XFEL distribution section: Model of magnetic elements for the kicked beams

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Update 1: 08.08.2022
Update 2: 09.08.2022
Update 3: 09.12.2022

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DESY, 18.07.2022

Update 1

- Definitions of first septa to SA2 and TLD dump are added.
  First septa to SA2 and TLD are tilted.

- Definitions of all others septa (not tilted) are also added.

Update 2

Definitions of element lengths are added

- LEN_KL
- LEN_KS
- LEN_QF_eff
- LEN_QK_eff
- LEN_BZ

Update 3

- Definitions of all needed elements with numbers to simplify the checking

General Remarks

1. In the extraction section, two beams (straight and kicked) pass through the same quadrupoles and see different magnetic fields:
   - straight beam only quadrupole component
   - kicked beam - quadrupole component and an additional dipole component

2. Nothing is different for both beams from the point of view of the setup of these quadrupoles (calibration, excitation current).

3. The only difference is the model of these quadrupoles for beam optics. The model for the kicked beam is created in the frame of the MAD8 code.

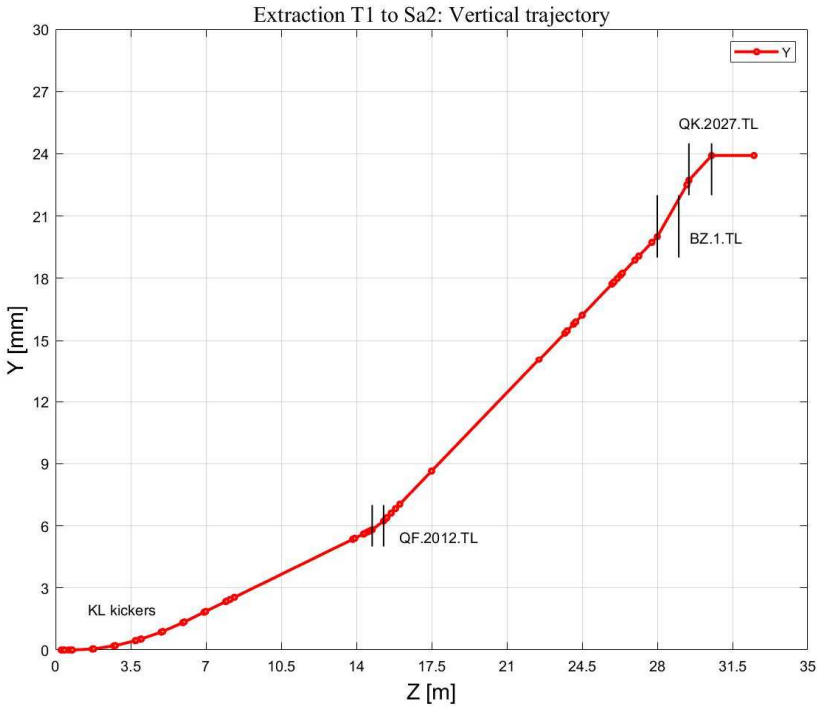
Important note

1. Kicked beam passes through the quadrupole off-axis, that creates an additional kick (dipole component)

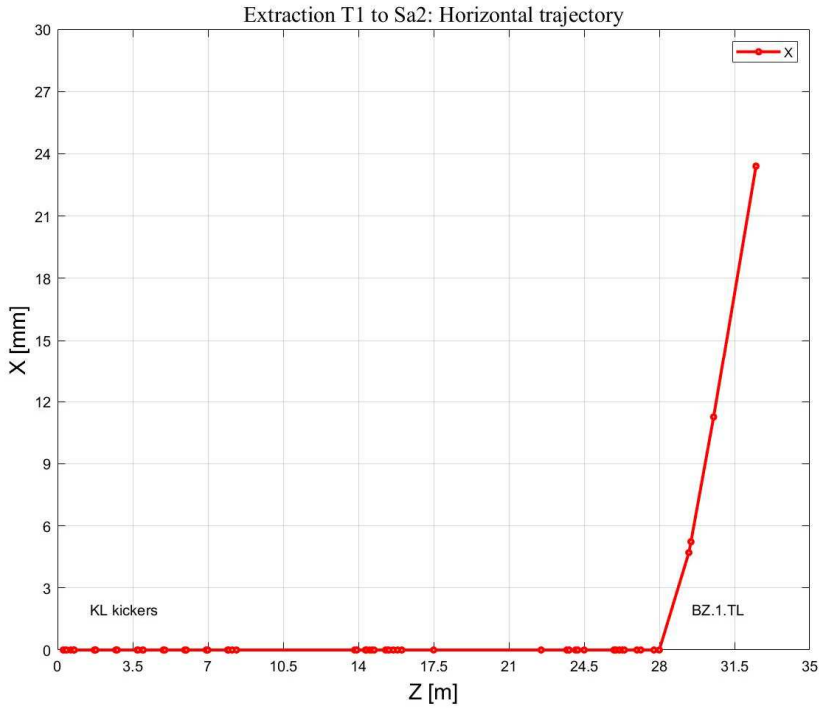
2. To generate this dipole component for quadrupoles, the trajectory of the kicked beam is calculated separately for the design optics and then used in the model of quadrupoles for the kicked beam.

3. If the design optics in the separation section is changed, a new trajectory of the kicked beam must be calculated and a new model for the quadrupoles must be created.

Extraction to SA2 in TL section: Trajectory



Kick in Y plane to positive Y
(kickers KL)



Deflection in X plane to positive X
(septum BZ.2025.T1)

Right hand coordinate system

Extraction to SA2: Elements with different models

Different description for the following elements:

- Kickers KL (5 kickers in the design used)
- Quadrupole QF.2012.TL (in the circuit QF.1.TL)
- First septum to SA2 BZ.2025.T1
- QK.2027.TL (in the circuit with QK.2057.TL)

Extraction to SA2: KL kicker setup

KL kickers

- Vertical dipole magnets, RBEND type (change the reference orbit)
- 5 kickers: KL.1998.TL, KL.1999.Tl, KL.2000.TL, KL.2001.TL, KL.2002.TL
- KL.2003.TL - not used in the design optics

LEN_KL = 0.93;

T4D line: KL.1.TL: Rbend, L = LEN_KL, ANGLE = 0, TILT = pi/2; or DRIFT
KL.2.TL: Rbend, L = LEN_KL, ANGLE = 0, TILT = pi/2; or DRIFT

T5D line: KL.1.TL: Rbend, L = LEN_KL, ANGLE = -1.019145219189237e-04, TILT = pi/2;
KL.2.TL: Rbend, L = LEN_KL, ANGLE = 0, TILT = pi/2;

Extraction to SA2: QF.2012.TL (QF.1.TL) setup

QF.2012.TL:
- Quadrupole in T4D line
- Combine function magnet in T5D line (quadrupole and vertical dipole components)

L_QF_eff = 0.5321;

T4D line: QF.1.TL: Quadrupole, L = L_QF_eff, K1 = +0.17919084758504; sign (+) focusing in X plane

Trajectory of kicked beam at the entrance and exit of quadrupole (from MAD8):
E1_QF1_T1 = +1.444493782E-04;
E2_QF1_T1 = +7.159698661E-04;
ANG_QF1_T1 = -(E2_QF1_T1 - E1_QF1_T1); % -5.715204879e-04 rad

T5D line: QF.1.T1.TL: SBEND, L = L_QF_eff, ANGLE = ANG_QF1_T1, sign (-) for deflection to positive Y
E1 = E1_QF1_T1, E2 = E2_QF1_T1,
K1 = -0.17919084758504, sign (-) because V-dipole
TILT = pi/2;

Or with numbers:
T5D line: QF.1.T1.TL: SBEND, L = 0.5321, ANGLE = -5.715204879e-04,
E1 = +1.444493782E-04 , E2 = +7.159698661E-04,
K1 = -0.17919084758504,
TILT = pi/2;

Extraction to SA2: First septum BZ.2025.T1 (BZ.1.T1)

First septum **BZ.2025.T1** to SA2, deflection in horizontal plane:

- T4D: Drift
- T5D: Horizontal dipole, tilted

Remark:
For the simplicity 3 untilted BZ septa are defined with equal entrance E1 and exit E2 angles (RBEND type installation).

T4D line: BZ.0.TL: Rbend, L = LEN_BZ, ANGLE = 0; or DRIFT

T5D line: (MAD8 definition)

```
LEN_BZ  = 1.0;
CUR_BZ_T1   = -0.0055;
ANG_BZ_T1   = asin(LEN_BZ*CUR_BZ_TD1);
ARC_BZ_T1   = ANG_BZ_T1 / CUR_BZ_T1;
E12_BZ_T1   = 0.5 * ANG_BZ_T1;
TILT_BZ1_T1 = +(12.216344266902098 / 180.0) * pi;

!--- First (tilted) septum
BZ.1.T1:  Sbend, L  =  ARC_BZ_T1,  ANGLE = ANG_BZ_T1,
                       E1 = 0.0,  E2 = ANG_BZ_T1,
                       TILT = TILT_BZ1_T1;
!--- Three (untilted) septa
BZ.2.T1:  Sbend, L  = ARC_BZ_T1,  ANGLE = ANG_BZ_T1,
                       E1 = E12_BZ_T1, E2 = E12_BZ_T1;
```

Or with numbers:

```
!--- First (tilted) septum, BZ.2025.T1
BZ.1.T1:  Sbend, L  = 1.000005041735297,  ANGLE = -0.005500027729544,
                       E1 = 0.0,  E2 = -0.005500027729544,
                       TILT = 0.213215430014575;

!--- Three (untilted) septa, BZ.2030.T1, BZ.2031.T1, BZ.2033.T1
BZ.2.T1:  Sbend, L  = 1.000005041735297,  ANGLE = -0.005500027729544,
                       E1 = -0.002750013864772,  E2 = -0.002750013864772;
```

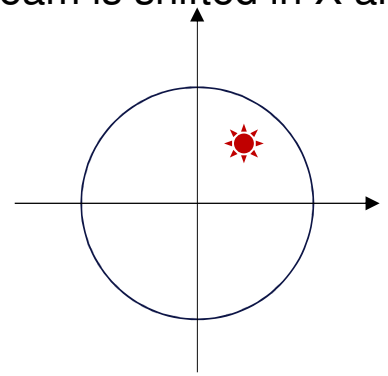
Extraction to SA2: QK.2027.TL (QK.2.TL) setup (1)

QK.2027.TL:
- Quadrupole in T4D line
- Exception in T5D line
  (quadrupole, horizontal and vertical dipole components)
- Splitted in N pieces: Sequence of horizontal and vertical combine function magnets

L_QK_eff = 1.0552;

T4D line: QK.2.TL: Quadrupole, L = 1.0552, K1 = -0.090359600075815;

T5D line: Beam is shifted in X and Y planes at the entrance of QK.2027.TL quadrupole



QK.2.T1.TL is splitted in N slices: 10 hor and 190 ver

```
z2_slice = 200;                 % total number of slices
x2_slice = 10;                  % number of X-slices, for angle
y2_slice = z2_slice - x2_slice; % number of Y-slices, for angle
```

See nest page

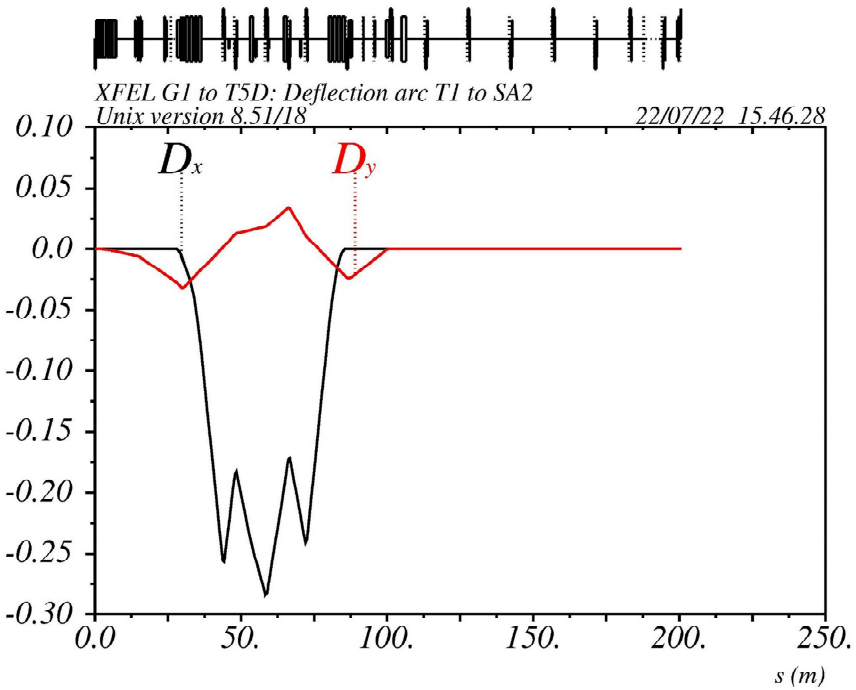
Extraction to SA2: QK.2027.TL (QK.2.TL) setup (2)

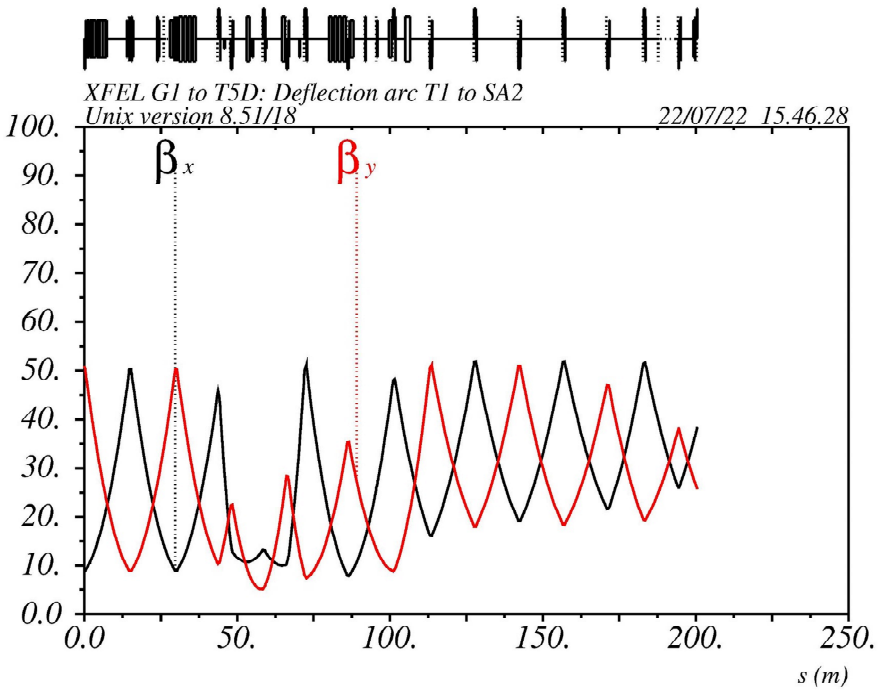
QK.2027.TL

```
%--- Horizontal trajectory at entrance and exit of QK.2.T1.TL (from MAD8)
E1_X_QK2_T1 = +5.375491030E-03;
E2_X_QK2_T1 = +6.154668757E-03;
ANG_X_QK2_T1 = -(E2_X_QK2_T1 - E1_X_QK2_T1)*1.00002;    % -7.791933105545398e-04

xQK.2.T1.TL: SBEND, L = L_QK_eff/z2_slice, ANGLE = ANG_X_QK2_T1/x2_slice,
                    E1 = 0, E2 = 0,
                    K1 = -0.090359600075815;

%--- Vertical trajectory at entrance and exit of QK.2.T1.TL (from MAD8)
E1_Y_QK2_T1 = +1.879779622E-03;
E2_Y_QK2_T1 = -3.651167252E-04;
ANG_Y_QK2_T1 = -(E2_Y_QK2_T1 - E1_Y_QK2_T1)*0.9999975;    % +0.002244890734959

yQK.2.T1.TL:  SBEND, L = L_QK_eff/z2_slice, ANGLE = ANG_Y_QK2_T1/y2_slice,
                   E1 = 0, E2 = 0,
                   K1 = +0.090359600075815,
                   TILT = pi/2;

QK2.T1_slice10: Line = (19 * yQK.2.T1.TL, 1 * xQK.2.T1.TL);
QK.2.T1.TL:  Line = (10 * QK2.T1_slice10);
```

```
xQK.2.T1.TL: SBEND, L = 0.005276, ANGLE = -7.791933105545399e-05,
                    E1 = 0, E2 = 0,
                    K1 = -0.090359600075815;

yQK.2.T1.TL:  SBEND, L = 0.005276, ANGLE = + 1.181521439452105e-05,
                   E1 = 0, E2 = 0,
                   K1 = +0.090359600075815,
                   TILT = pi/2;
```

Extraction to Sa2: Dispersion and Betatron Functions



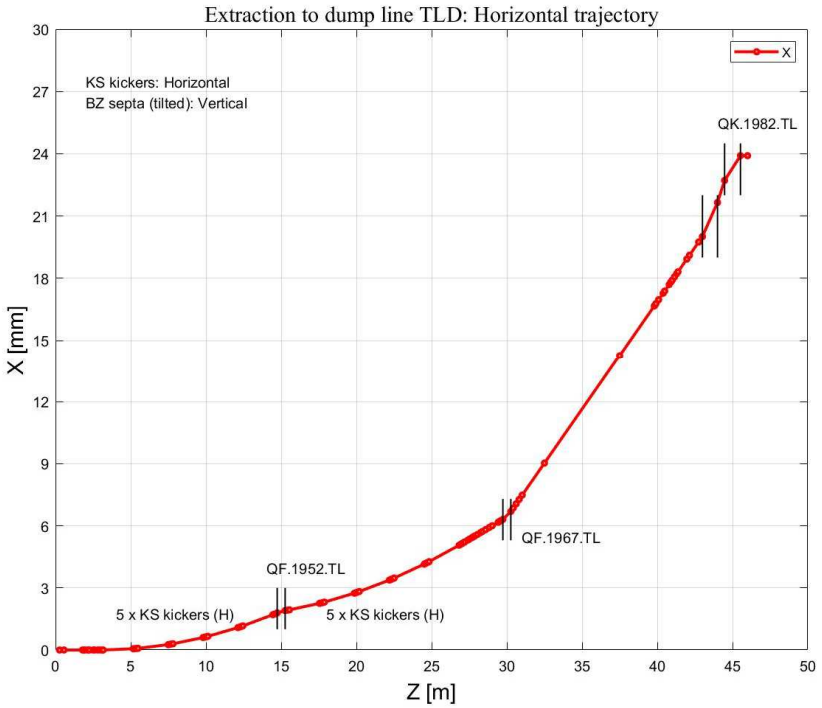


Both dispersions are closed in the end of arc

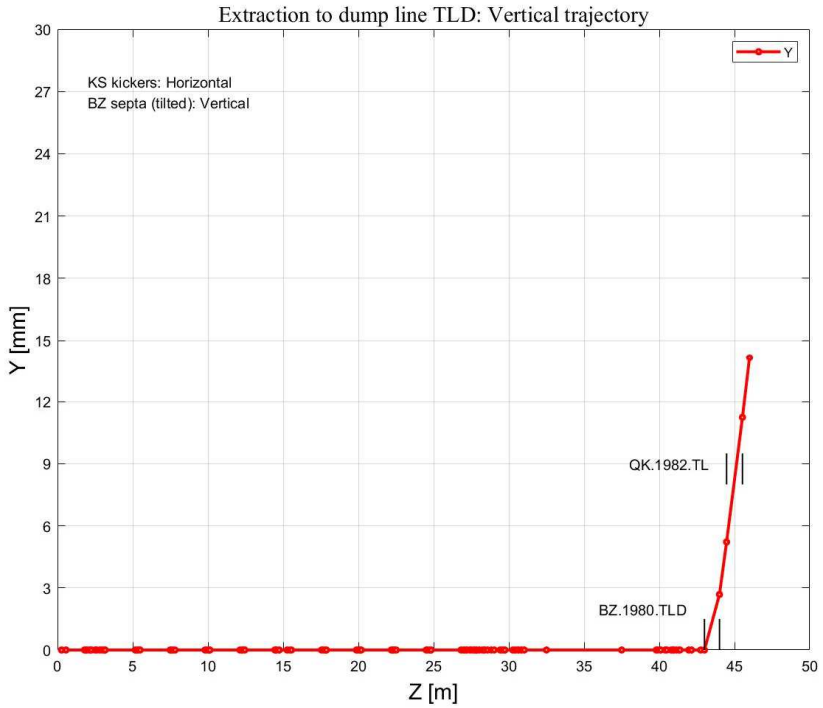
Extraction to TLD

- Kick in horizontal plane (KS kickers)
- Deflection by septa in vertical plane (vice versa with respect to SA2)
- KS kickers are placed around quadrupole (KL after quadrupole for deflection to SA2) that brings one more quadrupole which the kicked beam passes off axis

Extraction to TLD: Trajectory



Kick in X plane to positive X
(kickers KS)



Deflection in Y plane to positive Y
(septum BZ.1.TLD)

Right hand coordinate system

Extraction to TLD dump: Magnets with other model

Different models for the following elements:

- Kickers KS (10 kickers)
- Quadrupole QF.1952.TL (in the circuit QF.1.TL) between KS kickers
- Quadrupole QF.1967.TL (in the circuit QF.2.TL) after KS kickers
- First septum to TLD: BZ.1980.TLD
- Quadrupole QK.1982.TL (QK.1.TL) after first septum

Extraction to TLD: KS kicker setup

KS kickers (all 10 kickers)

- Horizontal dipole magnets, RBEND type

LEN_KS = 2.0;

KS.1.TL: MARKER;

T4D line: KSPOS.1.TL: Rbend, L = LEN_KS/2, ANGLE = 0;
KSNEG.1.TL: Rbend, L = LEN_KS/2, ANGLE = 0;

Kick_KS: Line = (D0100, KSPOS.1.TL, KS.1.TL, KSNEG.1.TL, D0100); % L = 2.2 m

TLD line: KSPOS.1.TL: Rbend, L = LEN_KS/2, ANGLE = -3.025448745461549e-05;
KSNEG.1.TL: Rbend, L = LEN_KS/2, ANGLE = -3.025448745461549e-05;

Kick_KS: Line = (D0100, KSPOS.1.TL, KS.1.TL, KSNEG.1.TL, D0100); % L = 2.2 m

Extraction to TLD: QF.1952.TL (QF.1.TL) setup

QF.1952.TL:
- Quadrupole in T4D line (between KS kickers)
- Combine function magnet in TLD line (quadrupole and horizontal dipole components)

L_QF_eff = 0.5321;

T4D line: QF.1.TL: Quadrupole, L = L_QF_eff, K1 = +0.17919084758504;

% Trajectory at the entrance and exit of quadrupole (from MAD8)
E1_QF1_TLD = +3.025448949E-04;
E2_QF1_TLD = +1.253694976E-04;
ang_QF1_TLD = -(E2_QF1_TLD - E1_QF1_TLD); % +1.771753973e-04 rad

TLD line: QF.1.TLD.TL: SBEND, L = L_QF_eff, ANGLE = ang_QF1_TLD,
E1 = E1_QF1_TLD, E2 = E2_QF1_TLD,
K1 = +0.17919084758504;

Or with number:
TLD line: QF.1.TLD.TL: SBEND, L = 0.5321, ANGLE = +1.771753973e-04, (QF.1952.TL)
E1 = +3.025448949E-04, E2 = +1.253694976E-04,
K1 = +0.17919084758504;

Extraction to TLD: QF.1967.TL (QF.2.TL) setup

QF.1967.TL:
- Quadrupole in T4D line (after KS kickers)
- Combine function magnet in TLD line (quadrupole and horizontal dipole components)

L_QF_eff = 0.5321;

T4D line: QF.2.TL: Quadrupole, L = L_QF_eff, K1 = -0.17919084758504;

% Trajectory at the entrance and exit of quadrupole QF.1967.TL (from MAD8)
E1_QF2_TLD = +4.279143925E-04;
E2_QF2_TLD = +1.044797476E-03;
ang_QF2_TLD = -(E2_QF2_TLD - E1_QF2_TLD); % -6.168830834999999e-04 rad

TLD line: QF.2.TLD.TL: SBEND, L = L_QF_eff, ANGLE = ang_QF2_TLD,
E1 = E1_QF2_TLD, E2 = E2_QF2_TLD,
K1 = -0.17919084758504;

Or with numbers:
TLD line: QF.2.TLD.TL: SBEND, L = 0.5321, ANGLE = -6.168830834999999e-04, (QF.1967.TL)
E1 = +4.279143925E-04, E2 = +1.044797476E-03,
K1 = -0.17919084758504;

Extraction to TLD: BZ.1980.TLD (BZ.1.TLD) septum

First septum **BZ.1980.TLD** to TLD, deflection in vertical plane:

- T4D: Drift
- TLD: Vertical dipole, tilted

Remark:
For the simplicity 3 BZ septa are defined with equal entrance E1 and exit E2 angles (RBEND type installation).

T4D line: BZ.0.TL: Rbend, L = LEN_BZ, ANGLE = 0; or DRIFT

TLD line (MAD8 definitions)

```
LEN_BZ  = 1.0;
CUR_TLD1  = -0.0055;
ANG_TLD1  = asin(LEN_BZ * CUR_TLD1);
ARC_TLD1  =  ANG_TLD1 / CUR_TLD1;
E12_TLD1  =  0.5*ANG_TLD1;
TILT_TLD1 = -(12.5823302221 / 180.0) * pi;

!--- First (tilted) septum
BZ.1.TLD:  Sbend, L = ARC_TLD1,  ANGLE = ANG_TLD1,
                  E1 = 0.0, E2 = ANG_TLD1,
                  TILT = +1.570796326794897 + TILT_TLD1;
!--- Three (untilted)  septa
BZ.2.TLD: Sbend, L = ARC_TLD1,  ANGLE = ANG_TLD1,
                 E1 = E12_TLD1, E2 = E12_TLD1,
                 TILT = +1.570796326794897;
```

Or with numbers;

```
!--- First (tilted) septum,  BZ.1980.TLD
BZ.1.TLD:  Sbend, L = 1.000005041735297,  ANGLE = -0.005500027729544,
                  E1 = 0.0, E2 = -0.005500027729544,
                  TILT = +1.351193236846063;

!--- Three (untilted)  septa, BZ.1983.TLD, BZ.1985.TLD, BZ.1986.TLD
BZ.2.TLD: Sbend, L = 1.000005041735297,  ANGLE = -0.005500027729544,
                 E1 = -0.002750013864772, E2 = -0.002750013864772,
                 TILT = +1.570796326794897;
```

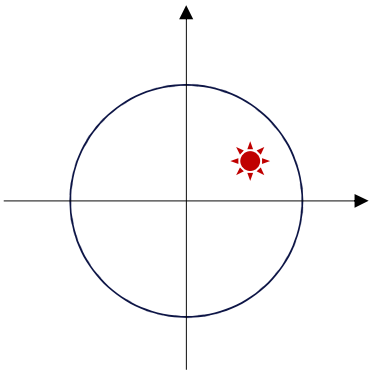
Extraction to TLD: QK.1982.TL (QK.1.TL) setup (1)

QK.1982.TL:
- Quadrupole in T4D line
- Exception in TLD line
  (quadrupole, horizontal and vertical dipole components)
- Splitted in N pieces: Sequence of horizontal and vertical combine function magnets

L_QK_eff = 1.0552;

T4D line: QK.1.TL: Quadrupole, L = L_QK_eff, K1 = +0.090359600075815;

T5D line: Beam is shifted in X and Y planes at the entrance of QK.1982.TL quadrupole



QK.1.TLD.TL is splitted in N slices: 190 hor and 10 ver

```
z1_slice = 200;                 % total number of slices
x1_slice = 190;                 % number of X-slices, for angle
y1_slice = z1_slice – x1_slice; % number of Y-slices, for angle
```

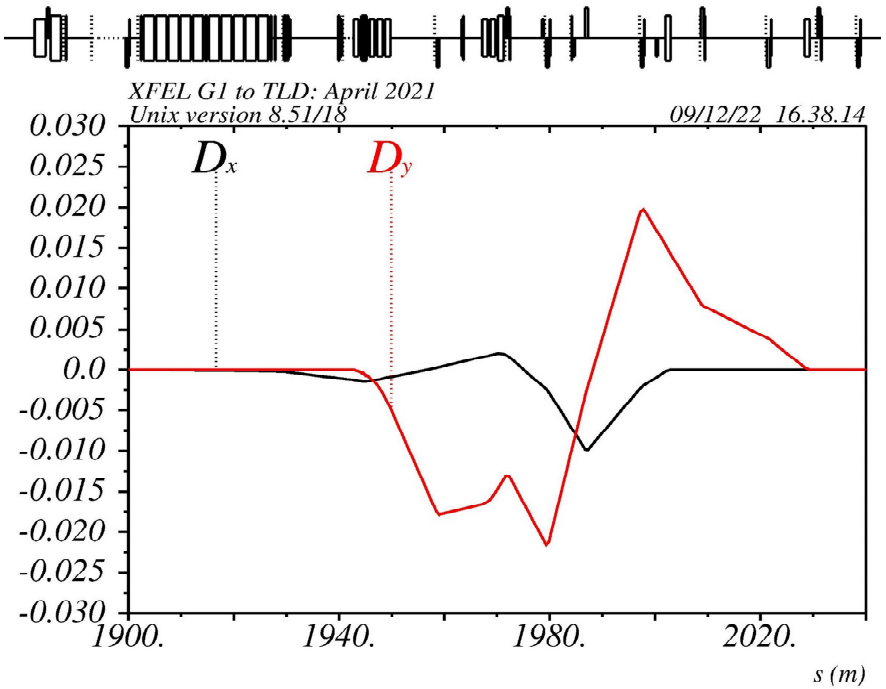
Extraction to TLD: QK.1982.TL (QK.1.TL) setup (2)

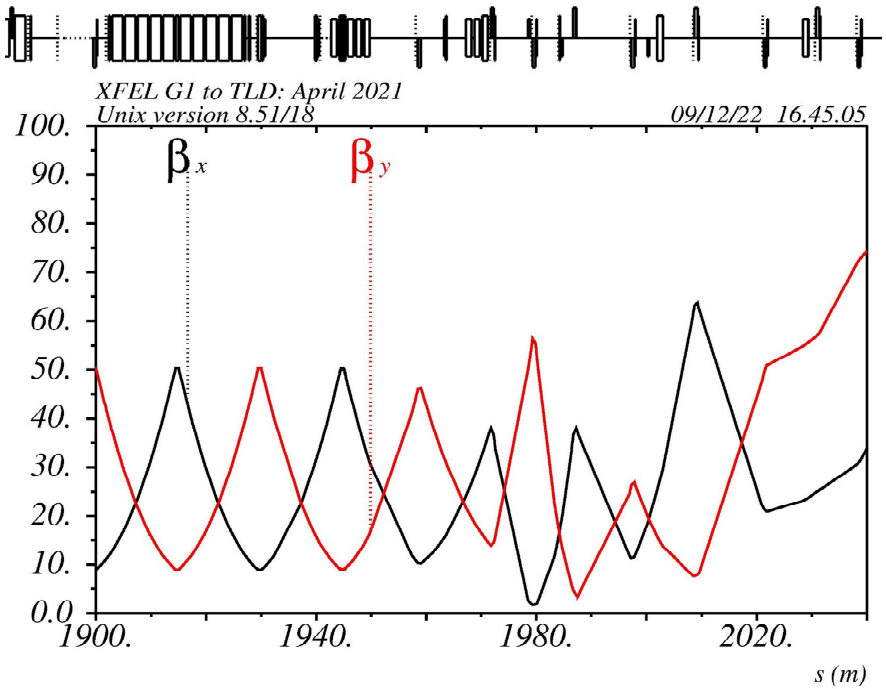
QK.1982.TL

```
%--- Horizontal trajectory at entrance and exit of QK.1.TLD.TL (from MAD8)
xE1_QK1_TLD = +2.242943152E-03;
xE2_QK1_TLD = -5.119037480E-10;   % must be zero
angX_QK1_TLD = -(xE2_QK1_TLD - xE1_QK1_TLD)*0.999984;

xQK.1.TL: SBEND, L = L_QK_eff/z1_slice, ANGLE = angX_QK1_TLD/x1_slice,
          E1 = 0, E2 = 0,
          K1 = +0.090359600075815;

%--- Vertical trajectory at entrance and exit of QK.1.TLD.TL (from MAD8)
yE1_QK1_TLD = +5.002815411E-03;
yE2_QK1_TLD = +5.780895902E-03;
angY_QK1_TLD = -(yE2_QK1_TLD - yE1_QK1_TLD);

yQK.1.TL:  SBEND, L = L_QK_eff/z1_slice, ANGLE = angY_QK1_TLD/y1_slice,
           E1 = 0, E2 = 0,
           K1 = -0.090359600075815,
           TILT = pi/2;

QK.1.TLD_slice10: Line = (19 * xQK.1.TL, 1 * yQK.1.TL);
QK.1.TLD.TL:  Line = (10 * QK1.TLD_slice10);
```

```
xQK.1.TL:  SBEND, L = 0.005276, ANGLE = +1.180477777265855e-05,
           E1 = 0, E2 = 0,
           K1 = +0.090359600075815;

yQK.1.TL:  SBEND, L = 0.005276, ANGLE = -7.780804909999998e-05,
           E1 = 0, E2 = 0,
           K1 = -0.090359600075815,
           TILT = pi/2;
```

Extraction to TLD: Dispersion and Betatron Functions

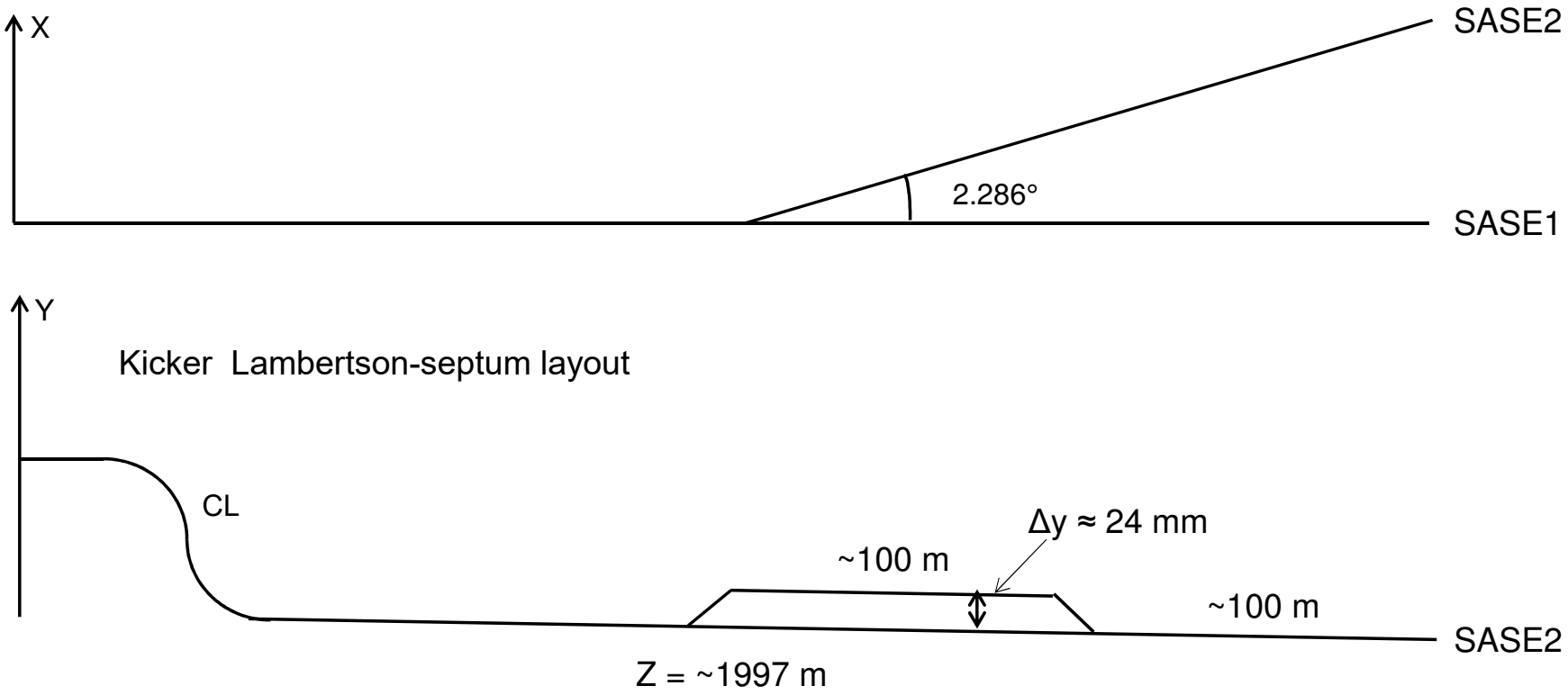




Both dispersions are closed in the end of arc

Additional slides

Extraction to SASE2: Geometry



Top view

Side view

Design of Deflection Section: Specifications, requirements

- Kicker-Lambertson-septum layout
  - different bending planes by kickers and septa
  - horizontal and vertical dispersions Dx and Dy
- Extraction to Sa2 - from FODO lattice in the straight line TL
  - constraints on possible location of kickers and septa
  - Twiss functions at the entrance of deflection section are fixed (no matching section in the front)
- Accept bunches with different energies (up to ±1.5% from nominal energy)
- First-order achromatic beamline (R16, R26, R36, R46 = 0 in the transfer matrix)
- First-order isochronous beamline (R56 = 0 in the transfer matrix)
- The need to avoid collisions of magnets from different beamlines

Deflection section to SASE2: Two parts

Extraction elements (kickers, first septum) are located in the straight line TL leading to SASE1

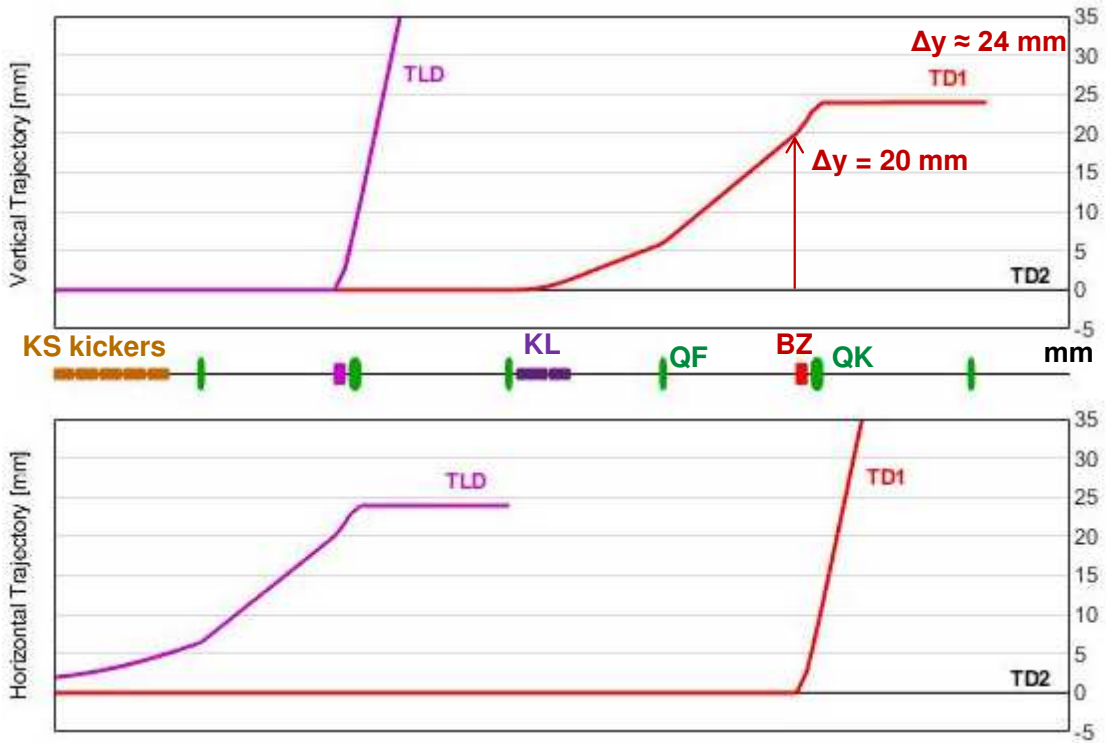
- Part 1: Part of TL beamline with KL kickers and first BZ septum
  - the beam to Sa1 is going straight in this section
  - the beam to Sa2 is off-axis

These is a shift of the beam in the kicker bending plane (vertical),
which is taken into account in the geometrical layout
of the downstream beamline.

- Part 2: Deflection arc T1 for the beam to Sa2
  - start is at the entrance of second septum
  - the beam to SA2 is on-axis in this section
  - in the end of the arc the beam is brought back to the horizontal plane Y=0

First part (Part 1): Trajectory

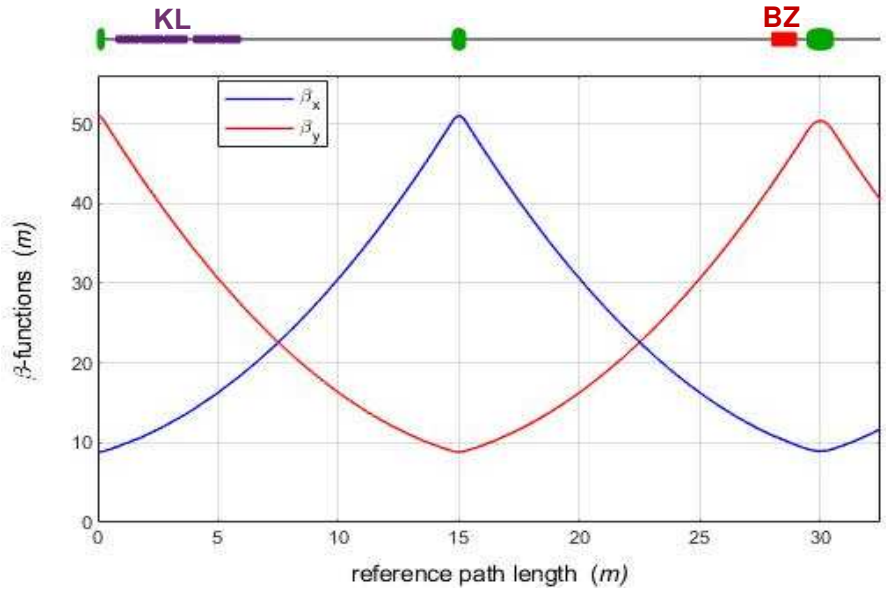
Part 1: Joint line for two beams (Sa1 and Sa2).



Beam to Sa2 is off-axis in this section

Kick in vertical plane (KL kickers),
≈0.51 mrad kick angle
Additional kick from QF quadrupole
At the entrance of first BZ (H) septum:
20 mm vertical separation
First BZ (H) septum is tilted by ~12°
(slight bend also in Y-plane)
First septum BZ (H) and downstream
QK quadrupole remove the beam slope

Part 1: Optics



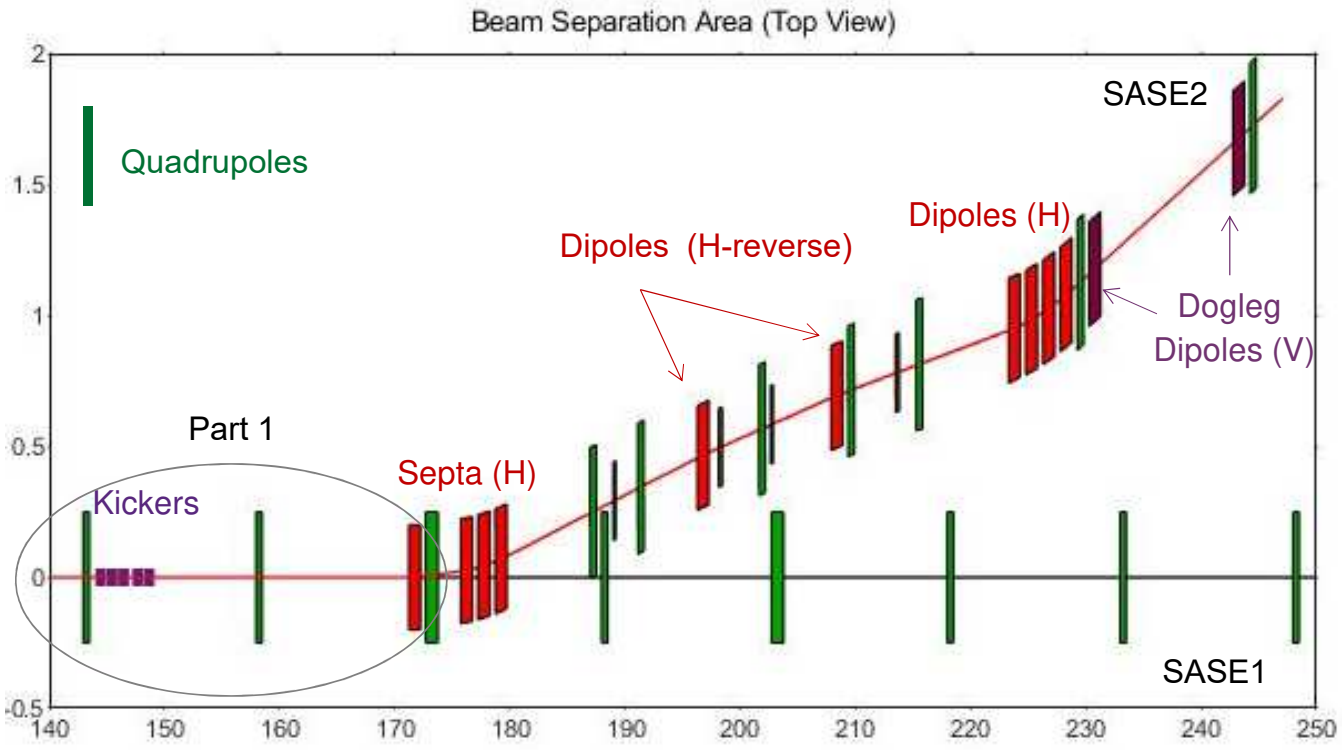
Twiss functions: Periodic solution of FODO lattice in TL section

Dispersions:

- in vertical plane starts from KL kickers, at the exit Dy ≈ -0.0265 m
- in horizontal plane is generated by BZ (H) septum, at the exit Dx ≈ -0.025 m
- R56 ≈ +22.7 μm

Second part (Part 2): Magnet Lattice

Part 2: Start at the entrance of second BZ septum – Deflection arc T1



X-plane: 2.286º (total) deflection

- 4 BZ septa (1st septum is tilted)
- 4 dipoles (H)
- 2 dipoles (H-reverse), for R56

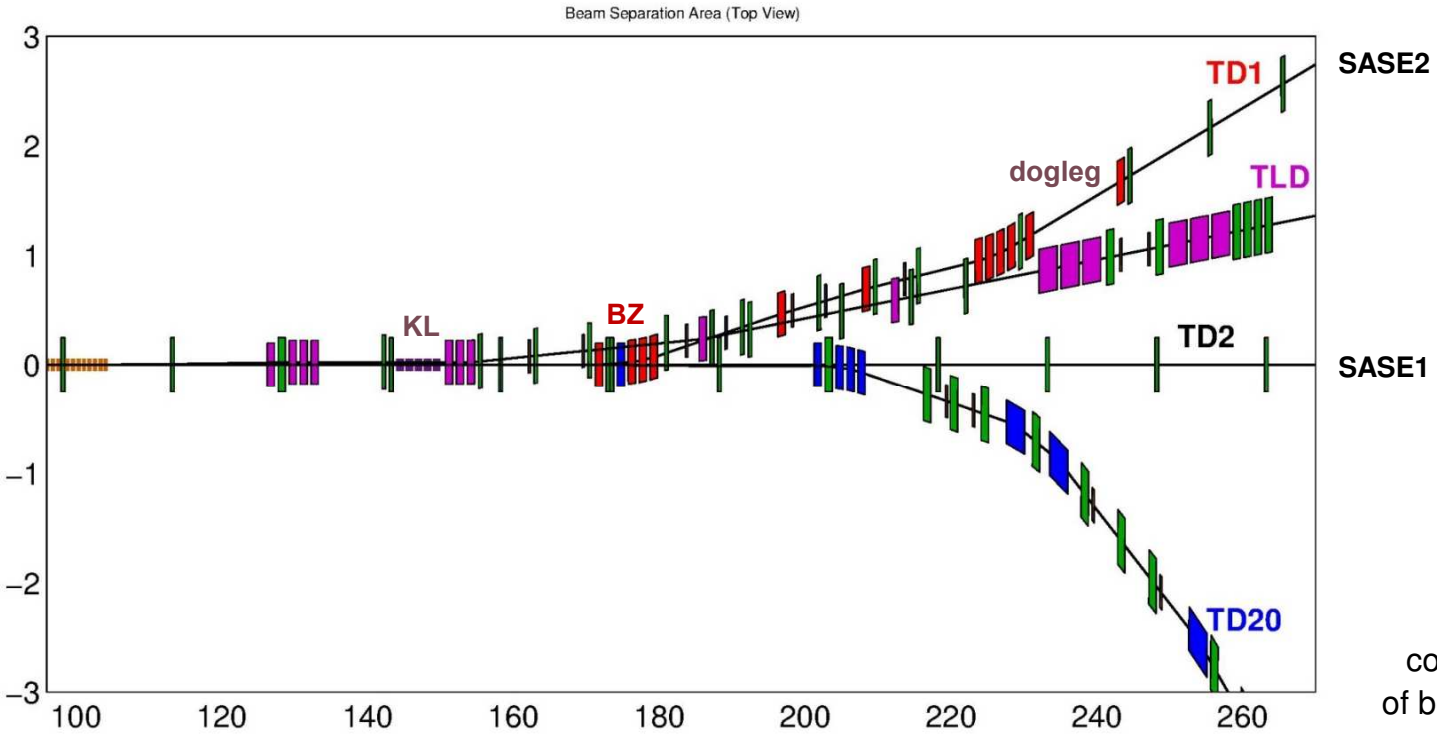
Y-plane: Dogleg in the end

- close the linear vertical dispersion
- bring the beam back to the horizontal plane y = 0
- no quads between dipoles

Multipoles for correction of chromatic aberrations

Quadrupoles (6)

Separation area (Top view)



Red, magenta and blue colors mark septa and dipoles of beamlines to Sa2, TLD, TD20

Third beamline TD20 for the future upgrade has been also considered during the design of the separation area.