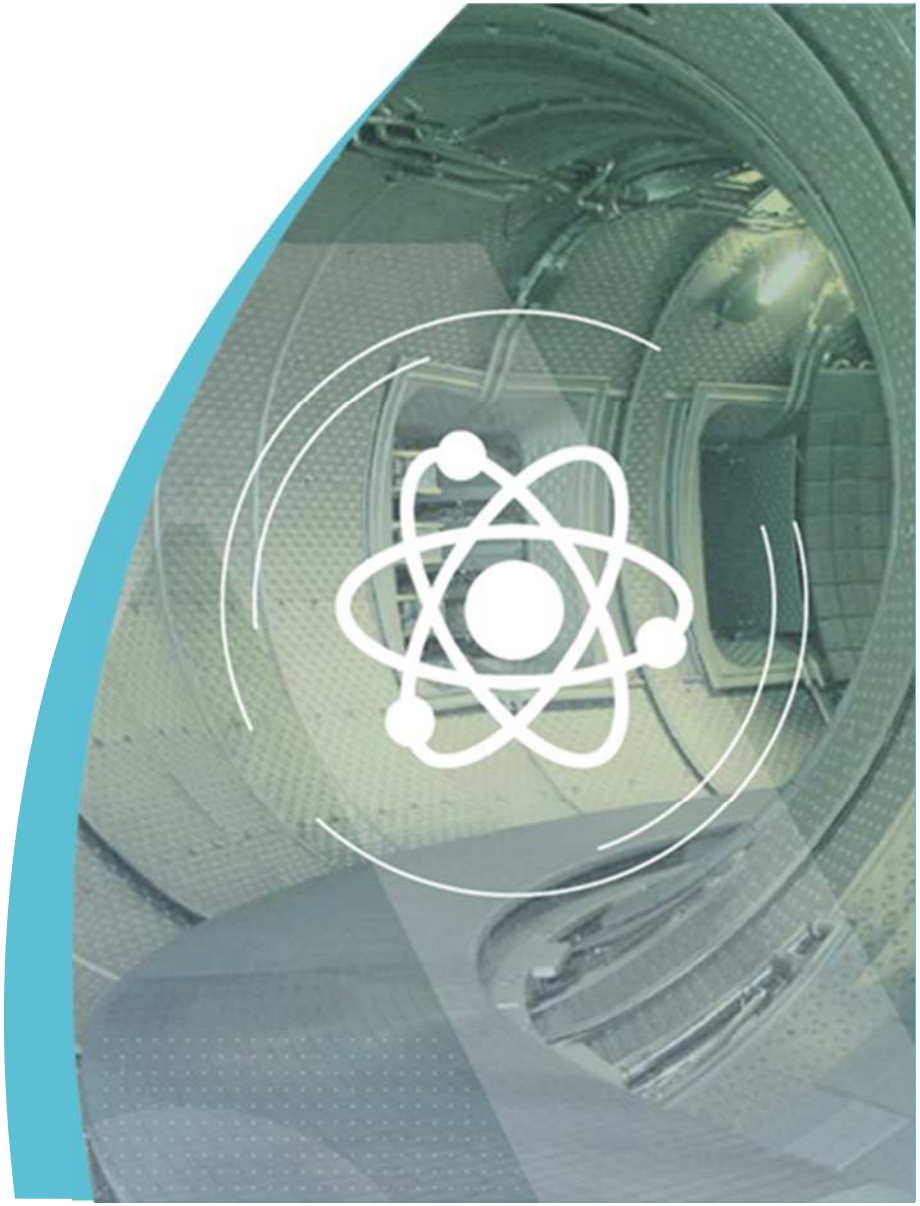
THALES

TOWARDS HIGH EFFICIENCY KLYSTRONS FOR LHC



Armel Beunas, Thales AVS MIS

Igor Syratchev, Olivier Brunner, Jinchi Cai CERN

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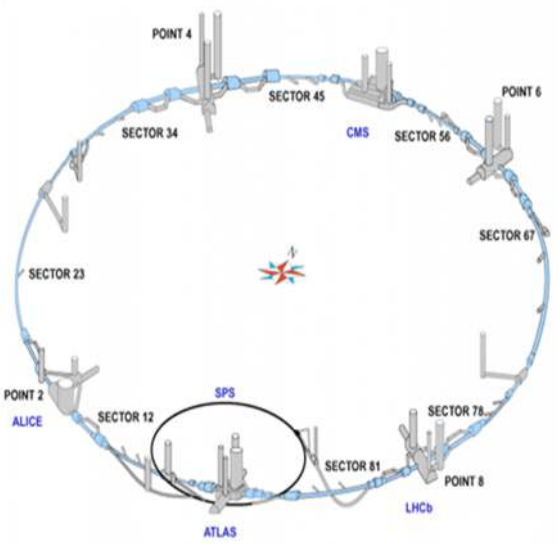
Outline

- Need for a higher efficiency LHC klystron
- TH2167 klystrons in operation at LHC
- TH2167 High Efficiency preliminary design
- Conclusion &Perspective

LHC ACS RF system

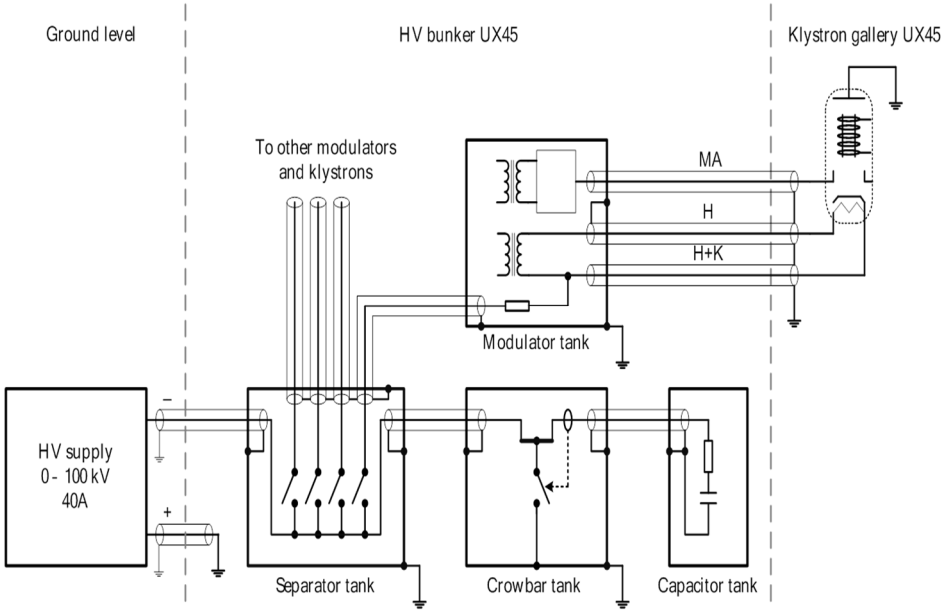
LHC ACS RF system partly located in the underground cavern UX45 at point 4

- x16 klystrons 400MHz 300kW and auxiliaries
- x16 circulators and RF ferrite loads
- x 4 HV bunkers each connected to 4 klystrons and including 4 modulators, a separator and a fast protection system



Pictures courtesy of CERN

x4 power converters (100kV, 40A) located in surface



TH2167 upgrade objectives

Total 16 THALES TH2167 klystrons

- 300kWCW saturated output power at 58kV 8.4A (62% efficiency)
- Presently operated at ~220kW (-1.5dB below saturation)

High Luminosity LHC upgrade will require more RF power for LS3

At least 350 kW saturated output RF power per klystron (the exact value is not yet 100% confirmed)

At an operating point compatible of the existing power supplies (~58 kV x 9A)

Need to increase the klystron efficiency to 67% min.

Picture courtesy of CERN

TH2167 upgrade objectives

Increase the beam wave interaction efficiency

- Implement a modified interaction structure designed by CERN with predicted efficiency in excess of 70%
- Minor B field profile modification to reduce beam scalloping and beam interception in output cavity

Minimize redesign

- Same gun and same coaxial RF window

Plug-in replacement

- All interfaces unchanged (same mechanical configuration)
- Re-use the supporting frame, the gun tank and HV connectors, the electromagnet, the coax to waveguide transition

FCC future needs could take benefit of TH2167 redesign towards high efficiency

Klystrons TH2167 400MHz 300kW

Prototype developed in 2002 and first batch of 16 tubes commissioned in 2008

30 klystrons delivered to CERN

- 16 installed POS with average life of 30,000hrs
- 14 spares TH2167 in stock (average life ~15,000hrs)

Main issues/modifications

- Localized overheating of collector conical end part due to a inhomogeneous water velocity distribution

⇨ reviewed the water jacket I/O configuration

- Air ionisation in the vicinity of the HV gun terminals

⇨ reviewed the corrona ring geometry to reduce DC electrical gradient

Klystrons TH2167 400MHz 300kW

Main design features

- Gun with modulating anode
- Five factory tuned copper cavities with third one operating on 2nd harmonic
- Output cavity coupled to a coaxial window with a water cooled coupling loop
- Coaxial to WR2300 HH waveguide transition
- Built-in electromagnet (natural air cooled)
- Built-in air tank
- Built in supporting frame
- Vertical or horizontal position

Main requirements

Parameters	Unit	Limits	TH2167 (current)
Frequency	MHz	nom	400.8
RF Output Power	kW	min	300 (mode II)
RF Input Power	W	max	60
Cathode Voltage	kV	max	58
Cathode Current	A	max	8.4 (mode II)
Anode Voltage	kV	max	35
-1dB Bandwidth at -1dB below saturation	MHz	min	+/- 1
Group delay	ns	max	120
Phase variation versus beam current	°/A	max	15
Phase variation versus beam voltage	°/%	max	10
Output power variation versus beam voltage at saturation	dB/%	max	0.1
Harmonics (2nd and 3rd)	dB	min	-30
Signal to noise ratio within bandwidth	dB	min	-60

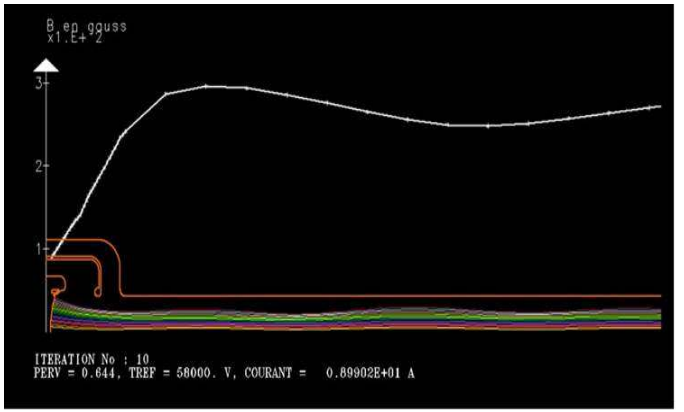
Klystrons TH2167 400MHz 300kW

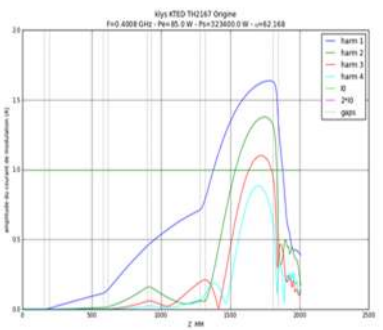
Beam optics

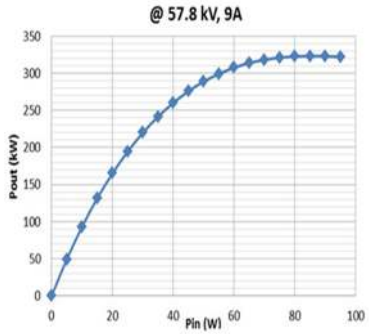
- Beam generated from a triode gun equipped with a modulating anode
- Low convergence laminar beam with a theoretical radius of 15 mm; envelope ripple is about 25% (= rmax - rmin / rmoy)
- Focussing magnetic field = 275 Gauss
- Collector power handling = 522 kW (58kVx9A, locally 500W/cm² power density)

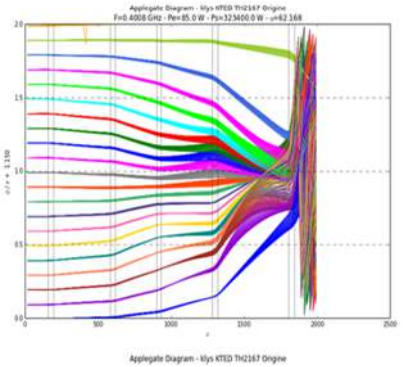
Interaction structure

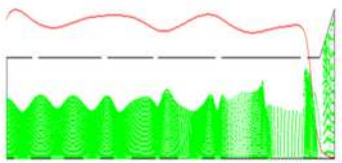
- 322 kW power predicted with KLYS2D at 57.8kV x 9A with 62% efficiency and 36 dB gain; consistent with measured values





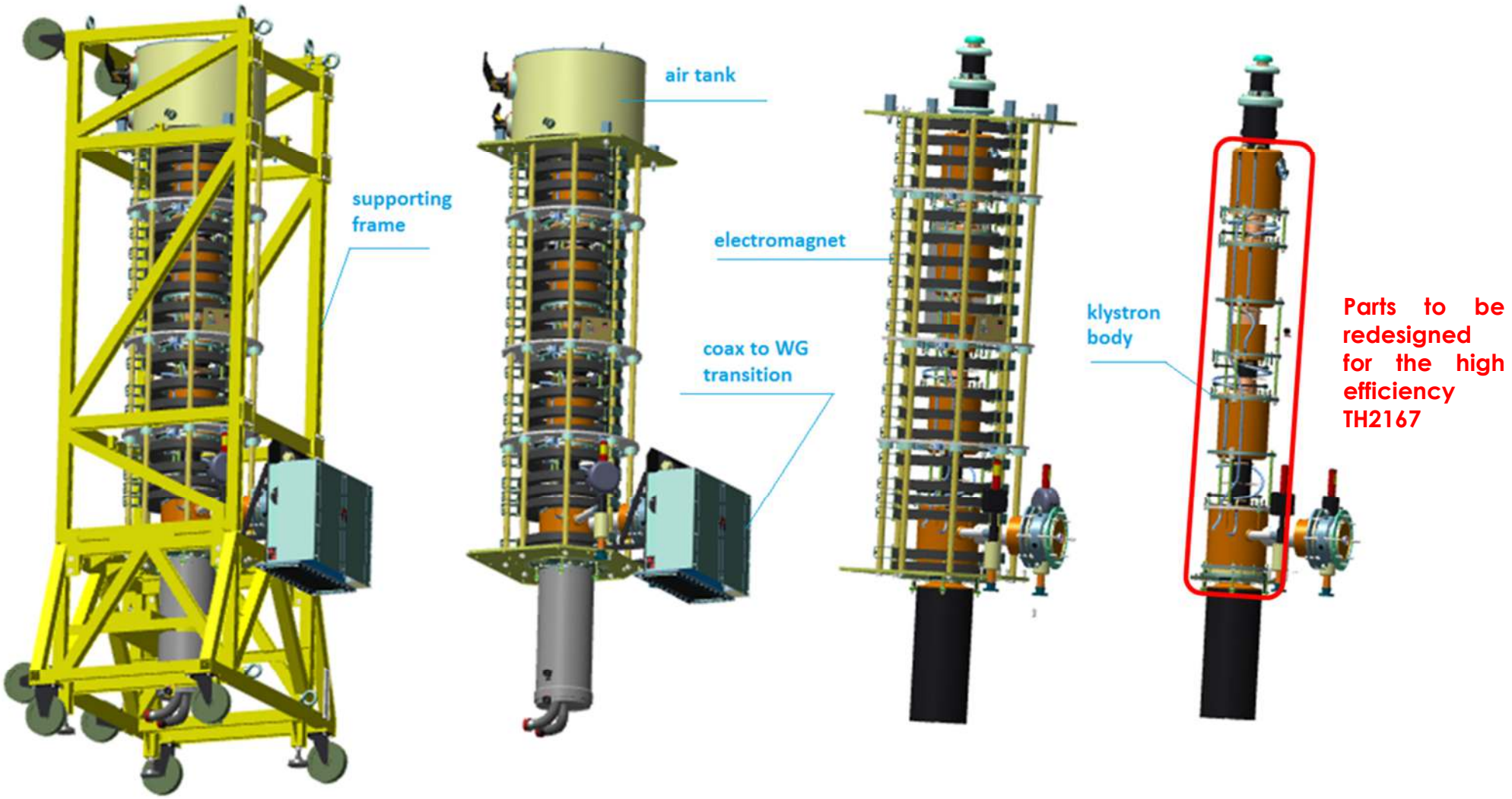






Klystrons TH2167 400MHz 300kW

Re-use the housing parts



TH2167 EFFICIENCY UPGRADE

New high efficiency beam wave interaction structure

- Designed by CERN (Igor Syratchev and Jinchi Cai) with 1.5D klystron CERN code KlyC
- CSM (Core oscillation Method) structure with 6 cavities including a second harmonic cavity in 3rd position and a third harmonic cavity in 4th position
- Same beam and drift tube radii than TH2167 (b =15mm, a= 25mm)
- 174 mm shorter than the initial structure (1648 mm)

NEW TH2167 STRUCTURE

cavity	F0 (MHz)	R/Q (Ω)	gap (mm)	Qx	z (mm)
1	400.2	136.5	36	179	0
2	403.7	144.2	36		423
3	795.2	76.7	13		609
4	1192.6	80.3	14		854
5	412.4	135.5	42		1217
6	399.5	146.6	38	30	1474

INITIAL TH2167 STRUCTURE

F0 (MHz)	R/Q (Ω)	gap (mm)	Qx	z (mm)
399.4	150	37.3	170	0
405.2	150	36.7		423
793.9	102	30.7		738
409	150	36.6		1124
402	140	38.7	35	1648

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TH2167 EFFICIENCY UPGRADE

- Predicted power is 345 kW at 54kV 9A with and a gain of 36.5 dB and 71% efficiency
- 9 points (%) more than the initial structure

Beam Para.	eff. optimizer
Beam Voltage (kV)	54.000
Beam Current (A)	9.000
Outer Radius (mm)	15.000
Inner Radius (mm)	0.000
Tube Radius (mm)	25.000
Beam Number	1
Layer Number	4

Accuracy Setting	plot setting
Space Charge Field Order	8
Division Number in λ_e-	256
Division Number in RF	126
Max Iterations	60
Iteration Residual Limit	0.0001
Iteration Relaxation	0.5

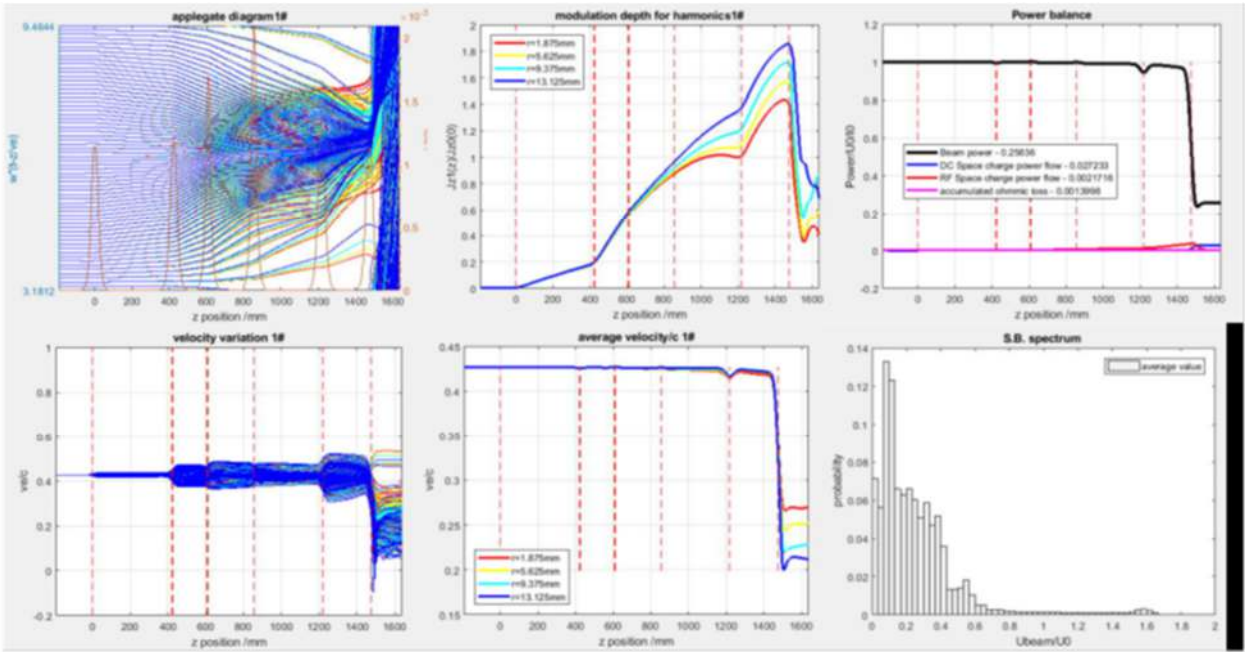
Reflection from output: amp 0, degree 0

Excitation source: Pin (W) 80.000, degree 360.000, chirp 0.000

Simulation results summary

Pout=	345.5	kW	Gain=	36.35	dB
Eff.RF=	72.58	%	Eff.BI=	71.09	%
Re.RF=	8.138e-05		Re.EI=	0.00112	
|J1/J0|.i=	1.432		|J1/J0|.o=	1.859	
ve/c.min=	-0.1171		|Gama|=	0.6325	
Successful iteration	Yes		pha.s=	12.72	°

[Vg](kV)
3.2137
13.0055
11.5121
10.1726
23.3335
55.6846

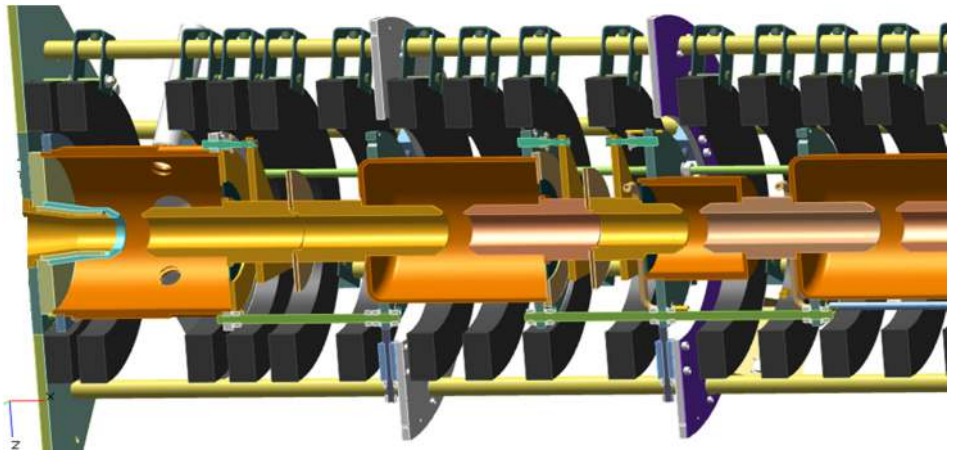


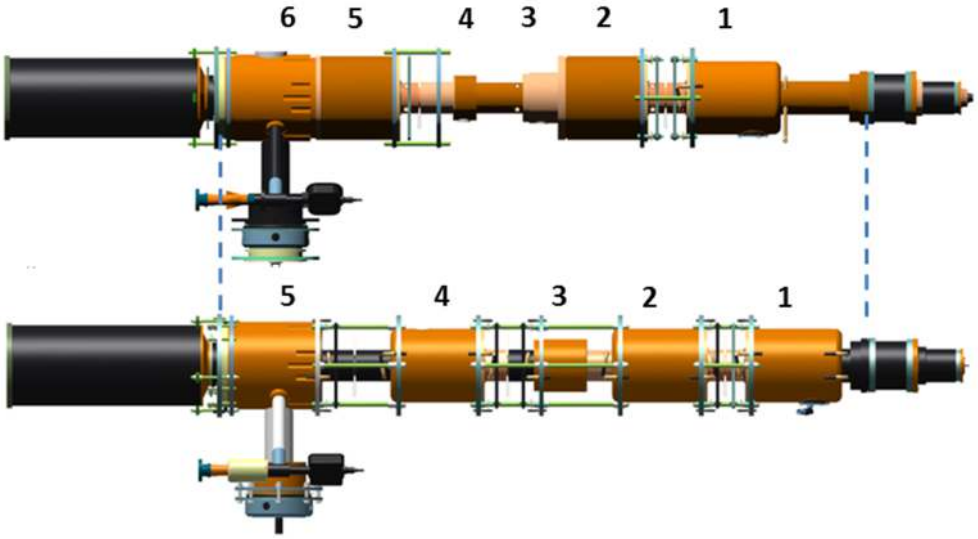
Picture courtesy of CERN

TH2167 EFFICIENCY UPGRADE

Mechanical design changes

- Very first design of cavities with RF parameters from KlyC (gap, frequency, R/Q)
- Short drift tube length between penultimate cavity n°5 and output cavity n°6 and to a lower extent between cavities n°2 and n°3
  - increase cavity outer diameter to shorten cavity height (limited by coil inner diameter)
  - use dissymmetric gaps and shape the cavity noses to compensate R/Q reduction

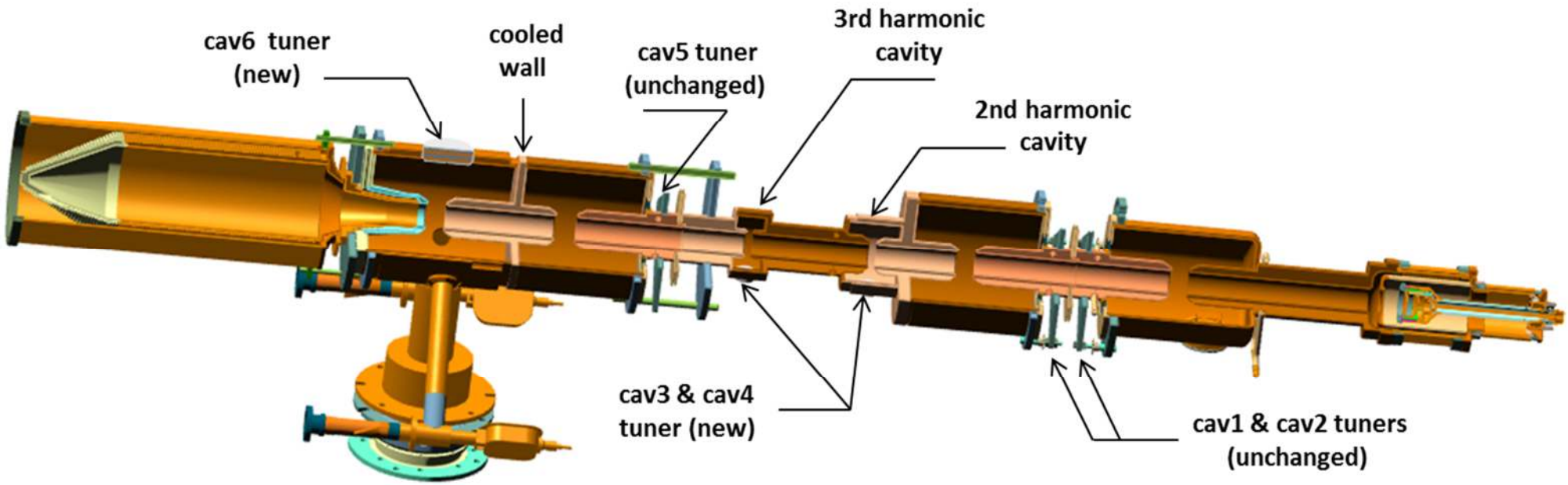




TH2167 EFFICIENCY UPGRADE

Change the assembling technology (cavities 5-6)

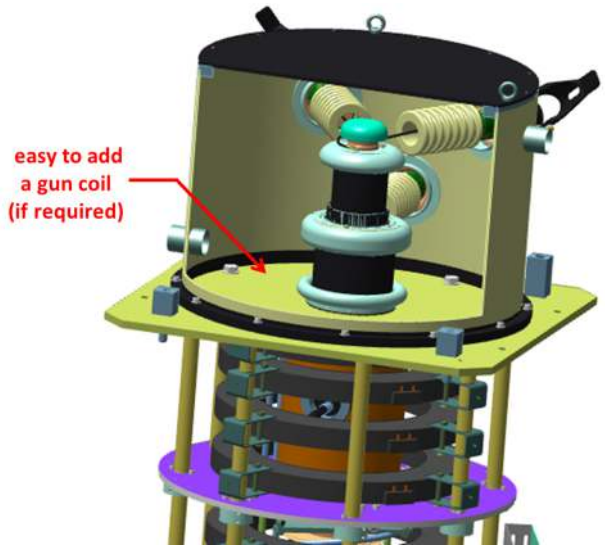
- Welding is no more practicable (no room)
- Braze cavity 5 and 6 together to constitute a single sub-assembly
- Need to redesign the output cavity tuner (radial position)
- Need to integrate a cooling circuit in the separating wall (15 mm thick)
- Braze cavity 2, 3 and 4 together to constitute a single sub-assembly
- Need to redesign the tuner of 2nd harmonic cavity because of higher frequency sensitivity to gap dimensions (radial position)

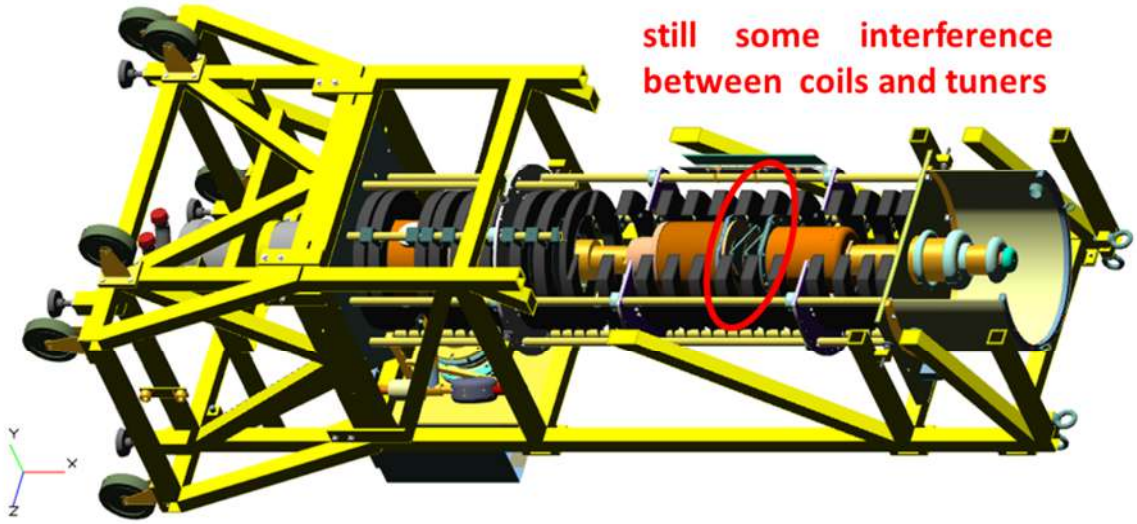


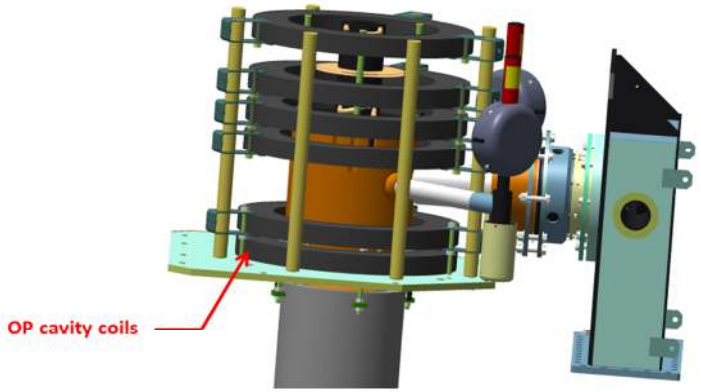
TH2167 EFFICIENCY UPGRADE

Electromagnet modifications

- Possible to implement larger coils around the output cavity to increase the magnetic field in case the beam interception is too large (to be confirmed with 2.5D simulations).
- Also possible to add a gun coil in the air tank to better adjust the cathode fied and to reduce the beam ripple (to be confirmed with 2.5D simulations).
- Re-adjust the position of some coils to allow the access to cavities tuners.







TH2167 EFFICIENCY UPGRADE

Next step

- Additional beam optics simulation with optimized magnetic field profile to reduce the beam ripple (be as close as possible to Klyc assumptions)
- Further beam wave simulations with Klys2D, Klyc, Magic and/or CST to validate the proposed design
- HFSS design of the 2nd and 3rd harmonic cavities (including tuners)
- Mechanical design of the whole interaction structure
- Modification of the electromagnet (additional gun coil, more field near the output cavity, fix the interference betwen some coils and some tuners)
- Increase collector ID (10%) to provide larger margin in case more beam power is needed to achieve the required RF output power

Conclusion & Perspectives

- TH2167 klystron saturated output power limited to 300kW CW
- Need to improve the beam wave interaction efficiency to increase power up to 350 kW with an operating point compatible of existing power supplies
- Six cavities CSM structure designed by CERN with predicted efficiency in excess of 70%
- Preliminary mechanical study have shown that the CERN structure can be integrated in the existing tube housing
- Plug-in klystron system replacement and re-use of external sub-assemblies (supporting frame, electromagnet, gun tank, output transition..)
- High efficiency TH2167 version will be a CSM proof of concept device for next FCC klystron
- On going discussion with CERN to commit into a development collaboration

THANK YOU FOR YOUR ATTENTION

Fifth International Future Circular Collider (FCC) Conference, Brussels, Belgium, 24 - 28 June 2019