

Dynamique des faisceaux He^3 , d et p dans le RFQ du projet SPIRAL II

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Introduction

Le Quadripôle Radio Fréquence (RFQ), proposé pour le projet SPIRAL II, est un accélérateur linéaire fonctionnant en régime continu (CW). Il devra produire un courant faisceau de 1 mA pour des Z/A de 1/3 (de l'hélium 3 au Xénon). Pour cela, sa transmission devra être la plus élevée possible, le courant utile de la source étant déjà de l'ordre du milliampère. Le lecteur est supposé être familier avec la dynamique de faisceaux dans un RFQ. Le but de ce rapport est la présentation détaillée, ainsi qu'une justification, des paramètres de ce RFQ afin d'en évaluer la faisabilité.

Le tableau suivant résume le cahier des charges :

Paramètres	Valeurs
Z/A	1/3
Intensité en entrée	1 mA
Intensité en sortie	$\rightarrow 1$ mA
ϵt norm. rms en entrée	$.36 \pi$.mm.mrad
énergie en entrée	20 keV/nucléon
énergie en sortie	1.67 MeV/nucléon
Cycle utile	100 %
Fréquence RF	87.5 MHz
$\Delta p/p$	± 0.5 %
ϵl norm. rms en sortie	$< 1.3 \pi$.mm.mrad

Tableau 1. Cahier des charges.

A ces requêtes, s'ajoute la contrainte d'accélérer également 5 mA de deutons et 10 mA de protons avec la plus grande efficacité.

Le choix de la fréquence est fonction de nombreux paramètres (disponibilité et performance des sources de puissance, faisabilité mécanique, contrôle des modes RF, insertion du RFQ dans le schéma général de la machine...). Du point de vue de la dynamique du faisceau, plus basse est la fréquence meilleure sera la focalisation transverse (proportionnel à la longueur d'onde au carré). Ceci est particulièrement pertinent pour des Z/A de 1/3 et des courants de plusieurs milliampères (10 mA pour les protons). D'un autre côté, des fréquences trop basses induisent des structures volumineuses. Cette étude se base uniquement sur la fréquence de 87.5 MHz (cahier des charges). Nous rediscuterons de ce choix dans la conclusion.

Une autre contrainte dimensionnant le design est la valeur du champ électrique maximum. Cette valeur est un compromis entre la tenue en tension de la cavité et une forte focalisation qui est requise pour un faisceau intense. Le projet LEDA a démontré que 1.8 fois le champ Kilpatrick est une valeur raisonnable [1].

Nous verrons que la compilation de toutes ces contraintes (champ crête, faisceau intense, $Z/A=1/3, 1/2, 1$) permet tout de même de converger vers une structure remplissant le cahier des charges.

Codes pour le design du RFQ

Conception

Un effort important a été réalisé pour produire des logiciels de design pour des linéaires à fort courant au SEA dans le cadre de projet comme IPHI [2]. Pour la conception du RFQ, le code BELENOS est utilisé [3]. Ce code est basé sur une approche analytique pour décrire le processus de capture caractéristique du RFQ. Une description en détail de la méthode n'est pas pertinente dans le cadre de cette étude, mais nous pouvons rappeler les points principaux.

Le faisceau réel est représenté par un paquet à forme ellipsoïdale à symétrie radiale équivalent, avec une densité de charge uniforme et les mêmes paramètres rms. La dynamique du faisceau peut alors être modélisée par des équations enveloppes 2D (R-Z). Afin de minimiser les pertes, la taille transverse du faisceau est imposée constante. La conséquence immédiate est l'annulation de la dérivée seconde en radial. L'évolution de la taille longitudinale (mise en paquet) peut être forcée à l'aide d'une fonction arbitraire. Les deux seules inconnues restant dans ce système à deux équations sont les forces requises pour obtenir un tel processus.

Ceci est l'essentiel de la méthode. Les limites dans la façon de produire les forces requises proviennent du champ crête et de considérations mécaniques et géométriques. Par exemple, afin de simplifier le refroidissement, BELENOS maintient la tension inter électrode constante le long de la structure.

Compte-tenu du cahier des charges pour le RFQ de SPIRAL II, le code BELENOS a été utilisé pour l'accélération d'un faisceau d'hélium 3 d'une dizaine de milliampères avec une émittance de $0.4 \pi \cdot \text{mm} \cdot \text{mrad}$. Nous verrons que ces marges permettent de satisfaire les différentes requêtes.

Transport

La validation du design est réalisée à l'aide du code de transport TOUTATIS [4]. Ce code utilise le temps comme paramètre indépendant pour une intégration précise du mouvement. Les champs sont calculés dans des grilles 3D en utilisant les méthodes multigrilles. Le schéma permet de prendre en compte :

- la charge d'espace
- les effets d'image
- le profil exact des électrodes

Les défauts mécaniques et discontinuités de la structure peuvent ainsi être simulées.

Paramètres du design

En compilant toutes les doléances du cahier des charges détaillé dans la section précédente, la phase de conception a permis de converger vers la structure décrite par le tableau suivant :

Paramètre	Valeurs
Longueur	13,832 m
Ouverture minimum (a)	6,88...7 mm
Ouverture moyenne (R0)	4,93...7 mm
Modulation (m)	1...1,79
Fréquence	87,5 MHz
Tension ($Z/A=1/3$)	100 kV
Champ crête ($Z/A=1/3$)	1,65..1,74 E_k
Phase synchrone	-90...-30 deg

Tableau 2 : Principaux paramètres.

L'évolution de plusieurs de ces paramètres est représentée par les figures 1 à 3 . La figure 4 montre l'évolution du champ crête sur la surface des pôles le long du RFQ. La valeur maximum est 1,74 fois le champ Kilpatrick. Il est intéressant de noter que cette valeur est inférieure à la valeur utilisée pour les RFQ de LEDA (LANL) et de Chalk River, ces deux RFQ ayant fonctionné en mode continu. Des champs crêtes de 2,1 fois le champ Kilpatrick ont d'ailleurs été atteints à Chalk River. L'évolution détaillée du design est présentée en fin de ce document sous la forme d'un fichier d'entrée de TOUTATIS.

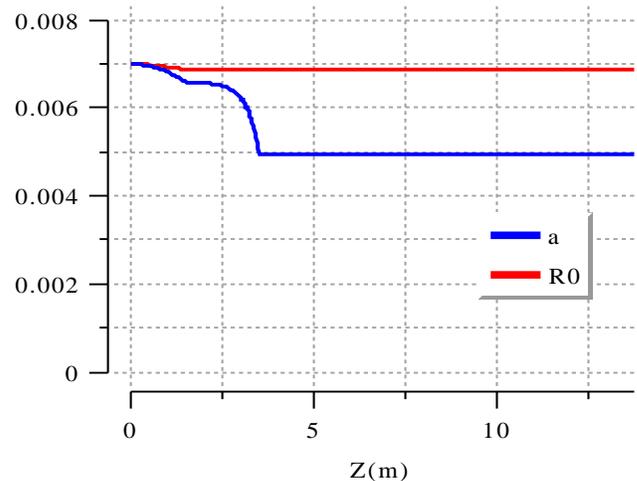


Figure 1: Evolution de l'ouverture minimum et moyenne.

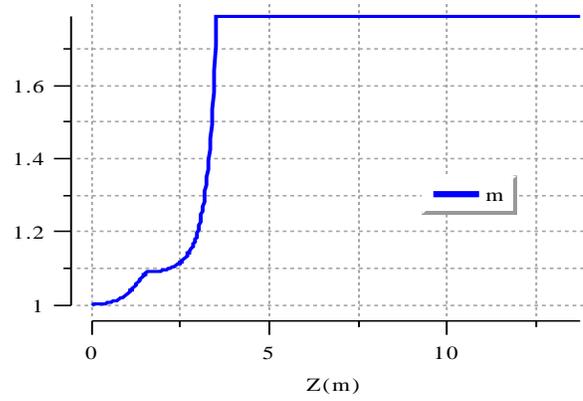


Figure 2: Evolution de la modulation.

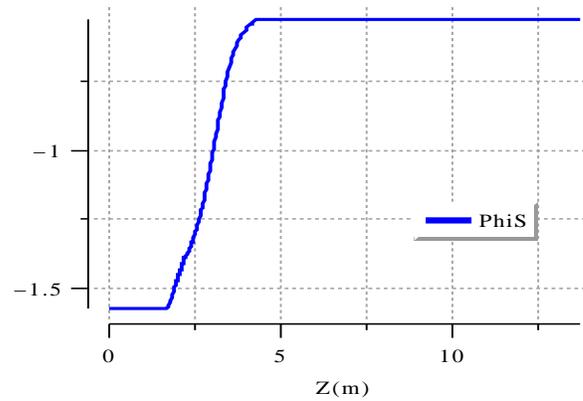


Figure 3: Evolution de la phase synchrone pour $Z/A=1/3$ (en radians).

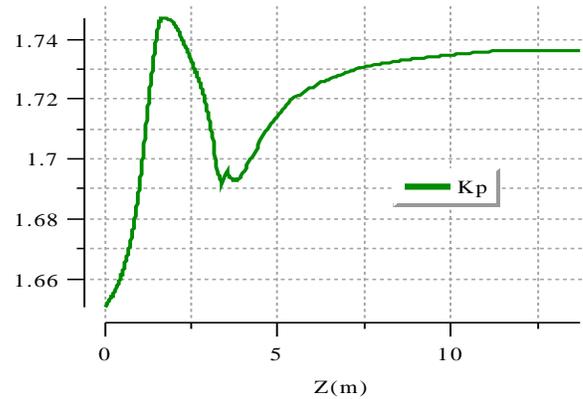


Figure 4: Evolution du champ crête.

Simulations pour chaque espèce

Cette section décrit les résultats obtenus pour chacune des configurations. La valeur de la tension est réévaluée pour chacune des espèces ainsi que les paramètres de Twiss

du faisceau en entrée de RFQ. La même émittance en entrée, $0,4 \pi \cdot \text{mm} \cdot \text{mrad}$, a été utilisée pour tous les calculs.

Helium 3 ($Z/A=1/3$)

C'est pour cette configuration que la structure a été optimisée. Le tableau 3 compile différents paramètres pour cette simulation. La figure 5 montre la distribution en sortie du RFQ dans l'espace des phases. Le tableau 4 rassemble plusieurs résultats.

Paramètres	Valeurs
Tension	100 kV
Champ crête (E_k)	1,74
α	1.587
β	10.106 cm/rad
Courant	1 mA

Tableau 3 : Paramètres caractéristiques en entrée pour $Z/A=1/3$.

Paramètres	Valeurs
Courant	1 mA
Transmission	100 %
ϵ_x norm. rms	$0,4 \pi \cdot \text{mm} \cdot \text{mrad}$
α_x	-1,4
β_x	21,61 cm/rad
ϵ_y norm. rms	$0,4 \pi \cdot \text{mm} \cdot \text{mrad}$
α_y	1,51
β_y	23,38 cm/rad
ϵ_z norm. rms	0,12 deg.MeV
α_z	-0,005
β_z	199 deg/MeV
Energie	4,982 MeV
$\Delta p/p$	$\pm 0,8\%$

Tableau 4 : Principaux résultats en sortie.

Il est intéressant de remarquer que la transmission est très élevée puisqu'aucune des 50 000 macro-particules n'a été perdue, soit environ 100 % de transmission. Le lecteur pourrait s'étonner de lire "environ" 100 % alors que le résultat brute donne exactement 100 %. Il y a deux raisons à cela. La première est que le principe même de représentation du faisceau à l'aide de macro-particules ne permet pas de prédire avec exactitude un zéro défaut et ce, quelque soit le nombre de macro-particules. La deuxième raison est qu'aucune erreur n'a été introduite dans le calcul et cette simulation n'est donc pas conforme à la réalité. Le résultat est cependant très satisfaisant.

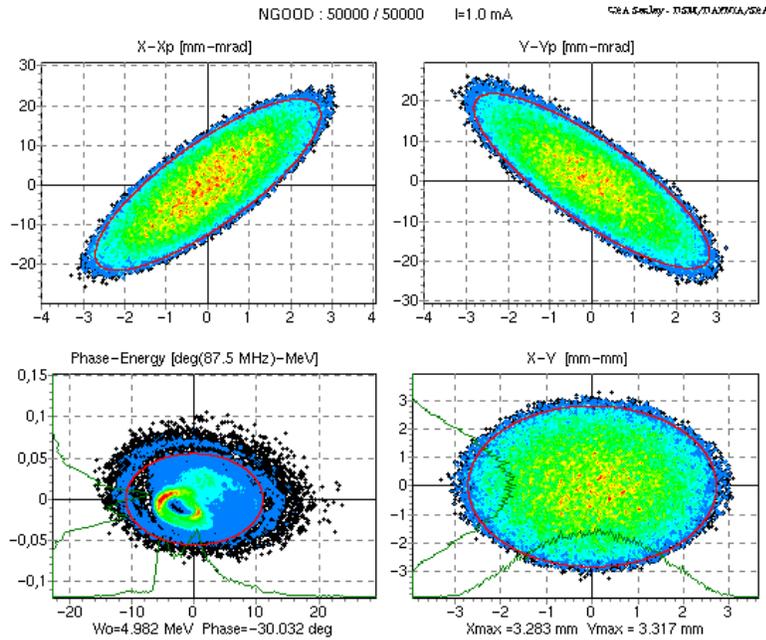


Figure 5: Distribution du faisceau en sortie dans l'espace des phases.

Les figures 6 et 7 montrent l'évolution des enveloppes transverse et longitudinale du faisceau. L'évolution de l'énergie cinétique est tracée sur la figure 8.

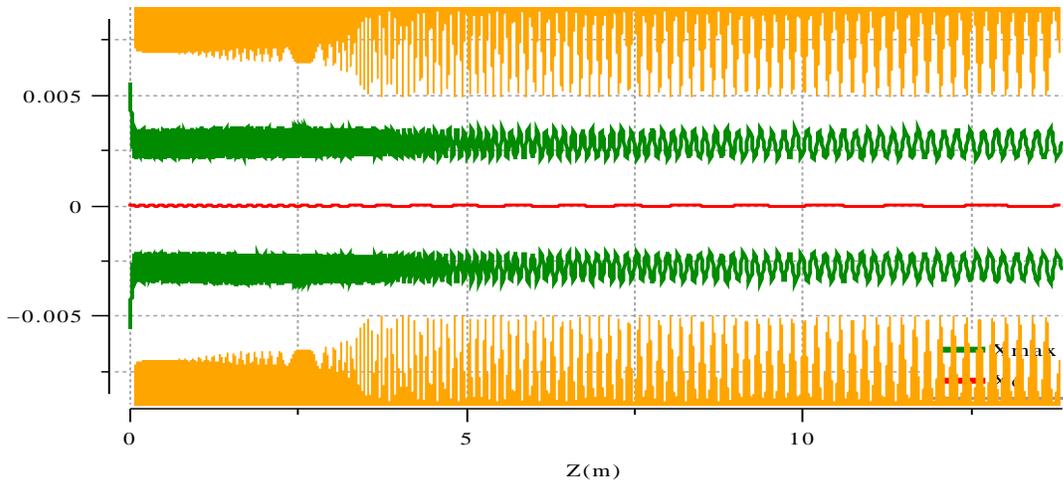


Figure 6: Evolution de l'enveloppe horizontale en mètre avec tracé des pôles.

Les figures 9 à 11 montrent l'historique de la simulation pour les avances de phases avec et sans charge d'espace et la dépression du nombre d'onde qui en résulte. Sur la figure 12 est tracée l'évolution des emittances rms normalisées.

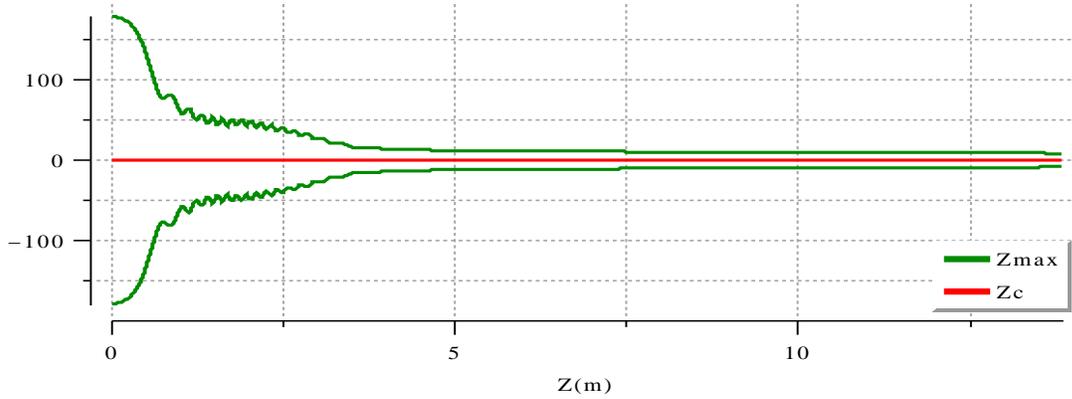


Figure 7: Evolution de l'enveloppe longitudinale en deg.

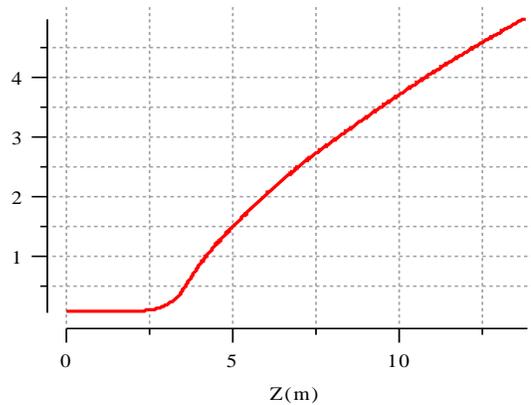


Figure 8: Evolution de l'énergie cinétique en MeV.

Deuton

Le lecteur pourrait s'attendre à une baisse de la tension qui compenserait exactement le gain en Z/A . Mais afin de compenser l'augmentation du courant (5 mA), un compromis est nécessaire. La tension est donc abaissée de 20 %. Le tableau 5 suivant compile différents paramètres pour cette configuration. La figure 13 montre la distribution en sortie du RFQ dans l'espace des phases. Le tableau 6 rassemble plusieurs résultats.

Paramètres	Valeurs
Tension	80 kV
Champ crête	$1,32...1,39 E_k$
α	1.887
β	11.074 cm/rad
Courant	5 mA

Tableau 5 : Paramètres caractéristiques en entrée pour les deutons.

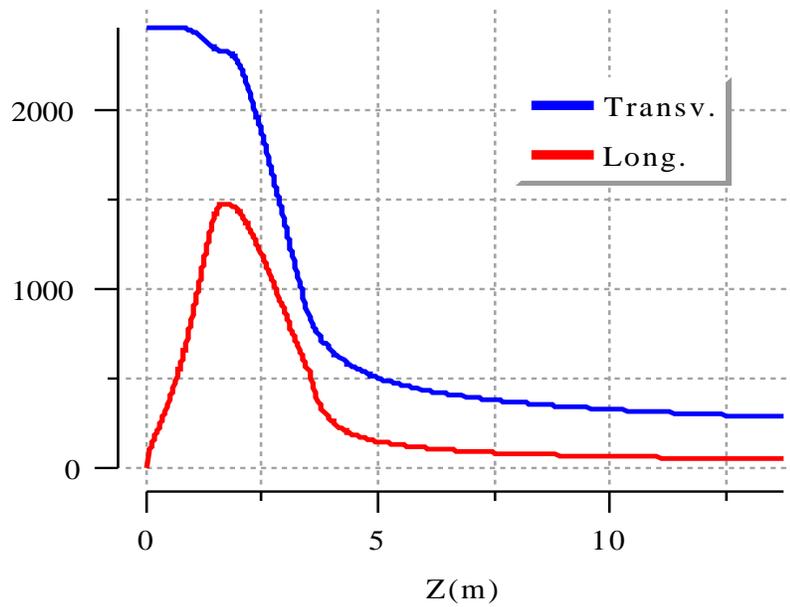


Figure 9: Evolution de l'avance de phase en deg/m à zero courant.

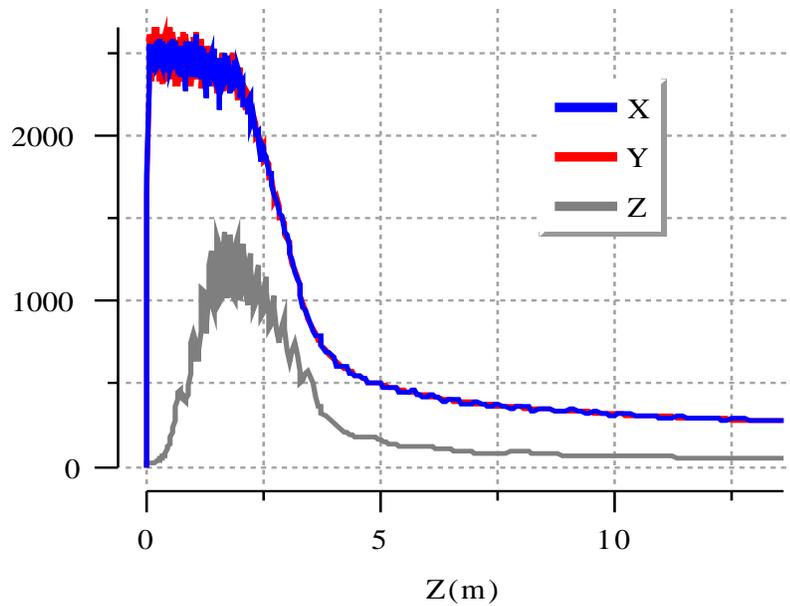


Figure 10: Evolution de l'avance de phase en deg/m avec charge d'espace.

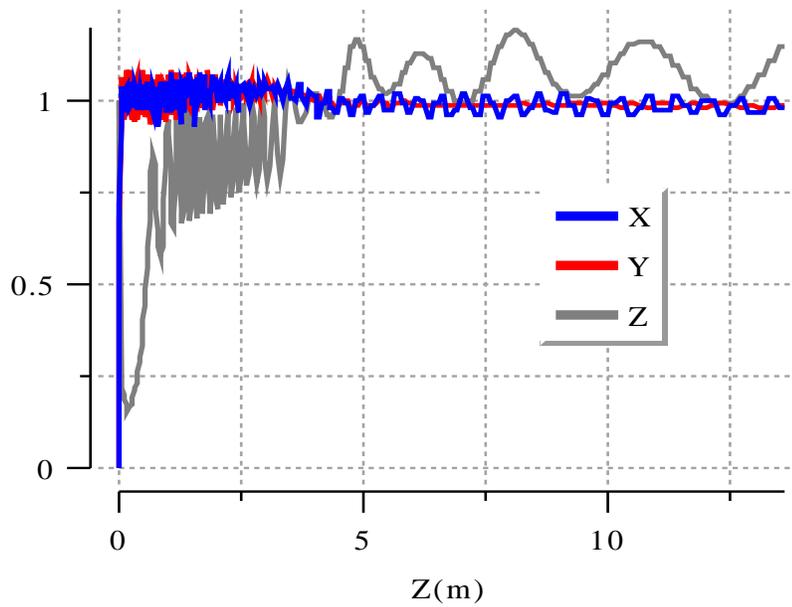


Figure 11: Evolution de la dépression du nombre d'onde.

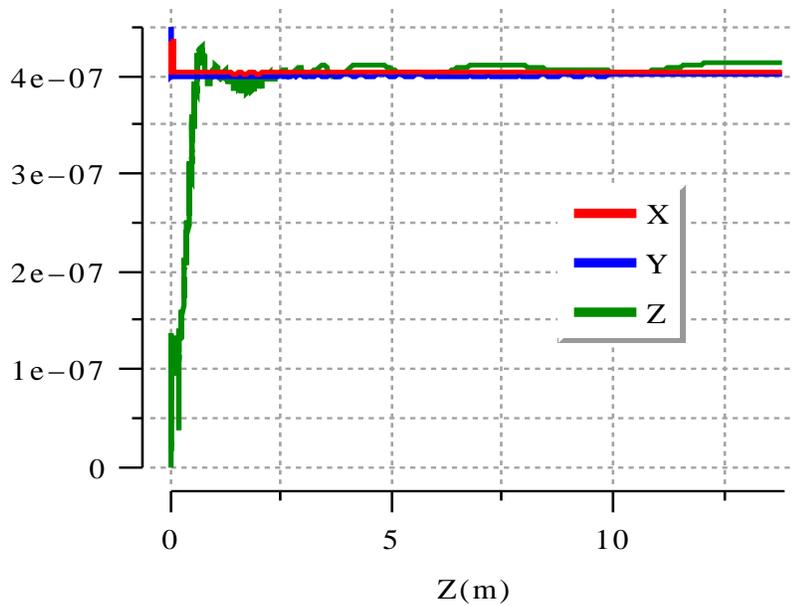


Figure 12: Evolution des emittances rms normalisées en π .m.rad.

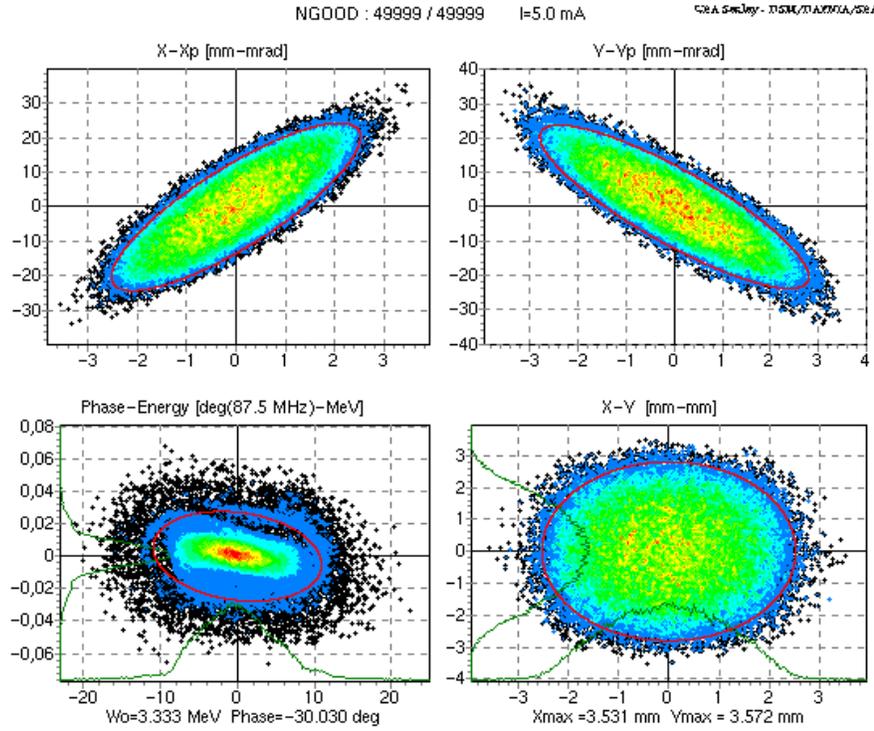


Figure 13: Distribution du faisceau en sortie dans l'espace des phases.

Paramètres	Valeurs
Courant	5 mA
Transmission	100 %
ϵ_x norm. rms	$0,4 \pi$.mm.mrad
α_x	-1,5
β_x	18,71 cm/rad
ϵ_y norm. rms	$0,4 \pi$.mm.mrad
α_y	1,67
β_y	22,97 cm/rad
ϵ_z norm. rms	0,06 deg.MeV
α_z	0,194
β_z	402 deg/MeV
Energie	3,33 MeV
$\Delta p/p$	$\pm 0,7$ %

Tableau 6 : Principaux résultats en sortie.

L'impact de la charge d'espace est particulièrement visible dans le plan longitudinal. La transmission est toujours de 100 %. Les remarques émises pour l'hélium 3 concernant la transmission demeurent valables.

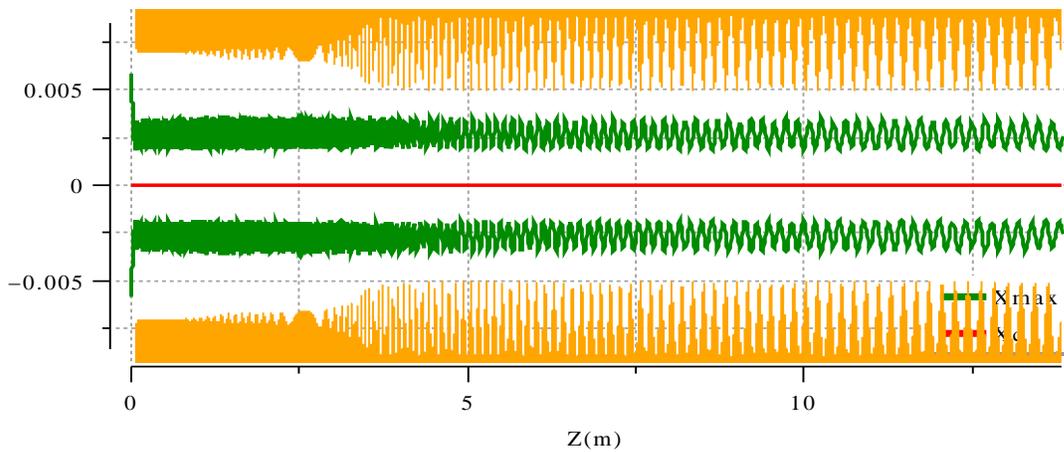


Figure 14: Evolution de l'enveloppe horizontale en mètre avec tracé des pôles.

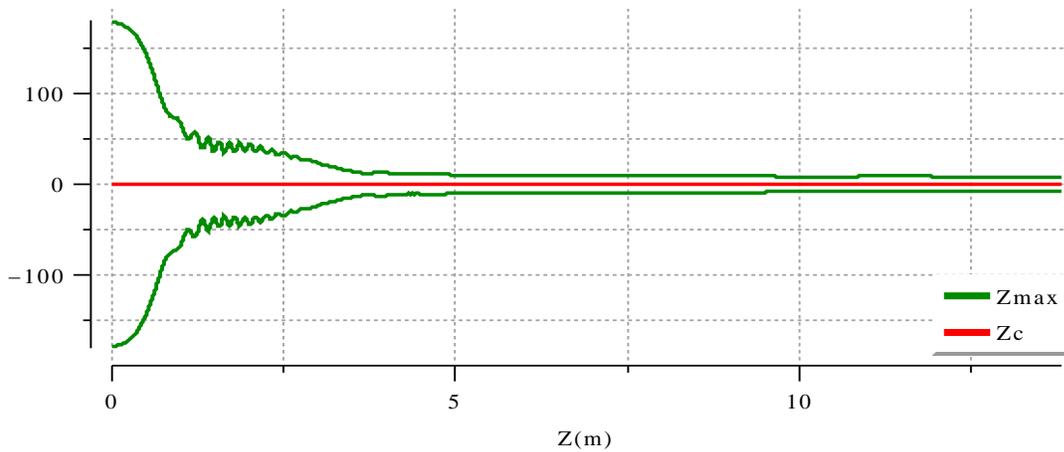


Figure 15: Evolution de l'enveloppe longitudinale en deg.

Les figures 14 et 15 montrent l'évolution des enveloppes transverse et longitudinale du faisceau. Les figures 16 à 20 montrent l'évolution de plusieurs quantités physiques.

Proton

Pour la baisse de tension, le cas des protons est très similaire à celui des deutons. Une baisse de 40 % est choisie. Le tableau 7 compile les paramètres pour cette simulation. La figure 21 montre la distribution en sortie du RFQ dans l'espace des phases. Le tableau 8 rassemble plusieurs résultats.

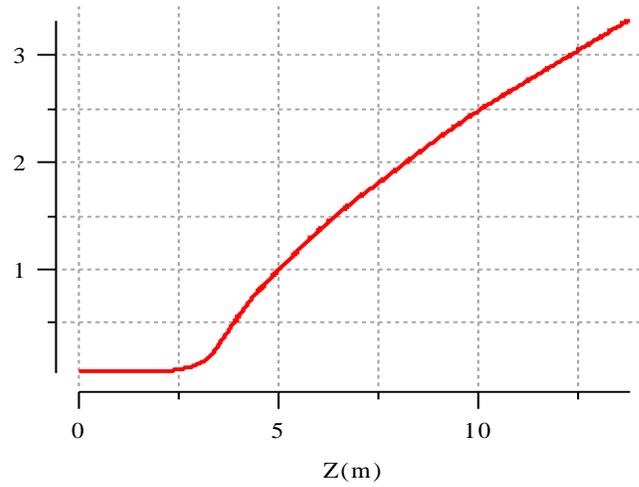


Figure 16: Evolution de l'énergie cinétique en MeV.

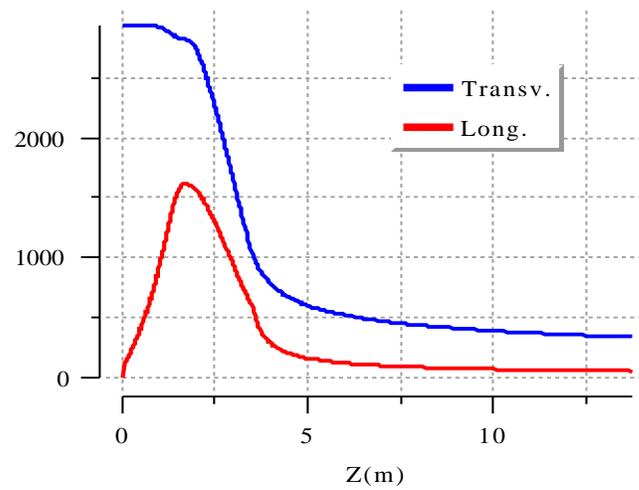


Figure 17: Evolution de l'avance de phase en deg/m à zero courant.

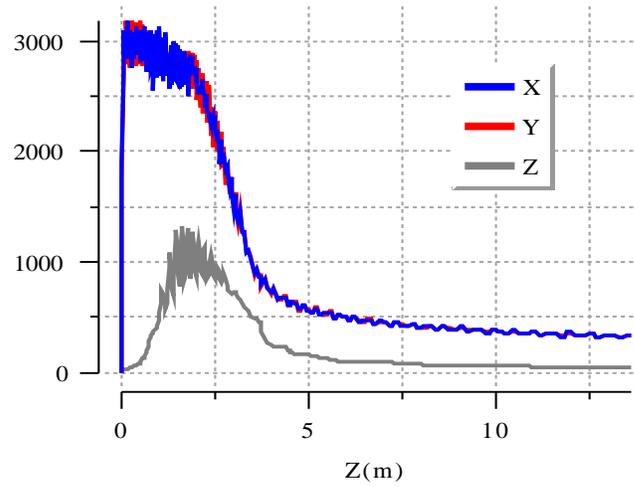


Figure 18: Evolution de l'avance de phase en deg/m avec charge d'espace.

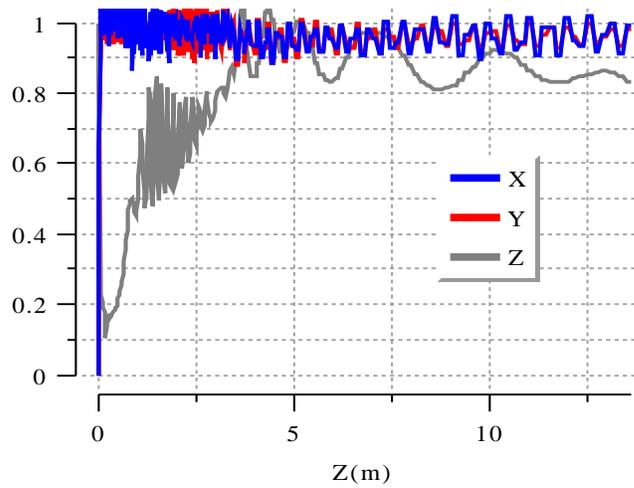


Figure 19: Evolution de la dépression du nombre d'onde.

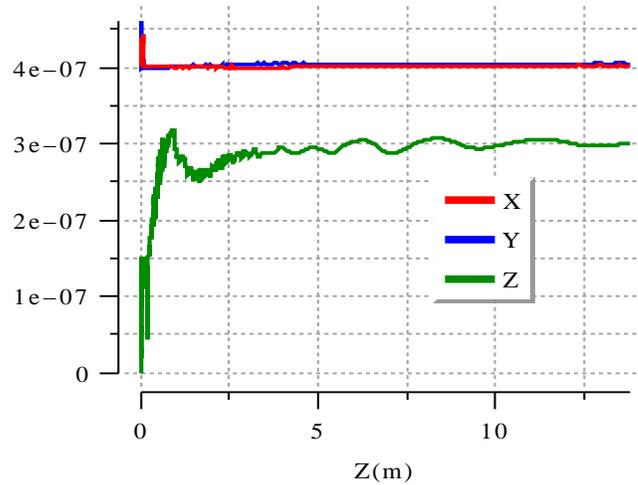


Figure 20: Evolution des emittances rms normalisées en $\pi.m.rad$.

Paramètres	Valeurs
Tension	60 kV
Champ crête	0,99...1,044 E_k
α	2.64
β	13.581 cm/rad
Courant	10 mA

Tableau 7 : Paramètres caractéristiques en entrée pour les protons.

Paramètres	Valeurs
Courant	10 mA
Transmission	100 %
ϵ_x norm. rms	0,44 $\pi.mm.mrad$
α_x	-1,28
β_x	9,25 cm/rad
ϵ_y norm. rms	0,45 $\pi.mm.mrad$
α_y	2,02
β_y	24,08 cm/rad
ϵ_z norm. rms	0,05 deg.MeV
α_z	-0,231
β_z	812 deg/MeV
Energie	1,669 MeV
$\Delta p/p$	$\pm 0,9$ %

Tableau 8 : Principaux résultats en sortie.

Pour pouvoir obtenir une bonne capture, il a fallu maintenir la tension à un niveau assez élevée. L'avance de phase transverse qui en résulte est assez élevée. Si bien que

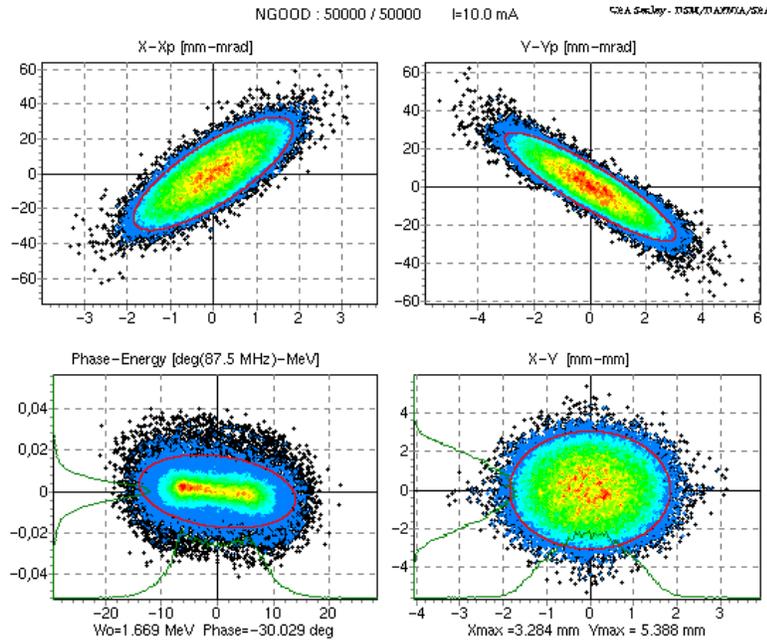


Figure 21: Distribution du faisceau en sortie dans l'espace des phases.

certaines particules ont gagné suffisamment d'énergie radiale pour créer un faible halo. Il serait intéressant, pour les protons, d'opérer à une fréquence plus élevée. Ceci permettrait de relaxer le transverse sans sacrifier le longitudinal. Les résultats demeurent tout de même satisfaisants.

Les figures 22 et 23 montrent l'évolution des enveloppes transverse et longitudinale du faisceau. L'évolution de l'énergie cinétique est tracée sur la figure 24. Les figures 25 à 28 montrent l'évolution des autres paramètres.

Conclusion

Cette étude démontre la faisabilité d'une structure RFQ répondant au cahier des charges. Le point le moins satisfaisant reste la dispersion en quantité de mouvement du paquet en sortie ($\Delta p/p$). Cette dispersion est de l'ordre de 1 % pour chaque cas, soit un facteur deux par rapport au 0,5 % requis. Il faut noter que cette requête est assez élevée pour un RFQ.

Par ailleurs tous les autres demandes ont été satisfaites par la structure présentée dans ce document. Il serait pourtant intéressant d'explorer les possibilités à 175 MHz. Cette fréquence permettrait d'obtenir une cavité moins volumineuse et un meilleur rendement pour les protons sans forcément pour autant sacrifier les Z/A de 1/3.

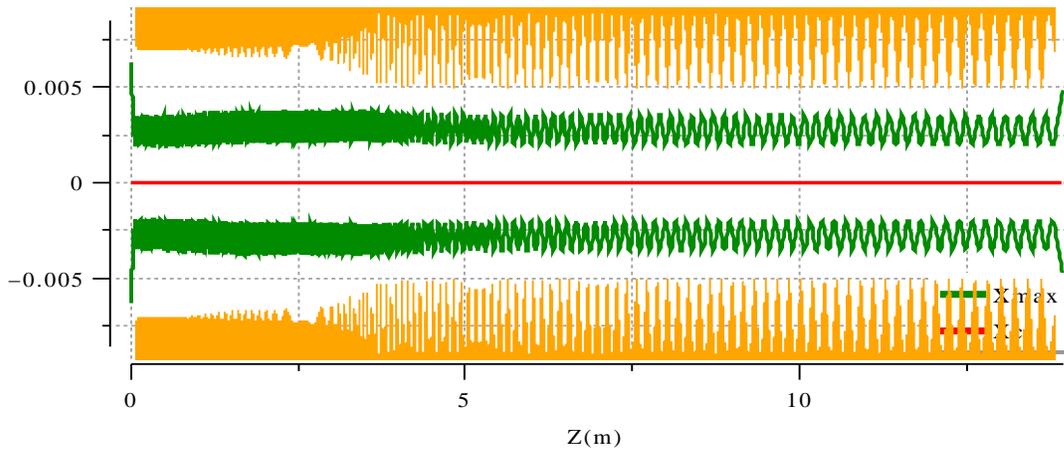


Figure 22: Evolution de l'enveloppe horizontale en mètre avec tracé des pôles.

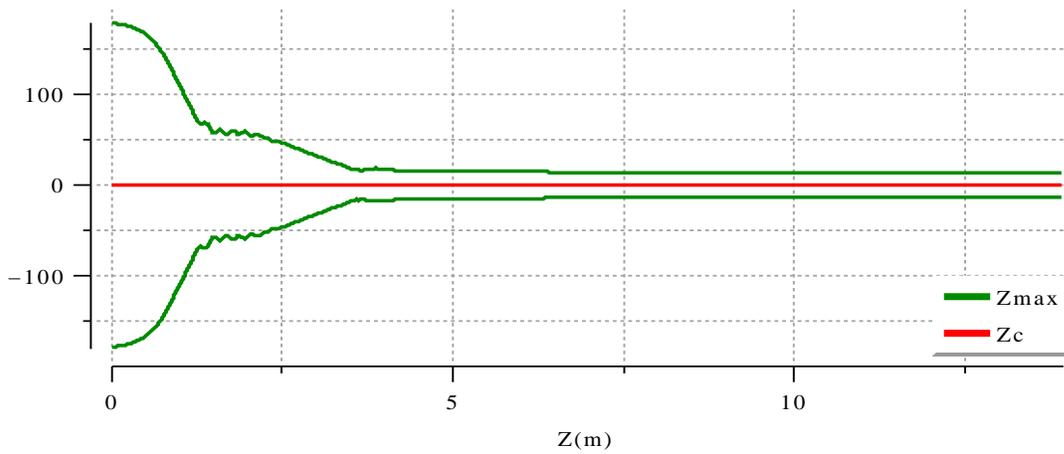


Figure 23: Evolution de l'enveloppe longitudinale en deg.

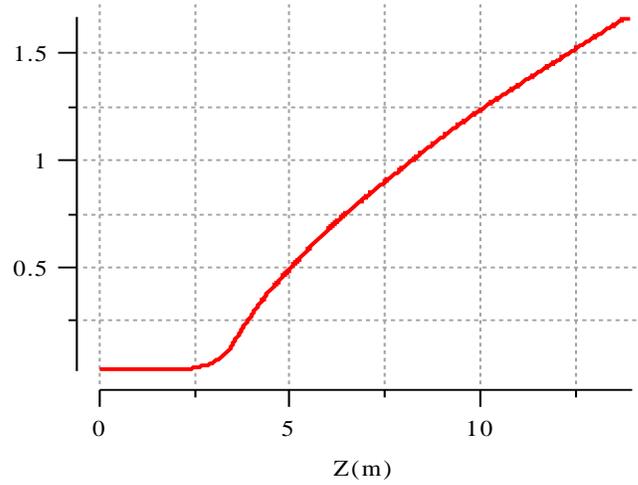


Figure 24: Evolution de l'énergie cinétique en MeV.

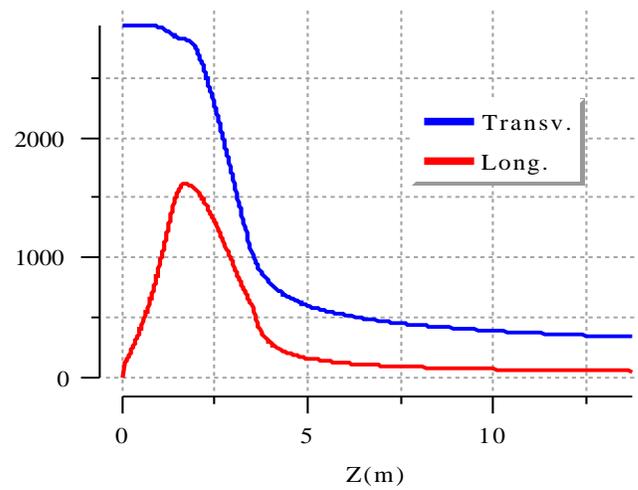


Figure 25: Evolution de l'avance de phase en deg/m à zero courant.

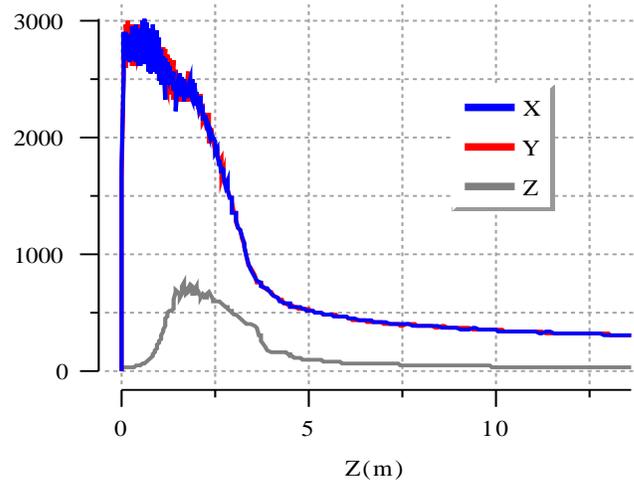


Figure 26: Evolution de l'avance de phase en deg/m avec charge d'espace.

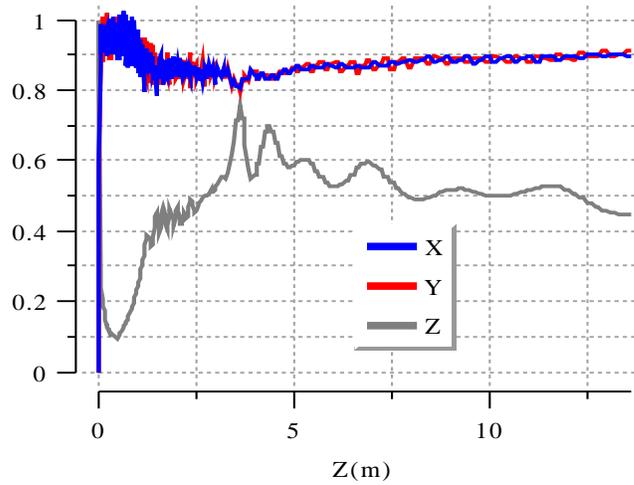


Figure 27: Evolution de la dépression du nombre d'onde.

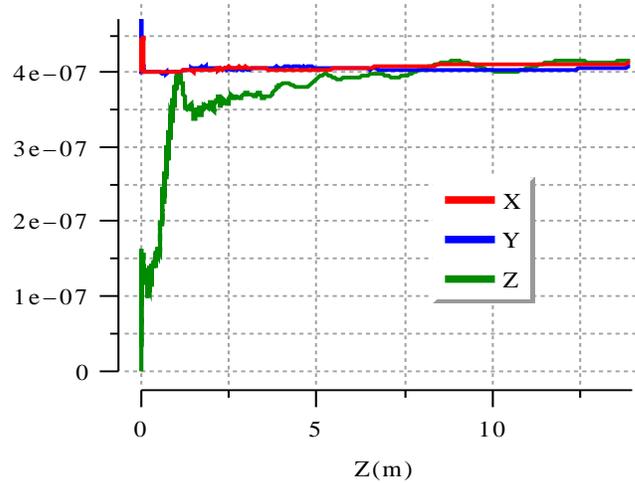


Figure 28: Evolution des emittances rms normalisées en $\pi.m.rad.$

Description détaillée du design (fichier d'entrée de TOUTATIS)

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theSpecialLostFlag 0
theAcceleratedFlag 1
theEquivalentBeamFlag 0
theNewPotFlag 0
theLossesCriteriaFlag 0
theSavingRunFlag 0
theRunCartoonFlag 0
theGeometryFileFlag 0 0
WallAperture 0.006
SemiWidthWall 0.0025
diaphragme 1.
theDirectionFlag 1.
LBECompensation 1.0
theStartingModulation -1
theRhoR0RatioInRMS 1
GapRMS 0.01679382
GapFFS 0.004705
thespacechargeperiod 1
theextfieldperiod 1
theTrancellFlag 1
theSpeciesFlag 0
theDistribution k none
NbRMSCell 6
theBreakOutAngle 10.
theAccuracyFlag 2
NStep 8
NumberOfCouplingGap 0
End
RHO 0.75
linac 1 0.06 87.5 3.01603 1.0
trancell
( ) Tank 1 Length= 11 cm, 414 cells
Cell cl tl curtl curll
0 100.000000 0.060000 0.006535 1.650717 0.000000 -90.000000 0.700000 1.000000 0.700000 0.525000 0.000000 1.119588 0.000000 0.000000 0.000000
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scheff 1.0
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