The JINA Center for the Evolution of the Elements

JINA-CEE

Separator Ion Optics School

NSCL, Michigan State University

Series of Four Lectures plus COSY Tutorials
September 10-14, 2018

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University of Notre Dame
JINA Center for the Evolution of the Elements

The Lecture Series

An Introduction to Ion-Optics

1st Lecture: 9/10/18: Formalism and ion-optical elements

2nd Lecture: 9/12/18: Ion-optical systems and spectrometers

3rd Lecture: 9/12/18: Recoil separators for nuclear astrophysics, St. GEORGE

4rd Lecture: 9/13/18: The recoil separator SECAR for FRIB

Hands-on seesions in the afternoon: 9/10/18 – 9/14/18: COSY Infinity

Review 3rd Lecture

Measurements at 0 degree

Inverse kinematics for radiative capture using unstable Rare Isotopes

Recoil separators, overview

The recoils separator St. GEORGE for stable isotopes (α,γ)

The recoils separator SECAR for unstable RI beams, A < 65, Overview

Broad Set of Reactions Define Rigidity and Acceptance Parameters

Reaction	E_{cm} Beam MeV	Q-value MeV	dE/E Range %	Recoil Charge q	Half Angle, Recoil mrad	$B\rho$ Recoil Tm	$E\rho$ Recoil MV	$B\rho$ Beam Tm
$^{15}O(\alpha,\gamma)^{19}Ne$	0.5	3.529	±3.1	3	±15.6	0.29	1.25	0.14
	3	3.529	±2.1	6	±10.3	0.35	3.75	0.35
$^{44}Ti(\alpha,\gamma)^{48}Cr$	0.5	7.696	±2.3	4	±11.7	0.58	2.74	0.19
	3	7.696	±1.3	10	±6.2	0.57	6.59	0.48
$^{19}Ne(p,\gamma)^{20}Na$	0.2	2.193	±1.3	4	±6.4	0.31	1.88	0.21
	3	2.193	±0.71	9	±3.6	0.54	12.5	0.81
$^{23}Mg(p,\gamma)^{24}Al$	0.2	1.872	±0.92	4	±4.6	0.38	2.28	0.15
	3	1.872	±0.56	11	±2.8	0.53	12.4	0.58
$^{25}Al(p,\gamma)^{26}Si$	0.2	5.517	±2.3	4	±11.7	0.41	2.48	0.15
	3	5.517	±0.90	11	±4.5	0.58	13.5	0.58
$^{30}P(p,\gamma)^{31}S$	0.2	6.133	±2.2	4	±10.8	0.49	3.97	0.15
	3	6.133	±0.80	12	±4.0	0.63	14.8	0.58
$^{33}Cl(p,\gamma)^{34}Ar$	0.2	4.663	±1.5	5	±7.6	0.43	2.6	0.31
	3	4.663	±0.6	14	±3.1	0.59	14.0	1.19
$^{34}Cl(p,\gamma)^{35}Ar$	0.2	5.897	±1.8	5	±9.2	0.44	2.7	0.32
	3	5.897	±0.7	14	±3.5	0.61	14.4	1.22
$^{37}K(p,\gamma)^{38}Ca$	0.2	4.548	±1.3	5	±6.6	0.48	2.9	0.27
	3	4.548	±0.54	15	±2.7	0.62	14.6	1.04
$^{38}K(p,\gamma)^{39}Ca$	0.2	5.763	±1.6	5	±8.1	0.49	3.0	0.27
	3	5.763	±0.61	15	±3.1	0.64	15.0	1.06
$^{65}As(p,\gamma)^{66}Se$	0.2	2.030	±0.35	6	±1.8	0.70	4.3	0.18
	3	2.030	±0.21	21	±1.0	0.77	18.4	0.71

- These reactions define the following required design parameters
  - Even at highest energy most beams can be used for setup of experiments with sufficient count rate
  - Otherwise less-abundant higher charge states can be used

Min. - Max. Bρ 0.14- 0.80 Tm
Min. – Max Eρ 1.0 – 19 MV

Angle Accept., x, y +/- 25 mrad
Energy Acceptance +/- 3.1 %

$$B\rho = p/q$$
$$E\rho = 2T_{lab}/q$$

Requirements Arise from Science Requirements

- Science requires a broad range of reactions and reaction parameters, not just some key reactions
- This translates into Technical Requirements:

• Transmission	~100	%
• Min. - Max. Magnetic Rigidity Bρ	0.14 - 0.80	Tm
• Min. – Max. Electric Rigidity Eρ	1.0 - 19	MV
• Angle Accept., vert. & horiz.	+/- 25	mrad
• Energy Acceptance	+/- 3.1	%
• Beam rejection from separator	$\sim 10^{-13}$	
• Additional rejection from Detector System	$\sim 10^{-4}$	

SECAR, Ref.: G.P.A. Berg, M. Couder et al, Nucl. Instr. Meth. Phys. Res. B 877 (2018) 87

Mass Resolution Related to Mass Resolving Power

Mass Resolving Power: $R_m = \frac{(x|dm)}{(x'|x) * 2x_0}$

Image size

$(x|dm)$ = M_{17} = Mass dispersion

$(x'|x)$ = M_{11} = Magnification

$2x_0$ = Target spot size

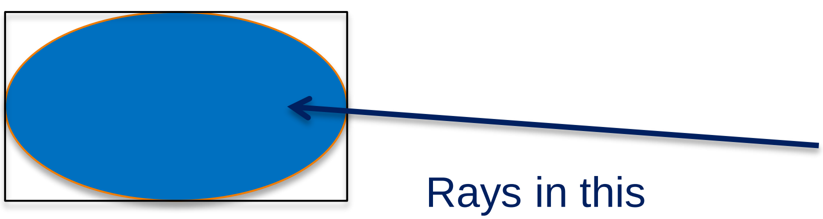
Resolution: $R_{HO} = \frac{(x|dm)}{x_{HO}}$

$$x_{HO} = (x'|x) * 2x_0 + Higher\ Orders$$

- Image size x_{HO} defined by **Ion-optical Calculations** using the distance in the mass-dispersive planes between extreme rays of 189 rays within an "ellipsoid" given by the horiz. (A), vert. (B) angle, and energy (E) acceptances and the horiz. (X) and vert. (Y) object sizes on target

A = B = +/-25 mrad, E=+/-3.1%, and X = Y = +/- 0.75 mm

A



E

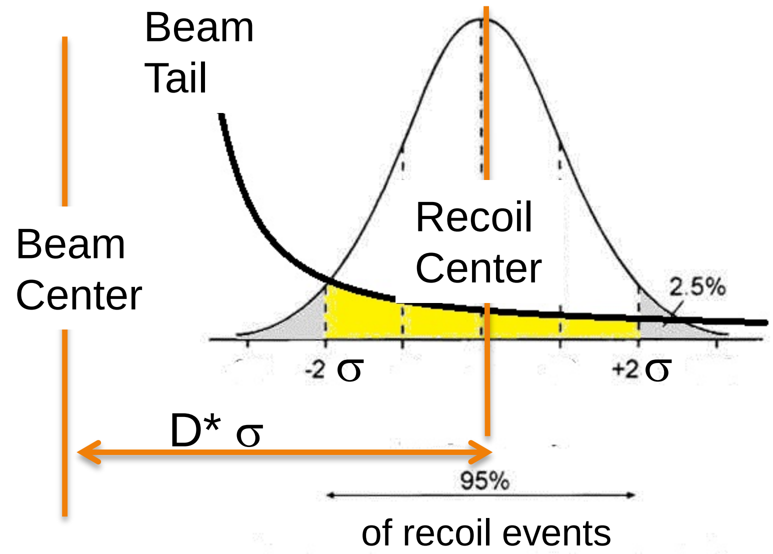
Rays in this Ellipsoid only

$$\frac{a^2}{A^2} + \frac{b^2}{B^2} + \frac{\delta E^2}{E^2} \cdots \lesssim 1$$

Mass Resolution Requirement

- **Introductory remark:**
  The smallest mass difference for SECAR is dm/m=(66-65)/65 for $^{65}As(p,\gamma)^{66}Se$ or a mass separation of m/dm = 65. A resolution R_{HO} 10 – 12 times larger than m/dm = 65 is required so that the recoil events are not buried under the events of the beam tails.

- **Definition:**
  The Nominal Beam Rejection NBR is the ratio of beam background events (yellow area) under the recoil peak (+/- 2σ, 95% of all counts) and the total beam events for a distance of D*σ from beam to recoil peak center. Assumption Gaussian distribution ($\sigma = x_{HO}$)

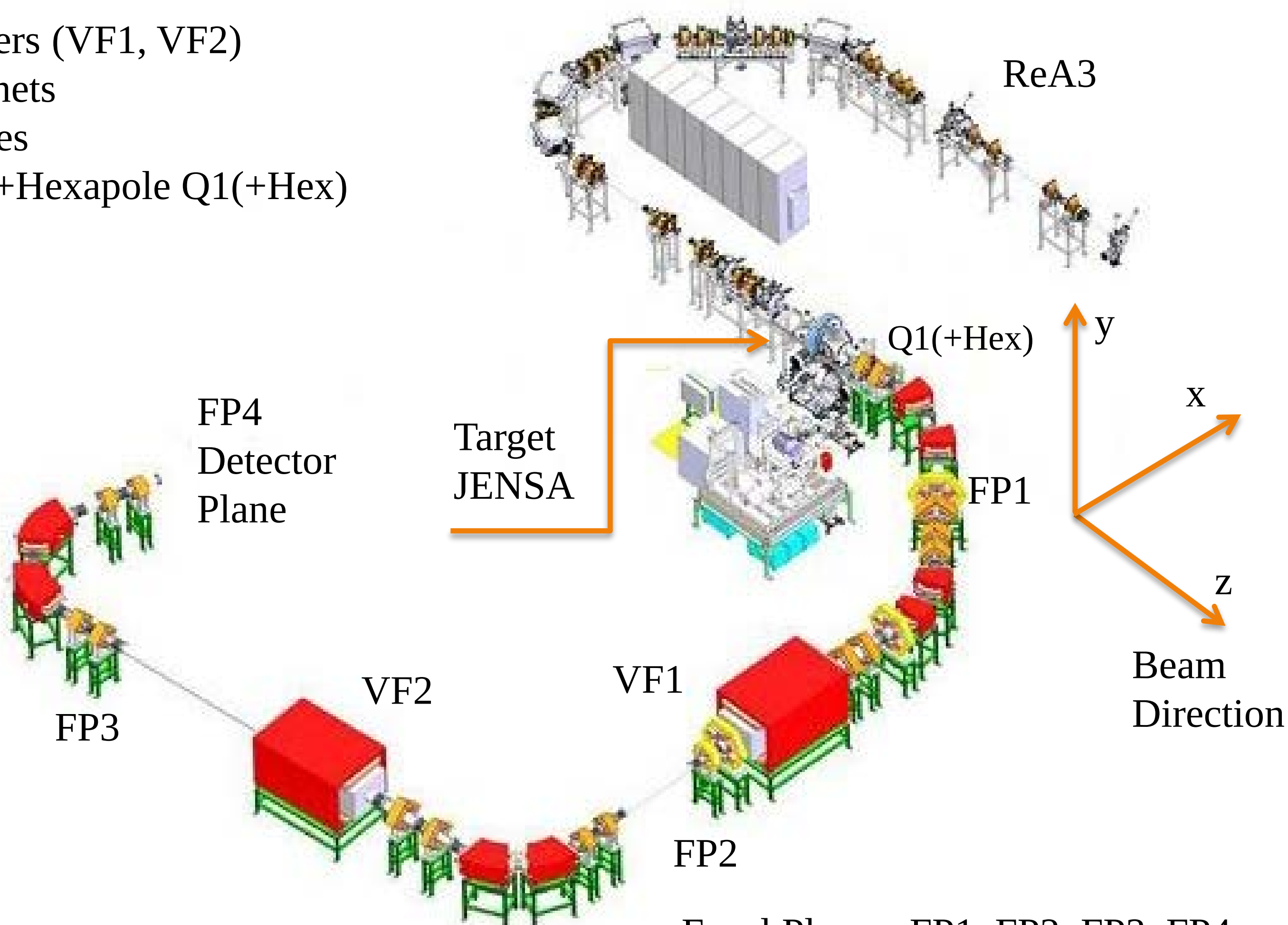


- **Mass resolution R_{HO} based on experience**:
  DRAGON R_{HO}=340-480 for A <30 and beam rejection of 10^{-13}.
  SECAR designed for A<65 requires R_{HO} ~ 750 for a similar rejection.
  Director's Review, p.21: The criterion is reasonable.

- **Mass resolution based on Nominal Beam Rejection NBR(D)**
  NBR(9.5σ) = 10^{-13} requires R_{HO} = 620

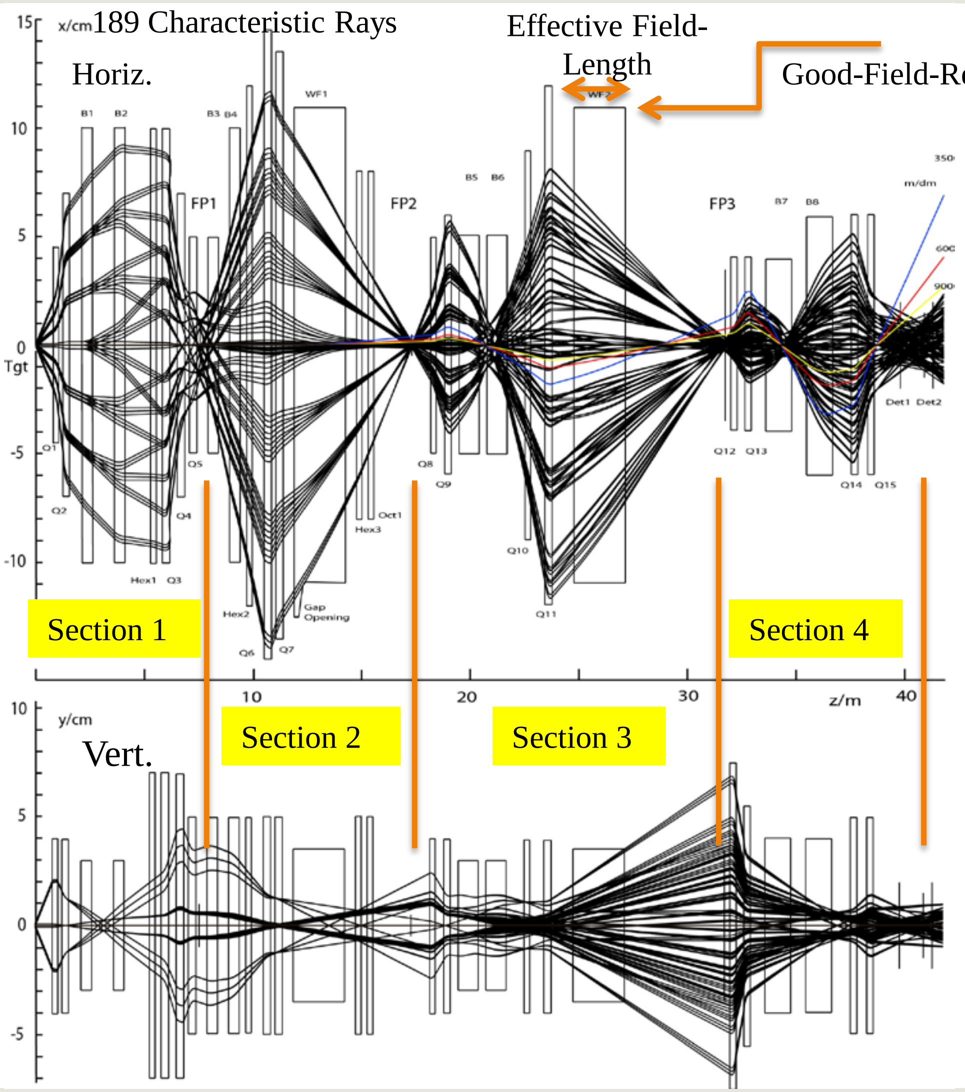
SECAR Layout

- SECAR consists of:
  - 2 Velocity filters (VF1, VF2)
  - 8 Dipole magnets
  - 14 Quadrupoles
  - 1 Quadrupole+Hexapole Q1(+Hex)
  - 3 Hexapoles
  - 1 Octupole



Focal Planes: FP1, FP2, FP3, FP4

Ion Optics Optimized



Section 1 Target to FP1
Charge state Selection
Dispersive focus

Section 2 FP1 to FP2
Mass Resolv. Power R_m = 747
Mass Resolution R_{HO} = 508
Achromatic focus

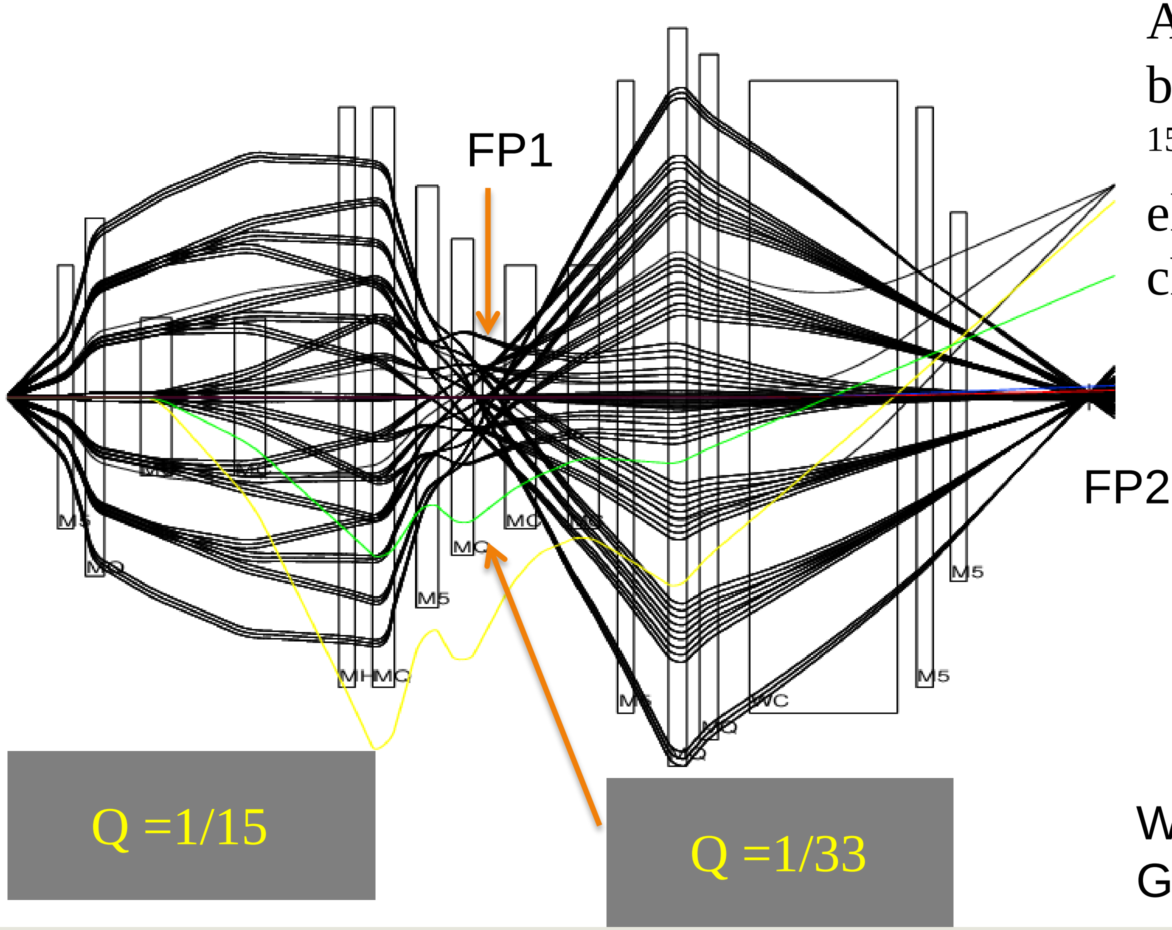
Section 3 FP2 to FP3
Mass Resolv. Power R_m =1283
Mass Resolution = 767
Disp. R_{16}=0, focus R_{12} = 0

Section 4 FP3 to Det1/Det2
Particle detection, HO correction
Cleanup section

Optimized up to 4th order, using
4 Hexapoles, 1 Octupole
Dipole edges up to 4th order

Ion Optics
Charge State Separation is Effective for Worst Case

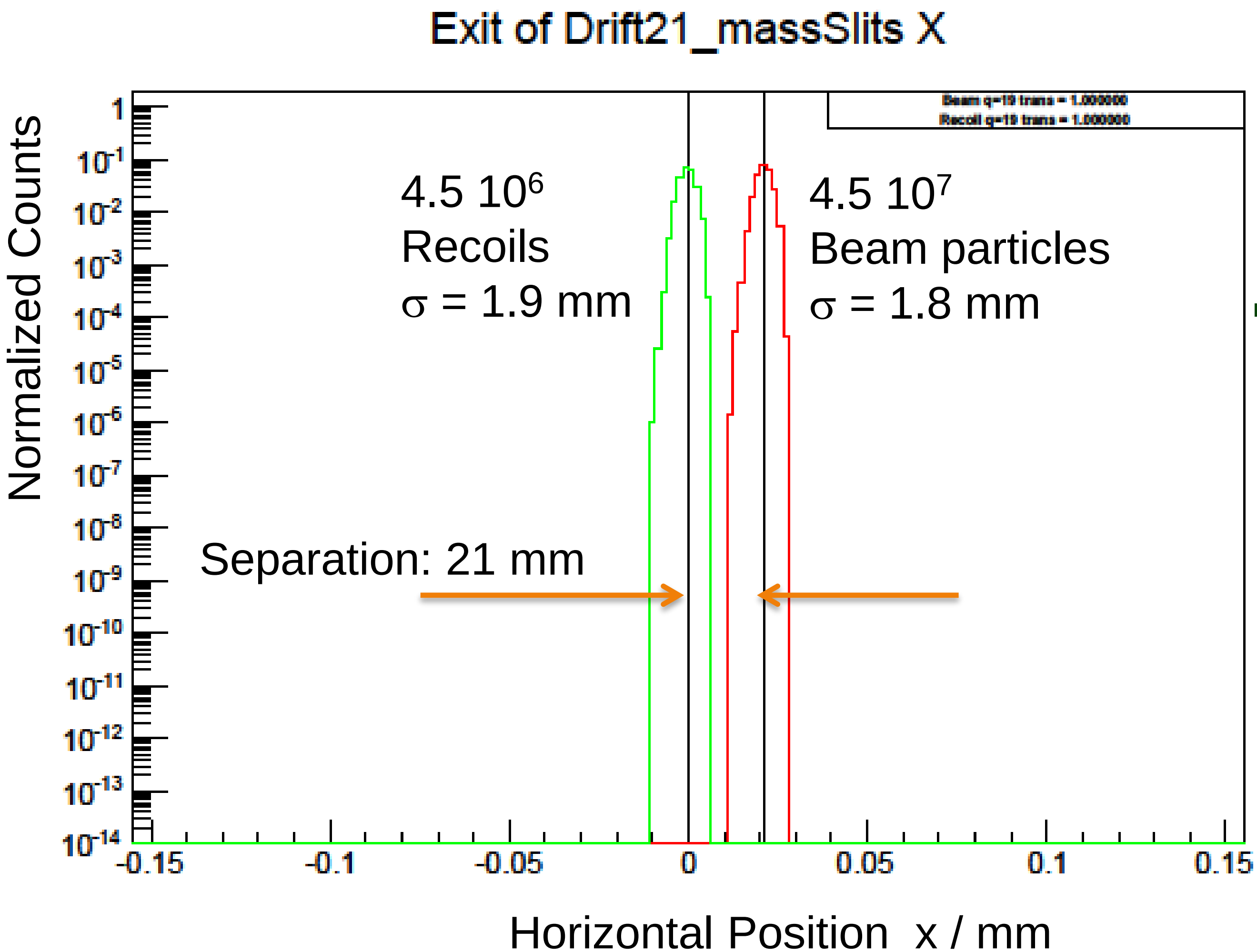
Horizontal plane



Also checked that ^{15}O beam (+/- 15 mrad) of $^{15}O(\alpha,\gamma)$, does not hit electrodes or vacuum chamber

Worst case, fully stripped,
Good separation at FP1

Ion Optics
Beam and Recoil Separation at FP2



$^{65}As(p,\gamma)^{66}Se$

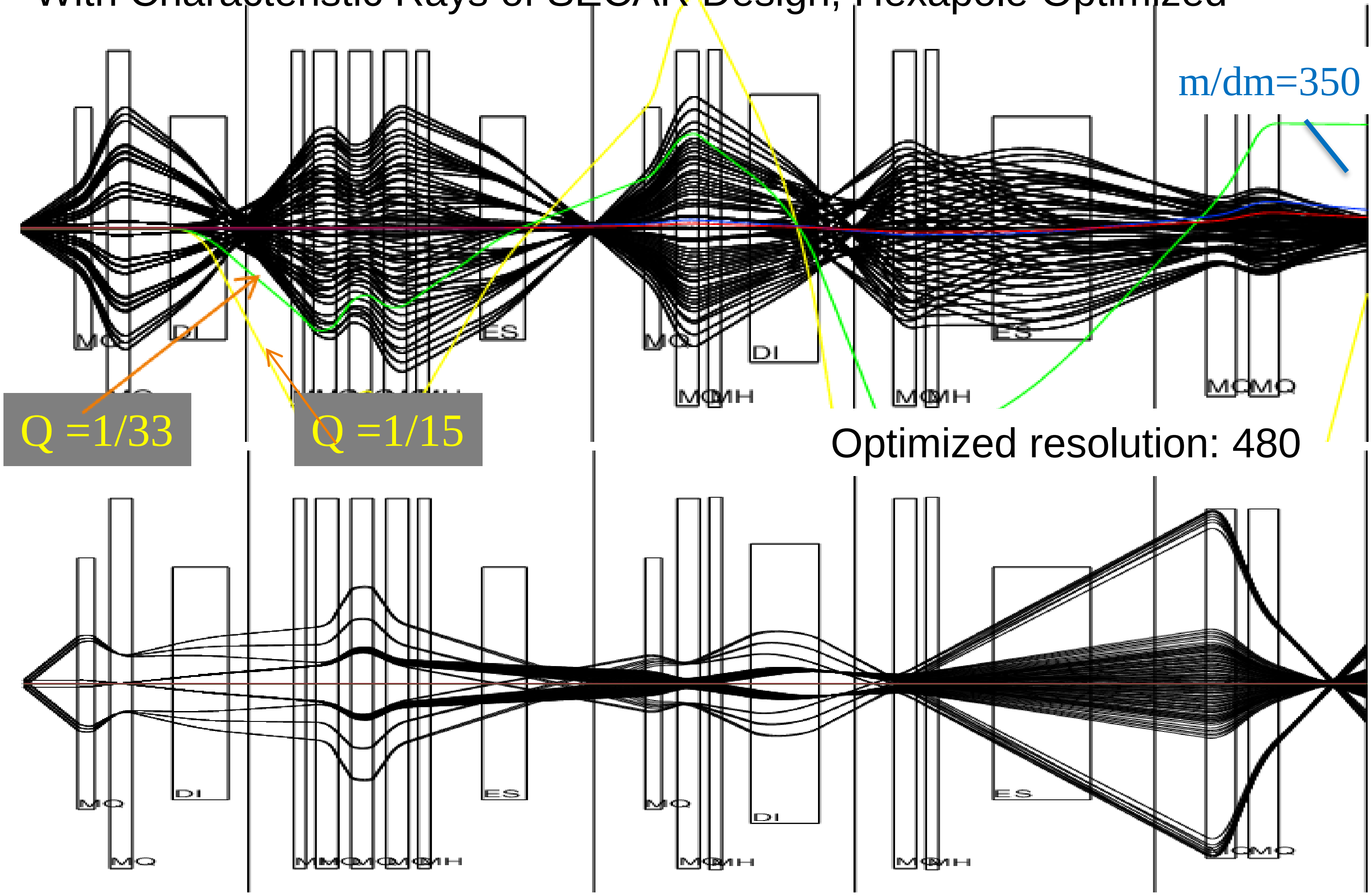
E = 1 MeV/A
q = 19

- Monte Carlo simulation assuming Gaussian distribution **M. Couder**

Charge 2

Comparison with DRAGON

With Characteristic Rays of SECAR Design, Hexapole Optimized



Resolving power: 600 (1st order)

Resolution: 340 - 480

Angle accept. < 20 mrad

Extended Target, Effect on Mass Resolution

Table 3.5. Mass resolutions at FP3 for an object size of 1.5 mm as a function of resonance location in an extended target of +/- 0.05 m

Resonance Location dz Unit of m	Image size at FP3 Units of mm	Mass Resolution at FP3
-0.05	+/- 5.14	437
-0.04	+/- 4.63	485
-0.03	+/- 4.12	545
-0.02	+/- 3.61	622
-0.01	+/- 3.10	726
0	+/- 2.61	863
0.01	+/- 2.98	754
0.02	+/- 3.53	638
0.03	+/- 4.07	552
0.04	+/- 4.62	486
0.05	+/- 5.17	434

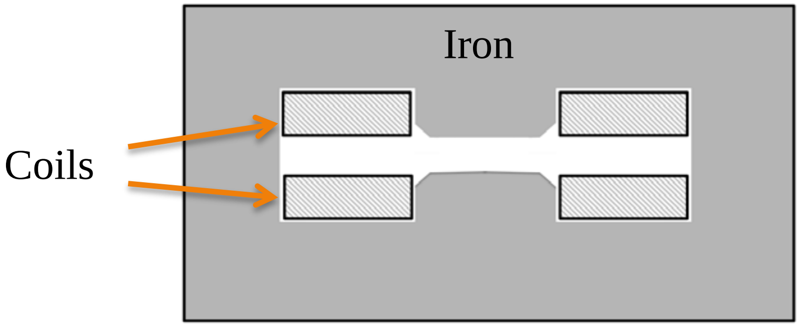
Mass resolution > 540 at FP3 for +/- 30 mm distance from Target center

Ion-optics during the project execution

- Overview ion-optical design requirements for science program
- Ion optical model allowed definition of specifications to ensure system's performance, critical mass resolution
- Verified vendor's design of magnets that fulfilled all performance requirements. Example B1, entrance EFB
- After construction, measured parameters including tolerances were verified
- After installation, alignment locations and orientations were verified
- The final "realistic" ion-optical model including all measured parameters will be used for commissioning, experiment planning and operations

Dipole magnet B1 – B8 Are Specified

- Normal-conducting, iron-dominated, water-cooled, H-type dipole magnets
- Bending radii: 125 cm
- Magnetic field, range: 0.14 – 0.64 T
- Bend angles: 22.5 – 55.0 deg
- Gaps: 60 – 100 mm
- Horizontal GFR: 100 – 200 mm
- Edge angles: 6.6 – 11.5 deg (vertical focusing), B5 exit -9.8 deg (vert. defoc.)
- Tolerances as required by ion-optics are specified and realistic
  - Homogeneity: dB/B < +/- 0.02% in GFR (horizontally and vertically)
  - Effective field lengths in GFR +/- 0.02%, Effective field boundary +/- 0.1 mm
- Higher order corrected entrance and exit edge boundary up to order 4
- Soft magnetic iron (AISI1006) cold rolled



H-type magnet design

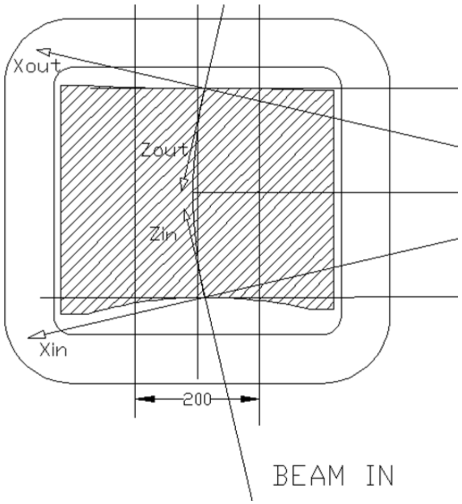
Specifications for all dipole magnets are defined and listed in Pre-Conceptual Design Report, see also backup slide

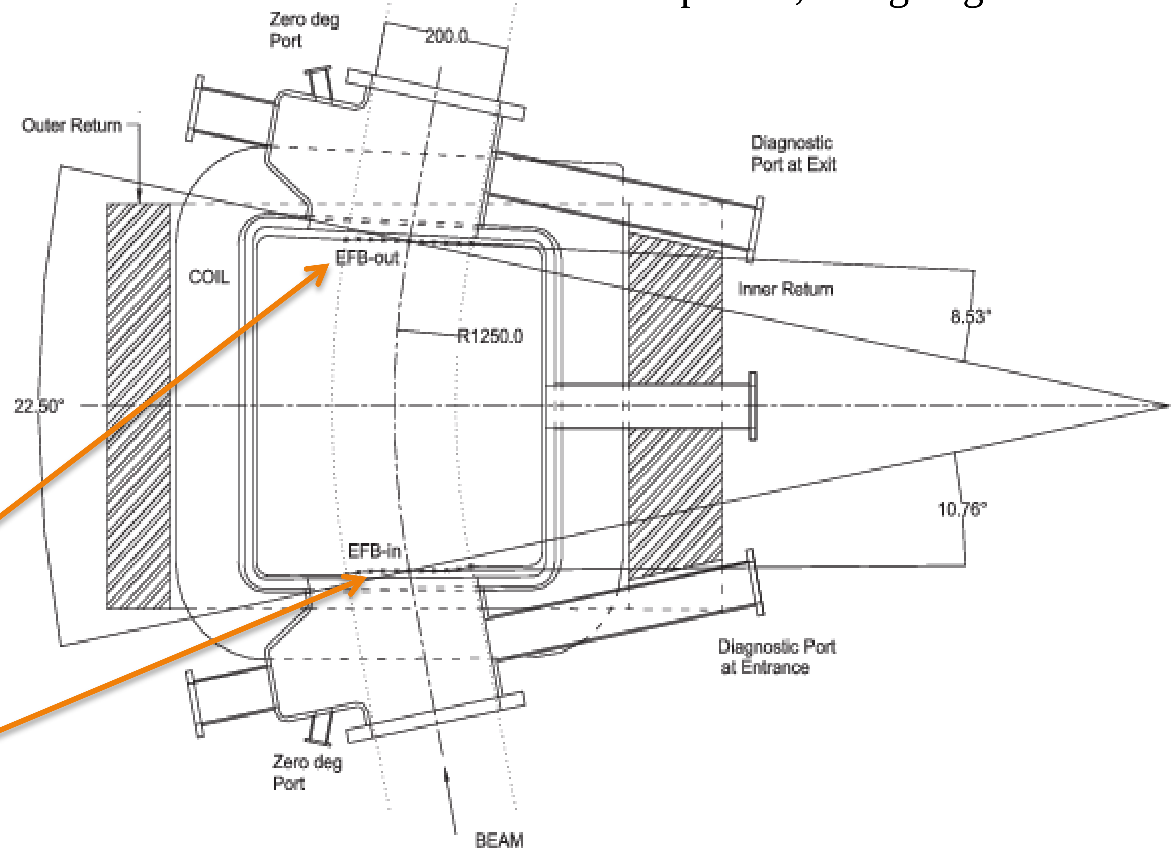
Example of Dipole Magnet B1 Layout

Charge B

Coordinate system of edge shapes

Note: Access ports for diagnostics, slits, NMR/Hall probes, 0 deg alignment





exits $z(x) = \sum_{i=1}^{4} s_{2i} \cdot x^{i}$

entrances $z(x) = \sum_{i=1}^{4} s_{1i} \cdot x^{i}$

- Entrance and exit edges shapes provide corrections up to order 4

Design of Dipole B1 using OPERA 3D

Table 1: Summary of requirements specific to the B1 dipole and obtained design values. The obtained effective length and EFB polynomial terms are averaged over the model results at 15, 50 and 100% excitation.

Requirement or result	Unit	Nominal	Obtained
Bending radius	mm	1250	-
Bending angle		22.5	-
Maximum pole tip field	T	0.64	0.639
Excitation ampere-turns per coil	A-turns	-	16000
Excitation current in calculation	A	-	177.8 A
Horizontal good field width	mm	200	
Central field variation in good field width |dB/B|	%	< 0.02	<0.018%
Effective magnetic length	mm	490.9 ± 0.5	491.1 ± 0.2
Entrance s11		0.19	0.190
Entrance s12	1/m	0.0025	0.0041
Entrance s13	$1/m^2$	0.154	0.164
Entrance s14	$1/m^3$	0.78	0.64
Exit s21		0.15	0.150
Exit s22	1/m	-0.019	-0.0256
Exit s23	$1/m^2$	0.147	0.128
Exit s24	$1/m^3$	0.10	0.75

Table 2. Shows the obtained fringe field harmonics for the entrance

	100%	50%	15%	Avr
s10	-0.2455	-0.2457	-0.2455	-0.24558
s11	0.190	0.190	0.191	0.190
s12	0.0060	0.0049	0.0013	0.0041
s13	0.174	0.163	0.157	0.164
s14	0.48	0.69	0.76	0.64

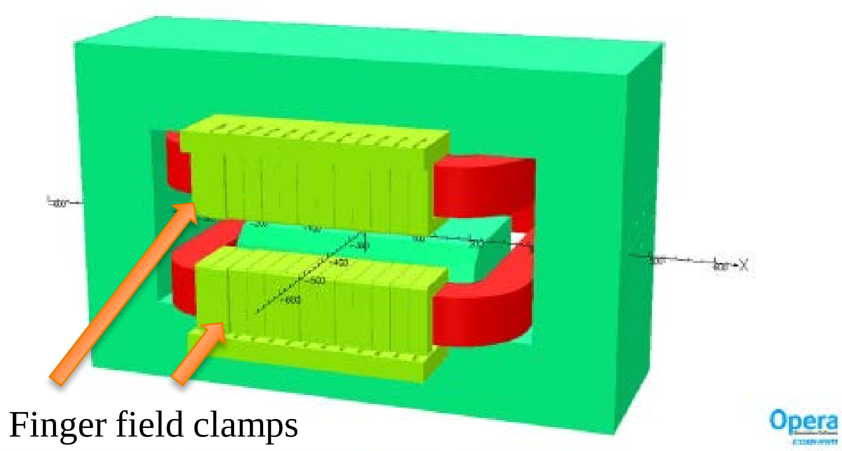


Figure 1: Opera-3D model of the entrance half part of the B1 dipole magnet.

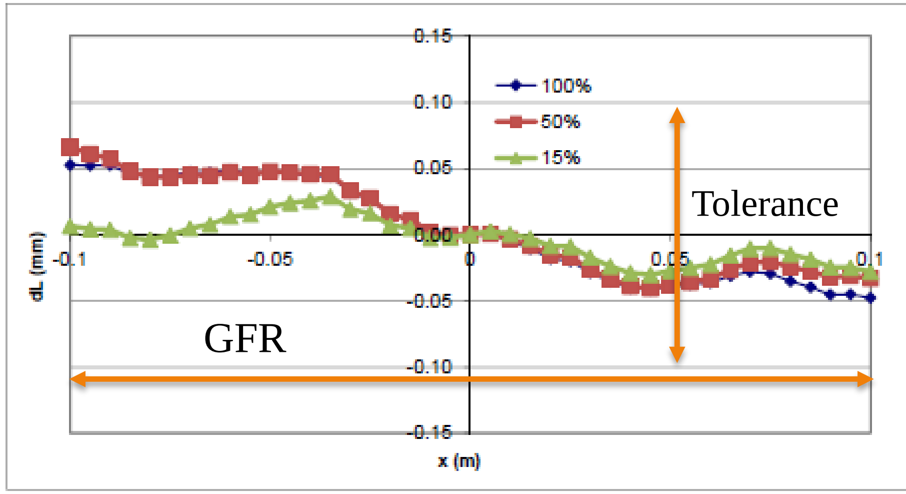
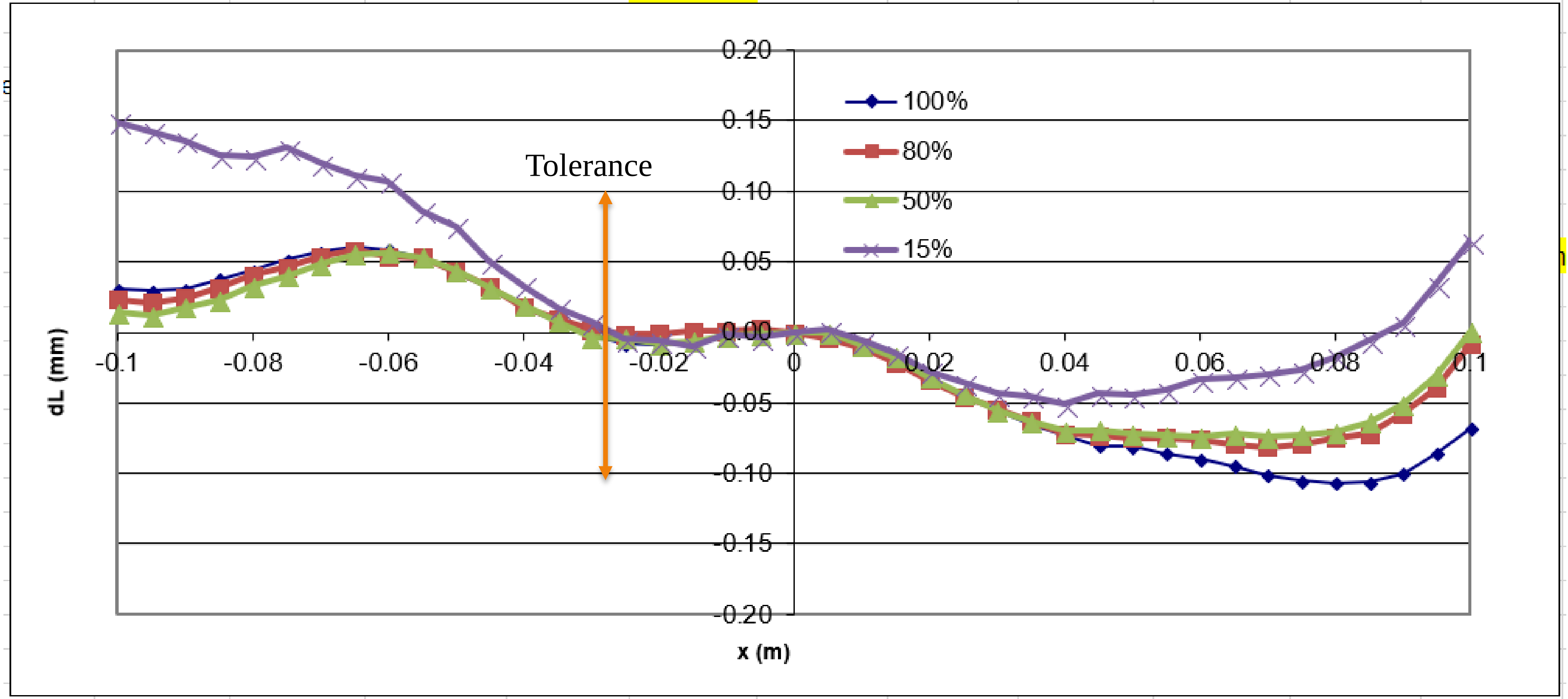


Figure 6: The deviation of the effective field boundary variation from the nominal variation as calculated for the entrance end at 15, 50 and 100% excitation.

Measurement of Dipole B1, Entrance EFB

Charge B

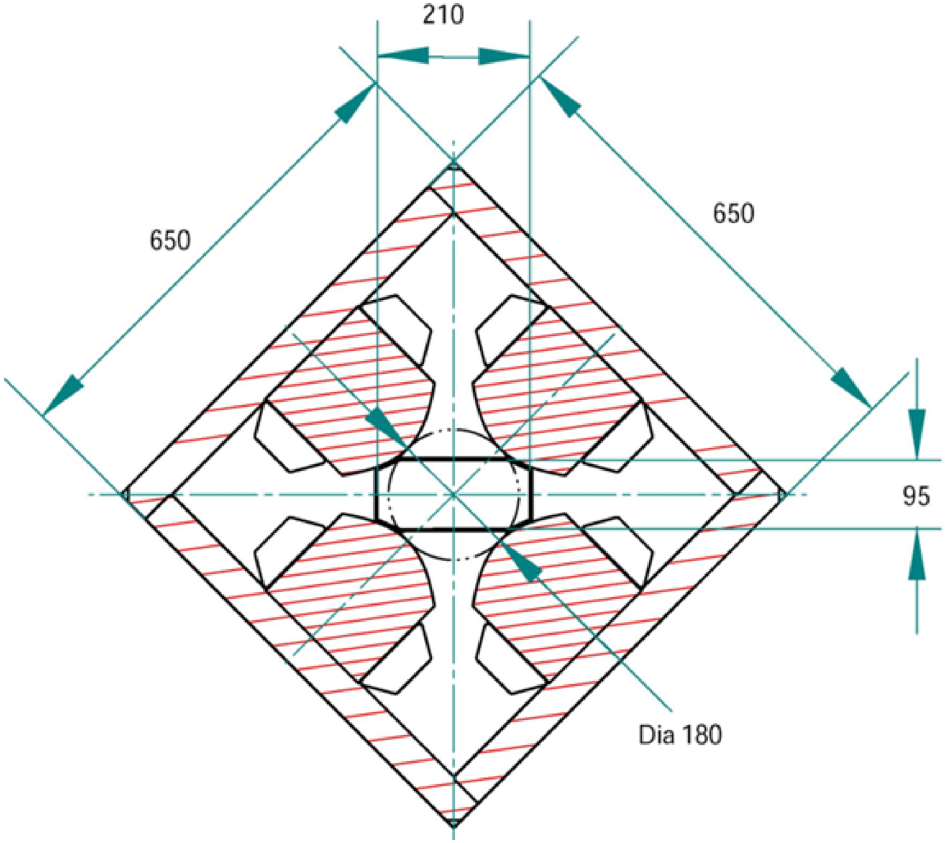
	Target	Now	Needed_avr	Need_2	Shim dz	100%	80%	50%	15%	Avr	
s10	-0.24545	-0.24527	**-0.00001**	-0.00005	*-0.0001*	-0.24558	-0.24558	-0.24572	-0.24488	-0.24544	s10
s11	0.19	0.189	0.0014	0.0055	*0.0055*	0.1886	0.1886	0.1886	0.1887	0.189	s11
s12	0.0025	-0.0004	0.0000	0.0000	*0.0000*	-0.0016	-0.0013	-0.0004	0.0132	0.0025	s12
s13	0.154	0.277	-0.0983	-0.393	*-0.3933*	0.234	0.271	0.277	0.227	0.252	s13
s14	0.78	1.191	-0.3249	-1.299	*-1.2994*	1.08	1.28	1.19	0.87	1.10	s14



Quadrupole Magnets are Standard Design and Specified

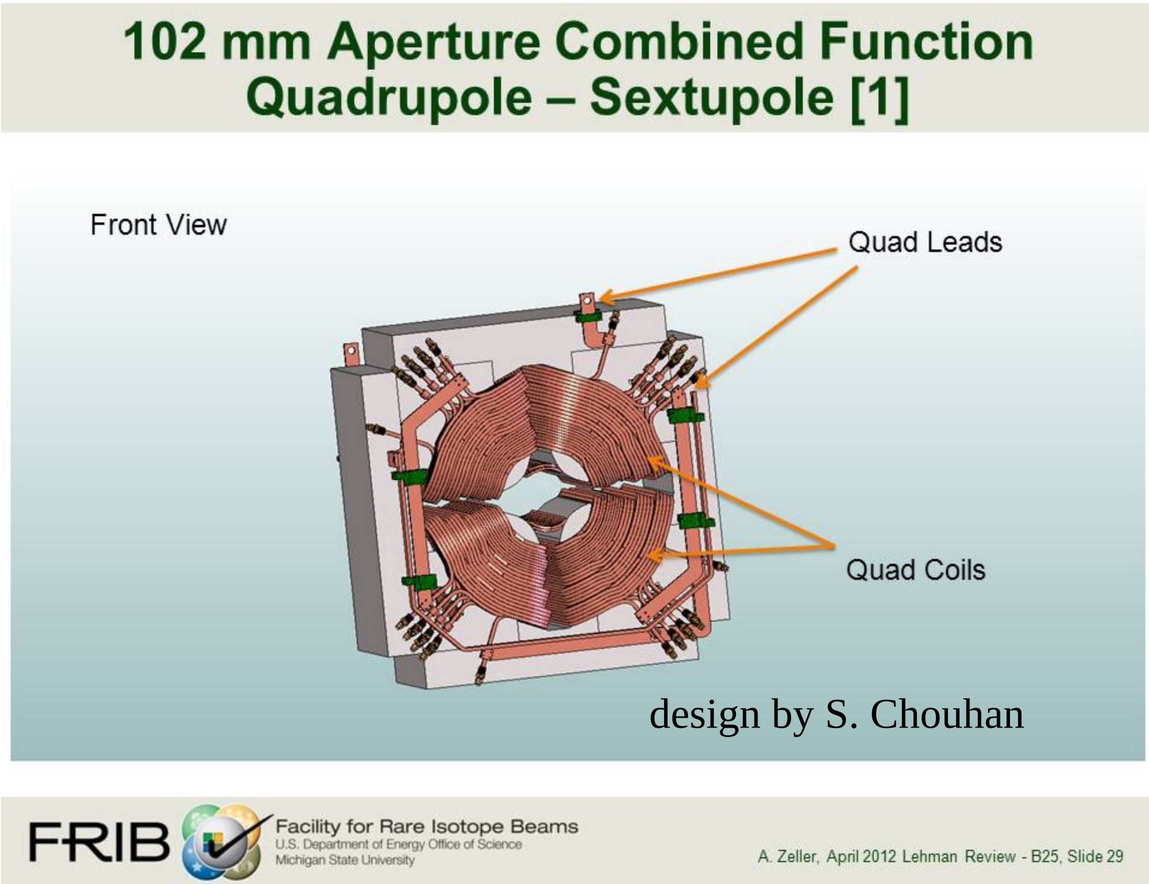
Charge 2

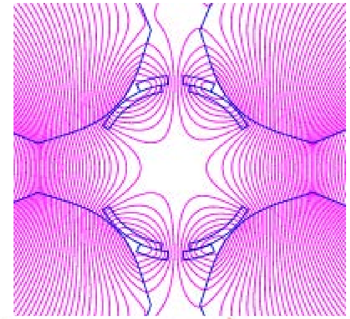
Typical design



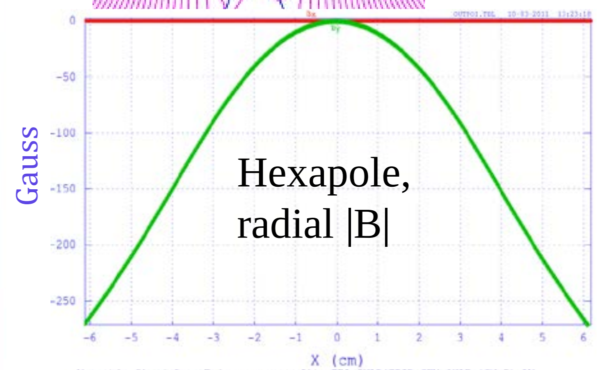
- SECAR consists of 15 quadrupoles
- All quadrupole magnets Q2 – Q15 are standard design, normal conducting, iron dominated, water cooled. Exception: Q1 is combined quadrupole plus hexapole
- Vacuum chamber (GFR) horizontally typically larger than vertically, as required by ion-optics, may require modified hyperbolic pole surface shape

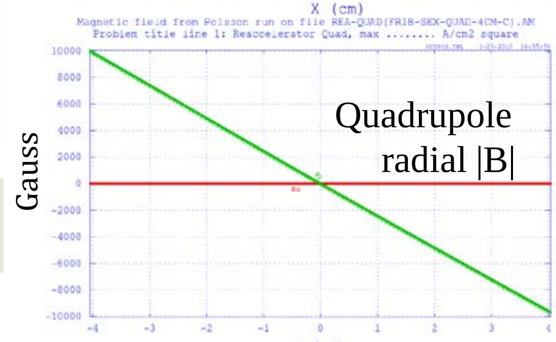
Q1 Design with Quadrupole and Hexapole Exists





Hexapole flux





Hexapole dipole-correction leads on backside, not shown in this front view

Charge 2

Examples Q1, Q2 Specifications

Parameter	Quadrupole Magnet		
		Q1(Hex)	Q2
Overall length	mm	390	440
Focusing strength	T	-2.25	1.32
Eff. field length	mm	250	300
Gradient	T/m	-9.00	4.41
Good field, horizontal	mm	90	140
Aperture, diam.	mm	100	136
Max. pole tip strength	T	-0.45	0.30
Maximum DC Power	kW	5.7	4.0
Maximum inhomogeneity		0.20%	0.20%
Iron weight, (approx.)	kg	260	320
Horizontal pipe, inner diameter	mm	90	160
Vertical pipe, inner diameter	mm	80	100

Specifications for all other quadrupole magnets are listed in Conceptual Design Report, see also backup slide

- Combined function Q1(Hex) design includes hexapole, design by S. Chouhan, MSU, see next slide

Hexapole / Octupole Specifications Defined

Type	EFL/m	Pole tip strength (T)	Aperture Diameter (m)	Power (kW)	Approx. Weight (kg)	Horiz. GFR/m	Vert. Vacuum Chamber/m
Hex(Q1)	0.250	0.02	0.10	1.1	-	0.09	0.08
Hex1	0.260	0.02	0.22	0.5	200	0.20	0.14
Hex2	0.260	0.03	0.24	0.5	200	0.24	0.10
Hex3	0.260	0.08	0.18	0.5	200	0.16	0.10

Type	EFL/m	Pole tip strength (T)	Aperture Diameter (m)	Power (kW)	Approx. Weight (kg)	Horiz. GFR/m	Vert. Vacuum Chamber/m
Oct1	0.260	0.02	0.18	0.1	100	0.16	0.10

Note: Standard design, air cooled coils are sufficient

Tolerances and Alignment verified to Ensure System's Performance

- **TOLERANCES verified**
  - Tolerance of dipoles, homogeneity in Good-Field-Region (GFR) 0.02%, 0.1mm on EFL and edges shapes)
  - Tolerances of quadrupoles, homogeneity in GFR 0.2%
  - Wien filter magnet and electric dipoles design specifications, homogeneity +/- $2*10^{-4}$
  - Ion-optical calculation determine tolerances for power supplies: Current stability for dipoles: +/- $1*10^{-5}$ for quadrupoles: +/- $1*10^{-4}$
  - Current stability of Wien filter magnet power supply: < $1*10^{-4}$
    HV velocity filter: ripple < +/- $1*10^{-4}$, drift over 8 hours < $5*10^{-4}$

- **ALIGNMENT verified**
  - Tolerance of 0.1 mm in location and 0.1 deg in orientation angles of all magnetic elements

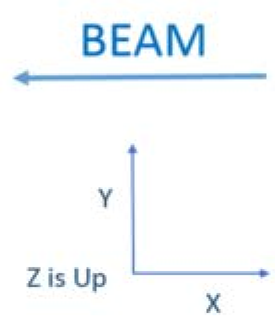
Alignment (Example: DL1 - Q1 - DL2)

NAME	THEORETICAL CENTER			THEORETICAL ORIENTATION			ACTUAL CENTER			
	X	Y	Z	AZIMUTH	SLOPE	ROLL	X	Y	Z	
	meter						meter			
Q1 SECAR	306.518015	525.419071	51.279400	269.955003	0.000000	0.000000	306.51812	525.419	51.2794	Q1
Q2 SECAR	306.053015	525.418705	51.279400	269.955003	0.000000	0.000000	306.05295	525.42	51.27928	Q2
B1 SECAR	305.079134	525.441959	51.279400	281.204807	0.000000	0.000000	305.07916	525.442	51.27929	B1
B2 SECAR	303.704208	526.010207	51.279400	303.704377	0.000000	0.000000	303.70426	526.01	51.27925	B2

Alignment data, A. Hussein and Alignment Group

CENTER ERROR (T-A) (Magnetic/Mechanic				ORIENTATION ERROR		
ΔX	ΔY	ΔZ		ΔA (Yaw)	ΔS (Pitch)	ΔR (Roll)
-0.000106	-0.000290	-0.000002		-0.0435°	-0.0299°	0.0035°
0.000068	-0.000838	0.000120		0.0620°	0.0496°	0.0252°
-0.000021	0.000036	0.000112		0.0108°	0.0094°	0.0058°
-0.000054	0.000007	0.000147		0.0044°	0.0044°	0.0012°
Global FRIB Coord. System X, Y, Z			COSY:	Optic coor. System		x, y, z

Transformation
X --> -z
Z --> y
Y --> -x



Implemented in COSY (DL1, Q1, DL2)

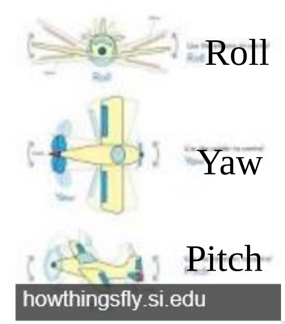
```
DL 0.80+0.000106;                                        {DL1}

TA -0.0299 -0.0435; {Pitch Yaw}
RA 0.0035; {Roll}
SA 0.000290 -0.000002; {x, y}
M5 0.250 -0.400180+0.0008 -0.004421+0.0041 0 -0.00318 0 0.055;{Q1+Hex}
SA -0.000290 0.000002;
RA -0.0035;
TA 0.0299 0.0435;

DL 0.19+0.00105-0.0000106;                               {DL2}
```

Definition: Pitch, Yaw, and Roll

An aircraft in flight is free to rotate in three dimensions: **pitch**, nose up or down about an axis running from wing to wing; yaw, nose left or right about an axis running up and down; and **roll**, rotation about an axis running from nose to tail.



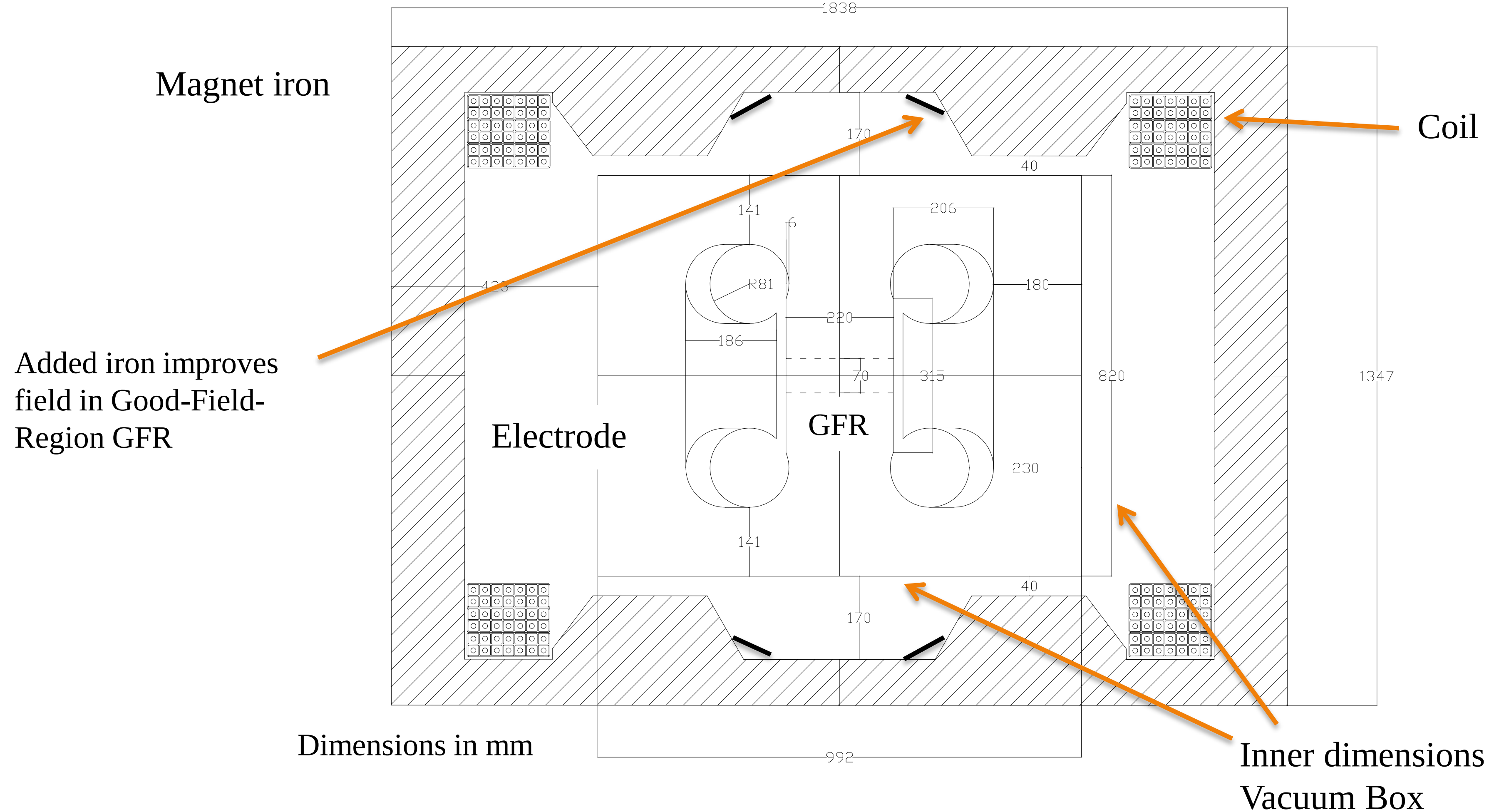
m/dm = 481 at F2, 773 at F3

Specifications of SECAR Velocity Filters Defined

SECAR Velocity Filters			
Good-field Region	Horizontal	mm	+/- 110
	Vertical	mm	+/- 35
Magnet	Min. - Max. B field in GFR	T	0.02 - 0.12
	Effective field length	mm	2365
	Pole gap, vertical	mm	900
	Pole width, approx..	mm	1020
	B field, homogeneity		+/- 0.0002 in GFR
	Estimated power	kW	50
	Iron weight	kg	12800
	2 Coils Weight	kg	2300
Electrostatic system	Max. E field in GFR	kV/m	2.7
	Max. Voltages on electrodes	kV	+/- 300
	Effective field length	mm	2365
	Electrode gap, horizontal	mm	220
	Electrode height, vertical	mm	538
	E-field homogeneity		+/- 0.0002 in GFR
	Distance electrode to ground	mm	141
	Max. E-field in gap to wall	kV/m	3.8
	2 Electrodes, Ti, other material	m	approx. 1200 kg
	Vacuum chamber, SS, non-magn.	kg	approx. 3300 kg

Velocity Filter Design Completed for Bidding Process

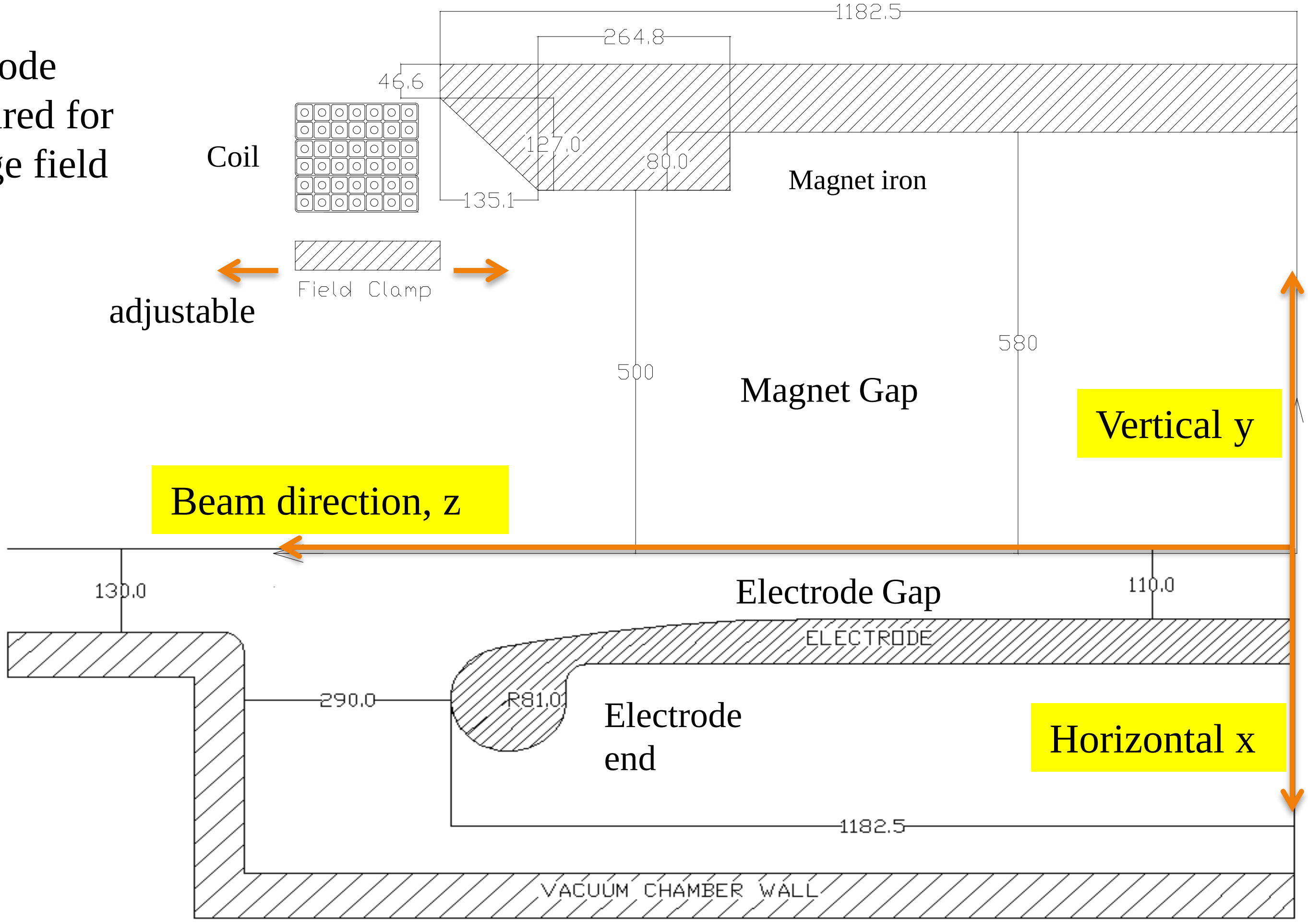
Optimized magnet iron/coil and electrode shape design meets all design requirements



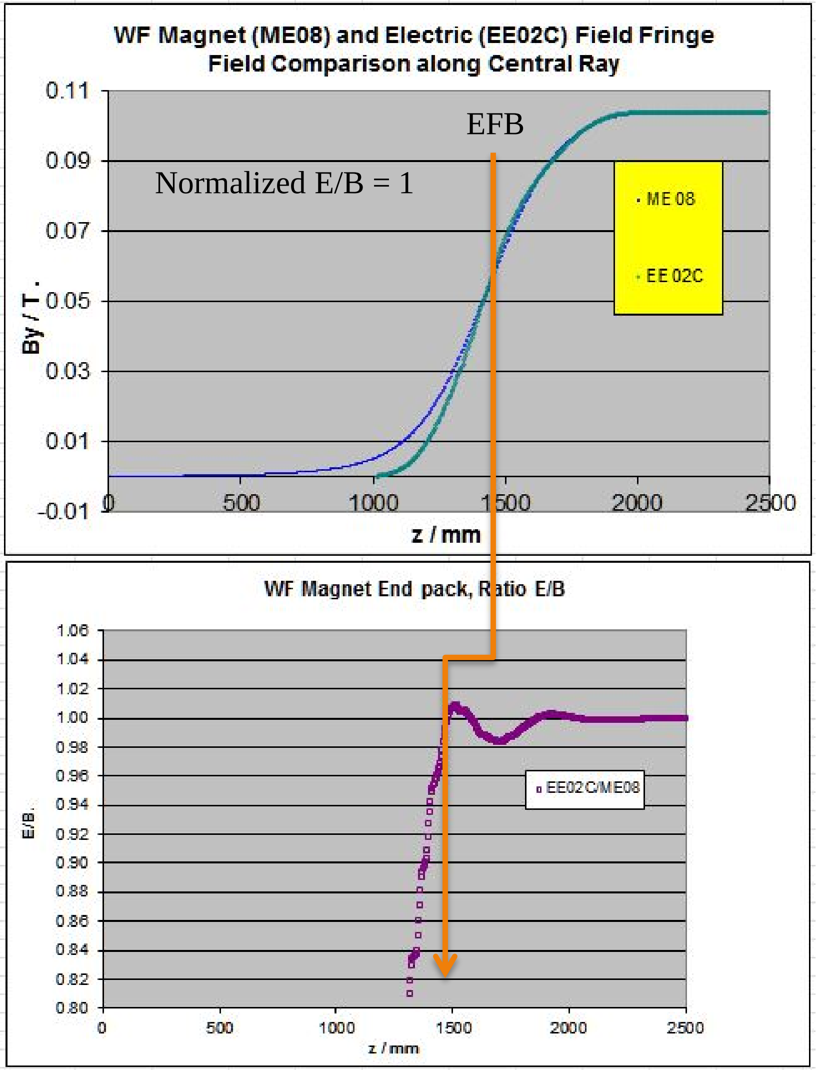
Electrode and Magnet Ends Designed for E/B = Constant in Fringe Field

Charge 2

These shapes of the Electrode and Magnet ends are required for E/B = constant in the fringe field region.



Fringe Field of E- and B-field Designed for E/B = Constant



- Special design of electrode and magnets ends to ensure constant v= E/B Velocity Filter condition in fringe field region

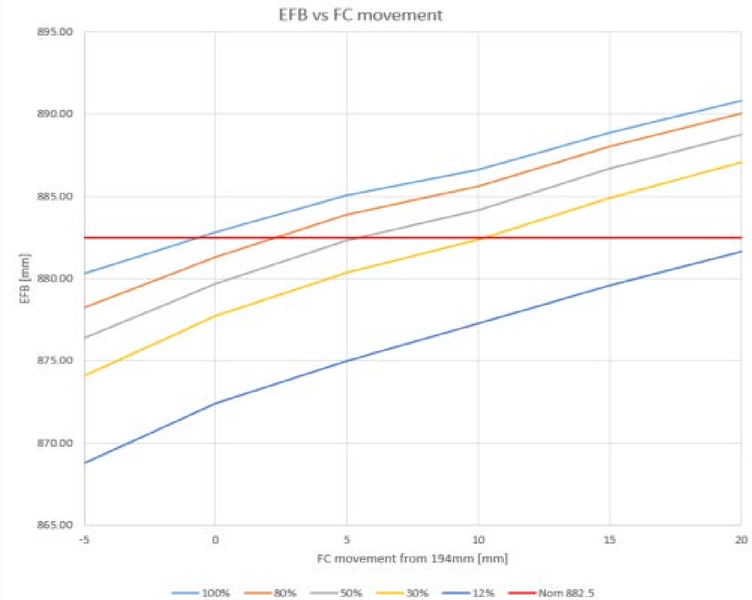
Wien Filter 1 during assembly at manufacturer

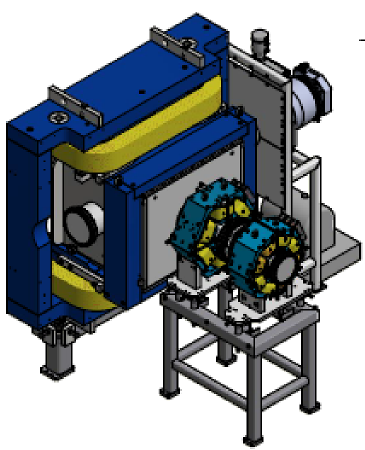
Wien Filter Magnet with yokes, coils and field clamps

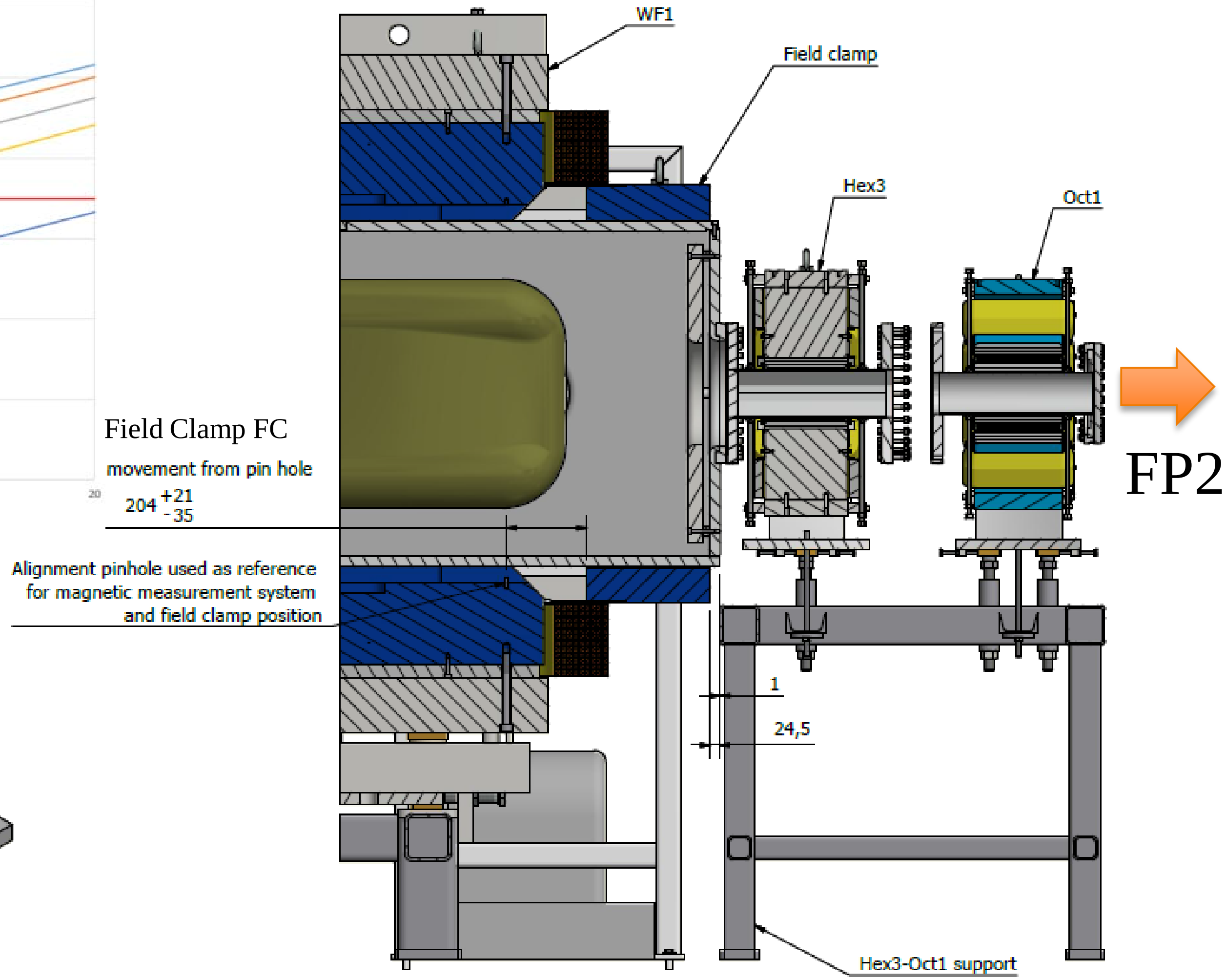
Wien Filter Electrodes installed in vacuum box

Wien Filter with 300kV PS and Turbo pump

Wien Filter 1 exit with adjustable field clamp







Ion Optics, Summary and Path Forward

- The ion-optical model has been used during the design, construction, measurement, and alignment phases of the project to update measured fields (EFL, HO, tolerances, alignment) to verify systems performance.
- This process is complete except for the Wien filters that are still under construction.
- The updated ion-optical model will be used in the commissioning, operation and experimentation, when all measured parameters are included.
- We have scheduled, a Lecture Series on the Introduction in the Ion-Optics and a Hand-on Training for the ion-optical model of SECAR using COSY Infinity for the benefit of the User Community, MSU Oct. 17 -21, 2018

End Lecture 4

Specifications of All Dipole Magnets

		Parameter							
	Units	B1	B2	B3	B4	B5	B6	B7	B8
Bending radius	mm	1250	1250	1250	1250	1250	1250	1250	1250
Maximum rigidity	Tm	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Max. magnetic field B	T	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64
Bending angle, to right	deg	22.5	22.5	22.5	22.5	42.5	42.5	55.0	55.0
Central ray, arc length	mm	490.9	490.9	490.9	490.9	927.2	927.2	1199.9	1199.9
Vertical gap, full size	mm	60	60	100	100	60	60	60	60
GFR, dB/B <+/-0.02%	mm	200	200	100	200	100	100	100	100
Pole width	mm	380	380	400	500	300	300	280	280
Entrance s_{11}		0.1900	0.1150	0.1900	0.1900	0.1890	0.1970	0	0
Entrance s_{12}	1/m	0.0025	0.0125	1.07	-0.339	0.696	-1.66	0	0
Entrance s_{13}	1/m²	0.154	0.198	-9.10	-5.51	-0.953	-50..	0	0
Entrance s_{14}	1/m³	0.78	-40.77	0.	-0.84	-53.	0.	0	0
Exit s_{21}		0.1500	0.1150	0.1150	0.1900	-0.172	0.200	0	0
Exit s_{22}	1/m	-0.019	-0.2448	0.0410	-0.030	-5.928	-4.00	0	0
Exit s_{23}	1/m²	0.147	1.411	32.7	-0.364	-26.5	69.	0	0
Exit s_{24}	1/m³	0.10	37.47	-57.	-0.15	-940..	0.	0	0
Maximum DC Power	kW	5.8	5.8	11	11	8.7	8.7	10	10
Weight, approx.	kg	700	700	1500	1500	1300	1300	1600	1600

Corrected up to order 4, as recommended by Director's Review

Specification of All Quadrupole Magnets

Parameter	Quadrupole Magnet															
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15
Overall length	mm	390	440	490	490	490	480	480	390	440	400	480	440	440	440	440
Focusing strength	T	-2.25	1.32	0.95	-1.31	0.88	0.61	-0.26	-1.25	1.50	-0.29	0.71	-1.29	1.62	1.20	-1.20
Eff. field length	mm	250	300	350	350	350	340	340	250	300	260	340	300	300	300	300
Gradient	T/m	-9.00	4.41	2.73	-3.75	2.50	1.79	-0.77	-5.00	5.00	-1.11	2.08	-4.29	5.40	4.00	-4.00
Good field, horizontal	mm	90	140	200	140	100	290	270	100	120	180	240	140	80	120	120
Aperture, diam.	mm	100	136	220	160	120	280	260	100	120	180	240	140	100	100	160
Max. pole tip strength	T	-0.45	0.30	0.30	-0.30	0.15	0.25	-0.10	-0.25	0.30	-0.10	0.25	-0.30	0.27	0.20	-0.20
Maximum DC Power	kW	5.7	4.0	4.7	5.2	1.7	6.4	1.0	1.0	1.8	0.6	4.9	1.8	1.6	1.0	1.0
Maximum Inhomogeneity		0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.20%	0.20%	0.20%	0.20%	0.20%
Iron weight, (approx.)	kg	260	320	1030	490	280	1060	450	160	290	210	800	280	270	170	170
Horizontal Pipe inner diameter	mm	90	160	240	140	100	300	280	100	140	210	270	200	90	120	120
Vertical pipe inner diameter	mm	80	100	140	120	100	100	80	80	80	80	80	150	100	80	100