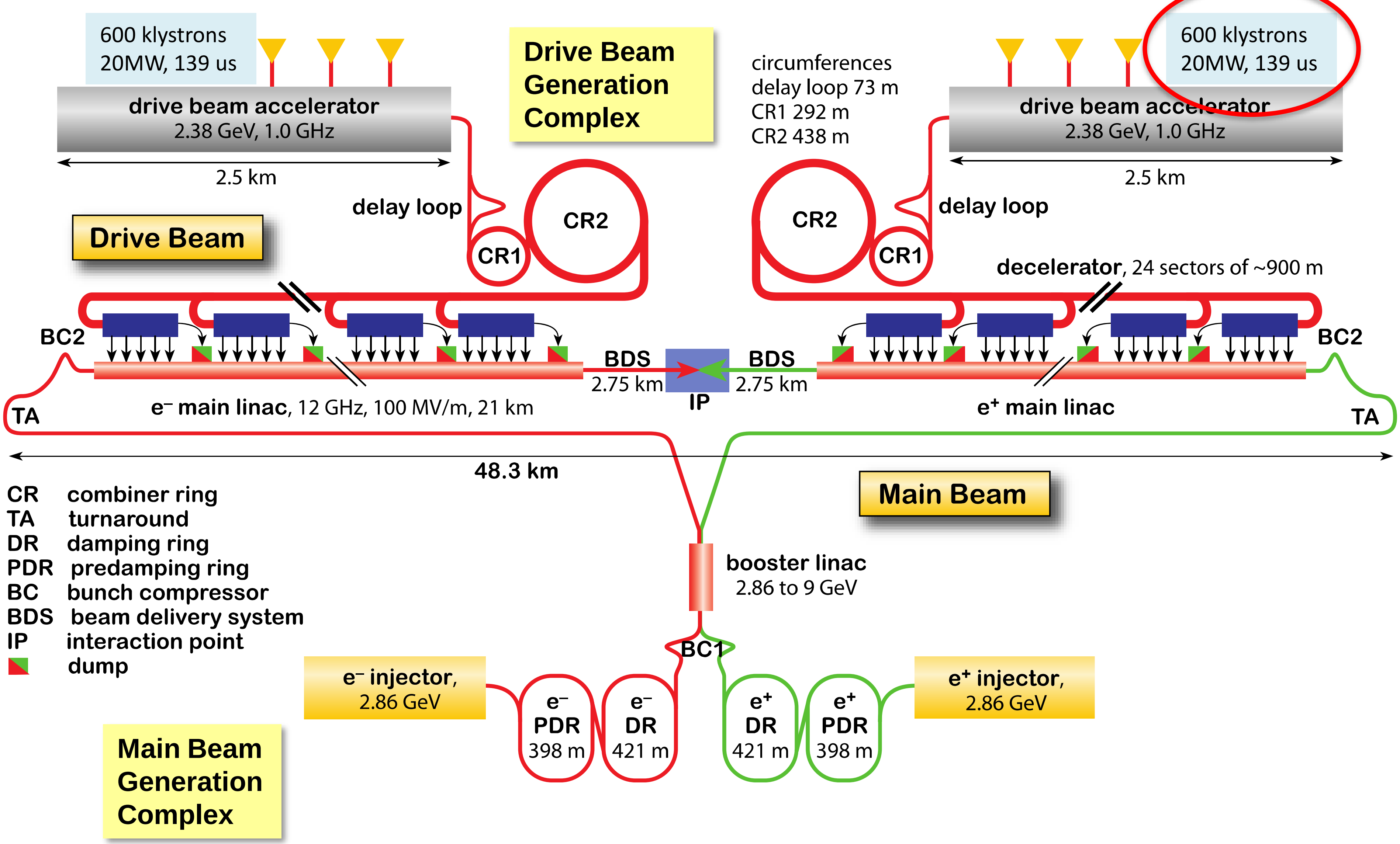
High-efficiency klystrons designs and prototypes

- Introduction to CLIC drive beam rf system
- Thales and Toshiba (Canon) prototype
- Modulator R&D
- Novel high efficiency klystron designs (Igor Syratchev)

Steffen Döbert, BE-RF

CLIC Layout at 3 TeV



CLIC Drive Beam requirements

3 TeV CLIC (CDR):

1230 klystrons, 20 MW, 150 μs, 50 Hz , 70 % efficiency

24.57 GW peak power, 184 MW average

0.05 ° phase jitter, 0.2% amplitude

380 GeV < 500 klystrons and factor 3 less in average power

Main energy 'consumer' in CLIC (~50 % for 3 TeV)

Peak power was optimized in cost study in the past, since limited by average power one could go higher for 380 GeV

CLIC Drive Beam requirements

CLIC efficiency challenge; Example 3 TeV (CDR):

Total wall plug power for rf system: 257 MW

Efficiencies:
$\eta_{mod} = 0.89$
$\eta_{kly} = 0.7$
$\eta_{RF\text{-}DB} = 0.89$
$\eta_{Pets} = 0.98$
$\eta_{Decel} = 0.81$
$\eta_{RF\text{-}MB} = 0.25$

Final Main beam power: 28 MW
$\eta_{tot} = 0.11$

Each percent counts !

	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%

Development strategy for the CLIC L-band klystron

- <u>Strategy</u>: Try to develop prototypes with two different vendors to minimize technical and financial risk
- Launched two contracts for the klystron development in 2014
  One with Thales and one with Toshiba
  Design approved in 2015 for both klystrons
- In parallel modulator development program in the power group
  First modulator being build by ETHZ and second designed by Laval University (Canada)

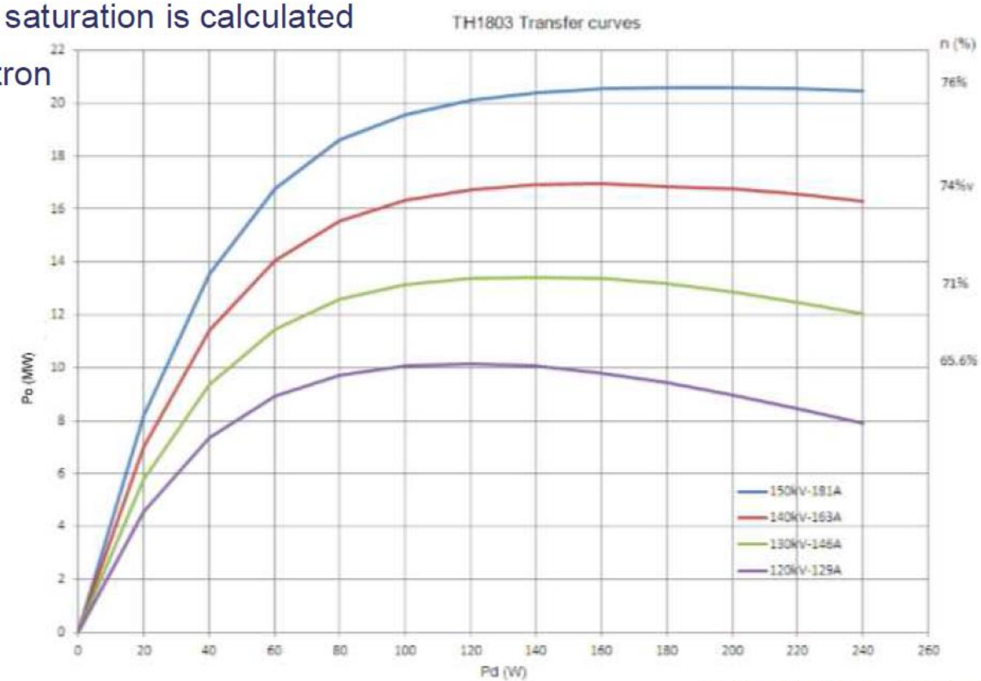
Thales TH1803

10 beam multi beam klystrons, 153 kV, 76 % efficiency calculated
Design approved, delivered November 2017

TH1803 DESIGN REVIEW

Transfer curve

- Output power > 20 MW is obtained at saturation for beam power 150kV x 181 A
- Saturated drive power = 180 W
- 76% efficiency at saturation is calculated
- No reflected electron



THALES

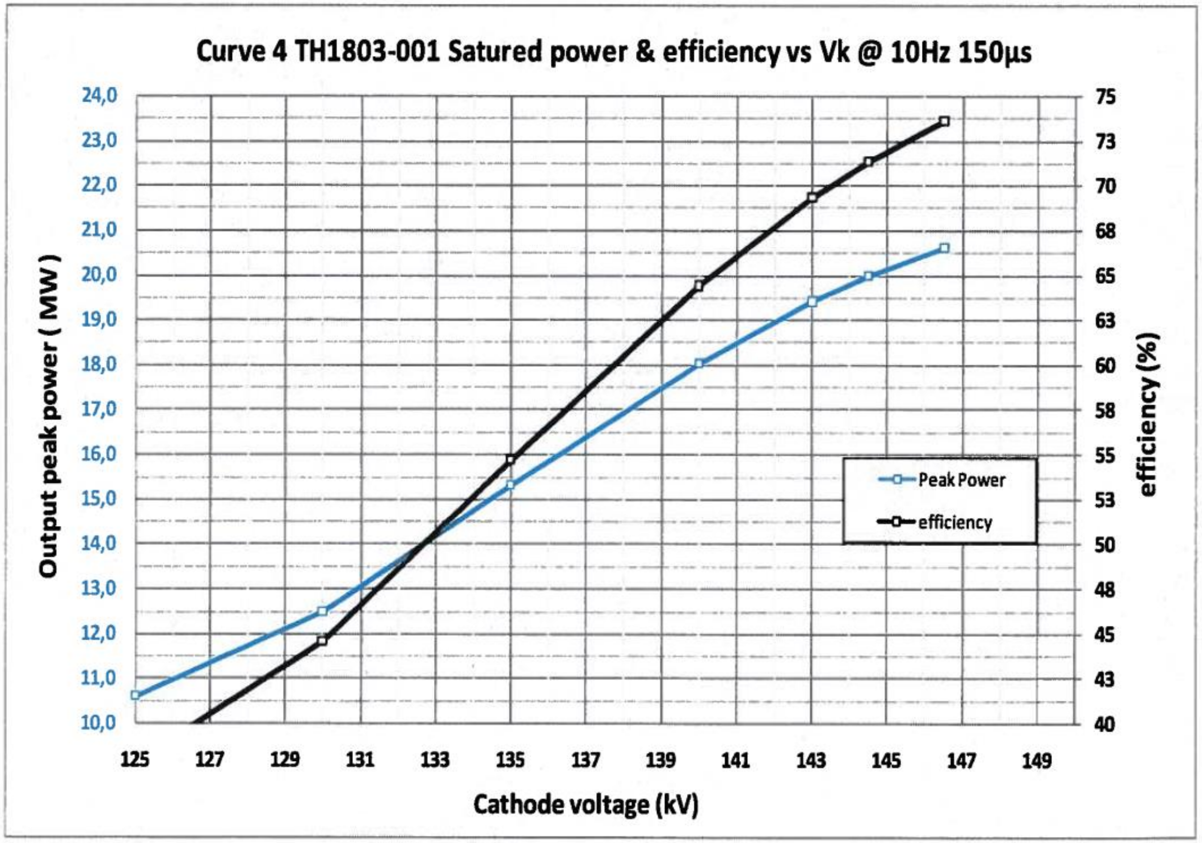
Designer: Rodolphe Marchesin

Thales Electron Devices TH1803

Test results:

f= 999,5 MHz
P_{max}= 21 MW
P_L = 150 µs
V= 146.5 kV
I= 191 A
η= 73.5 %
G= 3.41 $\mu A/V^{3/2}$
Gain = 51.5 dB

Efficiency > 73% measured during test



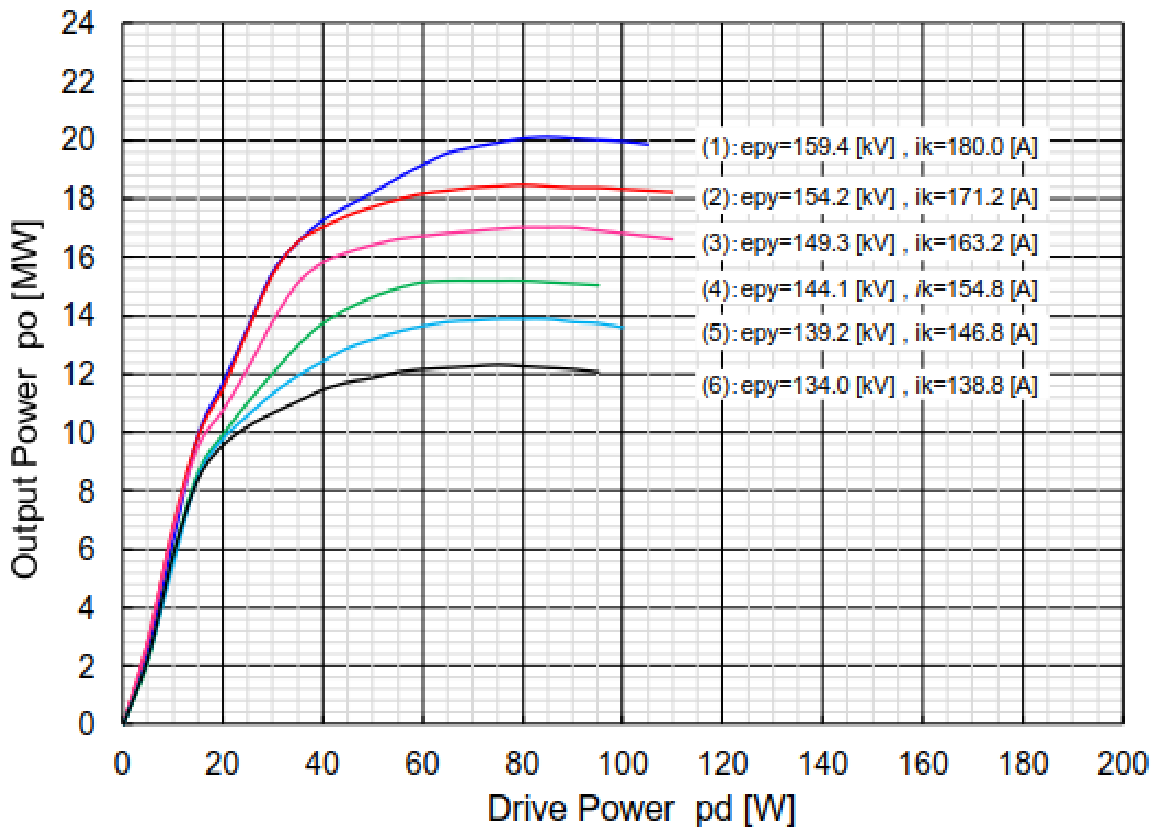
Problems:
Only useable up to 10Hz for time being
Beam loss to high close to output cavity
Large power output asymmetry, 30 %
Instable regions for operation

Toshiba E37503 factory test
6 beam MBK

<u>Status:</u>
Factory acceptance test successful!
All specs fulfilled !
Klystron was delivered to CERN in fall 2016 and is installed in our test stand
Almost ready for testing

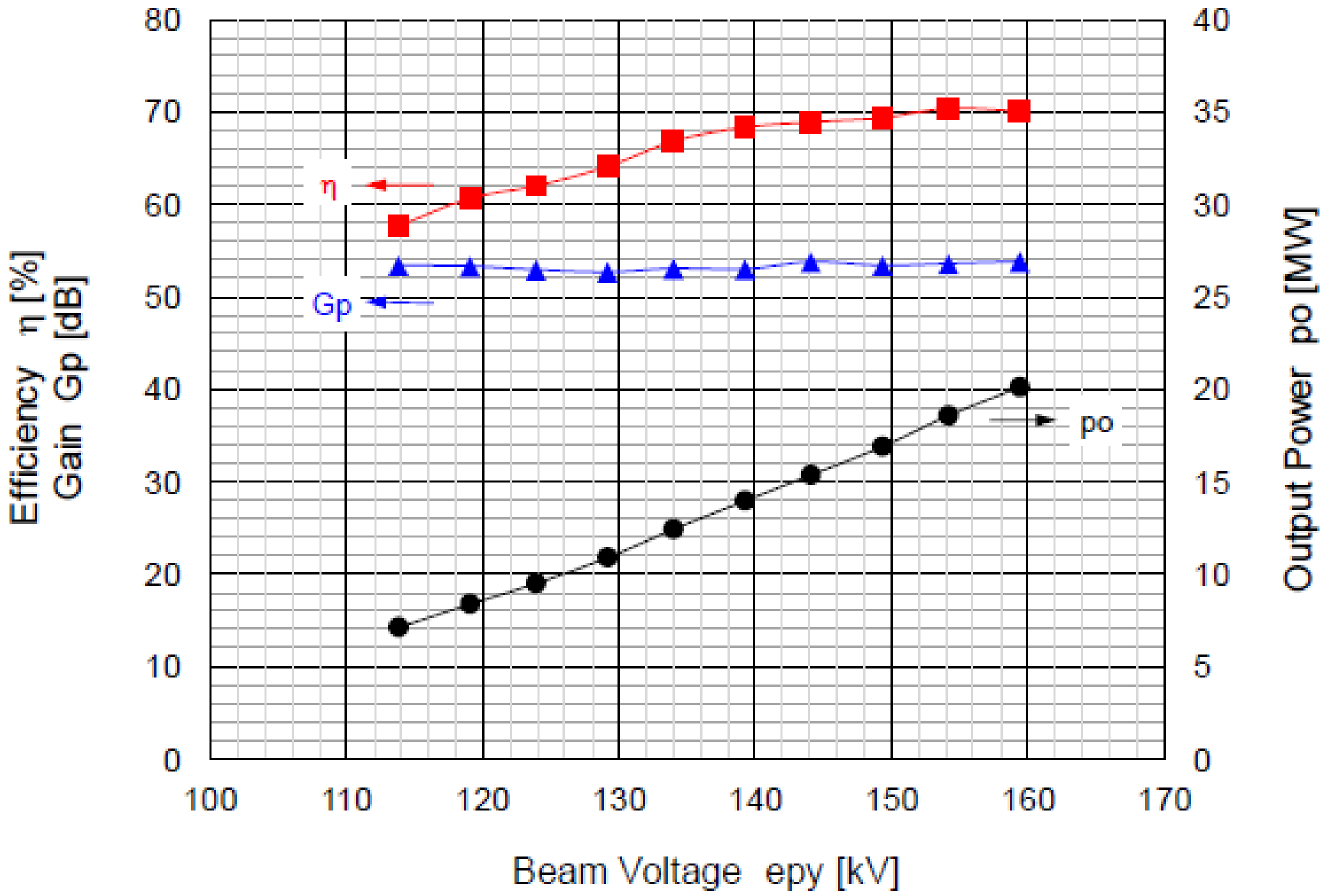
Toshiba E37503 factory test

Power curves, Drive vs. Output, very nice and stable behaviour
Simulated efficiency ~ 75 %



RF pulse width 150 μs, repetition rate 25 pps
(I_{sol1} = 41.0 A, I_{sol2} = 41.0 A, I_{sol3} = 41.0 A)

Toshiba E37503 factory test



Test results:

f= 999,5 MHz
P_{max}= 21 MW
P_L = 150 μs
V= 159.4 kV
I= 180 A
η= 71.5 %
G= 2.83 $\mu A/V^{3/2}$
Gain = 53.9 dB

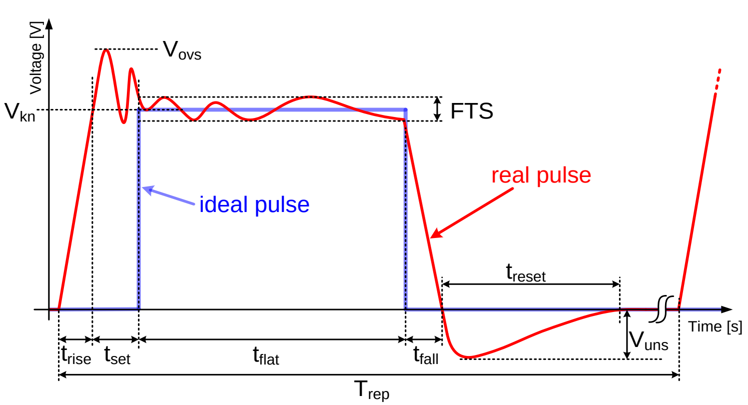
Tests done at 25 Hz and double HV pulse length, nominal 50 Hz
Stable operation over a wide range of parameters

CLIC modulators R&D

1300 modulators synchronously operated

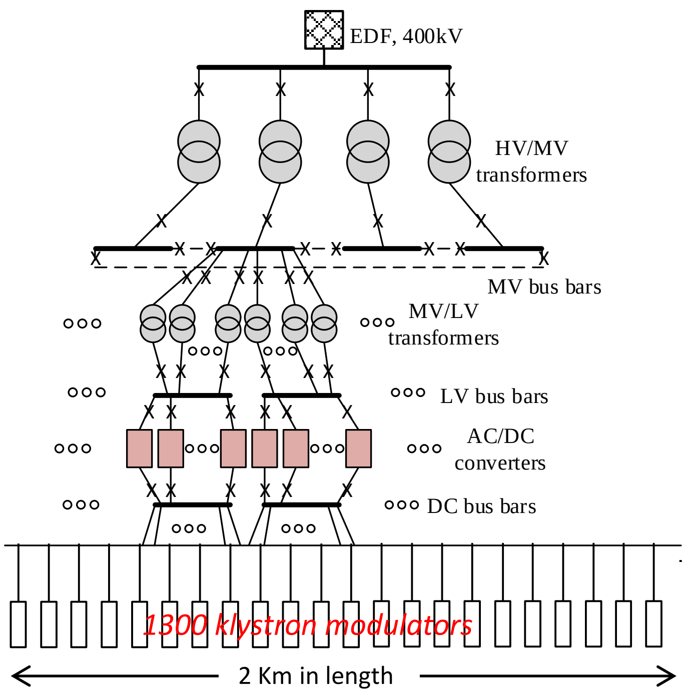
29 MW x 1300 klystrons =
38GW of pulsed power!

CLIC Klystron modulators main specs			
Pulsed voltage	V_{kn}	180	kV
Peak nominal power	P_{out}	29	MW
Rise/fall times	t_{rise}	3	µs
Flat-top length	t_{flat}	140	µs
Rep. rate	Rep_r	50	Hz
Pulse repeatability	PPR	10-50	ppm

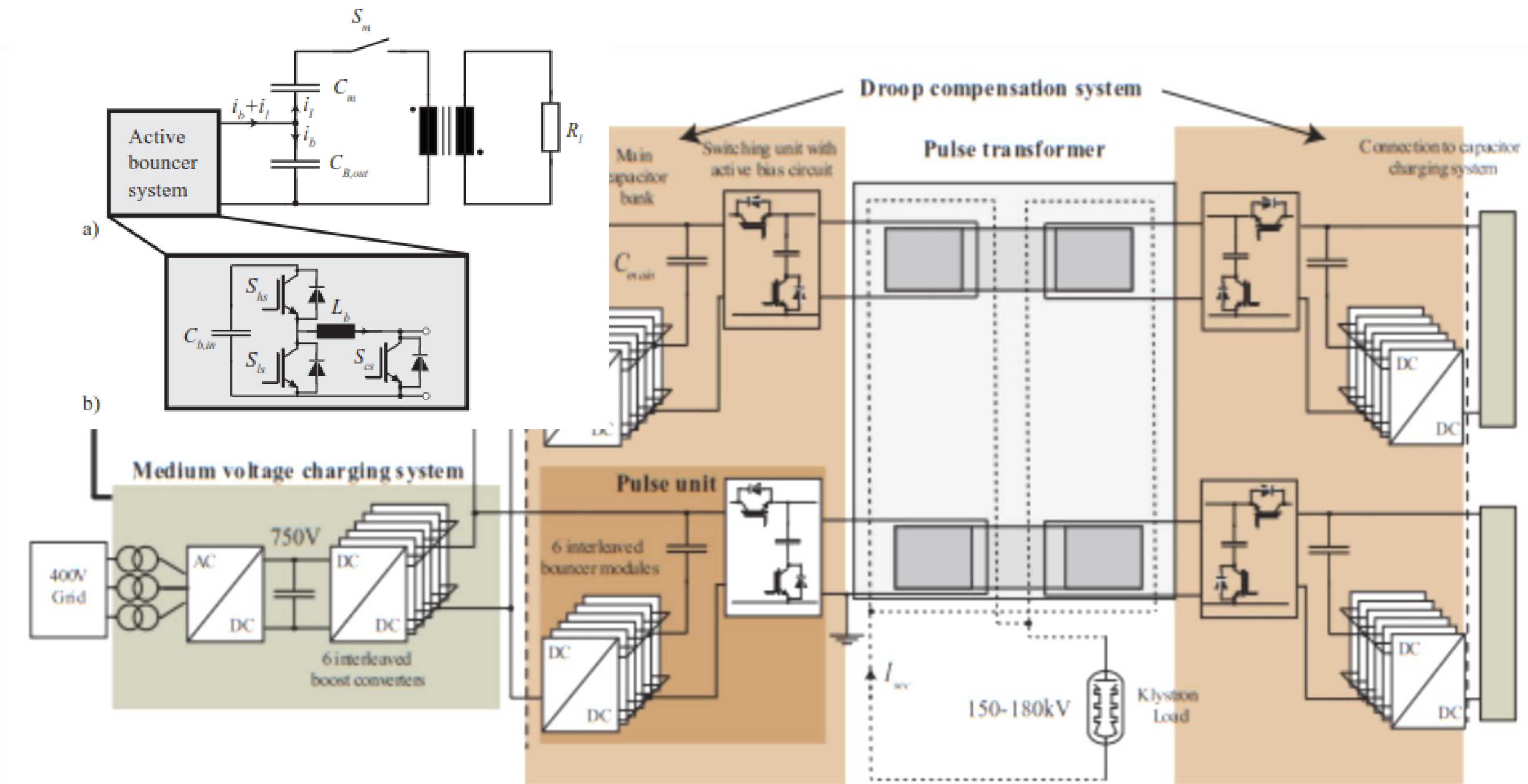


Hot R&D topics:

- Distribution grid layout optimization
- Active compensation of power fluctuation (new converters topologies)
- High efficiency, high bandwidth, high repeatable power electronics
- HV fast pulse transformers design
- Highly repeatable HV measurements
- Redundancy, modularity, availability

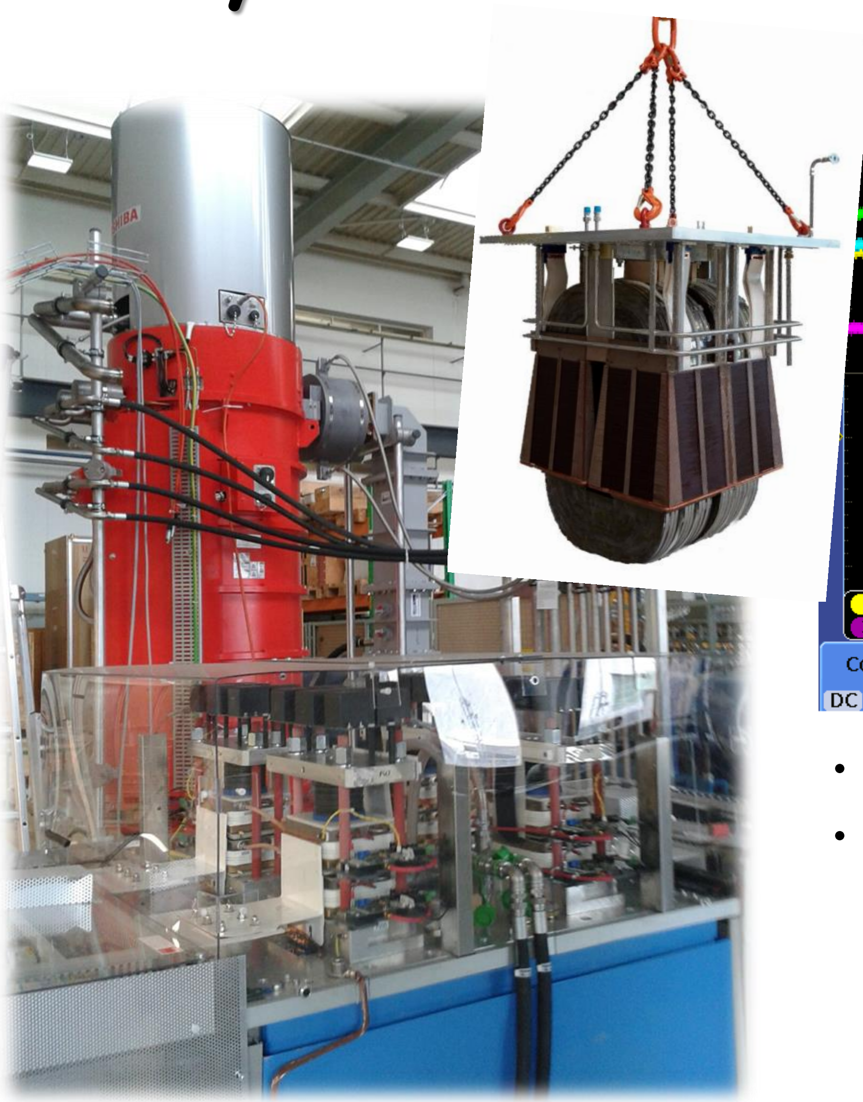


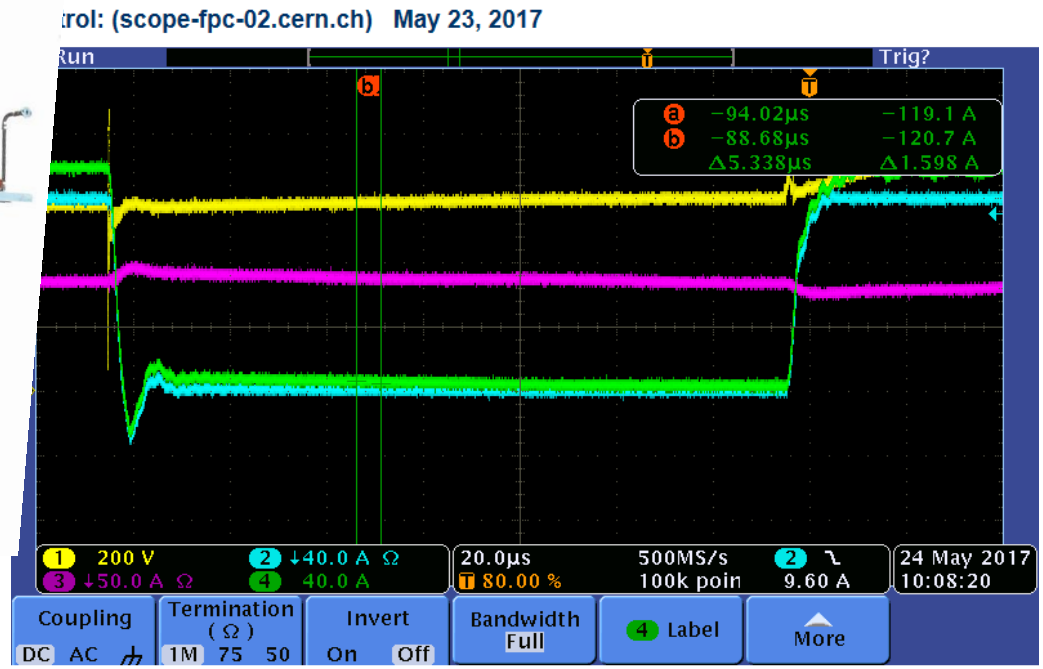
Klystron modulator R&D achievements



Modulator schematic layout (thesis. S. Blume)

Klystron modulator R&D achievements

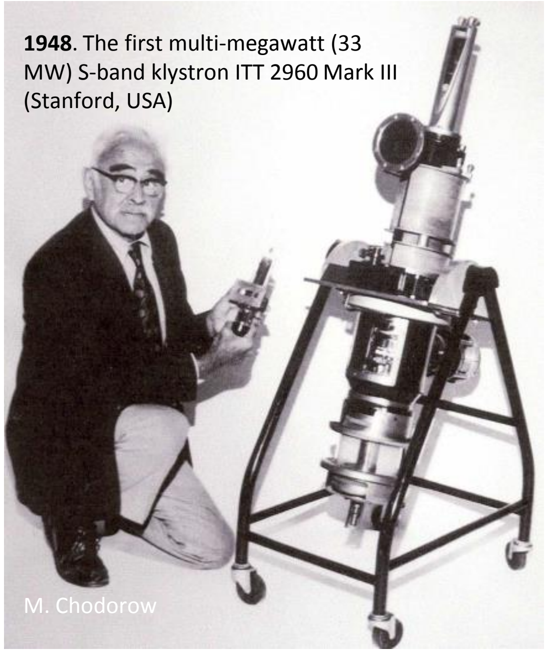


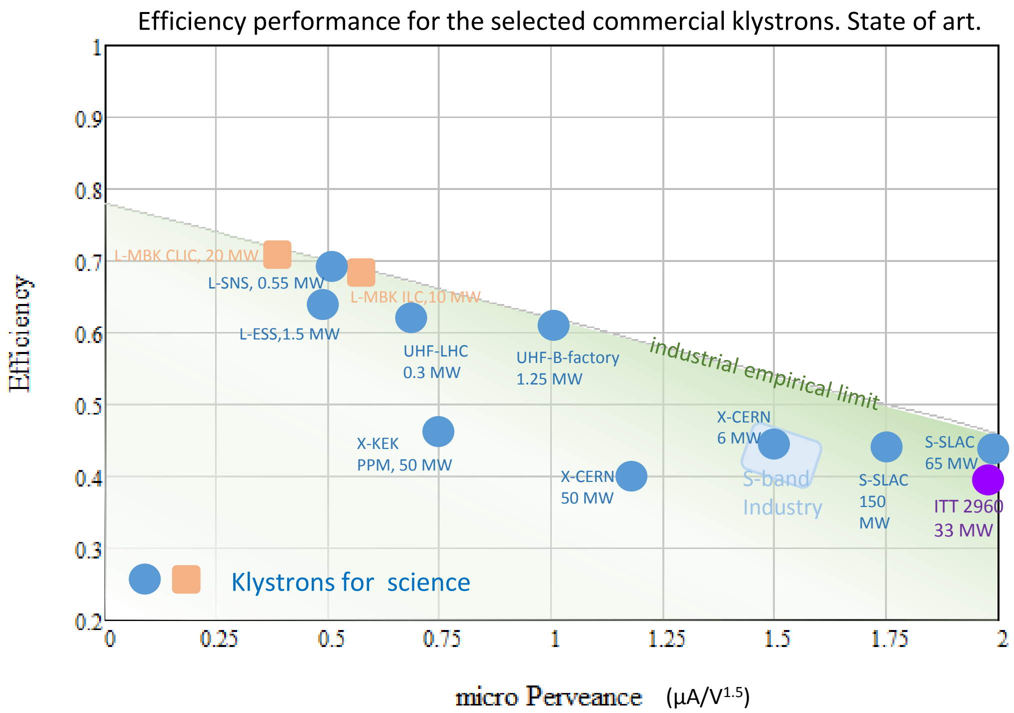


- Validation on resistive dummy load at CERN
- Experimental validation
  - Operation at 50 Hz
  - Full power operation
  - 186 kV peak voltage, 30 MW, 3 us rise/fall time
  - Pulse stability better than 0.1 %
- Remaining validation
  - Pulse-to-pulse repeatability with klystron

High efficiency klystrons, state of the art

- 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.





High efficiency klystron effort at CERN

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 (2nd and 3rd) 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.

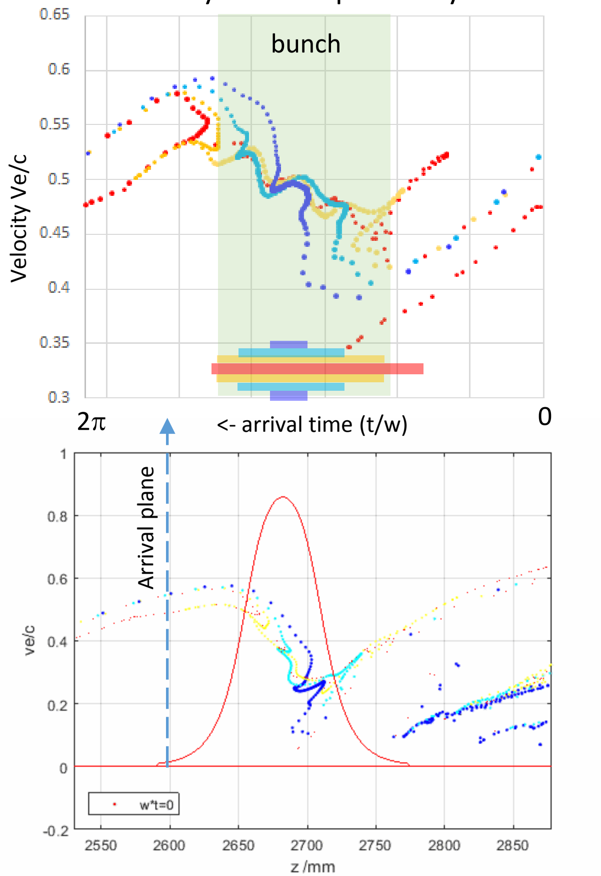
Using the new tools and methods, a number of the high efficiency klystrons for the large scale accelerators (**LHC, FCC and CLIC**) has been developed at CERN and few completed designs have already been communicated to the industry for the technical evaluation and prototyping.

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



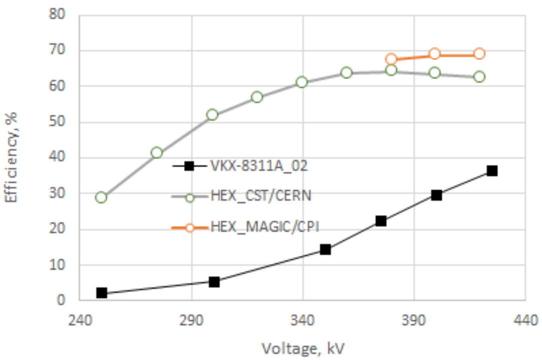
- E field expansion in the drift tubes causes beam reacceleration when it leaves the output cavity.
- Ohmic loses are proportional to the operating frequency.
- Space charge depression is a partial conversion of the beam kinetic energy into the potential DC energy of beam traveling in the drift tube.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

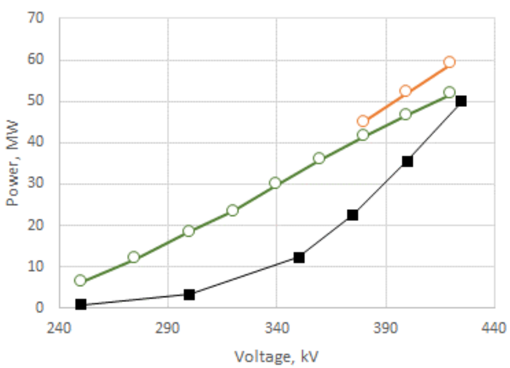
Driven by klystron general parameters.

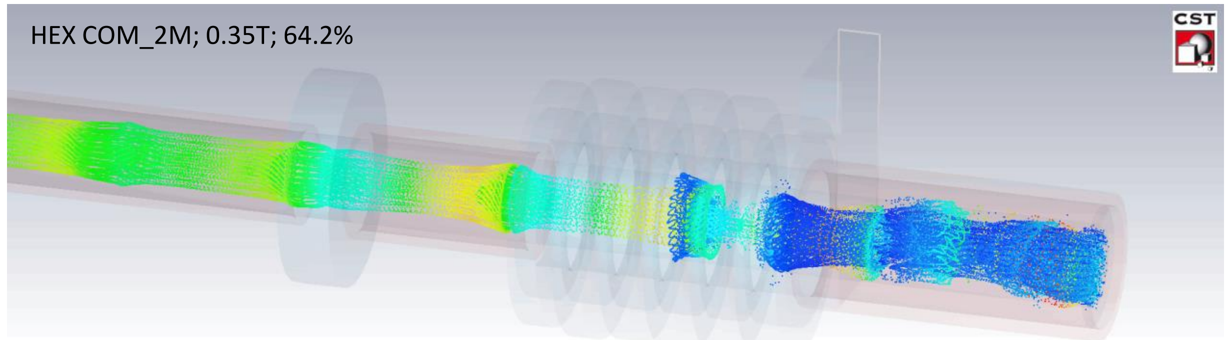
Driven by RF design and space charge effects.

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

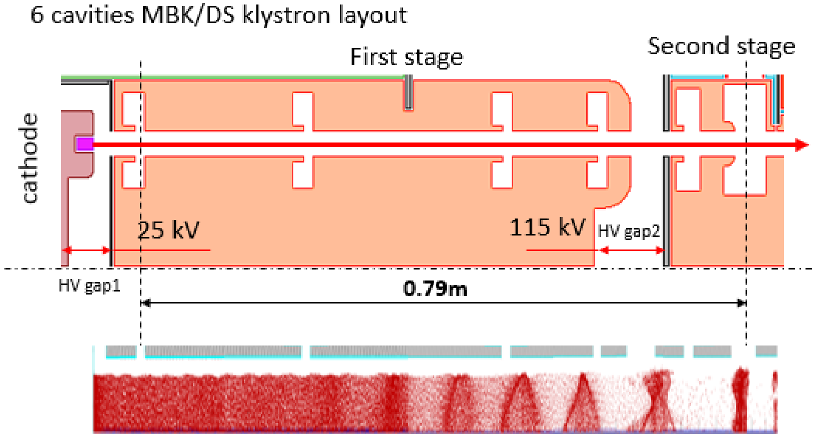
Tailored Technologies. High Efficiency (85%) 24 MW, 1 GHz, CLIC MBK/2S klystron

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**.
Electron efficiency measured in PIC simulations is **84%**.



Conceptual features:

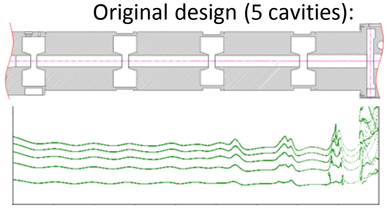
1. Bunching at a low voltage (high perveance). Very **compact RF bunching circuit.**
2. Bunched beam acceleration and cooling (reducing $\Delta p/p$) along the short DC voltage gap.
3. Final power extraction from high voltage (low perveance) beam. **High efficiency.**

V. Teryaev

High Efficiency klystrons industrialization efforts stimulated by this work

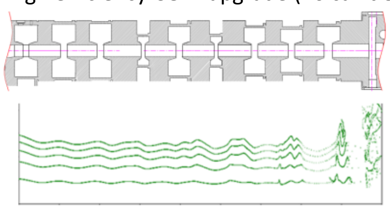
The first ‘off shelf’ commercial 7.5 MW S-band (2.856 GHz) HE klystron by Canon

Original design (5 cavities):

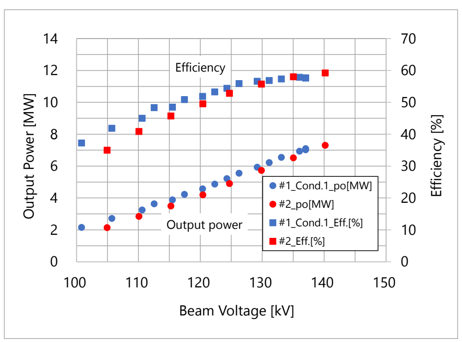


Voltage: 155 kV
Current: 109 A
Peak power: 7.5 MW
Efficiency: 45%

High efficiency COM upgrade (10 cavities):

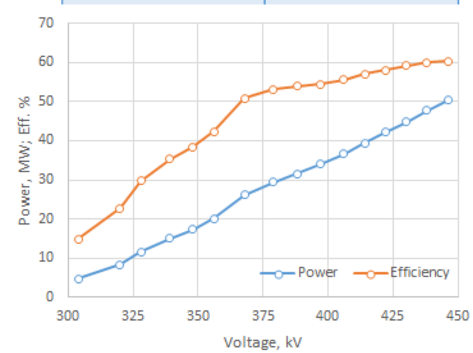


Voltage: 140.2 kV
Current: 88 A
Peak power: 7.3 MW
Efficiency: 59.2%

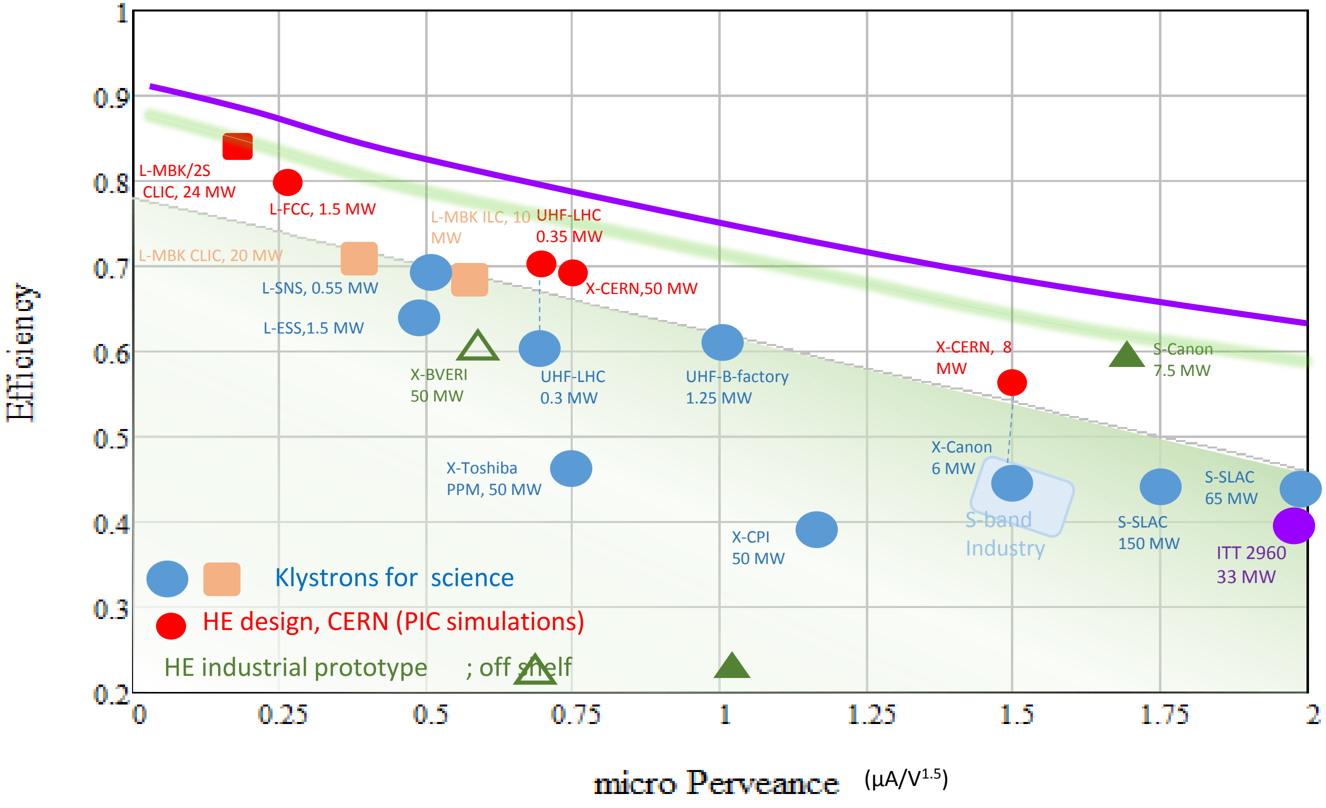


Commercial prototype of the 50 MW HE X-band (11.424 GHz) COM klystron by BVERI (China)

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).



Conclusion and outlook

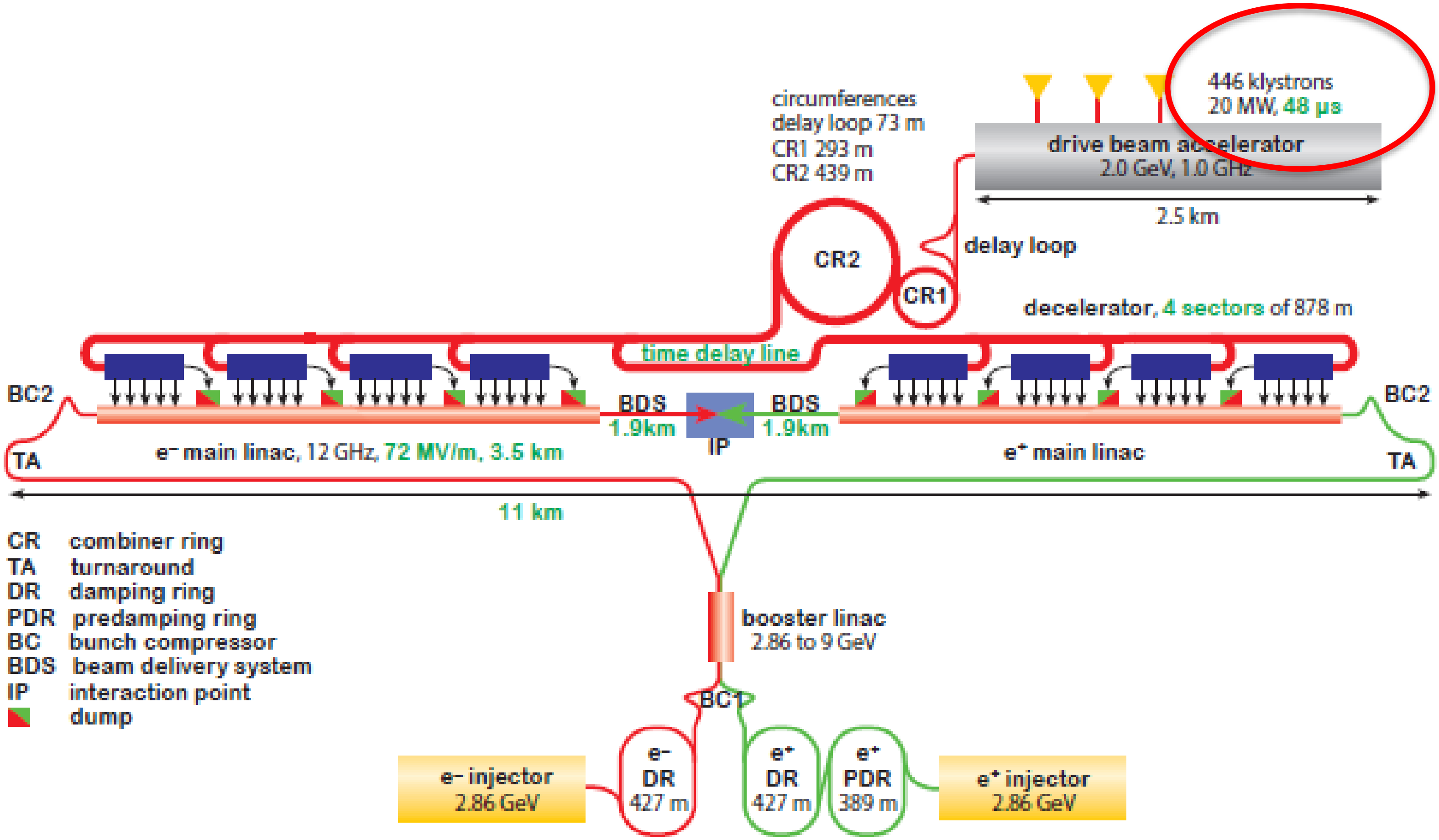
- Thales and Toshiba delivered 1 GHz multi-beam klystron, accepted by CERN after factory tests. Main parameters not far from simulations. Prototypes still very important because there are always surprises
  Important milestone for the CLIC project !
- Novel modulator developed at ETHZ fulfilling CLIC specifications
- Novel klystron concepts developed which promise > 80% efficiencies
- Very good collaboration with industry

End

Special thanks to many colleagues from Labs, Universities and industry who have been actively involved into the high efficiency klystrons development:

T. Anno, A. Baikov, A. Beunas, O. Brunner, G. Burt, J. Cai, D. Constable, I. Guzilov, P. Hamel, V. Hill, A. Jensen, E. Jensen, T. Kimura, A. Leggieri, R. Kowalczyk, C. Lingwood, Z. Liu, R. Marchesin, C. Marrelli, J. Neilson, F. Peauger, J. Plouin, V. Teryaev, B. Weatherford…

New CLIC layout 380 GeV



Klystron parameters

PARAMETER	VALUE	UNITS
RF Frequency	999.516	MHz
Bandwidth at -1dB	≥ 1	MHz
RF Power:		
Peak Power	≥ 20	MW
Average Power	150	kW
RF Pulse width (at -3dB)	150	µs
HV pulse width (at full width half height)	165	µs
Repetition Rate	50	Hz
High Voltage applied to the cathode	tbd, ≤ 180	kV
Tolerable peak reverse voltage	tbd	kV
Efficiency at peak power	67 ≤ 70	%
RF gain at peak power	tbd, > 48	dB
Perveance	tbd	$\mu A/V^{1.5}$
Stability of RF output signal at nominal working point:		
RF phase ripple [*]	±1 (max)	RF deg
RF amplitude ripple	±1 (max)	%
Pulse failures (arcs etc.) during 14 hour test period	≤ 1-2	
Matching load, fundamental and 2nd harmonic	tbd	VSWR
Average radiation at 0.1m distance from klystron	≤ 1	µSv/h
Output waveguide type,	WR975	2-3 bar

High efficiency RF power sources.

I. Syratchev, CERN.

- 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.

Electro vacuum devices for science

USA

France

Japan

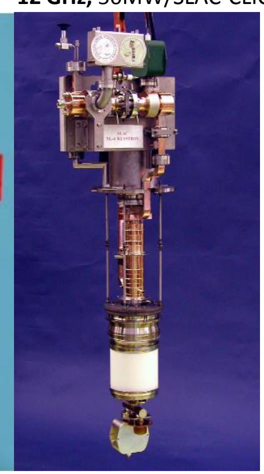
0.7 GHz, 1.5MW/ESS

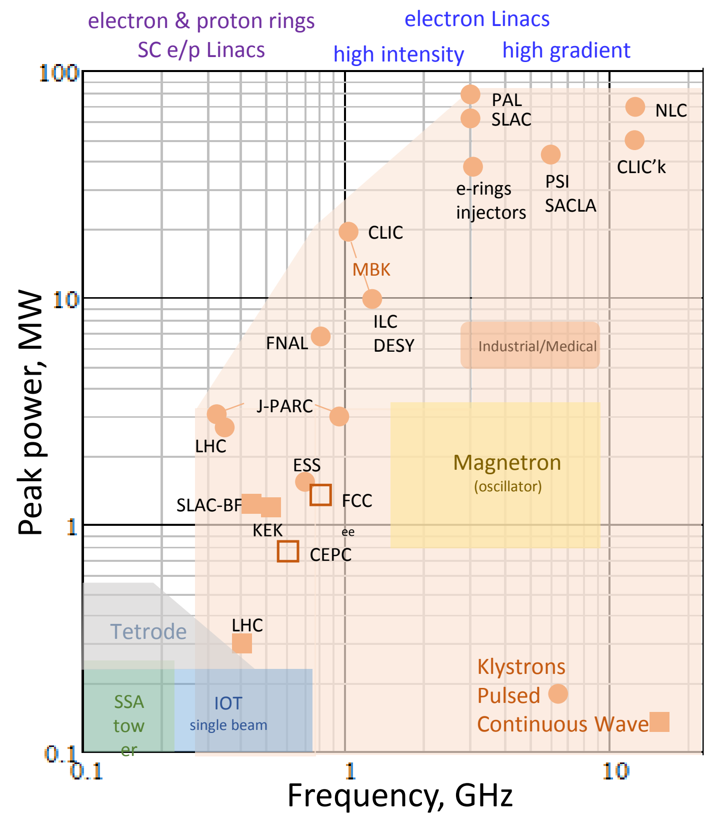
1.3 GHz, 10MW/DESY

3 GHz, 60MW/SLAC

6 GHz, 50MW/PSI

12 GHz, 50MW/SLAC-CLIC

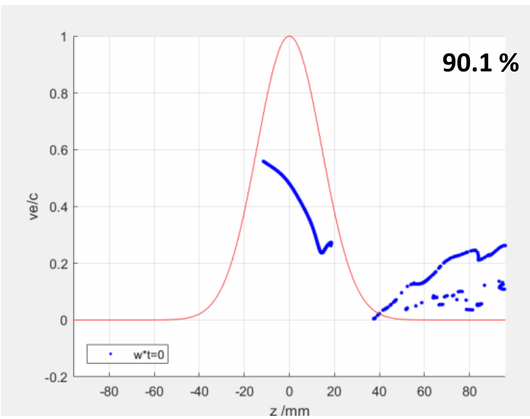




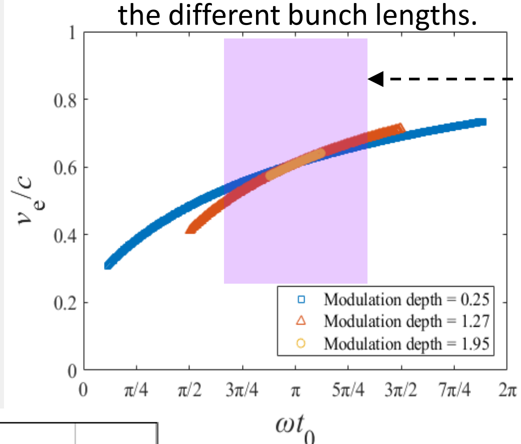
The ultimate power extraction efficiency in the linear beam devices

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

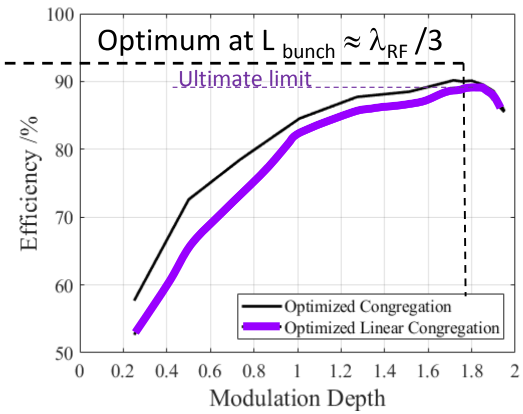
Fully saturated bunch with optimised congregation

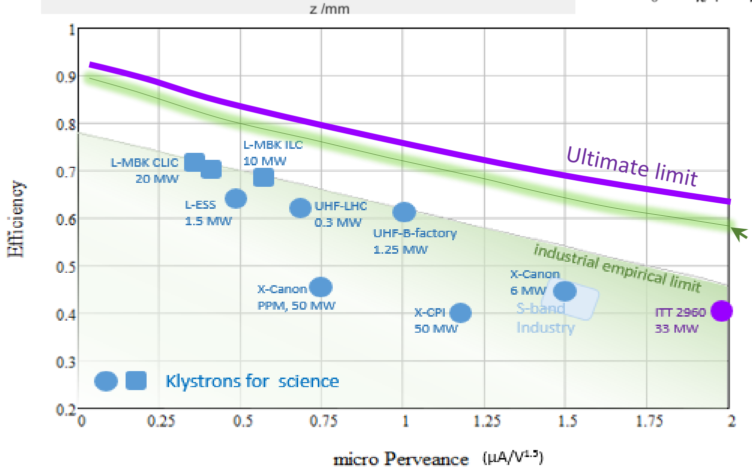


Optimised congregation for the different bunch lengths.



Effect of the bunch length





High efficiency Klystrons design objectives

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

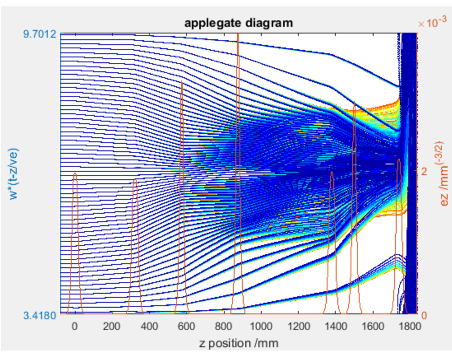
Optimised RF bunching circuit

- Bunch saturation
- Bunch congregation
- Bunch stratification
- Radial bunch expansion

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

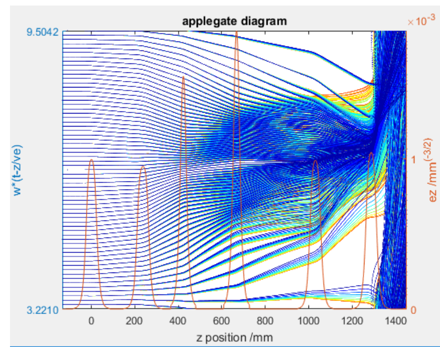
Design of any new klystron is rather time consuming. It requires high level of the related experience/expertise. The **PSP** was developed at CERN as a set of semi-analytical procedures that allow to scale the existing klystron design to the new one (beam power, frequency and perveance) and to preserve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

Design cycle ~ 6 month



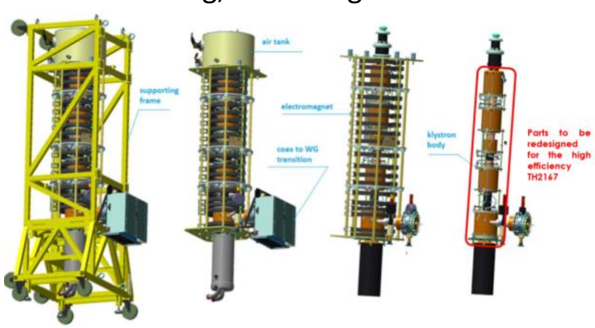
	FCC
Frequency, GHZ	0.8
Beam power, MW	1.68
Perveance,	0.26
RF power, MW	1.34
Efficiency, %	80

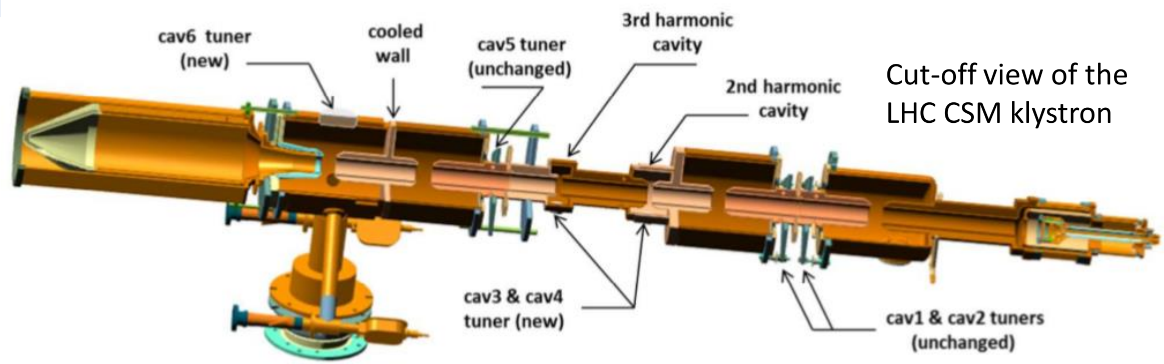
Design cycle ~ 2 weeks



	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





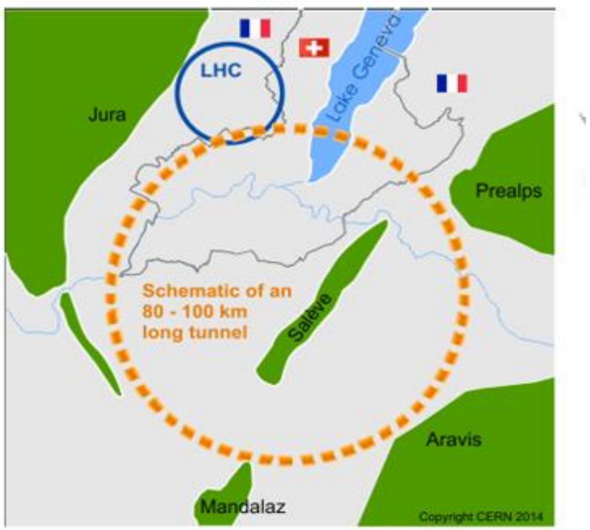
Cut-off view of the LHC CSM klystron

REF: F057-TH2167 HE FCC week june19 rev 001 – 2019-06-15

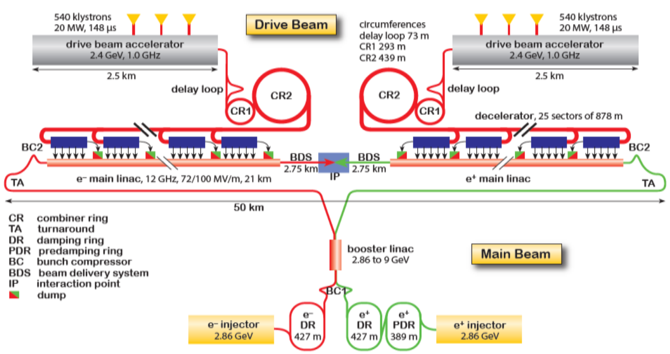
3 Microwave & Imaging Sub-Systems / Template: 83270274-DOC-MIS-EN-002

OPEN

THALES



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

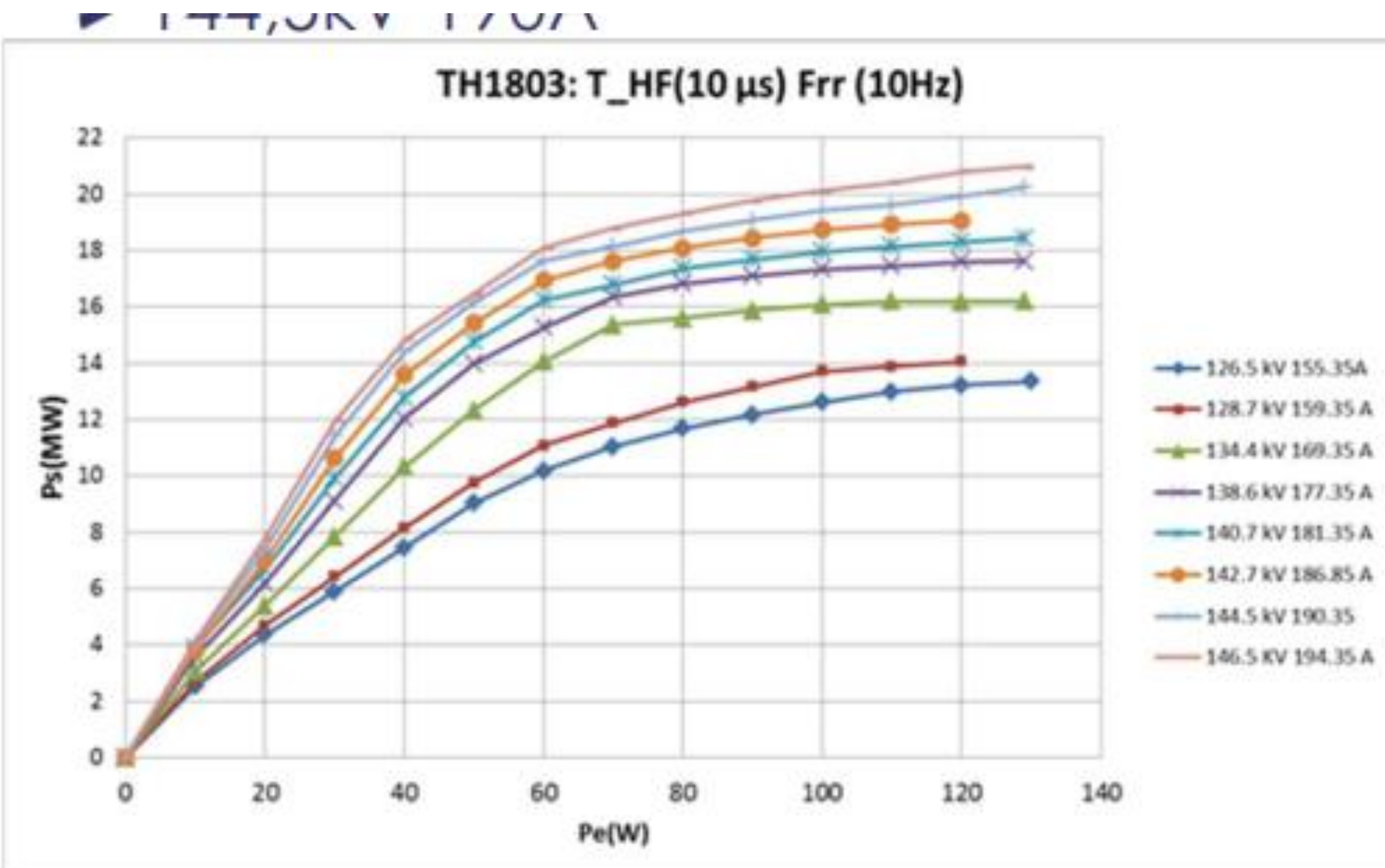
The klystron efficiency impact on the CLIC 3TeV power consumption.
Example of the efficiency upgrade from 70% to 85%.

	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%

- Reduced installation cost (stored energy in modulators).
- Reduced maintenance cost (klystron life time).

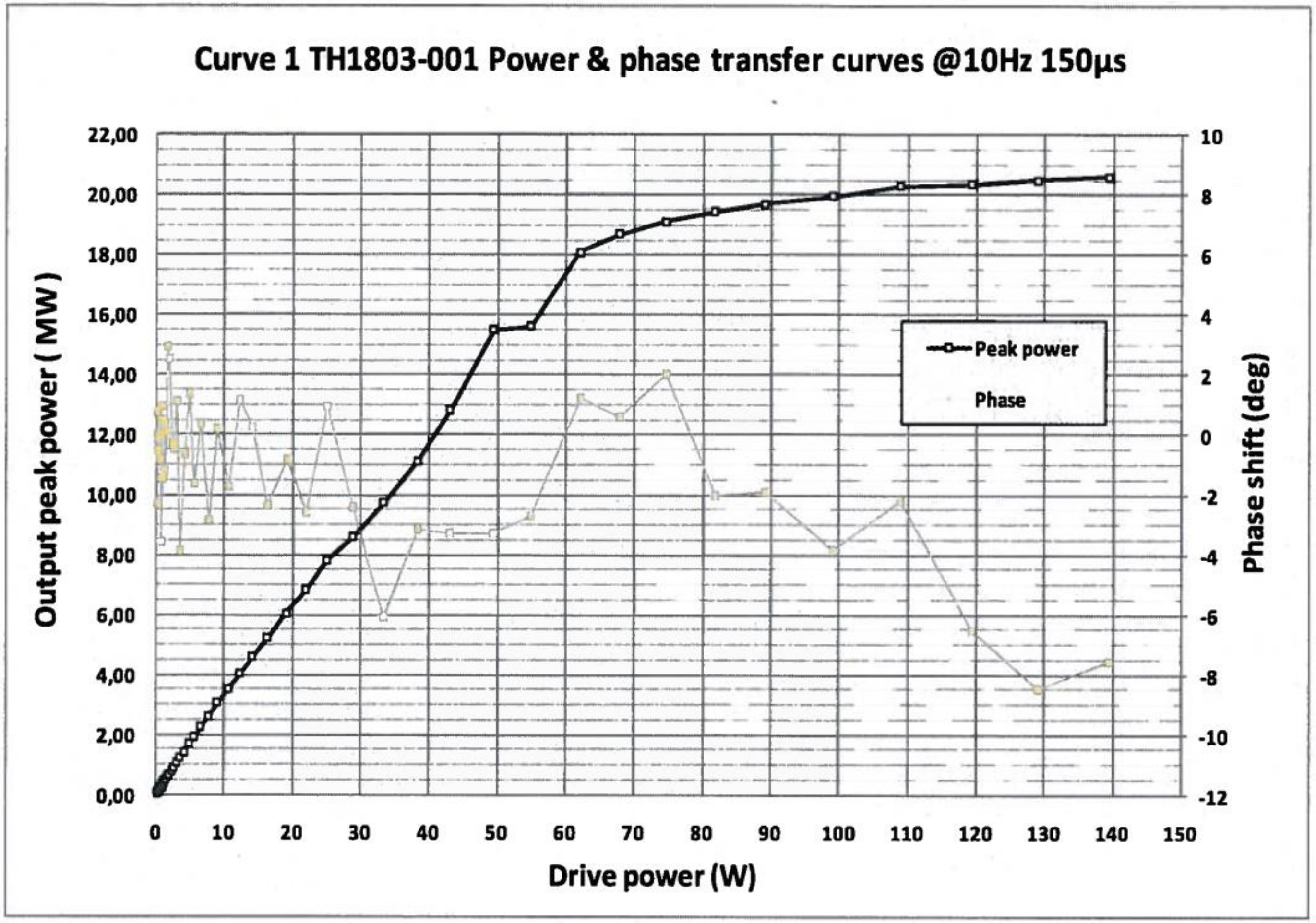
R&D on increasing the useable efficiency is worth every penny/cent invested!

Thales TH1803 Factory Test results



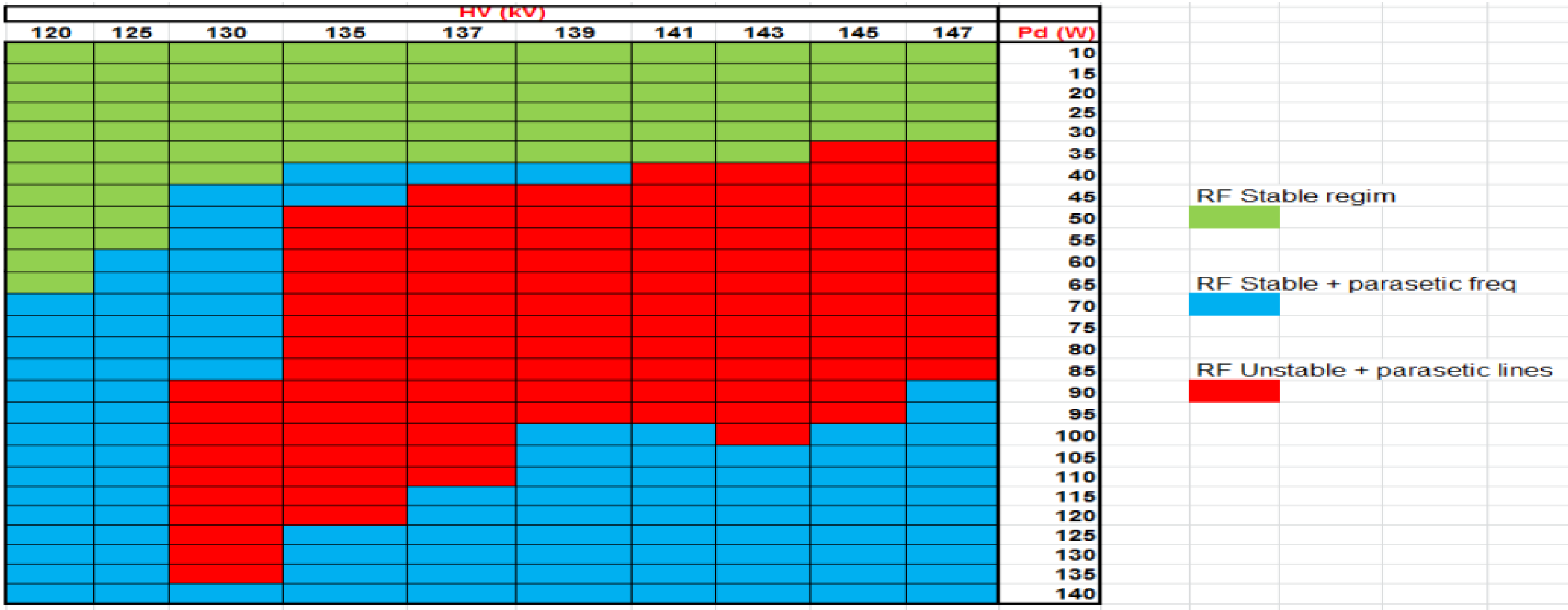
Short pulse operation

Thales TH1803 Factory Test results



Full peak power and pulse length but lower rep. rate

Thales TH1803 Factory Test results



Test results:

f= 999,5 MHz
P_{max}= 21 MW
P_L = 150 μs
V= 146.5 kV
I= 191 A
η= 73.5 %
G= 3.41 $\mu A/V^{3/2}$
Gain = 51.5 dB

Problems:
Only useable up to 10Hz for time being
Beam loss to high close to output cavity
Large power output asymmetry, 30 %
Instable regions for operation

Toshiba Electron Tubes E37503

Design simulations

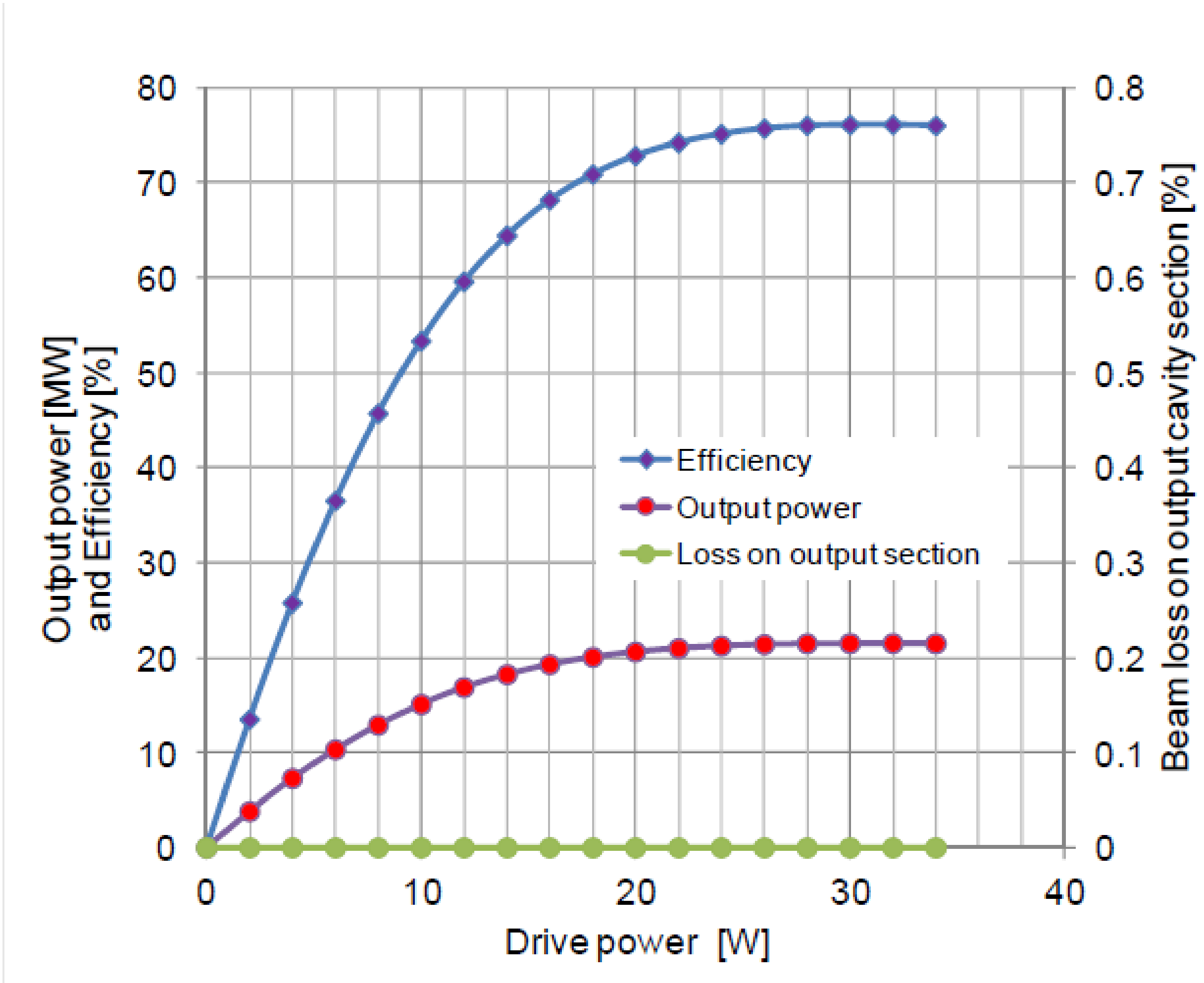
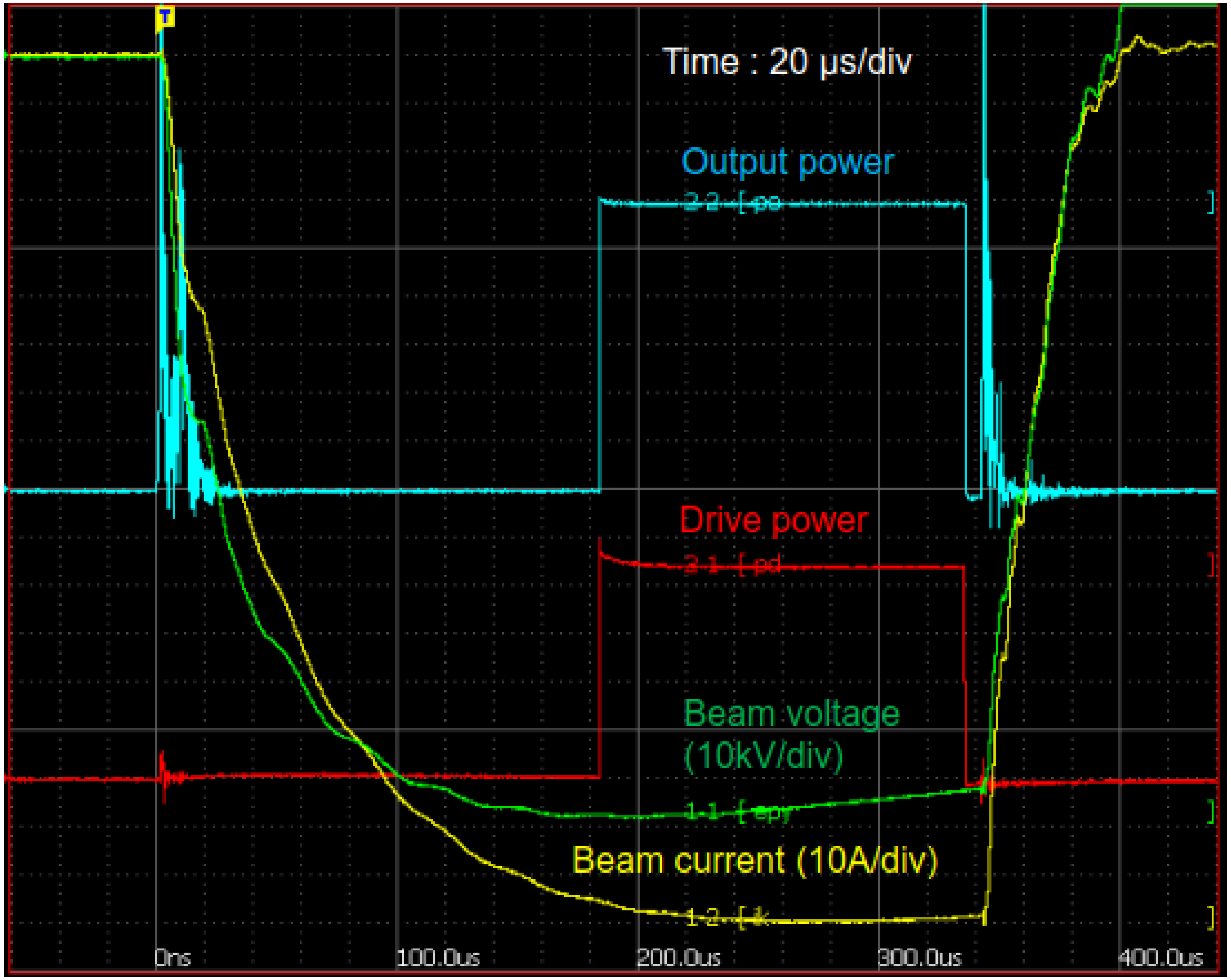


Figure 13: Transfer characteristics (simulation results by EMSYS)

(Beam voltage: 166 kV, Beam current: 170.5 A(total))

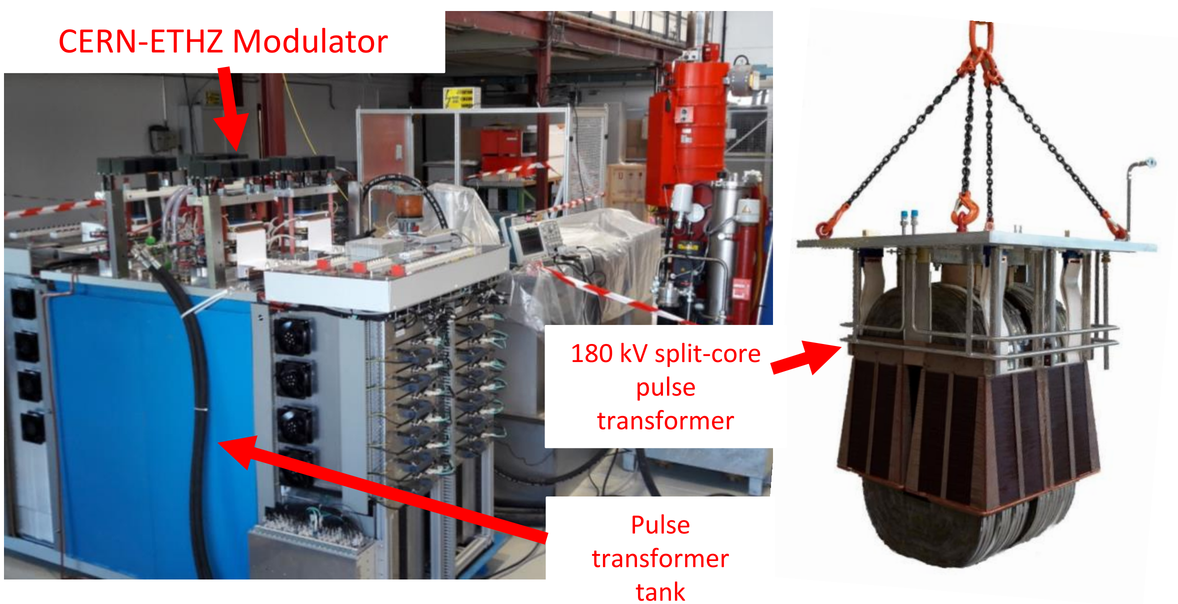
Toshiba E37503 factory test

Testing waveforms



Klystron modulator R&D achievements

- CERN-ETHZ collaboration for design & delivery of a CLIC's Drive Beam klystron modulator
- Modulator installed, tested and ready for commissioning with klystron in building 112
- World *première* for precise 180 kV – 30 MW pulse with 3µs rise/fall times & a "long" flat top (150µs)!
- Collaboration with ETHZ successfully ended



- **4 years of R&D studies achievements:**
  - Feasibility to create voltage pulse verified
  - Solutions found to decouple 39 GW of pulsed power from electrical grid
  - Optimal number of powering sectors found (For civil engineering)
  - Optimal grid layout for power distribution proposed
  - Proposal of a new very high repeatable / precise measuring system for high voltage pulses
  - Discovery of excellent R&D partners in Canada, UK, Italy, & Switzerland!

Klystron Test Stand

Location: CERN Bldg: 112