International Vacuum Electronics Workshop 2024

ITG Information Technology Society within VDE

August 28–30, 2024, Bad Honnef, Germany

Industrial Qualification of the THALES TH1509U European 170 GHz 1 MW CW Gyrotron

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Outline

1. **Nuclear fusion: Enabling technologies**
2. Gyrotron: Features & Thales baseline
3. TH1509U: Requirements & design
4. TH1509U gyrotron: Design validation and prototype tests
5. Conclusions: New solutions & improved production means

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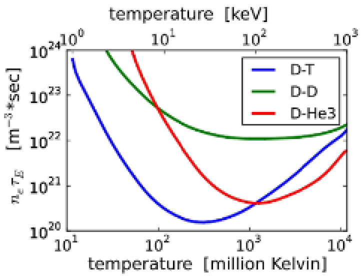
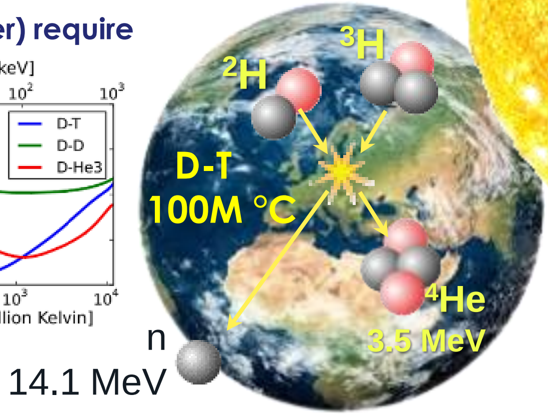
Nuclear Fusion: ENABLING TECHNOLOGIES

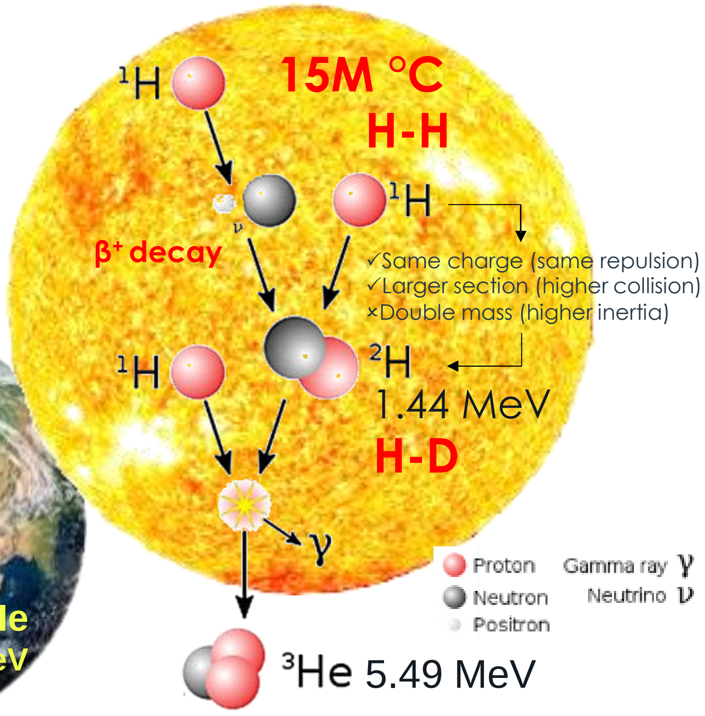
BASIC PRINCIPLE AND DIFFICULTIES:

- Almost **no toxic waste or CO_2**, based on **abundant & ubiquitous fuels**, with inherent **safety** → Disruptive alternative in 21st century energy mix.
- To overcome **Coulomb repulsion barrier**.
- In the sun core: A **beta decay** is needed and only some protons on the **tail of the velocity distribution** reach the required energy.
- Reactions on the heart **(lower density matter) require**
  - **Higher temperature**
  - **Specific reactions**
  - **Constrained plasma**
  - **Optimal confining time**

Lawson criterion:
Self heating threshold $\eta.\tau_e \geq L(T)$







Deuterium – Tritium reaction is the most convenient for artificial operations

Nuclear Fusion: ENABLING TECHNOLOGIES

TOKAMAK

- **Magnetic confinement fusion technology.**
- **Pulsed transformer** (the secondary is the plasma).
- **Poloidal field created by the plasma current.**
- Suitable to demonstrate fusion **net energy gain.**
- The **constructive simplicity** of the Tokamak makes it the **most diffused solution.**

Transformer current (Oh~~m~~mic heating) coil to accelerate electrons:(collisions resistive) to **create plasma** (ionize gas) and **current flow**.

Toroidal field (constant) **coil** to **confine the plasma.**

Poloidal field (to twist field lines) **to compensate plasma vertical drift**

Vertical field (constant) **coil** to control the **horizontal plasma position** to prevent radial drift.

IAEA Agence internationale de l'énergie atomique

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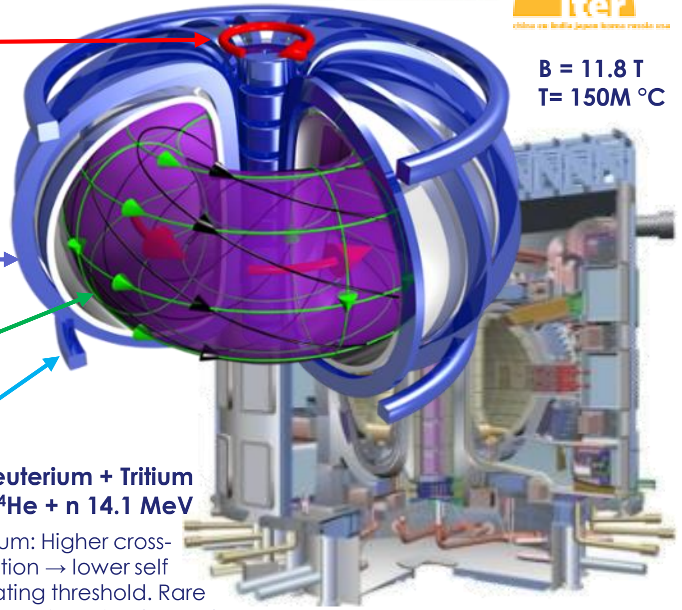


B = 11.8 T
T= 150M °C

Fuel: Deuterium + Tritium
→ ^{4}He + n 14.1 MeV

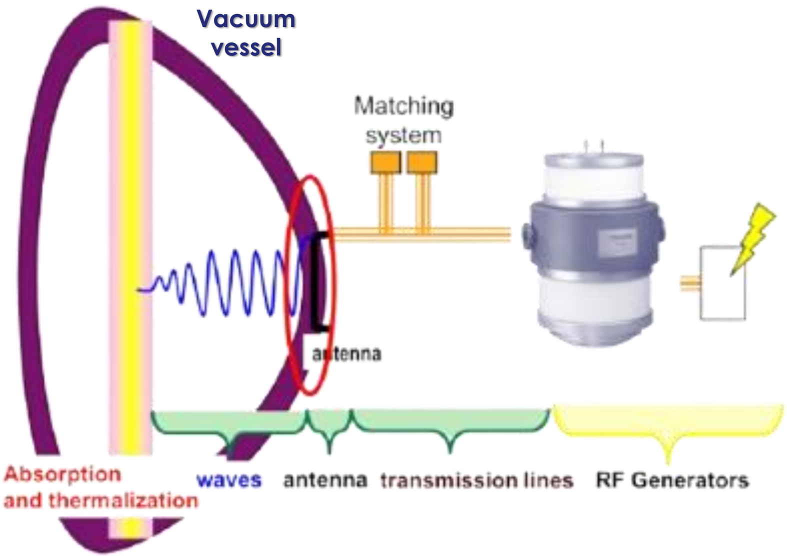
Tritium: Higher cross-section → lower self heating threshold. Rare and radioactive (12.3 yr)

- ✓ Simple construction (axisymmetric) & Good confinement (symmetry)
- ✗ Pulse driven transformer: Low efficiency respect to permanent current drive
- ✗ Current instabilities, disruptions & Greenwald (MHD) density limit $n < \frac{I_p}{\pi r^2}$

Nuclear Fusion: ENABLING TECHNOLOGIES

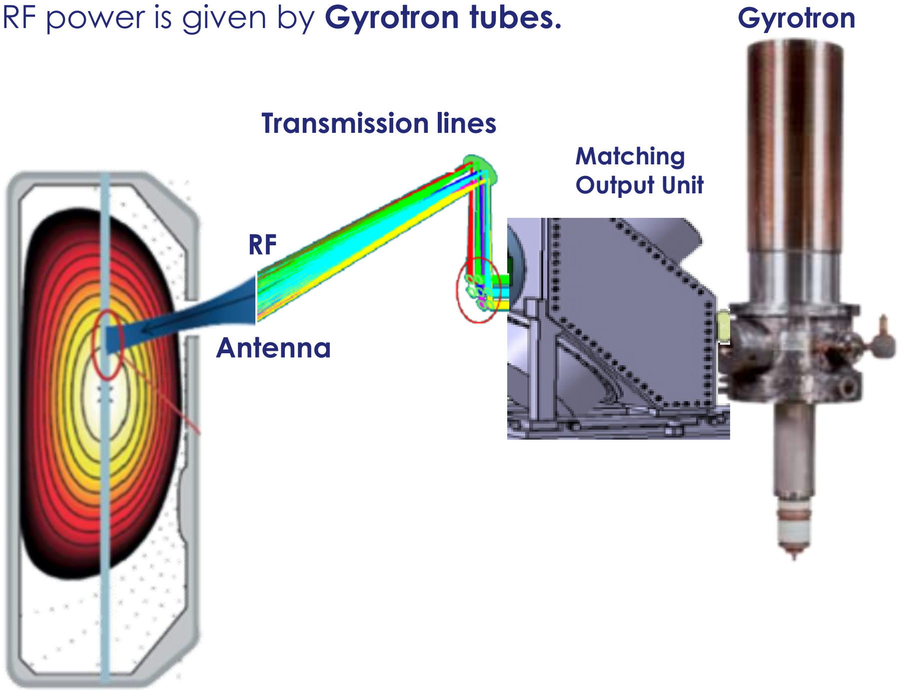
Ion Cyclotron Resonance Heating : ICRH

- EM wave coupling with plasma **ions.**
- Low frequency power **< 100 MHz** *(~50 MHz ITER).*
- RF power is given by **Diacrode tubes.**



Electron Cyclotron Resonance Heating : ECRH

- EM wave coupling with plasma **electrons.**
- High frequency power **> 100 GHz** *(170 GHz ITER).*
- RF power is given by **Gyrotron tubes.**



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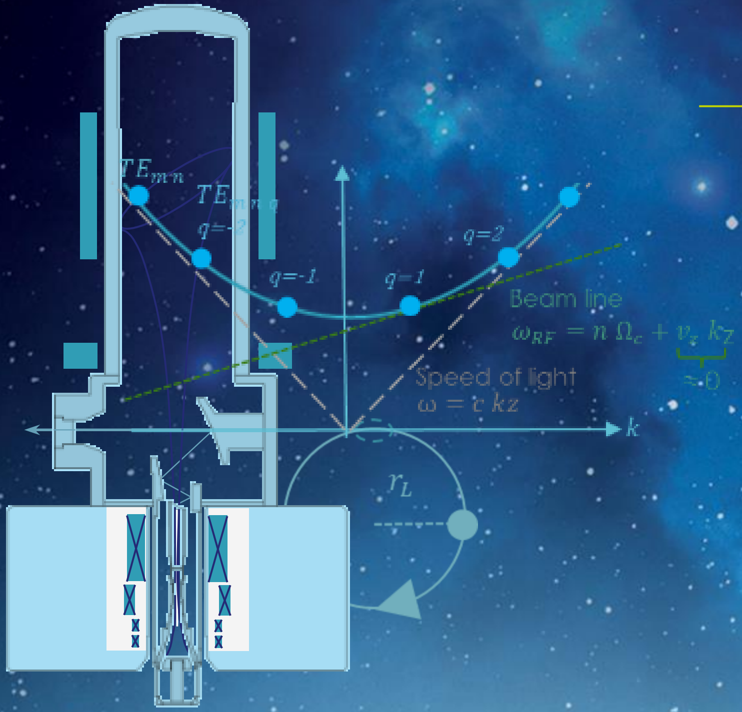

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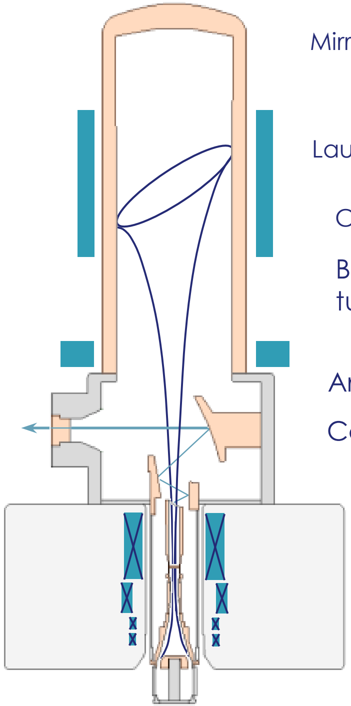
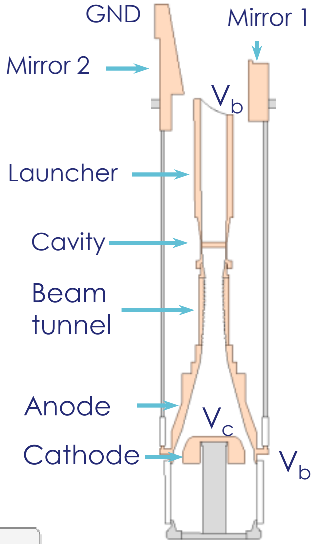
Gyrotron: FEATURES & THALES BASELINE

OPTIMIZED DESIGN TO EXPLOIT STATE OF THE ART TECHNOLOGIES

- Single stage **depressed collector**.
- **Advanced beam sweeping** (Φ and Z) and **cavity cooling** technologies for **high power handling** in long pulses.
- **Optimized quasi optical system** integrating harmonically deformed wall tapered launcher & CVD diamond window to ensure a good **output mode purity**.
- **Optimized cavity** mode for best compromise beam coupling / Ohmic-losses.
- **SCM Reversed bucking coil** for independent field control enabling **minimization of cathode-cavity distance** (energy spread↓) & specific **beam tunnel** to mitigate parasitic activity.
- **Diode-type MIG**.





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Gyrotron: FEATURES & THALES BASELINE

EUROPEAN DEVELOPMENT COLLABORATION

- Thales gyrotrons are developed in collaboration with **European research institutions.**
- Each partner provides its **best expertise** and the confrontation allow **for efficient decision making.**

Product specification and design review

RF and optical design

Technological design, cooling, HV configuration and manufacturing

Cavity & collector cooling
Gyrotron driving and test means

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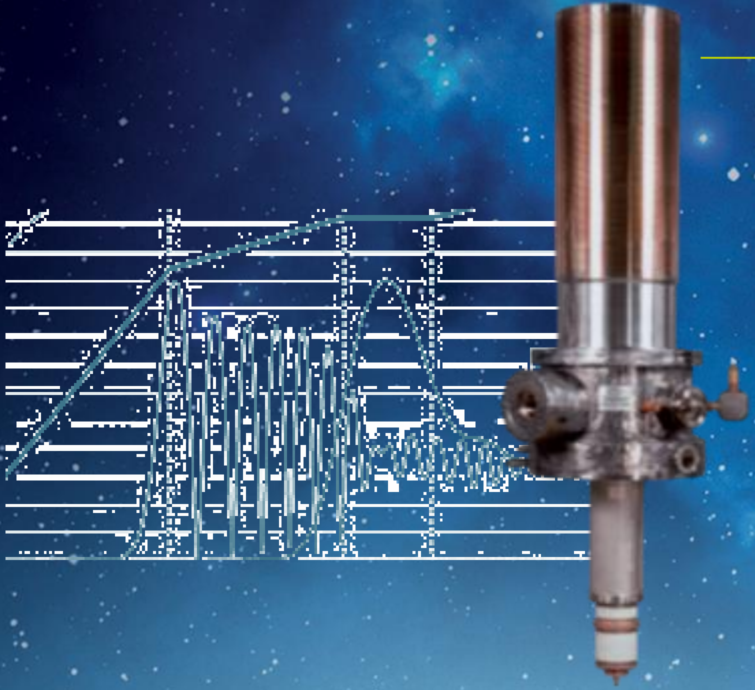
Outline



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TH1509U: REQUIREMENTS & DESIGN

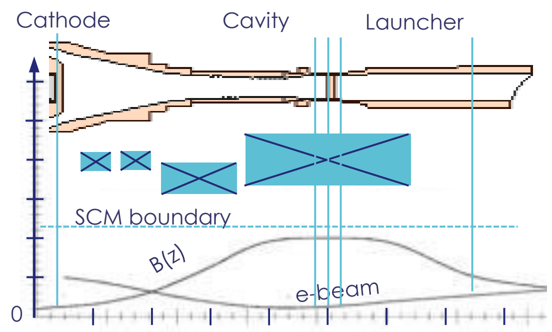
MAIN TECHNICAL REQUIREMENTS

- **Pout = 1 MW**
- **τ = 3600 s (CW)**
- **η ≥ 40 %**
- **F_{RF} = 170 ± 0.3 GHz**
- Reliability (RF pulses/DC pulses) > 95%
- DC in:
  - Electron beam features compatible with ITER PSU
  - Technology compatible with fast switch on/off
  - **I_{beam}= 48 A (peak)**
  - **V_c = -55 kV, V_{body} = +25 kV**
  - **Velocity factor <a>=1.3**
  - Nominal magnetic field B_C = 6.77 T

    Double independent SC coils for the control of the magnetic field slope at the emitter.

Main Optical Parameters	
Beam radius at window W	20.69 mm
Beam waist (in air, 50 mm from the window)	20.1 mm
Gaussian TEM purity at the window	95 %

Main Magnetic Parameters	
Cavity axial magnetic induction B_c	6.77 T
Gun axial magnetic induction B_g	0.232 T
Compression factor B_c /B_g	29.2

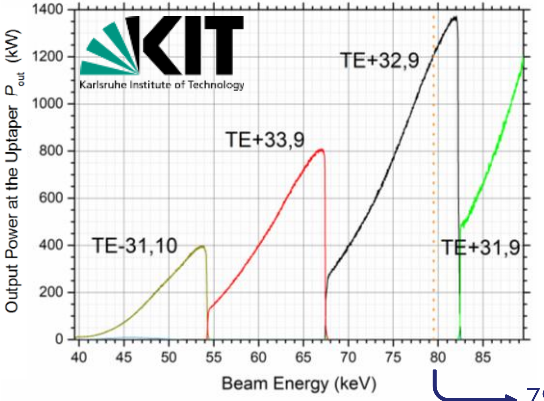


TH1509U: REQUIREMENTS & DESIGN

OPTIMIZED DESIGN ADRESSING ITER/DTT REQUIREMENTS

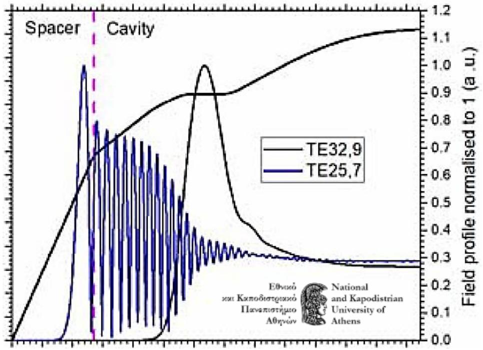
- **$TE_{32,9}$ cavity mode.**
- **Optimized cavity down-taper** to minimize the backward-waves.
- **Optimized Beam tunnel** (ceramics and geometry) to minimize coupling between beam and spurious modes.
- **Alternative spacer profile** to create hard boundary conditions for undesired cyclotron interaction.
- **Improved cathode centering** structure for strict tolerances on emitter alignment.

Multi-mode start-up at I=45 A, B=6.77 T

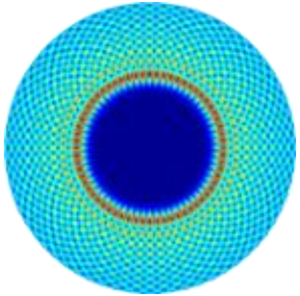


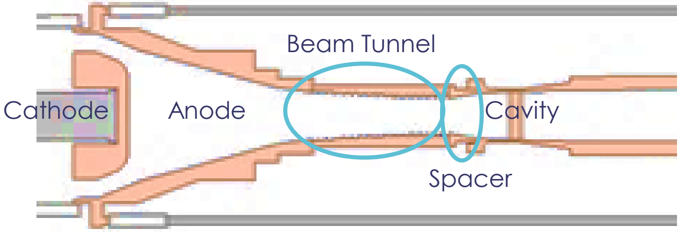
→ 79.5 kV

Backward wave excitation



→ ~2.5% ΔE_{RMS} → -3.5 % η





Undesired interaction → **Spurious oscillations** E_{beam} spread → η↓

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TH1509U: REQUIREMENTS & DESIGN

RELIABLE HIGH VOLTAGE STANDOFF

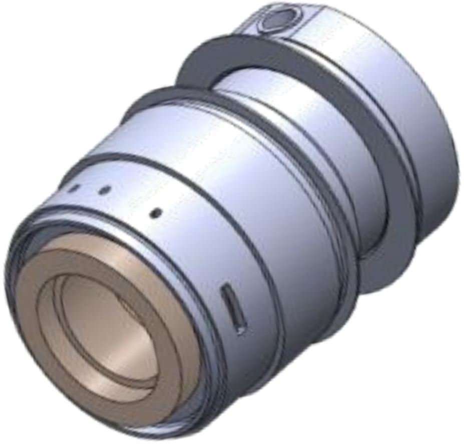
- Improved HV **feedthroughs** and arrangement.
- Enabling 35 kV high voltage standoff.

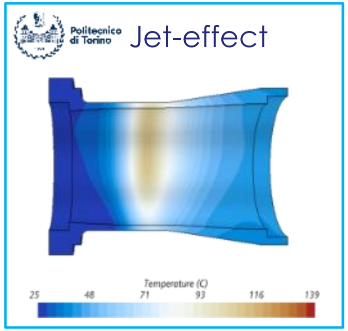
Values @ V_{beam}=80kV	V_{body}	$V_{cathode}$	Depression factor
TH1509U	35 KV	- 45 kV	1.78

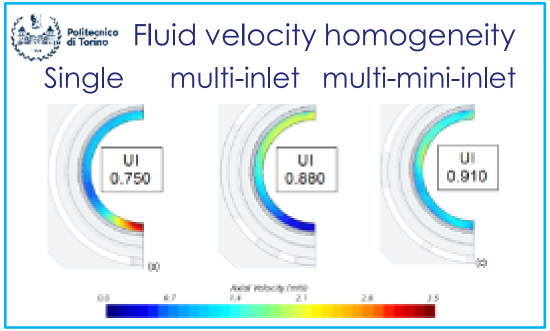
$$\eta_{tot} \approx \frac{P_{RF}}{P_{DC}} = \eta \frac{I_{beam} \cdot (V_{body} - V_{cathode})}{I_{beam} \cdot (-V_{cathode})} = \eta \left(1 - \frac{V_{body}}{V_{cathode}}\right)$$

RASCHIG RINGS MULTI-INLET CAVITY COOLING

- **Increased fluid velocity homogeneity**.
- Reproduction of **Jet-effect** by water homogenizer equipped by Multi- Inlets.
- **Reduced pressure drops** respect to single inlet.
- **Patent** EP4167264.







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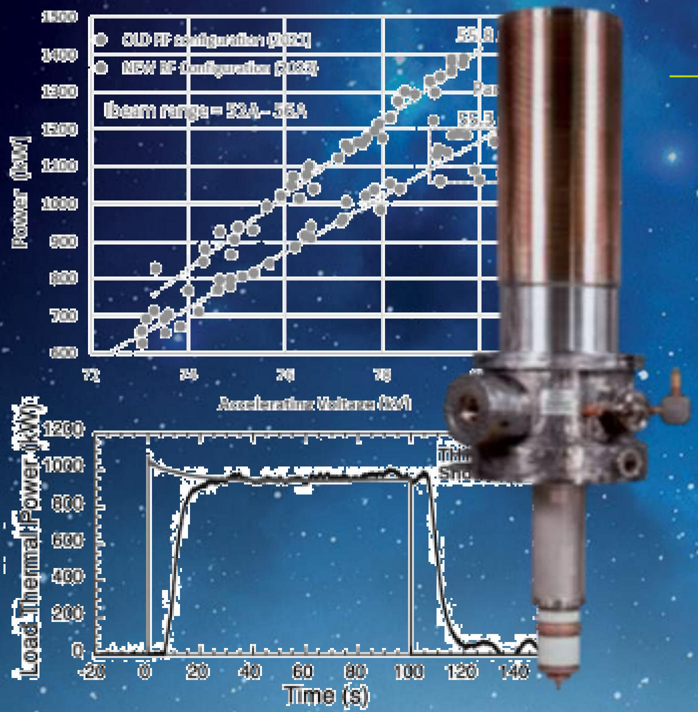

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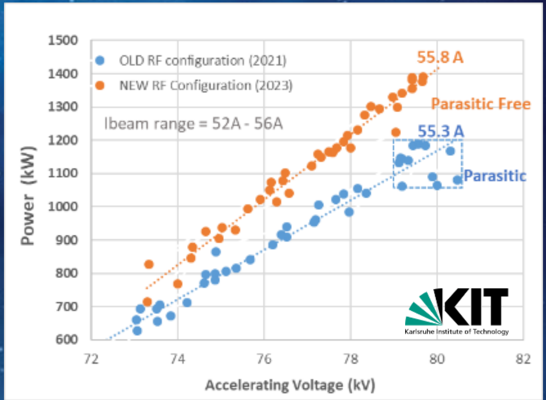
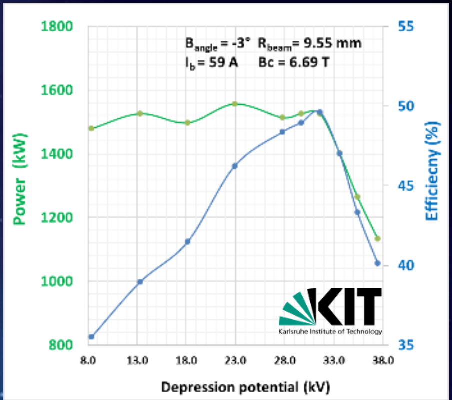
TH1509U GYROTRON
Design validation and prototype tests

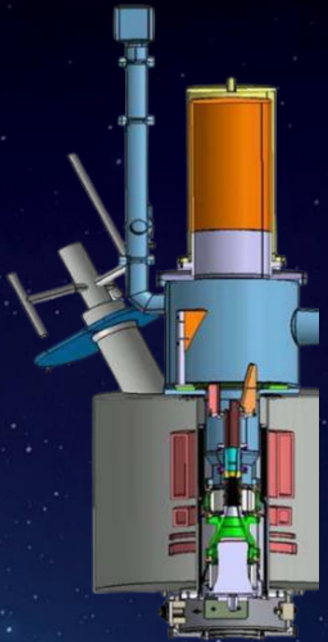
DESIGN VALIDATION ON SHORT-PULSE PRE-PROTOTYPE AT KIT

Representative environment:
- ➢ No neutralization
- ➢ No thermalization

Test campaign results:
- ➢ P ≈ 1.6 MW
- ➢ η > 50 %
- ➢ T = 0.5 ms







- ➢ Absence of parasitic, instabilities and saturation up to 66A and 80 kV as well with 37.5 kV depression (test stand limit).
- ➢ Very stable operation, even at beam parameters significantly above the nominal values.

TH1509U GYROTRON
Design validation and prototype tests

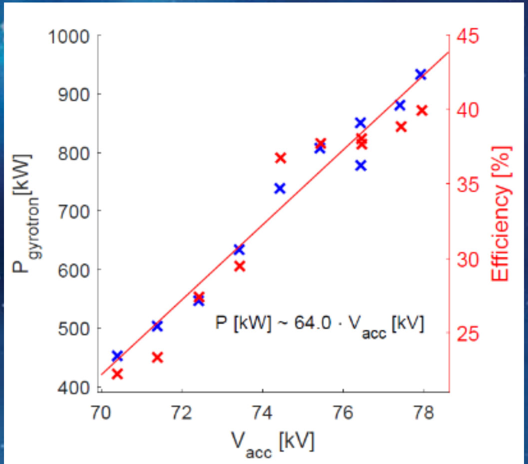
CW PROTOTYPE TEST RESULTS

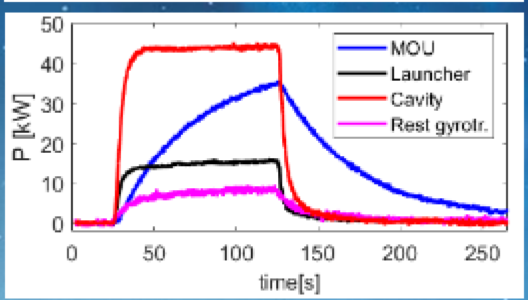
Test on operative environment:
- **Nominal neutralization**
- **Full thermalization**

Voltage ($V_c + V_{body}$) scan:
- $B_c = 6.69$ T
- $V_c = 51 - 52.5$ kV
- $V_{body} = 20 - 26$ kV
- $I_b = 40 - 46$ A
- a = 1.13 to 1.27

Power balance (±6 %):
- **Inner circuits: 71.6 kW**
- **Collector: 1550.2 kW**

Presentation by F. Braunmuller at EC22 workshop Daejeong, Korea





- **Super Conducting Magnet that allows to vary the beam profile** at gun and cavity.
- **Evacuated RF Conditioning Unit** (RFCU).
- **HE_{11} Transmission line** (TL): $\Phi = 50$ mm, $L_{tot} = 8.65$ m with 2 miter bends (MB) cooled by 2 axially running tubes.
- **Calibration**: 1.36 % losses in the TL (of which ¼ from MB) considered in the load and 4.0 % losses in the RFCU, giving $P_{window} = 1.04 \cdot P_{load}$.

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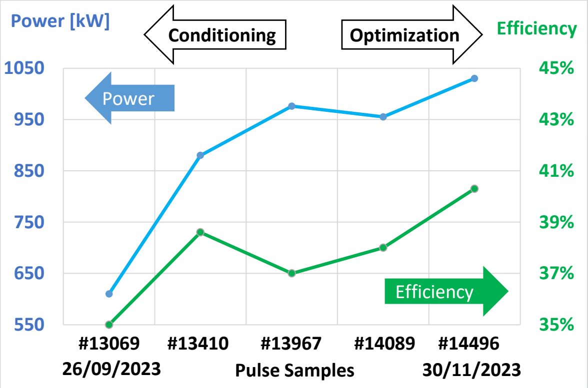
TH1509U GYROTRON
Design validation and prototype tests

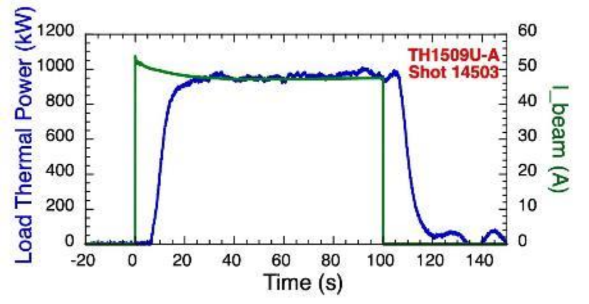
CW PROTOTYPE TEST RESULTS

Assessment of DTT Requirements:
- ➢ P ≈ 1.03 MW
- ➢ η > 40 %
- ➢ T = 100 s

Longer pulse and efficiency optimization in progress.

Assessment of ITER requirements in progress.





- ➢ **Measured beam waist:** w_{0x} = 21.1 mm, w_{0y} = 20.8 mm (simulated w_{0x} = 19.4 mm / w0y = 19.6 mm)
- ➢ **Average frequency: 169.946 GHz for 1.03 MW** (acquired by 250 samples of 1μs every 400 ms, down-converted via heterodyne mixer and recorded with sampling rate of 40 GS/s).
- ➢ **Power variation during the pulse: less than +/- 20 kW or 2 %** (the experimental fitting provided ΔP [kW] ∝ 3.0 · Δf [MHz] and between 20 s to 100 s the max. deviation was +/- 6 MHz)

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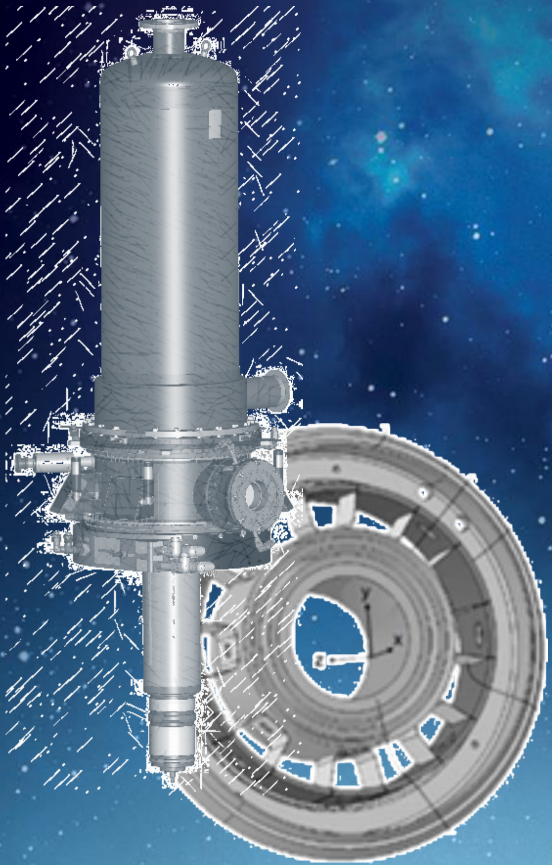

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CONCLUSIONS

New solutions & improved production means

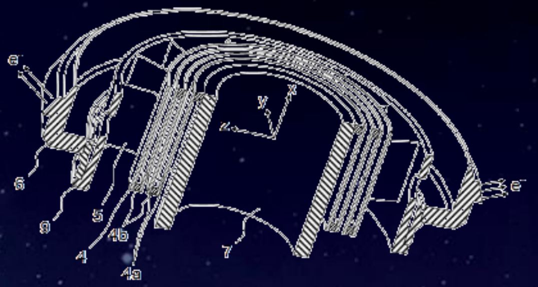
NEW SOLUTIONS

- **Star Sleeves Cathode** (patent A. Leggieri et Al. US20210012994) to optimize **cathode isotropic expansion for increased beam quality** by maintaining the cathode position while limiting the heat flow.

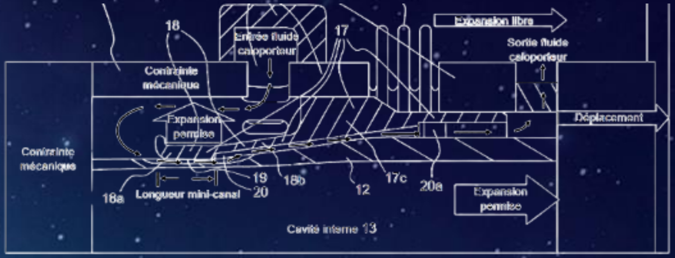
- **Mini-channel cavity cooling** (patent A. Leggieri et Al. EP4167264) to **maximize heat exchange while limiting stress and avoid friction** by counterbalancing the inner pressure of channels.

- **Alternative cavity spacer** to create hard boundary conditions to **avoid undesired cyclotron interactions**.

Star Sleeves Cathode
patent S20210012994



Mini-channel Cavity Cooling
patent EP4167264



Simulation of the TH1507U Mini-channel cavity compared to Raschig rings for a +28% higher heat load			
Peak cavity temperature	Max Von Mises Stress	Stress margin before plasticization (Max VM Stress - Yield Strength)	Fatigue life
-17%	-26%	+48%	+69%

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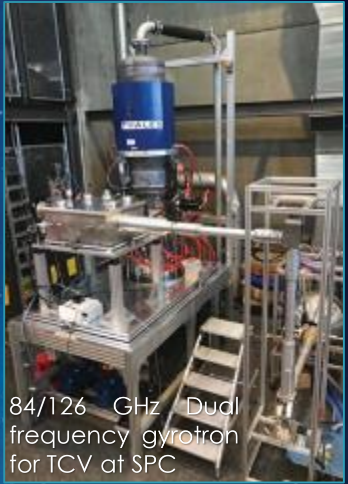
CONCLUSIONS

New solutions & improved production means

A SERIES OF INDUSTRIAL SUCCESSES

- **Nine TH1507 140 GHz gyrotrons daily energizing the W7-X** stellerator with outstanding reliability.
- **Two TH1510 Dual frequency** (84-126 GHz P_{out} ≥1MW η ≥ 40 %) gyrotrons **operative at EPFL-SPC** and 1 unit being deployed.
- **New TH1509U 170 GHz gyrotron qualified for DTT**: P_{out} ≥1MW η ≥ 40 %.
- **New TH1507U 140 GHz 1.5 MW Gyrotron dedicated to W7-X** successfully tested at IPP.
- **New TH1511 105 GHZ 1 MW CW** gyrotron being tested for CEA WEST (Tore-Supra transformed from a limiter to a divertor configuration).
- **New TH1512 117.5 GHz 1 MW long pulse gyrotron** under manufacturing for General Atomics DIII-D (non-circular plasma cross sections to suppress plasma instabilities).



84/126 GHz Dual frequency gyrotron for TCV at SPC

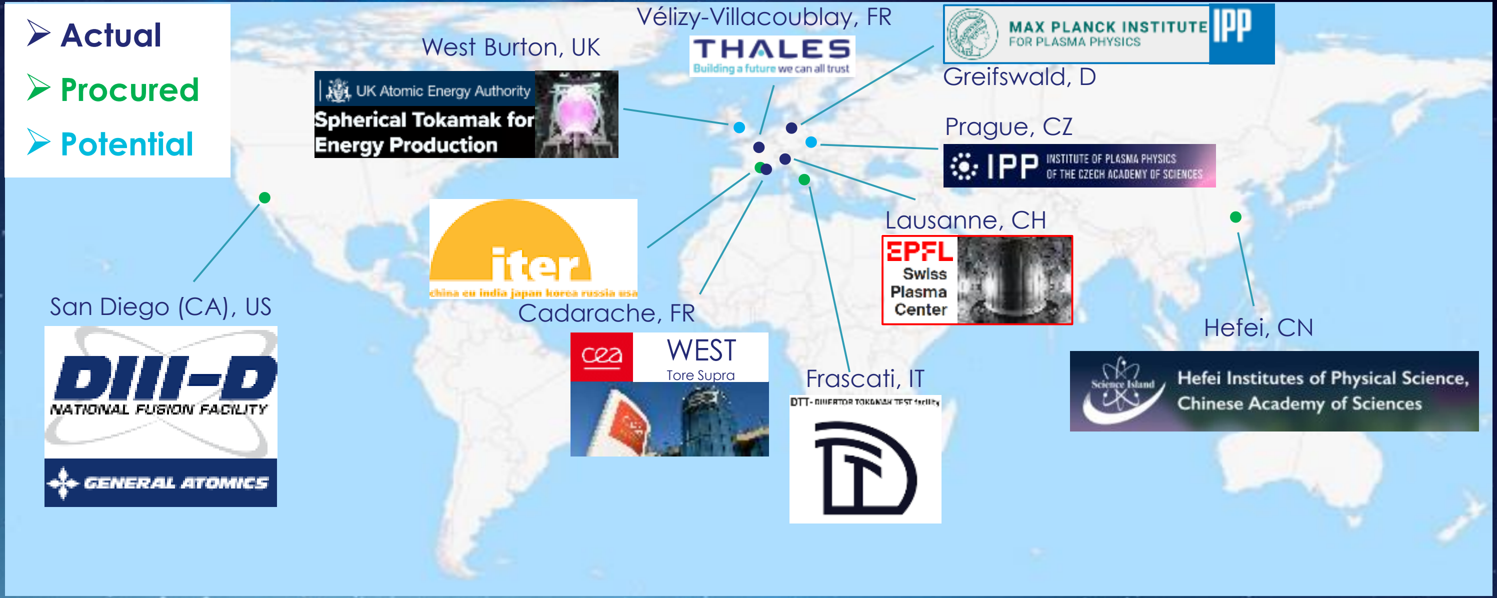
TH1507 Upgrade 140GHz 1.5 MW


New cathodes and cavity cooling for DEMO


170 GHz 1 MW CW Gyrotron for DTT & ITER

CONCLUSIONS
New solutions & improved production means

THALES GYROTRON INSTALLATIONS WORLDWIDE

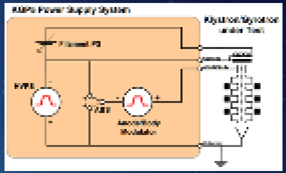


CONCLUSIONS
New solutions & improved production means

NEW ASSEMBLY CLEAN ROOM

- Clean room dedicated to scientific products.
- Modernization and **new assembly tools** for klystron and gyrotron manufacturing and automated measurement.
- **Increased industrial capability for improved series production.**

NEW GYROTRON TEST FACILITY



- New high power test stand for gyrotrons & auxiliaries:
  - $V_{Cathode}$ = 160 kV
  - $V_{body / anode}$ = 110 kV
  - T_{pulse}= 1 µs – 3600 s
  - P_{DC} = 3.2 MVA

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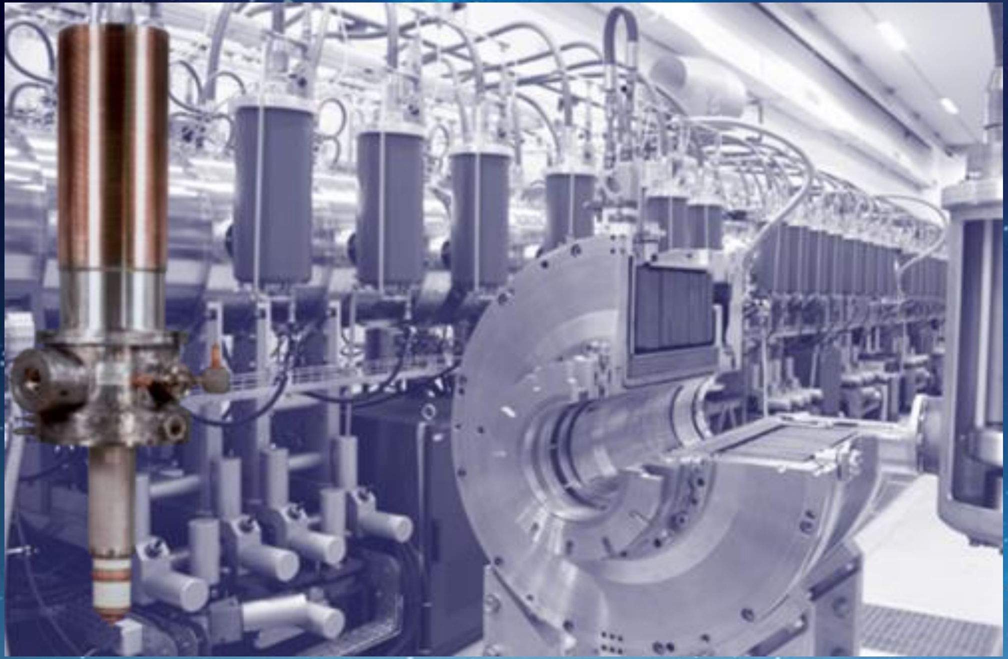
Industrial Qualification of the THALES TH1509U European 170 GHz 1 MW CW Gyrotron

On behalf of the Thales gyrotron technical division



Thanks for the Attention

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