Simulation Study on Ion Irradiation Uniformity of Large-area Heavy-ion Microporous Membranes

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Abstract

Heavy ion irradiation finds extensive applications in semiconductors, medicine, materials science, and biology, among other fields, and irradiation uniformity constitutes a critical performance metric for these applications. For heavy ion track-etched membranes, for instance, the uniformity of micropore distribution is directly determined by ion irradiation. Heavy ion track-etched membranes exhibit excellent characteristics such as controllable pore size, pore density, and straight pore channels, thereby offering promising application prospects. Currently under construction, the TR-3 terminal of the Lanzhou Heavy Ion Research Facility can rapidly irradiate large-area heavy ion track-etched membranes, achieving high-efficiency continuous production by irradiating wide-format films during continuous conveyance. For wide-format, continuously moving films, ensuring ion irradiation uniformity has emerged as an urgent research challenge. This study develops a path-integration-based simulation program to calculate the irradiation fluence distribution of heavy ion track-etched membranes. The results demonstrate that two-dimensional scanning with constant-velocity conveyance irradiation exhibits a series of discrete coupling velocities that yield uniform irradiation outcomes, while deviation from these coupling velocities induces periodic fluctuations in fluence distribution; one-dimensional scanning demonstrates higher adaptability to non-ideal beam spot shapes, whereas two-dimensional scanning shows greater adaptability to beam intensity transients. When the fluence error tolerance and available beam intensity are specified, the required coupling conveyance velocity for conveyance irradiation can be calculated using the formulas presented herein, along with recommendations for selecting one-dimensional or two-dimensional scanning. The simulation results on heavy ion irradiation uniformity from this study can serve as a reference for related research and production endeavors.

Full Text

Simulation Study on Ion Irradiation Uniformity for Large-Area Heavy Ion Track Membranes

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Abstract

Heavy ion irradiation finds extensive applications across semiconductor, medical, material, and biological fields, with irradiation uniformity serving as a critical performance metric. For heavy ion track membranes, the uniformity of micropore distribution is directly determined by the irradiation process. These membranes exhibit excellent characteristics including controllable pore density and diameter, as well as straight pore channels, offering promising application prospects. Currently, the TR-3 terminal of the Heavy Ion Research Facility in Lanzhou (HIRFL) is under construction for rapid irradiation of large-area track membranes, enabling high-efficiency continuous production through simultaneous wide-format film transmission and irradiation. However, ensuring uniform ion irradiation for wide-format, continuously moving films has emerged as an urgent research challenge. This paper develops a path-integral-based simulation program to calculate the fluence distribution in heavy ion track membrane irradiation. Results demonstrate that for two-dimensional scanning with constant film motion, a series of discrete coupling velocities exist that yield uniform irradiation; deviation from these coupling velocities induces periodic fluctuations in fluence distribution. One-dimensional scanning exhibits greater adaptability to non-ideal beam spot shapes, while two-dimensional scanning shows higher tolerance to beam intensity fluctuations. When fluence error limits and available beam intensities are specified, the formulas provided herein enable calculation of the required coupling transmission velocity and recommendations on whether one- or two-dimensional scanning is preferable. This simulation study on heavy ion irradiation uniformity can provide valuable guidance for related research and production.

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Heavy ion irradiation plays a vital role in semiconductor processing [1], energy [2], medical treatment [3], biological research [4], and materials science [5-7], with irradiation uniformity representing a key performance indicator in many applications. For instance, non-uniform ion implantation in semiconductor fabrication reduces device yield [1]; in inertial confinement fusion, irradiation nonuniformity decreases fusion energy output [8]; in tumor radiotherapy, magnetic scanning errors and locally non-uniform dose distributions enable tumor cells in low-dose regions to survive more readily, diminishing treatment efficacy [9]; and both biological and materials research applications demand uniform ion irradiation [10].

Among the various applications of ion irradiation, heavy ion track membranes have experienced rapid development in recent years due to their superior properties. When polymer films are irradiated with swift heavy ions and subsequently processed, they can produce uniformly sized, density-controllable, strictly straight pores—forming heavy ion track membranes. These membranes demonstrate excellent potential in filtration [11], precision separation [12], nanostructure growth templates [13], metamaterial fabrication [14,15], and other fields. For track membranes, area, pore diameter, and pore density constitute the primary performance parameters. Recent expanding applications have imposed more stringent requirements: battery separators, hemodialysis membranes, and ion separation membranes [16-18] require nanometer-scale or even sub-nanometer pore diameters, while nanophotonic structures, mechanical metamaterials, and gas separation membranes demand pore densities reaching or exceeding 10^9 pores/cm^2 [13]. Furthermore, filtration/separation membranes and optical materials require sufficiently large membrane areas to meet device requirements (e.g., automotive batteries, satellite light-absorbing shields) while avoiding performance-degrading, cost-adding processes like splicing. Consequently, track membrane research and applications are trending toward higher fluence, smaller pore diameters (greater precision), and larger effective areas. For high-value applications such as precision separation and ultra-high absorptivity materials, strict micropore distribution uniformity becomes a prerequisite.

Since membrane pores form through ion track etching, their distribution directly depends on ion distribution during irradiation, making irradiation uniformity a core quality control metric in track membrane fabrication.

Over the past decades, numerous methods have been employed to improve irradiation uniformity, including diffusion, magnetic defocusing, pixelation, and scanning techniques [19-22]. Except for diffusion—which relies on natural beam spot expansion to achieve uniform irradiation—all other methods fundamentally involve superimposing multiple beam spots (or a separated single spot) to create a uniform fluence region. Scanning methods, due to their relatively simple hardware configuration and adjustable scanning range and frequency, are widely used in heavy ion irradiation [23-27]. Scanning patterns can be categorized as Lissajous-like [28], spiral [29], or square-wave [30], while the physical principles involve either magnetic [31] or electrostatic scanning [32].

Electrostatic scanning requires extremely high alternating electric fields, making magnetic scanning the preferred approach for swift heavy ion beams. For example, a 5.97 MeV/u ^{129}Xe^{22+} ion beam requires an electric field strength of at least 1.22$×10^{7}$ V/m to deflect by 1° in a 100 mm deflection field, whereas a magnetic field of only ~0.35 T suffices for the same deflection length, offering significantly greater feasibility.

Currently, magnetic scanning performs well for relatively small, stationary samples. However, further research is needed to enhance performance for emerging materials like heavy ion track membranes. Next-generation track membrane irradiation equipment demands large membrane areas, high fluence, and high operational efficiency. For instance, the TR-3 terminal under construction at the Institute of Modern Physics features an effective irradiation range of 600 mm × 300 mm with maximum ion fluence exceeding 1$×10^{10}$ ions/cm^2. Moreover, continuous film motion via winding transmission improves efficiency. Moving wide-format films require wider scanning amplitudes and higher scanning frequencies, imposing greater demands on magnetic scanning systems. However, systematic research on irradiation uniformity for large-area moving targets remains lacking. Given these emerging requirements and the construction of related equipment—particularly track membrane irradiation facilities—investigating how to achieve uniform large-area film irradiation under the physical constraints of magnetic scanning systems (volume, heat dissipation, power, etc.) holds significant practical importance and will advance research and applications of advanced materials including precision track membranes.

To investigate uniformity issues in wide-format, high-speed moving film irradiation, this study employs a path integral method to calculate post-irradiation fluence distribution by determining the relative fluence at each sampling point on the membrane. Section 2 briefly introduces the path integral calculation model, Section 3 presents and discusses relevant research results, and Section 4 provides concluding remarks.

2 Calculation Model

The magnetic scanning methods employed in this simulation include two-dimensional scanning and one-dimensional scanning. Two-dimensional scanning applies periodically varying electromagnetic fields in two perpendicular directions (denoted x and y) transverse to the beam, causing the beam spot to scan across the entire target area. One-dimensional scanning, used in transmission irradiation, scans the beam spot only in the direction perpendicular to the film motion (x-direction), relying on uniform film motion to distribute ion tracks across the entire membrane. For magnetic scanning with sufficiently small deflection angles, beam spot displacement can be approximated as proportional to the deflection magnetic field strength. In actual equipment like the TR-6 terminal at the Heavy Ion Research Facility in Lanzhou, the deflection magnet is 4200 mm from the target, while the irradiated film width is 400 mm, making the maximum beam spot deflection slightly over 200 mm—sufficiently small to treat magnetic field variation as proportional to beam spot coordinate offset.

The Heavy Ion Research Facility in Lanzhou currently uses triangular wave scanning for track membrane irradiation. During scanning, the beam spot velocity remains nearly constant, and the triangular wave scanning path can be regarded as a superposition of parallel lines with equal-sized and uniformly distributed grid points in the central region, which helps maintain overall uniformity. Accordingly, this study adopts triangular wave scanning.

Under triangular wave scanning, the parametric time equations for beam spot scanning paths are given by Equations (1) and (2):

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where A and A are scanning amplitudes in the x and y directions, f and f are scanning frequencies, and t is scanning time. Since the two-dimensional scanning path resembles a Lissajous figure—a regular, stable closed curve synthesized from two perpendicular periodic motions with integer frequency ratios—it is termed Lissajous-like scanning. With total scanning time determined, Equations (1) and (2) define the scanning path. Adopting a reference frame where the beam spot remains stationary, the membrane center point moves relative to the beam spot along the same pattern. For a given point and its surrounding area, this is equivalent to continuous irradiation by a beam of varying intensity. Therefore, after beam spot normalization, the central point fluence can be obtained through integration:

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Here, g(x,y) is the beam spot intensity distribution function (units: ions/(s $\cdot$ cm^2)); C is the beam current (ions/s); and T is the total irradiation time. Under ideal conditions, the beam spot follows a Gaussian distribution. The integration result Int represents ion fluence (ions/cm^2). For non-central points, the coordinate offset relative to the central point is simply added to the beam spot distribution function.

Unless otherwise specified, this study employs an ideal Gaussian beam spot distribution expressed as:

r represents the beam spot' s 5% height radius (radius at 5% of maximum intensity), which approximates the full width at half maximum (FWHM). The default value is r = 10 mm. Since this study uses relative range (difference between maximum and minimum values divided by average) to measure fluence uniformity on the membrane, the constant coefficient in Equation (4) can be omitted. In our simulations, the ideal beam spot has a 5% height radius of 10 mm. Using mm as the length unit and combining Equations (4) and (5) while omitting the constant coefficient from Equation (4) yields the integral used in calculations:

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Matlab is used to compute the integral in Equation (6) with an integration step size of 10 ns. Considering physical and engineering constraints on scanning magnets in practical applications (volume, power, heat dissipation, etc.), f and f are limited to 200 Hz or below.

3.1 Stationary Target Two-Dimensional Scanning Irradiation

Two-dimensional scanning of stationary targets represents the mainstream approach in materials irradiation. The triangular wave scanning path consists of two sets of parallel, equally spaced line segments. The spacing between segments determines whether beam spots overlap sufficiently, thereby controlling scanning uniformity. When scanning amplitude increases while beam spot size remains constant, higher scanning frequencies maintain uniform fluence, but lower frequencies produce periodic fluctuations due to insufficiently dense scanning paths—representing a key challenge in achieving large-area uniform irradiation. Referencing the resolution limit of two Gaussian optical spots, when the distance between adjacent beam spot centers exceeds their FWHM, a noticeable fluence depression region appears between closely spaced parallel scanning paths, creating the source of periodic fluctuations.

Based on triangular wave properties, for coprime scanning frequency combinations, the Lissajous-like pattern formed by triangular wave scanning within one period can be divided into two sets of line segments that are parallel and equally spaced within each set. The parallel line spacing is a function of scanning frequency and amplitude, with two cases:

1. When f and f are coprime and both odd:
2. When f and f are coprime, with one odd and one even:

Here f and f are scanning frequencies in the x and y directions, and A and A are scanning amplitudes. Uniformity in the stationary state is ensured when d is smaller than the Gaussian beam spot’ s FWHM. For a beam spot with 5% height radius of 10 mm and scanning area of 600 mm × 300 mm, if f and f are coprime with similar values (|f - f | « f + f), the minimum frequencies required to maintain scanning uniformity can be calculated: 55 Hz when both frequencies are odd, and 28 Hz when one is odd and the other even. If beam spot size decreases further, required scanning frequencies increase accordingly. With a 10 mm beam spot 5% height radius, 110 Hz is needed when both frequencies are odd, and 56 Hz when one is odd and one even. Since precisely maintaining beam spot size during actual film irradiation is difficult, it is recommended to use coprime scanning frequencies that are as high as possible to ensure large-area scanning uniformity.

3.2 Uniform Motion Transmission Irradiation

Continuous film motion represents an effective method for improving irradiation efficiency. For transmission irradiation, scanning can be implemented in two ways: two-dimensional scanning and one-dimensional scanning. Two-dimensional scanning resembles the stationary target case, while one-dimensional scanning irradiates only in the direction perpendicular to the transmission velocity, relying on film motion to distribute ion tracks across the entire membrane. The scanning trajectory is shown in Figure 1: see original paper. For analysis convenience, we adopt the film as the reference frame with the scanning region moving at constant velocity. Taking the film transmission direction as y, the scanning path parametric equations are:

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where v is the transmission velocity. One-dimensional scanning corresponds to f = 0 Hz, while two-dimensional scanning has both f and f non-zero. Substituting Equations (9) and (10) into Equation (7) or (8) yields simulation results for film transmission irradiation. Under transmission conditions, transmission velocity also affects irradiation uniformity, so we primarily discuss the influence of scanning frequency and transmission velocity.

[Figure 1: see original paper] compares one-dimensional and two-dimensional scanning paths and simulated fluence distributions: (a) shows the one-dimensional scanning path after 1 s at 41 Hz scanning frequency and 80 mm/s transmission velocity; (b)-(d) show one-dimensional scanning irradiation results for 600 mm-wide films at transmission velocities of 300 mm/s, 400 mm/s, and 500 mm/s; (e) shows the two-dimensional scanning path after 1 s at 41 Hz & 43 Hz scanning frequencies and 80 mm/s transmission velocity; (f)-(h) show two-dimensional transmission irradiation results at various velocities with x-direction scanning amplitude of 600 mm and y-direction amplitude of 300 mm. The simulations reveal that for two-dimensional scanning, obvious stripes appear at 300 mm/s and 500 mm/s, with only the 400 mm/s case achieving relatively uniform distribution. In contrast, one-dimensional scanning achieves relatively uniform distribution at all three velocities because the scanning frequency is sufficiently high relative to transmission velocity.

Compared with stationary target irradiation, two-dimensional scanning transmission irradiation covers a larger area in the same time, making the overall scanning path sparser and requiring higher frequencies. Besides scanning frequency, transmission velocity significantly impacts irradiation uniformity. Notably, two-dimensional scanning transmission irradiation does not simply require velocities below a certain threshold; instead, there exists an optimal transmission velocity that maximizes uniformity, termed the coupling velocity. This demonstrates that transmission velocity effects cannot be ignored even at relatively high scanning frequencies.

Under transmission irradiation, the original two-dimensional scanning path becomes distorted by target motion. This distortion manifests visually as inflection points in the scanning path—positions where beam spot center displacement reaches maximum in the x or y direction (when the triangular waveform current from the scanning power supply reaches positive or negative extremes).

[Figure 2: see original paper] illustrates the scanning trajectory decomposition schematic over 1 s at 197 Hz & 199 Hz. The scanning path within each quarter-time segment bounded by inflection points can be approximated as a trapezoid. A 1 s duration is selected because when scanning frequencies are integers, the beam spot position and velocity direction return to initial states after 1 s, completing one period.

[Figure 2: see original paper] shows: (a)-(d) scanning trajectory decomposition; (e)-(g) scanning region superposition schematic. From 0 s to 0.25 s and 0.5 s to 0.75 s, upper boundary inflection points appear sequentially from right to left while lower boundary inflection points appear left to right, making the overall scanning path a right-short trapezoid. From 0.25 s to 0.5 s and 0.75 s to 1 s, the opposite occurs, producing left-short trapezoids. Letting s be the film transmission distance in 1 s, the short side length of the decomposed trapezoid is A - s/4 and the long side is A + s/4 due to Lissajous figure properties. The actual irradiated region consists of numerous such trapezoids superimposed as shown in Figure 2: see original paper-(g). To achieve the ideal superposition form in Figure 2: see original paper and ensure optimal transmission irradiation uniformity, each trapezoid' s leg must coincide with another trapezoid' s leg—meaning the lengths of the upper and lower bases must be integer multiples of s/2. The nth irradiated region should be equivalent to the (n-2)th region shifted downward by s/2:

Velocities satisfying these conditions are called coupling velocities. For A = 300 mm, the integer values s can take are exactly 400 mm, corresponding to v = 400 mm/s. Additional values include 240 mm/s and 80 mm/s, with corresponding n values of 1, 2, and 7. When transmission velocity exactly matches a coupling velocity, trapezoids couple to produce uniform irradiation. Deviating from coupling velocities creates zigzag stripes in the fluence distribution: slightly lower velocities cause trapezoids to approach each other, creating overlapping regions with higher fluence stripes; slightly higher velocities cause separation, creating gaps with lower fluence stripes. This matches the simulation results in Figure 1: see original paper-(g). When trapezoids reposition to couple again, the system transitions to the next coupling velocity. For example, n = 1 corresponds to 400 mm/s; reducing velocity creates overlap, and sufficiently slow speed transitions to the next slower coupling velocity (n = 2, 240 mm/s). Similarly, increasing velocity creates gaps, and sufficiently high speed transitions to the next faster coupling velocity (n = 0, 1200 mm/s).

Equation (12) for coupling velocities applies only when each period’ s scanning path can be divided into four trapezoids. Calculations show that for other integer frequency combinations with 2 Hz frequency difference, the 1 s scanning path is identical to the 197 Hz & 199 Hz case and can also be divided into four trapezoids. For integer frequency combinations with frequency difference f’ , the path can be divided into 2f’ trapezoids. Therefore, the coupling velocity condition for integer frequency combinations should be:

where f’ is the difference between scanning frequencies in the two directions. Assuming required fluence σ and membrane length L, with beam current C (particles passing through cross-section per second), the total scanning time and transmission velocity are:

Equation (14) shows that, under uniform conditions, post-irradiation membrane fluence is inversely proportional to transmission velocity and directly proportional to the n value corresponding to the coupling velocity. Equations (13) and (14) yield the n value closest to the target fluence:

In practice, n must be adjusted to modify fluence—i.e., selecting different coupling velocities. For example, with a 200 nA Xe^{27+} ion beam (C 4.63$\times 10^{10}$ ions/s), scanning range of 600 mm × 300 mm, and scanning frequencies of 197 Hz & 199 Hz, the optimal transmission velocity is the coupling velocity corresponding to n = 63: 9.45 mm/s, with an error of -0.096%. If f’ takes a larger value (e.g., f’ = 20), the optimal velocity becomes n = 634 (9.46 mm/s), reducing the error to -0.017%. Larger f’ yields larger n values, making 2n+1 less sensitive to n variations and enabling finer control.

However, excessively large scanning frequency differences also affect irradiation uniformity. [Figure 3: see original paper] shows the impact of frequency difference on uniformity, with fixed y-direction scanning frequency at 199 Hz and integer x-direction frequencies.

[Figure 3: see original paper] illustrates that when x-direction frequency exceeds 194 Hz, irradiation uniformity is superior to all other frequency combinations, particularly at 197 Hz and 198 Hz, where the central region’ s relative range is half that at 196 Hz. When x-direction frequency is below 196 Hz, the minimum relative range of scanning region fluence remains around 10%. Due to simulation precision limitations, the apparent high uniformity at some lower frequencies may result from sampling points arranging into regular patterns that cannot occur in practice under specific frequency and scanning range conditions. Since scanning frequencies are more easily adjusted precisely than A and A , x-direction frequency should be maximized for optimal uniformity and coprime conditions (e.g., 197 Hz or 198 Hz). Based on Equations (13), (15), and [Figure 3: see original paper], the 197 Hz & 199 Hz combination enables higher transmission velocities and more precise fluence selection, while the 198 Hz & 199 Hz combination allows lower transmission velocities and higher fluence. Similar principles apply for other y-direction frequencies: excessively large frequency differences degrade uniformity, so the highest possible scanning frequencies and smallest possible differences should be selected, with 1 Hz or 2 Hz differences being optimal. Since a 2 Hz difference yields larger n values for finer fluence control, this study adopts the 2 Hz difference condition.

3.3 Applicability of One-Dimensional vs. Two-Dimensional Scanning

Due to the discrete coupling velocities in two-dimensional scanning transmission irradiation, the selectable fluence values are also discrete (termed coupling fluence) when maximizing uniformity under constant beam intensity. In practice, the expected fluence can be used to calculate the most suitable expected transmission velocity via Equation (14), with the closest coupling velocity selected via Equation (15). However, this may introduce non-negligible error between expected and actual coupling fluence.

According to Equations (13) and (15), fluence is proportional to 2n+1 under otherwise identical conditions, so the spacing between discrete fluence values increases with n. For relatively fast transmission velocities (small n), significant gaps may exist between expected and coupling fluence.

For example, a 200 nA Xe^{27+} ion beam corresponds to C 4.63$×10^{10}$ ions/s. With a scanning range of 600 mm × 300 mm, typical expected fluence values and their closest coupling fluence are shown in :

**** Closest coupling transmission velocities and errors for common irradiation fluence values

Expected fluence (ions/cm^2)	Expected velocity (mm/s)	Coupling velocity (mm/s)	Actual fluence (ions/cm^2)	Error (a.u.)	n value
1$×10^{7}$			7.882$×10^{6}$	-21.2%	
1$×10^{8}$			1.025$×10^{8}$	-2.46%	
1$×10^{9}$			1.001$×10^{9}$	0.09%	

Note: All cases use 200 nA Xe^{27+} ion beam irradiation.

When expected fluence is 1$×10^{7}$ ions/cm^2, the low value forces selection of the fastest coupling velocity (1200 mm/s), resulting in over 20% error. At 1$×10^{8}$ ions/cm^2, the expected velocity decreases to 94.58 mm/s, corresponding to a larger n value and enabling selection of a coupling velocity close to the expected value. At 1$×10^{9}$ ions/cm^2, the even larger n value allows coupling velocities very close to the expected velocity, theoretically yielding excellent irradiation results.

In general, higher expected fluence corresponds to lower transmission velocity, making discrete coupling velocities closer together and reducing the maximum error. Current track membrane applications require fluence σ typically ranging from 1$×10^{5}$ to 1$×10^{10}$ ions/cm^2. For low-fluence track membranes, one-dimensional scanning is more suitable—the approach currently used at the TR-6 terminal (for 1\$×10$^{\{5\}-1\times 10}${7}\$ ions/cm^2 membranes).

One-dimensional scanning irradiates only in the x-direction while using uniform transmission to distribute the beam across the entire membrane, producing a path identical to the triangular wave pattern—two sets of parallel, equally spaced line segments. With sufficient scanning frequency, the parallel line spacing is v/f. Uniformity is achieved when this spacing is smaller than the beam spot FWHM d. For a 10 mm beam spot FWHM and maximum scanning frequency of 200 Hz, the maximum transmission velocity ensuring uniformity is 2000 mm/s.

In one-dimensional scanning paths, parallel line spacing is v/f. Comparing with Equations (7) and (8) reveals that at identical transmission velocities, one-dimensional scanning produces much smaller parallel line spacing than two-dimensional scanning, indicating superior irradiation uniformity under ideal conditions. However, in practice, one-dimensional scanning suffers more interference from beam intensity variations and unstable beam spot shapes, necessitating further discussion.

3.4 Effect of Beam Spot Size on Scanning Uniformity

For stationary irradiation, Section 3.1 described how larger beam spots yield more uniform scanning results. For transmission irradiation, this requires reexamination. We examine transmission velocities of 400 mm/s, 240 mm/s, and 80 mm/s with Gaussian beam spots of 5 mm, 10 mm, and 20 mm FWHM to determine the minimum required frequencies and frequency combinations for one-dimensional scanning and two-dimensional scanning with 2 Hz frequency difference. Results are shown in :

**** Minimum frequencies (combinations) for achieving 5% uniformity under different transmission velocities and beam spot sizes for one-dimensional scanning and two-dimensional scanning with 2 Hz difference

Transmission velocity	Beam spot 5% radius 5 mm	Beam spot 5% radius 10 mm	Beam spot 5% radius 20 mm
400 mm/s	10 Hz		
400 mm/s		45 Hz & 47 Hz	
240 mm/s		29 Hz & 31 Hz	
80 mm/s		7 Hz & 9 Hz	

The results show that for transmission irradiation, larger beam spots still require lower frequencies to maintain scanning uniformity. Additionally, for all three beam spot sizes, slower transmission velocities require lower frequencies. Under identical transmission velocity and beam spot size conditions, one-dimensional scanning requires lower frequencies than two-dimensional scanning.

3.5 Non-Ideal Beam Spots

Previous assumptions considered strictly Gaussian beam spot intensity distributions. However, actual beam spots deviate from ideal, sometimes significantly. Common non-ideal shapes include double-center, triangular, and elliptical distributions. To simulate these cases, the ideal beam spot distribution g(x,y) can be replaced with the non-ideal distributions g' (x,y) shown in [Figure 4: see original paper] (units in mm):

1) Double-center distribution

2) Triangular distribution

3) Elliptical distribution

[Figure 4: see original paper] shows irradiation results for these three non-ideal beam spots under 400 mm/s constant transmission with 197 Hz one-dimensional scanning and 197 Hz & 199 Hz two-dimensional scanning. Compared with [Figure 2: see original paper], one-dimensional scanning is less affected by non-ideal beam spots, maintaining good overall uniformity, while two-dimensional scanning is more severely impacted. At 197 Hz & 199 Hz, the central region' s relative range far exceeds that of one-dimensional scanning because one-dimensional scanning' s parallel line spacing is smaller than two-dimensional scanning' s. For non-ideal beam spots in transmission irradiation, coupling transmission velocities must still be satisfied. Generally, slower transmission velocities and higher scanning frequencies improve uniformity. For non-Gaussian beam spots, the lowest possible coupling velocity and highest possible coprime frequencies should be selected to mitigate effects.

Non-ideal beam spot size also impacts uniformity. Simulations using the distributions from [Figure 4: see original paper] at half size, original size, and double size examine the minimum frequency combinations for two-dimensional scanning with 2 Hz difference to maintain 5% uniformity at 240 mm/s transmission velocity over a 600 mm × 300 mm range. Results are shown in :

**** Minimum frequencies (combinations) for two-dimensional scanning with 2 Hz difference to achieve 5% uniformity under different beam spot shapes and sizes

Beam spot shape	Half size	Double size
Double-center		
Triangular	Cannot reach 5%, minimum 77 Hz & 79 Hz gives 41%	Cannot reach 5%, minimum 101 Hz & 103 Hz gives 9.6%
Elliptical		29 Hz & 31 Hz

Compared with the 240 mm/s, 2 Hz difference two-dimensional scanning case in , double-center and triangular distributions significantly impact uniformity, increasing the minimum frequency for 5% uniformity by ~20 Hz. Elliptical distribution has less impact because the projection width along parallel paths still exceeds the scanning path spacing, making it nearly unaffected at large beam spot sizes. At small beam spot sizes, none of the three non-ideal shapes achieve 5% uniformity.

3.4 Unstable Beam Intensity

Ion source fluctuations and variations in high-voltage and magnet units along the acceleration path cause beam intensity fluctuations that affect irradiation uniformity. Due to complex beamline structures, beam intensity jumps in actual irradiation are nearly random. Figure 5: see original paper shows a simulated beam intensity vs. time curve using random beam intensity that jumps every 1 s following a normal distribution. With preset intensity = 1 and variance = 1/300, most random values fall within $±$10% of the mean.

[Figure 5: see original paper] shows: (a) random beam intensity jumps within 10% deviation; (b) one-dimensional and (c) two-dimensional scanning irradiation simulation results under random beam intensity fluctuations at different transmission velocities. [Figure 6: see original paper] shows the central region relative range for one- and two-dimensional scanning under beam intensity fluctuations. Under ideal conditions, one-dimensional scanning uniformity is always superior to two-dimensional scanning. However, considering non-Gaussian beam spots and random beam intensity fluctuations, one-dimensional scanning non-uniformity remains consistently high, while two-dimensional scanning uniformity improves at larger n values (lower transmission velocities) because slower transmission increases membrane fluence, offsetting random effects. One-dimensional scanning' s adaptability to beam intensity fluctuations is clearly weaker than two-dimensional scanning because each spatial point in two-dimensional scanning experiences multiple scans, with fluence being the superposition of many beam spots, whereas one-dimensional scanning concentrates fluence in a single band without multiple superposition.

In practical heavy ion track membrane irradiation, the appropriate magnetic scanning method can be determined based on beam intensity fluctuations and required fluence:

1. If beam intensity fluctuations are below tolerable error and required fluence is low, one-dimensional scanning is recommended.

2. If beam intensity fluctuations exceed tolerable error and required fluence is high, two-dimensional scanning is recommended, with the lowest possible coupling velocity, highest scanning frequencies, and smallest frequency differences to maximize uniformity.

3. If beam intensity fluctuations are below tolerable error and required fluence is high, the scheme with better uniformity should be selected based on simulation results.

This study developed a path-integral-based method to simulate swift heavy ion irradiation uniformity. The method can simulate both stationary and transmission target irradiation results and evaluate the impact of beam intensity fluctuations and beam spot shape. Through simulation, the following conclusions and recommendations are obtained:

1. Under conditions where the focused beam spot possesses certain symmetry, larger beam spot size and higher scanning frequency produce more uniform irradiation results for both stationary targets and one-dimensional scanning transmission irradiation.

2. For two-dimensional scanning transmission irradiation, high coprime scanning frequencies in both directions should be selected, and a series of discrete coupling velocities exist that achieve ideal overall irradiation uniformity. These coupling velocities are determined by the y-direction scanning amplitude and the difference between scanning frequencies in the two directions.

3. Due to the existence of coupling velocities in two-dimensional scanning, one-dimensional scanning should be considered for cases with low expected fluence and high transmission velocity. For actual irradiation with non-Gaussian beam spots and unstable beam intensity, the irradiation method and parameters should be determined based on specific conditions such as beam fluctuation and required fluence. This paper provides corresponding recommendations and a simulation model.

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