High efficiency klystron technology.

I. Syratchev, CERN

7th Low Emittance Rings Workshop

High Efficiency International klystron activity [2]

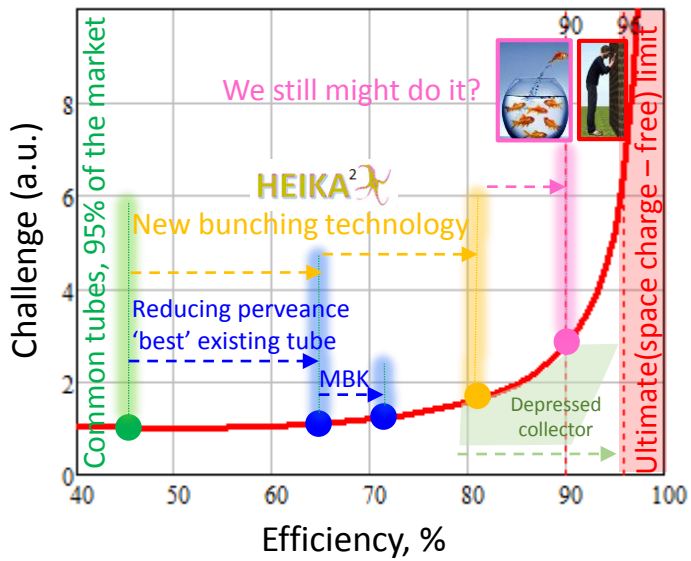
HEIKA[2]

J. CAI, CERN
Z. L. Liu, CERN
C. Marrelli, ESS
A. Baikov, MUFA
D. Constable, Lancaster U
V. Hill, Lancaster U
G. Burt, Lancaster U
B. Weatherford, SLAC
A. Leggieri, Thales

Since 2013

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

Personal outlook and challenges in efficiency reach with single beam klystron amplifiers.

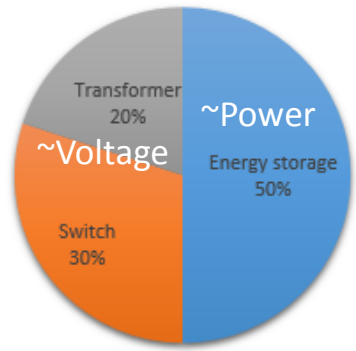


Complimentary technologies

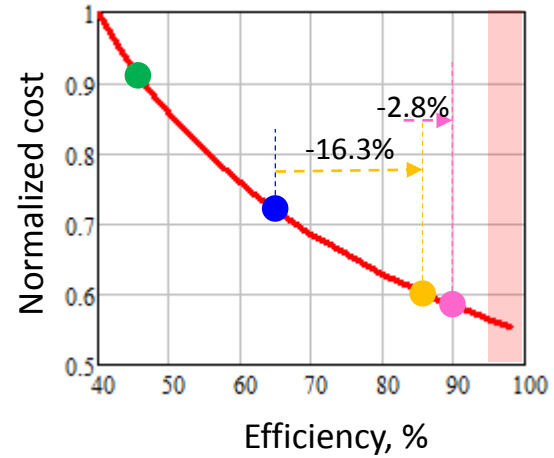
- **Multi Beam** technology. Reduced voltage and perveance. Cost and efficiency.
- **Gated Cathode** (triode gun). No HV switches. Modulator cost and efficiency.
- **SC or PPM solenoid**. System efficiency.
- **Depressed Collector**. System efficiency

Efficiency impact on investment cost

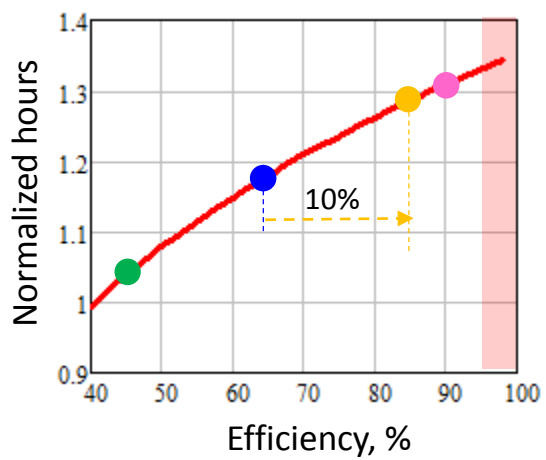
'Simple" **modulator** breakdown cost model



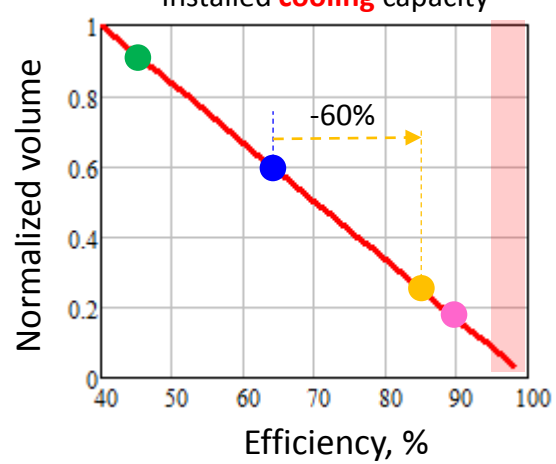
Fixed RF power and beam perveance



Klystron lifetime $\approx exp(^{-I}/_{3.4}) \times V^{-0.5}$



Installed **cooling** capacity



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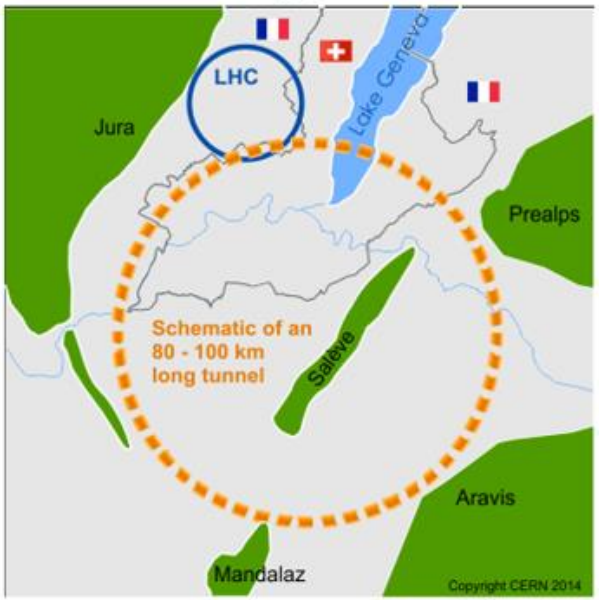
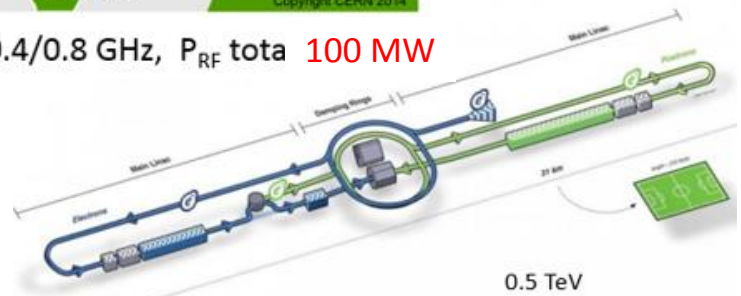
High efficiency! How high it could/should be!?

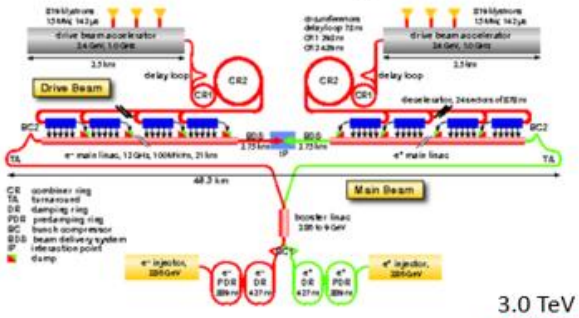


FCC ee: CW, 0.4/0.8 GHz, P_{RF} tota 100 MW



0.5 TeV

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

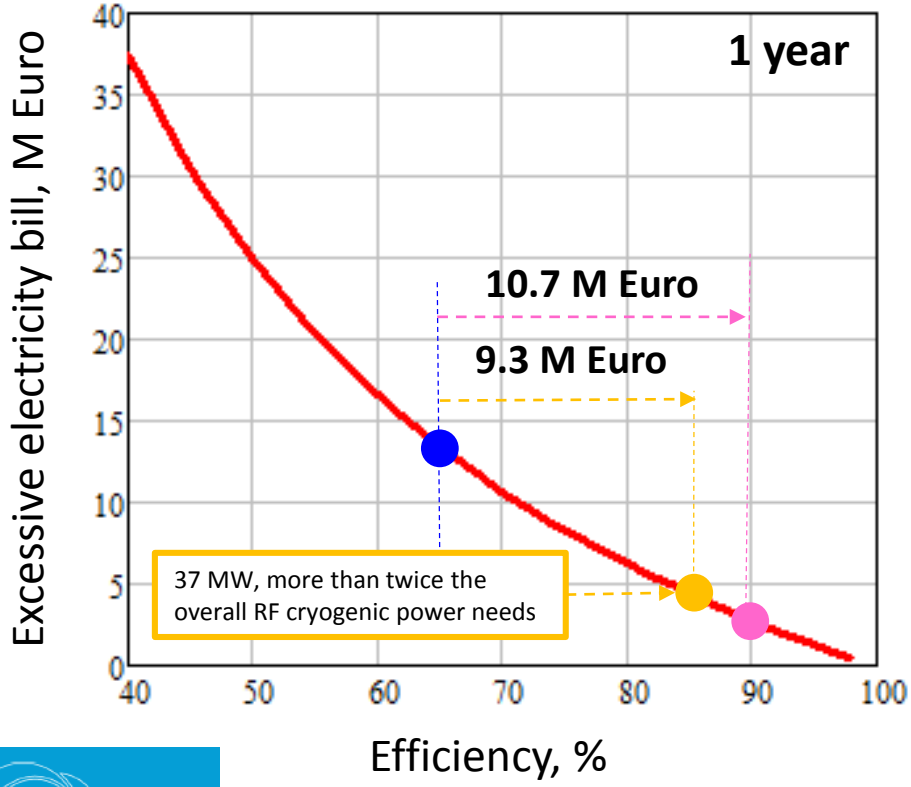


3.0 TeV

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

Efficiency impact on operation cost

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



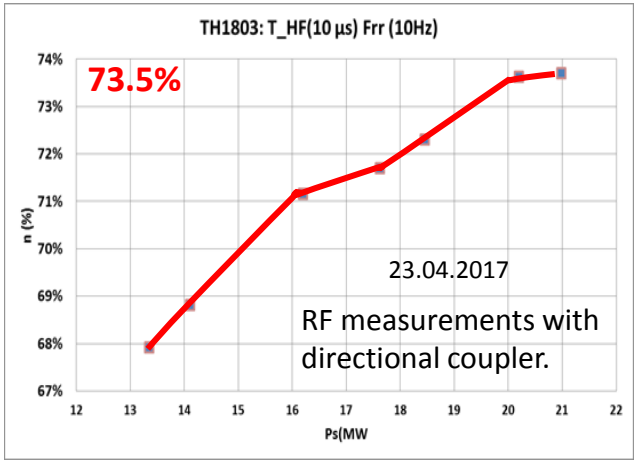
EUROPEAN SPALLATION SOURCE

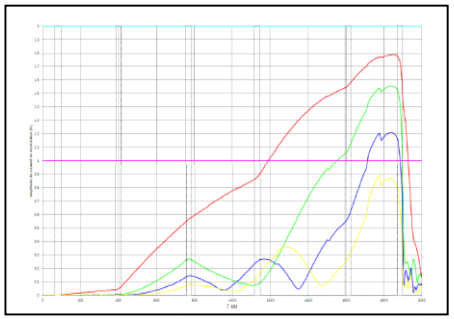
Pulsed, 0.7 GHz,
92 MW

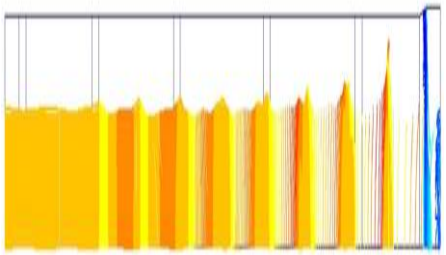
State of the art.

Commercial MBK (low perveance) tubes with high efficiency.

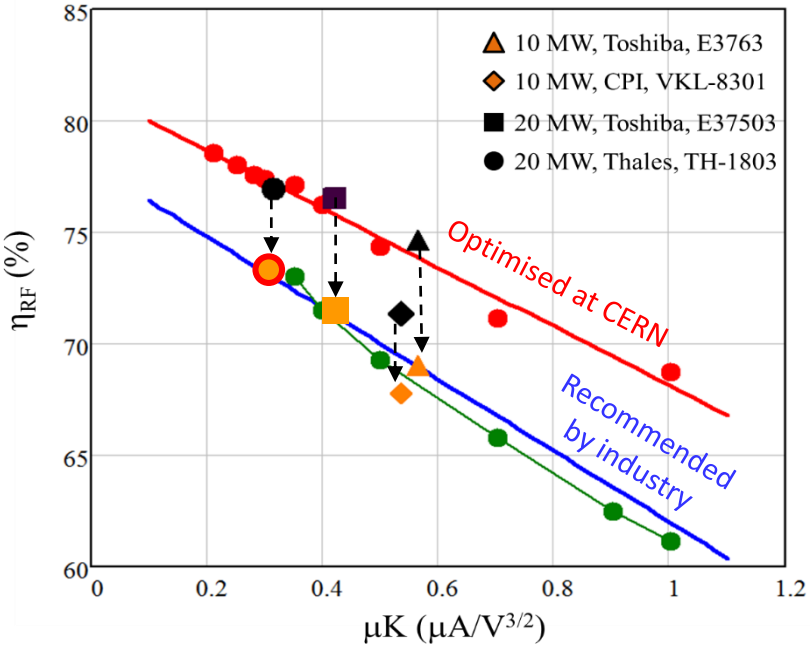
After 8 decades of development the klystron technology was considered to be saturated. The experimental results from hundred's of different devices have shown that higher efficiency is associated with lower perveance. Accounting for technological and cost reasons (μK>0.2), **the 75% efficiency was predicted to be the utmost limit**.



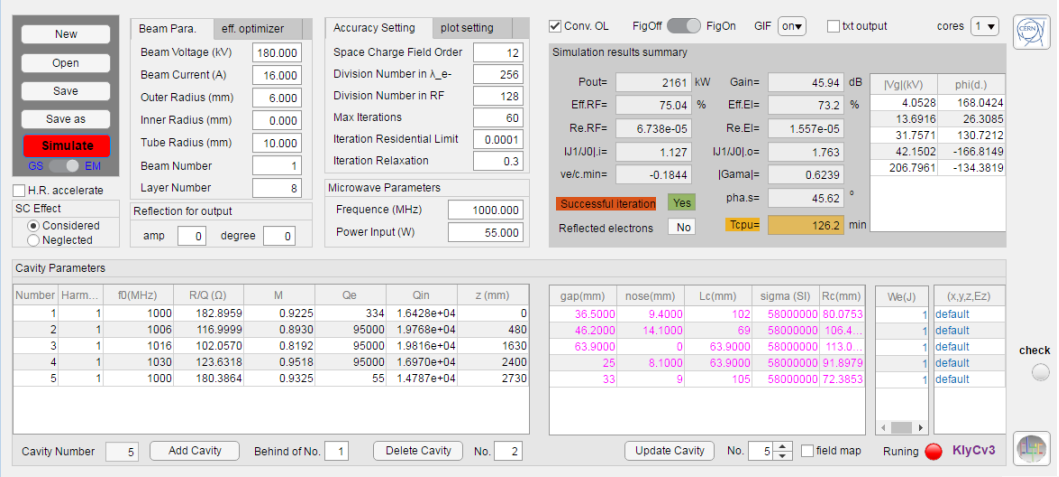




Klystron efficiency vs. perveance



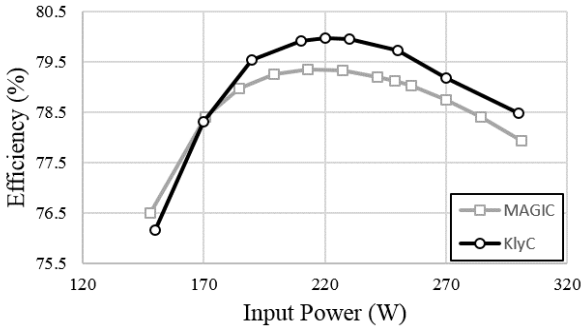
KlyC: The new (non-commercial) klystron computer code developed at CERN (J. Cai, I. Syratchev).



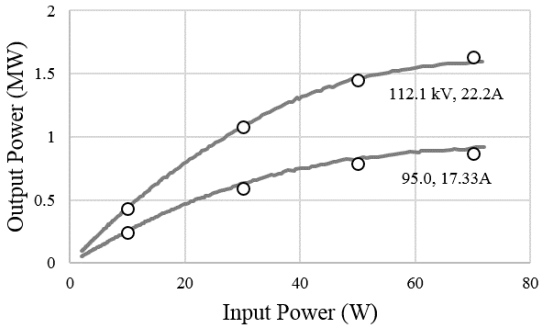
The success of HE klystrons development strongly depends on availability of accurate 2D/3D computer codes capable of performing massive computer optimizations within a reasonable amount of time.

KlyC is currently undergoing beta-testing with different Labs (CERN, CEA, SLAC and ESS) and industrial partners (Thales, CPI, VDBT and BVERI).

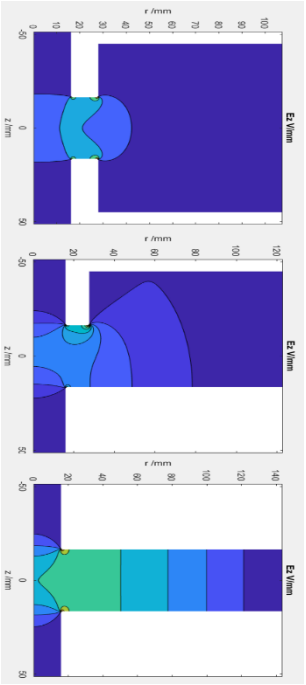
KlyC vs. MAGIC. FCC CSM.

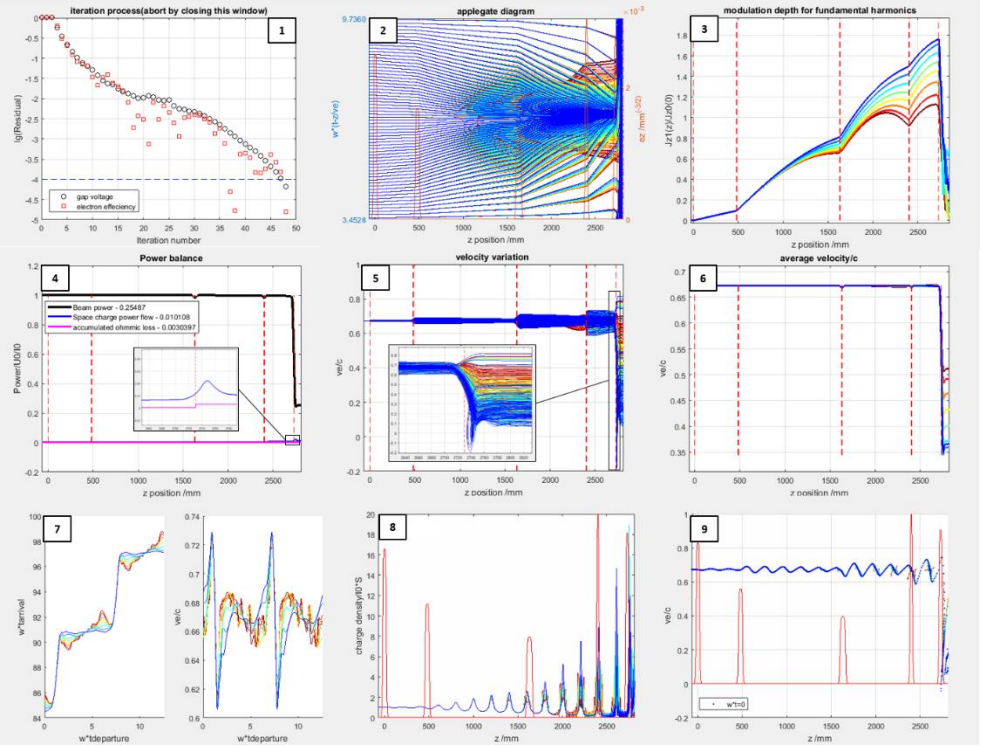


KlyC vs. experimental data. Thales TH2180.



KlyC EM module:





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CLIC 20 MW L-band (1 GHz) Multi-beam pulsed klystron.

20 MW, 50 Hz, 150 μsec
150 kW

180 kV

Modulator (η=0.9)
Energy storage
switch
HV transformer
150 kW + 88 kW

Cathode

RF circuit (η=0.7)

Solenoid 4 KW

Collector 60 KW

η_{Total} = 0.62

New/advanced technology

Lower (<60kV) voltage:
- 40 mini-cathodes
- No oil tank (cost)
- Shorter tube (cost)
- Faster switching (efficiency/cost)

Permanent Magnets:
- No power consumption
- Potential cost reduction

Vs. SC solenoid:
- More expensive solution

Depressed collector (η=0.5)

New klystron RF circuit (η=0.8)
(+) Reduced Collector dissipation (16 kW)

Gated mini-cathode:
- No switches (cost)
- Modulator efficiency ~1.0

(+) Improved stability

Power from grid:
~~280~~ 200 MW

η_{Total} = 0.9

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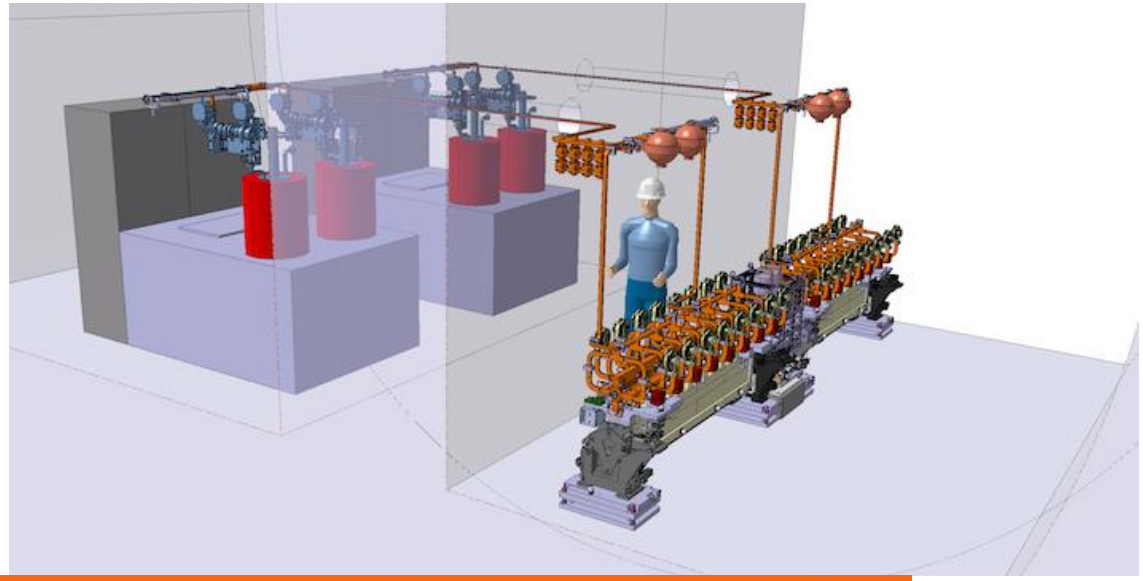
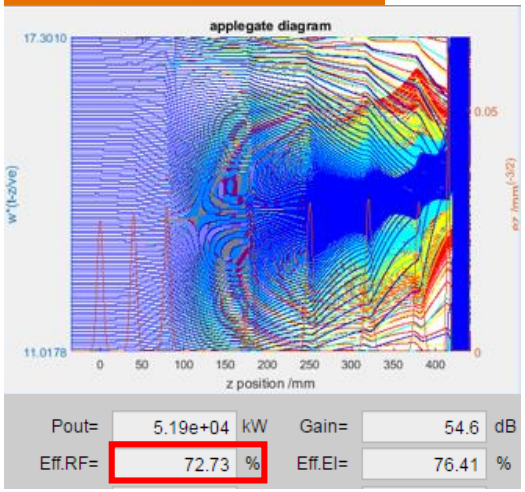
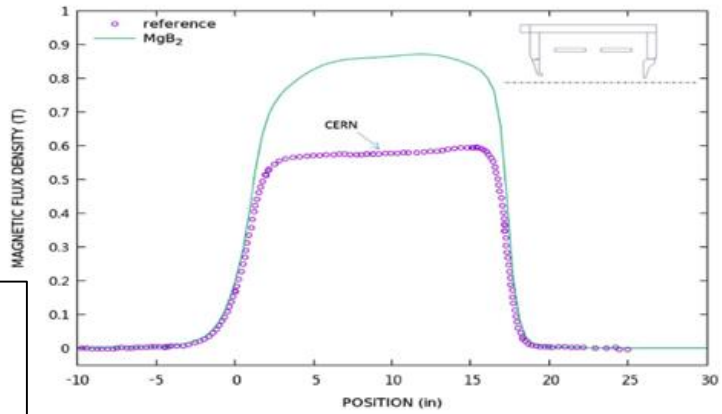
CLIC'k 50 MW X-band (12 GHz) klystron.



High Efficiency X-band Klystron Design Study **CERN/SLAC collaboration**



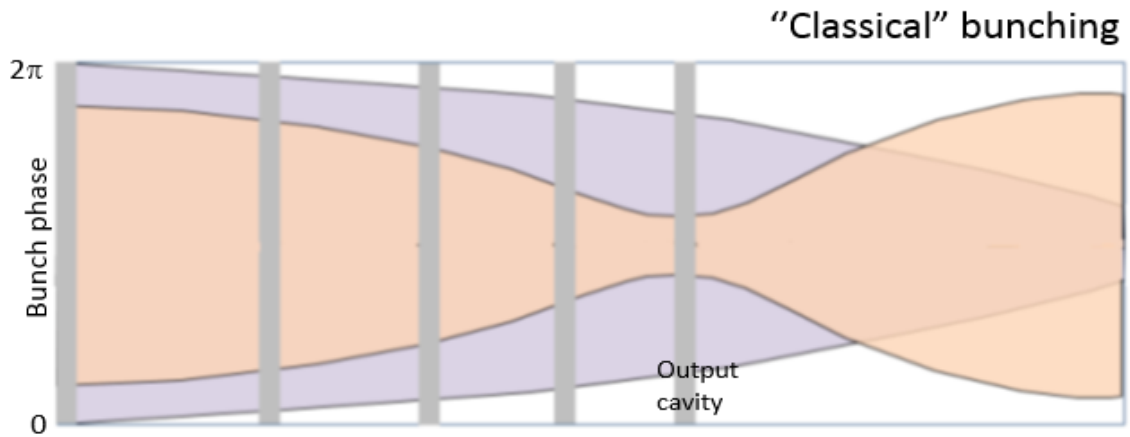
A Superconducting Solenoid applicable for X-band Klystrons
A. Yamamoto. CERN/KEK collaboration

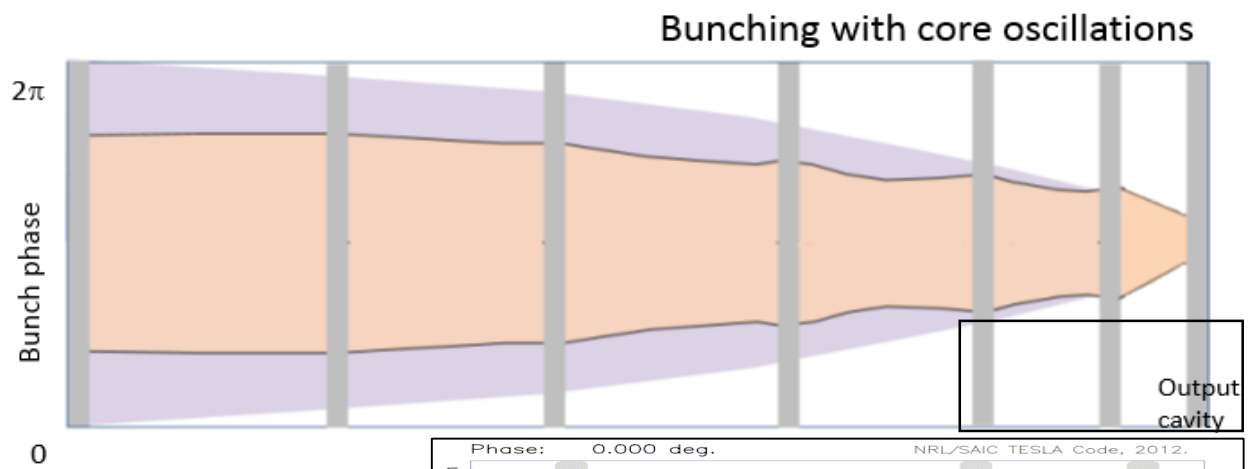


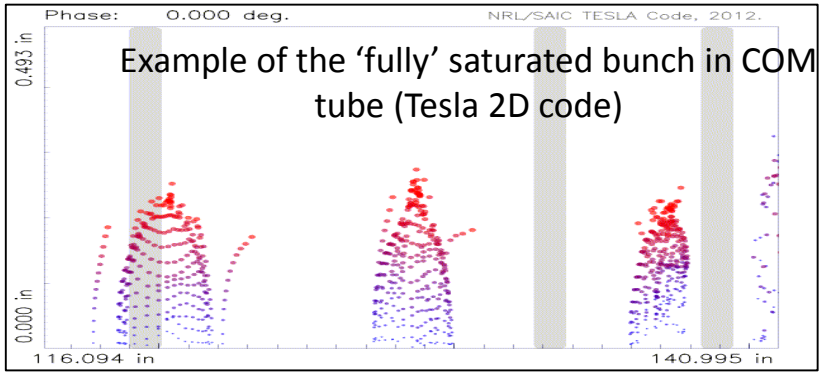
24.01.18; 09.00 – 13.00 Accelerator - Parallel sessions: Power Sources (*503-1-001 - Council Chamber, CERN).*

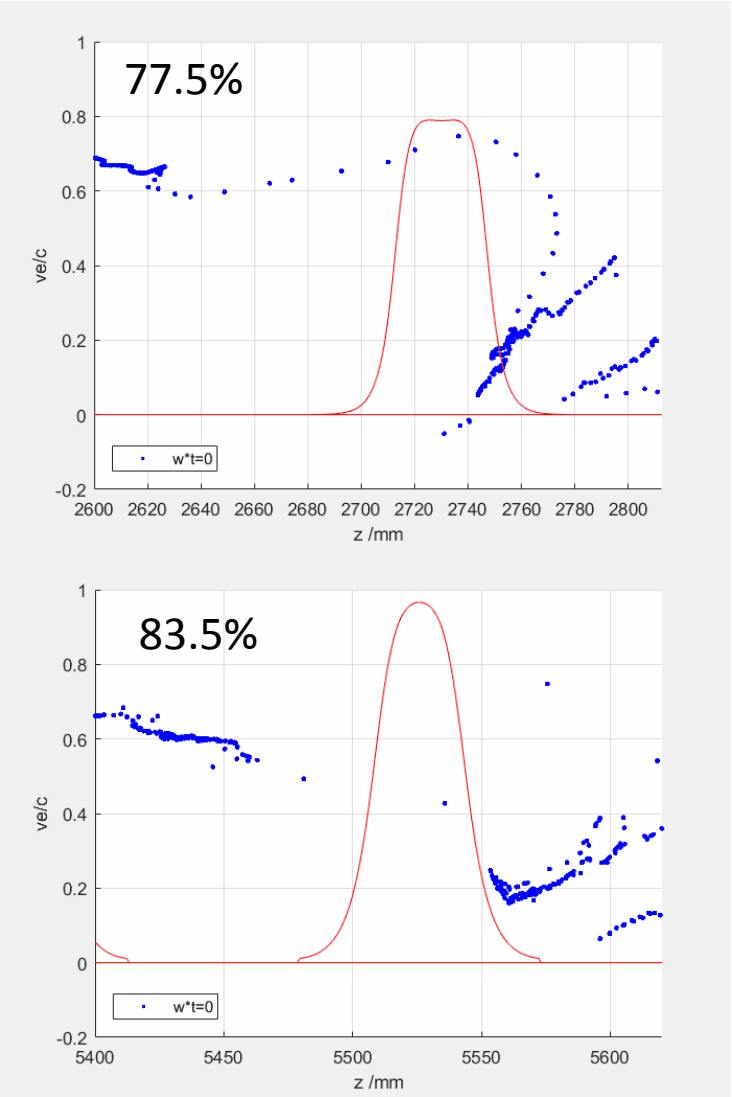
09.25 B. Weatherford: ' **HE 50 MW X-band** (COM) klystron design progress report'.
09.50 J. Neilson: ' **Depressed collector** option for HE 50 MW X-band klystron'.
10.15 A. Yamamoto: 'Status of **Superconducting solenoid** development for X-band 50 MW klystron'.

Advanced bunching technologies. First method (COM) proposed in 2013 (A. Baikov).









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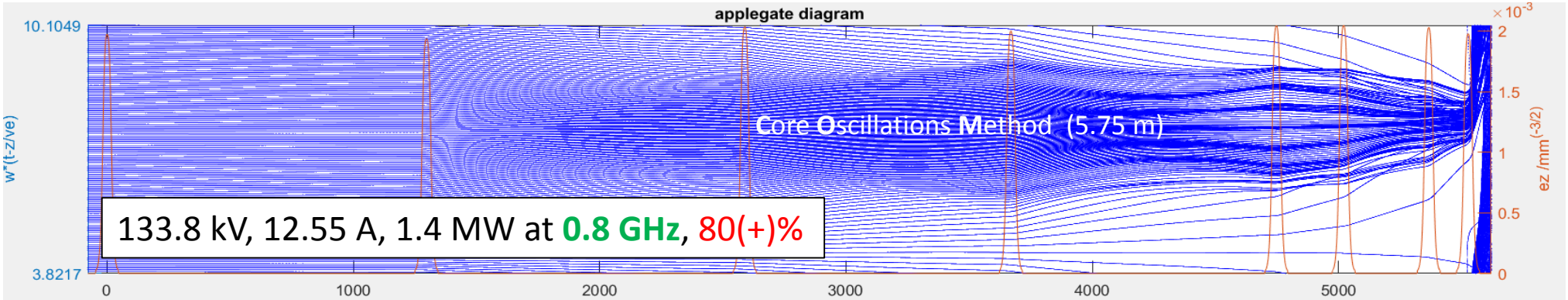
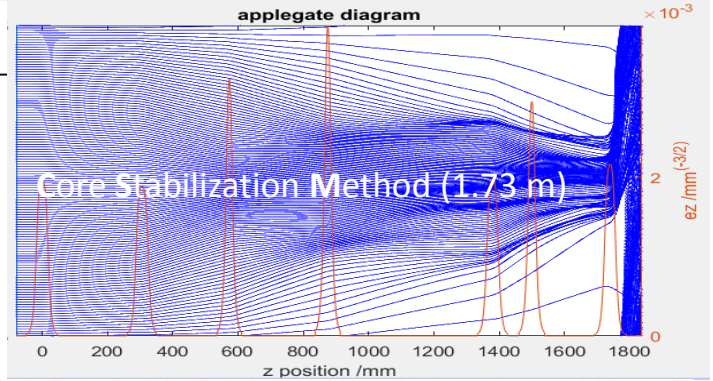
New bunching technologies.
Bunch saturation.





The choice of bunching technology may drive the applicable frequency range and multi-beam options (cost/performance):

L-band	S-band	C-band	X-band

CSM/modest MBK

Medical/industrial

Kladistron

LHC,FSS,ESS,ILC

BAC/MBK

CLIC, klystron based X-band FEL

1/6 MW

Circular machines & proton linac drivers

5-10 MW, <60kV

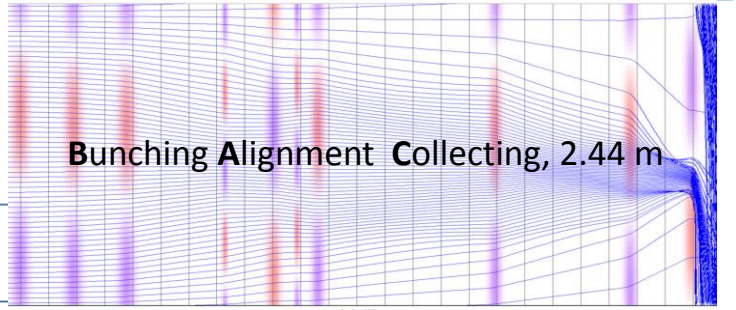
COM/single beam

CLIC, TBA

High perveance MBK HE tubes (!?)

50+ MW

10-20 MW



Power conversion. Ultimate efficiency reach.

>TED-2015-06-0796-R.R1<

Towards high power klystrons with RF power conversion efficiency in the order of 90%

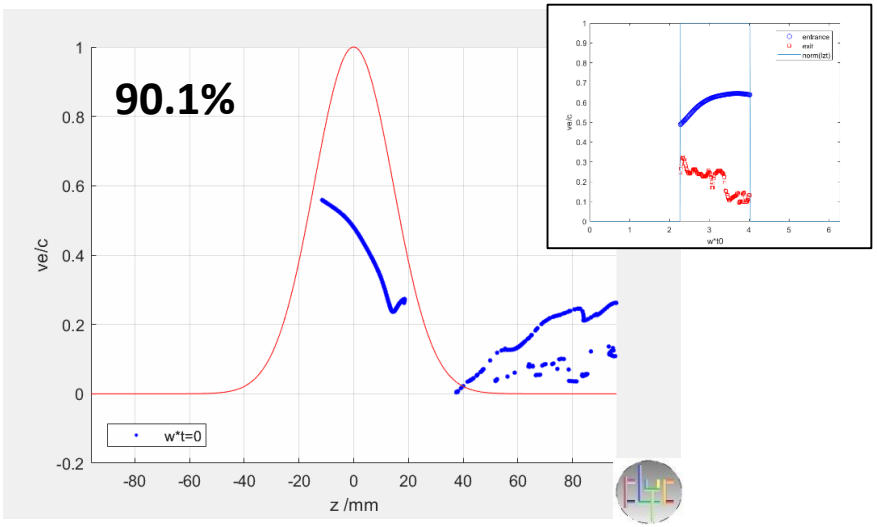
A. Yu. Baikov, *MFUA, Russia*, C. Marrelli, *ESS, Sweden*, and I. Syratchev, *CERN, Switzerland*

Ultimate high power conversion efficiency conditions:

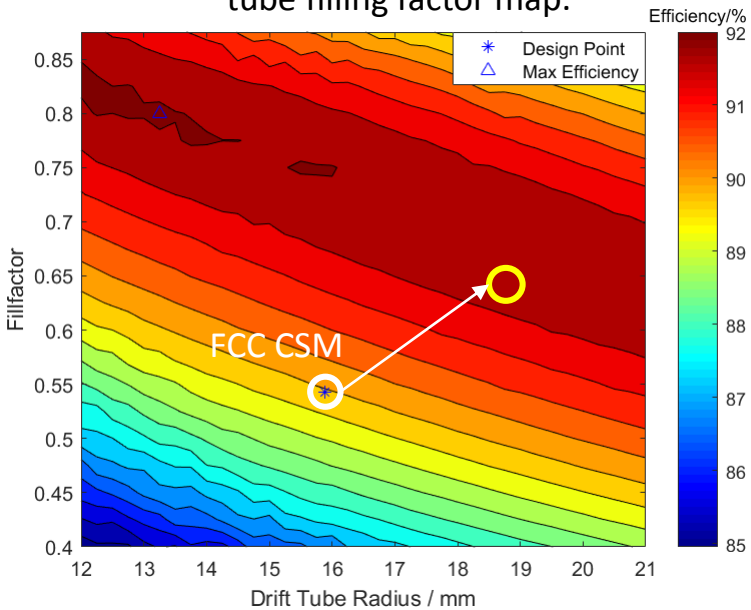
- To avoid migration of the electrons from bunch to anti-bunch during deceleration in the output cavity, the incoming bunch with non-zero length should have optimal velocity dispersion: **Congregated Bunch**, when the leading electrons are slower than the tailing ones.
- Congregated bunch should be gradually transformed at the cavity exit into **monochromatic bunch** with least velocity.

Fully saturated bunch with optimal congregation can deliver **90(+)%** RF power production efficiency (in simulations).

Fully saturated bunch with optimal congregation. FCC CSM output cavity, drift channel and beam.



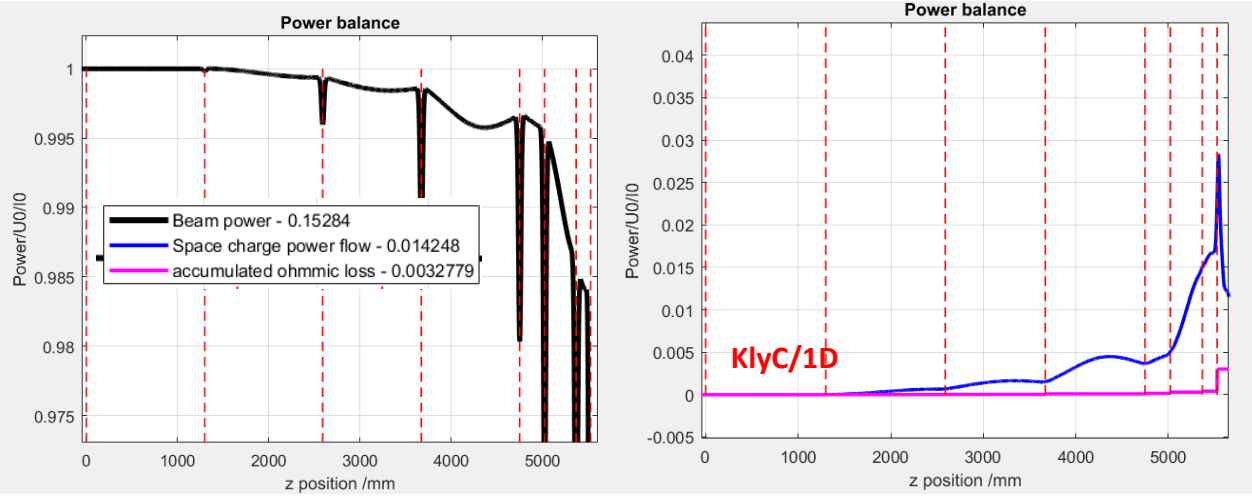
Optimal congregation. Efficiency/Drift tube filling factor map.



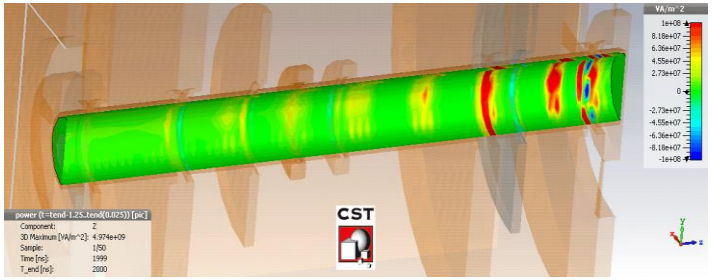
Optimised FCC COM tube

Power conversion efficiency. Limiting factors.

Ohmic losses and **"Sabre" effect** . The later one comes from the fractional conversion of the kinetic energy of the non-modulated beam into a) electrostatic energy of the bunched beam and b) differential potential energy of the spent beam. All together they give **1.75%** efficiency reduction.

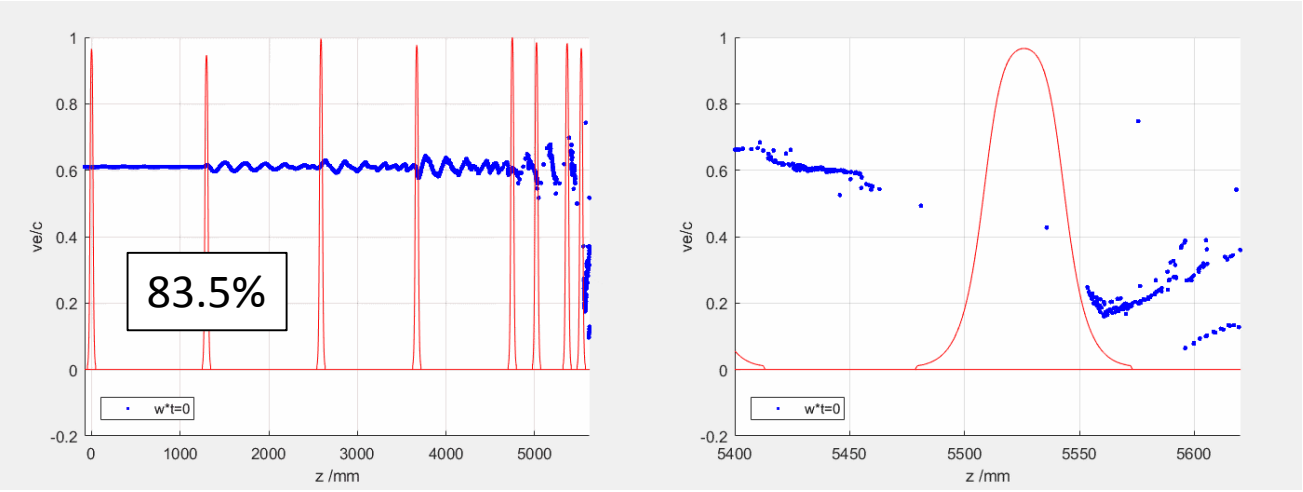


Space charge E-field power flow in the drift tube.



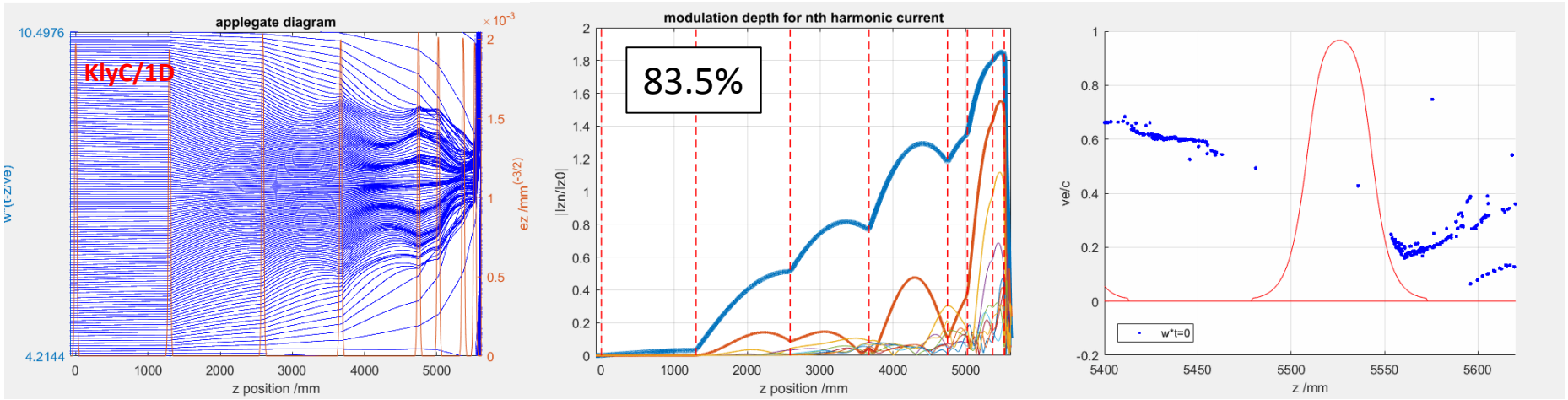
In 'real' tube design efficiency is reduced further:

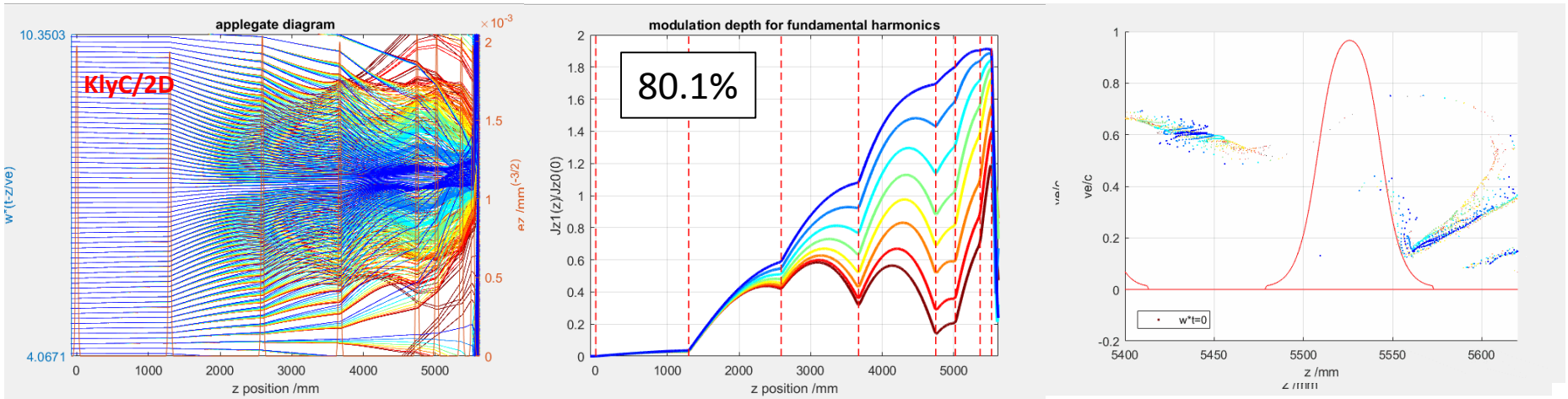
- bunch saturation (**-1%**)
- bunch congregation 'as received' **(-3.8%)**



Power conversion efficiency. Limiting factors.

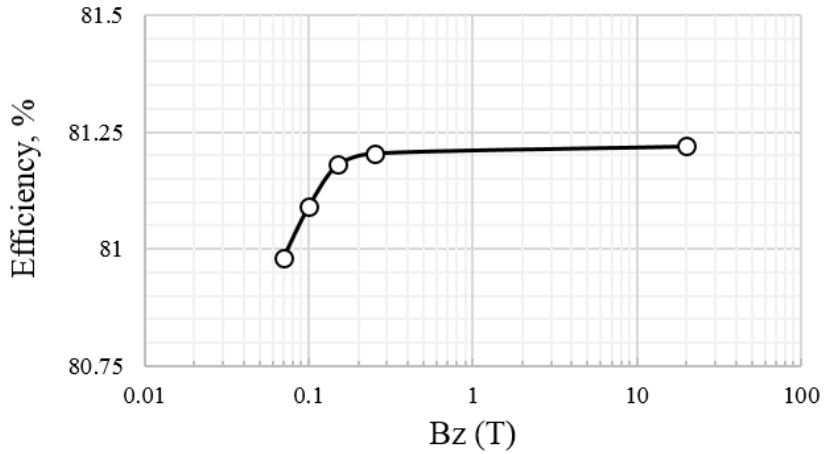
The **Radial Bunch Stratification** is a radial variations of the RF current modulation depth. In a system with axial symmetry with respect to the beam centre, such effect is originated by radial variations of the space charge forces and cavities impedances.

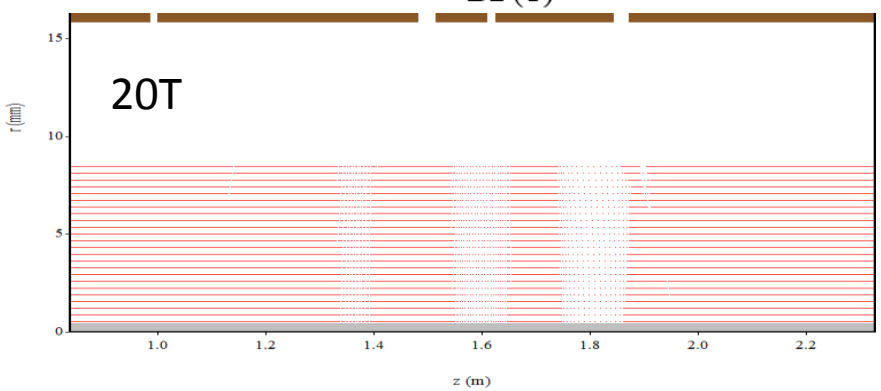


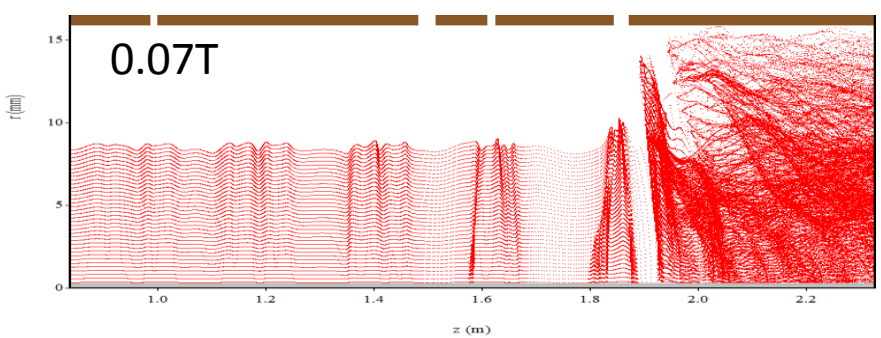


Power conversion efficiency. Limiting factors.

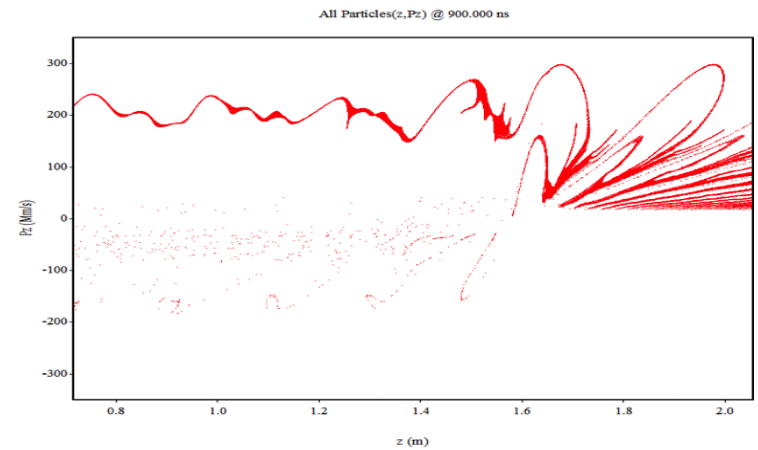
Magnetic focusing (solenoidal) field. Radial beam expansion has little effect **(-0.25%)** on the RF power production (MAGIC (PIC) simulations).

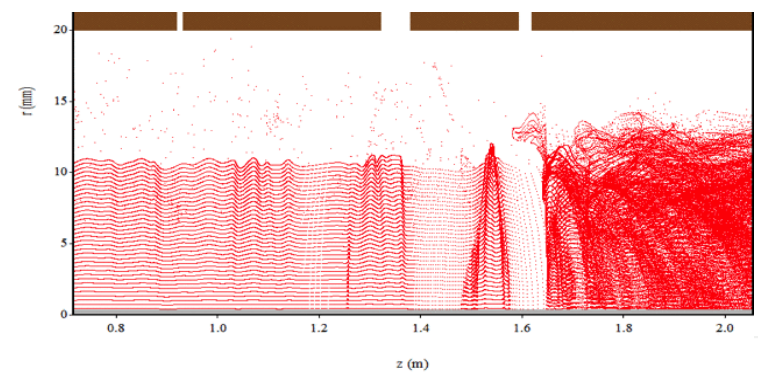


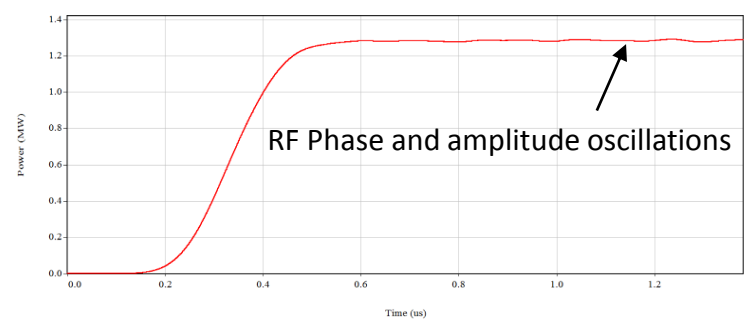




Ultimate limit: reflected electrons generation.







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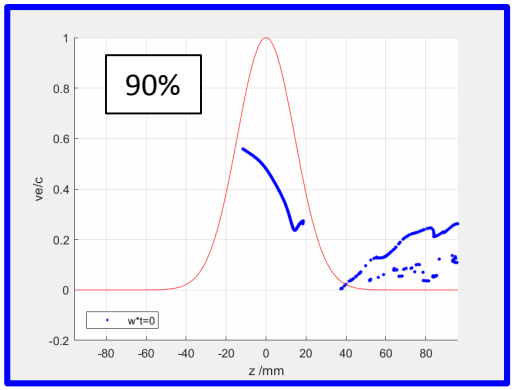
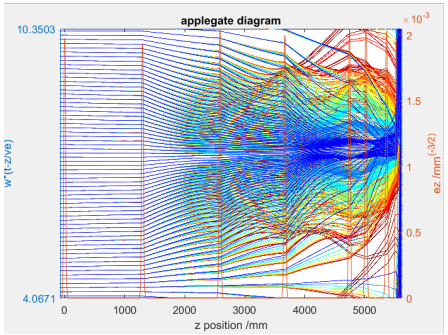
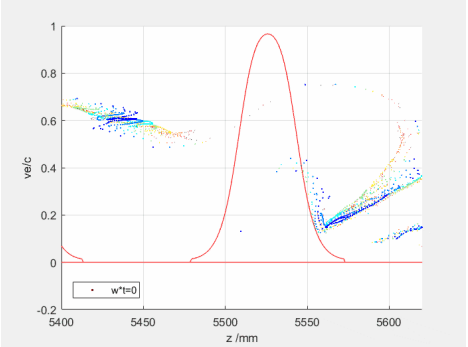
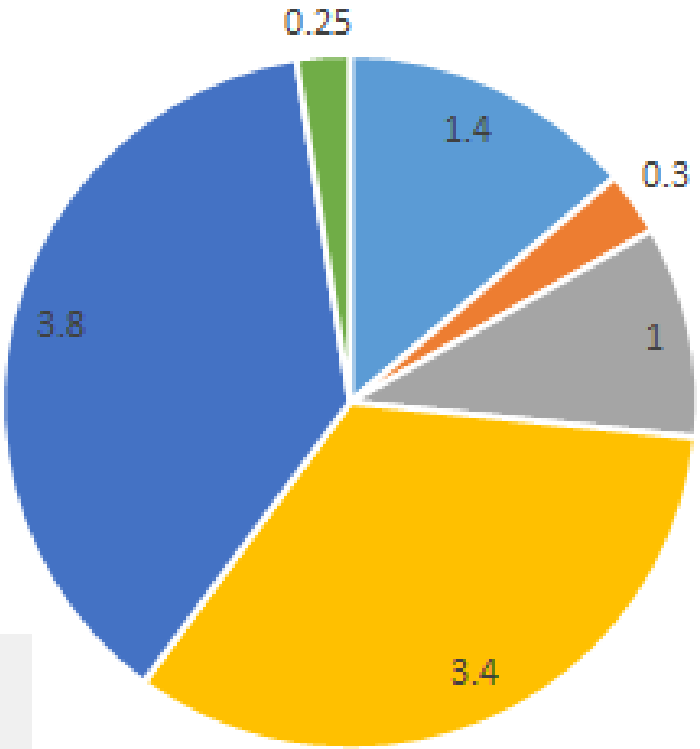
Power conversion efficiency. Limiting factors. Summary.

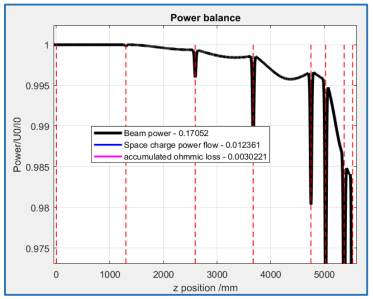
In a low perveance tube, the accumulated effect of all the limiting factors that are inherent to the bunching and deceleration processes may results in 10% efficiency reduction (from 90% to 80%).

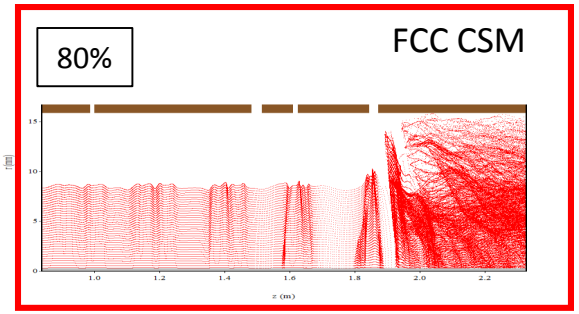












I. Syratchev, CERN

Thanks for your attention!
I hope I was **efficient**.