Improving the RF power production efficiency of the 50 MW X-band RF power station.

I. Syratchev, G. McMonagle and N. Catalan
CERN

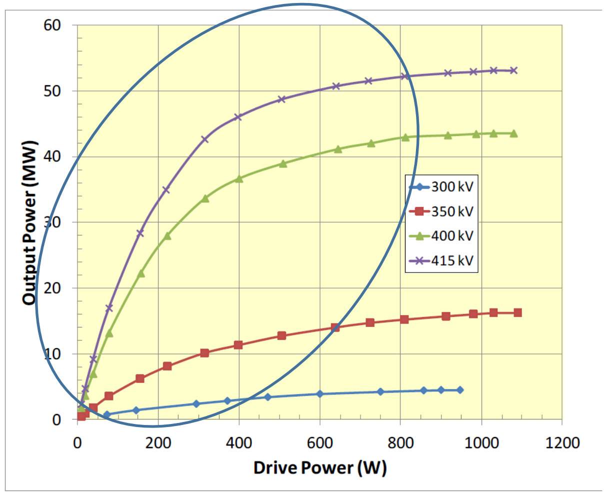
ScandiNova at CERN

420 kV,322 A
50MW
1.5 µS , 50Hz

Xbox 1
2010

CPI VKX-8311A

Xbox 2
2012

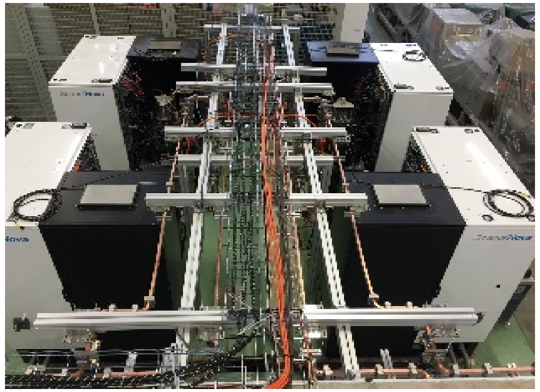


S Band Klystron
Thales TH2100

300 kV, 320 A
45MW
5.5 µS , 100Hz

CTF3
2016

Due to excellent pulse to pulse stability
Do not need to run in saturation at different klystron voltages for RF stability
Can run at max voltage and use linear region
Ideal for RF conditioning of structure



Xbox 3
2014

Canon E37113

4 modulators
158 kV, 59 A
6MW
5 µS , 400Hz

2020

50% of Xbox 3
Melbourne University

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RF power production efficiency in the existing commercial system

50 MW X-band RF power source (CERN, XBOX#2)

Operating systems performance at 50 Hz rep. rate

ScandiNova modulator:

rise/fall time: 1.0 μsec (~400kV/ μsec)

Flat top: 1.5 μsec

Efficiency/t: 1.5/2.5=0.6

Efficiency/e=0.82

Voltage: 420 kV

Current: 322 A

Average Power: **20.6kW**

NC solenoid:

B=0.6T

Average Power: **18 kW**

CPI Klystron:

Flat top: 1.5 μsec

Peak power 50MW

Efficiency: **0.37**

Average Power: **3.75 kW**

The overall RF power production efficiency is **9.7%**

Since 2013, the series of dedicated efforts has been undertaken at CERN in order to increase the efficiency of the RF power production for the various accelerators and different frequency bands.

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High Efficiency 50 MW X band klystron development.

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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.

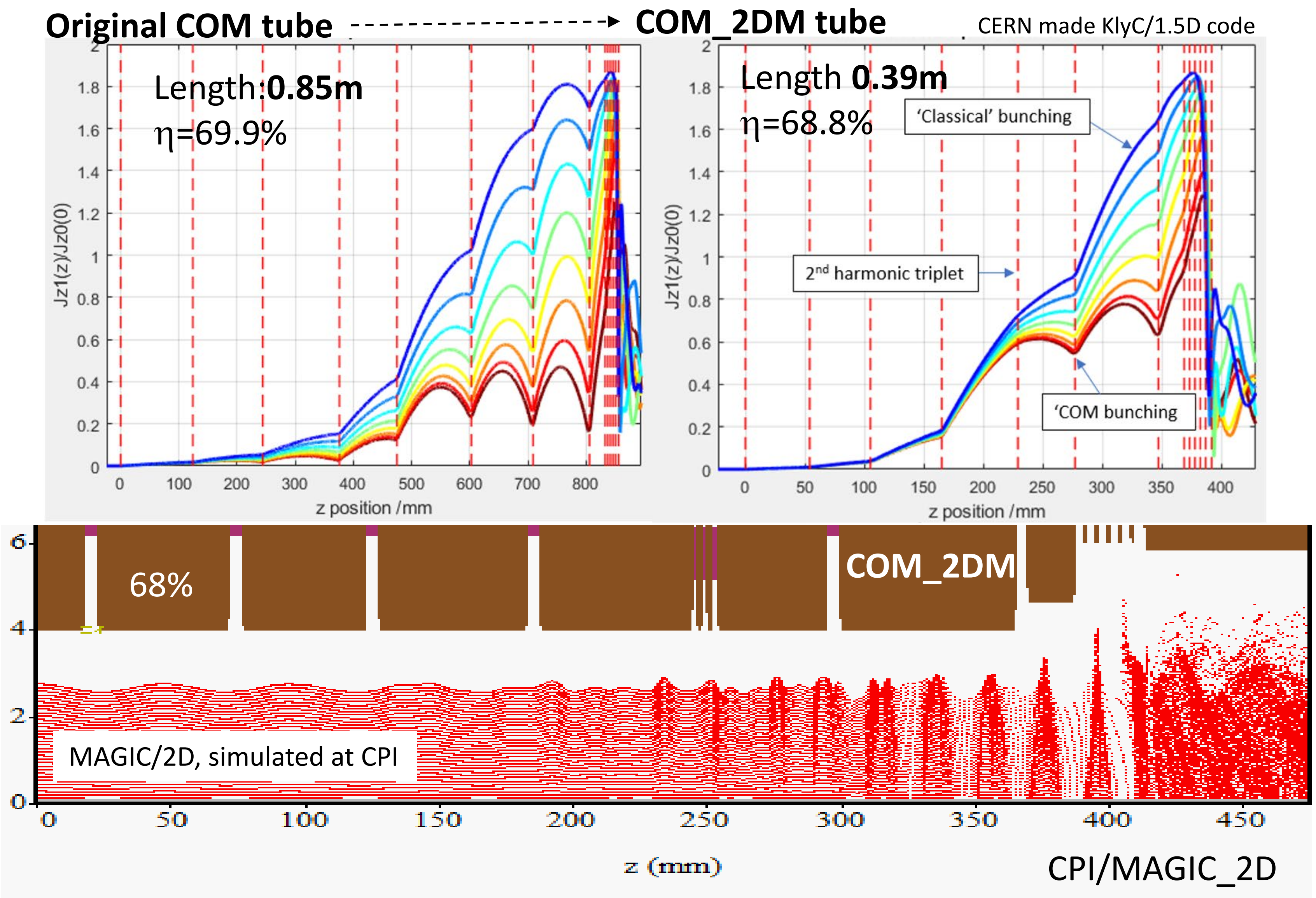
The new bunching technologies have been developed to balance the space charge forces and RF impedances in order to provide the full bunch saturation with an optimal congregation:

- **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.

High Efficiency (70%) 50 MW, 12 GHz, CLIC COM_2DM klystron (CERN/CPI).



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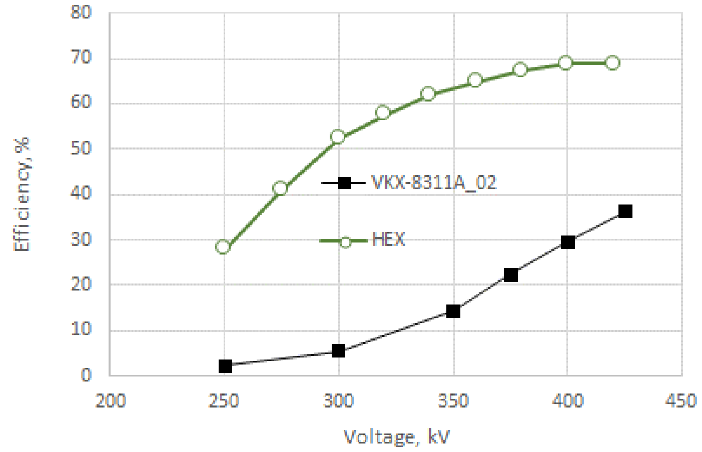
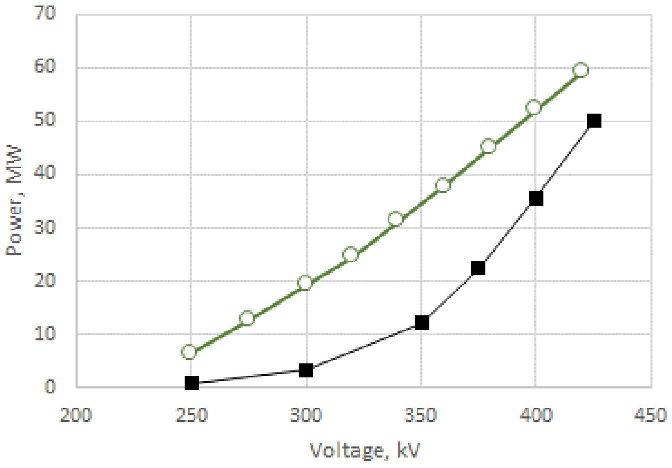
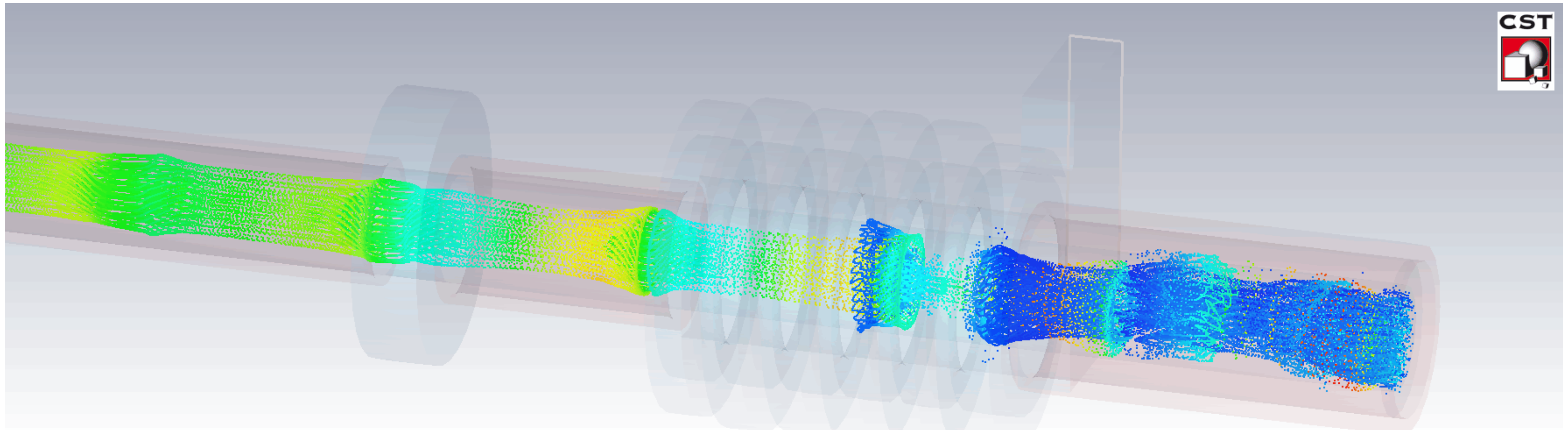
High Efficiency (70%) 50 MW, 12 GHz, CLIC COM_2DM klystrons (CERN/CPI).

Saturated efficiency & RF power







	VKX-8311A	HEX COM_2DM (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	58
Sat. gain, dB	48	58
Efficiency, %	36.2	68 / MAGIC.2D
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.35
RF circuit length, m	0.31	0.39

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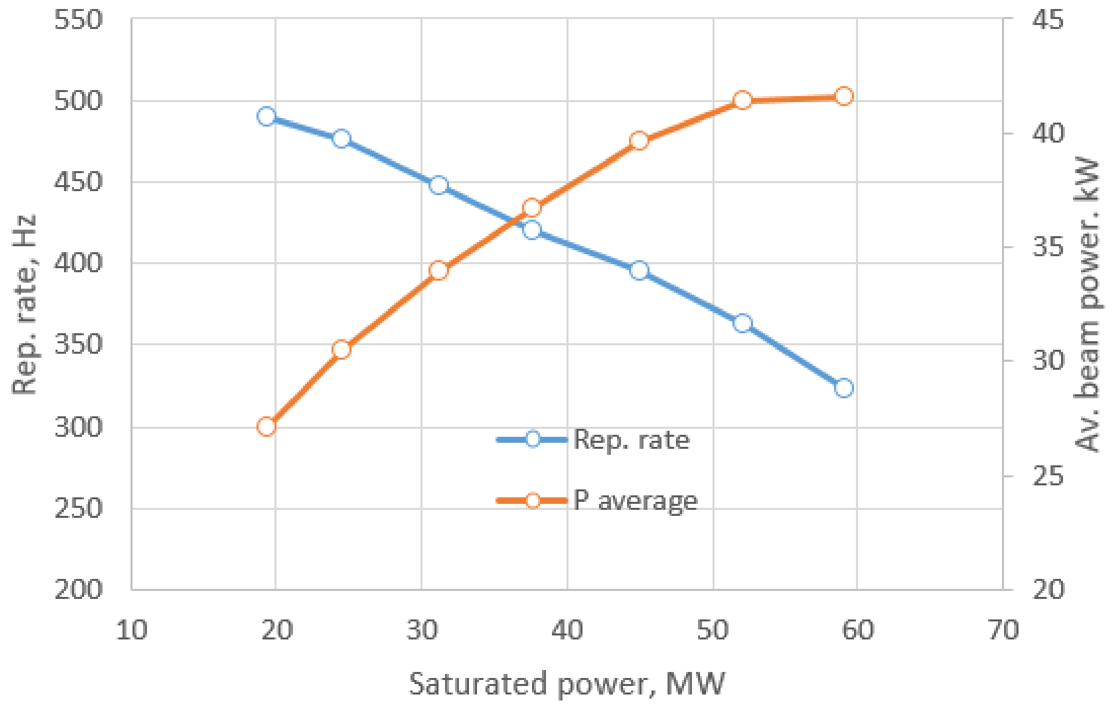
A number of applications are looking for the increased repetition rate of the high power pulsed RF system.

Example of the HEX 50 MW tube. RF pulse length 1.5 microsecond. The average power in collector (RF ON) is fixed to be 13 kW (similar to VKX-8311A):



Critical components (average power)

- Modulator (HV switches and HV transformer)
- RF window
- Waveguide and components Ohmic losses (mostly flanges).
- **Power dissipated in the klystron collector.**

The high efficiency klystron naturally allows to operate at a higher repetition rate, though the modulator average power will be increased proportionally.

Super Conducting (HTSC) klystron solenoid prototype.

CERN,KEK and Hitachi collaboration

Reducing the power consumption in the focusing solenoid

- The power consumption in the commercial solenoid of the 50MW X-band klystron at CERN is about 20 kW.
- We can use superconducting technology to drastically reduce the power consumption.
- The required magnetic field is below 1T, thus HTSC (MgB_2) can be used to improve the cryo-cooler efficiency and minimize the cost.

Coil technology	Unit	Cu	MgB_2
Central field	T	0.6	0.8
Current	A	2x300	57
Voltage	V	35	0
Cooling method		Water	Cryo-cooler
Temp	K	300	~25
Wall plug power	kW	**20**	**<3**

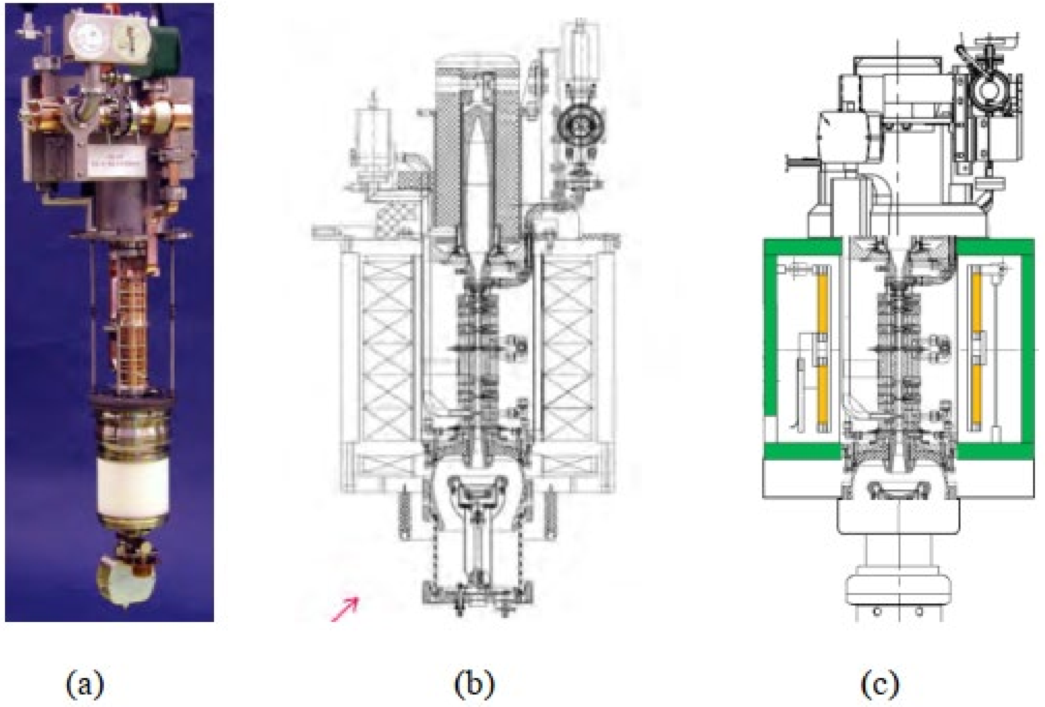
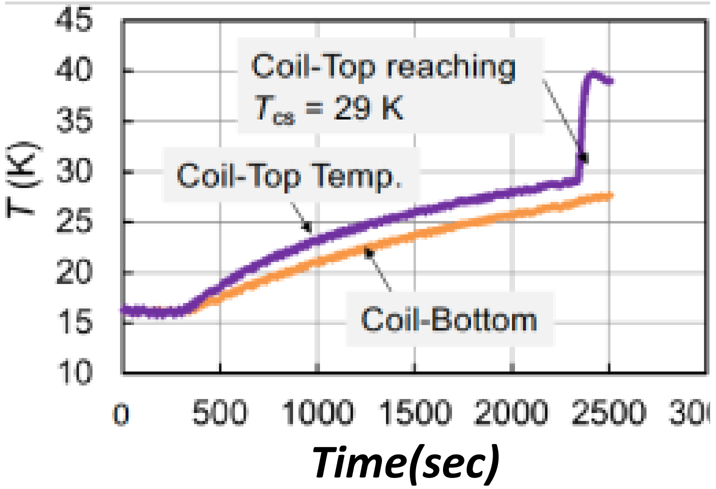


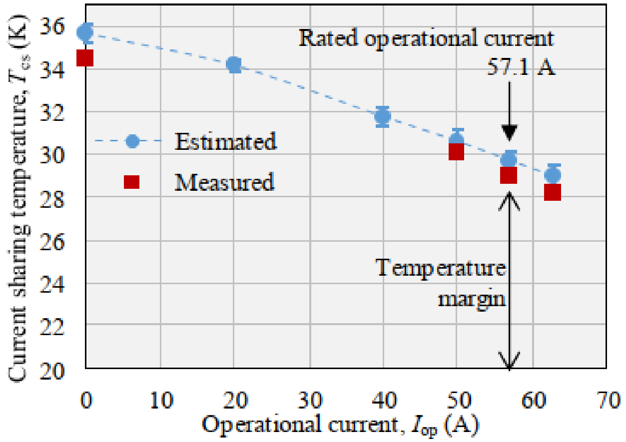
Fig. 3. (a) 12 GHz Klystron (main RF part), (b) Klystron assembled with conventional Cu solenoid, and (c) Klystrons assembled with a superconducting solenoid magnet.

"Applying Superconducting Magnet Technology for High-efficiency Klystrons in Particle Accelerator RF Systems" A. Yamamoto et al. MT26 Proceedings.

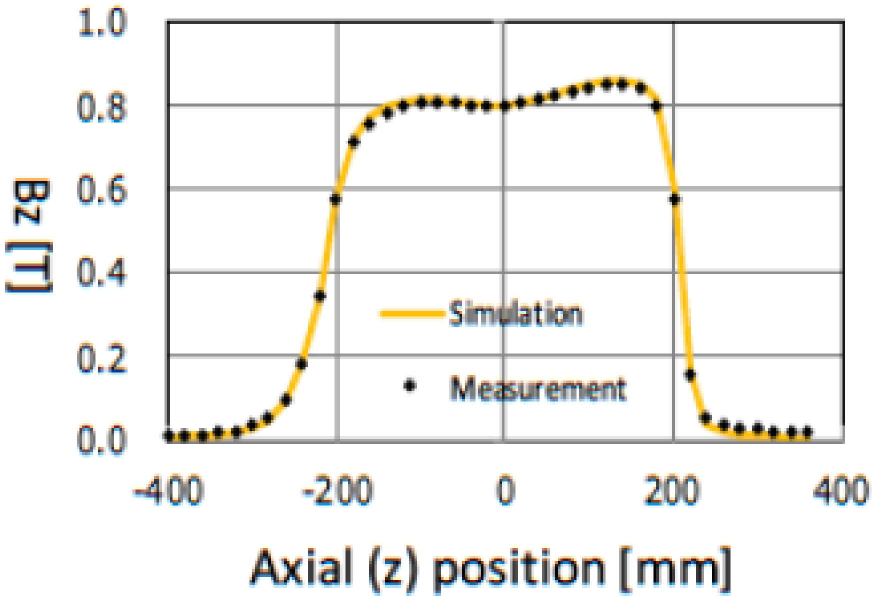
Measured performance of the first commercial MgB_2 solenoid prototype

Magnetic field measured using a hall probe showed excellent homogeneity. It reproduces the design profile required for the electron beam focusing along the Klystron consistent with the original Cu solenoid provided by SLAC/CPI.





Comparison of measured and estimated values of T_{cs}.



Very large margin in temperature > 8K translates in a very stable behaviour against quench and powering failures.

The solenoid was delivered to CERN and is ready for the installation on the klystron.

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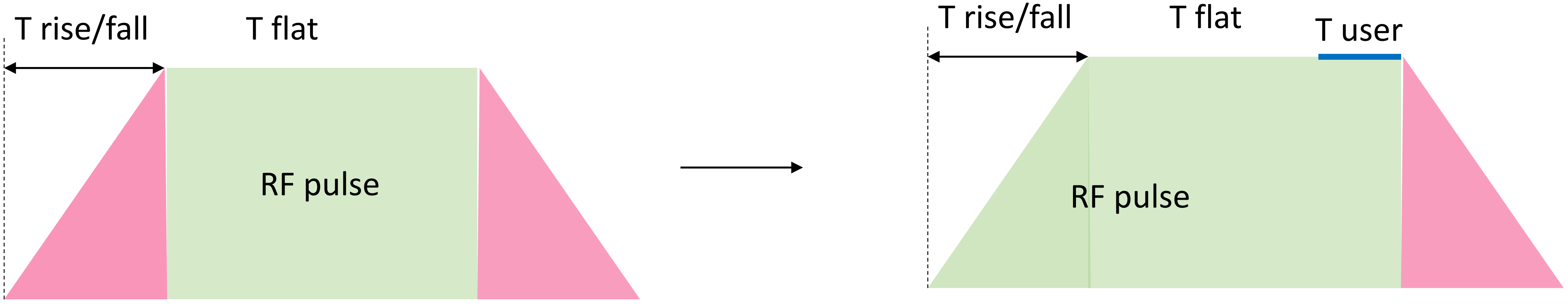
The possible measures to increase temporal efficiency of the modulator.



1. The conventional operation of the klystron requires that RF pulse length will be equal to the flat top of the modulator pulse. The temporal modulator efficiency is: **T flat/(T flat + T rise/fall); 60%**

2. When the RF pulse compressor is in use (T user), the rise time of the modulator can be used to store the extra energy in the PC cavity. Thus, temporal modulator efficiency is increased: **T flat/(T flat + (T rise/fall)/2); 75%**

3. Ultimately, the pulse forming network of the modulator can be designed for the very fast rise/fall time (100ns-200ns). In this case the overshoot and ringing on the flat top cannot be avoided. However, similar to the case 2), only T user period needs to be flat. The rest of the time, LLRF shall compensate for the RF phase modulation along the pulse. With such an approach, the efficiency of the modulator in a system with RF pulse compression can reach **90%**. We are ready to explore such an option using CERN klystron simulation tools and in collaboration with ScandiNova.

RF power production efficiency in the existing commercial system

Expected RF power production efficiency in the optimized system

Operating systems performance at 50 Hz rep. rate

ScandiNova modulator:
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Voltage: 420 kV
Current: 322 A
Average Power: **20.6kW**

CPI Klystron:
Flat top: 1.5 μsec
Peak power 50MW
Efficiency: **0.37**
Average Power: **3.75 kW**

NC solenoid:
B=0.6T
Average Power: **18 kW**

The overall RF power production efficiency is **9.7%**

Future modulator:
fall time: 0.3 μsec (option 3)
Flat top: 1.5 μsec
Efficiency/t: 1.5/1.65= 0.9
Efficiency/e=0.82
Voltage: 400 kV
Current: 194 A
Average Power: **7.8 kW**

CERN/CPI Klystron:
Flat top: 1.5 μsec
Peak power 52MW
Efficiency: **0.68**
Average Power: **3.9 kW**

HTSC solenoid:
B=0.6T
Average Power: **2.5 kW**

The overall RF power production efficiency is **38%**

Assuming 5000 hours/year of operation, the potential overall electricity savings could be 130 MWy (26 kWh).
With electricity price of 0.50 CHF/kWh the annual electricity bill reduction could be 65kCHF.
Operating small linac (Compact Light for example) with about 20 klystrons, one will save 1.3 MCHF per year.