New Damping Ring at 2.86 GeV

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WP4 Team update

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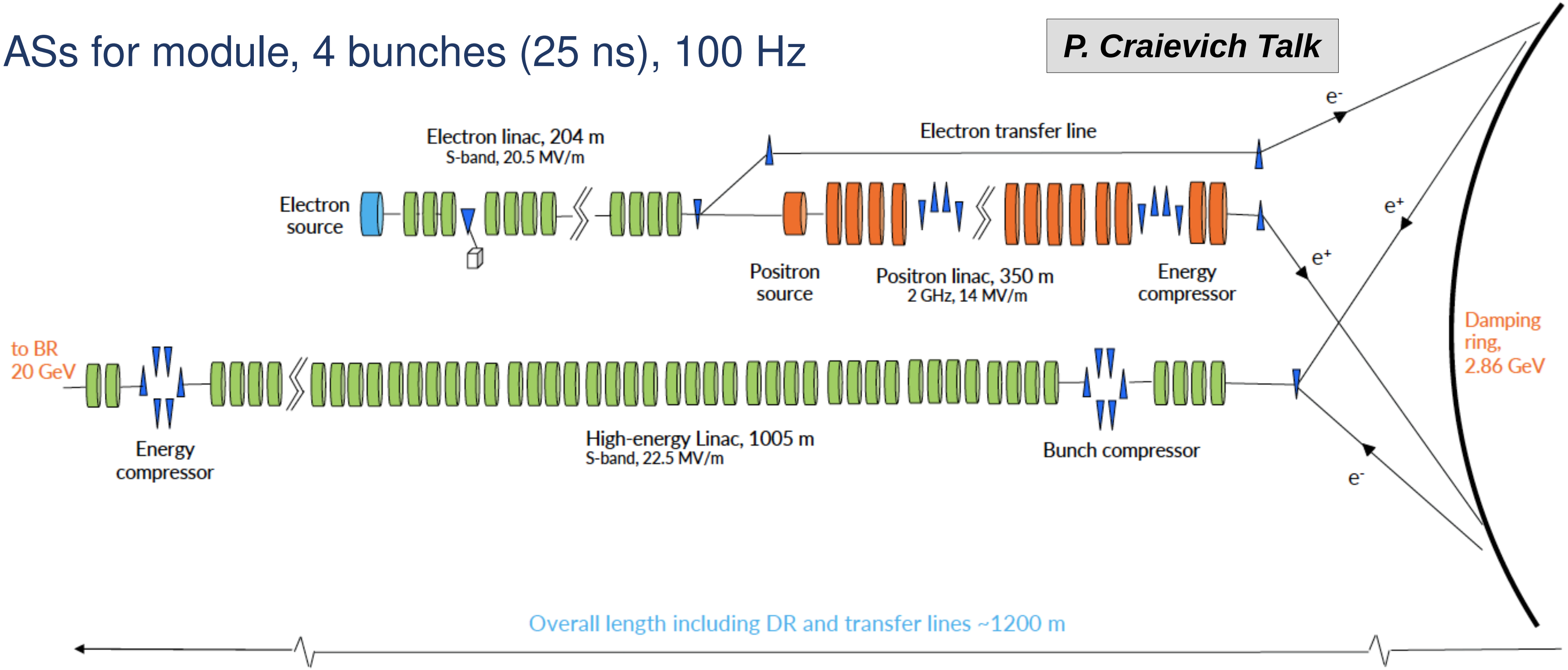
Now left the activity

MoU FCC–GOV–CC 0205 (KE 4907) + ADDENDUM

Feasibility Study baseline layout

4 ASs for module, 4 bunches (25 ns), 100 Hz

P. Craievich Talk



- New damping ring at higher energy 2.86 GeV,
- No common LINAC which requires doubling repetition rate, for both species with flat emittances

General considerations

The DR requirements are fixed by the Booster Ring (BR) parameters (see Injector Table)

Land footprint is defined by the available space (~120x120 m^2)

Realistic design would imply:

- Dipoles Field < 1T (normal conducting)
- Wiggler Field < 1.9 T (normal conducting)
- Quadrupole Gradient k_Q < 50 T/m (5.25 m^{-2} in MADX units)
- Sextupole strength k_S< 1700 T/m^2 (182 m^{-3} in MADX units)
- Minimal element spacing L_δ > 8 cm
- Element length: L_{QUA} > 20 cm, L_{SXP} (L_{OCT}/L_{KCK}/...)> 10 cm

Ring layout

Hexagonal shape: 6 Arcs + 6 Straight

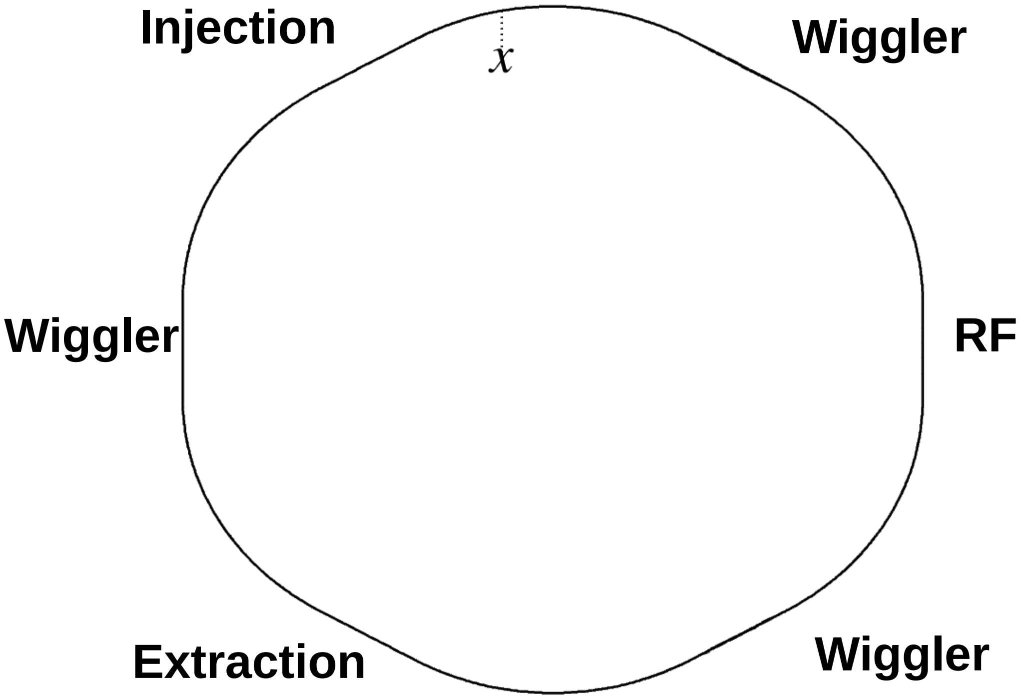
Arcs based on Multi-Bend cells

Straight sections used for specialized purpose: Injection or extraction, wigglers, RF cavity

Playing with optical functions possible to have super-periodicity of three (as for the triangle shaped DR)

Different options considered:

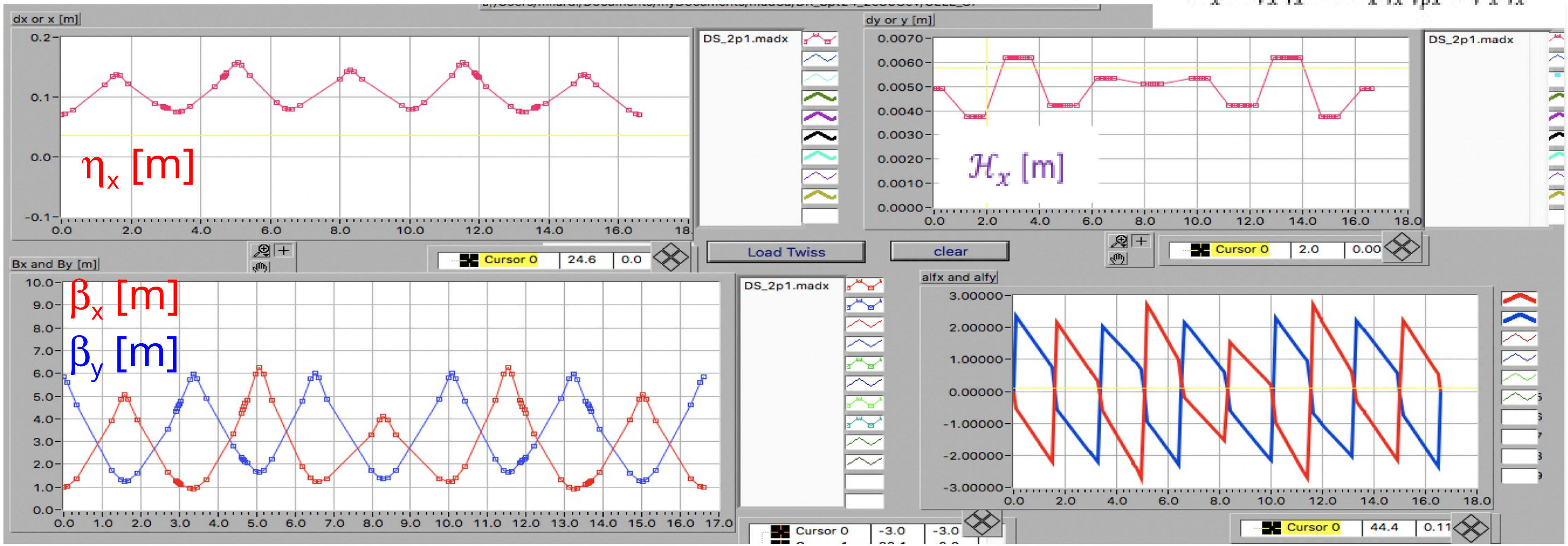
- Same basic layout
- Similar arc cell philosophy



Ten Bend arc cell (FS)

Arc cell optical function

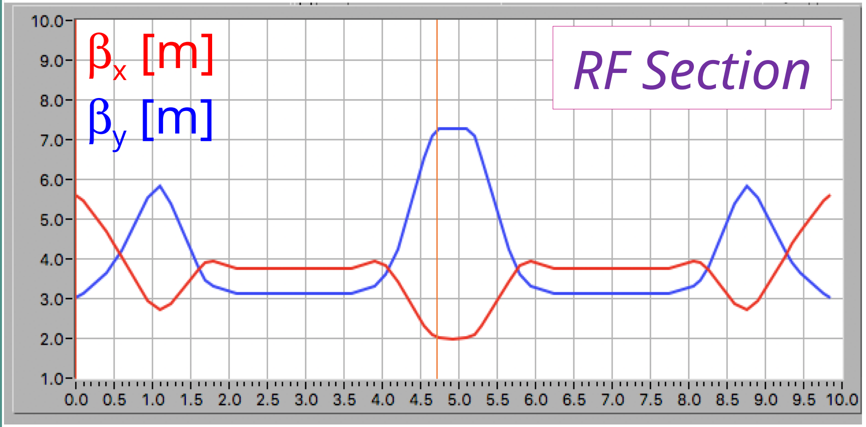
$$\mathcal{H}_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_{px} + \beta_x \eta_x^2$$

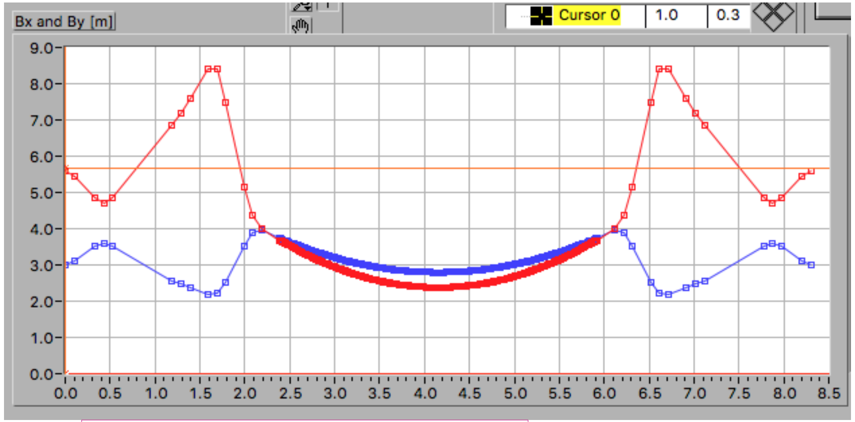


10 Bends of 5 different type, 11 Quads, 4 SXTs

This approach allows keeping the maximum excursion of the horizontal dispersion, optimising damping time, and shaping the H_5 function along the cell to achieve low emittance.

Straight sections





Wiggler Insertion

RF straight section could host
One or two RF modules (cryostat)

Wiggler magnet specs:

- Total length 3.5 m
- Pole Field 1.8 T
- Angle 0.01625 degree
- Pole length ~0.02 m
- # Periods 69

$\varepsilon \sim$ 1.3 nm rad
$\tau_{x,y}$ ~ 16.9 msec (3 WGL)

RF parameters

RF as in the CDR

LHC type 400 MHz,
SC cavities.
two RF modules providing 2 MV each, 1.5 m long (3.5 with cryostat).

RF system to use is still under discussion

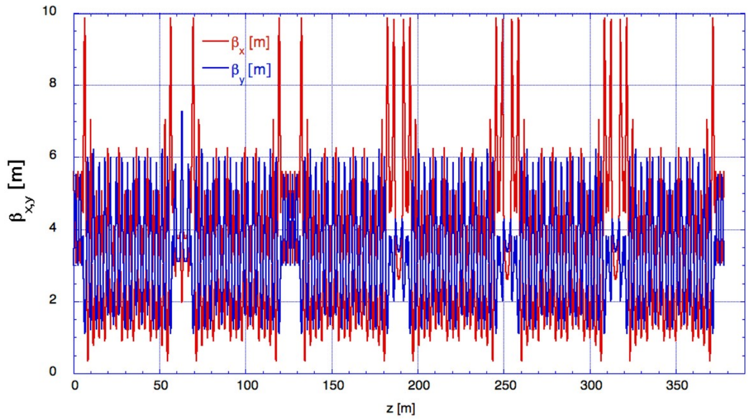
Assuming that each pulse from the e(p)LINAC consists of 4 bunches carryng at least 5 nC each, filling the DR with 10 pulses implies to reach the following upper limits:

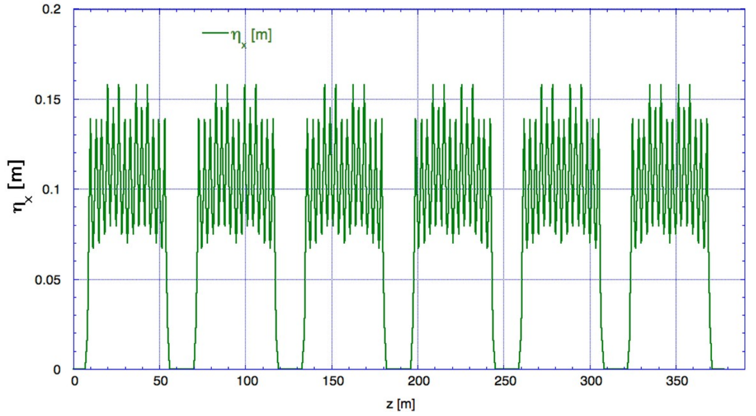
Npart ~ 3.12075E+10
I_{bunch} ~ 0.00396402 A
I ~ 0.158561 A

	V= 4MV	V= 8MV
U_0 [KeV]	422.13	
DE	$0.7219 \cdot 10^{-3}$	
Ω_s [KHz]	10.4545	14.7849
T_0 [μsec]	1.26134	
ω_0 [s^{-1} rad]	4.98134E+6	
ν_s	0.00209874	0.002968
L_{bunch}[m]	**0.00511**	**0.00361**
φ_s [rad]	0.10573	0.0527913

Ring parameters (FS)

Parameters	Value
Energy [GeV]	2.86
Circumference [m]	373.46
Arc Cell	multi-bend
Lattice shape	six-fold symmetry
Nat. emittance [nm rad] (WGL on/off)	1.3 / 2.3
Bunch Lenght [mm]	5.1
Damping time $\tau_{x,y}$ (WGL on/off) [ms]	16.9 / 29.4
Nat. Cromaticity (x/y)	-38.2/-28.3
Nat. energy spread (WGL on/off) [10^{-4}]	7.1 / 5.2
Betatron amplitude max (x/y) [m]	9.66 / 6.49
Betatron amplitude min (x/y) [m]	0.5 / 1.1
Tune (Q_x,Q_y)	27.8707 / 22.3728
Momentum compaction (WGL on/off) [10^{-3}]	1.55 / 1.57
Revolution period [μs]	1.2457
Dipole #, length [m], field [T]	180 , 0.7 1.13, 0.34 0.39
Wiggler #, length [m], field [T]	3, 3.5 , 1.8
Cavity #, length, voltage [MV]	1.5, 4
Max. # Bunch stored, Bunch Curr. [mA]	40 / 4
Store time	5 τ_y
Energy loss per turn (WGL on/off) [keV]	422.2 / 246.7
SR power loss wiggler [kW]	27.83
Kicker rise time [ns]	50





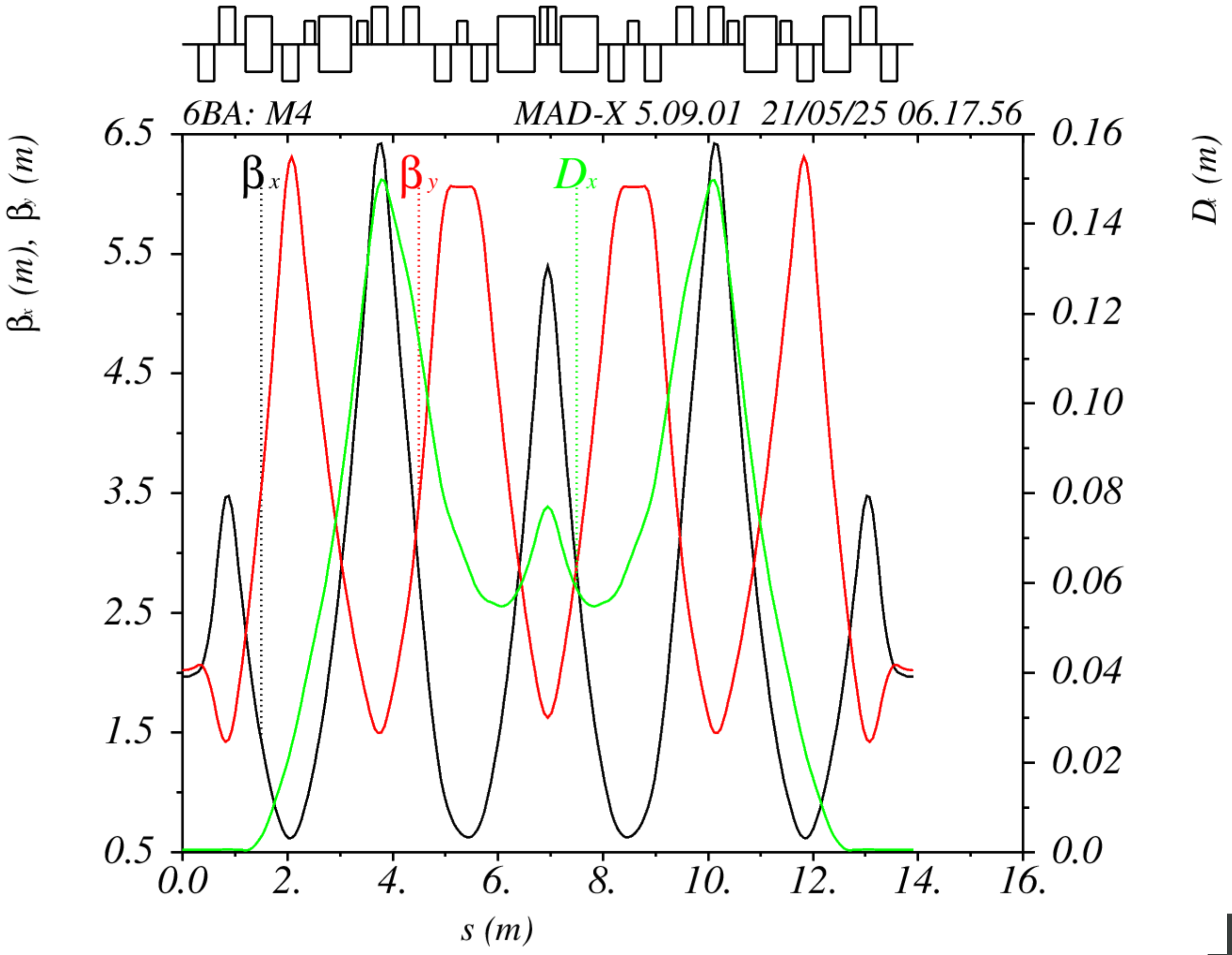
21 May 2025

Six Bend Achromat arc cell

Six Bend Achromat cell

L_{cell} = 13.60 m
L_{dipole} = 0.5-0.7 m (B_d = 0.6933 T)
N_{qua} = 15
L_{qua} = 0.30 m
N_{sxp} = 6
L_{sxp} = 0.20 m
MAD-X Output:

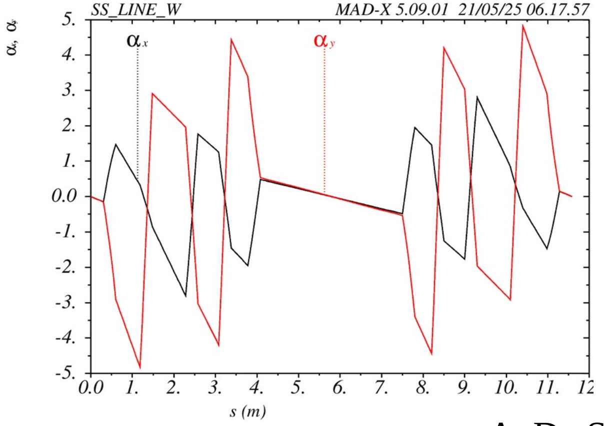
```
-----------------------------------------
  B6A CELL
-----------------------------------------
d_delta          =              0.08 ;
d_0              =              0.3 ;
d_1              =              0.1 ;
d_2              =              0.2 ;
d_3              =              0.2 ;
d_4              =              0.4 ;
d_5              =              0.4 ;
d_6              =              0.3 ;
d_7              =              0.3 ;
d_8              =              0.4 ;
d_9              =              0.2 ;
d_10             =              0.1 ;
-----------------------------------------
b6a_kq1          =          -2.49899 ;
b6a_kq2          =           4.77148 ;
b6a_kq3          =          -3.03173 ;
b6a_kq4          =           3.36248 ;
b6a_kq5          =          0.803115 ;
b6a_kq6          =          -1.95099 ;
b6a_kq7          =          -1.48641 ;
b6a_kq8          =           3.98903 ;
-----------------------------------------
b6a_ks1          =      -72.69646614 ;
b6a_ks2          =       130.7022659 ;
b6a_ks3          =      -155.2964227 ;
-----------------------------------------
```



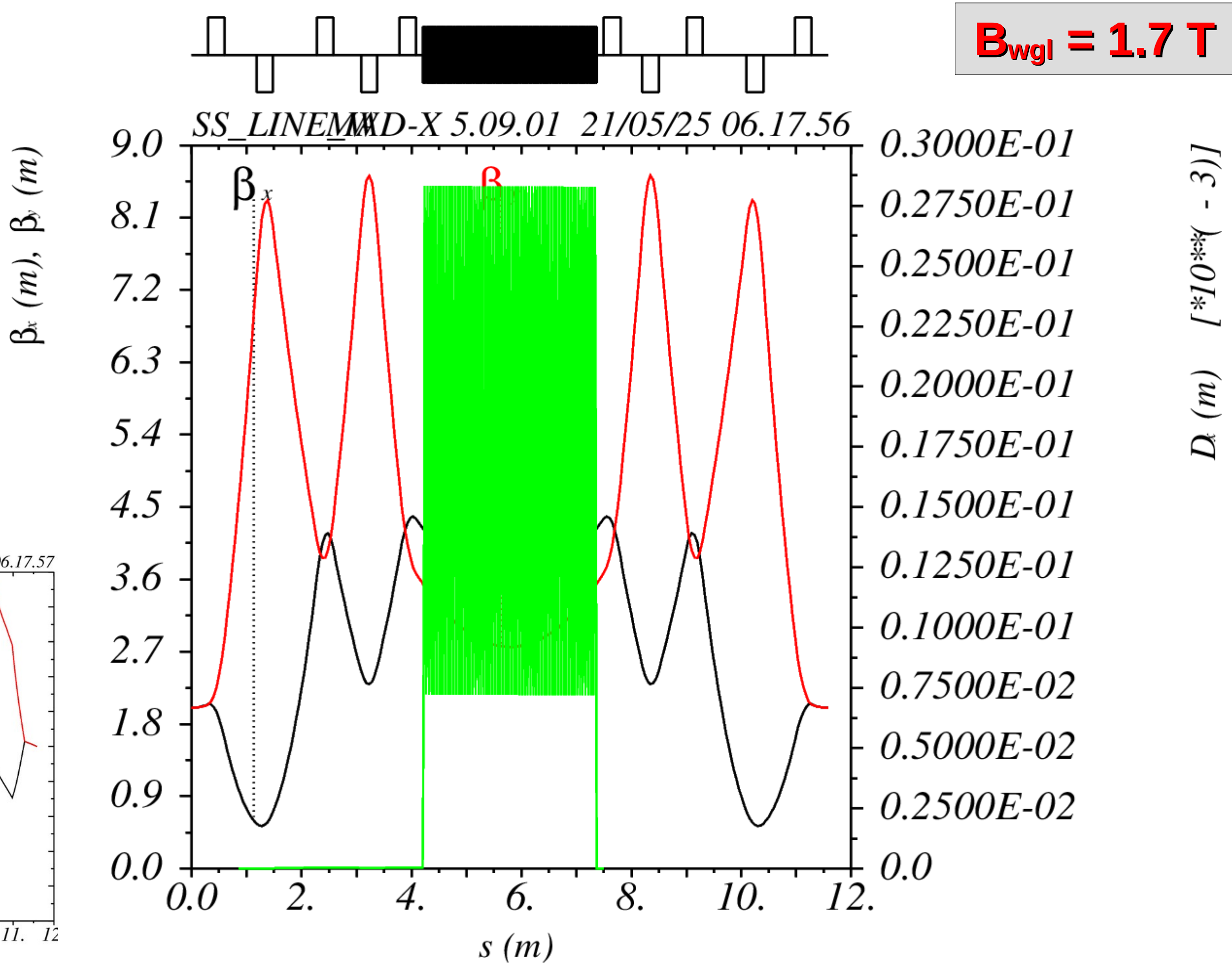
Wiggler sections

L_{SS} = 11.58
L_{free} = 3.42 m

```
----------------------------------------
 STRAIGHT SECTIONS:
----------------------------------------
ss_ld1      =      0.3 ;
ss_ld2      =     0.58 ;
ss_ld3      =      0.8 ;
ss_ld4      =      0.5 ;
ss_ld5      =      0.4 ;
ss_ld6      =     1.71 ;
----------------------------------------
sswkq1      =  3.333698249 ;
sswkq2      = -3.307536882 ;
sswkq3      =  3.976927425 ;
sswkq4      = -3.535394196 ;
sswkq5      =  2.033934488 ;
----------------------------------------
```



B_{wgl} = 1.7 T



Full ring parameters (6BA)

L = 403.08 m
T_{per} = 1.343 μs ;
α_c = 0.000758
Ncel = 24

Q_x = 39.566
Q_y = 21.867

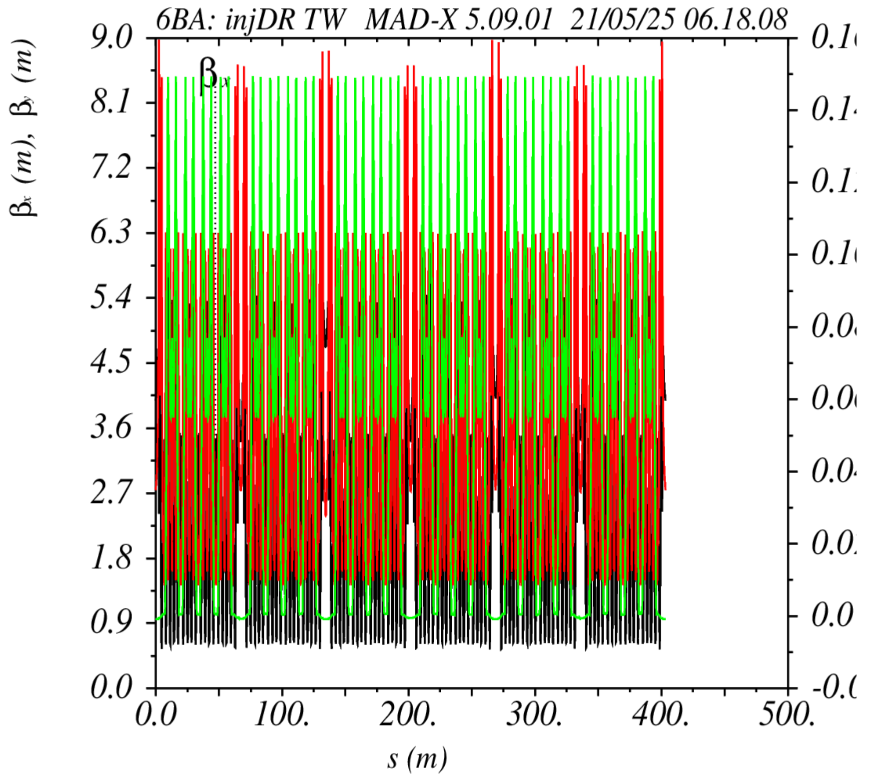
ξ_x = 7.1e-9 (corr) / -50.48 (nat)
ξ_y = 1.4e-8 (corr) / -36.87 (nat)

β_x(max) = 6.09 m
β_y(max) = 8.32 m

U_0 = 571 keV
ΔE = 7.3e-4

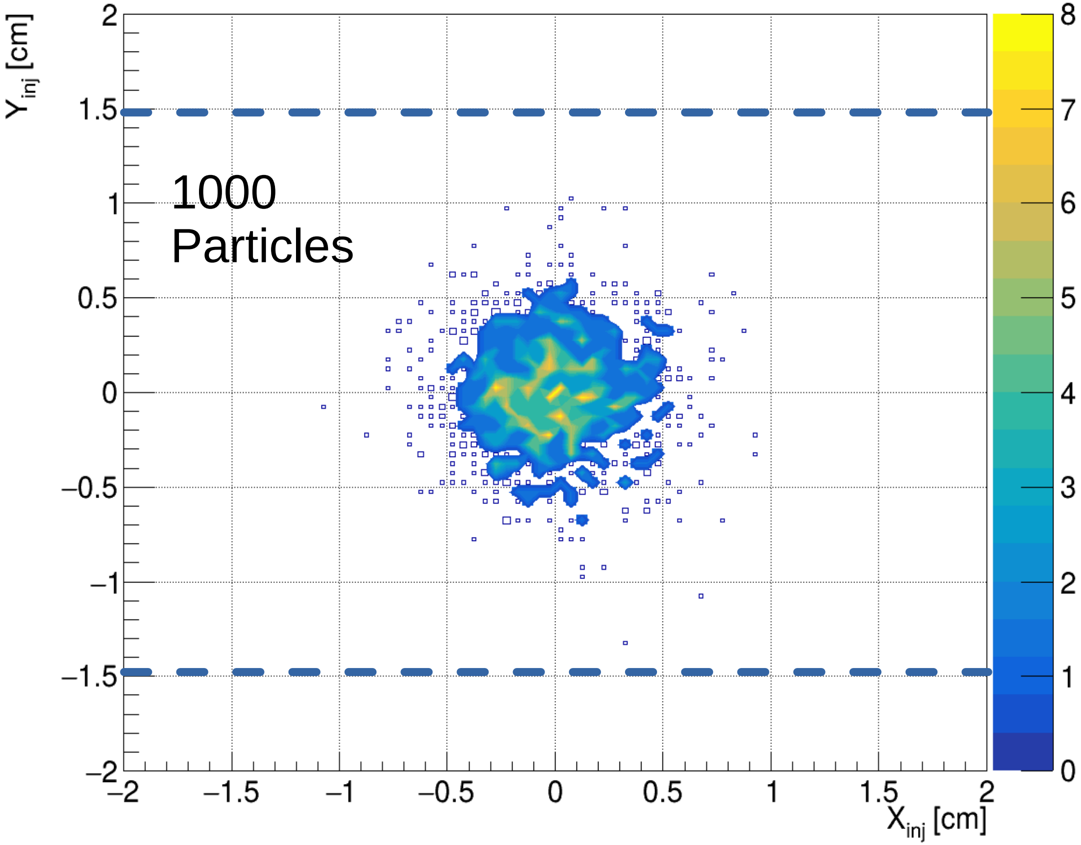
ε = 1.82 nm rad

$\tau_{x/y}$ = 13.5 ms



Synchrotron integrals:
I_1 = 0.30527316
I_2 = 0.6063789197
I_3 = 0.0541043725
I_4 = 0.001614382676
I_5 = 9.174328584e-05

Preliminary tracking results



Only Transverse motion (4D)

SXP ON

Beam injected in SS section with expected emittance (2.36/2.32 mm mrad) in x/y planes [FS].

Tracked for 1000 Turns

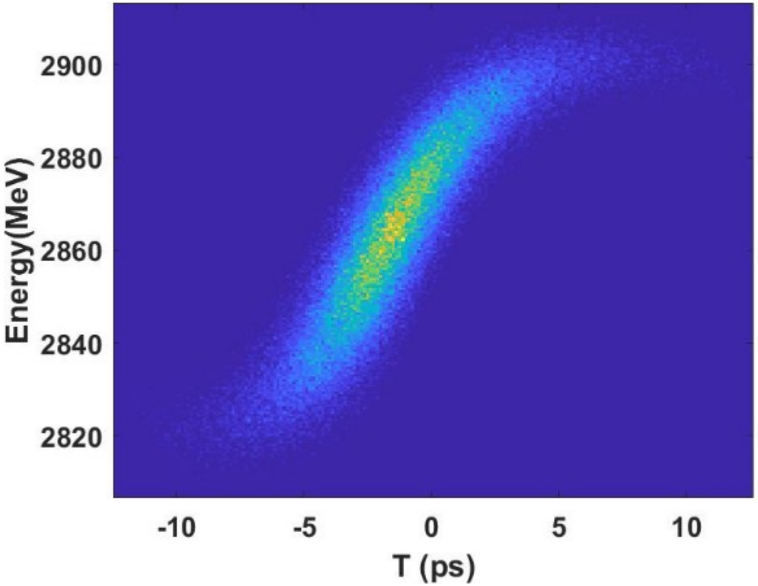
Beam Pipe physical apertures:
Horizontal: ± 3.0 cm
Vertical: ± 1.5 cm

$$\varepsilon_{acc} = \frac{472}{1000} = 47\%$$

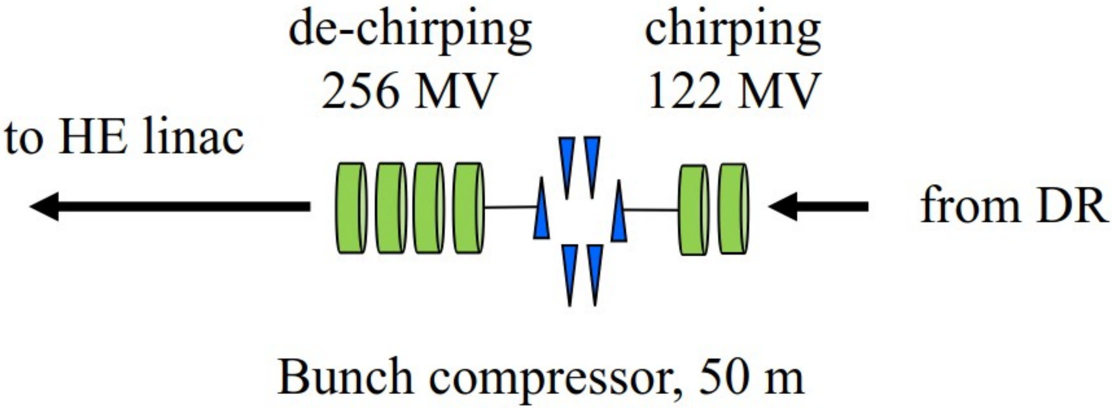
Transfer lines

Extraction line: bunch compressor

Bunch length 5mm (DR) to 1 mm (HE-LINAC)



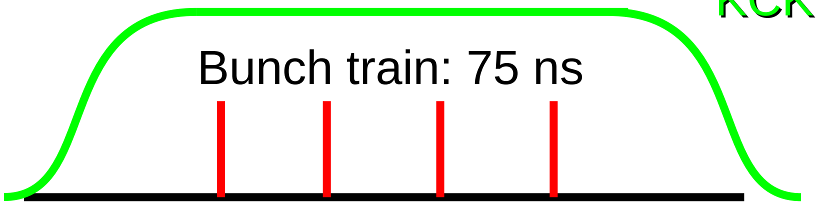
Bend: 1.9 m 1 T
R56 = -0.336 m,



Residual energy spread of 0.7% after de-chirping with a compression factor of 5.75, and a reduction in the bunch length from 4.6 mm to 0.8 mm.
The horizontal emittance growth is approximately 20% (vertical emittance growth below 1%)

Timing considerations

Minimal damping time



$$n_{MAX}(train) = \frac{T_{per}}{\Delta t + t_K} \simeq 10$$

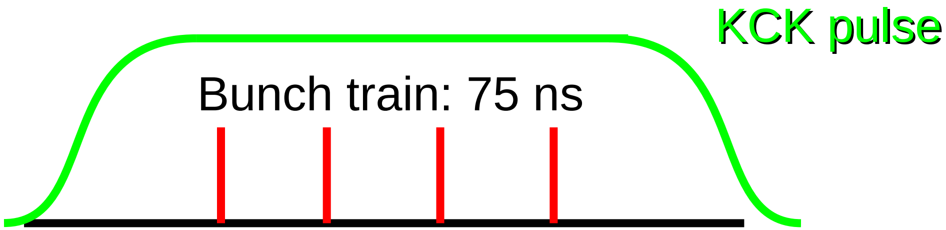
$$\epsilon(t) = \epsilon_{inj} e^{-\frac{2t}{\tau}}$$

$$T_{store} = -\frac{\tau}{2} \ln \frac{\epsilon_{ext}}{\epsilon_0} \simeq 5\tau$$

$$\tau \leq \frac{n_{MAX}(train) T_{pulse}}{5(\Delta t + t_K)} \simeq 20 \text{ ms}$$

Minimal damping time (after injector synchronization)

H. Bartosik Talk



$$n_{MAX}(train) = \frac{T_{per}}{\Delta t + t_K} \simeq 10$$

$$\epsilon(t) = \epsilon_{inj} e^{-\frac{2t}{\tau}}$$

$$T_{store} = -\frac{\tau}{2} \ln \frac{\epsilon_{ext}}{\epsilon_0} \simeq 5\tau$$

$$\tau \leq \frac{n_{MAX}(train) T_{pulse}}{5(\Delta t + t_K)} \simeq 20 \text{ ms}$$

$$n_{MAX}(train) \leq 7$$

$$\tau \leq 14 \text{ ms}$$

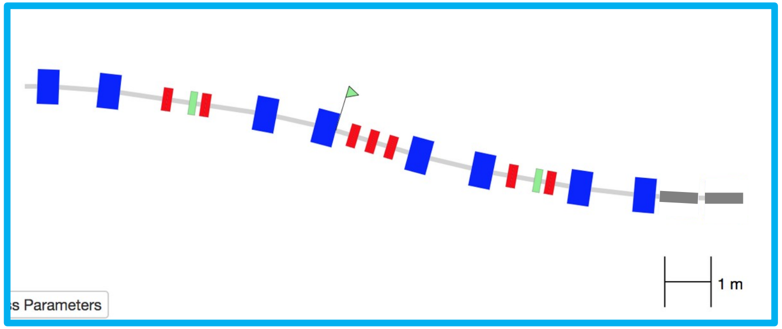
Lenght of the DR is fixed to the BR

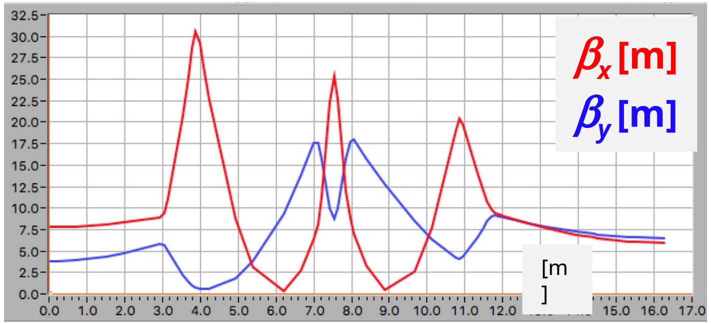
Conclusions

- General layout established
- Preliminary optics evaluated
- DA/MA smaller than needed
- Timing and synchronization under study
- TL (injection/extraction) needs update

SPARES

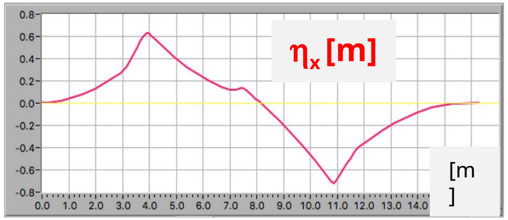
TL injection/extraction

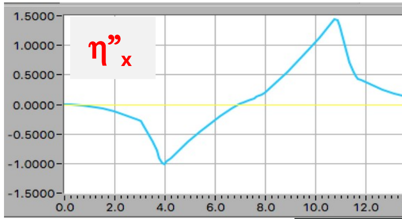




- *flexible*
- *achromatic*

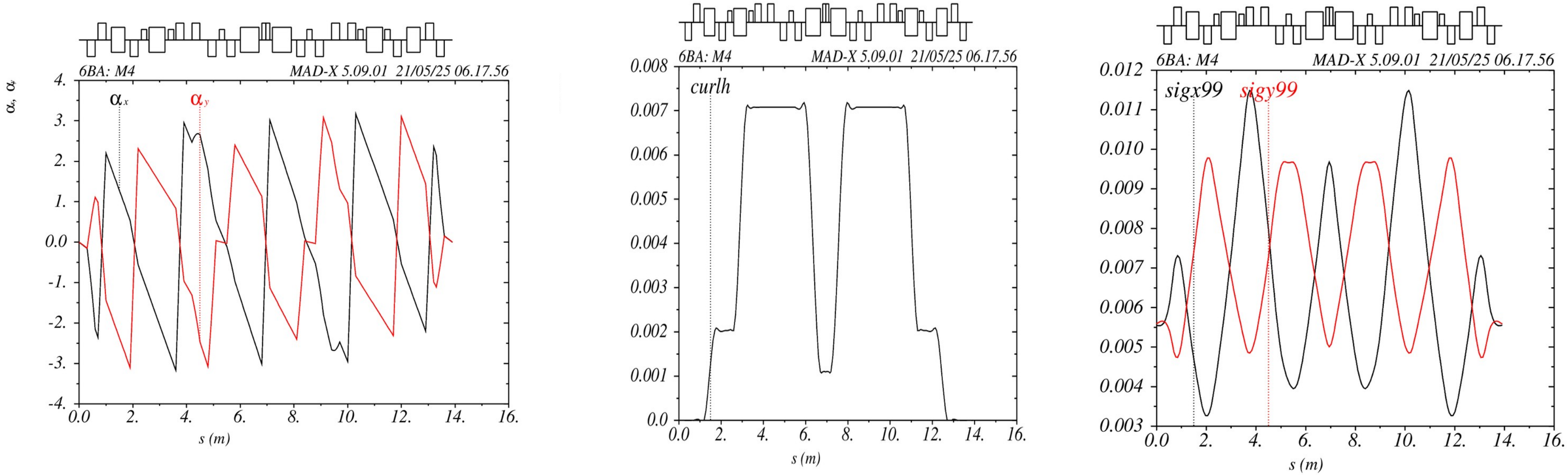
	Angle [degree]	Length [m]	Field [T]	Thickness [mm]
B1	4.2	0.47	0.8	
B2	-3.4	0.47	-0.65	
SPT1	-2	0.8	-0.044	7
SPT2	-1.2	0.8	-0.026	2 - 4





Six Bend Achromat cell (6BA)

Beam envelope (98%)



$$\epsilon_{inj}(h/v) = 2.35/2.32 \text{ mm m}$$

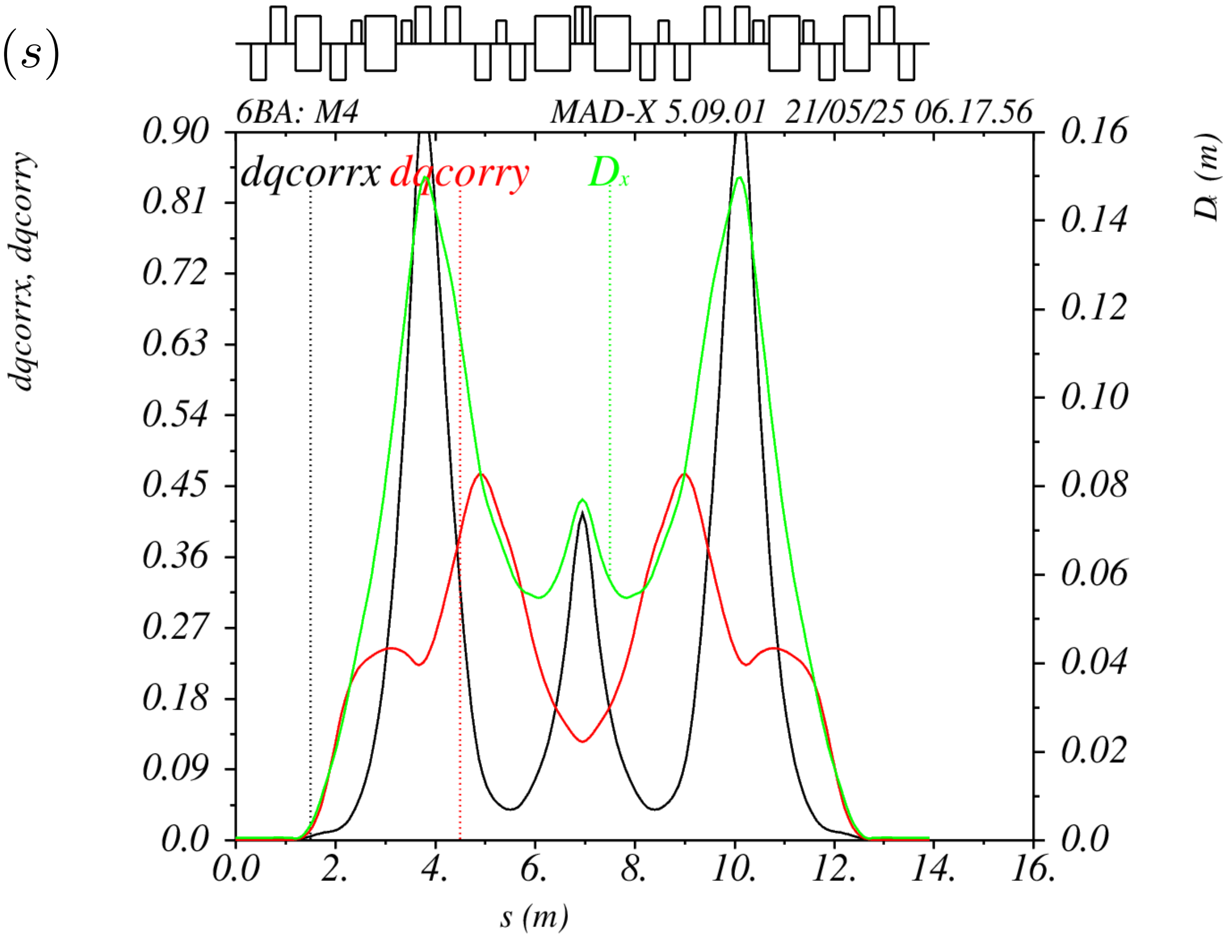
6BA Cell: Sextupoles

$$\Delta\xi_{xy}(m_S) \propto m_S \int ds \beta_{x,y}(s) D(s)$$

Sextupoles placements have been optimized in order to ensure the minimal strengths

Three family have been defined two for the vertical correction and one for the horizontal

The chromaticity correction is localized only in the arcs for the whole ring.



Injection/extraction sections

L_{SS} = 11.58

L_{free} = 3.42 m

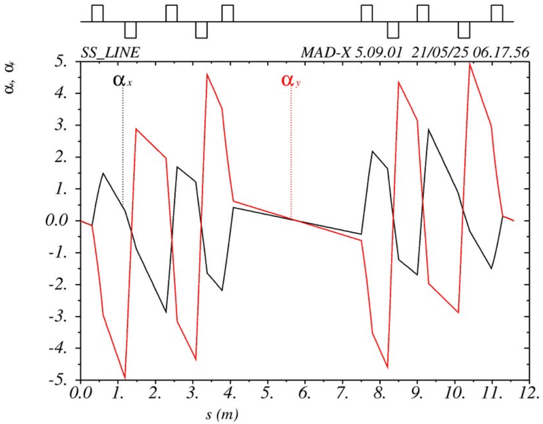
STRAIGHT SECTIONS:

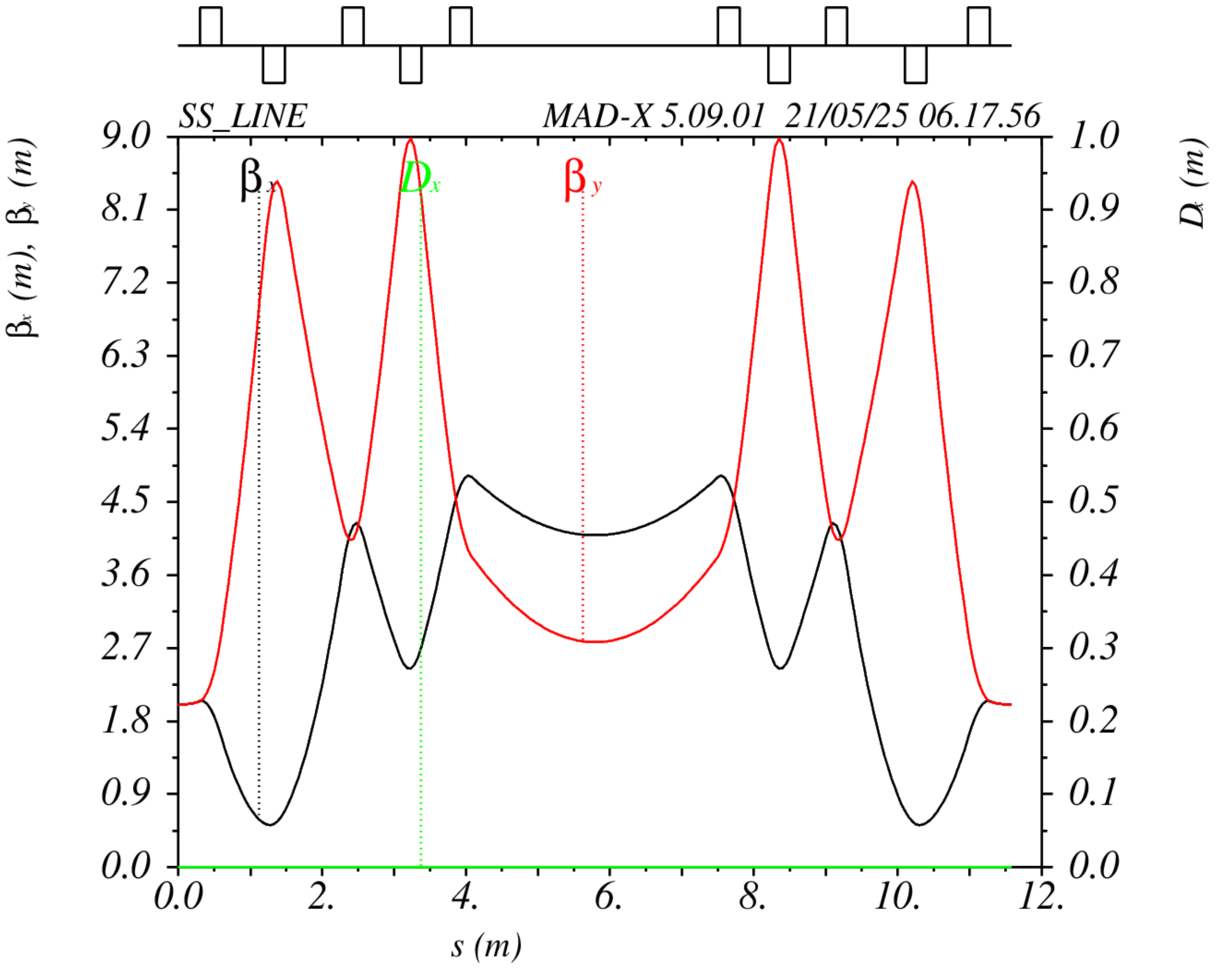
----

ss_ld1	=	0.3 ;
ss_ld2	=	0.58 ;
ss_ld3	=	0.8 ;
ss_ld4	=	0.5 ;
ss_ld5	=	0.4 ;
ss_ld6	=	1.71 ;

----

sskq1	=	3.38578576 ;
sskq2	=	-3.287172054 ;
sskq3	=	3.906317017 ;
sskq4	=	-3.514177296 ;
sskq5	=	1.976167573 ;





RF sections

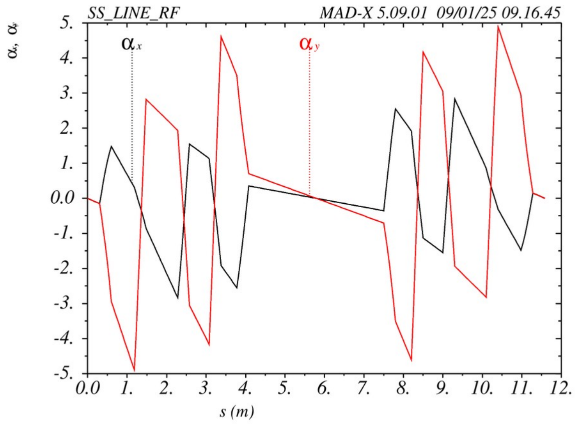
L_{SS} = 11.58
L_{free} = 3.42 m

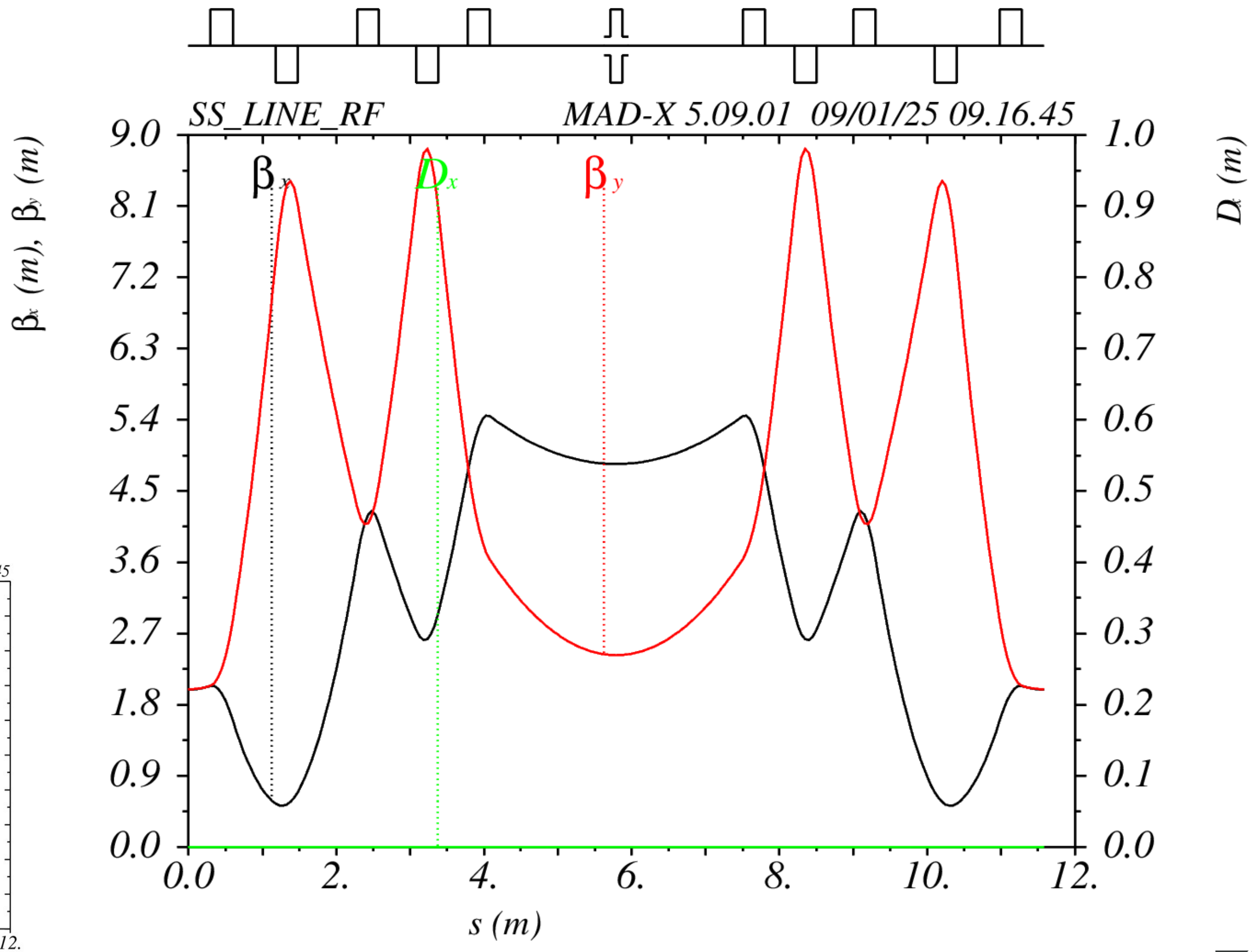
STRAIGHT SECTIONS:
----

ss_ld1	=	0.3 ;
ss_ld2	=	0.58 ;
ss_ld3	=	0.8 ;
ss_ld4	=	0.5 ;
ss_ld5	=	0.4 ;
ss_ld6	=	1.71 ;

----

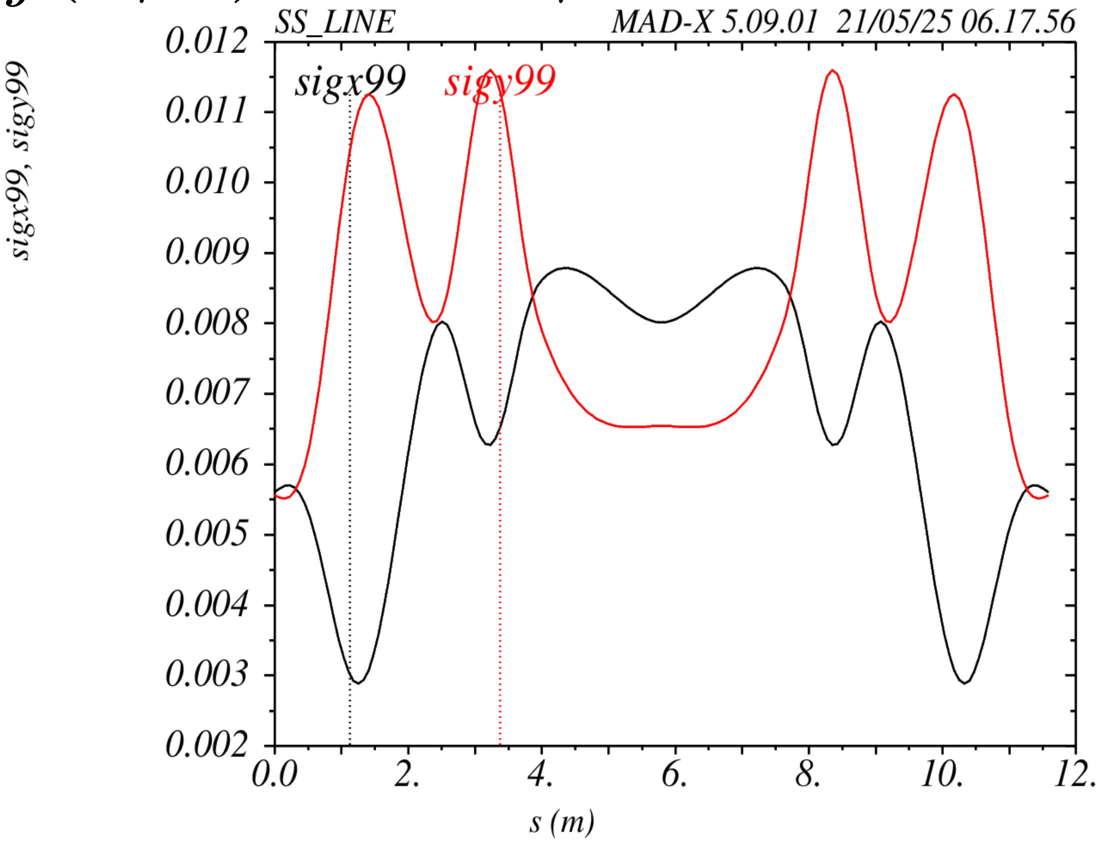
ssrfkq1	=	3.374849605 ;
ssrfkq2	=	-3.263965846 ;
ssrfkq3	=	3.771890122 ;
ssrfkq4	=	-3.513106207 ;
ssrfkq5	=	1.962597868 ;



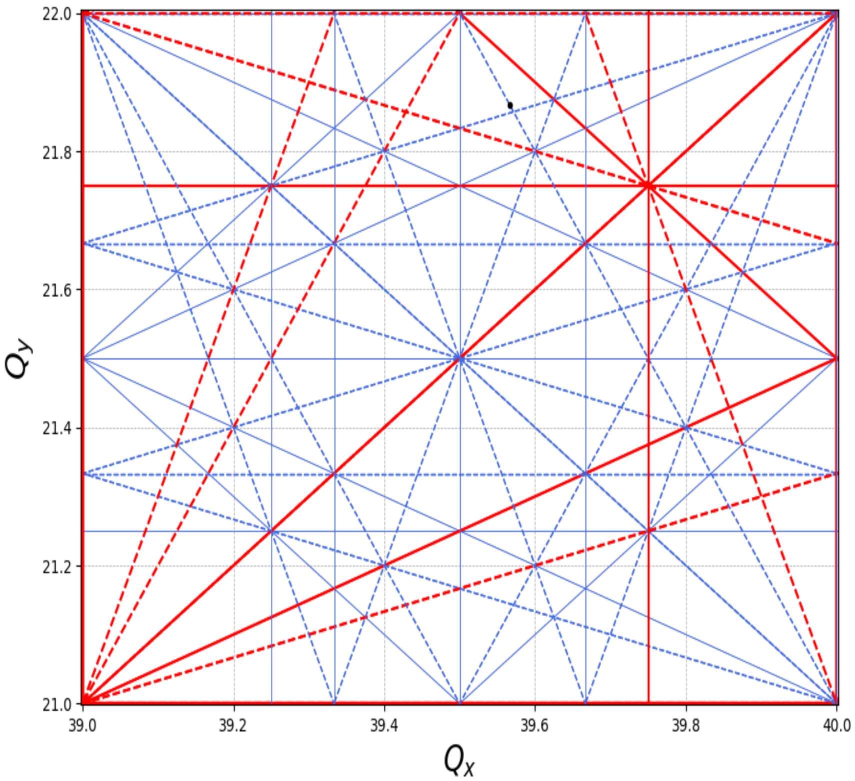


Beam envelope in the Straight Sections

$$\epsilon_{inj}(h/v) = 2.36/2.32 \text{ mm mrad}$$



Working point



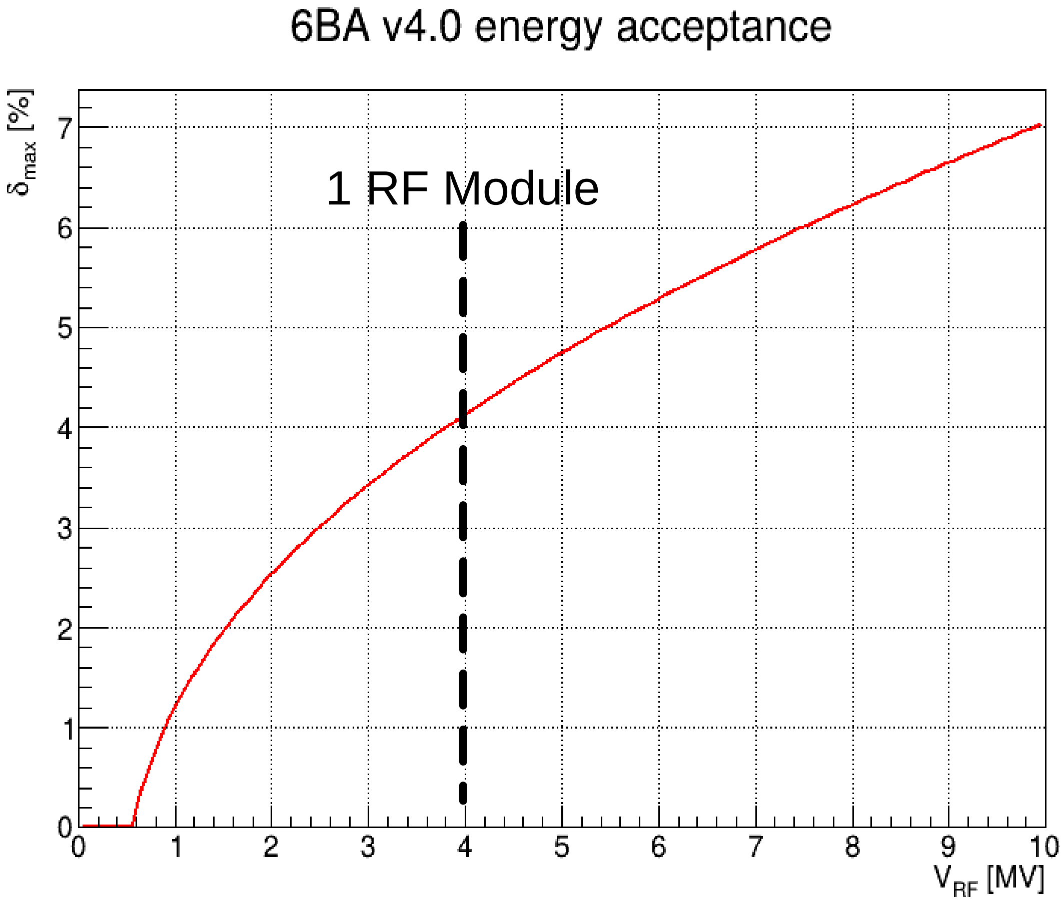
Resonance Diagram:

Solid lines are normal and dashed lines are skew resonance

Red and Blue are systematic and non-systematic resonances, respectively.
Superperiodicity of three (3) has been considered:
SS+Arc+SS_WGL+Arc

Working point have to be revised.
Too close to systematic resonances

Energy acceptance



α_p = 0.000758
h = 537
E_{beam} = 2.86 GeV

Sync. phase

$$\phi_s = \pi - \sin^{-1}\left(\frac{U_0}{eV_{RF}}\right)$$

Sync. tune

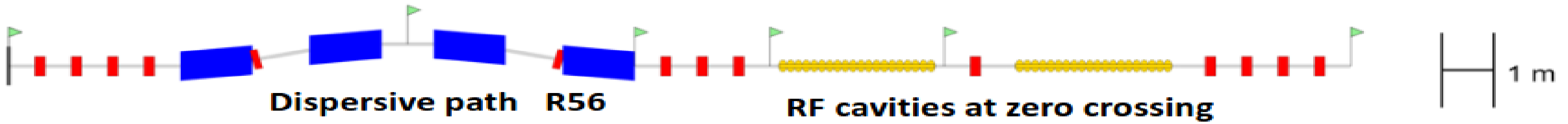
$$\nu_s = \sqrt{-\frac{eV_{RF}}{E_0}\frac{h\alpha_p}{2\pi}\cos\phi_s}.$$

RF Acceptance

$$|\delta|_{\max,\mathrm{RF}} = \frac{2\nu_s}{h\alpha_p}\sqrt{1-\left(\frac{\pi}{2}-\phi_s\right)\tan\phi_s},$$

Transfer lines

Energy compressor layout



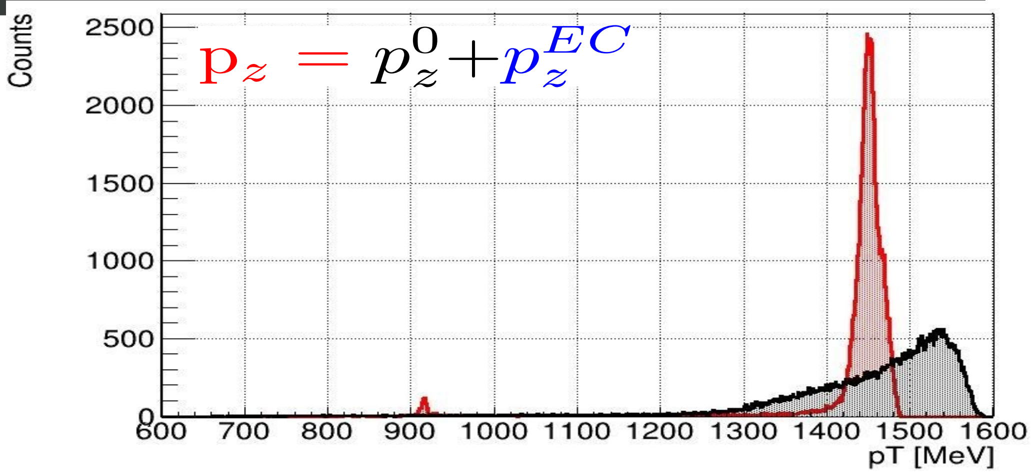
- In a four bending C-shape chicane dispersion and second order dispersion are intrinsically closed.
- Two cavities of the type used for the positron LINAC **(PSI design. LINAC THPOJO08 LINAC 2022)**
- The beam exit ECS on the same LINAC axis, thus same diagnostics can be used for LINAC and ECS tuning.

FCCWeek2024

Parameters	Value	Unit
Dipole Bending angle	0.2256 (12.9)	rad (deg)
Dipole Magnetic length	1.395	m
Distance between dipoles	1	m
R56	0.205	m
Max dispersion	0.56	m
Number of Cavities	2	
RF frequency	2	GHz
Accelerating Gradient	20	MV/m
Accelerating Voltage	99	MV

Simplified Energy Compressor optimization

$$\delta t = t_0 - t_{ref}$$
$$\delta p_z = p_z^0 - p_z^{ref}$$

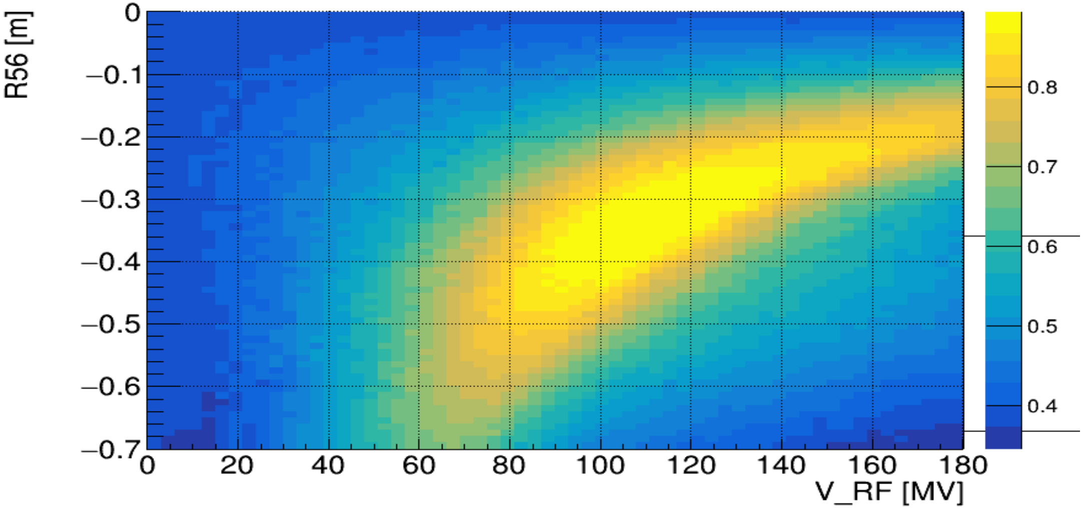


R_{56} + zero-crossing cavity transform:

$$t_{56} = \delta t + R_{56}\frac{\delta p_z}{p_T}$$

$$p_z^{EC} = V_{RF}\sin(2\pi f_{RF} t_{56})$$

FCCWeek2024



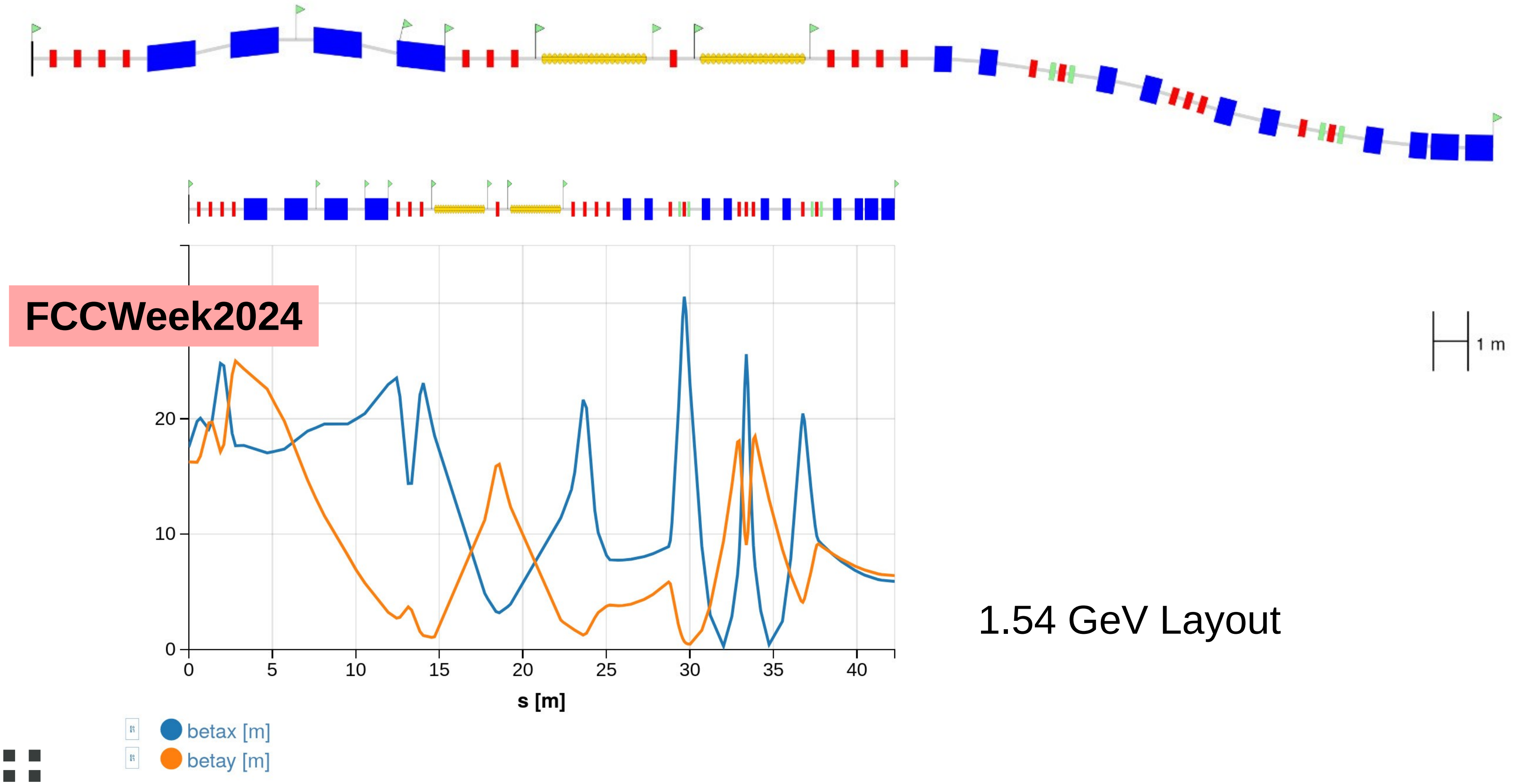
V_{RF} and R_{56} parameter scan:

Maximize the fraction of particle within 2% of the central energy.

Result (only analytical):
V_{RF} = 100 MV
R_{56} = -0.35 m

Results with Elegant simulation slightly different.

Injection line: Energy compressor

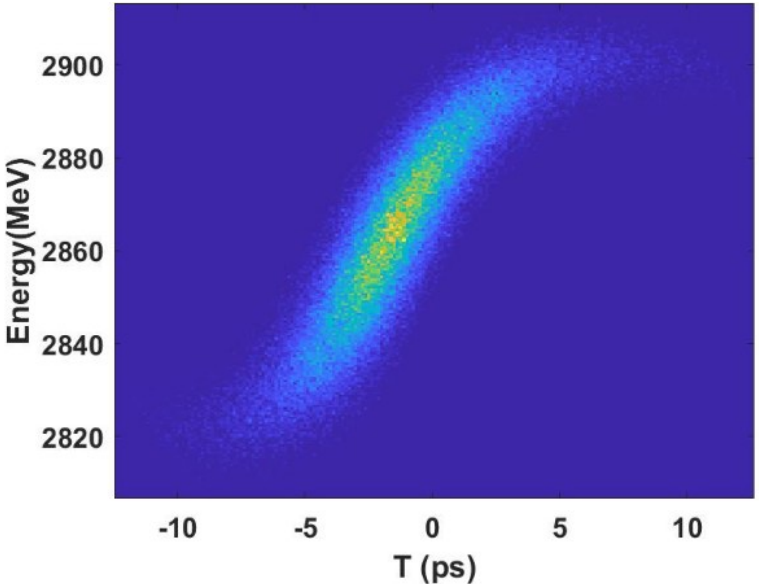


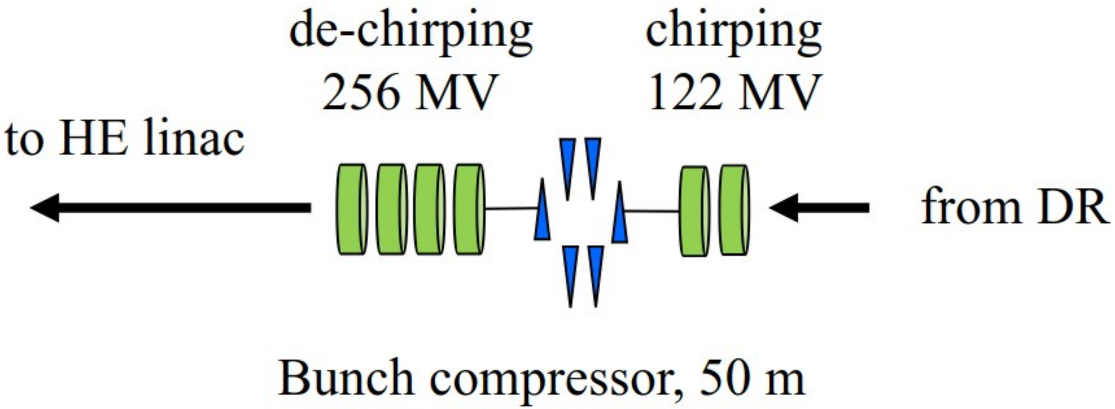
1.54 GeV Layout

Extraction line: bunch compressor

Bunch length 5mm (DR) to 1 mm (HE-LINAC)

Bend: 1.9 m 1 T
R56 = -0.336 m,





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The horizontal emittance growth is approximately 20% (vertical emittance growth below 1%)