High Efficiency Klystrons

High-efficiency klystrons from a dream to a reality

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Introduction

- The klystron tube
- State of the art
- Bunching techniques and efficiency limitations

The HE program at CERN

- KlyC development
- Aims and objectives

Latest developments

- X-band medium power
- CW UHF klystron for LHC
- Two stage klystron for FCC

General system efficiency

- Solenoids

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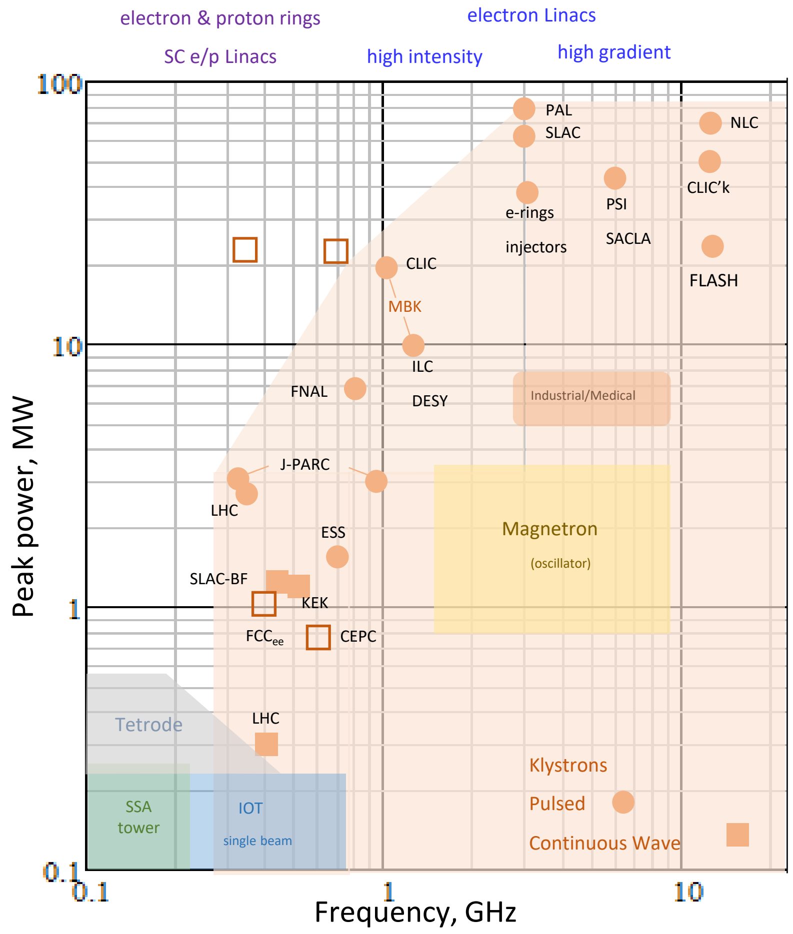
Klystrons for accelerators



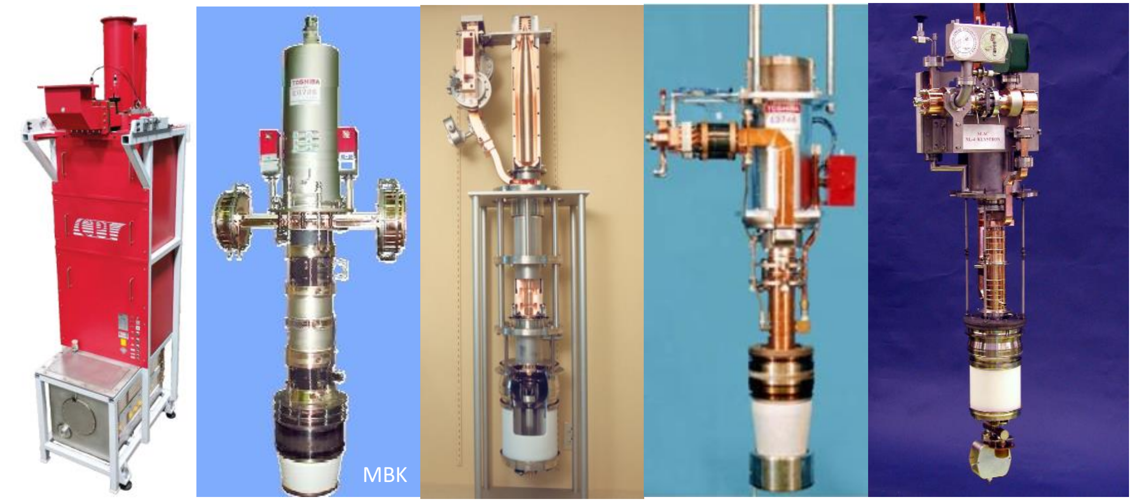
Electro vacuum devices for science

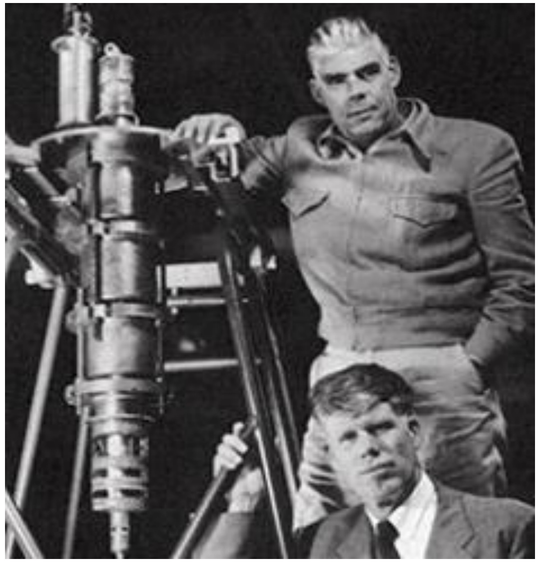
CPI — USA

THALES — France

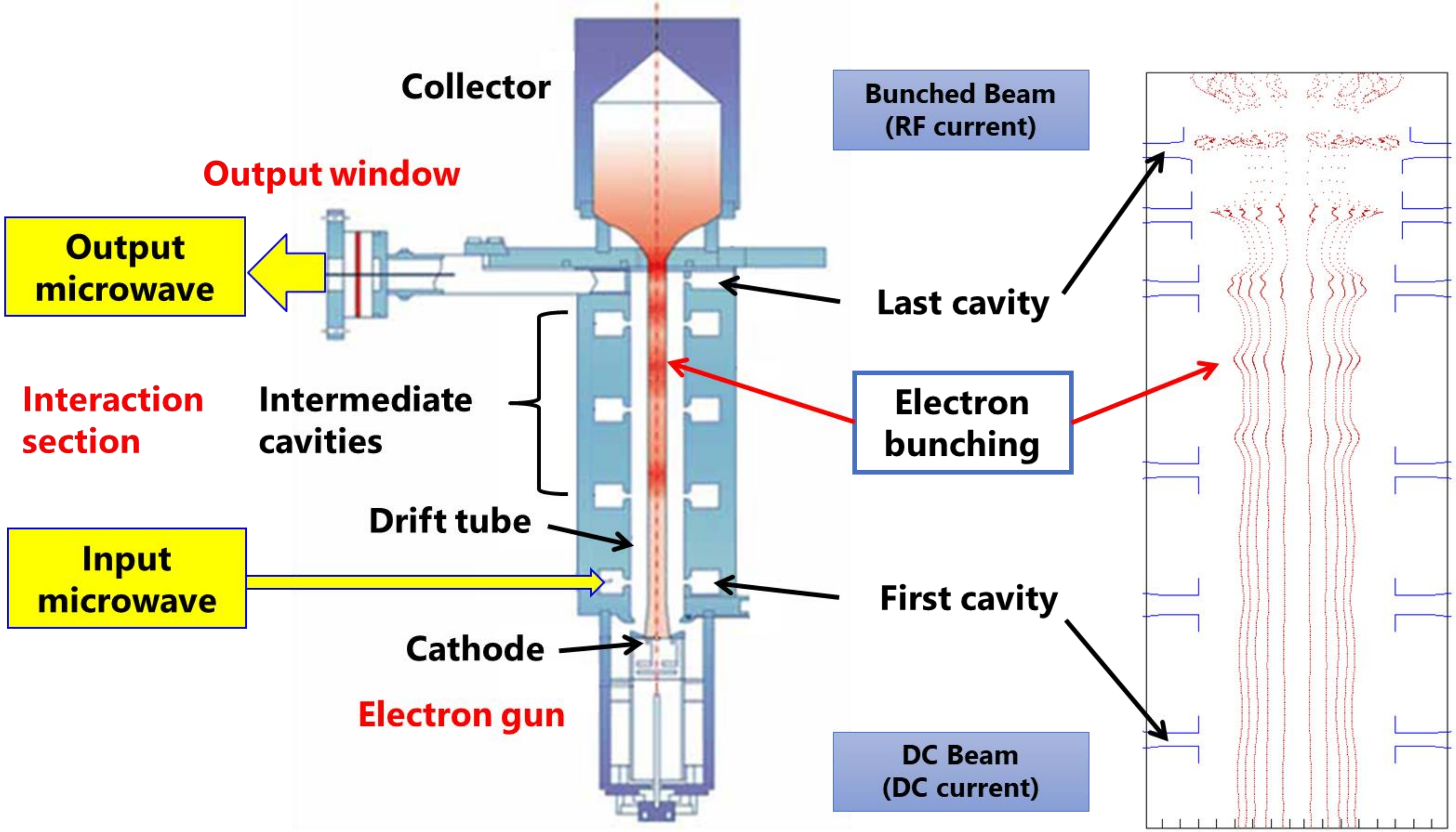
Canon — Japan

0.7 GHz, 1.5MW/ESS | **1.3 GHz**, 10MW/DESY | **3 GHz**, 60MW/SLAC | **6 GHz**, 50MW/PSI | **12 GHz**, 50MW/SLAC-CLIC





Russell and Sigurd Varian. 1937

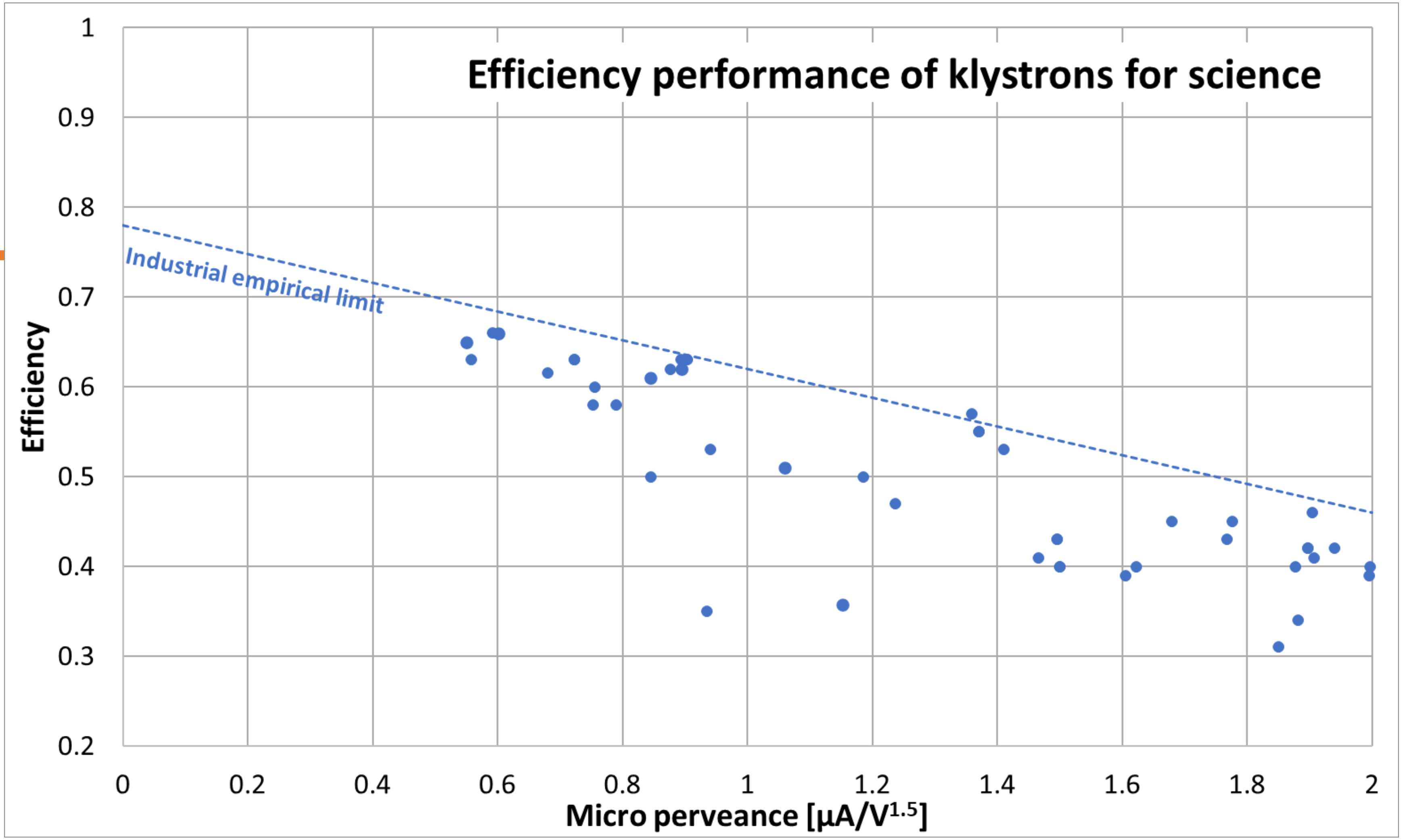


Courtesy of CETD

The klystron

Available klystrons for science

- $P = \frac{I}{V^{\frac{3}{2}}}$
- $\eta = \frac{P_{RFout}}{P_{Beam}}$

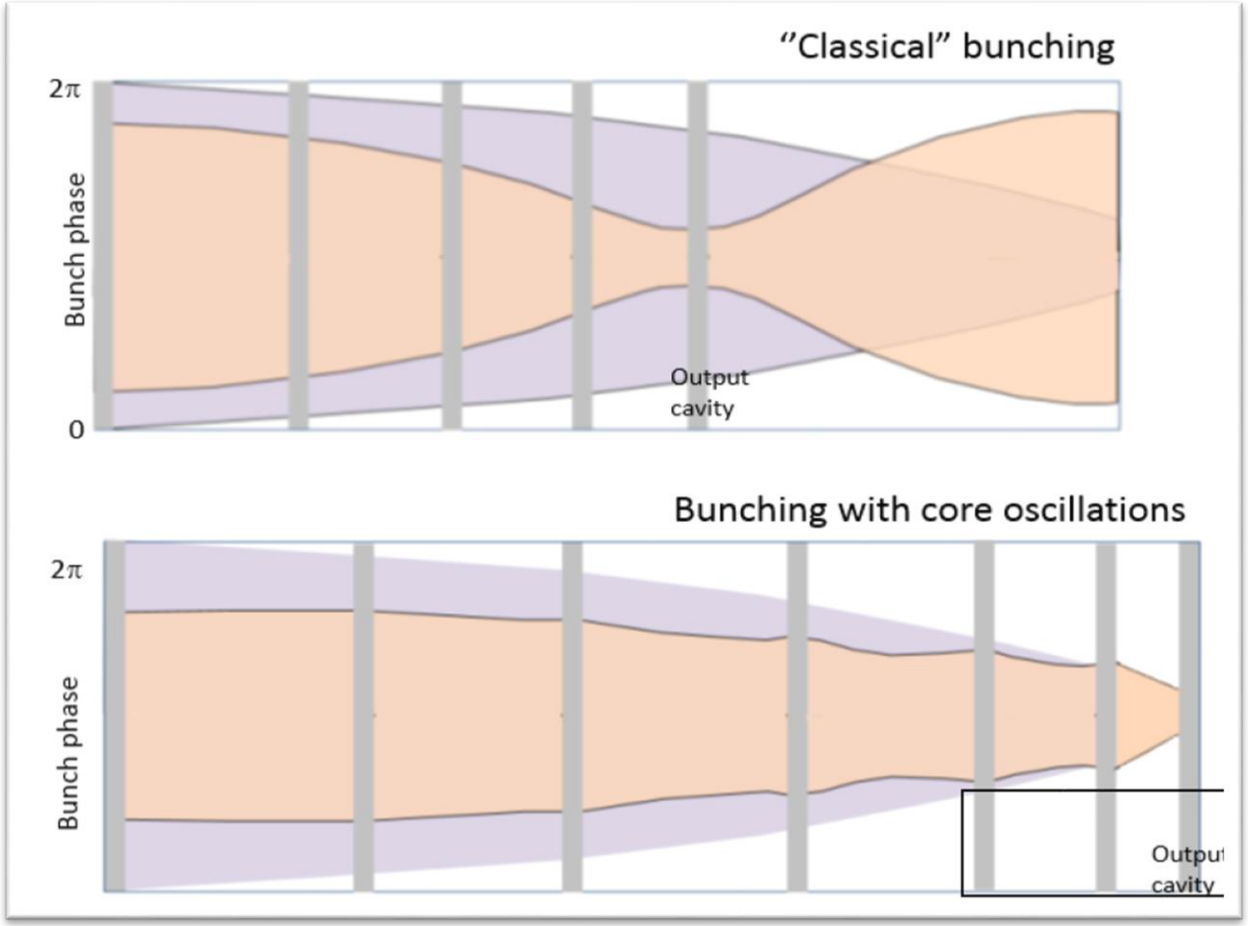


Bunching strategies and limiting factors

COM Core oscillation method

BAC Bunch Align Collect

CSM Core Stabilization method



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.

Radial bunch expansion happens during beam deceleration in the output cavity in the presence of external solenoidal magnetic field.

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.

Reflected electrons could be generated if some of the above effects are not balanced.

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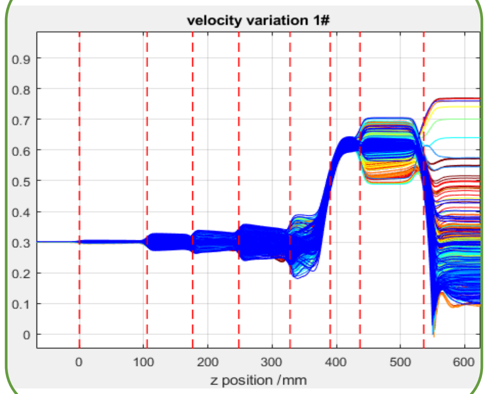
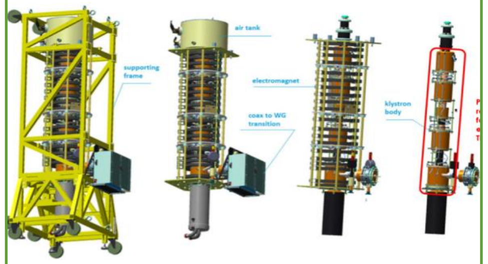
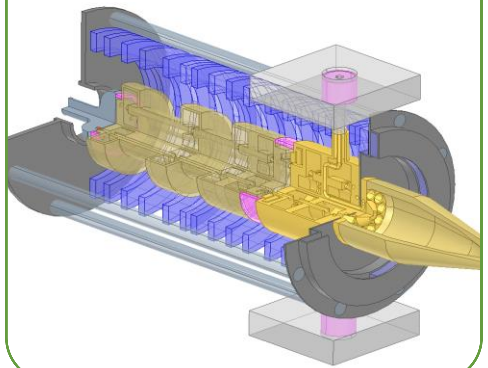
The HE program at CERN

- **High Efficiency klystrons** activity was initiated at CERN in 2014. In 2021 it was transformed into a CERN's **project**.
  - Project leader: Igor Syratchev
  - Project team @CERN: Zaib Un Nisa, Nuria Catalan Lasheras and Chiara Marrelli
  - Project team @ Lancaster: Graem Burt, (Anisullah Baig), Lee Millar
  - **Objectives**: Development, design, fabrication and testing of new HE klystrons for various accelerators projects in **collaboration with industry**.

Programme







Task 1: Design & simulations

Maintenance and distribution of the CERN made klystron code KlyC.

High level expertise in using commercial tools like CST PIC., HFSS etc.

Task 2: HE LHC 400 MHz klystron

- Retrofit upgrade of Thales klystron (60% to 70%) in close collaboration with industry.
- A base line option for HL-LHC.

Task 3: Novel two-stage klystron technology with 80%+ RF production efficiency

- Design, fabrication and testing of the 400 MHz 1MW CW klystron for FCC in collaboration with industry.
- Promote this new technology towards CLIC, ILC and Muon_C.

Task 4: HE X-band klystrons in the power range 10-50MW

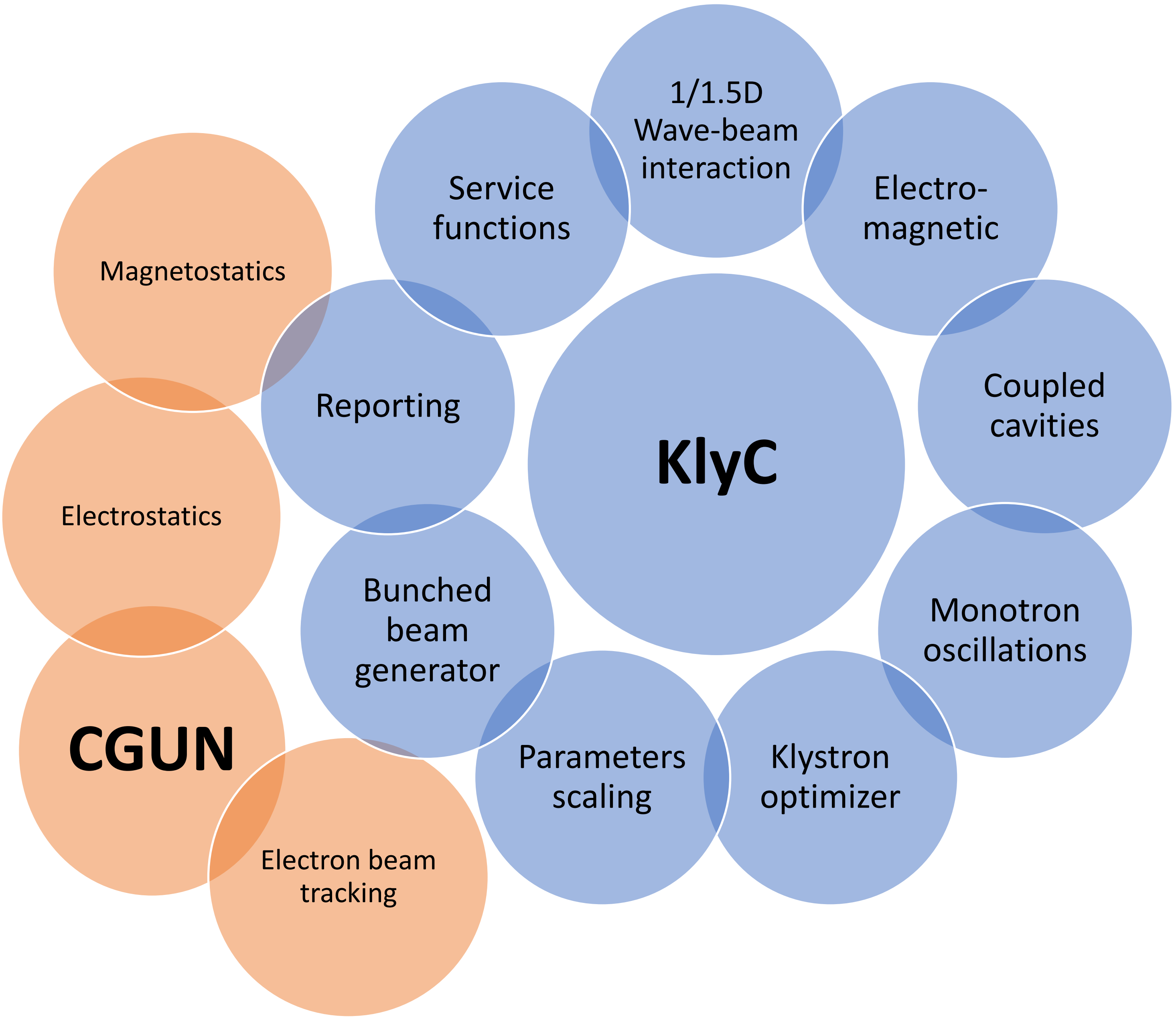
- Strong Collaboration with industry (Canon, CPI and Thales).
- Important for multiple projects (CompactLight, DEFT, EUPRAXIA etc.).
- Great show case for CERN’s technology and contribution to worldwide society.

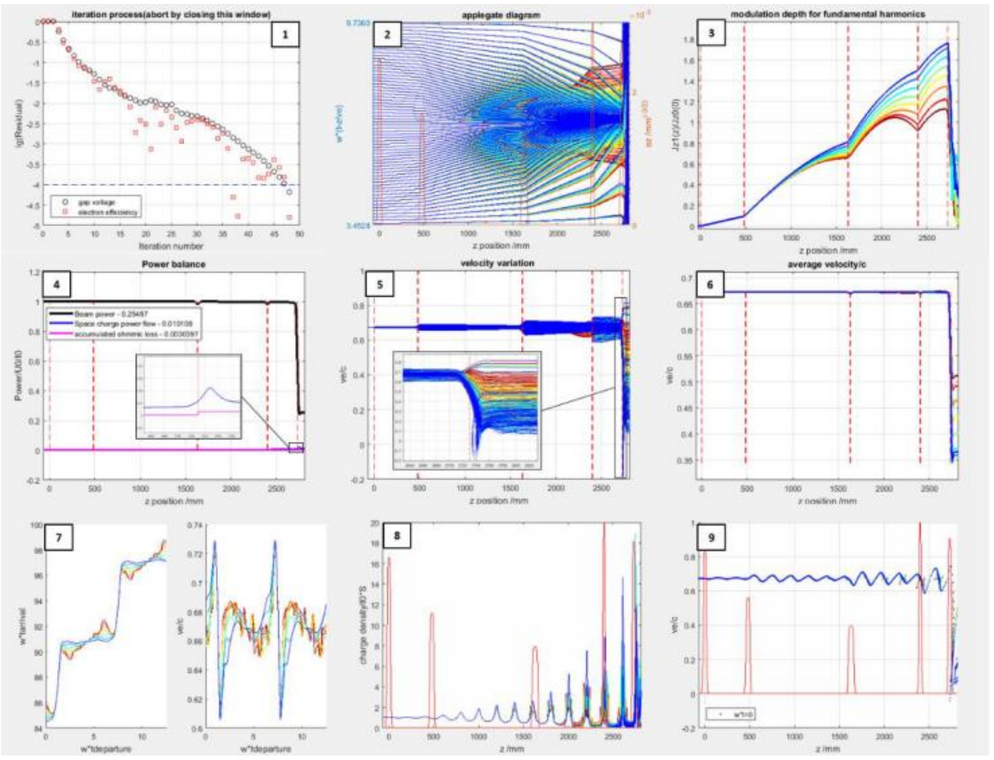
High Efficiency Klystrons

High Efficiency Klystrons

Development of KlyC

[Principal developer Prof. J. Cai , UESTC]





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High Efficiency Klystrons

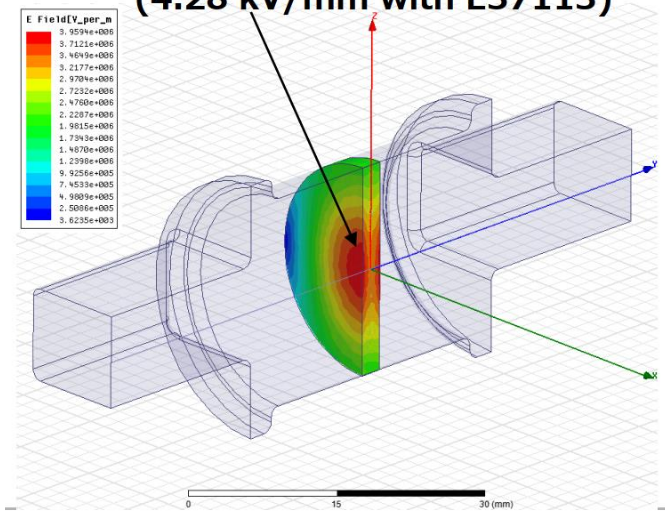
HEK

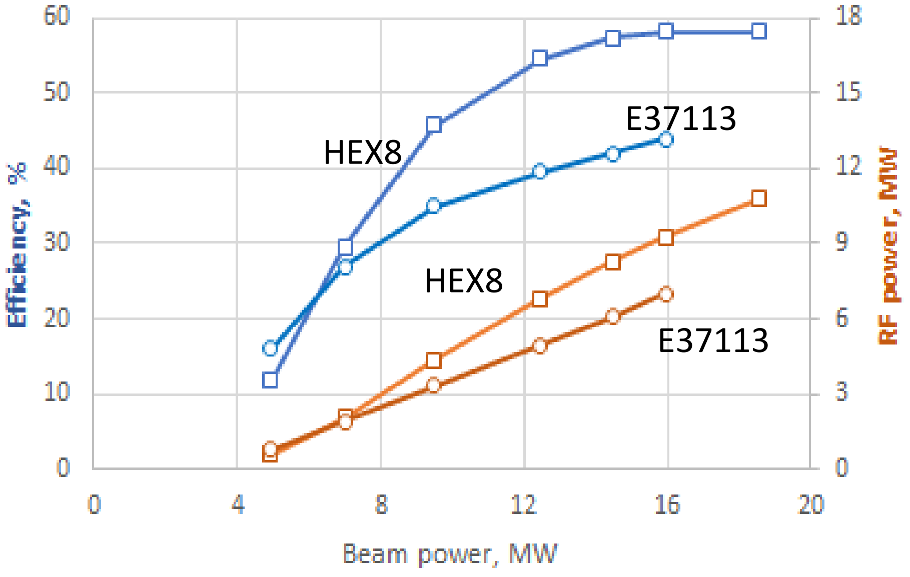
Canon
CANON ELECTRON TUBES & DEVICES CO., LTD.

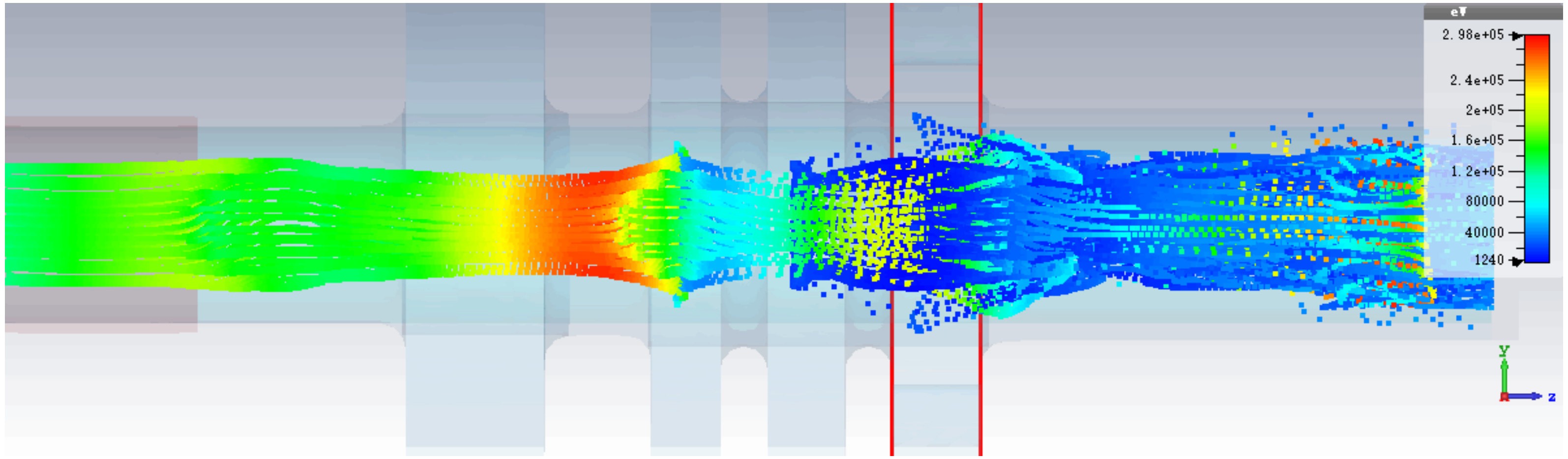
X-band medium power pulsed

- CANON ETD 37113
  - 12 GHz, 6MW, 400 Hz
- Currently used in X-band facilities
  - CLIC prototypes @CERN and Melbourne University
- Equipped with a new window designed by CERN
- Retrofit with a COM circuit plus 2nd harmonic cavities
- ~60% efficiency

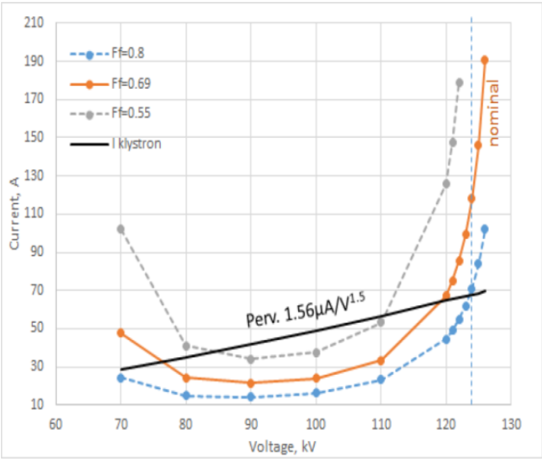
Ceramic
3.04 kV/mm at 6MW
(4.28 kV/mm with E37113)

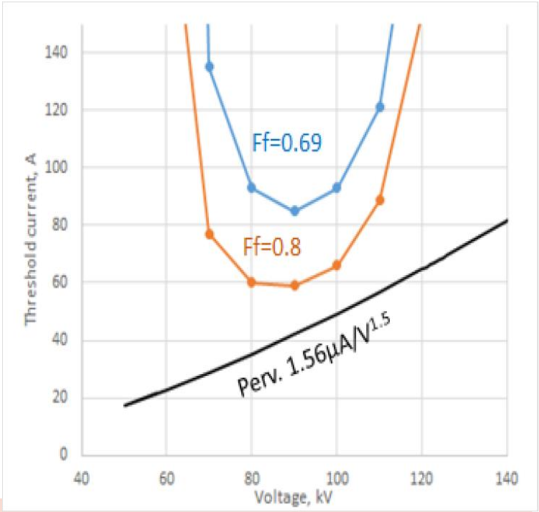


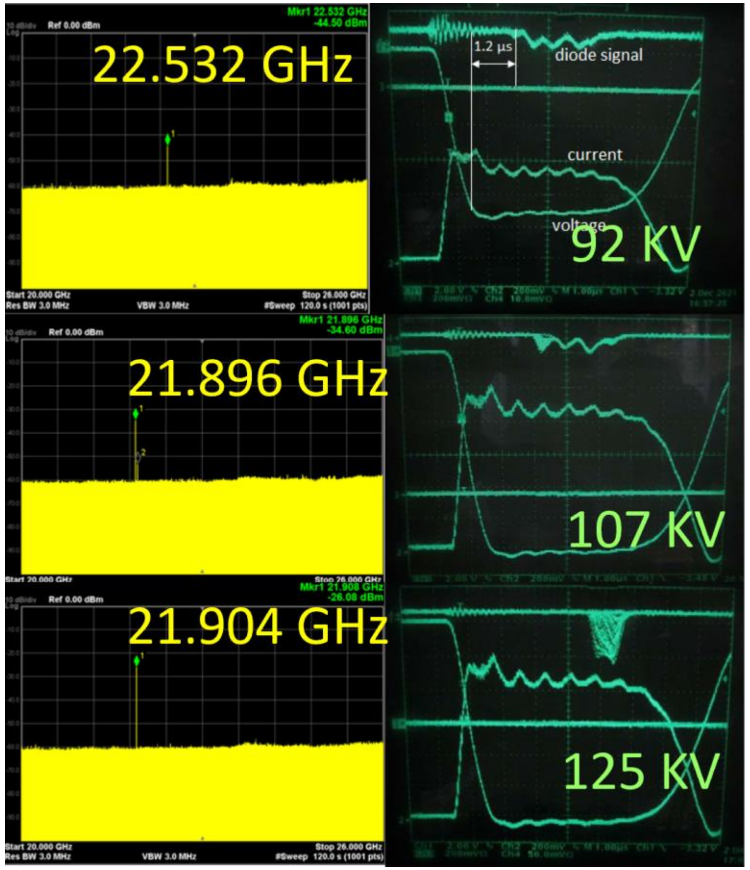




Observed instabilities after manufacturing the first tube





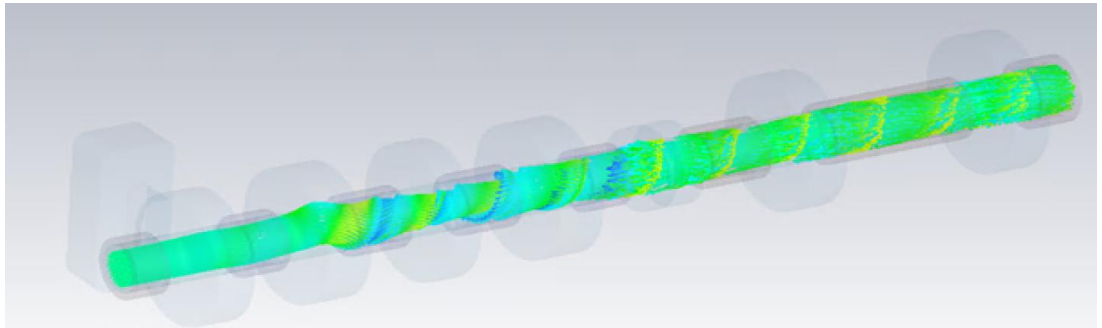


Monotron oscillations on the 2nd harmonic triplet

- Use of doublet instead

TE11 coupled modes instabilities in the bunching cavities

- Different gap length for each cavity (~20%)
- Damping using stainless steel



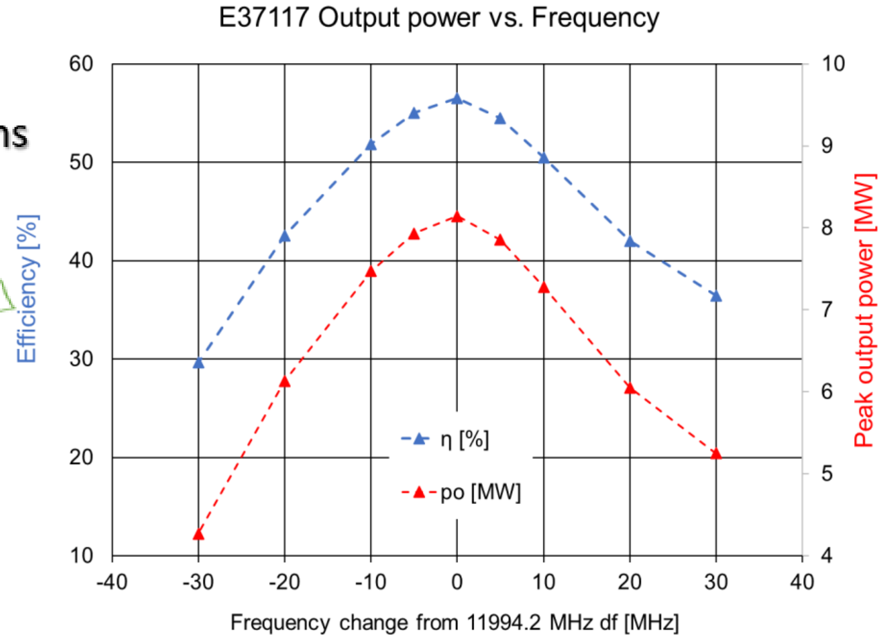
CANON ELECTRON TUBES & DEVICES CO., LTD.

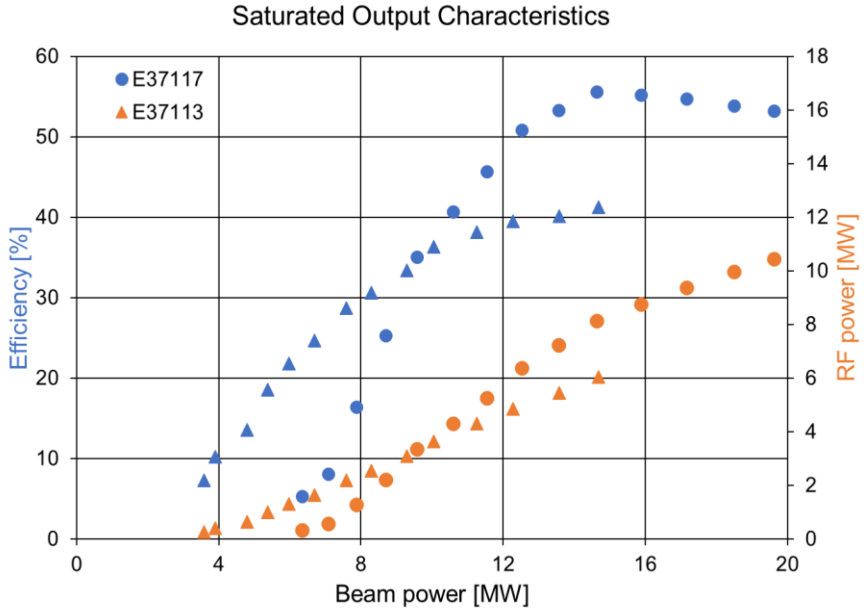
New CETD E37117

High Efficiency Klystrons

Retrofit design

	E37113 at factory	E37117 at factory
Voltage, kV	154	154
Current, A	93	94
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.12
Sat. gain, dB	49	46
Efficiency, %	42	**57**
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.42
RF circuit length, m	**0.127**	**0.127**

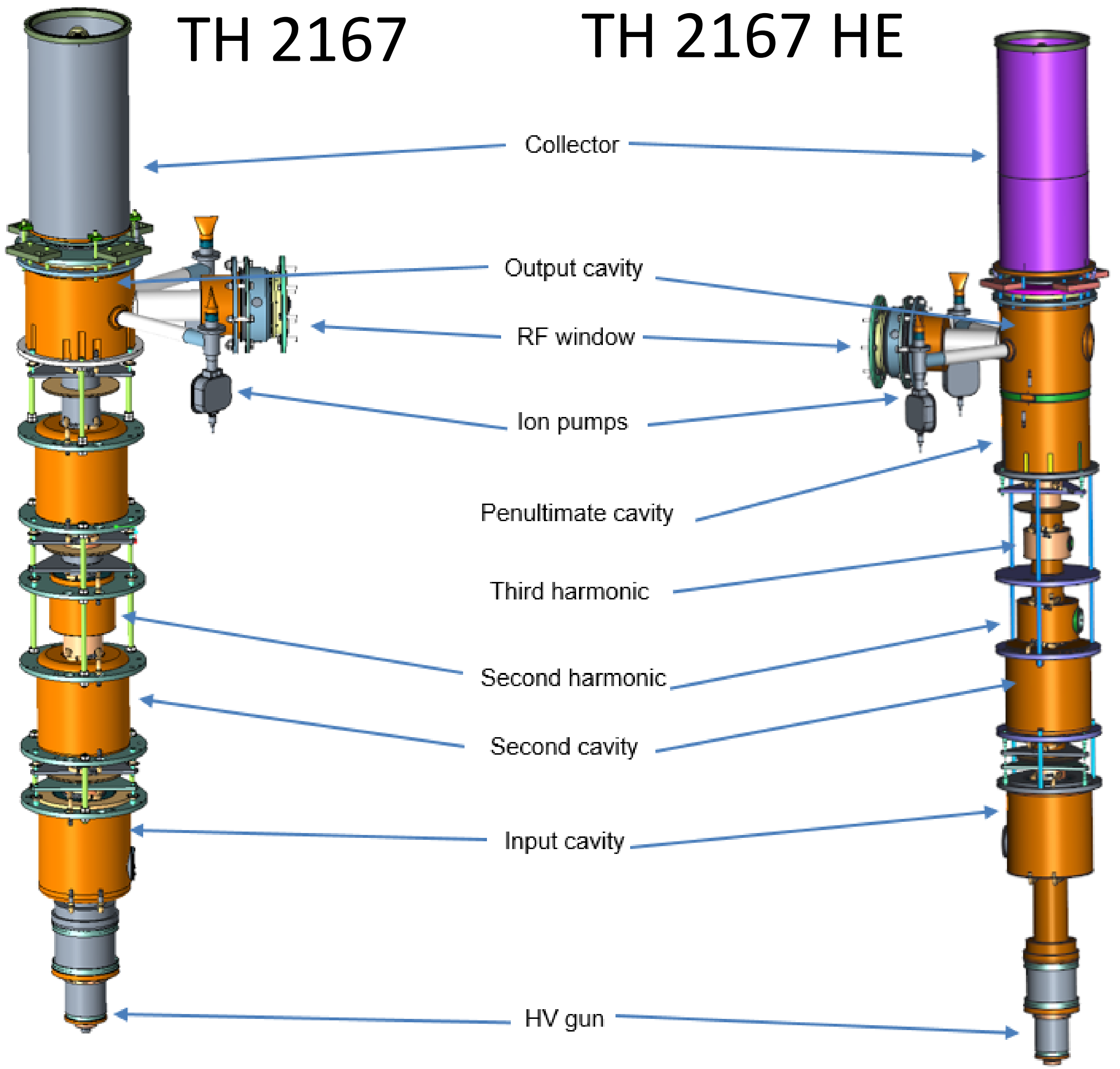




CW UHF klystron for LHC

- Thales TH2167
  - 400 MHz, CW
  - Used in the LHC at CERN
  - Currently 60% efficient
- Retrofit intended to reach 72% and 350 kW required for the HL-LHC
- CSM bunching method with 2nd and 3rd harmonic cavities
- Collaboration CERN-Thales co-financed by EU through the IFAST programme

High Efficiency Klystrons



CW UHF klystron for LHC

Cavity #	Qx initial meas.	Qx after correction	Targeted Qx	Status
6	35.94	36.24	36.7± 1	OK

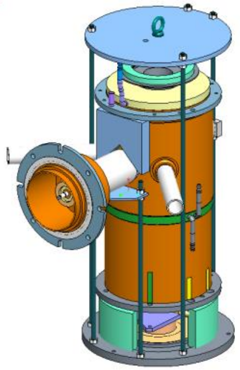
Cavity #	initial Freq. (MHz)	Freq. after correction (MHz)	Targeted Frequency	Status
5	411.3	413.02	413.0 ± 0.1	OK
6	400.36	400.1	400.1 ± 0.1	OK

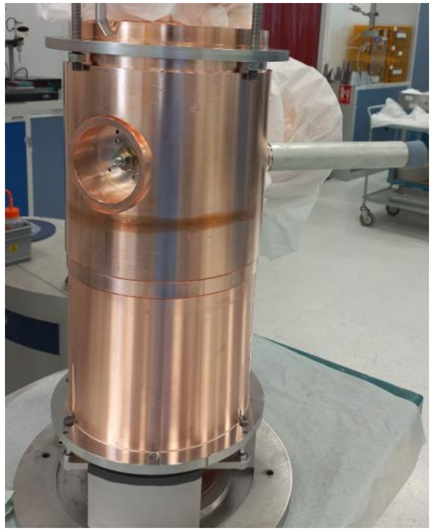
THALES

High Efficiency Klystrons

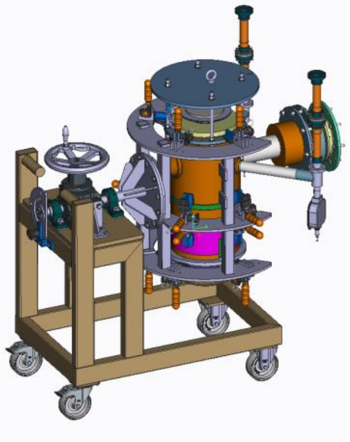
iFAST

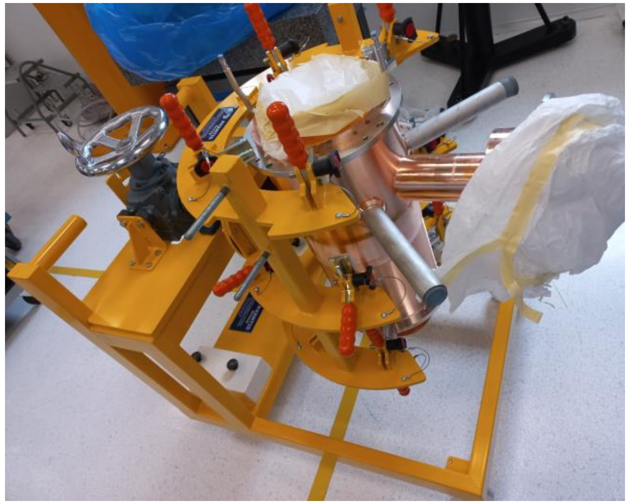
HEK

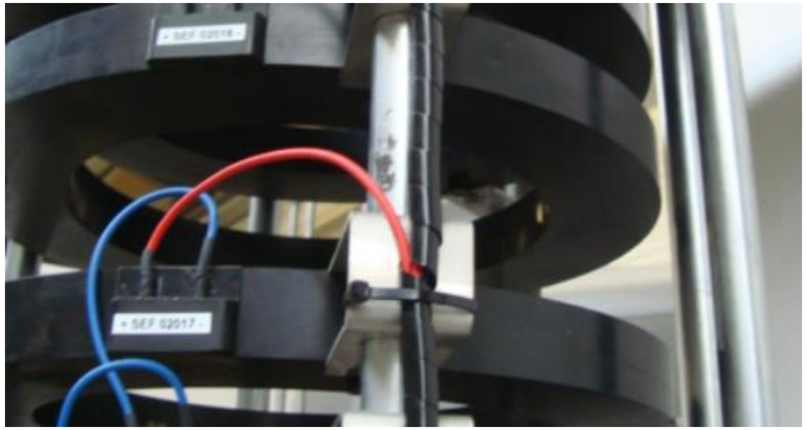


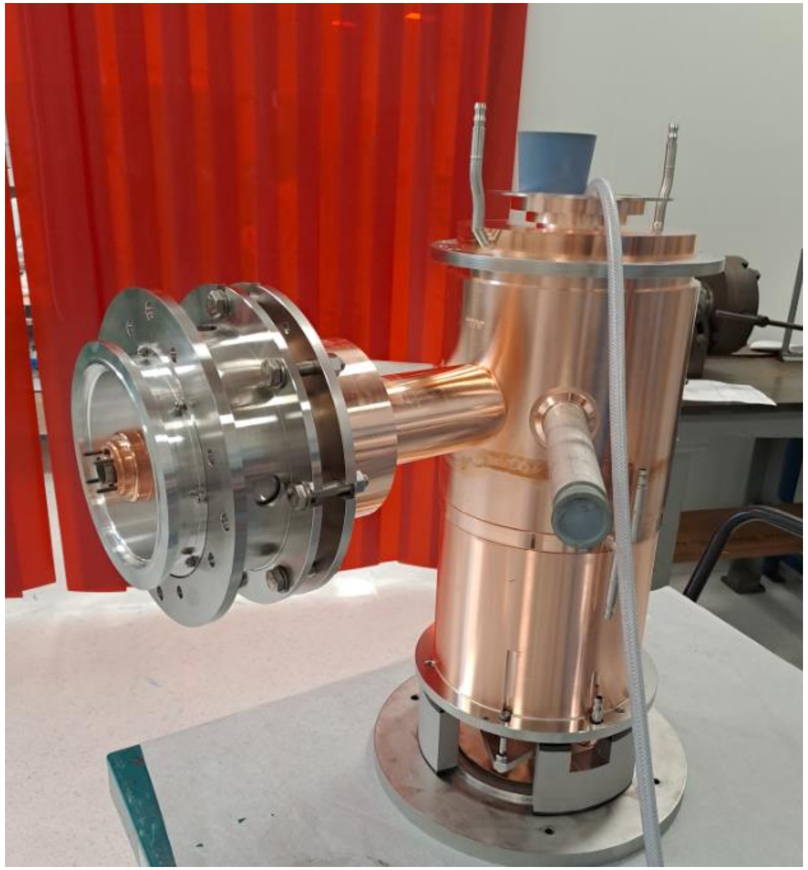


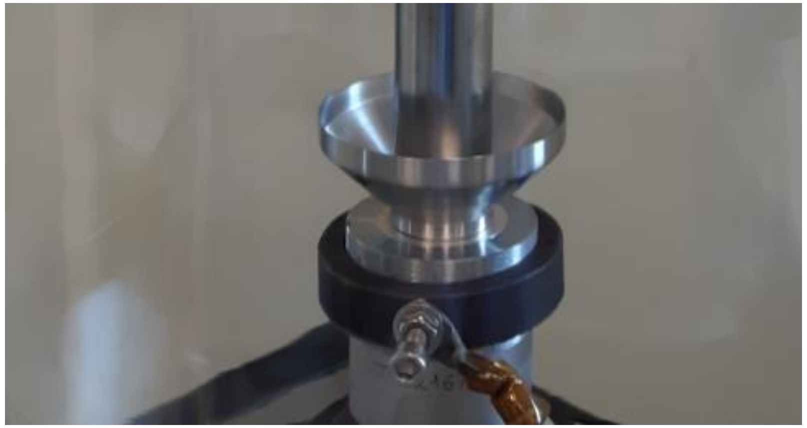
- Validation done on the Test Vehicle = Cavities 5&6:
  - Assembly and the different soldering stages : **Ok**
  - Vacuum-tightness (Leak rate : 10^{-9} mbar.l/s) : **Ok**
  - Sealing of cooling circuits (10^{-9} mbar.l/s) : **Ok**
  - RF performance (cold measurement): **Ok**
    - The possibility of adjusting cavity 6 with a radial tuning system









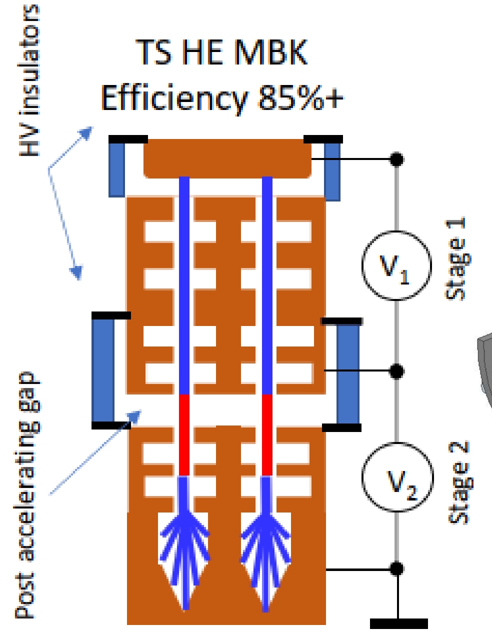


CW UHF klystron for LHC

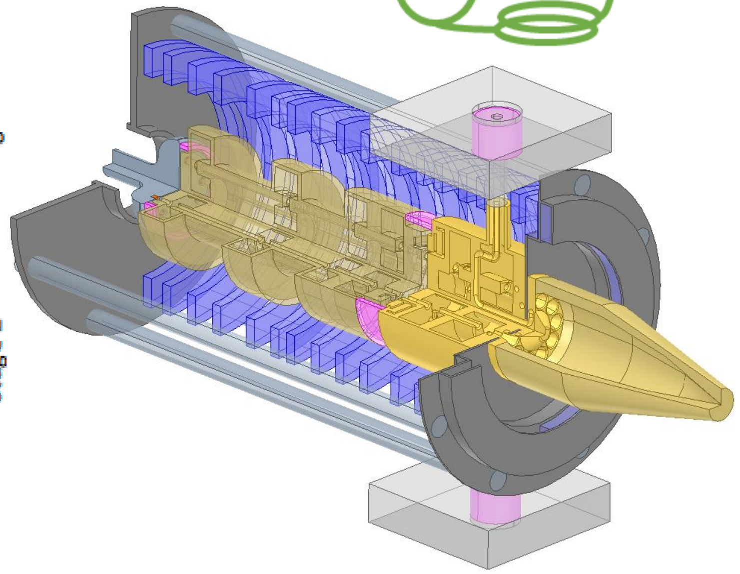
Expected delivery to CERN summer 2024

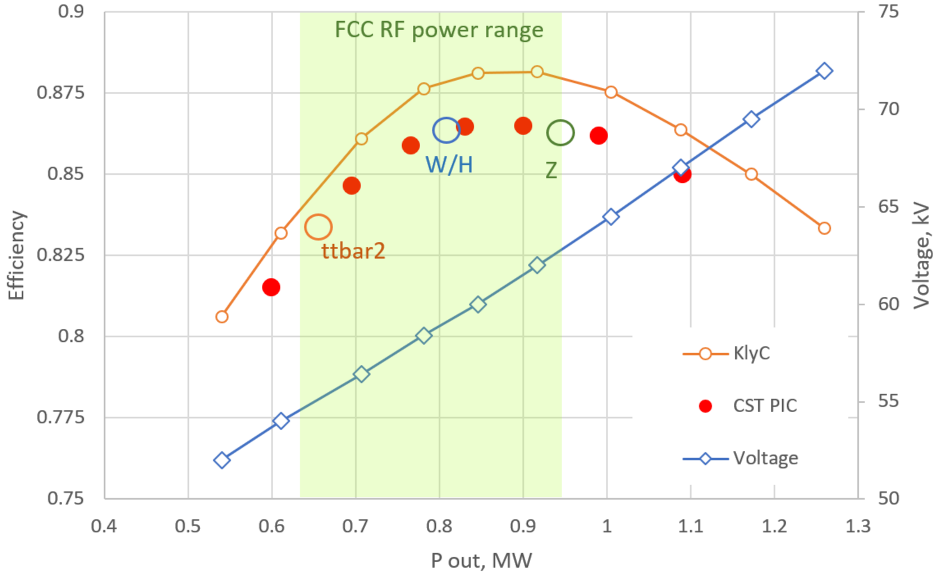
TS-MBK for FCC

- Two stage klystron for FCC
  - 400 MHz, 1 MW, CW
  - Multibeam klystron MBK
- New topology with low and high perveance section
  - Very high efficiency above 86% in simulations
  - Low operating voltage to work without oil
  - Above 80% efficiency in all four operation points across the FCC physics program
  - Very compact solution (2.8m in total)



High Efficiency Klystrons

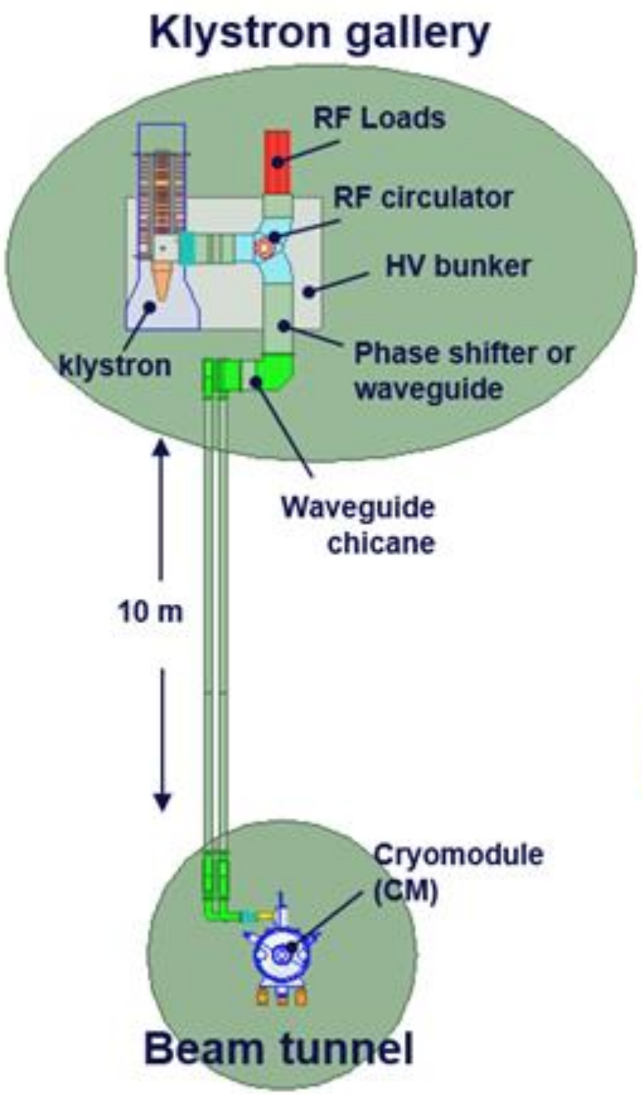


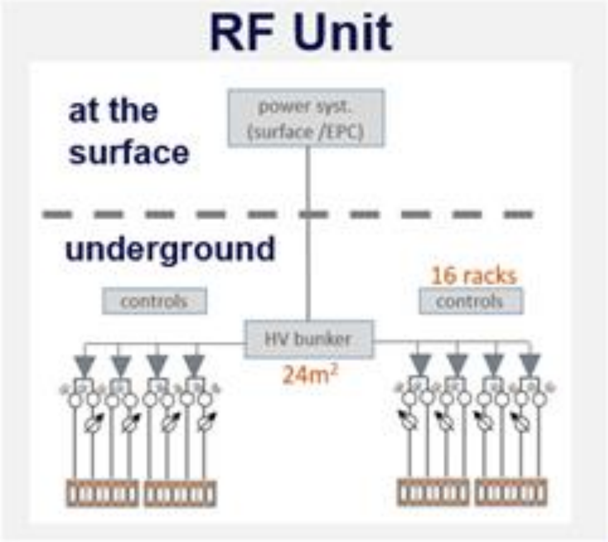


Accelerator tunnel and klystron gallery

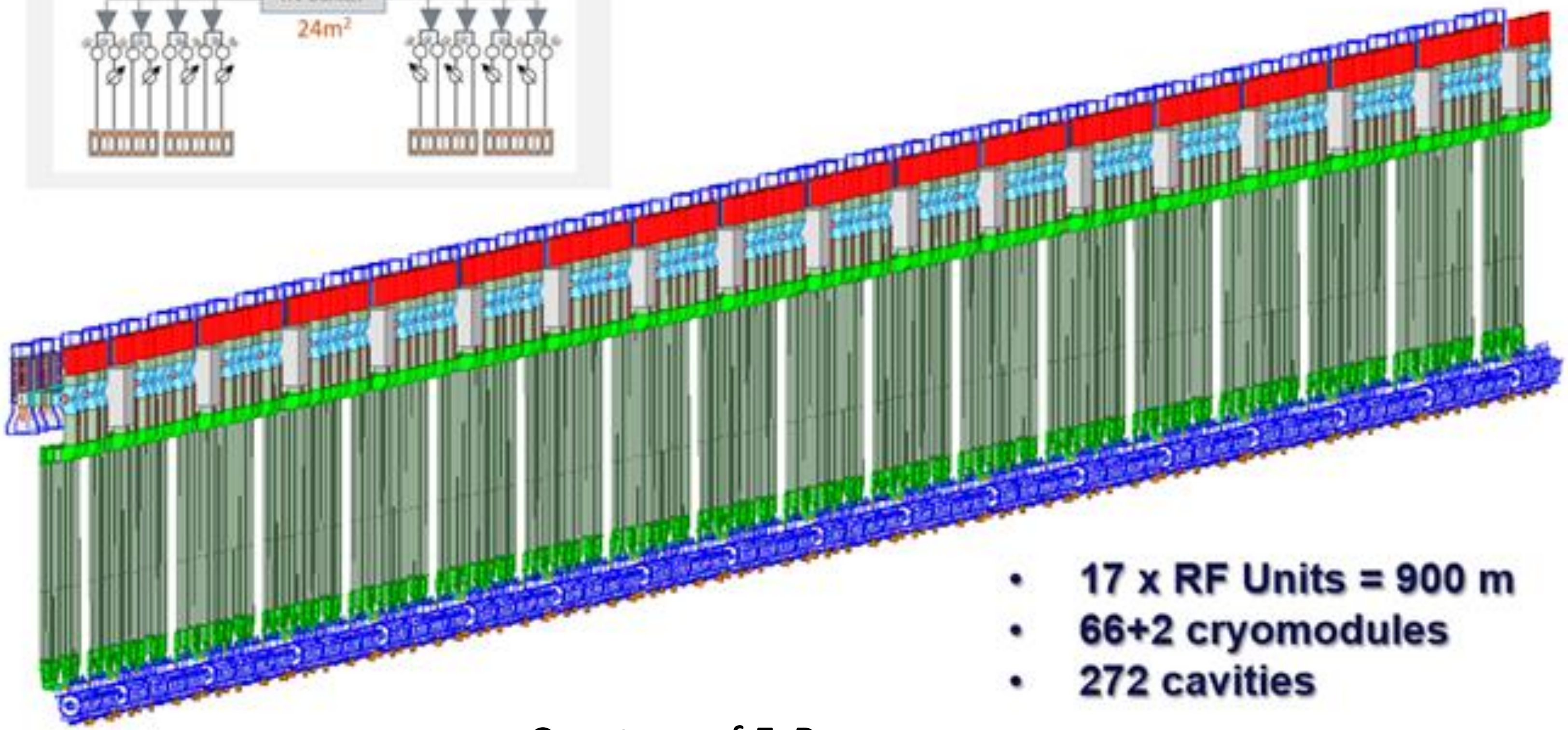
High Efficiency Klystrons

RF system configuration for the Higgs factory





- To reduce tunnel cost (cross-section) and RF power sources/HV integration in the tunnel, compact (~3m long), vertical klystron solution is desirable.
- Operating tubes at moderate HV (60kV) is beneficial to avoid oil tanks in the tunnel (MBK option).



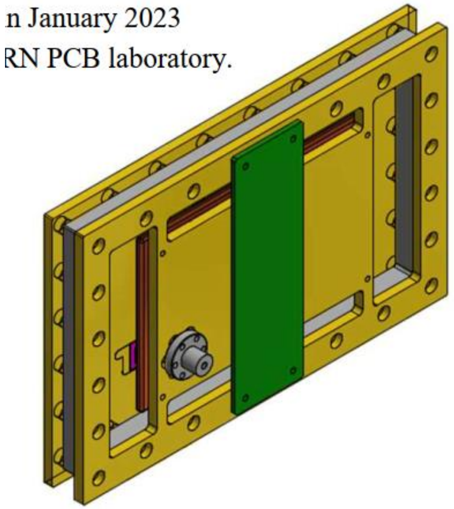
- 17 x RF Units = 900 m
- 66+2 cryomodules
- 272 cavities

Courtesy of F. Peauger

TS-MBK for FCC

Challenges:

- RF power radiation into DC gap
- High voltage isolated RF Feedthrough
- Large insulating ceramic between stages
- Prototype construction is currently the highest priority for CERN
- Very similar tube in L-band for CEPC, CLIC, ILC and MC



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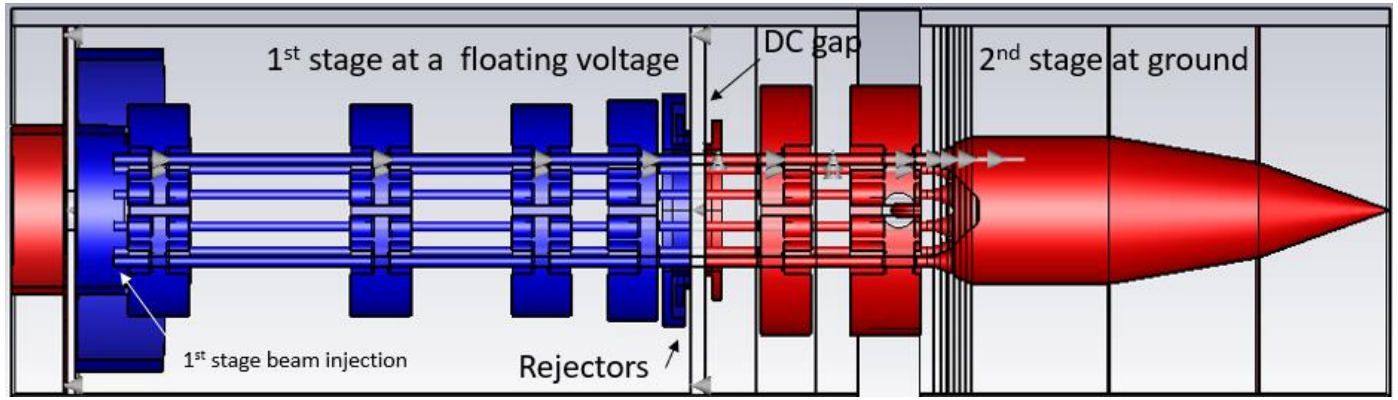
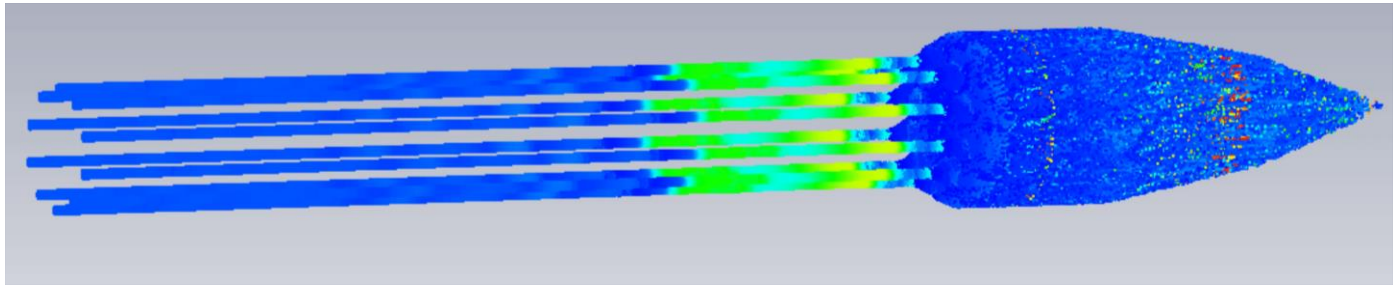
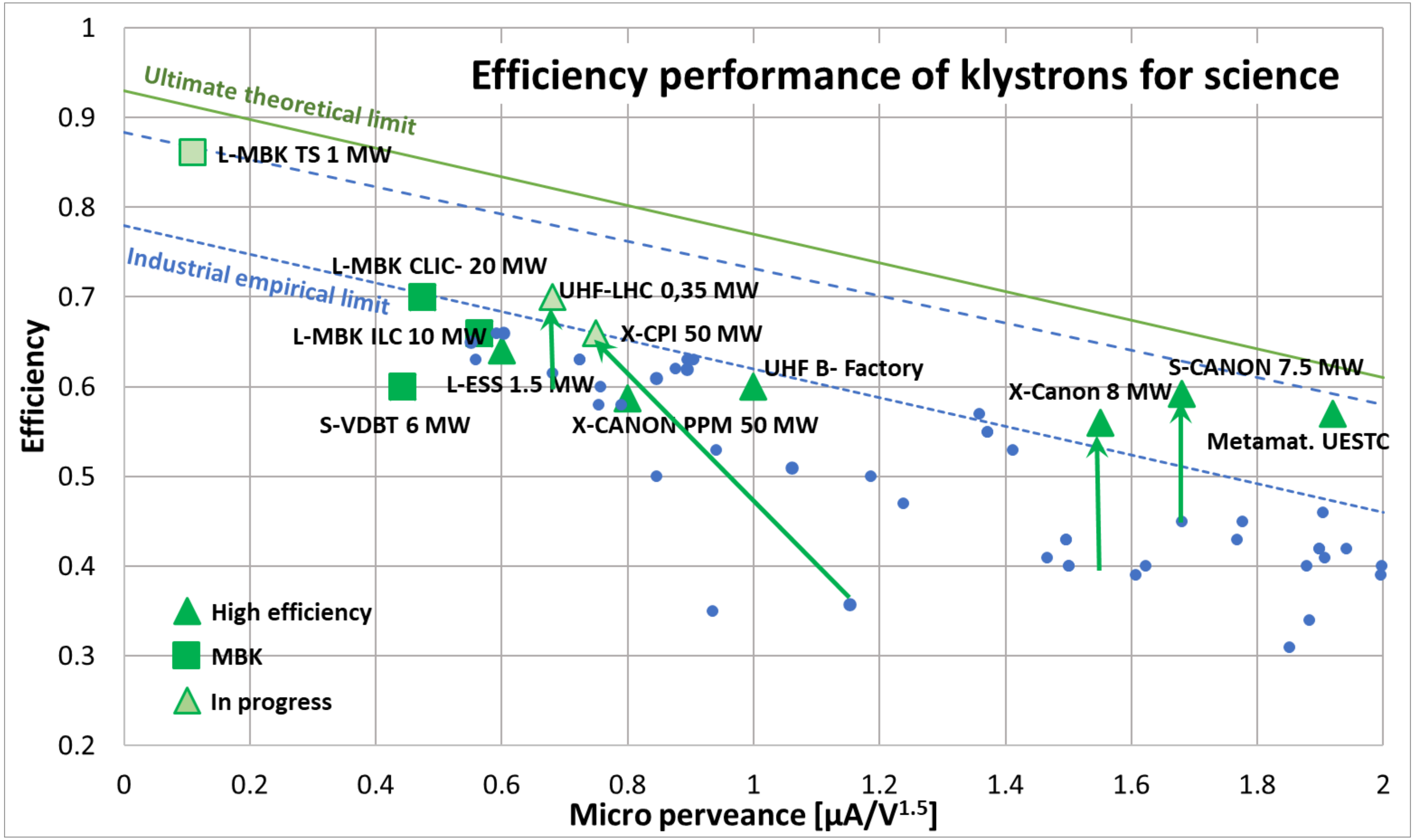




Available klystrons for science

- Many klystrons built on the last decade have overcome the empiric limit
- Born from the collaboration of industry with research centres
- New practical limit well above state of the art



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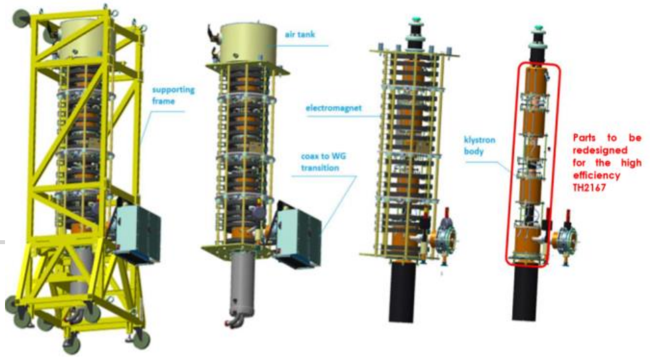
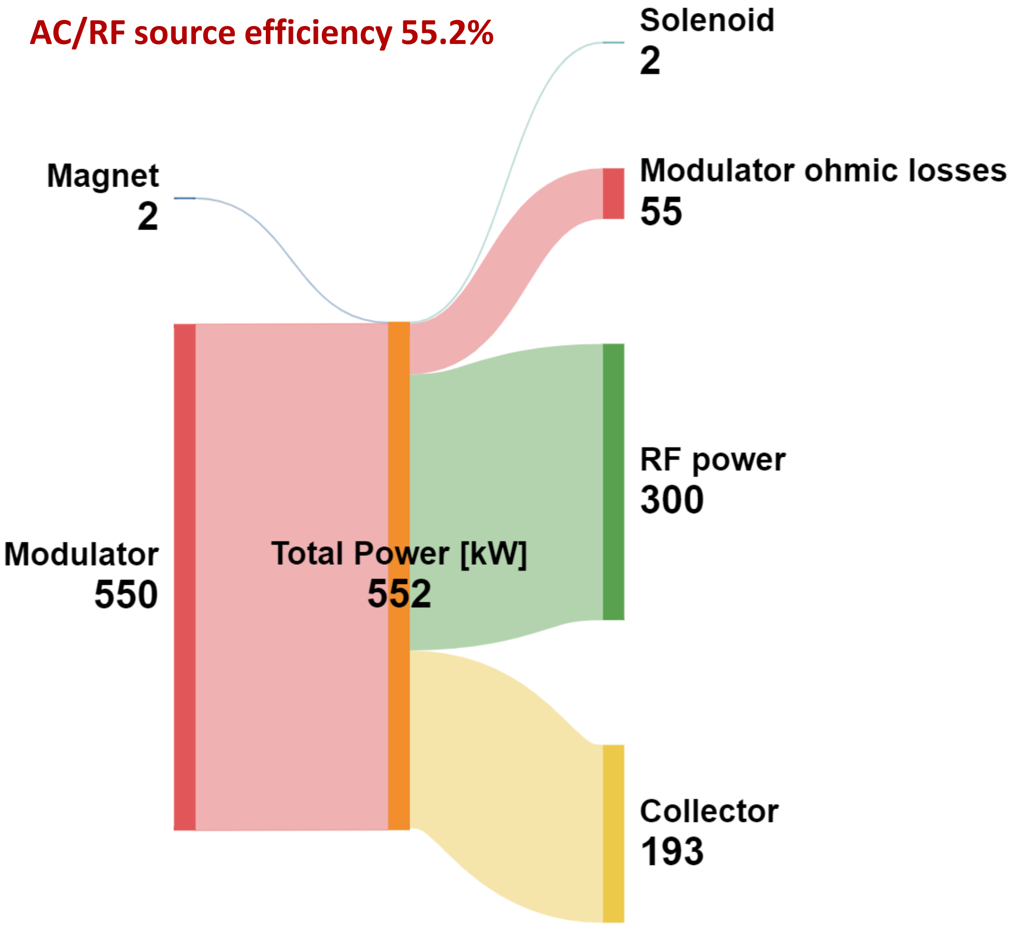
Power balanced for CW Klystrons



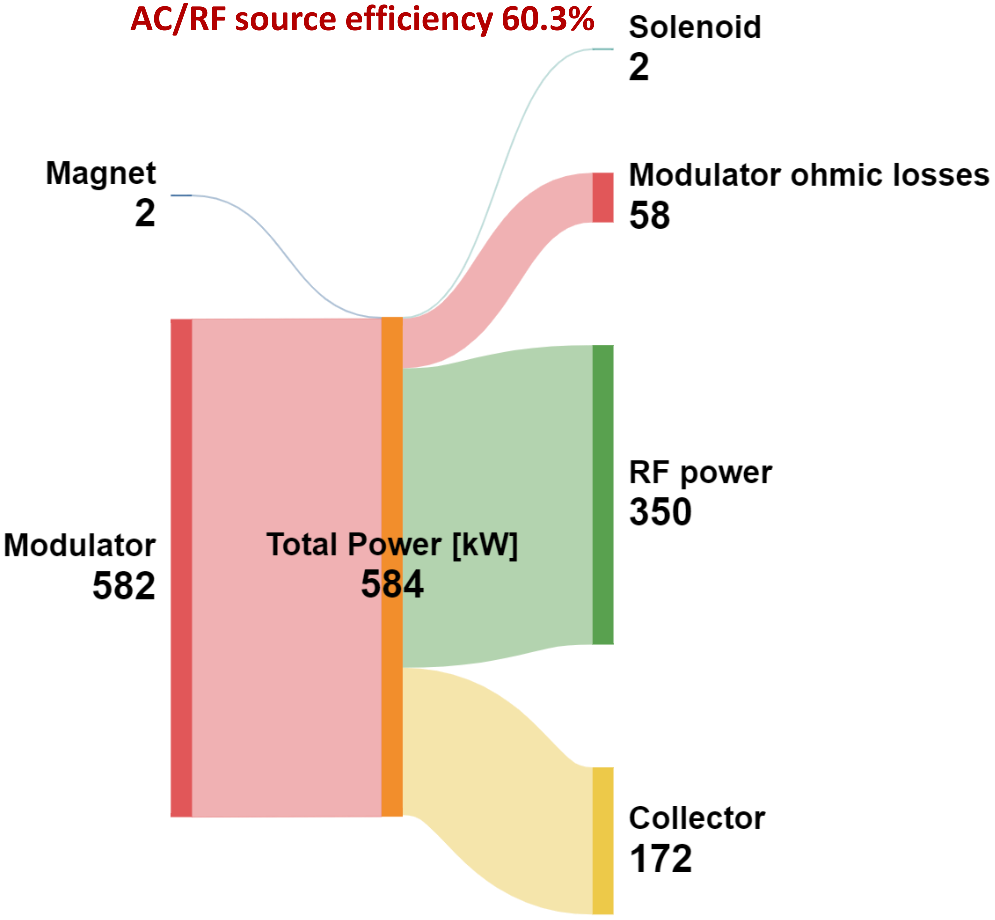
TH2167

AC/RF source efficiency 55.2%

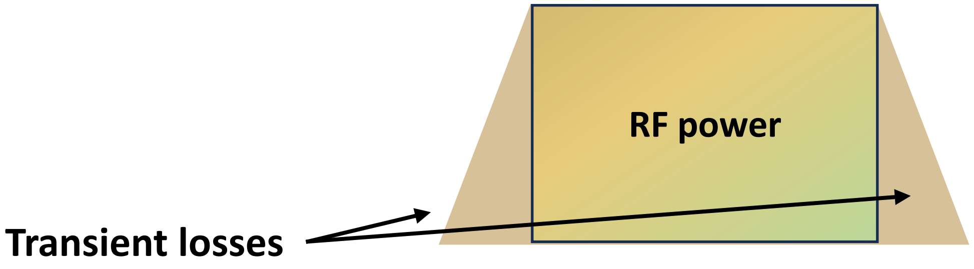


HE TH2167

AC/RF source efficiency 60.3%

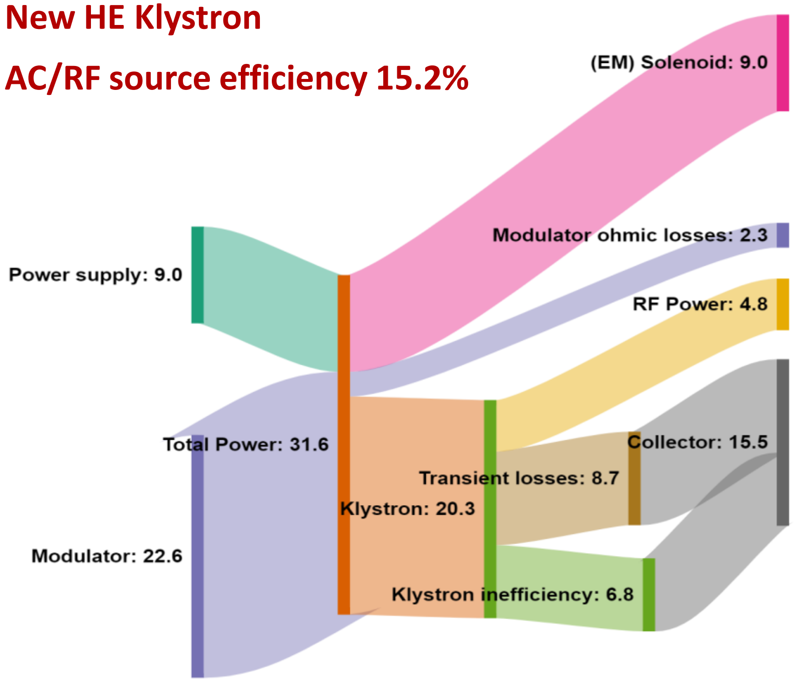


Power balance for pulsed RF sources

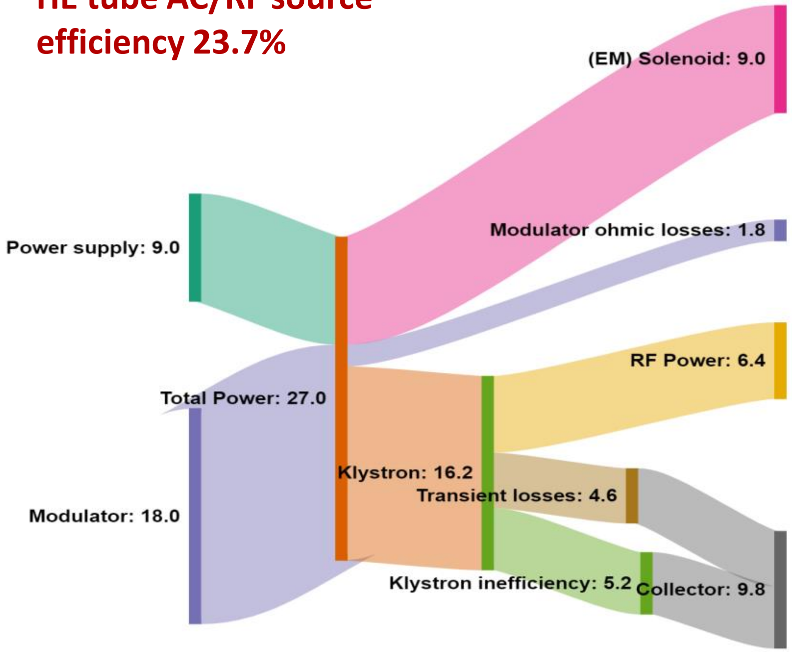


New HE Klystron

AC/RF source efficiency 15.2%



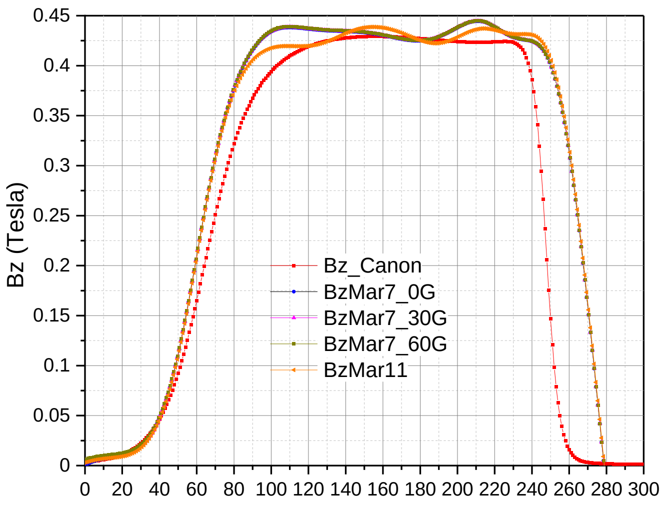
HE tube AC/RF source efficiency 23.7%

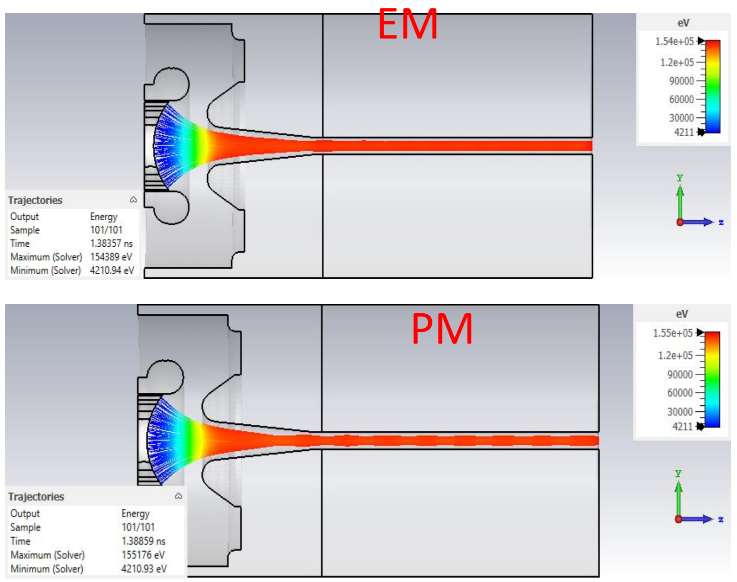


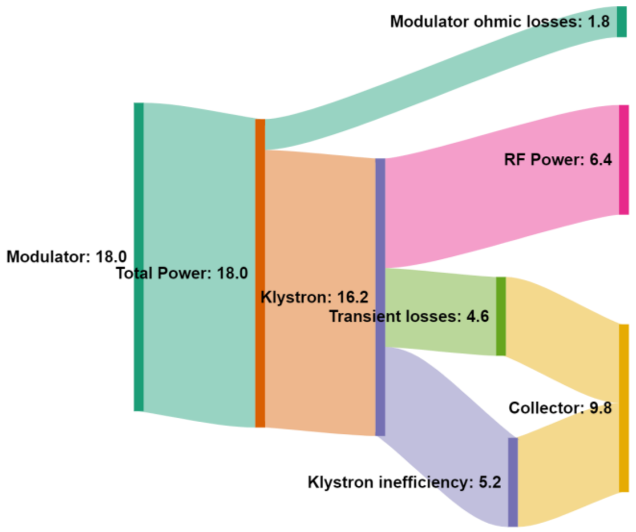
PM Solenoid for CETD E37117

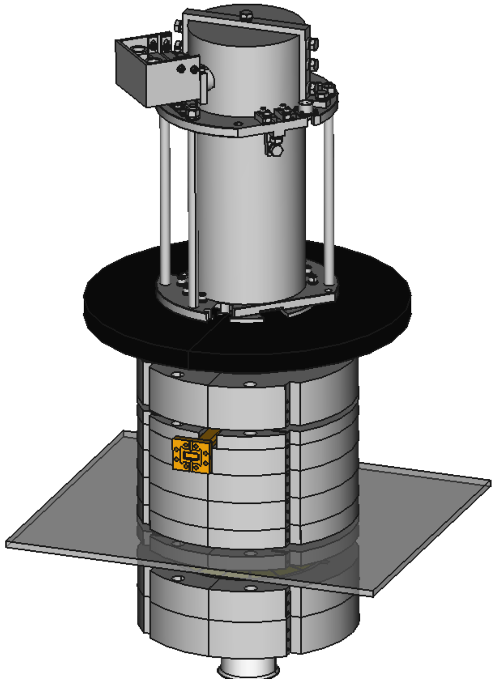
- New initiative inside IFAST program
- In collaboration with ELYTT
- Electromagnetic design checked against tube beam dynamics
- Mechanical design and procurement ongoing

- **HE tube with PM solenoid AC/RF source efficiency 35.5%**









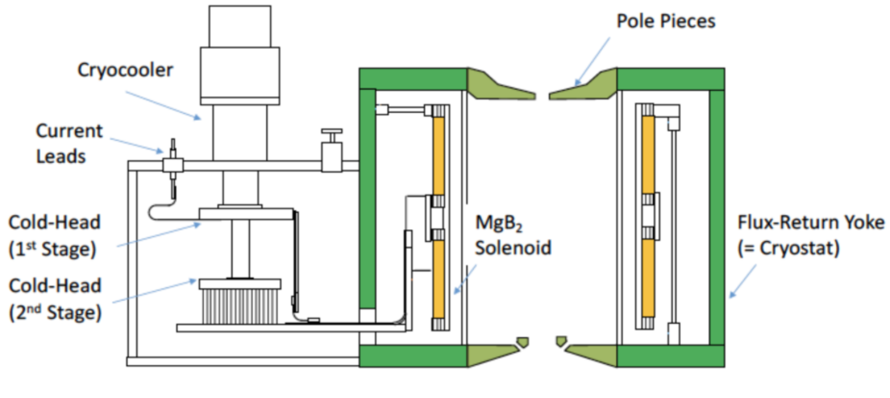
SC Solenoid for CPI VKX-8311A

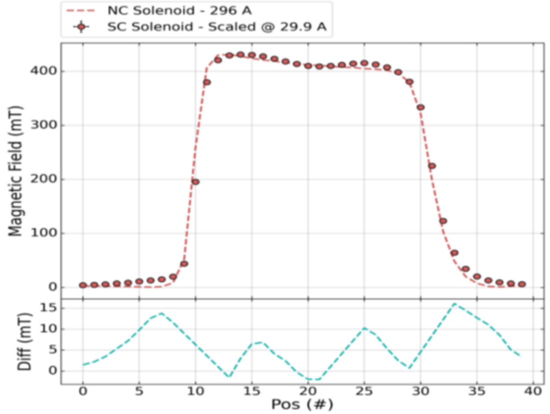
MgB2 conductor, conduction cooling

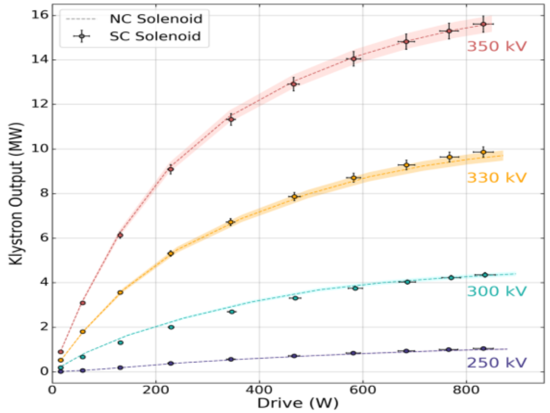
Collaboration with KEK and HITACHI

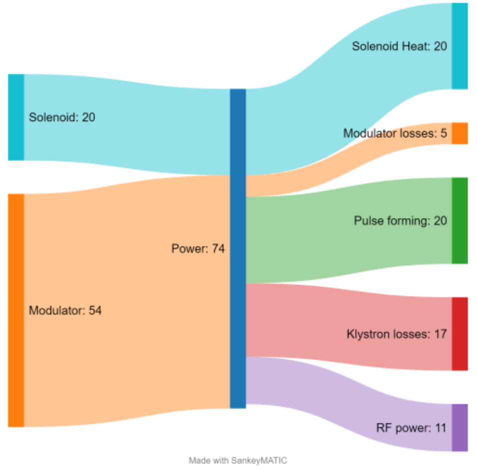
Currently operating at CERN since 2022

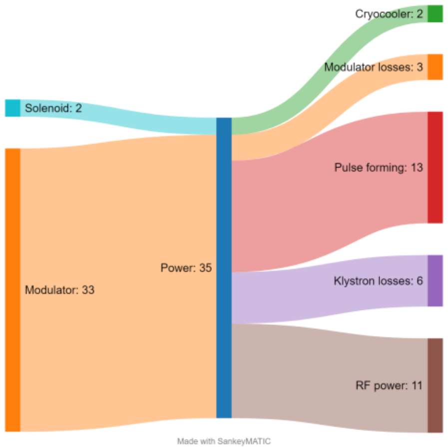
System efficiency from 21% to 31.7% in CLIC conditions









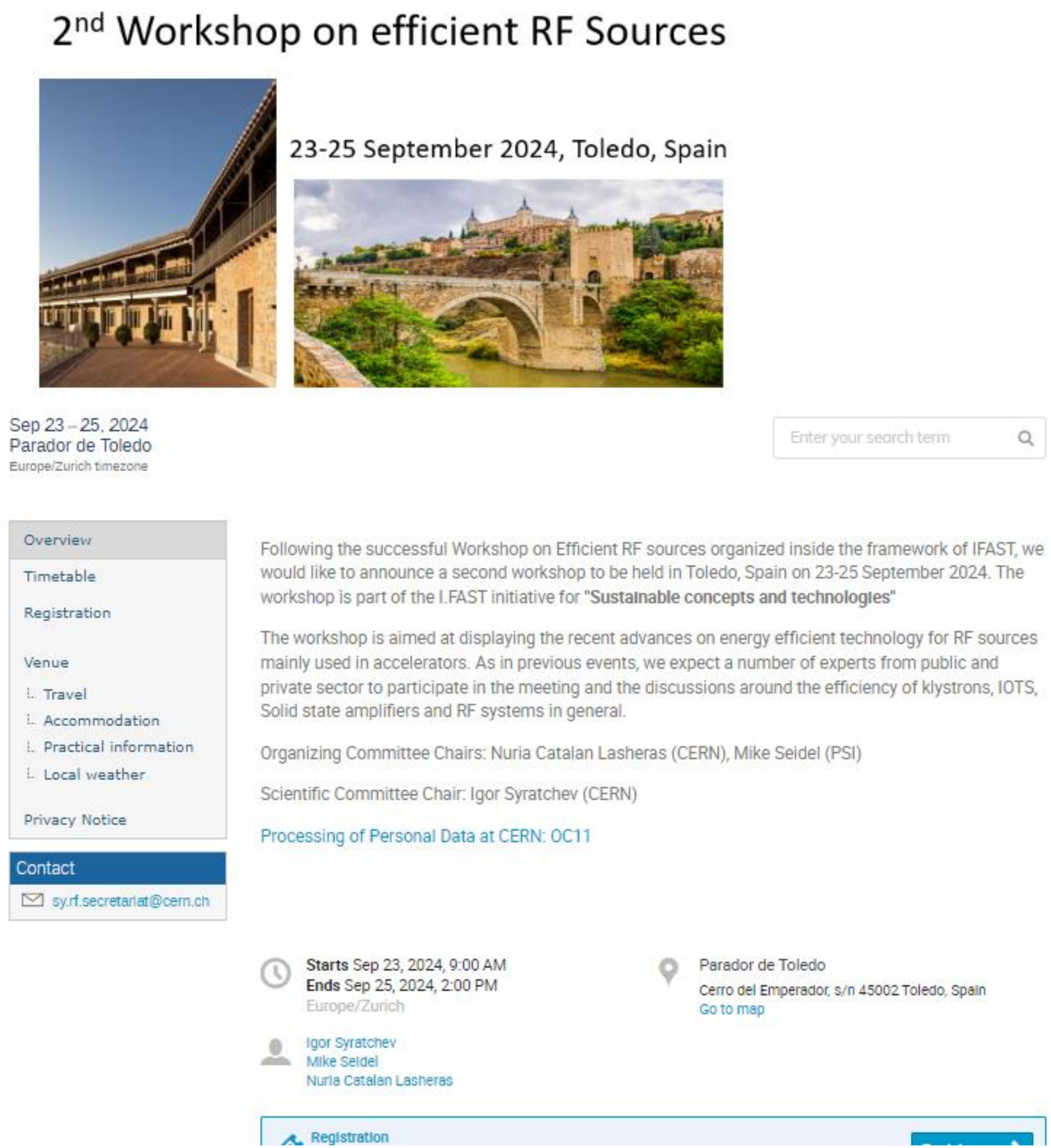


Second workshop on Efficient RF sources

Funded by IFAST and the high efficiency Klystrons program

https://indico.cern.ch/event/1407353/

Previous workshop: https://indico.cern.ch/event/1138197/



2nd Workshop on efficient RF Sources

23-25 September 2024, Toledo, Spain

Sep 23 – 25, 2024
Parador de Toledo
Europe/Zurich timezone

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sy.rf.secretariat@cern.ch

Following the successful Workshop on Efficient RF sources organized inside the framework of IFAST, we would like to announce a second workshop to be held in Toledo, Spain on 23-25 September 2024. The workshop is part of the I.FAST initiative for **"Sustainable concepts and technologies"**

The workshop is aimed at displaying the recent advances on energy efficient technology for RF sources mainly used in accelerators. As in previous events, we expect a number of experts from public and private sector to participate in the meeting and the discussions around the efficiency of klystrons, IOTS, Solid state amplifiers and RF systems in general.

Organizing Committee Chairs: Nuria Catalan Lasheras (CERN), Mike Seidel (PSI)

Scientific Committee Chair: Igor Syratchev (CERN)

Processing of Personal Data at CERN: OC11

Starts Sep 23, 2024, 9:00 AM
Ends Sep 25, 2024, 2:00 PM
Europe/Zurich

Parador de Toledo
Cerro del Emperador, s/n 45002 Toledo, Spain
Go to map

Igor Syratchev
Mike Seidel
Nuria Catalan Lasheras

Registration

Conclusions

High efficiency klystrons are no longer a dream	
Fruitful collaboration between industry and academia	
Important energy savings	
Very advantageous also from capital investment point of view	Less power, voltage, water cooling, etc
Attention should be paid to other systems!	Modulators, solenoid, LLRF, working point operation

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Thanks