Ion-optical design and performance analysis of High energy FRagment Separator (HFRS) at HIAF

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Abstract:

The High energy FRagment Separator (HFRS), a new generation in-flight radioactive separator in the intensity Heavy Ion Accelerator Facility (HIAF), is under construction in China. It is characterized by large ion-optical acceptance, high resolution power, high magnetic rigidity, and excellent particle identification. In combination with the HIAF accelerator facility, which will provide high-intensity beams, a wide range of neutron-rich and proton-rich exotic nuclei far from the stability using not only projectile fragmentation but also in-flight fission can be produced and studied. In addition, some experiments which need high beam energy like hypernuclei and Δ-resonances studies in exotic nuclei can be also carried out in the HFRS. In this paper, the development of ion-optical calculation and the high-order correction of aberrations are demonstrated using the detailed measured and simulated magnetic field distribution first. Then, the performance of the separator are studied using fission products and heavy fragmentation products. This work will guide future experimental designs at the HFRS.

1. First-order beam optics design

HFRS consists of two stages, pre-separator and main-separator. Pre-separator is an achromatic and a point-to-point focusing optical system. An achromatic wedge degrader is placed at the dispersive focal plane PF2 to enhance the purity of the fragments of interest from contaminants. Main-separator can be operated as a separator or spectrometer with two different ion-optical modes. In the separator, the ion optics is designed to be achromatic mode, and the second degrader is placed at the MF4 dispersive plane to further purify the RIBs. In the spectrometer, the ion optics is designed to be dispersive mode, the second degrader is placed at the MF1 dispersive plane, and a small achromatic focus point at the MF4 is implemented.

Currently, all magnets are in series production. To check the design, prototype such as the superferric dipole magnet and DCT multipole magnet, have been fabricated and tested. Therefore, the detailed measured and simulated magnetic fields are considered here for more accurate ion-optical calculation, including the effective length, the fringe field, and the multipole field components of magnets. The ion-optical design is carried out by codes of Winagile and GICOSY.

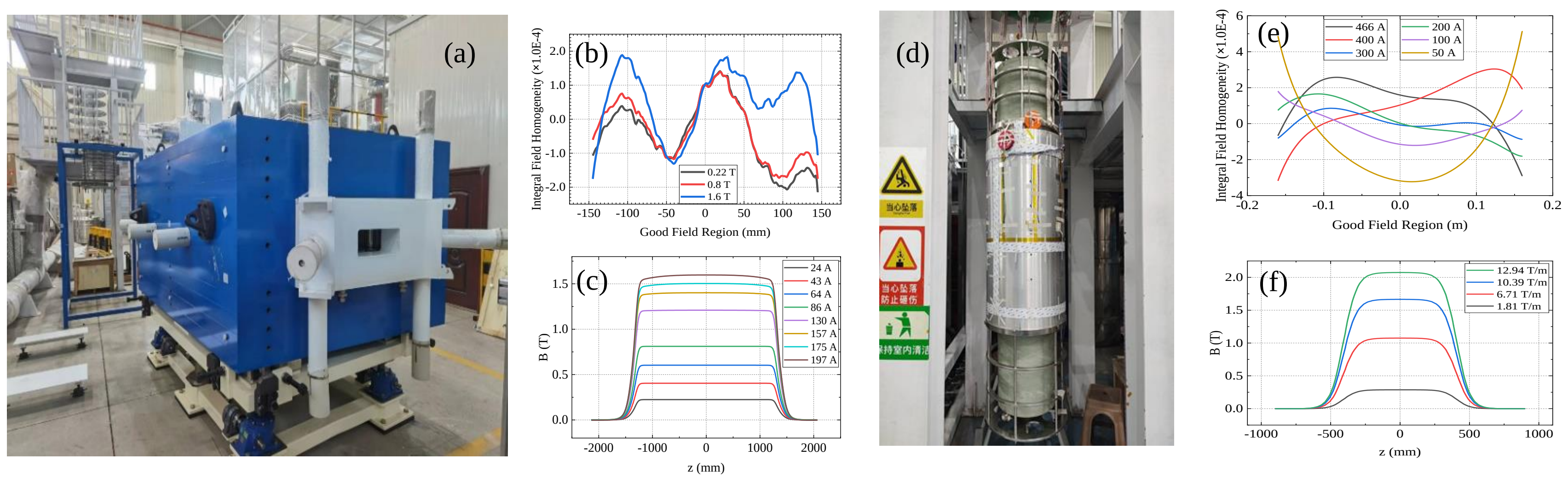

Fig.3 Photograph of the prototype of the superferric dipole magnet (a), its measured integral field homogeneity at low, medium, and high magnetic fields (b) and its measured field distribution (c). Photograph of L800 mm DCT prototype (d), its measured integral field homogeneity at a radius of 160 mm (e) and its simulated field distribution (f).

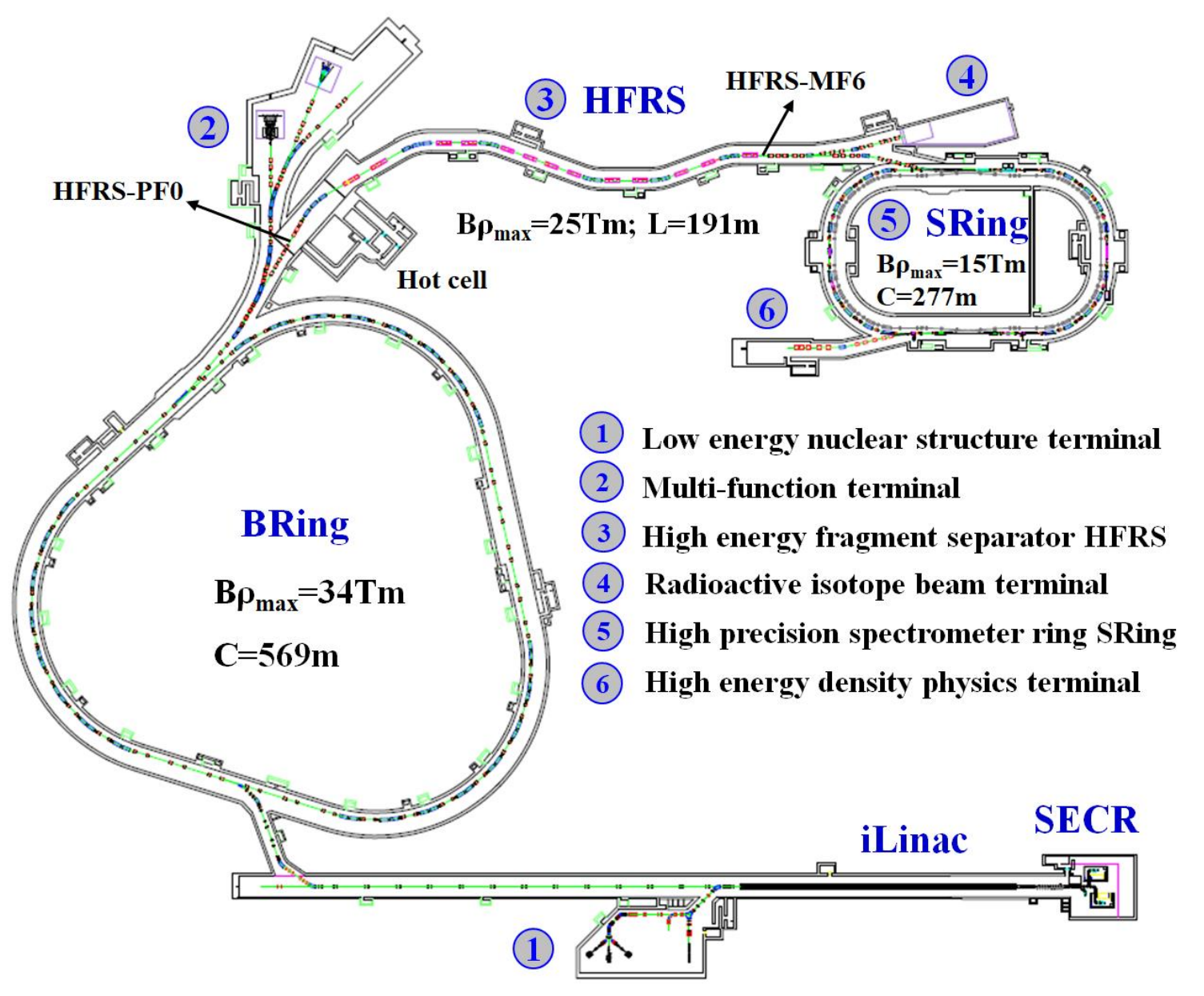

Fig.1 Schematic layout of HIAF

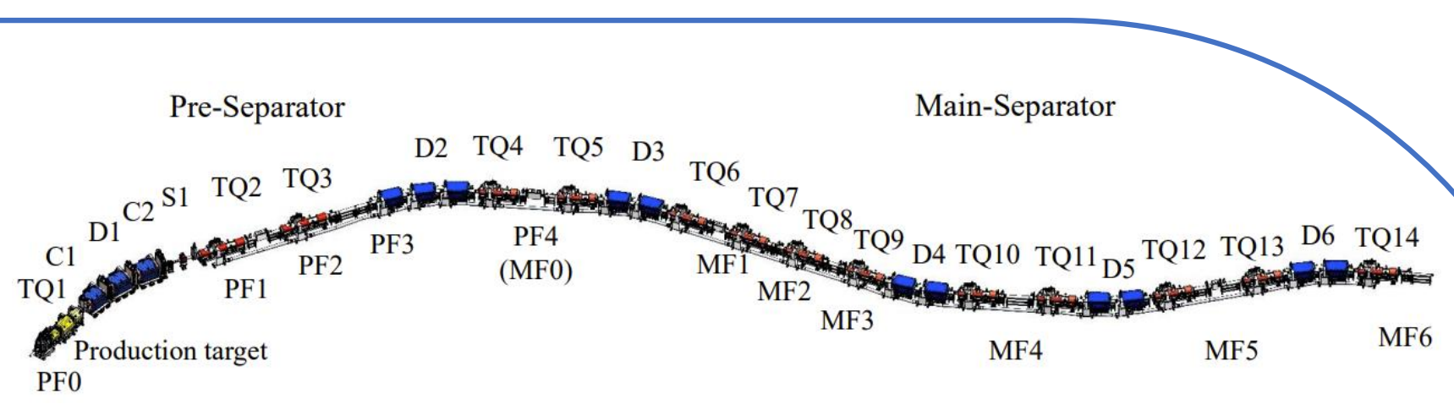

Fig. 2 Schematic layout of HFRS

Table 1 Main beam parameters of HFRS

Max. magnetic rigidity/ Tm	25
Beam size at target/ mm	± 1/ ± 1.5
Angular acceptance/ mrad	± 30/ ± 25
Momentum acceptance	± 2.0%
Ion-optical mode	Achromatic mode, Dispersive mode
First order Momentum resolution (pre/main)	850/700/1100
Total optical length	191.38m

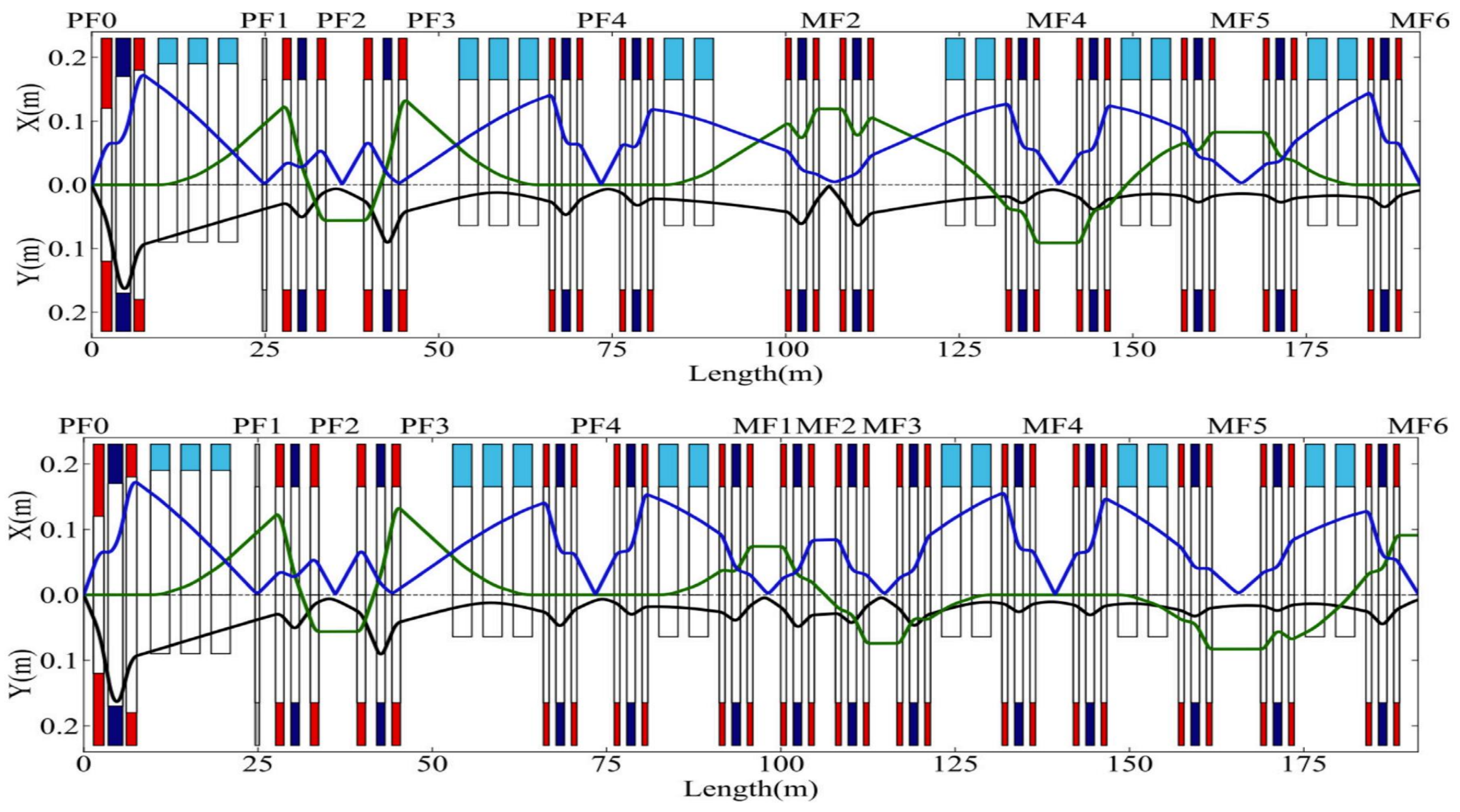

Fig.4 Beam envelopes of HFRS in first-order for achromatic mode (up) and dispersive mode (down). The blue line and the black line correspond to an emittance in x-direction and y-direction of 30π and 37.5π mmmrad, with an object size of ±1 mm and ±1.5 mm at PF0, respectively, while the dispersion line (green) stands a momentum deviation of +2%.

2. High-order beam optics correction

Due to the large divergence angles, the longitudinal momentum distribution of the fragments, and the imperfection of magnetic elements, sizable high-order aberration effects are expected in the HFRS. The main high-order aberration are chromatic aberration and geometric aberration, which can be corrected by sextupole and octupole magnets through minimizing the aberration coefficients. To correct the high-order aberration of HFRS quickly, a self-compiled program by Python combined with GICOSY code is adopted. It uses particle swarm algorithms to minimize the aberration coefficients and the ion loss at each focal plane by varying multipole fields. This program can optimize the beam phase space and ion transmission efficiency automatically and rapidly.

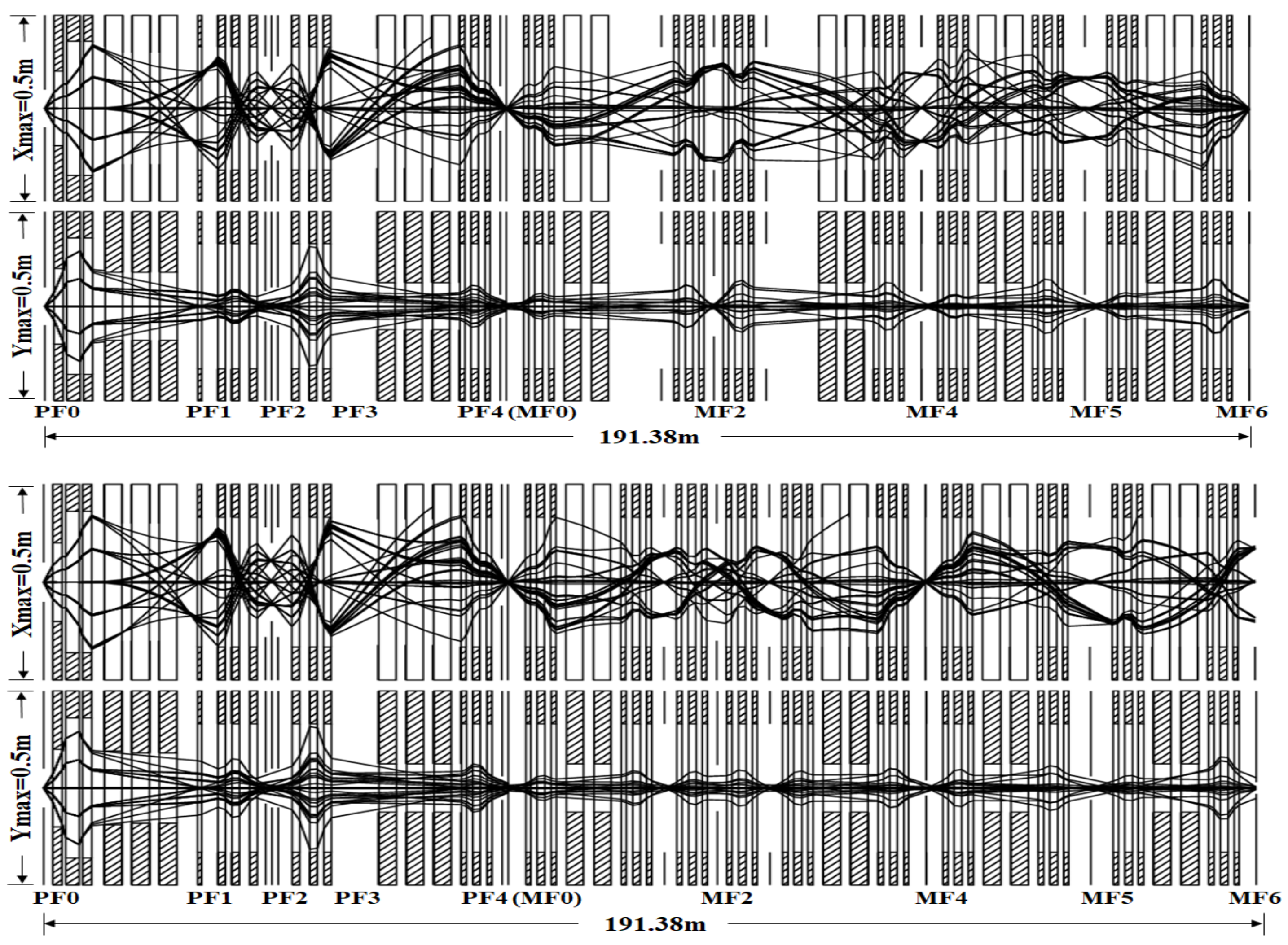

Fig.5 Beam envelopes of HFRS in third-order for achromatic mode (up) and dispersive mode (down). The emittance, object size and momentum deviation are all the same as Fig.4.

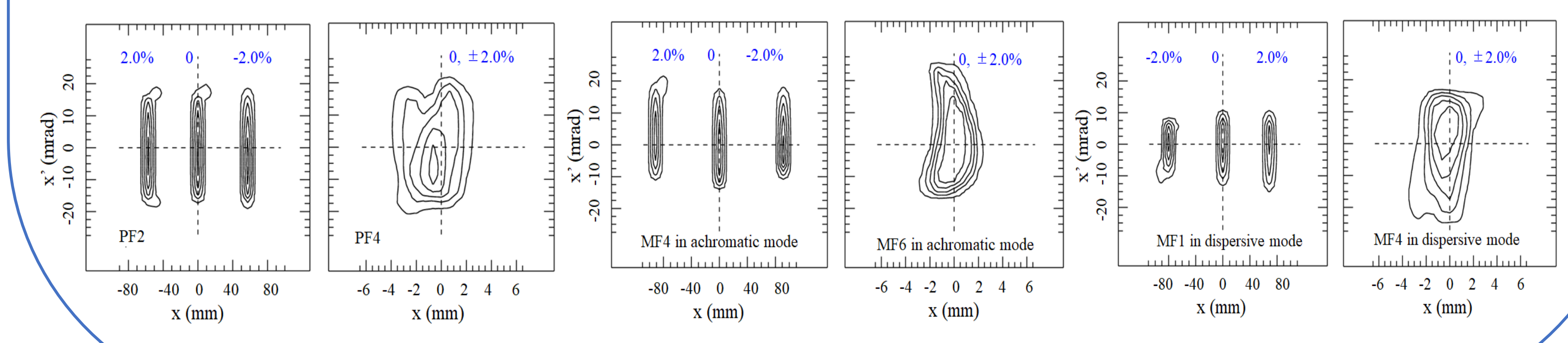

Fig.6 Beam phase space at crucial focal planes after third-order aberration correction

3. Simulation of the separator performance

The HFRS performance, such as the transmission and separation, are studied with the Monte-Carlo simulation program MOCADI by two challenging examples. One is the production of the neutron-rich double magic nucleus ^{132}Sn produced via ^{238}U projectile fission, and the other is the production of the heavy nucleus ^{202}Os from ^{238}U fragmentation. In the simulation, the energy of ^{238}U^{35+} projectiles is 833.15 MeV/u, and a carbon target with a thickness of 1.85 g/cm^2 is used. To purify the target fragments, two achromatic Al degraders placed in the pre- and main- separators are used. In both cases, the degrader thickness (d_1/r_1=0.25 and d_2/r_2=0.4) is selected in the pre- and main-separators, respectively. Here d_1/r_1 represents the degrader thickness in units of the range corresponding to the energy behind the target, and d_2/r_2 denotes the thickness of the second degrader corresponding to the range at the energy behind the first degrader.

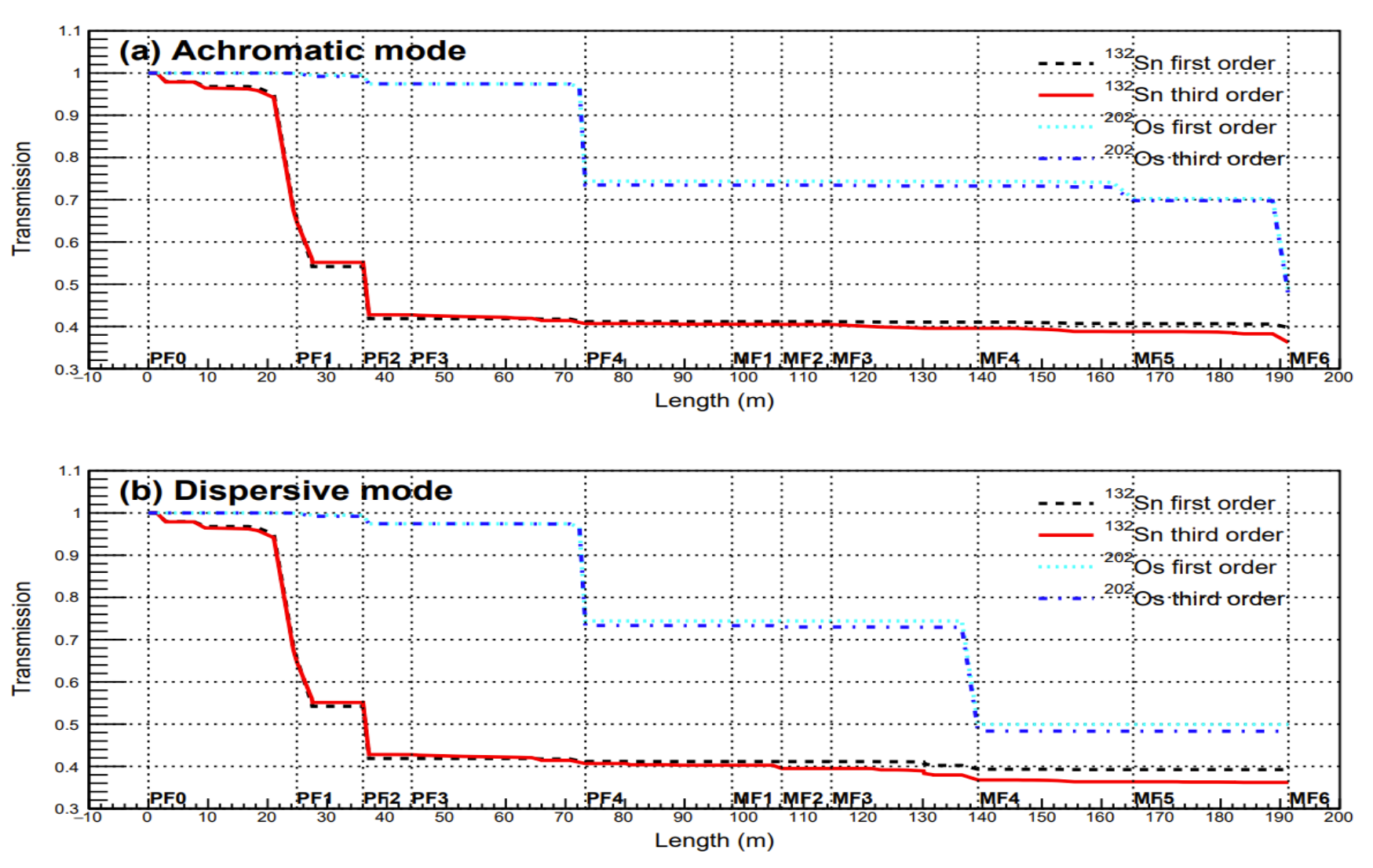

Fig.7 Transmissions efficiency of the fission fragments ^{132}Sn and fragmentation product ^{202}Os with the length of HFRS

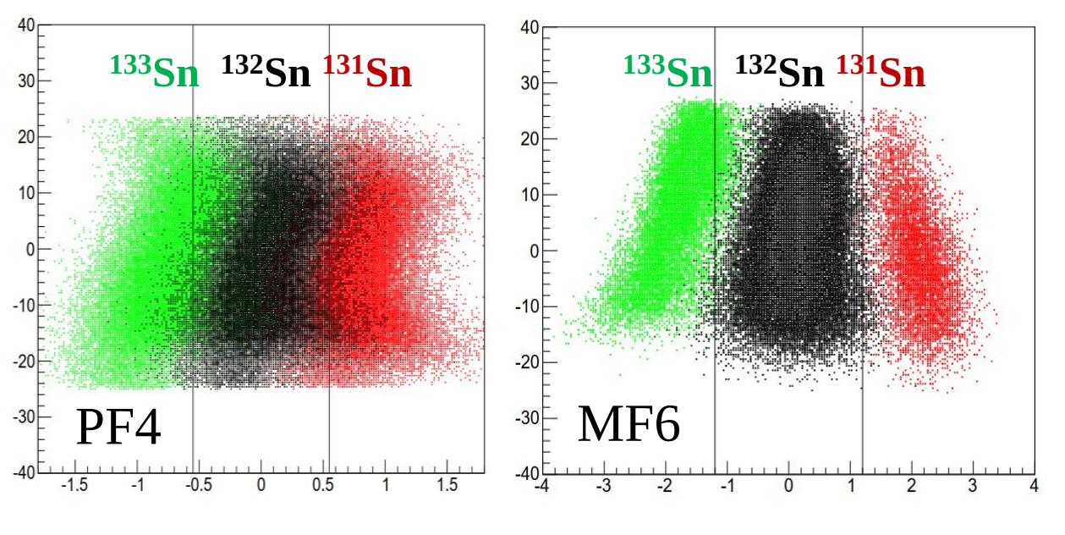

Fig.8 ^{132}Sn and its isotopes at focal planes

Table 2 Transmission efficiency and purification of ^{132}Sn at achromatic mode

Focal planes	PF4	MF6
Transmission efficiency	44.08%	36.54%
Purification	62.31%	95.64%

4. Conclusion and outlook

More accurate beam optics of the HFRS has been optimized using the measured and simulated magnetic field distribution for the first order and third order. An automatic optimization program compiled by Python has been self-developed for high-order aberration correction. The separator performance under the optimized ion-optical calculation has been investigated, including the transmission efficiency and the purification. Next, the corresponding calculation will be carried out for different magnetic rigidities with more measured field distributions.

Generally, all equipment of HFRS has been put into processing. Partial devices have finished joint commissioning and are ready for installation, such as the production target chamber, graphite target and pillow seal. It is expected to complete the fabrication and testing at the end of 2024, then the equipment can be installed on site.

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