RF-only ST plasma confinement, sustainment,

and interactions with wall materials

Hiroshi Idei

Vladimir Shevchenko

A program of the Workshop which was held on 1-2 February 2018 and was as following:

6th Workshop Agenda, RIAM 2018

1 February AM

9:30 -9:40

Vladimir Shevchenko / Kazuaki Hanada

WS purpose and agenda

9:40 - 10:30

Vladimir Shevchenko

ECRH and ECCD Potential on ST40

10:30 - 11:10

Hiroshi Idei

Progress and Plans on Non-Inductive Plasma Current Ramp-up Experiment in QUEST

Additional

Hatem Elserafy

HFS injection for EBW excitation in QUEST

11:10 - 11:20

Coffee Break

11:10 - 11:50

Satoru Yajima

Comparison of Ip Start-up by Outboard-Launch and Top-Launch LHW on TST-2

11:50 - 12:20

Yuichi Takase

LH Ip Start-up Experiments on TST-2: Past and Future

12:20 - 13:00

Masayuki Uchida

Progress and Plans of LATE Experiments (Tentative)

1 February PM

14:30 - 15:20

Masayuki Ono

Status of NSTX-U recovery and solenoid-free start-up / current ramp-up program

15:20 - 16:00

Nicola Bertelli

Initial & preliminary Fokker-Planck simulations by using the CQL3D code for QUEST plasmas

16:00 - 16:40

Luis F. Delgado-Aparicio

Multi-energy SXR imaging and its applications to QUEST plasmas

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

2 February AM

9:30 - 10:10

Kengoh Kuroda

CHI Experiments in QUEST

10:10 - 10:50

Taiichi Shikama

Spectroscopic measurements of intrinsic toroidal rotation in QUEST

10:50 - 11:30

Sadayoshi Murakami

Simulation study of toroidal flow generation by ECH in non-axisymmetric toroidal plasmas

11:30 - 12:10

Shin Kubo

Plan for a direct detection of EBW by sub-THz gyrotron scattering in QUEST

2 February PM (Drafting of proposals for experiments, diagnosis, and analysis)

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

16:30 - Vladimir Shevchenko

Summary

The presentation summaries are as following:

Vladimir Shevchenko, **ECRH and ECCD Potential on ST40**

Overview of present status of the ST40 project was presented. Main objectives of the project, parameters of the tokamak, physics program issues are described, and physics and engineering challenges of this device are discussed. A set of ST40 diagnostics were discussed briefly. Fast cameras, visible and UV spectroscopy, magnetics and dual color interferometry were installed on the machine for the first plasma operation.

ST40 power supplies for toroidal field, merging compression coils, vertical field and divertor coils are currently under commissioning. However, first plasma has been achieved in ST40 using merging compression technique in a relatively low toroidal field of 0.3T. Plasma currents up to 30kA have been measured transiently even in the absence of vertical field. Merging compression plasma formation with vertical field will be attempted this week during commissioning of the vertical field power supply.

ECRH and ECCD have a great potential in ST40. During full scale operation the magnetic field should reach 3T at the magnetic axis. This corresponds to the frequency of 170GHz for the second EC harmonic at the plasma centre. Gyrotrons with output power up to 1MW are widely available for this frequency (developed for ITER). Detailed ray-tracing and Fokker- Planck modelling has been conducted for ST40 around fundamental EC resonance and second harmonic EC resonance. It was found that heating and current drive can be achieved at both harmonics. For the fundamental EC resonance RF power around 84GHz must be launched from the high field side (HFS), which possible in ST40 but technically challenging. Second EC harmonic allows more convenient low field side (LFS) launch at the frequency around 170GHz. In both configurations the current drive efficiency around η_{20} = 40 kA·10^{20}m^{-3} · keV^{-1} is expected. However, the HFS launch can also provide very efficient non-inductive plasma start-up and current ramp-up while LFS launch requires presence of the optically thick plasma in the vessel. Both options are considered for potential use on ST40 in addition to NBI heating.

Hiroshi Idei, **Progress and Plans on Non-Inductive Plasma Current Ramp-up Experiment in QUEST**

The EC heating and current drive (ECHCD) system with a 28 GHz gyrotron has been prepared for non-inductive EC plasma ramp-up in the QUEST. Non-inductive plasma start-up using the EC waves is a key issue for advanced tokamak reactor concepts as well as for the ST concept. There are two important aspects of conducting the present ECHCD current ramp-up experiments. One is a beam focusing, and the other is incident polarization control. A new transmission line (TL) and an antenna system composed of polarizers and a large focusing mirror has developed for the local ECHCD. The waist-size of the launched beam was about 0.05 m at the ECR layer. The incident beam can be steered from perpendicular to tangential injection. The steering capability with focusing property was confirmed at the low power test facilities. The local ECHCD effect was observed with the focusing beam in the incident polarization scan. The 86 kA plasma current was achieved using the new TL and launcher. The right-hand cut-off density n_{cut} of the 2nd harmonic 28 GHz-wave is ~ 3 x 10e18 m^-3 for the oblique injection with $N_{//}$ = 0.78 at the ECR layer. The temperature Te decreased with the increasing ne beyond the cutoff density, then the HX count started to increase. The HXs with 60 keV energy range were measured at the forward tangential viewing radius of 0.32 m for current-carrying electrons. Electron density was one order of magnitude higher compared to the previous experiments with no beam focusing. The current might be generated by energetic electrons, accelerated at the relativistic Doppler-shifted resonance, due to the local ECHCD effect with the incident focused beam, as well as the multiple reflection effect after the cut-off.

Hatem Elserafy, **HFS injection for EBW excitation in QUEST**

This presentation contains the High Field Side (HFS) injection scenario for QUEST spherical tokamak. There are several methods for Electron Bernstein Wave (EBW) excitation including O-X-B (Ordinary-eXtranordinary-Bernstein) mode conversion injected from the Low Field Side (LFS), and X-B (eXtraordinary-Bernstein) mode conversion injected from the HFS. O-X-B mode conversion from LFS was attempted in QUEST without any successful EBW conversion. The primary issue was aligning the injection antenna with the polarizing mirror at the HFS that is responsible of the conversion from O-mode to X-mode. X-B mode conversion takes it one step closer, which guarantees not to suffer from the alignment problem. X-B mode was proposed in previous literature mentioning conversion efficiency from X-mode to EBW of 100% at the upper hybrid resonance (UHR) layer. However, those systems used mirrors to transmit the wave to the HFS causing undesired power loss. Our proposed system is to extend the waveguide all the way from the LFS to the HFS to maximize power transmission. One drawback is that the waveguide has to pass through the ECR layer and will induce breakdown inside of the waveguide. To avoid that problem, the waveguide will be filled with SF6 gas to suppress breakdown, while using a sapphire safety window to prevent SF6 leakage inside the vessel. This scenario was externally tested using an electromagnet to emulate the ECR layer and 12 kW were successfully transmitted without arcing. Another problem that might arise is the wave absorption at ECR layer, decreasing the amount of power reaching UHR, and thereby decreasing the efficiency. To tackle this problem, optical absorption coefficient was calculated in order to design the horn antenna parameters. The optical absorption dictates that the antenna should be highly directive in order to maximize conversion efficiency at the UHR. However, due to physical space limitation, the antenna has to be as compact as possible. Antenna size was optimized trading off size and directivity, and the experiment is yet to be conducted. Future plans include integrating 2 other klystrons, and reverting plasma current based on antenna location.

Satoru Yajima, **Comparison of Ip Start-up by Outboard-Launch and Top-Launch LHW on TST-2**

Significant increase of the plasma current and the soft X-ray intensity is obtained by top injection. So far, achievable current is 21.5 kA by outboard launch and 26.7 kA by top launch with top limiter position of z=350 mm and bottom limiter position of z=-390 mm.

GENRAY/CQL3D calculation showed the different characteristics among top, outboard, and simulated bottom injection (TF CCW with top launch). Top launch can extend the tail of velocity distribution by the absorption in wide parallel wavenumber range. Simulated bottom launch can further extend the tail due to initial downshift in wavenumber.

Achievable plasma current is mainly proportional to Bt, but top & bottom limiter can reduce the plasma current and induce fast electron loss.

From full wave calculation

Top launch: Optimum distance between antenna and plasma is 17-27 mm

Outboard launch: Reflection is suppressed when the limiter is displaced 70 mm

Yuichi Takase, **LH Ip Start-up Experiments on TST-2: Past and Future**

ST plasma initiation and I_p ramp-up by the lower hybrid wave (LHW) were demonstrated on the TST-2 spherical tokamak. Progressive improvements in the achieved I_p were accomplished using different methods of wave excitation. High wave directivity of the newly-developed capacitively-coupled combline (CCC) antenna was confirmed by the co/counter asymmetry of hard X-ray emission. Since numerical modeling indicates $n_{||}$ upshift and strong single-pass absorption for top-launched LHW, the top-launch CCC antenna was installed in addition to the outboard-launch CCC antenna. In LHW-driven plasmas, both p_e and j are dominated by energetic electrons, n_e profile is peaked whereas the T_e and j profiles are hollow, and the driven I_p increases with n_e, and higher n_e requires higher B_t. The top-launch LHW is found to be more effective than the outboard-launch LHW for both directions of B_t, and I_p ramp-up to > 25 kA has been achieved with less than 100 kW of RF power. The improvements being considered based on numerical modeling include: TF power supply upgrade to enable higher B_t for longer pulse, optimization of launcher positions and $n_{||}$ spectra, 3-D control of wavevector (toroidal and poloidal wavenumbers), combination of 450 MHz (for core heating) and 200 MHz (for current drive), and reduction of SOL losses by improved single-pass damping. Since orbit losses of high energy electrons should decrease at higher I_p and n_e, a substantial improvement in the I_p ramp-up efficiency may be possible

Masayuki Uchida, **Progress and Plans of LATE Experiments**

- Formation of highly overdense ST plasmas by EBW
    - Highly overdense plasma is obtained with the core heating by EBW excited in the 1st propagation band
2.45GHz, 65kW ; Ip ~ 12kA, n_e~6x10^{17}m^{-3} (~8 n_{cutoff})
5GHz, 70kW ; Ip ~ 9kA, n_e~1.5x10^{18}m^{-3} (~5 n_{cutoff})
    - Electron density rises when the UHR become inside of the 2nd ECR layer
- Formation of ST with 2.45GHz and 5GHz microwaves
    - Ip ramped up from 8.5 kA to 14 kA by additional 5GHz power of 70kW

- Strong HX observed during 5GHz injection
- UHR layer fluctuates around 3rd ECR for 5GHz

Masayuki Ono, **NSTX-U Plasma Start-up Research Program and Collaboration Strategy**

National Spherical Torus Experiment Upgrade is a low-aspect-ratio (A ~ 1.6 – 1.8) spherical tokamak facility at PPPL with B_T ~ 1 T, I_p ~ 2 MA, P_{NBI} ~ 14 MW, and P_{RF} ~ 4 MW. The unique operating regimes of NSTX-U can contribute to important physics issues for the ST development path. After the PF-1A (a divertor control coil) failure, a recovery project was formed. A number of internal and external reviews were conducted, and it was concluded that the NSTX-U lower ceramic insulation will be removed which preclude the conventional coaxial helicity injection (CHI) capability. This resulted in a reexamination of our plasma start-up program. The NSTX-U Ramp-Up studies will continue using inductively generated targets with HHFW & NBI, as in original plan. NSTX-U solenoid-free start-up activities will be conducted in other ST facilities in the near term: The NSTX-U team will support the more reactor relevant CHI research being conducted on QUEST. If successful, it would be possible to implement an CHI system on NSTX-U without toroidally continuous ceramic insulator. It should be also noted that the PEGASUS group is developing the localized helicity injection (LHI) system. The NSTX-U team would like to enhance collaboration on ECH / EBW start-up studies being conducted on QUEST through theory/modeling and multi-energy soft x-ray camera collaborations. The ultimate goal of NSTX-U is to start-up and sustain high ��plasma fully non-inductively without use of central solenoid.

Nicola Bertelli, **Initial & preliminary Fokker-Planck simulations by using the CQL3D code for QUEST plasmas**

1. Performed initial Fokker-Planck CQL3D simulations for QUEST plasma
    a. Parabolic profiles
    b. Work still in progress
2. Found very strong tail representing high energetic electrons on the location of 2nd harmonic resonance
3. Total current driven by high energy electrons lower than experiment
    a. Probably need to improve some parameters for the simulations

COLLABORATION with QUEST

Tasks:

1) Continue work on CQL3D simulations in collaboration with Idei-sensei
    a. More realistic data (?)

    b. Different dispersion relations

2) Comparison of SXR data with CQL3D synthetic diagnostic

    a. Including future data from Luis F. Delgado-Aparicio's camera

3) Collaboration also with R. Harvey (waiting answer from a proposal to work on QUEST submitted in 2017)

<u>Luis F. Delgado-Aparicio, **Multi-energy SXR imaging and its applications to QUEST plasmas**</u>

<u>Summary points for QUEST talk</u>:

- Measurement of power losses in the x-ray range enables the characterization of local plasma parameters to study MHD, transport and confinement.
- Multi-energy SXR/HXR diagnostic probes mainly the electron channel (e.g. T_e and $n_{e,fast}$) but also n_Z, ⍰Z_{eff} and Z_{eff} from the continuum & line-emission.
- Pilatus3 technology allows for individually selecting (64) energy ranges from 1.6 keV and above for all its 100k pixels (minimum).
- New imaging concept based on PILATUS3 detectors combines best features from PHA & multi-foil methods
- ME-SXR systems can also be used at QUEST for studying the fast-electron emission between 2 and 30-40 keV.
- Limitation of Si above 20-30 keV. Use CdTe up to ~100-200 keV.

<u>Kengoh Kuroda, **CHI Experiments in QUEST.**</u>

Quest is developing a new design CHI electrode configuration that is more suitable for a fusion reactor.

・Reliable discharge initiation successfully obtained with the new design electrodes on QUEST.

However, some improvements were needed to achieve appropriate evolution for forming a closed flux surface.

・By improving capacitor bank power supply and PF coil programming, the plasma evolved closer to the appropriate shape, in which toroidal current increased up to 46kA and a large plasma persisted for a short time after the injector current decreased to zero.

<u>Taiichi Shikama, **Spectroscopic measurements of intrinsic toroidal rotation in QUEST**</u>

We measured toroidal and poloidal flow velocities of C^{2+} and O^{+} ions in QUEST using an optical emission spectroscopy system equipped with multiple viewing chords. In 8.2 GHz (IL) and 28 GHz discharges, the toroidal and poloidal velocities of these ions were less than 10 and 1 km/s, respectively. Among the possible driving and damping mechanisms, we investigated the effects of charge-exchange momentum loss by atoms and thermal ion loss-cone. As for the former, we found that the friction force by charge exchange increases at the outboard side, so that small velocity there could be a consequence of atom penetration. The latter effect was checked by calculating the ion loss-cones using ion orbit calculation. The ensemble averaged toroidal velocity became larger for O^{+} than C^{2+} by a few km/s in the edge region, and this may explain observed velocity difference between C^{2+} and O^{+} ions.

Sadayoshi Murakami, **Simulation study of toroidal flow generation by ECH in non-axisymmetric toroidal plasmas**

The important role of the plasma flow and its shear in the transport improvement is suggested by many experimental observations. The spontaneous toroidal flow driven by ECH was observed in many tokamak and helical devices. In LHD, when ECH was applied to the NBI heated plasma, the toroidal velocity profile changed drastically and turned over in the core region. ECH generates a radial flux of suprathermal electrons in non-axisymmetric plasmas. We assume that the energetic electron current enhances the bulk ion current to cancel the electron current, and the j×B torque has a significant role in generating a toroidal flow. In this study, we investigate the roles of the J×B torque due to the radial current of energetic electrons and the collisional torque by the energetic electrons, and compare with the LHD experiment results. As a result, the J×B torque generated by ECH has the same order as the NBI torque, and its direction is opposite to NBI torque in the inner region. Also, we evaluate the torque by ECH in the tokamak with finite toroidal field ripple.We find that the significant torque by ECH is obtained in the case the toroidal field ripple > 0.1%.

Shin Kubo, **Plan for a direct detection of EBW by sub-THz gyrotron scattering in QUEST**

The electron Bernstein wave (EBW) heating/current drive is the most attractive method in QUEST, because EBW can propagate over the cut-off density and give a chance to drive current steadily at over the cut-off density. Since the EBW can be excited through mode conversion process, it is important to clarify and optimize the injection condition by checking the excited EBW near the core region.

Direct detection of the density fluctuations associated with the EBW is planned. Expected wavenumber in the perpendicular to the magnetic field ranges 104-105 m−1. The direct and detailed measurement of the density fluctuation associated with the EBW gives clear evidence of the excited EBW inside the core, since it is an electro-static wave. Such measurement can be performed by measuring the sub-Tera-Hz wave scattering. The adoption of Littrow mount grating enables flexible scattering configuration under limited port access.

Sub-THz gyrotron at 300-400 GHz gyrotrons at the power level of more than 50 kW have been developed in the Univ. of Fukui. One of such gyrotrons is planned to be introduced in the the QUEST as well as highly sensitive detectors developed for CTS in LHD.

<u>Several Proposals were submitted:</u>

Luis F. Delgado-Aparicio:

PPPL scientists (Luis F. Delgado-Aparicio with Nicola Bertelli and Masayuki Ono) are establishing collaboration with scientists at Kyushu University to discuss the possibility of installing a Multi-Energy Soft X-ray (ME-SXR) system at QUEST. A silicon PILATUS3 detector can be used to resolve details of SXR emission between 2 and 30 keV with adequate time-resolution (~1 ms), excellent spatial resolution (~1-2 mm) and coarse photon energy (~500 eV) resolution. This new imaging capability can support experiments aiming at studying start-up and sustainment of non-inductive plasma current in spherical tokamaks. Delgado-Aparicio has requested a tangential view aligned with the equatorial midplane at QUEST in order to circumvent the complications from performing a conventional (radial) poloidal tomography. A parallel activity will take place to obtain a synthetic non-Maxwellian x-ray spectra using CQL3D.

Nicola Bertelli:

All the codes above can be used for EC/EBW studies on QUEST plasmas under the collaboration between NSTX-U and QUEST teams.

Tasks:

1) Continue work on CQL3D simulations in collaboration with Idei-sensei
    a. More realistic data (?)
    b. Different dispersion relations
2) Comparison of SXR data with CQL3D synthetic diagnostic
    a. Including future data from Luis F. Delgado-Aparicio’s camera
3) Collaboration also with R. Harvey (waiting answer from a proposal to work on QUEST submitted in 2017)