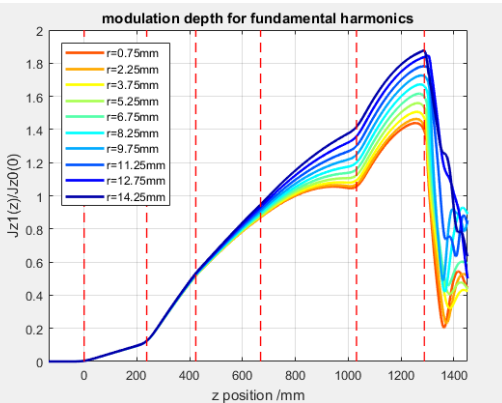
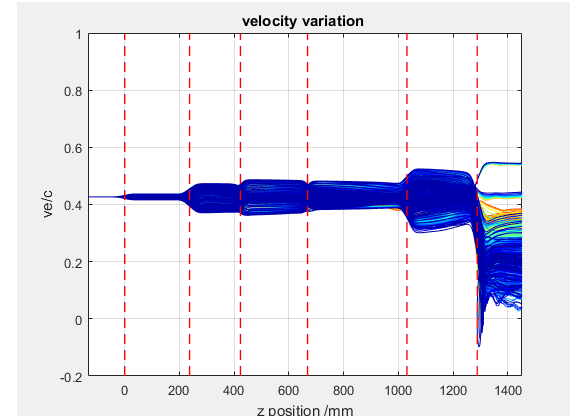
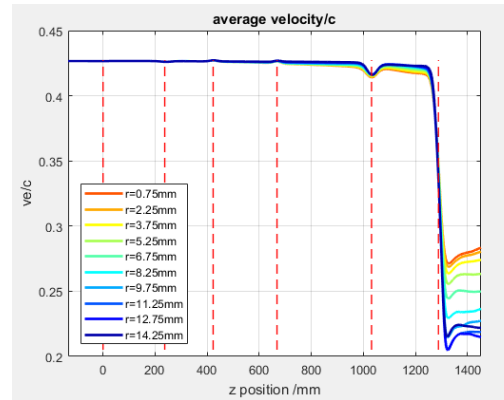
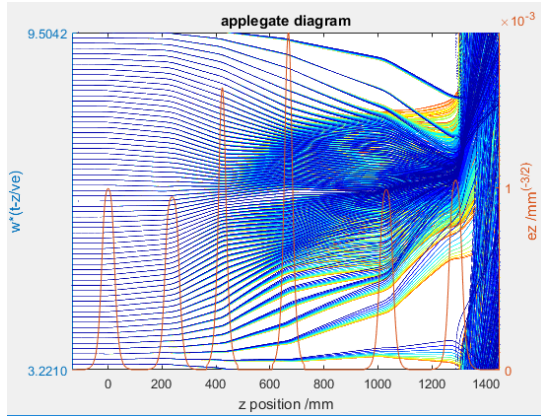
In a low perveance tube, the accumulated effect of all the limiting factors that are inherent to the bunching and deceleration processes may results in 10% efficiency reduction (from 90% to 80%).



- sabre effect
- Ohmic Losses
- Bunch saturation
- Bunch congregation
- Bunch stratification
- Magnetic field



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



Magic Efficiency = 69.46%  
KlyC Efficiency = 70.06%

Benchmark work is done by Victoria Hill

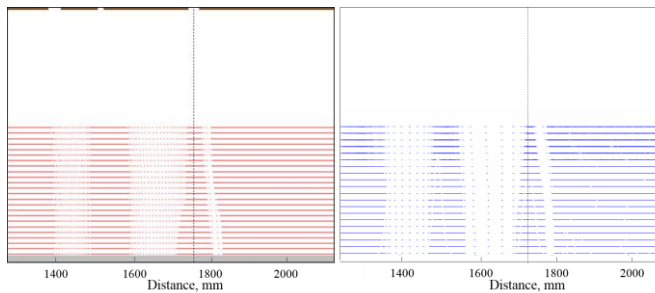


# Thanks for your attention!

## ACKNOWLEDGMENT

Authors would like to thank Z.L. Liu for his help in developing the KlyC GUI, D. Constable for providing MAGIC simulations of FCC tube

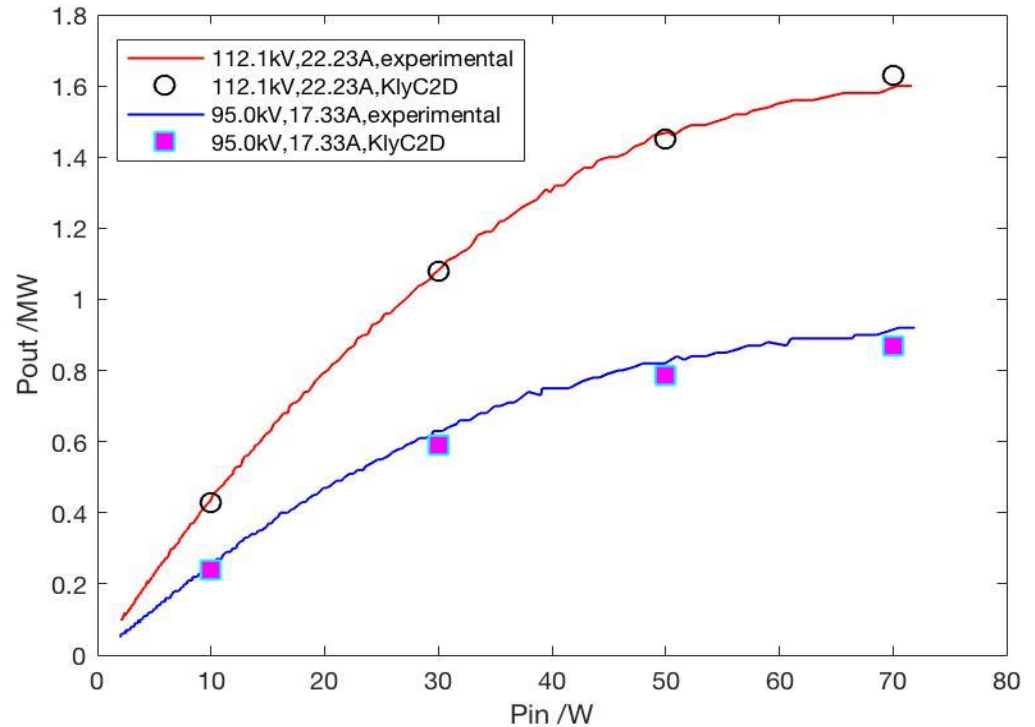
MAGIC PIC



Scan QR code for More benchmark work done



# Thales tube TH2180



A. Leggieri made comparison between TH2180 experimental data and KlyC simulations