High efficiency RF power sources.

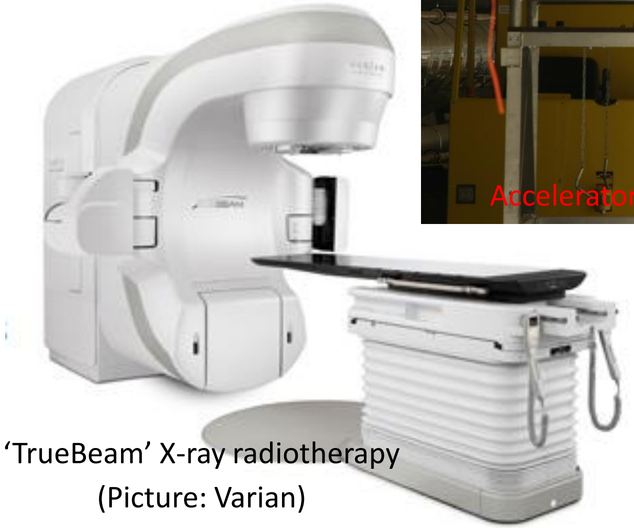
I. Syratchev, CERN.

Every modern accelerator needs RF power sources to provide the electromagnetic field for the charged particle acceleration.


Accelerator tunnel at the LHC (Picture: CERN)


Accelerator tunnel at the European XFEL (Picture: DESY)


Accelerator tunnel at the C-band XFEL (Picture: PSI)


‘TrueBeam’ X-ray radiotherapy
(Picture: Varian)

- 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

USA

France

Japan

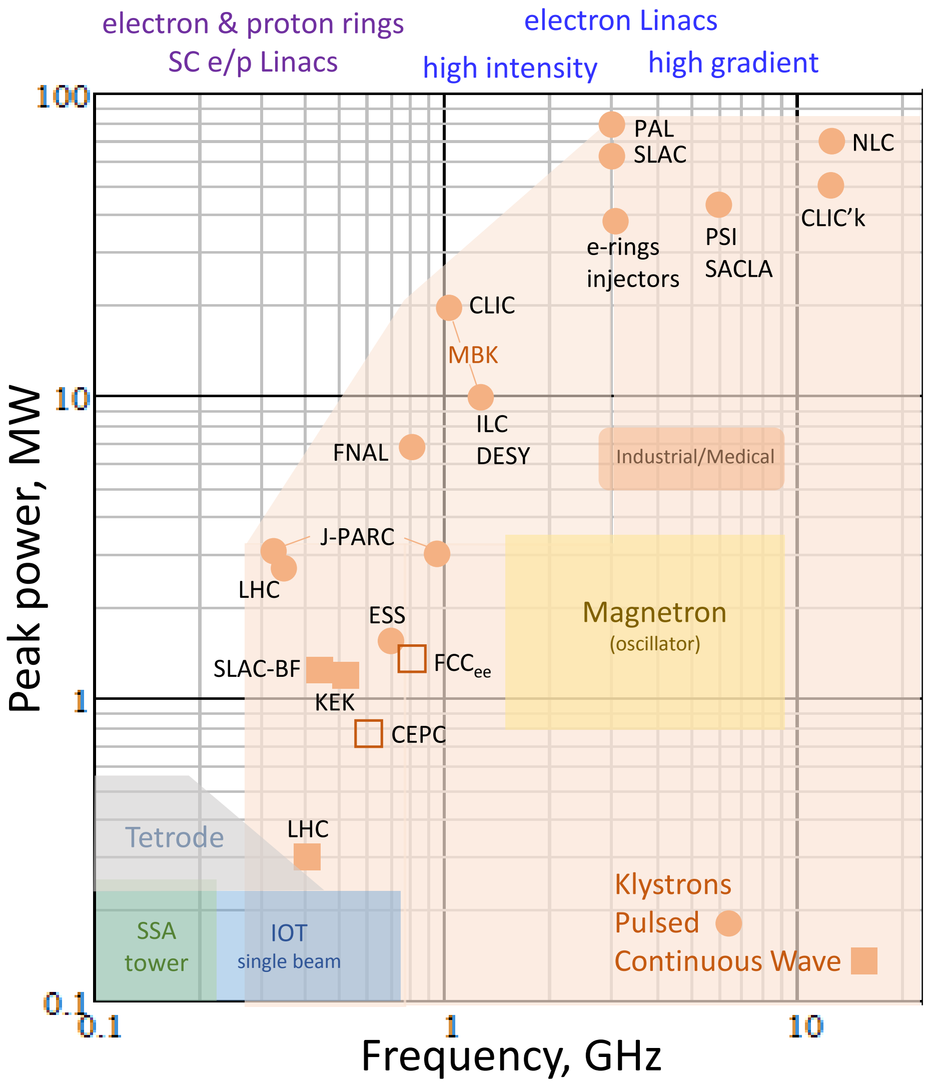
0.7 GHz, 1.5MW/ESS

1.3 GHz, 10MW/DESY

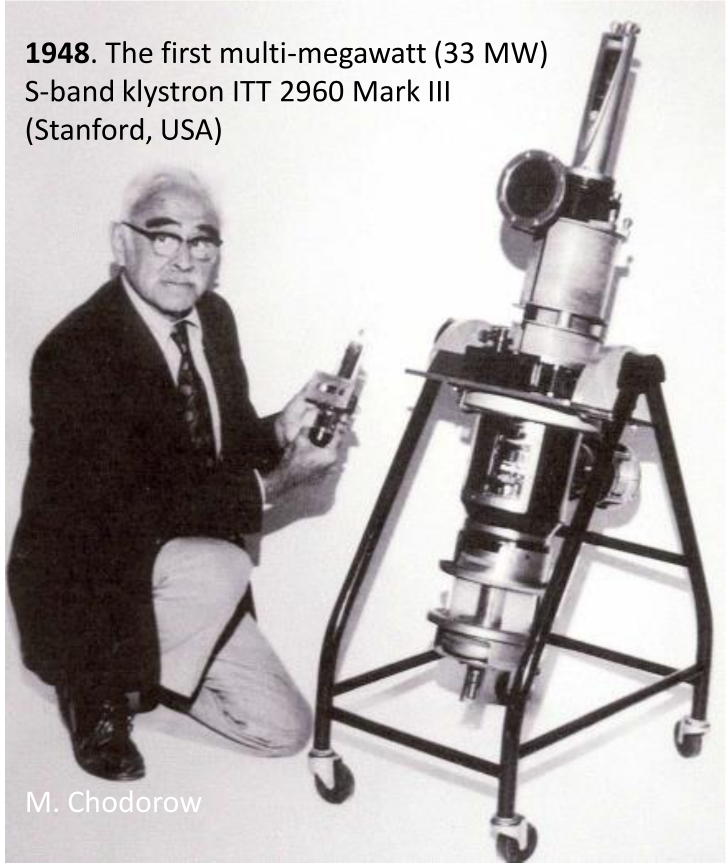
3 GHz, 60MW/SLAC

6 GHz, 50MW/PSI

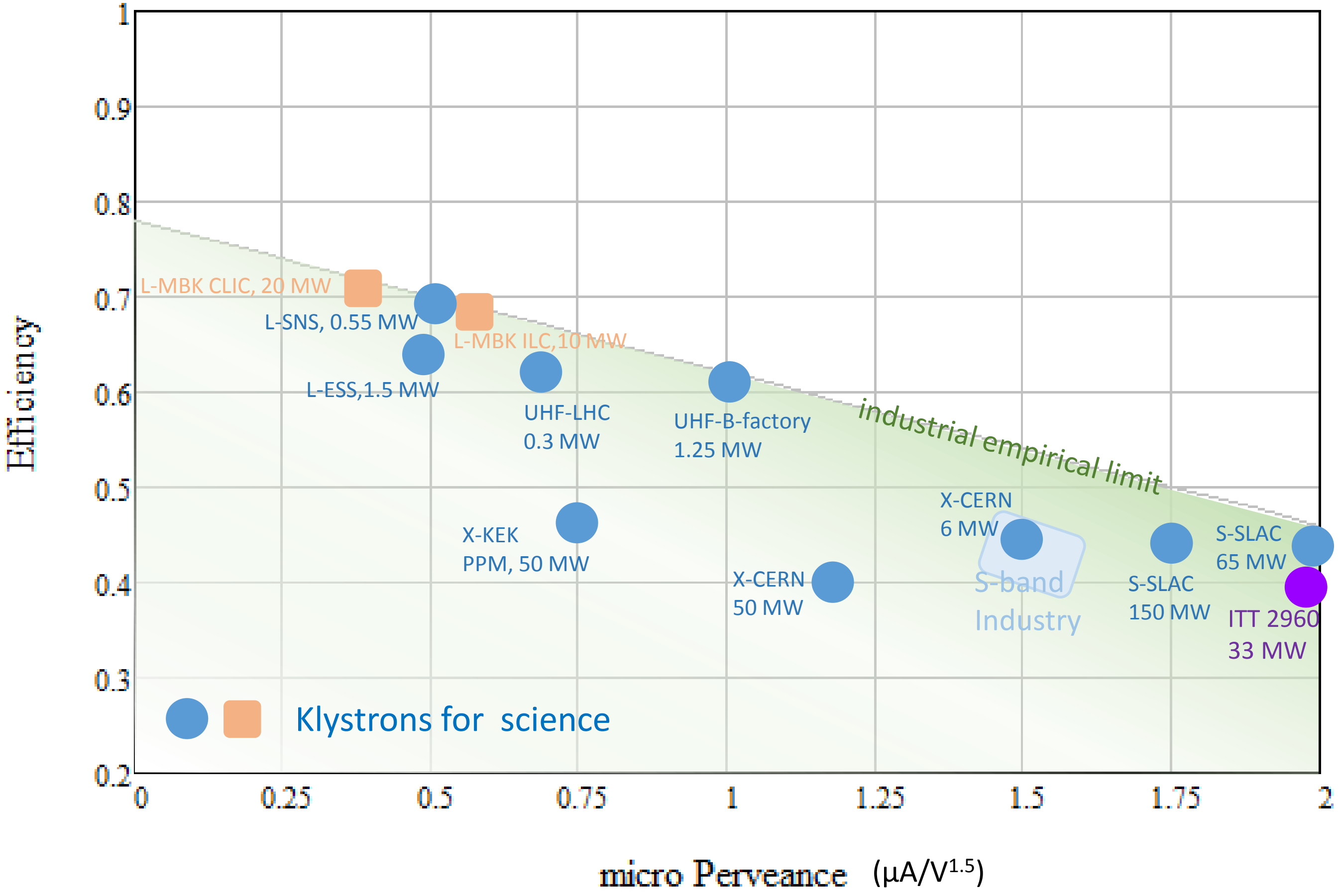
12 GHz, 50MW/SLAC-CLIC



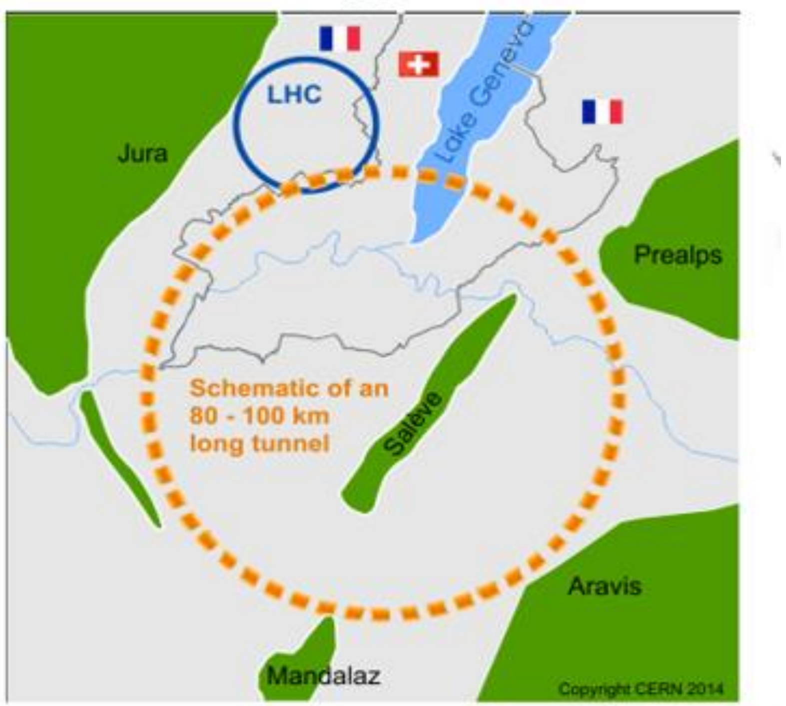
- The klystrons have been used in the particle accelerators for more than 7 decades.
- The experimental results from hundred's of different devices have shown that higher efficiency is associated with lower perveance.
- Accounting for technological and cost reasons ($\mu A/V^{1.5}>0.25$), the 73% efficiency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



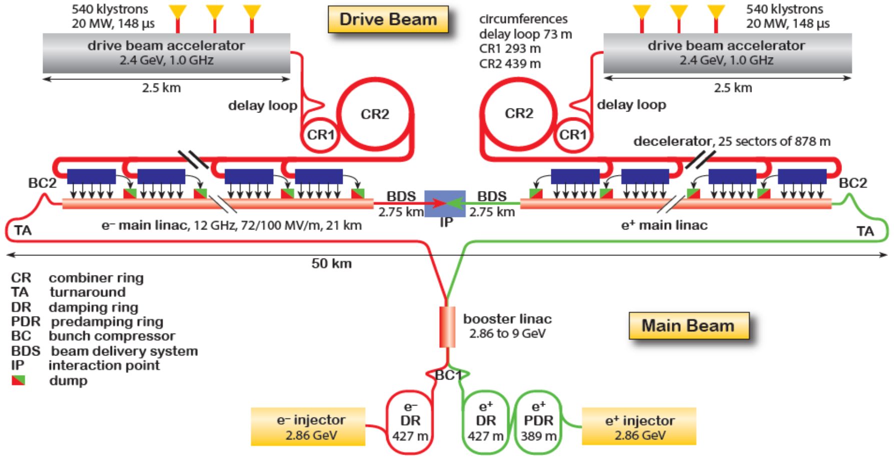
Efficiency performance for the selected commercial klystrons. State of art.



Average RF power needs of the large-scale HEP Accelerators Projects



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 CLIC 3TeV power consumption.
Example of the efficiency upgrade from 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!

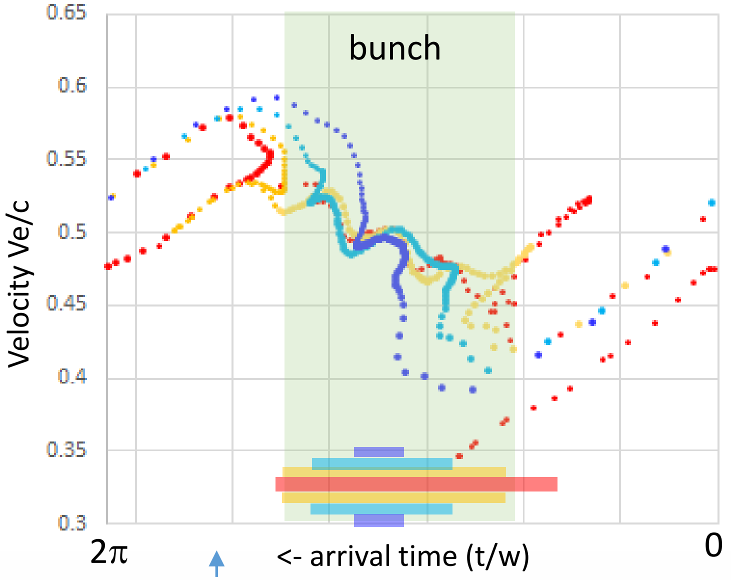
I. Syratchev, LCWS, Japan, Sendai, October 28 – November 1, 2019

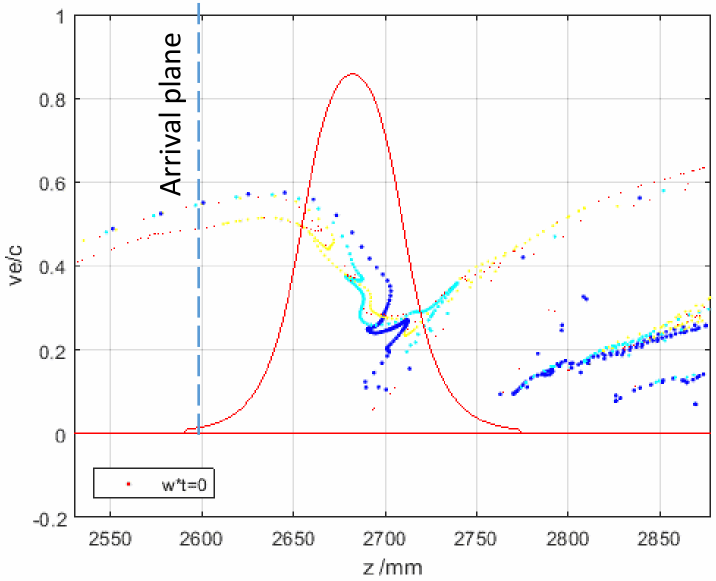
The factors limiting efficient RF power extraction from the bunched beam in RF cavity

SLAC B-factory CW
0.478GHz, 1.25 MW

Efficiency **61%**

Bunch phase space in the vicinity of the klystron output cavity





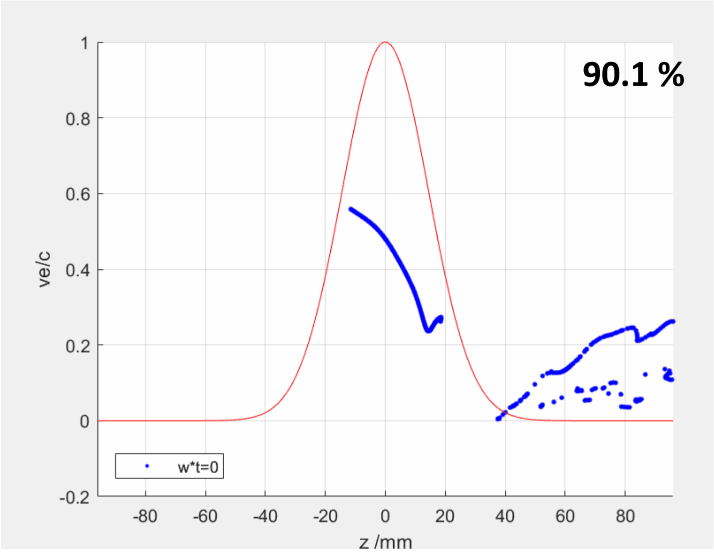
- E field expansion in the drift tubes causes beam reacceleration when it leaves the output cavity.
- Ohmic loses are proportional to the operating frequency.
- Space charge depression is a partial conversion of the beam kinetic energy into the potential DC energy of beam traveling in the drift tube.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

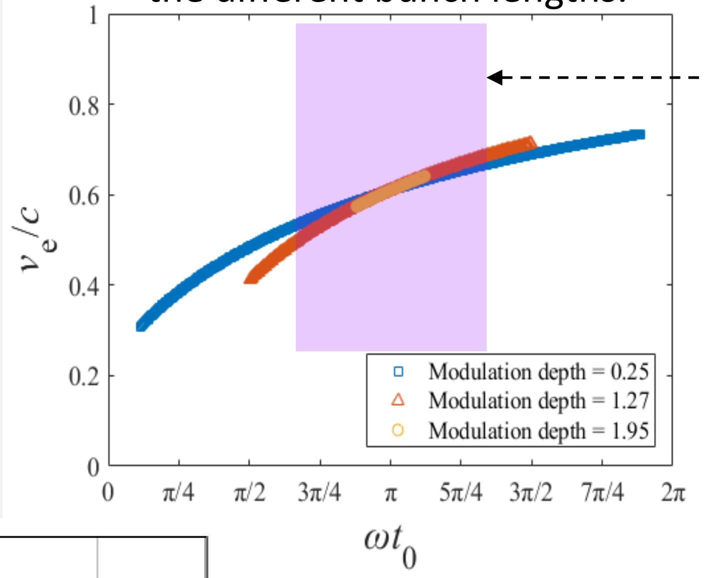
The ultimate power extraction efficiency in the linear beam devices

Example of **0.8 GHz FCC_{ee} klystron output cavity**. Voltage 133 kV, Current 12.6 A ($\mu P = 0.26\ \mu A/V^{3/2}$)

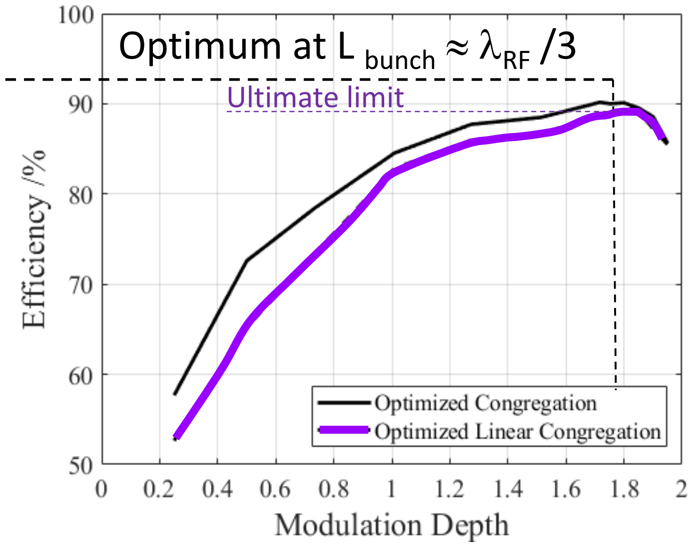
Fully saturated bunch with optimised congregation

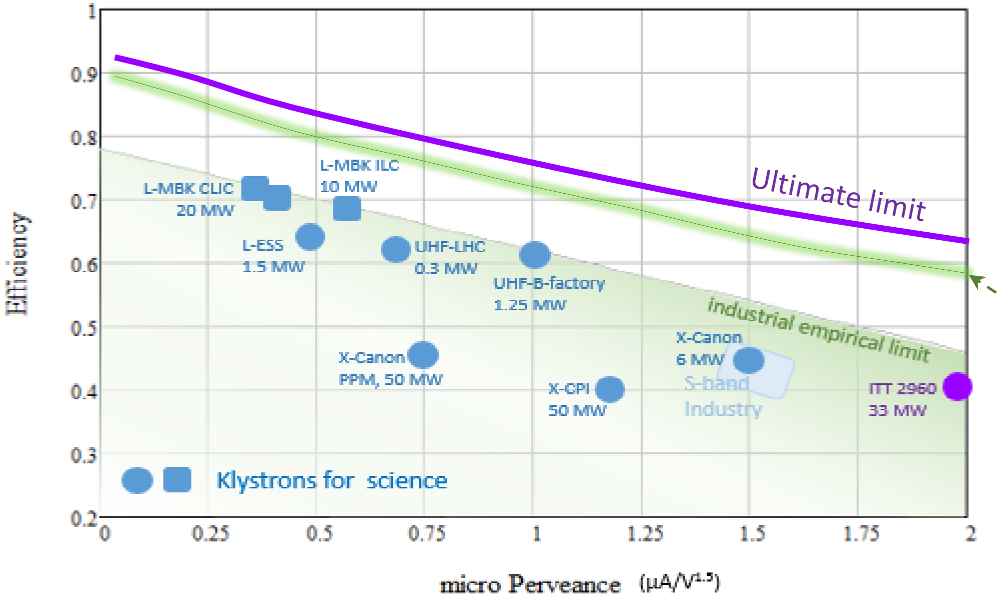


Optimised congregation for the different bunch lengths.



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 **High Efficiency International Klystron Activity** has been initiated at CERN (2013-2017) targeting the improvement of klystron efficiency performance through the development of the new electron **bunching methods** and the new reliable **simulation tools** adopted for the massive optimization processes.

The new bunching technologies have been developed to balance the space charge forces and RF impedances in order to provide the full bunch saturation with an optimal congregation:

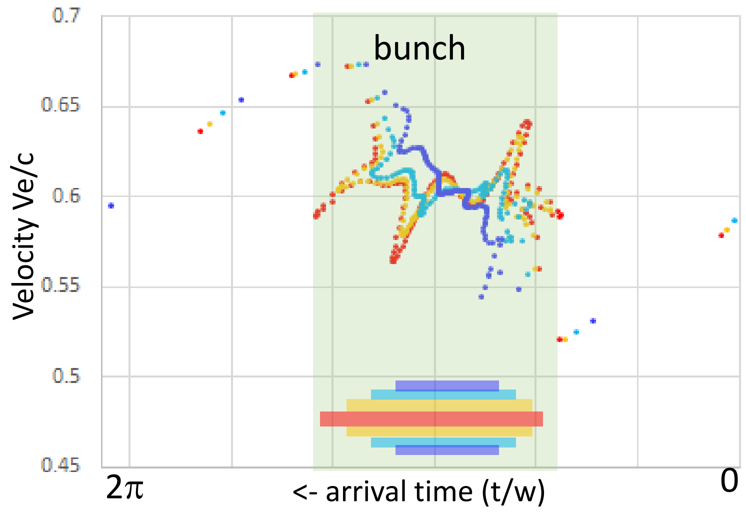
- **Core Oscillation Method (COM)** relies on the de-bunching/bunching alternation between space-charge forces and impedances of the RF cavities. COM requires the long bunching circuit. Cost effective solution for the **high frequency** devices.
- **Core stabilization Method (CSM)** implies the RF cavities with higher harmonic number (2^{nd} and 3^{rd}) that allows the fast collecting of the peripheral electrons into the bunch. Most suitable for the **low frequency** devices.

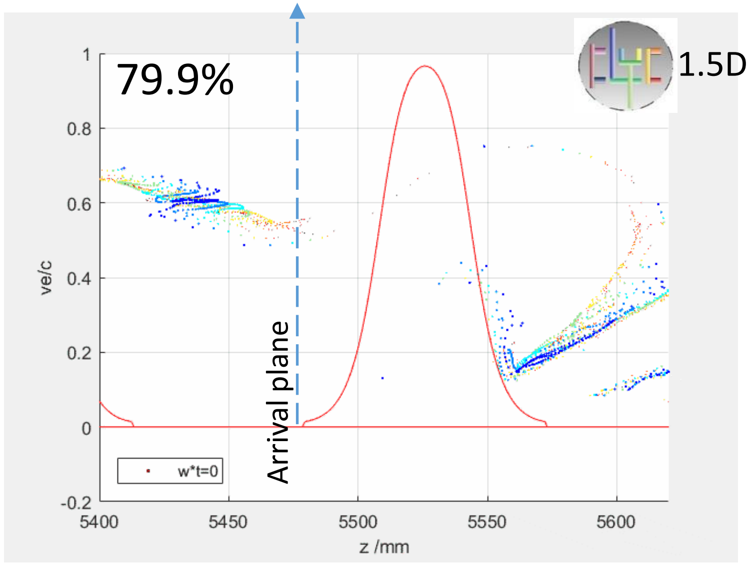
The fast and reliable computer code for the klystron simulations (**KlyC**) has been developed at CERN. KlyC is in a public domain and now is adopted by Labs, Universities and industrial partners in Europe, USA, Japan, China, Russia and India.

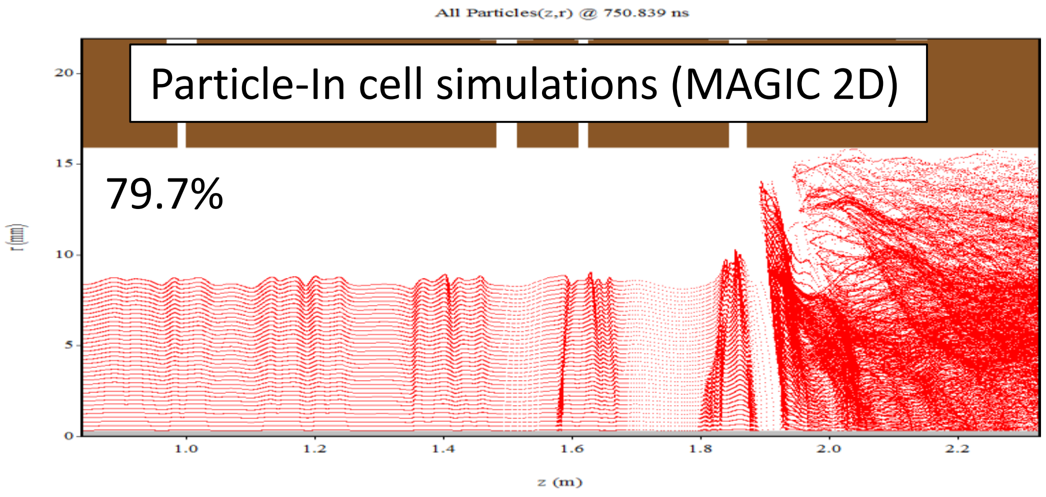
Using the new tools and methods, a number of the high efficiency klystrons for the large scale accelerators (**LHC, FCC and CLIC**) has been developed at CERN and few completed designs have already been communicated to the industry for the technical evaluation and prototyping.

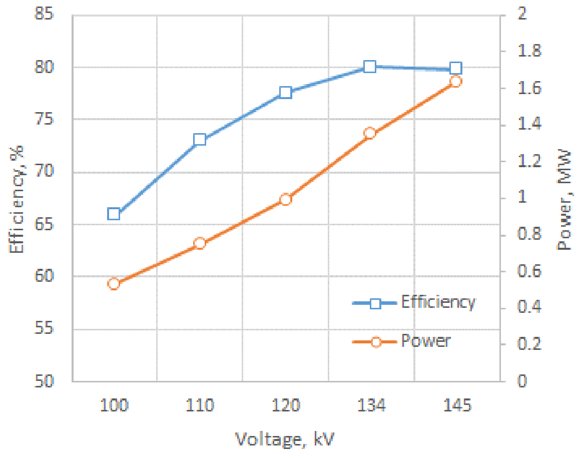
High Efficiency (80%) 1.4 MW, 0.8 GHz, CW FCC_{ee} CSM klystron (CERN/Thales).

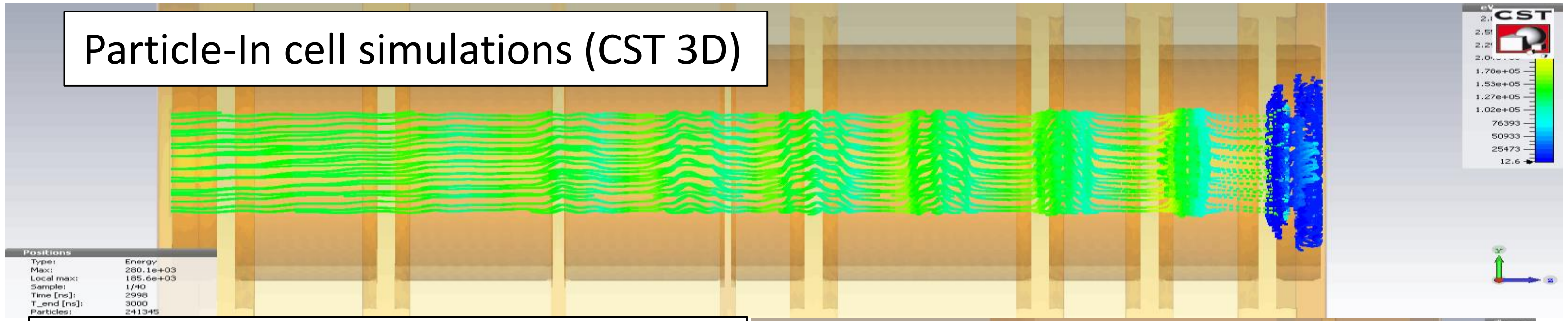
Bunch phase space in the vicinity of the klystron output cavity

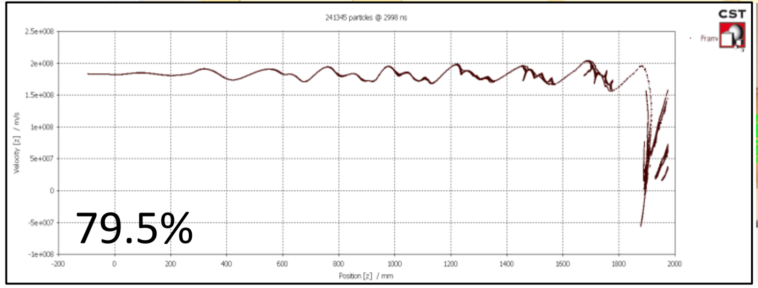


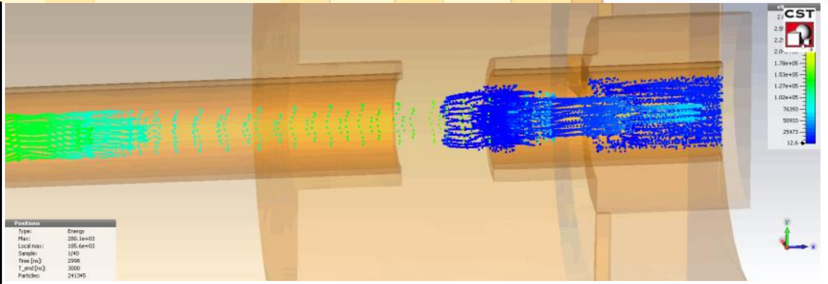








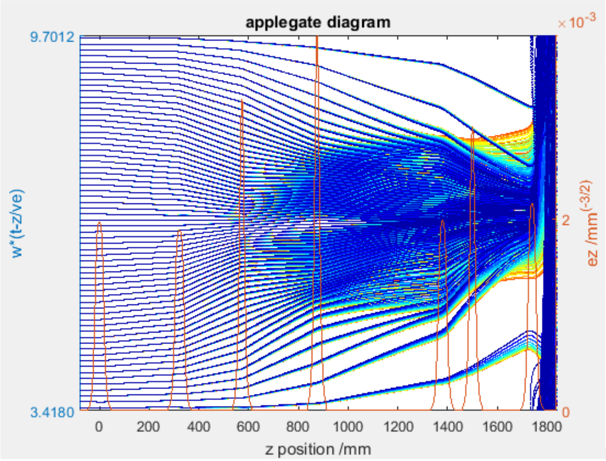




Parametric Scaling Procedure. High Efficiency (70%) 350kW, 0.4 GHz, LHC klystron upgrade.

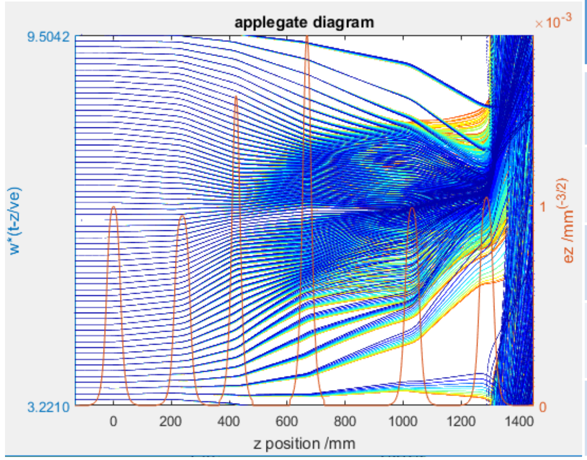
Design of any new klystron is rather time consuming. It requires high level of the related experience/expertise.
The **PSP** was developed at CERN as a set of semi-analytical procedures that allow to scale the existing klystron design to the new one (beam power, frequency and perveance) and to preserve the bunching processes.

Design cycle ~ 6 month



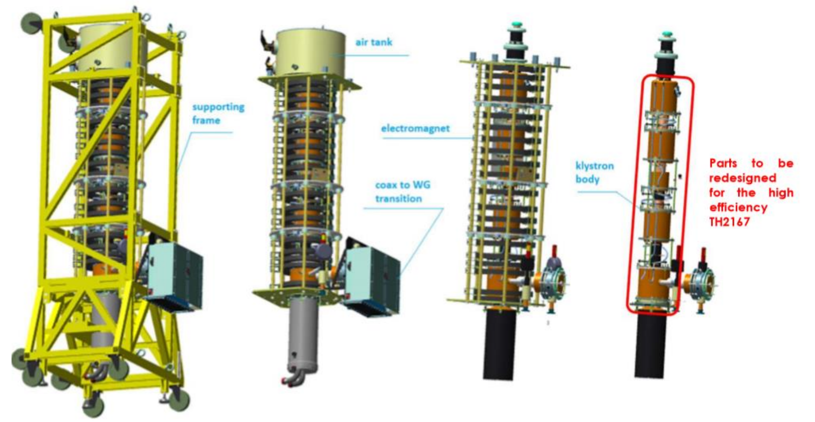
	FCC
Frequency, GHZ	0.8
Beam power, MW	1.68
Perveance,	0.26
RF power, MW	1.34
Efficiency, %	80

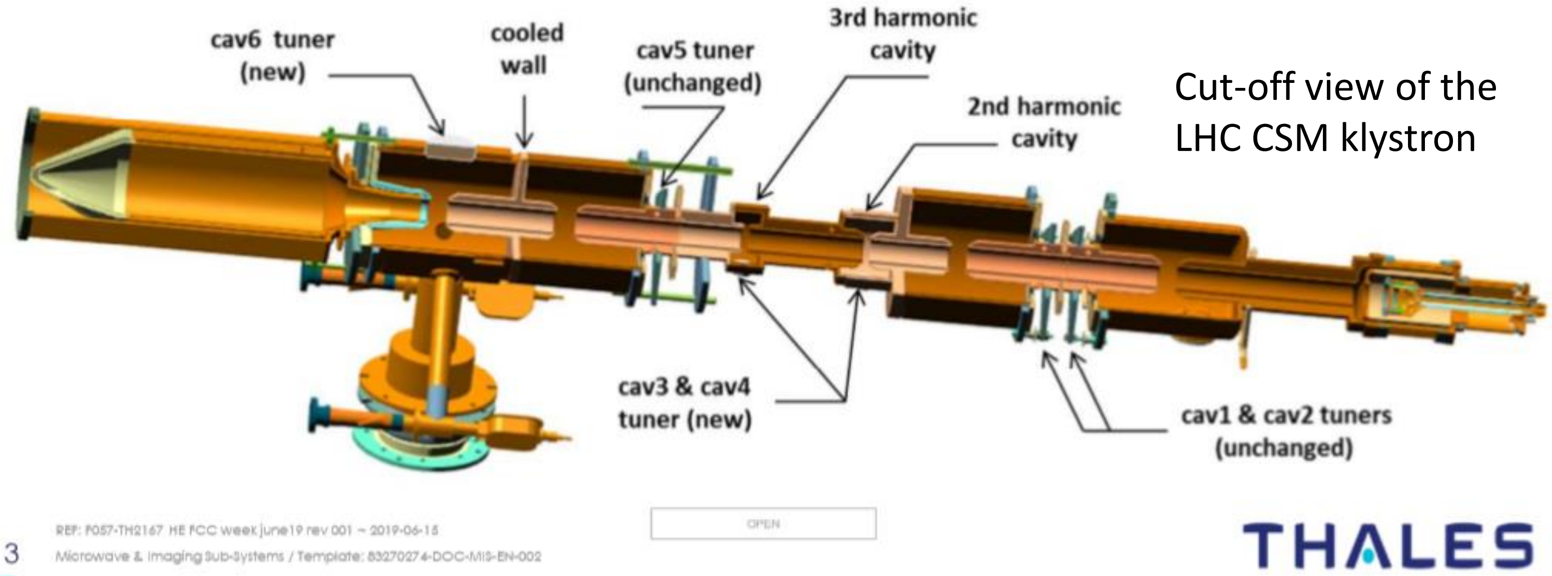
Design cycle ~ 2 weeks



	LHC	LHC/Thales
Frequency, GHZ	0.4	0.4
Beam power, MW	0.5	0.5
Perveance,	0.72	0.72
RF power, MW	**0.35**	**0.30**
Efficiency, %	70	60

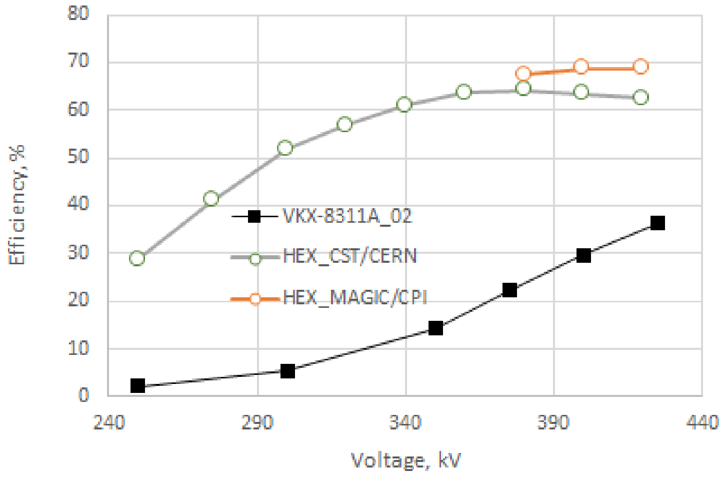
Re-used housing, electron gun and solenoid

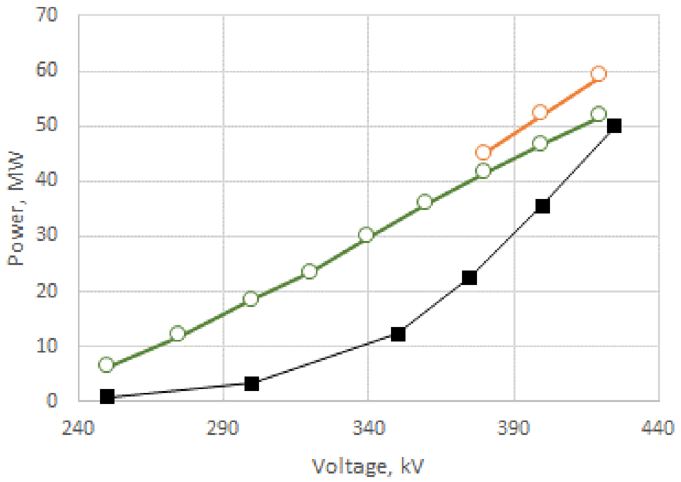


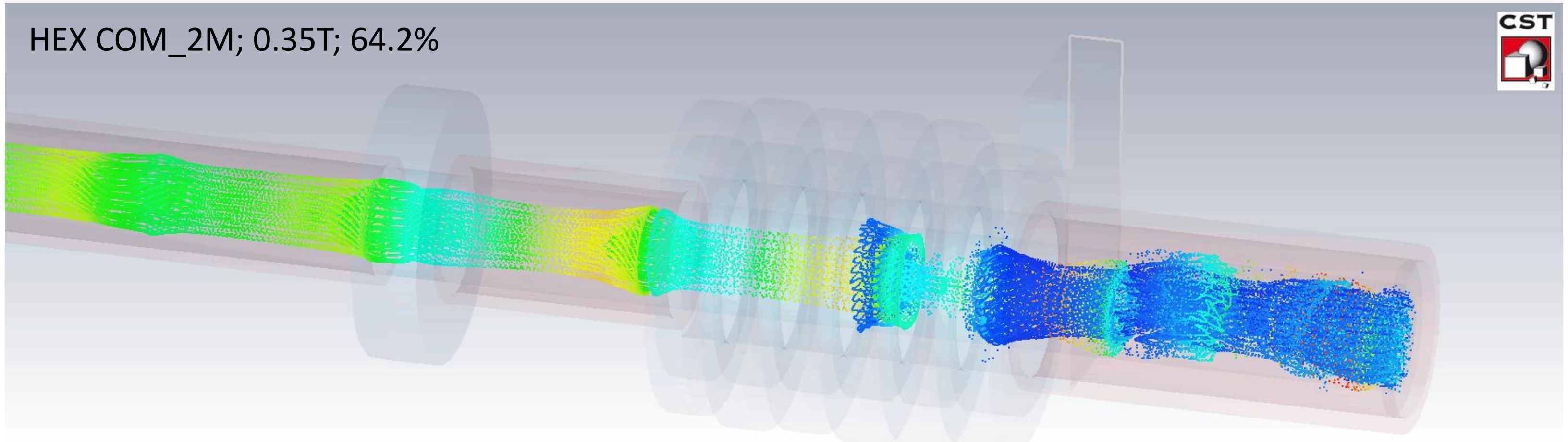


High Efficiency (70%) 50 MW, 12 GHz, CLIC COM_M klystrons (CERN/CPI).

Saturated efficiency & RF power







	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	68.8/ MAGIC.2D
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.35
RF circuit length, m	0.32	0.39

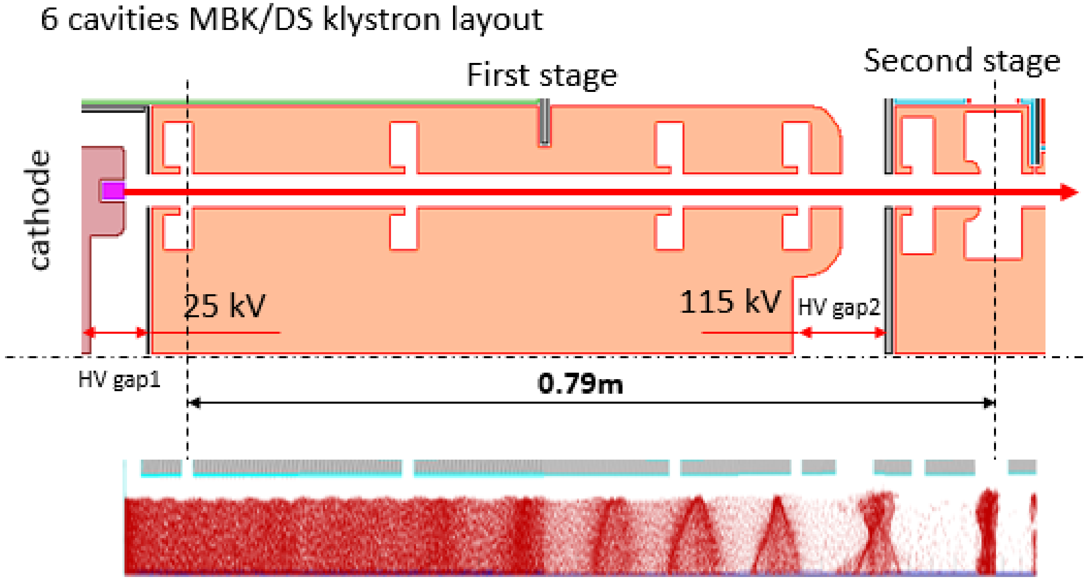
Tailored Technologies. High Efficiency (85%) 24 MW, 1 GHz, CLIC MBK/2S klystron.

Industrial CLIC MBK prototypes delivers **~70 %** RF power production efficiency

The new klystron bunching technologies cannot be directly adopted to the CLIC MBK:

- **COM** requires very long (5m) RF circuit.
- In **CMS**, the 3rd harmonic cavity is not compatible with MB-type cavities layout.

The CLIC MBK with **two high voltage stages**.
Electronic efficiency measured in PIC simulations is **84%**.



Conceptual features:

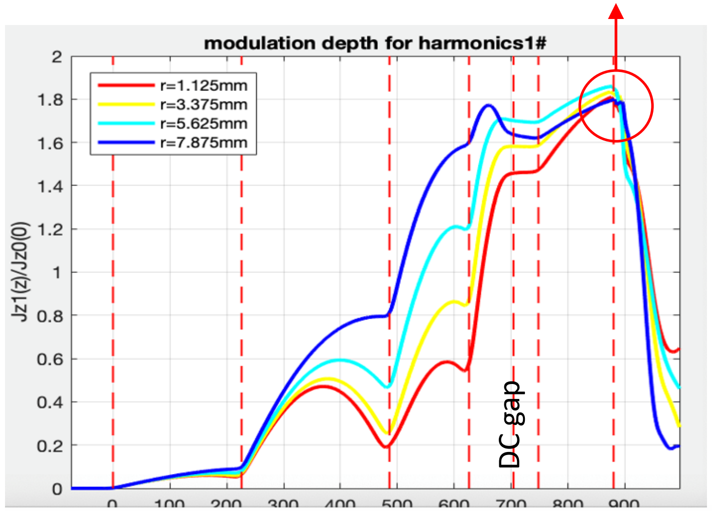
1. Bunching at a low voltage (high perveance). Very **compact RF bunching circuit.**
2. Bunched beam acceleration and cooling (reducing $\Delta p/p$) along the short DC voltage gap.
3. Final power extraction from high voltage (low perveance) beam. **High efficiency.**

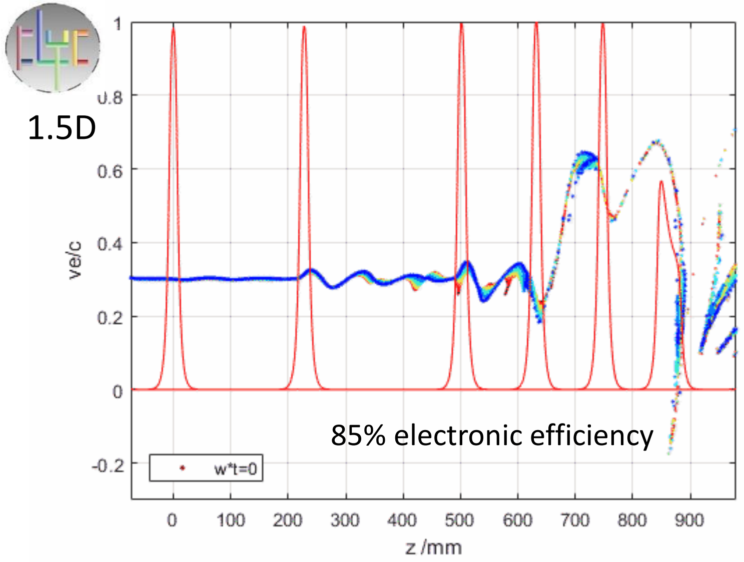
Tailored Technologies. High Efficiency (85%) 24 MW, 1 GHz, CLIC MBK/2S klystron.

To facilitate massive optimization of the MBK/2S, the Poisson module has been developed and implemented in KlyC. (DC gaps, cathodes and collectors can be now simulated)

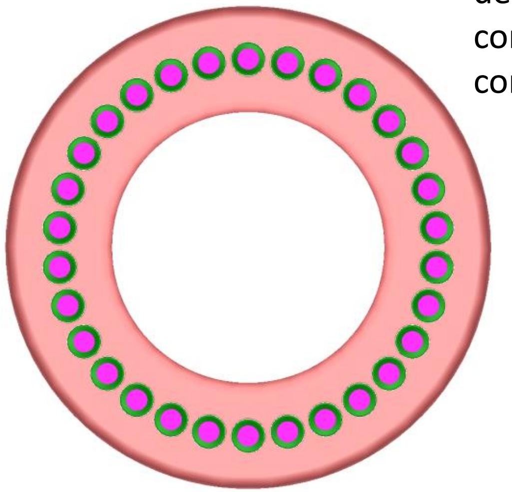
KlyC vs. MAGIC/2D benchmarking

Bunch with almost '0' stratification

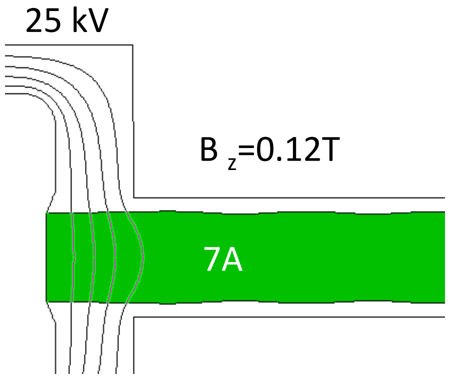


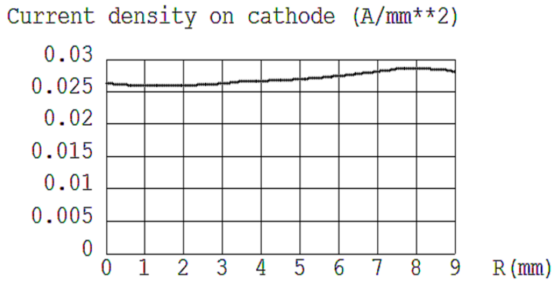


30 beams/RF 24MW



The simple (cost effective) magnetized gun optics with surface current density below 3A/cm^2 (life time ~10^5 hours) provides the most compact packing arrangement of the individual beamlets (no beam compression) together with high beam quality in the drift channels.





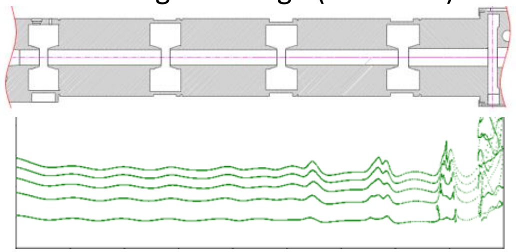
Additional advantages:

1. The second HV stage can be operated in DC mode. Thus simplifying the modulator topology (cost) and increasing the modulator efficiency (transients).
2. Simplified feedback for the first stage pulsed voltage. Improved klystron RF phase and amplitude stability.
3. Gap's accelerating DC voltage is a natural barrier for reflected electrons. Improved tube stability.

High Efficiency klystrons industrialization efforts.

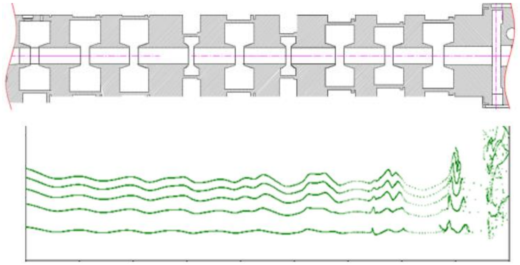
The first 'off shelf' commercial 7.5 MW S-band (2.856 GHz) HE klystron by Canon

Original design (5 cavities):

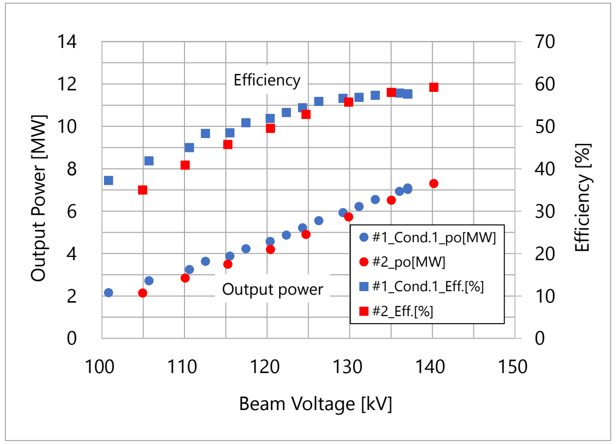


Voltage: 155 kV
Current: 109 A
Peak power: 7.5 MW
Efficiency: 45%

High efficiency COM_2 upgrade (10 cavities):

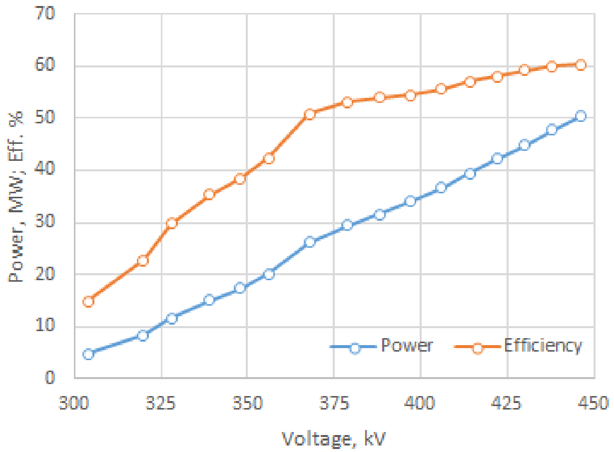


Voltage: 140.2 kV
Current: 88 A
Peak power: 7.3 MW
Efficiency: 59.2%

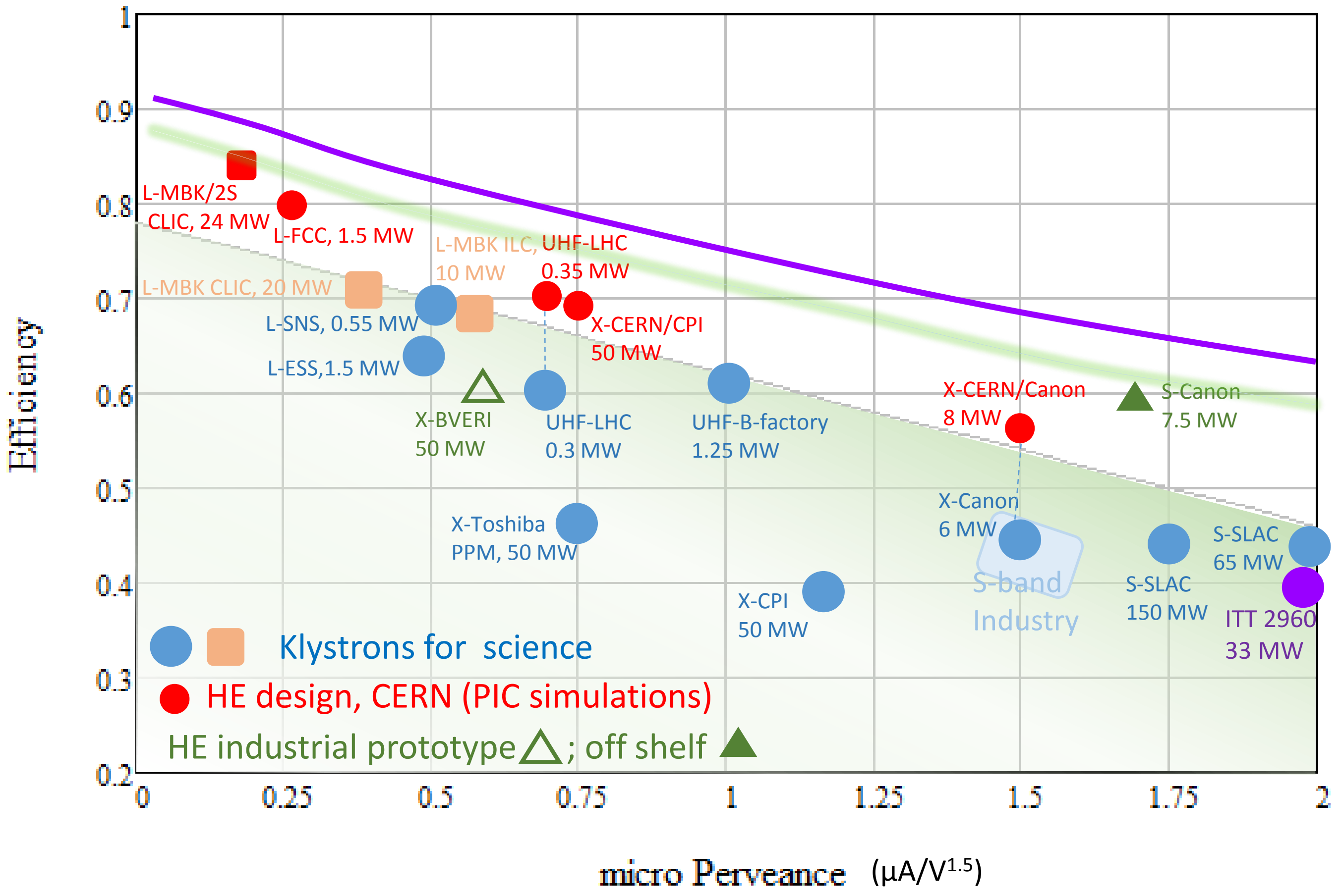


Commercial prototype of the 50 MW HE X-band (11.424 GHz) COM klystron by BVERI (China)

Frequency	11.424GHz
Peak power	50.4MW
Repetition rate	10Hz
Pulse width	1.5μs
Power Gain	50.9dB
Efficiency	60.4%
-3dB bandwidth	36MHz
Beam voltage	446kV
beam current	187A
Focusing	Solenoid



Efficiency performance of the selected commercial klystrons and the new HE klystrons (October 2019).



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