Status of HEDA2 Design

S. Rimjaem

Introduction

Tasks:

1. Measurements of momentum and momentum distribution for electron momentum up to 40 MeV/c
2. Longitudinal phase space measurements for momentum spread resolution ~1 keV/c by using combination of:
    - a dipole magnet, an RF-deflector and a beam monitor screen
    - a dipole magnet and a Cherenkov radiation equipped with a streak camera readout system
3. Transverse slice emittance measurements at off-crest booster phases

Priority:

The off-crest booster operation for the transverse slice emittance measurements leads to the large momentum spread and therefore momentum spread resolution. Since the resolution of the transverse slice emittance measurement at HEDA1 is very small, the design of HEDA2 devotes to the resolution of the resolution of the momentum spread measurement.

Requirements:

- The maximum electron momentum up to 40 MeV/c (30 MeV/c nominal)
- The dipole deflects the beam in horizontal direction since the RF-deflector deflects the beam vertically
- The possibility to be operated with full pulse length of the trains up to 7200 pulses, 1 nC and 10 Hz repetition rate

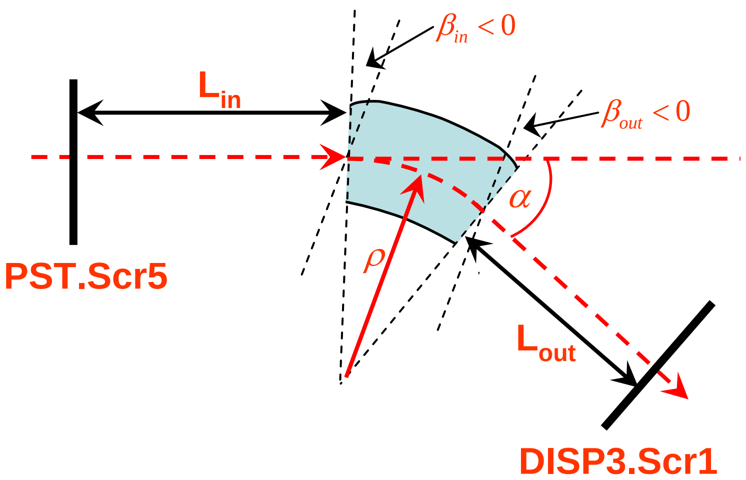
$\Rightarrow$ A huge beam dump ~ 2m $\times$ 2m $\times$2m is needed, but the space is limited. Therefore, the beam is planned to be transported to the beam dump of the main beam line with reasonable transverse beam size.

The first dipole magnet (D1)

- The dipole deflects the beam of nominal momentum of about 30 MeV/c in horizontal direction since the RF-deflector deflects the beam vertically.
- The momentum spread measurement at the screen after the dipole magnet has the momentum resolution as small as 1 keV/c

Transportation Matrices (1)

Dipole magnet and drift lengths



A particle state at any position along the beam transport line can be described by a matrix transformation from its relative coordinates as

$$\begin{bmatrix} x \\ x' \\ y \\ y' \\ z \\ \delta \end{bmatrix} = M \begin{bmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \\ z_0 \\ \delta_0 \end{bmatrix} = \begin{bmatrix} R_{11}x_0 + R_{12}x'_0 + R_{16}\delta_0 \\ R_{21}x_0 + R_{22}x'_0 + R_{26}\delta_0 \\ R_{33}y_0 + R_{34}y'_0 \\ R_{43}y_0 + R_{44}y'_0 \\ R_{51}x_0 + R_{52}x'_0 + R_{55}z_0 + R_{56}\delta_0 \\ R_{66}\delta_0 \end{bmatrix}$$

excluded $R_{56}\delta_0$ in simulation

M is the transport matrix of the beam line elements

$$M = \begin{bmatrix} R_{11} & R_{12} & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & R_{34} & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ R_{51} & R_{52} & 0 & 0 & R_{55} & R_{56} \\ 0 & 0 & 0 & 0 & 0 & R_{66} \end{bmatrix}$$

Transportation matrix for the dipole and its wedge edges

$$M_{dipole} = M_{\beta_{out}} M_{sector} M_{\beta_{in}},$$

Transportation matrix for a particle travels from the reference screen (PST.Scr5) through the first dipole (D1) and reaches the dispersive screen (DISP3.Scr1)

$$M = M_{L_{out}} M_{\beta_{out}} M_{D1} M_{\beta_{in}} M_{L_{in}}$$

$$M_{drift} = \begin{bmatrix} 1 & L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \frac{L}{\gamma^2} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad M_{sector} = \begin{bmatrix} \cos\alpha & \rho\sin\alpha & 0 & 0 & 0 & \rho(1-\cos\alpha) \\ -\frac{\sin\alpha}{\rho} & \cos\alpha & 0 & 0 & 0 & \sin\alpha \\ 0 & 0 & 1 & \rho\alpha & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \sin\alpha & \rho(1-\cos\alpha) & 0 & 0 & 1 & \frac{\rho\alpha}{\gamma^2} - \rho(\alpha - \sin\alpha) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad M_\beta = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ \frac{\tan\beta}{\rho} & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -\frac{\tan(\beta-\psi)}{\rho} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Transportation Matrices (2)

Streak & RF-deflector measurement

Transport matrix of streak camera TOF measurement

$$M_S = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & s \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

where s is the resolution of the streak TOF measurement

Matrix transportation including the streak camera TOF measurement

$$M = M_S M_{L_{out}} M_{\beta_{out}} M_{D1} M_{\beta_{in}} M_{L_{in}}.$$

The final particle coordinates becomes

$$\begin{aligned} x &= R_{11}x_0 + R_{12}x_0' + R_{16}\delta_0 \\ x' &= R_{21}x_0 + R_{22}x_0' + R_{26}\delta_0 \\ y &= R_{33}y_0 + R_{34}y_0' \\ &= y_0 + (L_{in} + L_{out} + \rho\alpha)y_0' \\ y' &= R_{43}y_0 + R_{44}y_0' \\ &= y_0' \\ z &= R_{51}x_0 + R_{52}x_0' + R_{55}z_0 + (R_{56} + sR_{66})\delta_0 \\ &= R_{51}x_0 + R_{52}x_0' + z_0 + (R_{56} + s)\delta_0 \\ \delta &= R_{66}\delta_0 \\ &= \delta_0 \end{aligned}$$

Transport matrix of measurement with RF-deflector

$$M_{RFD} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & k & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & k & 0 & 0 & 1 \end{bmatrix}$$

where k is the RF-deflecting factor $k \equiv \frac{eV_0}{aE}$

Matrix transportation including the RF-deflector measurement

$$M = M_{L_{out}} M_{\beta_{out}} M_{D1} M_{\beta_{in}} M_{L_{in}} M_{RFD}.$$

The final particle coordinates becomes

$$\begin{aligned} x &= R_{11}x_0 + R_{12}x_0' + R_{16}\delta_0 \\ x' &= R_{21}x_0 + R_{22}x_0' + R_{26}\delta_0 \\ y &= R_{33}y_0 + R_{34}y_0' + R_{34}kz_0 \\ &= y_0 + (L_{in} + L_{out} + \rho\alpha)y_0' + kz_0 \\ y' &= R_{44}y_0' + R_{44}kz_0 \\ &= y_0' + kz_0 \\ z &= R_{51}x_0 + R_{52}x_0' + kR_{56}y_0 + R_{55}z_0 + R_{56}\delta_0 \\ &= R_{51}x_0 + R_{52}x_0' + kR_{56}y_0 + z_0 + R_{56}\delta_0 \\ \delta &= R_{66}\delta_0 \\ &= \delta_0 \end{aligned}$$

Note: Consider the deflection in horizontal plane, non-deflection in vertical plane and excluded $R_{56}\delta_0$ in simulation

Optimization of Momentum Spread from Matrix Transportation

While electron beam is deflected by the a dipole magnet, particles with different electron momenta are deflected with different deflecting angles and result in different transverse positions at the dispersive screen. The transverse beam size (x) can be derived from

$$x = R_{11}x_0 + R_{12}x'_0 + R_{16}\delta_0.$$

In order to have good resolution of the momentum spread (δ_0) measurement, the influence of the other contributions (x_0, x'_0) should be as small as possible.

$$D = R_{16}\delta_0 \gg R_{11}x_0 + R_{12}x'_0,$$
$$\delta_0 \gg (\frac{R_{11}}{R_{16}})x_0 + (\frac{R_{12}}{R_{16}})x'_0.$$

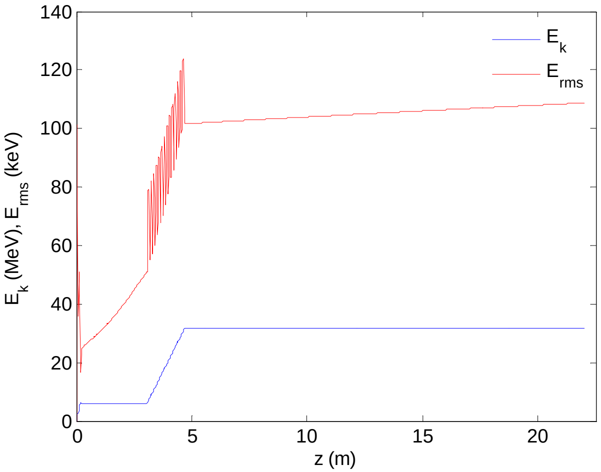
Therefore, the ratios $|\frac{R_{16}}{R_{11}}|$ and $|\frac{R_{16}}{R_{12}}|$ should be as increased in order to increase the momentum spread resolution.

Selected parameters for the first dipole magnet

case	α (^{o})	β_{in} (^{o})	β_{out} (^{o})	ρ (mm)	L_{eff} (mm)	L_{i1} (mm)	L_{o1} (mm)	$D(L_{o1}+L_{i2})$ (mm)	R_{16} (mm)	L_{D1} (mm)
60-1	60	0	0	600	628.32	1950	650	1079.42	862.92	1528.32
60-2	60	30	-27	700	733.04	1550	861	1029.11	876.30	1844.04
60-3	60	30	-30	750	785.40	1550	866	1019.32	874.98	1901.40
60-4	60	30	-28	700	733.04	1700	869	1021.59	871.55	1852.04
60-5	60	30	-30	750	785.40	1700	898	1037.80	893.46	1933.40
60-6	60	30	-30	700	733.04	1950	843	981.04	836.71	1826.04
60-7	60	30	-30	750	785.40	1950	909	1044.15	899.81	1944.40
60-8	60	30	-30	750	785.40	900	909	1044.15	899.81	1944.40
90-1	90	0	0	650	1021.02	1700	250	1150.00	900.00	1521.02
90-2	90	30	-30	700	1099.56	1550	452	996.70	891.04	1801.56
90-3	90	30	-29	700	1099.56	1700	447	1010.65	899.22	796.56
90-4	90	30	-30	700	1099.56	1950	425	985.29	879.62	1774.56
90-5	90	30	-24.21	650	1099.56	1950	420	1018.75	881.16	1691.02
90-6	90	30	-30	700	1099.56	900	473	1005.58	899.91	1822.56

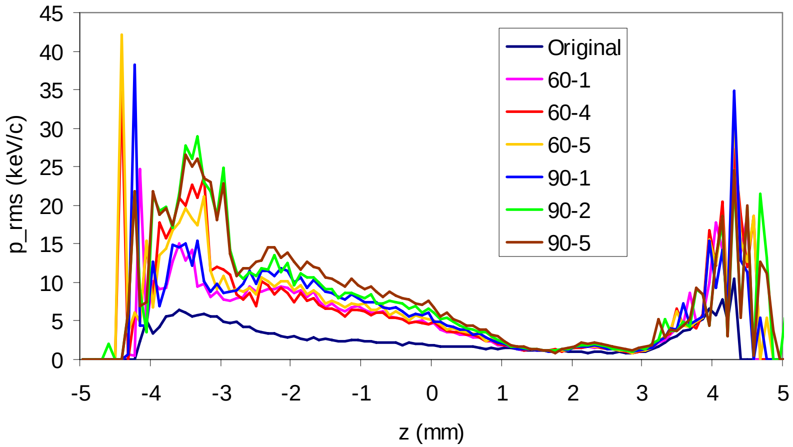
Simulation with Astra distribution at zero gun & booster phase

- **Gun phase = 0, gradient = 60 MV/m**
- **Booster phase = 0, gradient = 28.55 MV/m**
- **B_{main} = 0.2156 T, $B_{bucking}$ = -0.0076 T (zero B-field at cathode)**
- **p_{meam} ~ 32.07 MeV/c**
- **p_{rms} = 106.17 keV/c**
- **min $p_{rms, slice}$ = 0.826 keV/c**
- **mean $p_{rms, slice}$ = 2.371 keV/c**

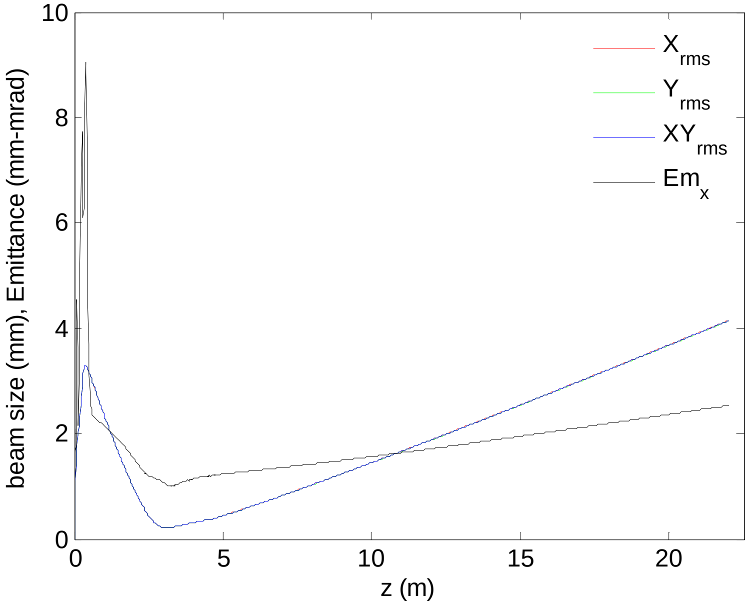


Slice momentum spread for the particles tracing through the first dipole magnet for selected parameters

case	α (°)	β_{in} (°)	β_{out} (°)	ρ (mm)	L_{i1} (mm)	L_{o1} (mm)	Q (T/m)	$(\frac{\delta p}{p})_{mean}$	$(\frac{\delta p}{p})_{rms}$	$(\frac{\delta p}{p})^{slice}_{min}$	$(\frac{\delta p}{p})^{slice}_{mean}$
60-1	60	0	0	600	1950	650	1.98	2.4×10^{-9}	-3.4×10^{-6}	0.26	1.23
60-2	60	30	-27	700	1550	861	2.07	-3.7×10^{-8}	2.4×10^{-4}	0.88	1.88
60-3	60	30	-30	750	1550	866	2.06	-3.6×10^{-8}	2.3×10^{-4}	0.91	1.89
60-4	60	30	-28	700	1700	869	2.04	6.7×10^{-12}	-1.1×10^{-8}	0.12	1.66
60-5	60	30	-30	750	1700	898	2.03	2.1×10^{-10}	-3.5×10^{-7}	0.11	1.74
60-6	60	30	-30	700	1950	843	1.99	4.0×10^{-8}	1.4×10^{-4}	1.64	1.71
60-7	60	30	-30	750	1950	909	1.99	3.1×10^{-8}	7.2×10^{-5}	1.10	1.70
90-1	90	0	0	650	1700	250	1.97	9.1×10^{-10}	-1.4×10^{-6}	0.25	1.53
90-2	90	30	-30	700	1550	452	2.06	1.4×10^{-10}	-2.4×10^{-7}	0.19	2.19
90-3	90	30	-29	700	1700	447	2.06	-1.8×10^{-10}	3.1×10^{-7}	0.37	2.27
90-4	90	30	-30	700	1950	425	2.04	-4.6×10^{-10}	7.9×10^{-7}	0.62	2.45
90-5	90	30	-24.2	650	1950	420	1.97	2.4×10^{-11}	-4.0×10^{-8}	0.37	2.33



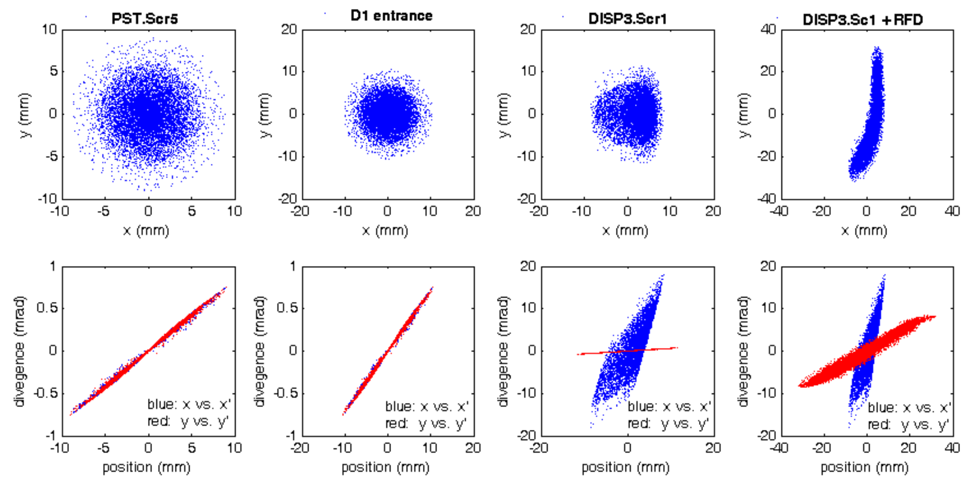
No Quadrupole Focusing



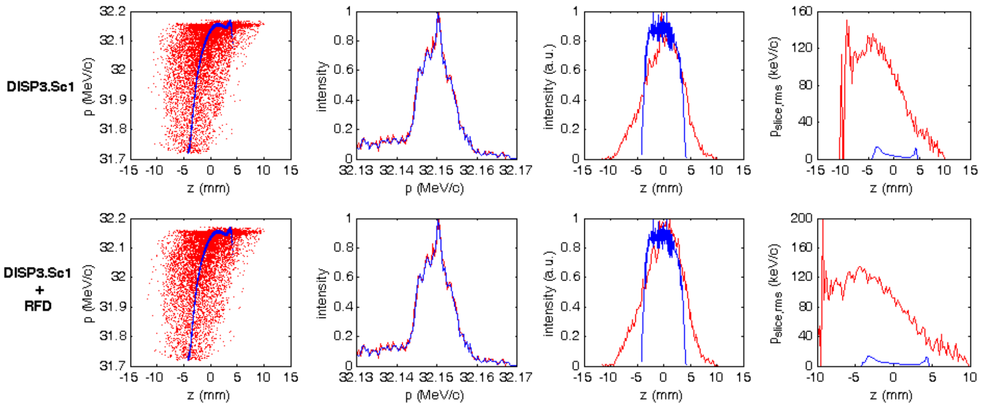
Gradient of Q1 (T/m)	Gradient of Q2 (T/m)	Gradient of Q3 (T/m)
0	0	0

Reconstruction resolution	dipole	dipole +RFD
$\delta p_{rms,\ slice,min}$	3219.8 %	2630.5 %
$\delta p_{rms,\ slic,mean}$	3265.8%	3393.9%

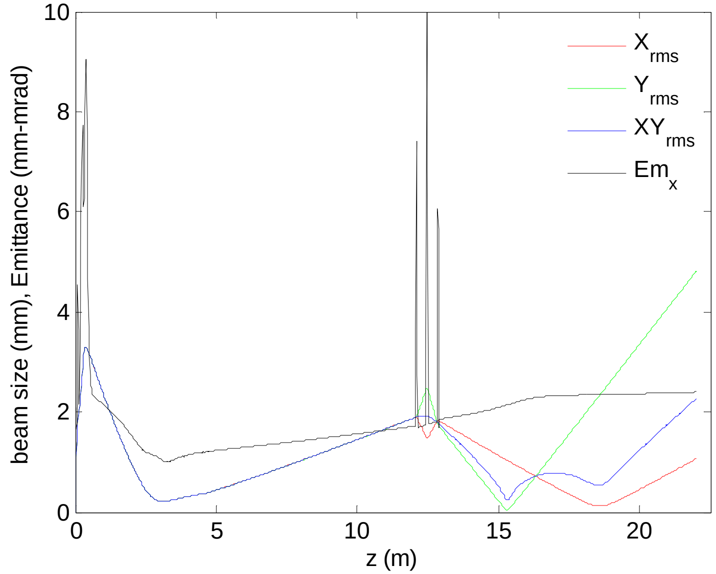
Simulated beam size and divergence at the reference screen (PST.Scr5), dipole D1 entrance, dispersive screen after the first dipole (DISP3.Scr1) and with RF-deflector measurement (RFD)



Simulated longitudinal particle distributions at the dispersive screen after the first dipole (top) and with RF-deflector measurement (bottom)



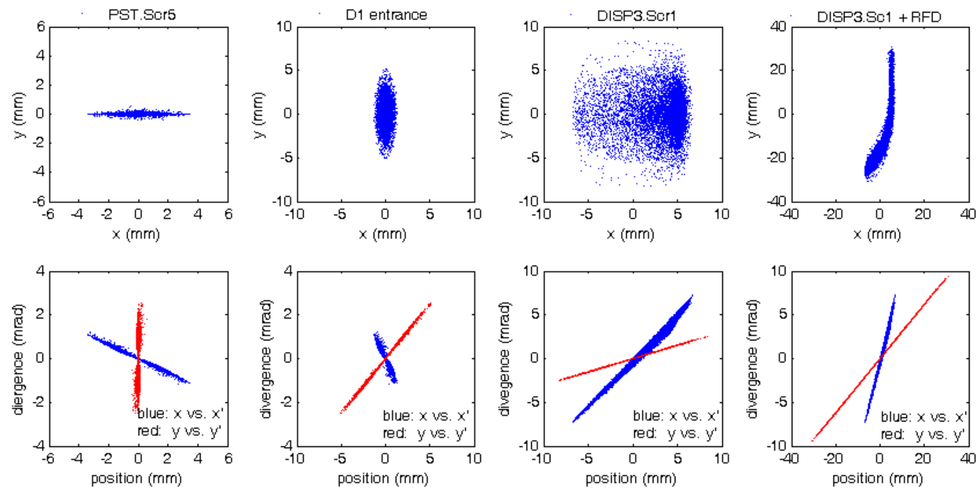
Vertical Focusing at PST.Scr5



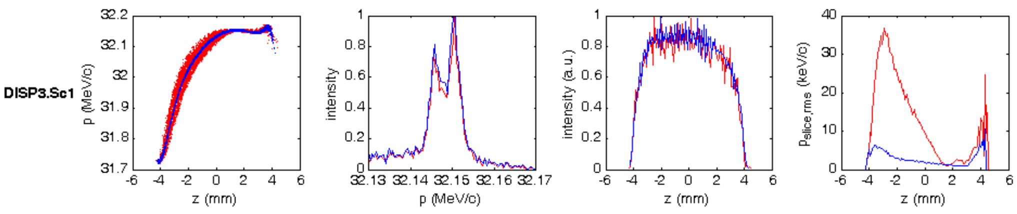
Gradient of Q1 (T/m)	Gradient of Q2 (T/m)	Gradient of Q3 (T/m)
1.9	-3.8	1.9

Reconstruction resolution (keV/c)	dipole	dipole +RFD
$\delta p_{rms,\ slice,min}$	74.4%	3.0%
$\delta p_{rms,\ slic,mean}$	353.6%	154.1%

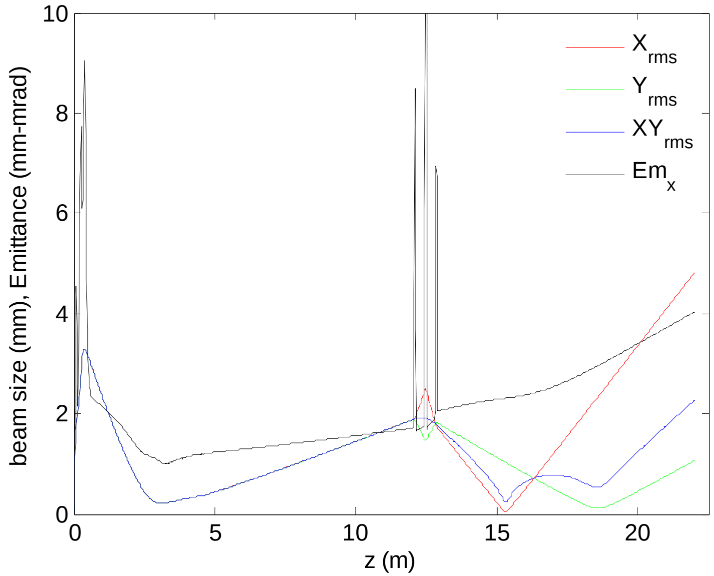
Simulated beam size and divergence at the reference screen (PST.Scr5), dipole D1 entrance, dispersive screen after the first dipole (DISP3.Scr1) and with RF-deflector measurement (RFD)



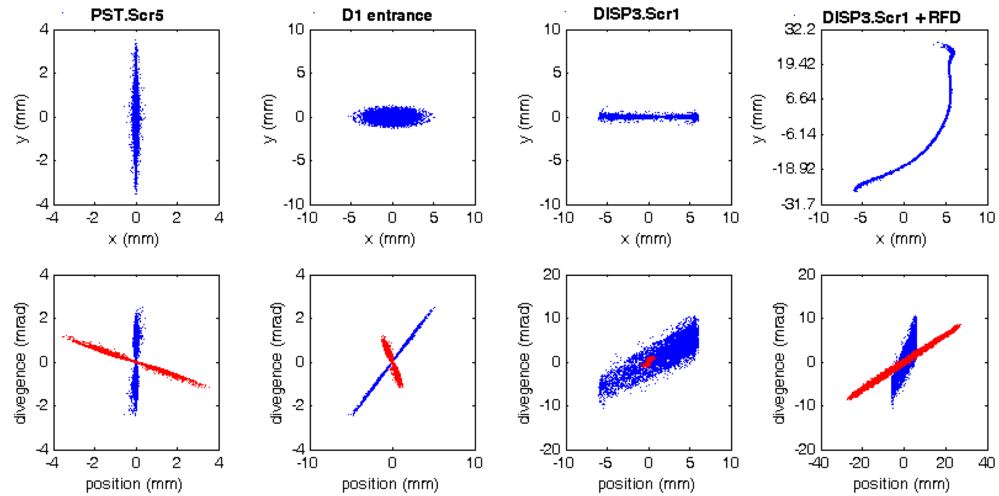
Simulated longitudinal particle distributions at the dispersive screen after the first dipole (top) and with RF-deflector measurement (bottom)



Horizontal Focusing at PST.Scr5



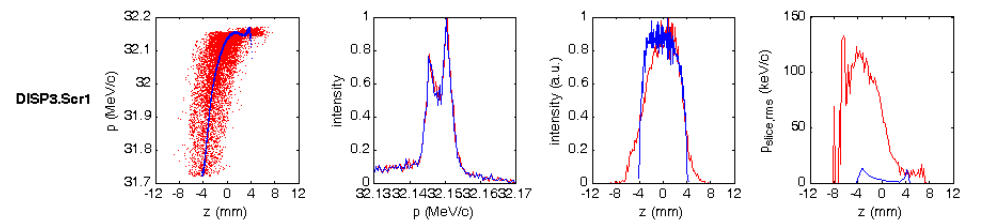
Simulated beam size and divergence at the reference screen (PST.Scr5), dipole D1 entrance, dispersive screen after the first dipole (DISP3.Scr1) and with RF-deflector measurement (RFD)



Gradient of Q1 (T/m)	Gradient of Q2 (T/m)	Gradient of Q3 (T/m)
-1.9	3.8	-1.9

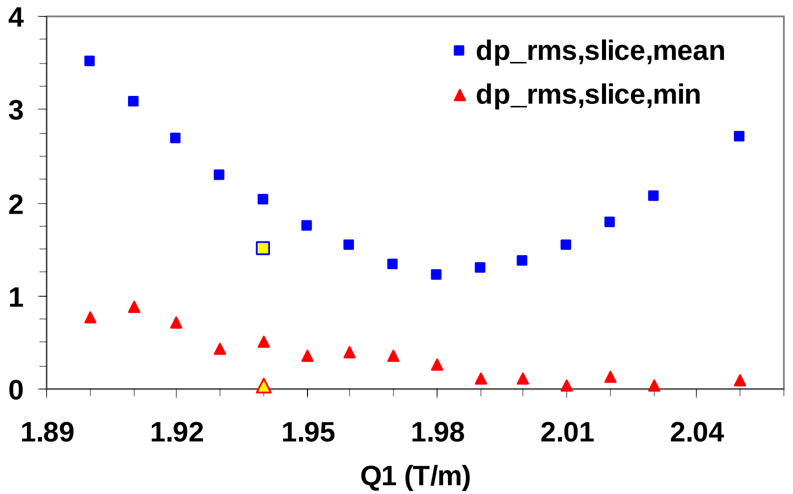
Reconstruction resolution (keV/c)	dipole	dipole +RFD
$\delta p_{rms,\ slice,min}$	561.2%	971.3%
$\delta p_{rms,\ slic,mean}$	1984.0%	1961.5%

Simulated longitudinal particle distributions at the dispersive screen after the first dipole (top) and with RF-deflector measurement (bottom)



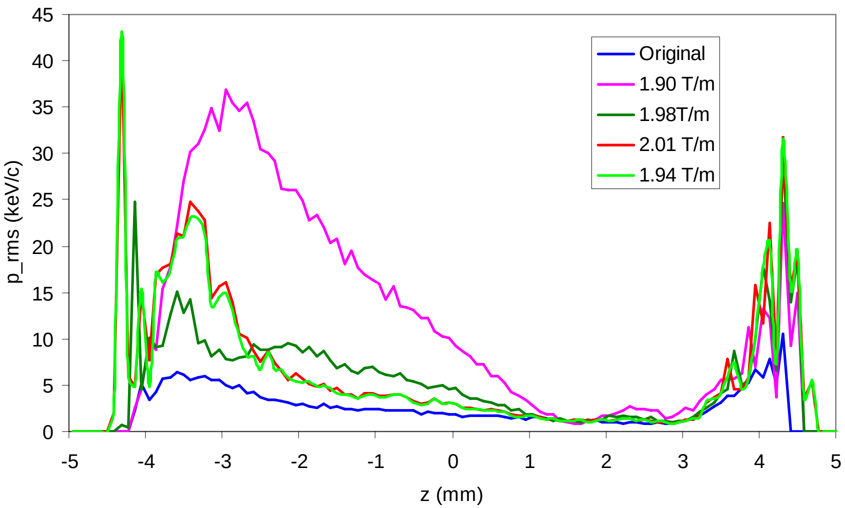
Focusing Optimization

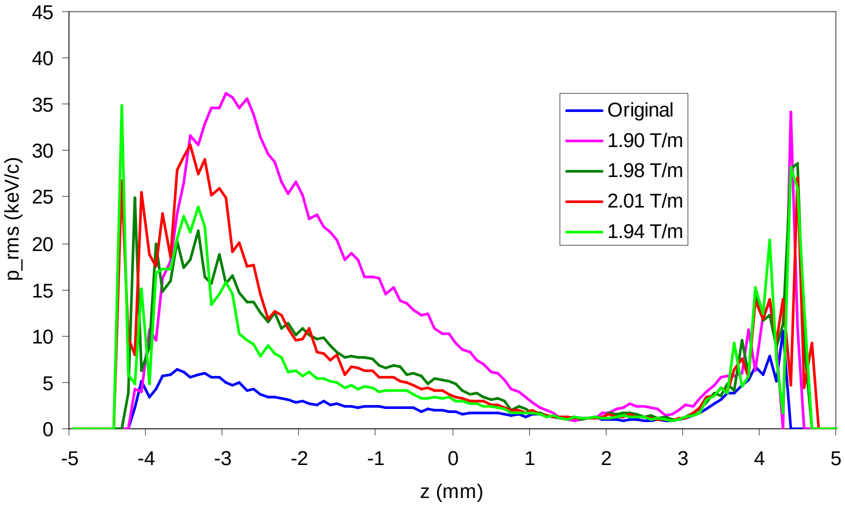
Optimization of the quadrupole focusing for good resolution of momentum spread



Case 1.90, 1.98, 2.01 → Q1=Q3 & Q2=-2Q1
Case 1.94 → Q1=Q3, vary Q2 to get good resolution

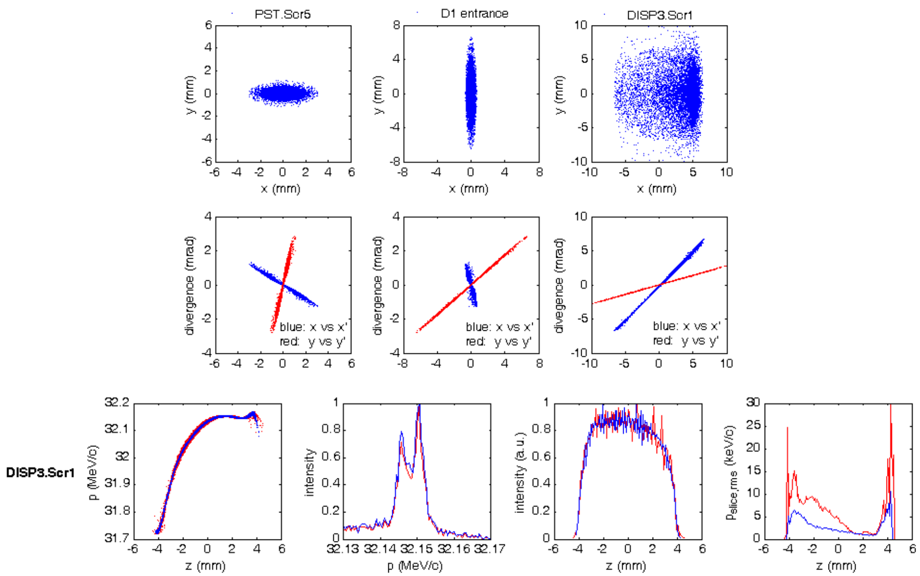
Slice momentum spread for the particles tracing through the first dipole magnet for different quadrupole focusing without (top) and using RF-deflector (bottom)



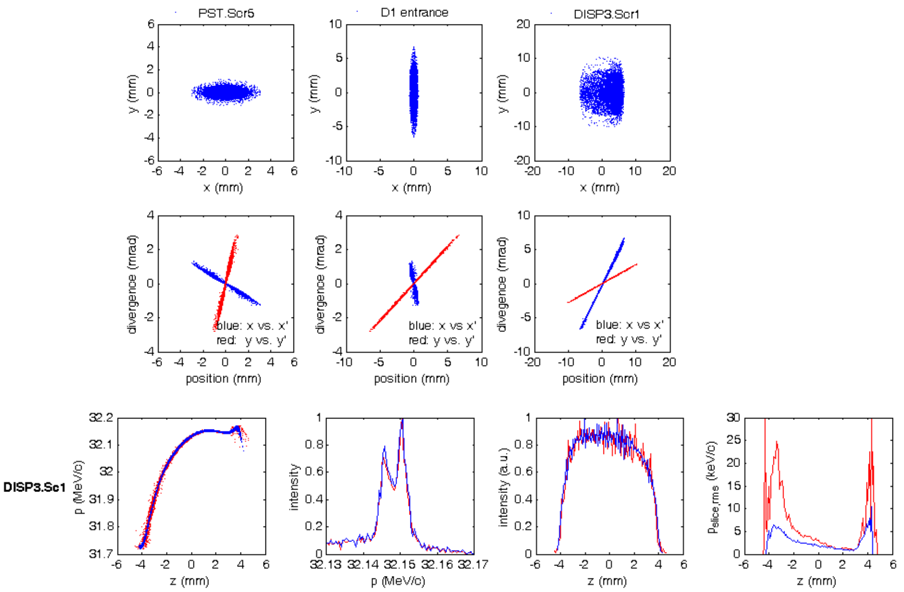


Optimum deviation of $p_{rms,\ slice}$ for Q1=Q3, Q2=-2Q1

Q1=1.98 T/m (optimum deviation in mean $p_{rms,\ slice}$)



Q1=2.01 T/m (optimum deviation in min $p_{rms,\ slice}$)



Reconstruction resolution	dipole
$\delta p_{rms,\ slice,min}$	25.97%
$p_{rms,\ slice,min}$	1.081 keV/c
$\delta p_{rms,\ slic,mean}$	122.91%
$p_{rms,\ slice,mean}$	5.285 keV/c

Reconstruction resolution	dipole
$\delta p_{rms,\ slice,min}$	3.03%
$p_{rms,\ slice,min}$	0.851 keV/c
$\delta p_{rms,\ slic,mean}$	154.14%
$p_{rms,\ slice,mean}$	6.026 keV/c

Optimized Focusing for reducing effect of dipole for the longitudinal particle distribution

Conclusion

The 60º sector dipole magnet has complex contribution from the beam size and divergence, which has to be extracted from simulations

Gradient of Q1 (T/m)	Gradient of Q2 (T/m)	Gradient of Q3 (T/m)
1.94	-3.8	1.94

Reconstruction resolution	Dipole effect	Dipole + Measured	Dipole + RFD
$\delta p_{rms,\ slice,min}$	3.7%	1131%	7.5%
$p_{rms,\ slice,min}$	0.857 keV/c	10.168 keV/c	0.888 keV/c
$\delta p_{rms,\ slic,mean}$	150.5%	286%	152.9%
$p_{rms,\ slice,mean}$	5.940 keV/c	9.152	5.996 keV/c

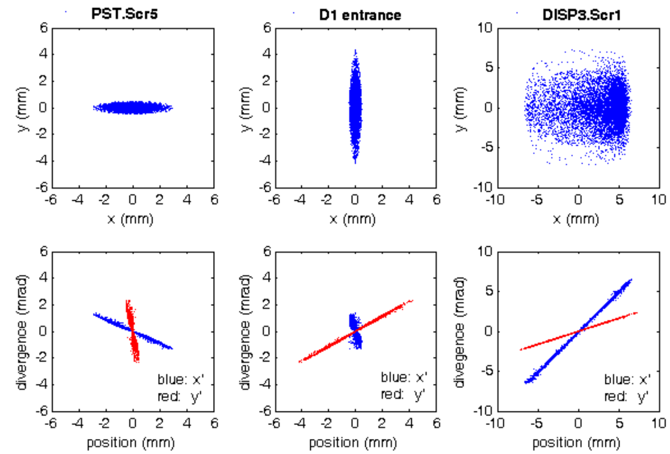
$$p = (\frac{x - R_{11}x_0}{R_{16}}) p_{mean} + p_{mean}$$

Reconstructed momentum

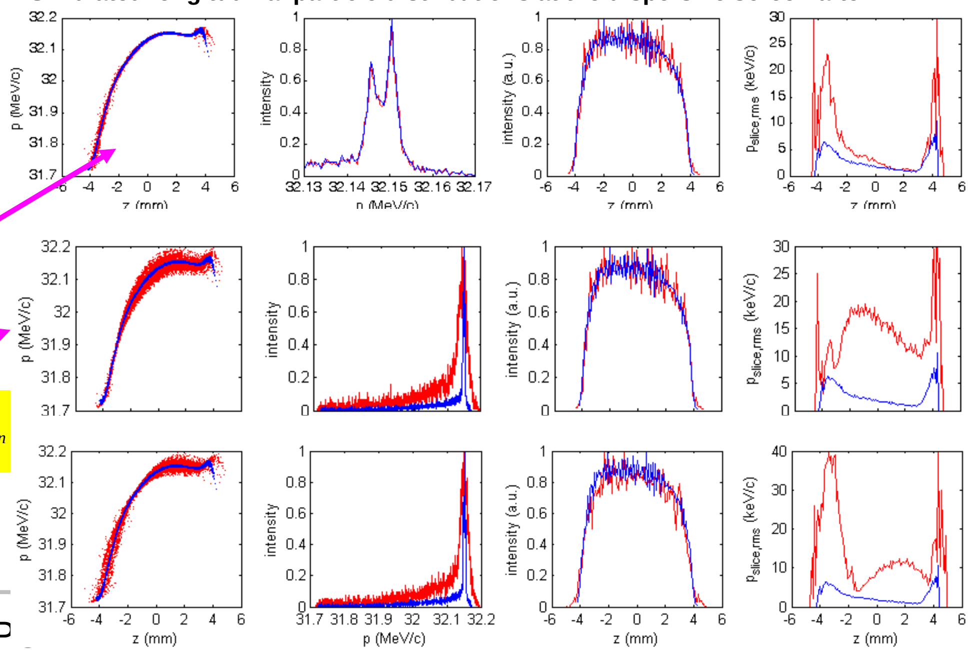
$$p = (\frac{x - x_{mean}}{R_{16}}) p_{mean} + p_{mean}$$

resolution	Dipole + Measured	Dipole + Measured
$\delta p_{rms,\ slice,min}$	1131%	819.5%
$p_{rms,\ slice,min}$	10.168 keV/c	7.591 keV/c
$\delta p_{rms,\ slic,mean}$	286%	459.1%
$p_{rms,\ slice,mean}$	9.152	13.256 keV/c

Simulated beam size and divergence at the reference screen (PST.Scr5), dipole D1 entrance, dispersive screen after the first dipole (DISP3.Scr1) and with RF-deflector measurement (RFD)



Simulated longitudinal particle distributions at the dispersive screen after D1



PP

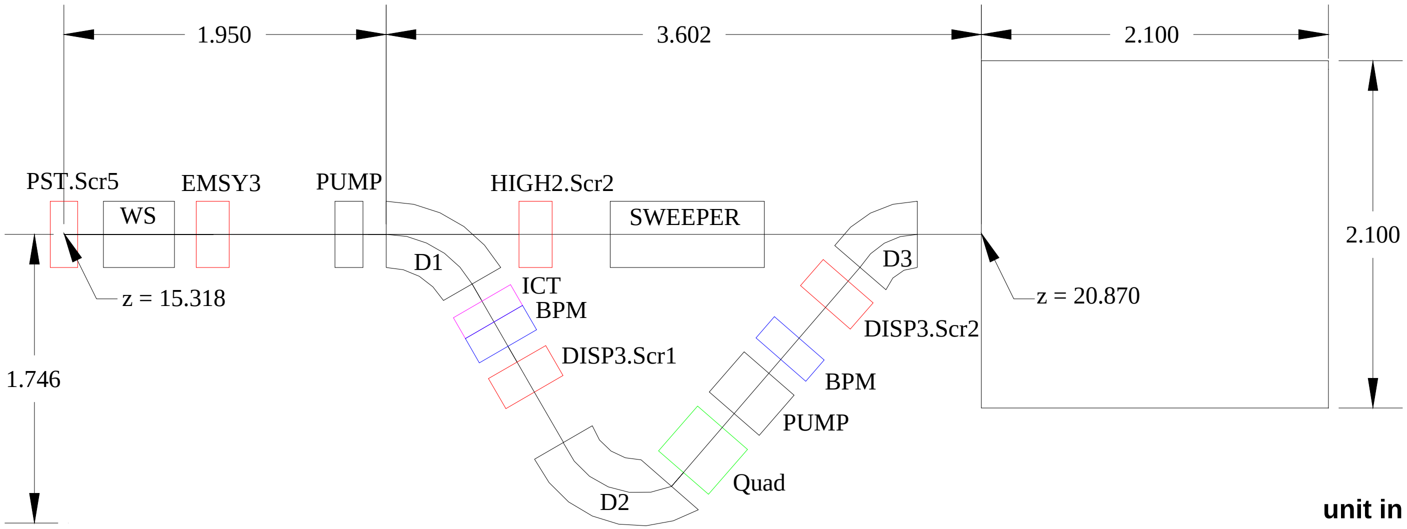
PITZ2-OPFF Scenery: booster off-crest phases

- Gun phase = 0, gradient = 60 MV/m
- Booster phase = 0, gradient = 28.55 MV/m
- B_{main} = 2,156 T, $B_{bucking}$ = -0.0076 T (zero B-field at cathode)
- Pmeam ~ 32.07 MeV/c
- prms = 106.17 keV/c
- minimum prms, slice = 0.826 keV/c
- mean prms, slice = 2.371 keV/c

For transverse slice emittance measurements using the quadrupole scan method
YI: @ CDS booster off-crest 0f +60o the mean energy ~18.4 MeV, Erms = 1.1 MeV, dEmax-dEmin=5MeV

Therefore, the beam size = 5/18.5*Dispersion

Foreseen HEDA2 setup



unit in meter

Dipole	α (degree)	ρ (mm)	β_{in} (degree)	β_{out} (degree)	L_{eff} (mm)	Est. Width (mm)	Est. Length (mm)
D1	60	600	0	0	628.32	600	693
D2	-90	500	-7	26	785.4	992	606
D3	60	400	-11	0	418.9	500	535
Location	DISP3.Scr1	D2 entrance	Quad. center	DISP3.Scr2	D3 entrance	Dump entrance	
Position (mm)	650 after D1	456 after DISP3.Scr1	290 after D2	1243 after Quad	215 after DISP3.Scr2	388 after D4	
Dispersion (mm)	862.9	1257.8	351.4	-285.3	-395.4	536	

Note: **The width (in x-direction) of the magnets was estimated by adding about ±200 mm around the ideal trajectory.**

Requirements of the dipole magnets

D1:

- The dipole deflects the beam of nominal momentum of about 30 MeV/c in horizontal direction since the RF-deflector deflects the beam vertically.
- The momentum spread measurement at the screen after the dipole magnet has the momentum resolution as small as 1 keV/c

D2:

- Lengthen the beam path for fulfil the requirements of the transverse slice emittance

  (Dispersion ~300 mm @ DISP3.Scr2)
- Good beam transport to the entrance of the 3rd dipole magnet

D4:

- Transports the beam to the beam dump in the straight section with reasonable beam size (not too big nor too small)