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Paper

Transient Coaxial Helicity Injection Plasma Start-up in NSTX and CHI Program Plans on NSTX-U

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Transient Coaxial Helicity Injection (CHI) in NSTX has generated toroidal plasma currents up to 300 kA. When induction from the central solenoid is then added to these discharges they maintain up to 300 kA additional current compared to discharges initiated by induction only. Standard inductive discharges in NSTX require 50% more solenoid flux than a CHI started discharge to reach 1 MA. The CHI-initiated discharges have low plasma density and normalized internal plasma inductance of 0.35 through the inductive ramp, typical of advanced scenarios planned for future STs. The Tokamak Simulation Code (TSC) has been used to understand the scaling of CHI generated toroidal current with variations in the external toroidal field and injector flux. These simulations show favorable scaling of the CHI start-up process with increasing machine size, consistent with theory. Scaling based on the analysis of experimental results and TSC simulations indicates the possibility for substantial current generation by CHI in the planned upgrade to NSTX. These results demonstrate that CHI is a viable solenoid-free plasma startup method for future STs.

Keywords : CHI, plasma start-up, NSTX, solenoid-free

1. Introduction

Tokamaks and spherical tokamaks (STs) have hitherto relied on a central solenoid to generate the initial plasma current and to sustain that current against resistive dissipation. However, a central solenoid cannot be used for plasma current sustainment indefinitely. The inclusion of a central solenoid in a tokamak for plasma start-up alone limits the minimum aspect ratio and adds cost and complexity. For reactors based on the ST concept, elimination of the central solenoid is necessary so alternate methods for plasma start-up would be needed.

Coaxial Helicity Injection (CHI) was originally developed as part of spheromak research(1) and has now been used on several spheromak experiments including on the SSPX, CTX and RACE devices(2)-(4). Groups in US and Japan have used the method for reconnection merging research(5)(6) and for spherical torus plasma formation(7)(8).

CHI research on NSTX initially used the method of *driven* or *steady-state* CHI for plasma current generation(8). Although substantial toroidal currents were generated using the steady-state approach, it was found that these discharges could not be successfully ramped up in current when induction was applied. Supporting experiments on the HIT-II experiment at the University of Washington demonstrated that the method of *transient* CHI could generate high-quality plasma equilibrium in a ST that could be coupled to inductive drive(9). Since then the transient-CHI method has been successfully applied to NSTX for solenoid-free plasma start-up followed by inductive ramp-up(10). These coupled discharges have now achieved toroidal currents >1 MA using significantly less inductive flux than standard inductive discharges in NSTX.

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2. Experimental Results

CHI is implemented in NSTX by driving current along field lines that connect the inner and outer lower divertor plates as described in detail in Ref. (8)-(10). In NSTX the inner vessel and lower inner divertor plates are the cathode while the outer divertor plates and vessel are the anode. Prior to initiating a CHI discharge the toroidal field coils and the lower divertor coils are energized. The lower divertor coils produce magnetic flux linking the lower inner and outer divertor plates which are electrically isolated by a toroidal insulator in the vacuum vessel. A programmed amount of gas is then injected into the vacuum chamber and voltage is applied between these plates which ionizes the gas and produces current flowing along magnetic field lines connecting the plates. In NSTX, a 5 to 30 mF capacitor bank charged to 1.7 kV provides this current, called the injector current. As a result of the applied toroidal field, the field lines joining the electrodes wrap around the major axis many times so the injector current flowing in the plasma develops a much larger toroidal component.

Significant improvement in the performance of CHI discharges in NSTX were achieved by reducing the low-Z impurities, mainly oxygen and carbon in the initial electrode-driven plasma(10). Ref. (10) describes this work in detail so the methods are briefly summarized here. The lower divertor plates, which are used as the CHI electrodes were initially cleaned using an extended electrode discharge. The CHI system itself was used for this purpose by running many discharges at high injector current but with greatly increased injector flux connecting the lower divertor plates. By maintaining the injector current below the level required (by MHD considerations) for ejecting the flux, the discharge was maintained near the lower divertor plates. This cleaning was followed by coating the lower divertor plates with lithium from a pair of evaporator ovens mounted at the top of the vacuum chamber, as described in Ref. (11). Finally, during the CHI discharges, two poloidal field coils located in the upper divertor region were energized to provide a "buffer" flux to reduce contact of the growing CHI discharge with the upper divertor electrodes[10]. Without this buffer flux, the growing CHI discharge could contact the upper divertor plates. This usually generated an arc between the plates which injected low-Z impurities into the CHI discharge, causing it to become more resistive which rapidly consumed the poloidal flux in the plasma.

Detailed results on the coupling of CHI started discharges to induction are described in recent references (12), (13). The results on the reduction in central solenoid flux required to reach normal plasma current are briefly summarized here. In Fig. 1 we are comparing the plasma current trace for a recent CHI started discharge that was followed by inductive ramp-up to a standard discharge on NSTX initiated and ramped up by induction only. The inductive-only discharge is from the NSTX database, assembled over 10 years of operation that reached 1 MA in a shorter time than other L-mode discharges. At 132 ms the CHI-started discharge consumes a total of 258 mWb of central solenoid flux to ramp up to 1 MA. At this time the reference inductive-only discharge gets to about 0.7 MA and it does not reach 1 MA until 160 ms, by which time 396 mWb of central solenoid flux had been consumed. Typical L-mode discharges in NSTX require at least 50% more inductive flux than discharges assisted by CHI. It is important to note that, due to failure of one of the lithium evaporators, the recent CHI discharges did not benefit from full lithium coverage of the lower divertor plates, so that the achieved flux savings may have been hindered by exposed graphite that may have contributed some low-Z impurities.

These new results[12][13] also show that these plasmas have both a very high elongation of $\kappa \approx 2.6$ and, as a result of the hollow electron temperature profile and rapid inductive ramp, very low internal inductance $l_i \approx 0.35$ from the start of the discharge. Finally, these plasmas are relatively free of MHD activity despite having low density, which has previously been associated with increased instability during normal inductive startup.

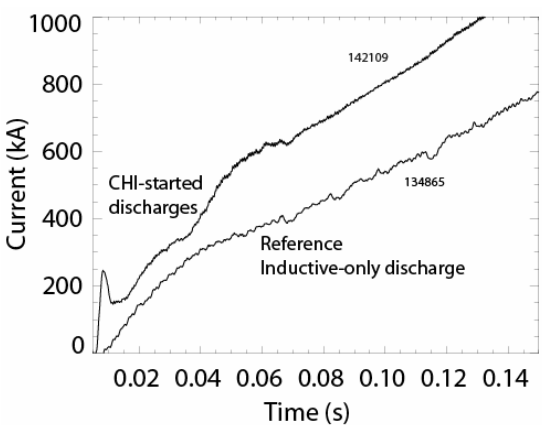

Fig. 1. Shown are a CHI started discharge and a reference inductive-only discharge

3. TSC Simulations

TSC is a time-dependent, free-boundary, predictive equilibrium and transport code[14][15]. It has previously been used for development of both discharge scenarios and plasma control systems. It solves fully dynamic MHD/Maxwell's equations coupled to transport and circuit equations. The device hardware, coil and electrical power supply characteristics are provided as input. It models the evolution of free-boundary axisymmetric toroidal plasma on the resistive and energy confinement time scales. The plasma equilibrium and field evolution equations are solved on a two-dimensional Cartesian grid. Boundary conditions between plasma/vacuum/conductors are based on poloidal flux and tangential electric field being continuous across interfaces. The circuit equations are solved for all the poloidal field coil systems with the effects of induced currents in passive conductors included. Open field lines are included, and the toroidally symmetric part of the "halo current" on these field lines is computed. For modeling CHI in NSTX, the vacuum vessel is specified as a metallic structure with poloidal breaks at the top and bottom across which an electric potential difference is applied.

For the first simulations, an early NSTX transient CHI discharge (118340) was used that successfully demonstrated current persistence[16], that is the CHI produced toroidal current persisted after the injector current had been reduced to zero. The same poloidal field (PF) coil current time histories as in discharge 118340 was used in the simulations. The experimentally measured injector voltage was not used. Instead we specified a voltage V across the lower vessel gap and adjusted this to give approximate agreement with the measured injector current. Because the key parameters for CHI discharge evolution are the injector current and injector flux[17] this approach avoids the ambiguity related to sheath resistance, which is not measured and could vary widely. The voltage is simply a control parameter on the calculation that is adjusted to obtain a given injector current. This will be seen in the later part of this paper. In Fig. 2 we illustrate the results of the

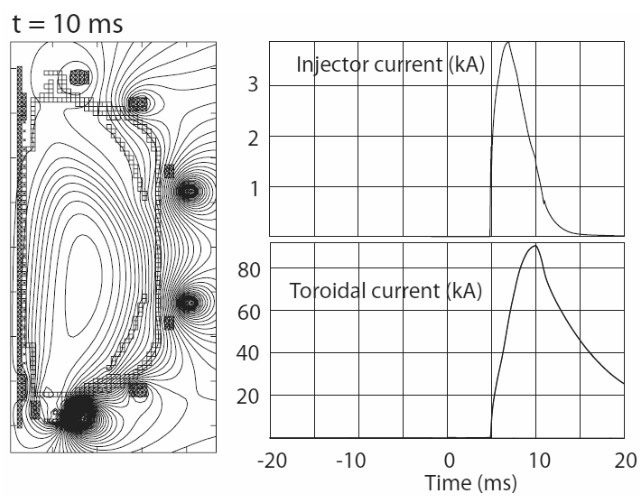

Fig. 2. Shown are the poloidal flux contour, injector current and CHI produced toroidal current for NSTX discharge 118340 (Ref. (16))

TSC simulations of the CHI experimental data shown in Fig. 2 in Ref. (16). In the simulations, it is assumed T_e is constant at 15 eV. With this assumption, about 60 kA of toroidal current is generated, and as in the experiment, the injector current at the time of peak toroidal current is similar to the experimental value.

Generation of closed flux in TSC is as a result of an effective toroidal loop voltage induced by the CHI ejected poloidal flux that decreases as the injector current is reduced to zero. Reference (18) also provides additional details including showing consistency with earlier theoretical predictions[17]. It also shows that CHI scaling with toroidal field is favorable for larger machines and that with acceptable amounts of injector current, peak plasma currents on the order of 600 kA could be generated using the injector poloidal flux capability of the present NSTX if the toroidal field were increased to 1 T. The higher toroidal field allows the same level of poloidal flux to be produced in the plasma at lower level of injector current.

4. CHI Research Plans on NSTX-U

NSTX-U is an upgrade to NSTX now underway and expected to be completed in 2014. It will provide higher toroidal field, additional solenoid flux and an additional neutral beam injector (NBI). The goal for CHI research on NSTX-U is to demonstrate the possibility for future elimination of the central solenoid. This will require that the current generated by CHI be ramped up and maintained entirely by bootstrap current, the neutral beams and RF current drive. Current ramp-up by NBI, in turn, requires that the initial current generated by CHI be sufficiently high that the energetic ions produced by NBI are well confined. Starting at a current of 400 kA, TSC simulations[19][20] predict that the second more tangential NBI system on NSTX-U would be capable of ramping-up the current to the 1 MA level planned for physics studies. As presented in Ref. (12) and summarized here, analysis of results from NSTX suggests that this level of start-up current may be achievable in NSTX-U using CHI.

A CHI discharge is generated by injecting poloidal flux into the vacuum vessel. This flux, referred as the injector flux, initially connects the inner and outer lower divertor plates. In the absence of flux amplification, the poloidal flux contained in a CHI-generated plasma must be less than or, at best equal to, the injector flux. Flux amplification, which refers to the condition when the poloidal flux contained in the resulting plasma discharge exceeds the injector flux, generally requires the presence of non-axisymmetric MHD modes and dynamo activity to generate additional poloidal flux. Extending the transient CHI process to driven CHI might enable flux amplification, but it is not essential on NSTX-U because transient CHI alone has the potential to generate all of the required poloidal flux.

In the discharge 142109 shown in Fig. 1, soon after coupling to induction, the normalized plasma internal inductance, computed by the EFIT code analysis of the external magnetic data, reaches about 0.35 and is maintained at this level through most of the inductive ramp, until the inductive loop voltage becomes too small to sustain the plasma current. The EFIT computed location of the plasma major radius for this discharge is 0.87 m, approximately at the geometric center of the vacuum vessel. For NSTX-U we assume that the same normalized internal inductance of 0.35 can be obtained with the plasma centered at a major radius of 0.93 m. At a closed flux current of 400 kA, the enclosed poloidal flux given by the relation $\psi_p = I_p R_p l_i \mu_0 / 2$ is 81 mWb. This is the injector flux capability on NSTX. However, the injector coils on NSTX-U are capable of providing 340 mWb. This is considerably more than the poloidal flux required to confine the energetic ions from NBI. For comparison, the poloidal flux contained in a 1 MA plasma would be about 206 mWb.

At its design toroidal field of 1 T (at R = 0.93 m), the toroidal flux in NSTX-U is 3.78 Wb. The resulting current multiplication factor, given by the ratio of the toroidal to injector flux is 47. Thus, in order to reach the toroidal current of 400 kA needed for energetic ion confinement, the required injector current would be only ~9 kA. By increasing the injector current and the magnitude of injected flux, the CHI generated toroidal current could be increased well beyond the needed 400 kA.

Although the injector flux capability in NSTX-U is much larger than in NSTX, the amount of useful injector flux, defined as the amount of flux that can be injected without producing unacceptable amounts of low-Z impurities, may be determined by electrode conditions. This is because a larger value of injector flux requires a higher level of injector current. The injector current requirements are given by the relation $I_{inj} = 2\psi_{inj}^2 / (\mu_0^2 d^2 I_{TF})$ [17] where ψ_{inj} is the injector flux, d the distance between the injector flux "footprints" on the electrodes and I_{TF} the total current in the toroidal field coil. Present NSTX experiments with a graphite inner divertor electrode have been able to achieve injector current as large as 10 kA with acceptable impurity levels, so this could be assumed to be a lower injector current bound on NSTX-U. Experience on HIT-II, that had a mostly metallic vessel except for the inner electrode which was graphite, showed that 30 kA of injector current could be driven without impurity issues[21]. If metallic divertor plates are installed on NSTX-U, injector currents greater than 10 kA should be possible, since electrode current densities would be lower on the larger NSTX-U than on HIT-II.

The peak electron temperature of NSTX CHI discharges is typically 25 eV, with peak temperatures up to 50 eV having been measured. The observed decay time of the current from its peak is on the order of 20 ms, similar to expectations for classical resistivity at those temperature calculated with TSC. In order to ramp up the plasma current with neutral beam injection after CHI in NSTX-U, both the CHI-produced toroidal current and the electron temperature in the CHI plasma need to be increased to confine the beam ions and to increase their slowing-down time on the electrons, respectively. Electron Cyclotron Resonance (ECH) heating at a power level of about 1.0 MW should be capable of boosting the initial electron temperature of the low-density CHI plasma to a few hundred eV. Experience on NSTX has shown that its HHFW heating can rapidly the boost the electron temperature of a 300 kA, 300 eV discharge to over 1 keV[22]. This would produce a target with low density and high electron temperature well suited for neutral-beam current drive. We are now undertaking detailed modeling of the neutral-beam current ramp-up phase for NSTX-U using the TSC.

It is also possible that a further reduction of low-Z impurities, such as for example through the use of full metallic divertor plates or full lithium coverage of the divertor plates or a higher temperature vessel bake-out, or a combination of these methods, may naturally increase the electron temperature of CHI discharges.

To assess the benefit of electron temperature on CHI discharges we have run simulations with the TSC code in which the electron temperature is increased from 25 eV to 50 eV and 100 eV, such as

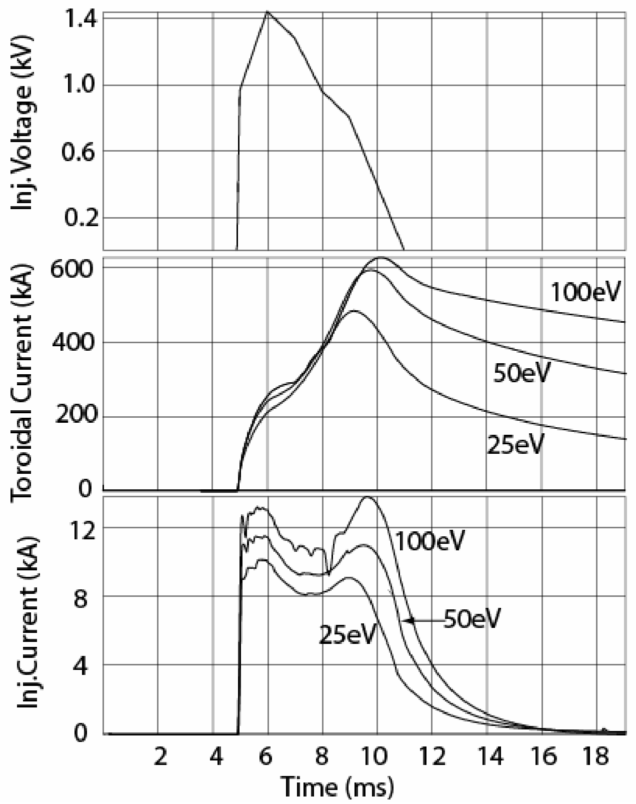

Fig. 3. Shown are the injector voltage, CHI produced toroidal current and injector current for CHI discharges with electron temperatures of 25, 50 and 100 eV

could be expected from an efficient electron heating system. The results in Fig. 3 show that for the same applied injector voltage, the initial CHI generated current increases with increasing electron temperature. For the present NSTX injector flux conditions, the peak toroidal current increases to over 600 kA at 100 eV and drops to below 500 kA at 25 eV. An examination of the injector current trace shows that the increase in toroidal current is due to an increase in the injector current, which must increase because the plasma resistivity is lower at the higher electron temperature. In addition, as could be expected the current decay time rapidly slows down at an electron temperature of 100 eV.

Figure 4 shows that at the lower electron temperature of 25 eV, the initial higher toroidal current could be reestablished if the injector voltage is further increased, in this case by 25%. The additional voltage compensates for the increased resistivity at the lower electron temperature and increases the injector current back to the levels required to generate the 600 kA target. However, as shown by the toroidal current trace, the current decay would remain rapid.

Note that at 9 ms, the peak toroidal current is over 600 kA, similar to the 100 eV case shown in Fig. 3. However, later on in time, the current decay rate is similar to the 25 eV trace shown in Fig. 3. This shows that simply operating the external CHI circuit at a higher voltage is not sufficient to obtain a discharge that persists for a longer time. It is also necessary to heat the discharge to increase its temperature during the current decay phase so that more time is available for the neutral beam ions to couple to the decaying discharge.

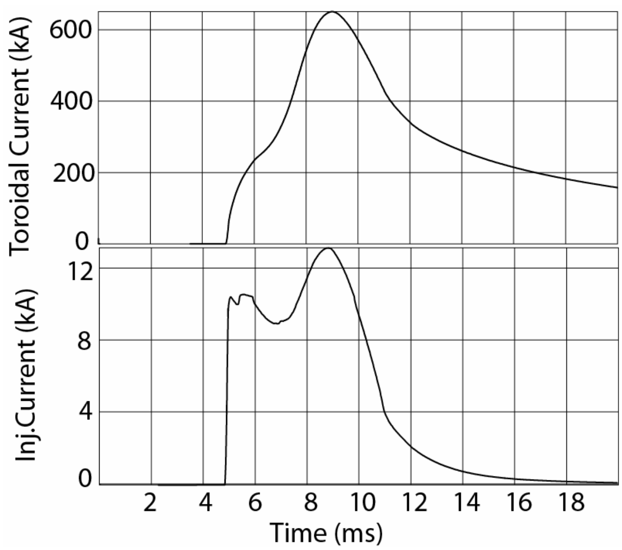

Fig. 4. Toroidal current and injector currents for the 25 eV case shown in Fig. 3, but with the applied voltage increased by 25%

These simulations indicate that the CHI system on NSTX-U would benefit from a higher voltage as this provides an important capability for optimizing the discharge evolution. These results also indicate that NSTX-U CHI discharges could significantly benefit from an efficient electron heating system and such a capability may be quite important for NSTX-U to demonstrate direct coupling to neutral beam current drive and thus to demonstrate the possibility for eventual elimination of the solenoid.

5. Summary

The application of CHI on NSTX and on HIT-II combined with recent simulations with the TSC code has revealed many important aspects of CHI physics and its application to future machines. The key results, not all of which are covered in this paper but described in the supporting references, are briefly summarized below.

- NSTX and HIT-II, two machines of quite different size (NSTX plasma volume is 30 times that of HIT-II), have both achieved significant levels of start-up current through CHI.
- On NSTX, the method is highly efficient, producing more than 10 Amps/Joule of initial stored capacitor bank energy.
- The scaling to larger machines with higher toroidal field is quite favorable: NSTX achieves 10 times the current multiplication factor of HIT-II.
- The CHI generated plasmas on NSTX have desirable properties including low inductance and electron density and high elongation needed for subsequent non-inductive sustainment utilizing the bootstrap current and NBI and RF waves.
- Simulations with the TSC code show agreement with the theoretical prediction for CHI as it is scaled to larger machines. These simulations indicate the importance of an auxiliary electron heating system to boost the temperature of CHI discharges.
- The TSC simulations show that CHI has the potential to generate nearly all of the steady-state current required in

NSTX-U.

These considerable improvements to CHI discharge performance were enabled by developing methods to reduce the low-Z impurities in the initial electrode-driven discharge. As a result, 300 kA of start-up current has been produced using just 29 kJ of stored capacitor bank energy. When induction is applied to these CHI started discharges, it is found that they require about 40% less inductive flux from the solenoid to reach 1 MA plasma current than inductive-only discharges.

These new results from NSTX demonstrate that CHI is a viable plasma startup method for future STs, and also possibly for higher aspect-ratio tokamaks.

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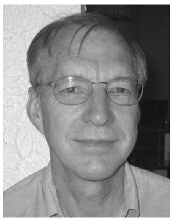

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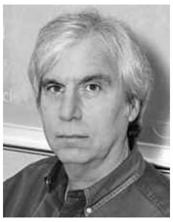

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Michael G. Bell (Non-member) [Photo not available] is a Principal Research Physicist at the Princeton Plasma Physics Laboratory. He received a Ph.D. from Cambridge University in 1974 and worked on the LT-3 and LT-4 tokamaks at the Australian National University before joining Princeton in 1980, where he has worked on the PDX, TFTR and most recently NSTX experiments. His research interests include tokamak plasma control, heating and performance optimization and non-inductive current drive.

Jonathan E. Menard (Non-member) Princeton Plasma Physics Laboratory (PPPL), is presently the Program Director for the National Spherical Torus eXperiment (NSTX) and is responsible for guiding the scientific research program of NSTX working with the NSTX national research team. Dr. Menard's research interests include the magnetohydrodynamic (MHD) equilibrium and stability properties of spherical torus (ST) and tokamak plasmas, advanced operating scenarios in the ST, and the development of next-step ST options for fusion energy. After receiving a bachelor's degree in nuclear engineering from the University of Wisconsin-Madison in 1992, Dr. Menard went on to receive a master's and a Ph.D. in plasma physics from Princeton University, Department of Astrophysical Sciences, in 1994 and 1998, respectively. He conducted post-doctoral research at PPPL before joining the research staff in 1999. Among his honors, Menard was awarded a U.S. Department of Energy Magnetic Fusion Science Fellowship in 1993, the Princeton University Honorific Fellowship in 1996, received the "Best Student Paper" award from the American Nuclear Society Fusion Energy Division in 1998, received the Presidential Early Career Award for Scientists and Engineers in 2004, a was a recipient of the Kaul Prize in 2006. The PPPL is funded by the DOE and managed by Princeton University.

Masayuki Ono (Non-member) received his B.Sc. in Physics from California Institute of Technology in 1973, and Ph.D. in Plasma Physics from Princeton University in 1978. Since 1978, at Princeton Plasma Physics Laboratory (PPPL) at Princeton University, he led a number of research project teams including ACT-1 (Advanced Concept Torus), CDX (Current Drive Experiment), and CDX-U (Current Drive Experiment – Upgrade). He is currently the Project Director and the Head of the National Spherical Torus Experiment (NSTX) Department at PPPL. Dr. Ono is the author of more than 250 refereed scientific papers.

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