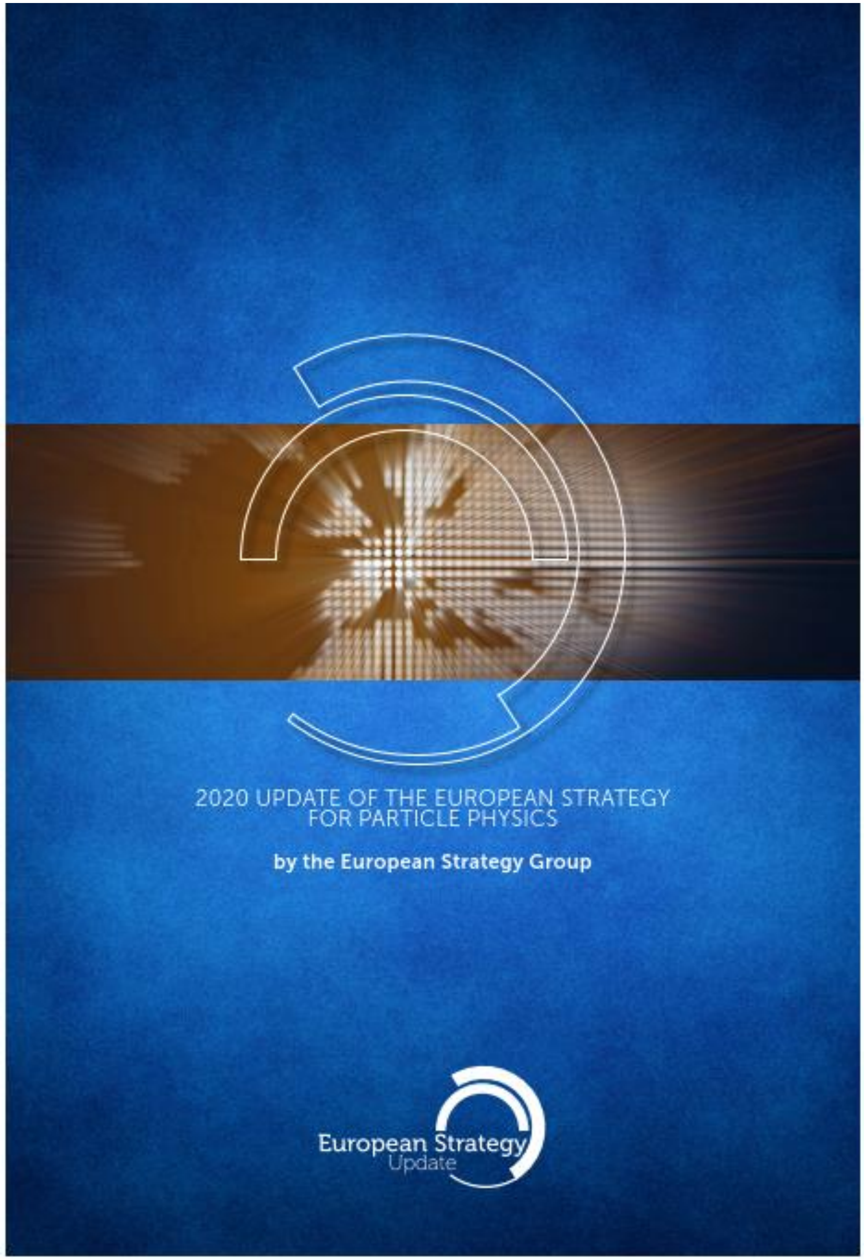
Workshop on efficient RF sources

Jul 4 – 6, 2022
Chateau de Bossey

High Efficiency klystrons technologies.

I. Syratchev, CERN



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Environmental and societal impact

A. The energy efficiency of present and future accelerators, and of computing facilities, is and should remain an area requiring constant attention. Travel also represents an environmental challenge, due to the international nature of the field. ***The environmental impact of particle physics activities should continue to be carefully studied and minimised. A detailed plan for the minimisation of environmental impact and for the saving and re-use of energy should be part of the approval process for any major project. Alternatives to travel should be explored and encouraged.***

C. Particle physics has contributed to advances in many fields that have brought great benefits to society. Awareness of knowledge and technology transfer and the associated societal impact is important at all phases of particle physics projects. ***Particle physics research centres should promote knowledge and technology transfer and support their researchers in enabling it. The particle physics community should engage with industry to facilitate knowledge transfer and technological development.***

https://europeanstrategy.cern/home

The accelerators technology is very diverse and could require the RF signals in a wide range of the frequencies (few 100 MHz – 12 GHz), peak power levels (few 100 kW – 100 MW) and pulse lengths (CW -100ns). The **klystron** amplifiers technology is the one that covers almost all RF frequency/power demands of the modern accelerators.

0.4 GHz, 0.3MW/LHC

Electro vacuum devices for science

CPI — USA

THALES — France

Canon — Japan

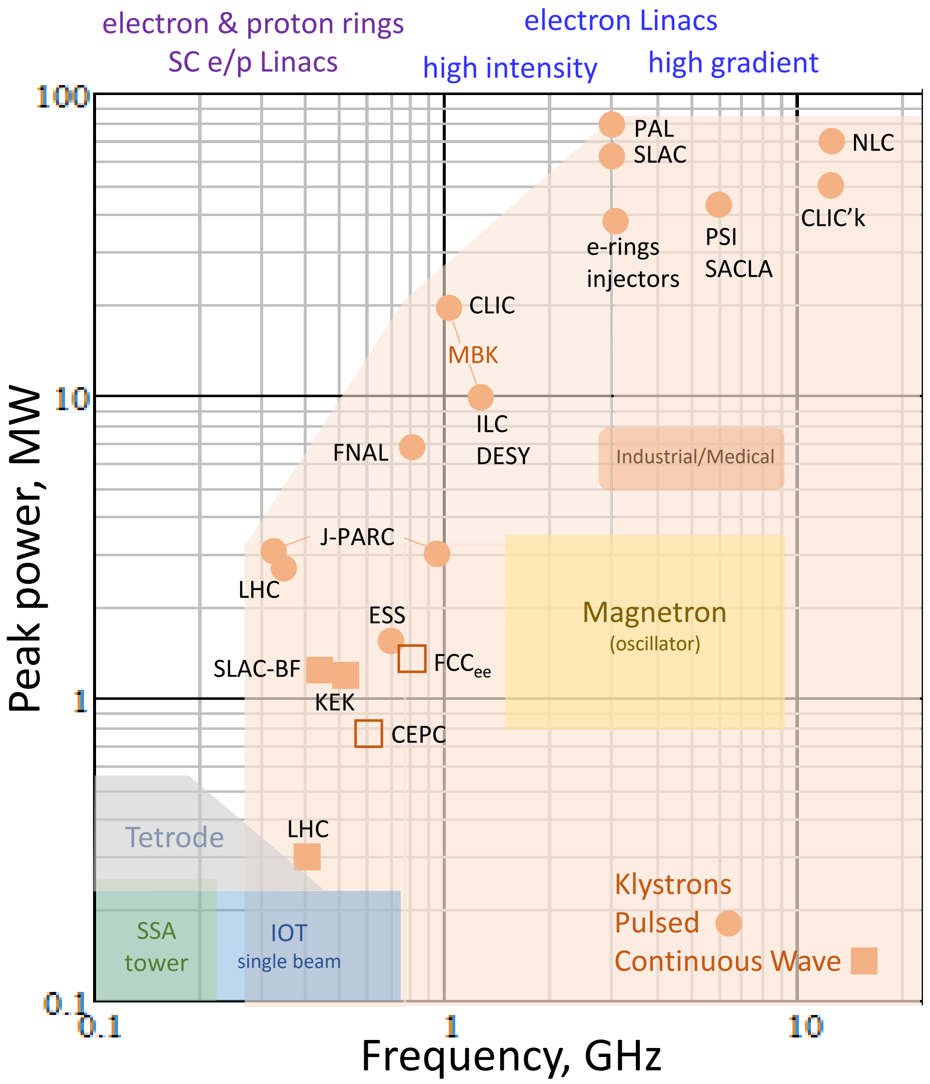
0.7 GHz, 1.5MW/ESS

1.3 GHz, 10MW/DESY

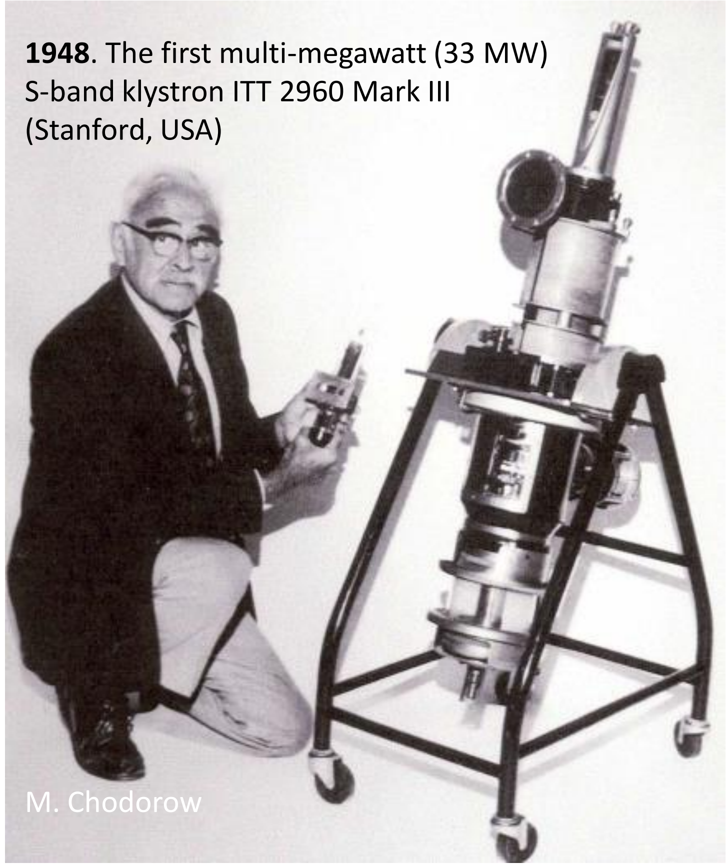
3 GHz, 60MW/SLAC

6 GHz, 50MW/PSI

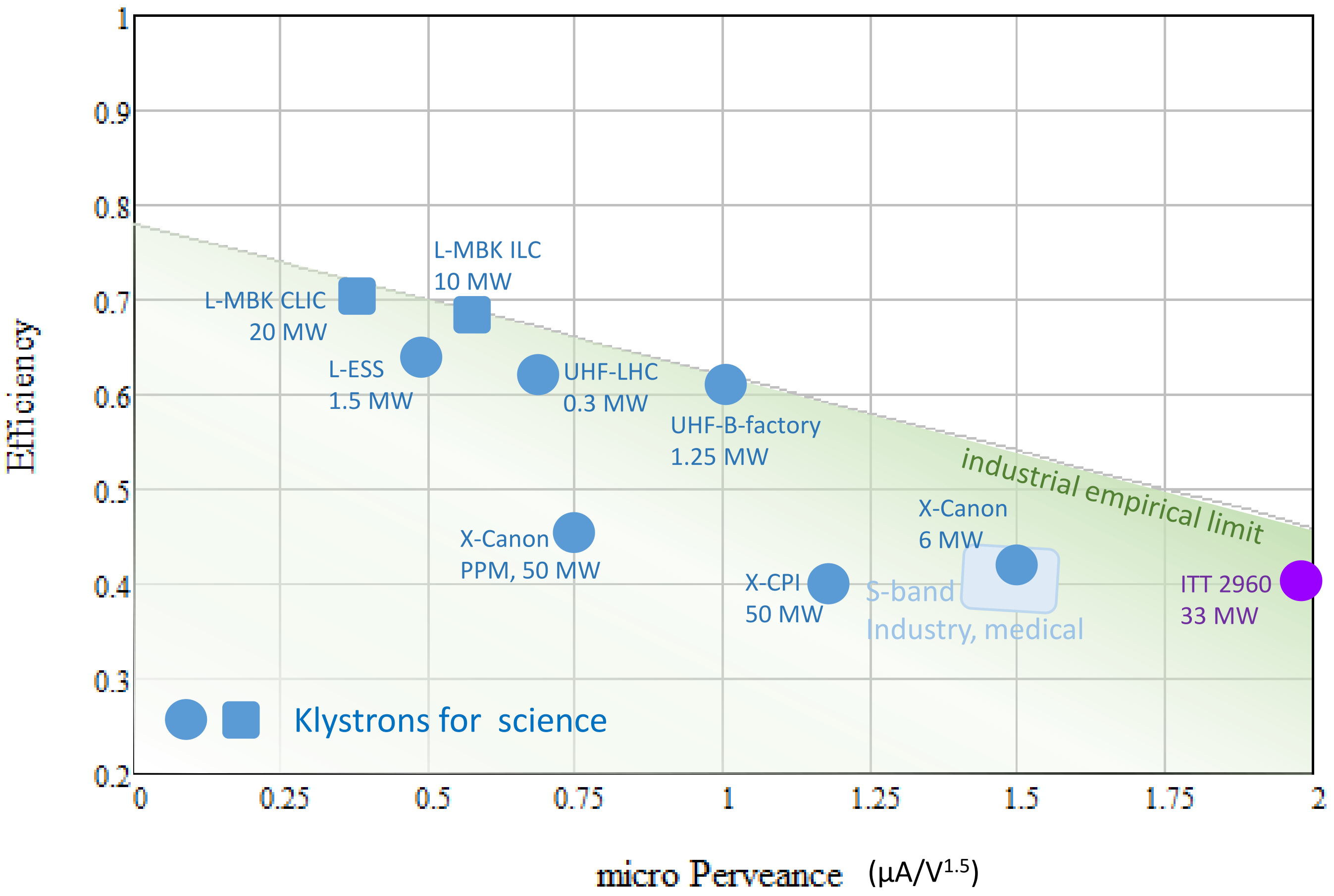
12 GHz, 50MW/SLAC-CLIC



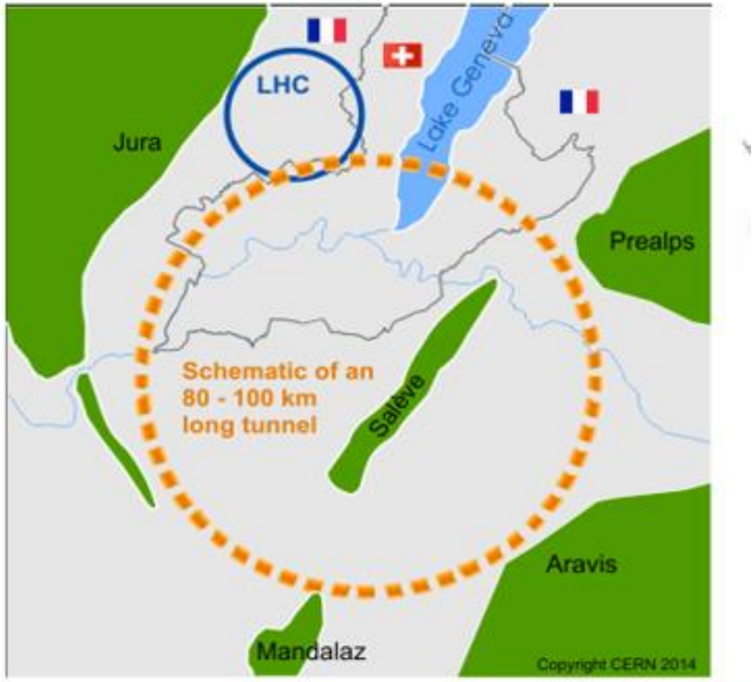
The klystrons have been used in the particle accelerators for more than 7 decades. The experimental results from hundred's of different devices have shown that higher efficiency is associated with lower perveance. Accounting for technological and cost reasons (μA/$V^{1.5}$>0.25), the 73% efficiency was predicted to be the utmost limit.



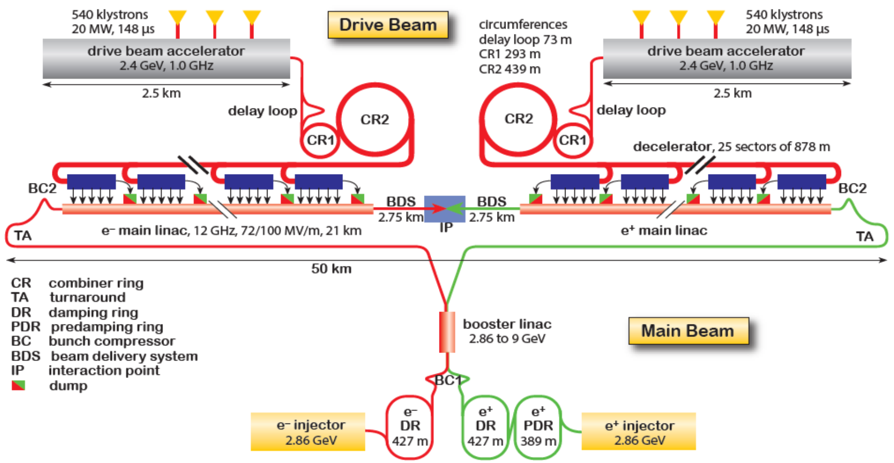
Efficiency performance of few selected commercial klystrons



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 FCC^{ee} power consumption.
Example of the efficiency upgrade from existing 65% to 80%.

	Klystron eff. 65%	Klystron eff. 80%	Difference
RF power needed for 3TeV CLIC	105 MW		
DC input power	161.5MW	131.25MW	-30.25MW
Waste heat	56.5MW	26.25MW	-30.25MW
Annual consumption (5500 h assumed)	888 GWh	721.9GWh	-166.1 GWh
Annual cost (50MCHF/MWh assumed)	44.5 MCHF	36.1 MCHF	-8.4 MCHF
Electricity installation dimensioned for	161.5MW	131.25 MW	-20.6%
CV installation dimensioned for	56.5 MW	26.25 MW	-53.54%

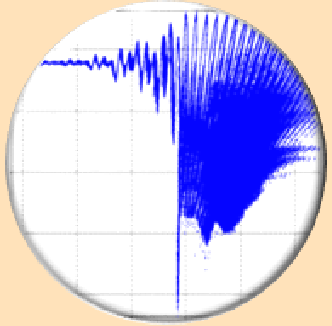
- Potential saving are 1.04 TWh in 10 years (**84 MCHF in 10 years**).
- Reduced environmental impact (cooling and ventilation)
- Reduced installation cost (stored energy in modulators).
- Reduced maintenance cost (klystron life time).

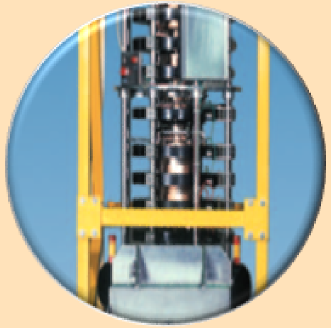
R&D on increasing the useable efficiency is worth every penny/cent invested!

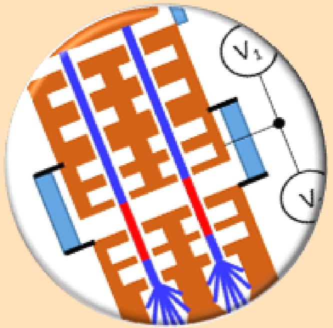
High efficiency klystrons projects at CERN

- T1. Development and maintenance of the fast and accurate computer codes (KlyC and CGUN) for massive optimization of the new klystrons, accompanied by mastering the expertise in using commercial simulation suits like CST 3D PIC.
- T2. In-depth understanding of the electron beam dynamic and factors that limit klystrons performance. Studying and mitigating phenomena associated with parasitic beam instabilities.
- T3. Development of the new klystron bunching methods, new klystron topologies and associated technologies. Dissemination of the obtained advancements and progress to the community (publications, presentations etc.)
- T4. Communication of the new klystron design to industrial partners and collaboration with industry during klystron technical design phase, prototype fabrication and testing.
- T5. The new klystron acceptance tests and operation at CERN facilities.

High efficiency klystrons projects at CERN







-Task 1: HE Design and simulation

- Development and maintenance of the fast and accurate 2D klystron codes.
- Klystron simulation code KlyC version 5 was released in May 2021. About 50 users worldwide.
- New KlyC version 6 will include CGUN tracking module for the beam optics simulation (gun, solenoid and collector). Will be released in January 2021.

Task 2:HE LHC 400 MHz klystron

- Validate the HE klystron technology (~70%) while upgrading and retro-fitting current LHC klystrons
- The klystron design is accepted by Thales. **Expected delivery of the prototype to CERN is in March 2023.**
- Prepare the acceptance tests at CERN

-Task 3: HE-TS MBK L-band klystron

- **Demonstrate two-stage multibeam technology with 80%+ RF production efficiency**
- Complete design of TS MBK for CW FCC_{ee} : 400 MHz, 1.2 MW
- built demonstrator -> WP5 of the FCC SRF R&D Program
- Promote this new technology towards CLIC, ILC, CEPC, by means of design , collaboration with industry and fabricating a prototype

Task 4: HE X-band klystrons (8MW and 50MW) with high rep-rate

- Built klystrons and demonstrate ~60% efficiency. Collaboration with industry: Canon CETD (Japan) and CPI (USA).
- Reinforce synergies with CLIC, FLASH, Compact Light, Compton sources…
- great showcase for CERN's technology. Contribution to the worldwide society.

See the talks during this workshop:

J. Cai
Chengdu U

A. Beunas
Thales

Z. Un Nisa
CERN

T. Anno
CETD

T. Kimura
CPI

Fast and accurate klystron simulation tools developed at CERN (T1,T2)

Large signal 1/1.5D klystron simulator [6].

1/1.5D Wave-beam interaction module[1].
Beam dynamic simulation (single beam and MBK).

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 arbitrary 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)

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).

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

Electron beam tracking module.
- 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)

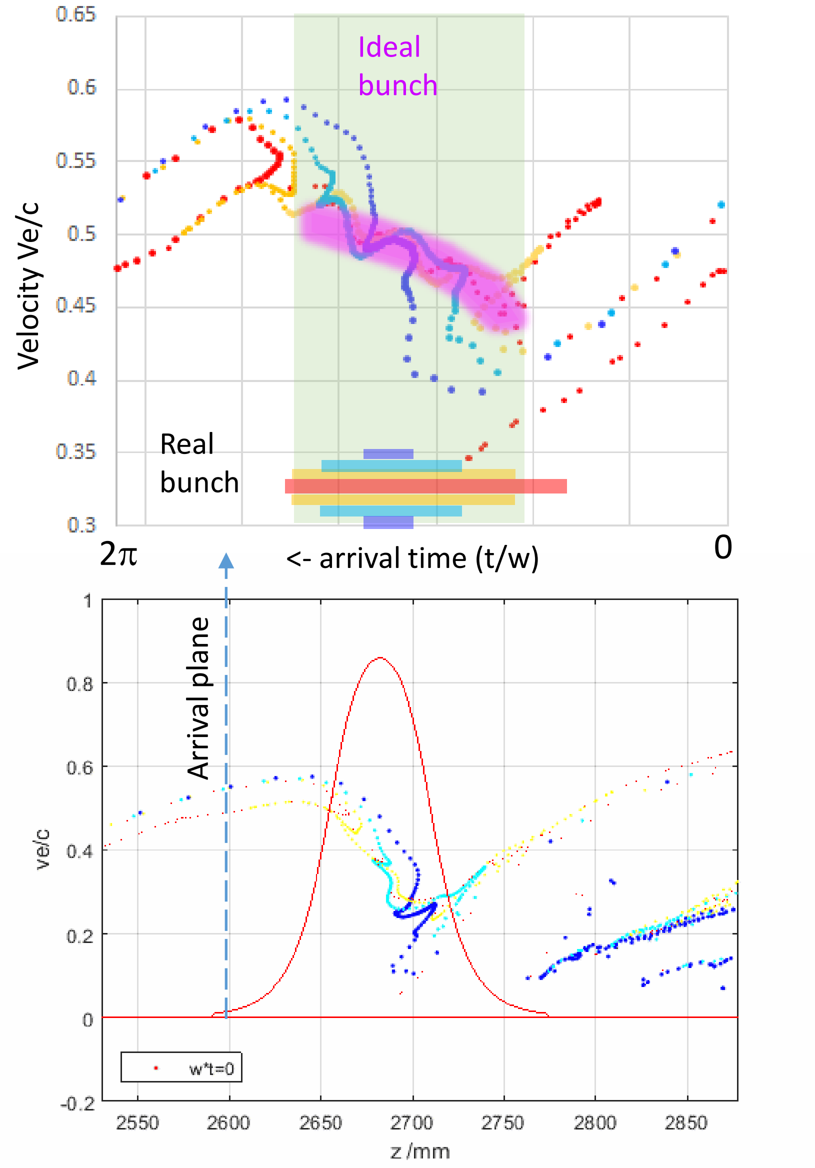
[6] J. Cai, I Syratchev, G. Burt 'KlyC. The 1D/1.5D large signal computer code for the Klystron simulations. User Manual. Version 6. (included CGUN for the 2D electron beam optics simulation).
CERN-ACC-2022-0008 ; CLIC-Note-1177, Link: https://cds.cern.ch/record/2812568?ln=en.

The factors limiting efficient RF power extraction from the bunched beam in RF cavity (T2)

SLAC B-factory CW
0.478GHz, 1.25 MW

Efficiency **61%**

Bunch phase space in the vicinity of the klystron output cavity



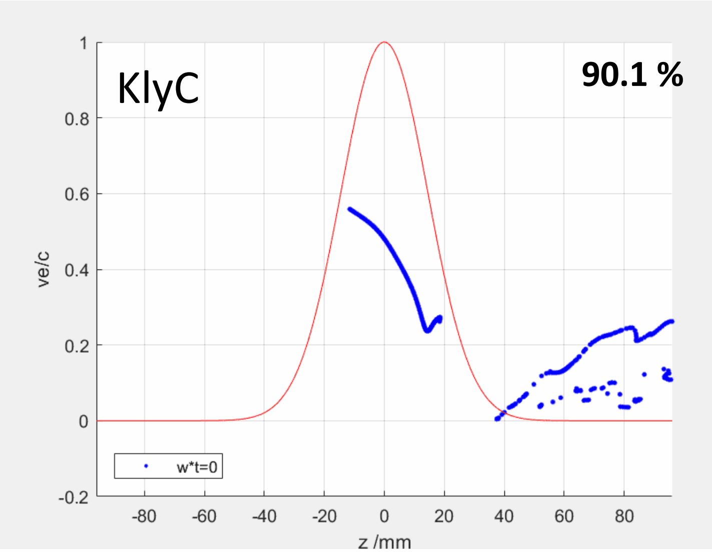
- E field expansion in the drift tubes causes beam reacceleration when it leaves the output cavity.
- Ohmic loses are proportional to the operating frequency.
- Space charge depression is a partial conversion of the beam kinetic energy into the potential DC energy of beam traveling in the drift tube.
- 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.

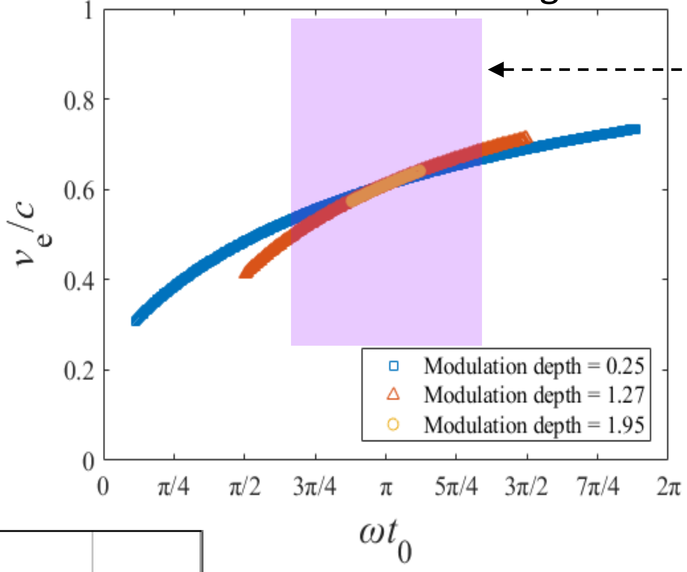
The ultimate power extraction efficiency in the linear beam devices (T2)

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

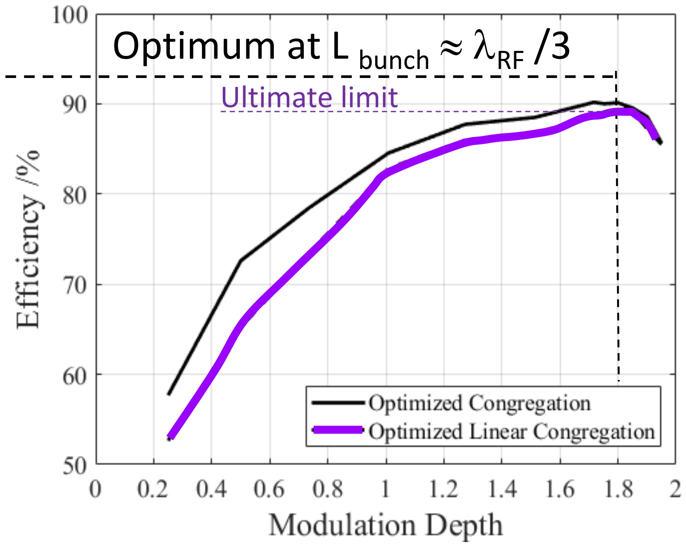
Fully saturated bunch with optimised congregation

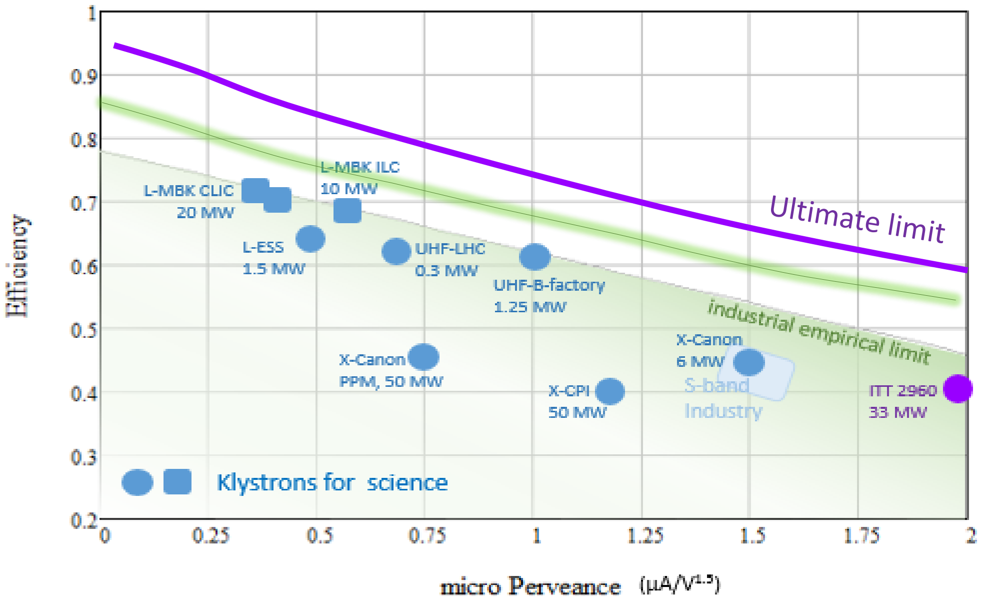


Optimised congregation for the different bunch lengths.



Effect of the bunch length





High efficiency Klystrons design objectives

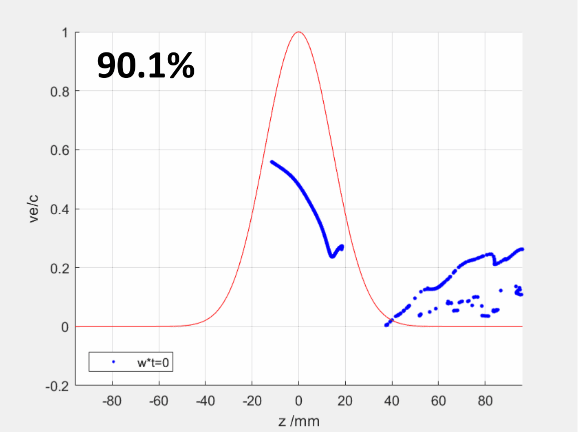
- E field expansion in the drift tubes
- Ohmic Losses
- Space charge depression
- Bunch saturation
- Bunch congregation
- Bunch stratification
- Radial bunch expansion

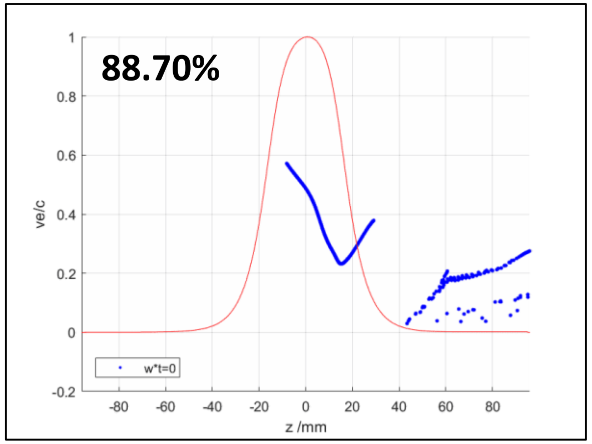
Optimised RF bunching circuit

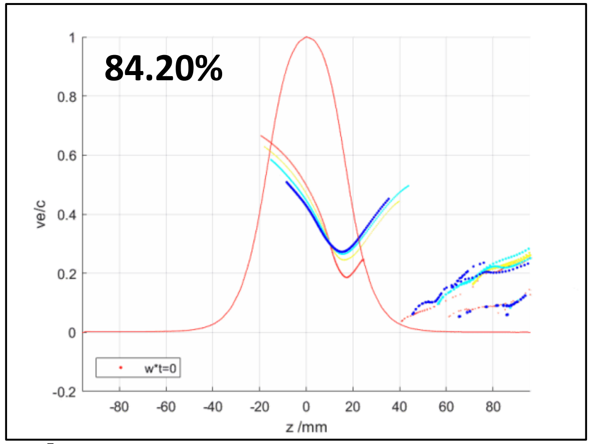
The ultimate power extraction efficiency in the linear beam devices (T2)

Fully saturated bunch

1D bunch Optimised congregation → **1D bunch Linear** congregation → **Stratified 2D bunch** with linear congregation

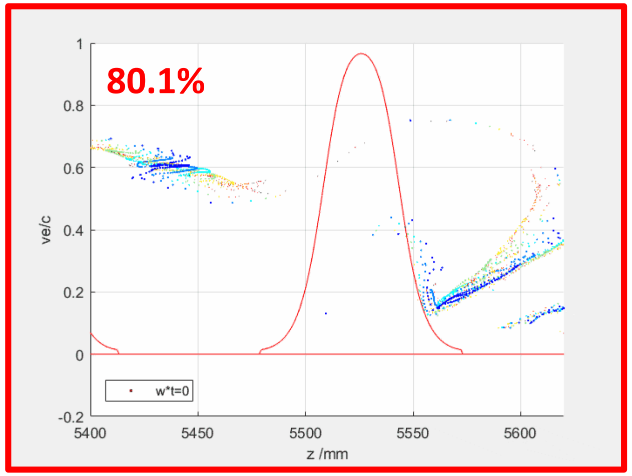


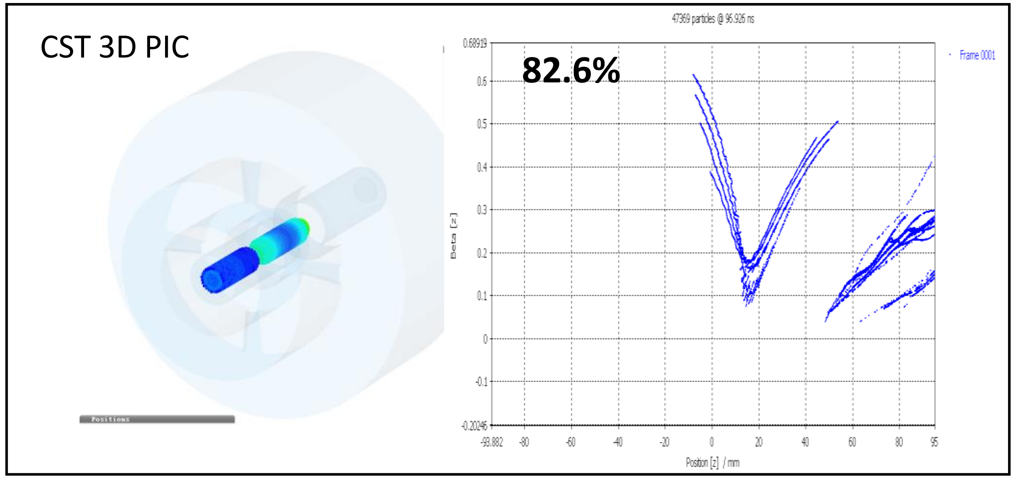




Benchmark with CST 3D PIC
for the same bunch quality

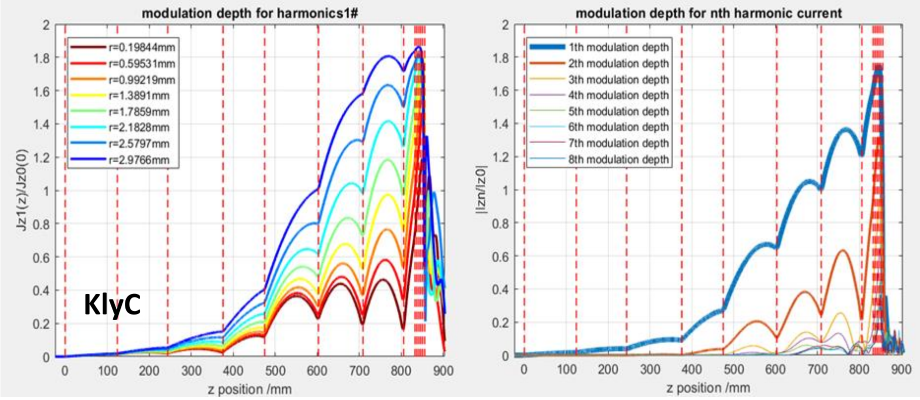
'Real' bunch: Saturation, Ohmic losses, Space charge depression.



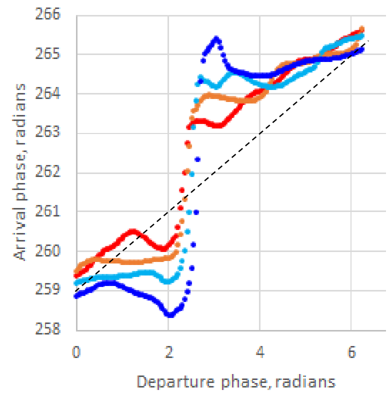


Klystron’s RF circuit optimization (T3)

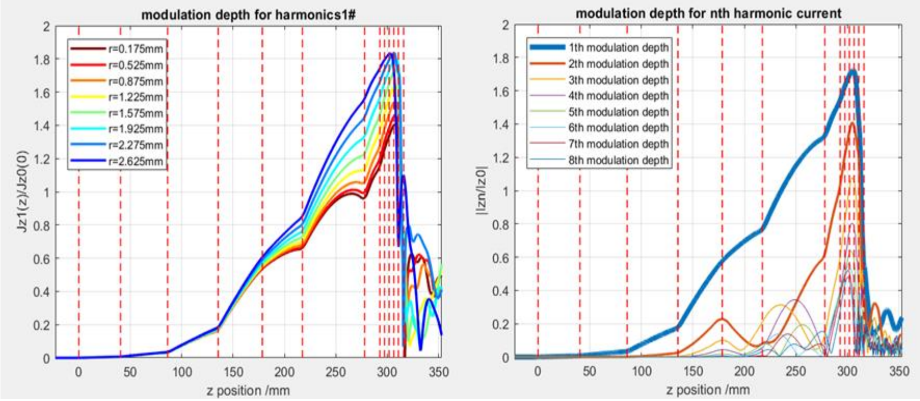
COM RF bunching circuit (**0.86m**). 70.2%.

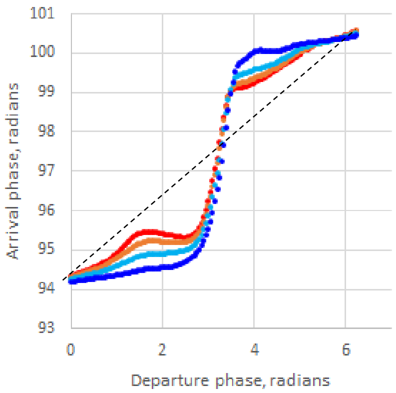


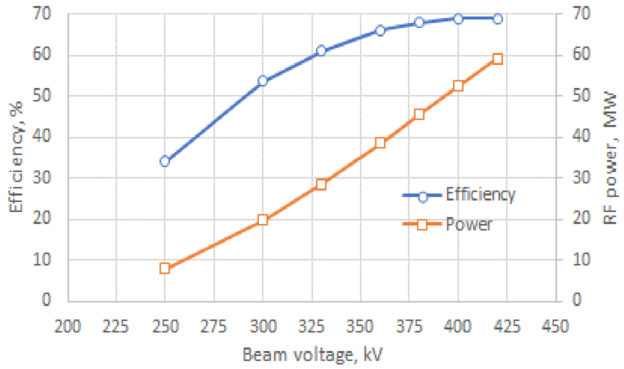
X-band 50MW tube

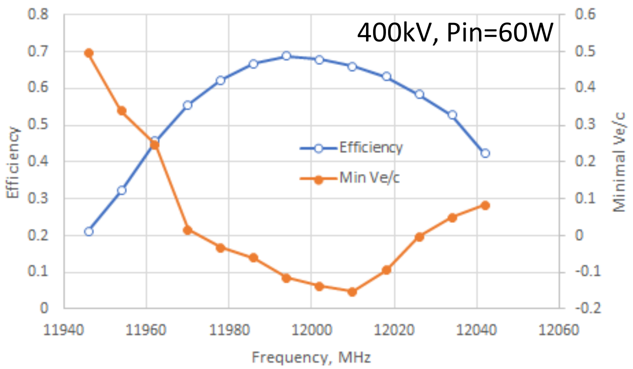


Generic/compact HE-X RF bunching circuit (**0.32m**). 69.3%







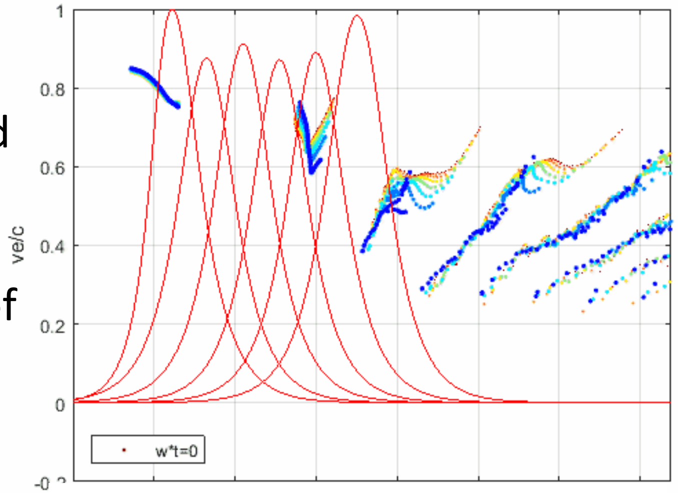


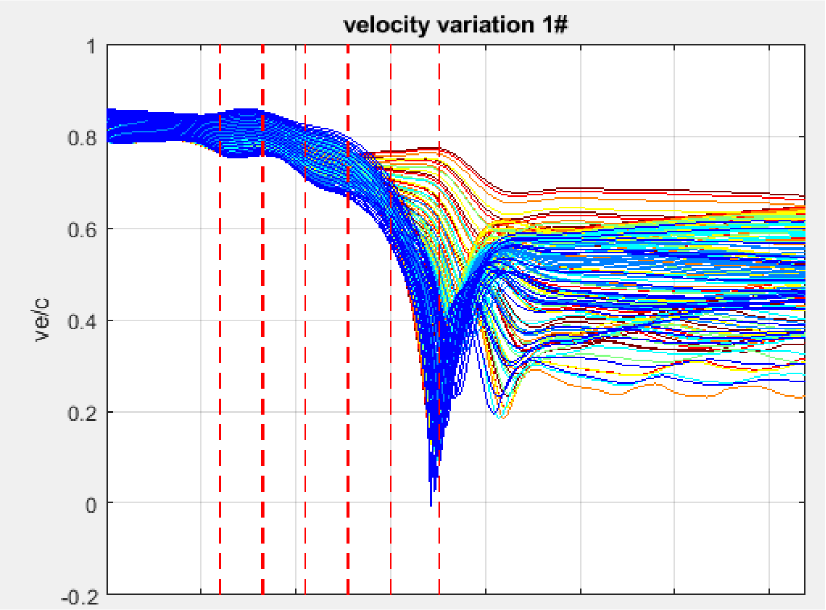
- COM (core oscillation method) provides strong bunch **saturation**, but it requires long RF circuit.
- In klystrons, bunching processes are space charge dominated, thus long circuits increase radial bunch **stratification**.
- Employing 2nd harmonic impedance (and even 3rd harmonic at L-band; CSM tube) allows to boost bunching process and to reduce the circuit length dramatically, providing ‘optimal’ balance between bunch **saturation** and radial **stratification**. That also reduces the solenoid cost and power consumption.
- Bunch **congregation** is controlled by the penultimate cavity. With given cavity geometry, it shall be located close possible to the output circuit.

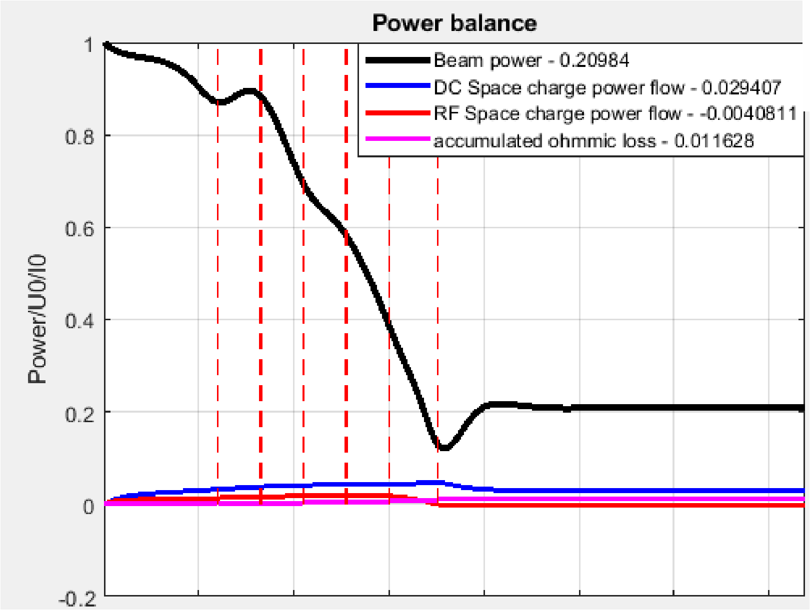
50 MW HE X-band klystron. Output multi-cells coupler optimisation.

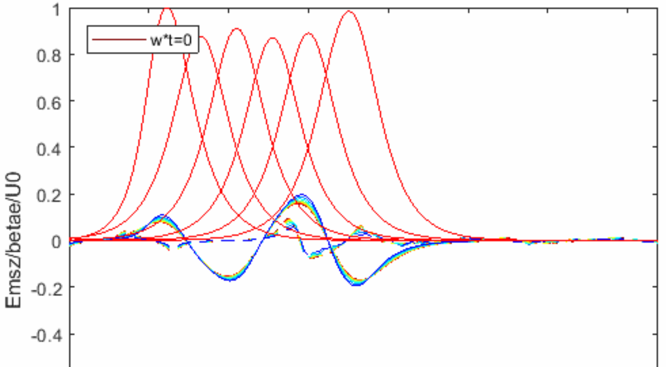
- Surface E filed limited to 100 MW at 50MW -> ‘large’ (15 mm) aperture.
- Low perveance (0.75μA/$V^{1.5}$) -> ‘low’ current (190A)+ large aperture -> more cells (6)
- Constant impedance structure to simplify the fabrication.

Coupler was optimized with idealized (fully saturated) pre-bunched (120^0) congregated (0.25) beam using KlyC' s internal optimization module.
Individual cells frequencies and Q external were automatically adjusted to get highest efficiency (almost 75%) with given constrains on the surface field and lowest velocity of the electrons (>0) in the spent beam.





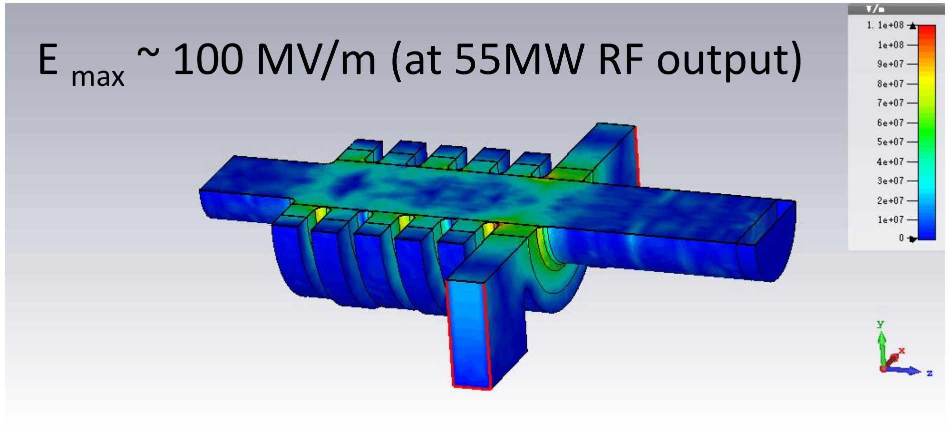


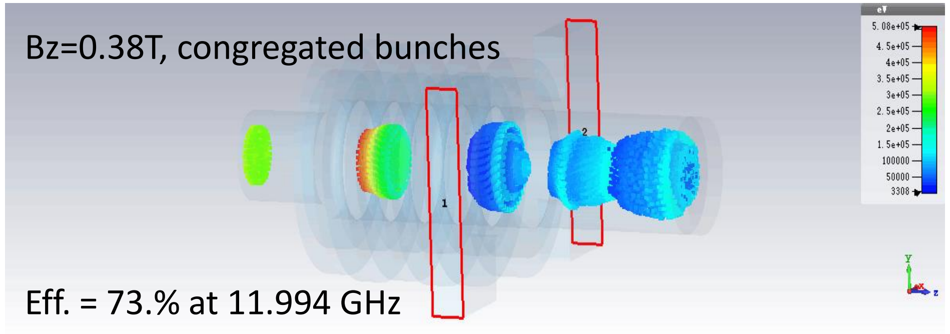


Good synchronism between decelerated bunches and RF field

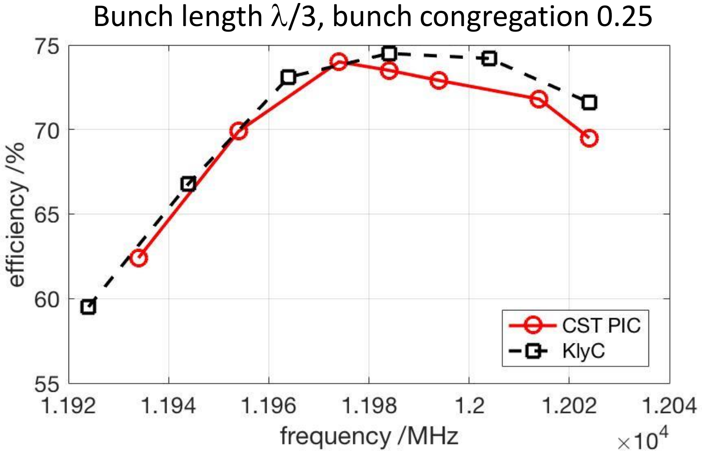
The coupler performance benchmark KlyC vs. CST PIC 3D

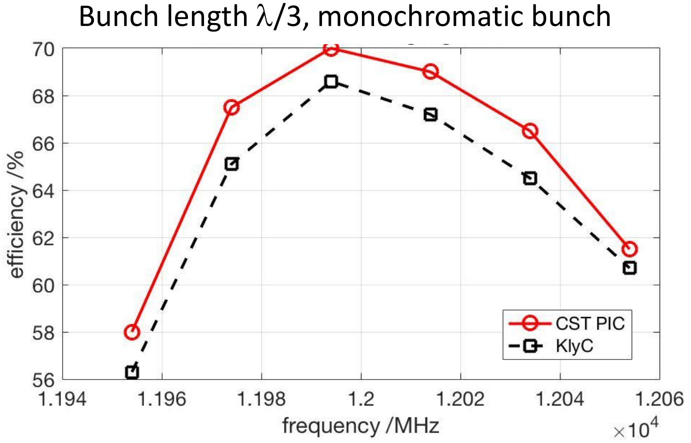
- In this comparison, the idealized bunches parameters are identical for both codes.



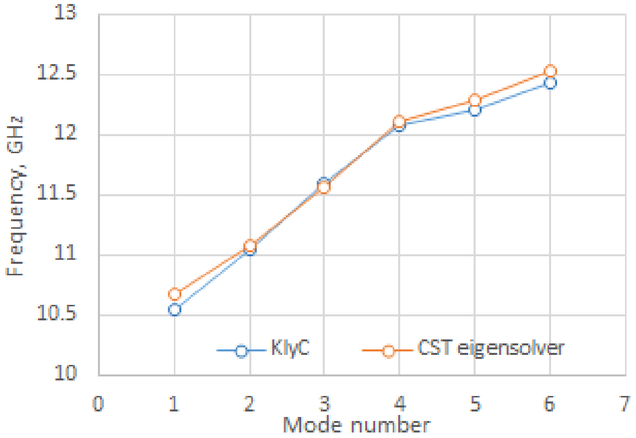


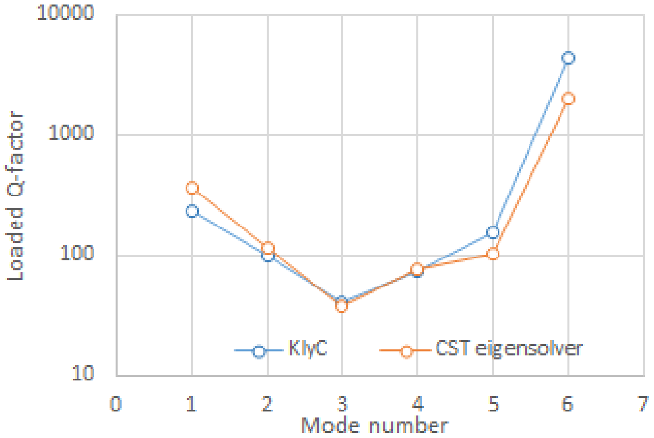
No beam interception





'cold' measurements





IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 66, NO. 2, FEBRUARY 2019 1075

Scaling Procedures and Post-Optimization for the Design of High-Efficiency Klystrons

Jinchi Cai, Igor Syratchev, and Zening Liu

https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8595427

Klystrons' General Scaling Procedure (GSP) (T3)

GSP is a built-in option in the KlyC v5/6.

General scaling procedure

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

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

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

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

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

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

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

Bunch circuit

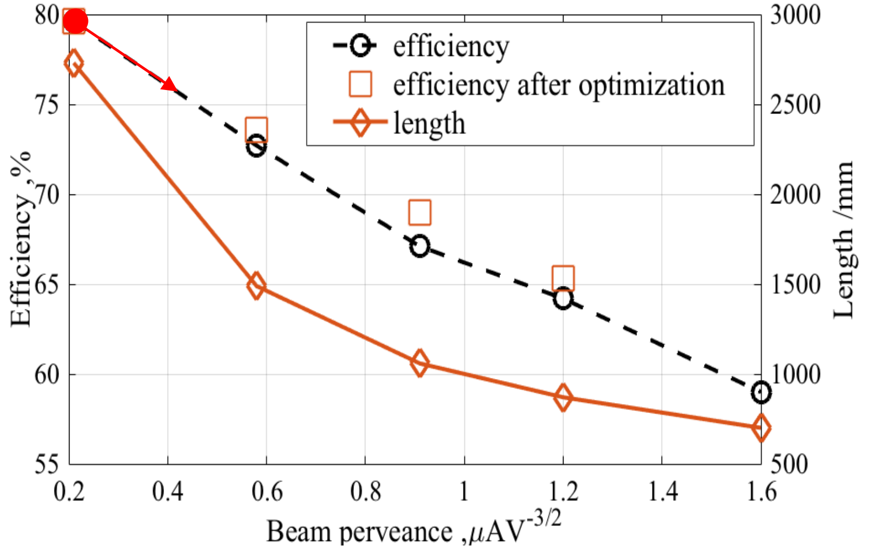
Simplified Extraction theory

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

Output cavity

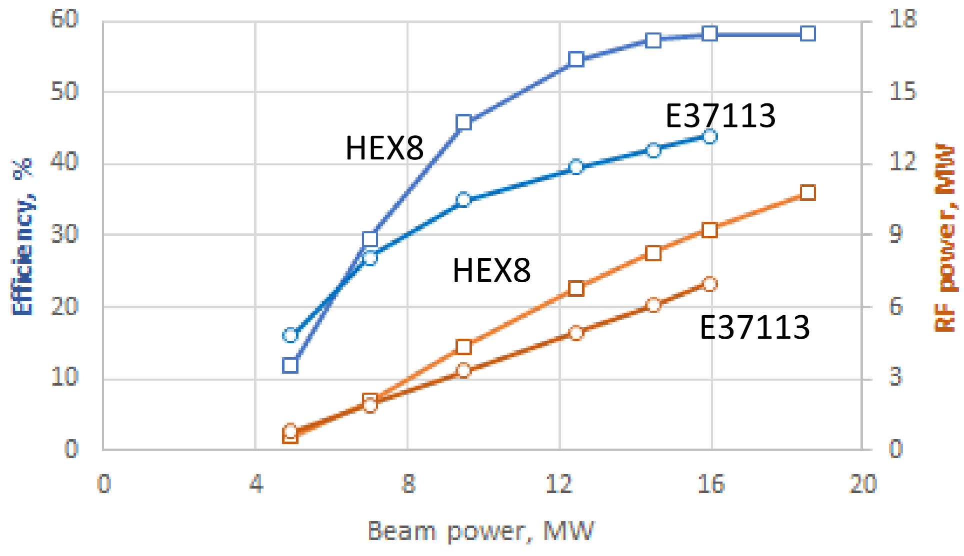
Input power

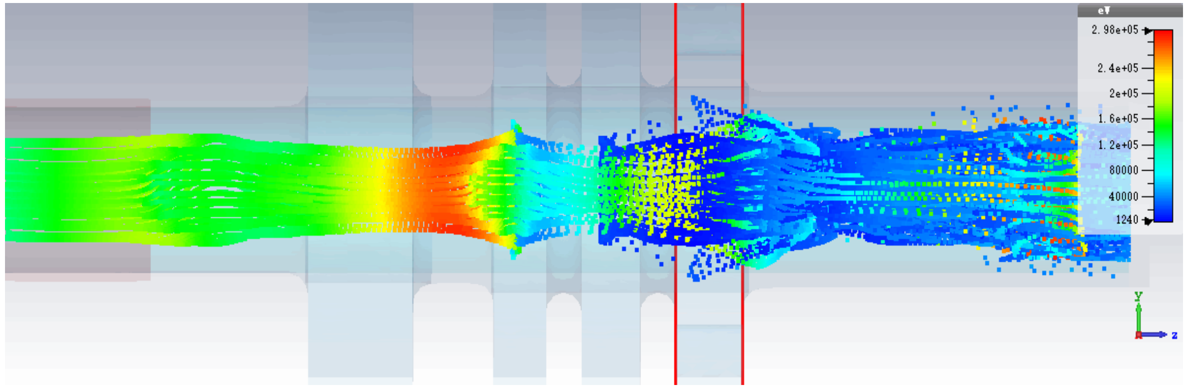
Example of 5 cavities 2MW, 1GHz HE (COM) klystron scaling (constant beam power)



- Any optimized klystron design can be scaled using GSP to another frequency, beam power and/or perveance.
- If the perveance is not changed, the scaled tube will preserved original RF power efficiency.

Retro-fit High Efficiency (57%), 8 MW 12 GHz klystron (CERN/Canon) (T4).





- Re-used solenoid.
- Re-used cathode
- Increased power gain (10 dB)

Second Prototype is in fabrication at Canon
To be tested at factory 07.2022.

Canon

Retrofit design

	E37113 at factory	E37117 design
Voltage, kV	154	154
Current, A	93	94
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.16
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**

CLIC – Note – 1176

DC BEAM STABILITY ISSUES IN THE FIRST COMMERCIAL PROTOTYPE OF A HIGH EFFICIENCY 8MW X-BAND KLYSTRON.

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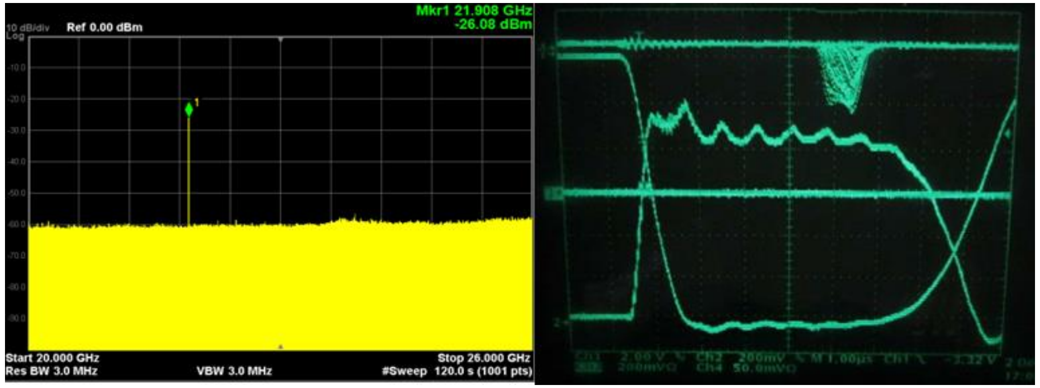
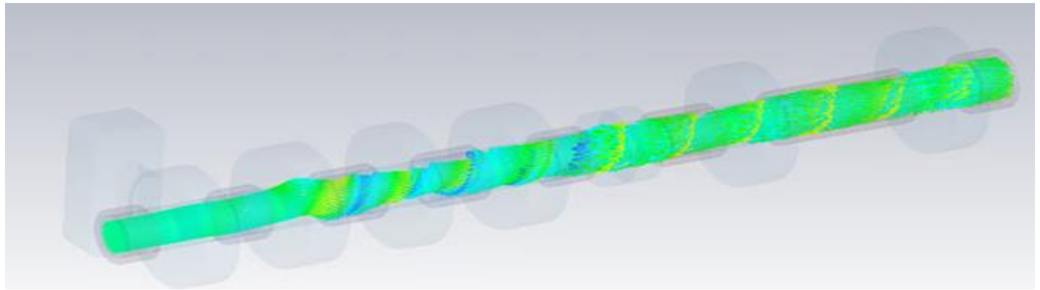
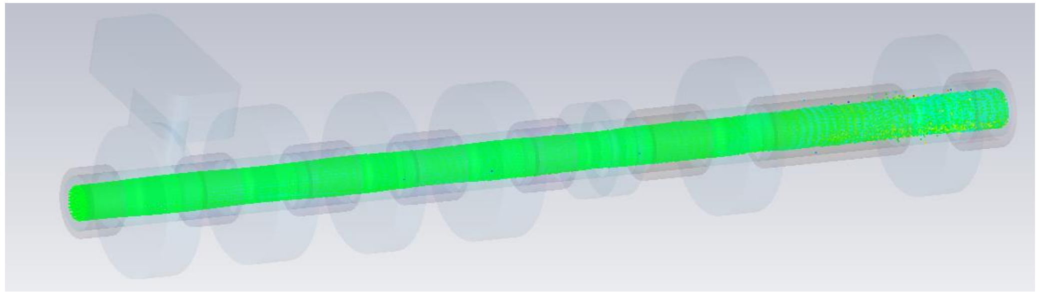
The first commercial prototype of the new High Efficiency (HE) 8MW klystron was built and tested at CETD in the fall of 2021. Unexpectedly, in the first tests with DC beam at different beam voltages, a number of instabilities (self-oscillations) at 21-23GHz were found. As a result, at CERN, we have launched and completed a dedicated investigation program to analyse these instabilities and developed special mitigation measures for minimization of their impact on the klystron fabrication processes. In this paper, we will report the outcome of these studies.

DC beam instabilities in X-band HE 8MW tube (T4).



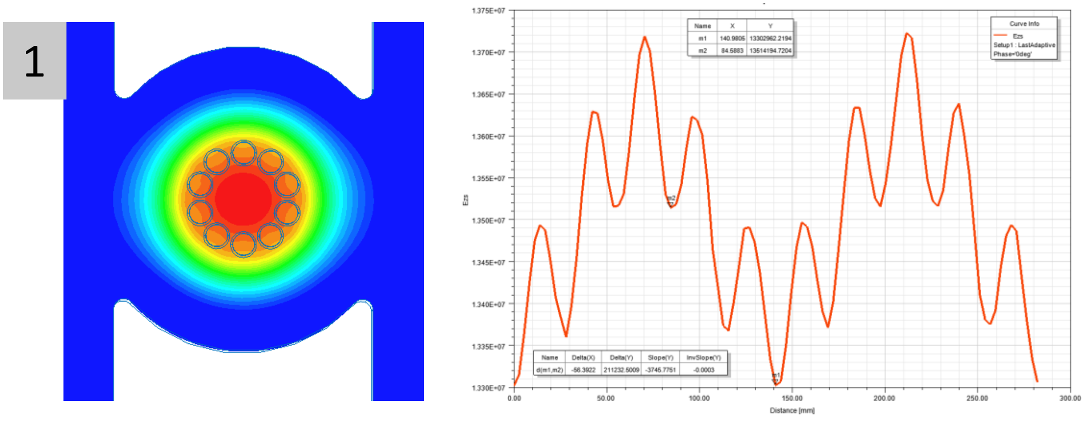


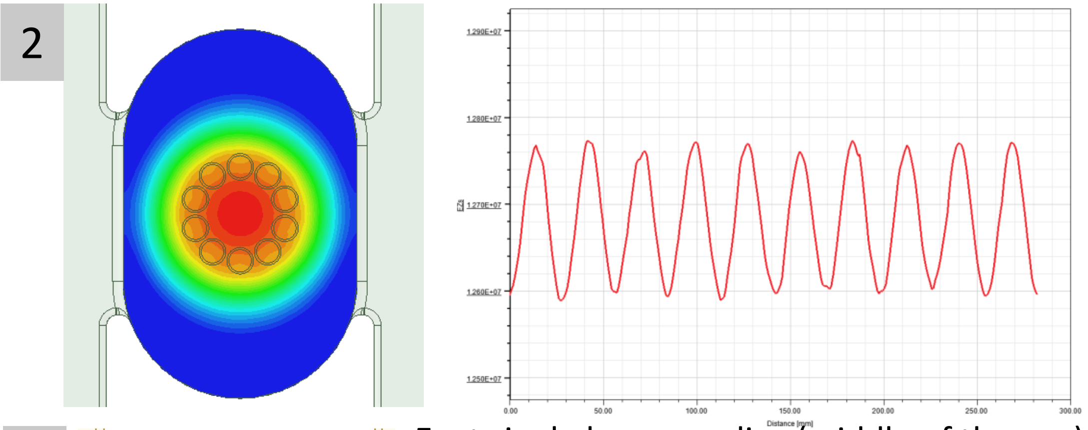
All the instabilities were analyzed/understood and mitigated (**yet in 3D PIC simulations**) by correcting the cavities impedances and other special measures [**https://cds.cern.ch/record/2812566?ln=en**].

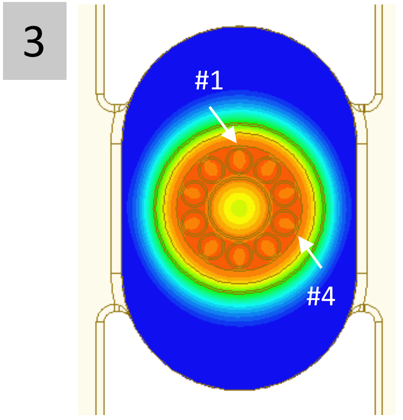


Output coupler of the HE UHF (400 MHz) MBK.

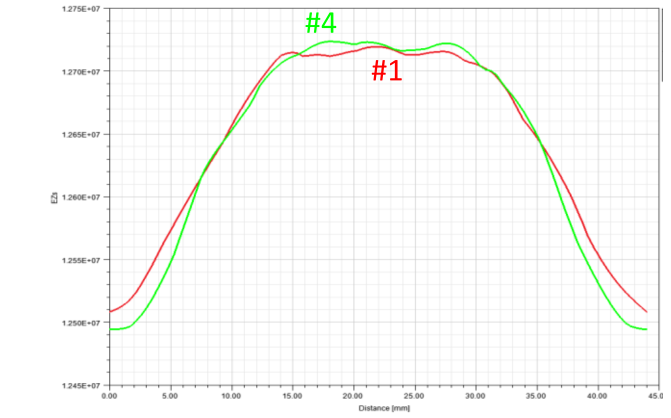
E_z at beams centers radius (middle of the gap)







E_z at single beams radius (middle of the gap)

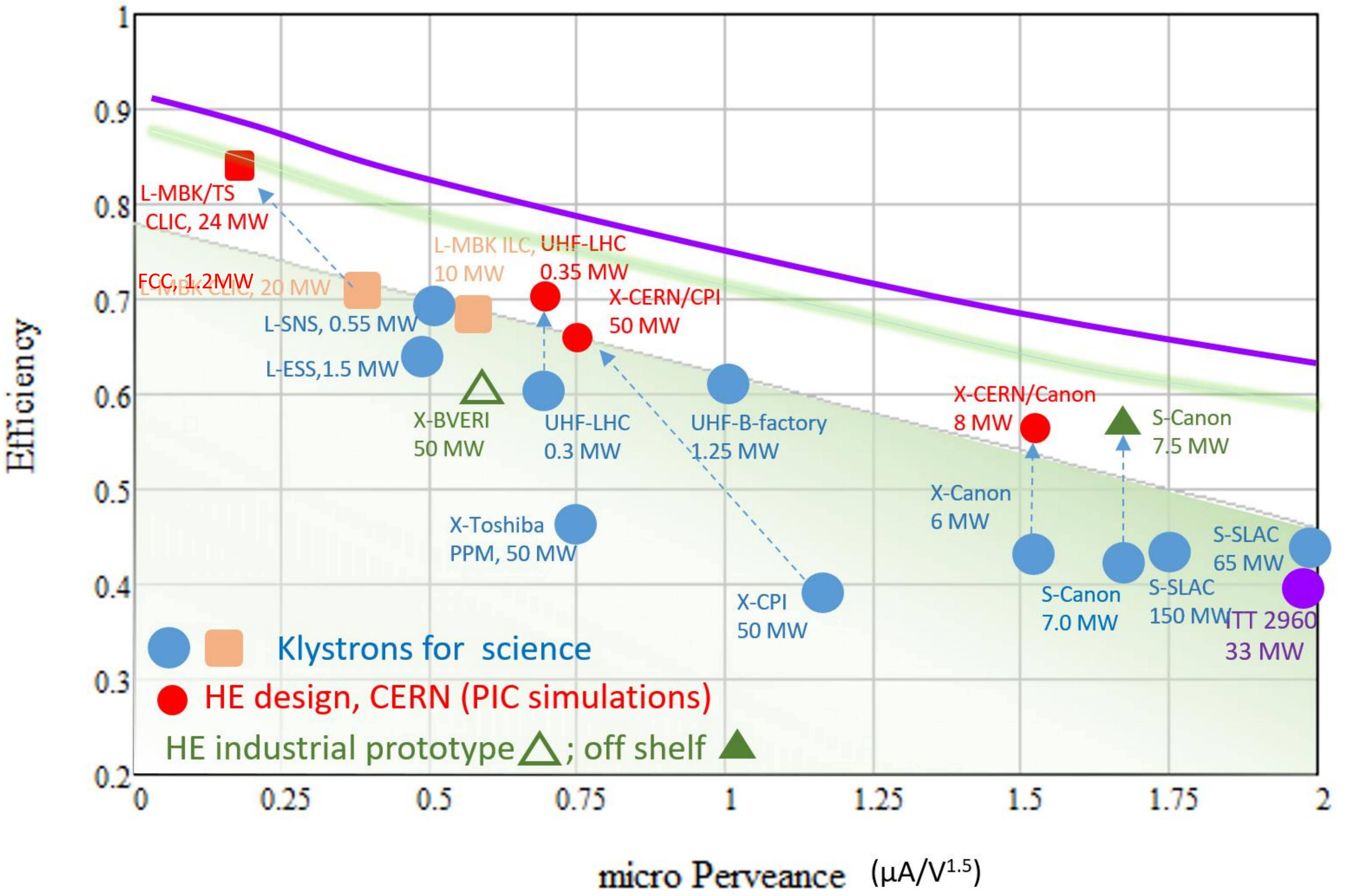


TS technology will profit from the compact arrangement of RF cavities. TM01 reentrant cavities were selected and adopted to host 10x2.7A beams.

1. The original output cavity is coupled to two orthogonal waveguides. In this case we found that reflected electrons are originated not from every channel, but from the ones that have highest (azimuthally) impedance.
2. This effect was compensated by introducing racetrack shape of the cavity to compensate for the quadrupolar filed distortion. Then, reflected elections origin showed azimuthal dependence within the individual beamlet, that followed 6% dipolar distortion of the electric field.
3. This effect was compensated with **L-C tuners,** which reduced dipolar component down to about 1.5% and preserved compensation of the quadrupolar component.

With all these measures 'reflected electrons free' operation can be achieved with about 3%-5% higher RF power production efficiency.

Efficiency performance of the selected commercial klystrons and the new HE klystrons.



http://cds.cern.ch/record/2742978?ln=en

Spare slide

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THE DESIGN UPDATE OF X-BAND RF PULSE COMPRESSOR WITH CORRECTION CAVITIES FOR THE CLIC 380 GEV KLYSTRON BASED ACCELERATOR

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To improve the system efficiency further, it was decided to introduce the RF driving power during the rise time of the modulator HV pulse. In this case, with proper RF phase compensation, the klystron will produce effectively longer (~15%) pulses, which will increase the compressed power level after the PC.