A High Rigidity Spectrometer for FRIB

Ion-optics Status Report

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HRS Working Group

Presented at the 2017 Low-Energy Community Meeting

hrs.lbl.gov

ION-OPTICAL AND ASSOCIATED MAGNET FEASIBILITY STUDY FOR A HIGH RIGIDITY SPECTROMETER
DOE Office of Science, Nuclear Physics DE-SC0014554

FRIB

U.S. DEPARTMENT OF ENERGY

Office of Science

Status ion-optical design of the HRS

Outline

- HRS Spectrometer (this presentation) and Beam Line (Shumpei Noji)
- 5 Experiment types, design goals, design parameters and technical constraints
- Preferred ion-optical solution, 2 Modes (QQD, DQQ)
- Layout in planned building, ion-optics of 2 Modes
- Lattice files, disp. matching, magnet specifications
- Staging study
- Path forward for HRS

How well does the preferred layout accomplish the design requirements?

Optimize luminosity of experiments with fast rare-isotope beam at FRIB		
1. Beam line and spectrometer that operate up to 8 Tm	achieved	✓
2. Transport beams of ±15 mrad (disp), ±34 mrad (non-disp), and ±1.5% (p) to spectrometer	100% transmission in achromatic mode	✓
Accommodate the Scientific program envision in the HRS white paper		
3. In-beam γ-ray spectroscopy		
a) at least 123 cm around target to place GRETA	Exceeded (138 cm)	✓
b) ±5% acceptance (dE/E)	Achieved	✓
4. Invariant mass spectroscopy with neutrons		
a) >90% geometrical acceptance for neutrons emitted from 180 MeV/u A=40 nucleus for E_x< 2 MeV	Achieved	✓
b) neutron coverage in dispersive plane: -6° to +20°	Achieved	✓
c) Accommodate part of GRETA with only minor loss in neutron geometrical acceptance	80% geometrical acceptance achieved	✓
d) >10m flightpath to perform PID up to medium-mass nuclei (at least Sn region)	Exceeded (12.5 m)	✓
e) ±10% acceptance (dE/E)	Achieved	✓

How well does the preferred layout accomplish the design requirements?

Accommodate the Scientific program envision in the HRS white paper		
5. Knock-out experiments with beams up to A~200		
a) Dispersion-matched beam transport with optimized transmission through beam line	~50% achieved for ±8cm beamspot size	✓
b) PID up to mass 200 requires flightpath >25m from HRS target to focal plane	Exceeded (31.4 m)	✓
c) Resolving power > 1300 (momentum)	~10000 for ±0.5 mm beamspot size	✓
6. Time-of-flight mass measurements		
a) Dispersion-matched beam transport with optimized transmission through beam line	Achieved	✓
b) Mass resolution of better than 1 in 10000 requires >90m flight path from fragment separator target to HRS focal plane	Exceeded (112 m)	✓
c) Position resolution of <0.35 mm; Time-of-flight resolution of <30 ps	Achievable – further detector development in progress	…
7. In-flight fission experiments in which both fission fragments are measured in the focal plane of the HRS		
a) angular acceptances of ±60mrad in dispersive and non-dispersive plane	Exceeded: ±60mrad (dispersive) ±90mrad (nondisp.)	✓
b) PID up to mass 200 requires flightpath >25m from HRS target to focal plane	31.4 m	✓

Technical Considerations and Constraints

- Feasibility and Cost of large dipole and quadrupole magnets with Higher Order (HO) components (details see next slide)
- Realistic ion-optics that allows mechanical magnet design without interferences
- Space between magnets for detectors and diagnostic devices, GRETA needs 1.23 m along the beam, partial GRETA needs less space e.g. 0.9 m radius or smaller.
- Building constraints (design in progress)
  - North and South walls are existing
  - Shielding walls of about 2 m thickness
  - Clear passages of 96 inch around HRS
  - Beam line height is 1.25 m above floor, requires a 1.2 m pit below floor to accommodate large magnets

Magnet design and Field Strength limits

- All magnet fields are iron dominated with superconducting coils
- Quadrupole magnets with Hex and Oct components Warm Bore radius is 10 cm smaller than the Cold Bore, warm bore determines maximum envelop

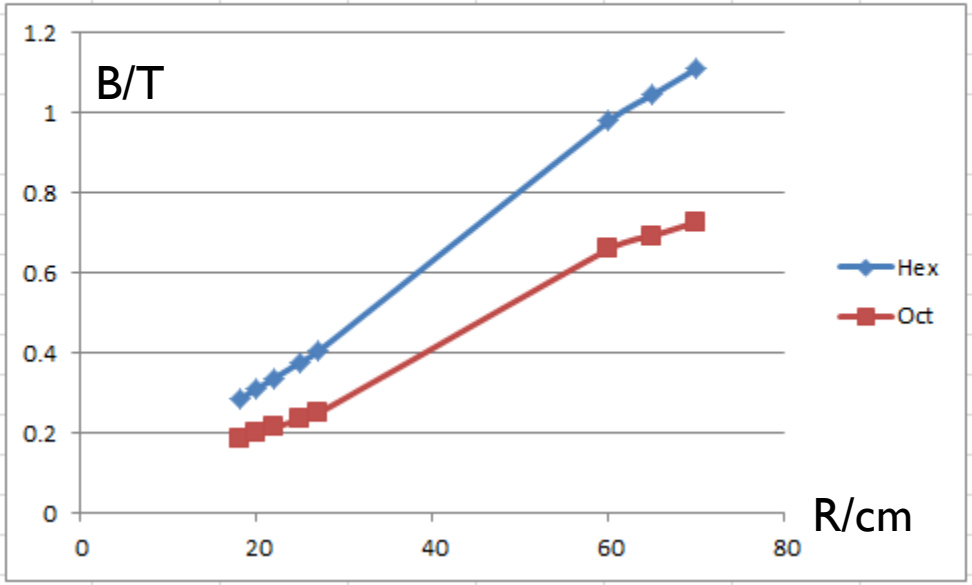
Dipole field strength maximum: Approx. 2.5 T

Quadrupole pole tip strength maximum at Cold Bore Radius: Approx. 2.5 T

Max. HO pole tip strength B depends on the radius R (Ref. Shailendra Chouhan)

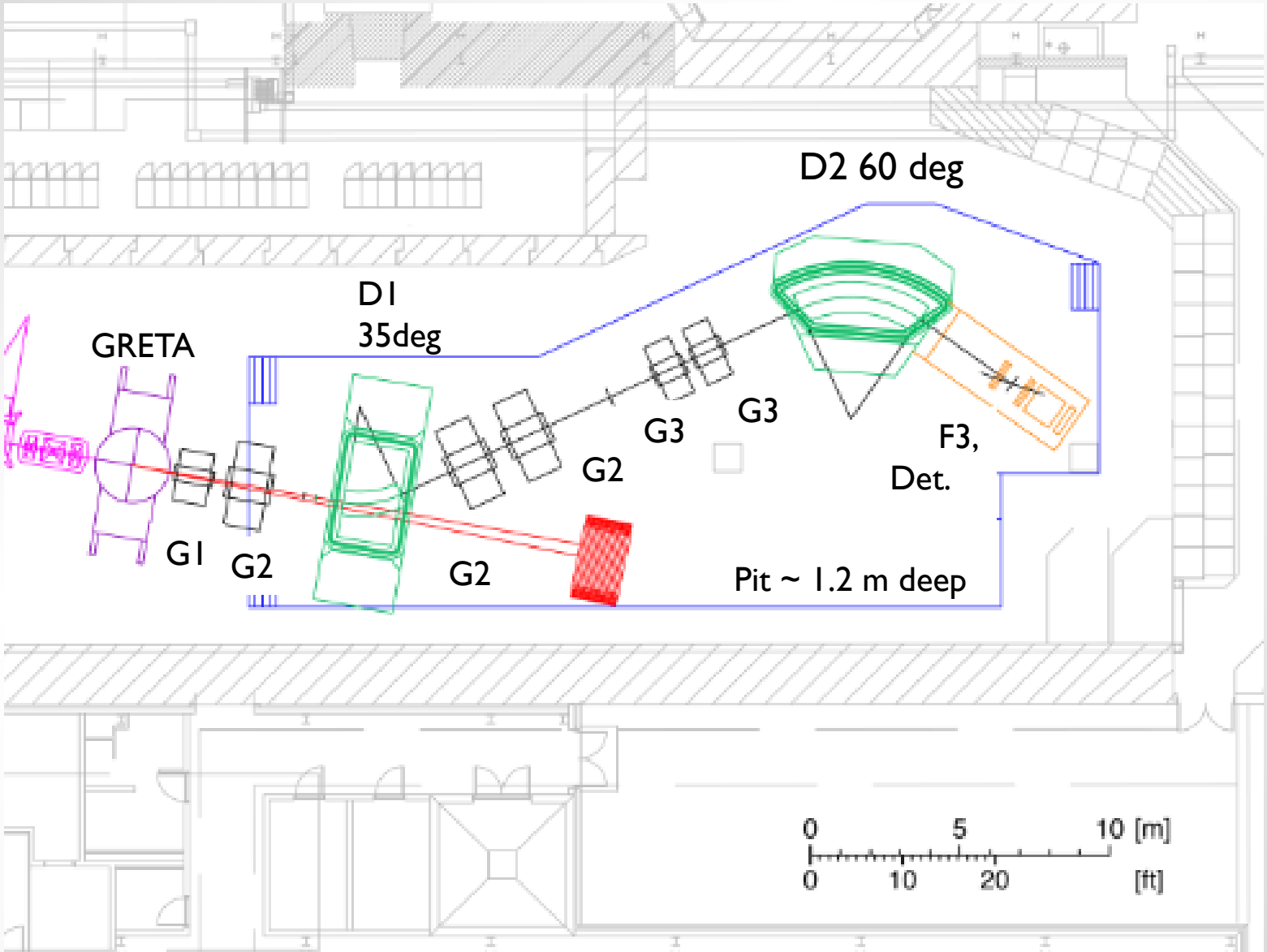
Max HO			Radius	for COSY	Poletip	
Hex	5	T/m^2	0.5	m	1.25	T
Oct	20	T/m^3	0.5	m	2.5	T

	Sextupole	Octupole Pole tip
R(PT)	S(PT) scaled	O(PT) scaled
in cm	in Tesla	in T esla
18	0.284516	0.185432
20	0.311111	0.199546
22	0.337835	0.213909
25	0.378086	0.235768
27	0.405	0.250489
60	0.98	0.66
65	1.045581	0.693497
70	1.111574	0.727816

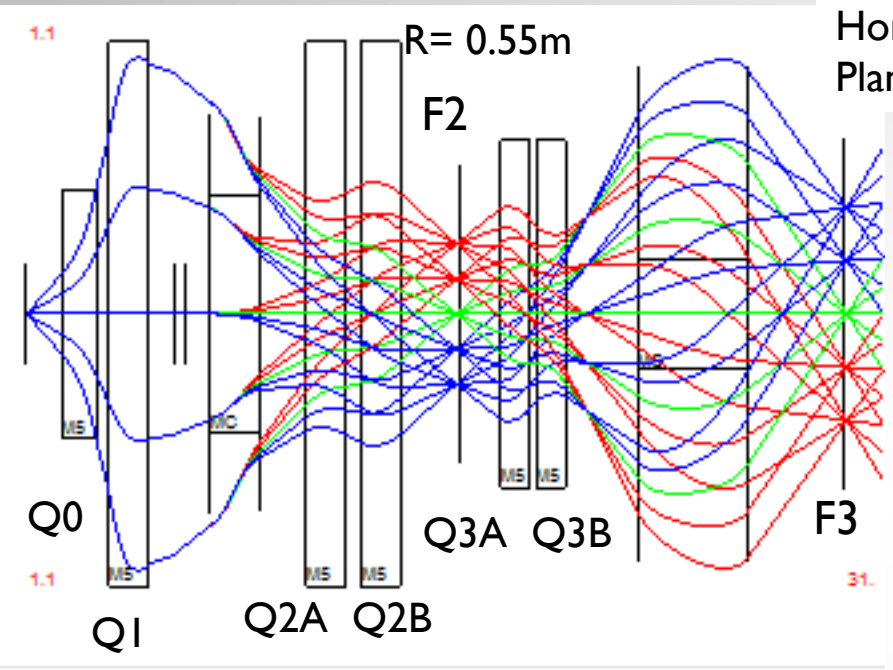


Preferred Optics, Layout QQD Mode

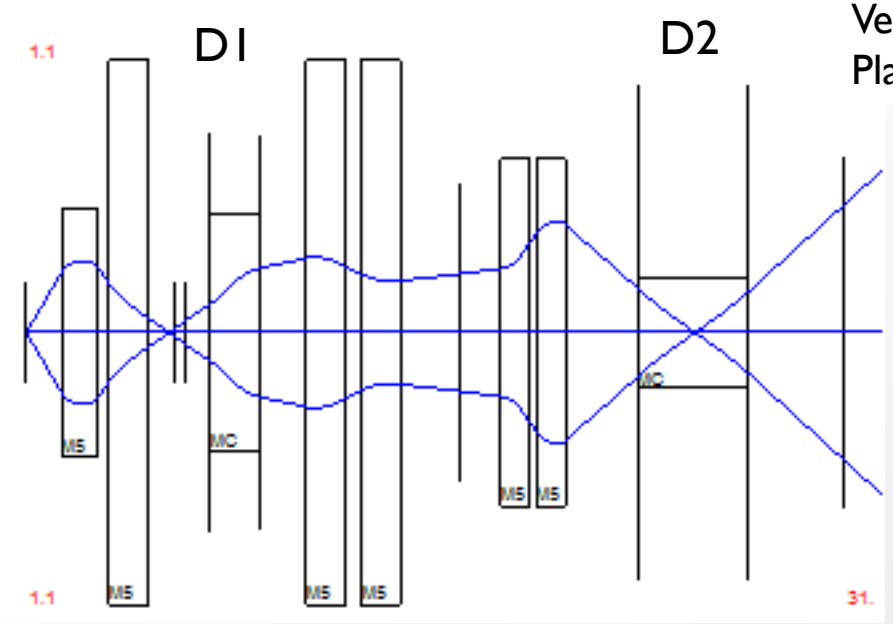
Quadrupole Groups G1, G2, and G3



QQD Preferred Optics, 1st order calc.



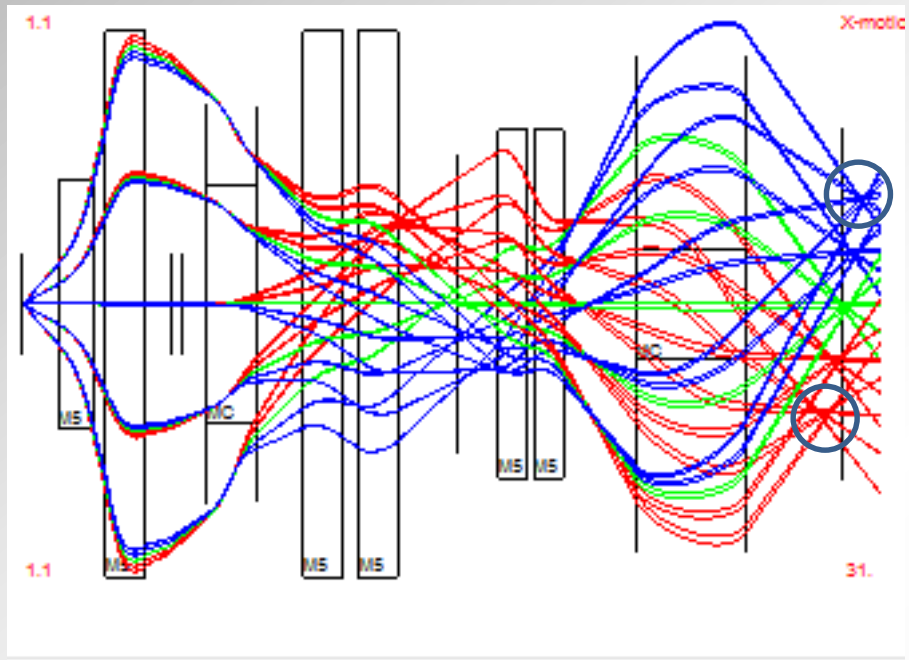
Horizontal Plane

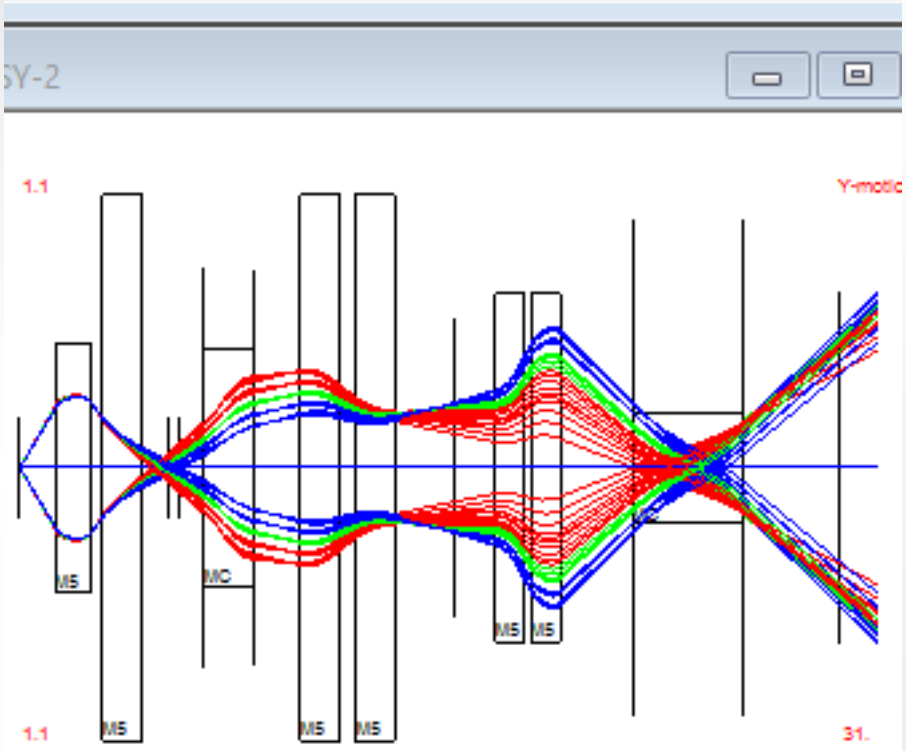


Vertical Plane

y= 35 cm

- Horiz. focus at F2 and F3
- Point-to-parallel from target to F2
- Vert. focus in D2 to minimize dipole gap





QQD Preferred Optics, 2nd order calc.

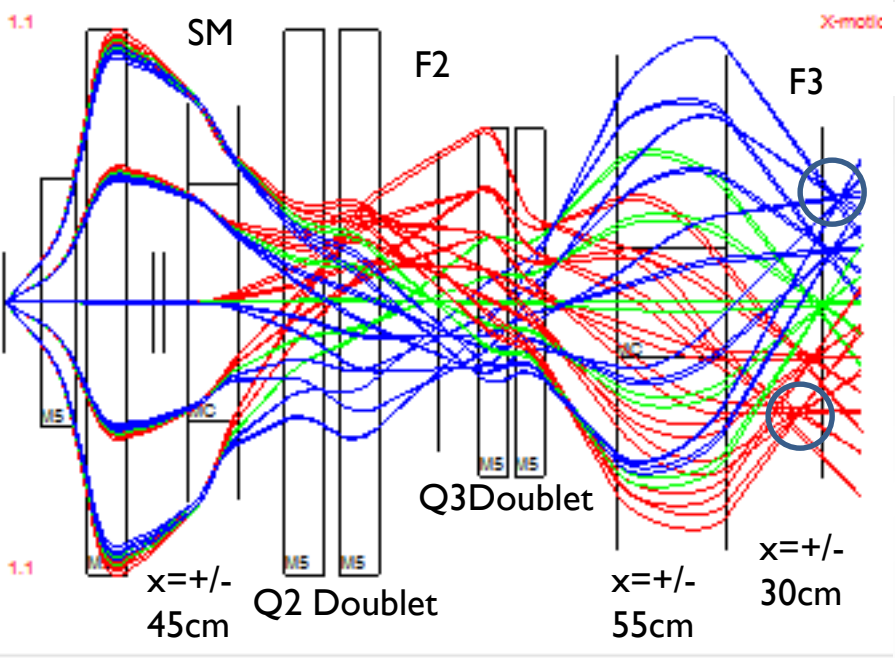
Focal Plane tilt angle: 74.0 deg

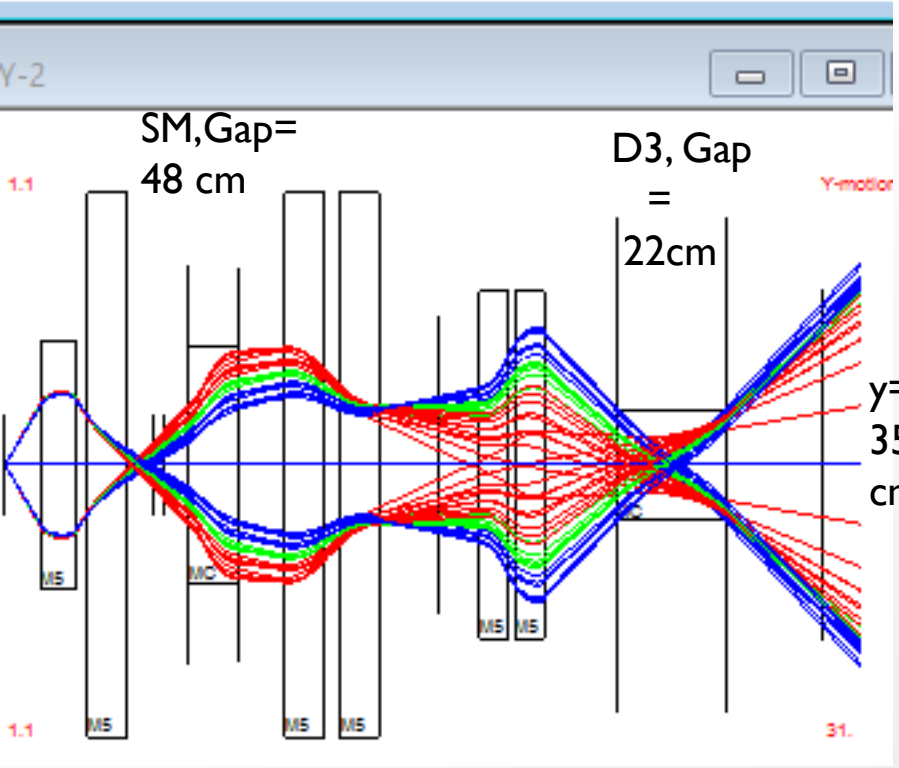
Atan(-ME(1,26)/ME(2,2)/ME(1,6))*180/PI

Notes:

- Good focal points at F3
- In this drawing the warm bore R is shown, available for the particle envelop.

Pref. Optics Optimized, QQD Mode, 7th order





Horizontal and vertical foci, F2/F3
DA = +/- 60 mrad (Hor. Accept. Angle)
DB = +/- 90 mrad (Vert. Accept. Angle)
dE/E = +/- 5% (Energy Acceptance)
M11 = 1.343/-0.71158 (Hor. Magnif.)
M16 = 2.835/-4.2821(Energy Disp.)
M21 = 0.217/-0.329
M26 = 0.08/-0.142 M33 =-1.11/4.41 Vert.Magn.
For x_0=+/-1mm, E-Res. Power(E) = -1055/3009
For x_0=+/- 0.5 mm, Res.Power d/dp ~ 12000

Q0A:= -2.4700;	H0A := 0.0;	O0A := 0.21;
Q1A:= 2.1450;	H1A := 0.0;	O1A := -0.10;
Q2A= -0.9800;	H2A := 0.0;	O2A := 0.0;
Q2B= 1.1500;	H2B := 0.0;	O2B := 0.0;
Q3A= 1.693194;	H3A := 0.0;	O3A := 0.0;
Q3B= -2.01293;	H3B := 0.0;	O3B := 0.0;

Focal Plane tilt angle: -84.2/74.0 deg
Atan(-ME(1,26)/ME(2,2)/ME(1,6))*180/PI

File: HRS_QQD_12June_Q_length.fox

Lattice File: Preferred Optics HRS, QQD Mode

HRS Spectrometer layout		6/17/2017		Preferred Optics, optimized						
HRS_Lattice_Pref_QQD_061717.xlsx		QQDQQQ mode	File	HRS_QQD_12June_Q_length.fox					Cold bore	
									Pole tip	
Element	Note	Element properties		Cold bore Radius/	Warm bore (m)		Length(m)		T	
Technical Name	Description	Effect. Length(m)		Half gap (m)	Dipole half gap	Note			Quad	Hex	Oct
		Dipole Bend Angle								
						FP1				
DL1	Drift	1.4					1.4			
Q0A	Quad+Oct	1.3		0.35	0.25		2.7		-2.47	0.01	0.212
DL2	Drift	0.45					3.15			
Q1A	Quad+Oct	1.5		0.65	0.55		4.65		2.145	0	-0.094
DL3	Drift	1.1					5.75			
DL4	Drift	0.4					6.15			
DL5	Drift	0.9					7.05			
D1/SM	Dipole	35		3.2	0.24	GFR=0.9m	9.0048			
DL6	Drift	1.75					10.75477			
Q2A	Quad	1.5		0.65	0.55		12.25477		-0.98	0.1	0
DL7	Drift	0.6					12.85477			
Q2B	Quad	1.5		0.65	0.55		14.35477		1.15	0.1	0
DL8	Drift	2.25				F2	16.60477			
DL9	Drift	1.6					18.20477			
Q3A	Quad	1.1		0.45	0.35		19.30477		1.693194	0	0
DL10	Drift	0.3					19.60477			
Q3B	Quad	1.1		0.45	0.35		20.70477		-2.01293	0.2	0
DL11	Drift	2.8					23.50477			
D2	Dipole	60		4	0.11	GFR=1.1m	27.6936			
DL12	Drift	3.7				FP3	31.39356			

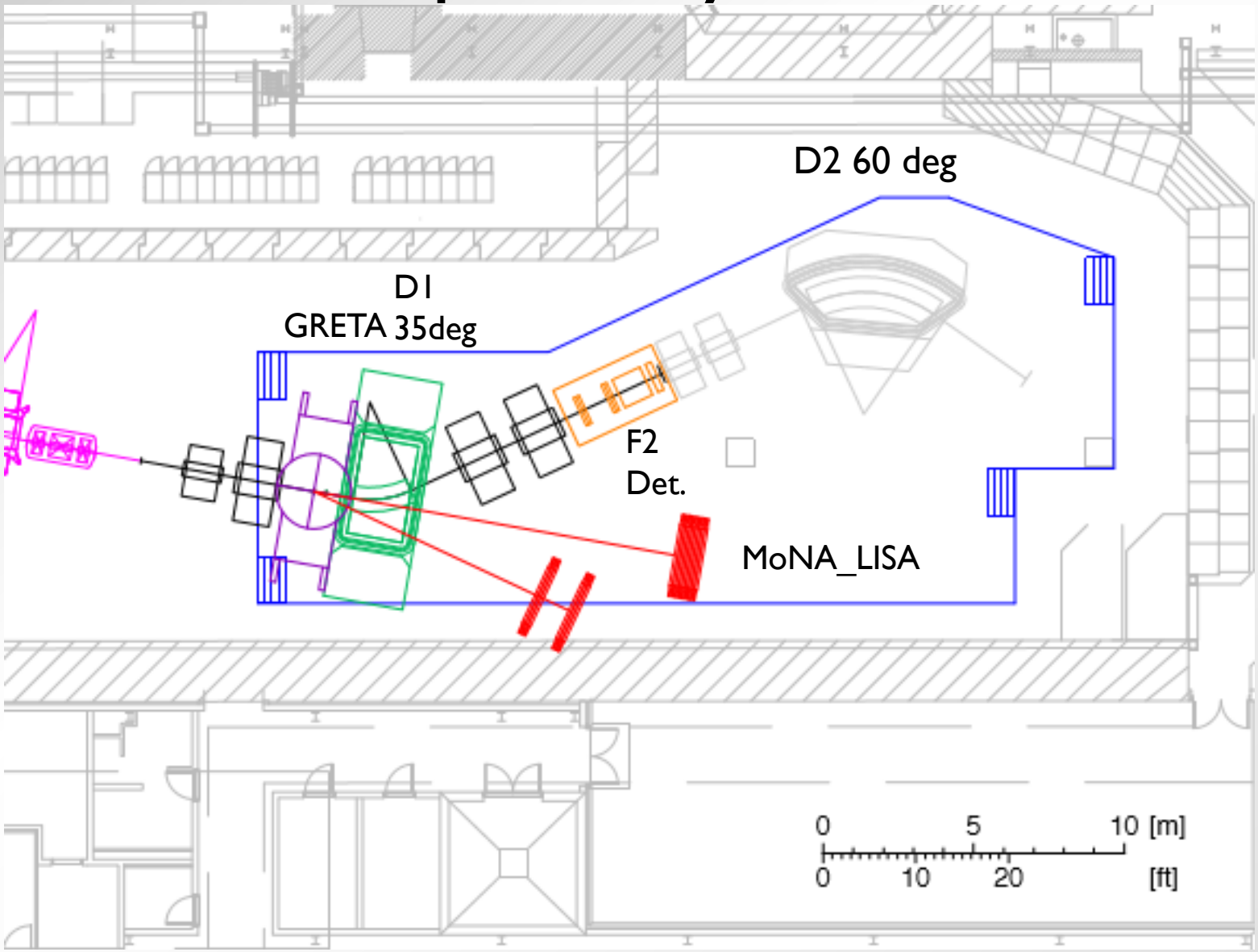
HRS Length

Design Note: All quadrupoles are assumed to have Hexapole and Octupole components, so the Cold Bore Radius is 0.1 m larger than the Worm Bore Radius.

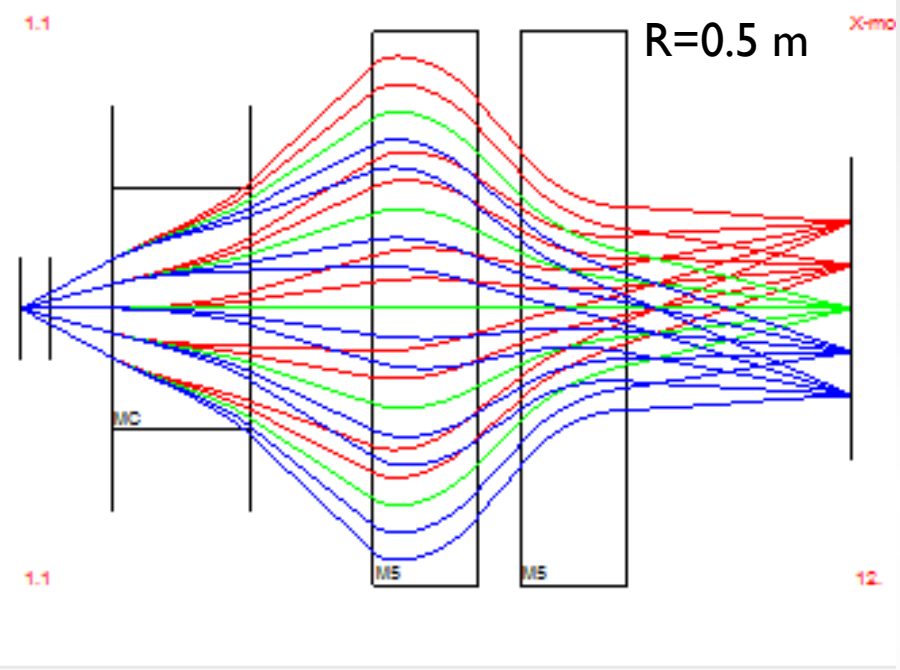
Although not all quads used all HO coils, it is assumed that in the further optimization the radial HO components in the dipoles and quads will require such components.

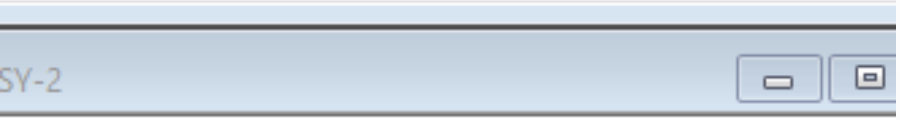
Also all types of quads (Q0A, Q1A = Q2A = Q2B, Q3A = Q3B) are kept identical .

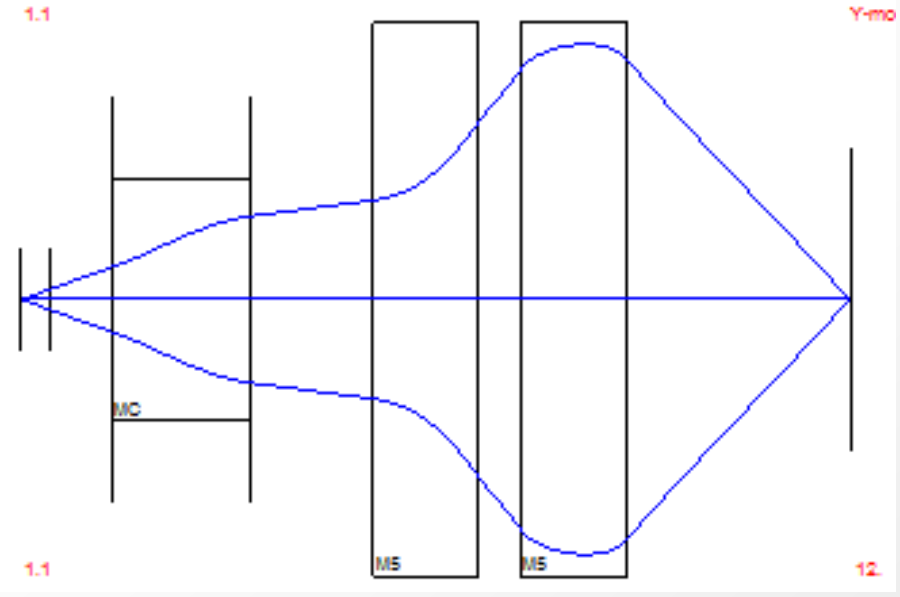
Preferred Optics, Layout DQQ Mode



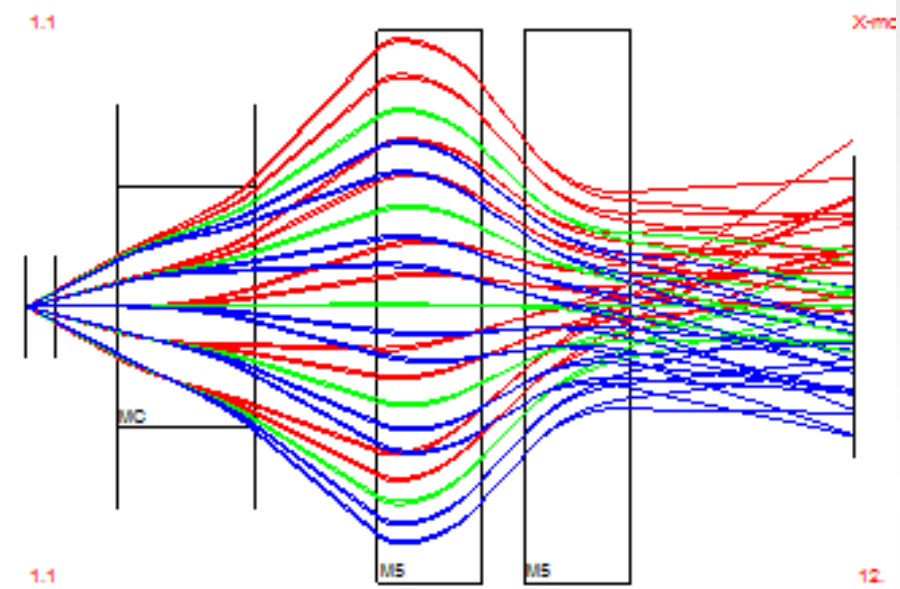
Full GRETA is shown. In this mode only partial GRETA (Distance 1.3 m to D1 one detector ring removed, 0.9 m two detector rings removed) will be used.

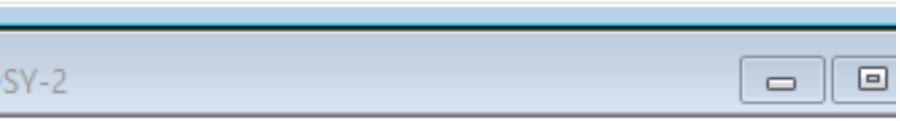


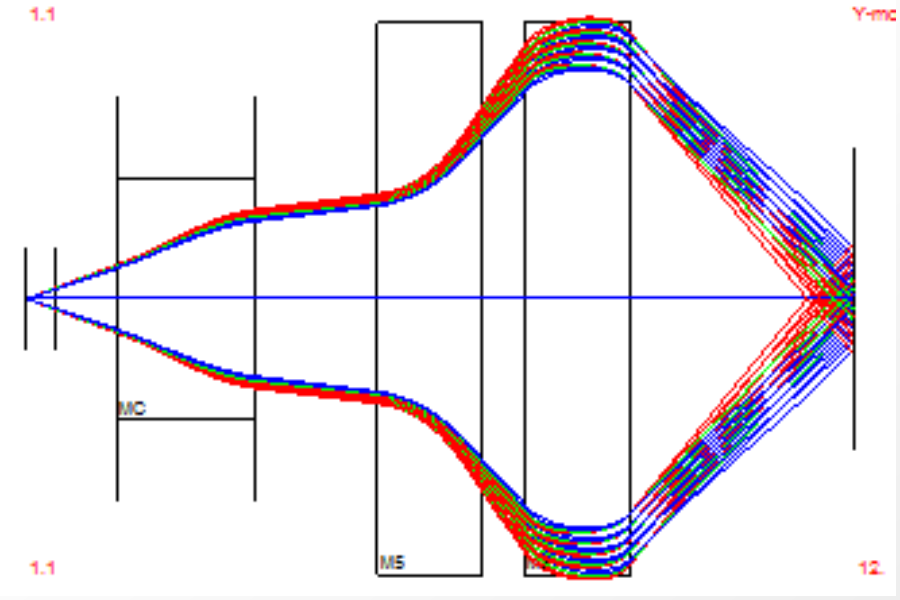




Preferred DQQ mode, 1st order calc.



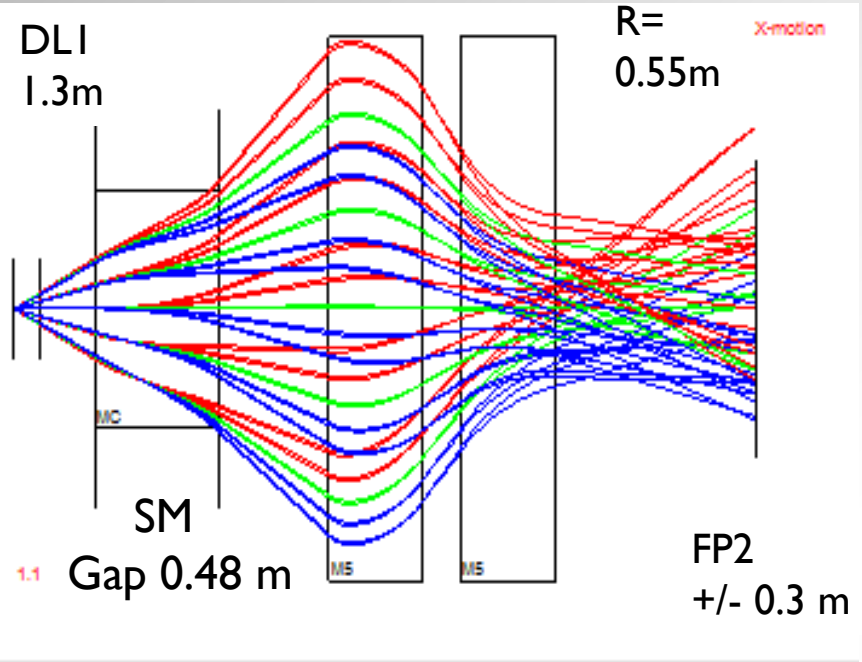


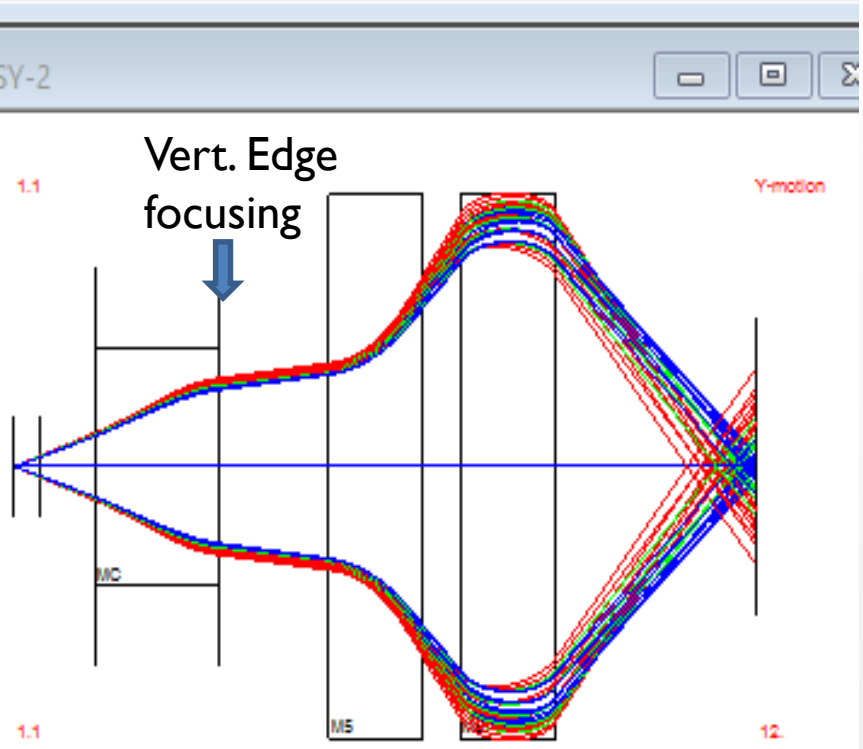


Preferred DQQ mode, 2nd order calc.

Note:
In this drawing the warm bore R is shown, that is available for the particle envelop .

If no HO components are needed the Cold Bore = Warm Bore





Preferred DQQ Mode, 4th order
DLI = 1.3 m

Horizontal and vertical foci, F2

DA = 75 mrad (Hor. Accept. Angle)
DB = 50 mrad (Vert. Accept. Angle)
dE/E = 10% (Energy Acceptance)
M11 = 2.222 (Hor. Magnif.)
M16 = 1.721 (Energy Disp.)
M21 = 0.552
M26 = 0.277
For x_0 = +/- 1 mm, E-Resolv. Power 387
x_0 = 0.5 mm, p-Resol. Power p/dp ~ 1500
M33 =-0.329

Cold Bore 0.65m
Q2A:= 2.420;
Q2B:= -2.560

H2A= 0.1 O2A :=0;
H2B= 0.1 O2B :=0;

File: HRS_DQQ_12June_Q_length.fox

Lattice File: Preferred Optics HRS, DQQ Mode

HRS_Lattice_Pref_DQQ_062117.xlsx		DQQ mode	File	HRS_DQQ_12June_Q_length.fox					
							Pole tip		
Element	Note	Element properties	Cold bore Radius/	Warm bore (m)		Length(m)	T		
Technical Name	Description	Effect. Length(m)	Half gap (m)	Dipole half gap	Note		Quad	Hex	Oct
		Dipole Bend Angle							
					FP1				
DL4	Drift	0.4				0.4			
DL5	Drift	0.9				1.3			
D1/SM	Dipole	35	3.2	0.24	GFR=0.5m	3.2548			
DL6	Drift	1.75				5.004769			
Q2A	Quad	1.5	0.65	0.55		6.504769	2.42	0.1	0
DL7	Drift	0.6				7.104769			
Q2B	Quad	1.5	0.65	0.55		8.604769	-2.56	0.1	0
DL8	Drift	3.2			F2	11.80477			
DL9	Drift	0.65			shifted!	12.45477			
Design Notes: Focal Plane F2 have different locations for the QQD and DQQ modes. GFR for D1 in QQD mode is 0.9 m but only 0.5 m in DQQ mode.									
	Polarities of Q2A and Q2B are reversed for QQD and DQQ mode. Bipolar power supplies or switches are needed.								

Dispersion Matching Preferred Optics

following solutions are obtained [12] for the beam-line parameters b_{16} and b_{26} to realize lateral dispersion matching and angular dispersion matching, respectively.

$$b_{16} = -\frac{s_{16}}{s_{11}}(1 + s_{11}s_{26}K - s_{21}s_{16}K)\frac{C}{T} \quad (7)$$

and

$$b_{26} = (s_{21}s_{16} - s_{11}s_{26})C. \quad (8)$$

See e.g. H. Fujita, NIM A484 (2002) 17

b = beam line 1st order matrix elements
s = spectrometer 1st order matrix elements

Assumptions:
K = 0 at 0 deg Scatt. Angle
T = 1 at 0 deg and perpend. Target

C = (p_in/p_out)/(dp_out/dp_in)
C = 1 for elastic scattering

Matching conditions:

$b_{16} = - s_{16}/s_{11}$
$b_{26} = s_{21}s_{16} - s_{11}s_{26}$

HRS Preferred, update 7/24/2017									Test Rays		
COSY: *. fox file		HRS_dispersion_Matching.xlsx					[m]	[rad]	DE =		
	Focal Plane	s11	s16	s21	s26		b16	b26		x/m	DA/rad
HRS_QQD_12June_Q_length.fox	F2	1.343	2.835	0.217	0.08		-2.111	0.508	0.010	-0.021	0.005
HRS_QQD_12June_Q_length.fox	F3	-0.712	-4.282	-0.33	-0.142		-6.018	1.308	0.040	-0.241	0.052
HRS_DQQ_130_Pref_12May_2017.fox	F2	2.222	1.721	0.552	0.277		-0.775	0.334	0.100	-0.077	0.033
HRS_Staging_D_40deg.fox	F3	-0.981	-4.81	-0.34	0.0344		-4.903	1.669	0.100	-0.490	0.167

Dipole Specifications, HRS Preferred Optics

	Units	D1	D2
Bending radius	m	3.2	4
Max. rigidity	Tm	8	8
Max. magn. field	Tm	2.5	2
Bending angle, + to right	deg	-35	60
Central ray arc	m	1.9548	4.1888
Vert. gap, full size	m	0.48	0.22
GFR, dB/B < +/- 0.5%	m	0.9	1.1
Pole width, approx.	m	2.34	1.6
Edge angle, entrance	deg	0	-20
Edge angle, exit	deg	35	-20
Total height, approx.	m	4.8	2.8
Weight, approx.	metric tons	650	400

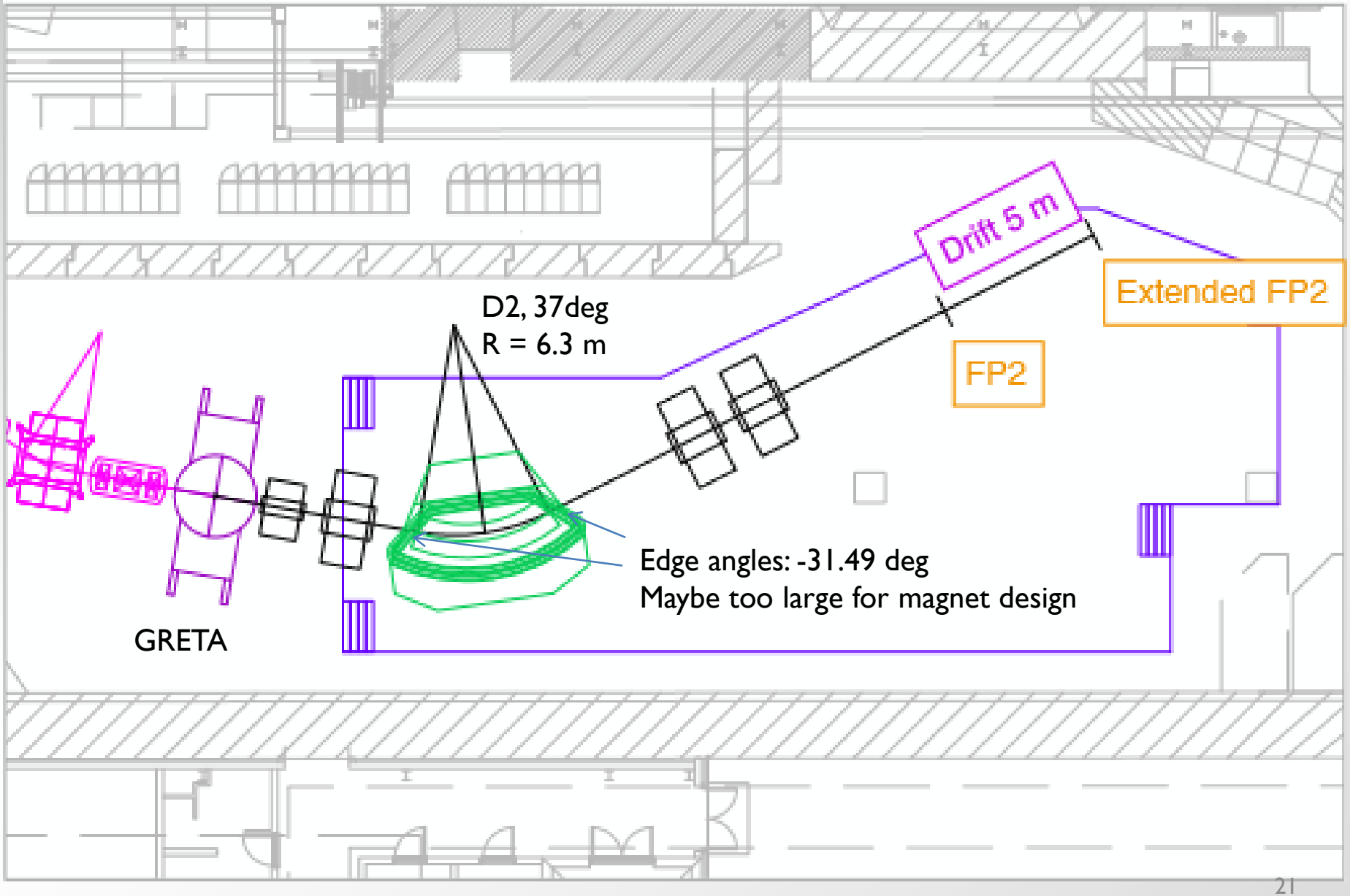
Quadrupole Specifications
HRS Preferred Optics (QQD Mode)

	Units	Q0A	Q1A	Q2A	Q2B	Q3A	Q3B
Focusing strength	T	-9.64	5.31	-2.71	2.71	4.28	-5.14
Eff. Field length	m	1.25	1.25	1.25	1.25	1.1	1.1
Max. gradient	T/m	-7.71	4.25	-2.17	2.17	3.89	-4.67
Cold bore, radius	m	0.35	0.6	0.6	0.6	0.45	0.45
Warm bore, radius	m	0.25	0.5	0.5	0.5	0.45	0.45
Max. pole tip strength	T	-2.7	2.55	-1.3	1.3	1.75	-2.1
Max. inhomogeneity	%	0.2	0.2	0.2	0.2	0.2	0.2

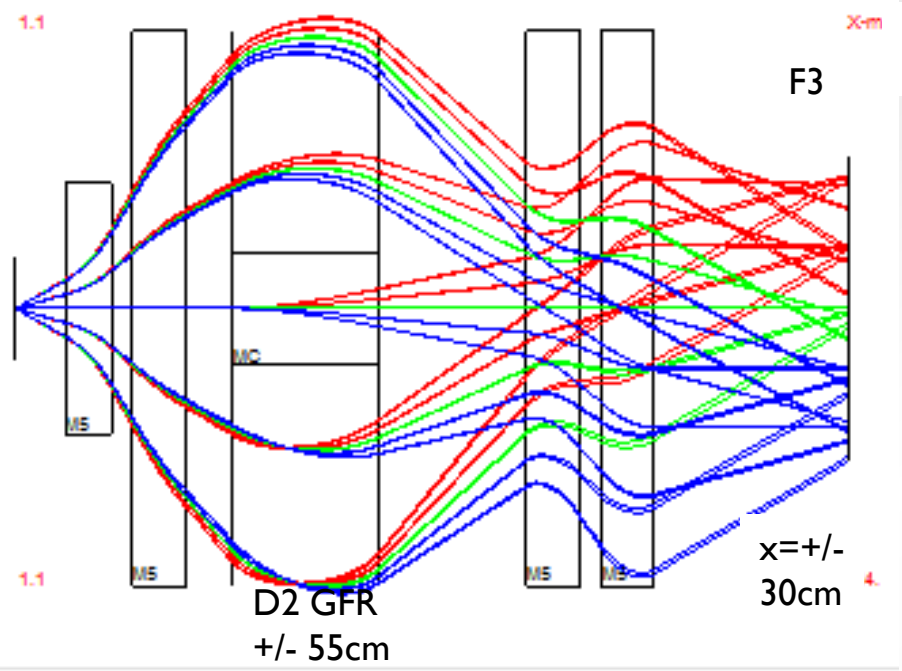
Staging

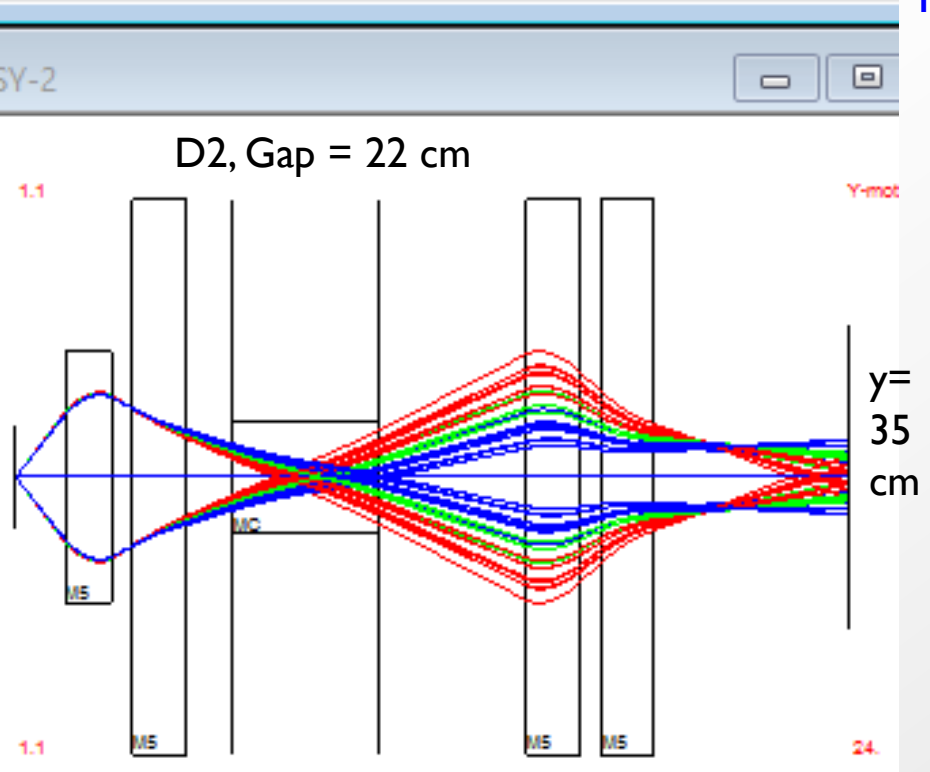
- Staging study to stretch the HRS project in time to avoid spikes in funds and manpower.
- Consider impact on science program.
- All large magnets of Stage 1 have to be used in Stage 2, to make staging affordable.
- Stage 2 has to fulfill all of the spectrometer requirements.
- We studied several concepts, the present Staging Option is the most promising.
- Consider impact on science program for shutdown, additional cost for staging, like vacuum chambers, longer management, risk

Staging Layout (QQD Mode)



Stage Optics, 3rd Order





Horizontal and vertical foci, F3
DA = +/- 40 mrad (Hor. Accept. Angle)
DB = +/- 90 mrad (Vert. Accept. Angle)
dE/E = +/- 5% (Energy Acceptance)
M11 = -0.981 (Hor. Magnif.)
M16 = -4.810(Energy Disp.)
M21 = -0.340
M26 = 0.0344 M33 =3.851 Vert.Magn.
For x_0=+/-1mm, E-Res. Power(E) = 2451
For x_0=+/- 0.5 mm, Res.Power d/dp ~ 9600

Q0A:= -1.824;	H0A := 0.0;	O0A := 0.0;
Q1A:= 0.521;	H1A := 0.0;	O1A := 0.0;
Q2A= -1.856;	H2A := 0.0;	O2A := 0.0;
Q2B= 1.110;	H2B := 0.0;	O2B := 0.0;
	H3A := 0.0;	O3A := 0.0;
	H3B := 0.0;	O3B := 0.0;

Focal Plane tilt angle: -79.0 deg
Atan(-ME(1,26)/ME(2,2)/ME(1,6))*180/PI)

File: HRS_Staging_D_40deg.fox

Lattice File: Staging Optics HRS (QQD Mode)

HRS Spectrometer layout		7/24/2017		Stage D						
HRS_Lattice_Stage_D_072417.xlsx		QQD Mode	File	HRS_Staging_D_40deg.fox					Cold bore	
									Pole tip	
Element	Note	Element properties		Cold bore Radius/	Warm bore (m)		Length(m)		T	
Technical Name	Description	Effect. Length(m)		Bending radius	Dipole half gap	Note		Quad	Hex	Oct
		Dipole Bend Angle								
						FP1				
DL1	Drift	1.4					1.4			
Q0A	Quad+Oct	1.3		0.35	0.25		2.7	-1.824	0	0
DL2	Drift	0.6					3.3			
Q1A	Quad+Oct	1.5		0.65	0.55		4.8	0.520999	0	0
DL3	Drift	1.35					6.15			
DL4	Drift	0					6.15			
DL5	Drift	0					6.15			
D2	Dipole	37.02		6.3	0.11	GFR=1.1m	10.2206			
DL6	Drift	4.2					14.42056			
Q2A	Quad	1.5		0.65	0.55		15.92056	-1.8561	0	0
DL7	Drift	0.6					16.52056			
Q2B	Quad	1.5		0.65	0.55		18.02056	1.11	0	0
DL8	Drift	5.5				F3	23.52056			

Design Notes: All quadrupoles and dipole D2 in this stage are identical (same specifications) as those with the same name in the full HRS system, magnet settings are different.

In this Stage , there is no Sweeper magnet (D1) and also Q3A and Q3B are not presents.

In this Stage dipole D2 is used with different bending radius and edge angles.

In this Stage several drift lengths are different from the full HRS system, requiring new vacuum chambers in the transition from Stage to full HRS system.

All quadrupoles are assumed to have Hexapole and Octupole components, so the Cold Bore Radius is 0.1 m larger than the Warm Bore Radius.

Although not all quads used all HO coils, it is assumed that in the further optimization the radial HO components in the dipoles and quads will require such components.

Also all types of quads (Q0A, Q1A = Q2A = Q2B) are identical .

Path forward for HRS

- Field calculations of magnets to minimize size of large magnets, extract HO (inside, ends, and fringe fields), perform ion-optical calculations, iterate if necessary.
- Specify Hexapole and Octupoles built into quadrupoles.
- Tolerances, calculate and specify.

END