

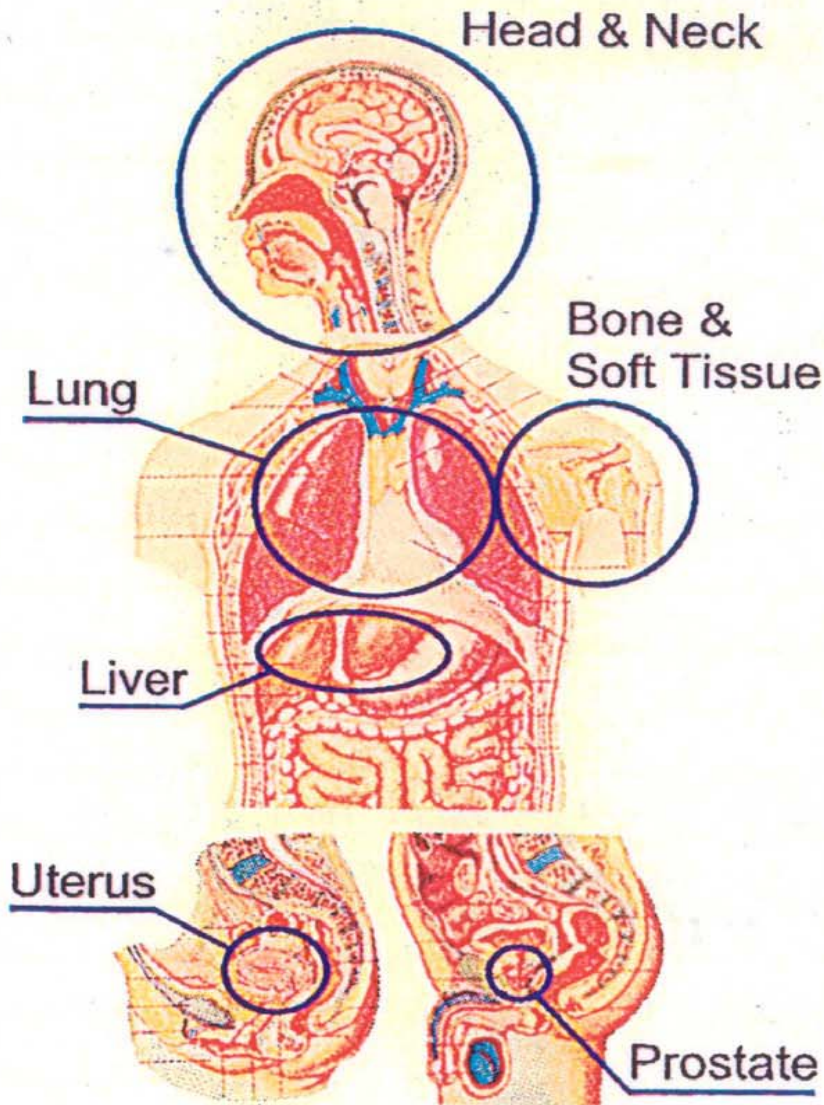
Development of Compact Medical FFAG Accelerator at NIRS

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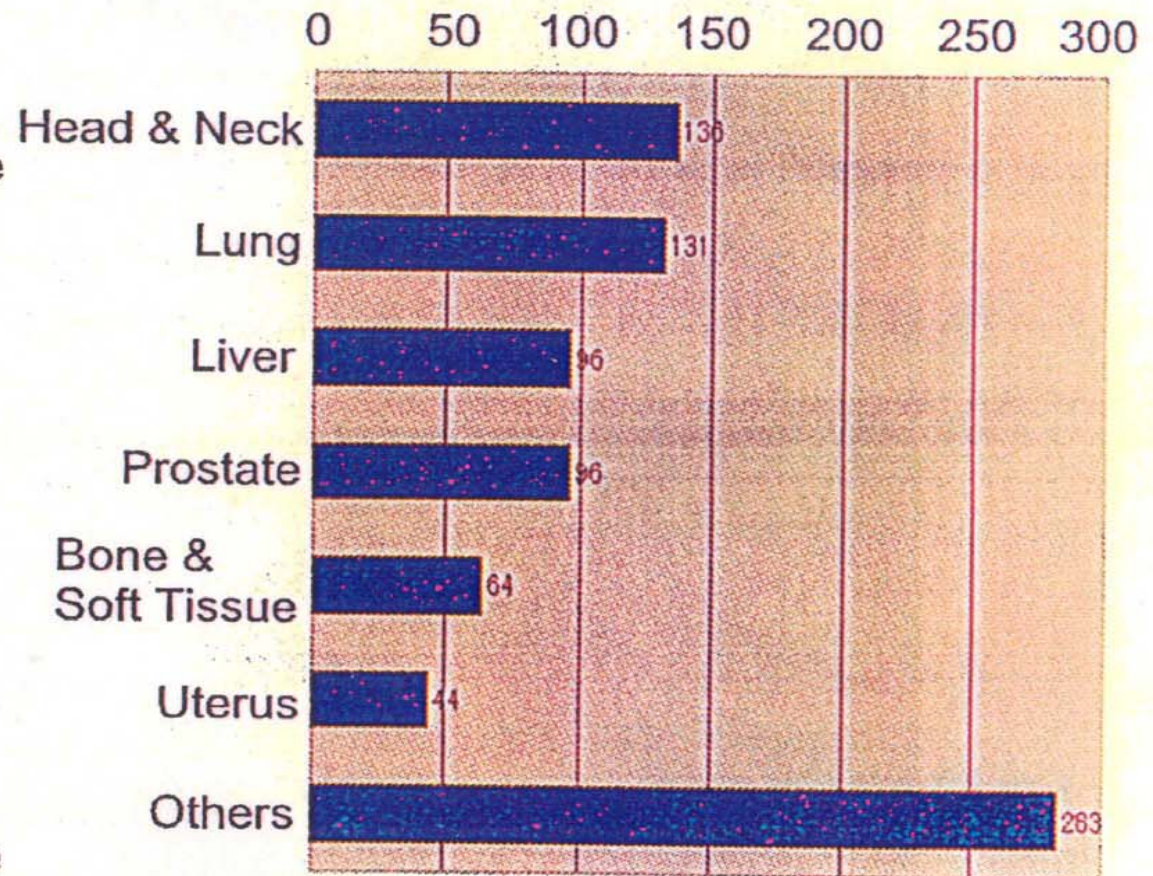
Abstract

Based upon the success of cancer treatment using carbon beam at the Heavy Ion Medical Accelerator in Chiba (HIMAC), we are currently investigating the potential clinical usage of a compact Fixed Field Alternating Gradient (FFAG) accelerator, which is aimed to accelerate carbons up to 400 MeV/u. Since the static magnetic field of FFAG allows us to increase its repetition rate, and a high gradient accelerating cavity has also become available, our satisfactory clinical results at HIMAC are now being extended to the revival of an FFAG machine for medical use. In the present talk, I briefly present our current design status.

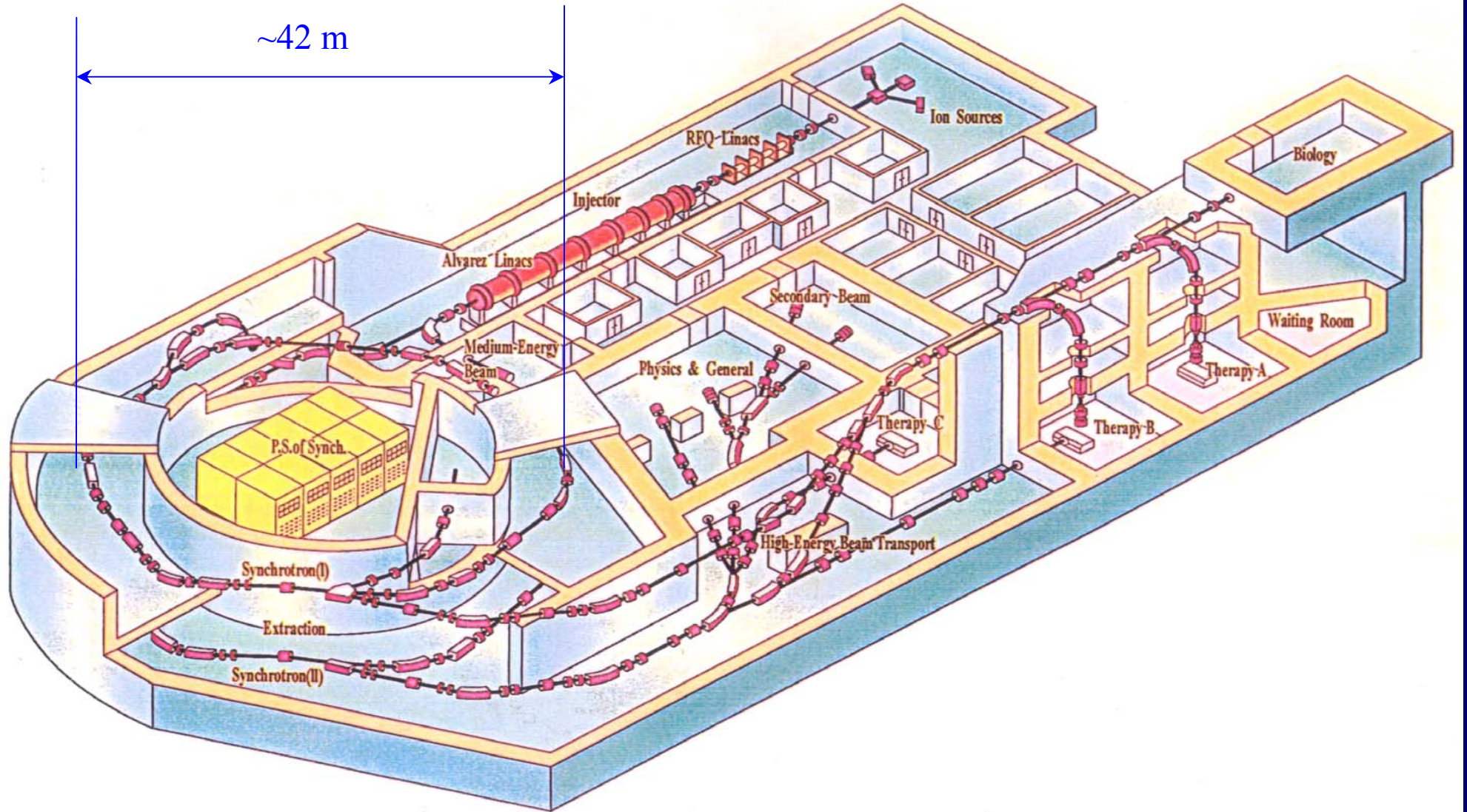
Cancers treated with HIMAC



No. of Patients (Feb., 2001)



HIMAC at NIRS



Objectives

- Compact Size
- High Efficiency & Low Cost
- Simple to operate
- Stable and Reliable

Present Parameters

Particle: C^{4+} \longrightarrow C^{6+}

Charge-to-Mass Ratio: $1/3$ \longrightarrow $1/2$

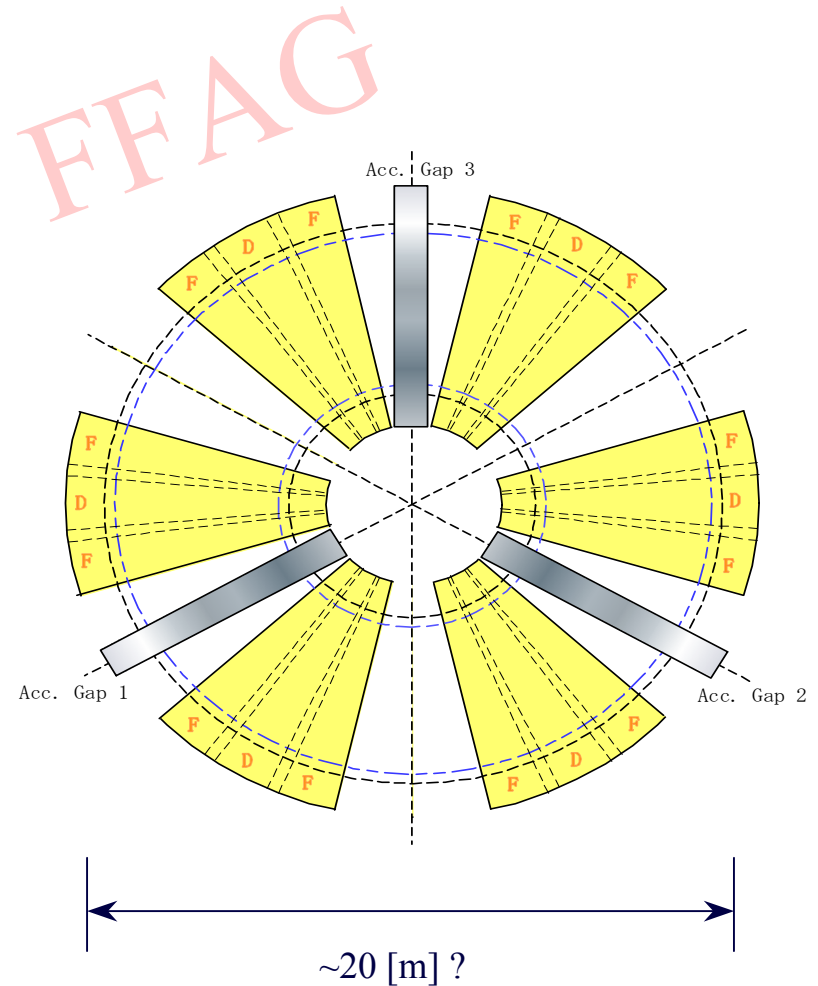
Injection Energy: 40 keV/u (Br=0.086 Tm)

Extraction Energy: 400MeV/u (Br=6.34 Tm)

of Particles: $\sim 2 \times 10^9$ pps

Repetition Rate: 100Hz or up

Configuration: Injector FFAG + Main FFAG

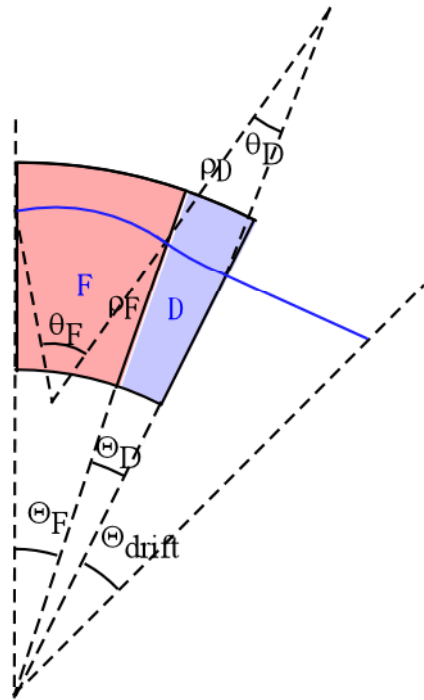


Preliminary Search for Minimal Parameter Set

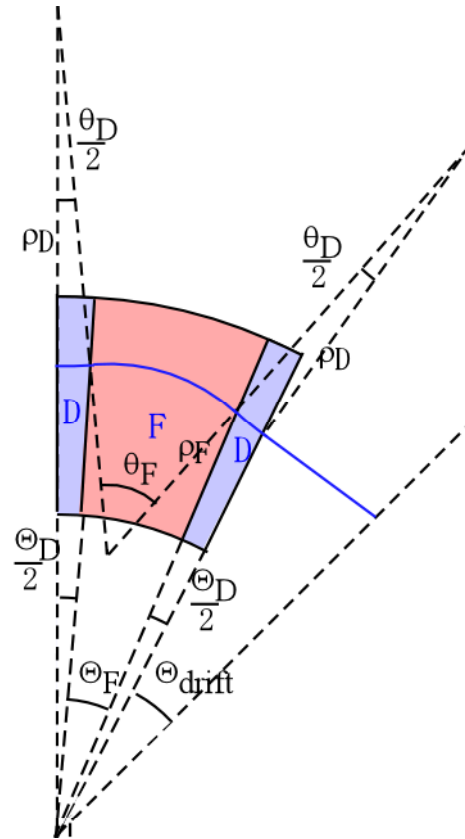
- Small ring size
 - lower circumference (size) factor $\langle r \rangle / \rho_F$
where $\langle r \rangle$: average orbit radius
 ρ_F : radius of curvature at maximum magnetic field (F)
- Short orbit excursion
 - higher field-index k
- Small magnet size
(not necessarily equivalent to “short orbit excursion”)
 - depends on both field-index k & $\langle R \rangle / \rho_F$
- Large drift-space with minimal dead-space
 - larger drift-space angle per sector Θ_{drift}

Investigation of Radial Sector Types in FFAG

F-D Doublet



D-F-D Triplet

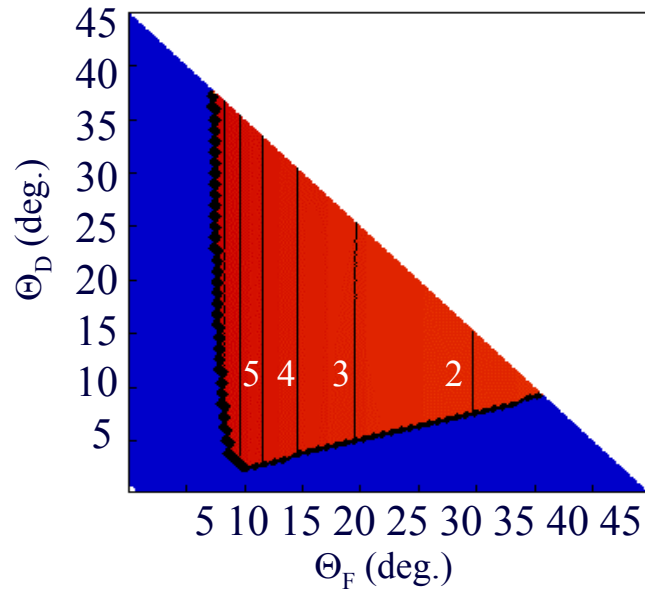


- Θ_F : Open angle for F magnet
- Θ_D : Open angle for D magnet
- Θ_{drift} : Open angle for drift-space
- θ_F : Bending angle for F magnet
- θ_D : Bending angle for D magnet
- ϕ_F : Drift-space angle between F magnets
- ϕ_D : Drift-space angle between D magnets
- ρ_F : Radius of curvature for F
- ρ_D : Radius of curvature for D

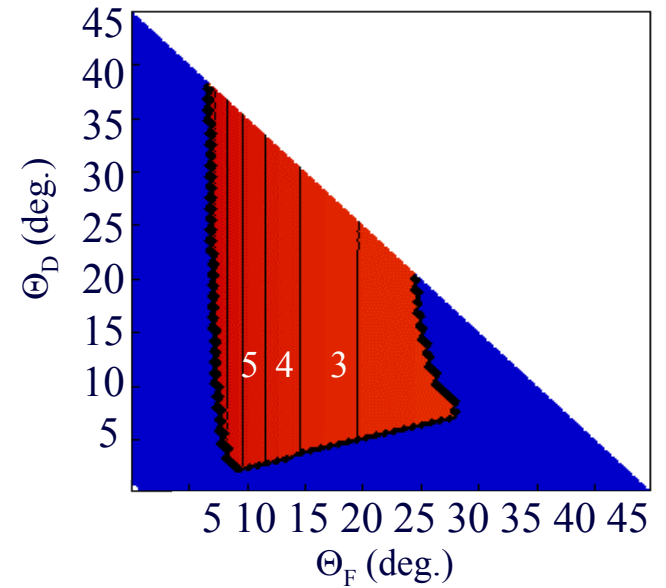
Field-Index k & Stability

(D-F-D Triplet ; $N=8$; $\theta_F=60^\circ$)

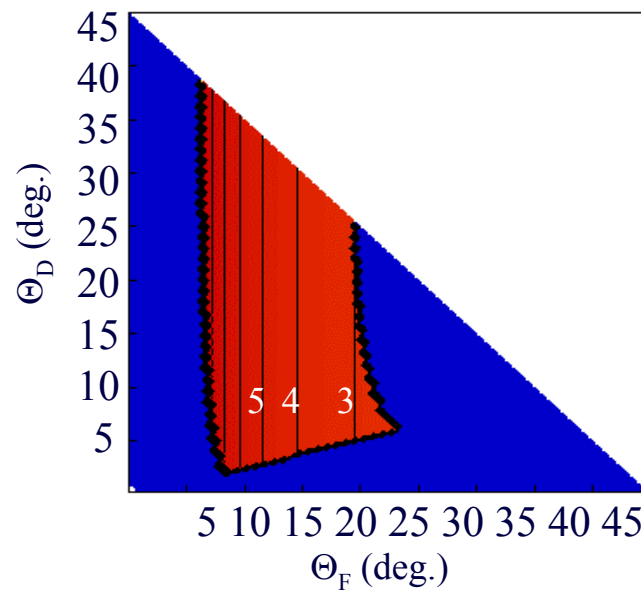
$k=2$



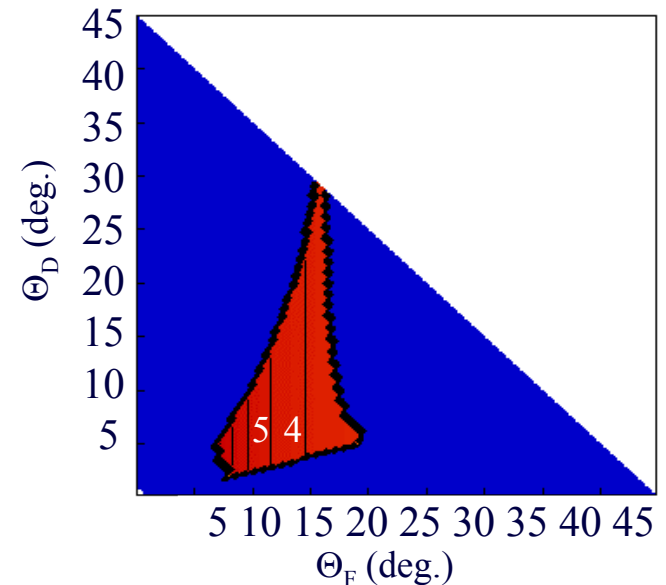
$k=3$



$k=4$



$k=5$



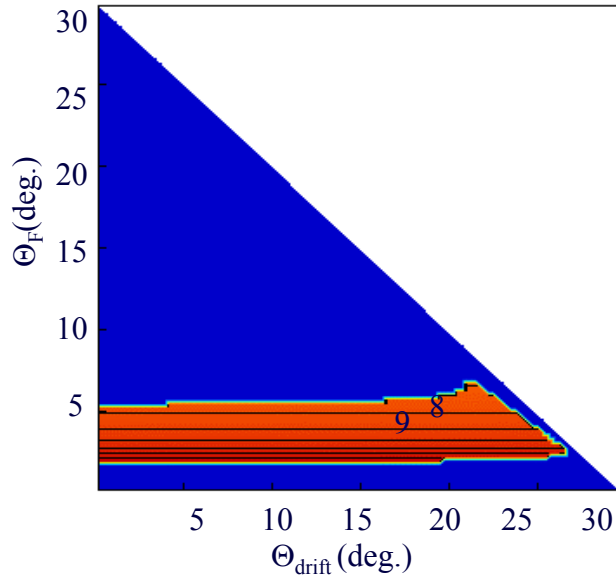
Contour: $\langle r \rangle / \rho_F$

Stable Region

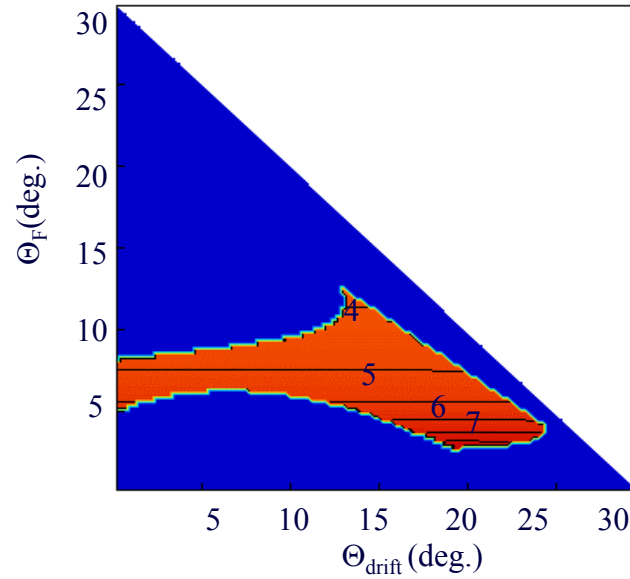
F-D Doublet Sector Type with N= 12

(Field-index : k=10.0)

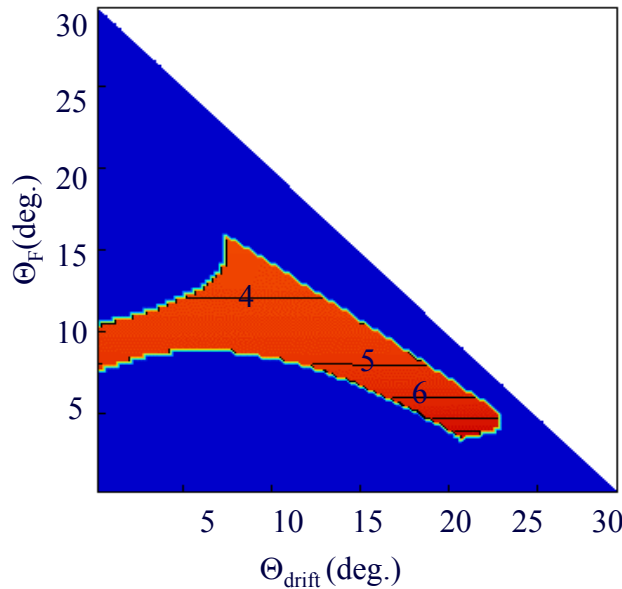
$\theta_F=40^\circ$



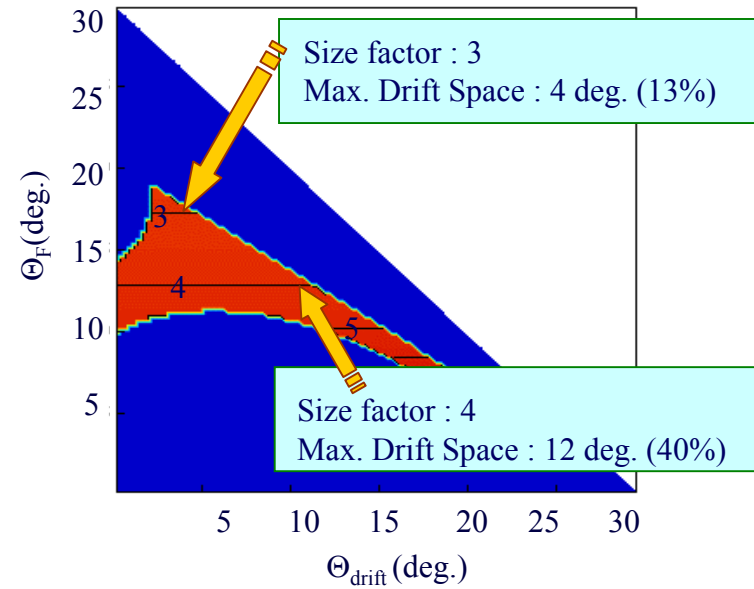
$\theta_F=46^\circ$



$\theta_F=49^\circ$



$\theta_F=52^\circ$



Contour:

$\langle r \rangle / \rho_F$



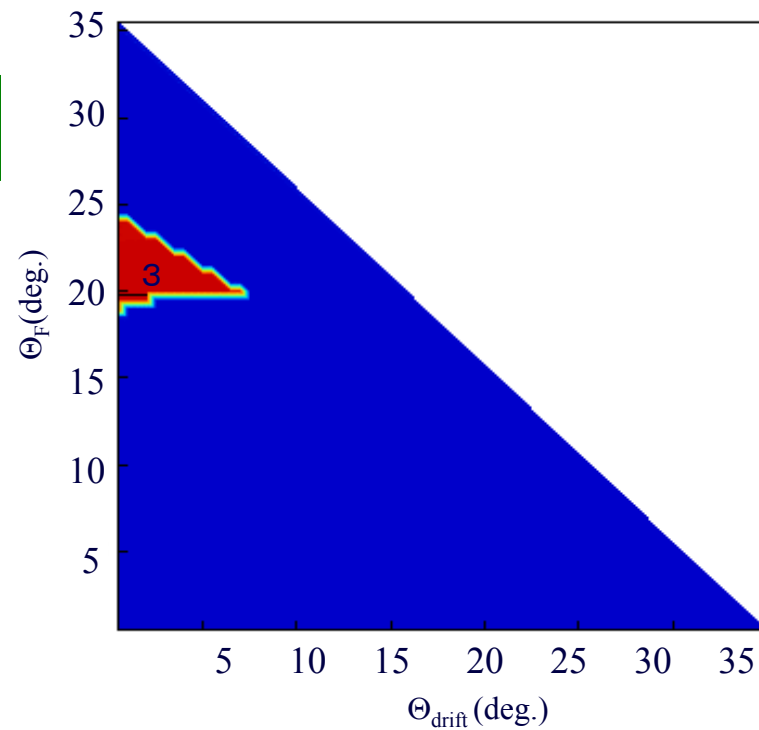
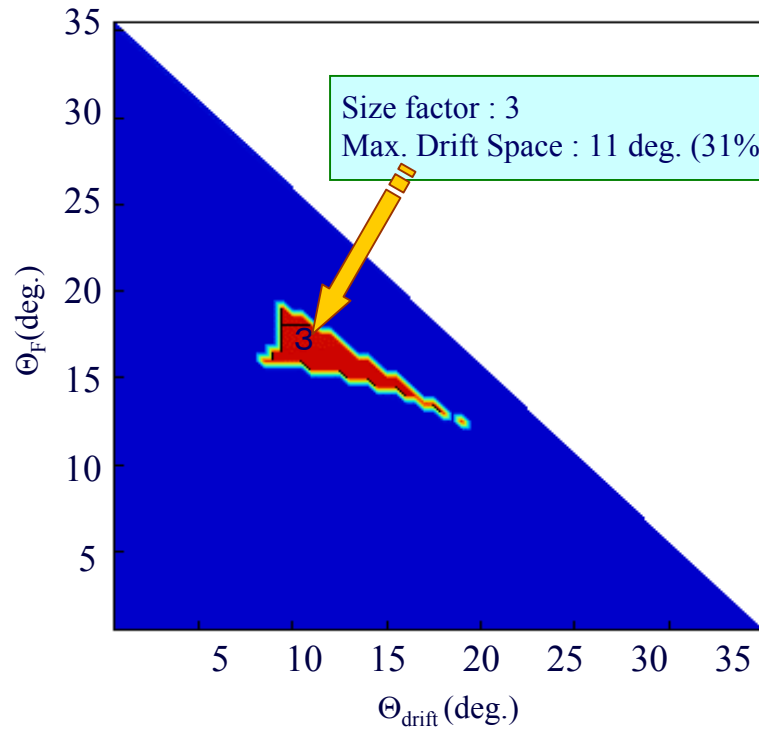
Stable Region

F-D Doublet Sector Type with N= 10

(Field-index : k=8.0)

$$\theta_F = 55^\circ$$

$$\theta_F = 60^\circ$$



 Stable Region

Contour: $\langle r \rangle / \rho_F$

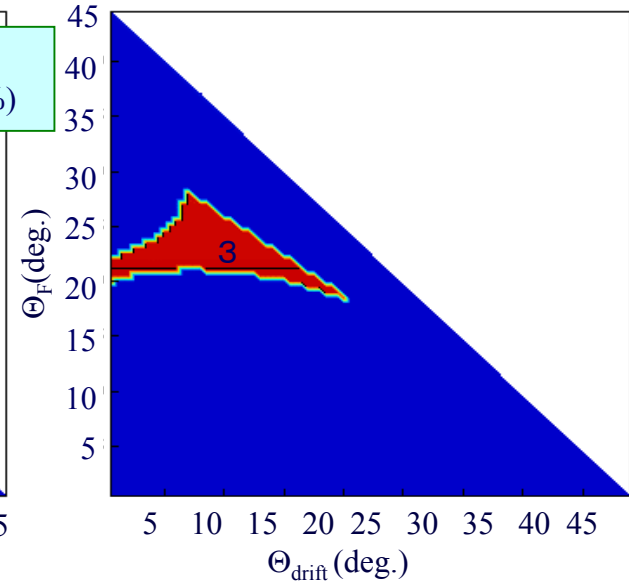
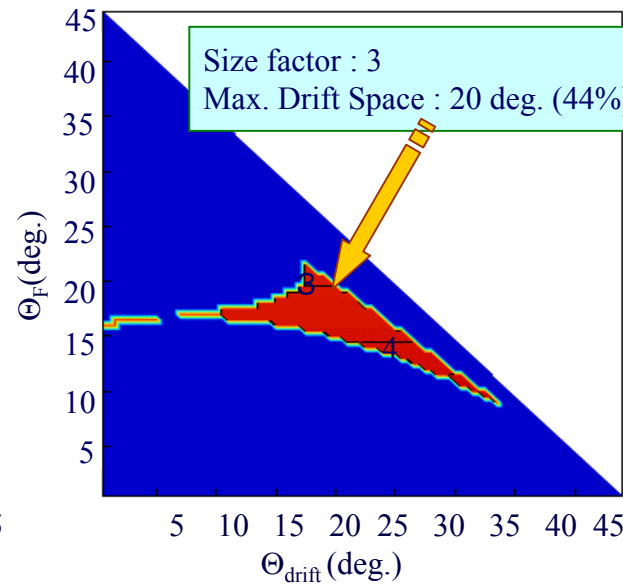
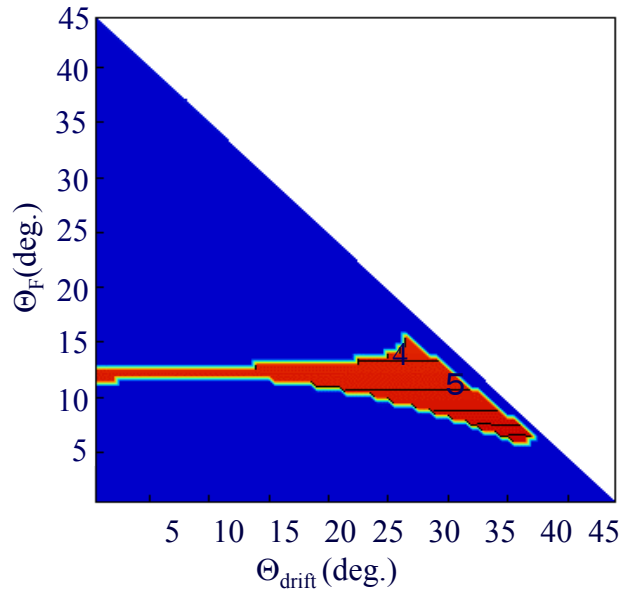
F-D Doublet Sector Type with N= 8

(Field-index : k=5.0)

$\theta_F = 55^\circ$

$\theta_F = 60^\circ$

$\theta_F = 65^\circ$

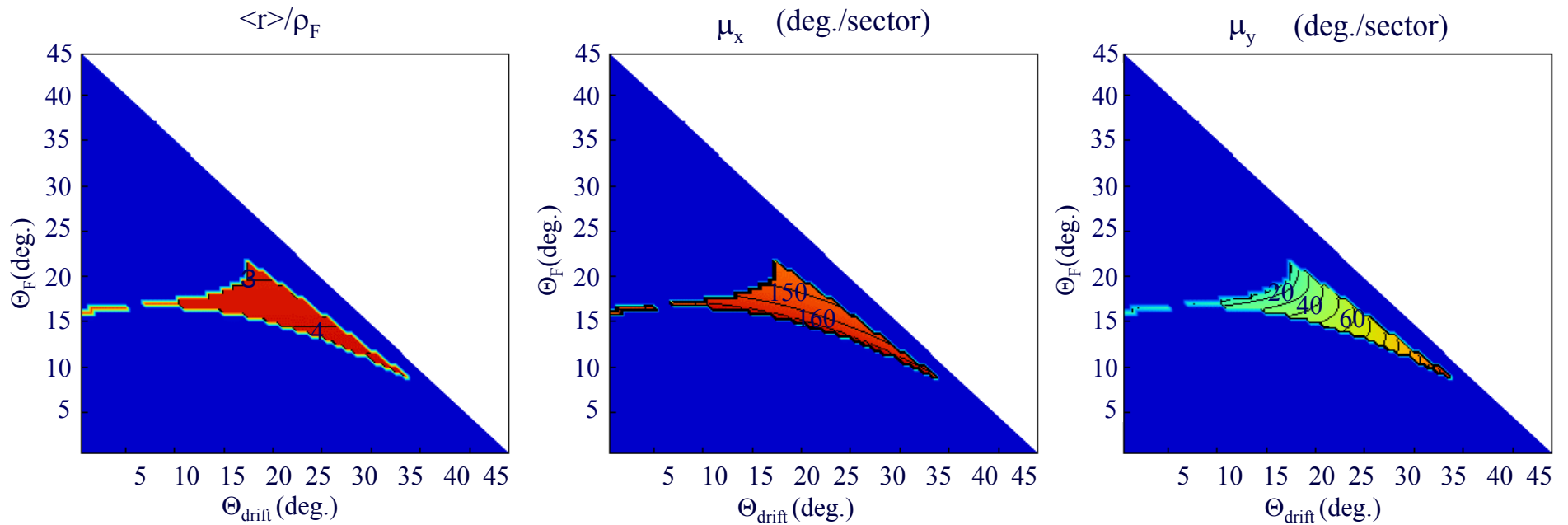


Stable Region

Contour: $\langle r \rangle / \rho_F$

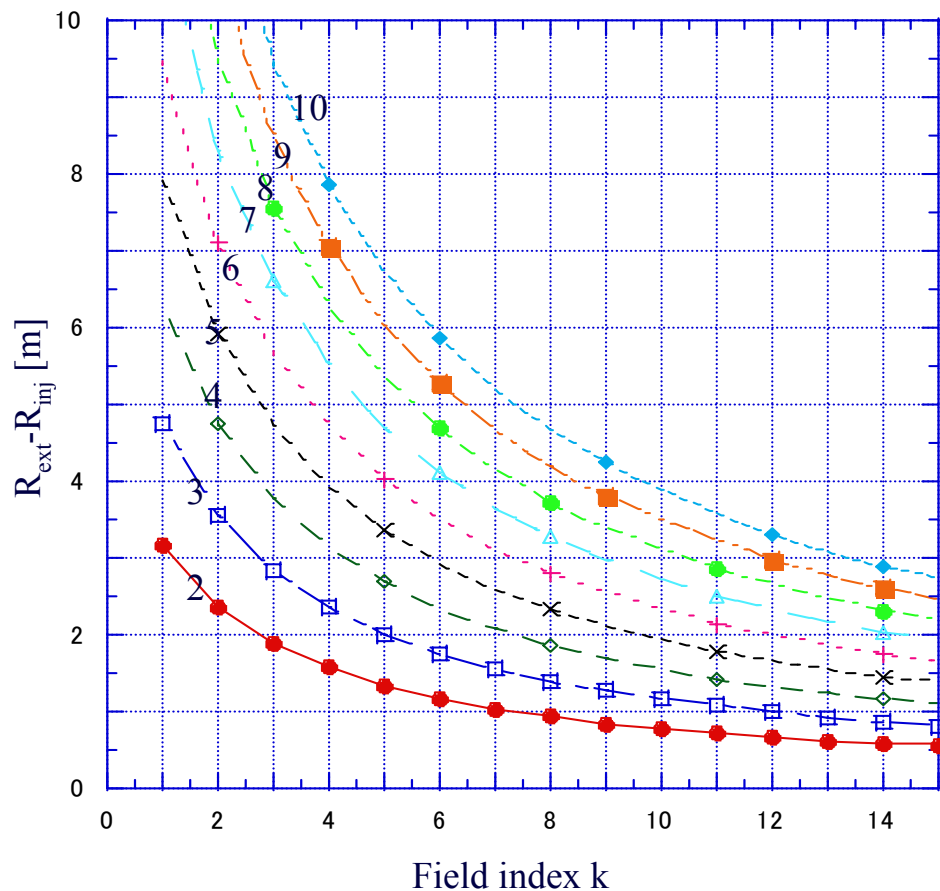
F-D Doublet Sector Type with N= 8

(Field-index : $k=5.0$; F bending angle : $\theta_F=60^\circ$)

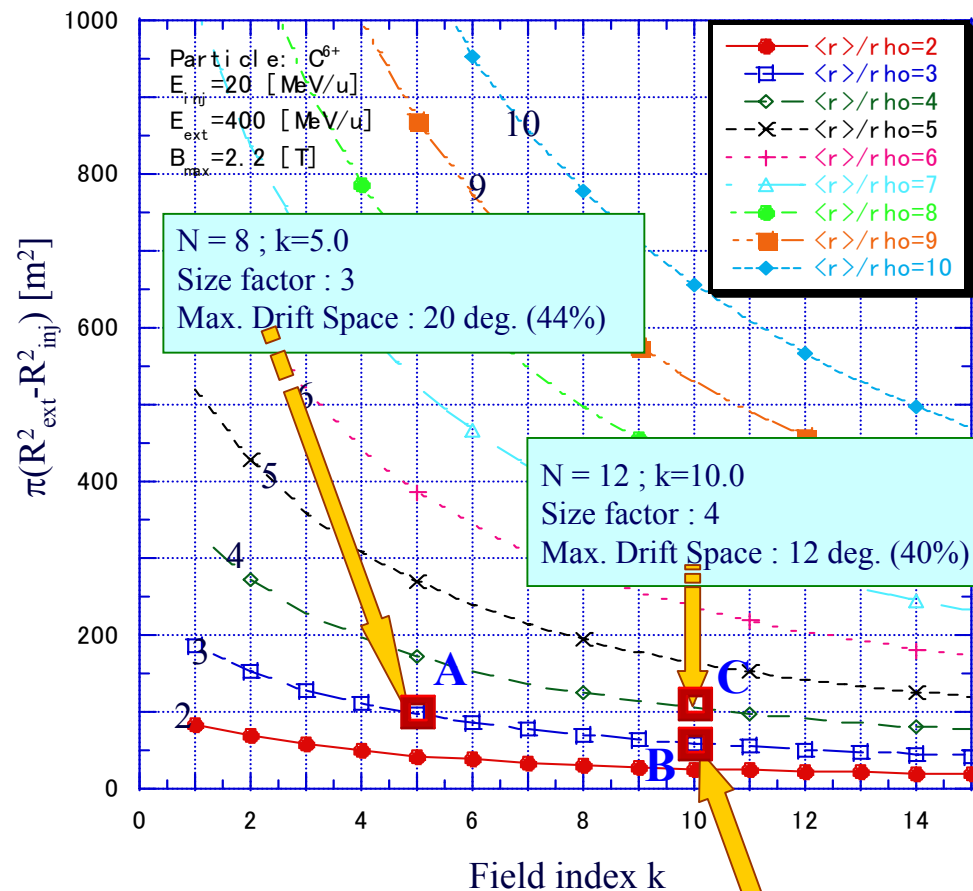


 Stable Region

Orbit Excursion vs. Field Index



Size of Magnet vs. Field Index k



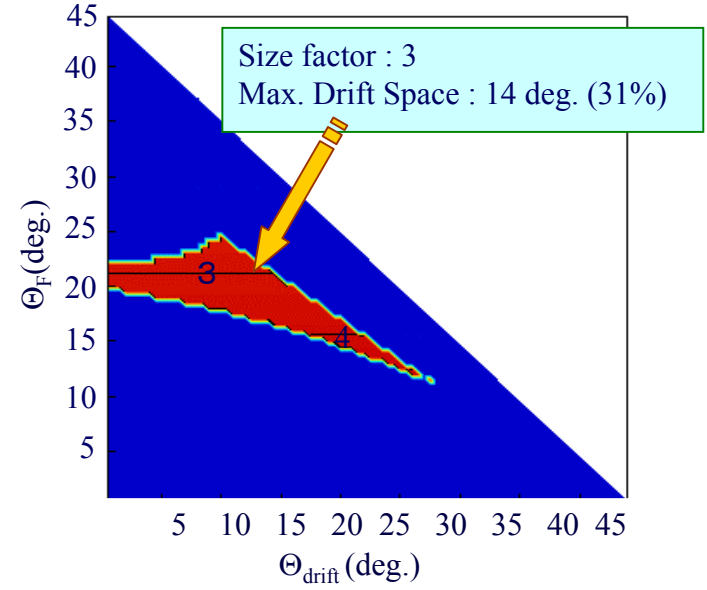
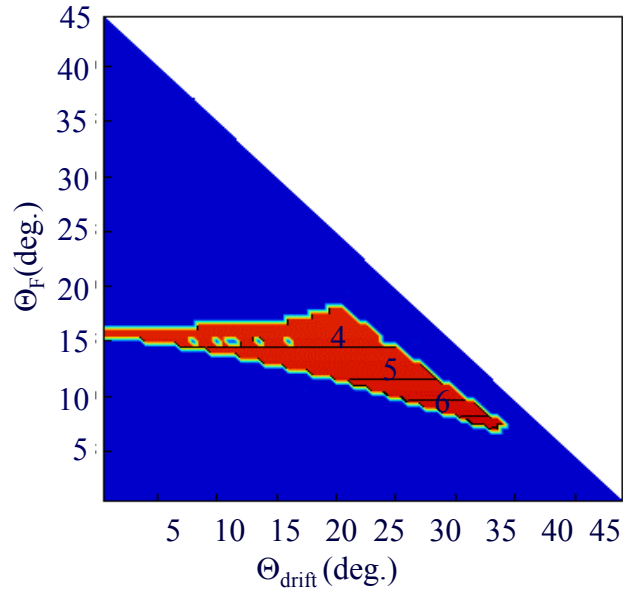
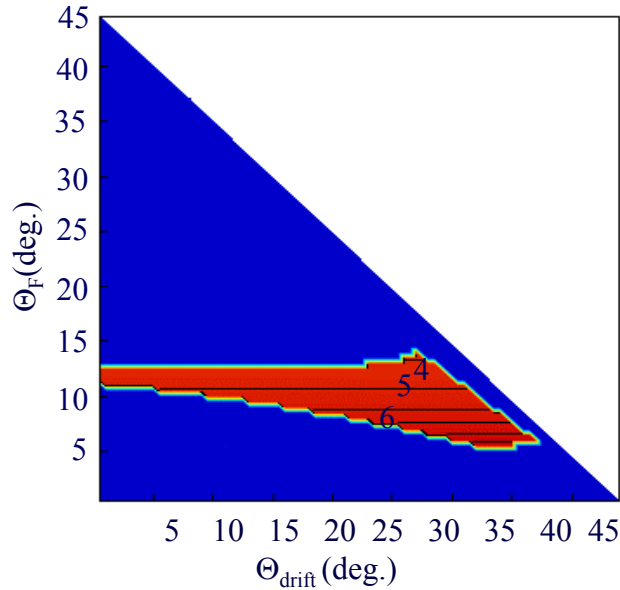
D-F-D Triplet Sector Type with N=8

(Field-index : k=5.0)

$\theta_F = 55^\circ$

$\theta_F = 60^\circ$

$\theta_F = 65^\circ$

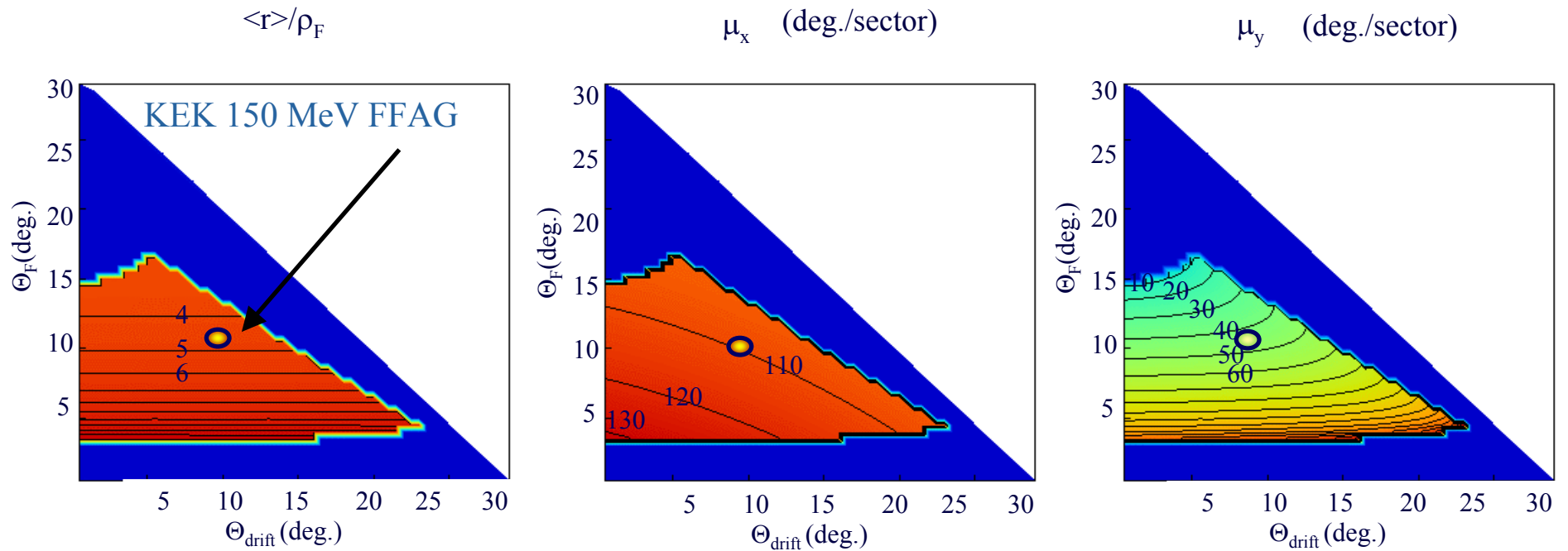


 Stable Region

Contour: $\langle r \rangle / \rho_F$

D-F-D Triplet Sector Type with N=12

(Field-index : $k=7.5$; F bending angle : $\theta_F=50^\circ$)



Stable Region

Example of 2-stage F-D Doublet FFAG configuration

Injector FFAG

Energy Range : 40keV/u~20MeV/u

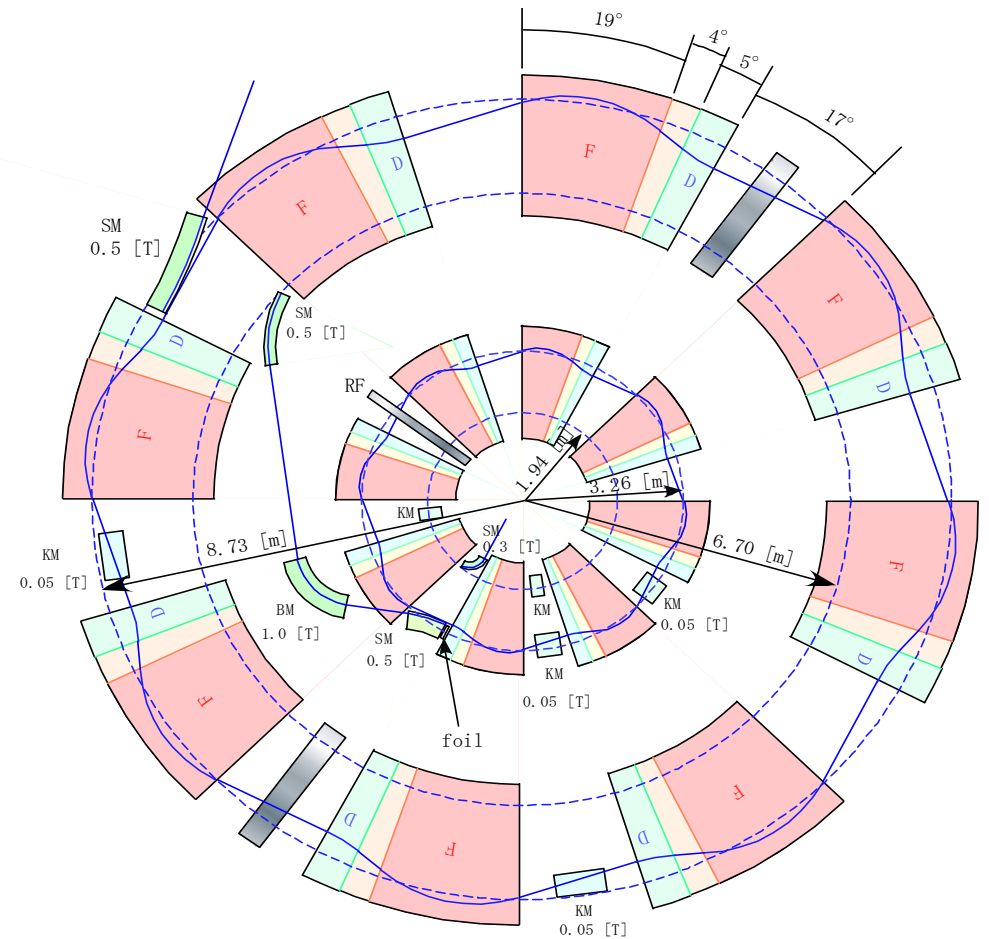
Particle : C⁴⁺

Main FFAG

Energy Range : 20MeV/u~400MeV/u

Particle : C⁶⁺

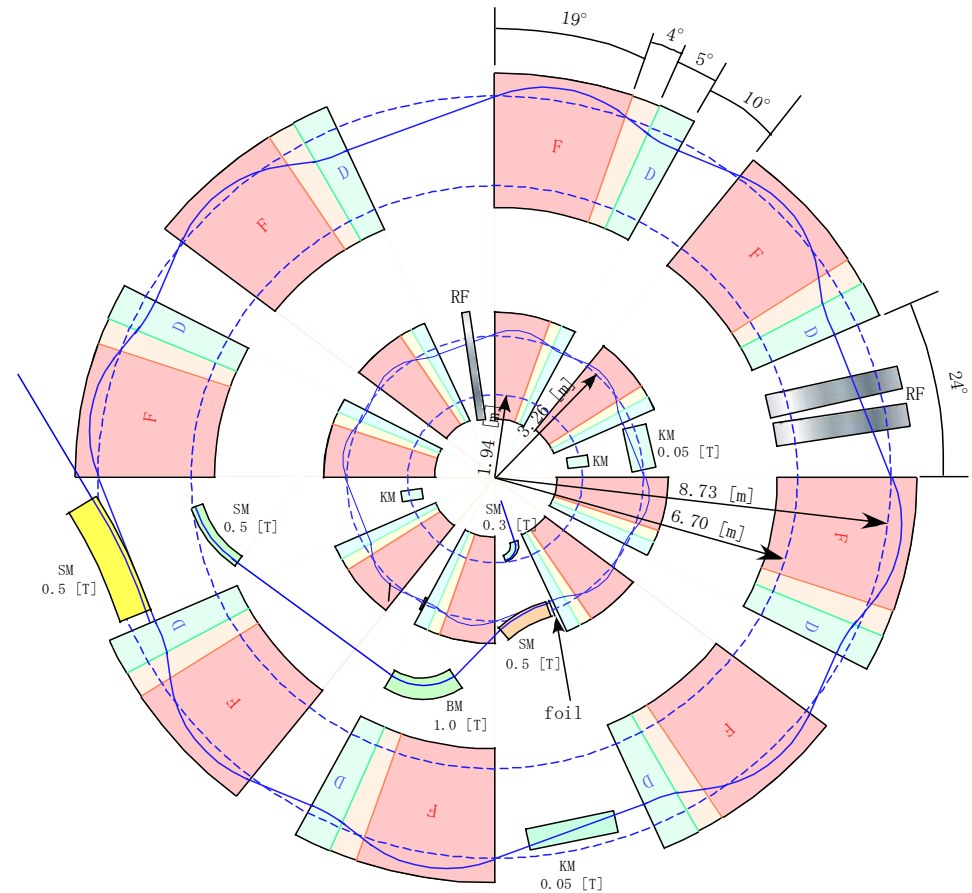
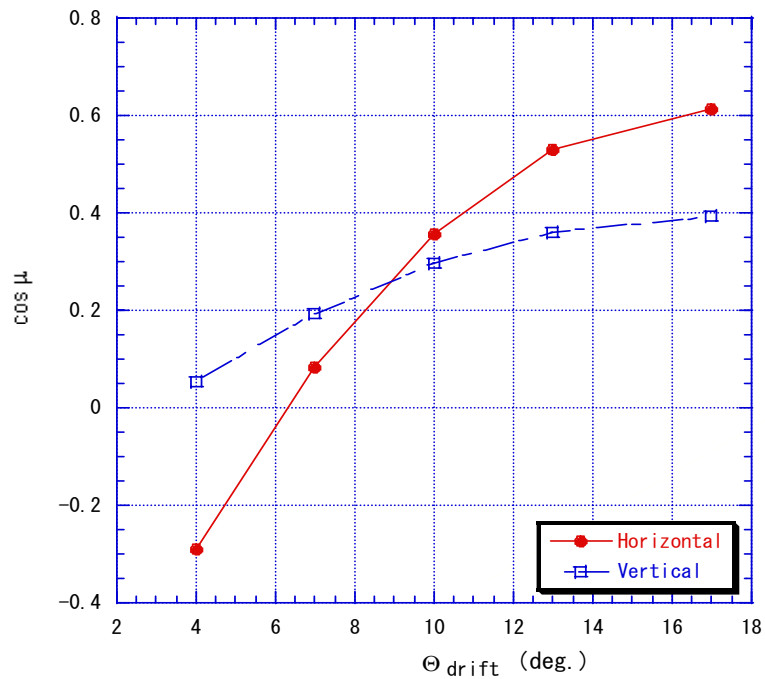
Number of Sector	8
Sector Angle	Drift: 4.+17.[deg.] F: 19.0 [deg.] D: 5.0 [deg.]
Bending Angle	F: 59.0 [deg.] D: 14.0 [deg.]
Orbit Radius of 1 st FFAG 2 nd FFAG	1.94 – 3.62 [m] 6.70 – 8.73 [m]
Frequency of 1 st FFAG 2 nd FFAG	0.23 – 2.98 [MHz] 1.45 – 3.91 [MHz]
Acc. Volt. of 1 st FFAG 2 nd FFAG	~6.6 [kV/turn] ~50.3 [kV/turn]
Betatron Frequency	[Horizontal] 3.42 [Vertical] 0.74
Field Index k	5.0
Maximum Magnetic Field	2.2 [T]



Size Factor $\langle r \rangle / \rho_F = 3.03$

Example of Modified 2-stage F-D Doublet FFAG configuration

By combining two sector magnets as one and adjusting its drift-space angle between them, one can obtain more usable space to place injection/extraction elements and RF cavity.

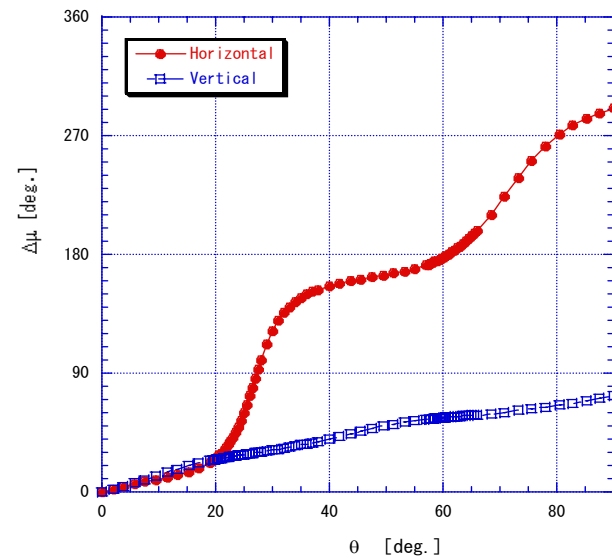
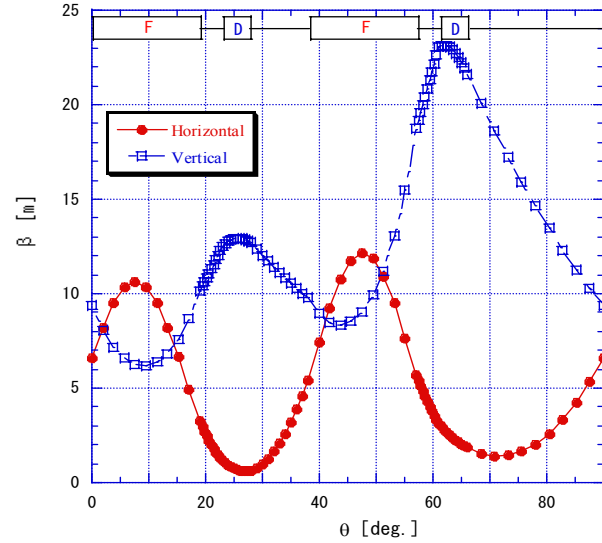
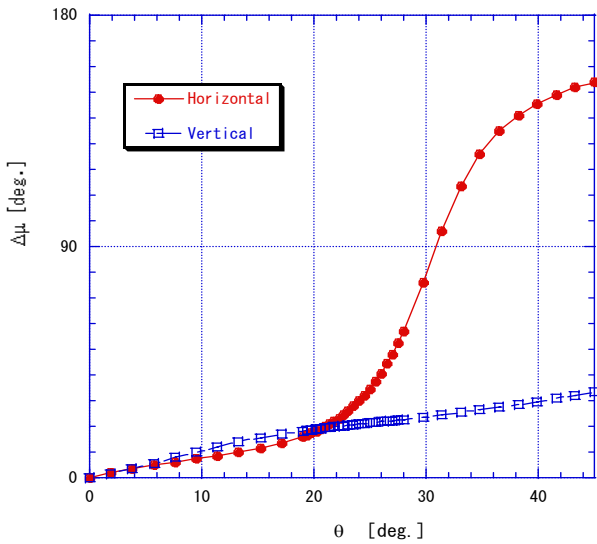
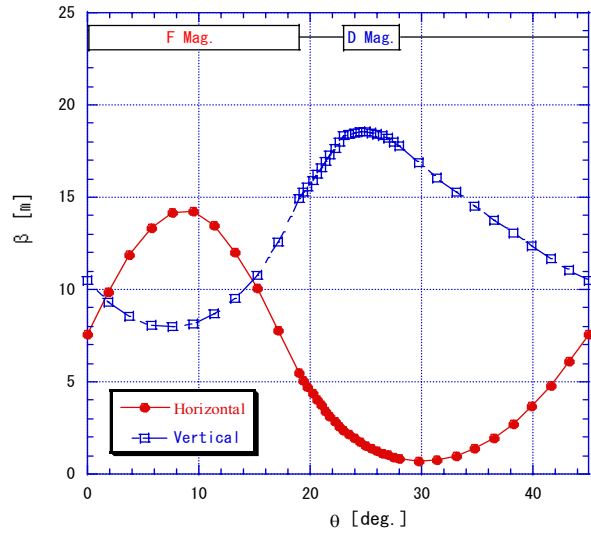


β -function of 2-stage F-D Doublet FFAG configuration

Maximum drift-space angle : 17°



Maximum drift-space angle : 24°



Schedule for NIRS FFAG Development

Year	2001	2002	2003	2004	2005
FFAG Prototype Design	█				
Magnets	█				
RF Cavity		█			
Vacuum			█		
Injection & Extraction				█	
Control System				█	
FFAG Total Design					█

Summary

- We have just started developmental studies on FFAG accelerator for medical use.
- For the popularization of cancer therapy accelerator using the carbon beam, the system needs to be optimized within cost reduction, miniaturization, power saving, etc.
- We investigated several FFAG sector types, including KEK D-F-D triplet type, in terms of various parameters (size of accelerator/magnets, drift-space, field-index k , sector number, acceleration voltage, etc.).
- At present, our basic studies show a F-D doublet sector configuration with field-index $k \sim 5.0$ as a possible candidate.
- To accelerate carbons from 40 keV/u up to 400 MeV/u, we assume the 2-stage acceleration (FFAG+FFAG). Our future investigation may possibly lead to 3-stage acceleration?
- Further examination from various angles (e.g., ease the assumption of the rotational symmetry and/or scaling condition, etc.) is still necessary to optimize overall FFAG configuration.