UPGRADE OF THE EUROPEAN ITER 170 GHz 1 MW CW INDUSTRIAL GYROTRON (TH1509)

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Outline

01

Introduction

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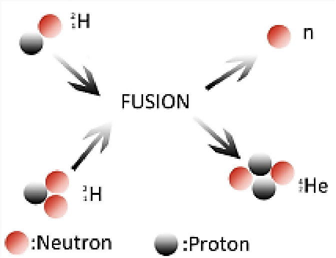
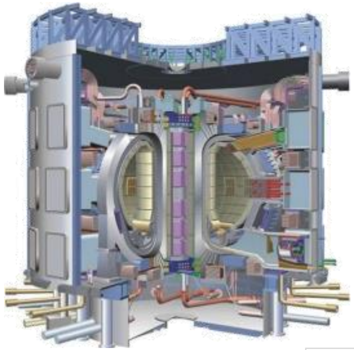
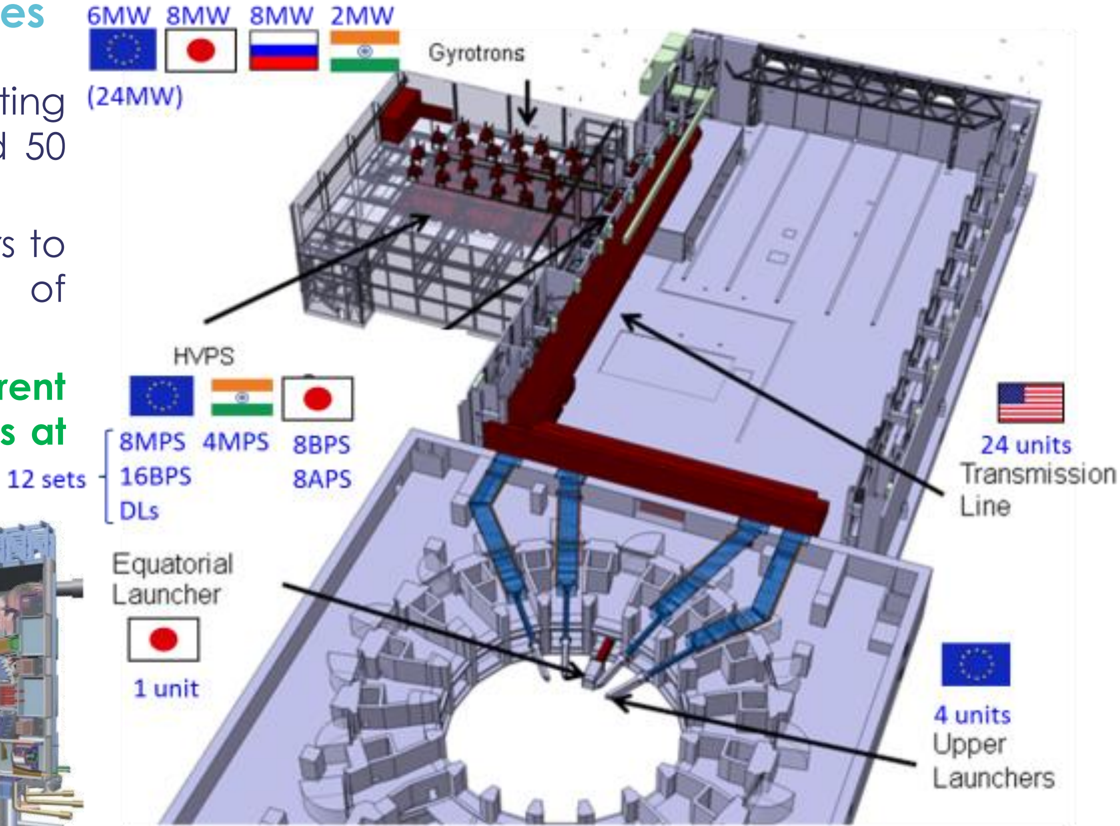
Introduction

ITER Tokamak heating main features

- Ion Cyclotron Resonance Heating (ICRH), Tetrode or Diacrode around 50 MHz
- Neutral Beam Injection. Two injectors to deliver two deuterium beams of 16.5 MW at 1 MeV particle energies
- **Electron Cyclotron Heating and Current Drive (ECH&CD) system: 24 gyrotrons at 170 GHz 1 MW CW**







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Introduction

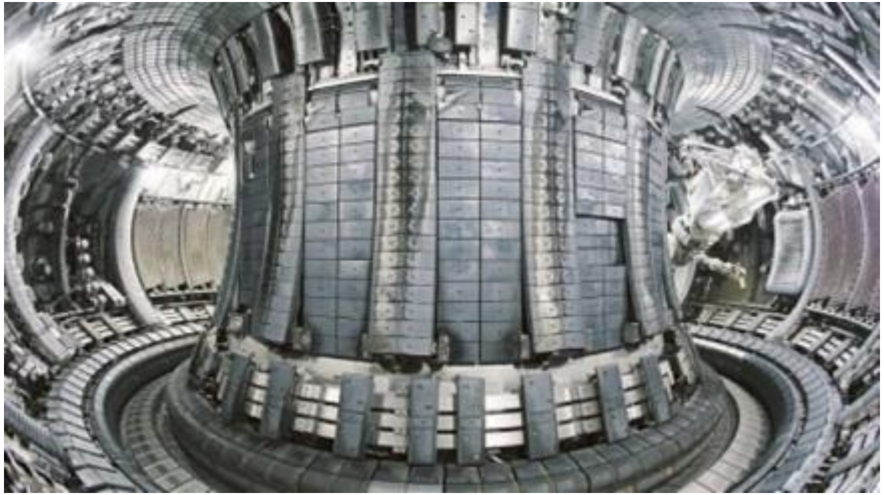
European Gyrotron Team

- The European contribution managed by the European Joint Undertaking for ITER, Fusion for Energy (F4E), under the control of EURATOM Agency.

- Fusion for Energy (F4E) → Tube specification, Magnet design (FUSION FOR ENERGY)
- Karlsruhe Institute of Technology (KIT), → RF Design, Gun optimization (KIT Karlsruher Institut für Technologie; EPFL)
- Swiss Plasma Center at EPFL Lausanne (SPC),
- National and Kapodistrian University of Athens, → Beam Tunnel, Cavity cooling, Test set (National and Kapodistrian University of Athens; Politecnico di Torino; ISTP Consiglio Nazionale delle Ricerche)
- Politecnico di Torino (PoliTO)
- Istituto per la Scienza e Tecnologia dei Plasmi (ISTP-CNR)
- THALES Microwave and Imaging Subsystems → Technological design (THALES)

02

Tube design and technical details



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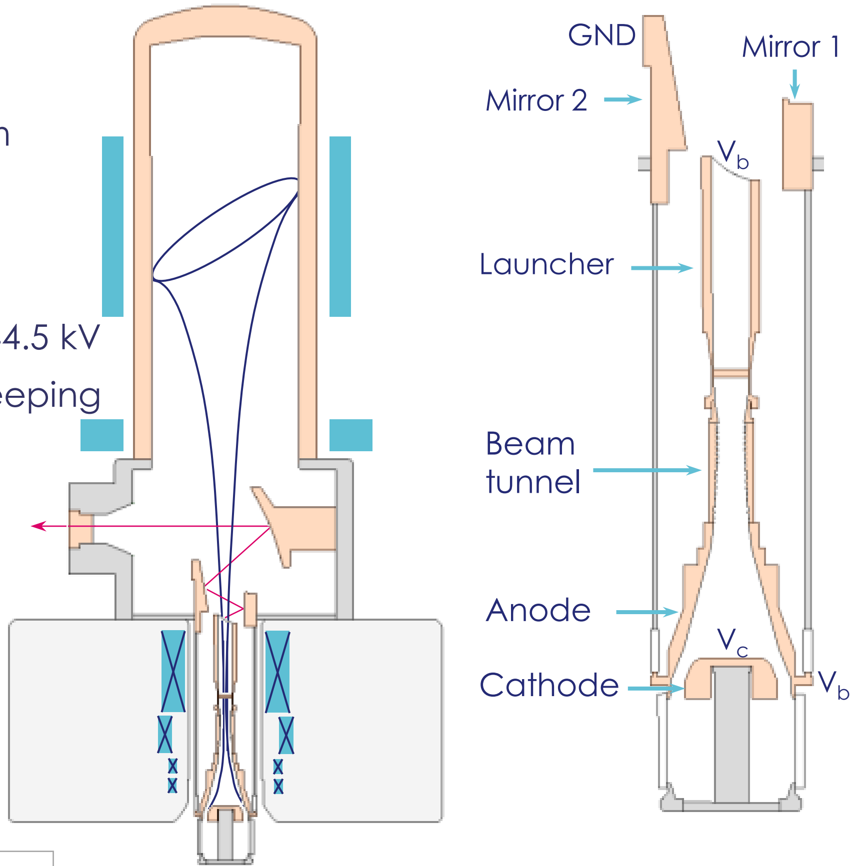
Tube design and technical details

Main design requirements

- Electron beam features compatible with ITER HV PSU
- Cavity mode selected to optimize electron beam coupling at 170 GHz with reduced Ohmic losses

Design baseline

- Depressed collector configuration: V_b = +35 kV, V_c = -44.5 kV
- Improved collector cooling and advanced beam sweeping
- Gaussian TEM beam lateral output
- Specific CVD diamond window
- Four coils SCM
- Diode-type MIG with reduced gun-cavity distance
- Specific corrugated BeO-SiC beam tunnel
- $TE_{32,9}$ cavity mode with B_c =6.78 T
- Specific tapered launcher



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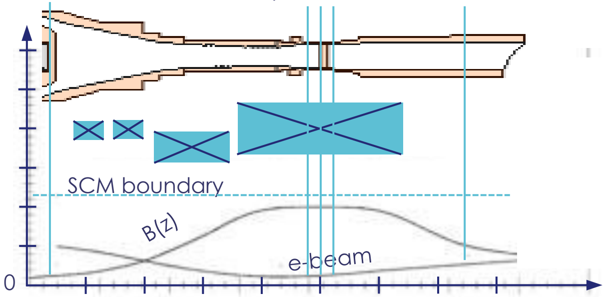
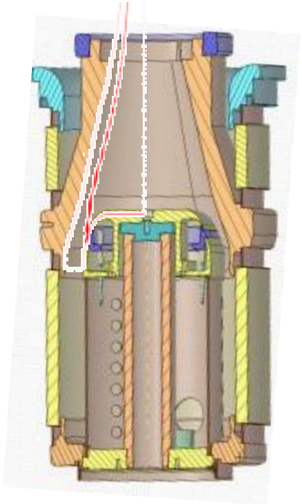
Tube design and technical details

Magnetic configuration

- Main coils for the cavity field
- Reversed bucking coil for independent field control and reduced cathode to cavity spacing
- 2 Gun control coils
- low ∝ mitigates parasitic modes and magnetic electron trapping





Main Design Parameters		
	HVOP	LVOP
Beam current I_b	40A	45A
Average pitch factor <α>	1.29	1.22
Cathode voltage	-44.5kV	-41.0 kV
Collector depression voltage V_b	35 kV	30 kV
Nominal accelerating voltage V_a	79.5 kV	71.0 kV

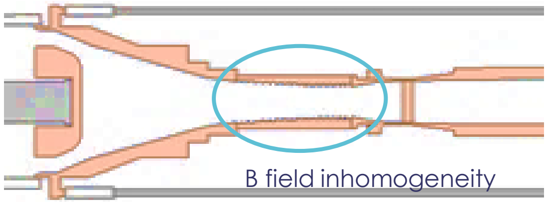
Electric configuration

- Robust technology compatible with fast switch on/off
- Flexible DC input (two working points: HVOP, LVOP)
- Diode MIG gun
  - Beam calculated with ESRAY and ARIADNE (KIT)
  - Electrode designed with E-field safety margin
  - Mature design for concentricity and electronic homogeneity

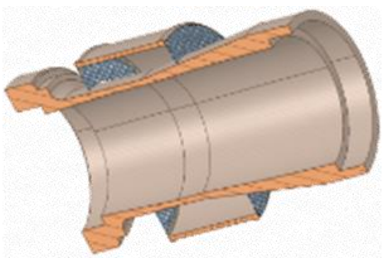
Tube design and technical details

Beam tunnel

- Energy spread calculated with 2D time-dependent code g2DRZ developed by SPC
- Minimized cathode-cavity distance for minimizing energy spread
- EU patent (KIT): cascade of dielectric (BeO–SiC) and indented metal (copper) rings



Large variations of beam properties (instabilities) ⇒ Spurious oscillations E_{beam} spread ⇒ η↓



Main Design Parameters	
Cavity mode	$TE_{32,9}$
Axial magnetic field B_c	6.78 T
Cavity mode purity	99.9 %
Long pulse operative frequency F_0	170 ± 0.3 GHz

Interaction cavity

- Interaction studied by the European code EURIDICE
- Same beam radius at cavity for both working points
- Non linear up-taper to the launcher
- Glidcop structure: conductivity/thermal expansion compromise
- EU patent (THALES): Raschig rings circuit pressure drops and mass flow compromise
- Enhance exchange surface and *h* by turbulent water flow in a porous media

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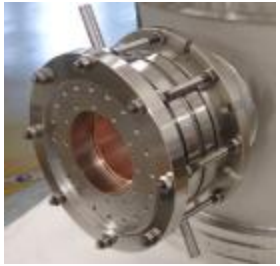
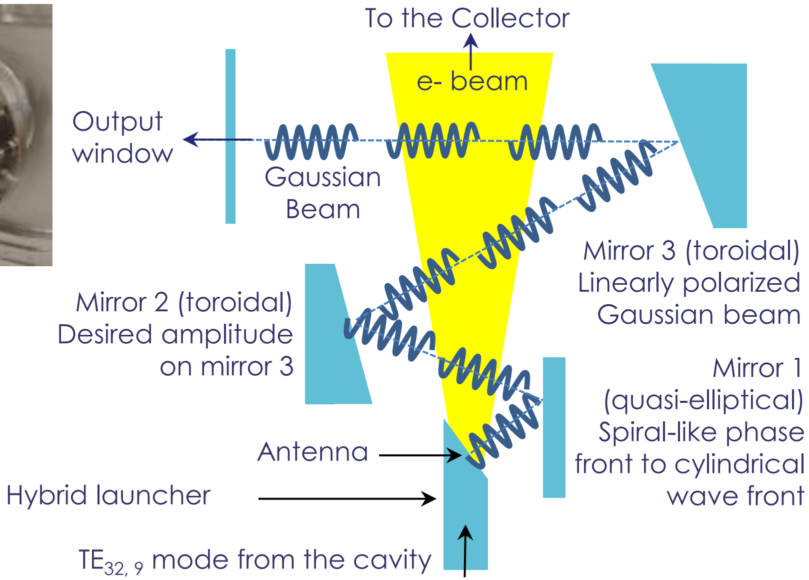
Tube design and technical details

Quasi-optical mode converter

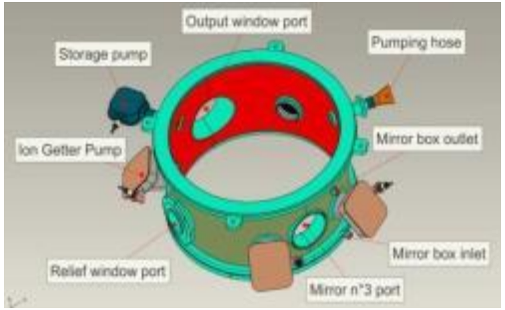
- A slightly tapered helically cut hybrid launcher (helical perturbations dependent by λ(z))
- The tapering reduces the quality factor to suppress spurious oscillations in the launcher itself





CVD-diamond window

- Edge-cooled single-disk CVD-diamond window for low-diffraction losses
- 97 % Gaussian TEM purity at the window



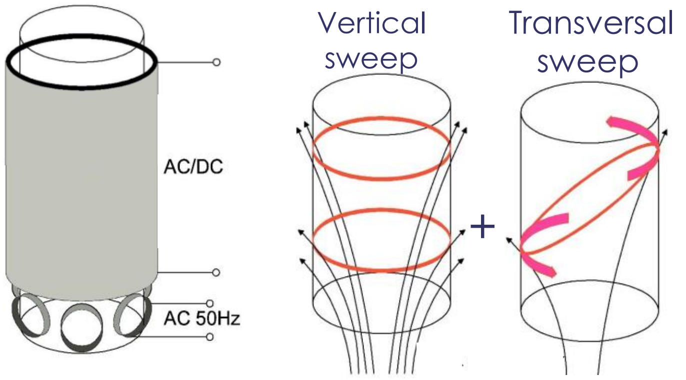
Stray radiation management

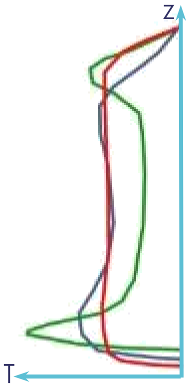
- Stray radiation partially extracted by a dedicated relief-sapphire window
- Remaining radiation dissipated onto the mirror box walls
- Mirror box cooled by a water filled double wall

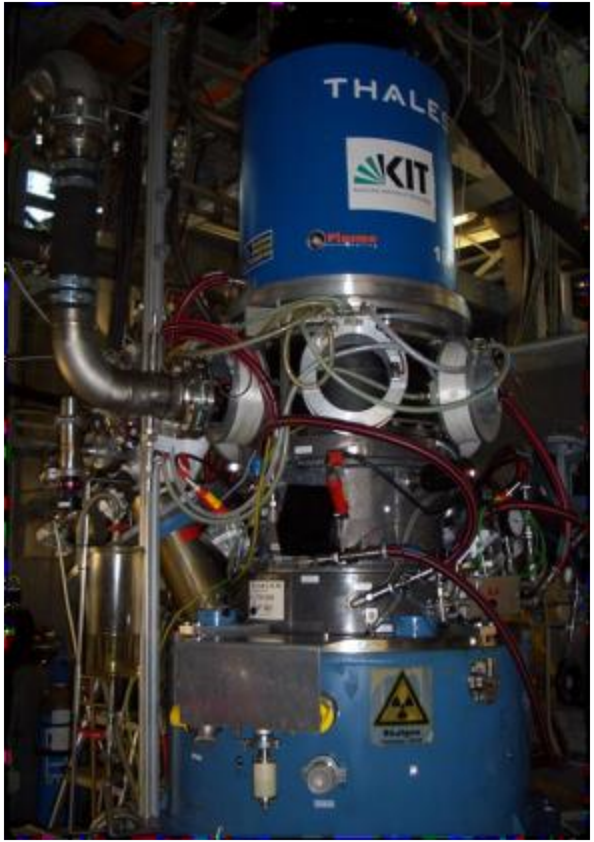
Tube design and technical details

Collector

- Designed to dissipate the full electron beam power up to 2 MW
- Power dissipation capability ~ 1 kW/cm²
- Max temperature < 300°C
- EU Patent (KIT/IPP): optimized beam spread by axial and transversal magnetic sweeping







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First prototype test result summary

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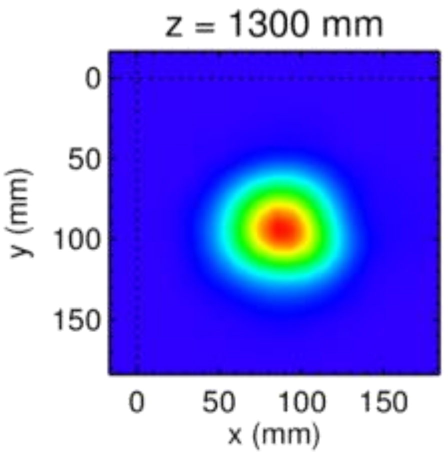
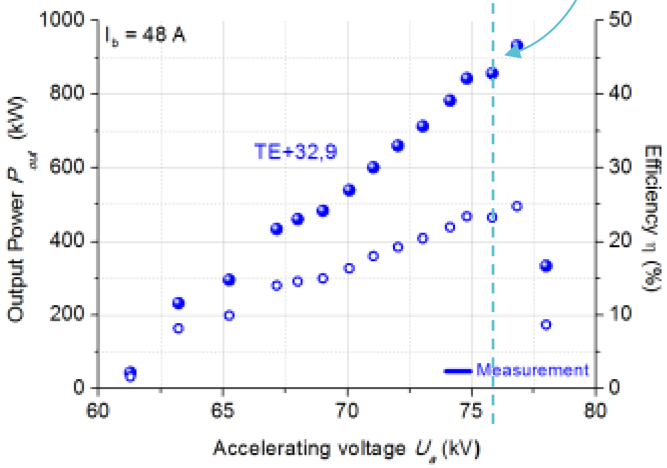
First prototype test result summary

Short pulse test at KIT in 2016

- 1 MW P_{out} for 5 ms pulse (I_{beam}~48 A)
- 850 kW for 180 s - stable at 170.22 GHz (pulse duration limit of the KIT test stand)
- Measured frequency shift: 400 MHz at 800 kW
- Verified modulated regime up to 5 kHz for neoclassical tearing mode (NTM) stabilization





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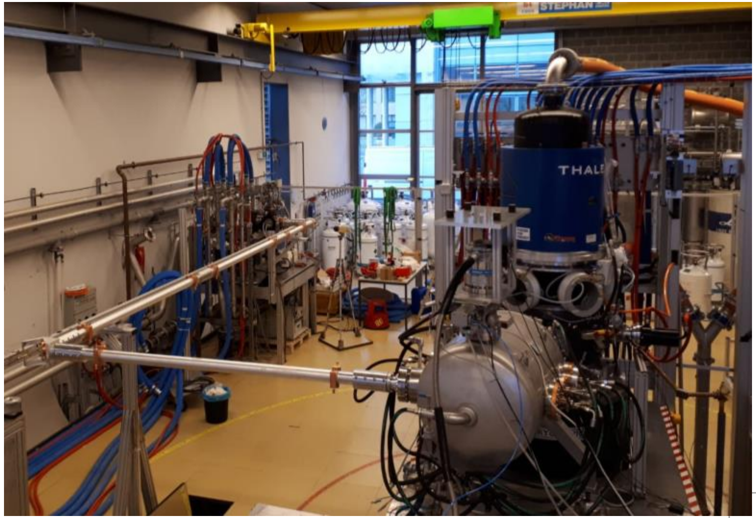
First prototype test result summary

CW test at EPFL-SPC in 2018

- Operation in ITER relevant conditions (MOU, corrugated waveguide transmission line)
- Results similar to 2016 campaign
  - Maximal pulse length 250 s, limited by external factors (overheating in MOU)



P ~ 0.8 MW

Item	Target value & range	Outcome (EGYC)
HV design of the gyrotron	96 kV for cathode	**Validated**
Nominal frequency	170 ± 0.3 GHz	**Validated**
TEM_{00} mode purity at the window	>95%	**Validated**
Alignment of the output RF beam	<10 mm	**Validated**
Pulse length and stability of vacuum & temperature	180 s	**Validated**
Vacuum level, temperatures and stray losses	Operation at 180s compatible with CW conditions	**Validated**
Nominal output power	1.0 MW	0.8 MW < P < 1MW
RF power generation efficiency (in depressed-collector operation)	50%	38 % < η < 50% (Limited body voltage)

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04

First prototype expertize

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First prototype expertize

Subject

- While waiting for test stand repairing, the 1st prototype has been opened for status investigations

Collector and mirror box

- Standard operation signatures
- Collector perfectly vacuum tight
- Minor mechanical deformations
- No traces of typical process (nickeling, sand-blasting..)
- Four ion getter pumps perfectly maintained and isolating structure still compatible with 5 kV operation

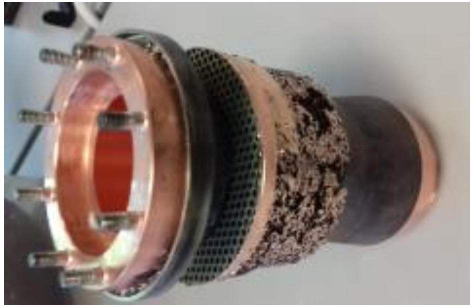
Gun and beam Tunnel

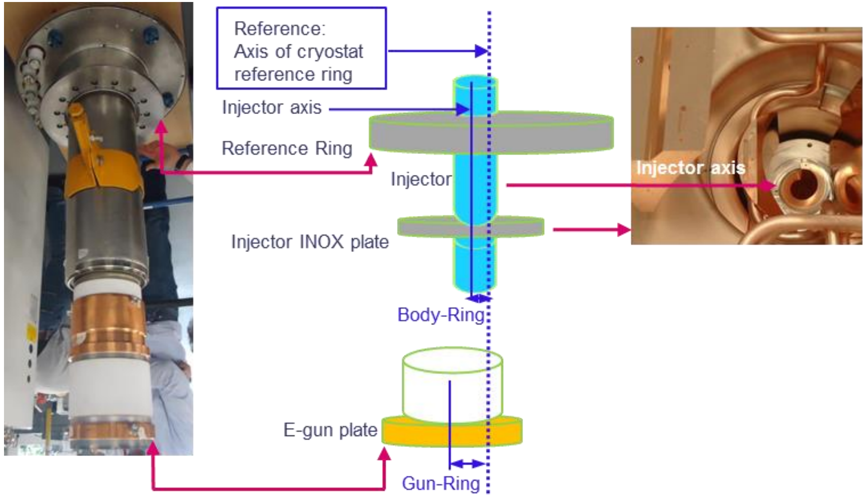
- No arcing, outgassing or oxidation signatures
- Emitter homogeneity ΔT≤19°C
- Considerable emitter shrank. Cause production yield: in~0.1% cases after high temp cycles
- Beam tunnel in excellent status

First prototype expertize

Interaction cavity

- Minor overheating signatures
- Plastic deformations in the order of 10µm radial deviation





Mechanical measurements

- Robotized arm measurements of subassemblies respect to desired position
- Base plate ring as reference element
- Misalignments detected on body and gun. Cause: severe constraints exerted by complex hydraulic circuit (served for isolated cavity calorimetry)

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First prototype expertize

Expertize resume

- Body misalignment compensated by adjusting gyrotron position in the SCM
- Defects can critically influence the output capability:
  - Emitter misalignment
  - Cavity deformation

Sub assembly	Diagnosis	Status
Collector	Minor deformation	✓
Vacuum pumps	Clean, tight	✓
Mirror box	Clean, tight, no arcing	✓
Body (Mirror plate)	Misalignment	✘
CVD Window	No oxidization, no arcing	✓
Relief window	Clean, tight	✓
Cooling circuits	Clean, tight	✓
Launcher	No oxidization, no arcing	✓
Cavity	Deformations, Misalignment	✘
Beam tunnel	No oxidization, no arcing	✓
Electron gun	Misalignment, Emitter shrinking	✘

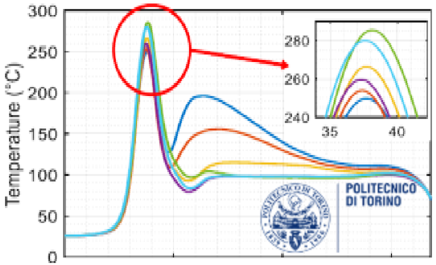
05

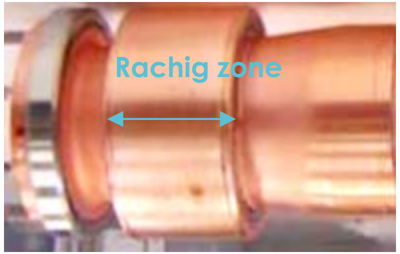
Gyrotron evolution

Gyrotron evolution

Alignment improvement

- Simplification of the cooling circuit to reduce mechanical constraints exerted by pipes
- Implementation of systematic iterative measurements after each welding





Electric feedthrough improvement

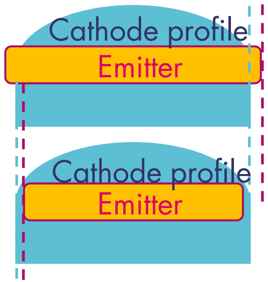
- Increase feedthrough dimension and distances from shield to permit higher HV depression
- Optimized shape: the max E field is 4.5kV/mm @ 35 kV of body voltage

Cavity improvement

- Extended interaction region => P_{cav}+15%
- Extended Raschig zone towards the up-taper
- Adoption of a qualified (TH1510-like) up-taper structure => improve water speed

Emitter improvement

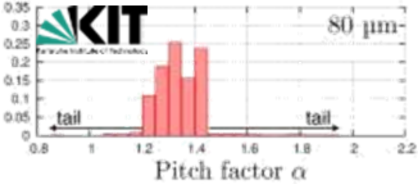
- Cathode upgrade with improved centering structure
- Adoption of cathode checking procedure before and after activation



Emitter inside: Safer

Emitter outside: Dangerous

- Pitch factor tails
- Transverse velocity spread



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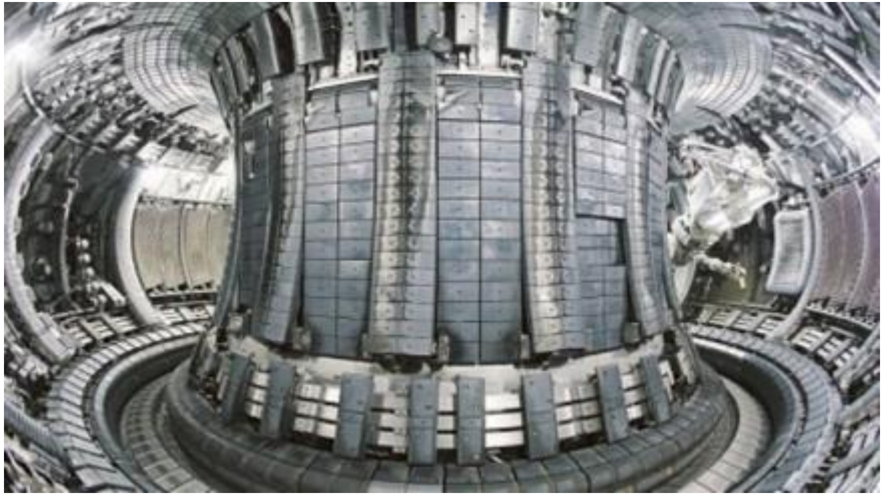
06

Summary and perspective



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Summary and perspective

Continuous progress

- First 170 GHz ITER gyrotron TH1509 prototype manufactured, tested and expertized
- The upgraded prototype, TH1509U is being manufactured and it will be tested in 2020
- Two dual frequency (84-126 GHz) gyrotrons operative on TCV tokamak at EPFL-SPC
- Nine 140 GHz gyrotrons daily energizing the W7-X stellarator with outstanding reliability

84/126 GHz Dual frequency gyrotron for TCV at EPFL

TH1507 Upgrade
- 1.5 MW
- $TE_{28,10}$
- 56 A e-beam
- hybrid launcher
- Improved collector
- 175GHz @ $TE_{36,12}$

170 GHz Gyrotron prototype for ITER

Final considerations

- Example of synergy between academic institutions and the industry to overcome the state of the art
- Important contribution to fusion community
- Large confidence in the robustness of the future ITER and TCV Thales programs and the upstarting W7-X 1.5 MW tube upgrade

Summary and perspective

Gyrotron Workshop: New assembly clean room

- Clean room dedicated to scientific products
- Modernization and new assembly tools for klystron and gyrotron manufacturing
- Increase the production capability

Gyrotron Workshop: New assembly clean room

- Precise alignment of sub-assemblies during final integration
- High temperature bake-out for high vacuum quality and quick tube conditioning
- Final 3D control before shipment

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Summary and perspective

Actual delivered tubes

- 2003-2011: 10 TH1507 tubes delivered (140 GHz)
- 2013-2017: 1 TH1509 prototype delivered (170 GHz)
- 2016-2019: 2 TH1510 tubes delivered (84/126 GHz)

Model	TH1507	TH1509 (Proto 1)	TH1510 (Tube 1)
Frequency (GHz)	140	170	84 - 126
Pulse length (s)	1800	3600	2
Measured P_{out} (MW)	1.0	$0.8 < P < 1.0$	0.95 – 1.0
Measured Efficiency	40%	$38\% < \eta < 50\%$	35% - 36% (Undepressed)
Interaction Mode	$TE_{28\ 8}$	$TE_{32\ 9}$	$TE_{17\ 5}$ - $TE_{26\ 7}$
Acceleration Voltage	80	80	80
B_{cav} (T)	5.6	7.0	3.0-5.0
Beam Current (A)	40	40	40

The 140 GHz gyrotron for the stellarator W7-X

The European 170 GHz gyrotron prototype for ITER

The true dual frequency gyrotron
~Same power output by two different interaction modes

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On behalf the TH1509 gyrotron team

FUSION FOR ENERGY

EUROPEAN GYROTRON CONSORTIUM

KIT IHE
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EPFL

Εθνικό και Καποδιστριακό Πανεπιστήμιο Αθηνών
National and Kapodistrian University of Athens

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