Historical overview to the next step of FRC study at Osaka

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1. Introduction

It is clearly stated that the world-wide nuclear fusion research before 1990 had come into social standpoint from the military request, the national prestige and the oil crisis subsequently. In Japan, the first oil crisis of 1973 had pushed the boom of new energy developments including the fusion research. As a consequence, the large tokamak JT-60 project had started in JAERI, and the alternative approaches holding small tokamaks were advanced in universities.

The high temperature plasma study in our laboratory was mainly focused to the fast heating in linear magnetic configuration and some turbulent heating in a small tokamak in 1970's. The former issue had a scope of future high beta toroidal confinement. Also, both heating experiments were a natural planning from the historical and original resources of our research group. The present study of FRC began in 1980, based on the same consideration as the former experiment, too.

However, all of social situations had dramatical transitions around 1990. A large amount of finance from our government can not be expected which has supported the university fusion research activities. The national university systems will be also altered to be in something like the state university cooperation in US from 2004, and all of us will become non-government officials.

In my presentation here, the historical view is given mainly on the technological resources of our laboratory, since the finance could be used in Japan for hard components and the technology development. The near future policy is discussed on how our researches could grow out of the historical restrictions and could overcome the financial problem.

2. Research activities before establishment of PPL

The daybreak of fusion experiment in Japan was the linear z-pinch experiment at Osaka University just after the first conference on Peaceful Uses of Atomic Energy (Geneva, 1955). This work was the similar as Columbus II in US, targeting the high temperature and high beta plasma production by a fast rising intense current. The 100KJ capacitor bank of 100kV attained the total current of 1MA with $1\mu s$. The plasma temperature was the order of 100eV in

$\sim 1\times10^{22}m^{-3}$ of the density, although the temperature of 10keV was initially expected by a snow-plow model. This project became shutdown because of the macroscopic instability appearance.

The new project had been conducted from 1961, by new staffs, which had in herited the technological resource from the former work. In order to overcome or avoid the hard difficulty of the instability, the new group employed the spindle cusp geometry and developed a high power z-pinch plasma gun for the cusp injection of the plasma flow. The quick acting gas valve was also developed for the compatibility of the plasma production and its effective ejection.

The experimental result was that the stable confinement of high beta plasma lasted for $30\mu s$ in the parameter range of 1keV and $5\times10^{21}m^{-3}$. This was taken to be the oral session of IAEA (Culham, 1964). This is the first experience for Japanese fusion activity, and also makes the roots of PPL at Osaka.

Summarizing the above, the key issues were the follows for the inheritant of our laboratory.

(1) high beta plasma production

(2) high voltage, fast-rising current technology and some materials for this

(3) plasma gun technology with the fast-acting valve

(4) related diagnostics with high speed

3. First dozen-year activity of PPL established in 1967

Being the future toroidal confinement of high beta plasma in one's mind, we changed the system to the linear theta-pinch from the z-pinch. For this purpose, a new type of the current crowbering circuit was developed which used the air and the vacuum gap-switches. Also, the initial plasma for theta compression was made by the encounter of two plasma streams from both ends. This was done being based on the gun technology, which was modified to be the theta pinch type. Then the main physics was focused to the heating by collisiless shock type at that time. The result was succeeded in giving temperature of 4keV with the density of the order of $1\times10^{21}m^{-3}$ without macro-instability. The heating mechanism was also studied and the good efficiency of this heating was found to be due to the high ion temperature at the initial state which was performed by the plasma stream encounter.

Unfortunately, it was very difficult path to find a suitable toroidal system, although the high beta helical or bumpy type was discussed. Only a re-entrant type of two linear theta systems was dimly expected as a straightforward process. Although there was no experiment or no theoretical work on the re-entrant of the plasma, fairly big budget had come prior to the provision. Thus, a new machine PIACE was founded. The combination of theta and toroidal currents was also examined like as a high beta tokamak, which had been experimentally studied by another team of PPL. The international situation on high beta toroids was however in very difficult phase due to the instability problem except the RFP experiment of ETA-BETAⅡin 1979.

Here the resources were the following.

(1) fast bank of 246KJ and 50kV with the start and the crowber systems for each capacitor of 82 pieces. This has 10channels and independently operating discharge control system.
(2) slow banks of $2\times200KJ\,10KV$ and $2\times50KJ\,10KV$ with the diversion in each.
(3) experience on a small tokamak and a small toroidal z-pinch experiment.
(4) diagnostics technology on Thomson scattering, spectroscopy, neutron and soft X-ray detection, electrostatic and magnetic probes and so on, including the electrical noise prevention technique.
(5) experimental area with commercial electricity supply and air-conditioner

4. FRC study I (1980～1988)

By the simple modification in operation of original PIACE, PIACE-I began to work as the FRC machine. The first result showed the realization of 1KeV of FRC plasma. This change was easy because of the perfect existence of resources for FRC experiment, and also was good timing since the US-Japan collaboration had just started at the time as one of alternative programs, that is, the compact toroid concept. Subsequently, PIACE-Ⅱ was constructed by replacing PIACE-I coil to slightly large bore theta coils of FRC confinement. One topics here was the experiment on suppression of n=2 rotational instability by a quadra-pole magnetic field. The lifetime of FRC in PIACE-Ⅱ extended to 50～80μs, and then the physics study on the transport had been taken by the density profile measurement and the trial of fluctuation detection.

In parallel program, OCT was built to research the translation action of the formed FRC, by using the 30% of the original PICAE bank. The translation experiment in OCT realized that the FRC formed in a quartz tube by the fast pinch was able to be translocated inside a metal chamber with a quasi-stationary mirror field. The translation dynamics stayed unclear, but a simple relationship between the initial and the translated FRC plasmas was suggested which did not indicate some simple adiabatic relation. A peculiar neutral beam spectroscopic diagnostics was also applicable since the density range became down to the order of $1\times10^{20}m^{-3}$ by volume expansion of FRC. Note that the $n=2$ instability scarcely appeared for the translated FRC, though the rotation still existed according to the beam probe measurement. The original expectation for the translation was to prolong the confinement time due to the Xs scaling, but the remarkable dependence was not found.

The annual budget to hold these experiments was fairly enough due to the maintenance and improvement fee of the original PIACE, which had been supported for 10 years at least by the government, but remarkable investments to the technological resource were none. New tools were the following diagnostics.

(1) interferometers with He-Ne near-infrared laser and CO_2 laser

(2) multichannel digitizers with PCs

5. FRC study Ⅱ (1988～1995)

In the early of this second phase, it had been definitely understood that the organization with the big budget of fusion research in Japan was settled to be the two, <u>NIFS and JAERI.</u> Then, <u>university finances</u> including the research center projects remained the similar level at 1990, or slightly decreased year by year.

Taking into consideration this situation, it was normally judged that our PPL had pursued some different policy with the prior course before it was too late, if we wanted to continue FRC experiment, or unless it was not so. If it was so, the key point was to find a <u>root to overcome the expensive fast bank problem.</u> In addition, it was desirable that the newly selected course could <u>bring spin-off effects</u> as the plasma based technology or science. The following was chosen for this

(1) Development of conventional **NB technology**

It was reasonable approach for FRC experiment to aim at NB injection and/or wave heating in near term plan. There were, however, two problems. <u>One was accessibility to the FRC machine as the technology issue, and the other was the cost problem.</u> <u>The decision was that we tried to make our own technology on NB injector.</u> It was considered that the development of NBI by ourselves could response the accessibility and the cost problems, and also this would produce its application. As a matler of fact, it was found that the construction cost of NBI was highly dependent to the beam duration, and then we chose 10ms duration typically. The accessibility problem could be divided in two categories: the port size or the bore size of FRC to inject NB particles and the high voltage circumstance of theta pinch. In the NBI side as for the first one, geometrical focusing of NB was able to overcome the problem partly. The bore size and the high voltage problems could be relaxed by the translation of FRC as the following.

(2) Construction of FIX

In order to find a solution against the problems above, we expected a large diameter FRC holded inside a fairly big metal chamber to be able to sit in the existence area. Although there were disagreeable estimations with the OCT translation relation, in result, a new parameter-range of FRC has been obtained in FIX machine: 0.4m bore diameter and 3m length of FRC in the mirror field. The density range is $(3\sim 5)\times 10^{19}\,m^{-3}$ to be sufficient for deep penetration of neutral beam. N=2 rotational instability has not appeared again.

6.FRC study Ⅲ (1996～)

Some amount of finance was got from the government for construction of NB injectors and modification of FIX machine. The high beta nature of FRC less than s=1, however, exhibits particle trajectory problem: large Larmore radius of beam ions to hit the wall. This problem has been tentatively avoided by taking the inclined injection angle, and almost of ions can be confined by end mirrors with its ratio more than 8. Resultantly, the first experiment of NB injection into FRC has been successfully attained to extend the FRC lifetime.

The modification of the metal chamber of FIX machine enables to put some solid parts in it. Two sorts of electro-mechanical parts have been mounted for new trial experiments. One is a pair of loop antenna (m=0) or m=1 antenna for wave excitation and heating. The other is a fairly big set of internal coils for axial compression of FRC. Two experiments have attained the initially proposed targets. An additive end mirror coil will be also mounted for control of endloss flows. As for the diagnostics tools, too, various types of devices or parts can be easily inserted, for example, endloss analyzer, absorption boad for background light, diamagnetic pick-up arrays and so on.

Conclusively, let us state that the present FIX machine is appropriate for the idea-test or the preliminary experiment on FRC study. The annual budget will be kept for a while to continue the present level of experiment though it is not enough to construct a new machine. These are the inheritant for the next step.

7. To near future experiment

It is well known that human and the apes evolved from a common ancestor but man attains the highly evolutional state by two-legs walk and the associated intelligent brain. Metaphorically speaking, tokamaks and FRCs have evolved from the common concept: magnetic pinch or plasma current system by inductive coupling. As a figure of speech, modern tokamaks have developed technological evolution like as non-inductive CD and intense power injection corresponding to the two-legs walk, and acquire the intelligence like as H-mode and ITB. On the analogy of tokamak evolution, the FRC experiment should, firstly, grow out of the fast bank technology and introduce new technology.

The above issue on the technology may stress the equipment of the metal vessel for FRC containment. This is partly realized by the translation technique in FIX, but far from a perfect state. Two problems must be resolved at least. One is to produce the original FRC just as STX experiment without the fast bank even in case of quartz tube situation, and to be able to translocate it inside the metal chamber. The other problem is the lackness of the design flexibility on the translation process, or to have no physics foundation for getting an optimum state on the shape, the volume and so on, though the axial compression is giving some flexibility for the purpose.

The radical technology to be developed must be how to create and evolve the FRC inside the metal wall. The STX experiment gives us a good suggestion. It is expected that the quartz tube can be replaced by metal composition and the RMF antenna may be mounted on the inner place locally between the end mirrors of external field.

Taking into considerations the lengthy statement above, an experiment of RMF application in metal vessel has been planned in FIX, scoping the following two trials.

(1) It is to make a powerful tank-circuit using the commercial semiconductors and to apply it to FIX experiment. The RMF will be fed onto the translated FRC by the antenna loops of about one-third length of X-point distance inside the metal wall. The technical difficulties arise on insulating, current feed and coupling though the metal. Associated physics will be also

examined on the spatial relaxation along z-direction of the RMF induced current. This is just the equilibrium physics of FRC.

(2) It is <u>to try to form the FRC initially in the metal chamber,</u> using the same part antenna. How to introduce the working gas and to make pre-ionization is the first experimental gate to perform the experiment. The present formation system could assist this trial. No theoretical preparation on this exists in our laboratory, but the experiment itself may make a new way opened. If the technology is succeeded, we may, for example, form the original FRC with the comparatively short RMF antenna and can move out the FRC for the translation by the <u>fast acting driving coils apart from the antenna end.</u> This example may not be done in metal necessarily. The technology like here might give a merit for the future burning section to have no RMF antenna, through the repeating translation action, namely, FRC merging for sustainement of flux and fuel. Also, NB and wave accessibilities will become available.

One the contrary, there is only a poor scenario to be imagined for the <u>confinement intelligence.</u> The next step experiment sketched above indicates that we have to reset the start line for revival. But there really seems to have been even more some confinement improvements so that the group of U. Washington has proposed on the large s-value if the instability can be overcome. The NB injection can assist the suppression of the instability and moreover becomes very powerful tool for the heating due to the small orbital motion of the fast ions when the beam scattering loss by RMF could be reduced.

As the different way of confinement improvement, the following approaches are examined.

(1) The <u>strengthen of the end mirror field by additional coil</u> and the making of the <u>electrostatic potential barrier</u> around X-point by NB can moderate the endless flow.

(2) <u>Some amount of toroidal field</u> in the FRC core may construct the magnetic surface for transport improvement, if it could by capable.

Note here that the presented contents can be examined by the cheap experimental cost in accordance with the utilization of the existing resources.

8. Summary

Focusing our attention to the technological development and resources, the historical step of our laboratory is presented nearly over a half century. During these period the high beta study makes some significant growth but still stays far from the reactor level. The future study of the high beta system like as the FRC must be maintained by solving the cost problem of experiments because the strong government support to the university activities could not be expected for more than 10years in Japan at least. The cheap cost of experiments just before the reactor grade facility would guide the capital cost of the reactor to be less than the tokamak-based one. Furthermore, various kinds of homemade technologies for cost saving could help us to make spin-off efforts in the interdisciplinary area.