Ion Optics for the High Rigidity Spectrometer HRS Status Report

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Presented at the 2016 Fragment Separator Expert Meeting

OUTLINE

- HRS facility to meet science program
- Several Spectrometer Modes needed to meet experimental program
- First-order ion-optics and Layout consistent with all Modes
- First order magnet design parameters for magnet field calculations
- Full dispersion matching (b_{16}, b_{26}) determined for beam line
- Started higher-order corrections
- Path forward

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U.S. DEPARTMENT OF ENERGY
Office of Science

Bi-weekly HRS Zoom meeting

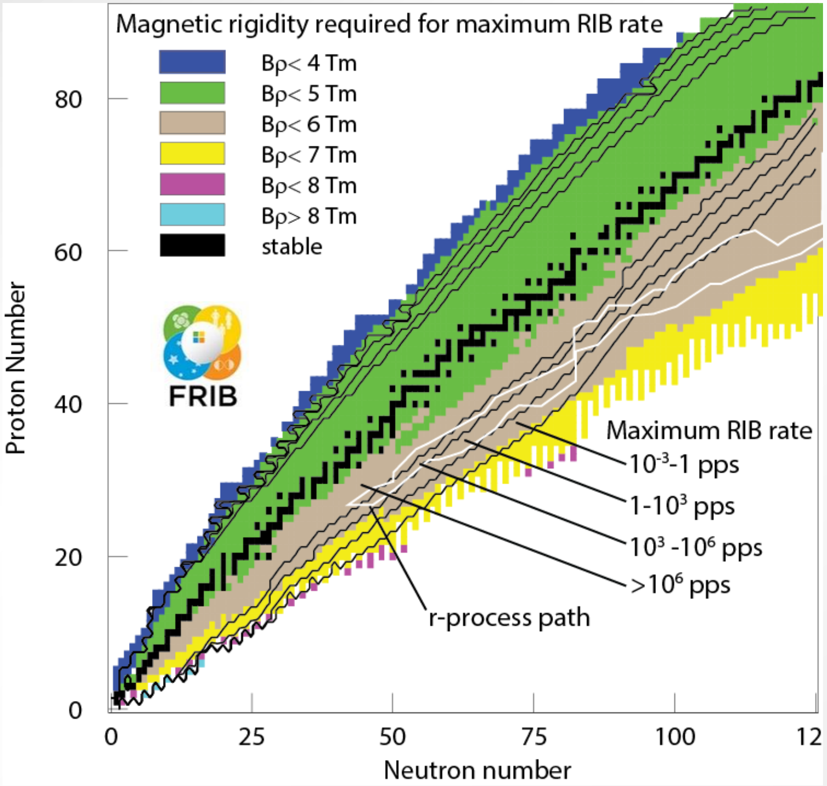
- Th. Baumann, MSU
- D. Bazin, MSU
- G. Berg, Notre Dame
- G. Bollen, MSU
- J. Brown, Wabash
- Sh. Chouhan, MSU
- J. Cizewski, Rutgers
- M. Couder, Notre Dame
- A. Couture, LANL
- H. Crawford, MSU
- A. Estrade Vaz, CMU
- A. Gade, MSU
- R. Grzywacz, UT
- M. Hausmann, MSU
- C. Hoffman, ANL
- R. Janssens, ANL
- K. Jones, UT
- D. Lawton, MSU
- W. Mittig, MSU
- S. Mosby, LANL
- S. Noji, MSU
- S. Pain, ORNL
- M. Portillo, MSU
- G. Rogachev, Texas A&M
- B. Sherrill, MSU
- O. Tarasov, MSU
- R. Zegers, MSU

Optimizing the scientific opportunities at FRIB

FRIB will produce the most exotic isotopes at unprecedented intensities by fast fragmentation of heavy-ion beams

To minimize losses, experiments with the most exotic species are best performed at the energy at which maximum production rate is achieved

Available spectrometers at NSCL lack necessary bending power – the proposed HRS overcomes this serious limitation



Luminosity gains with the HRS exceed a factor of 10 for experiments with neutron-rich rare isotopes for which the potential for scientific discovery is highest

- Beams produced at energy for which yield is maximum
- Reduce beam losses in beam line
- Use thick reactions targets
- Reduce charge state production

Endorsements

FRIB Scientific Advisory Committee (SAC): *"The HRS is necessary to conduct the scientific mission of FRIB."*

In the resolution of the **2014 APS Division of Nuclear Physics Town Meeting on Nuclear Structure**, timely construction of the HRS as a state-of-the-art instrument for FRIB was recommended.

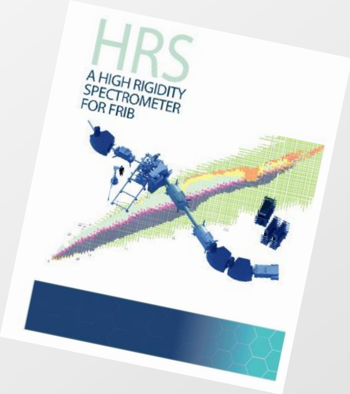
In the resolution of the **2014 APS Division of Nuclear Physics Town Meeting on Nuclear Astrophysics**, the HRS was listed as a critical piece of equipment, and the development and implementation was recommended.

2015 NSAC Long Range Plan: *"In addition to (…) facilities, the community has developed exciting ideas for new equipment key to the future research effort. Not all can be realized immediately, but a targeted suite to address the highest priority research programs is needed. Instruments such as GRETA, HRS, and SECAR (a recoil spectrometer for nuclear astrophysics research) will be essential to realize the scientific reach of FRIB"… "Another key addition to FRIB is the proposed High-Rigidity Spectrometer (HRS), which would enable in-flight reaction experiments with the most neutron-rich nuclei available from FRIB."*

HRS to meet the requirements of Science Program

Five guiding types of experiment were chosen to constrain the ion-optical and magnet feasibility studies.

1. Invariant mass spectroscopy – detection of fast neutrons at forward angles with MoNA-LISA
2. In-beam γ-ray spectroscopy far from stability using GRETA
3. Spectroscopy with heavy nuclei – momentum resolution and (partially) dispersion-matched modes, particle ID
4. Time-of-flight mass measurements – timing, mass, and momentum resolutions, particle ID
5. In-flight fission studies – particle ID, large acceptance



Goal: Develop an optimized Ion-optical and Magnet Design Concept for the HRS system that meets all Technical Requirements needed for the Science Program.

HRS has to match Science Program

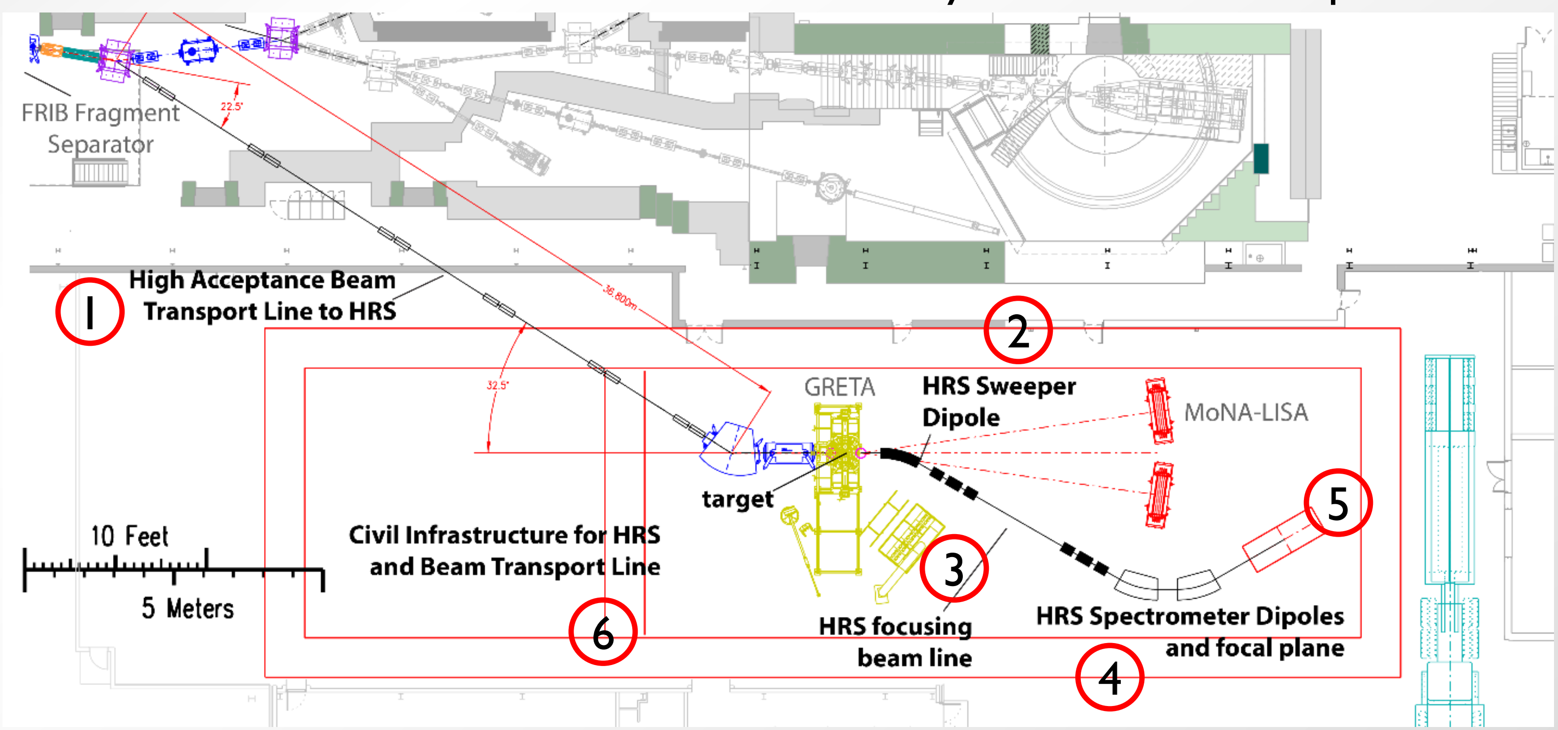
Presentations of HRS Science Program at LECM 2016, Notre Dame

- GRETA, Heather Crawford (LNBL)
- MoNA LISA, Jim Brown (Wabash Univ.)
- Knock-out, Daniel Bazin (NSCL/MSU)
- Fission, Shea Mosby (LANL)
- Mass measurem., Alfredo Estrade-Vaz (Central Michigan Univ.)

Scope of HRS

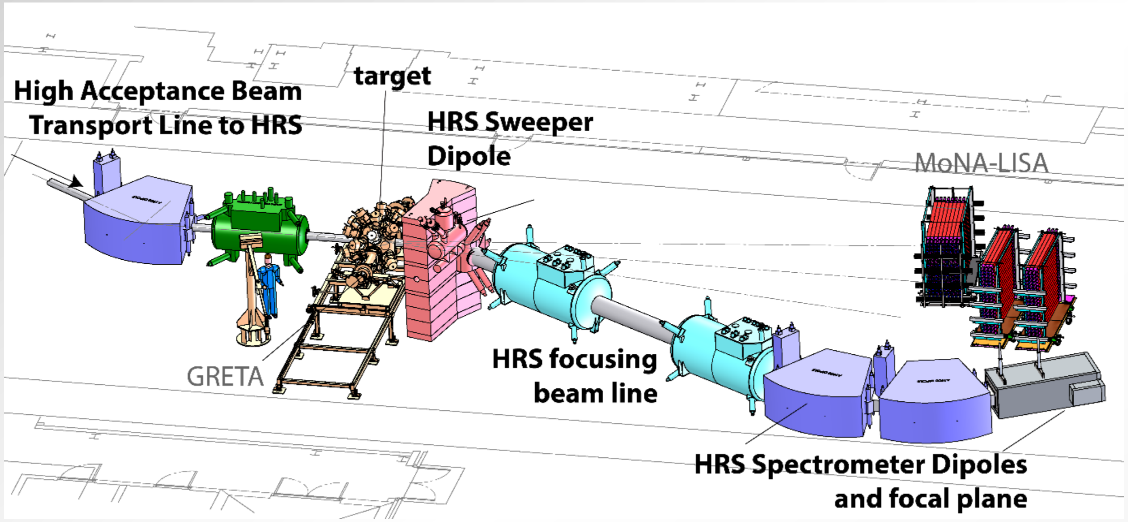
1. A high-rigidity, large-acceptance beam line to transport the rare isotopes with minimal losses from the FRIB fragment separator to the HRS spectrometer
2. A sweeper dipole behind the reaction target for diverting charged particles
3. A focusing beam line that transports the diverted particles from the sweeper dipole to two spectrometer dipoles for analysis
4. Two spectrometer dipoles for identifying and analyzing charged particles
5. Charge-particle detectors that are i) placed in the beam lines for tracking rare-isotopes that are impinged on the reaction target, and ii) placed in the focusing beam line and final focal plane to analyze the particles emerging from reactions in the target
6. Civil infrastructure to house the HRS

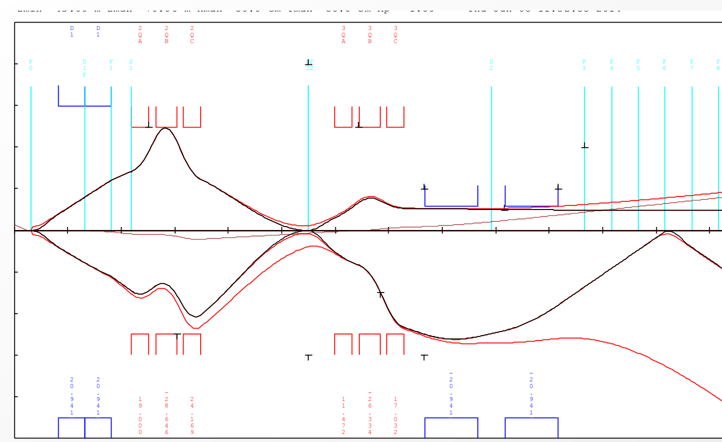
Possible layout from White Paper, Dec 2014



High Rigidity Spectrometer (DQQQ)

Pre-conceptual (first order) ion-optical design from White Paper





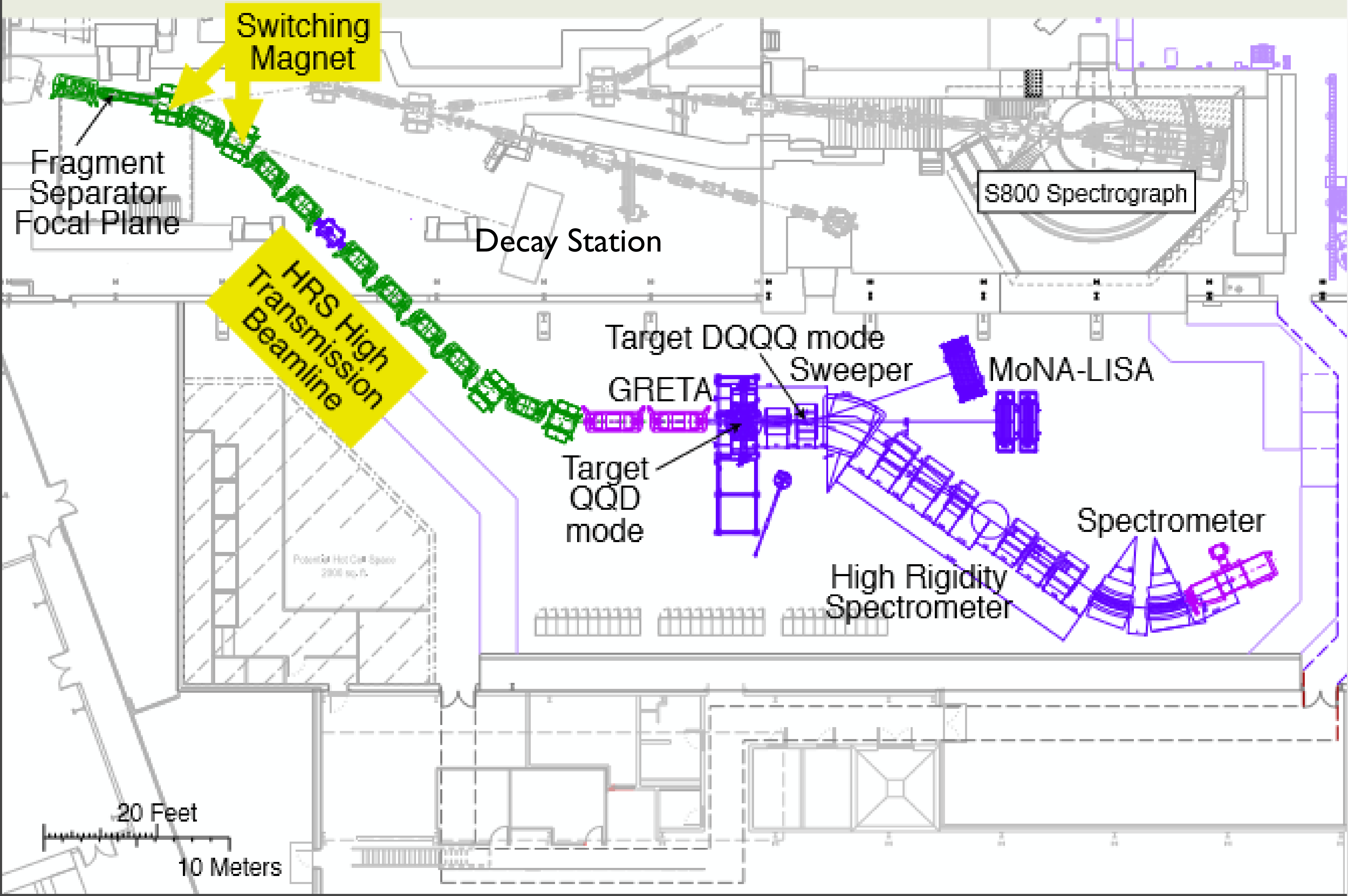
Spectrometer

- Magnetic bending power: up to 8 Tm (superconducting magnets)
- Large momentum (10% dp/p) and angular acceptances (80x80 mrad)
- Particle identification capabilities extending to heavy masses (~200)
- Momentum resolution 5000; intermediate image after sweeper
- Dispersion: 7cm/%
- Invariant mass spectroscopy: ±6° opening in sweeper dipole for neutrons

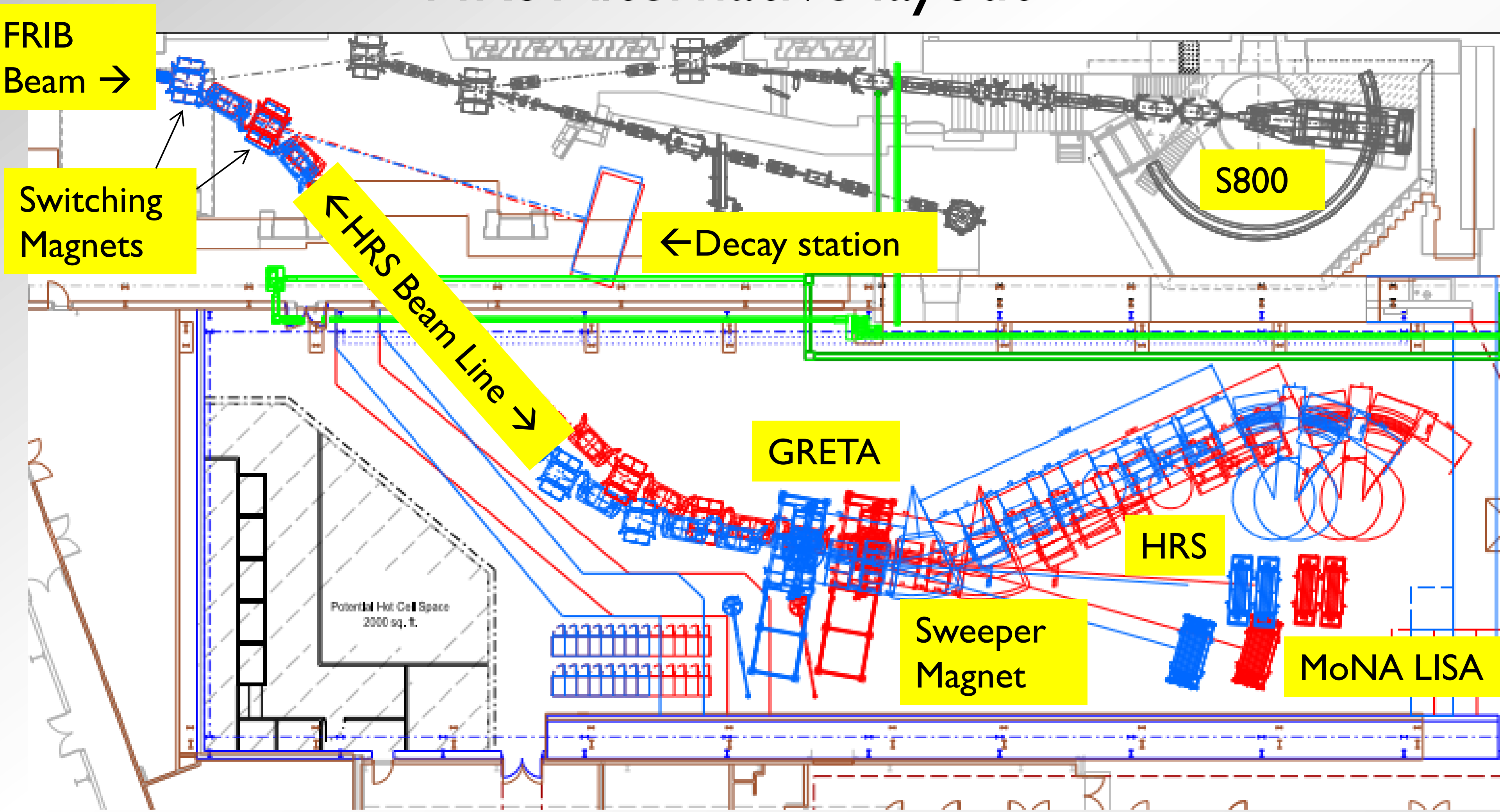
Beam Line

- Dispersion-matching capability
- Beam line from fragment separator designed to optimize transmission to HRS

Overview HRS Layout & Optics



HRS Alternative layout



Explored inverted layout, it fits building but difficult to achieve dispersion matching conditions

HRS Modes (needed to meet requirements of experiments

- Ion-optical calculations show initially envisioned **DQQQ** is needed for the MoNA LISA experiments, but is not able to meet several other experimental requirements (e.g. acceptances, resolving power). Therefore we are also pursuing
- **QQD+QQQDD**, including second part

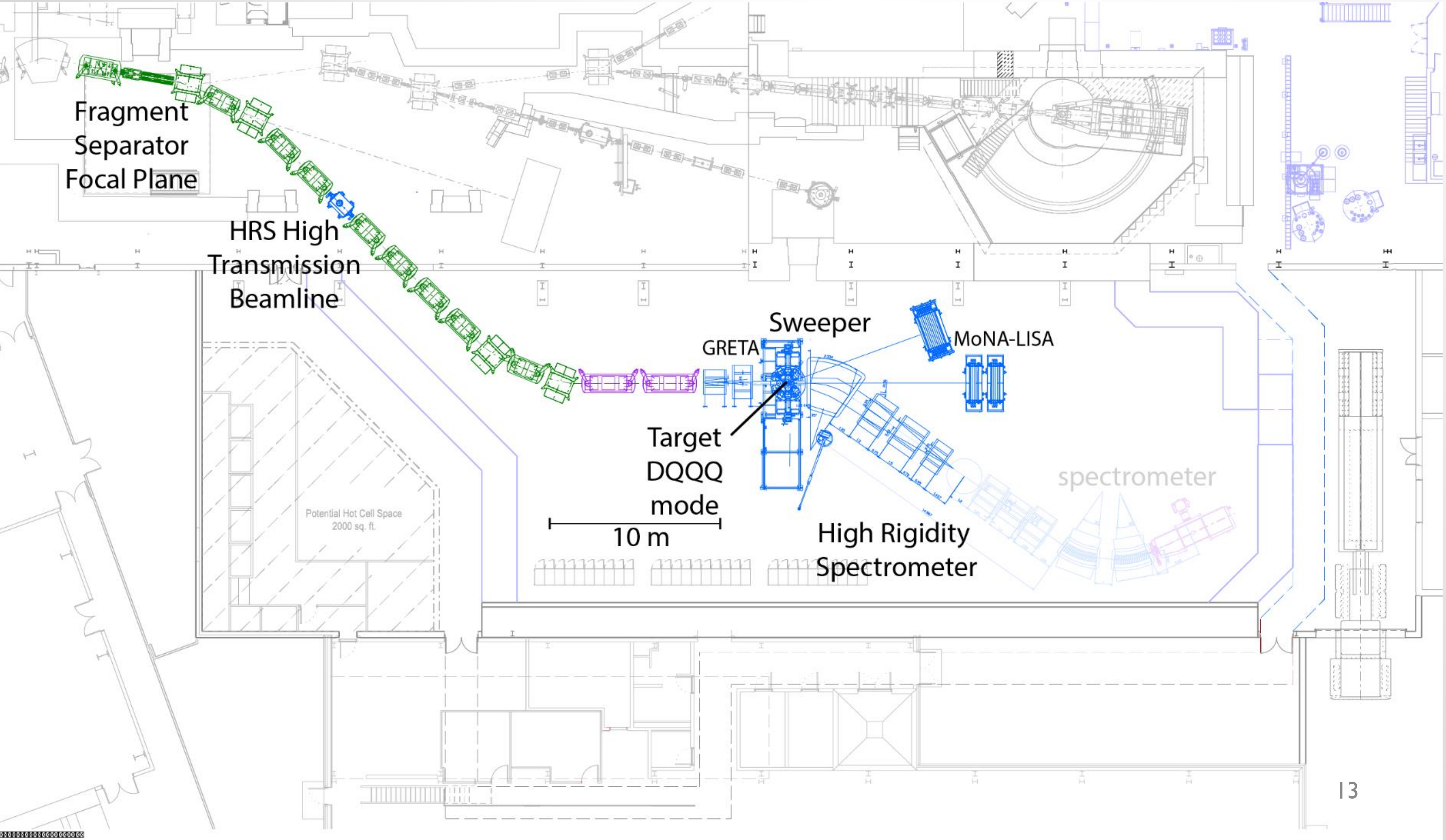
- Possible additional modes with one Q in front considered
- QDQ, first part, plus second part
- QDQQQ, first part, plus second part

Note: QDQ and QDQQQ modes may not be needed in addition to the QQD modes with 2 quads in front of the sweeper dipoles, depending of experiments

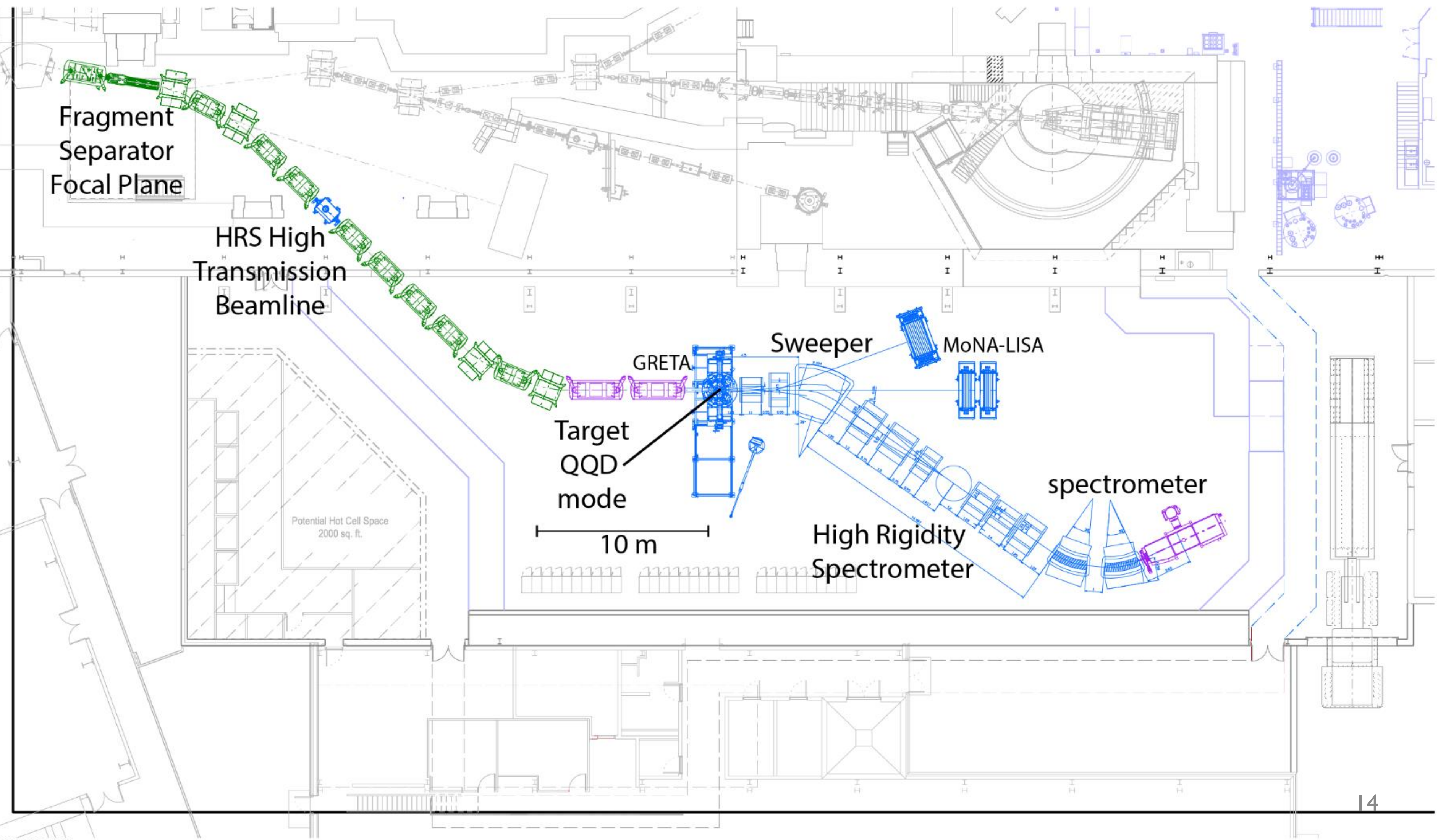
The following criteria were implemented in the 1st order HRS design

- All magnets identical for all modes
- Rearrangement of Q0A and Q1A in front of Sweeper Magnet (SM)
- Quad strengths < 2.5 T poletip, adjusted lengths (iron, superconducting coils)
- Dipole fields < 2.1 T in GFR, (iron, superconducting coils)
- Quad-radius = warm-bore + 0.10 m to accommodate Hexapoles and Octupoles in all quadrupoles
- Greta (1.38 m radius) at target FP1 (optional FP2 location)
- Neutron cone clearance about 6 deg (dependent on Q2A design and target location), Sweeper dipole with 35 deg bending angle
- Drift lengths between magnets adjusted for large 1st order acceptances and sufficient space for detectors, pumps and diagnostics
- Building not yet designed, but constraints by existing buildings

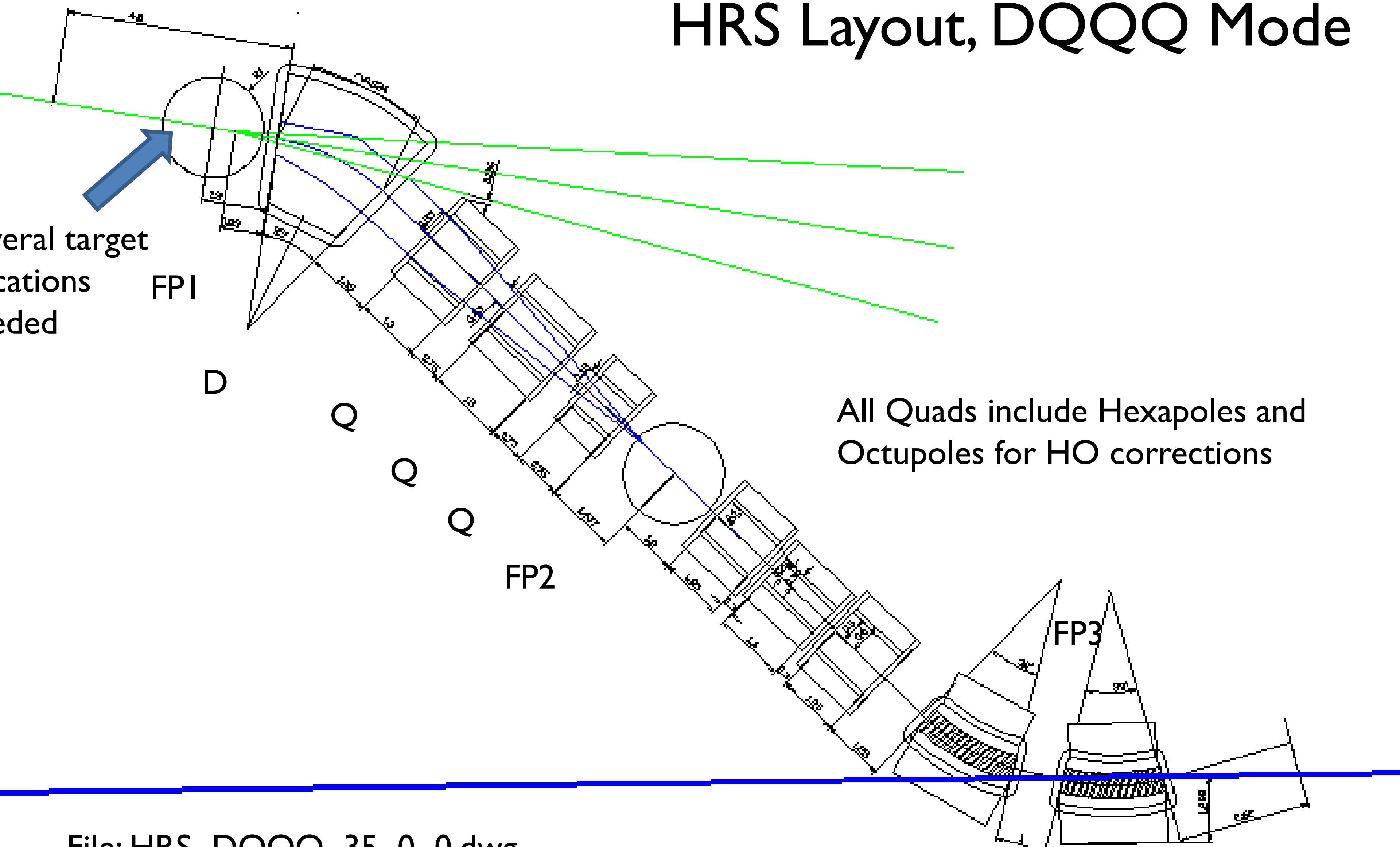
DQQQ mode – invariant mass spectroscopy MoNA LISA



QQD mode – higher resolution



HRS Layout, DQQQ Mode



All Quads include Hexapoles and Octupoles for HO corrections

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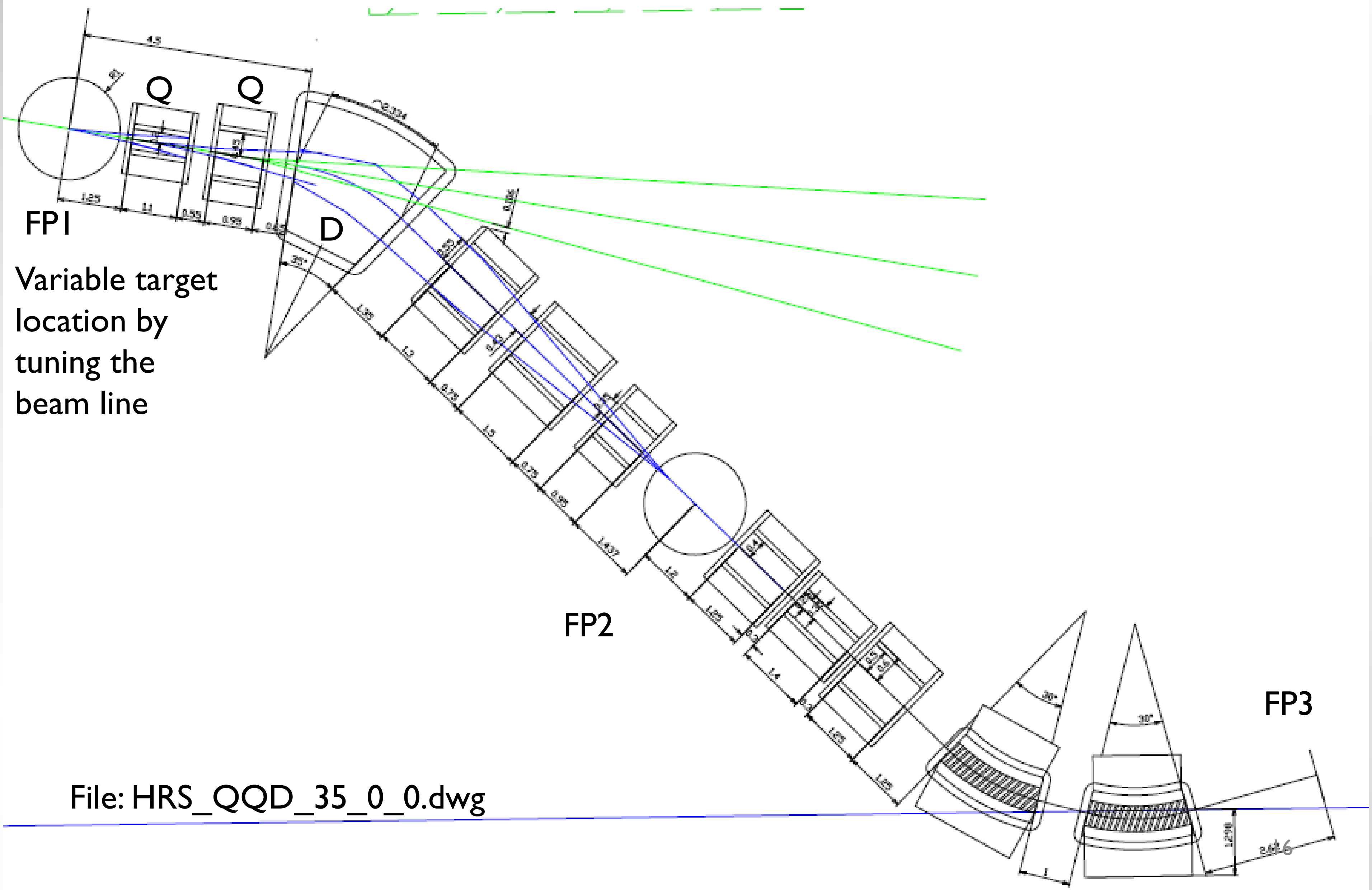
HRS Layout, QQD Mode



Variable target location by tuning the beam line

File: HRS_QQD_35_0_0.dwg

Preliminary HRS Lattice

may slightly change with higher order optimization

Gives basic input Parameters for the layout, field calculations and magnet design

Compatible with all Modes (1st order)

Element Technical Name	Note Description	Element properties Effect. Length(m) Angle	Radius/ Half gap (m)	Warm bore (m) Dipole half gap	
DL14	Drift	1.25			
Q0A	Quad+Hex+Oct	1.1	0.3	0.2	
DL15	Drift	0.55			
Q1A	Quad+Hex+Oct	0.95	0.55	0.45	
DL16	Drift	0.65			
B1/SM	Dipole	35 deg	3.8197	0.35	
DL17	Drift	1.35			
Q2A	Quad+Hex+Oct	1.3	0.65	0.55	
DL18	Drift	0.75			
Q2B	Quad+Hex+Oct	1.5	0.53	0.43	
DL19	Drift	0.75			
Q2C	Quad+Hex+Oct	0.95	0.45	0.35	
DL20	Drift	1.4366			FP2
DL21	Drift	1.2			
Q3A	Quad+Hex+Oct	1.25	0.5	0.4	
DL22	Drift	0.3			
Q3B	Quad+Hex+Oct	1.4	0.35	0.25	
DL23	Drift	0.3			
Q3C	Quad+Hex+Oct	1.25	0.6	0.5	
DL24	Drift	1.25			
B2	Dipole	30 deg	3.819719	0.14	
DL25	Drift	1			
B2	Dipole	30 deg	3.819719	0.1	
DL26	Drift	2.62			FP3

HRS Dipole Parameters

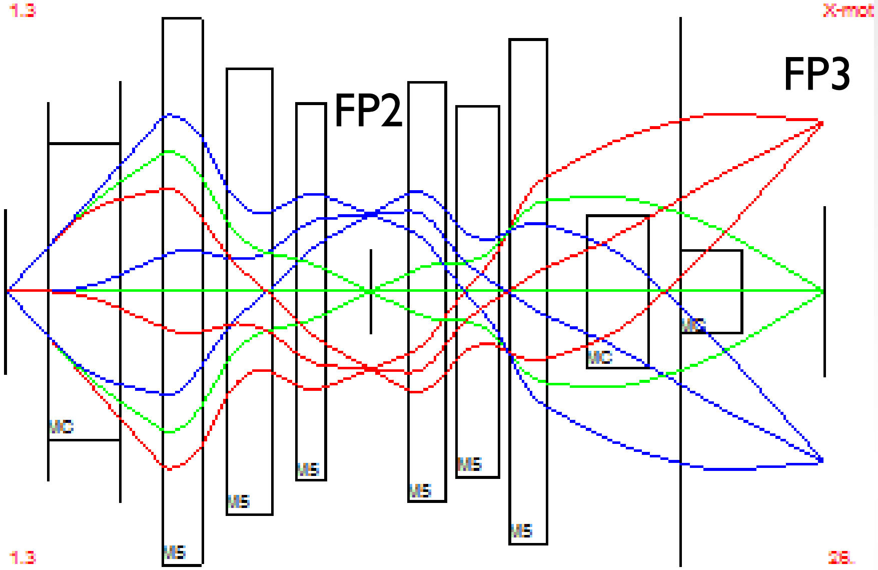
HRS	Dipoles	Parameter		
	Units	B1(SM)	B2	B3
Bending radius	m	3.82	3.82	3.82
Maximum rigidity	Tm	8	8	8
Max. magnetic field B	T	2.1	2.1	2.1
Bending angle, + to right - to left	deg	35	-30	-30
Central ray, arc length	m	2.334	2.000	2.000
Vertical gap, full size	m	0.70	0.28	0.20
GFR, dB/B <+/-<0.1%	cm	50	65	65
Pole width	m	tbd	tbd	tbd
Entrance s_{11}	0	0	0	0
Exit s_{12}	0	0	0	0
Maximum DC Power	kW	tbd	tbd	tbd
Weight, approx.	kg	tbd	tbd	tbd

HRS Quadrupoles Parameters (for magnet design)

Parameter	HRS Quadrupole Magnets								
		Q0A	Q1A	Q2A	Q2B	Q2C	Q3A	Q3B	Q3C
Overall length	m	1.30	1.15	1.50	1.70	1.15	1.45	1.60	1.45
Focusing strength	T	-9.17	-4.32	5.00	7.08	2.75	6.25	-8.00	3.75
Eff. field length	m	1.10	0.95	1.30	1.50	0.95	1.25	1.40	1.25
Gradient	T/m	-8.33	-4.55	3.85	4.72	2.89	5.00	-5.71	3.00
Good field, radius Warm bore	m	0.20	0.45	0.55	0.43	0.35	0.40	0.25	0.50
Quad bore, radius	m	0.30	0.55	0.65	0.53	0.45	0.50	0.35	0.60
Max. pole tip strength	T	-2.5	-2.5	2.5	2.5	[-0.5, 1.3]	2.5	-2	1.8
Maximum DC Power	kW	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Maximum Inhomogeneity		0.20%	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%
Iron weight, (approx.)	kg	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd

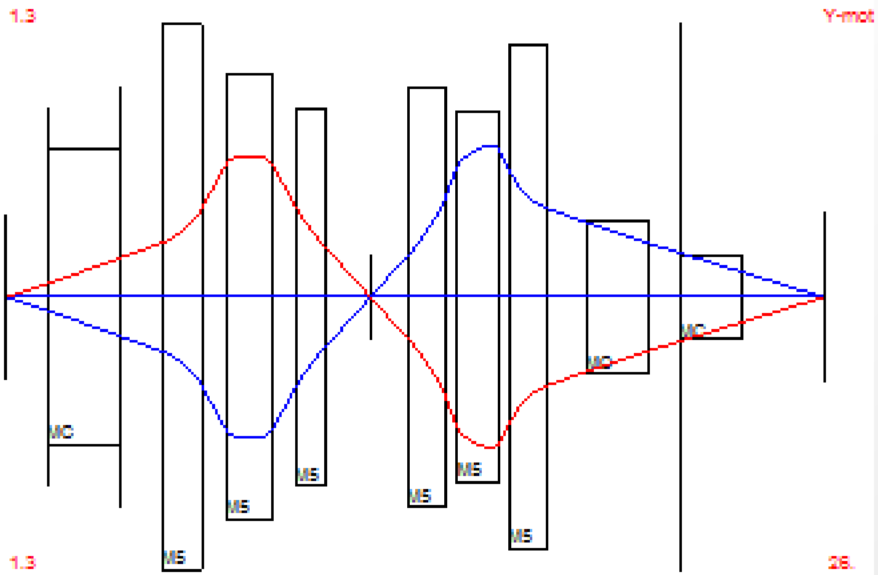
Notes:

1 Q2C requires a maximum pole tip strength of 1.3 T in the DQQQ Mode, and -0.5 T in the QDQQQ Mode
2 All quadrupoles include hexapoles and octupoles
3 The inhomogeneity refers to the integrated field within the Good-Field-Region
4 The quad bore is typically 10 cm larger than the worm-bore to provide space for the hex and oct coils
5 If the Overall Length is exceeded in the design, double check that there is no mechanical interference
6 The first quad Q2A after SM has to be cut at the beam left side to allow for max. neutron scattering angle
7 All parameters are preliminary, based on 1st order ion-optical calculations and are subject to modifications



Calc. using COSY Infinity

SY-2



DQQQ Mode, 1st order

Increased Q3B radius to 0.44 m

Horizontal and vertical foci, F3

DA = 80 mrad (Hor. Accept. Angle)
DB = ~~20~~ 25 mrad (Vert. Accept. Angle)
dE/E = 10% (Energy Acceptance)
M11 = ~~1.861~~ 1.791 (Hor. Magnif.)
M16 = ~~-4.114~~ -4.054 (Energy Disp.)
M21 = ~~0.0761~~ 0.1217
M26 = ~~-0.351~~ -0.382
For x_0 = 1 mm, E-Resolv. Power ~~1100~~ 1130
M33 = ~~1.084~~ 1.111

Q3B, Radius = 0.44m, B2 Half- gap = 0.18 m

Q2A:= 2.40302;
Q2B:= -2.34849;
Q2C:= 1.191394;
Q3A:= 2.1021708 ;
Q3B := ~~-1.93525;~~ → -2.51687
Q3C := ~~1.70997;~~ → 1.782110

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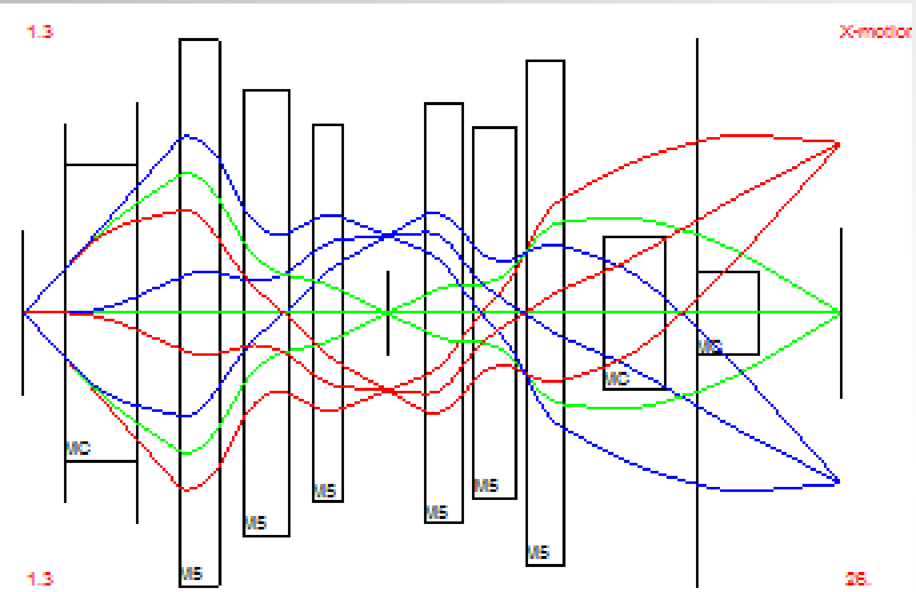
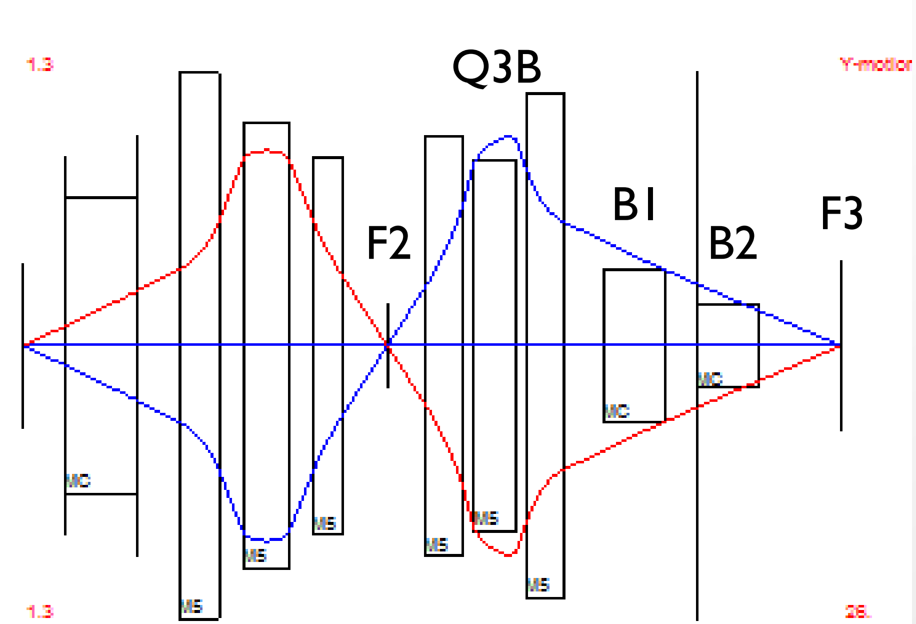
DQQQ Mode, 1st order





Increase Q3B radius to 0.44 m and B1, B2 gap to 0.23 m, 0.16 m

Horizontal and vertical foci, F3

DA = 80 mrad (Hor. Accept. Angle)
DB = ~~20~~ ~~25~~ 35 mrad (Vert. Accept. Angle)
dE/E = +/-10% (Energy Acceptance)
M11 = ~~1.861~~ 1.791 (Hor. Magnif.)
M16 = ~~-4.114~~ -4.054 (Energy Disp.)
M21 = ~~0.0761~~ 0.1217
M26 = ~~-0.351~~ -0.382
For x_0 = 1 mm, E-Resolv. Power ~~1100~~ 1130
M33 = ~~1.084~~ 1.111

Alternative: If E-Resolv. Power about 410 at F2 is sufficient for experiment, DB = 35 mrad is possible without increasing size of Q3B, B1 and B2

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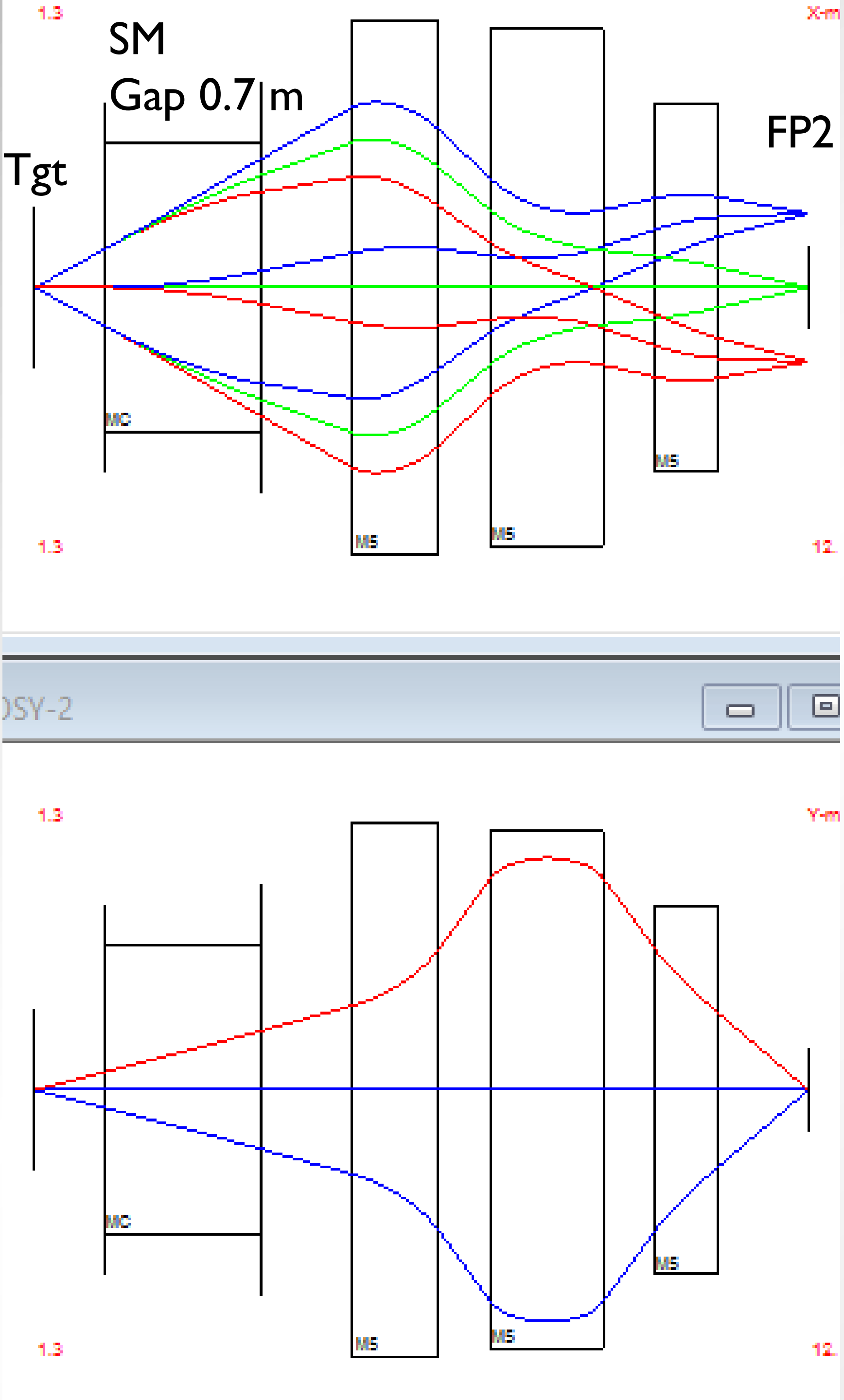
Optimizing DQQQ mode for invariant mass spectroscopy – detection of fast neutrons at forward angles with MoNA-LISA

Requirements

- Larger vertical acceptance needed
- Lower momentum resolution acceptable (dE/E ~ 400)

Solutions

- Use only Part 1 of HRS, Focal plane F2
- Short distance of target to SM EFB
- GRETA used with front detector rings removed



DQQQ Mode, 1st order
DL1 = 1.03 m

Increased Q2B radius from 53 cm to 63 cm
Increased EFL from 1.5 m to 1.7 m,
Decreased DL20 (F2 from 1.4366 m to 1.35 m

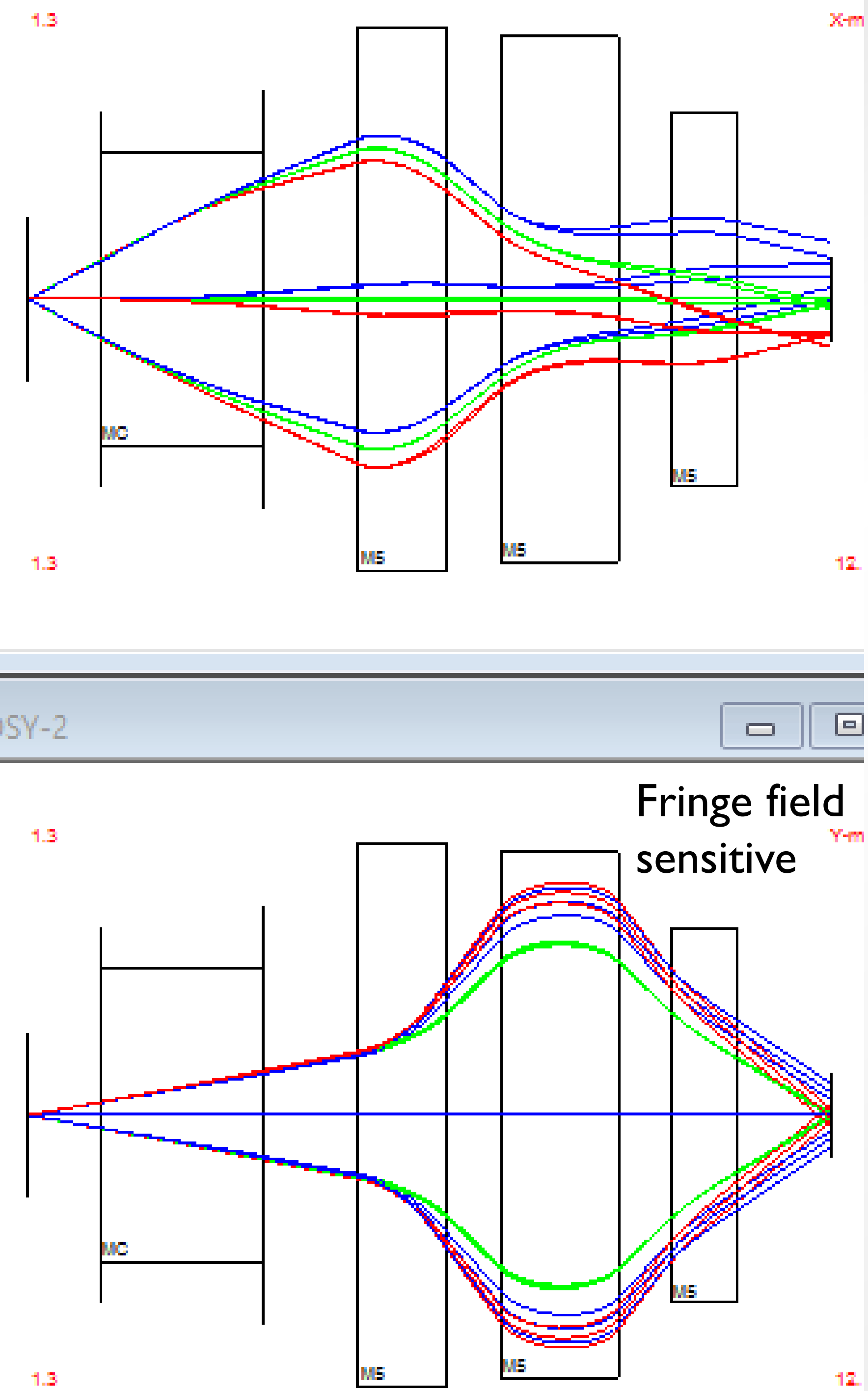
Horizontal and vertical foci, F2

DA = 90 mrad (Hor. Accept. Angle)
DB = 42 mrad (Vert. Accept. Angle)
dE/E = 10% (Energy Acceptance)
M11 = -2.47 (Hor. Magnif.)
M16 = 1.81 (Energy Disp.)
M21 = -0.2756
M26 = 0.06876
For x_0 = 1 mm, E-Resolv. Power 366
M33 =-0.301

Q2A:= 2.48821;
Q2B:= -2.5000;
Q2C:= 1.16142;

File: HRS_DQQQ_F2_103_order1.fox

DQQQ Mode, 2nd order DL1 = 1.03 m



Fringe field sensitive

Increased Q2B radius from 53 cm to 63 cm
And EFL from 1.5 m to 1.7 m

Horizontal and vertical foci, F2

DA = 90 mrad (Hor. Accept. Angle)
DB = 30 mrad (Vert. Accept. Angle)
dE/E = 4 % (Energy Acceptance)
M11 = -2.47 (Hor. Magnif.)
M16 = 1.81 (Energy Disp.)
M21 = -0.2756
M26 = 0.06876
For x_0 = 1 mm, E-Resolv. Power 366
M33 =-0.301

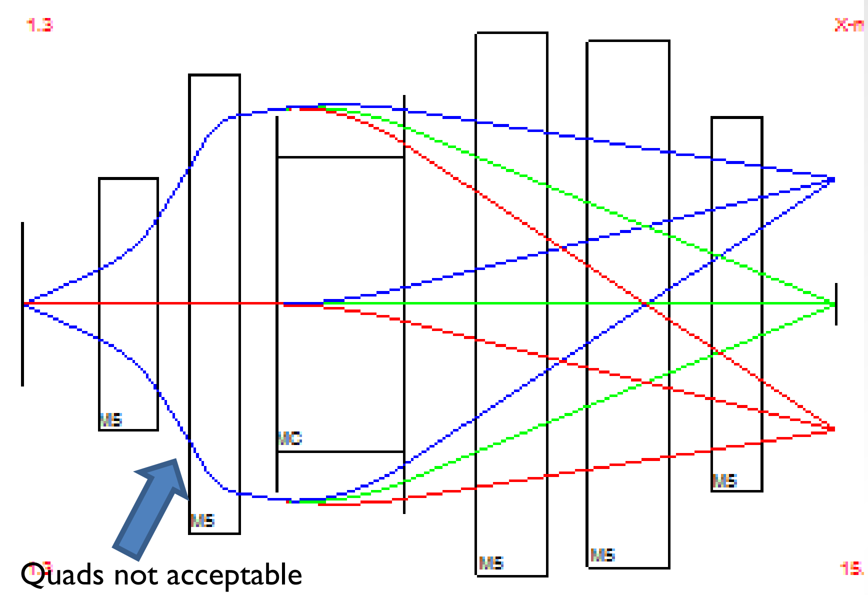
Q2A:= 2.48821;
Q2B:= -2.5000;
Q2C:= 1.16142;

File: HRS_DQQQ_F2_103_order2.fox

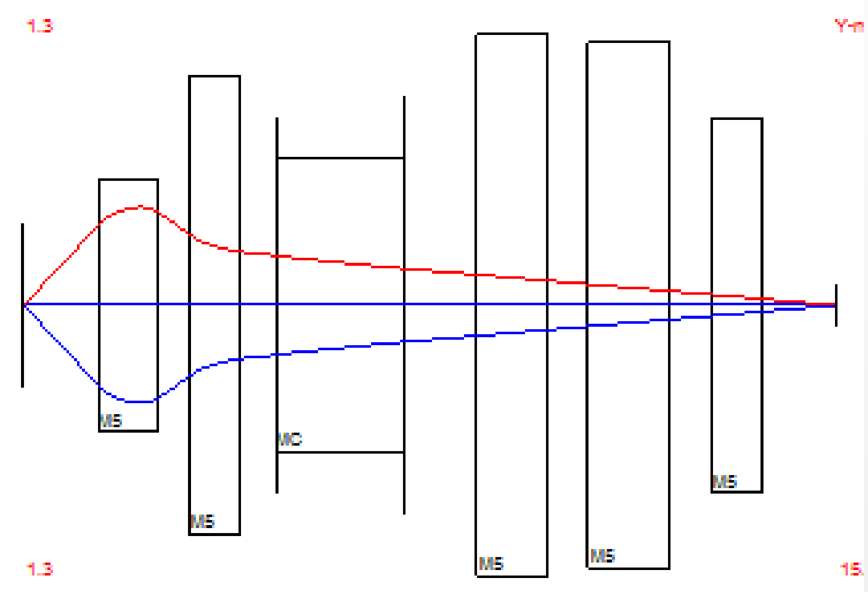
Comparison DQQQ Mode with different target to magnet drifts

Comparison		DQQQ	Different DL1	
			(Target to EFB(SM))	
DL1/m	1.03	1.16	1.3	
1st Order				
DA/mrad	90		80	
DB/mrad	42		40	
E_Resolv.Power	366		410	
2nd Order				
DA/mrad	90		80	
DB/mrad	30		30	

Increased Q2B radius from 53 cm to 63 cm
Increased EFL from 1.5 m to 1.7 m,
Decreased DL20 (F2 from 1.4366 m to 1.35 m)



Quads not acceptable
or forward neutron
measurements



QQD Mode, 1st order
DL1 = 1.38 m

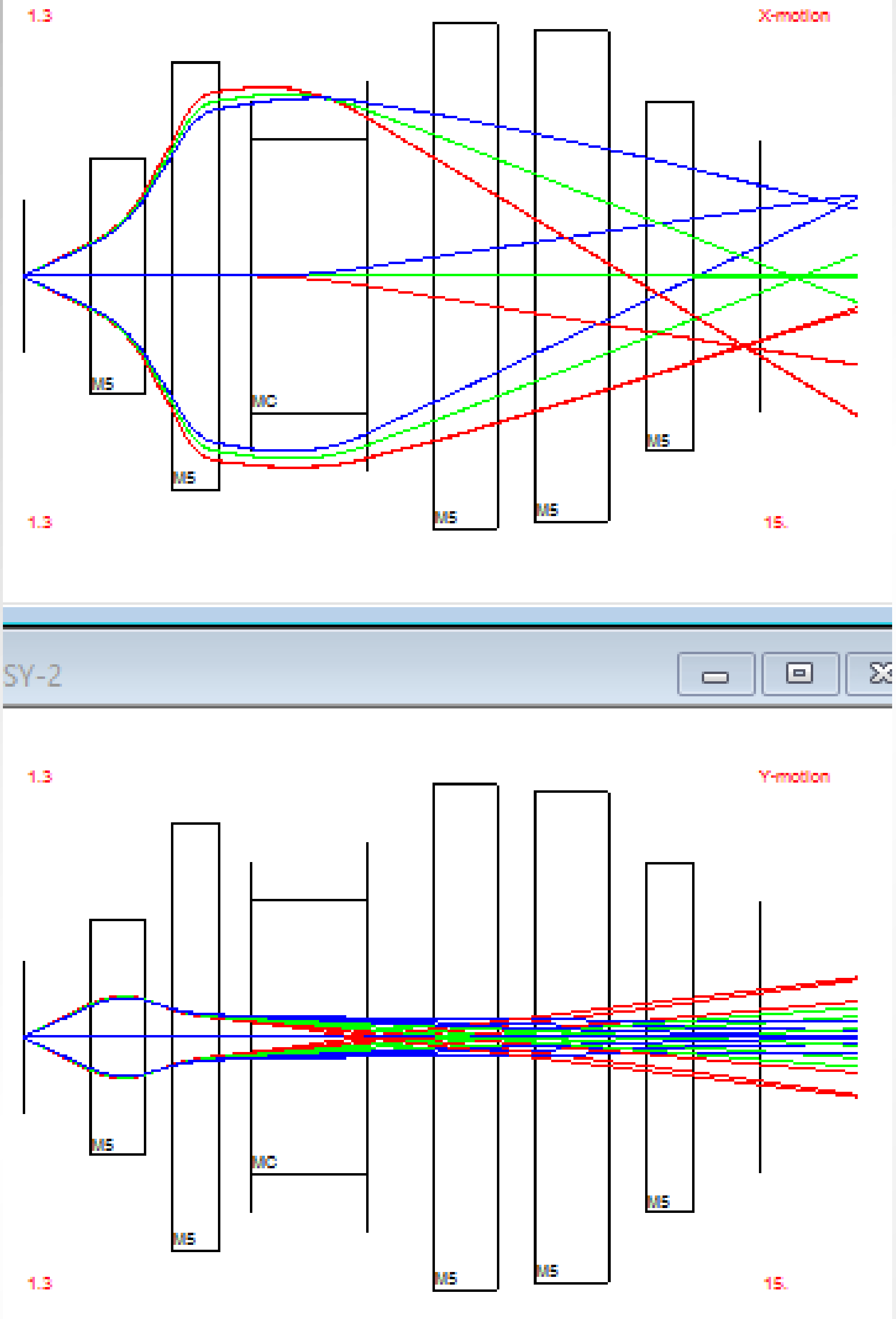
Increased Q2B radius from 53 cm to 63 cm
Increased EFL from 1.5 m to 1.7 m,
Decreased DL20 (F2) from 1.4366 m to 1.35 m

Horizontal and vertical foci, F2

DA = 60 mrad (Hor. Accept. Angle)
DB = 140 mrad (Vert. Accept. Angle)
dE/E = 10% (Energy Acceptance)
M11 = -1.12 (Hor. Magnif.)
M16 = 3.02 (Energy Disp.)
M21 = -0.465
M26 = 0.329
For x_0 = 1 mm, E-Resolv. Power(E) = 1350
M33 =-12.6

Q0A:= -2.31353;
Q1A:= 2.32624;
Q2A=Q2B=Q2C = 0

File: HRS_QQD_F2_138_order1.fox



QQD Mode, 6th order
DL1 = 1.38 m

Increased Q2B radius from 53 cm to 63 cm and EFL from 1.5 m to 1.7 m, DL20 = 1.35 m

Horizontal and vertical foci, F2

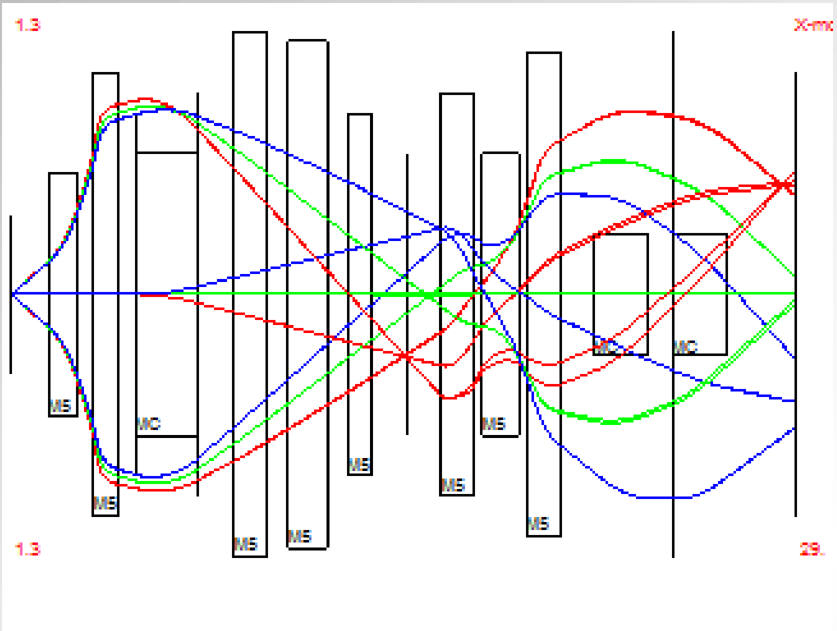
DA = 60 mrad (Hor. Accept. Angle)
DB = 60 mrad (Vert. Accept. Angle)
dE/E = 6% (Energy Acceptance)
M11 = -1.12 (Hor. Magnif.)
M16 = 3.02 (Energy Disp.)
M21 = -0.465
M26 = 0.329
For x_0 = 1 mm, E-Resolv. Power(E) = 1350
M33 =-12.6

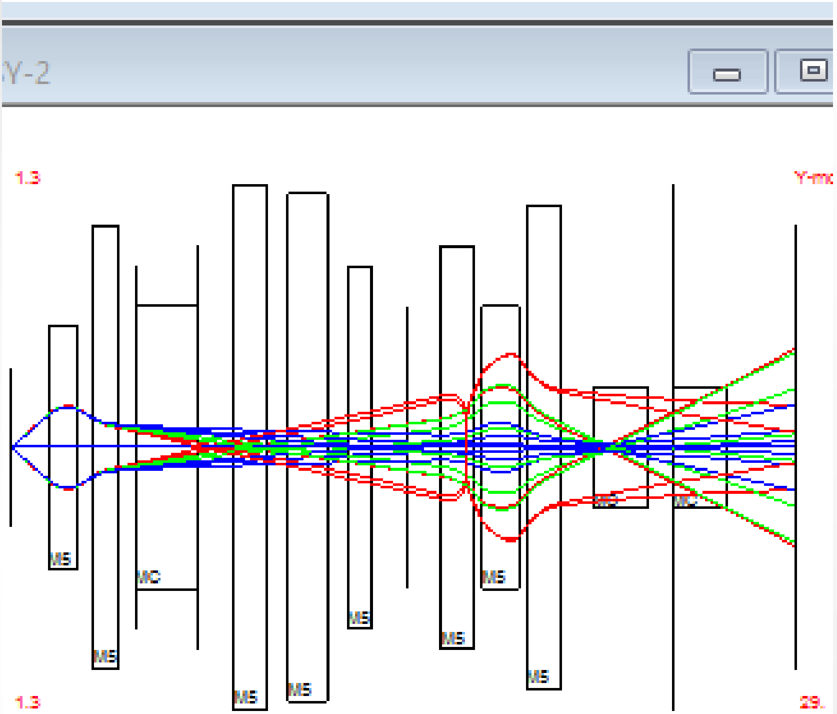
Q0A:= -2.31353;
Q1A:= 2.32624;
Q2A=Q2B=Q2C = 0

H0A=H1A=H2A,B,C=0

File: HRS_QQD_F2_138_order6.fox

QQD Mode, 6th order
DL1 = 1.38 m





Increased Q2B radius from 53 cm to 63 cm and EFL from 1.5 m to 1.7 m, DL20 = 1.35 m
Gap D2 = D3 = 0.15 m

Horizontal and vertical foci, F3

DA = 60 mrad (Hor. Accept. Angle)
DB = 60 mrad (Vert. Accept. Angle)
dE/E = 5% (Energy Acceptance)
M11 = -1.06 (Hor. Magnif.)
M16 = 5.44 (Energy Disp.)
M21 = 0.277
M26 = -0.235
For x_0 = 1 mm, E-Resolv. Power(E) = -2566
M33 =42.2

Q0A:= -2.31353;
Q1A:= 2.32624;
Q2A=Q2B=Q2C = 0

File: HRS_QQD_F3_138_order6.fox

Requirements for Beam Line (Ion-optics)

- Achromatic mode
- Dispersive mode, dispersion matching, lateral b_{16} and angular b_{26}
- Variable target location in front of Sweeper magnet
- Oriented so that HRS and MoNA LISA fits into available space
- Space for detectors, diagnostics, pumps etc.

Dispersion Matching

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.

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

and

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

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:

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

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

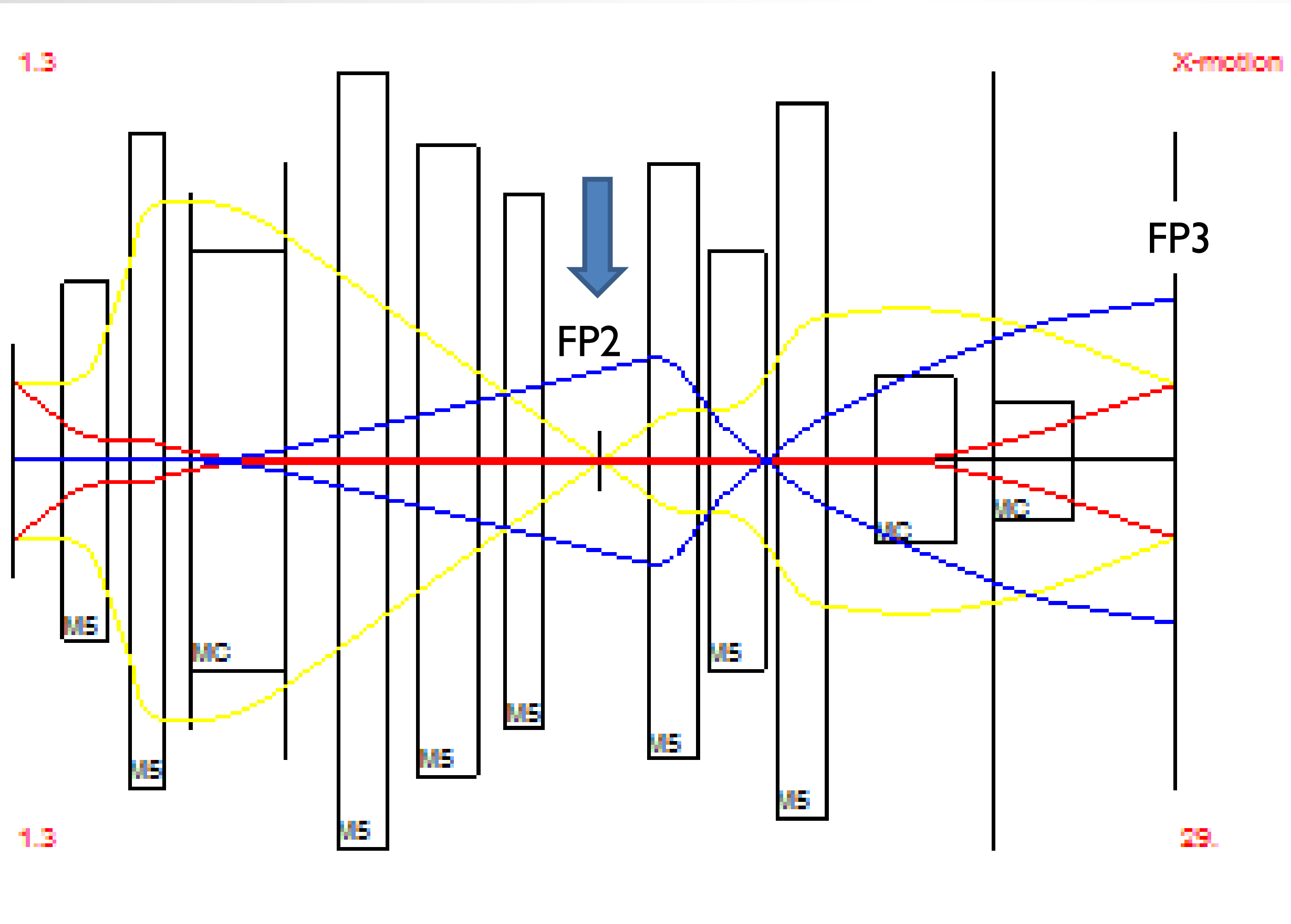
HRS Mode	Focal Plane F2								Test Rays		
COSY file	COSY file with						[m]	[rad]	DE =		
	Disp.Matching (DM)	s11	s16	s21	s26		b16	b26		x/m	DA/rad
HRS_QQD_35_0_0.fox	HRS_QQD_35_DM_F2.fox	-1.151	3.044	-0.483	0.3291		2.645	-1.091	0.050	0.132	-0.055
HRS_DQQQ_35.fox	HRS_DQQQ_35_DM_F2.fox	-2.238	1.841	-0.2505	0.0589		0.823	-0.329	0.100	0.082	-0.033
HRS_QDQ_35_0_0.fox	HRS_QDQ_35_DM_F2.fox	-0.465	1.248	-0.8926	0.0266		2.684	-1.102	0.050	0.134	-0.055
HRS_QDQQQ_35_0_0.fox	HRS_QDQQQ_35_DM_F2.fox	-1.162	2.802	-0.5906	0.617		2.411	-0.938	0.050	0.121	-0.047

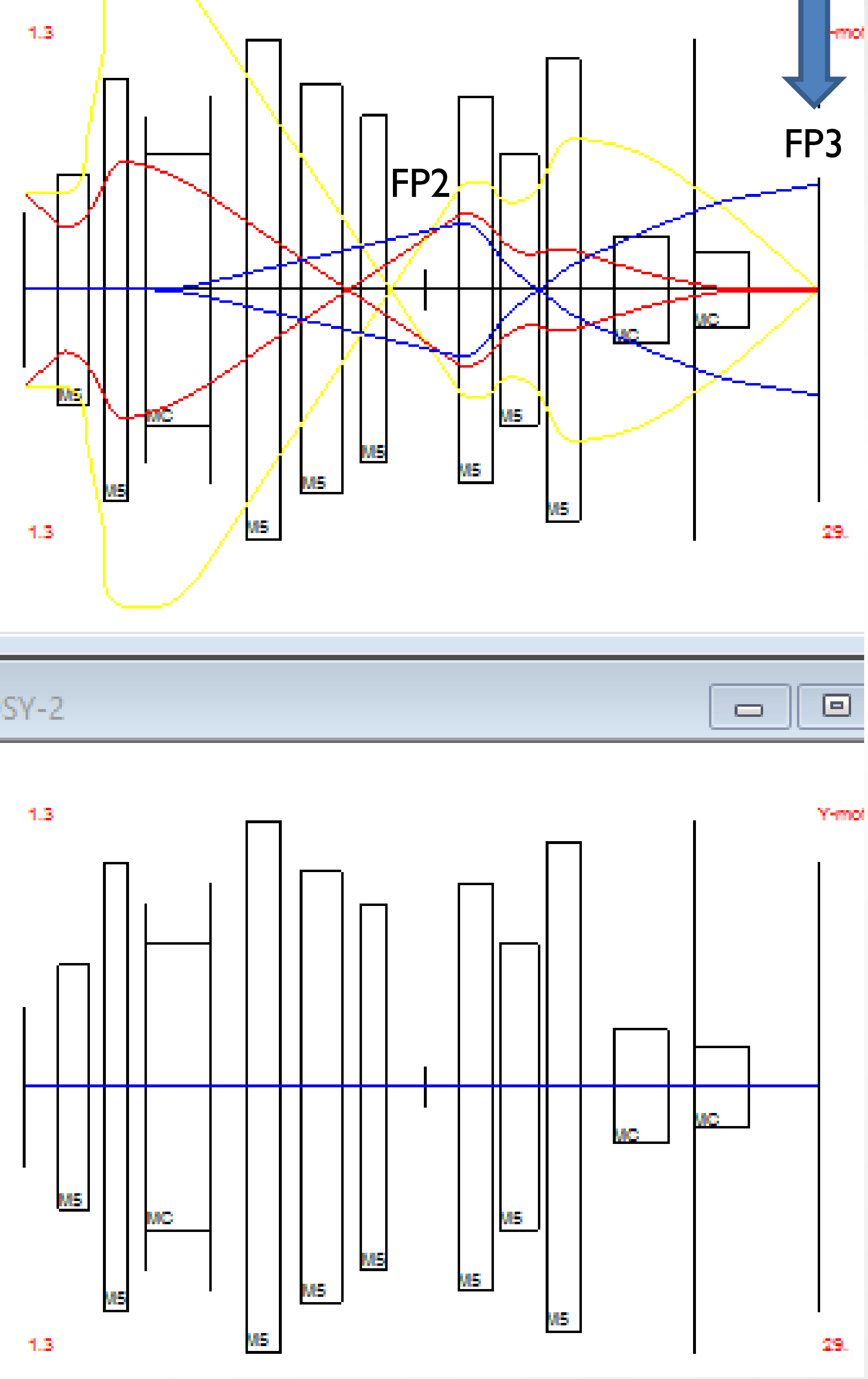
HRS, 35 deg bend, 0 deg edges angles QQD, Dispersion Matched, FP2

		Test Rays		
[m]	[rad]	DE =		
b16	b26		x/m	DA/rad
2.645	-1.091	0.050	0.132	-0.055

Blue: Achromatic beam
Green: Lateral Dispersion matched, only
Red: Fully Dispersion matched, incl. angular

File: HRS_QQD_35_DM_F2.fox





HRS, 35 deg bend, 0 deg edges angles QQD, Dispersion Matched, FP3

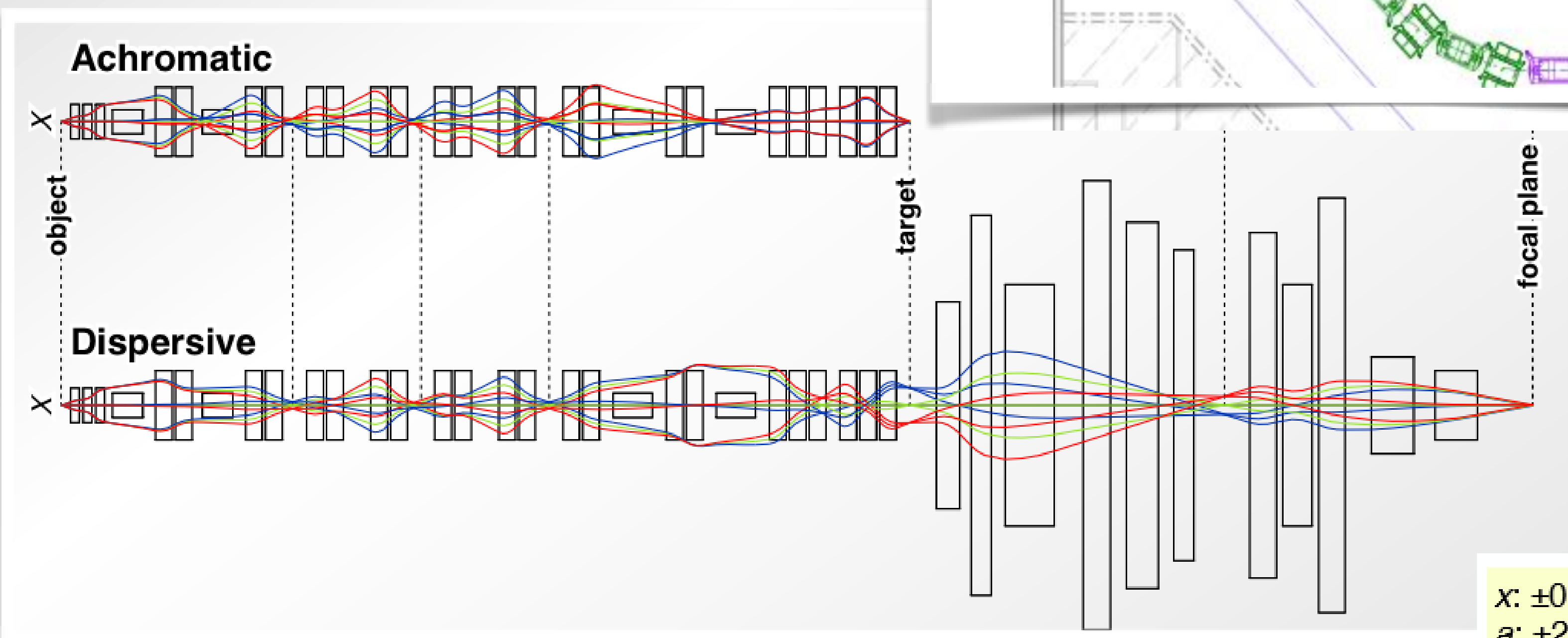
Blue: Achromatic beam
Green: Lateral Dispersion matched, only
Red: Fully Dispersion matched, incl. angular

		Test Rays	
[m]	[rad]	DE =	0.050
b16	b26	x/m	DA/rad
5.008	-1.329	0.250	-0.066

File: HRS_QQD_35_DM.fox

Preliminary Beam Line, By Shumpei Noji

- **Summary**
  - Overview — current layout/floor plan
  - Achromatic/dispersive modes



x: ±0.842 mm
a: ±22.4 mad
y: ±6.75 mm
b: ±24.6 mrad
E: **±1.0%**

- **Path forward**
  - Further optimize the transport modes
  - Estimate the higher-order aberrations, finalize a pre-conceptual design

Next steps

- Finalize the present modes to meet requirements of all(?) proposed experiments
- Final Beam Line configuration to meet all requirements
- Update lattice file
- Update dispersion matching conditions (after recent changes)
- Update magnet design parameter list
- Continue magnet field calculations (Shailendra Chouhan), evaluate effect on ion-optics. Feedback.
- Minimize S_{126} to reduce fp tilt angle in focal planes F2, F3.
- Finalize magnet design compatible with ion-optics (sufficient drift space)?
- Chromatic aberrations seem insensitive to Hex/Oct in Quads, keep only those that helpful.
- Analyze F2, F3 parameters to define detector specifications
- Circular instead of rectangular acceptances
- M33 (vert. magnif.) large in QQD mode, use QQD**QQQ** quads to reduce M33.
- Optics for DL1 = 0.4 m for largest possible neutron acceptance angle
- Other issues?

Thank you