DRAGON summer research report: differential pumping system

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Abstract

Constraints on the differential pumping system of the DRAGON are discussed, as are the weaknesses in the current design. An attempt is made to improve the system, so as to allow for a 30 mrad acceptance half-angle with a 4 mm beam spot size, and the production of recoils up to 1 cm upstream from the target center. Three new designs are presented. The new systems use either the same number of pumps as the exising one or require the purchase of 1-2 new turbo pumps. The new pumping systems are around 45 cm shorter than the existing one; this extra space could be used to incorporate another magnetic quadrupole doublet or a post-stripper gas cell into the DRAGON.

Contents

I. INTRODUCTION

A. Nuclear astrophysics

Most of the light elements (up to ^{7}Li) were formed during the big bang [1]. The heavier elements were formed later (and continue to be formed) by stellar processes (including hydrostatic burning stages and (super)novae). As a field, nuclear astrophysics seeks to explain the relative abundances of the elements based on our knowledge of the rates of the nuclear reactions that form them.

B. DRAGON apparatus

In order to measure the rates of astrophysically important nuclear reactions, the DRAGON apparatus [2, 3] has been constructed. The DRAGON (Fig. 1) (Detector of Recoils And Gammas Of Nuclear reactions) consists of a windowless gas target followed by a recoil separator that consists of magnetic and electric dipoles. This system allows for the separation of particles based on their charge/mass ratio, energy, and momentum.

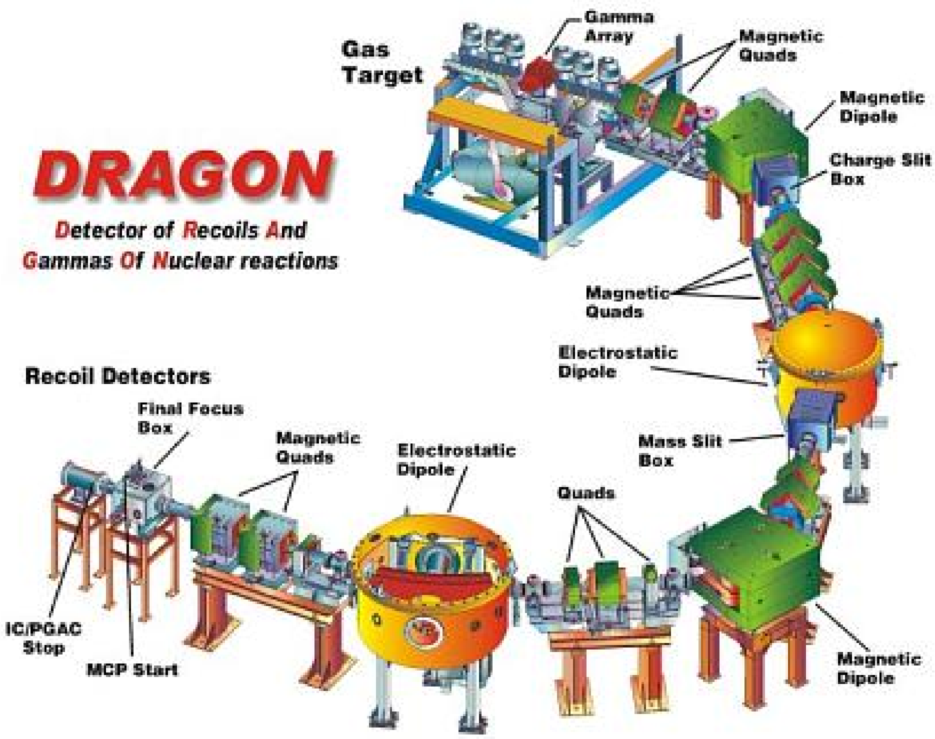

FIG. 1: Schematic overview of the DRAGON apparatus

The windowless gas target of the DRAGON apparatus can be operated at pressures as high as 8 Torr, while the residual gas pressure in the separator must be kept very low (around 10^{-6} Torr). In order to accomplish this, there is a differential pumping system (Fig. 2) upstream and downstream of the target which consists of a series of apertures and tubes followed by high-speed pumps (turbo pumps and roots blowers are utilized).

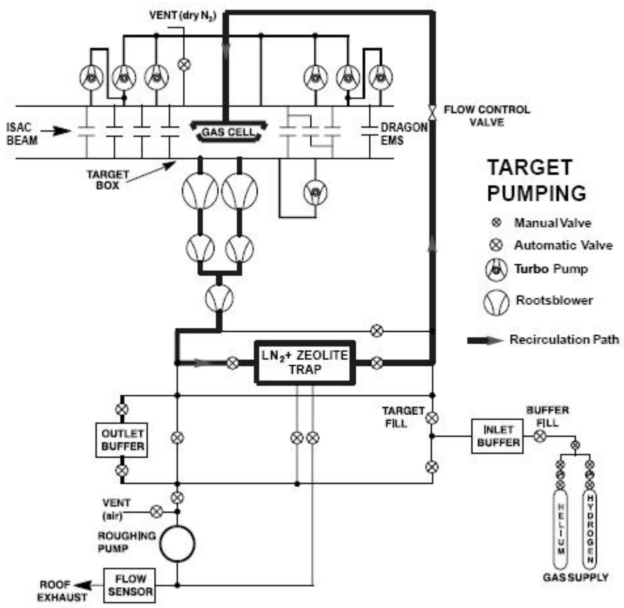

FIG. 2: Diagram of the DRAGON differential pumping system from Ref. [2]

In a DRAGON experiment, a beam of stable or radioactive ions from the ISAC facility is directed into the target, which consists of helium or hydrogen gas (depending on whether a ^{A}X(α,γ)${}^{A+4}$Y or a ^{A}X(p,γ)${}^{A+1}$Y reaction is being studied). Some of the beam ions undergo radiative capture of the target nuclei to form recoils (the fusion products of interest). Both the recoils and the unreacted beam particles then exit the target, and pass on to the separator.

C. Recoil cone angle

During the fusion reaction, a gamma ray (high-energy packet of light energy) is emitted. By conservation of momentum, the momentum of the recoils after the reaction is

$$\vec{P}_{recoil} = \vec{P}_{beam} - \vec{P}_{gamma}, \tag{1}$$

where $\vec{P_x}$ represents the momentum vector of particle x.

For a gamma ray emitted perpendicular to the beam axis (the direction in which the beam particle was travelling prior to the fusion reaction), the component of $\vec{P_{recoil}}$ perpendicular to the beam axis is maximized. The gamma ray can, however be emitted in any direction. As a result, the recoils are constrained to travel out from the reaction point within a cone whose opening angle is determined by $\vec{P_{gamma}}$. The maximum angle (with respect to the beam axis) that $\vec{P_{recoil}}$ can have, with the recoil still being transmitted through the differential pumping system, is called the angular acceptance of the system; the acceptance is defined by the diameters of the pumping tubes.

D. Trade-offs in pumping tube design

Obviously, smaller pumping tube diameters allow for the gas pressure after the target to be reduced faster; this increases the maximum target pressure, which can allow for the recoils to reach charge-state equilibrium (which is desirable!). On the other hand, larger pumping tube diameters allow for the study of reactions with larger recoil cone angles. The design of the differential pumping system must represent a compromise between these two constraints. Furthermore, the distance (along the beam axis) that the pumping system extends is restricted by the 25.4 cm flange diameter of the pumps; the system must be at least this long, or else tubes with smaller diameters are needed to connect the pumps to the beamline (which reduces S_{eff} of the pump). Care must taken to arrange the pumps so as to minimize the length of the system. This is discussed below, in section IV.

E. Current pumping tube design

The current pumping tube design (Fig. 3) has a nominal maximum recoil half-angle (angular acceptance) of roughly 21 mrad. This value is based on the assumption that the recoils come from a point-source at the center of the target; it does not allow for the non-zero beam spot size, nor for the production of recoils in the upstream half of the target. The actual acceptance is thus somewhat lower than the nominal value. Furthermore, the pumping system does not end until roughly 85 cm downstream from the target center.

If the pumping system could be modified to allow a larger angular acceptance and allow

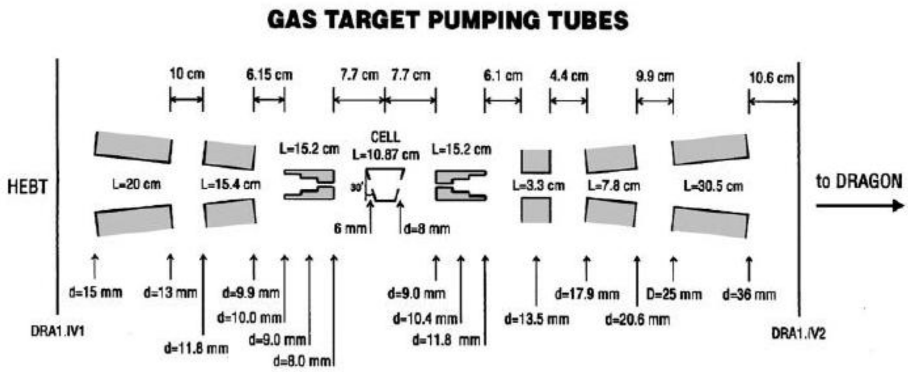

FIG. 3: Diagram of the current DRAGON pumping tubes from Ref. [4]

for a non-zero beam spot size (and the production of recoils in the upstream portion of the target), the transmission (portion of recoils that make it through the separator) would be increased (especially for reactions with large cone angles). Furthermore, if the pumping system could be shortened, there may be room for another pair of magnetic quadrupoles [5] or a post-stripper gas cell before Q1 (which is currently the first magnetic quad downstream of the target). Either of these additions would be advantageous to experimenters using the DRAGON apparatus: adding another quad doublet could improve the transmission of large-angle recoils [6]; a post-stripper gas cell would allow the recoils to reach charge-state equilibrium, in which case the fraction of recoils in the transmitted charge-state would be better known (see Ref. [7] for details).

F. Goals of this work

The current work represents an attempt to design a differential pumping system for the DRAGON which would have 30 mrad acceptance while allowing for a 4 mm beam spot diameter and the production of recoils 1 cm upstream of the target center. From these requirements, the minimum aperture (or tube) diameter (ϕ) can be calculated to be

$$\phi(z) = 0.4 + 0.06(z + 1), \tag{2}$$

where z is the distance downstream of target center, and all distances are in cm.

The pumping system should not require any more pumps than are currently used in the DRAGON apparatus (to save money), and should finish at most 40 cm downstream of the target center (to allow for the inclusion of additional elements into the DRAGON apparatus). Furthermore, the system should allow for the target to be operated at 8(4) Torr with He(H_2) gas, with the pressure after the pumping system being at most 2×10^{-6} Torr.

II. FLOW-RATE AND PRESSURE CALCULATIONS

In our differential pumping system, gas flows through a tube(aperture), and is then pumped away with a high-speed pump. This tube-pump step is repeated several times. The pressure in the beam line afer each tube-pump step can be calculated as

$$P_{after} = \frac{Q}{S_{eff}}, \tag{3}$$

where Q is the flow rate of gas through the tube, and S_{eff} is the effective pumping speed.

When calculating Q, the flow rate, one must take into account the type of flow that is taking place; this depends on the pressure regime in which the flow occurs and (in some cases), the dimensions of the tube through which the gas flows. The relevant pressure regimes and flow-rate equations (from Ref. [8]) are discussed below.

A. Rough vaccuum regime

The rough vacuum regime occurs for $P_o \cdot d \geq 0.6\ mbar \cdot cm$, where P_o is the pressure at the upstream end of the tube, and d is the tube diameter.

In this regime, the flow rate through an aperture is

$$Q = 15.7 d^2 P_o \sqrt{\frac{M_{air}}{M_{gas}}} \cdot 0.9, \tag{4}$$

where M_{air} and M_{gas} are the molar masses of air and the target gas, respectively, Q is in units of $mbar \cdot L \cdot s^{-1}$, and all other units are cm or $mbar$.

In this pressure regime, flow through a tube can be either laminar (where the gas flows in non-intermixing parallel layers) or turbulent (in which there is chaotic mixing of the gas), depending on the Q/d ratio.

For $\frac{Q}{d} \geq 3400\ mbar \cdot L \cdot s^{-1} \cdot cm^{-1}$, turbulent flow occurs. The flow rate is then

$$Q = 134\sqrt{\frac{M_{air}}{M_{gas}}} d(\frac{d^3}{L}\frac{P_o^2}{2})^{4/7}\ (mbar \cdot L \cdot s^{-1}), \tag{5}$$

where L is the tube length (cm). Equation 5 is only valid for $\frac{L}{d} \geq 50$.

If $\frac{Q}{d} \leq 1900\ mbar \cdot L \cdot s^{-1} \cdot cm^{-1}$, laminar flow occurs. The flow rate is, in this case,

$$Q = 135\frac{\eta_{air}}{\eta_{gas}}\frac{d^4}{L}\frac{P_o^2}{L}\ (mbar \cdot L \cdot s^{-1}), \tag{6}$$

where η_{air} and η_{gas} are the viscosities of air and the target gas, respectively. Equation 6 is only valid for $\frac{L}{Q} \geq 1.5$.

Obviously, there is a region intermediate between laminar and turbulent flow. In that case, the flow is a mixture of both cases, and the flow-rate calculation becomes much more difficult. It is thus best to work in either the laminar or the turbulent flow regime, and to avoid the middle ground.

B. Fine vaccuum regime

The fine vaccuum regime occurs for $0.6\ mbar \cdot cm \geq p \cdot d \geq 10^{-2}\ mbar \cdot cm$. In this regime, Knudsen flow occurs, and the flow rate is

$$Q = [135\frac{\eta_{air}}{\eta_{gas}}\frac{d^4}{L}\frac{P_o}{2} + 12.1\sqrt{\frac{M_{air}}{M_{gas}}}\frac{d^3}{L}\frac{1 + 189\sqrt{\frac{M_{gas}}{M_{air}}}\frac{\eta_{air}}{\eta_{gas}}d\frac{P_o}{2}}{1 + 235\sqrt{\frac{M_{gas}}{M_{air}}}\frac{\eta_{air}}{\eta_{gas}}d\frac{P_o}{2}}] \cdot P_o\ (mbar \cdot L \cdot s^{-1}). \tag{7}$$

Observant readers will have noticed by now that these equations are rather cumbersome. For this work, the equations were programmed into an Excel spreadsheet, so that the flow rate could be quickly recalculated for different tube designs. This is recommended for those pursuing work in this area.

C. High vacuum regime

In the high vacuum regime ($p \cdot d \leq 10^{-2}\ mbar \cdot cm$), molecular flow is encountered. The equations governing molecular flow are for the flow through an aperture. For flow through a tube (as in our apparatus), the flow rate is decreased by the limited conductance of the tube, and is given by

$$Q = \frac{P_o}{\frac{1+0.75\frac{L}{d}}{9.1\sqrt{\frac{M_{air}}{M_{gas}}}d^2}}(mbar \cdot L \cdot s^{-1}). \tag{8}$$

D. Pumping speeds

The effective pumping speed of our system of 5 roots blowers has been calculated to be 429 $L \cdot s^{-1}$ [8] for a H_2 gas target at 1.5 Torr. This pumping speed depends on the target pressure. The V1000HT turbo pumps used have a pumping speed which varies depending on the gas being pumped, but not the pressure. For He(H_2) gas, the effective pumping speed is 850(820) $L \cdot s^{-1}$ [9]; He gas tends to pump better than H_2. The calculations discussed in this report have assumed a pumping speed of 800(429) $L \cdot s^{-1}$ for the turbo(roots) pumps, for both He and H_2 gas; the pumping speed of the roots blowers systems was assumed to be independent of target pressure.

III. NEW PUMPING SYSTEM DESIGNS

The pumping system designs all start with apertures on the up(down)stream end of the target. The downstream aperture has a diameter given by Eq. 2, while the upstream aperture diameter was fixed at 6 mm. A smaller upstream aperture would reduce the flow of gas out of the cell, but may intercept some of the beam; for a radioactive beam, this would cause a problem as radiation from the decay of that intercepted beam would give a large background to the BGO array.

The pressure after the aperture was calculated using Eqs. 3,4 and the 429 $L \cdot s^{-1}$ pumping speed of the roots blower system. For the rest of the system, tubes were put into the design (with their diameters given by Eq. 2), and the pressures after each tube were calculated; the pressure after the first tube was P_o for calculating the flow rate through the second tube, and so on. After each tube, one turbo pump is used to pump away the gas, with one exception; after the first tube, 2 turbo pumps are used in parallel. This is because it has been found that, with the existing pumping system and 25 mrad tubes, the first turbo pump tends to get bogged down [6]. Running two pumps in parallel avoids this problem.

These calculations were repeated for a 4 Torr H_2 gas target and a 8 Torr He gas target to ensure that the design could satisfy the DRAGON's requirements.

The performances of three different designs are discussed below. One of these uses only the existing 4 turbo pumps downstream of the target, while the others would require the purchase of 1 (or possibly 2) new pumps.

Appendix A lists, for each pumping stage of each design, the following specifications: flow rate; pumping speed and pump type; aperture sizes and tube lengths; conductance (Q/P_o).

A. Design requiring no new pumps

Figure 4 shows a potential new pumping system for the DRAGON that would not require the purchase of any new turbo pumps to implement. With this system, and a 8(4) Torr He(H_2) gas target, the gas pressure after the pumping system can be reduced to 1.8(3.1)x10^{-6} Torr. This is close to the design requirement of 2×10^{-6} Torr. With a 5 Torr H_2 gas target, the pressure at the end of the pumping system is higher, 6.4×10^{-6} Torr; thus, with this system, the target pressure is quite limited. This may make the study of broad resonances more difficult.

This pumping system extends 40 cm downstream from the center of the gas target. This liberates 45 cm of space within the DRAGON apparatus for the inclusion of new elements.

B. Design requiring 1-2 new turbo pumps

Figure 5 shows a potential new pumping system for the DRAGON that would require the purchase of 1-2 new turbo pumps (at a cost of roughly $10,000 CDN each). With this system, using only 1 new turbo pump (TP5 in Fig. 5), and a 8(4) Torr He(H_2) target, the gas pressure after the pumping system is $1.8(3.5)\times10^{-7}$ Torr. This is better than the design requirement. It should be noted that this system can be used with a 5 Torr H_2 target, in which case the gas pressure after the pumping system is 6.5×10^{-7} Torr.

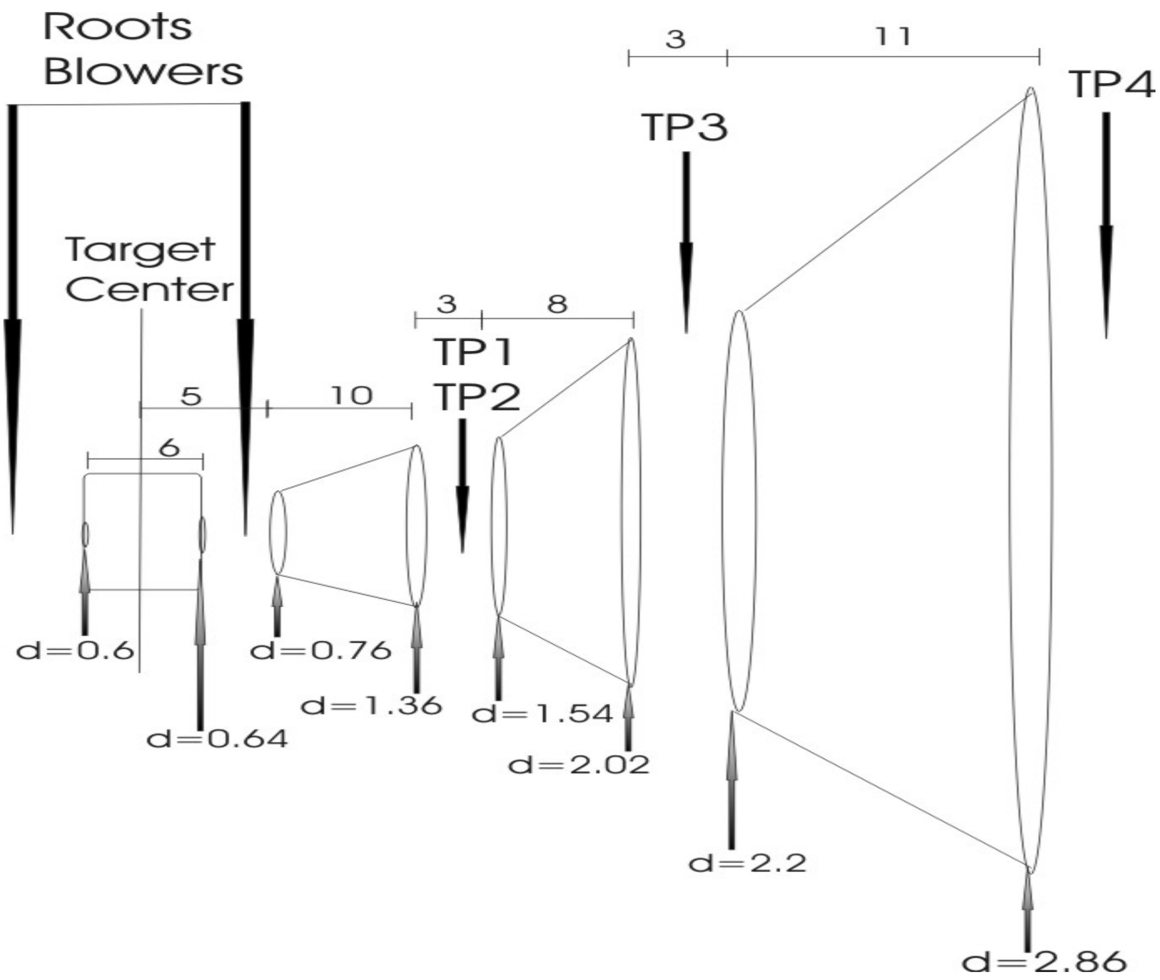

FIG. 4: Potential new differential pumping system for the DRAGON that would not require the purchase of any new pumps. The points from which the pumps draw gas from the system are labelled with arrows; TP denotes a turbo pump. All dimensions are in cm. The drawing is not to scale.

This pumping system was designed with the intent of including a new quadrupole doublet (as opposed to a post-stripper cell) into the DRAGON (as shown in Fig. 5). The design liberates enough space (roughly 40 cm) to include a doublet of small quadrupoles.

C. Discussion of these designs

The 2 new pumping system designs presented in this section could both increase the acceptance of the DRAGON, while reducing the length of the pumping system. This could allow for the inclusion of new elements into the DRAGON. Ion optics simulations will need

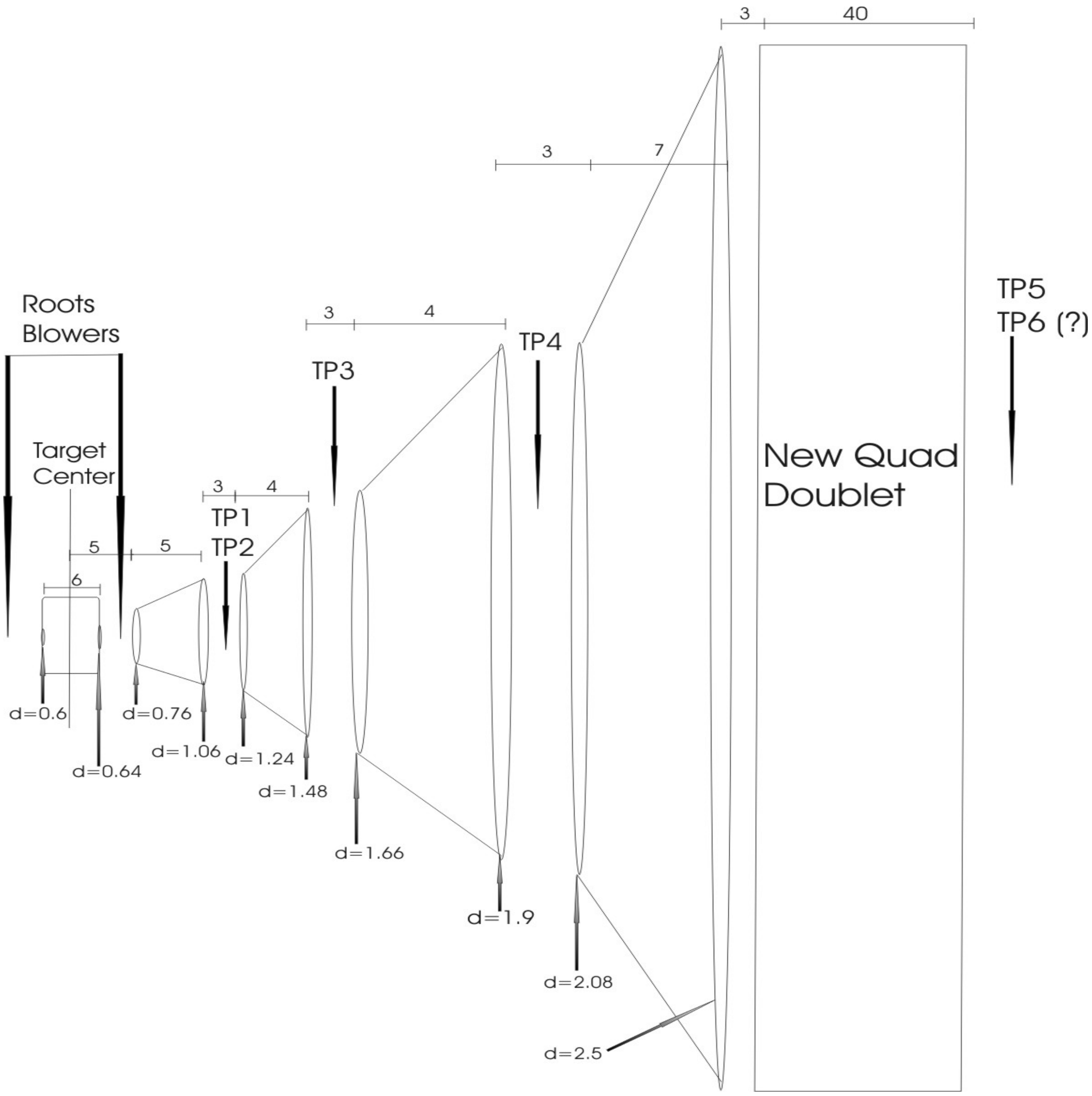

FIG. 5: Potential new differential pumping system for the DRAGON that would require the purchase of 1-2 new turbo pumps. The points from which the pumps draw gas from the system are labelled with arrows; TP denotes a turbo pump. All dimensions are in cm. The drawing is not to scale

to be performed in order to determine whether the large-angle recoils allowed by the new pumping tubes could actually be transmitted to the end of the separator. These simulations should also be able to determine whether or not a new quad doublet could be effectively incorporated into the system.

Both designs require a foreshortening of the DRAGON gas target to 6 cm (geometric length) from the current 11 cm length. This poses a challenge for narrow resonances, since these new targets have a much smaller energy-width (the amount of energy the ions lose in the target scales linearly with target length) than does the existing target. Thus, with the shorter target, it would be much more difficult to find the resonance energy of the reaction (if it is not already well known). It should be noted that, with the new-pump-requiring design (Fig. 5), a longer target could be used; this is discussed below.

D. Design requiring new turbo pumps and allowing for a 10 cm target length

Figure 6 shows a potential new pumping system for the DRAGON that allows for a 10 cm gas target length. This system would require the purchase of 1-2 new turbo pumps. Using this pumping system with 1 new turbo pump (TP5 in Fig. 6), and a 8(5) Torr He(H_2) target, the gas pressure after the pumping system is $1.4(4.1)\times10^{-6}$ Torr. This is close to, but above the required pressure of $\leq 2 \times 10^{-6}$ Torr. With the use of a second new turbo pump TP6 in Fig. 6), the end pressures would be halved to $7(21)\times10^{-7}$ Torr for a 8(5) Torr He(H_2) gas target. Thus, this system can meet the design requirement, provided that 2 new turbo pumps are used.

IV. PUMP CONFIGURATION

These designs all attempt to fit 4 turbo pumps (each with a flange diameter of 25.4 cm) into a 40 cm long section of beamline. At first glance, this appears to cause problems since there is not enough space for the flanges. This concern can be addressed by positioning 4 pumps around a cube (top, bottom, left, and right), the inside of which is divided into compartments (which are separated by the pumping tubes). This design follows from the existing 2-pump cubes used at DRAGON.

The division could be accomplished using saddle-shaped dividers (Fig. 7), which would allow each pump to "see" the full compartment (thus there should be no significant loss of conductance between pump and beamline, which would reduce S_{eff}).

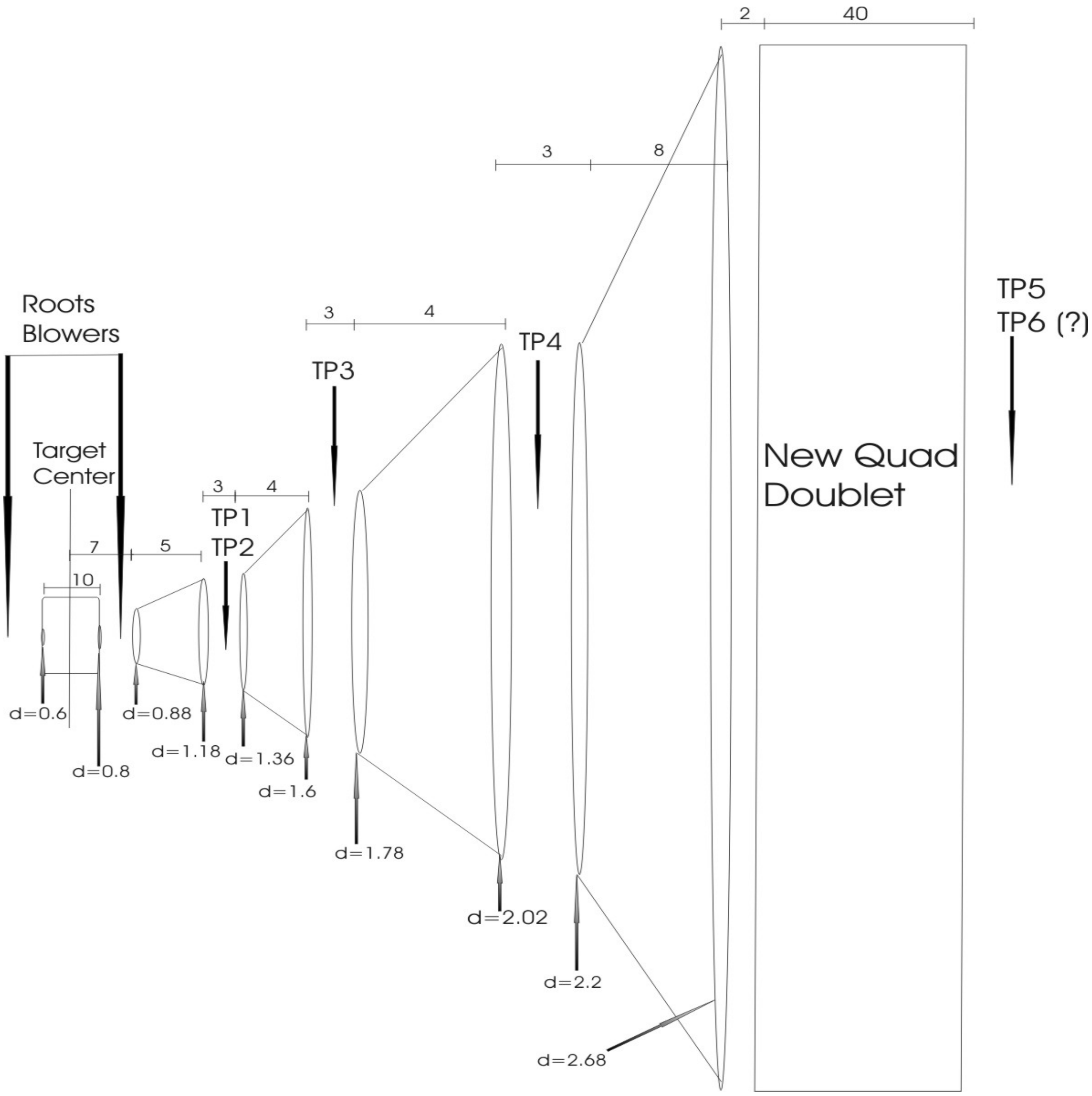

FIG. 6: Potential new differential pumping system for the DRAGON that allows for a 10 cm target length and would require the purchase of 1-2 new turbo pumps. The points from which the pumps draw gas from the system are labelled with arrows; TP denotes a turbo pump. All dimensions are in cm. The drawing is not to scale

V. CONCLUSIONS

The current differential pumping system of the DRAGON allows for a smaller acceptance and occupies more length (along the beam line) than it needs to. Three new designs have been presented herein that address these issues. Depending on the target length (and operating pressure) desired, the new designs require the purchase of 0–2 new turbo pumps.

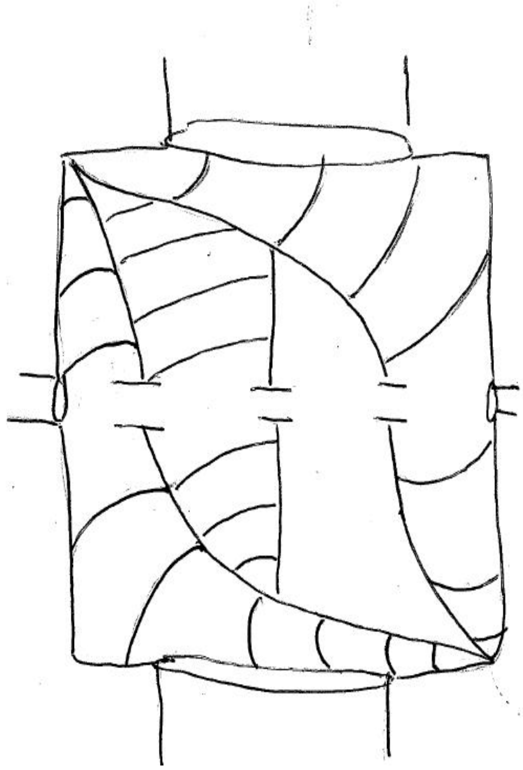

FIG. 7: Sketch of the saddle-shaped dividers for the pumping cube. The drawing is not to scale.

They all allow for a 30 mrad acceptance with a 4 mm beam spot diameter, which will allow the DRAGON to be used for reactions with larger cone angles than are accessible with the current system. Also, by allowing for a non-zero beam-spot diameter, the new designs should allow for better transmission than does the current system.

Further study will be needed in order to determine whether or not the large-angle recoils allowed by these new designs could by transmitted within the DRAGON ion-optics system.

Acknowledgments

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APPENDIX A: SPECIFICATIONS OF THE NEW PUMPING SYSTEM DESIGNS

This appendix lists, for each pumping stage of each design, the following specifications: pump type; pump speed (S_{eff}); flow type; flow speed (Q); conductance (Q/P_o); gas pressure after the pumping stage (P_{after}); tube length (L_{tube}) and average diameter ($\phi_{tube}^{average}$) . The following abbreviations are used to denote the flow types:

- RVA denotes flow through an aperture in the rough vacuum regime;
- RVL denotes laminar flow through a tube in the rough vacuum regime;
- RVT denotes turbulent flow through a tube in the rough vacuum regime;
- FV denotes the fine vacuum regime;
- HV denotes the high vacuum regime.

TABLE I: Specifications of the pumping system requiring no new pumps, as discussed in section III A and Fig. 4. The flow rates and pressures are based on the use of a 8 Torr He gas target.

Pump stage	Pump type	S_{eff} $(L \cdot s^{-1})$	flow type	Q $(mbar \cdot L \cdot s^{-1})$	Q/P_o $L \cdot s^{-1}$	P_{after} (mbar)	L_{tube}; $\phi_{tube}^{average}$ (cm)
1	Roots	429	RVA	312	29.3	0.73	0.6 and 0.64 cm apertures
2	Turbo(2)	1600	RVL	2.88	3.95	0.0018	10; 1.06
3	Turbo(1)	800	HV	0.032	17.8	4×10^{-5}	8; 1.78
4	Turbo(1)	800	HV	1.47×10^{-3}	36.8	1.8×10^{-6}	11; 2.53

TABLE II: Specifications of the pumping system requiring no new pumps, as discussed in section III A and Fig. 4. The flow rates and pressures are based on the use of a 5 Torr H_2 gas target.

Pump stage	Pump type	S_{eff} $(L \cdot s^{-1})$	flow type	Q $(mbar \cdot L \cdot s^{-1})$	Q/P_o $L \cdot s^{-1}$	P_{after} (mbar)	L_{tube}; $\phi_{tube}^{average}$ (cm)
1	Roots	429	RVA	276	41.4	0.64	0.6 and 0.64 cm apertures
2	Turbo(2)	1600	RVL	4.91	7.67	0.0031	10; 1.06
3	Turbo(1)	800	HV	0.078	25.2	9.8×10^{-5}	8; 1.78
4	Turbo(1)	800	HV	5.1×10^{-3}	52.0	6.4×10^{-6}	11; 2.53

TABLE III: Specifications of the pumping system requiring 1–2 new pumps, as discussed in section III B and Fig. 5. The flow rates and pressures are based on the use of a 8 Torr He gas target.

Pump stage	Pump type	S_{eff} $(L \cdot s^{-1})$	flow type	Q $(mbar \cdot L \cdot s^{-1})$	Q/P_o $L \cdot s^{-1}$	P_{after} (mbar)	L_{tube}; $\phi_{tube}^{average}$ (cm)
1	Roots	429	RVA	312	29.3	0.73	0.6 and 0.64 cm apertures
2	Turbo(2)	1600	RVL	9.6	13.2	0.006	5; 0.91
3	Turbo(1)	800	HV	0.08	13.3	1×10^{-4}	4; 1.36
4	Turbo(1)	800	HV	2.9×10^{-3}	29	3.6×10^{-6}	4; 1.78
5	Turbo(1)	800	HV	1.44×10^{-4}	40	1.8×10^{-7}	7; 2.3

TABLE IV: Specifications of the pumping system requiring 1–2 new pumps, as discussed in section III B and Fig. 5. The flow rates and pressures are based on the use of a 5 Torr H_2 gas target.

Pump stage	Pump type	S_{eff} $(L \cdot s^{-1})$	flow type	Q $(mbar \cdot L \cdot s^{-1})$	Q/P_o $L \cdot s^{-1}$	P_{after} (mbar)	L_{tube}; $\phi_{tube}^{average}$ (cm)
1	Roots	429	RVA	276	41.4	0.64	0.6 and 0.64 cm apertures
2	Turbo(2)	1600	FV	11.5	18.0	0.0072	5; 0.91
3	Turbo(1)	800	HV	0.144	20.0	1.8×10^{-4}	4; 1.36
4	Turbo(1)	800	HV	7.4×10^{-3}	41.1	9.3×10^{-6}	4; 1.78
5	Turbo(1)	800	HV	5.2×10^{-4}	55.9	6.5×10^{-7}	7; 2.3

TABLE V: Specifications of the pumping system which allows for a 10 cm target length while requiring 1–2 new pumps, as discussed in section III D and Fig. 6. The flow rates and pressures are based on the use of a 8 Torr He gas target.

Pump stage	Pump type	S_{eff} $(L \cdot s^{-1})$	flow type	Q $(mbar \cdot L \cdot s^{-1})$	Q/P_o $L \cdot s^{-1}$	P_{after} (mbar)	L_{tube}; $\phi_{tube}^{average}$ (cm)
1	Roots	429	RVA	405.5	38.1	0.95	0.6 and 0.8 cm apertures
2	Turbo(2)	1600	RVL	30.4	32.0	0.019	5; 1.03
3	Turbo(1)	800	FV	0.48	25.3	6.0×10^{-4}	4; 1.48
4	Turbo(1)	800	HV	0.021	34.7	2.6×10^{-5}	4; 1.90
5	Turbo(1)	800	HV	1.1×10^{-3}	43.1	1.4×10^{-6}	8; 2.44

TABLE VI: Specifications of the pumping system which allows for a 10 cm target length while requiring 1–2 new pumps, as discussed in section III D and Fig. 6. The flow rates and pressures are based on the use of a 5 Torr H_2 gas target.

Pump stage	Pump type	S_{eff} $(L \cdot s^{-1})$	flow type	Q $(mbar \cdot L \cdot s^{-1})$	Q/P_o $L \cdot s^{-1}$	P_{after} (mbar)	L_{tube}; $\phi_{tube}^{average}$ (cm)
1	Roots	429	RVA	358	53.8	0.83	0.6 and 0.8 cm apertures
2	Turbo(2)	1600	RVL	32	38.6	0.02	5; 1.03
3	Turbo(1)	800	FV	0.72	36.0	9.0×10^{-4}	4; 1.48
4	Turbo(1)	800	HV	0.044	48.9	5.5×10^{-5}	4; 1.90
5	Turbo(1)	800	HV	3.3×10^{-3}	60.0	4.1×10^{-6}	8; 2.44

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