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The Trapping of Ions at SPEAR: A Computational and Experimental Study*

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Abstract

A computer simulation of the motion of ions in the electron beam at SPEAR has been conducted to examine the role ion trapping might play in the performance of the beam. These predictions have been tested experimentally at SPEAR.

I. Introduction

In the presence of a beam of charged particles, the residual gas molecules in the vacuum chamber will be subject to ionization. The positive ions receive a kick with the passage of each electron bunch and, under certain circumstances, can become trapped in the beam, leading to tune shifts and diminished lifetimes. In this paper, we will briefly review the theory of this phenomenon and then describe the results of computational and experimental studies of the trapping of ions in the SPEAR ring.

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II. Linear Theory

In the linear theory (see Y. Baconnier, G. Brianti, CERN) [1], the bunches are treated as having uniform density in the transverse dimensions and giving delta-function kicks to the ion which are proportional to the ion's distance from the center of the bunch. The magnitude of the kick $a_{x,y}$ in the x and y directions is given by:

$$a_x = \frac{2\ Q\ N\ r_p\ c\ x}{A\ n\ \sigma_x(\sigma_x + \sigma_y)} \qquad a_y = \frac{2\ Q\ N\ r_p\ c\ y}{A\ n\ \sigma_y(\sigma_y + \sigma_x)},$$

where Q is the net charge of the ion, N is the number of electrons in the beam, c is the speed of light, n is the number of bunches, $\sigma_{x,y}$ are the transverse dimensions of the beam, r_p is the classical radius of the proton, x and y are the ion's coordinates in the transverse plane, and A is the mass of the ion in AMU.

One may then write two 2x2 transfer matrices $M_{x,y}$ which take x and dx/dt (or y and dy/dt for the M_y case) before the bunch passes at t = 0 and map them into x and dx/dt (or y and dy/dt) at the time just before the next bunch arrives. The matrices are the products of the matrix describing the impulsive kick given to the ion by the passing bunch and a drift matrix, which simply translates the ion's phase space coordinates in the time between the passes of the electron bunches. For the trace of this matrix to be less than two (i.e., for a stable ion), the mass of the ion must be greater than a critical value, A_c, where

$$A_c = \frac{Q\ N\ C\ r_p}{2\ n^2\ \sigma_x\ (\sigma_x + \sigma_y)}$$

Here C is the circumference of the ring, σ_x and σ_y are the transverse dimensions of the beam, and A_c is in AMU. From this simple treatment, we see an important aspect of ion trapping behavior emerge, namely the tendency for ions not to be trapped as bunch current density increases. It is worthwhile to note that bunch current density can be increased by decreasing the number of bunches while keeping the same total current in the ring. For the SPEAR ring running with four bunches symmetrically arranged around the ring (timing mode) at 20 mA total current, A_c = 12.5; thus, the linear model predicts that in this configuration all ion species more massive than carbon will be trapped.

It is also useful to think of the electron bunches as focusing elements and the lost ions as being overfocused. The criteria for an ion to be overfocused is that the gap between lenses be greater than four times the focal length. This is equivalent to requiring the trace of the transfer matrix M be less than 2. For equally spaced bunches, treating the electron bunches as lenses leads to the same A_c as above; however, if one breaks the symmetry, the transfer matrix M becomes much more complicated, and the stability criteria $A > A_c$ will no longer hold. In the case of a gap, certain ions predicted to be stable for a completely filled ring will become unstable [2].

The linear model can also take into account the effect of the space charge of accumulated ions on the stability of other ions and, in doing so, derive a limit on density accumulation [1]. For the case of an electron storage ring like SPEAR, the limit due to these considerations is simply the total neutralization of the beam. We will see, however, that there are other limiting factors more important than this.

III. Non-Linear Theory

In the non-linear model, the transverse density of the bunches is modeled by a bi-Gaussian distribution, and the size of the kick becomes a complicated function of the position of the ion [1]. In this case, it is no longer possible to have rigid analytical criteria for whether or not an ion will be trapped. Instead, we use a computer code to track the motion of the ion in the beam over a few thousand revolutions of the electrons around the machine. It is worthwhile to note that 2000 machine revolutions corresponds to only ~1.5 msec of the ion's motion. However, upon allowing the code to continue to track ions which are stable after 2000 revolutions out to 500,000 revolutions, we were able to conclude that tracking to 2,000 revolutions gives ~85% reliable results. 500,000 revolutions correspond to ~.3 sec; as we shall see, this is in general longer than the time required to populate the ions to their maximum density, and so we may treat ions stable to 2,000 revolutions as stable to eternity for all practical purposes (up to the previously mentioned ~85% level of confidence).

The computer code MOTION, written by Carlo Bocchetta (Trieste Synchrotron), will track the motion of an ion under the influence of non-linear kicks. The program also allows for the bunch pattern of the beam to be taken into account; investigating the dependence of ion-trapping behavior on the pattern of bunches used in the beam was the main point of interest in the computational study. The code also allows the ion masses and initial transverse coordinates and velocities to be input. The code does not track longitudinal motion nor does it take into account any magnetic fields or ion-ion interactions; however, these effects should be small compared to the effect of the electron bunch kicks.

IV. Results of the Computer Simulations

A number of bunch patterns were examined computationally for the low-emittance configuration at SPEAR, primarily at currents from 30 to 100 mA. The species of ions examined were those which had constituted ~2% or more of the residual gas analysis (RGA) signals in the tests performed in 1979 and 1982 [3]. These ions were:

Ion:	H+	H_2+	C+	CH_4+	OH+	H_2O+	CO_2+	CO_2+
A:	1	2	12	16	17	18	28	44
Partial pressure:	2%	70%	2%	5%	2%	6%	9%	2%

For each bunch pattern, each ion was tested at a range of initial coordinates in the x-y (transverse) plane, with both x and y ranging from .1 σ to 2.0 σ. In general, the bunch patterns were chosen to explore the effect of varying the spacing between successive filled buckets and varying the size of the gap left in the pattern. Graphs of the range of currents for which ions of these masses are trapped are included as figures. Figs. 1-5 show the effect of increasing gap length (gap is given in number of RF buckets). In these graphs, the dark bars correspond to the range of currents for which ions of certain species (labeled in order of mass on the horizontal axis) are stable. As is evident from these graphs, increasing the size of the gap tends to make the ions stable over a smaller range of currents, leading in general to less trapping. According to these simulations, however, "islands" of stability remain at least up to gaps of length 223 RF buckets (fig.4). Figs. 6-12 show the effect of decreasing bunch separation for symmetric patterns (i.e., increasing degrees of symmetry). Here, as the degree of symmetry in the bunch pattern increases, we see a very definite increase in the range of currents for which trapping occurs. Information on the area in the transverse plane in which the trapping occurs is not included, as the density of accumulated ions should not be strongly dependent on this (see section V for a discussion of the limits on ion density). In general, trapping tends to occur in the region within ~.5σ. Again, from the graphs, one can see as general trends the maximum trapping current decreasing as the gap length increases and increasing as the bunch-to-bunch spacing decreases, confirming general predictions made by the linear model.

V. Effects of Trapped Ions

We are left with the question of the limit of the density of the accumulated ions. The rate of change of the population of singly ionized ions of a particular species is given by:

$$\frac{dN+}{dt} = \sigma_+ \, d_0 \; - \; \sigma_{++} \, d_+ ,$$

where σ_+ and σ_{++} are the cross sections for first and second ionization, respectively, and d_0 and d_+ are the densities of neutral and singly ionized molecules, respectively. In general, the first ionization cross section σ_+ is approximately equal to the second ionization cross section σ_{++} [1]. For relativistic beams, a doubly ionized molecule will see double the current a singly ionized molecule sees and so will be unstable above one-half the maximum current for the singly ionized species of that mass. From figs. 3-12, we can see that for most standard operating cases (>20 mA), molecules stable for a single ionization will be unstable for a second ionization (recall that the twice-ionized molecule will see twice the current). For molecules for which this is the case, we see that when d_+ reaches d_0 , the population is at a stable equilibrium; the maximum density of any species of ion, then, is the background density of that species of neutral molecule and so, for example, $d_{+Max(H_2)} = d_{0H_2}$. The accumulation continues until the defocusing force of the ions in the drift region reaches the stability limit. In general, this will happen before $d_{+Max(H_2)} = d_{0H_2}$.

Effects such as tune shift and gas scattering will then be strongly dependent upon the neutral molecule density and the species of ions trapped. The gas scattering will also depend upon which ion species are trapped, as the total cross section for scattering for any given species goes as $d_s A^2$, where d_s is the density of the ion species of mass A. Since $d_{+Max} = d_0$ for any ion species, the total density of any species can, at most, be twice the density of its neutral molecules (i.e., $d_{+Max} + d_0 = 2\, d_0$). Thus, the gas-scattering effect of the ions can, at most, double the effect already present due to the neutral molecules.

A calculation of the non-linear tune shift is somewhat more complicated as it depends upon the actual distribution of the ions. For the nonlinear model, the distribution (calculated by David Sagan at Cornell University) is sharply peaked near the transverse center of the bunch and drops to ~zero well within 1σ. To calculate the linear tune shift due to the accumulated ions, we assume the distribution to be constant. From this, the calculation of the local quadrupole strength follows:

$$K(s) = \frac{dE_i}{dx,y} = \frac{d_i\ e}{1 + (\sigma_{x,y}, / \sigma_{y,x})},$$

where E_i is the electric field of the ions and d_i is the density of ions. In SPEAR, the background pressure is typically of order 10^{-9} torr. The x and y linear tune shifts are then given by:

$$\Delta \upsilon_{x,y} = \frac{r_e\ m_e\ c^2\ \ d_i\ \ <\beta_{x,y}>\ C}{E_e\ \ [1 + \ (\sigma_y/\sigma_x)]},$$

here E_e is the energy of the electrons in the ring, and $\beta_{x,y}$ are the horizontal and vertical Beta functions. For the case where all the ions are trapped (i.e., where $d_i = d_m = 3.1\mathrm{x}10^{13}$ / m^3), we get a tune shift of $\Delta\upsilon_y = 3\mathrm{x}10^{-2}$ and $\Delta\upsilon_x = 3\mathrm{x}10^{-3}$. In most operating scenarios, however, the density of trapped ions would be, at most, only ~10% of this, so one would expect to be able to observe tune shifts roughly an order of magnitude lower in cases of partial trapping.

VI. Experimental Results

We chose patterns which gave unambiguous predictions of total trapping and non-trapping and set them up in the SPEAR ring. The trapping pattern we chose was the 20-symmetric bunch configuration (fig. 12); the non-trapping configuration was the gap = 244 pattern (fig. 7). For each pattern, we measured the horizontal and vertical betatron tunes (to accuracies within ~$3\mathrm{x}10^{-4}$) as well as the horizontal and vertical betatron tune spreads. For each of the patterns that we loaded, we observed no tune shift or tune spreading above the sensitivity of our measurements. We observed some differences in lifetime, but these had a sharp dependence on the beam current and could well have been due to coupled bunch effect interactions. When no tune shift was apparent, we filled all 280 bunches for the most favorable trapping condition and turned off the ion pumps. If ions had been trapped, the tune should have depended linearly on the neutral molecule density. We observed the tune as the neutral molecule density rose by a factor of ten and saw no tune shift or spread, though the lifetime fell to a few minutes (as opposed to several hours) as the background density rose.

From this we conclude that it is not possible to trap ions with $A < 45$ at SPEAR. Ions of $45 < A < 90$ were not in evidence in the RGA mentioned above at levels greater than one part in 10^5. The absence of observable trapping is in contrast to the predictions of the non-linear theory, which indicated that for standard SPEAR operating parameters there should be observable levels of ion trapping, and under the conditions of the "trapping" pattern, ion effects should have been quite large. Reasons for the discrepancy between our computational studies and our experimental results could include:

- Longitudinal effects due to the gradient in $\sigma_{x,y}$ could pull ions around the ring to a point where they were unstable.

- Occasional close passes by bunch electrons could give ions kicks too large to be averaged out by considering the bunch to be a continuos distribution of charge. The cross sections of these close passes, however, are too small to be likely candidates.

- Beam instabilities and synchrotron oscillations could be leading to ion instability.

In any case, it does not seem that it is possible for ions to play an important part in the operation of SPEAR. This removes restrictions on bunch patterns which have dictated the use of a gap in the pattern up until now.

VII. Acknowledgment

I would like to thank Max Cornacchia and Heinz-Dieter Nuhn of SSRL for their guidance and assistance in each part of this study.

References:

[1] Baconnier, Y. and Brianti, G.B., "The Stability of Ions in Bunched Beam Machines", CERN/SPS80-2(DI) (1980).
[2] Bocchetta, C.J., and Wurlich, A., "The Trapping and Clearing of Ions in ELETTRA", Trieste ST/M-88/26 (Nov. 1988).
[3] Personal communication with Ben Scott, SSRL.

In figures 1-5 we see the effect of increasing the gap length (where the gap length is measured in accelerating radio frequency (RF) buckets). Each figure gives the range of currents for which each ion species is stable.

The pattern for figures 3-7 is a gap of a given number of RF buckets. Outside the gap, every third bucket is filled.

Fig. 1 Gap = 148

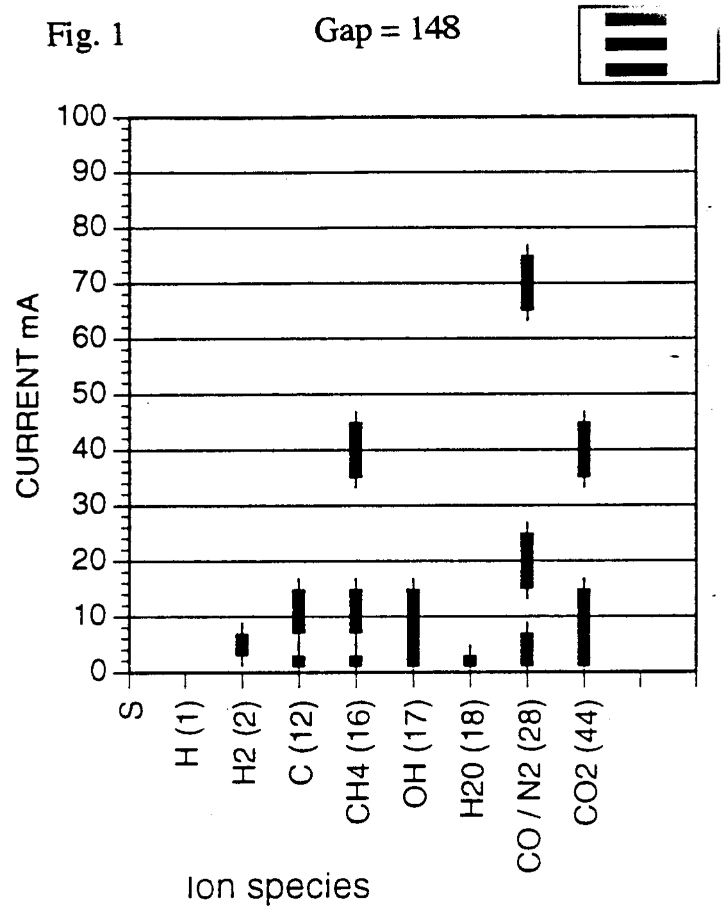


Fig. 2 Gap = 178

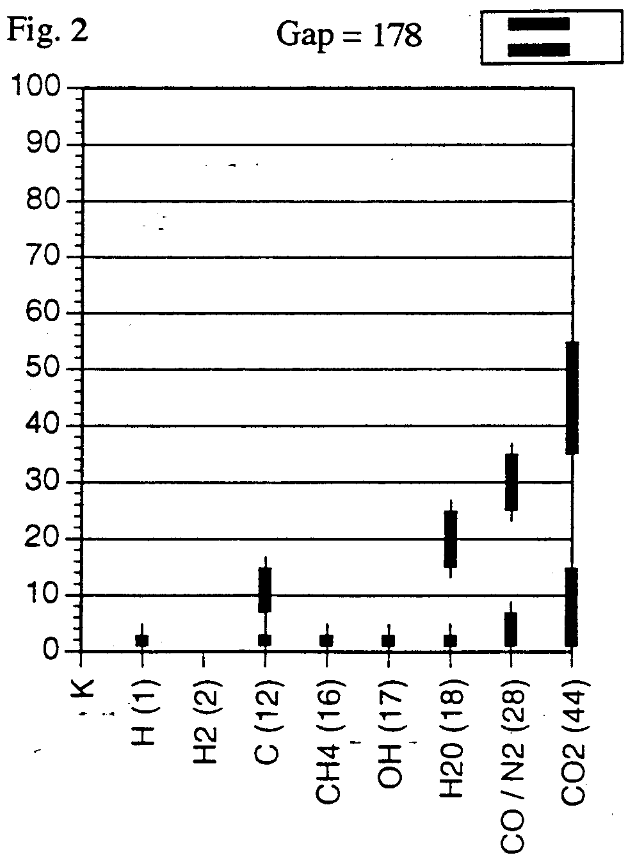


Fig. 3 Gap = 208

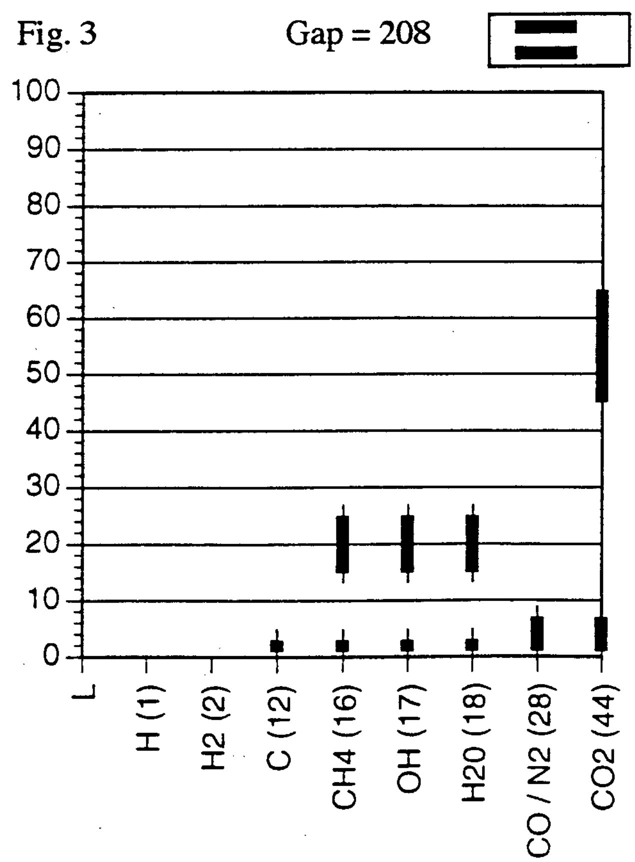


Fig.4 Gap = 223

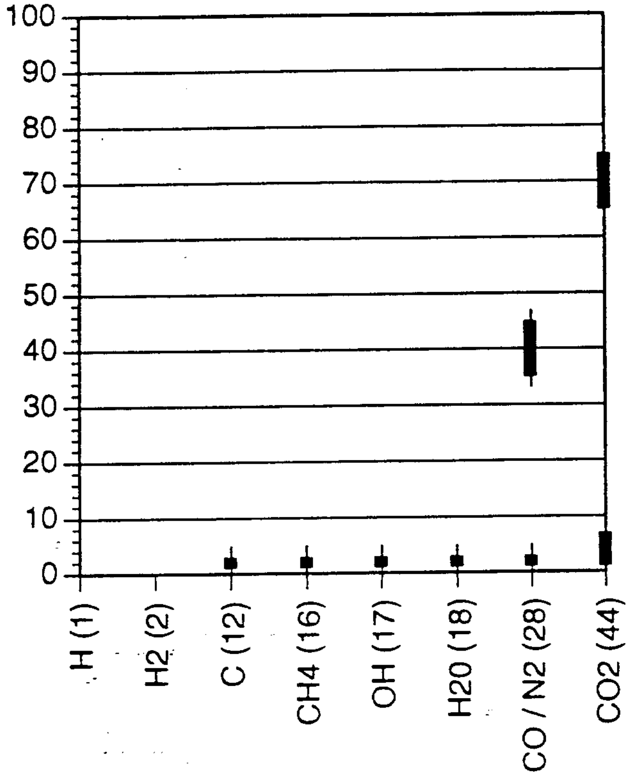
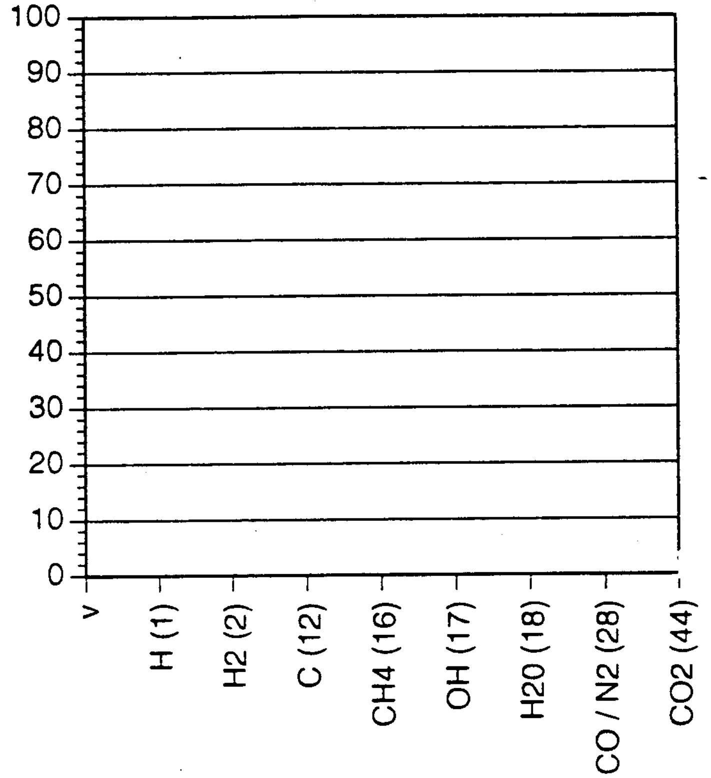


Fig.5 Gap = 244



Note: Gap = 244 configuration only tested at currents > 10mA.

In figures 6-12 we see the effect of decreasing bunch spacing in symmetric patterns. The title of each figure gives the number of degrees of symmetry of the bunch pattern. In each case, as close to 44 total buckets were filled as was possible while still preserving symmetry. So 3 sym has 15 consecutive buckets every $2\pi/3$, 7 sym has 6 consecutive buckets filled every $2\pi/7$, 14 sym has 3 consecutive buckets every $2\pi/14$, and so on.

Fig. 6 1 sym

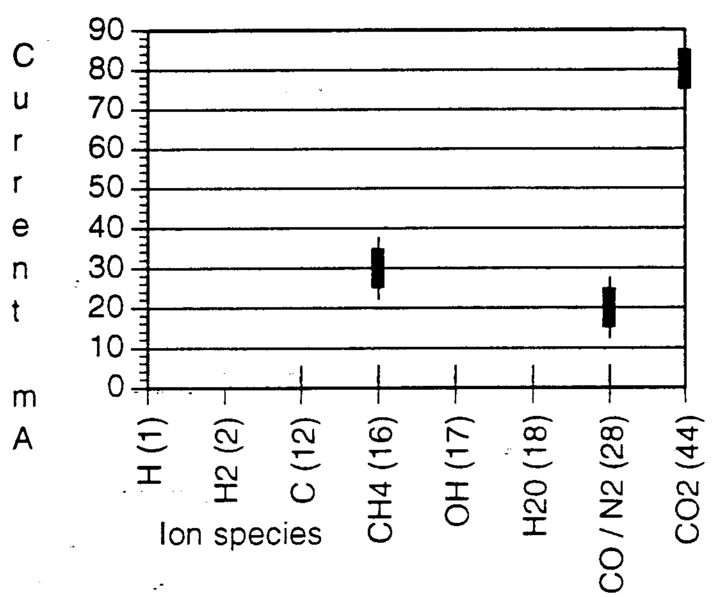


Fig. 7 2 sym

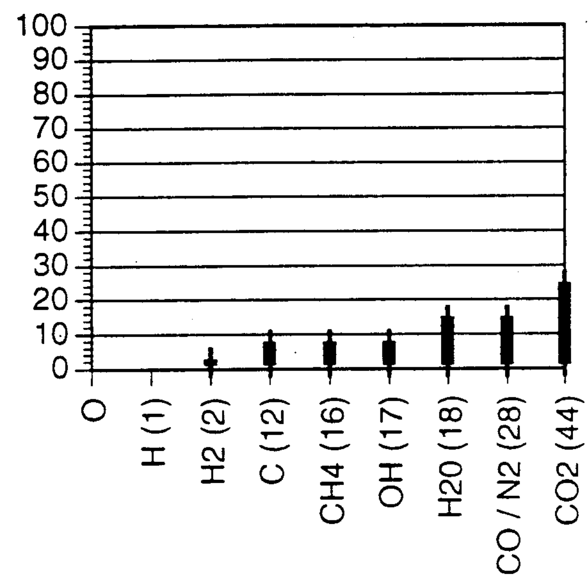


Fig. 8 3 sym

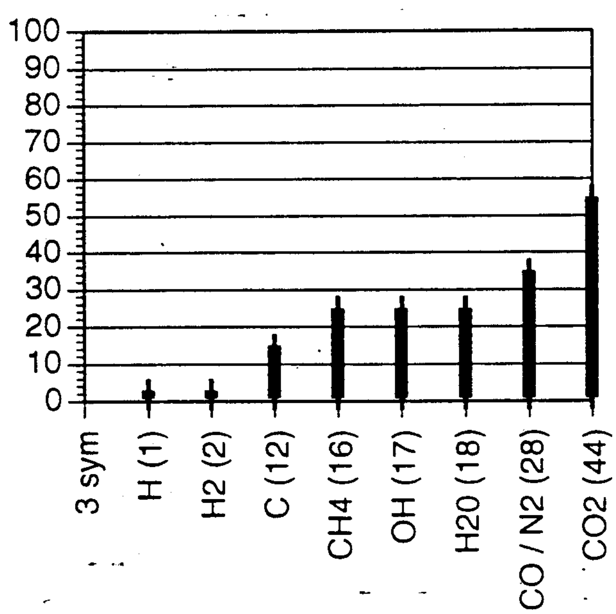


Fig. 9 4 sym

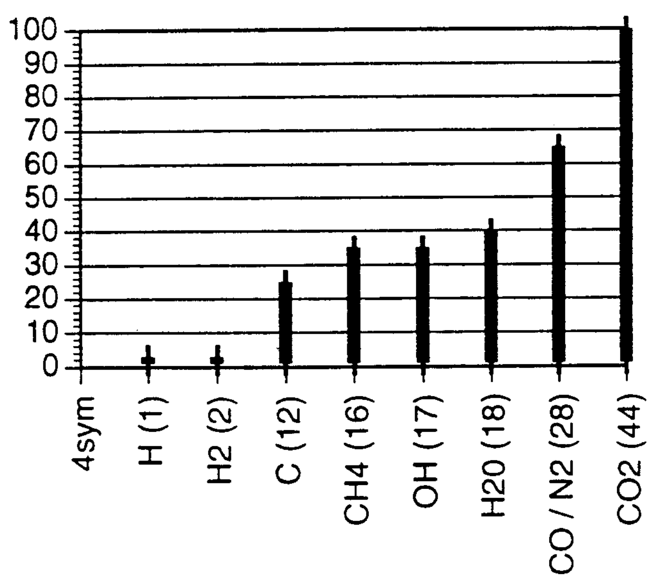


Fig. 10 7 sym

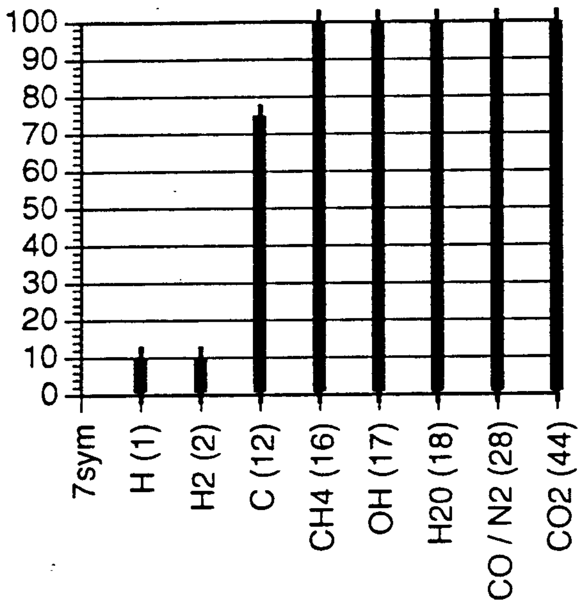


Fig. 11 14 sym

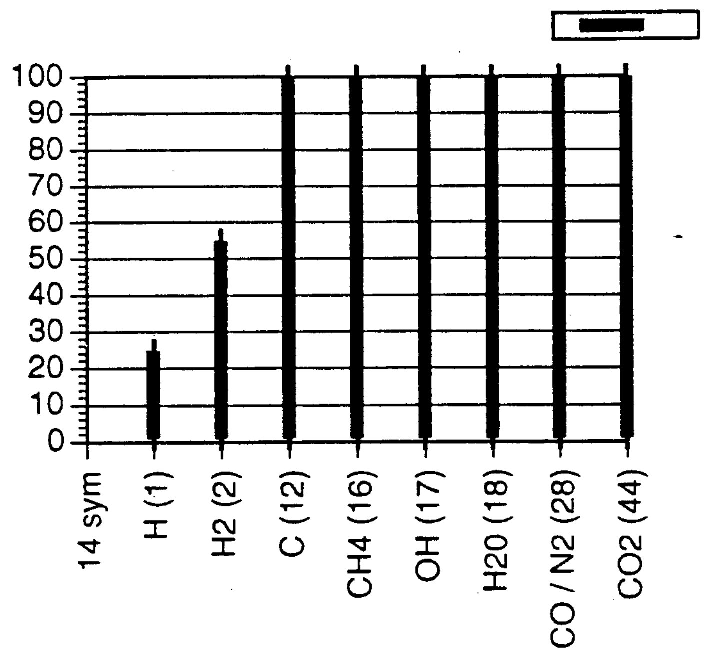


Fig. 12 20 sym