THEORETICAL and EXPERIMENTAL ASPECTS of HEATING of TOROIDAL PLASMAS

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VOL - 2

INVITED PAPERS
POST DEADLINE PAPERS

P R E F A C E

This second volume of the proceedings contains the texts of the 14 invited lectures and a few post deadline papers.

The invited papers, which were proposed by the Steering Committee, are concerned with theoretical, experimental and technological aspects of additional plasma heating in present and future generation of toroidal devices.

The present situation of additional heating emerging from the Conference can be summarized as follows :

1) - It has been possible to double or more the ion temperature by neutral beam injection without destroying the confinement and the stability of the plasma. The ion temperature T_i increases linearly with the injected neutral beam power (presently $P_N \gtrsim 650$ kW). R.F. emission around ω_{ci} has been observed. Its effect on the plasma stability with higher neutral beam power is not yet known. The extension of hydrogen or deuterium neutral beam technology to power $\gtrsim 1$ MW during 1 - 10 s for energies $\lesssim 200$ keV is feasible with the existing technique; above 200 keV a possible solution is provided by negative ions. A vertically asymmetric toroidal field ripple might permit ∇B drift injection and subsequent capture of energetic ions.

2) - Ion cyclotron R.F. heating experiments have given encouraging results in U.S.A and U.S.S.R. Nevertheless, the injected R.F. power in medium size devices was limited by the occurence of disruptive instabilities. High energy ion tail has also been observed. It is hoped that in larger devices with higher magnetic field these problems will be overcome.

3) - The possibility of using waveguide launching with very good coupling efficiency makes lower hybrid frequency a very attractive alternative. Its credibility will depend on the understanding of the parasitic absorption observed in the external plasma layers.

4) - Although the excellent results obtained in U.S.S.R. on electron cyclotron heating on present TOKAMAKS (in the limits of the injected R.F. power ~ 70 kW, 1 ms) are promising, their application to larger devices depends on the development of millimetric high power CW sources.

It is hoped that this situation will be improved and clarified at the next meeting in 1978.

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INVITED PAPERS

POSTDEADLINE CONTRIBUTED PAPERS

PLASMA HEATING BY CLUSTER INJECTION : BASIC FEATURES AND EXPECTED BEHAVIOUR

by

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I. INTRODUCTION :

In 1955 Becker and al at Karlsruhe { 1 } observed clustering phenomena in a supersonic hydrogen stream produced in a geometry previously described by Gray and Kantrowitz { 2 } .

In 1964 Henkes { 3 } proposed the injection of accelerated hydrogen clusters to build up a hot plasma in an open trap, pointing out that the growth of microinstabilities, resulting from a double humped velocity distribution, might have been counteracted. Actually clusters have a broad mass distribution due to their statistical growth process ; after being singly ionized and accelerated the mass distribution is transferred into a velocity distribution.

Furthermore, energetic cluster beams are expected both to carry high equivalent currents (1 Ampere equivalent $\simeq 6\ 10^{18}$ atoms/s) with fairly small divergence and not to need electrical neutralization before injection, since the low charge to mass ratio lessens the space charge spread and increases the Larmor radius. By taking advantage of these peculiarities both plasma production in open traps { 4 }{ 5 }{ 6 }{ 7 } and plasma heating or build up in toroidal geometry { 8 }{ 9 }{ 10 }{ 11} have been investigated or proposed. As far as we know, reactor refuelling by clusters has not called much attention so far, although some crude estimations let us think it could be within cluster's reach { 11 }{ 12 } . Experimental and theoretical research on cluster beams, aimed to plasma applications, has been developed in Karlsruhe, Culham { 13 }{ 14 }, Oak Ridge { 15 } and Fontenay-aux-Roses (FAR), but since it has been stopped in Culham and Oak Ridge, only Karlsruhe and FAR have high energy injectors operating and injector lines in progress { 9 }{ 10}
It must be mentioned a 400 KV cluster accelerator at the Institute of Physical and Chemical Research in Tokyo, thermonuclear fusion laboratory { 16 } .

Research on cluster beams deals with cluster formation and cluster beam properties { 13 }{ 15 }{ 17 to 23 } with cluster-electron interaction { 14 } {24 to 27},with interaction between clusters and ions or neutrals { 12 } and with cluster beam acceleration { 5 to 11 } . Although many experimental data, mainly on cluster collisions with heavy particles, are still lacking, so far the basic behaviour of clusters can be predicted with a fairly good accuracy. We only mention the theoretical and experimental work on the internal structure of clusters { 28 } , since not directly connected with plasma applications.
The technological effort deals mainly with cryogenics for both the beam source and the pumping system { 29 } , with electron beam systems for the cluster ionizing stage, and with the high voltage techniques for the accelerating section.
In this paper we shall discuss briefly each main component of an injection line, that is the beam source, the cluster ionizer and the accelerating tube, as well as the behaviour of clusters interacting with a plasma. Outlines of the experiment of cluster injection into TFR, in progress at Fontenay-aux-Roses, and expected results will be presented and discussed all along the paper.
Units are everywhere in MKSA system, excepted when other units are indicated.

II. CLUSTER SOURCE AND BEAM CHARACTERISTICS

A partial clustering of a molecular stream may occur during an adiabatic expansion through a cool nozzle. The oversaturated state, that may occur in gases when passing through the limit of the saturated vapor, seems to be necessary to start the clustering process. As the condensed fraction Y generally represents a few per cent of the total mass carried by the gaseous stream, a suitable pumping system must be provided to remove the uncondensed gas, scattered out of the beam core because of the great cluster to molecule mass ratio. FIG. 1 sketches out the cluster beam producing apparatus. The first diaphragm, or skimmer, is needed to produce an efficient differential pumping and to prevent a transition into a subsonic regime with strong shock waves, which can destroy clusters.
The gas stream carries :

$$\Gamma_i = 4\ 10^{29}\ P_i\ d_c^2/T_i^{1/2} \quad \text{molecules/s} \qquad (1)$$

or

$$\Gamma_i = 5\ 10^{10}\ P_i\ d_c^2/T_i^{1/2} \quad \text{litre TPN/hour}$$

For H_2 this gives :

$$\Gamma_i \simeq 1.2\ 10^3 \quad P_i\ d_c^2/T_i^{1/2} \qquad \mathrm{Kg/s} \tag{2}$$

where P_i is the gas pressure at the nozzle inlet in Bar, T_i is the gas temperature at the nozzle inlet in°K and d_c is the critical nozzle diameter in m.

The main part of Γ_i must be pumped out between nozzle and skimmer at a pressure P_1 smaller than the supersonic gas beam pressure P_o at the nozzle output, therefore the pumping speed S_1 must be such that :

$$S_1 \geq 1.7\ 10^{+4} \frac{P_i}{P_o}\ d_c^2/T_i^{1/2} \qquad \frac{m^3}{s} \tag{3}$$

Upper limit $P_1 = P_o$ is found in FIG. 2, showing the gas stream pressure P versus the cross section area A of the nozzle. Generally P_1 must be less 10^{-3} bar. Referring to notations of FIG. 1, the ratio β of the cluster mass flow to the gas flow in the cluster beam section, can be expressed at the output of the second diaphragm as :

$$\beta \simeq \frac{0.05\,\gamma}{tg^2 \vartheta}\ \frac{S_1 d_2}{d_1^2\, l_2} \tag{4}$$

When the collision mean free path of gas molecules between nozzle and skimmer, is much less than l_1.

If not, that is when collisions are so rare that molecules are no more scattered out of the beam, β tends towards the limiting value $\gamma/\ \gamma - 1$. FIG. 3 shows that it exists an optimum pumping speed to get the best value of β.

The increase of mass flow beyond the second diaphragm when clusters are produced is experimentally verified { 13 to 23 } and it represents one of the best proof of the cluster presence. FIG. 4 shows profiles of both condensed and uncondensed beam, for the same mass flow of gas Γ_i. The condensed fraction becomes better when increasing the inlet pressure P_i { 13 }{ 17 } and can reach 30 % for supercritical pressures P_i { 21 }

FIG. 5 shows the cluster beam intensity versus P_i measured at FAR, as well as the results from { 13 }

The mean number of mass of clusters, $\overline{N}$ (a.m.u.) increases with P_i, d_c and T_i { 13 }{ 18 }{ 19 }{ 30 } . Roughly $\overline{N}$ growths as $(P_i d_c)^3$. So far values of $\overline{N}$ ranging from a few molecules and 10^9 molecules have been produced. FIG. 6 shows the dependence on P_i of $\overline{N}$ (a.m.u.) measured at FAR { 31 }. Neutral cluster mass distribution has been inferred by mass spectra measurements on charged clusters, accelerated { 6 }{ 19 }{ 25 }{ 32 } or not { 37 } , and its results with a good accuracy,

$$f(N) \simeq N^{5/6} \exp(-2 \frac{N}{\bar{N}}) \qquad (5)$$

Typical figures of the cluster source at Fontenay-aux-Roses are listed below:

$P_i = 6 \div 10$ bar

$T_N = 18 \div 22$ °K nozzle temperature

$d_c = 1.5\ 10^{-4}$ m

$\frac{A_o}{A_c} = 45$

$\vartheta_N = 5°$

$\Gamma_i = 1 \div 2\ 10^{22}$ molecules/s $\simeq 3 \div 6\ 10^{-5}$ Kg/s

$\Delta t \simeq 5\ 10^{-2} \div 10^{-1}$ s gas pulse duration.

The total amount of gas per pulse is then about 10^{+21} molecules that is $3 \div 6\ 10^{-6}$ Kg. The cluster beam, with a total divergence of about 2° has an intensity of $80 \div 120$ A (equivalent) measured 100 cm away from the nozzle. It follows that the condensed fraction is about 3 %. The whole pumping system is cryogenic { 29 } with a speed for H2 of 10 m^3/s, half of that between nozzle and skimmer ; it keeps the pressure P_1 { condition (3) } in the range $10^{-3} \div 10^{-4}$ bar, therefore less than P_o which is ten times greater.

III. CLUSTER INTERACTION WITH ELECTRONS, IONS AND NEUTRALS

After leaving the beam producing section, clusters must be ionized. Before discussing the ionizing stage, it is useful to present a survey of the cluster cross sections that will be used later on.

All cluster cross sections σ_N can be represented by the expression :

$$\sigma_N = S_c \left[1 - \exp(- n_c \overline{D_c} \sigma F)\right] \qquad (6)$$

where σ is the cross section of the considered reaction between the primary particles and cluster molecules. F is the escape probability of secondary electrons, { 12 }{ 26 } , that must be accounted for when dealing with ionizing collisions. Otherwise F is taken equal to unity. S_c, $\overline{D_c}$, n_c are respectively the cross section, the mean diameter and the molecular density of a spherical cluster. In Table II are given the main Figures for H2 clusters.

TABLE 2

PROPERTIES OF H2 CRYSTALS

A	= 2
Z	= 1 per H
n_c	= 2.2 10^{28} molecules/m^3 or 73,6 Kg/m^3
d_o	= 3.57 10^{-10} m (intermolecular distance)
S_c	= 1.5 10^{-19} $N_M^{2/3}$ m^2 (N_M = molecular mass number)
$\bar{D}_c$	= 2.9 10^{-10} $N_M^{1/3}$ m
W_D	= 10^{-2} eV (intermolecular binding energy)
ε_2	= 1.21 (relative dielectric constant)
P	$\simeq$ 9 10^{-30} m^3 (polarizability)

Expression (6) means that a cluster interacts with a primary particle if two independent events occur ; the first one is the collision of the primary particle with the cluster (proportional to S_c), the second one is the effective interaction between the primary particle and cluster molecules.

a) Ionization : σ_{1jN}

For all collisional ionizing reactions (with primary particles of species j)

$$\frac{\sigma_N}{\sigma_{jH2}} \simeq N_M \qquad \text{for} \qquad N_M \leq 100 \qquad (7)$$

where σ_{jH2} is the ionization cross section of H2 by impact with a primary particle j. This because for $N_M \leq 100$ the exponential term of (6) can be developed at the first order. By reminding that : $n_c \bar{D} S_c = N_M$ the expression (7) becomes evident.

For $N_M \geq 500$ the escape probability is $F \simeq \frac{5.45}{N_M^{1/3}}$ so that the exponential term is independent on cluster mass. When first order expansion in (6) is possible that is whenever $\sigma_{jH2} \leq 2 \, 10^{-20}$ cm^2, the limit value of σ_{1N} is given by :

$$\frac{\sigma_{1eN}}{\sigma_{jH2}} \simeq 5 \, N_M^{2/3} \qquad \text{for} \qquad N_M > 500 \qquad (8)$$

In between these two regions σ_{1N} changes in order to join the two limit values.
For ionization by electron impact the values of the cluster ionization cross section are :

$$\frac{\sigma_{1eN}}{\sigma_{eH2}} \simeq N_M \qquad N_M \leq 100$$
$$\frac{\sigma_{1eN}}{\sigma_{eH2}} \simeq 4.4\, N_M^{2/3} \qquad N_M \geq 100 \tag{9}$$

or by expressing the cluster mass in atomic instead of molecular number :

$$\frac{\sigma_{1eN}}{\sigma_{eH}} \simeq N \qquad N \leq 200$$
$$\frac{\sigma_{1eN}}{\sigma_{eH}} \simeq 5.6\, N^{2/3} \qquad N \geq 200 \tag{10}$$

With σ_{eH} the ionization cross section of atomic H by electrons.
Cluster ionization leads to cluster break-up by multiple ionization, that will be discussed later, according to the following reactions :

$$C^+ + A \longrightarrow C^{++} + A + e, \qquad C^{++} \longrightarrow C_1^+ + C_2^+ \tag{11}$$

Several experimental and theoretical data are available { 14 }{ 25 }{ 26 } { 27 }.

b) Charge exchange reactions : σ_{2N} and σ_{3N}

$$C^+ + A \longrightarrow C + A^+ \qquad \sigma_{2N}$$

The direct charge exchange between primary neutral A and the charged H_2^+ cluster molecule occurs with the molecular charge exchange cross section. With respect to all previous reactions related to the cluster size (Volume or geometrical cross section) this reaction is very unlike. However, cluster neutralization could be achieved if the secondary electron issued from the primary atom ionized by collision with a cluster molecule, is trapped inside the cluster.

$$C^+ + A \longrightarrow C^+ + A^+ + e \longrightarrow (C^+ + e) + A^+ \longrightarrow C + A^+ \tag{12}$$

The corresponding cross section can be written as follows :

$$\sigma_{2N} \simeq S_c \left\{ 1 - \exp\left[- n_o \bar{D} \sigma_{o1} (1 - F) \right] \right\} \frac{\sigma_{o1}}{\sigma_{1o}} \qquad (13)$$

where σ_{1o} and σ_{o1} are respectively the ionization cross section of the primary atom and the neutralization cross section of the primary ion interacting with cluster molecules.

For H2 clusters passing through hydrogen the following reactions must be taken into account :

$$H2 + H2 \longrightarrow H_2^+ + H2 + e \qquad \sigma_{o1}$$

$$H_2^+ + H2 \longrightarrow H_2 + H2 \qquad \sigma_{1o}$$

Obviously $\sigma_{2N} \simeq 0$ for $N_M \leq 50$ since $F \simeq 1$.

As $\lim_{N_M \to \infty} F = 0$, σ_{2N} tends towards $S_c \frac{\sigma_{o1}}{\sigma_{1o}}$, which for energies of

1 - 10 KeV/atom represents about 10÷15 % of S_c.

This is not in disagreement with incomplete experimental evaluations giving :

$$\frac{\sigma_{2N}}{S_c} \simeq 10^{-1} \quad \text{for} \quad N_M \simeq 500$$

This charge exchange reaction does not lead to cluster fragmentation, contrary to the following one :

$$C^+ + A^+ \longrightarrow C^{++} + A, \quad C^{++} \longrightarrow C_1^+ + C_2^+ \qquad \sigma_{3N} \qquad (15)$$

$$\sigma_{3N} \simeq \sigma_{exc} N_M \qquad N_M \leq 10$$

$$\sigma_{3N} \simeq S_c \qquad N_M > 10 \qquad (16)$$

where σ_{exc} is the cross section of the following reaction :

$$H2 + H^+_{primary} \longrightarrow H2^+ + H_{primary} \qquad (17)$$

c) Break-up by momentum transfer : σ_{4N}

$$C^+ + A \longrightarrow C_1^+ + C_2 + A \qquad (18)$$

This reaction yields a neutral fragment.

σ_{4N} has been deduced from experiments on cluster interaction with hydrogen targets { 33 } in the cluster mass range $10 \leq N_M \leq 500$ and energy 0.6 to 6 KeV/molecule. It results that the experimental value of about 0.2 S_c is consistent with the expression :

$$\sigma_{4N} \simeq S_c \left[1 - \exp(-5.3\ 10^{-2}\ N_M^{1/3}) \right] \qquad (19)$$

We assume that atoms or ions have the same break up cross section that molecules impinging on clusters.

d) Evaporation by electrons and heavy particles impact σ_{5N}

So far no experimental data are available. Only computed values of evaporation cross section σ_{5N} { 12 } confirm qualitevely the experimental evidence that clusters are practically not evaporated in passing through gas targets with $nL \leq 3\ 10^{18}\ m^{-3}$ (1 meter at pressure of about 10^{-4} Torr). The quoted estimations give :

$$\sigma_{5N} \simeq 3.7\ 10^{-20}\ N_M^{2/3} \quad m^2 \qquad (20)$$

To conclude, the mean free path for cluster fragmentation in a plasma is given by :

$$\lambda_b \simeq \frac{v_c}{\left[n \quad \sigma_{1en} v_e + (\sigma_{1iN} + \sigma_{3N} + \sigma_{4N})\ v_c\right]} \qquad (21)$$

where $v_e = \left(\frac{3kTe}{Me}\right)^{1/2}$ is the plasma electron velocity, which is always much greater than the cluster velocity $v_c = \left(\frac{2\ e\ Vacc}{N_M\ M_{H2}}\right)^{1/2}$ and Vacc is the total accelerating voltage experienced by clusters.

FIG. 7 shows λ computed by the previous formula in a plasma similar to that of TFR and in FIG. 8 it becomes evident that for energies $E_o \leq 6$ KeV/atom cluster break-up is controlled by electrons. Results of FIG.8 are given for a cluster mass number N = 100 atoms.

IV. CLUSTER IONIZER

For plasma heating by injection of cluster beams, the ratio $\frac{Z}{\overline{N}}$ of cluster electrical charge to its mass number (a.m.u.) should be $10^{-2} \div 5\ 10^{-3}$. The large cluster mass at the output of the neutral beam source (FIG. 6) must be reduced before entering into the acceleratin section. The ionization and mass control of the mean mass number $\overline{N}$ is accomplished in the ionizer. Actually, when the coulomb electric force overcomes the intermolecular binding force

$$\left(\frac{qZ}{4\pi\varepsilon_o R_c^{\ 2}}\right) > E_{critical}$$

of a multicharged cluster, cluster breaks up in two fragments.

The value of E_C is about 10^8 V/m for H2. Consistent with experimental observations { 25 }{ 31 } only cluster with mass number exceeding a few thousands can take more than one electrical charge. The decreasing of $\frac{\overline{N}}{Z}$ with the raise of electron target density has been experimentally established { 14 }{ 25 } { 34 } { 35 } .

An ionizer is defined by the value $\frac{N}{Z}$ available at the output and by the current of charged clusters I^+_{ext} that can be extracted, which is, of course, bounded to the maximum current I_N^+ produced by the ionization of the neutral cluster beam.

a) The mean charge $\bar{Z}$ of the cluster is given by :

$$\bar{Z} \simeq \sigma_{1eN}\, n_e\, v_e\, \tau_g = \frac{\sigma_{1en}\, I_e}{q v_g} \frac{L}{S} \simeq \left(\frac{10^{-3}}{T^{1/2}} F \frac{I_e}{V_e^{1/2}} \frac{L}{S}\right) N \qquad (22)$$

where $\tau_g = \frac{v_g}{L}$ is the cluster transit time inside the ionizer, I_e the electron current, V_e the electron energy in eV, T the nozzle temperature in °K, S and L respectively the cross section and the length of ionizer, N the cluster atomic mass number (a.m.u.) and F the escape probability of a secondary electron. σ_{1eN} is given by eq(10) and it is related to the cluster ionization cross section σ_i used in { 27 } by :

$$\frac{\sigma_{1eN}}{\sigma_i} = \frac{1 - e^{-\bar{Z}}}{\bar{Z}} .$$

For small clusters $\bar{Z} \ll 1$ and therefore $\sigma_{1eN} = \sigma_i$.

For big clusters ($N_M > 10^3$) $\bar{Z}$ is practically independent on N_M (as shown in Section III) and its value is about $\frac{0.35}{V_e^{1/2}}$.

For electron energies usually used in the ionizer ($10^2 < V_e < 10^3$ V) $\bar{Z} \simeq 0.35 \div 0.1$ and therefore $\sigma_N/\sigma_i \geq 0.8$. The fact that $\bar{Z} < 1$ means that multiionized clusters can be produced only by successive collisions with clusters.

b) The current produced by ionization of the neutral cluster beam is

$$I_N^+ = \frac{\bar{Z}}{N} \Gamma_i\, Y = \frac{\bar{Z}}{N} \Gamma_0 \qquad (23)$$

where $\frac{\bar{Z}}{N}$ is deduced by eq(22) and Γ_0 is the current (Ampere equivalent) carried by the neutral cluster beam.

c) the maximum extracted current is

$$I^+_{ext} \simeq 10^{-6} \left(\frac{\Phi}{d}\right)^2 \frac{V^{3/2}}{\left(\frac{N}{Z}\right)^{1/2}} \qquad (24)$$