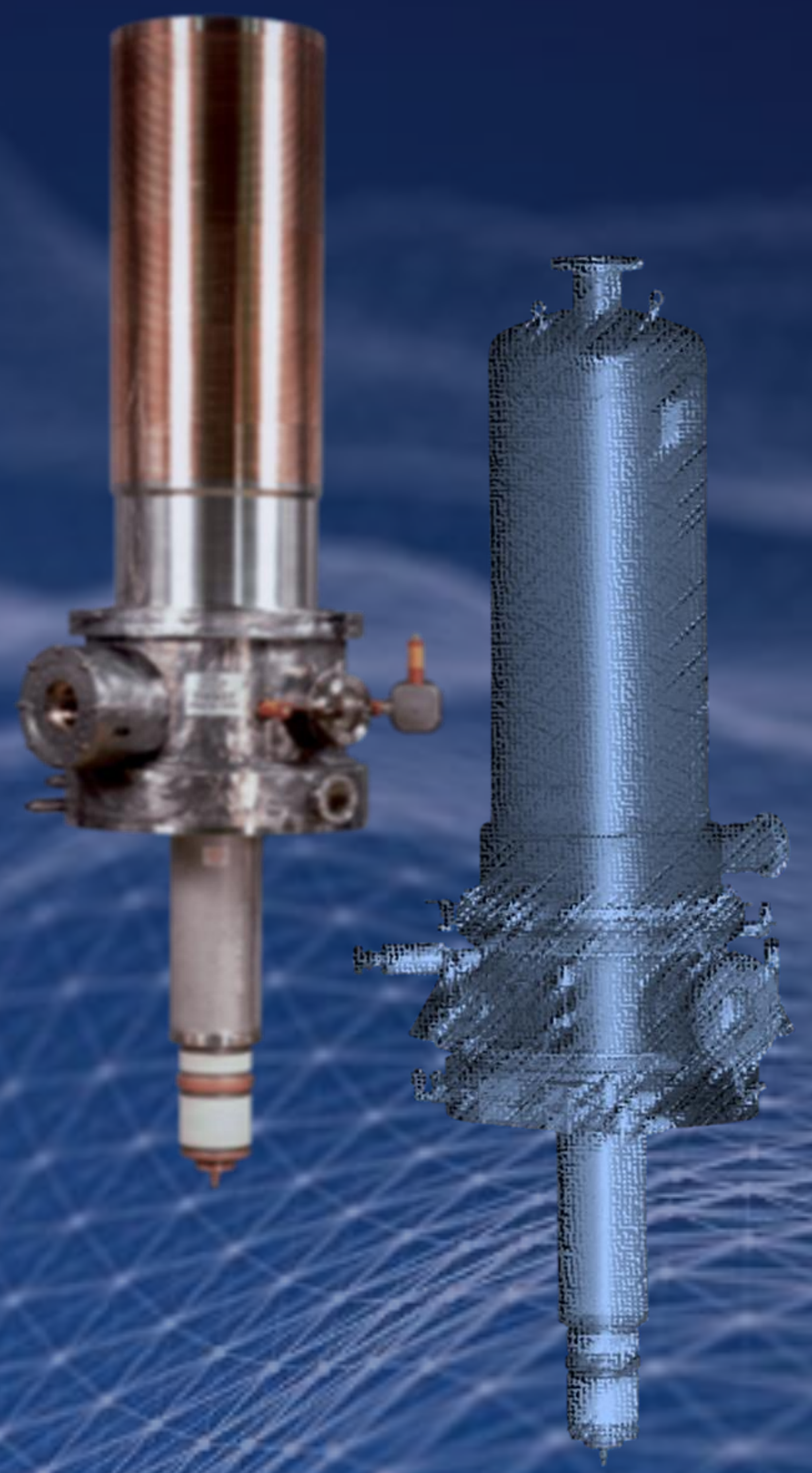
PROGRESS IN EUROPEAN COLLABORATIVE GYROTRON DEVELOPMENTS FOR CEA AND GENERAL ATOMICS

ALBERTO LEGGIERI
On behalf of the co-authors

Thales Microwave and Imaging Subsystems



European Development Framework

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

cea / GENERAL ATOMICS: Product specification, final design review, interfaces and auxiliary systems definition, integration and tests. End-user.

THALES: Technological design: Materials, thermomechanics & hydrodynamics, electrostatic & magnetostatic, high voltage & irradiation. Manufacturing.

KIT Karlsruhe Institute of Technology: Design of electron-optics & interaction structures, quasi-optical system & diamond window, validation test.

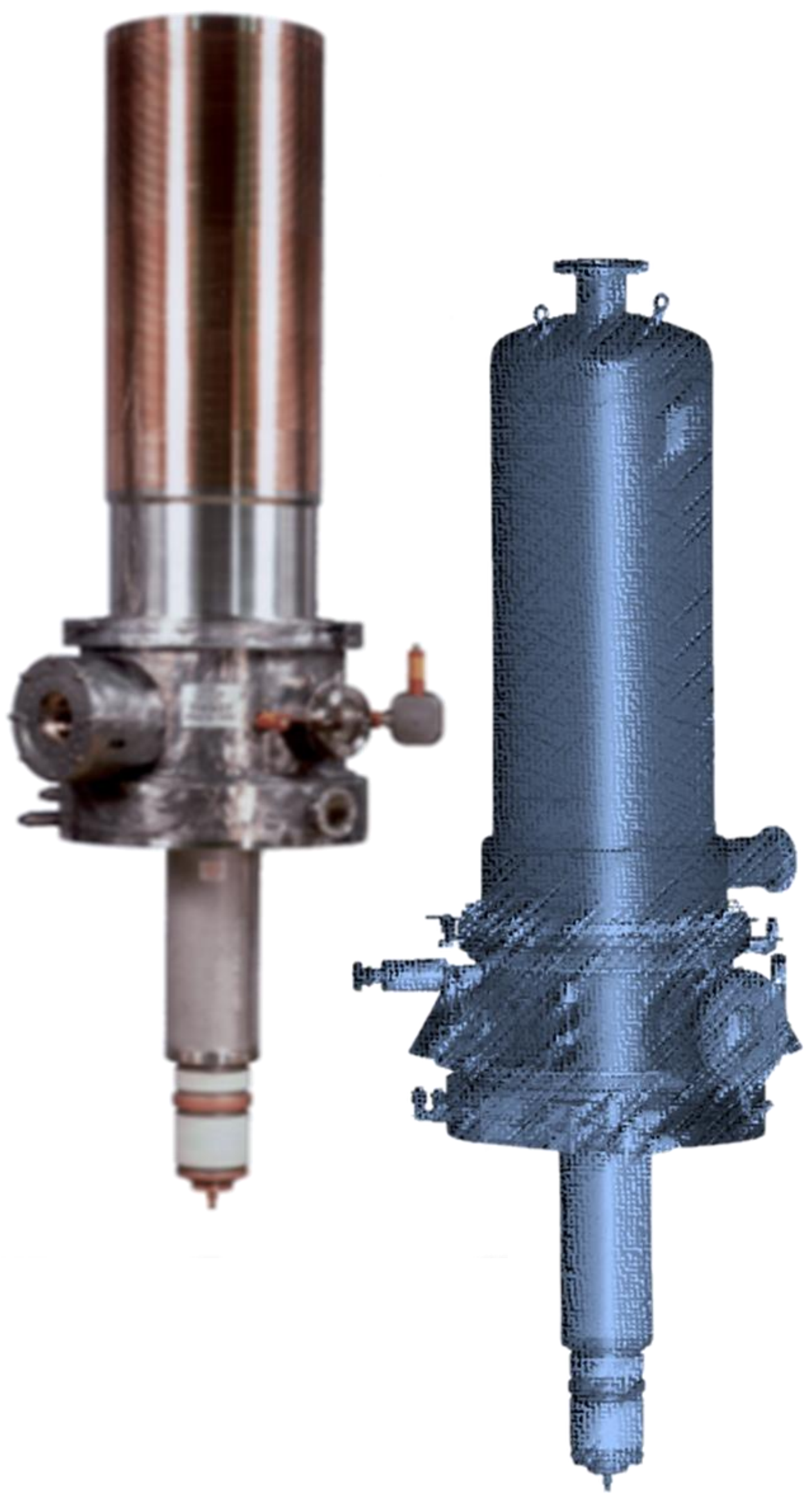
Hellenic Republic National and Kapodistrian University of Athens: Cavity & beam tunnel Optimization.

Politecnico di Torino: Cavity & collector cooling optimization.

Alberto Leggieri, Konstantinos A. Avramidis, Ioannis Chelis, Benjamin Ell, Lukas Feuerstein, Gerd Gantenbein, Stefan Illy, Jianbo Jin, John Jelonnek, François Legrand, Gérald Lietaer, Christophe Lievin, Rodolphe Marchesin, Cyrille Metayer, Moritz Misko, Ijaze M. Oumar, David Quetel, Tomasz Rzesnicki, Sebastian Stanculovic, Etienne Vallée and Manfred Thumm

Outline

- Thales solutions for science
- WEST & DIII-D upgrade programs
- Gyrotron requirements, design & test configuration
- TH1511 gyrotron: Validation and prototype tests
- TH1512 gyrotron: Validation and prototype tests
- Conclusions: Achievements and current developments

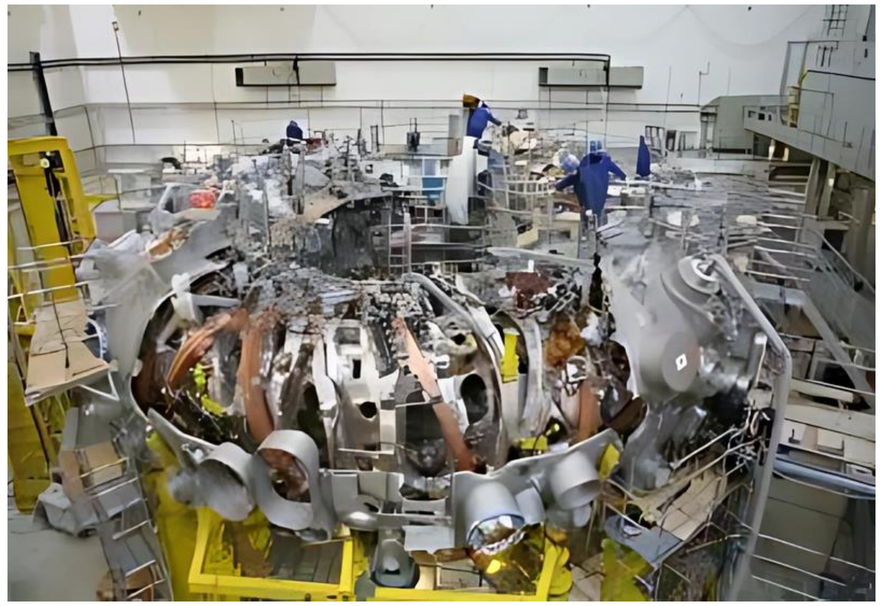


01

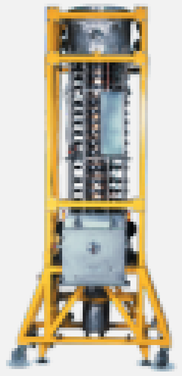
Thales solutions for science

THALES Solutions for Science

- RF sources for particle accelerators and fusion reactors.
- Thales power tubes contribute to cutting-edge scientific applications in the fields of particle physics, nuclear
- Physics and magnetic confinement fusion.



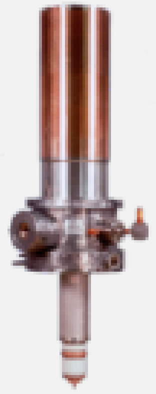
THALES, A TRUSTED PARTNER OF THE MOST PRESTIGIOUS LABORATORIES AND RESEARCH CENTERS



KLYSTRON

MULTI BEAM KLYSTRON

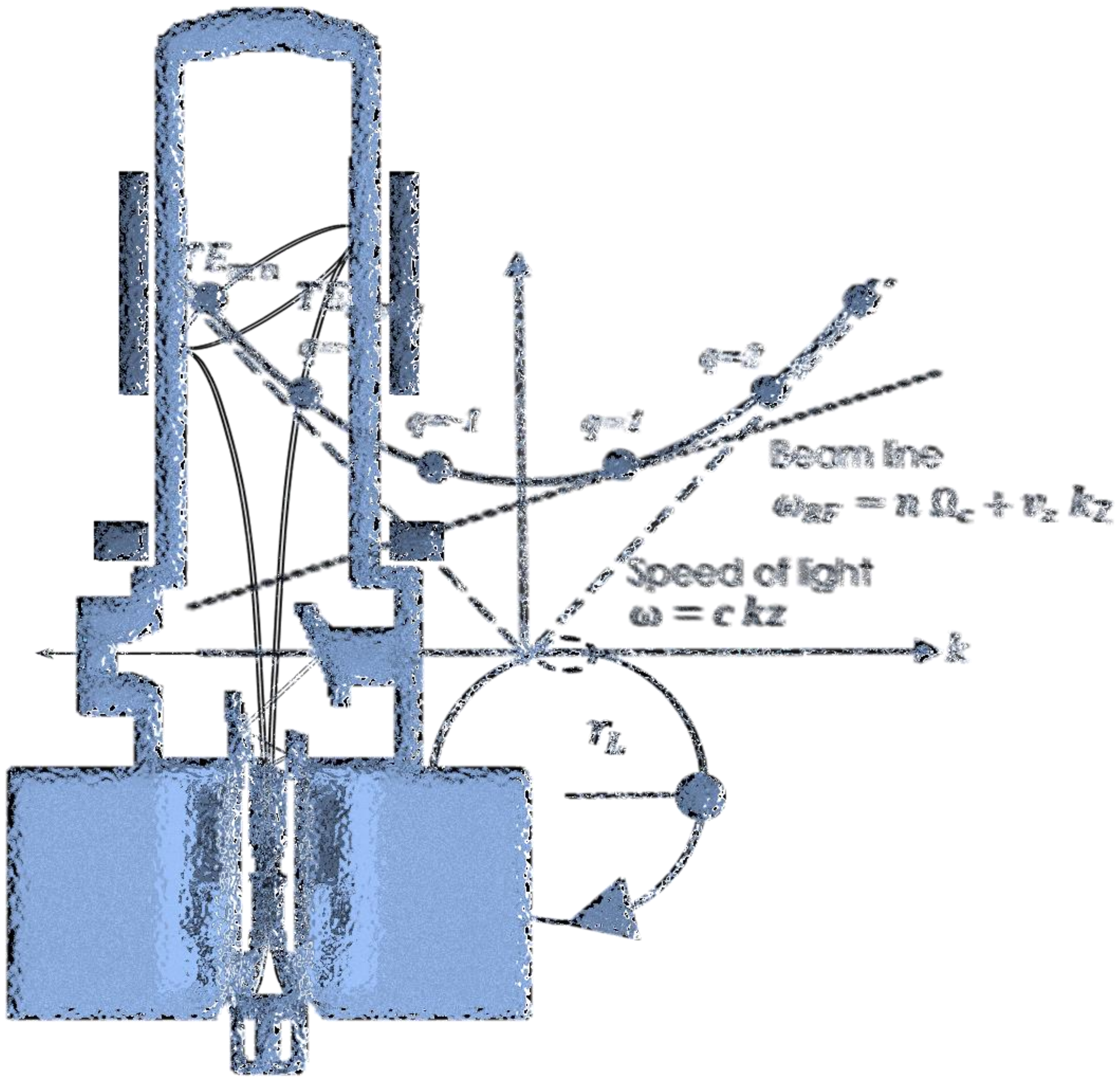
DIACRODE



GYROTRON

02

WEST & DIII-D upgrade programs



WEST Upgrade: Technical needs

- WEST targets:
  - 1000 s discharges,
  - tungsten divertor (>10 MW/m²),
  - tackling plasma-wall interactions,
  - heat-load & impurity control.

- 3 MW at 105 GHz ECRH system technical needs:
  - heating and Current Drive,
  - impurity mitigation,
  - MagnetoHydroDynamic & Internal Transport Barriers stabilizations.

- ECRH system :
  - 3 THALES TH1511 gyrotrons (1 MW, 1000 s each),
  - Φ63.5 mm HE corrugated waveguides,
  - diamond window–free transmission lines (using VAT valves).

DIII-D Upgrade: Technical needs

- DIII-D program targets:
  - 10 s discharges,
  - based on the earlier Doublet III for experiments with non-circular plasma cross sections,
  - focus on strongly shaped plasmas for better MagnetoHydroDynamic stability and confinement,
  - graphite divertor (>10 MW/m^2),
  - study targets: quasi-steady, non-inductive H-mode plasmas.

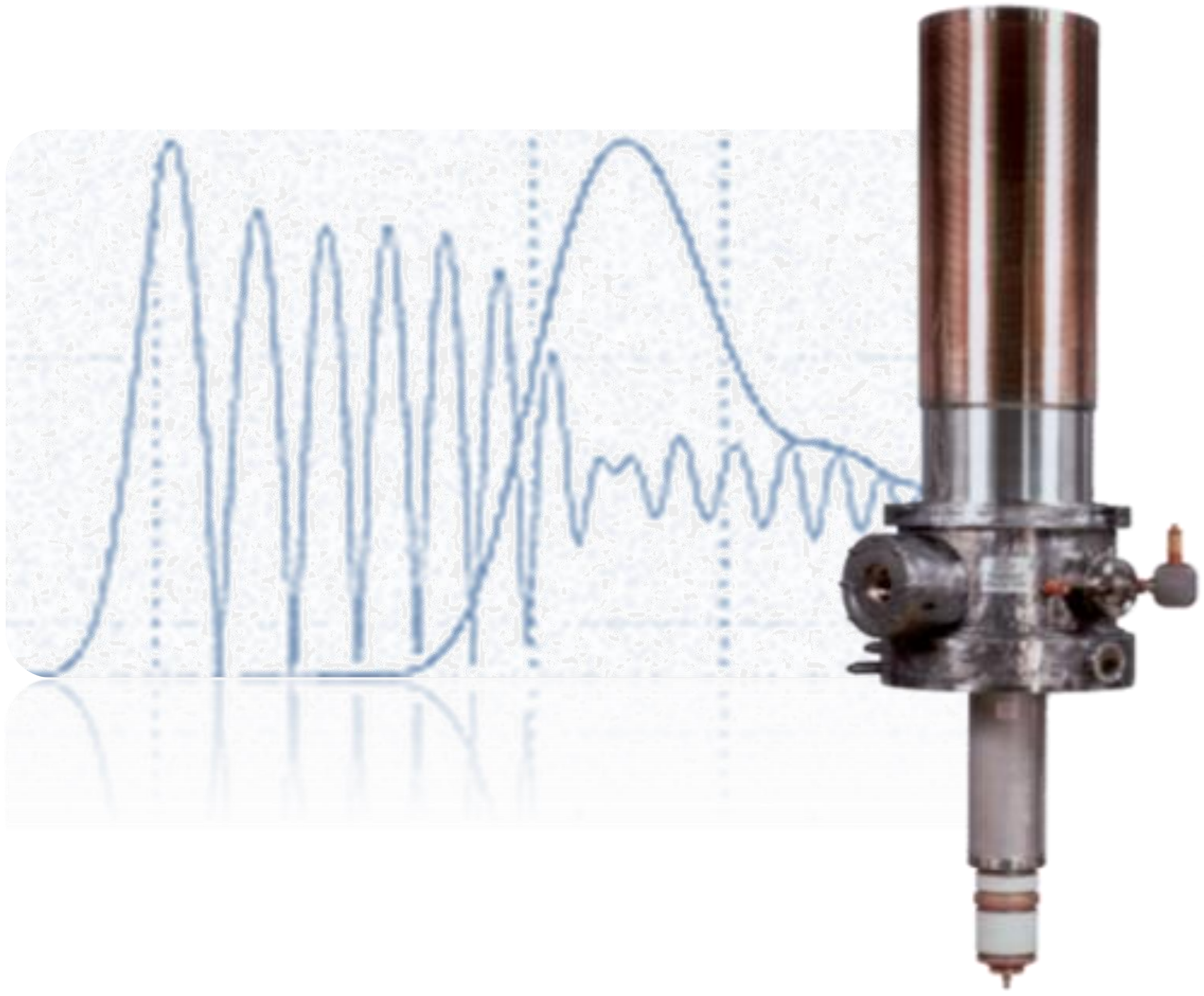
GENERAL ATOMICS

- Two 1 MW units ECRH system targets:
  - high-β and precise power deposition
  - Internal Transport Barriers and Edge-Localized Mode controls,
  - Neoclassical Tearing Modes suppression via precise Electron Cyclotron Current Drive.

- ECRH gyrotron units :
  - THALES 117.5 GHz, 1 MW gyrotrons for heating, current drive and modulation control.

03

Gyrotron requirements, design & test configuration

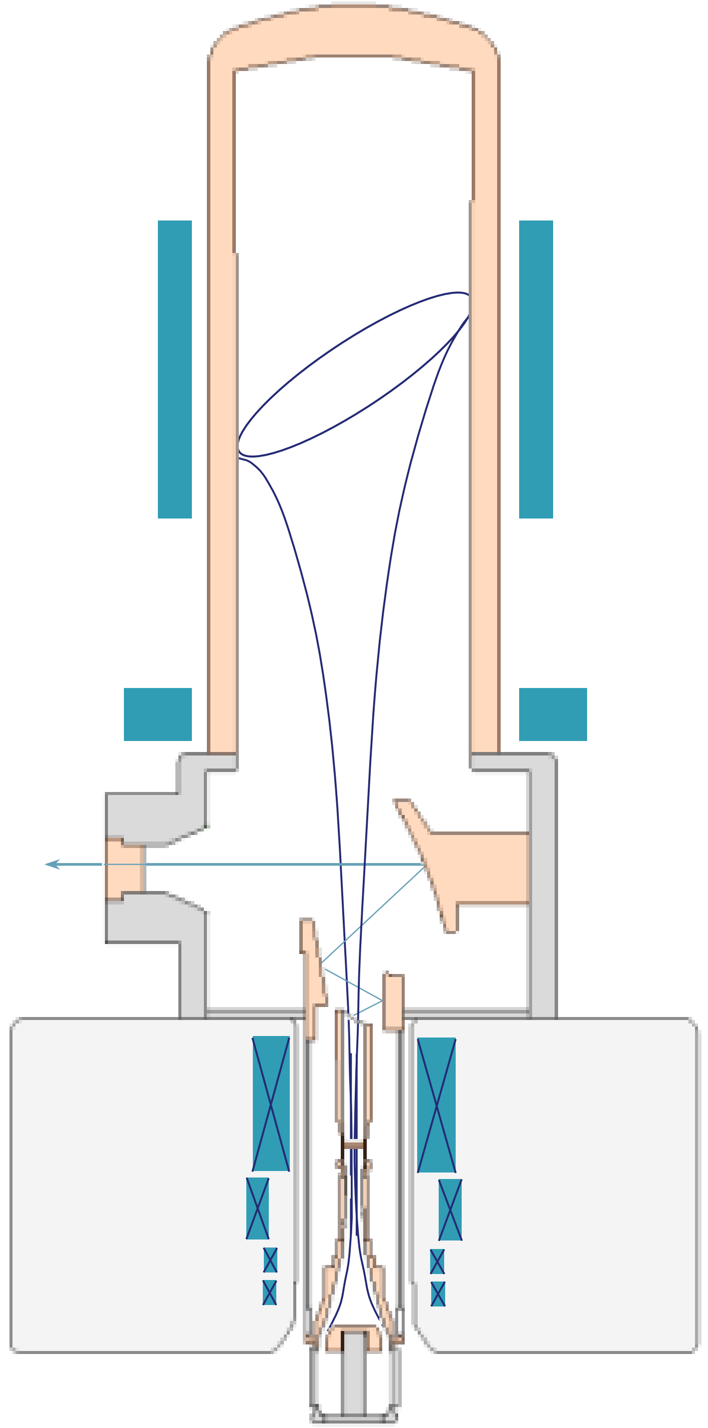


TH1511: Requirements & Design

MAIN TECHNICAL REQUIREMENTS

- P_{out} = 1 MW
- τ = 1000 s (CW)
- η ≥ 40%
- F_{RF} = 105 ± 0.4 GHz
- Reliability (RF pulses/DC pulses) > 95%

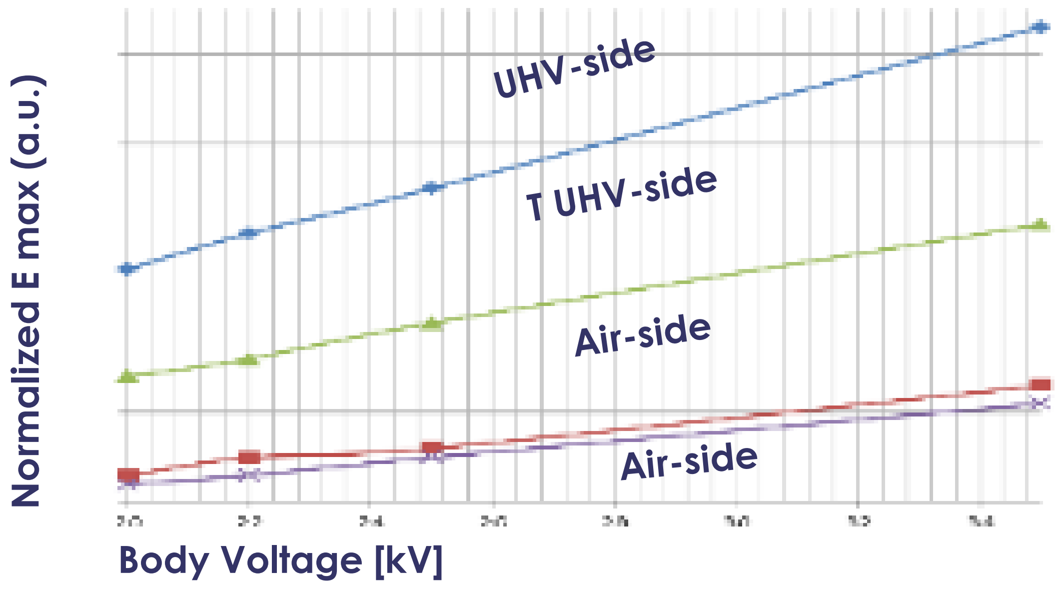
- DC in:
  - electron beam features compatible with WEST PSU,
  - diode-type MIG,
  - I_{beam} = 45 A (peak) compatible with fast switch on/off,
  - V_c = -55 kV, V_{body} ≤ +30 kV,
  - velocity pitch factor <α>≈1.3,
  - B_c = 4.13 T,
  - SCM reversed bucking coil for cavity independent field control enabling minimization of cathode-cavity distance.

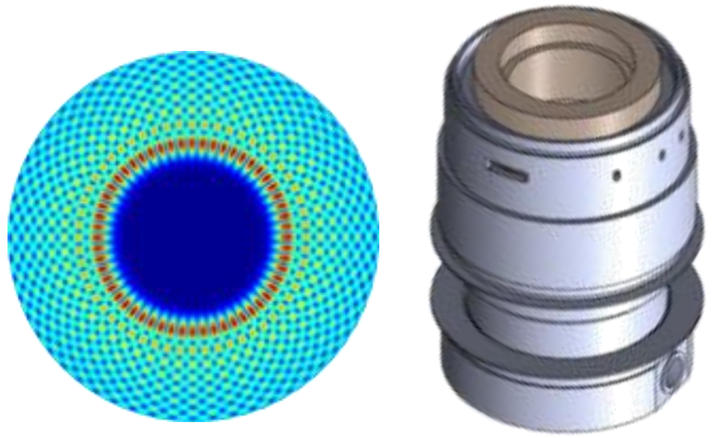


TH1511: Requirements & Design

OPTIMIZED DESIGN ADDRESSING HIGH REALIBILITY

- $TE_{-20,8}$ cavity mode design,
- optimized cavity mode for best compromise between beam coupling and Ohmic-losses,
- diode electron gun enabling 50 A current,
- advanced HV configuration enabling 35 kV depression,
- advanced beam tunnel for parasitic mitigation,
- upgraded cavity cooling for increased fluid velocity homogeneity & jet-effect with reduced pressure drops,
- optimized quasi-optical system integrating tapered helically-cut hybrid launcher.



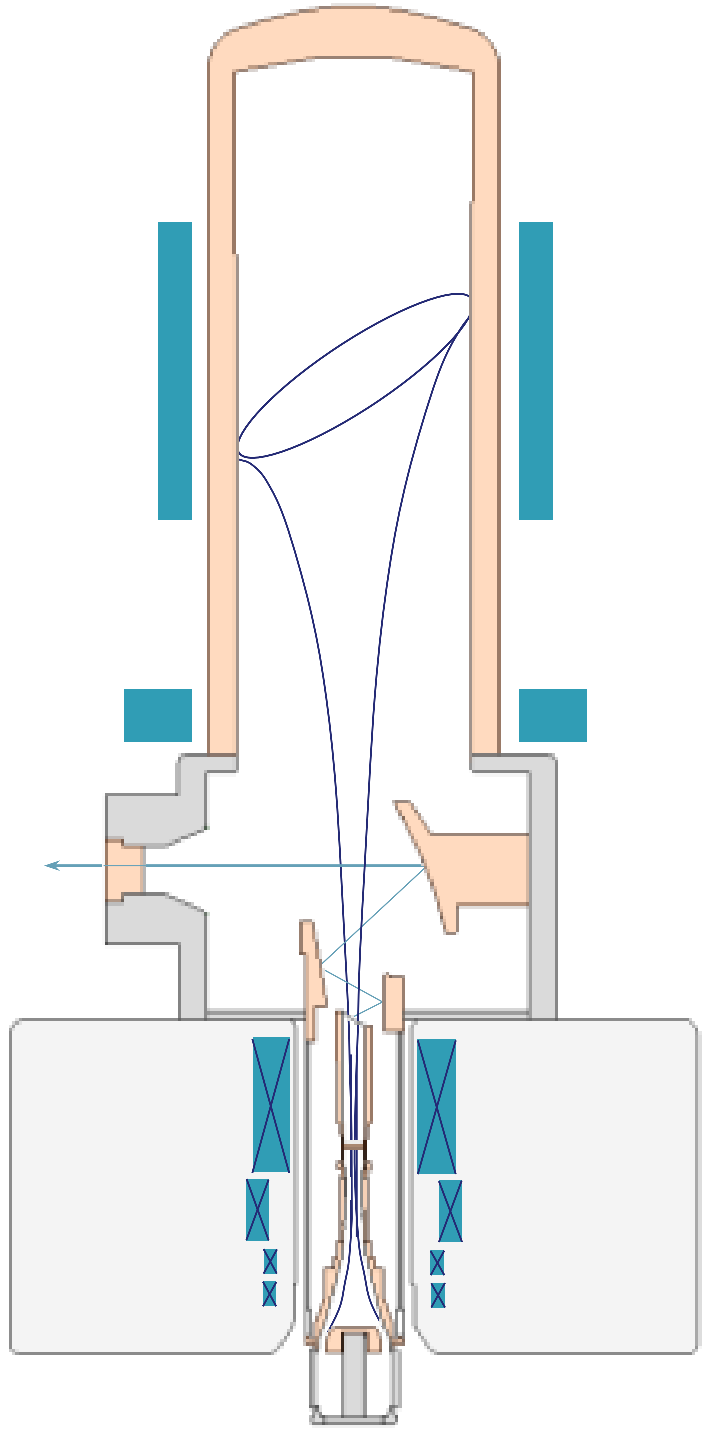


TH1512: Requirements & Design

MAIN TECHNICAL REQUIREMENTS

- P_{out} > 900 kW
- τ = 10 s (LP)
- $\eta \geq 35\%$
- F_{RF} = 117.5 ± 0.4 GHz
- Reliability (RF pulses/DC pulses) > 95%

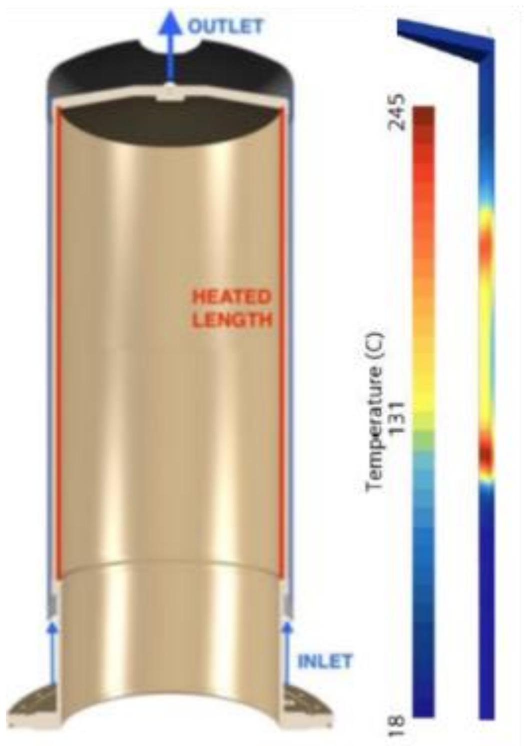
- DC in:
  - electron beam features compatible with DIII-D PSU,
  - diode-type MIG,
  - I_{beam} > 35 A compatible with fast switch on/off,
  - V_c = -65 kV, $V_{body} \leq$ +25 kV,
  - velocity pitch factor <α>≈1.3,
  - nominal magnetic field B_c = 4.7 T,
  - SCM reversed bucking coil for cavity independent field control enabling minimization of cathode-cavity distance.

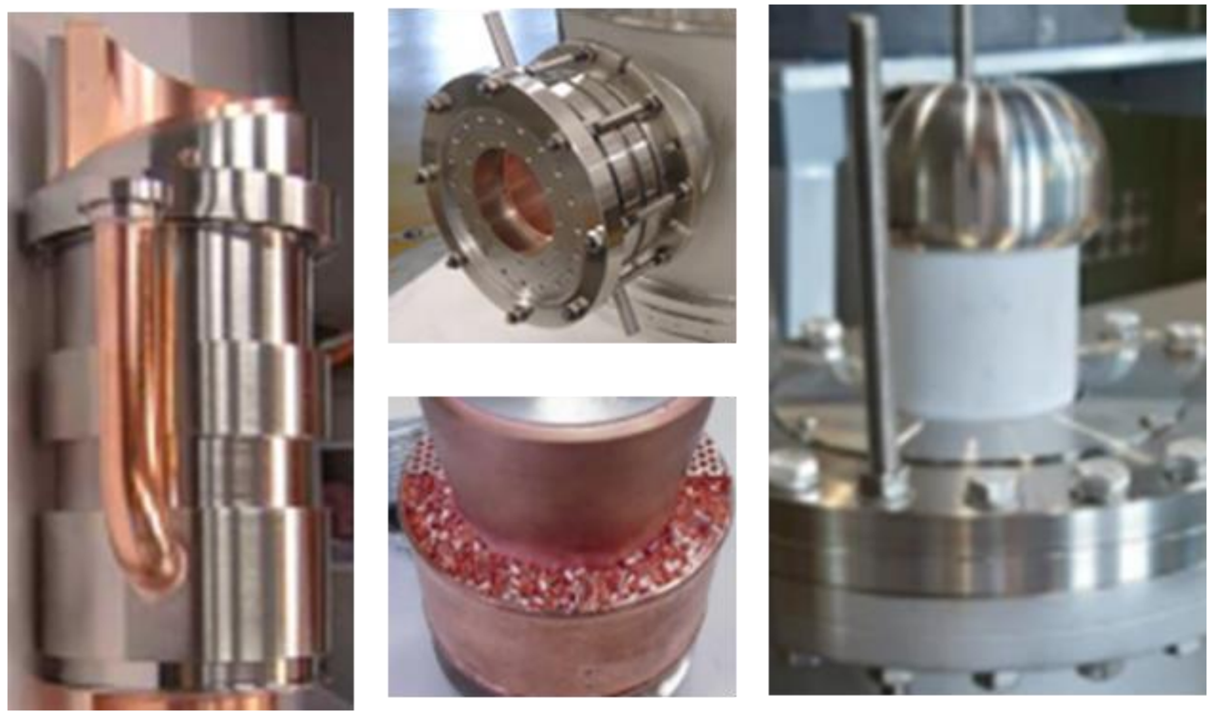


TH1512: Requirements & Design

OPTIMIZED DESIGN ADDRESSING HIGH RELIABILITY

- $TE_{24,8}$ cavity mode design at 117.5 GHz,
- optimized cavity mode for best compromise between beam coupling and Ohmic-losses,
- diode electron gun enabling 40 A current,
- electrostatic configuration enabling 92 kV beam acceleration,
- advanced heat-management collector corrugation,
- upgraded cavity cooling for increased fluid velocity homogeneity & Jet-effect with reduced pressure drops,
- optimized quasi-optical system integrating slightly tapered helically-cut hybrid launcher.





Gyrotron test configuration: KIT Fulgor ECRH test bench

KIT TEST BENCH

- High-power short-pulse & long-pulse tests setup
  - short pulse (<3 ms) calorimeter for gyrotron parametric studies,
  - diagnostic systems for frequency and beam profiling,
  - long pulse RF load.

- Superconducting magnet assembly verified for planarity and alignment with 3D metrology before RF operations.

- Gyrotron integration:
  - high-voltage interfaces,
  - sweeping coils,
  - thermocouples,
  - Interlocks,
  - cooling system,
  - calorimetric measurements.

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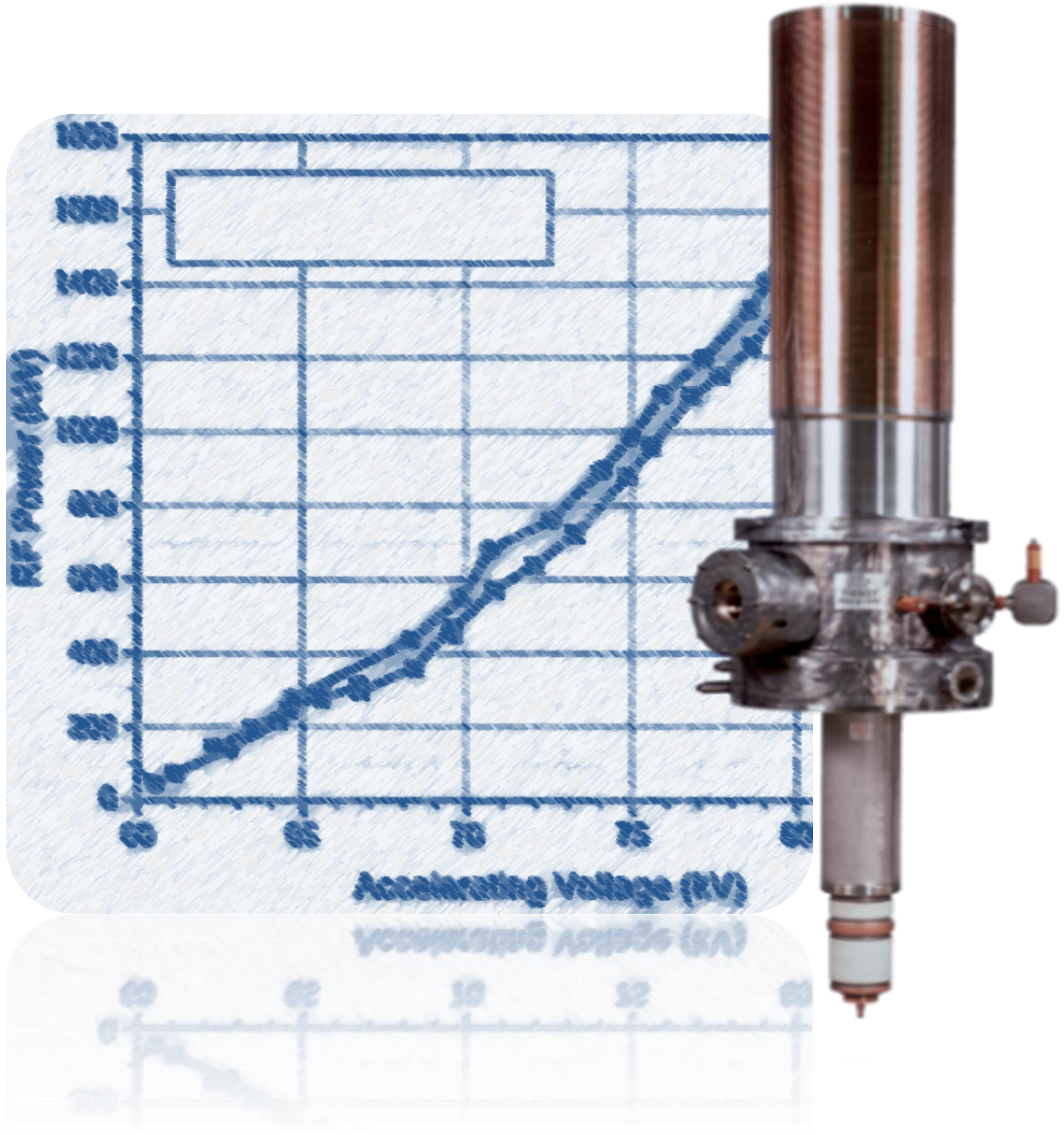
TH1511 gyrotron: Validation and prototype tests



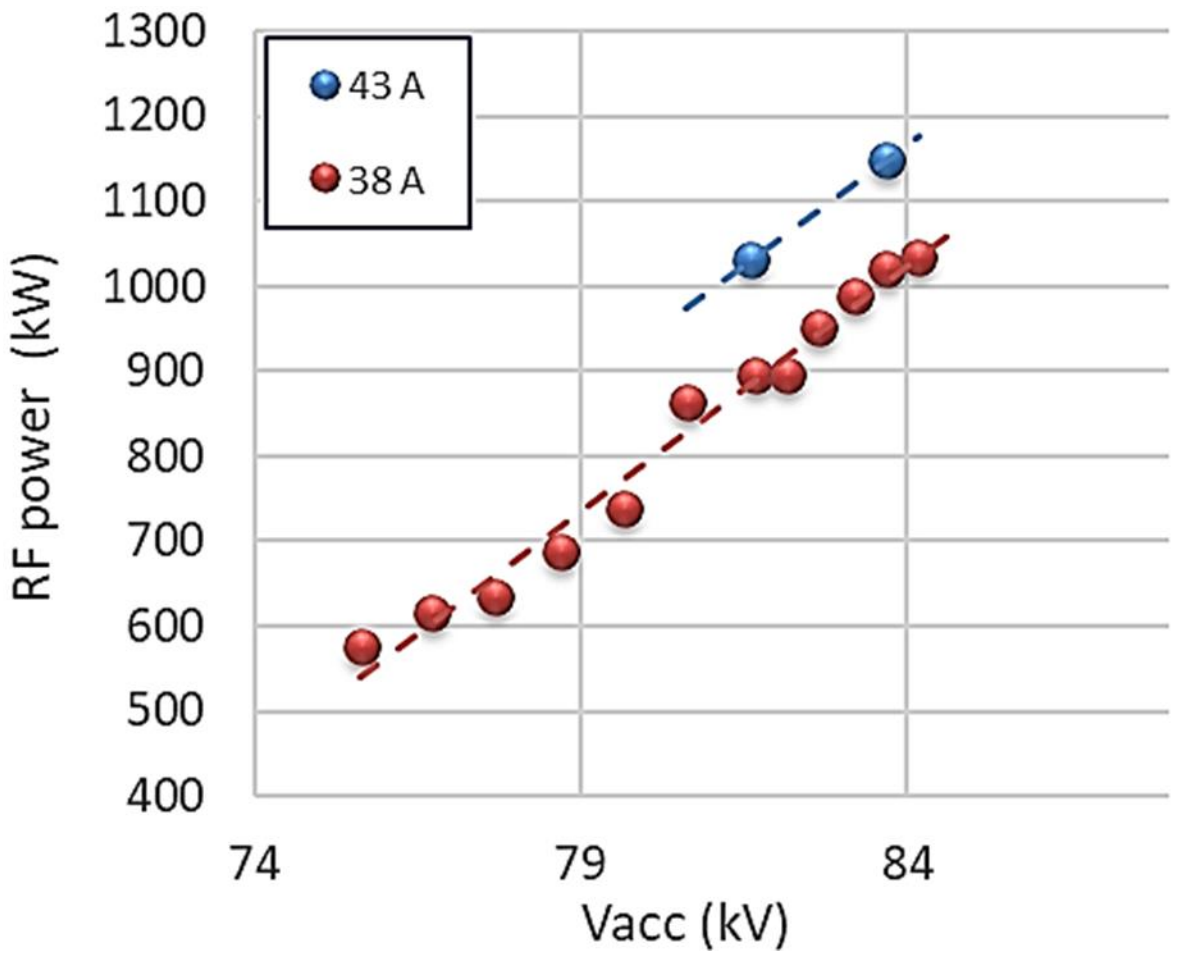
TH1511 GYROTRON: Design validation and prototype tests

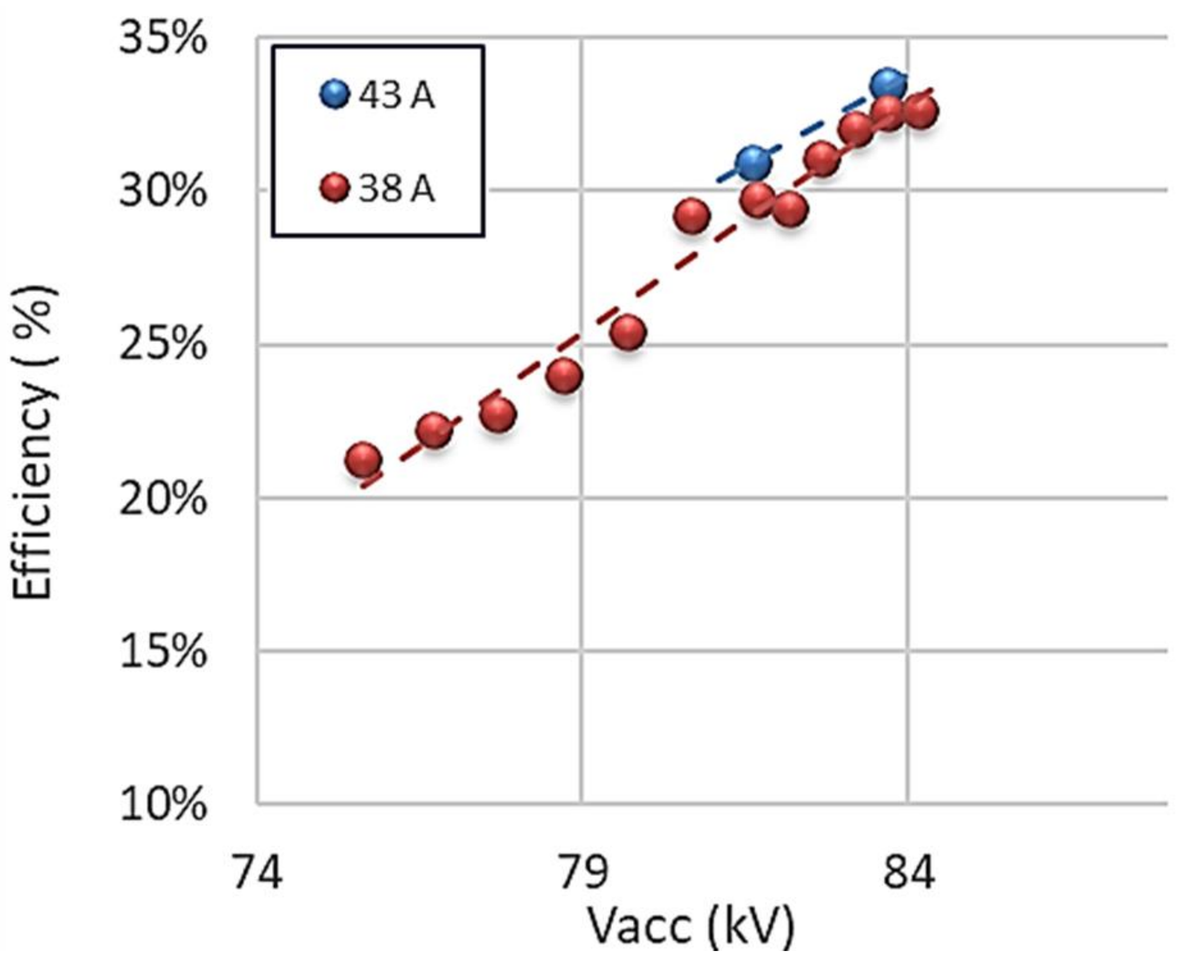
Karlsruhe Institute of Technology

Building a future we can all trust

PROTOTYPE TEST RESULTS: SHORT PULSE PERFORMANCE NON-DEPRESSED COLLECTOR CONFIGURATION

- **DC in :**
  - V_{acc} = 84 kV
  - I_{beam} = 40 A
- **RF out :**
  - P ≈ 1.2 MW
  - η ≈ 35%
  - T = 1 ms
- **Test on representative conditions :**
  - Full neutralization
  - No thermalization

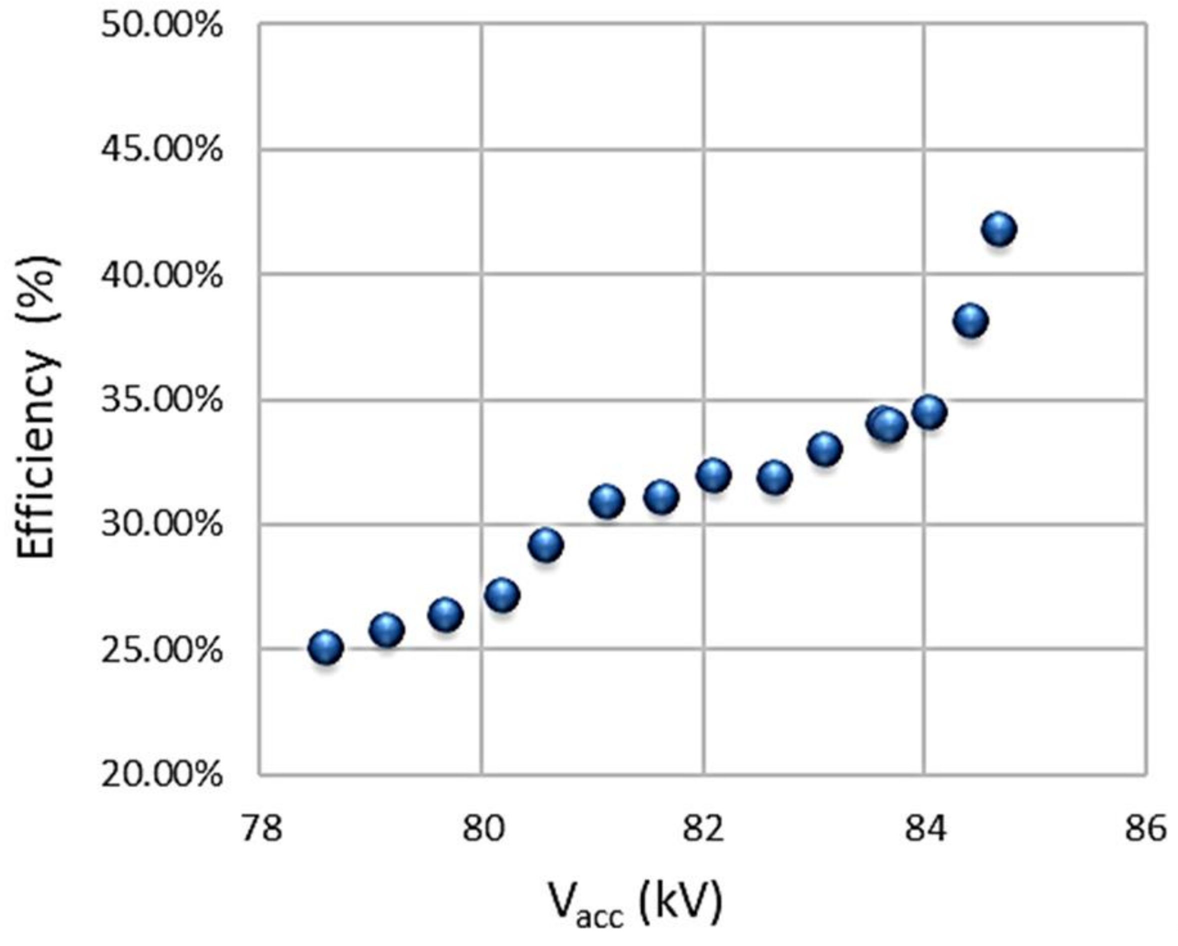


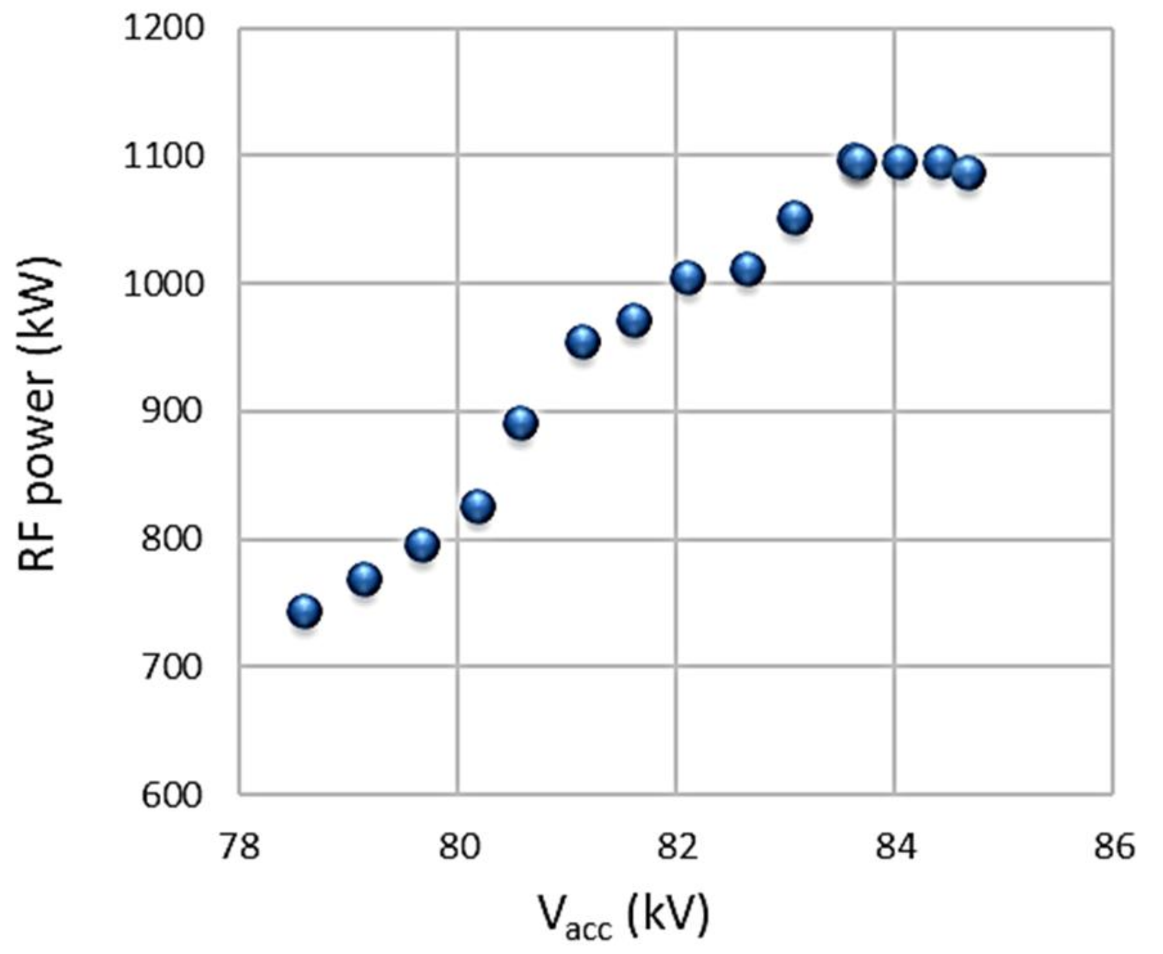


TH1511 GYROTRON: Design validation and prototype tests

PROTOTYPE TEST RESULTS: SHORT PULSE PERFORMANCE SINGLE-STAGE DEPRESSED COLLECTOR CONFIGURATION

- **DC in :**
  - V_b = 26 kV
  - I_{beam} = 40 A
- **RF out :**
  - P ≈ 1.03 MW
  - η ≈ 44%
  - T = 3 ms

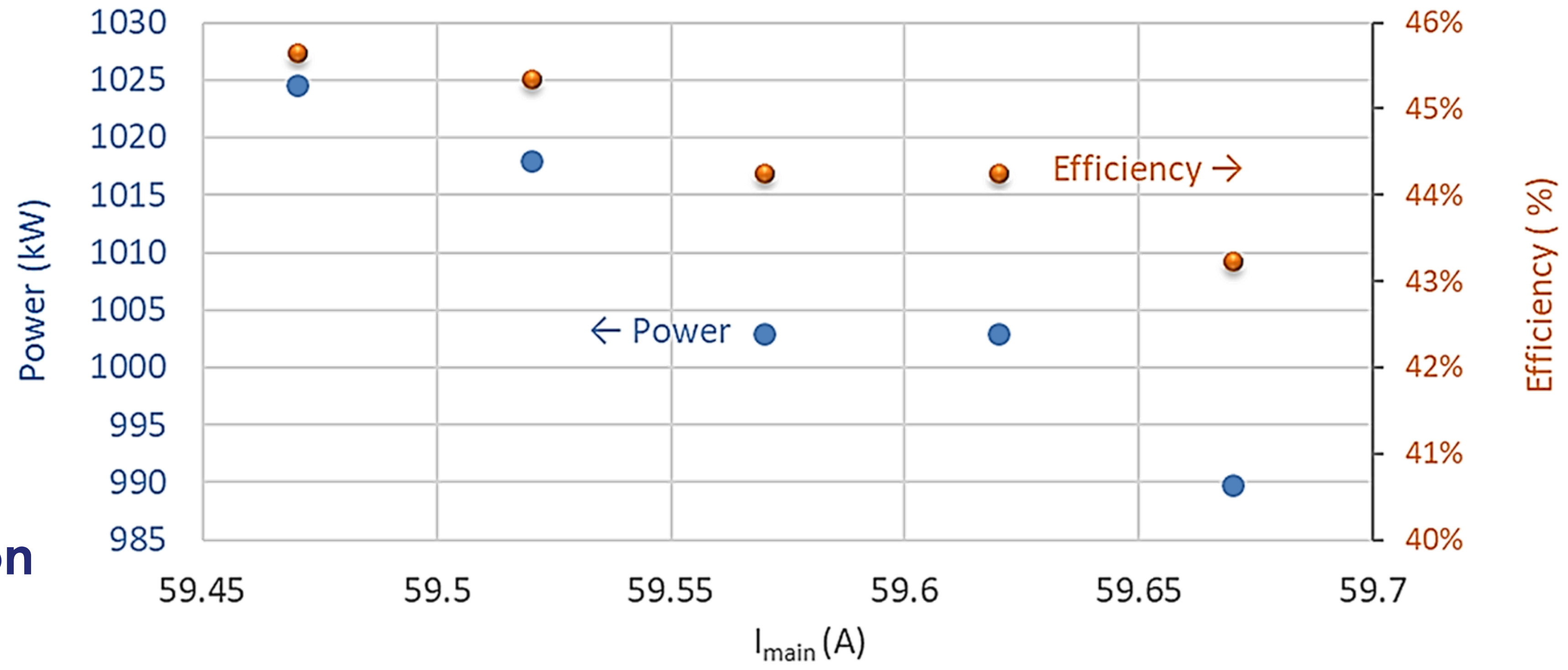




TH1511 GYROTRON: Design validation and prototype tests

PROTOTYPE TEST RESULTS: SHORT PULSE PERFORMANCE SINGLE-STAGE DEPRESSED COLLECTOR CONFIGURATION

- **DC in :**
  - V_b = 26 kV
  - I_{beam} = 40 A
- **RF out :**
  - P > 1 MW
  - η ≈ 46%
  - T = 3 ms
- **Magnetic field optimization (main coil current)**



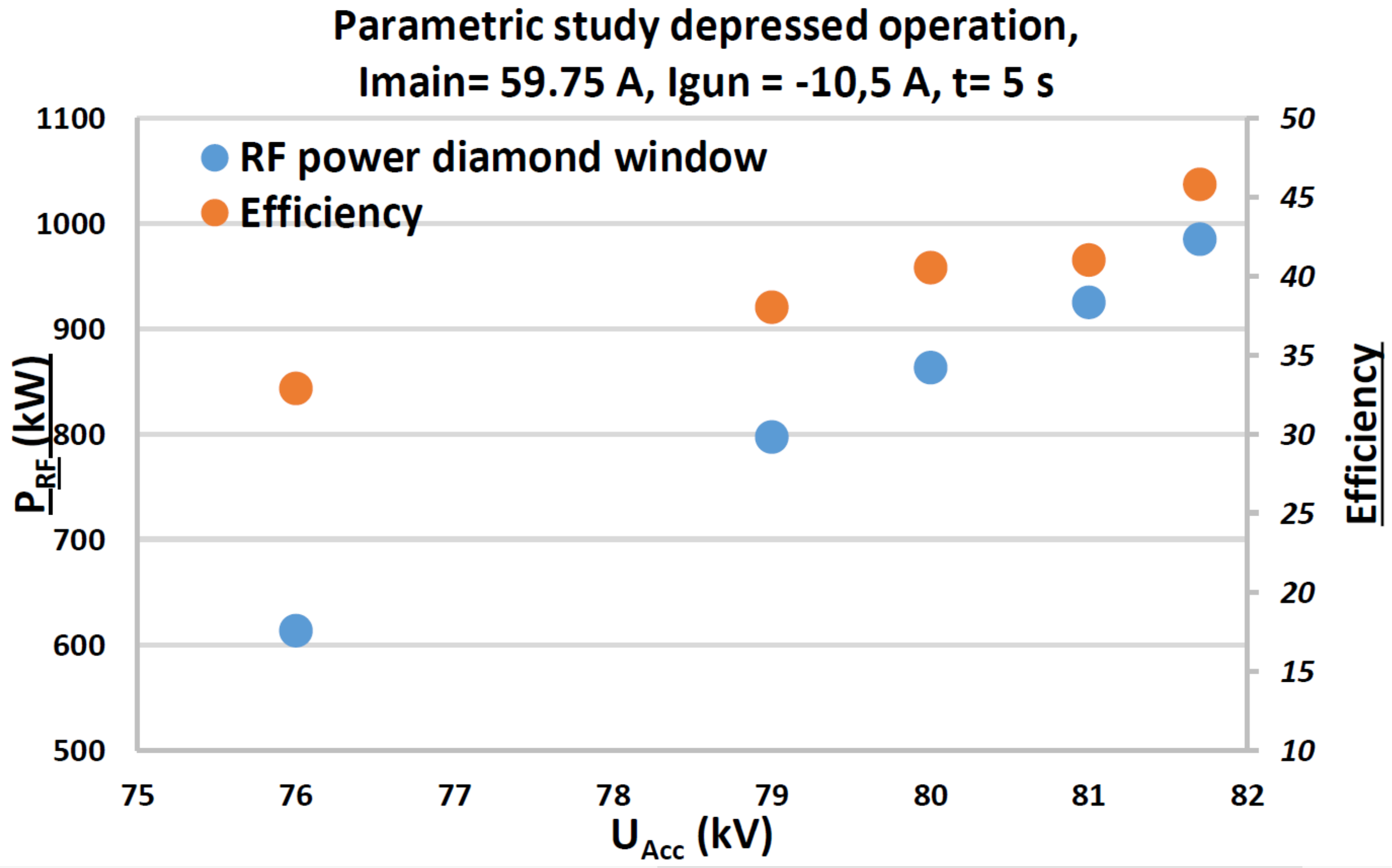
TH1511 GYROTRON: Design validation and prototype tests

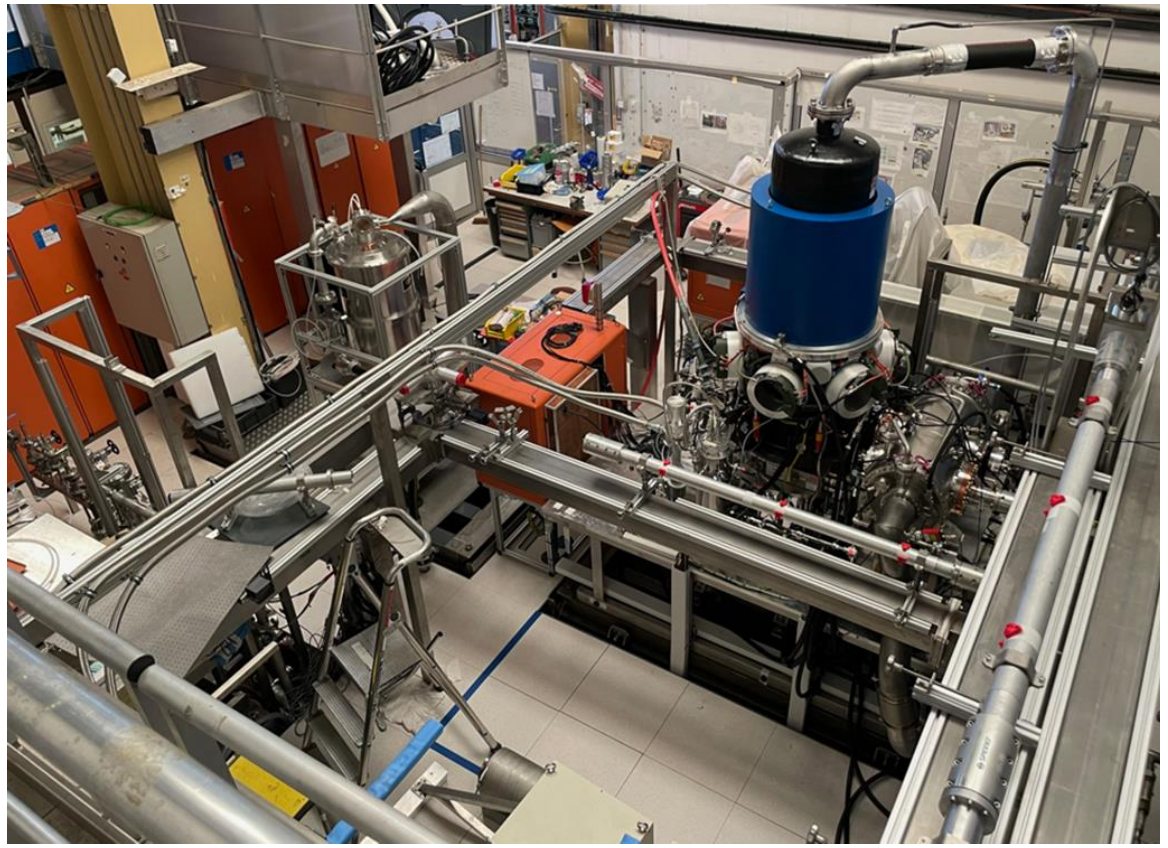
PROTOTYPE TEST RESULTS: LONG PULSE PERFORMANCE SINGLE-STAGE DEPRESSED COLLECTOR CONFIGURATION

- DC in :
  - V_c = 53.5 kV
  - V_b = 28.2 kV
  - I_{beam} = 40 A

- RF out :
  - P = 1 MW
  - η = 45 %
  - T = 5 s
  - F = 104.869 GHz stable operation

- The campaign continues at CEA toward longer pulses.





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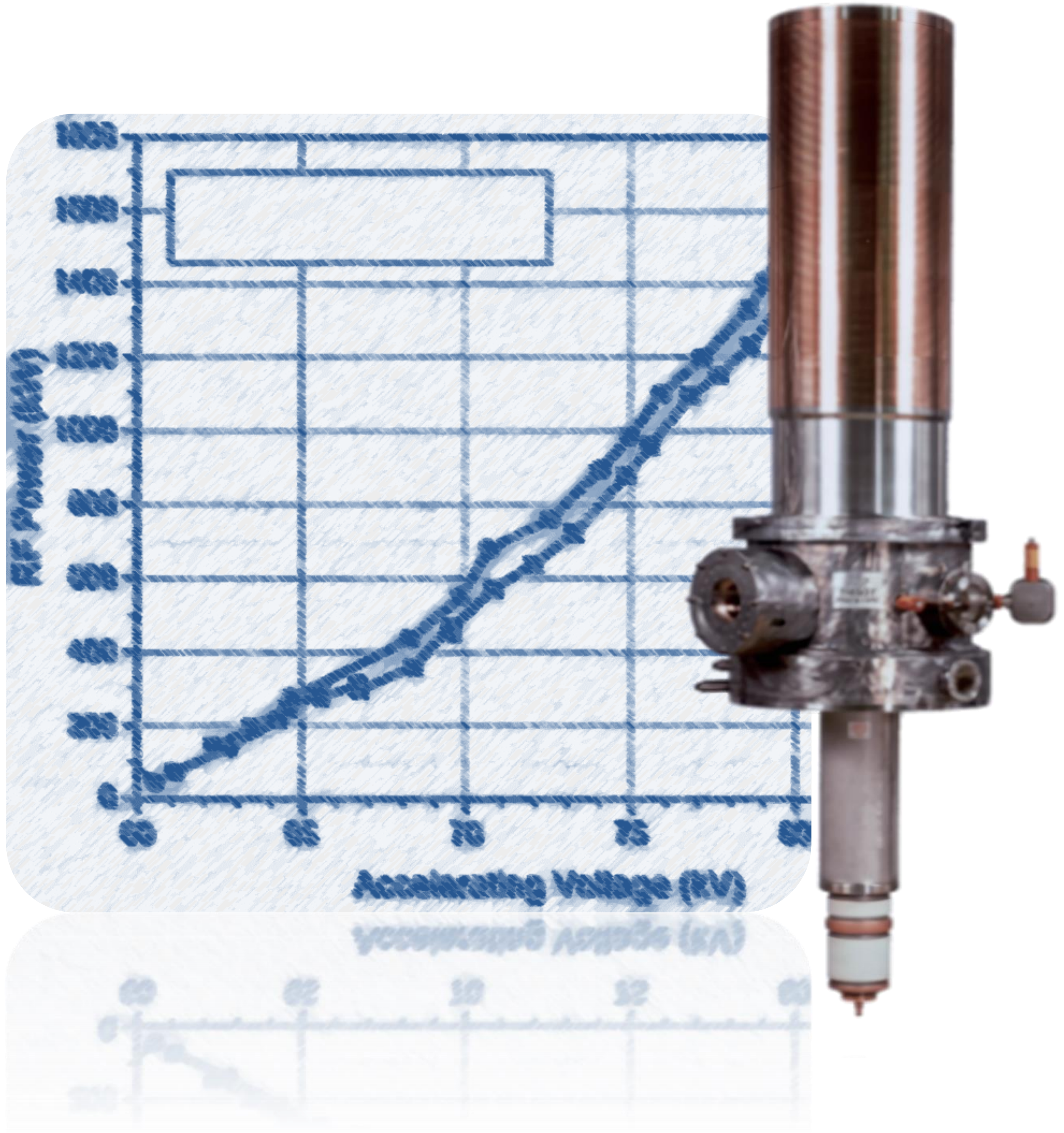
TH1512 gyrotron: Validation and prototype tests



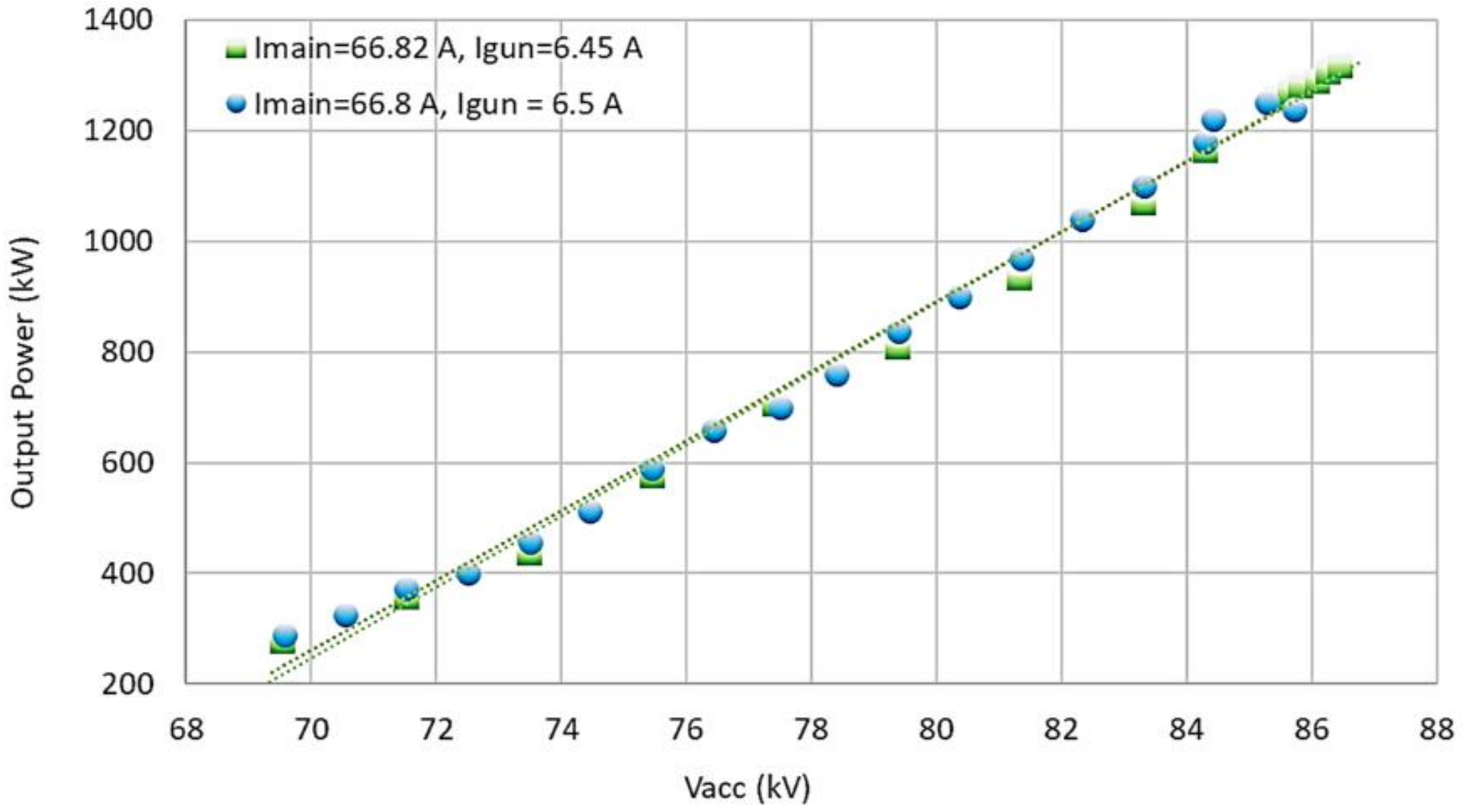
TH1512 GYROTRON: Design validation and prototype tests

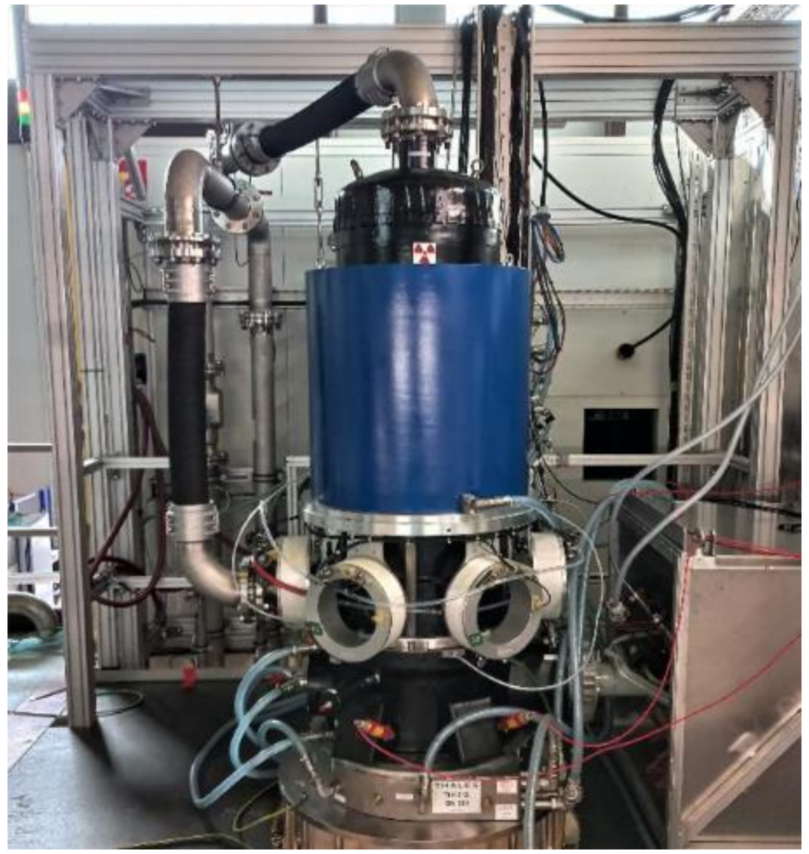
PROTOTYPE TEST RESULTS: SHORT PULSE PERFORMANCE NON-DEPRESSED COLLECTOR CONFIGURATION

- DC in :
  - V_{acc} = 86 kV
  - I_{beam} = 43 A

- RF out :
  - P ≈ 1.3 MW
  - η > 35.5%
  - T = 1 ms
  - Mode purity > 97.9%

- Test on representative conditions :
  - Full neutralization
  - No thermalization

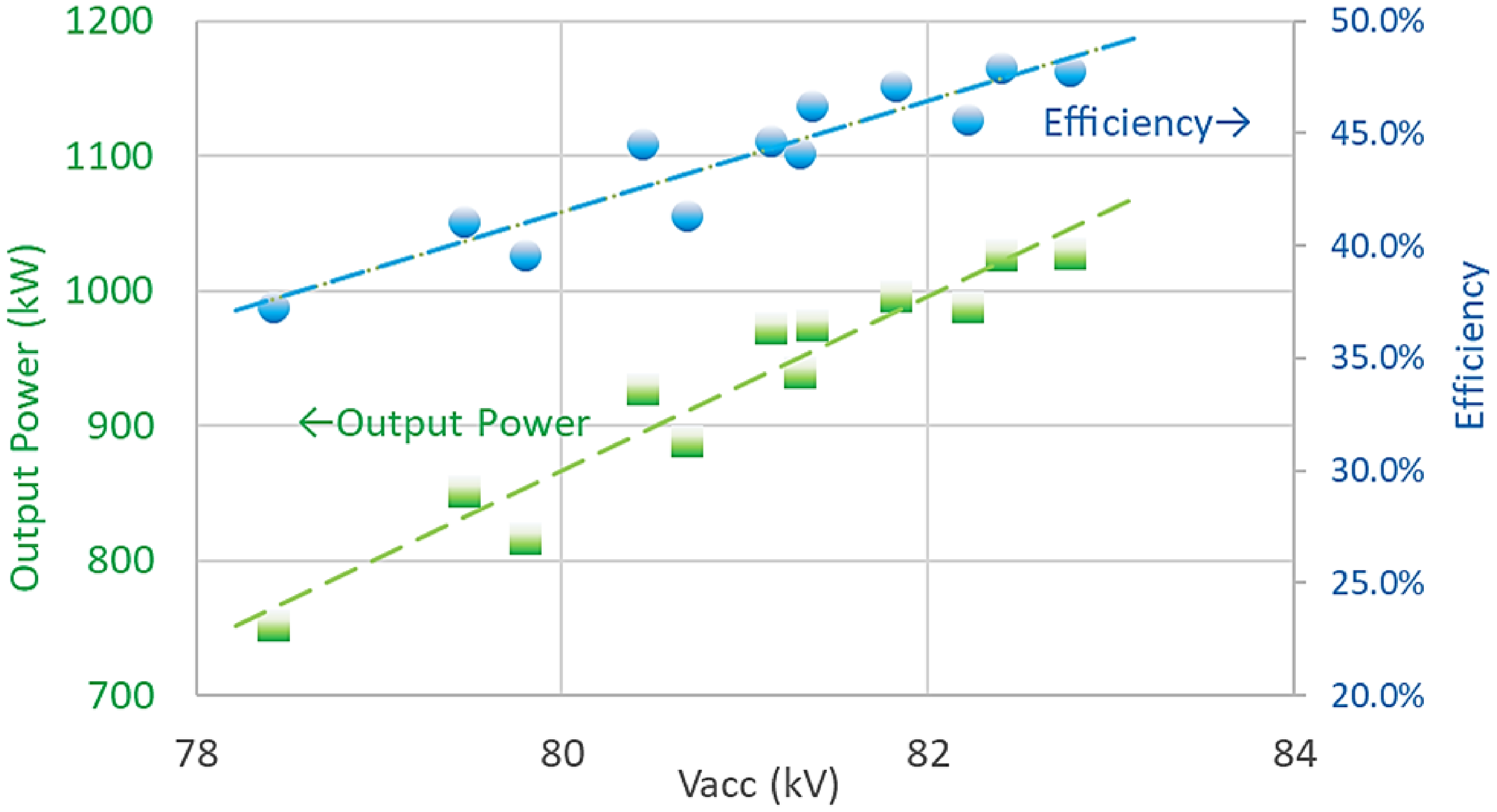


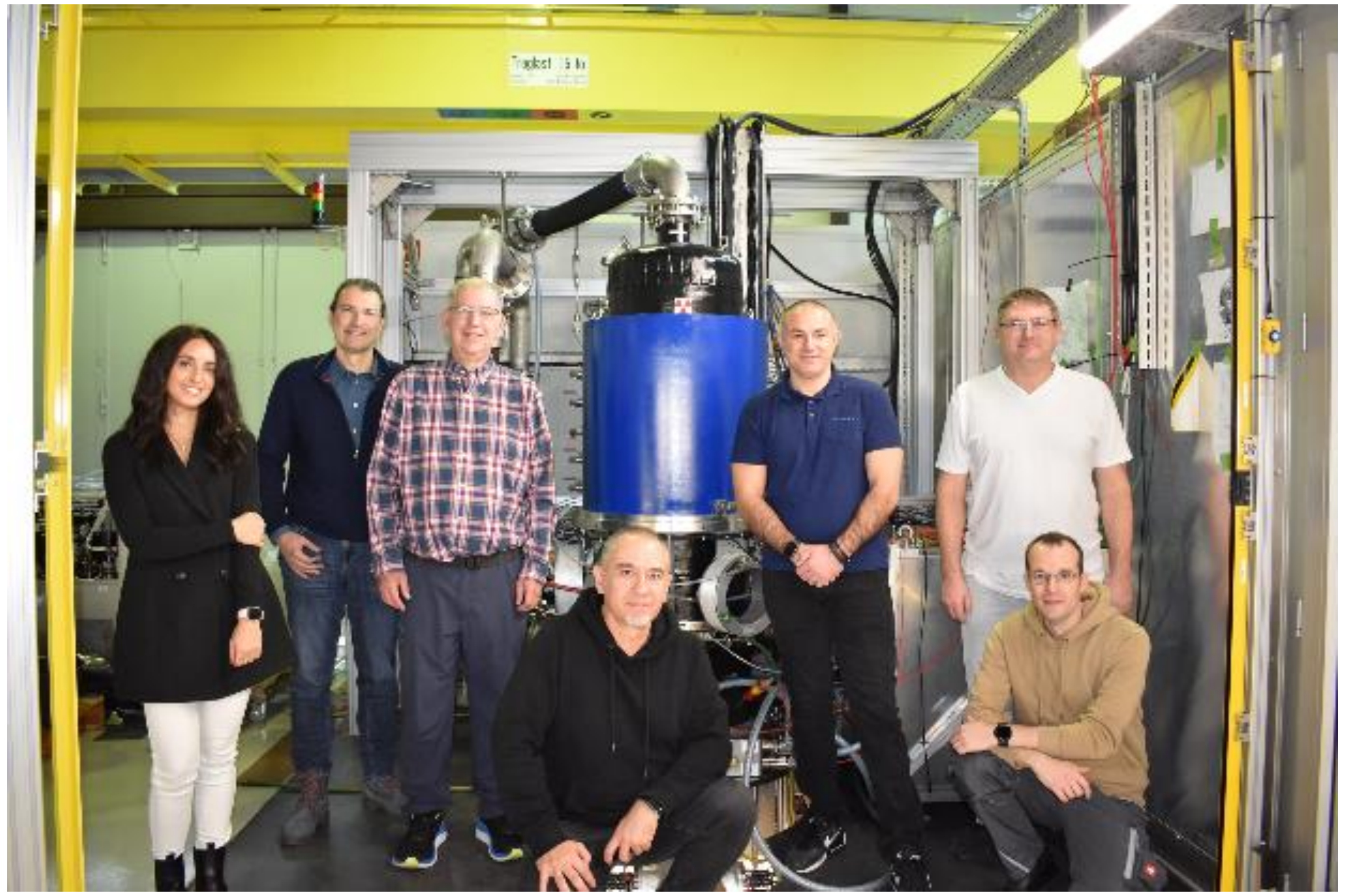


TH1512 GYROTRON: Design validation and prototype tests

PROTOTYPE TEST RESULTS: SHORT PULSE PERFORMANCE SINGLE-STAGE DEPRESSED COLLECTOR CONFIGURATION

- DC in :
  - V_b = 30 kV
  - I_{beam} = 40.1 A
- RF out :
  - P ≈ 1.03 MW
  - η ≈ 48%
  - T = 3 ms
  - Stable operation





TH1512 GYROTRON: Design validation and prototype tests

PROTOTYPE TEST RESULTS: LONG PULSE PERFORMANCE SINGLE-STAGE DEPRESSED COLLECTOR CONFIGURATION

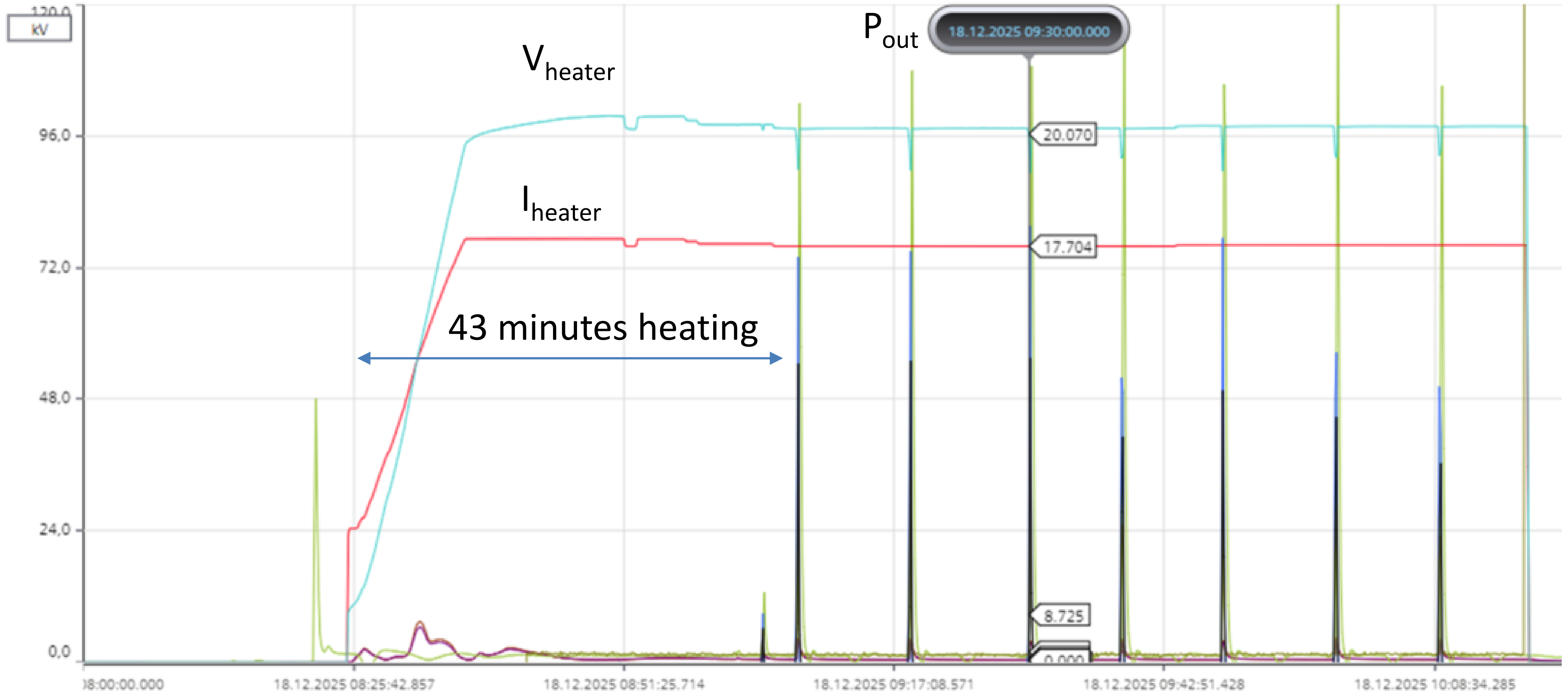
DC in :

- V_c = 53.4 kV
- V_b = 26.2 kV
- I_{beam} = 40.7 A

RF out :

- P = 949 kW
- η = 42.5 %
- T = 10 s
- F = 117.501 GHz stable operation
- The unit, codenamed “Asterix” by the DIII-D team, has succeeded the FAT at KIT and the SAT in San Diego.

Consecutive 10 s pulses from 762 kW to 949 kW



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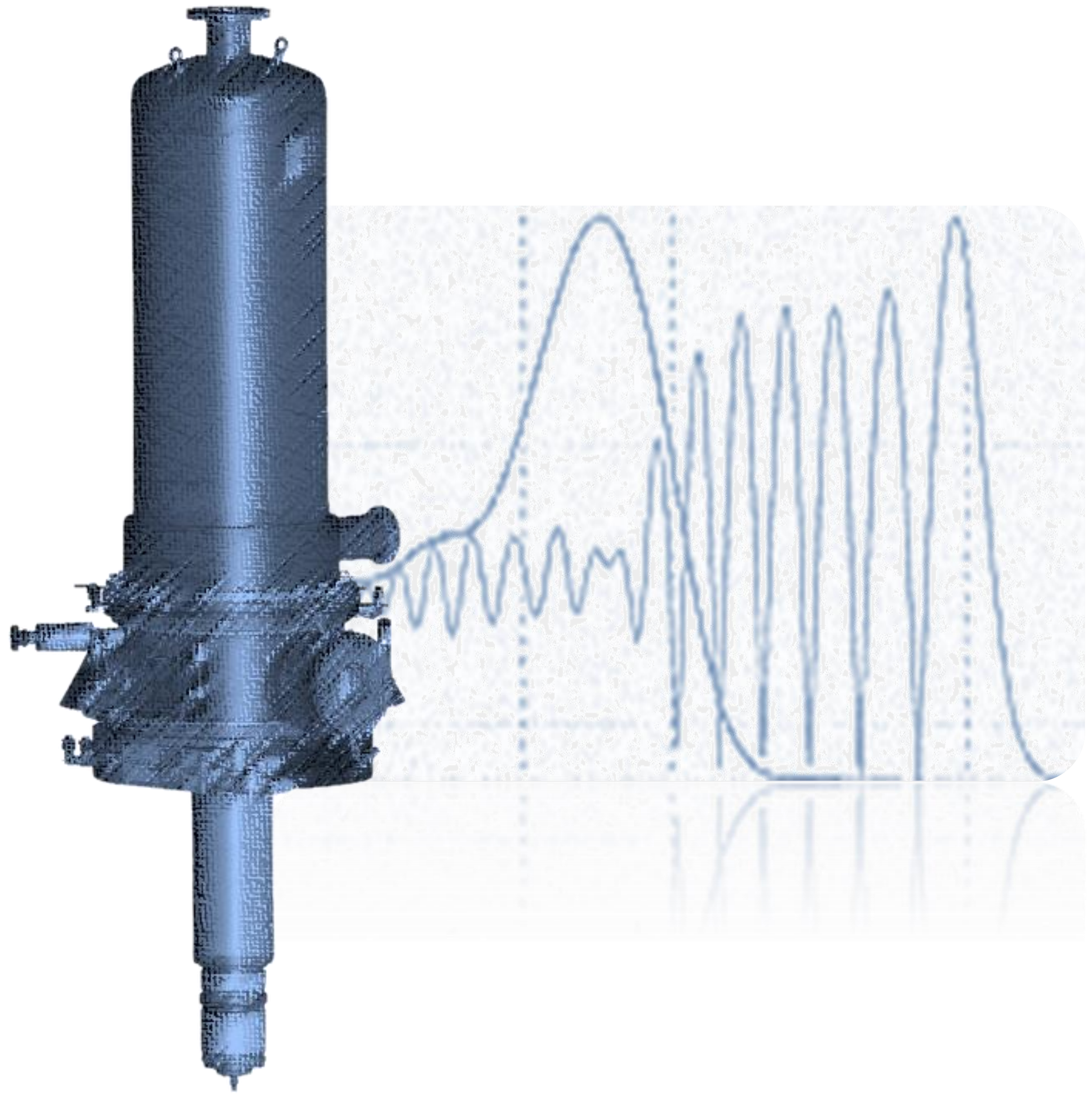
Conclusions:
Achievements and current developments



Conclusions: Achievements and current developments

- TH1511 Short Pulse test VALIDATED the gyrotron industrial design: P=1.2 MW, η > 46%, T=3 ms. Long pulse test in progress: P=1 MW, η = 45%, T=5 s. New TH1511 series units production in progress.
- TH1512 Short Pulse test VALIDATED the gyrotron industrial design: P=1.3 MW, η > 48%, T=3 ms. Long Pulse test SUCCEEDED, FAT gyrotron ACCEPTED: P=949 kW, η = 42.5 %, T = 10 s. Gyrotron installed at DIII-D in San Diego and SUCCEEDED the SAT.

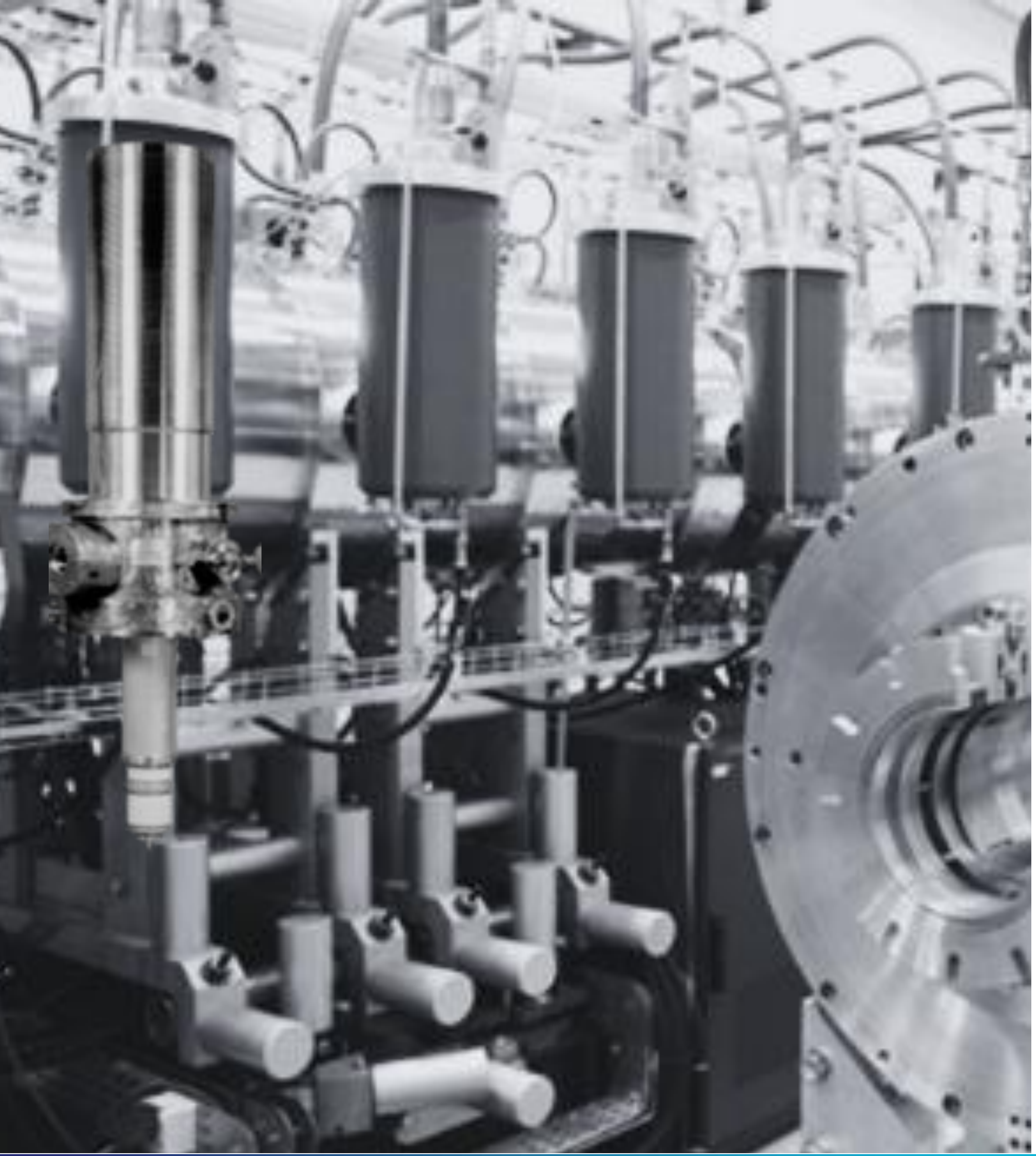
KIT Karlsruhe Institute of Technology

HELLENIC REPUBLIC National and Kapodistrian University of Athens EST. 1837

Politecnico di Torino 1859

cea

GENERAL ATOMICS



PROGRESS IN EUROPEAN COLLABORATIVE GYROTRON DEVELOPMENTS FOR CEA AND GENERAL ATOMICS

Thanks for your attention