# LATTICIES FOR MILLI-eV NEUTRAL MOLECULES *

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## *Abstract*

An electric dipole moment of neutral polar molecules interacts with non-uniform electric field; therefore it is possible to design electrodes that replace magnets for charged particles and a lattice that is a series of electrodes to circulate such molecules. We describe our recent result of designing a ring for $CH_3F$ in comparison with our previous design for $ND_3$.


## STARK POTENTIAL

The interaction between the dipole moment of a neutral polar molecule and an external electric field is defined by the Stark potential $W$. As a dipole always lines up to the field direction, the potential $W$ is a function of the field strength $E = |\overrightarrow{E}|$ of the external field $\overrightarrow{E}$. The x force is given by: $F_x = -\partial W/\partial x = -dW(E)/dE \cdot \partial E/\partial x$ and similarly for y and z. The molecule is called strong-seeking if $dW(E)/dE > 0$, or weak-seeking if $dW(E)/dE < 0$. $ND_3$ is an example of the weak-seeking case with the following potential:

$$W = \sqrt{C_1 + C_2 E^2} - C_3 - C_4 E^2 \tag{1}$$

where $E = |\overrightarrow{E}|$, $C_1 = 2.77 \cdot 10^{-49}, C_2 = 6.35 \cdot 10^{-60}, C_3 = 5.26 \cdot 10^{-25}$ and $C_4 = 1.78 \cdot 10^{-38}$.
$CH_3F$ is an example of the strong-seeking case with the following potential:

$$W = \frac{C_1 w_a^2 R}{1 + C_2 w_a} \tag{2}$$

where $w_a = d_e E/R, d_e = 1.86 \times 3.36 \cdot 10^{-30}, R = 0.85 \times 1.99 \cdot 10^{-23}, C_1 = -0.2085$ and $C_2 = 0.2445$.

## ELECTRODE

There are 3 kinds of static electrodes shown in Fig.1. The type 1 and 2 electrodes are lenses to focus or defocus the beam in the transverse planes. For weak-seeking molecules, Type 1 is horizontally defocusing, 2 is focusing, and 3 deflects towards the right. For strong-seeking molecules, the forces are reversed. The fields from these electrodes are gradients of the following potential:

$$\begin{aligned}\Phi(x,y) = \quad & -E_0(y + A_2 y + A_3(x^2 y - \tfrac{1}{3}y^3) \\ & + A_5(x^4 y - 2x^2 y^3 + \tfrac{1}{5}y^5))\end{aligned} \tag{3}$$

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In Type 3, $E_0 A_2$ determines the bending radius and $A_3$ becomes a knob to adjust the focusing forces. In arc sections we use cylindrical geometry for calculations and the potential differs slightly from Eq.3.[2]. There is also focusing in

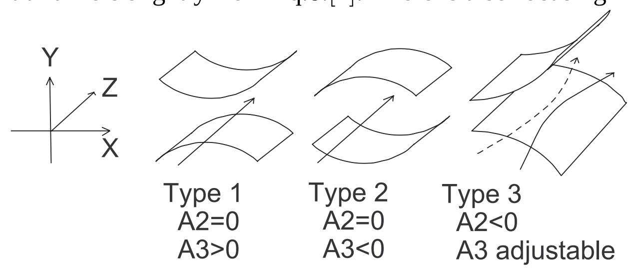


Figure 1: Electodes

the direction of the the fringe field at each longitudinal end of an electrode. It is approximated for small excursions, numerically integrated and replaced by a thin lens on or near the edge. It acts as a vertically focusing lens for weak-seeking molecules and defocusing for strong-seeking ones. See [2] and [3] for details.

## STORAGE RING

### *Design Principles*

**Requirements** We require the lattice to provide the following.
(1)Dispersion-free long straight sections for injection, RF bunchers and beam experiments.
(2)Adjustable betatron tunes and beta functions.
(3)Tolerance for the effect of the gravity force.

**Solutions** Solutions we have adopted are:
(1)Achromatic arc: Adjusting the horizontal betatron phase advance in each arc to be a multiple of $2\pi$, the straight sections become dispersionless. The vertical phase advance is also tuned in the same manner to keep the vertical closed-orbit distortion(COD) due to the gravity in a reasonable range.
(2)A triplet of focusing/defocusing straight electrodes on each end of long straight sections to adjust betatron tunes and beta functions.
(3) Vertical orbit correction to compensate the effect of gravity if needed.

### *Storage Ring for $ND_3$*

In case of a weak-seeking molecule, the bending electrode can be focusing in both horizontal and vertical planes. Therefore, it is possible to design a storage ring lattice with arc electrodes that bend the beam through a large angle [1]. The ring has the racetrack shape shown in Fig.2. Straight

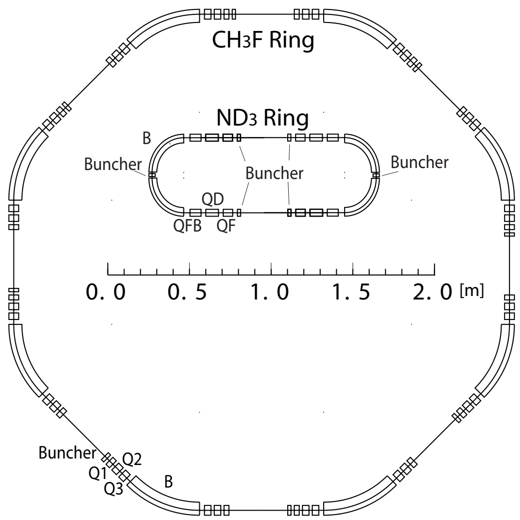


Figure 2: Storage Ring Lattices

sections are $40$ cm long. Acceptances are $35$ mm $\cdot$ mrad horizontal and $71$ mm $\cdot$ mrad vertical at its nominal velocity of $90$ m/sec. Other ring parameters are listed in Table.1. Simple adjustments allow one to reduce the velocity to $60$ m/sec [2].

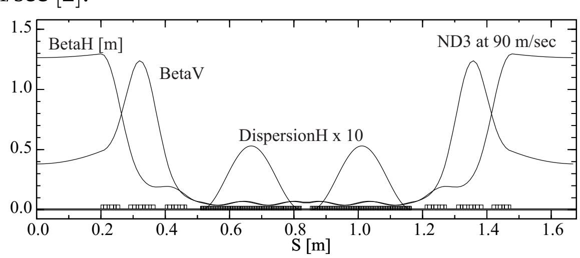


Figure 3: Beta and Dispersion of the ND3 Ring

## *Storage Ring for $CH_3F$*

For the strong seekers, a bending electrode can not focus in both planes simultaneously. Therefore, the arc must be an alternating sequence of focusing(BF) and defocusing(BD) bending electrodes; four cells with $90^\circ$ phase advance make up a $45^\circ$ arc sector with radius $60$ cm. Parameters listed in Table.(2). As a result, the $CH_3F$ ring becomes much larger than the $ND_3$ ring as shown in Fig.2.

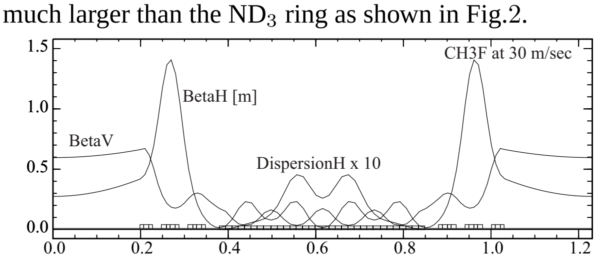


Figure 4: Beta and Dispersion of the CH3F Ring

The horizontal beta becomes large at Q2 which would cause strong amplitude-dependent tune shift. Therefore, the $A_5$ component is introduced to Q2 to reduce the amplitude-dependent tune shift and increase the dynamic aperture.

Table 1: Ring Parameters

| Paramter | $ND_3$ | $CH_3F$ |
|---|---|---|
| Circumference (m) | 3.357 | 9.850 |
| Circulation period (s) | 0.0380 | 0.3121 |
| Velocity in free space (m/s) | 90.0 | 30.0 |
| Symmetry of the ring | 2 | 8 |
| Bending radius (m) | 0.20 | 0.60 |
| Long Straight Section (m) | 0.40 | 0.40 |
| Beta horizontal [1]:$\beta_x$ (m) | 1.264 | 0.274 |
| Beta vertical [1]: $\beta_y$ (m) | 0.513 | 0.596 |
| Horizontal dispersion[1] (m) | 0.001 | 0.000 |
| Horizontal tune: $\nu_x$ | 5.250 | 13.368 |
| Vertical tune: $\nu_y$ | 5.200 | 10.398 |
| Chromaticity - H: $\zeta_x$ | -0.0885 | -73.8 |
| Chromaticity - V: $\zeta_y$ | -0.0942 | -38.1 |
| Momentum compaction: $\alpha$ | -0.99 | -0.899 |
| Dynamic aperture - H: $a_x$ (mm) | 6.5 | 1.75 |
| Dynamic aperture - V: $a_y$ (mm) | 6.0 | 3.50 |
| Acceptance - H: $\epsilon_x$ (mm - mr) | 35 | 11 |
| Acceptance - V: $\epsilon_y$ (mm - mr) | 71 | 21 |

Table 2: Bending Electrode Parameters for $CH_3F$ Ring,$E_0$ in MV/m, $R$ and $L$ in cm, $T$ in degree.

| | $Eo$ | $A_2$ | $A_3$ | $R$ | $T$ | $L$ |
|---|---|---|---|---|---|---|
| BF | 4.00 | -10.55 | -2296 | 60 | 5.625 | 7.85 |
| BD | 4.00 | -10.55 | 2343 | 60 | 5.625 | 7.85 |

The effect of gravity becomes an issue because of the lower velocity of the molecule. In case of the $ND_3$ ring, a small $0.17$ mm displacement of the closed orbit did not require orbit correction. Note that in the $CH_3F$ ring, the sequence inside the triplets is changed to D-F-D as listed in Table $3$. This reduces the effects of edge focusing but the vertical displacement still becomes as large as $2.6$ mm and the dynamic aperture is completely killed. A vertical kick is needed, one choice is to shift Q2 downwards $0.24$ mm to reduce the orbit distortion to $0.26$ mm as shown in Fig.$5$. The dynamic aperture in Fig.$6$ is then unaffected by gravity.

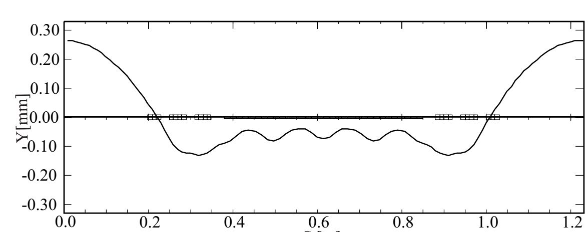


Figure 5: Corrected Vertical COD of the CH3F Ring

A buncher is a pair of parallel plates with field pulsed in an offset triangular waveform that sweeps between zero

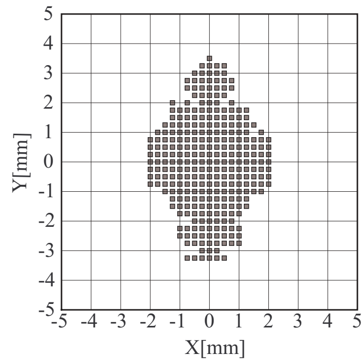


Figure 6: Dynamic Aperture of the CH3F Ring

Table 3: Parameters of Straight Electrodes for $CH_3F$ Ring, $E_0$ in MV/m and $L$ in cm.

| | $Eo$ | $A_2$ | $A_3$ | $A_5$ | $L$ |
|---|---|---|---|---|---|
| Q1 | 3.34 | 0 | 2000 | 0 | 3.0 |
| Q2 | 3.71 | 0 | -2000 | -1.283E+6 | 4.0 |
| Q3 | 2.85 | 0 | 2000 | 0 | 4.0 |

and $1.4$ MV/m at the bunch frequency, $625$ Hz. Eight bunchers in the ring (see Fig.2), each $1$ cm long, provide 205 longitudinal buckets to capture bunches that have $\pm 1.2\%$ velocity spread.

### *Source and Intensity*

Molecules from a source, typically at $310$ m/s, must be decelerated for injection into a ring. A linear decelerator array for this purpose consists of a series of pulsed field regions. A molecule of $CH_3F$ will enter each region at zero field and decelerate upon exit at full field. This sequence is reversed for $ND_3$. An a.g. pattern of static focusing lenses must be added to confine the beam transversely; for $CH_3F$ these must also overcome the vertical defocusing from fringe fields. $120$ pulsed decelerator electrodes and an equal number of lenses are required making an array of $15.1$ meter length. Bunches that emerge from this are $8$ mm long spaced $48$ mm. They are injected into $205$ buckets formed by the bunchers in the ring. The injection kicker electrode is a section of arc guide fields that is turned off rapidly after the buckets in the ring are filled. In the deceleration process, emittances of the bunches in the three orthogonal momentum-displacement spaces are conserved. These become the acceptances for molecules at the source and are amply filled by a typical xenon-seeded source. A $CH_3F$ bunch will have $1 \times 10^7$ molecules. At the $625$ Hz bunch rate this gives a circulating current of $6 \times 10^9$ molecules/sec.

## DISCUSSION

Designing a storage ring lattice for a strong-seeking molecule is far more complex than that for a weak-seeking one. The arc sectors must have an alternating-gradient structure. The higher-order component in a lens field, $A_5$ in this case, plays a crucial role in attaining a reasonable dynamic aperture. The vertical closed orbit due to gravity has to be corrected. However, in this initial effort, solutions are found.

## ACKNOWLEDGEMENTS

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