Critical Problems in Plasma Heating/CD in large fusion devices and ITER

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Abstract

We identify critical problems in Plasma Heating and Current Drive plasma-wave interaction physics and antennae concepts/technology for large fusion devices, including tokamaks, stellarators, mirror traps and constructing ITER for all major methods like ECRF, ICRF, NBI and LHH. Analysis is based on experiments in large machines and modelling with 3D ICRF and ECRF recently developed full wave PSTELION and STELEC codes, including mode conversion, 3D in-port antennae ANPORT and ANTRES3 codes and theoretical evaluations. We outline identified problems resolution by: 1) elaborated 3D RF full wave codes modeling, 2) proposing High Frequency Fast Waves (HFFW) numerically modelled scheme for DIII-D and ITER, 3) considering principally new approach for ICRH/CD method, especially in conditions of transient ELM activity, making use toroidally broad multi loop Travelling Wave Antenna (TWA) concept which naturally incorporates antenna's loops inter coupling through a plasma with elegant control of antenna-plasma coupling through a small generator frequency change to properly control toroidal wave's spectrum during plasma edge density profile reconstruction; 4) developing new ITER-like ICRF scenarios at fundamental deuterium harmonic, partially recently explored on JET [1].

1. Ion Cyclotron Frequency range (ICRF).
ICRF Travelling Wave Antenna concept for ITER and large machines

There are principal problems with ICRF power coupling for multi loop individually fed resonant antennae (recently again confirmed in JET ICRF experiments [1]) due to loops inter coupling through vacuum and weakly damped Fast Wave (FW) waves into plasma,

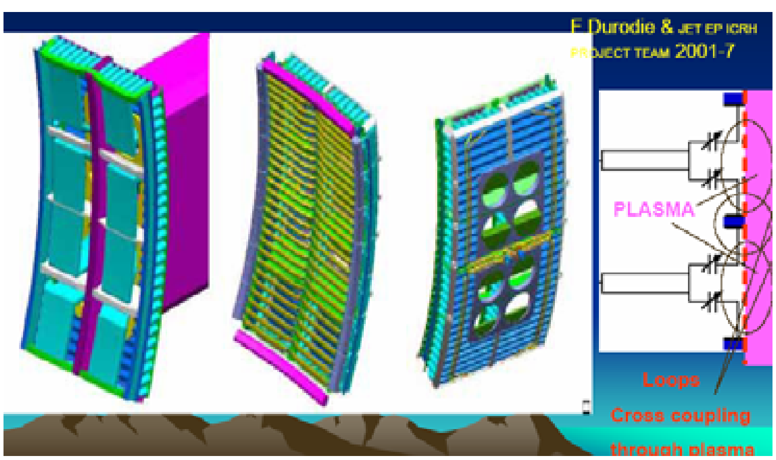

Fig.1 JET "ITER-like" 0-pi antenna (operation in 2008) Loops Cross coupling through a plasma

being especially severe for Current Drive (CD) mode, and designed for ITER. This is easy to understand looking on JET-EP ICRF 8 loops antenna design shown on Fig.1. Each resonating loop is located in **individual conducting housing** (thus decreasing

antenna power capability) and is supported by lumped capacitance. For ITER this approach doubles **simultaneously** resonating circuits number (16).
Physically loops coupling through a plasma is unavoidable one thus leading to mismatching of an antenna, with respective problems to generator matching. Coupling with ELMy plasma creates additional problems. Matching of this type antenna is even more difficult one in CD mode (0, pi/2, pi, 3/2pi) : loops radiate different RF power, and some loops start do not radiate but to receive RF power [3a].

We propose to use qualitatively new Travelling Wave Antenna approach [2], with ITER-DEMO concept and theory developed in [3] displayed in Fig.2. In TWA approach vacuum and plasma loop inter coupling is a positive effect, being intrinsical requirement for proper antenna operation. ITER TWA concept of multi poloidal loop toroidal array supported by ridge waveguide (last one is an essential feature of this TWA concept providing needed wave dispersion and no need for lumped capacitances) [3].

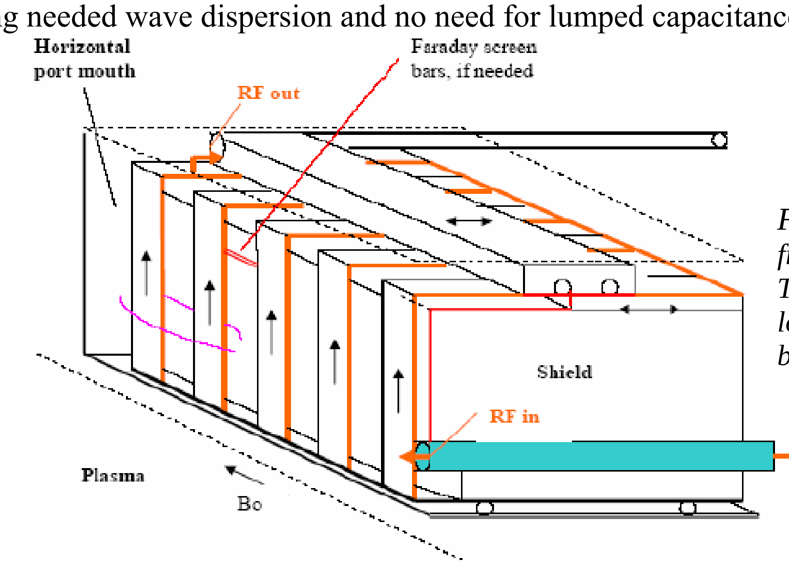

Fig.2 Advanced frequency broad band TWA antenna: toroidal loop array supported by ridged waveguide

This TW Antenna is integrated with neutron shield and has only TWO coaxes: for input and output RF power. Antenna operates as follows: at upper frequency each loop resonates at half of vacuum wave length (Fig.3). When generator frequency decreases the e.m. field is pushed into ridge waveguide legs with simultaneous increase of toroidal wave length. Respectively e.m wave more slowly decays in major radius direction thus still touching a plasma during ELM activity density profiles reconstruction. Simultaneously slowly radially decaying field start to touch “hump” of ridge waveguide, playing a “capacitance-like” role promoting e.m. wave pushing at reduced frequency to the ridge legs.

Thus we see that lower TWA frequency is simply cut off frequency of ridged waveguide because at cut off there are no toroidal RF currents and the cuts (loops) at top of waveguide do not play a role. It means that TWA proposed is narrow frequency band one, band defined by legs length. Proper generator quick frequency sweep provides **constant** power coupling to potentially ELMy plasma. We stress that antenna poloidal loop geometry is exactly the same one as in past and now day ICRF experiments, so coupling antenna characteristics are the same one. Really TWA coupling is remarkably larger one because NO Faraday shield is needed and loops are located more closely to plasma. In principal it is possible to install “O-mode” like conducting bars directly between nearby loops, as indicated in Fig.2.

We found a possibility to incorporate to this TW antenna a frequency broad band possibility installing at the top of the shield two horizontally moving matching conducting plugs providing resonating loops lengths increasing. Thus this concept

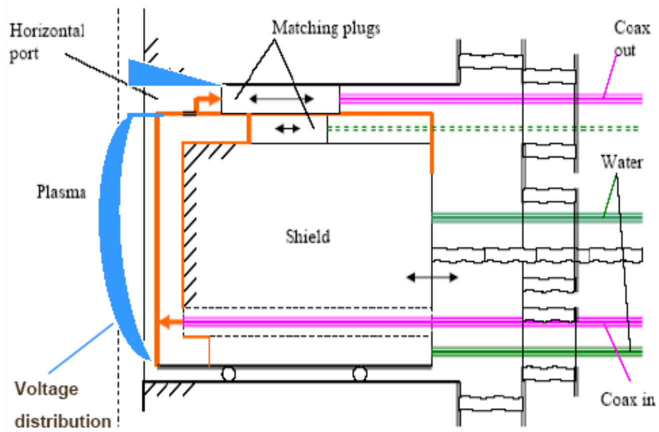

Fig.3 ITER-like TWA supported by ridge waveguide (lumped capacitances are not needed ones) Frequency band 40 – 80 MHz, only TWO coaxes

completely covers the ICRF frequency band 40 – 80 MHz to support majority ITER H/CD scenarios. Antenna has possibility for radial movement for power coupling increase and matching with a generator.

Non absorbed during TWA toroidally propagating wave power comes through output coax and again is combined in proper phase with RF generator TWA's input power through outside machine recirculator. This is shown in Fig.4. This recirculator is an extension of tested DIII-D recirculator for 4 loop individually loop fed ICRF antenna [4] with our extension of ferrite elements in 3 dB hybrids and phase shifters. These ferrite elements magnetization by outside low frequency solenoids is timely tracked in accordance with ELM activity process and generator needed frequency change to control appropriate toroidal wave slowdown.

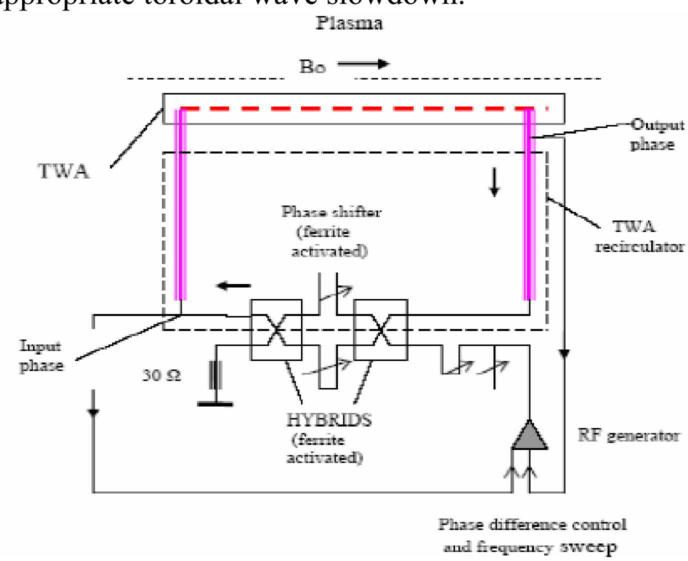

Fig.4 ITER TW antenna recirculator and the matching with RF generator

The TW antenna was successfully tested on JFT-2M tokamak at 200 kW RF power [5] LHD stellarator has prepared Fish_bone like TWA antenna for electron CD goals (LHD web side). Screen less ICRF antenna was successfully operated on AUG tokamak with very similar plasma heating characteristics for screened antenna [6].

ICRF screen less “O-mode” antenna very non efficiently excites the Fast Waves in ITER as shows STELION code modelling displayed in Fig.5 for |real(E_psi| field in ITER tritium second harmonic D-T scenario (F=53 MHz) and the Faraday screen looks not to be needed.

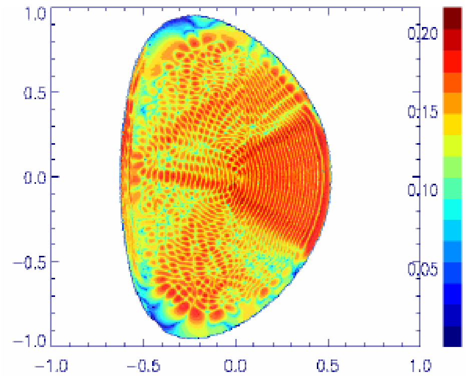
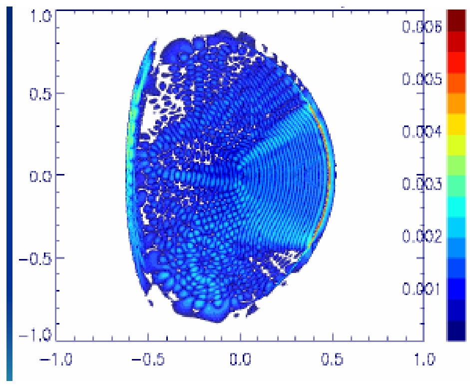

Fig.5a X-mode antenna in ITER, F=53 MHz D-T scenario *Fig.5b O-mode screen-less antenna in ITER F=53 MHz D-T scenario*

2. Electron Cyclotron Frequency range

Among identified problems in ECRF is the role of Upper Hybrid resonance at fundamental EC harmonic (previously ignored in ECH/CD ray tracing modelling) due to O-mode and X-mode coupling at fundamental [7] leading to power deposition broadening, important for NTM predictive suppression in ITER.

2.1 ECH full wave modelling in NSTX

Recently we have upgraded 3D ECH full wave STELEC code by proper addition far out off diagonal wave induced plasma response term which increased wave attenuation, as well known from ray tracing. Basic previous result on O-mode and X-mode coupling at fundamental harmonic in toroidal plasma was again confirmed just manifesting on important role of Electron Bernstein Waves (EBW), previously neglected in usual ECRF ray tracing modellings, including ITER , for O-mode antenna launch.

Well numerically resolved modelling of fundamental harmonic O-mode quasi perpendicular 2 MW outside launch in NSTX L-mode plasma is shown in Fig.6 displaying |E_minus| EC wave 2D e.m. field.

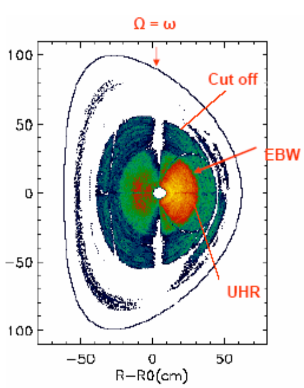

Fig. 6 |E_minus| in NSTX

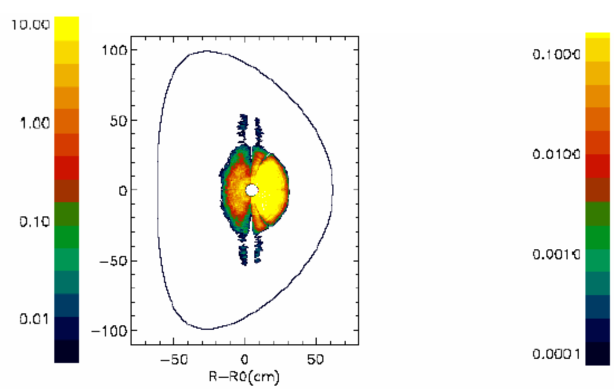

Fig.7 NSTX 2D power deposition to electrons

Respective 2D power deposition to electrons is shown on Fig.7. Main power absorption occurs at **right** resonance zone wing, while usual O-mode consideration at quasi perpendicular outside launch stress to power deposition at high magnetic field side due to relativistic effects involved. STELEC code results are another one due account to poloidal modes coupling, which broadens K_parallel spectrum, and huge amplitudes of EB waves approaching resonance zone.

Flux surface averaged power deposition is shown in Fig.8. All these Figures confirm the crucial role of EB waves. These waves have small group velocity at Upper Hybrid (UH) resonance and when approaching EC cyclotron resonance zone. Power deposition is broader one in compare with ray tracing and occurs in another space place.

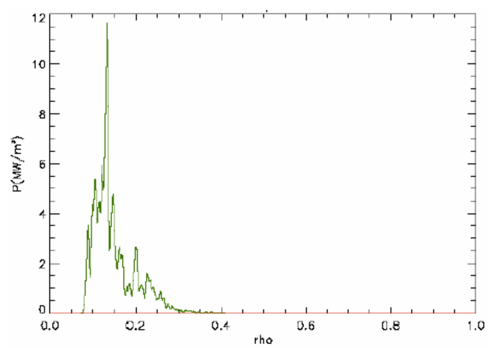

Fig.8 Fundamental harmonic O-mode launch in NSTX, radial power deposition to electrons EBW wave activity is crucial one

EBW activity is crucial one at fundamental harmonic. Similar results were obtained for ITER making use similarity laws technique [7] for modelling at reduced frequencies. Outside quasi perpendicular O-mode ECH launch the STELEC full wave code well resolved modelling shows:

- strong coupling to X-mode with respective mode conversion to small scale EBW
- Large amplitude EB waves and strong modification of K_parallel spectrum provide power absorption on right side of resonant zone (contrary to usual analytic and ray tracing approach)
- This effect must be accounted in analysis of ECRF power deposition in large fusion machines and in predictive ITER ECH/CD modelling
- Huge EBW amplitudes can create poloidal sheared velocities particles streams being important for ITB creation

3. HFFW CD in large machines and ITER

The JT-60U reported NNB CD experiments (E_{inj} = 340 keV) in conditions modelling the ITER scenario ($V_{BEAM} \sim V_{alfven}$) with unfavorable results [8], instabilities (waited from the theory) have appeared and expelled energetic ions before their slow down to thermal energies. This information became even more worse with recent off-axis ASDEX NB CD experiments [9] which demonstrated NO any change in driven current PROFILE (JT-60U previously also reported similar results) thus manifesting on ions and current profiles decoupling.

In such situation the High Frequency Fast wave CD (frequency ~ 10 cyclotron harmonics) may be a back up to substitute NBI in ITER/DEMO creating driven current peaked at HALF of plasma minor radius (goal of NNB) simply relying on large amount

FW wave lengths over fusion reactor plasma minor radius, sufficient to provide single pass wave absorption at classical damping mechanisms on electrons.

3.1 HFFW CD experiments

The HFFW Current Drive, with efficiency comparable to EC and NBI methods, was demonstrated in DIII-D [10]. Active program on HFFW Current Drive experiments is underway at NSTX [11] (efficient electron heating without density rise, RF driven current ~100 kA, plasma internal inductance drop,). We modeled HFFW CD scenario with MRAYS code (together with Yu.V. Petrov). Plasma ITER parameters are close to present design for weak negative steady state scenario #4 and are given in Table 1.

TABLE 1 PLASMA PARAMETERS OF REPRESENTATIVE ITER SCENARIO #4

- Central deuterium temperature T_{D0} 25.2 keV
- Central tritium temperature T_{T0} 25.2 keV
- Central electron temperature T_{e0} 24.4 keV
- Volume averaged electron temperature < Te> 10.5 keV
- Central electron density ne0 7.27×10^{19} m-3
- Volume averaged density $< n_e >$ 6.74×10^{19} m-3
- Impurity fractions f_{He}, f_{Be9} ,f_{Ar} , f_{Alphas} 0.039, 0.02, 0.0035, 0.0056
- Effective Z_{eff} 2.17
- RF power 20 MW

Power deposition to the electrons and driven current profiles for 3D STELION code Modeling with single toroidal harmonic N = 50 at frequency 300 MHz are given in Fig.9.

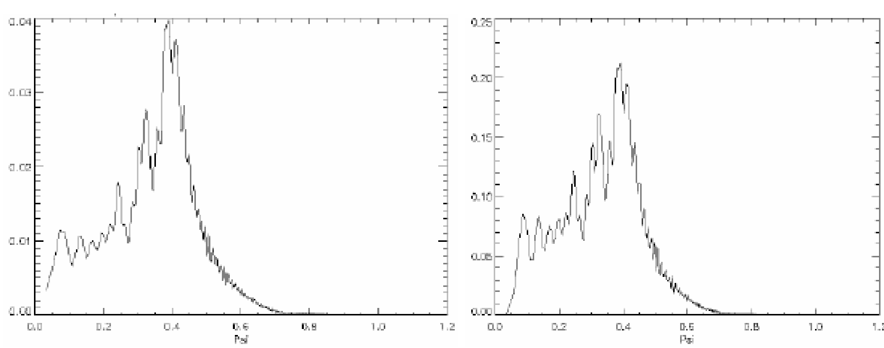

Fig.9a Electrons power deposition *Fig.9b Driven current profile in ITER*

The CD efficiency is high as 0.55 A/W/m^2. FW's absorption on Alphas cyclotron harmonics was not accounted in this STELION modeling. Modelling with multi rays MRAYS code [9,10] with account to full multi loop antenna poloidal and toroidal spectrums in SS-Active ITER: 12 loops, $5\pi/8$ phasing ($N_{||max}$ = 3) was performed. Power deposition profiles and the profile of driven current at $N_{||max}$ = 3 in ITER scenario #4 with 20 MW input power is displayed on Fig.10 (γ = 0.32 A/W/M^2 , MRAYS code, 990 rays).

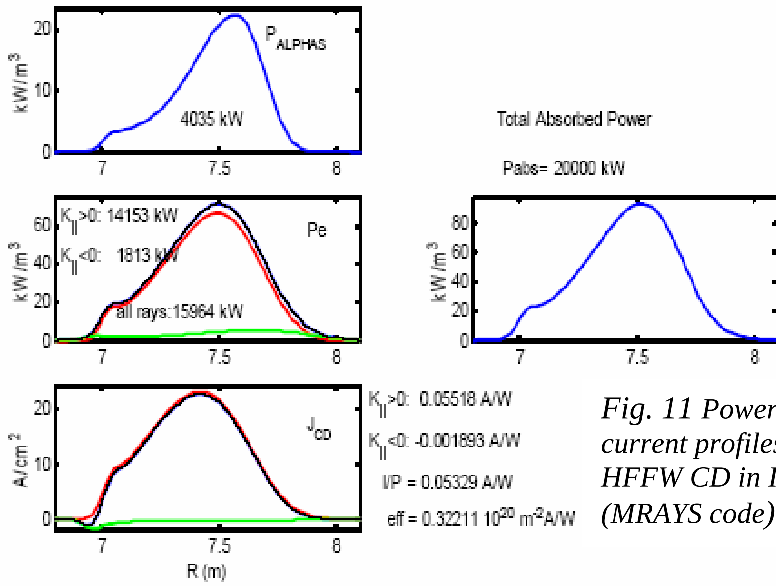

Fig. 11 Powers and current profiles at HFFW CD in ITER (MRAYS code)

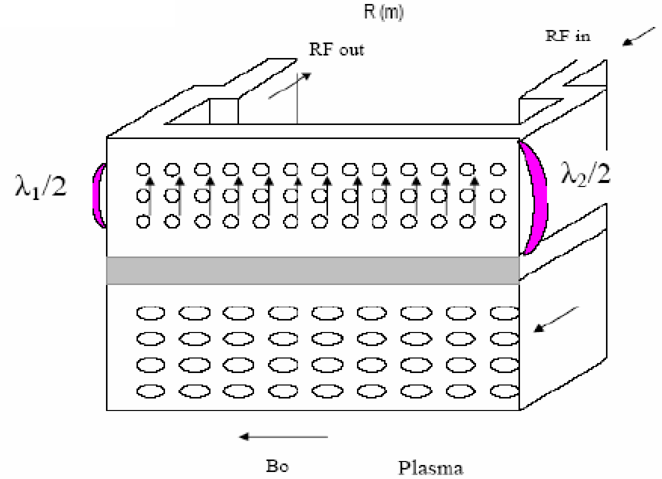

Fig.12 HFFW TWA waveguide antenna for ITER/DEMO

We propose to use electrically strong Waveguide slightly oversized narrow frequency band Travelling Wave Antenna radiating through periodic holes through a broader waveguide's side as shown by Fig.12. This antenna toroidal wave slow down also is controlled by small frequency sweep - similar to above TWA ICRF antenna concept. There are commercially available CW sources 1 MW/tube at 200 MHz (EU accelerator developments [7]).

4. Low Hybrid Frequency range (LHH)

Projection for ITER must overcome several problems: 1) coupling with the main plasma through the broad SOL region in ITER. "Plasma arm", appearing at plasma mouth in present LH CD experiments on Tore Supra and JET, must be properly modelled to predict correct toroidal LH wave spectrum near boundary of a bulk plasma needed for integrated ITER modelling3.

2) Viability of delicate grill antenna at severe ITER/DEMO conditions: relativistic electron tail generation, played dangerous role in ASDEX, Alcator-C,JT-60 etc: divertor plates damage, carbon/Be blooms due interaction with chamber wall.

Conclusions

A. ICRF Advanced ICRF Travelling Wave Antenna with power recirculator, based on Multi loop array supported by ridge waveguide, was proposed. This is electrically strong, frequency broad band antenna (40-80 MHz) resilient to the ELMy plasma.and with constant radiated power.

B. ECRH 1) 3D Full wave ECH STELEC code numerically well resolved modelling for NSTX tokamak supported our previous finding: O-mode and X-mode coupling in toroidal plasmas at fundamental EC harmonic. 2)Electron Bernstein waves play crucial role at O-mode antenna polarization (contrary to ray tracing) and lead to broader EC power deposition profiles. Last ones are located in another space positions in compare with usual ray tracing predictions. 3) This new role of huge amplitudes EB waves provides a possibility of particles velocity shear generation, important for ITB creation.

C. HFFW scheme being back up for NBI 1) To fulfill NBI role –CD creation in middle of minor ITER radius –we propose for ITER/DEMO new/old HFFW CD scheme (Kurchatov1960 –PPPL 2007 activity) operating at 200 –300 MHz. 2) 3D antenna - plasma modelling shows RF current generation peaked in middle of plasma minor radius with CD efficiency about 0.3 $A/W/m^2$ 3) Waveguide type Travelling Wave antenna, surviving ELMy plasma activity with constant power coupling to plasma, was proposed.
4) The CW power sources at 200 MHz are commercially available ones.

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