Sailing from Far Infrared and Submillimeter Waves Plasma Diagnostics towards THz-TDS, and beyond

"What Infrared and Millimeter Waves have done and what they can still do for Plasma Physics and NUCLEAR FUSION"

Marco Zerbini

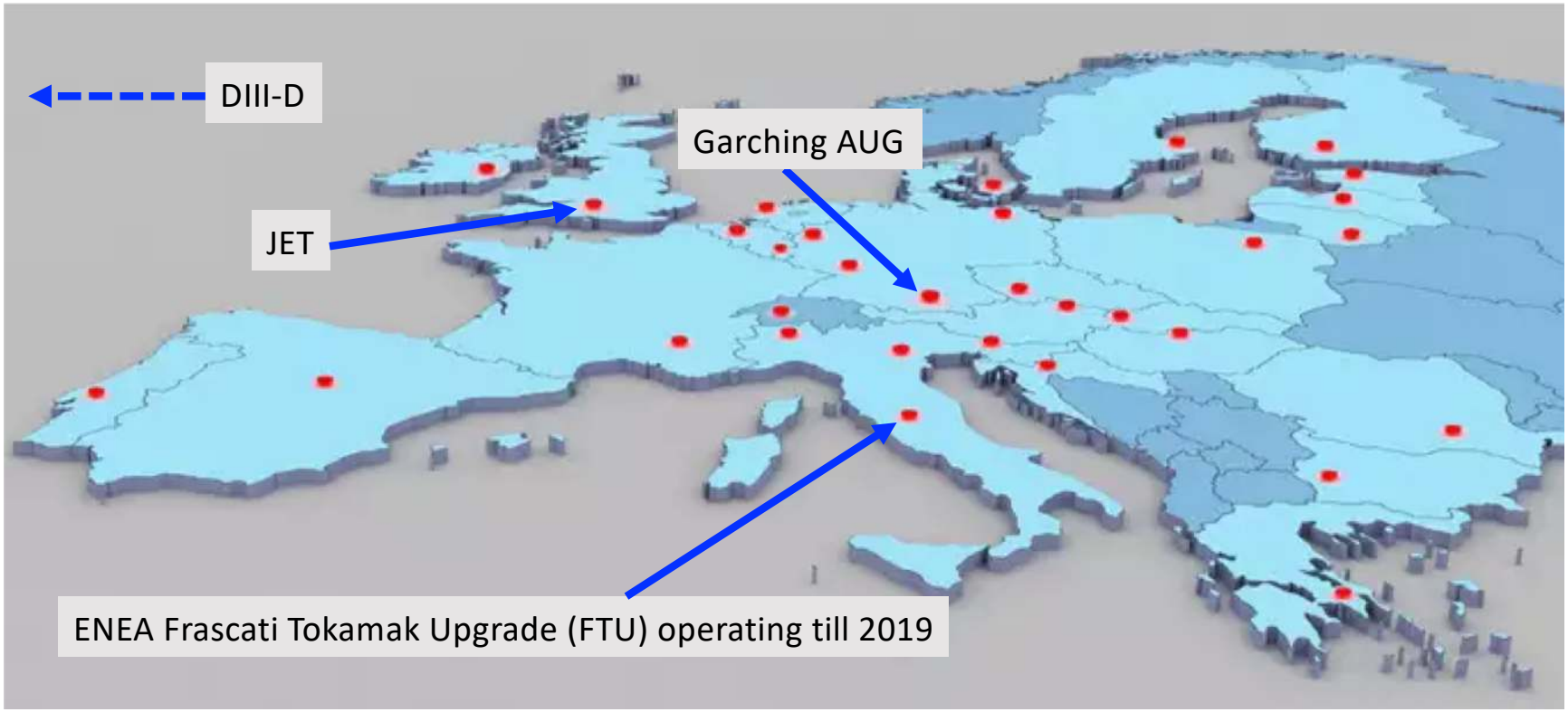
ENEA Frascati & Clarendon Oxford

IRMMW-THz 2022 Friday, September 2nd, 2022

Layout:

- Fusion & Tokamak concepts
- FIR, MM & THz Diagnostics landscape in plasma
- Applications:
  - ECE/ECRH
  - Reflectometry
  - Interferometry & Polarimetry
- Towards THz-TDS diagnostics

Fusion Research Network



The context: Fusion & Tokamaks

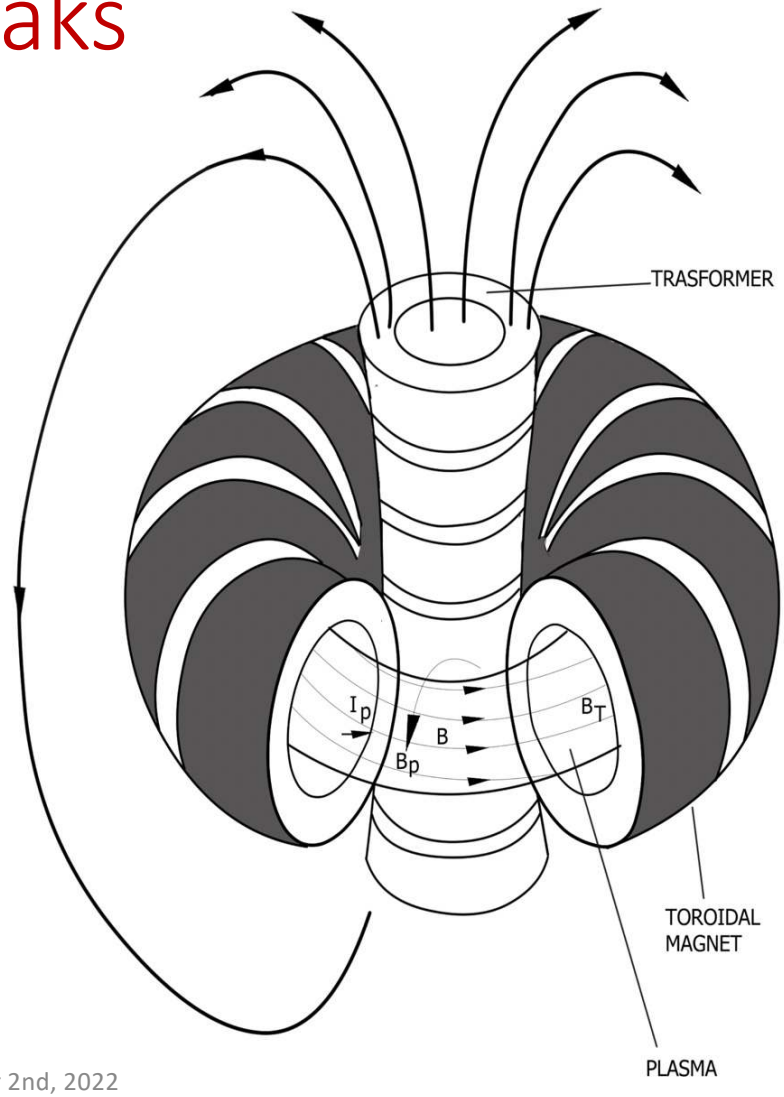
Tokamaks use a combination of toroidal and poloidal magnetic fields to create a “closed” or confined configuration to achieve fusion reactions via thermal collisions (i.e. “Thermo-Nuclear”).

Fusion-relevant parameters:

Major radius 3-6 m, Minor radius 1-2 m

Plasma density 10^{20}-10^{21} m^{-3} (particles/m^3)

Toroidal field 3-5 Tesla (*Poloidal field ~1/3 B_T*)



FIR, MM & THz landscape in plasma

Plasma poloidal crossection

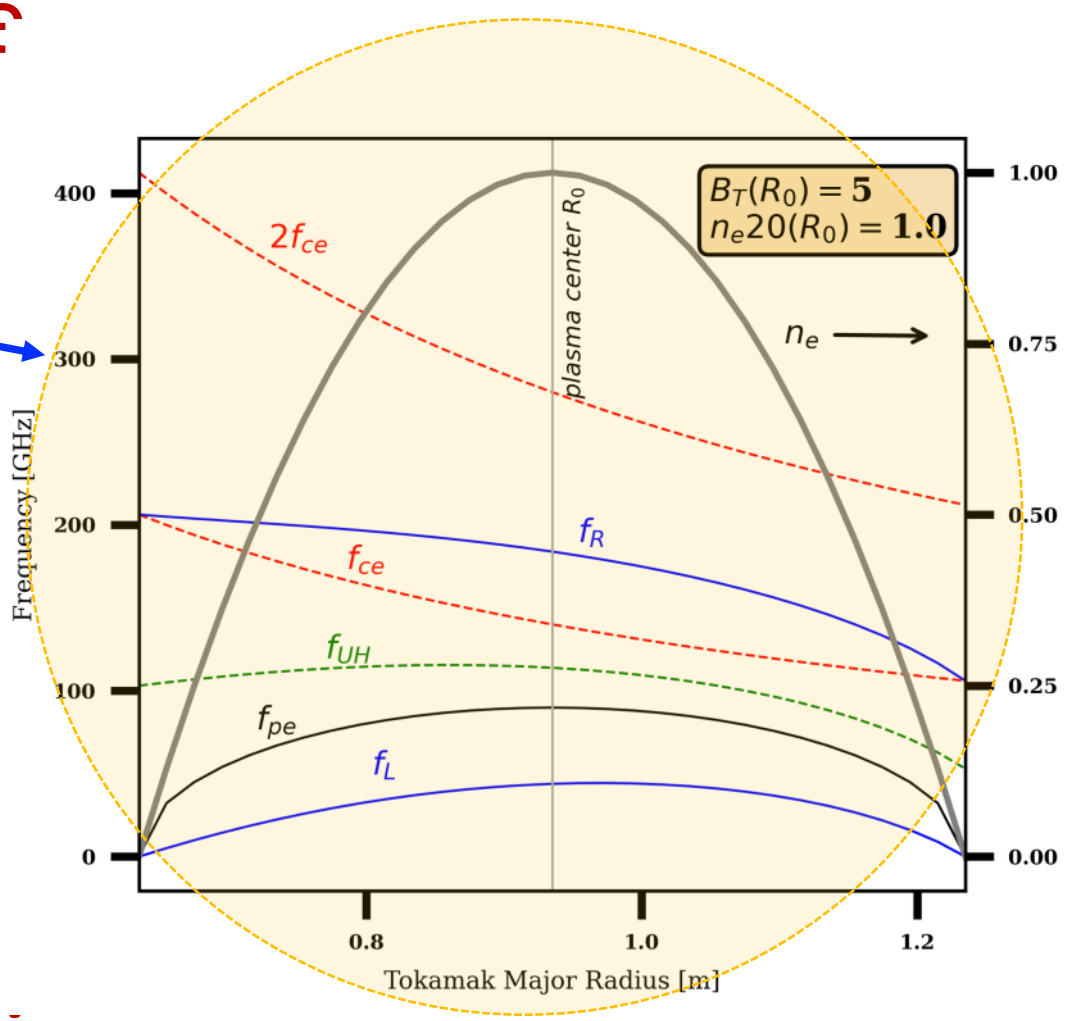
Magnetic Field: $B(R) = B_0 \times R_0 / R$

Parabolic density profile (***grey*** line)

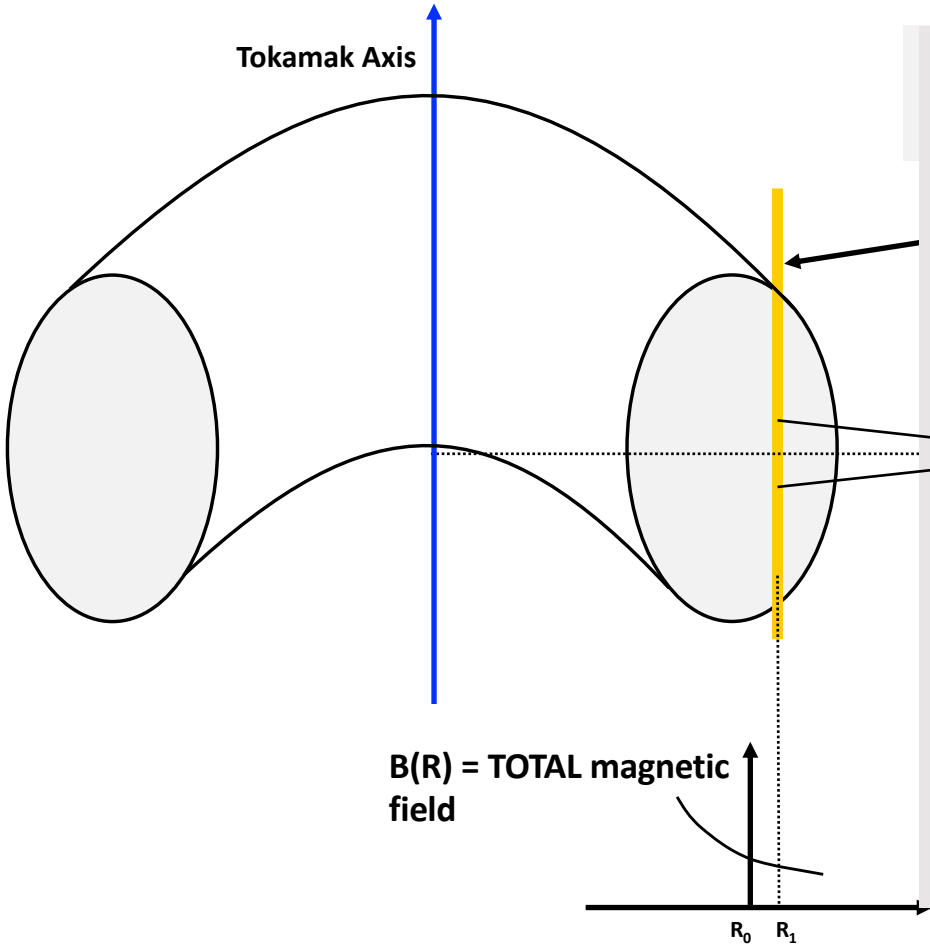
Solid lines: CUTOFFS (waves reflected)

Dashed lines: RESONANCES (waves are absorbed)

Many Diagnostics Options...



Electron Cyclotron Resonance applications

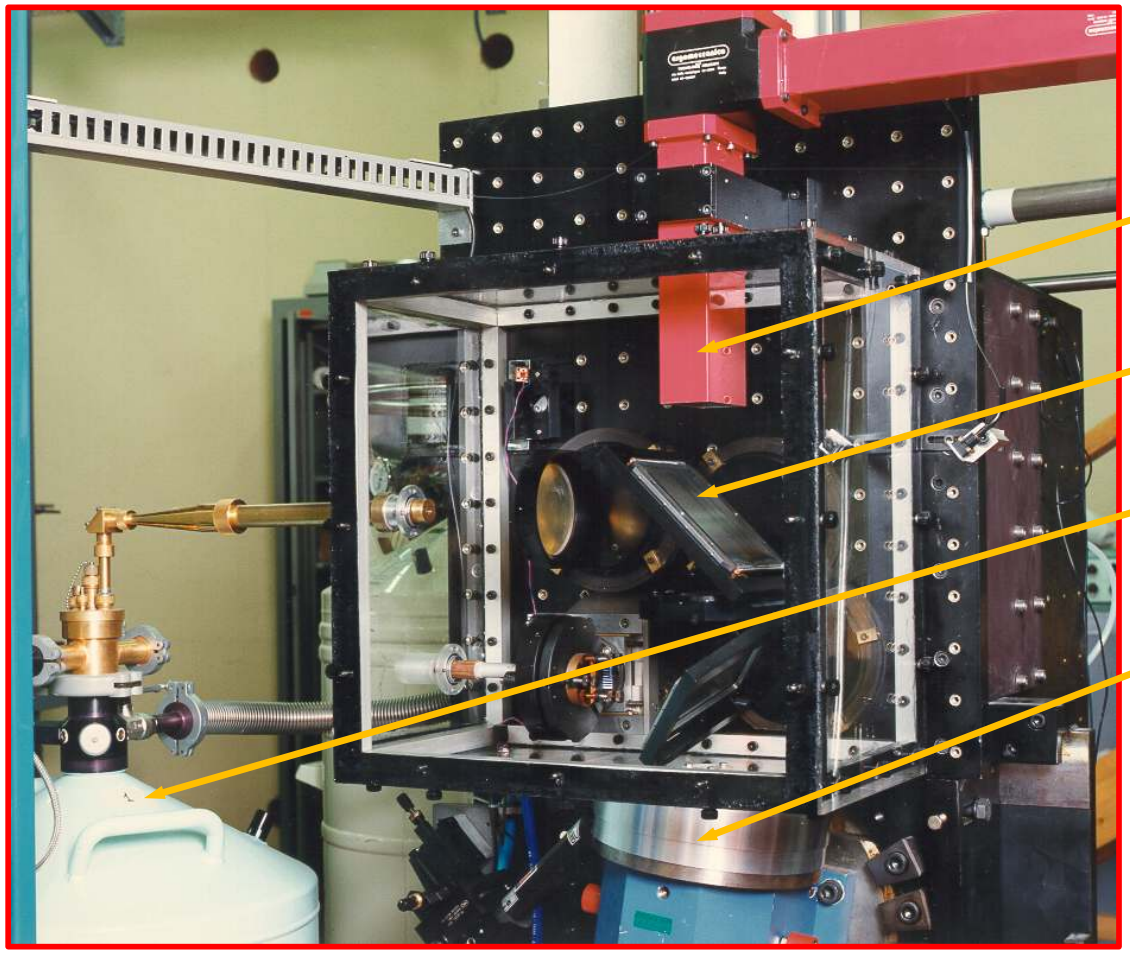


ECRH- Heating

EC Resonant layer @ $\omega(B(R_1)$

GYROTRONS:
~110-170 GHz
~MW's power
1st or 2nd harmonic resonance

ECE Michelson interferometer (FTU 1989-2019)



Detection of absolute intensity of electro-magnetic radiation 100-1000 GHz range ($\Delta\nu$=7GHz), vs. time.

ECE waveguide, from Plasma (N_2 flow)

Wire Grid Polarisers

Cryogenic Detector (InSB, 4K LHe)

Rotating Scanning Mirrors (Δt=5ms):

-----LINEAR SCAN----

Other ECE diagnostics options:

Heterodyne Radiometer (fast)

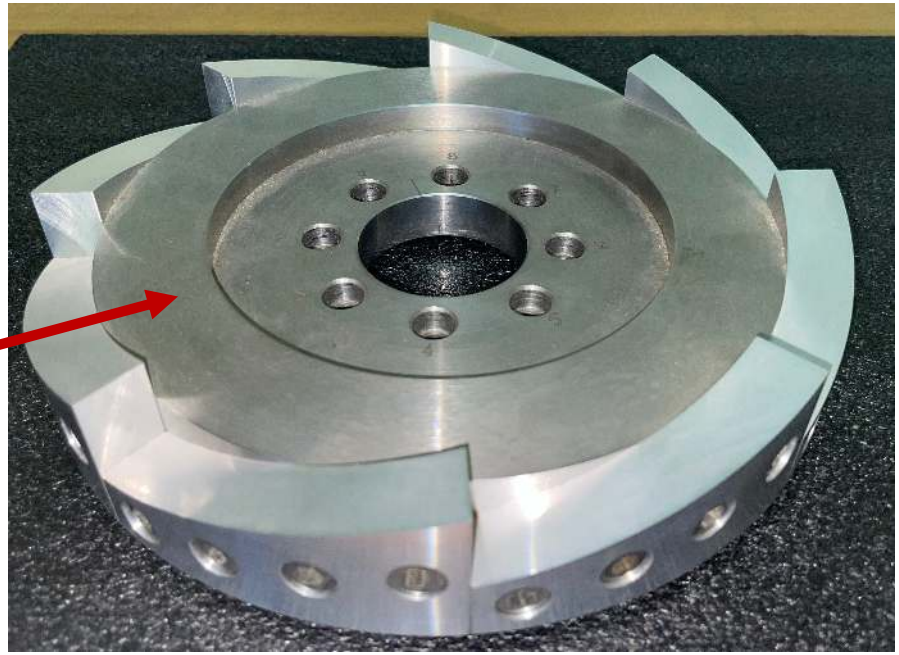
Polychromator (reliable)

P. Buratti and M. Zerbini, Rev. Sci. Instrum. **66**, 4208 (1995)

Rotating Helicoidal Reflectors: linear scan, improved spatial and temporal resolution.

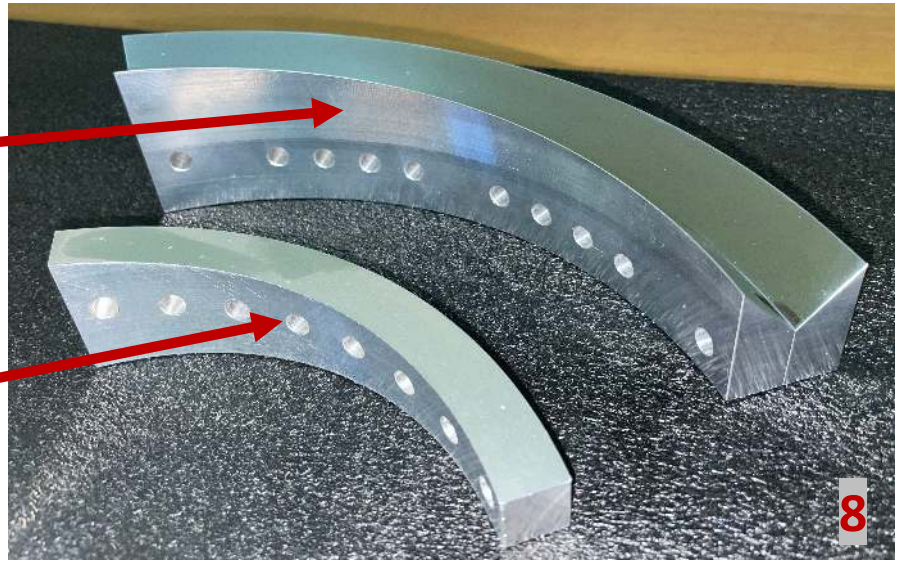
Prototype (*Pieroni-Ascoli-Bartoli, Frascati 1974*)

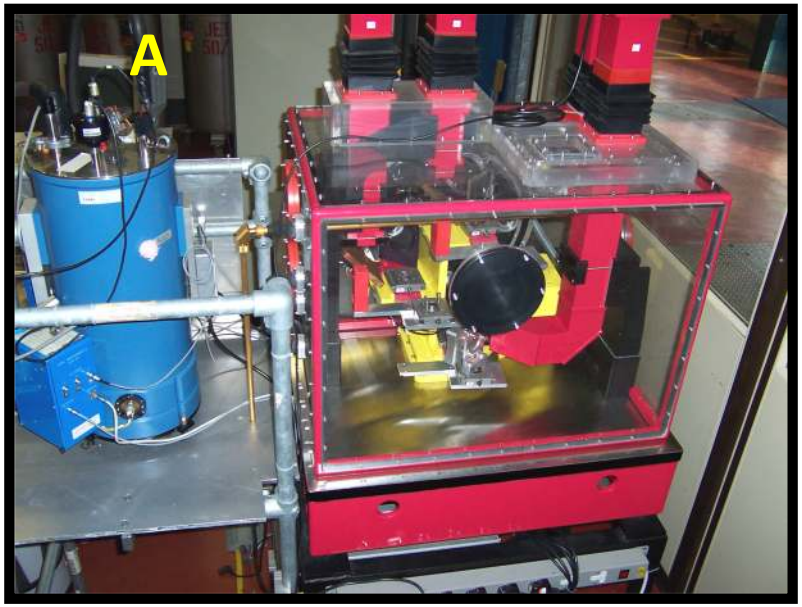
Fast scan
(1 ms)

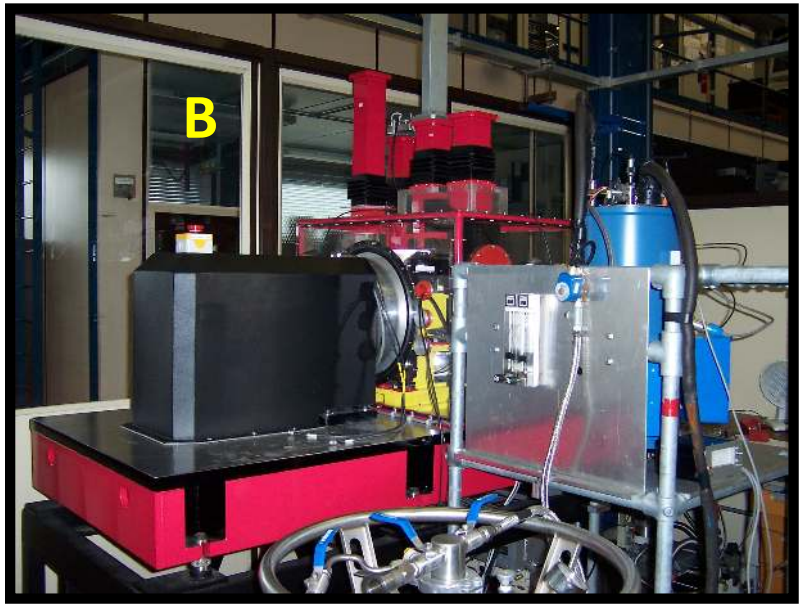


Roof-Top
JET (2002)

Long scan
(4cm path)





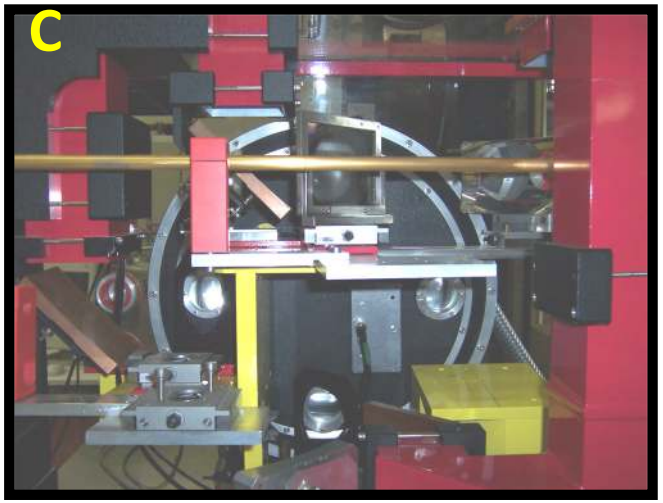


JET KK5 ECE Michelson (2005)

A: *TOP VIEW, N_2 BOX & Cryo-DETECTOR*

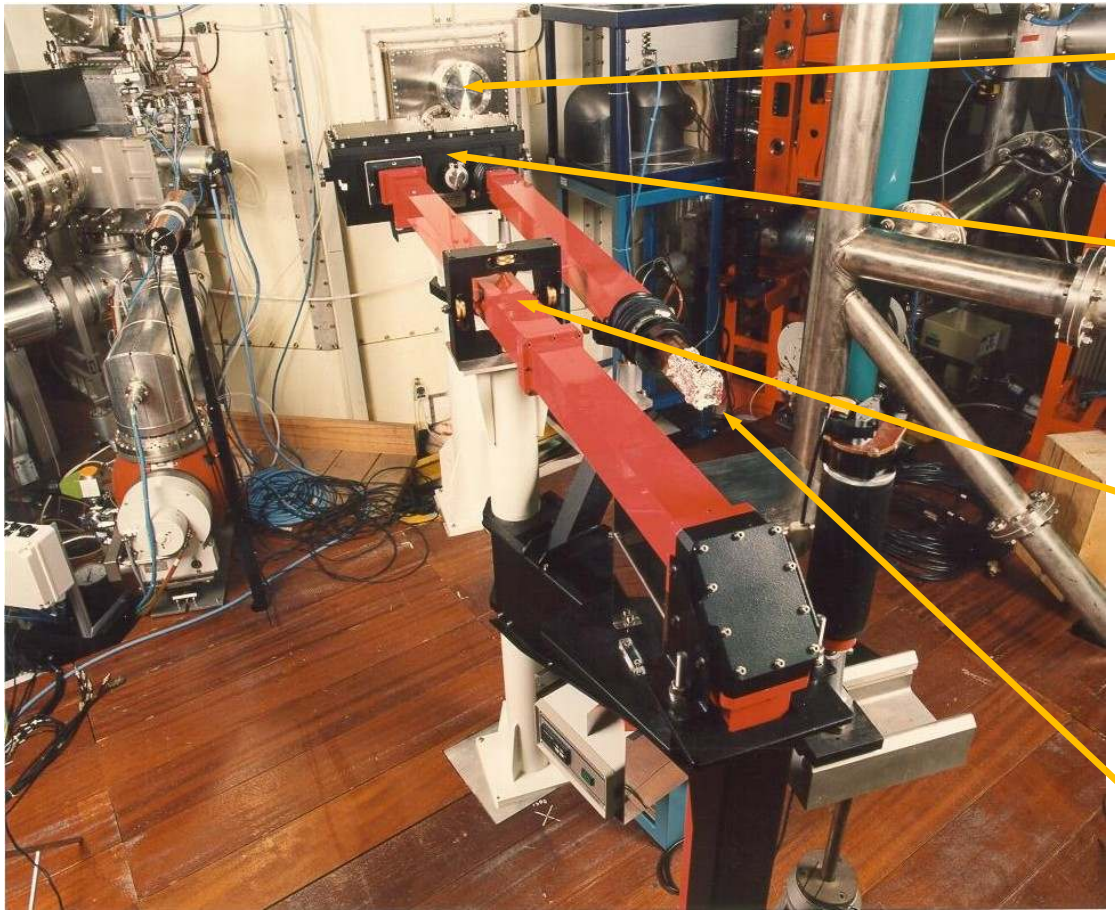
B: Motor cover & Cryogenics

C: *4 Interferometric channels ($\Delta\nu$ = 6 GHz, $\Delta\tau$ = 9 ms)*



M. Zerbini et al., in:
15th Topical Conference on High-Temperature Plasma Diagnostics (San Diego 2004)

ECE FTU: Collection optics, waveguides (90's)



Antennae port

Collection optics box, calibration switch (*ITER adopted this solution*)

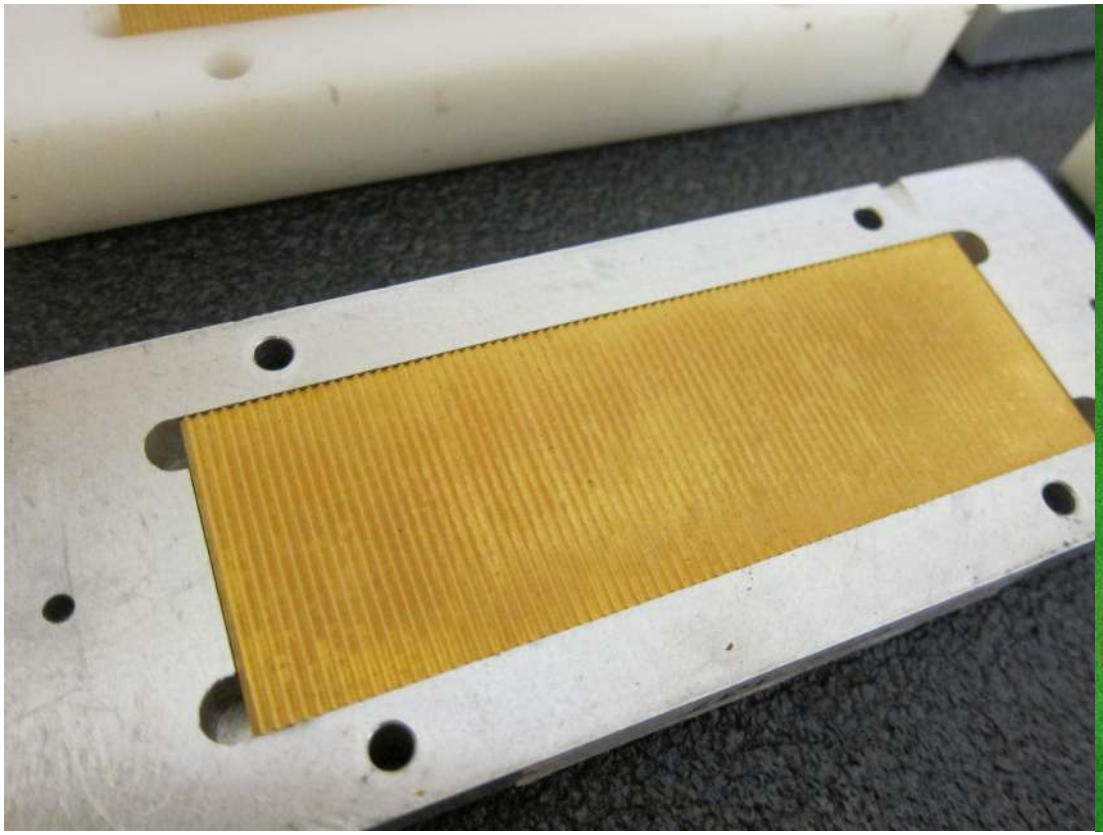
ECE waveguide, carries e.m radiation to Spectrometers

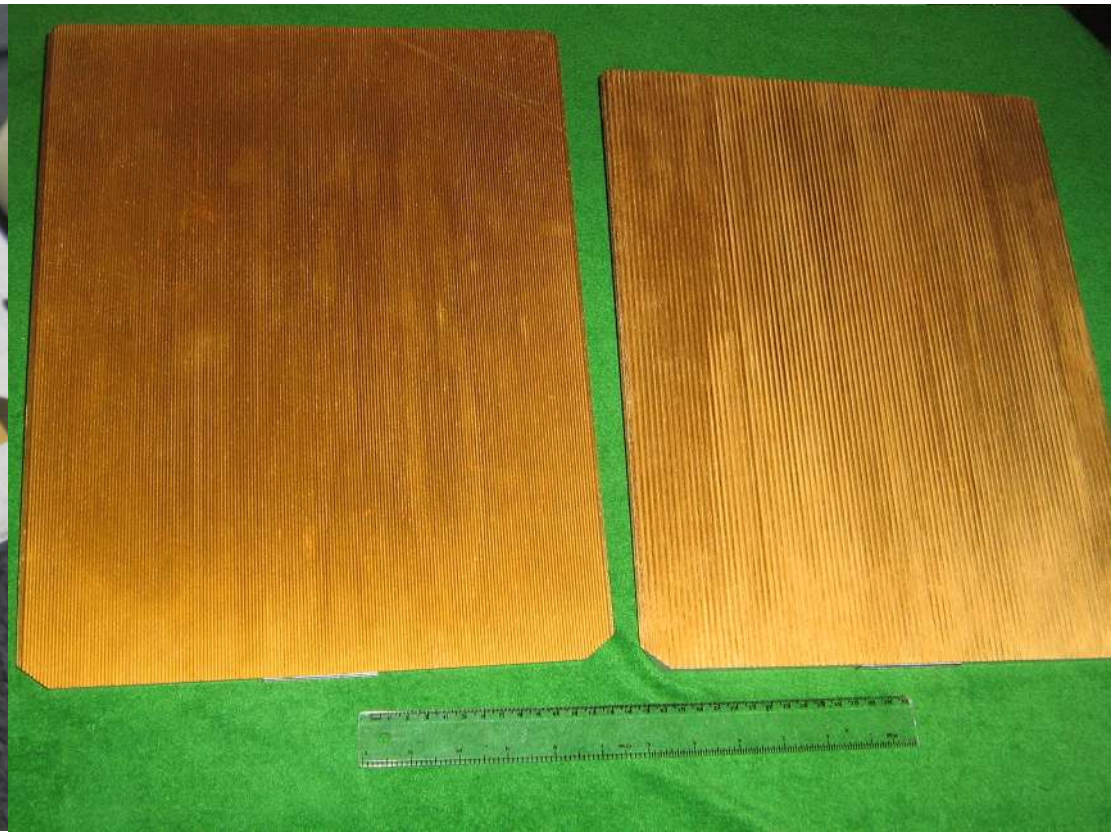
(N_2 flow prevents H_2O vapour absorption lines)

Calibration input (antenna replica)

*P. Buratti & M. Zerbini, Infrared Physics, **34**, p. 533 (1993)*

ECE Polychromator (JET 1980)



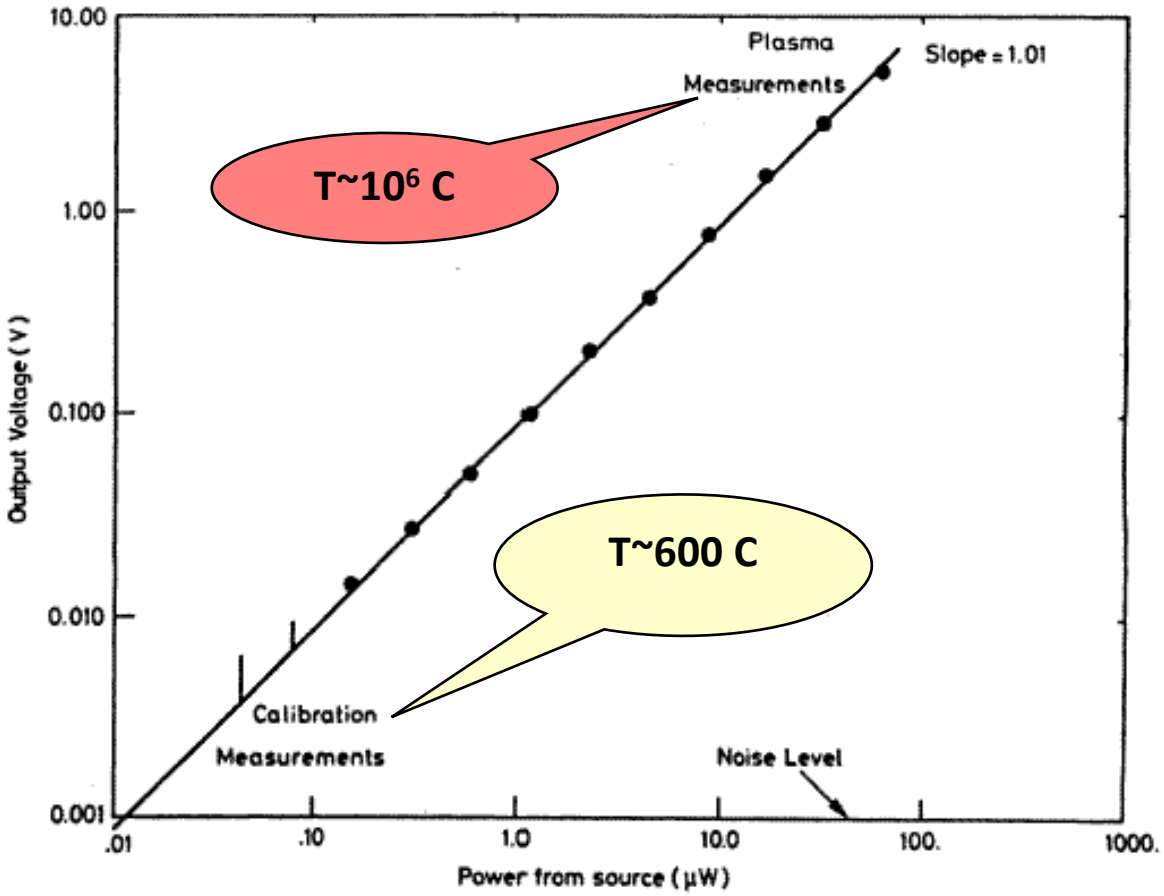


blazed copper gratings, gold coated, working at first order of diffraction

ECE Absolute calibration

Cryogenic LnSb bolometer: not a DETECTOR, it is a TRANSDUCTOR (power to voltage).

Remarkably LINEAR over 4 order of magnitude of power!



Detector Linearity test with Microwave source f=142.5 GHz

Courtesy: Baker, Costley et al EC-4 (1984)

To obtain the absolute temperature, ECE Spectrometer is calibrated against a known BB source (~600C):

Plasma temperature 5 keV ~ 60 Million C

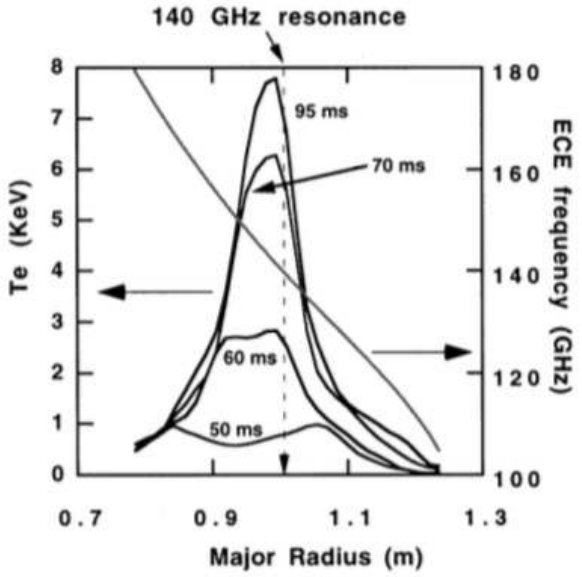
REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 70, NUMBER 1 JANUARY 1999

Electron cyclotron emission diagnostic of high temperature electron cyclotron resonance heated plasmas on Frascati tokamak upgrade

M. Zerbini, P. Buratti, O. Tudisco, G. Giruzzi,[a] A. Bruschi,[b] S. Cirant,[b] G. Granucci,[b] A. Simonetto,[b] C. Sozzi,[b] F. Gandini,[b] D. Pacella, K. B. Fournier,[c] and M. Finkenthal[d]
Associazione Euratom, ENEA sulla Fusione, CR-Frascati, C.P. 65, 00044 Frascati (Roma), Italy

(Presented on 10 June 1998)

The electron cyclotron emission (ECE) diagnostic on FTU tokamak is routinely performed with a Michelson interferometer with spectral range extending up to 1300 GHz. The diagnostic allowed accurate electron temperature measurements during the recent 140 GHz electron cyclotron resonance heating (ECRH) experiments on FTU. Very accurate measurements have been performed on a wide range of electron temperatures and profile peaking. The ECE measurements have been observations of x-ray spectra from highly stripped on in these conditions has been studied. © *1999* 9)70701-X]



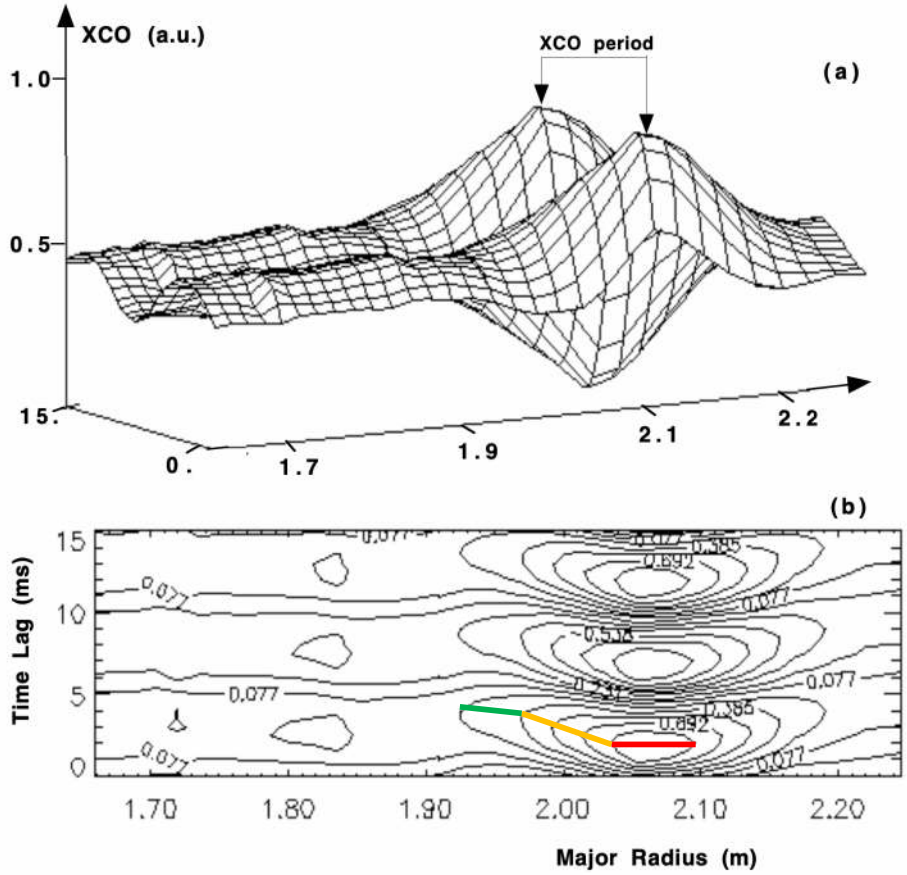
FTU "Record" 8 KeV temperature during 0.5 MW ECRH. Slope 115 keV/m.
Validated vs. Thomson Scattering and X-Ray independent Te measurements.

Correlation analysis of 110 GHz ECH modulation experiments on the DIII-D tokamak

Plasma Phys. Control. Fusion **41** (1999)

Combined use of ECE-ECRH for direct measurement of heat transport in plasma:

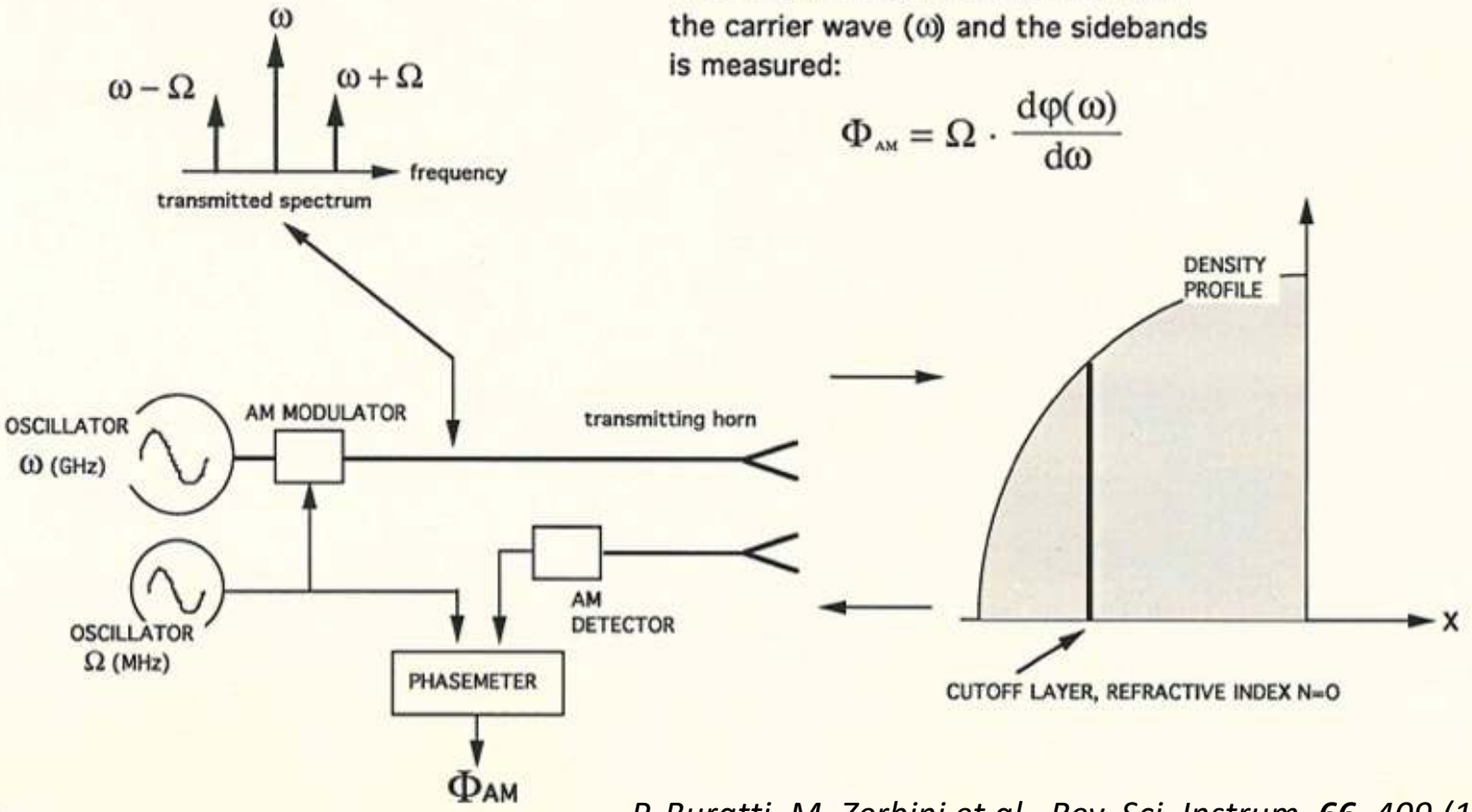
Cross-correlation (time lag) between modulated ECRH and ECE Electron Temperature.



AM REFLECTOMETRY *(Amplitude Modulation)*

The differential phase shift between the carrier wave (ω) and the sidebands is measured:

$$\Phi_{AM} = \Omega \cdot \frac{d\varphi(\omega)}{d\omega}$$

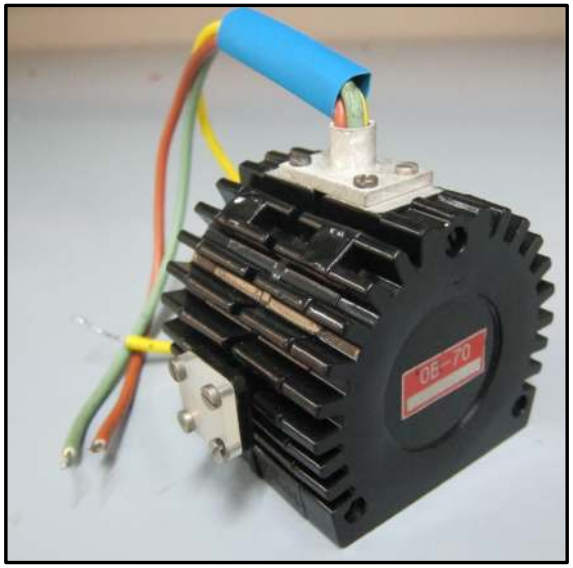


P. Buratti, M. Zerbini et al., Rev. Sci. Instrum. ***66****, 409 (1995)*

AM Reflectometry FTU (1994-97)

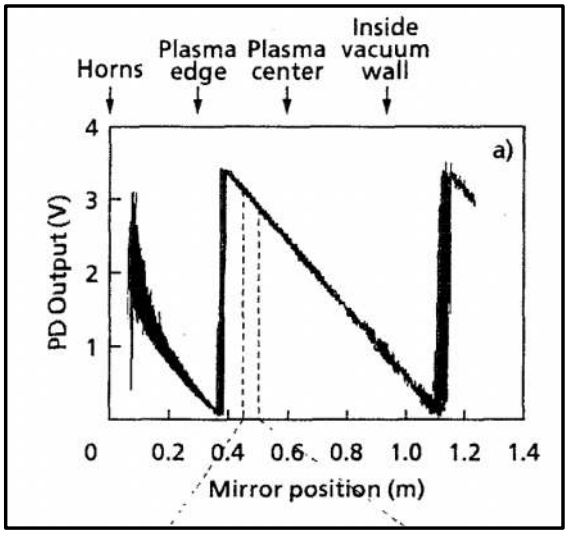
μ–wave BWO 52-90 GHz in 8 steps

vacuum device!



AM f=200 MHz λ=1.5 m

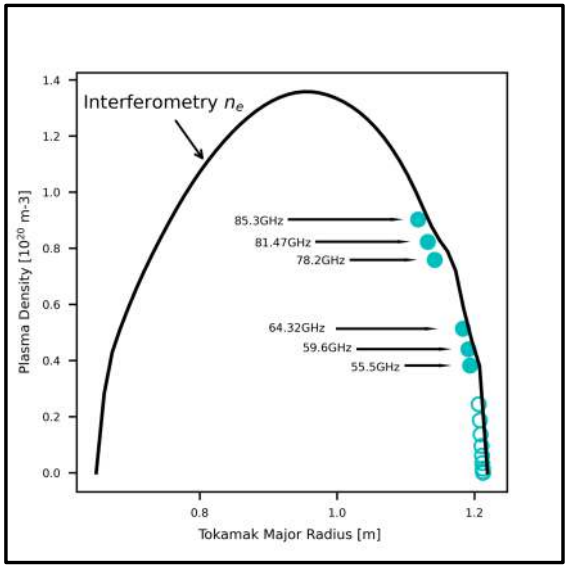
Unambiguous phase detection



FTU shot #8093, t=0.77–1.09 s

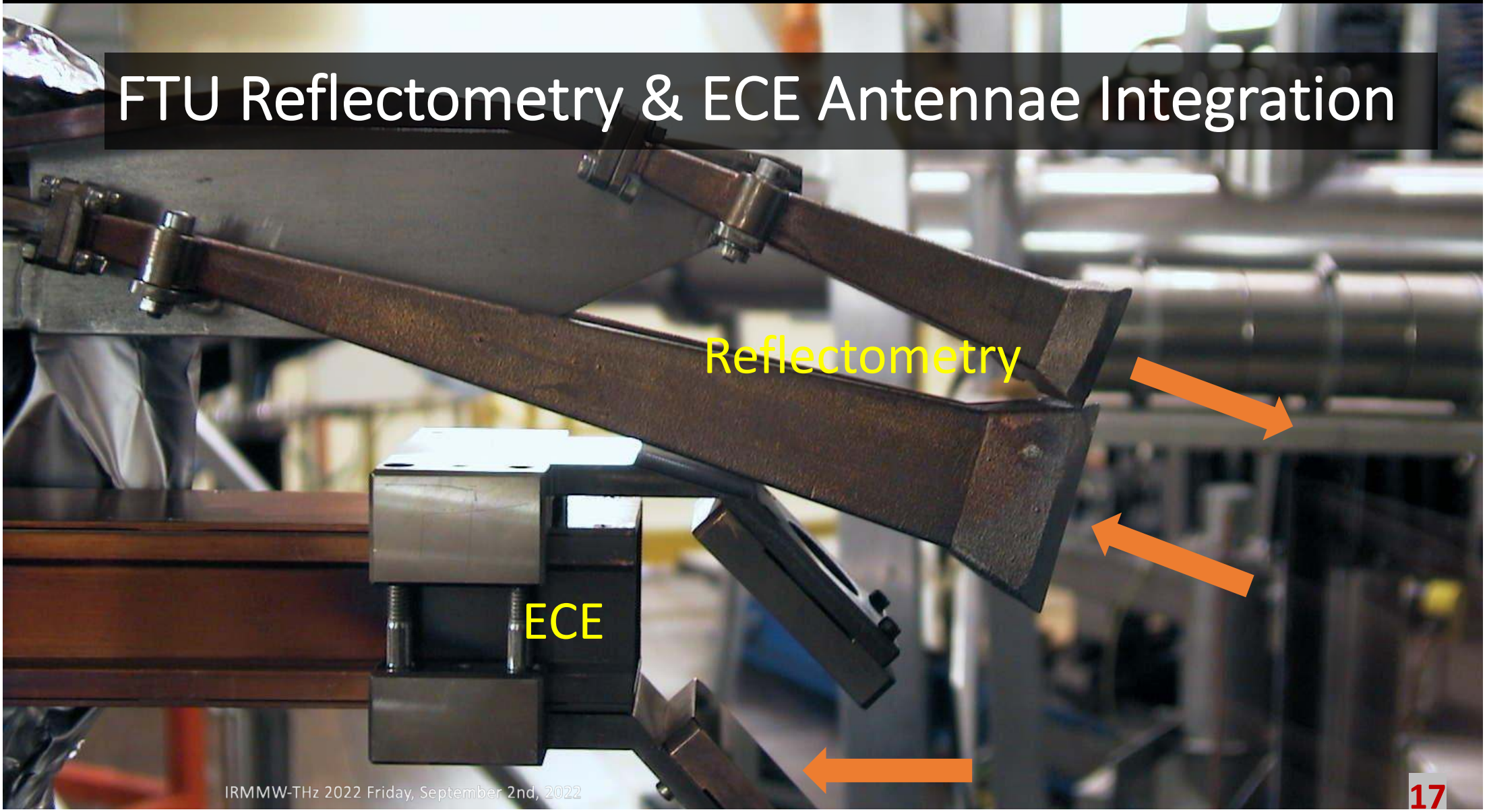
Reflectometry density profile (dots)

Open dots validate the algorithm with Interferometry data



P. Buratti, M. Zerbini et al., Rev. Sci. Instrum. ***68****, 428 (1997)*

FTU Reflectometry & ECE Antennae Integration



Interferometry & Polarimetry

Plasma refractive index (hence density) routinely measured via Interferometry, using vertical L.O.S. probe beams with $f_{pe} \ll f_{probe}$

Example: DCN laser $f_{pe} \sim 100GHz \ll f_{probe} \sim 1.5\,THz$

Faraday rotation of the beam polarization measured with same setup

First application of THz-TDS to plasma Diagnostics

Traditional FIR diagnostics proven stable and reliable

...but there is room for improvement...

ENEA Frascati and Michael Johnston's Lab in Oxford collaboration, to extend THz-TDS to Plasma Diagnostics

Aim: Redesign the instrumentation for tokamak geometry and scale

Potential advantages:

- *Frequency range covering many plasma scenarios*
- *Multi-functional diagnostic*
- *Compact instrumentation, optical fibers*

(ease up tokamak access)

THz Diagnostics Layout

INTERFEROMETRY (and Polarimetry)

REFLECTOMETRY

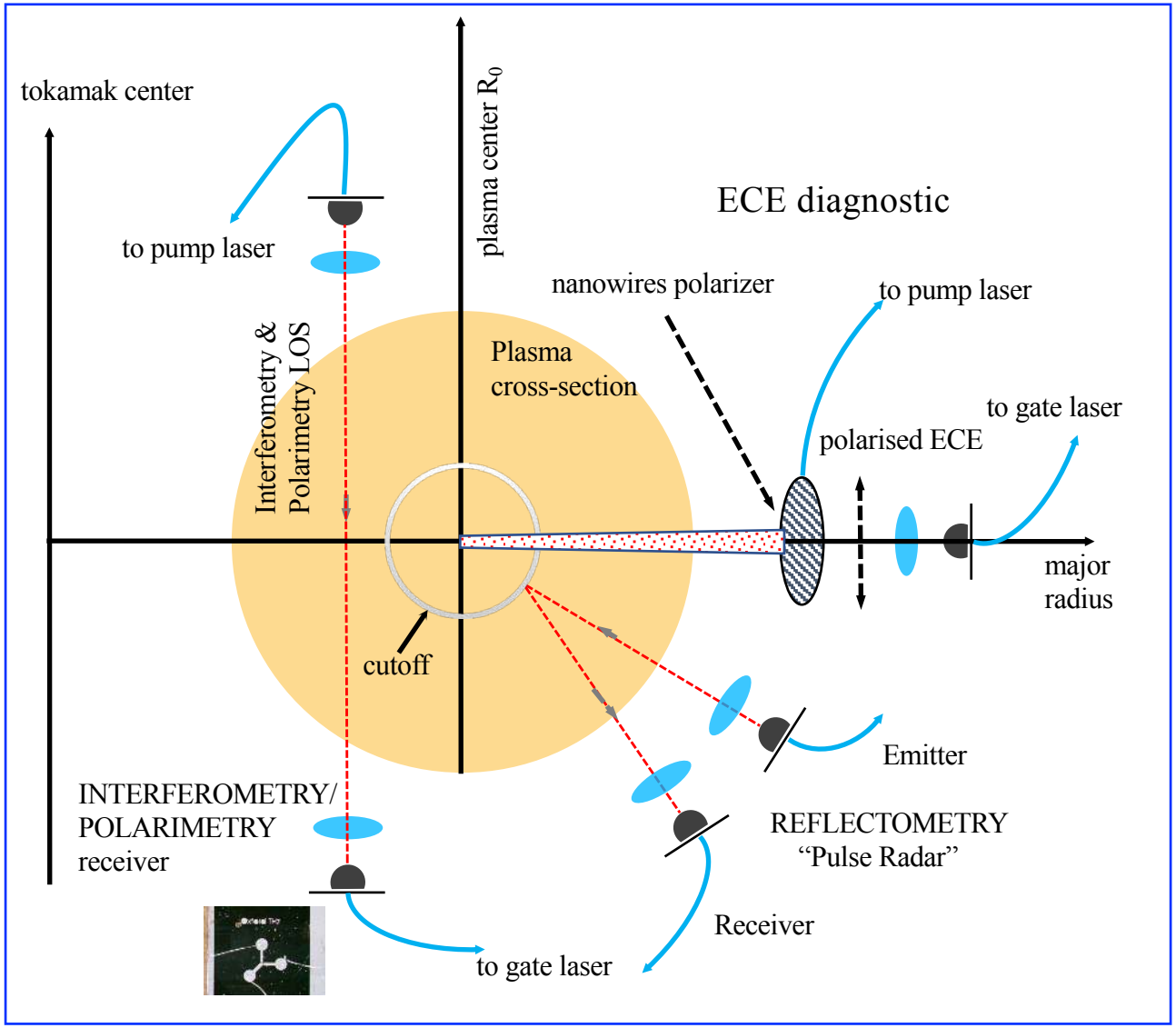
ECE (passive diagnostic)

"Tubular" Gaussian optics required to cover tokamak LOS scale (meters)

Criticalities:

SNR

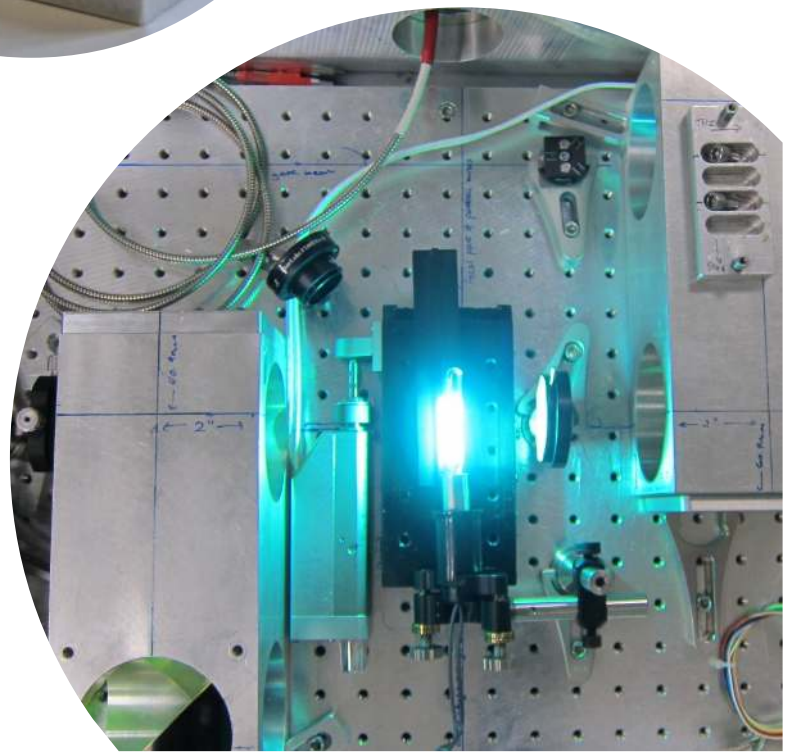
Diagnostic-grade time resolution ~ 10 ms



Pulse Radar: *Hugenholtz-Heijnen*
EOM-Instituut voor Plasmafysica Rijnhuizen
The Netherlands

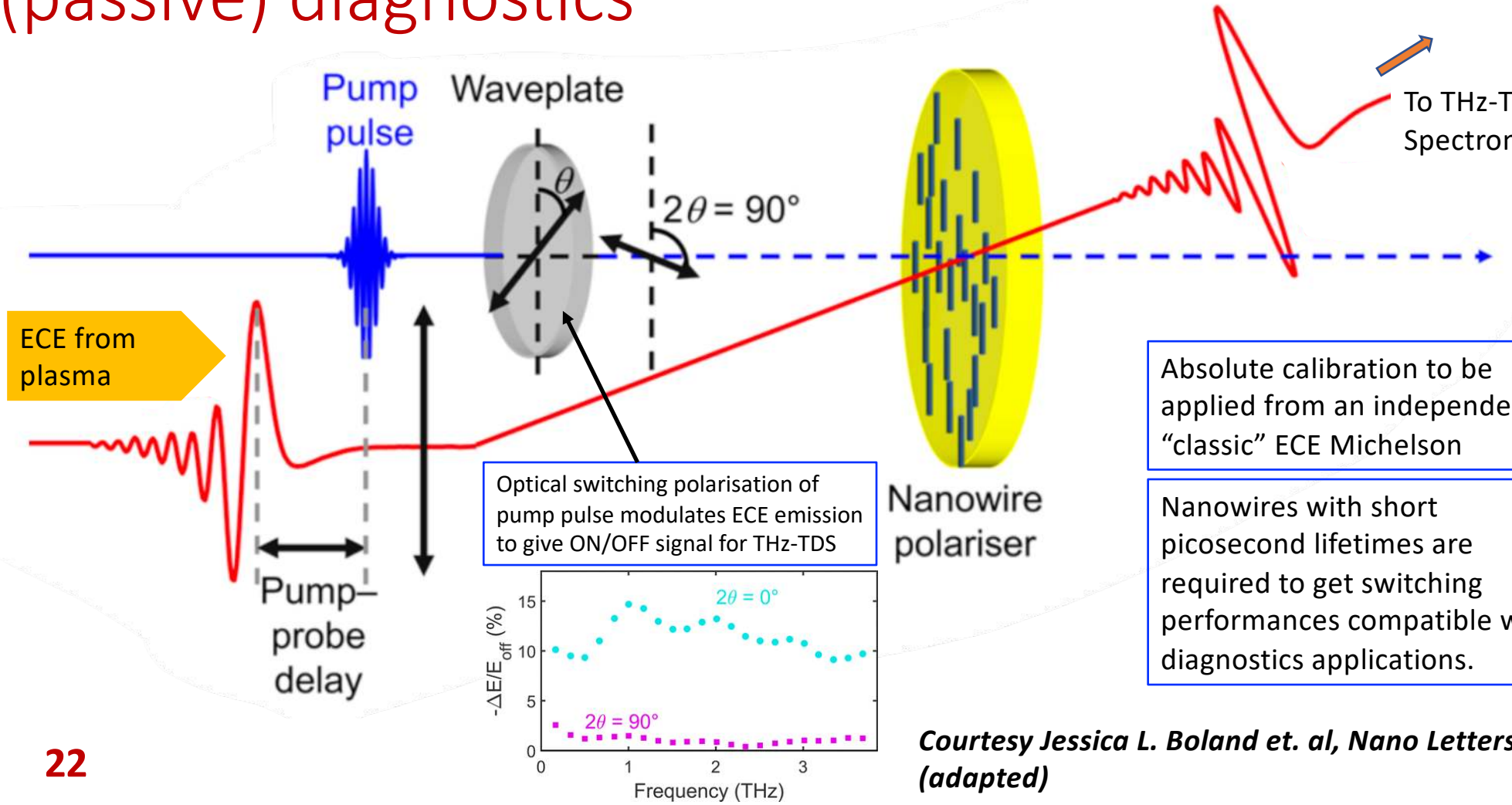
Front-end detector, Si-lens

Table-top Hg plasma density measurement (HPK-125)



G. Galatola-Teka et al. "THz-TDS Transmission Measurements of Spectroscopic Lamps Plasma", 43th IRMMW, Nagoya (Japan) (2018)

Nanowire polarisers: an application for ECE (passive) diagnostics



Absolute calibration to be applied from an independent "classic" ECE Michelson

Nanowires with short picosecond lifetimes are required to get switching performances compatible with diagnostics applications.

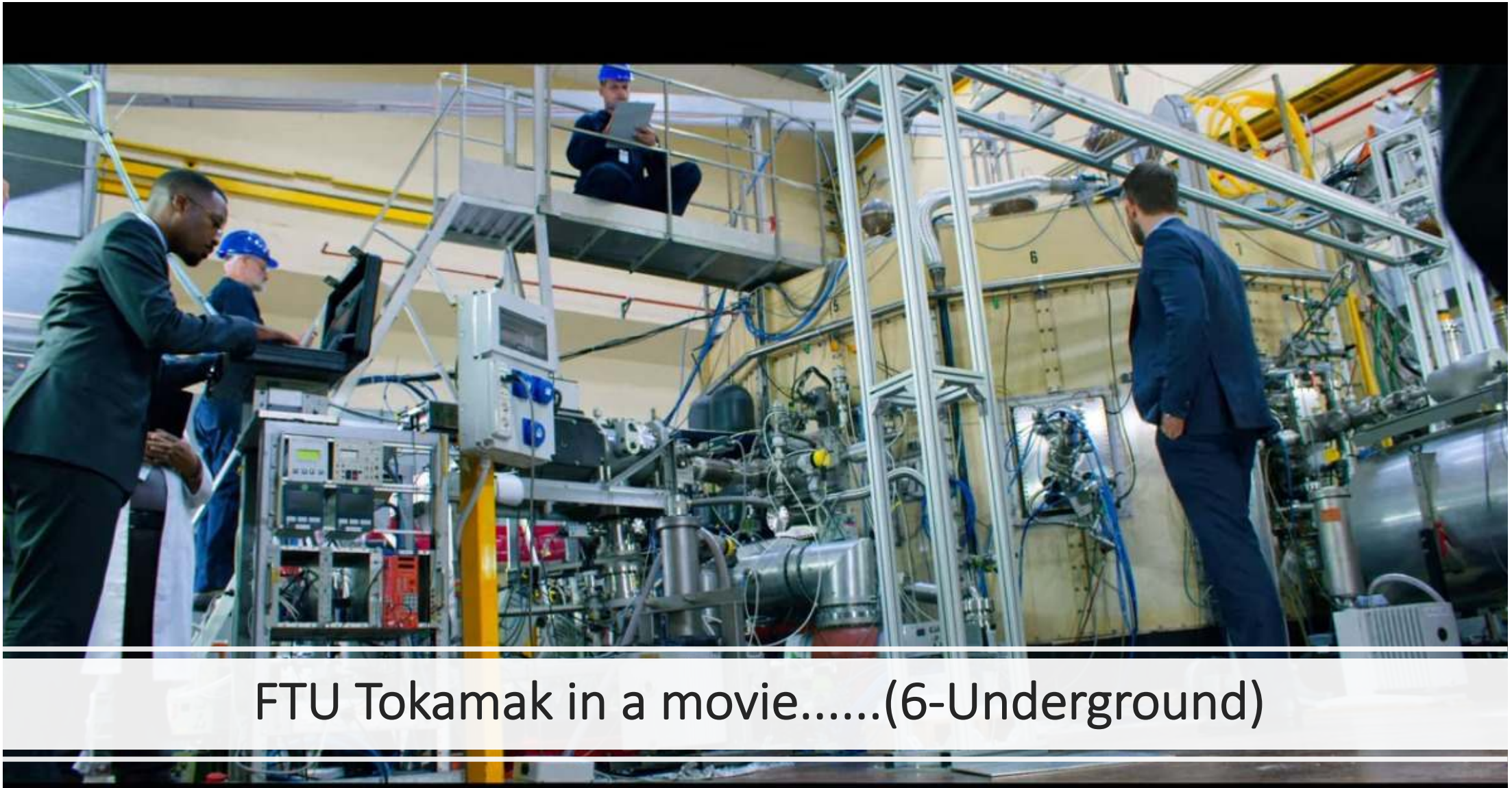
Courtesy Jessica L. Boland et. al, Nano Letters (2017) (adapted)

Diagnostics and Nuclear Fusion

"The general problem of plasma diagnostics is one of the most important and challenging aspects of controlled fusion research"
(R. Post, Rev. Mod. Phys. (1956)*...yes...still true today.....!)*

- Deep understanding of plasma physics concepts and complexity
- Multidisciplinary research area (applications beyond Nuclear Fusionn)
- Unfolding plasma knowledge from within:

original contributions, not only to diagnostics, but to the general approach to Controlled Thermo-Nuclear Fusion



FTU Tokamak in a movie……(6-Underground)

Acknowledgements *(covering 30+ years….)*

Ugo Ascoli-Bartoli, Giovan-Battista Righetti, Leonardo Pieroni, Paolo Buratti, Alan Costley, Doug Bartlett, Angelo A. Tuccillo, Onofrio Tudisco, Giovanni Bracco, Antonio Barone, Alberto Brusadin, Enrico Grilli, Bruno Conti, Giuseppe Pizzicaroli, Danilo Pacella, Francesca Bombarda, Sergio Mantovani, Patricia Amadeo, Edmondo Giovannozzi, Franco Alladio, Paolo Micozzi, Alessandro Mancuso, Giuliano Rocchi, Valerio Piergotti, Chris Gowers, Robin Prentice, Joelle Mailloux, Hans Oosterbeek, Matteo Fontana, Robin Nicholas, Michael Johnston, Enrique Castro-Camus, Samuel Jones, Hannah Joyce, Katherine Dunn, Kun Peng, Jessica L. Boland, Djamshid A. Damry, John Lohr, Ron Prater, Max Austin, Craig Petty, Francesco Volpe, Hans Jurgen Hartfuss, Matthias Hirsch, Thomas Geist, Sante Cirant, Carlo Sozzi, Silvana Nowak, Federica Causa, Massimo Alonzo, Luca Senni, Andrea Taschin, Andrea Doria, Emilio Giovenale, Gian Piero Gallerano, Francesco Mazzocchi, Giuseppe Galatola-Teka