LHCD and Coupling Experiments with an ITER-like PAM launcher on the FTU tokamak

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Experiment conducted jointly with CEA in the frame of the ENEA - CEA collaboration on electron dynamics studies

Why a Passive/Active Multijunction Launcher?

Robust LH launchers to face the harsh plasma environment of ITER:

Thick vertical walls between ***active*** waveguides ⇨ *Strong stresses ≈100 MPa*
(13.25 mm) *neutron flux ≈0.5 MW/m^2*
cooling system in the walls

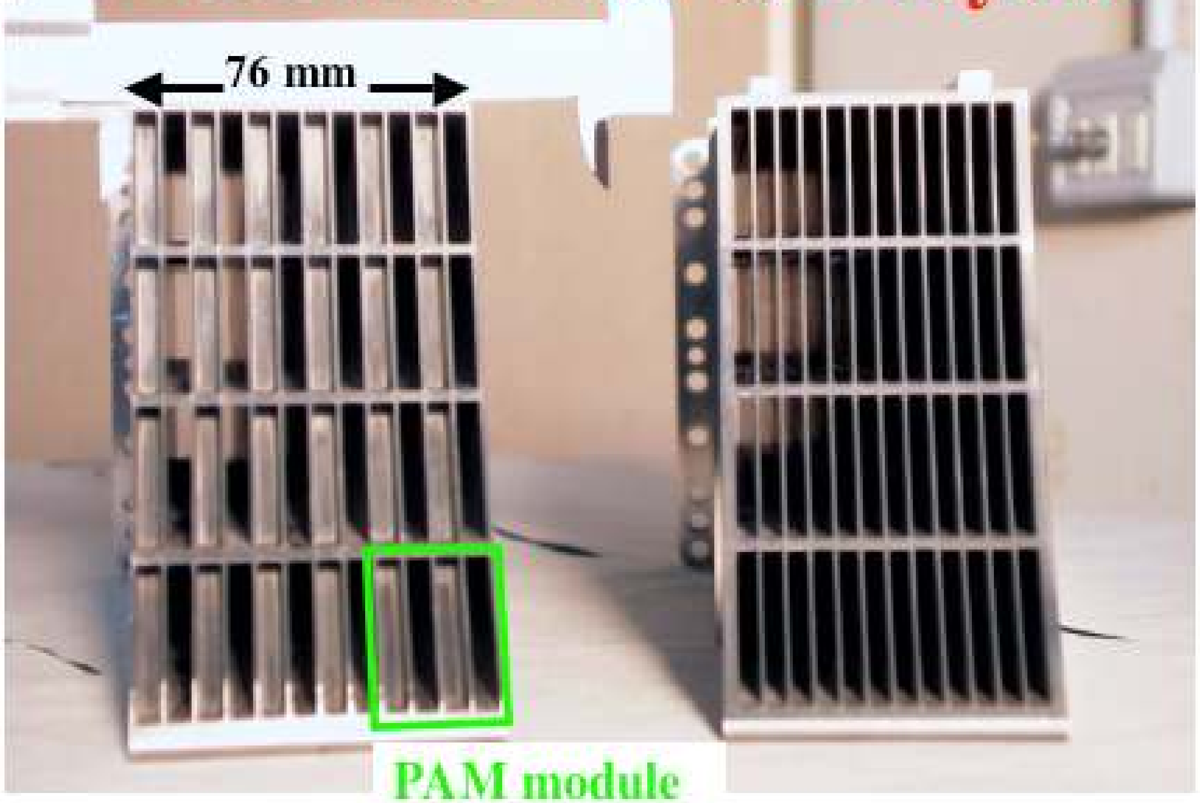
Passive (short-circuited) waveguides at the mouth (within the thick walls, depth= $\lambda/4$), to restore the usual multijunction periodicity

Main requests for a PAM

1) To maintain **good coupling** even operating in the full shadow of the vessel port to avoid damage from the large particle flow inside the SOL plasma
2) To tolerate the heating due to the neutron flux and plasma radiation losses
3) To preserve **power handling and CD efficiency** acceptable for ITER

FTU experiment was aimed to validate the PAM concept through testing mainly points 1 & 3 (coupling and CD)

FTU PAM view and layout



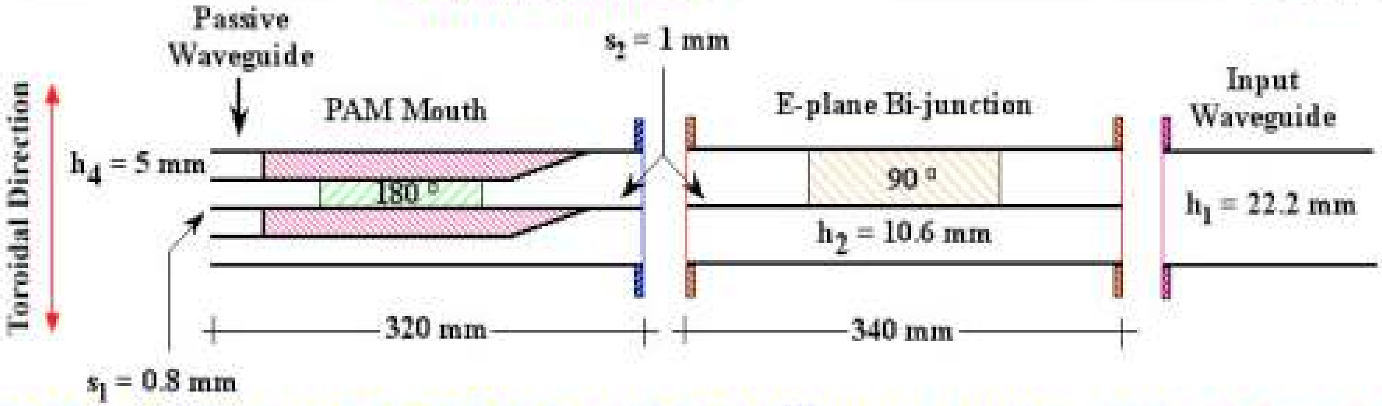
12 MJs in a 4x3 matrix
Waveguides: 28x5 mm
Frequency : f=8 GHz
Design power=80 MW/m^2

ITER:

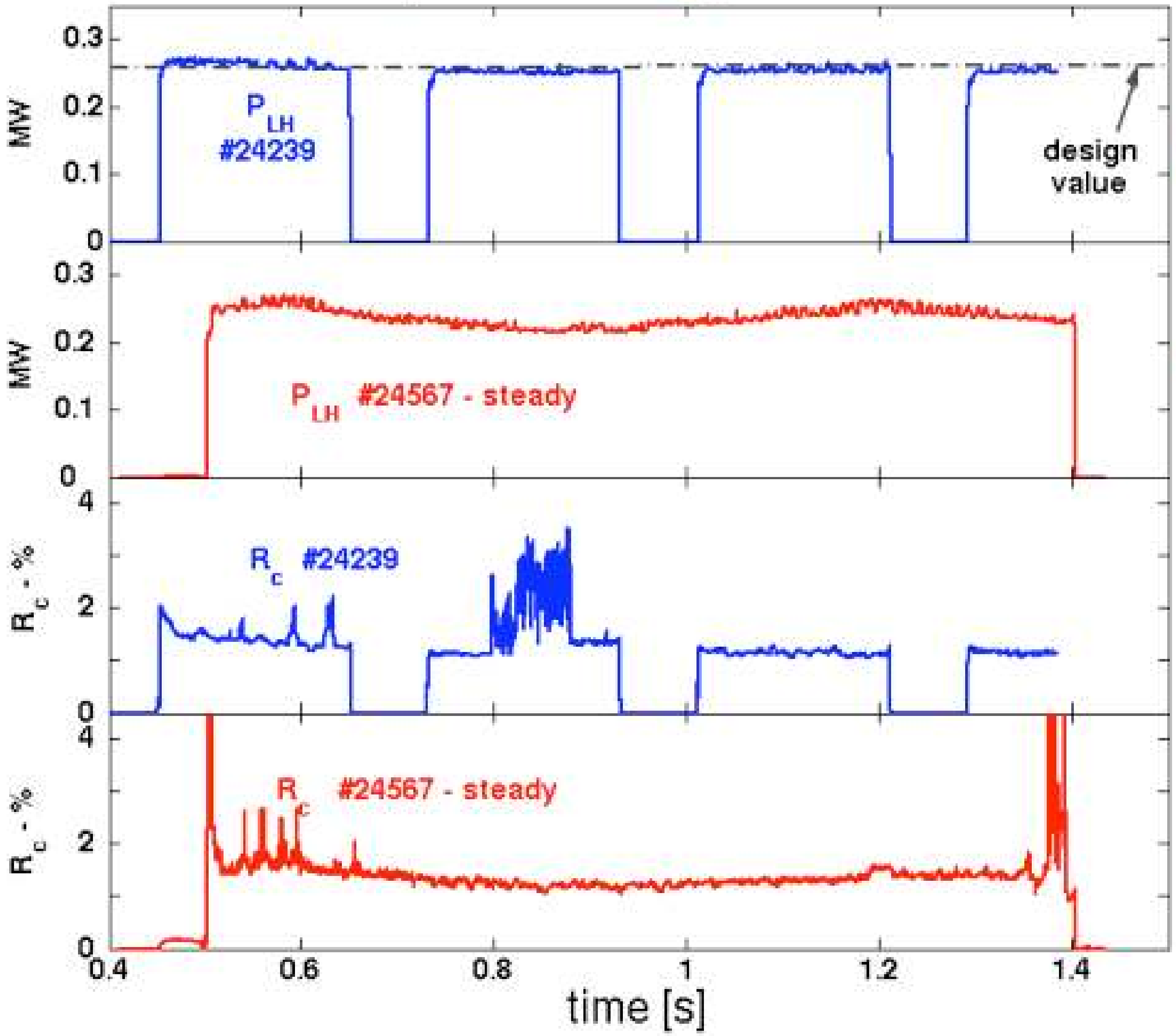
waveguides: 58x9.25 mm
f=5 GHz
power = 33 MW/m^2

The experimental scaling of power handling, linear with f :

33 MW/m^2 in ITER ➔
52 MW/m^2 in FTU



PAM power handling performances



Obtained with R_c< 1.6 %:

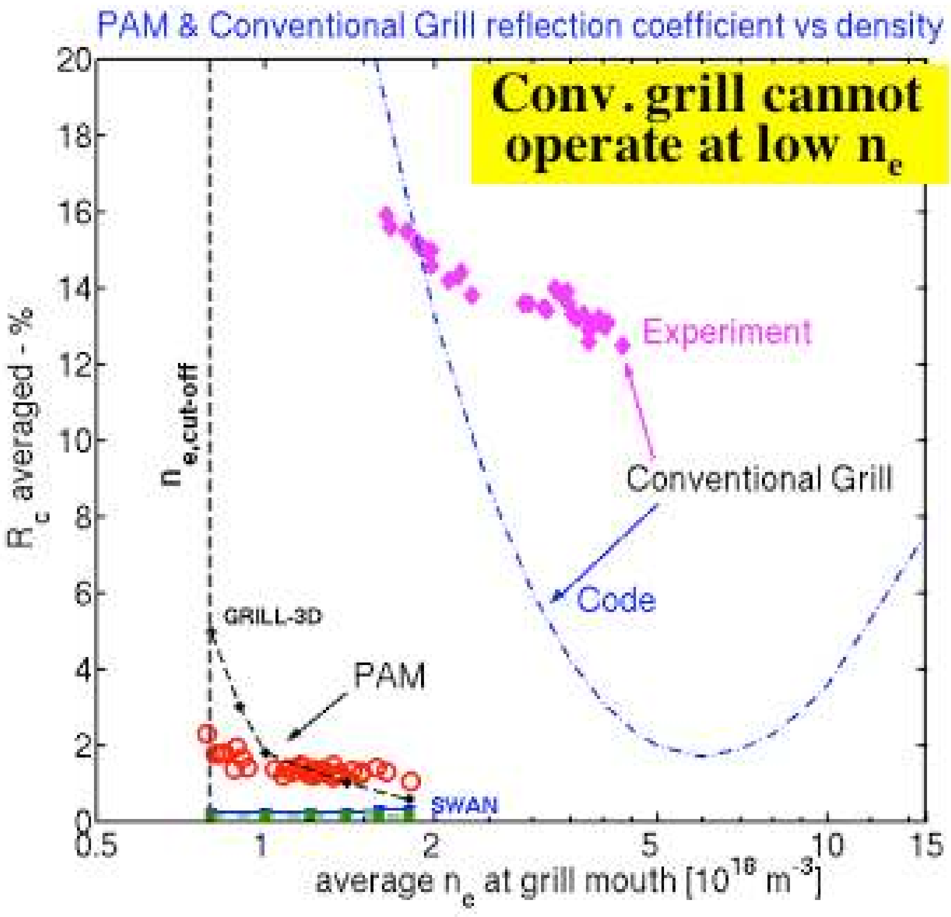
80 MW/m² (design value) with 200/80 ms ON/OFF modulation

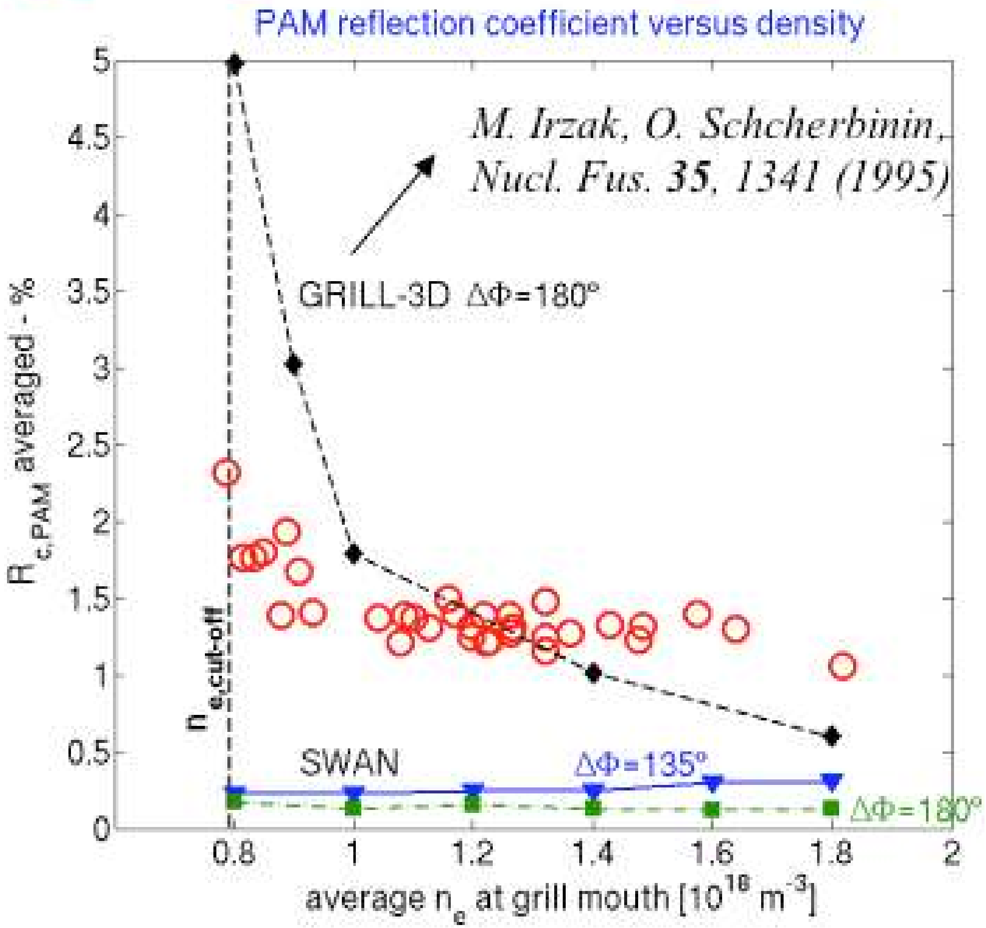
75 MW/m² for t>0.9 s, quasi steady, limited only by power sources

ITER equivalent: 52 MW/m²

> 90 MW/m² attainable with further conditioning

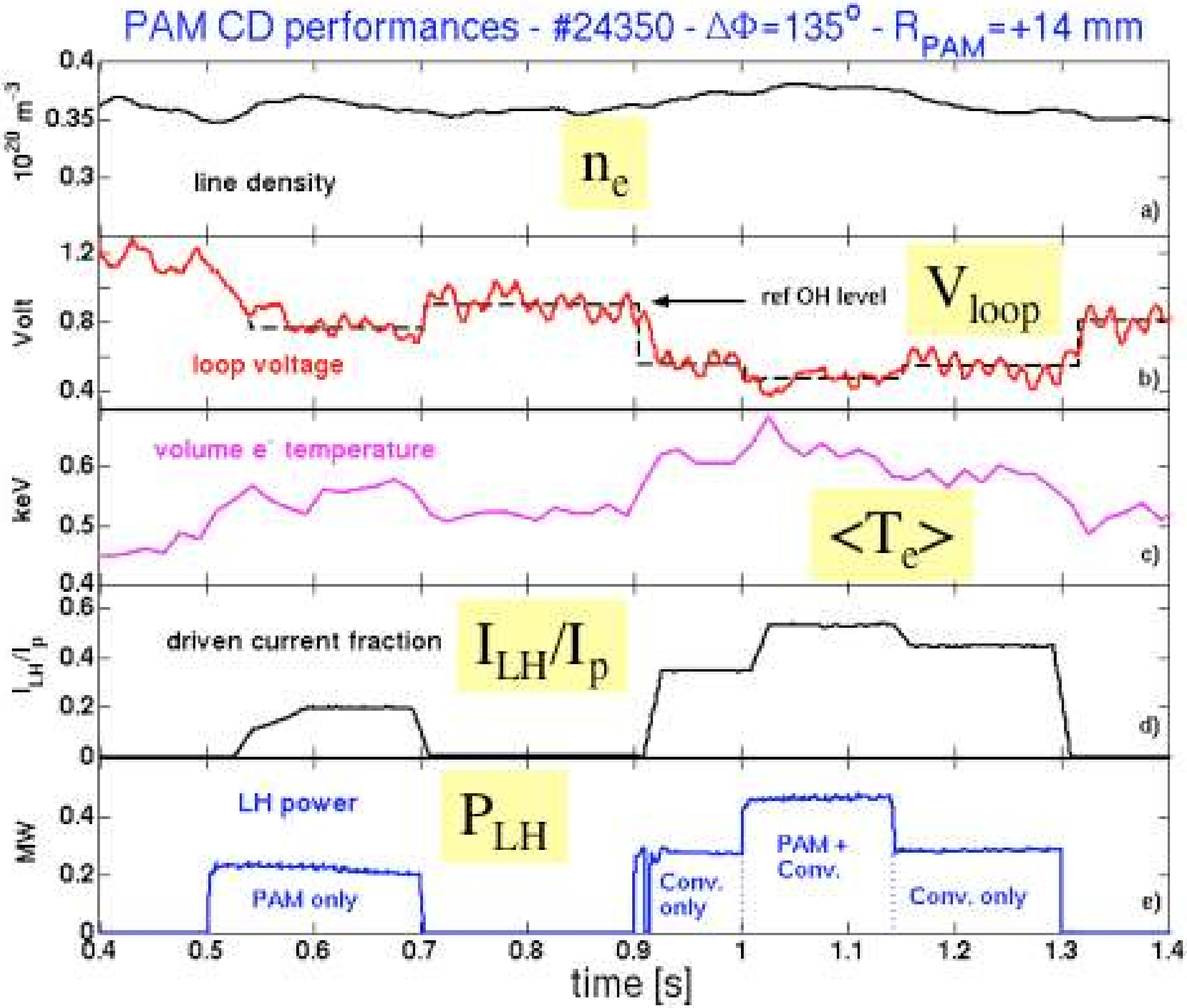
PAM / Conventional grill power coupling





Good coupling always for $n_e \geq n_{e,cut-off}$: $R_c \leq 1.5\%$ and decreasing with n_e
GRILL-3D foresees the rise close to $n_{e,cut-off}$

Current Drive capability



$$\frac{I_{LH}}{I_p} = 1 - \frac{V_{l,LH}}{V_{l,OH}} \frac{\left\langle T_{e,LH}^{3/2} \right\rangle}{\left\langle T_{e,OH}^{3/2} \right\rangle} \frac{Z_{eff,LH}}{Z_{eff,OH}}$$

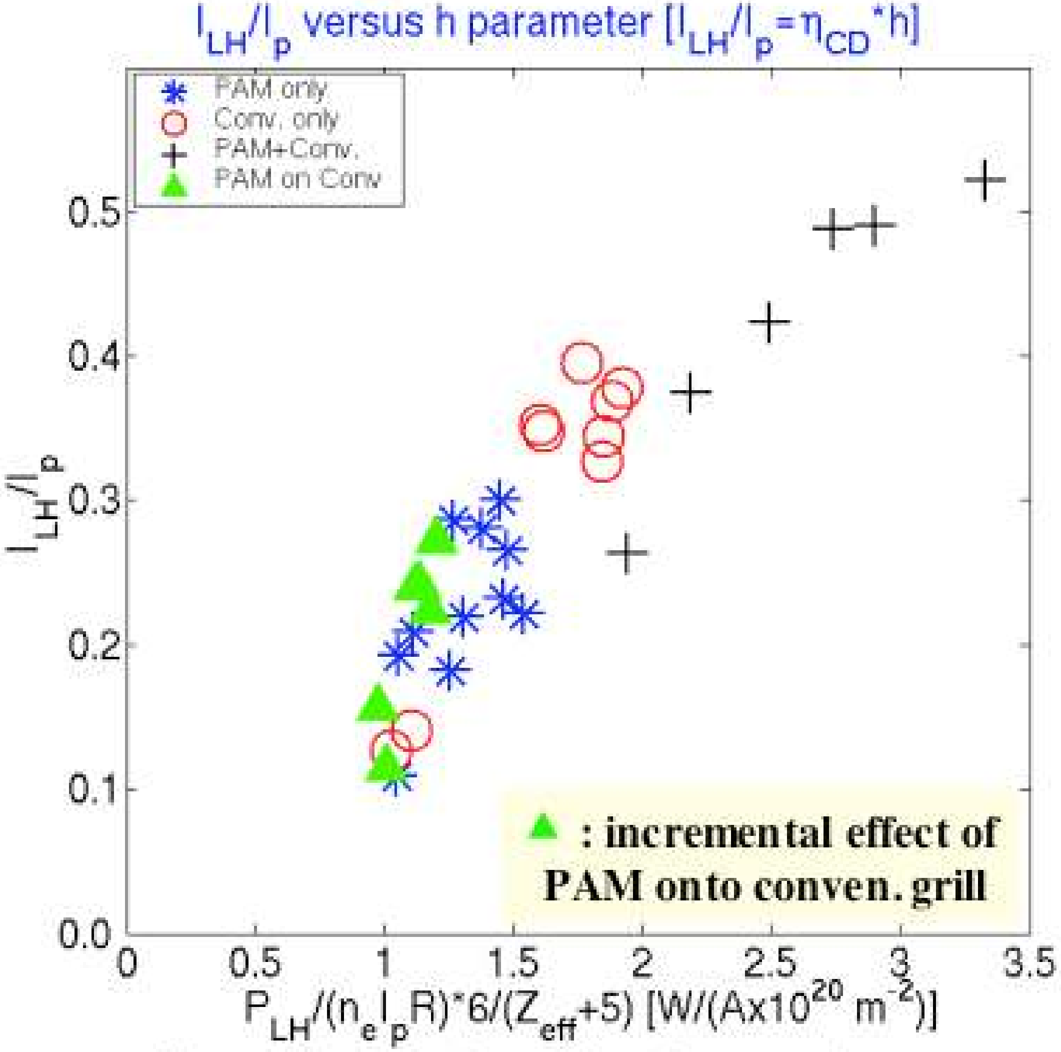
Same $N_{\|,pk}$=2.24 for PAM and conventional grill

PAM η_{CD} smaller due

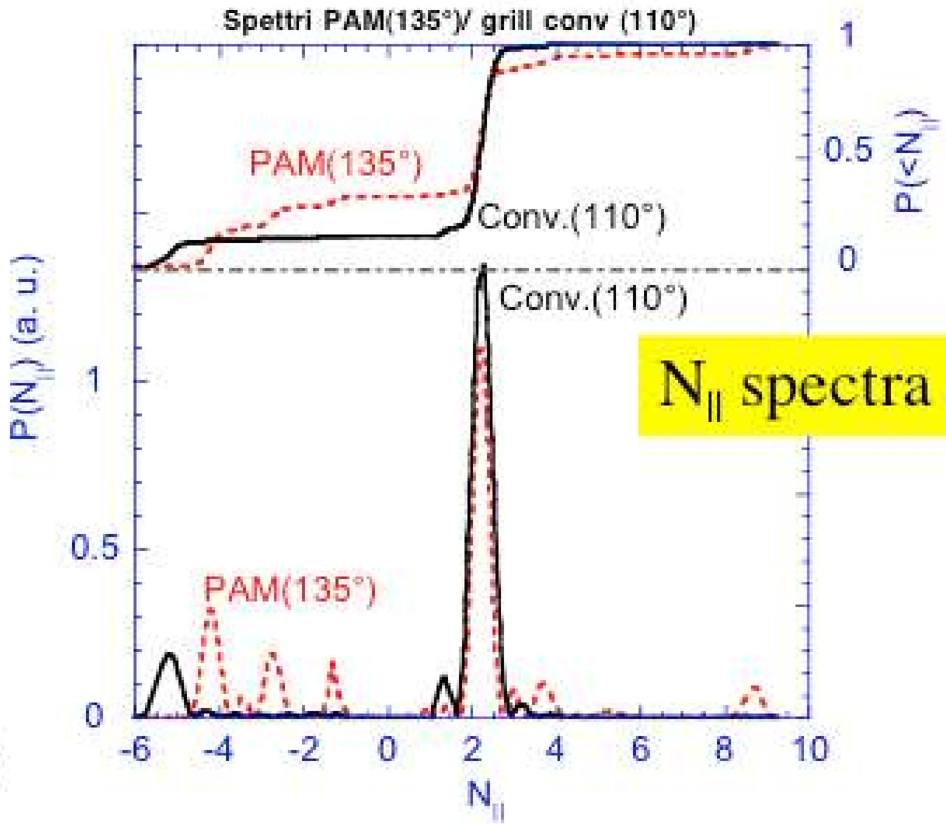
-) lower directivity: 65% against 80%

-) lower $\langle T_e \rangle$

CD performances on many shots basis

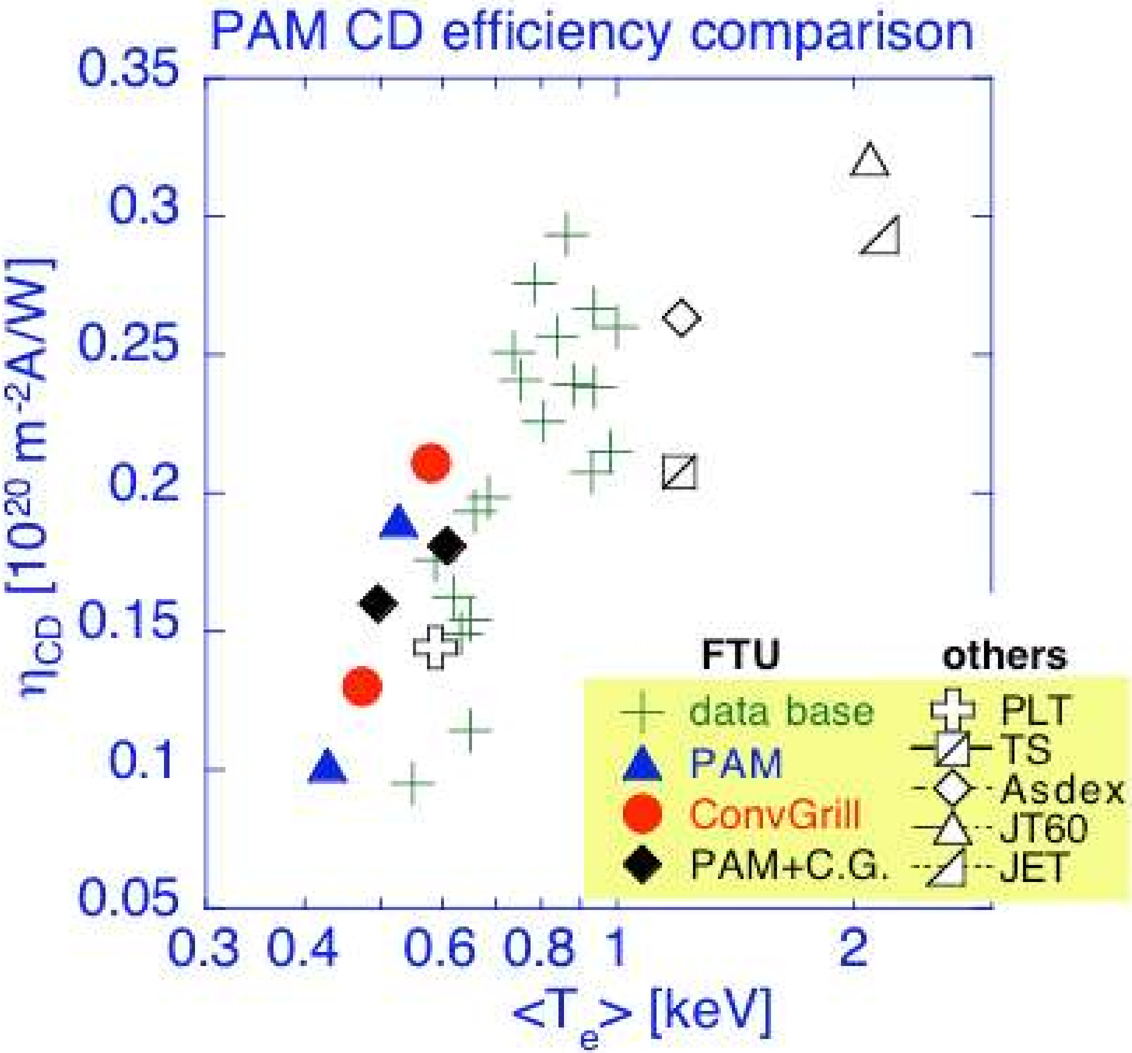


$$\frac{I_{LH}}{I_p}=1-\frac{V_{l,LH}}{V_{l,OH}}\frac{\left\langle T_{e,LH}^{3/2}\right\rangle}{\left\langle T_{e,OH}^{3/2}\right\rangle}\frac{Z_{eff,LH}}{Z_{eff,OH}}$$



Non-linearity at low h, due to low power / low collisionality reduced by considering directivities

Comparing PAM η_{CD} with FTU data base

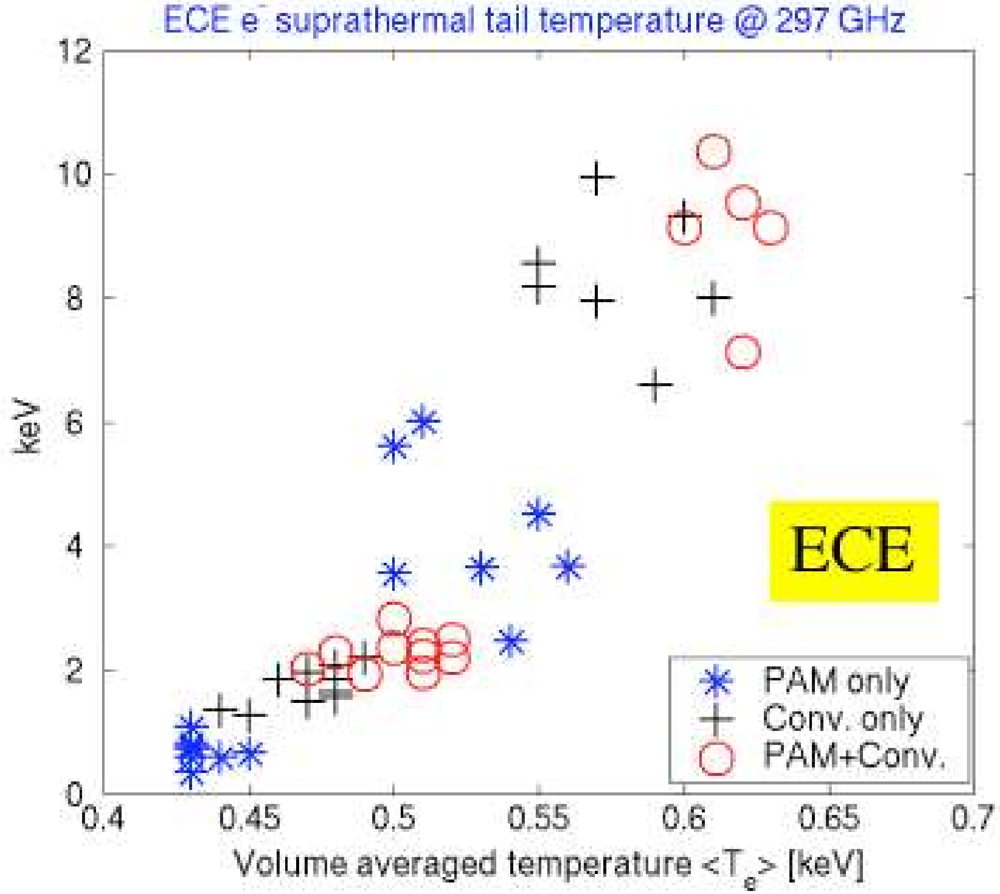


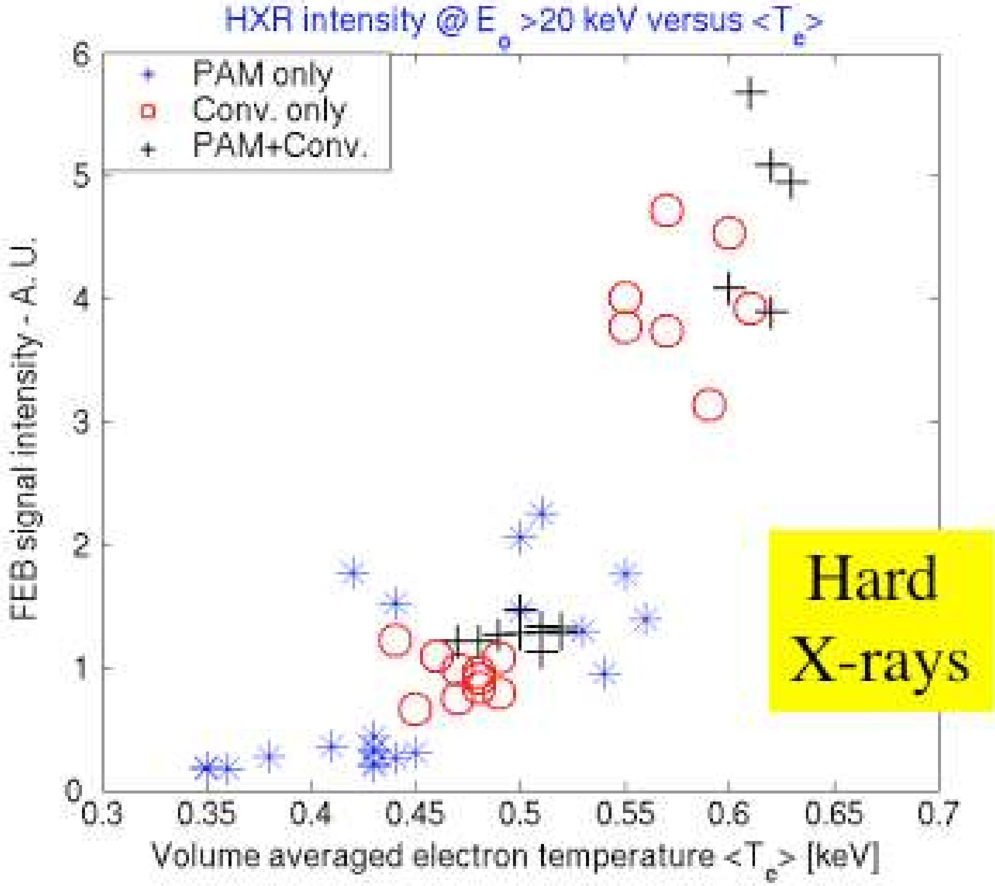
PAM and conventional grill behave very similarly either alone or together

The effects are additive

η_{CD} grows with <T_e>: points are aligned with FTU data base

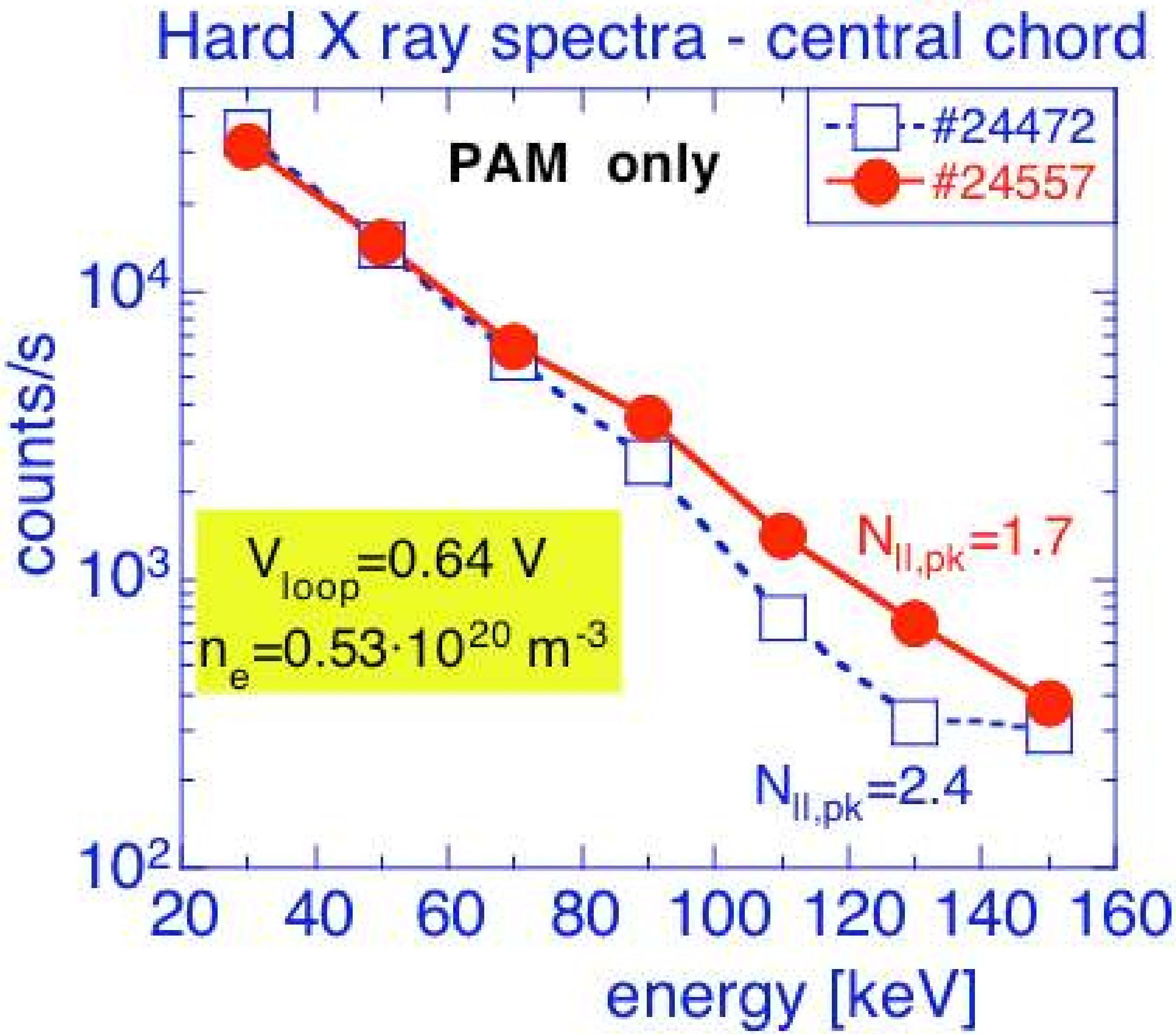
Amount of the fast e⁻ population PAM/Conv.





All data points consistent (i.e. PAM, Conv., PAM+Conv.) for both ECE and HXR if $\langle T_e \rangle$ is taken as the main guiding parameter as for η_{CD}

Varying PAM $N_{\parallel,pk}$ - Hard X-rays

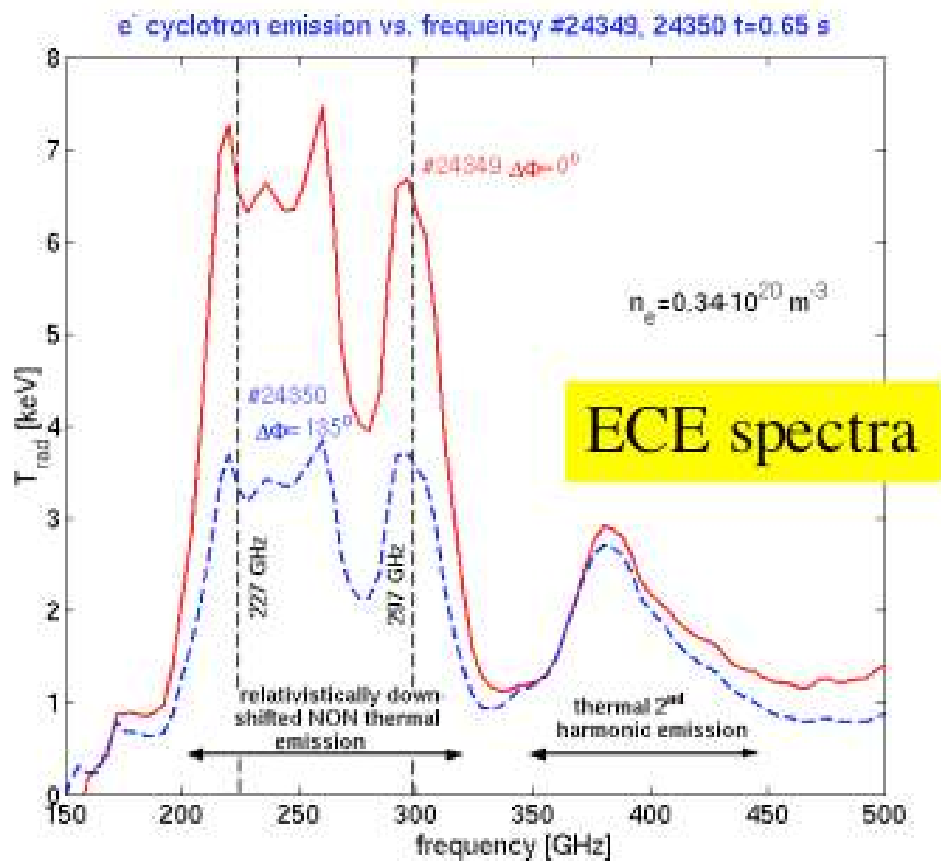


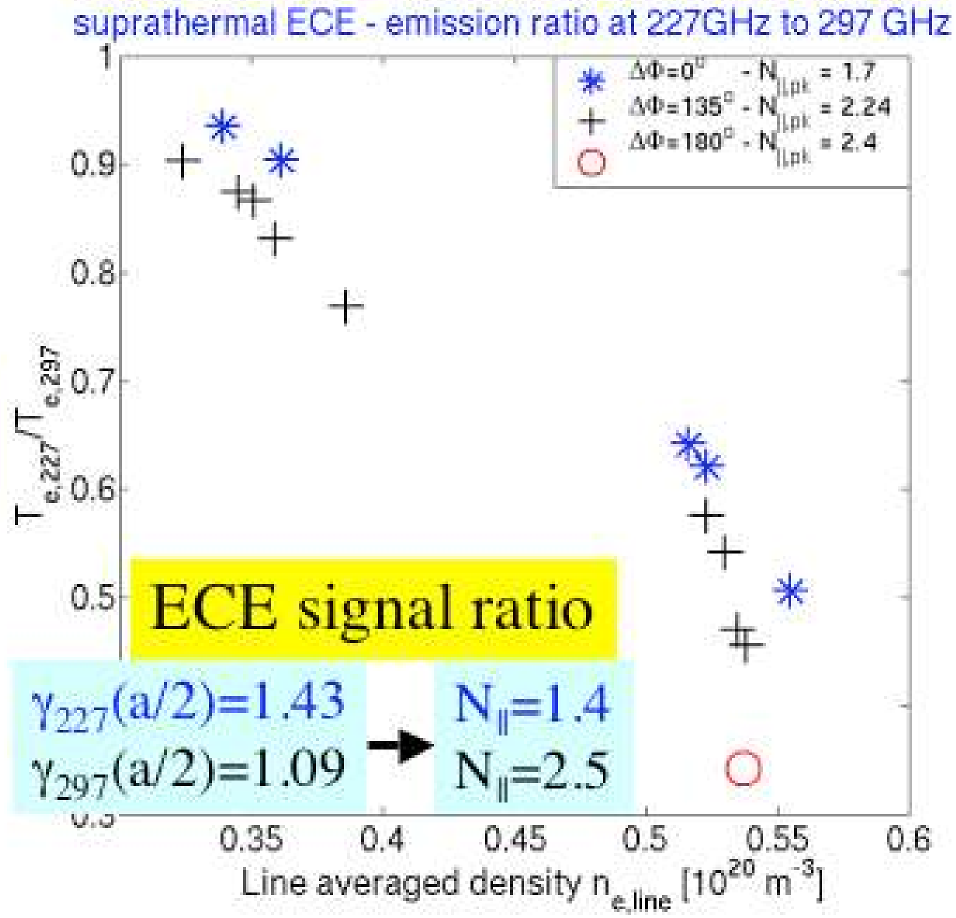
Same V_{loop} for both discharges

Fast tail more developed for the faster spectrum E=80 keV ⇔ c/v_e=1.85 (effect larger when PAM is alone)

PAM can change its $N_{\parallel}$

Comparing different $N_{\|,pk}$ - ECE

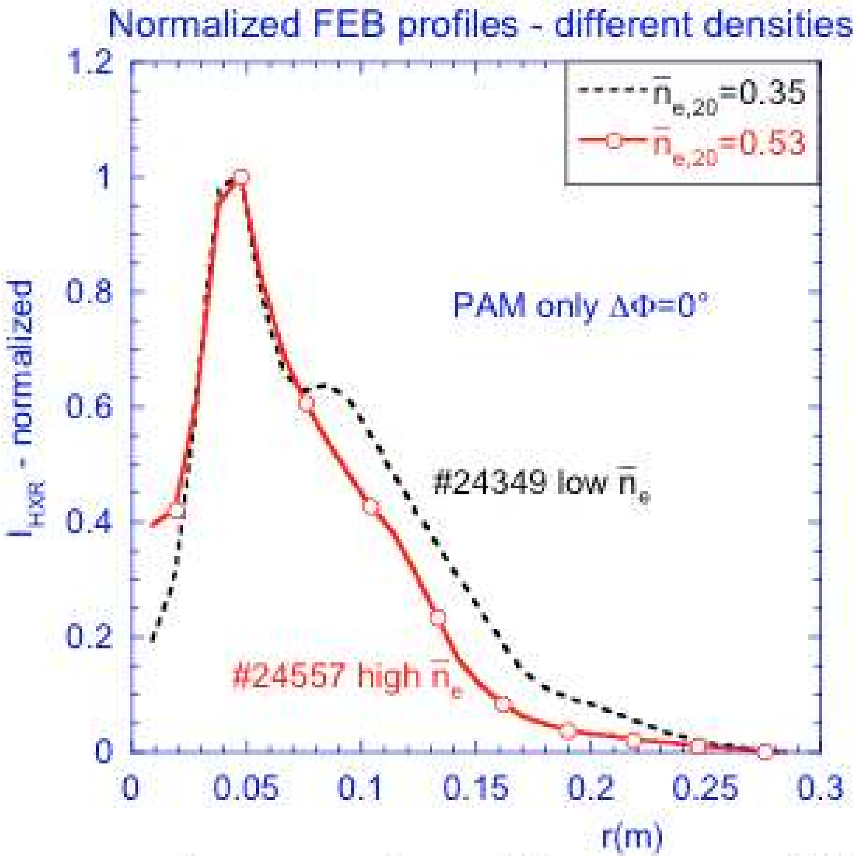


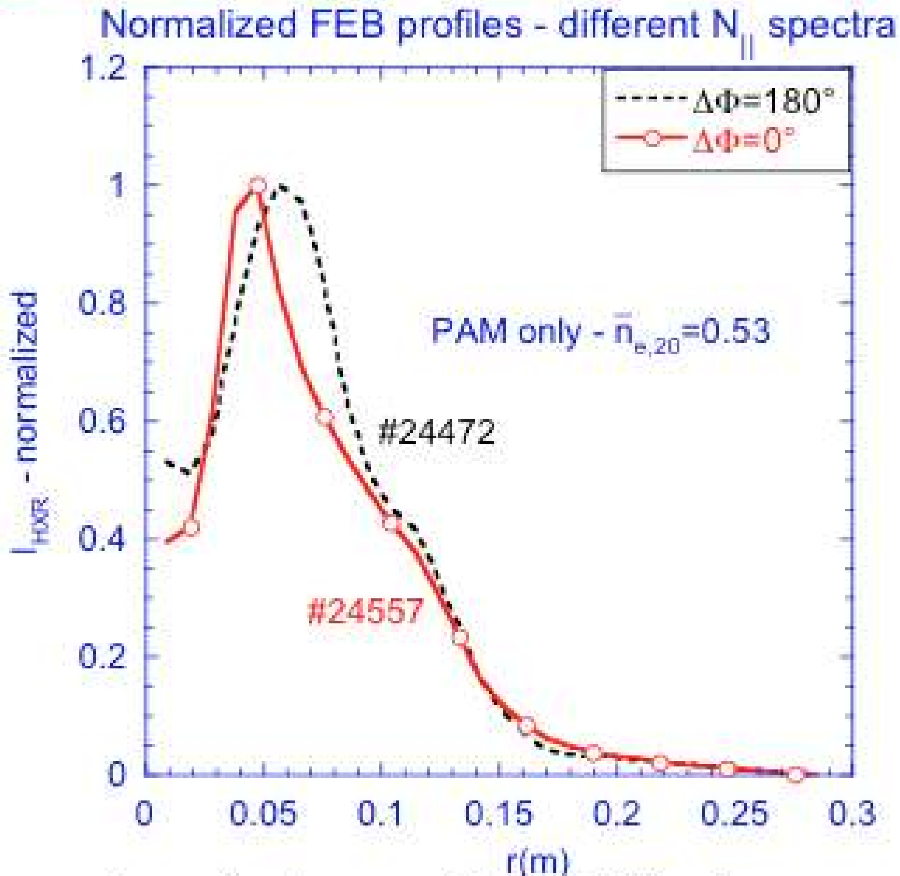


Ratio of more to less energetic e^- emission higher for faster $N_\|$ spectra

PAM does have some flexibility in $N_\|$

Hard X ray radial profiles (20-100 keV)



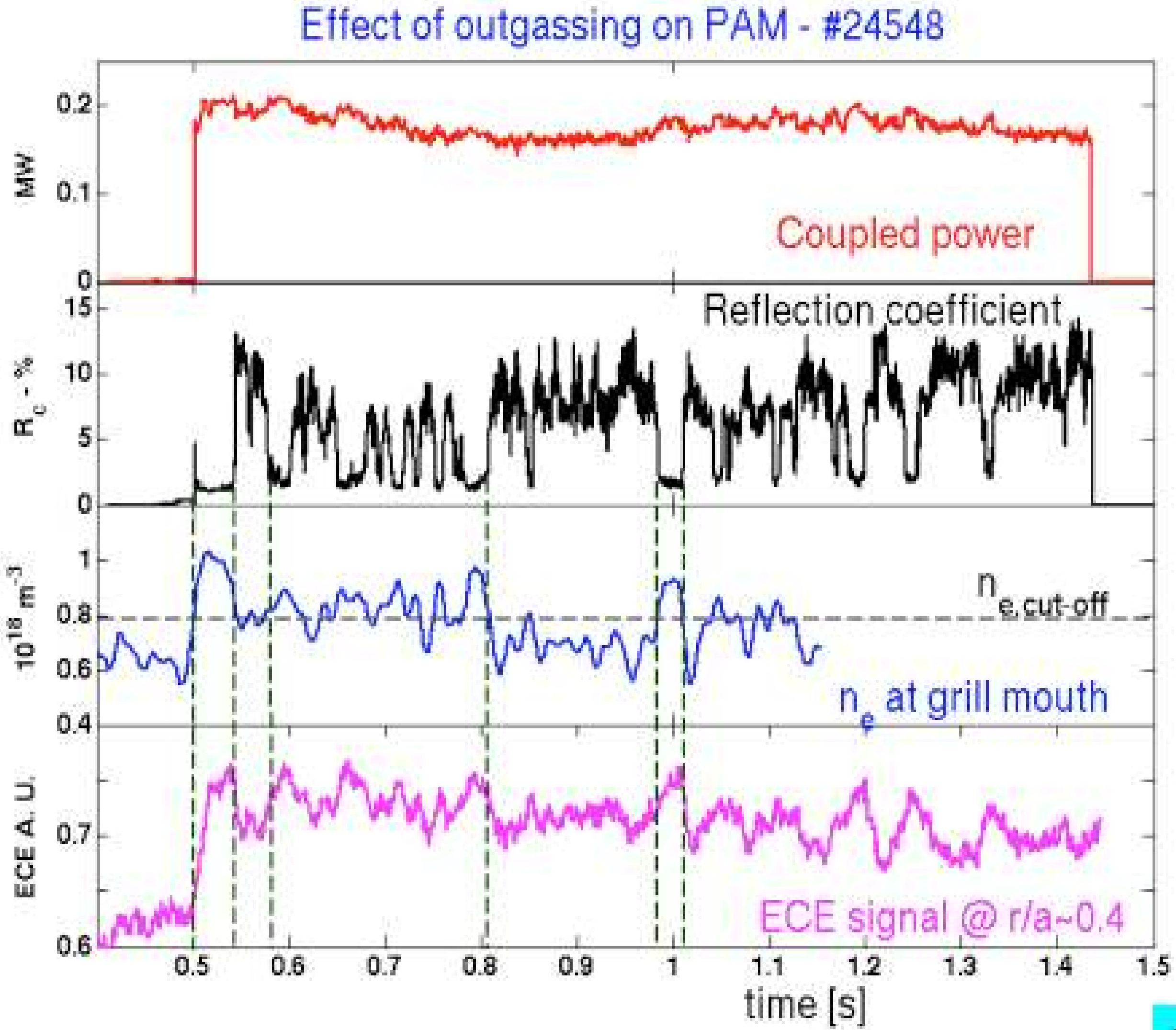


Lower densities -> profiles broader: fast e^- radial diffusion

Some differences due to $N_{||}$ spectra seen on HXR profiles

Consistency with calculated LH deposition (ASTRA) in: E. Barbato, EPS London 2004 P2.104

PAM coupling - modification of the edge



Building-up of density in front of the mouth

Large R_c (outgassing) => low n_e and low ECE power absorbed inside w.g.?

Note:

$n_e \leq n_{e,cut-off}$ before the LH pulse

R_{PAM}=-2 mm

Need of good conditioning

Conclusions – I

The test of the PAM at FTU has been successful:

Good coupling achieved with density close to or at the cut-off and antenna retracted up to 3 mm inside the port

Power more than 1.4 times that required for ITER safely managed in quasi steady state:

Actual values in FTU:	**75 MW/m^2**	(=> 250 kW total)
Request scaled from ITER:	**53 MW/m^2**	(=> 170 kW total)

Good current drive efficiency is maintained

Conclusions – II

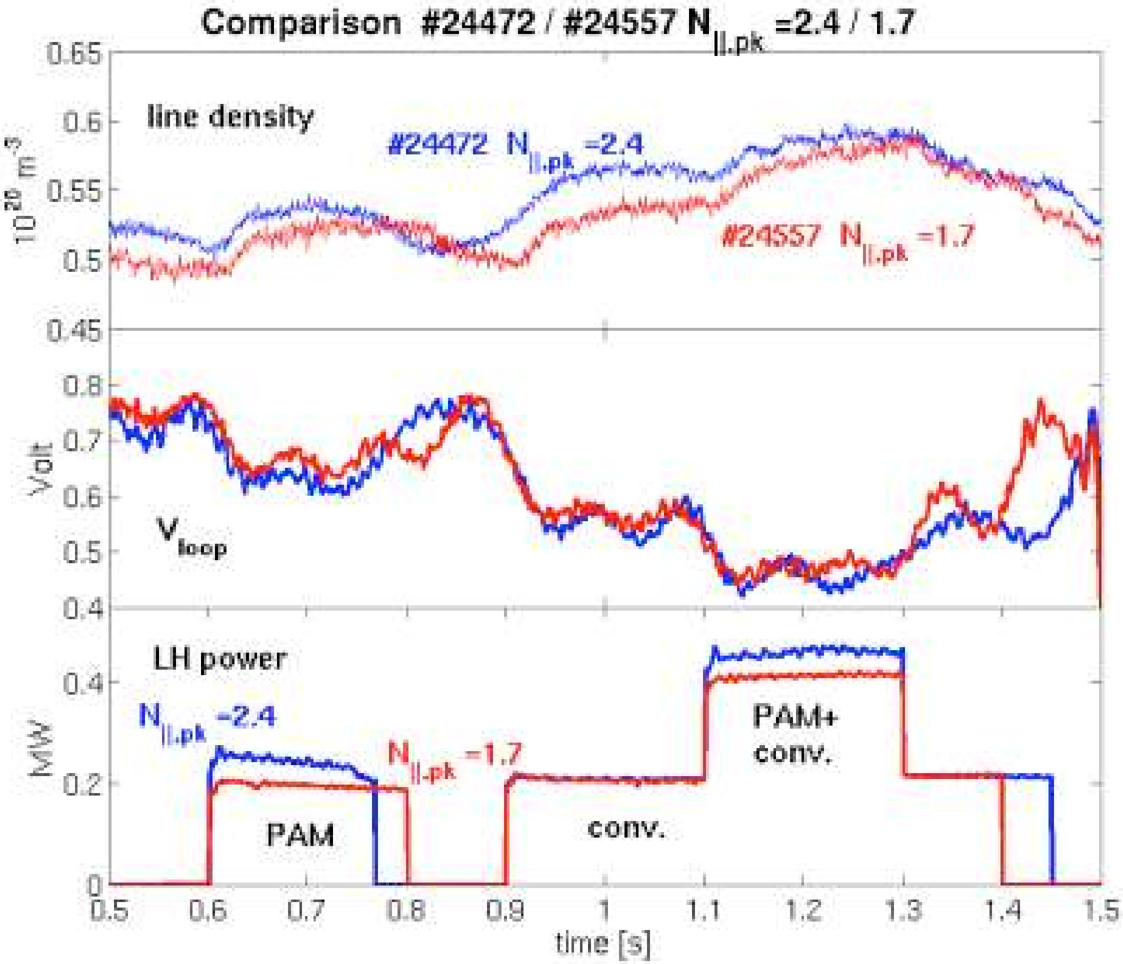
Actual power limit can be even exceeded with further conditioning (>90 MW/m^2 possible)

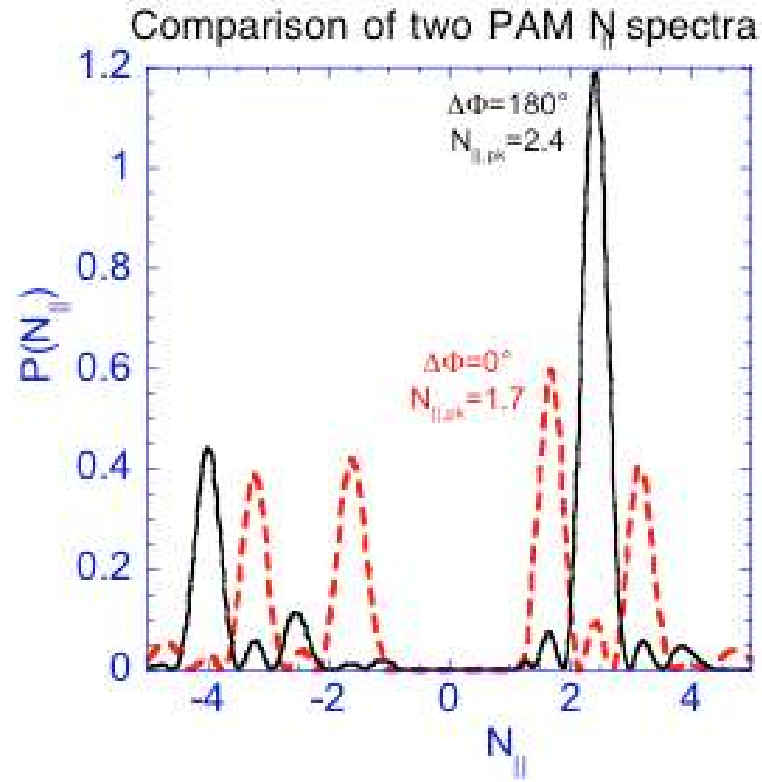
PAM and Conventional grill produce very similar CD and heating effects (considering the different directivities) and fast e$^-$ tails (from HXR and ECE signals)

Flexibility in $N_{||}$ with $\Delta\Phi$ (phase difference bwtween adjacent modules) found from both HXR and ECE

The first step towards developing an ITER LHCD launcher has been succesful

Comparing different $N_{\|,pk}$ PAM - CD



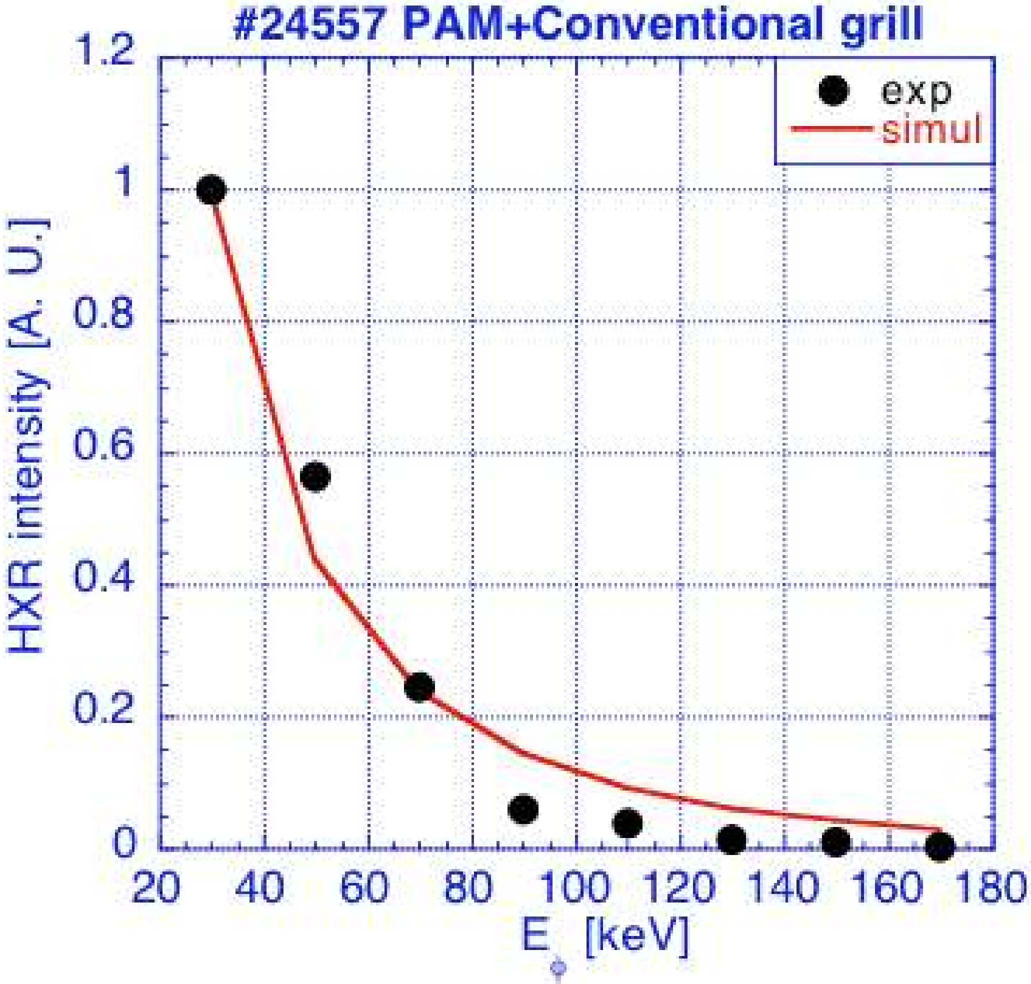


$N_{\|,pk}$=2.4 ($\Delta\Phi_{PAM}$=180°), directivity 65% P_{LH}=240kW

$N_{\|,pk}$=1.7 ($\Delta\Phi_{PAM}$=0°), directivity 53% P_{LH}=195 kW

} Same V_{loop} => η_{CD} higher for $N_{\|,pk}$=1.7

HXR emission simulation



HXR spectra calculation consistent with experiment

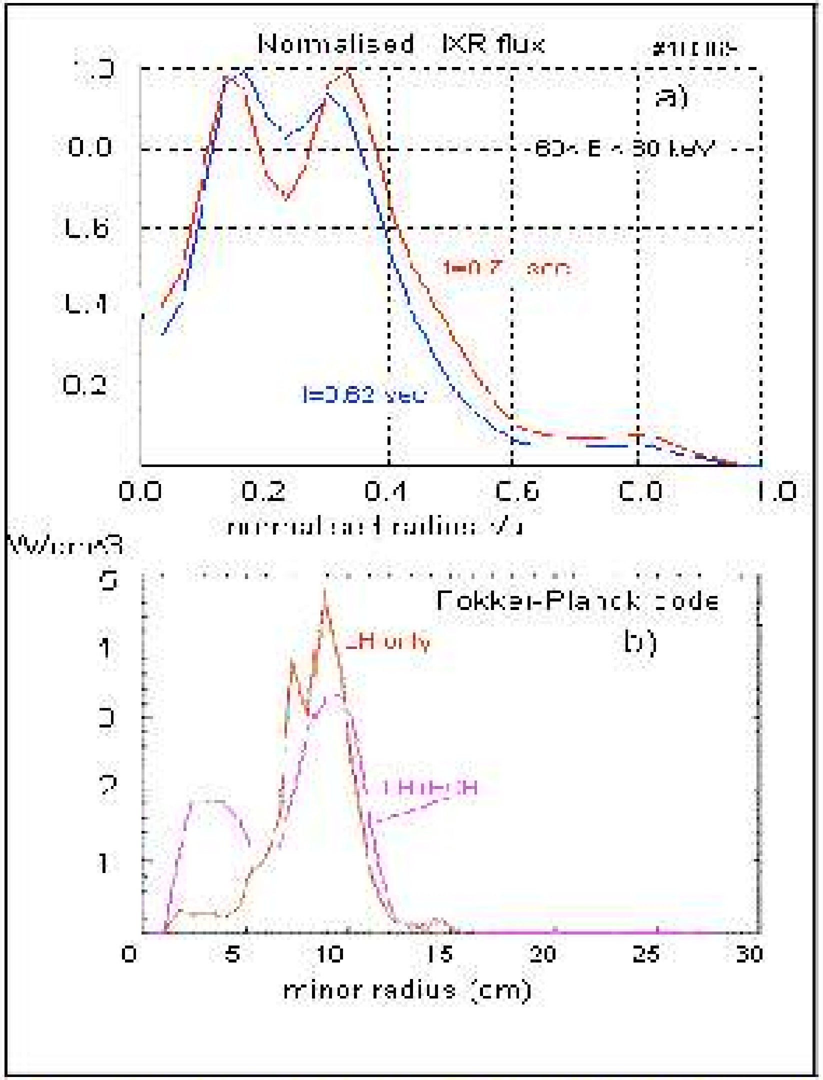
Assumptions:

e^- distribution function with a fast tail in $\mathbf{3.5v_{th,e}<w<c/N_{\parallel,pk}}$

Fraction of fast e^- (≈1‰) to account for the driven current

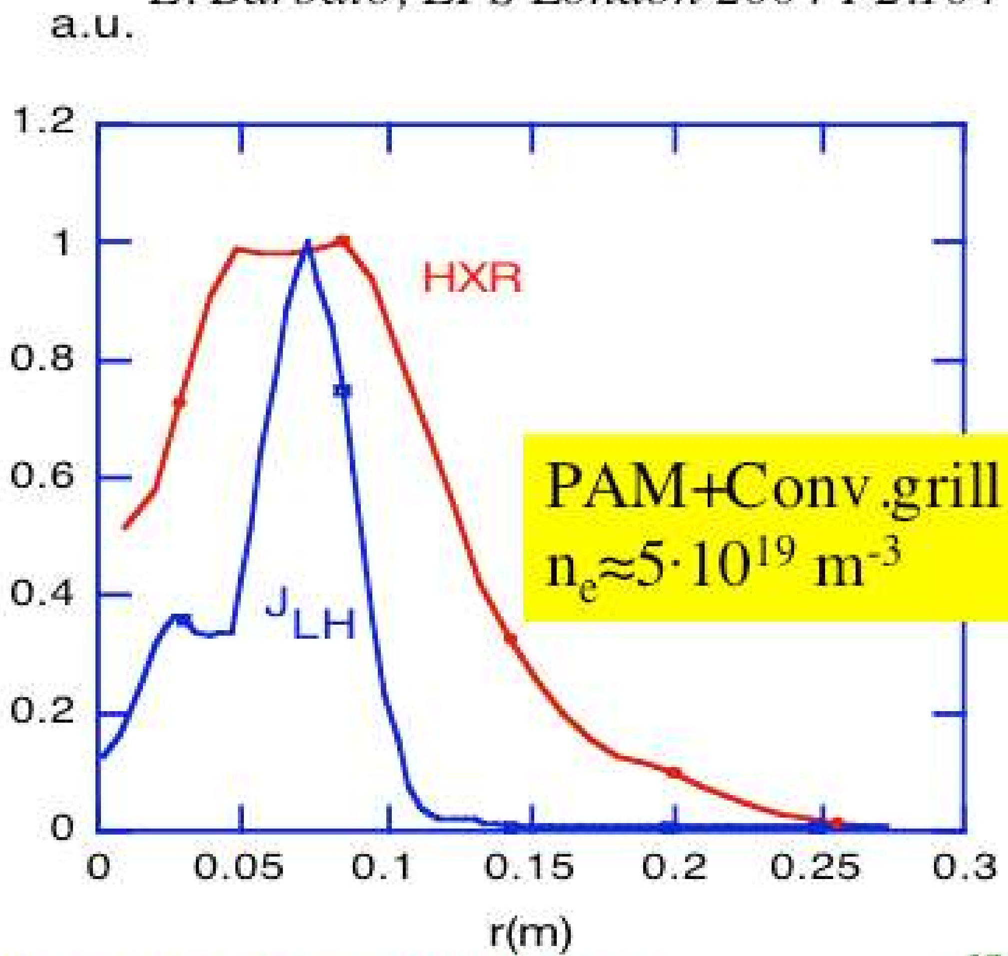
LH power deposition from a Bonoli-type code

Comparison HXR profiles /calculated LH deposition



ASTRA + Fast ray tracing

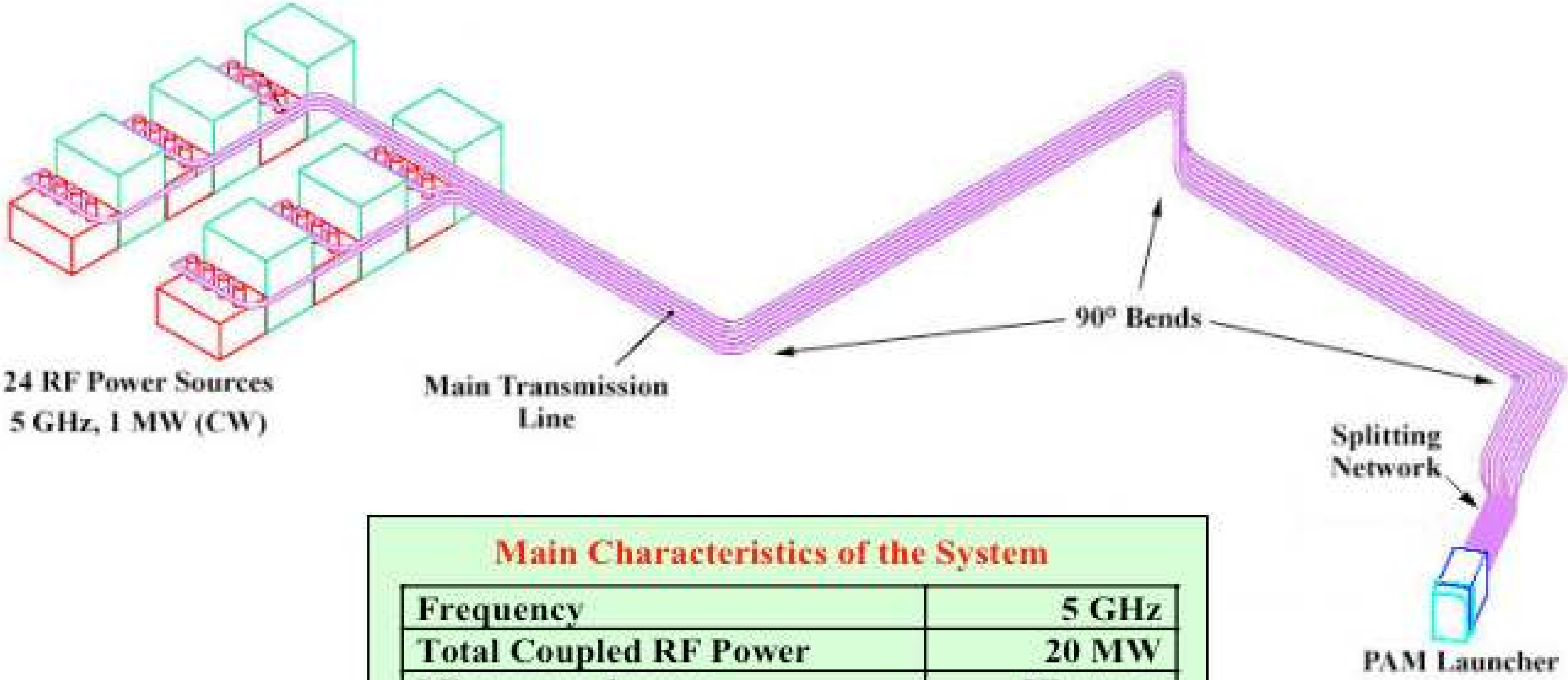
E. Barbato, EPS London 2004 P2.104



PAM+Conv.grill

$n_e \approx 5 \cdot 10^{19}$ m^{-3}

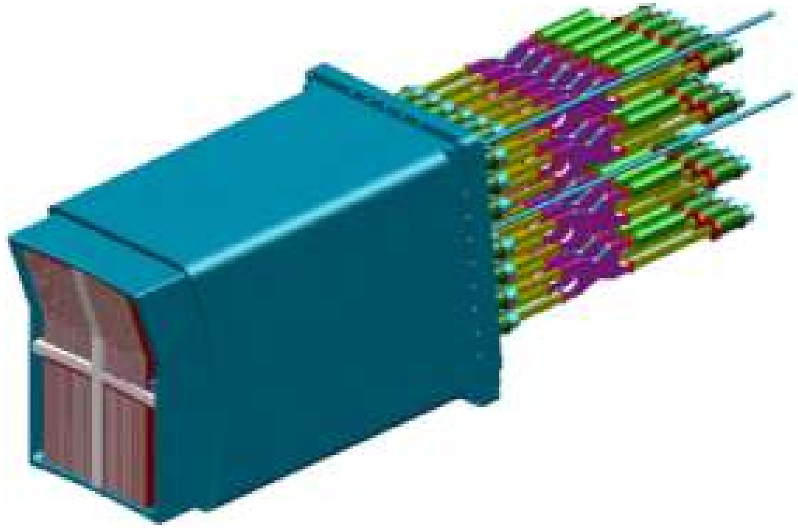
The proposed LHCD System for ITER



Main Characteristics of the System

Frequency	5 GHz
Total Coupled RF Power	20 MW
Microwave Source	Klystron
Transmitter Specific Power	1 MW (CW)
Total Number of Transmitters	24
Transmission efficiency (min)	83%
Launcher	PAM

The ITER LHCD launcher

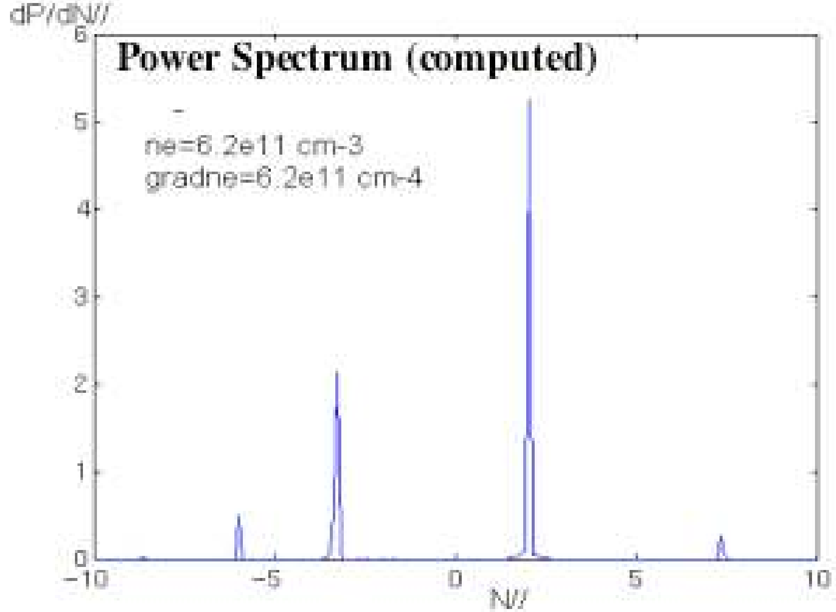


RF and Coupling Characteristics

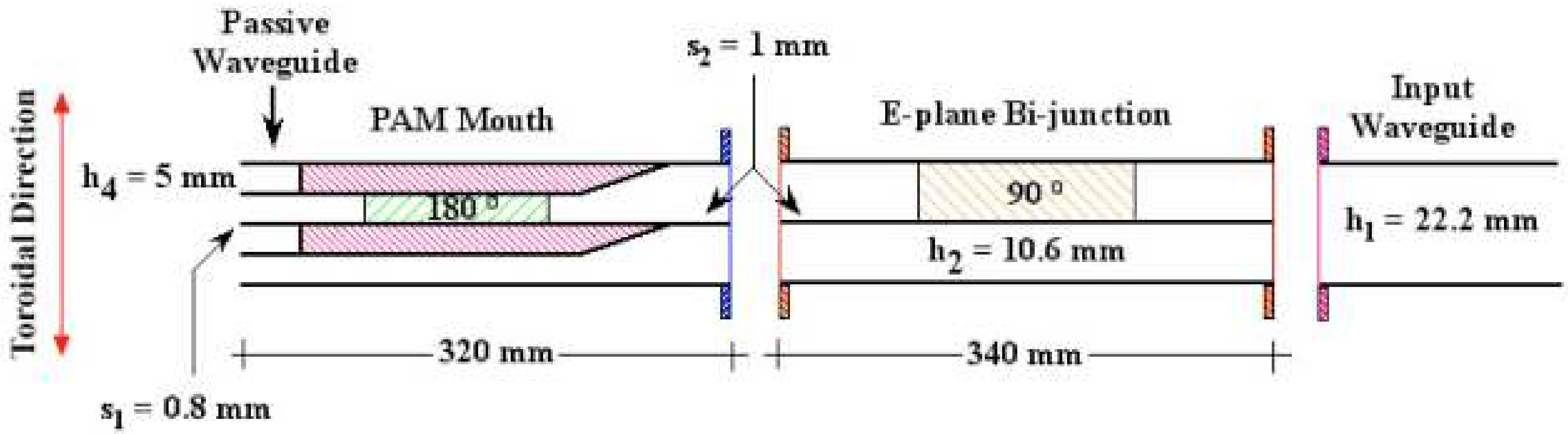
Power Density (Active Wgs)	33 MW/m^2
Electric field	≤ 6.2 kV/cm
Phase pitch (active wgs)	270°
$N_{\parallel}$ peak (Ø = 180°)	2
$N_{\parallel}$ (Ø = -90° ÷ +90°)	1.9 ÷ 2.1
Directivity	≈ 70%

Mechanical Characteristics

Independent Blocks	4
Rows per Block	12
Row Height	58 mm
Active/Passive Wgs per Row	24 / 25
Width of Active Wg	9.25 mm
Width of Passive Wg	7.25 mm
Depth of Passive wg. (optimised)	15 mm
Wall Thickness (mouth)	3 mm
Wall Thickness (between active wgs)	13.25 mm



Layout of a PAM module(top view)

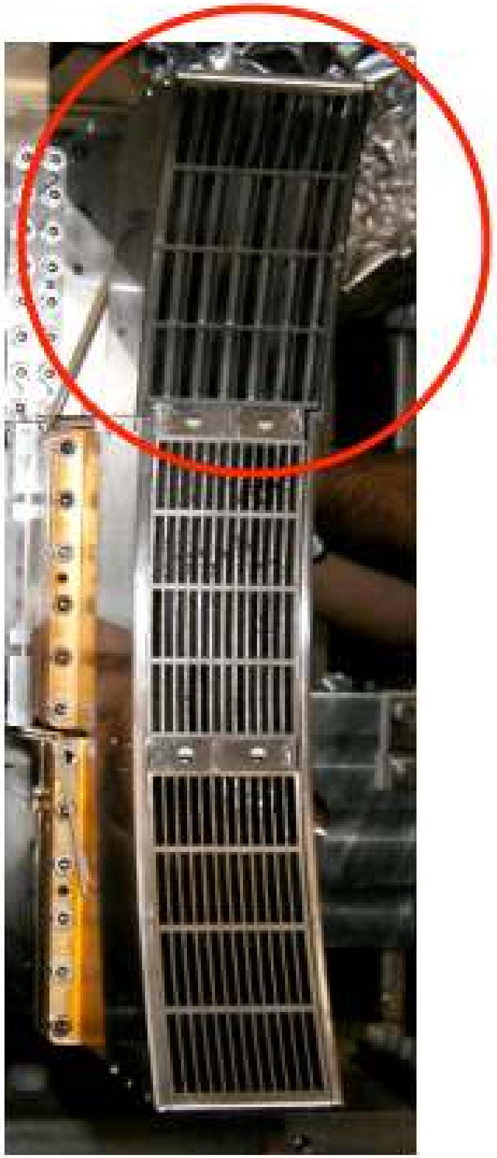


The launcher is longitudinally split in two parts:

the first part contains the E–plane bi–junctions and 90° phase shifters in every other waveguide,

the second part is the mouth with the passive waveguides and additional 180° phase shifters to have the required 270° between the two active waveguides of each module.

FTU PAM test



Mechanical dimensions determined by the cross-section of the FTU port (400 × 80 mm^2):

- Cross section of the waveguides: 28×5 mm^2
- Wall thickness (mouth): 0.8 mm

Depth of passive waveguides: 12.58 mm

Phase pitch (active waveguides): 270°

$N_{\parallel\, peak}$ (phase betw. modules $\varphi = 180°$): 2.4

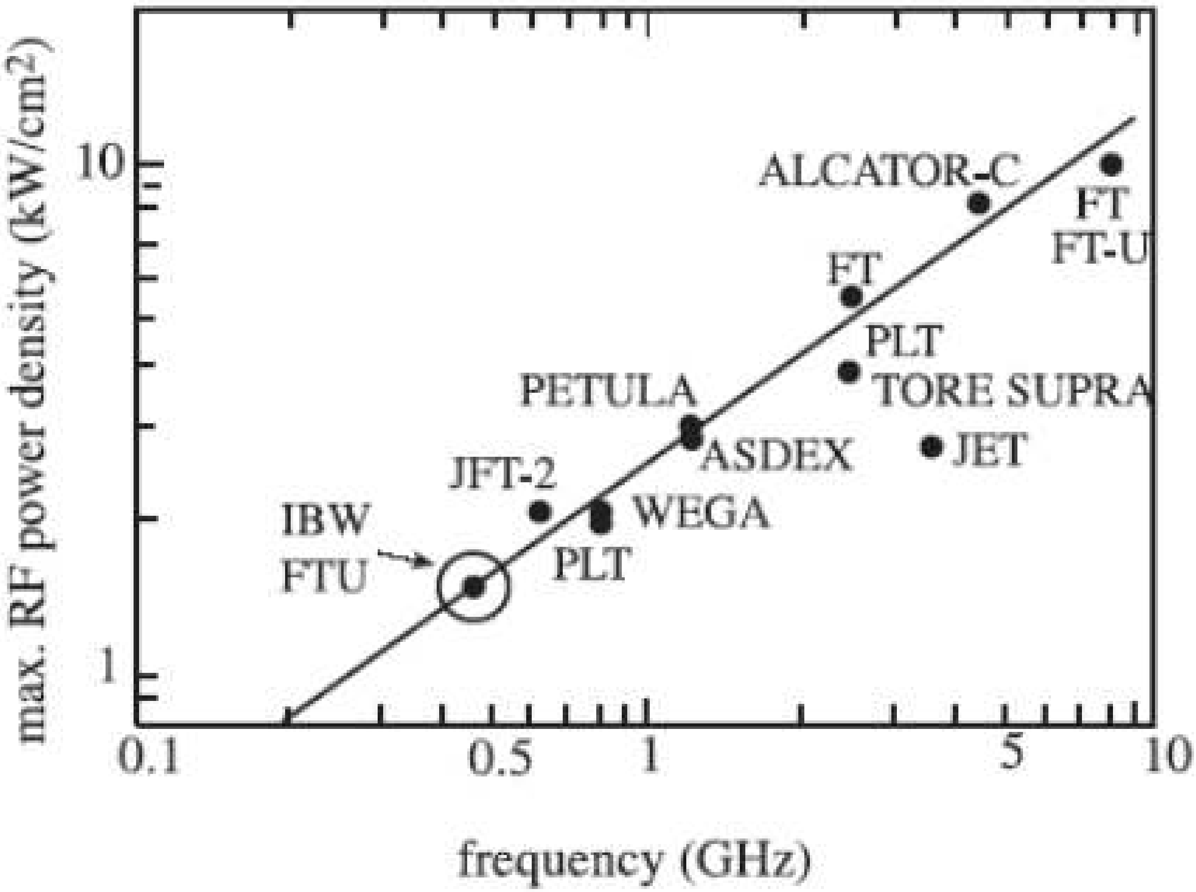
$N_{\parallel}$ ($\varphi = \pm 180°$): 1.6÷2.9

The PAM launcher has replaced the upper conventional grill (CG) of the launching structure installed in the port no. 10 of FTU.

To operate with the same value of $N_{\parallel}$ ($N_{\parallel}$ = 2.2), the feeding phase between adjacent toroidally PAM modules has been set to 135° and to 110° between toroidally adjacent waveguides in the CG.

The expected power directivity at twice the cut-off electron density (n_{ec} = 7.936 10^{17} m^{-3}) is respectively 65% for the PAM and 80% for the CG.

Experimental scaling of power in waveguides



Power safely managed with a phased waveguide antenna as it results from comparison between many tokamaks

M. Aquilini et al., Fusion Sci. & Techn. ***V. 45***, *p. 459 (May 2004)*