Using HEDA2 as a Bunch Compressor

Prach Boonpornprasert

PITZ Physics Seminar

24.03.2016

HELMHOLTZ ASSOCIATION

PITZ Photo Injector Test Facility Zeuthen

DESY

Outline

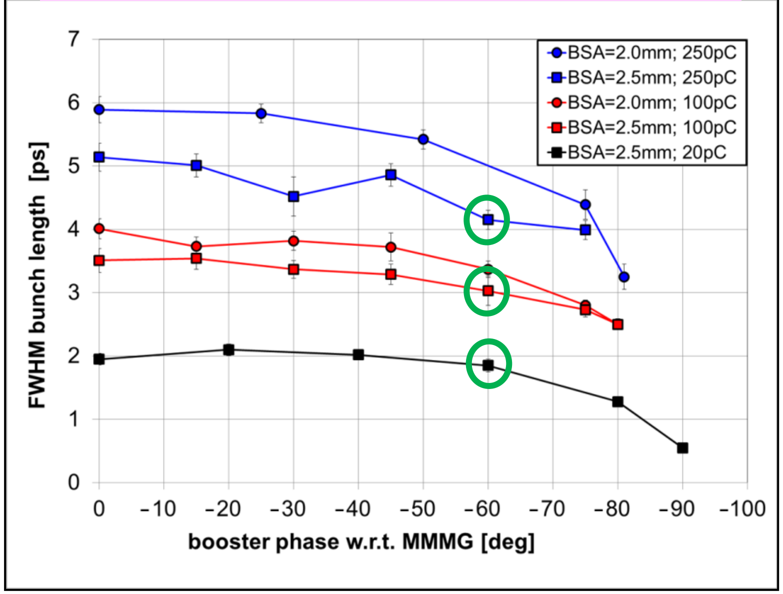
- Motivation
- Transformation Matrices
- 2nd High Energy Dispersive Arm (HEDA2)
- ASTRA Simulations for the Input Beams
- Calculation of Bunch Compression by HEDA2
- Summary & Outlook

Motivation

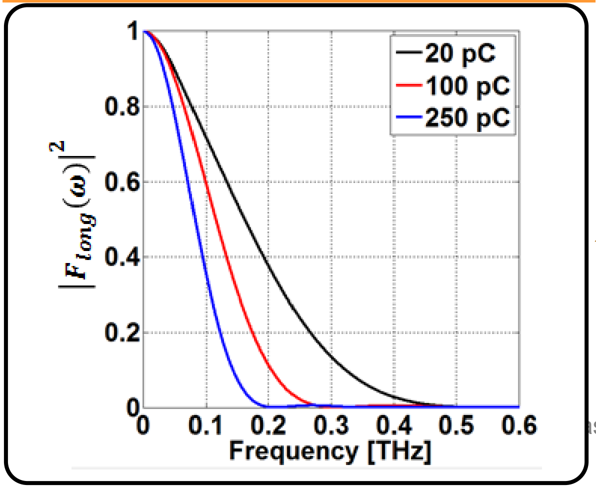
Results of velocity bunching experiment (shifts: 30-31.10.15)

Machine Parameters	
Laser pulse shape	Gaussian
Laser temporal length	**~2.5 ps FWHM**
BSA	2.0, 2.5 mm
Bunch charge	20,100,250 pC
Peak power of RF in the gun	6.3 MW
Peak power of RF in the booster	2.7 MW
Gun phase*	0 degree
Booster phase*	0 to -90 degree

FWHM bunch length VS booster phase



Calculated form factors

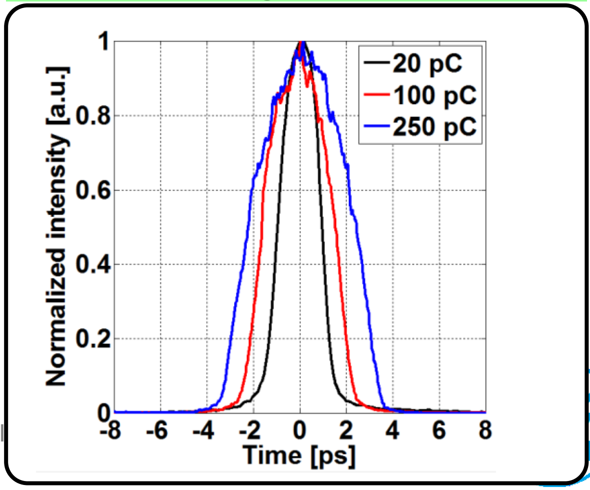


$$\frac{dU_{CTR}}{d\omega} \propto |F_{long}(\omega)|^2$$

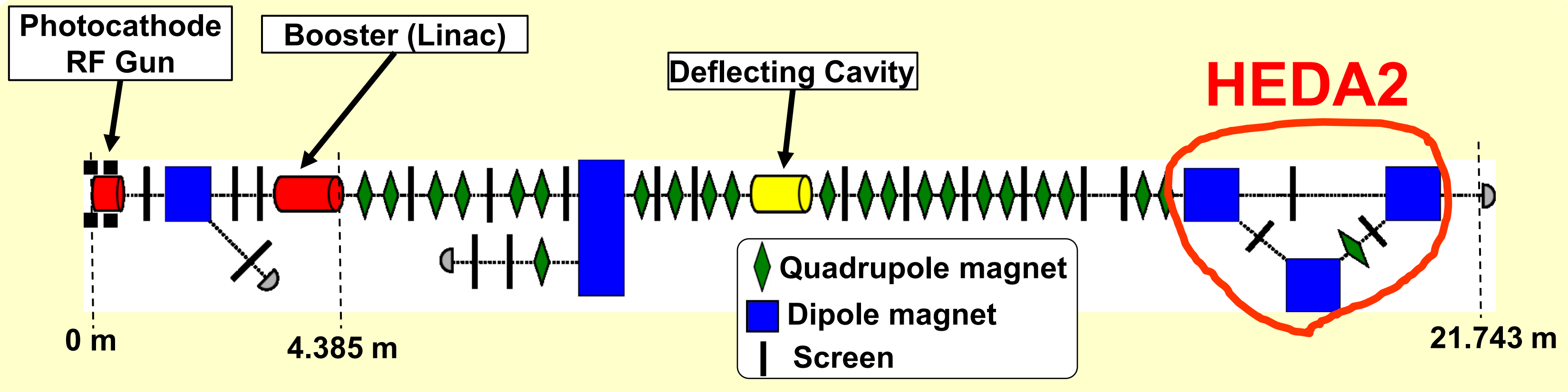
$$F_{long}(\omega) = \int_{-\infty}^{\infty} \rho_{long}\, exp(-i\omega t)dt$$

Shorter bunch is needed for covering higher frequency

Selected long. bunch profiles



Motivation



PITZ Beamline Layout

Can HEDA2 be used as a bunch compressor ?

Works in this presentation is trying to answer this question by using transformation matrices.

Transformation Matrices

Ref: A.Chao Handbook, p.56-59, 1999
S.Rimjaem, HEDA2 note, 24.9.09
D.C.Carey, SLAC-R-530,

- A charged particle is represented by a vector $\boldsymbol{X(s)}$

$$\boldsymbol{X^t}(s) = [x(s) \quad x'(s) \quad y(s) \quad y'(s) \quad \ell(s) \quad \Delta p/p_0]$$

- The vector $\boldsymbol{X}(0)$ at position 0 is transform to another vector $\boldsymbol{X}(s)$ at position $\boldsymbol{s}$ by

$$\boldsymbol{X}(s) = \boldsymbol{\mathcal{M}X}(0)$$

where $\boldsymbol{\mathcal{M}}$ is a 6x6 matrix characterizing lattice(s) between 0 and s.
It is so called "**transformation matrix**".

- By assuming Δp and p_0 are constant, x- and y-motions are decoupled and system have midplane symmetry about $y = 0$, $\boldsymbol{X}(s) = \boldsymbol{\mathcal{M}X}(0)$ can be expanded as

$$\begin{bmatrix} x(s) \\ x'(s) \\ y(s) \\ y'(s) \\ \ell(s) \\ \Delta p/p_0 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & R_{34} & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ R_{51} & R_{52} & 0 & 0 & R_{55} & R_{56} \\ 0 & 0 & 0 & 0 & 0 & R_{66} \end{bmatrix} \begin{bmatrix} x(0) \\ x'(0) \\ y(0) \\ y'(0) \\ \ell(0) \\ \Delta p/p_0 \end{bmatrix}$$

Transformation Matrices (2)

- The final vector of the electron can be written as

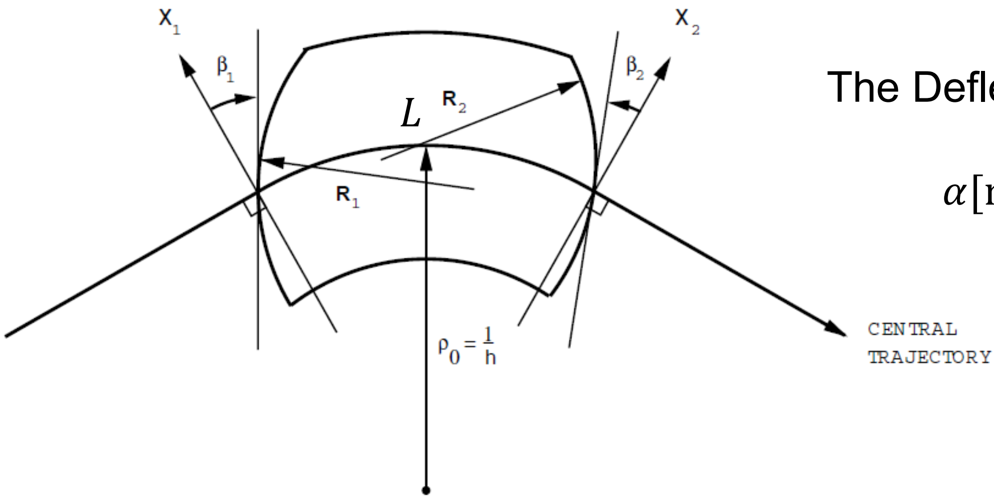
$$\begin{bmatrix} x(s) \\ x'(s) \\ y(s) \\ y'(s) \\ \ell(s) \\ \Delta p/p_0 \end{bmatrix} = \begin{bmatrix} R_{11}x(0) + R_{12}x'(0) + R_{16}(\Delta p/p_0) \\ R_{21}x(0) + R_{22}x'(0) + R_{26}(\Delta p/p_0) \\ R_{33}y(0) + R_{34}y'(0) \\ R_{43}y(0) + R_{44}y'(0) \\ R_{51}x(0) + R_{52}x'(0) + R_{55}\ell(0) + R_{56}(\Delta p/p_0) \\ R_{66}(\Delta p/p_0) \end{bmatrix}$$

- Transformation matrix of a drift space with length of L

$$\boldsymbol{\mathcal{M}}_{\boldsymbol{D}}(L) = \begin{bmatrix} 1 & L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \frac{L}{\gamma^2} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Transformation Matrices (3)

▶ Transformation matrix of a sector magnet



The Deflecting angle of the dipole magnet (α)

$$\alpha[\mathrm{rad}] = \frac{L[\mathrm{m}]}{\rho[\mathrm{m}]} = \frac{0.2998 B_0[\mathrm{T}] L[\mathrm{m}]}{\beta E[\mathrm{GeV}]}$$

$$\mathcal{M}_{\boldsymbol{RecD}} = \begin{bmatrix} \cos\alpha & \rho\sin\alpha & 0 & 0 & 0 & \rho(1-\cos\alpha) \\ -\dfrac{\sin\alpha}{\rho} & \cos\alpha & 0 & 0 & 0 & \sin\alpha \\ 0 & 0 & 1 & \rho\alpha & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \dfrac{\rho\alpha}{\gamma^2} - \rho(\alpha - \sin\alpha) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Transformation Matrices (4)

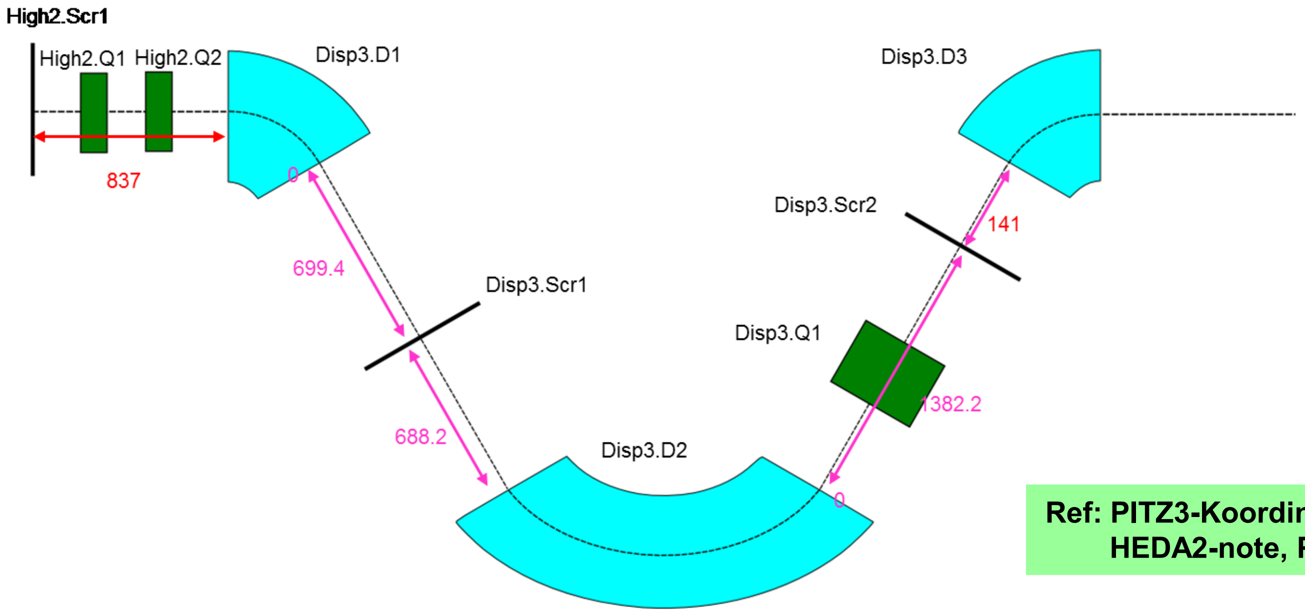
- Pole face rotation (wedge angle) matrix

$$\mathcal{M}_{\beta} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ \dfrac{\tan\beta}{\rho} & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -\dfrac{\tan\beta}{\rho} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

- Transformation matrix of a sector magnet including wedge angles

$$\mathcal{M}_{SecD} = \mathcal{M}_{\beta_{out}} \mathcal{M}_{RecD} \mathcal{M}_{\beta_{in}}$$

HEDA2: Layout and Parameters

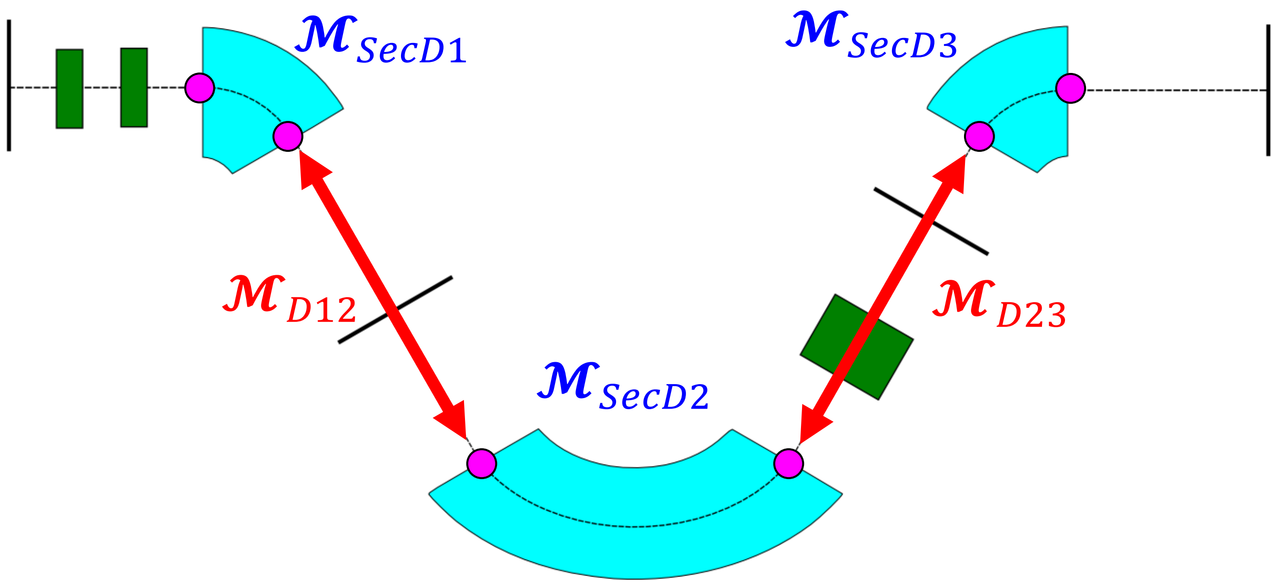


Ref: PITZ3-Koordinaten_15-10-15.xlsx
HEDA2-note, PITZ-wiki

Specifications of Dipole Magnets in the Second High Energy Dispersive Arm (HEDA2)

Parameter	Dipole 1	Dipole 2	Dipole 3
Type	sector	sector with exit wedge angle	sector
Bending angle, α (degree)	60	120	60
Entrance wedge angle, β_{in} (degree)	0	0	0
Exit wedge angle, β_{out} (degree)	0	9	0
Bending radius, ρ (mm)	600	400	400
Maximum magnetic field (T)	0.23	0.34	0.34
Effective length (mm)	628.3	837.8	418.9
Pole gab (mm)	60	60	60
Vertical field homogeneity (dB/B)	$\pm 5\times 10^{-4}$	$\pm 5\times 10^{-4}$	$\pm 5\times 10^{-4}$
Good field region in vertical direction (mm)	±25	±25	±25
Good field region in radial direction (mm)	±70	±50	±50

HEDA2: Tr. Matrices Used in This Work



$$X_{final} = \mathcal{M}_{SecD3}\mathcal{M}_{D23}\mathcal{M}_{SecD2}\mathcal{M}_{D12}\mathcal{M}_{SecD1}X_{initial}$$

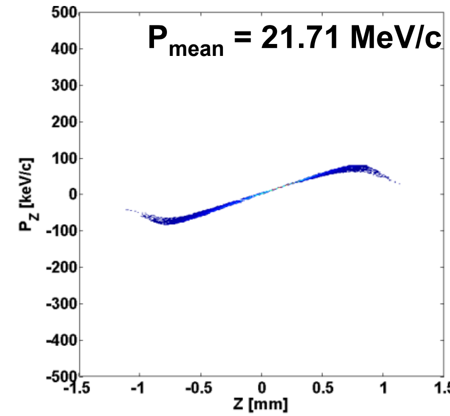
ASTRA Simulations for the Input Beams

Input for ASTRA Simulation	
Zstart ➔ Zstop	0 ➔ 6 m
# macroparticles	**20k**
Laser pulse shape	Gaussian
Laser temporal length	**2.43 ps FWHM**
Bunch charge	**100 pC**
Laser BSA size	**2 mm**
Main solenoid current	**(230:10:330) A**
Peak field in gun	60.5 MV/m
Peak field in booster	17.2 MV/m
Gun RF phase*	0 degree
Booster RF phase*	**(-90:30:90) degree**

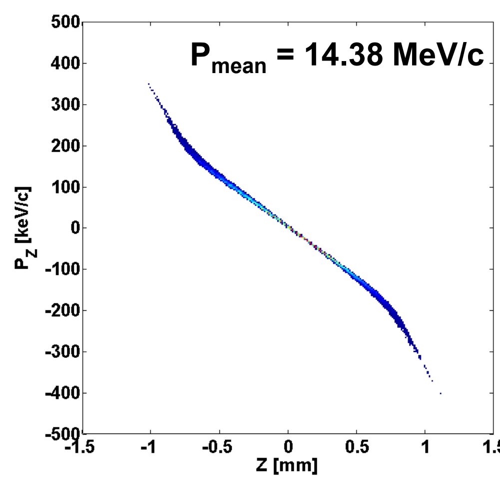
*With respect to the **M**aximum **M**ean **M**omentum **G**ain (**MMMG**) phase

Examples of Longitudinal Phase Space of the Output Beams with Imain = 330A

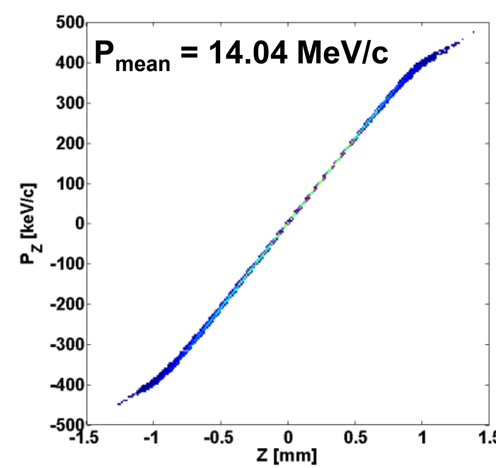
Boo.Phase = 0°



Boo.Phase = -60°

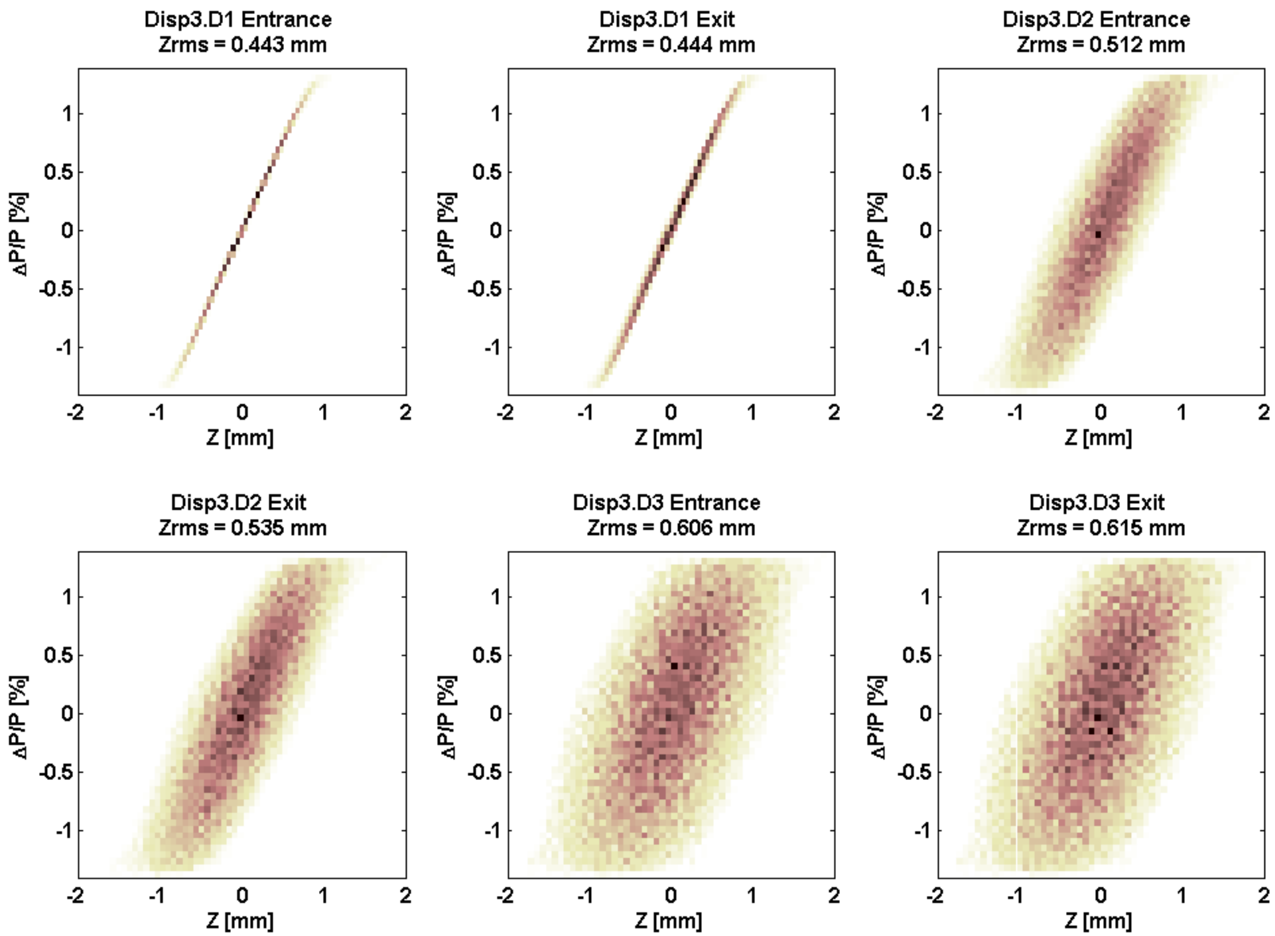


Boo.Phase = 60°



Calculation of Bunch Compression by HEDA2

- Energy-chirp with positive slope ($\Phi_{booster}$ = 30°), I_{main} = 330 A

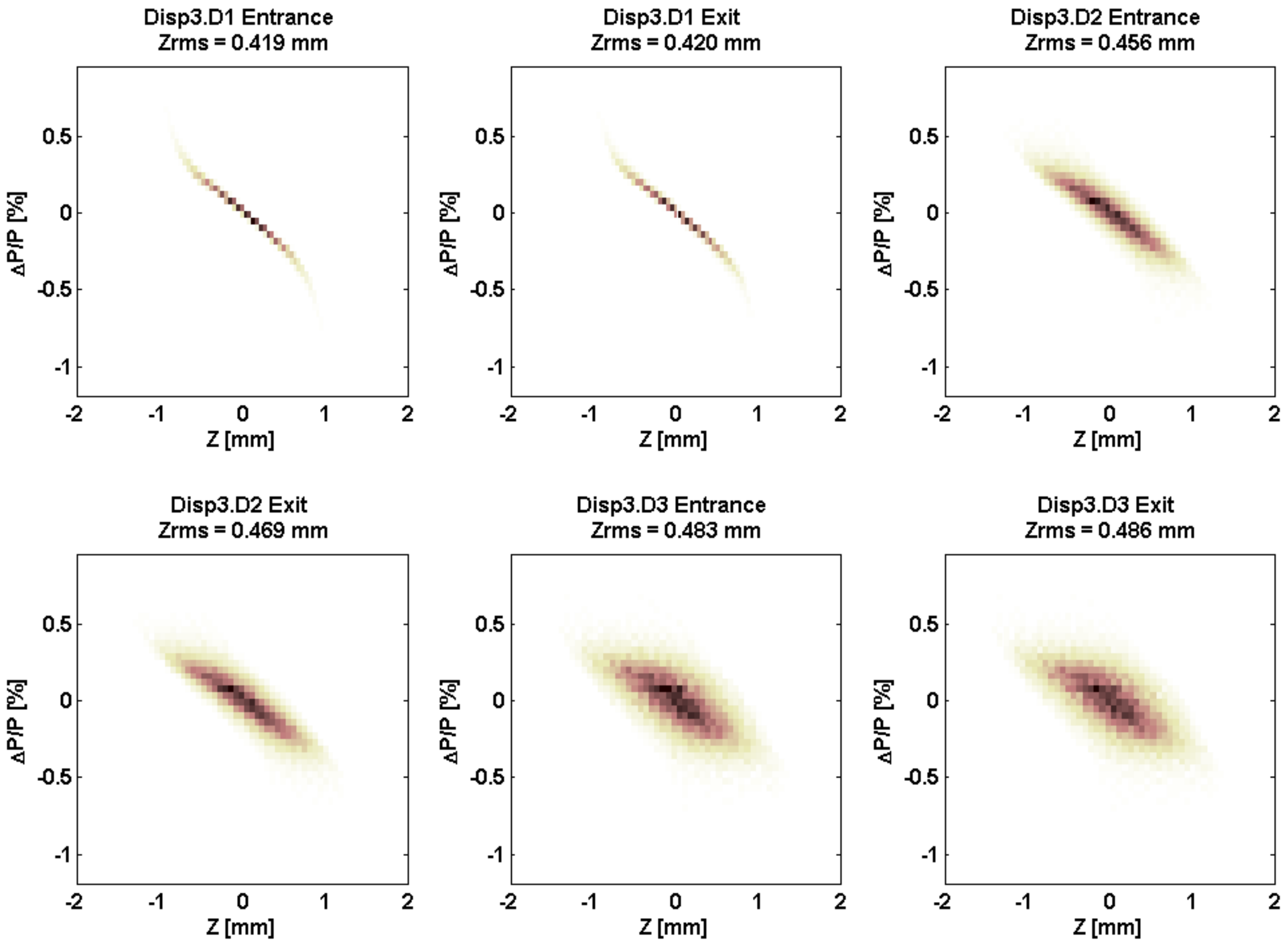


P_{mean} = 19.67 MeV/c

R56 = - 0.0232 m

Calculation of Bunch Compression by HEDA2

- Energy-chirp with negative slope ($\Phi_{booster}$ = -30°), I_{main} = 330 A

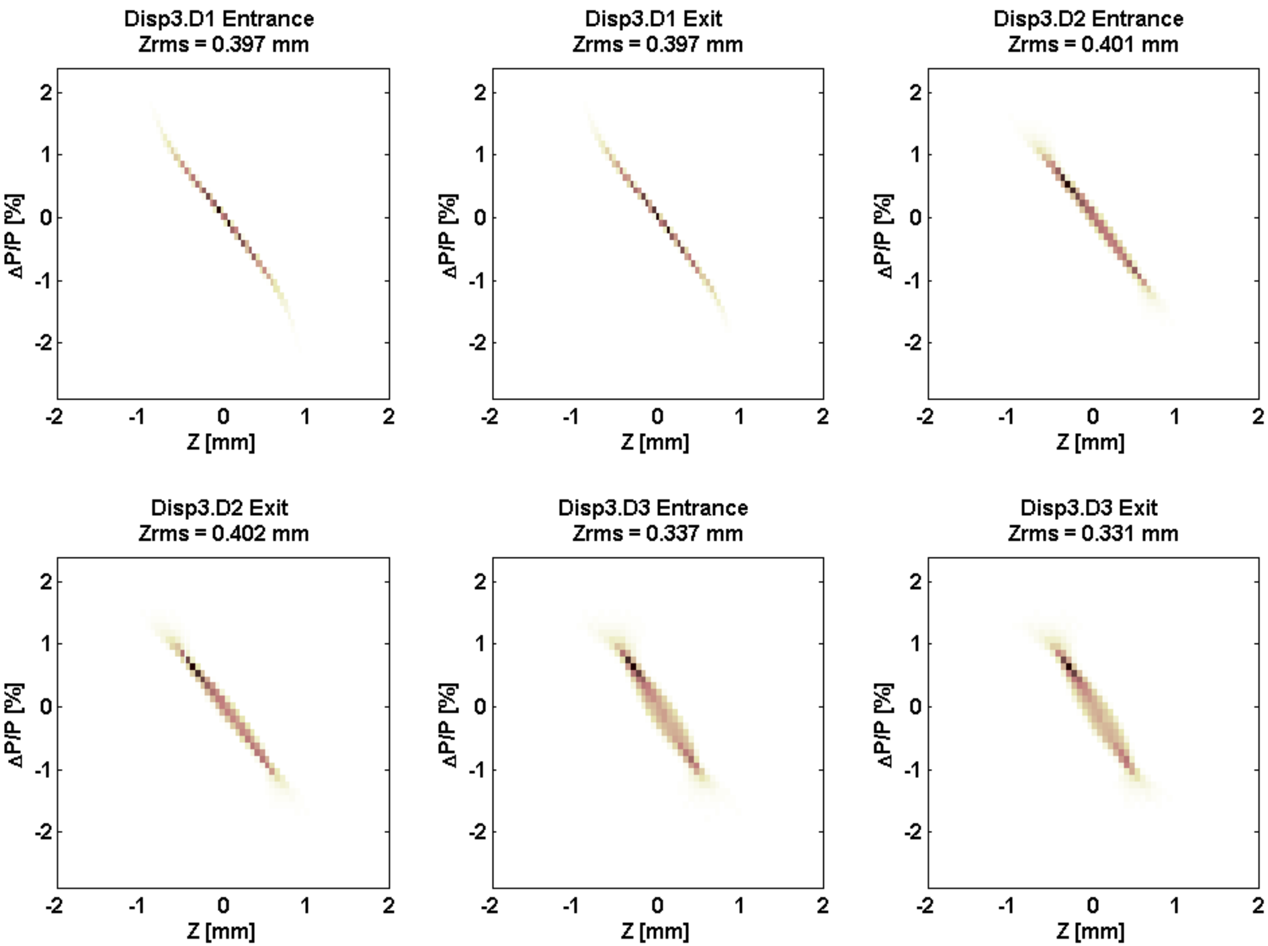


P_{mean} = 19.74 MeV/c

R56 = - 0.0232 m

Calculation of Bunch Compression by HEDA2

- Energy-chirp with negative slope ($\Phi_{booster}$ = -60°) , I_{main} = 330 A

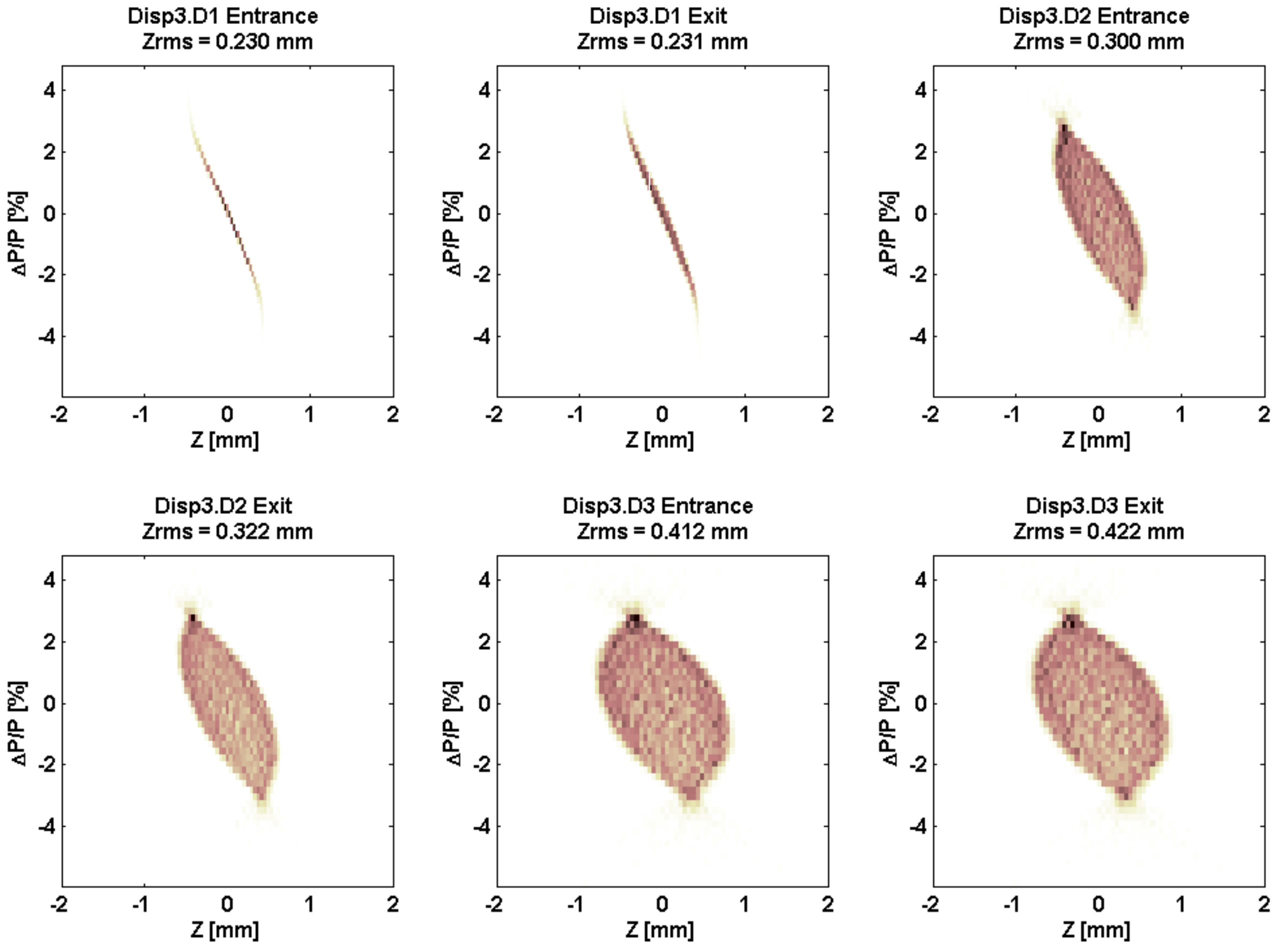


P_{mean} = 14.37 MeV/c

R56 = - 0.0213 m

Calculation of Bunch Compression by HEDA2

- Energy-chirp with negative slope ($\Phi_{booster}$ = -90°) , I_{main} = 330 A

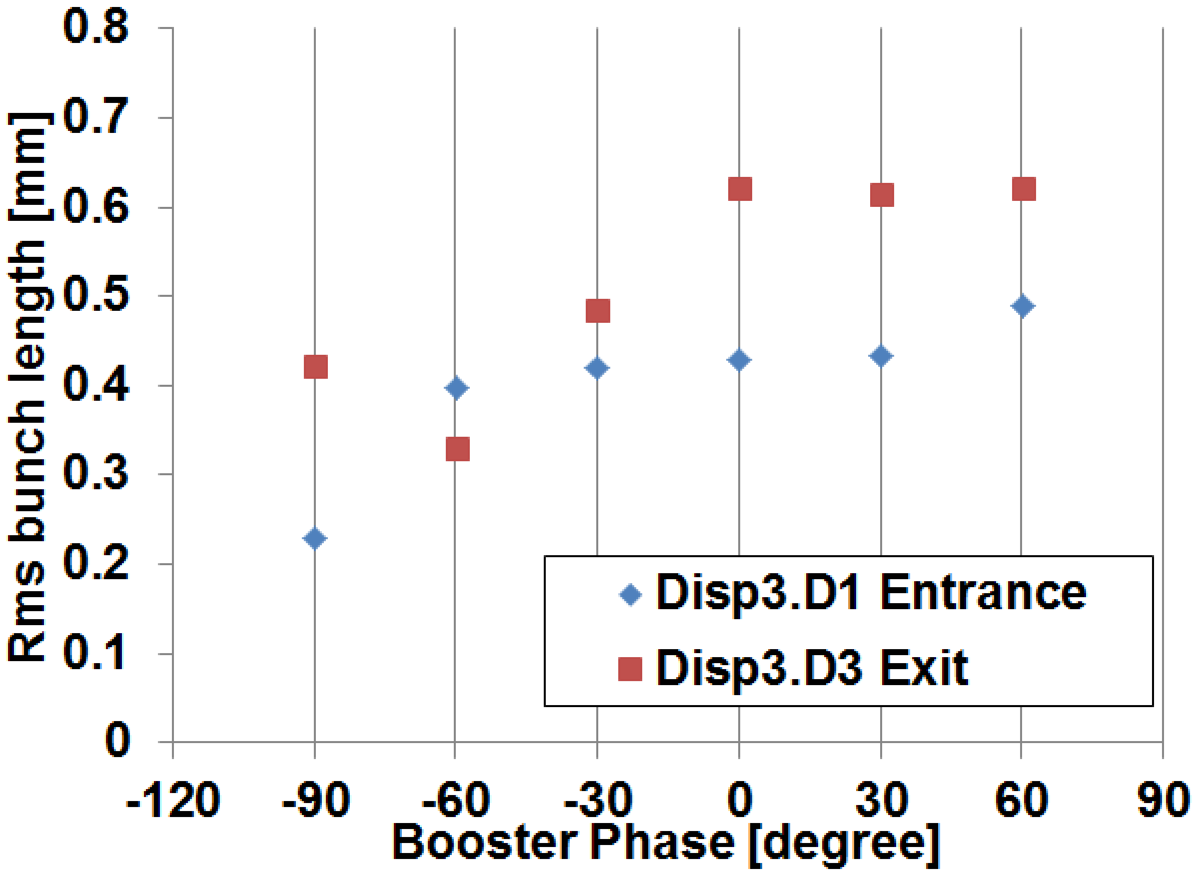


P_{mean} = 7.27 MeV/c

R56 = - 0.0103 m

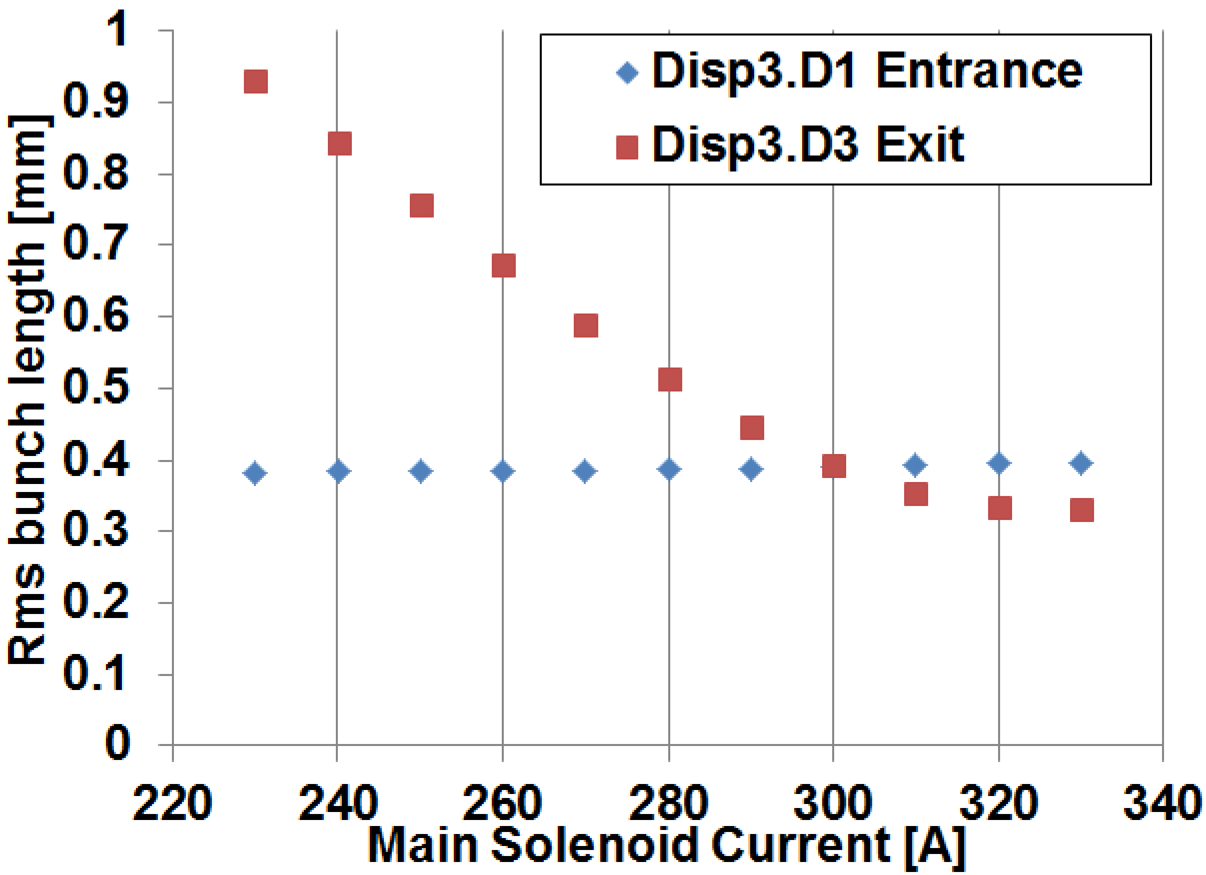
Calculation of Bunch Compression by HEDA2

► Summary Plot: bunch length VS booster phase



Calculation of Bunch Compression by HEDA2

- Summary Plot: bunch length VS main solenoid current



Summary

- Bunch compression by HEDA2 was calculated by using transportation matrices.
- Can we use HEDA2 as a bunch compressor?
  - Yes, we can! Some results show the compression but…
  - Beam size and booster phase should be optimized further.
  - Correction of the calculation script still has to be checked.

Outlook

- Check correction of the calculation script:
  - Different transformation matrices for HEDA2
  - Check with the Zeuthen Chicane
- Find the optimum transverse beam size and booster phase (investigation of the parameter space).
- More macro-particles for the initial beams
- HEDA2 transport simulations with ASTRA and CSRTrack
- S2E simulation, CTR Calculations
- Play with other bunch charges

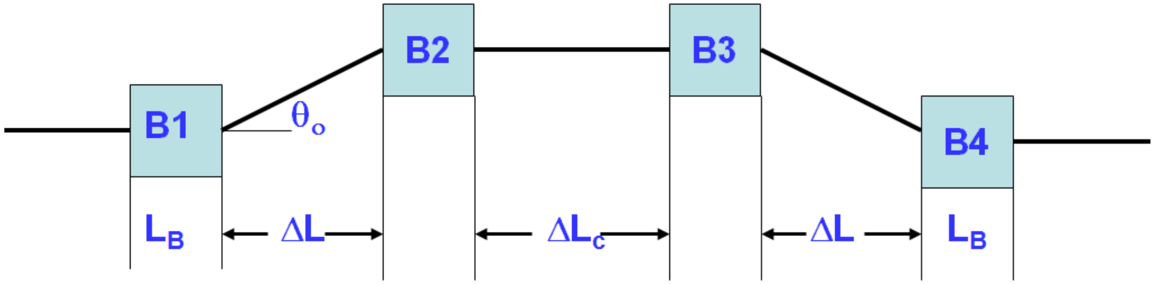
BACKUP

Zeuthen Chicane

Ref: Eun-San Kim, ILC Accelerator School lecture, May 20 2006

A simple case of 4-bending magnet chicane

- Zeuthen Chicane : a benchmark layout used for CSR calculation comparisons at 2002 ICFA beam dynamics workshop



- Bend magnet length : $L_B = 0.5$m
- Drift length B1-B2 and B3-B4(projected) : $\Delta L = 5$m
- Drift length B2-B3 : $\Delta L_c = 1$m
- Bend radius : $\rho = 10.3$m
- Effective total chicane length $(L_T - \Delta L_c) = 12$m
- Bending angle : $\theta_o = 2.77$ deg
- Momentum compaction : $R_{56} = -25$ mm
- 2^{nd} order momentum compaction : $T_{566} = 38$ mm
- Total projected length of chicane : $L_T = 13$ m

Bunch charge : q = 1nC
Electron energy : E = 5 GeV
Initial bunch length : 0.2 mm
Final bunch length : 0.02 mm

DESY

Matrix Transportation for Dipole Magnet and Drift Spaces

Ref: S.Rimjaem, "Optimization of HEDA2 Spectrometer Using Matrix Transportation", PITZ Note, 24.04.2009

1.3 Matrix Transportation for Dipole Magnet and Drift Spaces

Matrix transportation for the particle travels through the dipole magnet from the initial position (S_i) to the final position (S_f) as shown in Fig. 1 can be written as

$$M = M_{L_{out}} M_D M_{L_{in}}, \tag{14}$$

where $M_{L_{in}}$ and $M_{L_{out}}$ are the transport matrices for the drift spaces before and after the dipole magnet. The non-zero matrix elements in Eq. (14) are

$$\begin{aligned}
R_{11} &= \cos\alpha[1 + \tfrac{L_{out}}{\rho}(\tan\beta_{in} + \tan\beta_{out})] + \sin\alpha[\tan\beta_{in} + \tfrac{L_{out}}{\rho}(\tan\beta_{in}\tan\beta_{out} - 1)],\\
R_{12} &= L_{in}\tan\beta_{in}[1 + \tfrac{L_{out}\tan\beta_{out}}{\rho}] + \cos\alpha[L_{in} + L_{out} + \tfrac{L_{in}L_{out}}{\rho}(\tan\beta_{in} + \tan\beta_{out})] +\\
&\quad \sin[\alpha + L_{out}(\tan\beta_{out} - \tfrac{L_{in}}{\rho})],\\
R_{16} &= \rho(1 - \cos\alpha) + L_{out}[\sin\alpha + \tan\beta_{out}(1 - \cos\alpha)],\\
R_{21} &= \tfrac{\cos\alpha}{\rho}(\tan\beta_{in} + \tan\beta_{out}) + \tfrac{\sin\alpha}{\rho}(\tan\beta_{in}\tan\beta_{out} - 1),\\
R_{22} &= \cos\alpha[1 + \tfrac{L_{in}}{\rho}(\tan\beta_{in} + \tan\beta_{out})] + \sin\alpha[\tan\beta_{out}(1 + \tfrac{L_{in}\tan\beta_{in}}{\rho}) - \tfrac{L_{in}}{\rho}],\\
R_{26} &= \sin\alpha + \tan\beta_{out}(1 - \cos\alpha),\\
R_{33} &= 1 - \alpha\tan(\beta_{in} - \psi_{in}) + \tfrac{L_{out}}{\rho}[-\tan(\beta_{in} - \psi_{in}) - \tan(\beta_{out} - \psi_{out})] +\\
&\quad \tfrac{L_{out}\alpha}{\rho}\tan(\beta_{in} - \psi_{in})\tan(\beta_{out} - \psi_{out}),\\
R_{34} &= L_{in} + L_{out} + \rho[\alpha - L_{in}\tan(\beta_{in} - \psi_{in}) - L_{out}\tan(\beta_{out} - \psi_{out})] + \tfrac{L_{in}L_{out}}{\rho}\\
&\quad [-\tan(\beta_{in} - \psi_{in}) + \tan(\beta_{out} - \psi_{out}) + \alpha L_{out}\tan(\beta_{in} - \psi_{in})\tan(\beta_{out} - \psi_{out})],\\
R_{43} &= -\tfrac{\tan(\beta_{in} - \psi_{in})}{\rho} - \tfrac{\tan(\beta_{out} - \psi_{out})}{\rho} + \tfrac{\alpha\tan(\beta_{in} - \psi_{in})\tan(\beta_{out} - \psi_{out})}{\rho},\\
R_{44} &= 1 - \alpha\tan(\beta_{out} - \psi_{out}) + \tfrac{L_{in}}{\rho}[-\tan(\beta_{in} - \psi_{in}) - \tan(\beta_{out} - \psi_{out})] +\\
&\quad \tfrac{L_{in}\alpha}{\rho}\tan(\beta_{in} - \psi_{in})\tan(\beta_{out} - \psi_{out}),\\
R_{51} &= \sin\alpha + \tan\beta_{in}(1 - \cos\alpha),\\
R_{52} &= L_{in}[\sin\alpha + \tan\beta_{in}(1 - \cos\alpha)] + \rho(1 - \cos\alpha),\\
R_{55} &= 1,\\
R_{56} &= \tfrac{L_{in} + L_{out} + \rho\alpha}{\gamma^2} - \rho(\alpha - \sin\alpha),\\
R_{66} &= 1.
\end{aligned} \tag{15}$$

$$\ell(s) = R_{51}x(0) + R_{52}x'(0) + R_{55}\ell(0) + R_{56}(\Delta p/p_0)$$

DESY