RF-only ST plasma confinement, sustainment,

and interactions with wall materials

Vladimir Shevchenko

A program of the Workshop which was held on 30-31 January 2020 and was as following:

8th Workshop Agenda, RIAM 2020

30 January AM

10:00 -10:10

Vladimir Shevchenko / Kazuaki Hanada

WS purpose and agenda

10:00 - 10:40

Vladimir Shevchenko

ST40: Recent results and ECRH & HTS plans for future

10:40 - 11:20

Kazuaki Hanada

Recent results for steady state operation and plasma current start-up on QUEST （TBD）

11:20 - 12:00

Modification of plasma-facing surface in QUEST due to PWI and development of advanced W wall panel for ultra-long pulse operation

Naoaki Yoshida

31 January PM

12:00 - 13:00

Lunch Time

13:00 - 13:40

Recent results from TST-2

Yuichi Takase

13:40 - 14:10

Peng Yi

Thomson scattering system in TST-2

14:10 - 14:40

James Rice

Detection of Fast Electrons in SOL Plasma Using a Langmuir Probe Diagnostic

14:40 - 14:55

Yongtae Ko

Measurement of LH waves in TST-2

14:55 - 15:15

Coffee Break

15:15 - 15:55

Hitoshi Tanaka

Overview of Recent EBW Experiment in LATE

15:55 - 16:35

Kengo Kuroda

CHI Experiments in QUEST

16:40 - **Group Photo & QUEST Machine Tour**

31 January AM

9:30 - 10:10

X. Gao

Non-inductive current drive experiments on EAST tokamak

10:10 - 10:50

Masayuki Ono

Update on ECH /ECCD modeling

10:50 - 11:30

Nicola Bertelli

3D full wave simulations in NSTX-U plasmas with the recent developed Petra-M code

11:30 - 12:10

Sadayoshi Murakami

MHD equilibrium reproduction by visible light computed tomography in QUEST

12:10 – 14:00

Lunch

31 January PM (Drafting of proposals for experiments, diagnosis, and analysis)

14:00 - **All Suggested focus and output for this joint drafting session**

The presentation summaries are as following:

Vladimir Shevchenko

ST40: Recent results and ECRH & HTS plans for future

In September 2019 there was a short experimental campaign on ST40 after relocation of the machine into the new building. This campaign was conducted to re-confirm operational status of ST40 after re-commissioning. After that several new diagnostics have been installed and commissioned. Solenoid and additional vertical field power supplies were installed and tested. Diagnostic Neutral Beam (DNB) injector has been delivered and partly tested.

In Autumn 2019 installation of the second part of TF power supply was completed and 1 MW 25 keV Heating Neutral Beam (HNB) injector has been tested and installed. These installations were followed by commissioning on ST40 in December 2019 and January 2020. Both beams demonstrated good performance in hydrogen gas. An improved plasma performance has been demonstrated in this second 2019 campaign taking advantage of the plasma sustainment using solenoid and upgraded plasma diagnostics. Some plasma heating and fuelling were observed with HNB injection into plasmas. To date plasma currents achieved in ST40 are above 0.5 MA with the current flattop up to 100 ms. Toroidal fields in excess of 2 T at the major radius of 0.4 m have been delivered on a regular basis. Kiloelectron volt range electron and ion temperatures have been regularly achieved during this campaign. All diagnostics were commissioned and prepared for full scale experiments. Currently, installation of liquid nitrogen cooling for TF and Bv coils is progress. Next experimental campaign is planned after completion of the cooling system.

Further upgrades of ST40 include installation of the 2nd HNB 1 MW 50 keV in Summer followed by commissioning and plasma experiments in Autumn 2020. A dual (140/105 GHz) frequency 1 MW gyrotron is scheduled for delivery and commissioning in Q1 2021.

Another significant activity at Tokamak Energy (TE) is a high temperature superconductor (HTS) magnet development. We believe that HTS technology gives an opportunity to build a compact tokamak-reactor which would allow achievement of plasma parameters close to ignition. A special magnet winding and testing facilities have been built at TE. HTS tapes from several suppliers were tested and compared against requirements for the tokamak-reactor. Using the best tape, a test magnet was developed demonstrating a world record field of 24 T. It was shown that HTS based magnets are resilient to a thermal quench and can withstand internal damages without causing catastrophic degradation. The next step is a development of a full scale HTS toroidal magnetic system DEMO-4 with the target magnetic field of 10 T at a major radius of 0.25 m. This milestone is to be achieved by the end of 2020.

Kazuaki Hanada

Recent results for steady state operation and plasma current start-up on QUEST

• The QUEST project is focusing on plasma start-up with RFCD and steady state operation.

• The 28GHz RF injection system has the capability to regulate both the wave polarization and N//.   The system has also the capability to focus RF beam down to 5 cm in radius.

• More than 100kA could be obtained in N//=0.78 X-mode with a little OH provided from the poloidal field increment. According to the RF absorption, the RF is likely to absorb to energetic electrons. Which is useful to drive plasma current.

• Low N//=0.1, X-mode injection could successfully heat up bulk plasma up to 0.5 keV of Te. Single pass absorption of achieved plasma parameters is expected to be approximately 40%, therefore the effective bulk heating could be obtained with a sophisticated neutral control to avoid production of energetic electron.

• High field launch of RF has been tried to effectively excite EBW in the plasma. A new tentative waveguide and antenna was installed for the experiment. The designed value of mode conversion to EBW is 93%. The rest RF is absorbed at the fundamental ECR.

• Higher density and better absorption of RF in HFS launch than those in the LFS launch could be obtained. PDI signal was measured with a movable probe and larger PDI in the HFS launch was measured. This supports to higher mode conversion to EBW.

• To get evidence of EBWCD, TF and PF direction modification has been executed. The plasma reproducibility is insufficient to compare the value of plasma current. The flux loop signals denote the inversion of plasma current direction in the mid-plane, bur need to more confirmation.

• Plasma Breakdown has been investigated with 2nd harmonic ECW. The threshold power was much higher than fundamental ECW predicted by numerical calculation. The connection length dependence was different from fundamental ECW.

• The hot wall plays essential roles in reducing the amount of wall-stored H and facilitating H recycling. Only top hot wall has the capability to water cool down since 2018SS campaign.

• The clear reduction of Ha after water cooling of the top hot wall. This indicates the recycling could be control by wall temperature.

• The cooling down from 473K of only top hot wall with water can extend the plasma duration

• During long duration discharges, neutral compression could be achieved behind the bottom divertor plate. The reason is still unclear, because there are many candidates to make this to-bottom asymmetry. It is a future work.

Naoaki Yoshida

Modification of plasma-facing surface in QUEST due to PWI and development of advanced W wall panel for ultra-long pulse operation

Impurity deposition on the plasma facing surface in QUEST at preset is aggregation of nanocrystals of carbide and metallic oxide and little amount of amorphous carbon. TDS results indicate that its contribution to the retention and thermal desorption of H under plasma discharge is little. In contrast, large amount of H can be retained in hot wall liner APS-W and its thermal desorption continues up to around 1000K. It can be considered that active desorption of H from the APS-W liner causes the termination of long pulse plasma discharges.

For ultra-long pule discharges at higher temperatures (≤773K) we have already started development of advanced W liners, in which retention of H at high temperatures is low enough.

Yuichi Takase

Recent results from TST-2

The capacitively-coupled combline (CCC) antennas for exciting the traveling LHW for Ip start-up and ramp-up were developed. Outboard launch, top-launch, and “bottom-launch” (top-launch with reversed Bt) were compared. The driven current was higher for top-launch than outboard-launch as expected, but the highest driven current was achieved by “bottom-launch”, contrary to initial expectation. Thomson scattering measurements show peaked ne profile and hollow Te profile with the highest temperature in the inboard edge region, and equilibrium reconstruction using an extended MHD model shows a hollow j profile. Hard X-ray spectra show higher flux and effective temperature for top-launch compared to outboard-launch, especially in the inboard edge region, consistent with Te and j profiles. A large orbit loss fraction was inferred from the RF power modulation experiment. A combined ray-tracing and Fokker-Planck analysis indicate n|| upshift and strong damping around r/a ~ 0.5 for top-launch. For “bottom-launch”, n|| downshifts first, but upshifts after reflection. Once electrons are accelerated to high energies, these electrons can absorb the downshifted n|| LHW and very high energy electrons can be generated. The result of this analysis can explain the experimental results.

An EC-assisted inductive Ip start-up scenarios being developed for JT-60SA on TST-2. The trapped-particle configuration (TPC) with a weak Bv with positive decay index enlarged the operating window for reliable start-up compared to the usual field-null configuration (FNC). Application of EC power extended both the low pressure limit for breakdown and the high pressure limit for burn-through. The TPC was particularly beneficial at low pre-fill pressure and high EC power.

AC Ohmic coil operation is a reliable pre-ionization method. A small inboard coil can be used for pre-ionization. The breakdown voltage is nearly the same as the regular Ohmic coil. Positive and negative triangularities can be obtained using the small inboard coil. Recent results from TST-2

Peng Yi

Thomson scattering system in TST-2

It is useful to find the optimum operational conditions for fusion reactors if the electron temperature and density profile measured by the Thomson scattering measurements, as well as their scaling could be obtained.

In the study, the relation of the electron temperature (Te) and pressure (P) to the electron density (ne), RF power (Pw), toroidal magnetic field (Bt), and plasma current (Ip), for the scenario of D+CW+Top (deuterium, clockwise toroidal field, and top antenna), is obtained by separate fitting for the parameters in the presumed formula. In addition, the comparisons of different scenarios, such as hydrogen (H) and D, top and out antenna, CW and counter-clockwise (CCW), have been conducted to investigate the effects of them on the electron temperature. Compared with the D+CW+Top scenario, the results show the H fuel gas gives rise to higher electron temperature, CCW toroidal field would produce lower electron temperature, and the out antenna results in rough same electron temperature within error bars. On the basis of temperature relaxation time calculation for the TST-2 and the estimation of confinement time, as well as the heating power for bulk electrons and the equivalent heating power calculated by stored energy in the plasmas and confinement time, it is feasible to explain qualitatively the measured results of electron temperature by collisional heating.

In order to observe the temperature anisotropy in the plasmas, the double-optical-pass configuration for Thomson scattering system in TST-2 is also investigated. The effects of displacement of the focal points on the fiber's collection efficiency are estimated, as well as the deviation of the returned beam from the center of laser source, caused by the tilt angle of the distant mirror, is analyzed since the returned beam will pose the laser source in jeopardy. Also, the theoretical calculations of the displacement of returned beam are verified by corresponding measured results, and that indicates the possibility of blocking the returned beam by putting an aperture in front of the lens or the laser source. The optimization of the double-optical-pass configuration will be implemented in the next step.

James Rice

Detection of Fast Electrons in SOL Plasma Using a Langmuir Probe Diagnostic

Electron Energy Distribution Function (EEDF) analysis has been used to confirm the presence of fast electron populations in SOL plasma in TST-2. A full profile of TST-2's SOL plasma is desired for ray-tracing and plasma simulations. To this end, a new Langmuir probe has been installed as a prototype for a full profile of SOL parameters. This prototype has been used to refine the measurement methods used.

Recent results from power modulation experiments show strong alteration to Te and Vfl during RF power. The positive increase to Vfl indicates RF sheath rectification is not the dominant alteration. It is thought that the non-thermal electron energy distribution in TST-2 causes an overestimation of Te. To confirm this, EEDF analysis has been used to confirm the presence of fast electrons in SOL plasma. Preliminary results show low-temperature bulk electrons and a higher energy component at lower density. Further research is required to better classify this fast electron component and identify its effect on measured plasma parameters.

Yongtae Ko

Measurement of LH waves in TST-2

14-ch RF magnetic probe has been developed to detect LH waves (200 MHz). Parametric decay instability corresponding to ion cyclotron quasi-mode were observed in TST-2 LH driven plasma experiments. The interest is what the differences among launching mode, outboard-launch, top (CW) launch and top (CCW) launch. In the experimental results, large peak of PDI associated with ICQM was observed on sideband of the pump-wave frequency in hydrogen plasma with outboard and top (CW) launch case, while disappeared in deuterium plasma with top (CW and CCW) launch case. The fraction of side band power (100 – 199.9 MHz) was dominant (over 100%) in inboard region with the outboard launch and also dominant (over 200 %) in bottom-outboard region with top (CW) launch. However, with top (CCW) case, fraction was suppressed under 80 %, but direct relationship between current drive efficiency and PDI suppression is not realized.

Hitoshi Tanaka

Overview of Recent EBW Experiment in LATE

Microwave at 2.45 GHz is used to start-up and form ST plasmas. In order to excite the EBW via O-X-B mode conversion, three polarizations of microwave such as O-mode-like left-handed elliptically polarized ones and X-mode-like ones are used and compared. Results of effect on bulk electron heating are qualitatively related to the mode conversion rate calculated by the linear theory with the cold resonance absorption model in a slab model.
HIBP measurement have been carried out during the intermittent plasma ejection events which usually appear when the density exceeds several times of the plasma cut off density and the central safety factor becomes about 8. Fast space potential variations are observed during the event, which indicate the local escape of electrons and its recovery.
An electron beam is injected from a cold cathode installed at the bottom port into a ST plasma which is produced non-inductively by EBW. Investigation of synergistic effects of electron beam injection and EBW current drive has begun.

Kengo Kuroda

CHI Experiments in QUEST

CHI current start-up by using simple electrode has been tested in QUEST. Initial result, in which the injector flux forms between electrode and outer wall shows that the reliable gas breakdown is achieved under appropriate conditions and plasma evolves with increasing toroidal current which is dependent on the PF configuration, but keeping a “narrow footprint” is difficult and current multiplication I_tor/I_inj is low, ~1.

In the discharges, in which the injector flux forms between electrode and inner wall high current multiplication, 5~10 and long duration 10~30ms are achieved and plasma evolves to fill vessel with keeping “narrow footprint”.

We plan to improve and further test the second configuration by installing a new (temporary) injector flux coil that is much closer to CHI electrodes.

After verifying good closed flux surface formation a more permanent CHI coil design will be considered to support CHI + ECH studies.

X. Gao

Non-inductive current drive experiments on EAST tokamak

Overview of experimental progress on EAST is presented. Steady-state fully non-inductive scenarios (such as long pulse H mode, high beta-p plasma, and high beta-N plasma et al.) is demonstrated with extension of fusion performance. Regular and low loop voltage start-ups without resistors have been achieved on EAST tokamak in 2019.

Masayuki Ono

Update on ECH /ECCD modelling

The QUEST ECH solenoid-free start-up experiment utilizing the 28 GHz gyrotron at 2nd harmonic frequency has demonstrated remarkable efficiency and achieved record start-up current values [1]. The experiment provides rich opportunities to understand and optimize ECH-based tokamak/ST current start-up and ramp-up concept. Another potentially noteworthy aspect of the QUEST 28 GHz experiment is its very high frequency to toroidal magnetic field ratio, which is 28 GHz/0.25T or 112GHz/1T. The higher frequency enables higher density limit and for reactors with several Tesla toroidal field, this start-up scenario can largely avoid the usual density limit often encountered by ECCD. Conversely this higher harmonic scenario would enable utilization of ECH at lower magnetic field as in the case of many ST experiments. This scenario maybe also attractive for the ECH assisted start up for the initial phase of ITER where the toroidal magnetic field maybe relatively low ~ 2 T. To better understand the QUEST experimental results, we initiated a modelling effort at PPPL. Improved modelling should also help develop better predictive capability for future ST and tokamak-based reactors. An ST/tokamak start-up modelling is a highly coupled non-linear problem as the magnetic field topology evolves dramatically from an open vacuum field configuration to a closed configuration. The plasma temperature evolves from a very cold collisional regime to a very hot collision-less regime. For this task, we developed a grid-based start-up code where plasma parameters, generated plasma currents, and resulting poloidal magnetic fields are evolved from the vacuum fields. The grad-B drift driven current together with the processional currents can then create a closed flux surface configuration and then the bootstrap current in a closed configuration can further enhance the plasma current. The ECH heating efficiency increases with plasma current since the confinement is increased and resulting electron temperature rise would further increase the ECH absorption and plasma currents. Once the plasma temperature becomes sufficiently high ~ 1 keV, a single-pass absorption can rise sufficiently to transition to the ECCD phase. An important point to note is that two-component distribution (hot minority and colder bulk) is highly advantageous for hot electrons to be generated for efficient ECCD as observed in the QUEST start-up experiment. An update of the modelling is given including some benchmarking of RT-4 with Genray at higher temperature range of ~30 keV and also including the effects of particle loss to better simulate the experimental situation.

Nicola Bertelli

3D full wave simulations in NSTX-U plasmas with the recent developed Petra-M code

In this work we present the recently developed tool Petra-M and its current applications. Petra-M code [1] is a state-of-the-art generic electromagnetic simulation tool for modeling RF wave propagation based on MFEM [http://mfem.org], open source scalable C++ finite element method library. Commonly, RF simulation has been often limited to a relatively small volume in front of the antenna, and it involves physics simplification from the actual experimental situation such as stratifying antenna strap structure, flat antenna model and/or treating the antenna front volume as vacuum. This paper, instead, shows the full 3D NSTX-U device geometry including realistic antenna geometry in order to capture the 3D effects and the antenna-plasma interaction in the SOL plasma and, at the same time, the core wave propagation. A scan of the antenna phasing shows a strong interaction between FWs and the SOL plasma for lower antenna phasing, which is consistent with previous NSTX HHFW observations. Furthermore, the effect of the 3D wave field on the fast ion population from NBI beams in NSTX-U is quantified by using the 3D field obtained from the Petra-M simulations in the SPIRAL full-orbit following particle code [2]. Then we show the 3D full wave simulations of a new HHFW 4-straps antenna recently installed by Tri-Alpha Energy on LAPD with an initial comparison with the experimental data. Finally, initial Petra-M simulations on the JET ITER-like antenna, ICRH/LH in WEST machine, and helicon in KSTAR are discussed.

[1] S. Shiraiwa et al., EPJ Web of Conferences 157, 03048 (2017). [2] G. J. Kramer et al., Plasma Phys. Control. Fusion 55, 025013 (2013).

Sadayoshi Murakami

MHD equilibrium reproduction by visible light computed tomography in QUEST

We propose a method for reconstructing image of a poloidal plasma cross section from visible light information in the tangential direction of tokamak. We realize a robust reconstruction method using Laplacian eigenfunction expansion & L1 regularization. The MHD equilibrium is calculated from reconstructed image applying TASK/EQ code. Rotating toroidally the obtained outer flux surface, we obtain a similar image with the measured visible light.