HMBA developments

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Barcellona

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

outline

- Introduction
- H7BA:
  - Concept
  - Performances
- H9BA
- Transparency conditions
- H6BA
- H11BA
- Conclusions

introduction

- The Double Bend Achromat (DBA) has been the most successful and widespread lattice used for synchrotron-based light sources. It has (and still is) been fundamental for the realization and exploitation of high brightness X-rays.

- Multi-bend achromat (MBA) lattices have initiated a fourth generation for storage ring light sources with orders of magnitude increase in brightness and transverse coherence. A few MBA rings have been built (MAXIV, EBS, SIRIUS…), and many others are in design or construction worldwide, including upgrades of APS and ALS in the US.

- The H7BA (Hybrid 7 Bend Achromat), developed for the ESRF-EBS (Extremely Brilliant Source) upgrade has proven to be very effective in addressing the nonlinear dynamics challenges associated with pushing the emittance down by a factor > 30 with respect to the DBA

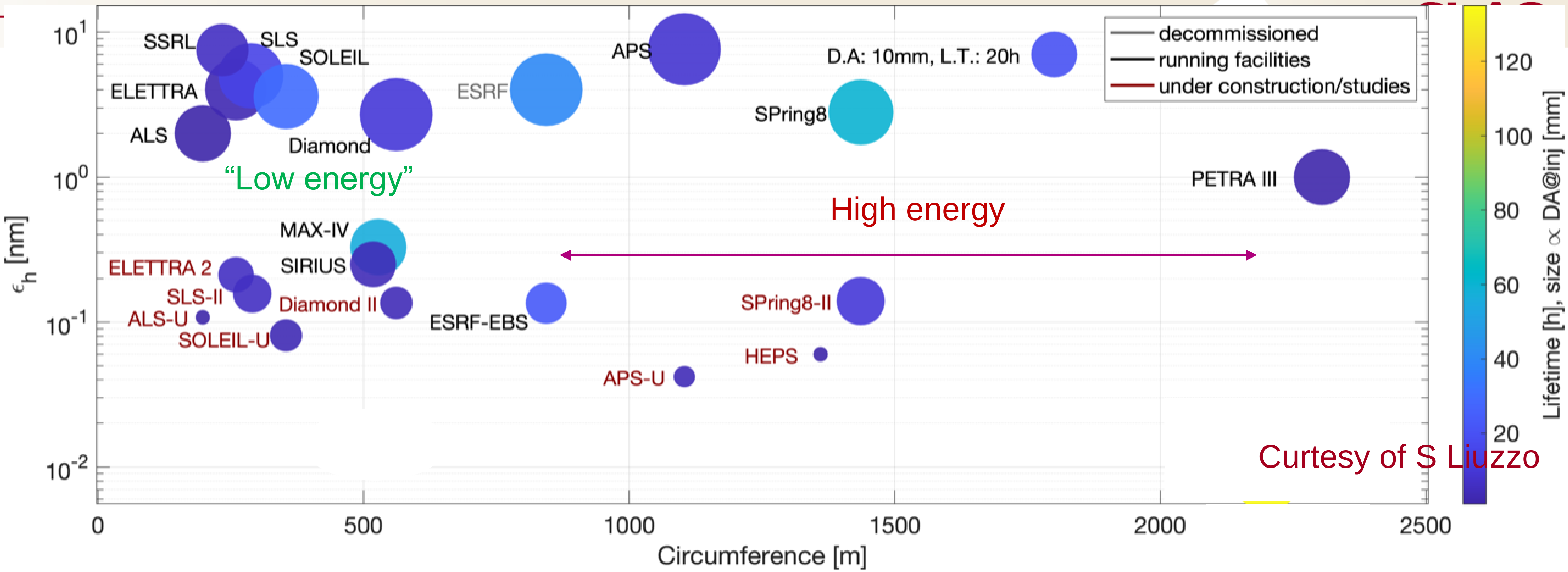
- To reach the Diffraction-Limit the horizontal emittance must be further decreased by at least another factor 10 with respect to current projects/designs. Designing a lattice that delivers such emittance while simultaneously preserving the other many features of the DBA is extremely challenging.
- HMBA can produce such performances taking advantage of:

  1) the flexibility of a green-field project

or

  2) the natural emittance scaling law of a large size facility

synchrotrons portfolio performances



The general performances of DBA are evident: large DA/EA but also large Ex

All the current upgrades do aim to shift the balance in favor of Ex

Projects with a design DA lower than 5mm become subcritical for operations with beam accumulation

Diffraction limited source challenges

DLS ideal machine parameters?

- Round beam with emittance in both planes of the order of 5-15pm
- Beam matched to the Xray beam: betax=betay = X-rays betas = L/2 (Insertion Device length)
  (This is a must at the diffraction limit)
- Tousheck lifetime (TLT) in excess of 10 Hrs (Vacuum LT > 100Hrs)
- Transverse dynamic aperture (DA) at the injection septum in excess of 10mm
- Injection consistent with InVac undulators half-gaps closed = 2-3mm in both planes

These parameters allows operations very similar to what is currently achieved in all facilities and are consistent with:

- relaxed injection complex requirements
- beam stability during injection and coasting
- different operation modes: multibunch, timing modes, hybrid etc
- comfortable radiation handling
- reduced component activation and Insertion Device (ID) radiation damage
- reduced operation costs and wall plug power

etc

Diffraction limited source challenges

A possible path to a factor 10 reduction in emittance

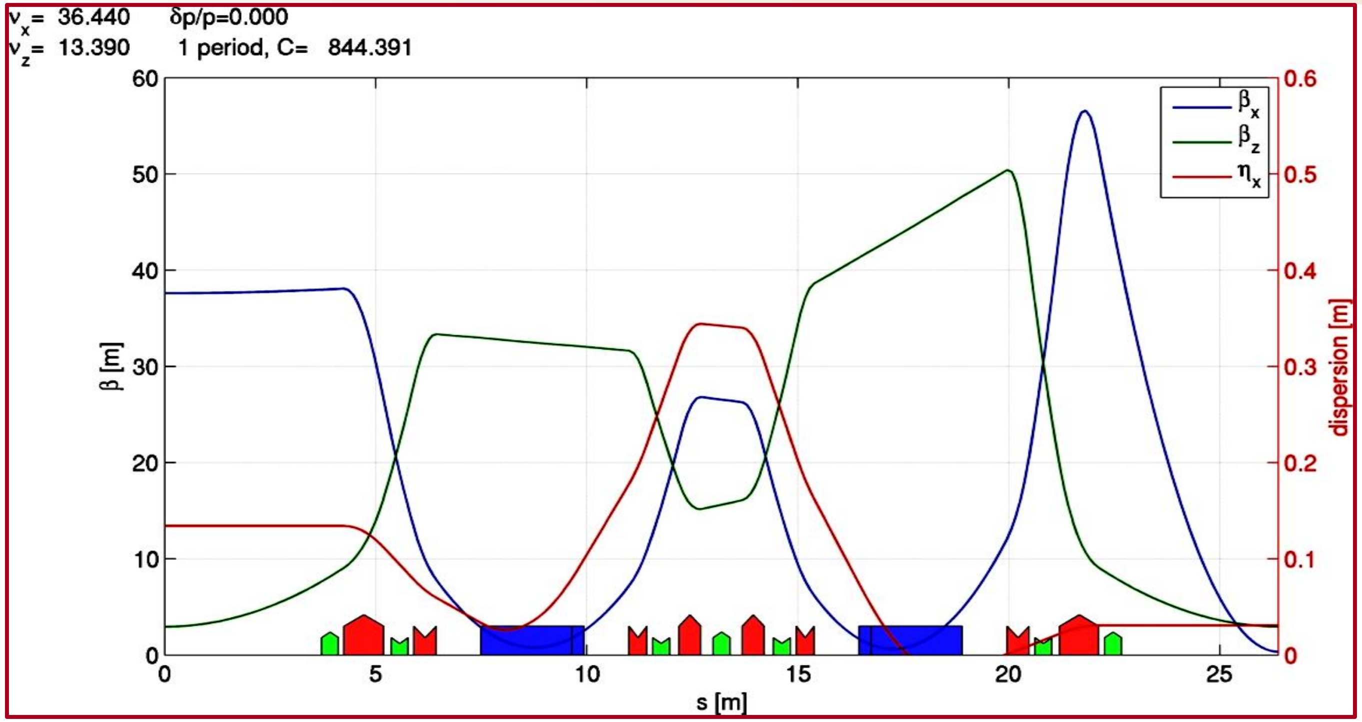
- Develop an HMBA that has an equilibrium emittance 2 times smaller wrt H7BA:
  the lattice should produce a natural emittance around 30-50pm

- Make a layout consistent with implementation of wigglers to further reduce the emittance:
  this is very efficient for the HMBA because it has a very reduced energy loss due to SR wrt DBA (&MBA).
For example EBS-H7BA has about half the energy loss of the former DBA (but no space for wigglers).

- Couple the horizontal and vertical plane in order to reduce the horizontal emittance by another factor 2 (the vertical emittance will be equal to the horizontal):
  this is possible only when the horizontal emittance is just a factor two larger than the desired vertical emittance (the diffraction limited one or the one requested by the users, typically 5-15pm)

- Add long straight sections for optimal injection and flexibility
  this must be done limiting as much as possible the drawbacks due to the reduced periodicity of the lattice

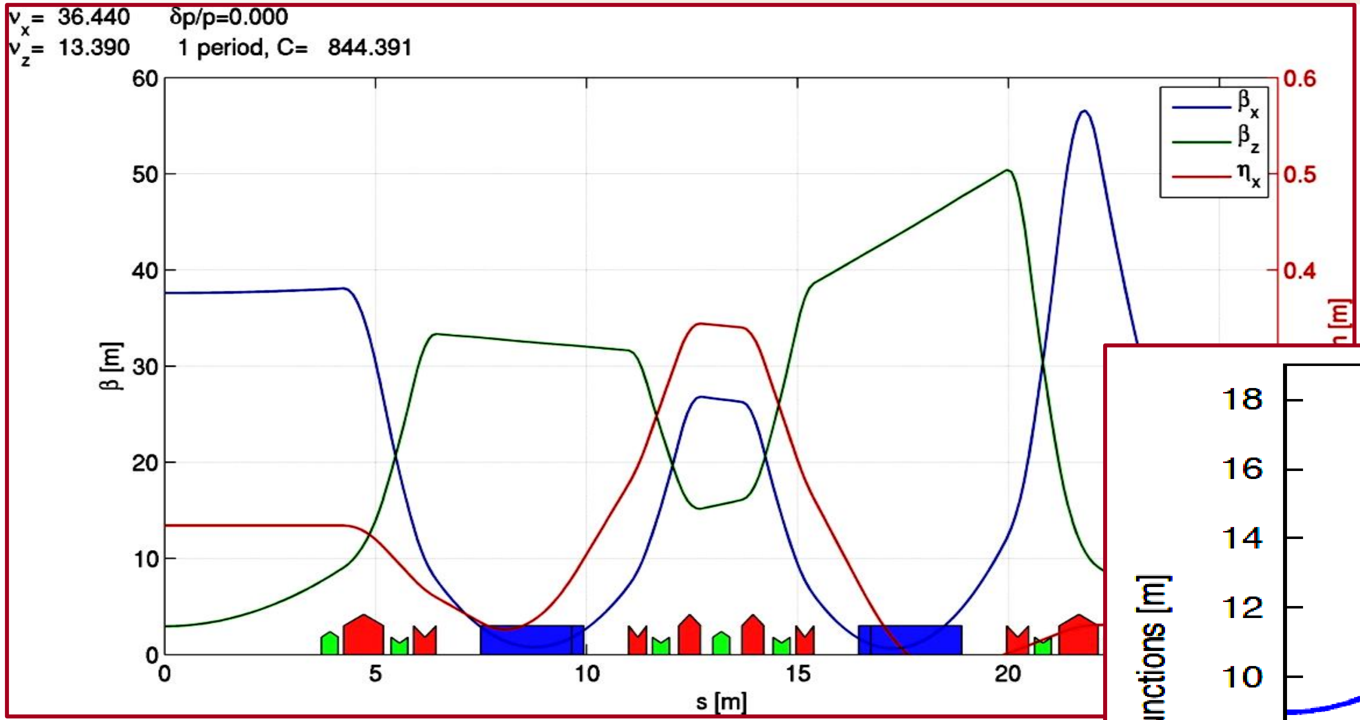
HMBA: The evolution of Multi-Bend Lattice



Double-Bend Achromat (DBA)

- Many 3rd gen. SR sources
- Local dispersion bump (originally closed) for chromaticity correction

HMBA: The evolution of Multi-Bend Lattice



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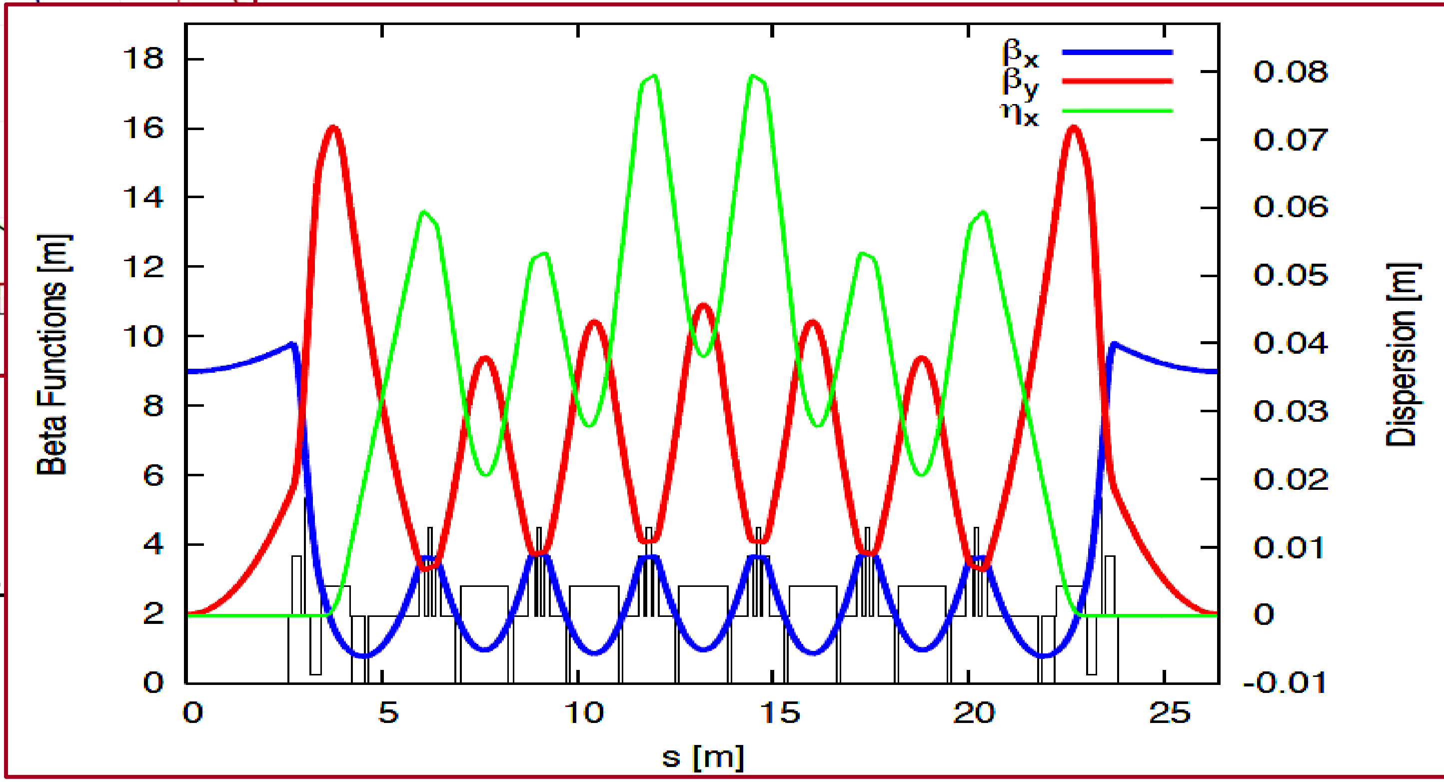
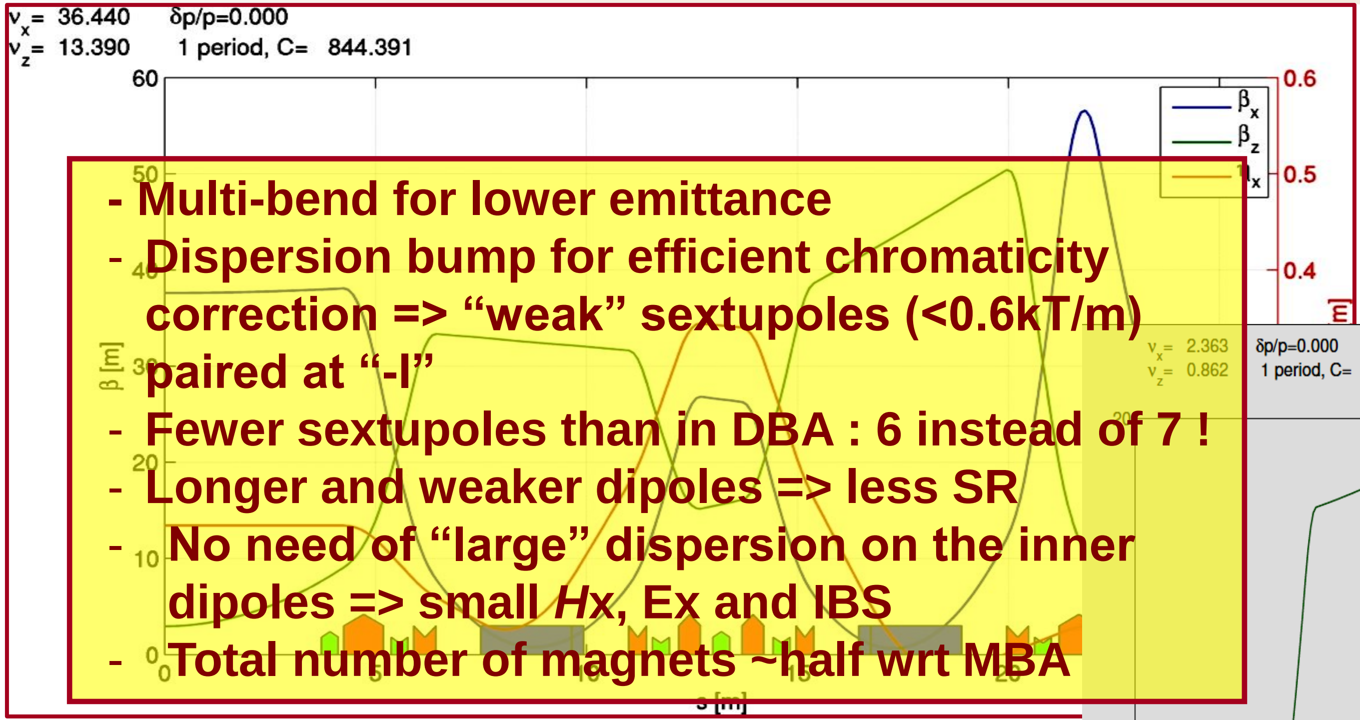


Multi-Bend Achromat (MBA)

- MAX IV and other USRs
- No dispersion bump, its value is a trade-of between emittance and sextupoles (DA)

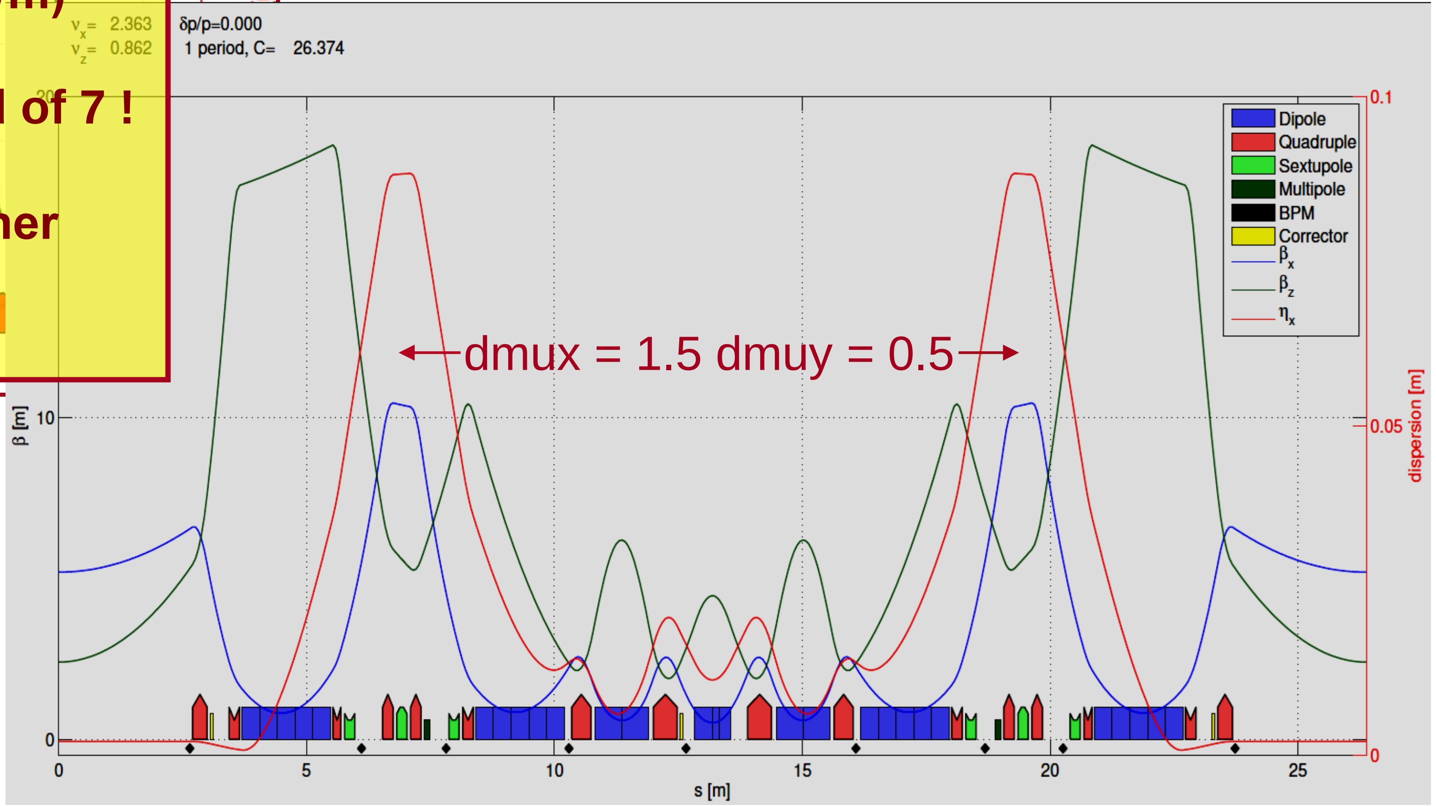
HMBA: The evolution of Multi-Bend Lattice



- Multi-bend for lower emittance
- Dispersion bump for efficient chromaticity correction => “weak” sextupoles (<0.6kT/m) paired at “-I”
- Fewer sextupoles than in DBA : 6 instead of 7 !
- Longer and weaker dipoles => less SR
- No need of “large” dispersion on the inner dipoles => small *Hx*, Ex and IBS
- Total number of magnets ~half wrt MBA

ESRF old (DBA) cell

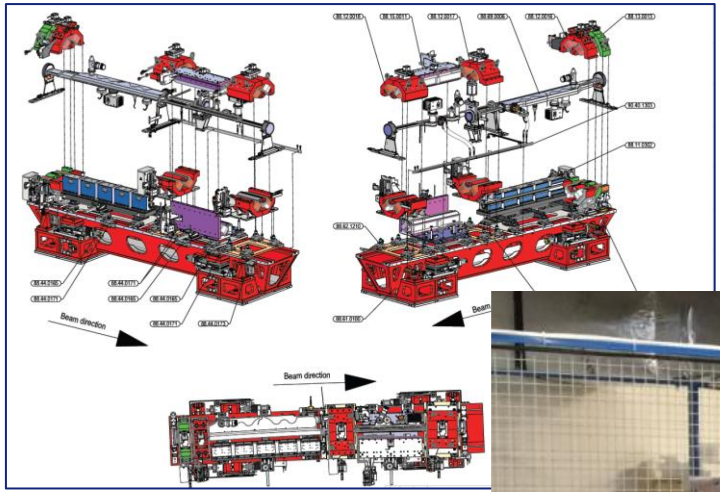
- Ex = 4 nm•rad
- tunes (36.44,13.39)
- nat. chromaticity (-130, -58)

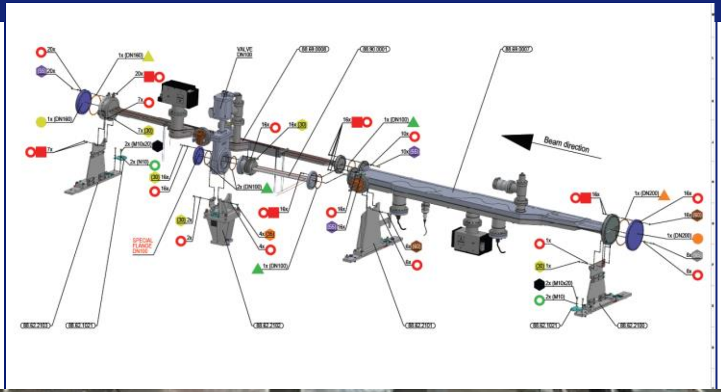


H7BA cell

- Ex = 133 pm•rad
- tunes (76.21, 27.34)
- nat. chromaticity (-99, -82)

EBS: 32*H7BA_CELLS





EBS COMMISSIONING: BEAM PARAMETERS GOALS (PRESENTED AT 2019 COUNCIL)

Parameters** ensuring that no major problem remain in the new hardware or tuning of the new machine
Goal: to be exceeded by 01-March-2020 Start of Beamline Commissioning

Achieved Jan 30

Parameters** that could allow "comfortable" USM operation
Goal: to be exceeded by 24-August-2020, start of USM

Achieved Mar 14

Design EBS parameters
Goal: to be exceeded by Dec 2021

All exceeded Sept 1, 2020
16 months ahead of schedule

Total current	> 50 mA * 120mA	200 mA 201mA	200 mA
MTBF	> 12h >12h	> 30h >100h	> 50h
Up-time	> 90% >90%	> 95% ***>98%	> 97%
Inj. Eff.	> 50% >90%	> 70% >90%	> 80%
Lifetime	> 5h 3.5H @50mAmps	> 10h >10.5h	> 20h
H emittance	[illegible]	[illegible]	[illegible]
V emittance	< 50 pm ~8pm@3mAmps	< 20 pm < 15pm@200mA	< 10 pm
stability	< 0.2 σ <0.05σ	< 0.1 σ < 0.02 σ	< 0.05 σ

EBS is a very solid design, it works!

⇒ TLT ~ 40Hrs in 2021
Theoretical TLT of the lattice with no errors

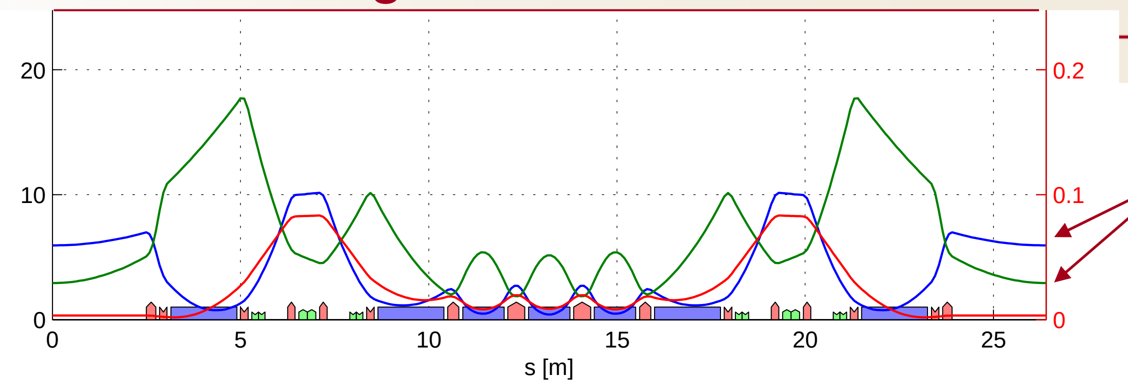
** Parameters have to be achieved simultaneously
*** increasing then 1-2% each year

DBA and H7BA scaling laws

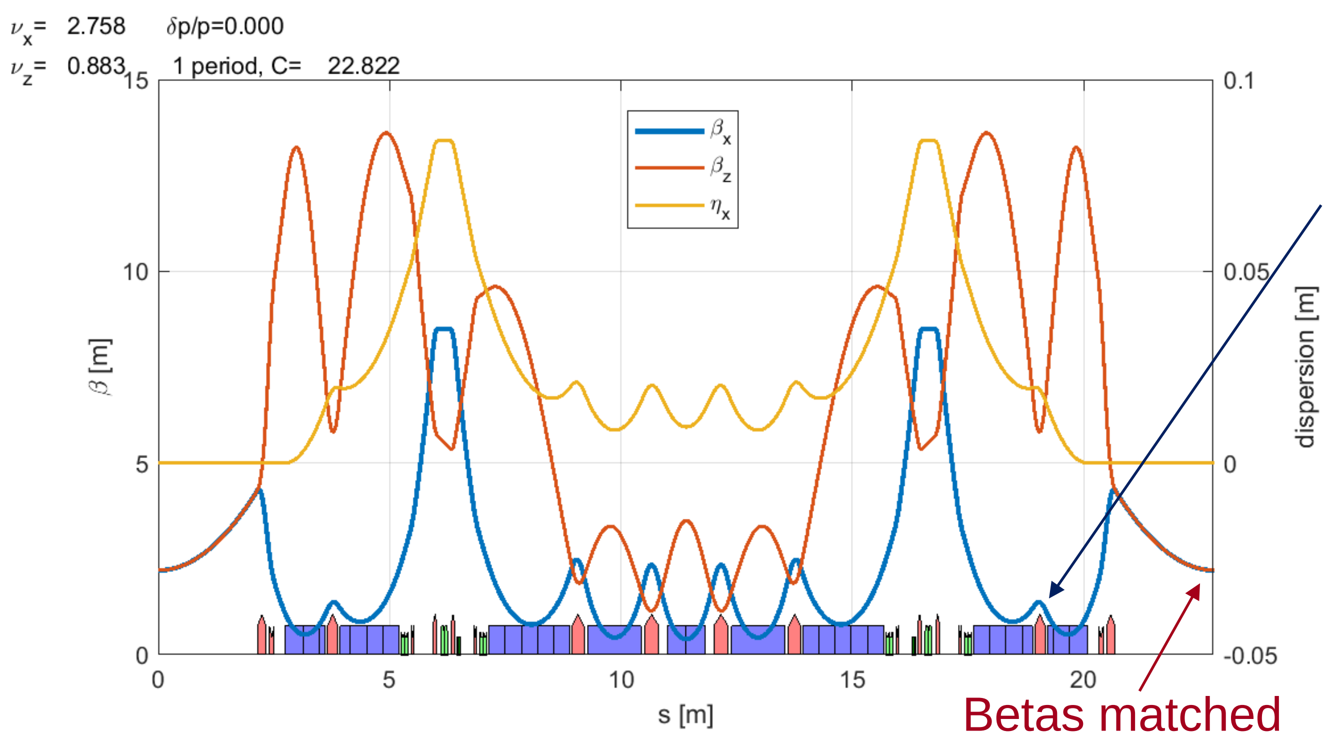
- DBA is a very relaxed optics.
- It has a “large for nowadays requirements” emittance
- DA and MA are so large that it is possible to just make rings with more cells, gaining in emittance roughly with the 3rd power of the ring circumference.
- The breakdown (lifetime<5hrs and DA<5mm) occurs around 80cells, supposing “typical” ~25mt long cells.
- Therefore it has been widely adopted, however leading to the assumption that a “good optic” can be easily rescaled

- H7BA is highly optimized for ESRF 32 cells layout.
- The breakdown occurs around 36cells.
- For a ring with fewer cells it becomes a relaxed optics as the DBA, for “nowadays requirements” does not provide the best possible emittance.

HMBA for a green field RING: SSRLX



H7BA has little control on the IDs betas, they can only be modified by large change of the overall cell phase advance. They have to be compromised with the other parameters (emittance, DA,MA etc)



One additional quadrupole (at least) is needed to have enough degrees of freedom to control the betas more effectively (Doublet => Triplet)

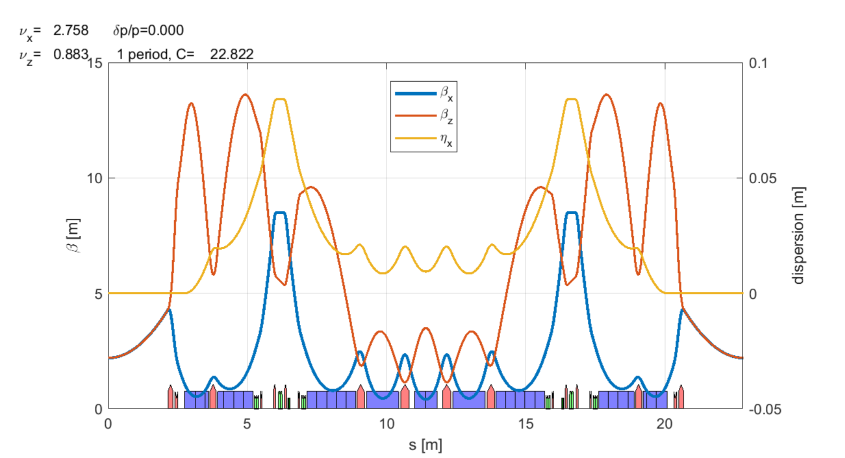
The quadrupole has been added in an optimized position the middle of the first dipole =>

H7BA becomes a very compact H9BA

A moderate gradient has been also added to all the remaining dipoles => matching improved and reduced vertical chromaticity

Horizontal phase advance increases by 0.5 wrt H7BA, but the horizontal chromaticity increases by about 10%

HMBA for a green field RING: SSRLX



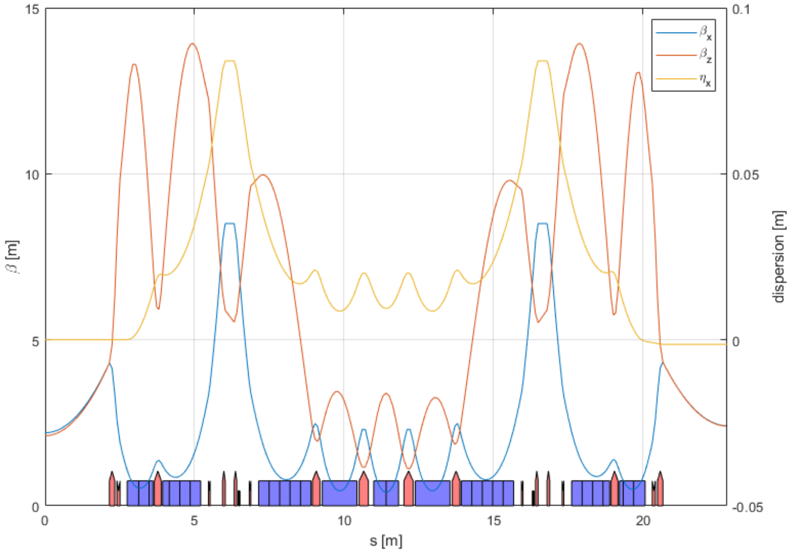
H9BA has been optimized for a 3.5GeV ring with 24 cells

The cell is dimensioned considering the EBS engineering:

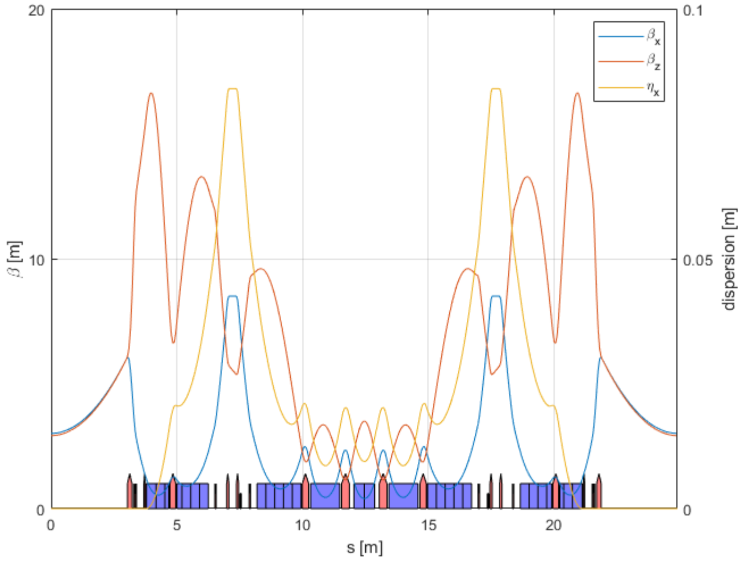
- all magnets are sized similarly: gradients, iron, coils etc, just longitudinal lengths do change (shorter), all spaces between the elements and the allocation for extra components (valves, flanges, bellows, bpms, steerers etc…) are kept as for EBS
- The vacuum chamber and the vacuum system (dimensions, antichambers, pumps etc) is supposed to be the EBS one
- Absorber heatload is about 25% of the EBS one. The geometry and the space allocation for the crotch chamber and FE is as in EBS.
- There are no components in the critical path for the finalization of the engineering of the H9BA cell

With this constraints the cell length results to be about 23m, supposing 4.3m (4.0m usable) long straight sections (SSs)

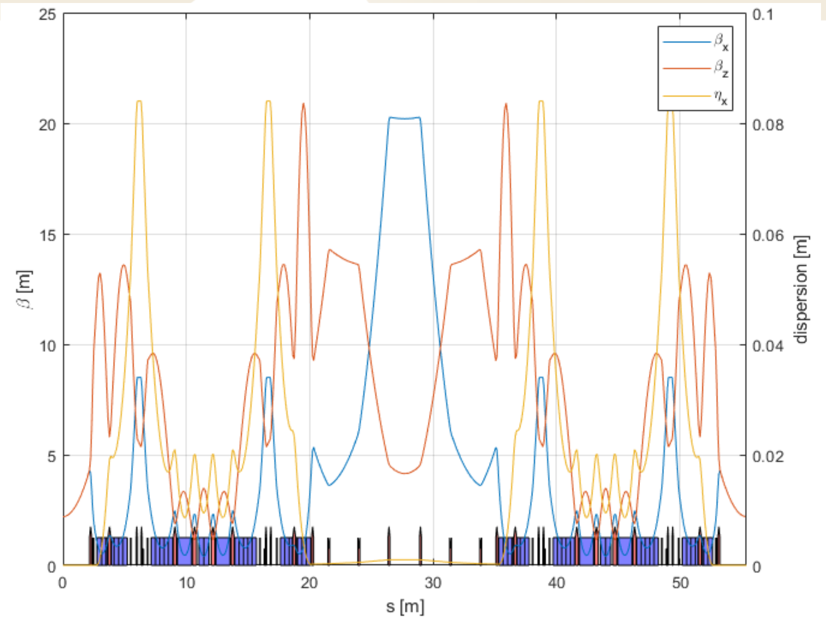
Injection and wigglers straight sections



4.3m Cell



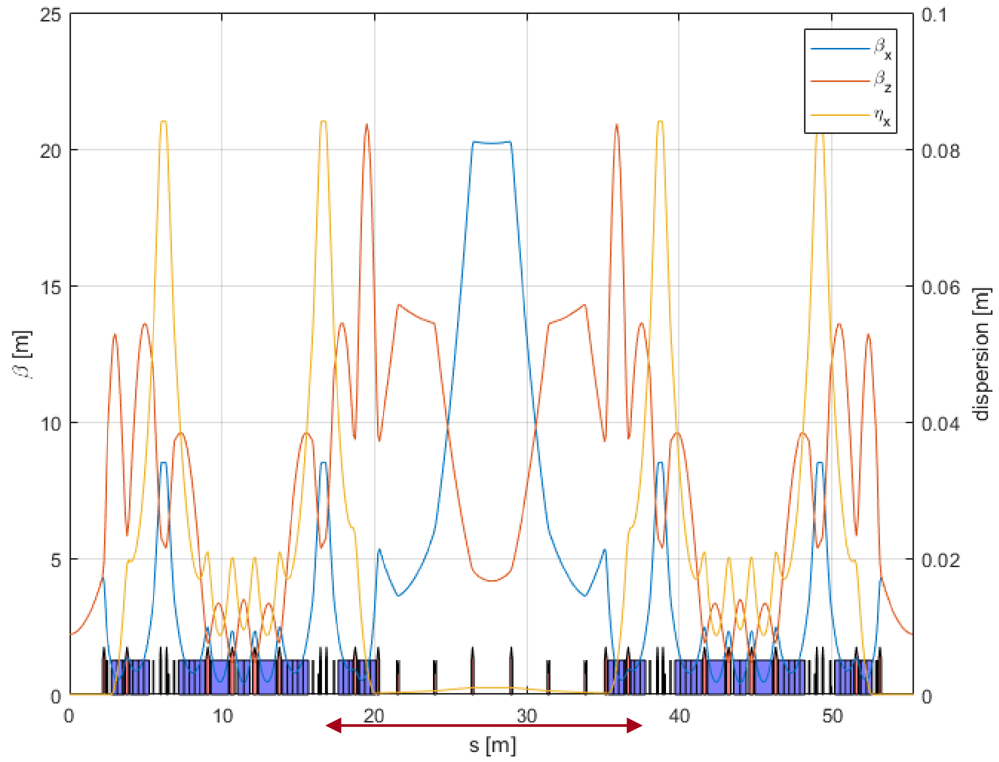
6.0m Cell



Injection Cell, section between last dipoles 10m longer wrt basic Cell

The injection cell has been optimized to reach a DA consistent with accumulation and have the injection consistent with small aperture IDs gaps in both planes (because the large demagnification (about 3) of the oscillation of the injected beam)

Transparency conditions of the insertions



Only the linear optic between the last and first sextupoles of the adiacent arcs is modified

In the middle of the cell supposing the arc a single pass line the optics must satisfy these constrains:

1) dmux = 0 +N (wrt the standard cell)
   dmuy = 0 +M/2 ("/2" comes from Hamiltonian reasoning)
   alphax=alphay=dpx=0

These conditions ensure that the periodicity is kept for the on-energy electrons

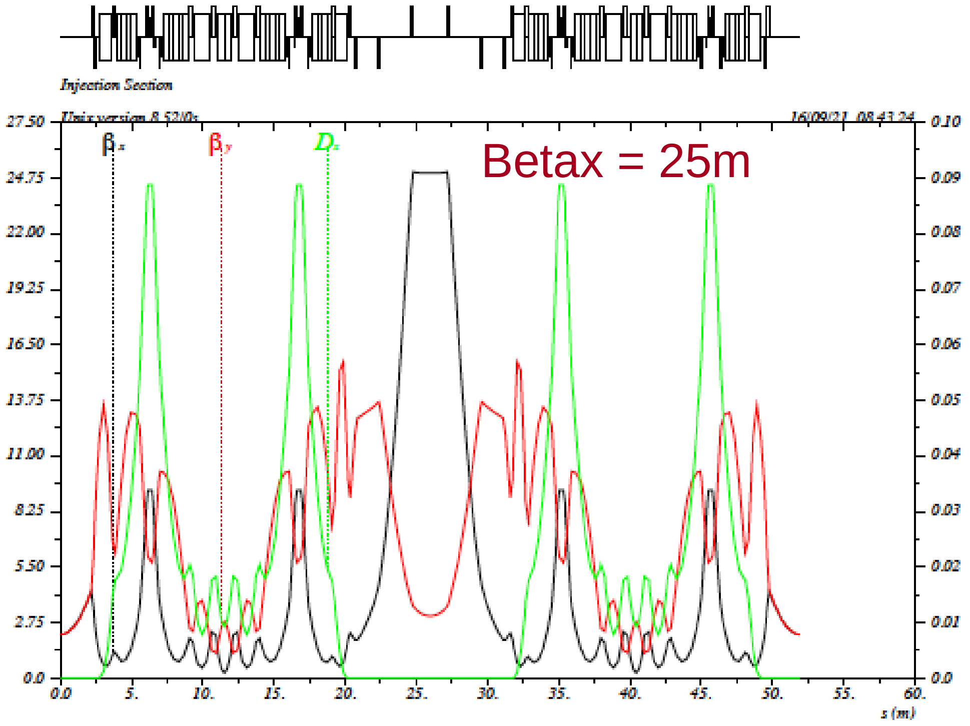
2) dWx=dWy=ddpx = 0

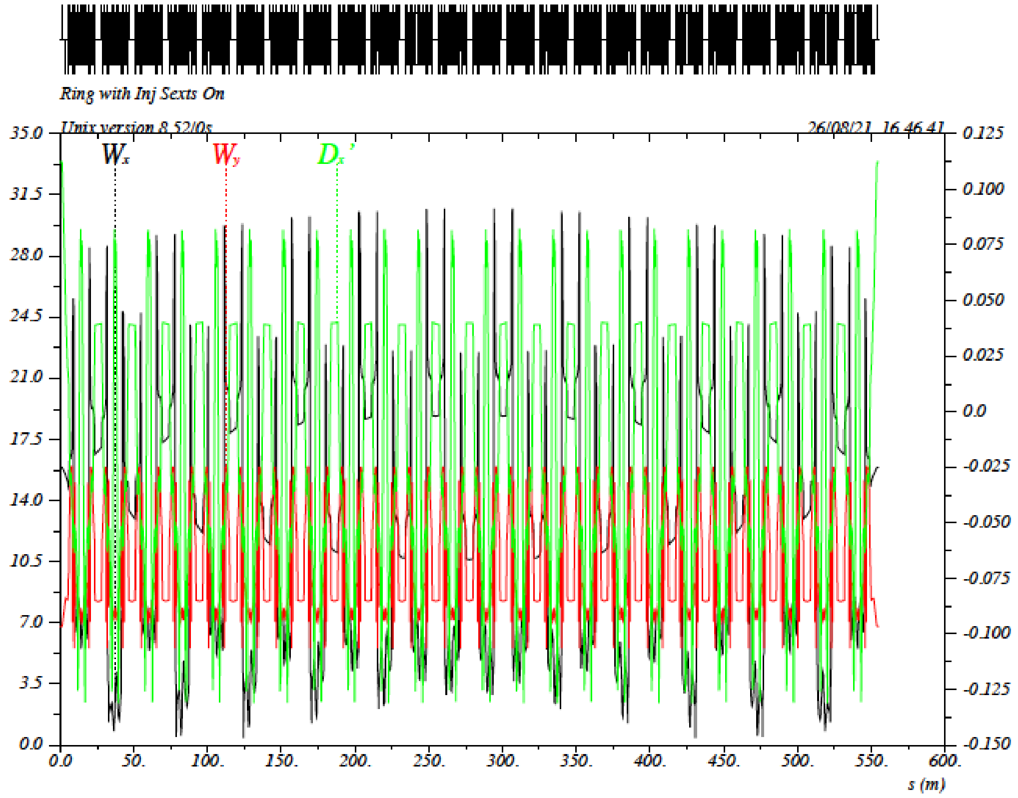
The first order derivatives wrt energy are also set to 0,
These conditions ensure that the full periodicity is kept for the off-energy electrons as well (at first order)
All these conditions can be achieved by properly adjusting the linear matching

3) For a superperiodic lattice (eg: ARCs+SSs) the phase advance between ARCs must be far from 0 and 0.5

In general, the overall chromaticity of the section should be as close as possible to the standard cell one.

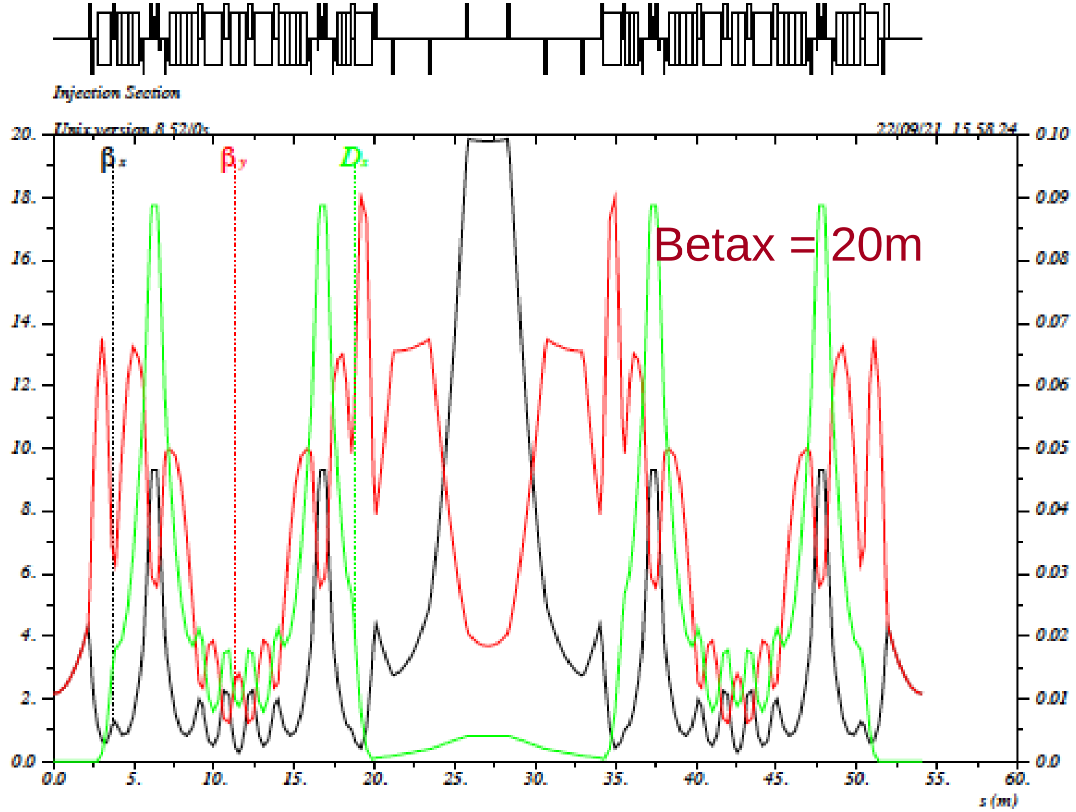
Injection & Long SS optimization



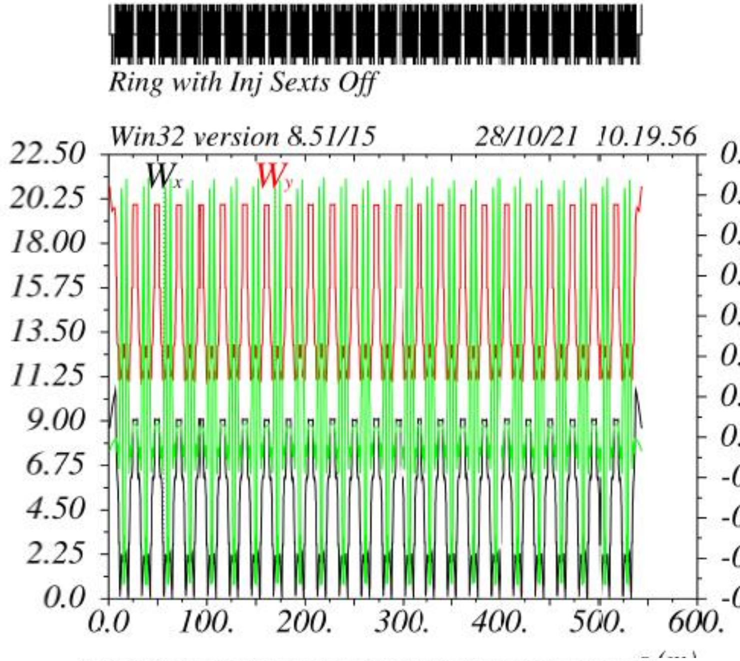


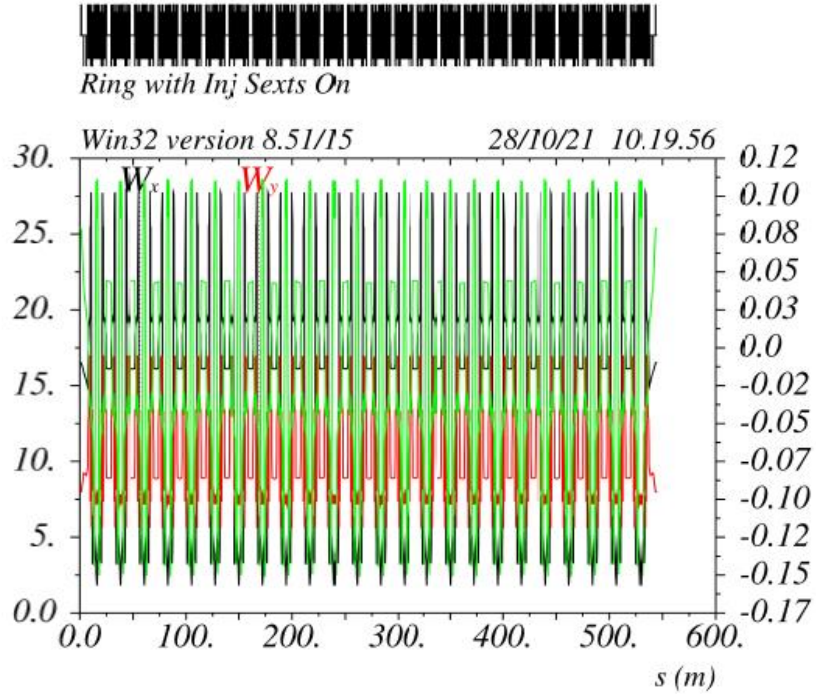
Injection cell without the conditions on the W's

Injection with (1) & (2) transparency conditions

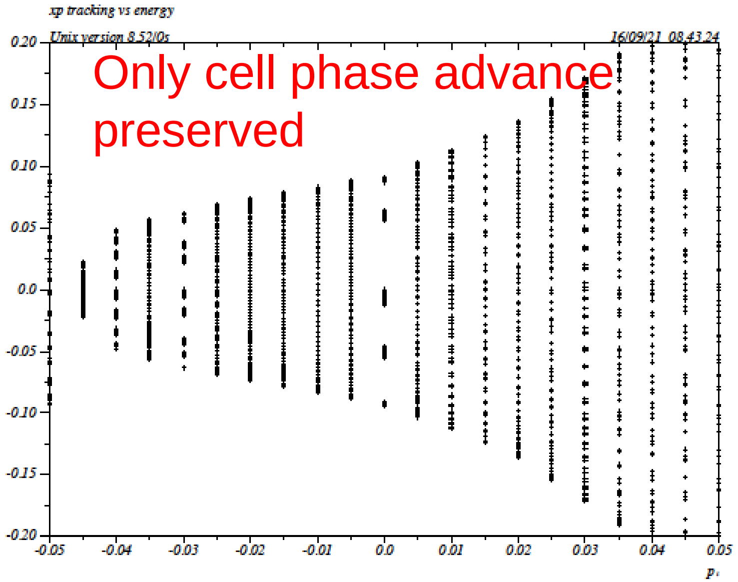


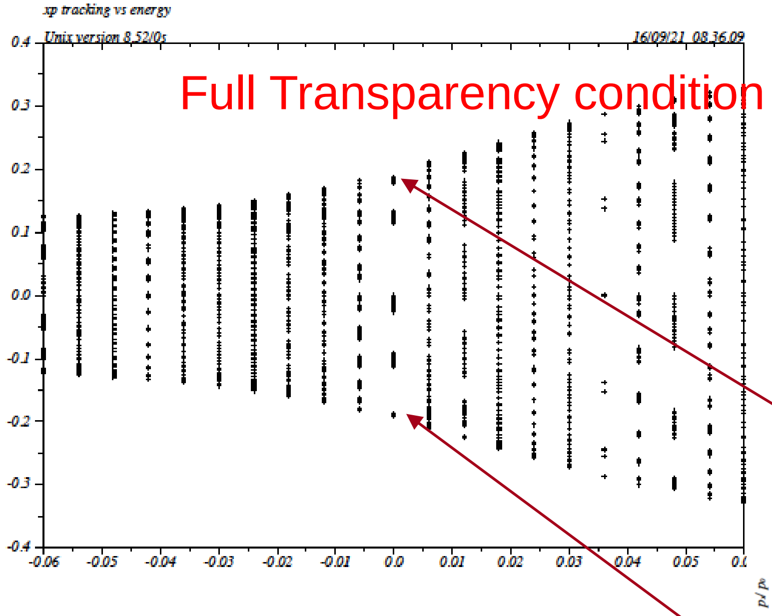
By rearranging the dispersion suppressor dipoles the transparency condition can be achieved
Condition (2) restores the periodicity of the chromatic functions. They remain periodic with sextupoles off and sextupoles on (because cond (1)).
No additional sextupole families are needed.



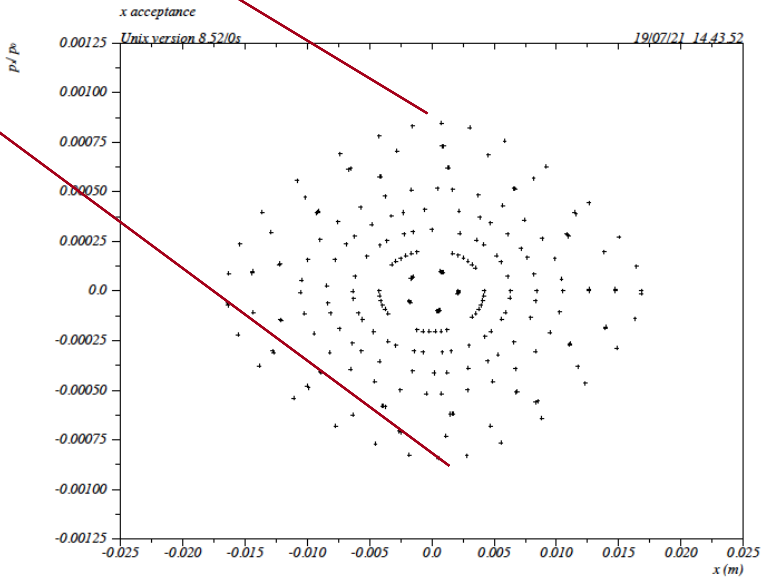


Full ring tracking





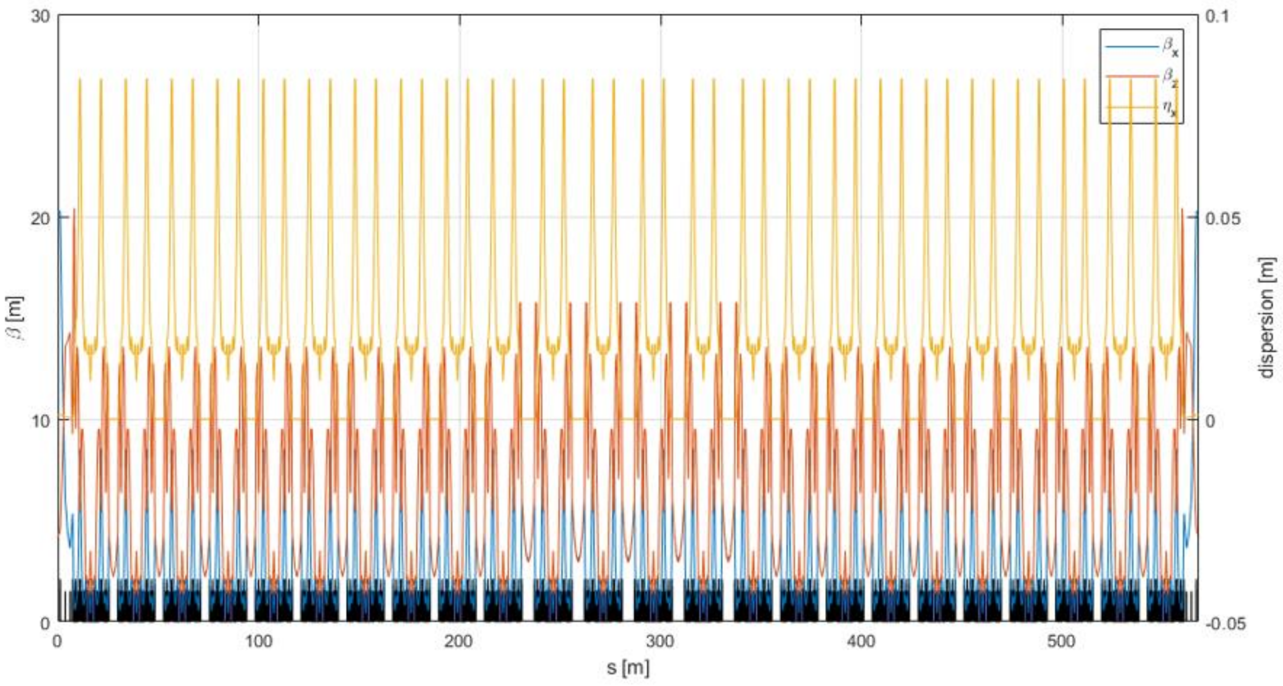
Inj_cell reduces MA (not DA btw)
A ring with two Long SS (~12mt) with nearly the same performaces of a full periodic one can be made



Xp tracking only is shown in the vertical axis (the projection) as function of different energies
The stopband for is at -4.5% for case on the left and >6% in the full TCs case

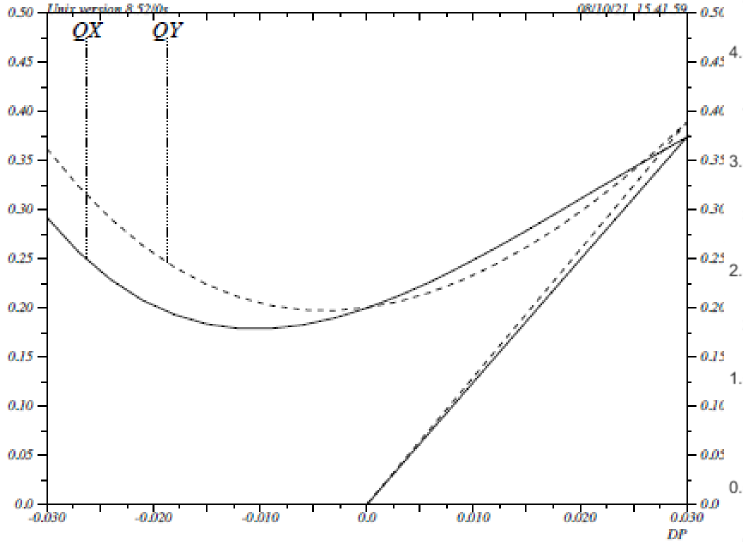
SSRL optic configuration

The SSRLX layout consists of:
24 arcs, 24 straight sections (SS)
1 SS for injection
1 SS dedicated to the RF
5 SS for wigglers
17 SS for IDs (beamlines)
The wigglers are used also for emittance-leveling
Circumference ~ 570m (including 20m lengthening from long SS)

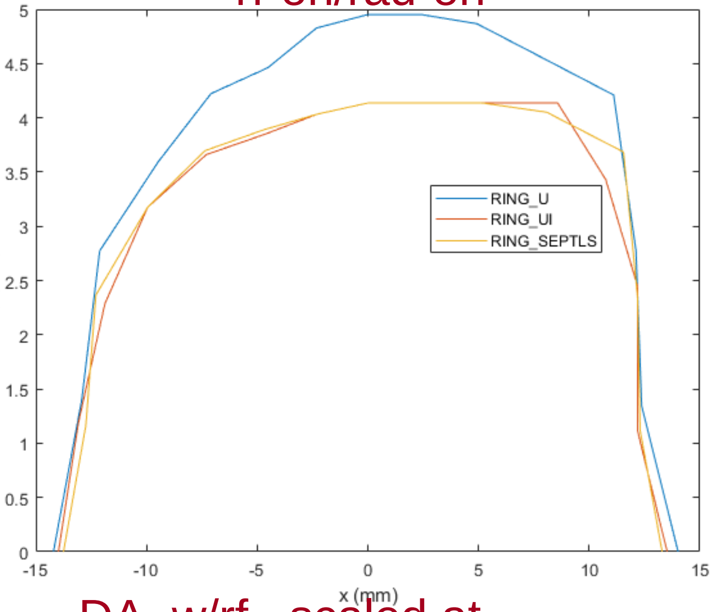


24 cells ring with one 14m long injection section and five 6m long wiggler sections (opposite)
All standard straight sections are 4.3m long

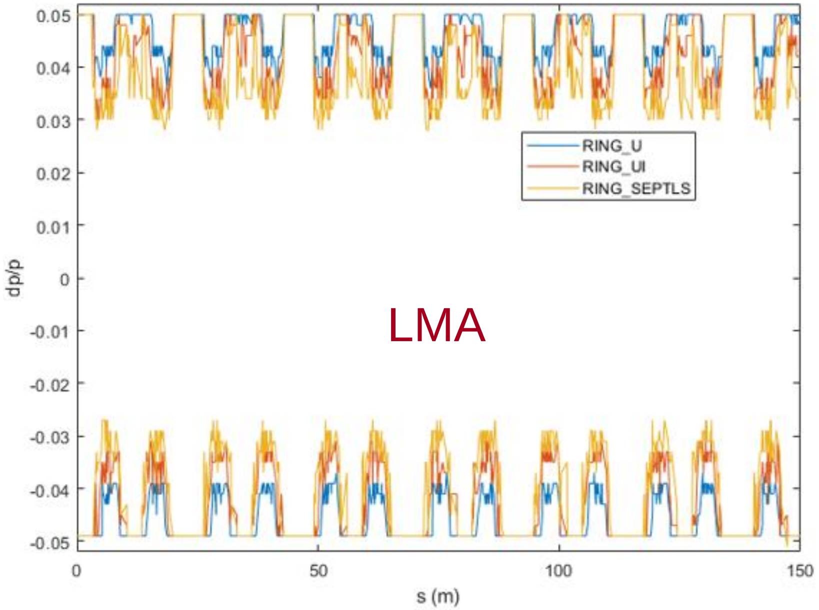
Second order chromaticity



rf-on/rad-on



DA, w/rf , scaled at
(β_x, β_y)=(20.20 m, 4.15 m)

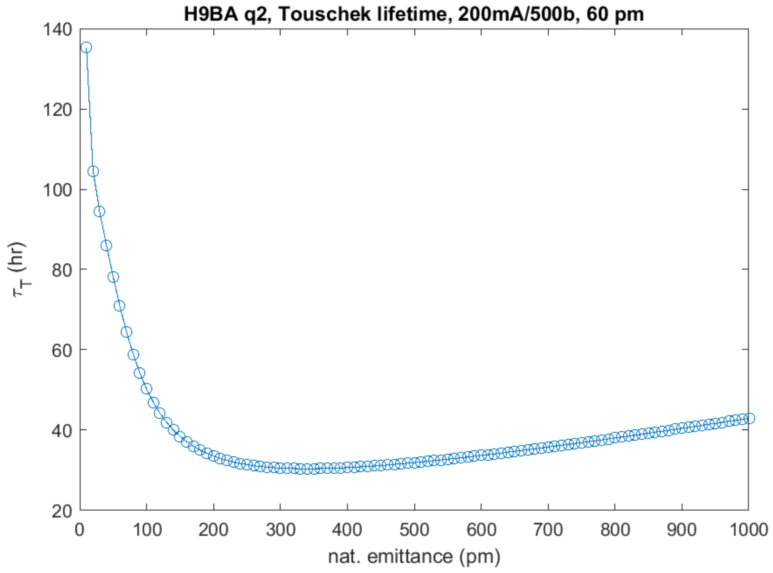


Ring_U full periodic
Ring_UI two Injection sections
Ring_SeptLS Injection and 5 wigglers sections
DA is almost unchanged for all cases
LMA decrease by about 25% => about a factor 2 decrease in TLT (because the third power scaling law)

Preliminary

Curtesy of Kim Jaehyun

TLT calculation (Piwinski's formula)



1 bunch = 0.6 mA (0.6mA*800 = 480 mA)

emittance	*TLT*
RING_U	
emitx = 60 pm , emity = 5 pm	: 8.1 h
emitx = 30 pm , emity = 30 pm	: 32.7 h
RING_UI	
emitx = 60 pm , emity = 5 pm	: 5.0 h
emitx = 30 pm , emity = 30 pm	: 18.9 h
RING_SEPTLS	
emitx = 30 pm , emity = 5 pm	: 5.09 h
emitx = 15 pm , emity = 15 pm	: 15.68 h

Thanks to the large momentum acceptance and the small emittance we are in a region where the TLT increases for smaller and smaller emittances
The beam is so cold that little energy can be transferred from the transverse to the longitudinal plane =>

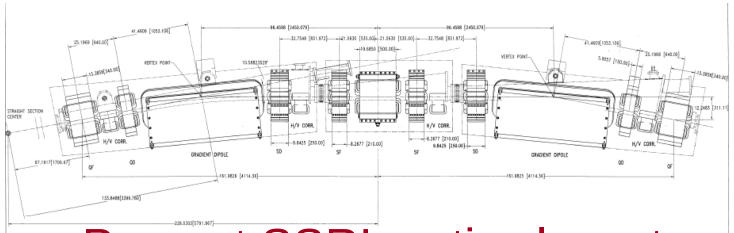
sigx'*gamma<MA

Preliminary

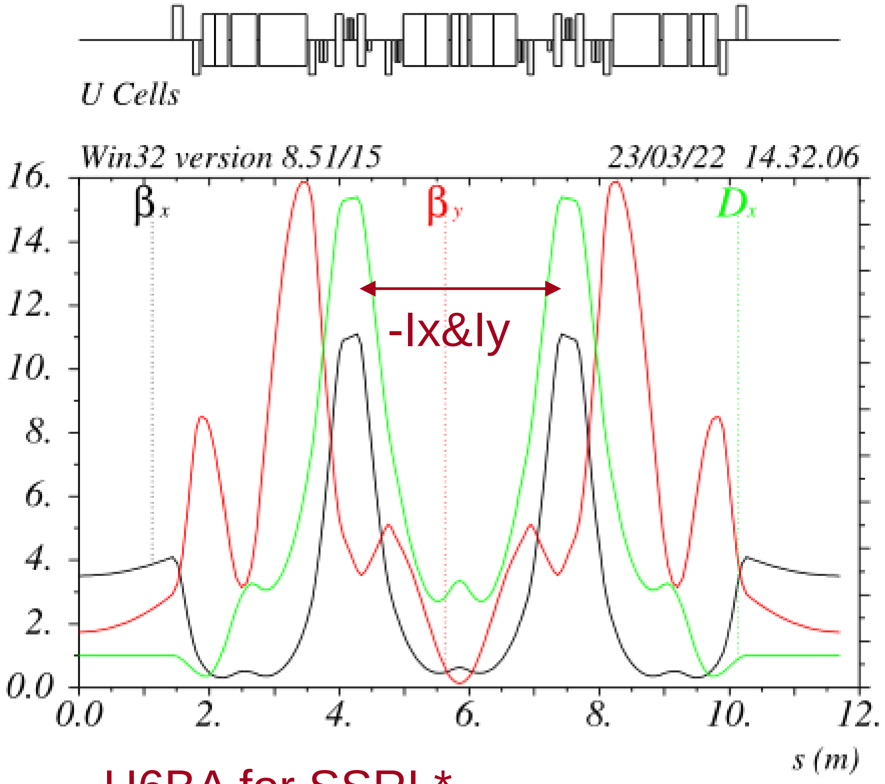
The H9BA-SSRLX TLT is larger than the SSRL operational TLT (with Ex=7.0nm)

Huang Xiaobiao, Kim Jaehyun

H6BA: a very compact and high performing cell



Present SSRL optics layout



H6BA for SSRL*

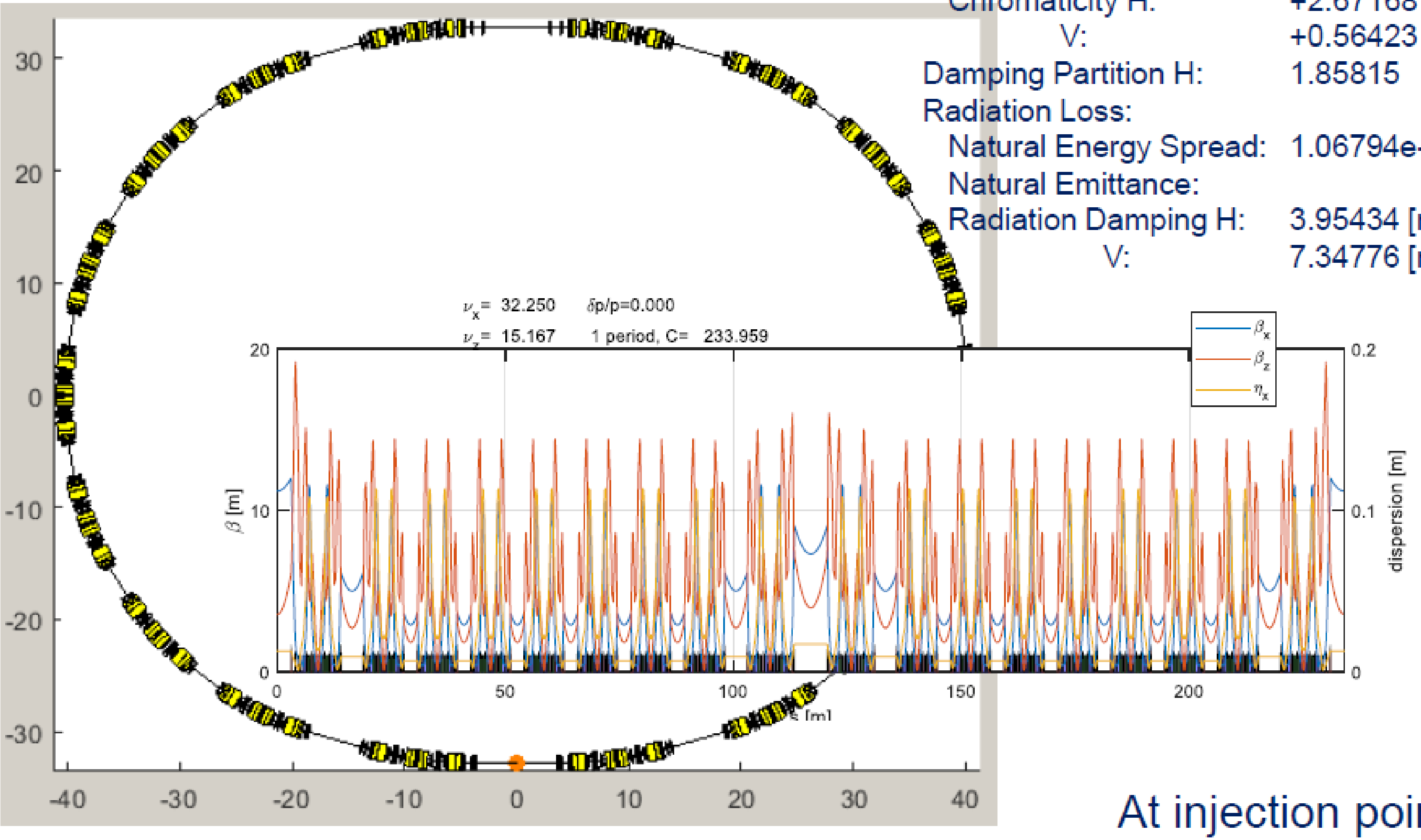
*SRRLUP is not diffraction limited, betax@ID is not matched

- H6BA first developed for Petra4 upgrade
- Potentially very large DA&MA, breakdown > 80cell
- Preliminary Petra4 cell had large detunings (x,y and de) leading to a performances reduction with errors
- H6BA has been extensively reoptimized:
  - all detunings have been nearly zeroed
  - reduced number of magnets
  - reduced gradients for quads/sexts/octs
- H6BA has been optimized for:
  - SSRL upgrade: replace the present 2BA
  - SSRLX: a green field option C~600m
  - SDLS (Slac Diffraction Limited Synchrotron) in the PEP tunnel C=2196m

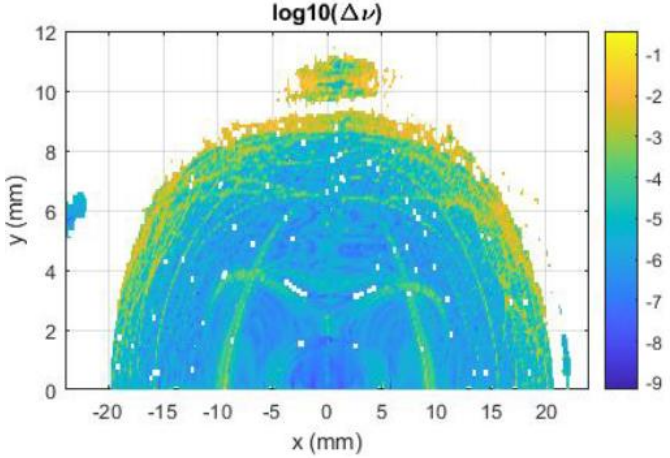
Linear lattice

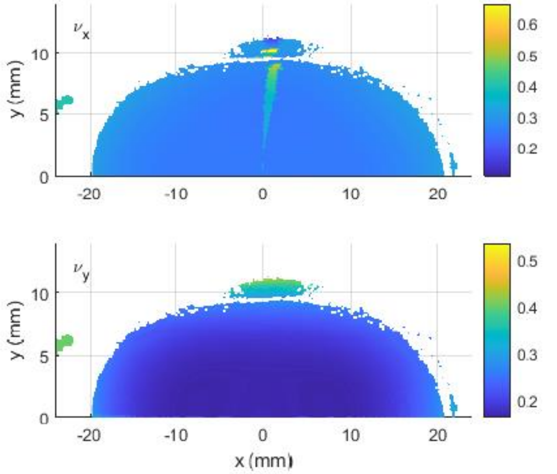
H6BA SSRLUP:
a very compact upgrade

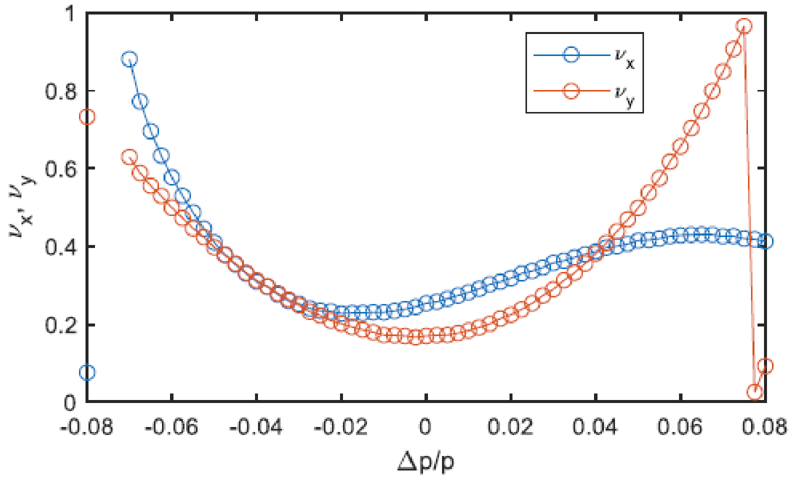
Energy:	3.00000 [GeV]
Circumference:	233.95945 [m]
Revolution time:	780.40472 [ns] 1.28139 [MHz])
Betatron tune H:	0.24999 (320.33348 [kHz])
V:	0.16679 (213.72707 [kHz])
Momentum Compaction Factor:	0.00044
Chromaticity H:	+2.67168
V:	+0.56423
Damping Partition H:	1.85815
Radiation Loss:	637.25949 [keV]
Natural Energy Spread:	1.06794e-03
Natural Emittance:	3.64531e-01 [nm]
Radiation Damping H:	3.95434 [ms]
V:	7.34776 [ms]

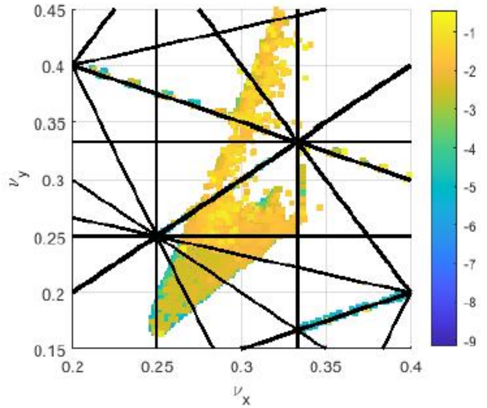


At injection point
beta: [11.1580 3.5813]







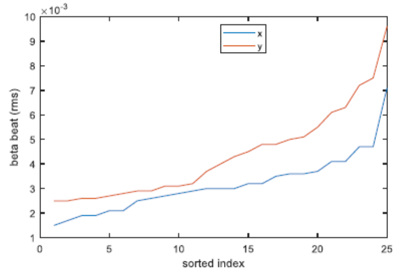


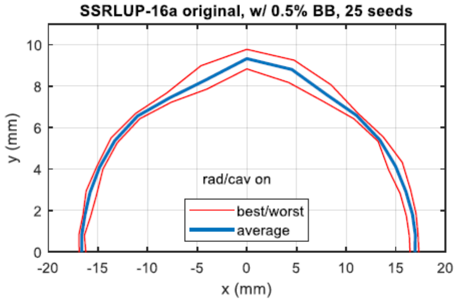
X. Huar

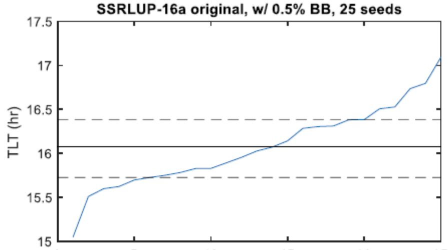
DA/MA w/ multiple error seeds

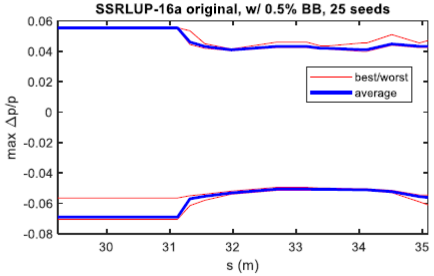
Ib = 1.79 mA
Vrf = 3.50 MV
nat. emit = 250.00 pm
sigz = 3.48 mm, sig_dpp=1.0684E-3

- Evaluated DA/MA with 25 random seeds
  - Generate errors with quadrupole and skew quadrupole errors on sextupoles





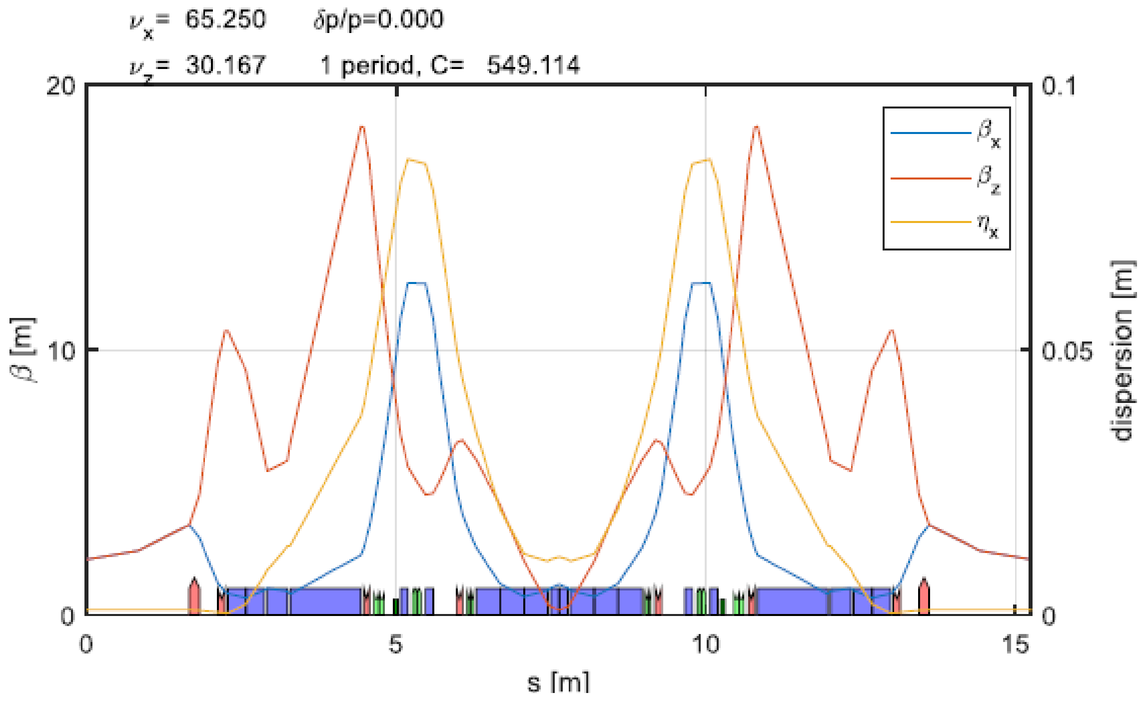




DA&MA very large
Performance degradation with errors very moderate

TLT = 19.88 hr
Ib = 1.79 mA
Vrf = 3.50 MV
nat. emit = 250.00 pm
sigz = 3.48 mm, sig_dpp=1.0684E-3

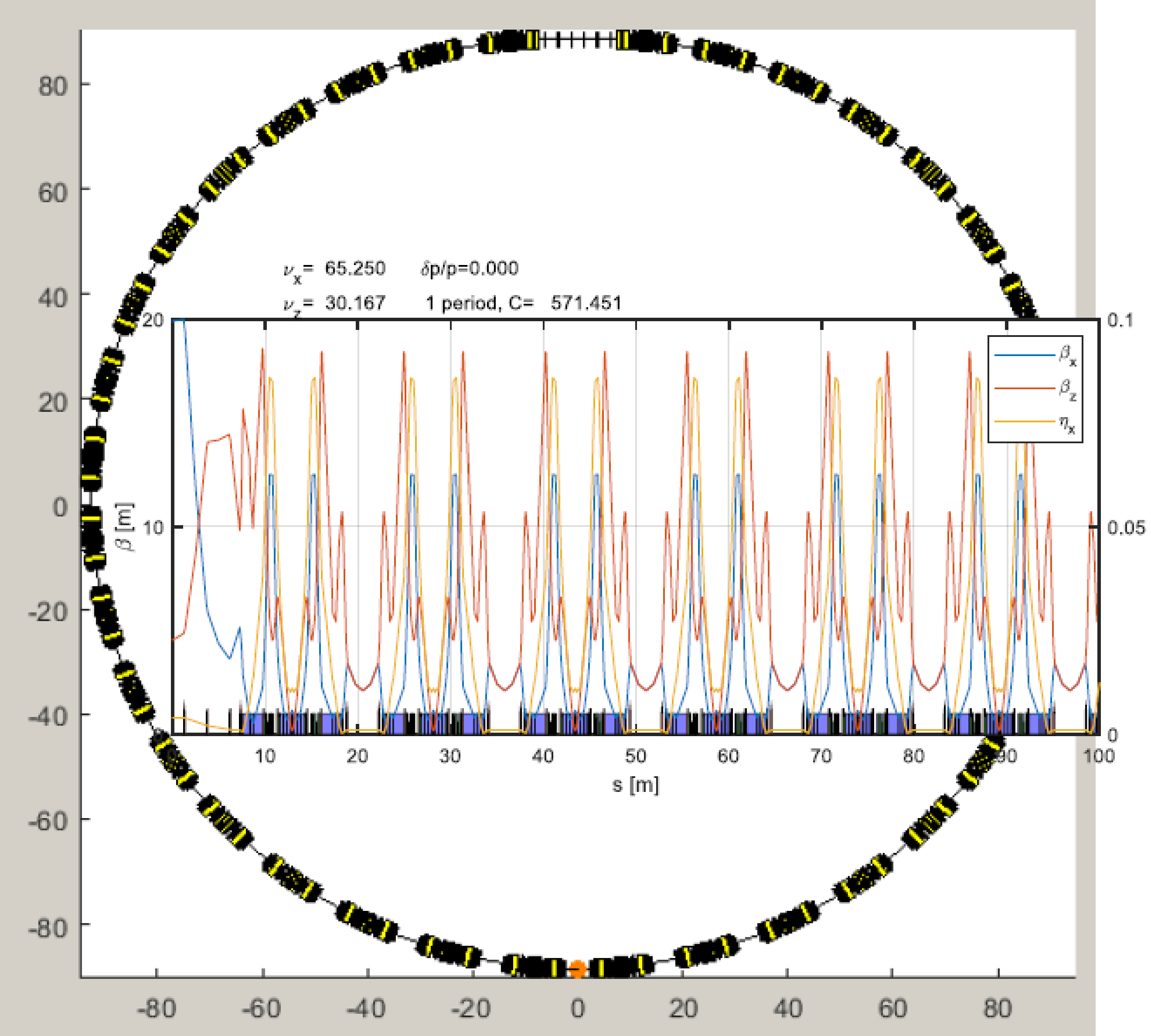
H6BA SSRLX@4GeV* (green field): 36 Cells



Energy:	4.00000 [GeV]	
Circumference:	549.11376 [m]	
Revolution time:	1831.64635 [ns] (0.54596 [MHz])	
Betatron tune H:	0.24999 (136.48246 [kHz])	
V:	0.16676 (91.04527 [kHz])	
Momentum Compaction Factor:		0.00013
Chromaticity	H:	+6.06286
	V:	+2.20201
Damping Partition H:	2.10561	
Radiation Loss:		697.92489 [keV]
Natural Energy Spread:	9.34790e-04	
Natural Emittance:		8.37871e-02 [nm]
Radiation Damping H:	9.97114 [ms]	
V:	20.99534 [ms]	
E:	23.47450 [ms]	

*4GeV preferrable for IBS

At ID location:
beta: [2.1000 2.1000]



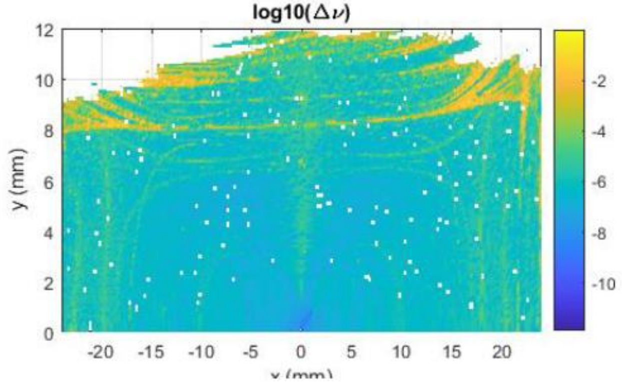
Energy: 4.00000 [GeV]
Circumference: 571.45056 [m]
Revolution time: 1906.15389 [ns] (0.52462 [MHz])
Betatron tune H: 0.24998 (131.14546 [kHz])
V: 0.16677 (87.49115 [kHz])
Momentum Compaction Factor: 0.00013
Chromaticity H: +4.85125
V: +1.79587
Damping Partition H: 2.11066
Radiation Loss: 697.85458 [keV]
Natural Energy Spread: 9.36207e-04
Natural Emittance: 8.53796e-02 [nm]
Radiation Damping H: 10.35295 [ms]
V: 21.85159 [ms]
E: 24.57066 [ms]

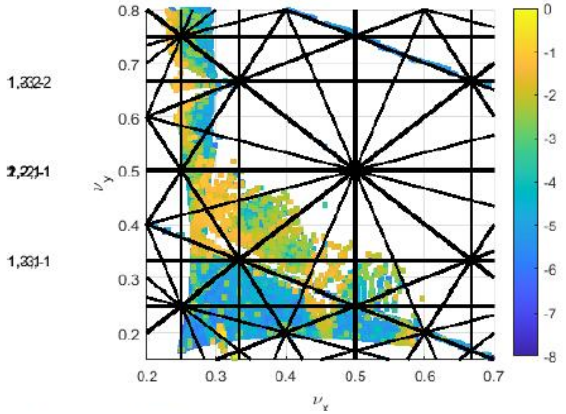
Injection Cell included

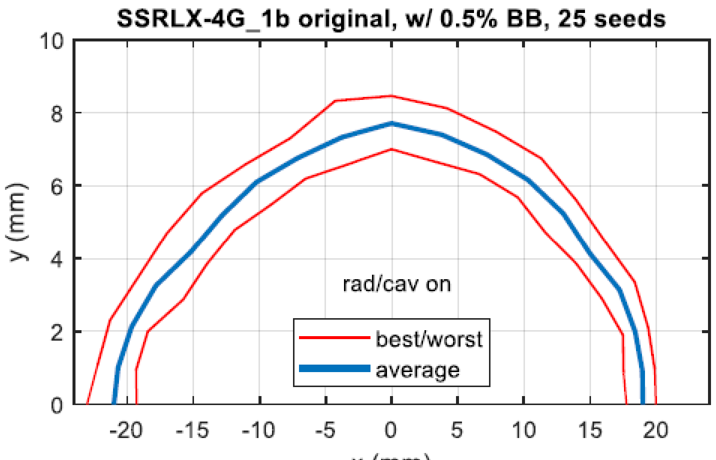
7 IDs opposite to IC are longer

At injection point
beta: [19.9001 4.5360]

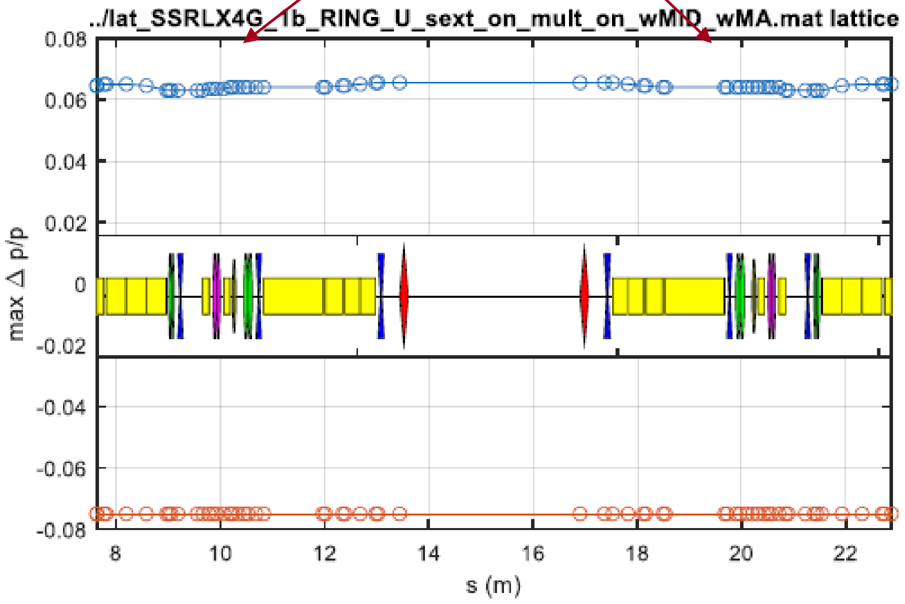
DA is so large that MA is not affected in the region were Curl_H<>0







X. Huang (SLAC)



Very large TLT

TLT = 472.00 hr

Ib = 0.10 mA

Vrf = 6.00 MV

nat. emit = 43.00 pm

sigz = 2.01 mm, sig_dpp=0.9353E-3

Pep tunnel: SDLS Separate Functions Arcs

A lattice to deliver the lowest possible emittances in the PEP tunnel is being studied: SDLS-SFA

SR energy: 5GeV

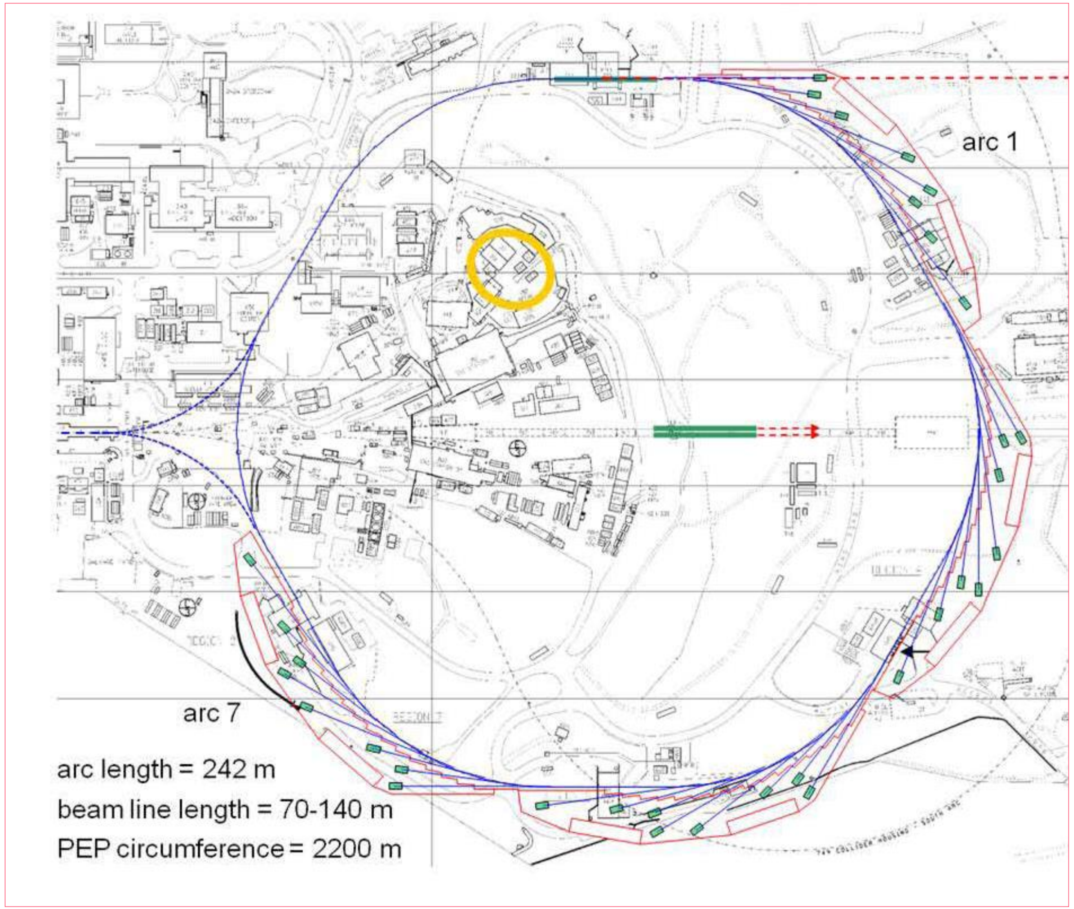
1 Arcs 243m long composed of 12 H6BA cells 20.25m each with 4.3m straight sections compatible with 4m mechanics

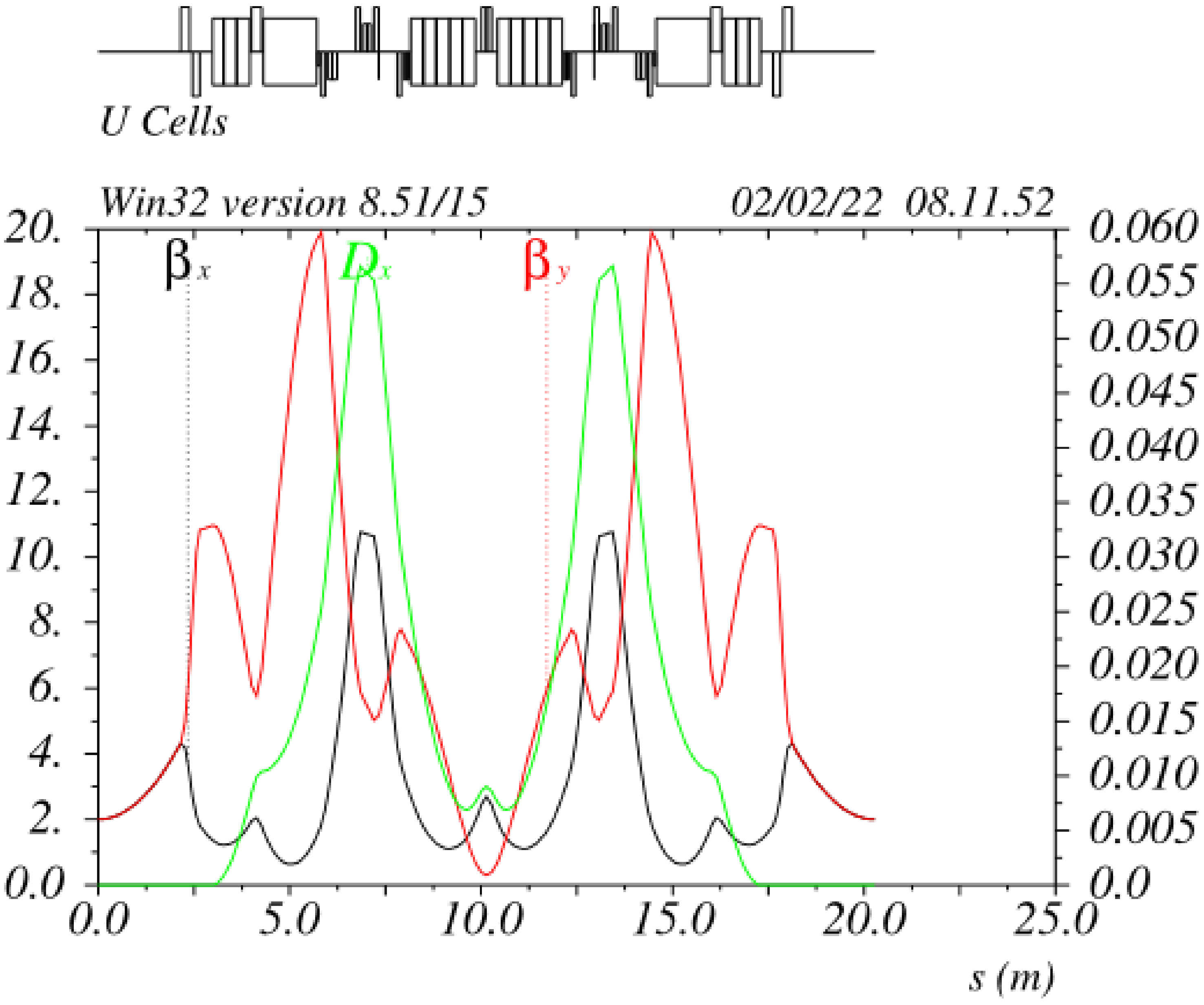
5 Arcs 243m long composed of 16 Hybrid Minimum Emittance (HME) cells 15.187m each*

6 straight section 123m long with 2 double-minibetas canted IDs 16m long

The straight sections are compatible with injection and RF needs

* Performances are shown for the case with 6 identical Arcs all equipped with IDs: 72 identical cells



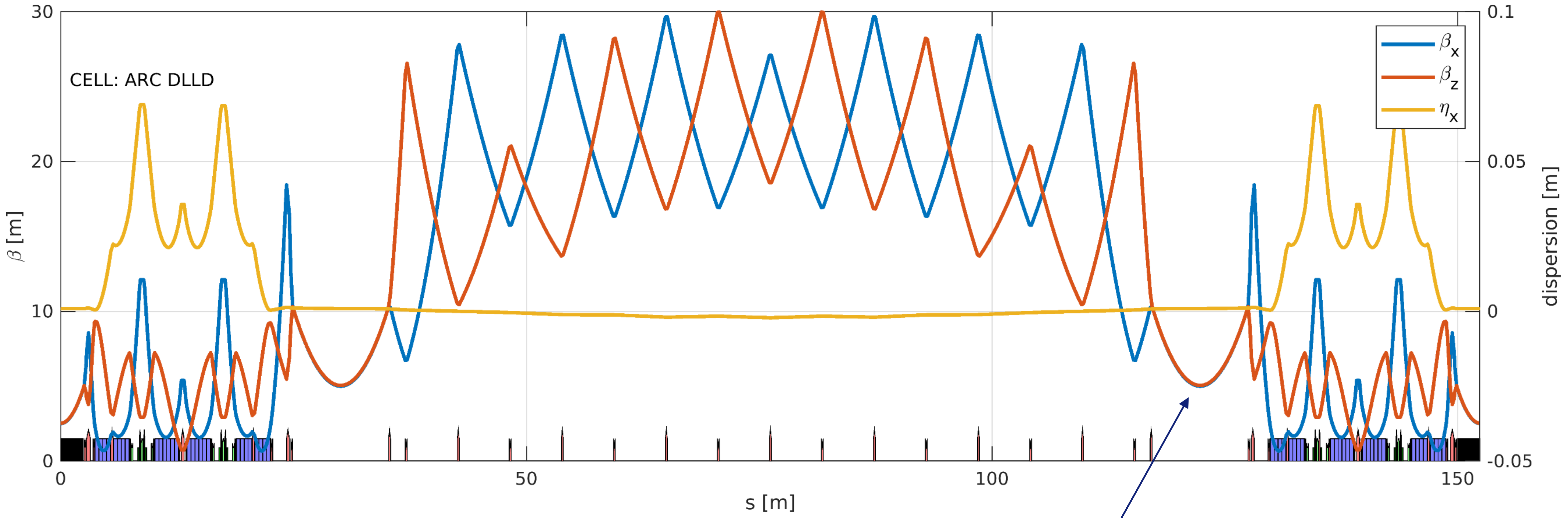


SDLS with 6 Arcs
with 12 H6BA12 Cells/Arc

Mux ~ 1.75
Muy ~ 0.85

Ex ~ 28pm
(Ex ~ 8pm with wgls&coupl)
Sige~0.7e-3
Jx~ 1.70
Eloss ~0.7MeV

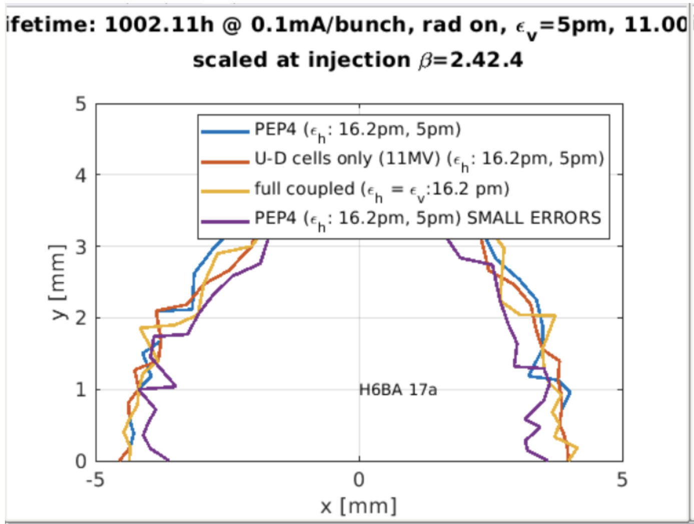
LONG STRAIGHT SECTION WITH LOW BETA INSERTIONS

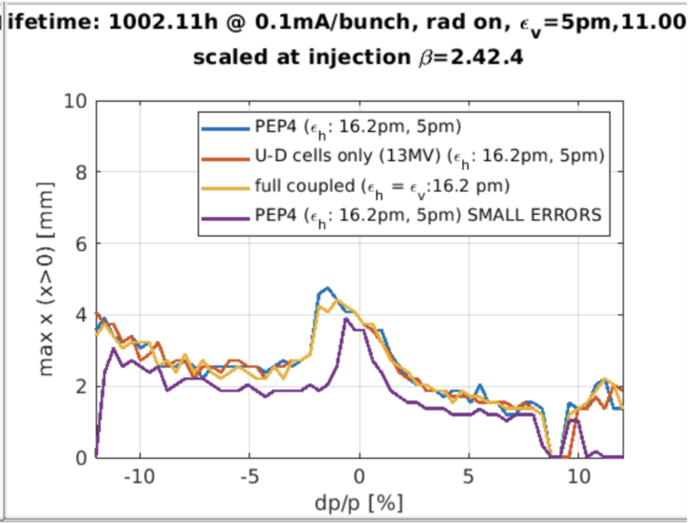


L = 10.3m, betx = bety = 5m

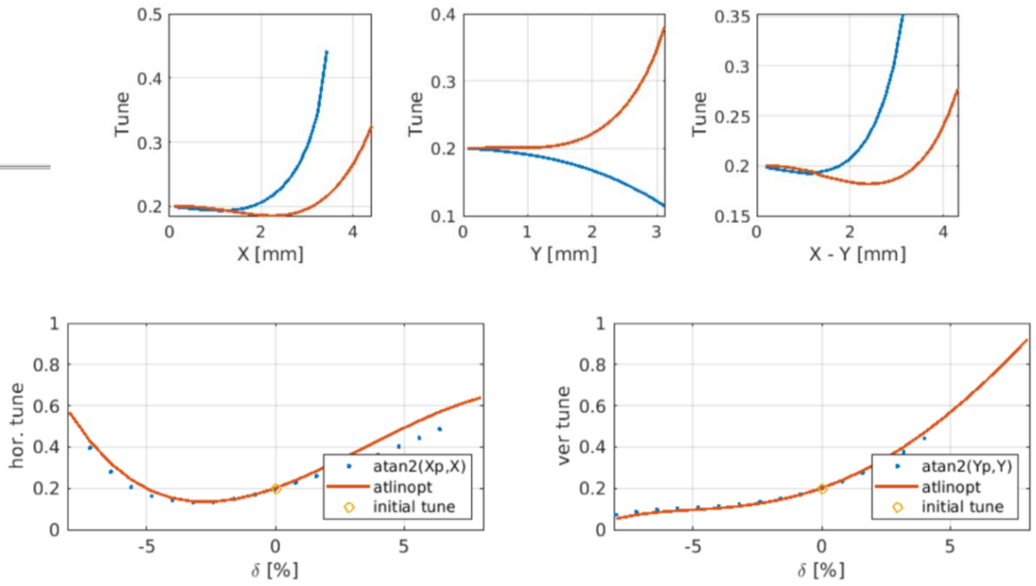
The chromaticy increase from each SSs is about 1% in both planes, about 8% total per plane
The expected reduction in DA/EA is about 16% and about 36% for the TLT

SDLS PERFORMANCES: DYNAMIC APERTURE AND ENERGY ACCEPTANCE





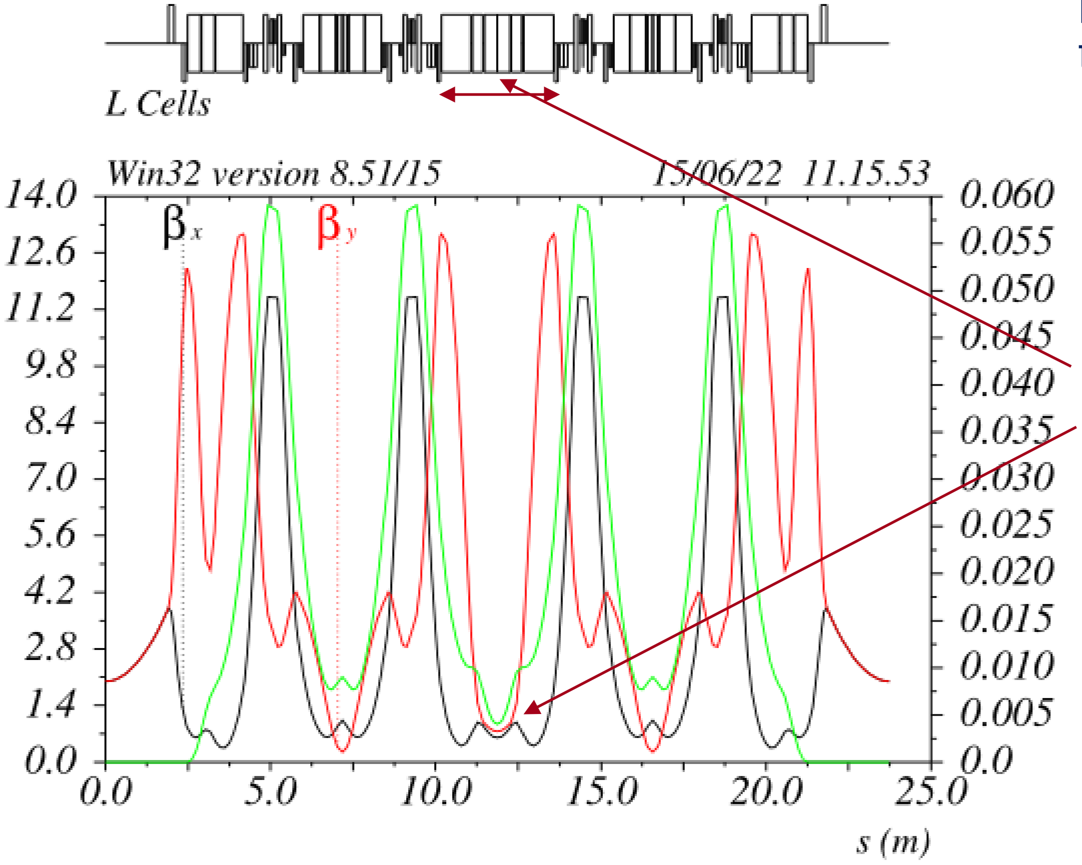
The DA at septum exeeds 15mm.
The MA is of the order of +/-8%
The TLT is of the order of 500hrs.
The drop in performances due to errors is very moderate, given the very moderate detunings



It is possible to design a Diffraction Limited Optics with unprecedented characteristics

Curtesy of S Liuzzo

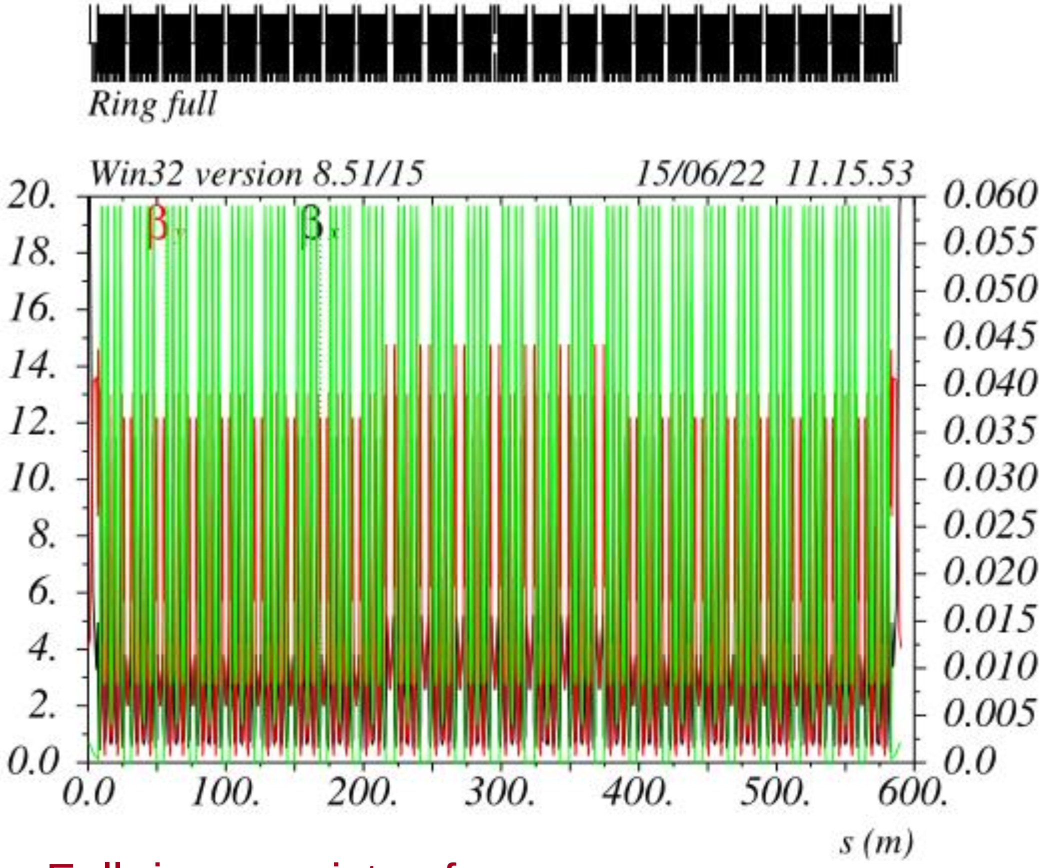
H11BA for 24 cells @ 4.0GeV

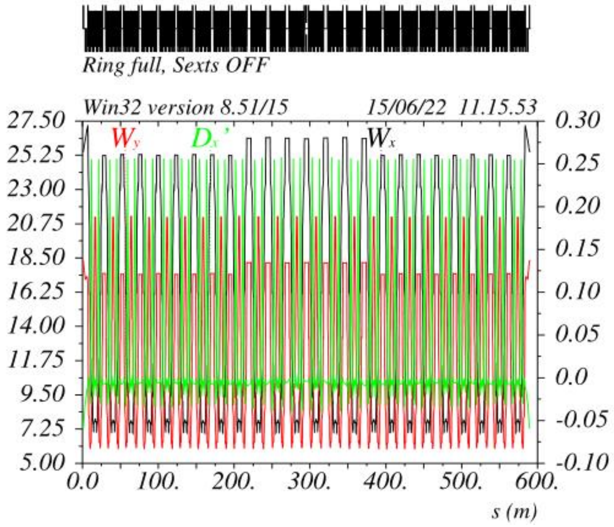


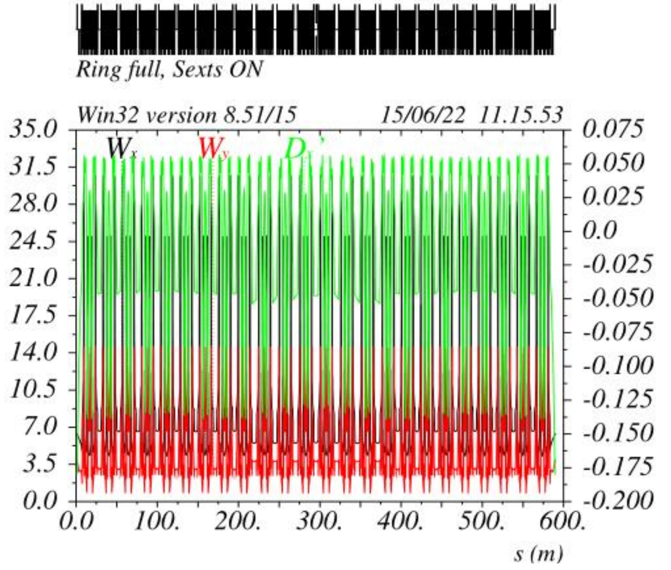
Two H6BA cells can be merged together, maintaing the phase advance between the sextupoles pairs Equal_Modulo_Pi to the ones cell-to-cells

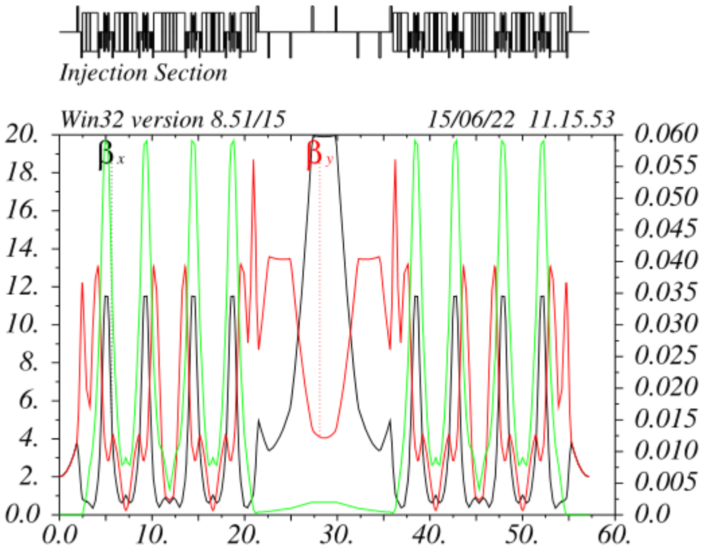
- Central section reoptimized: 3 bends instead of 4
- H12BA becomes H11BA
- Central dipole has no gradient
- Double minibeta (~0.5m) and small dx in the middle of the cell:
  - a superbend (~1-2T) could be very performing:
    Sigmax~3um, Sigmay~3um
    Xp~2mrad, Sigmayp~6urad
  - a microundulator, length~0.5m, gap~2mm could be conceivable as well
- In principle 22 additional “special” sources are available (2 not available upstream Inj&RF section)

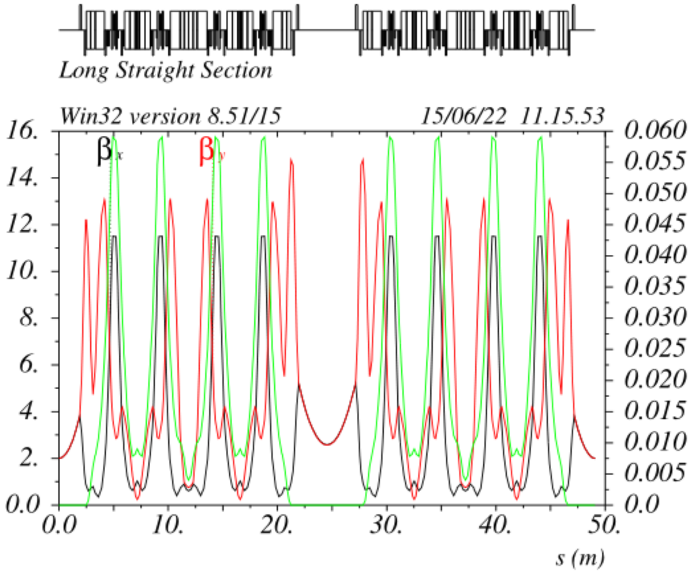
H11BA for 24 cells @ 4.0GeV



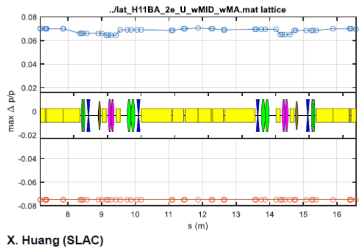








- Full ring consists of:
  1 injection cell ~ 10m long (quad to quad)
  1 RF section 5.1m long
  1 Wiggler section 5.1m long
  5 IDs sections 5.1m long
  16 IDs sections 3.8m long
  22 specialized “short sources” available



TLT = 349.18 hr
Ib = 0.10 mA
Vrf = 6.00 MV
nat. emit = 43.00 pm
sigz = 1.52 mm, sig_dpp=0.8254E-3

H6BA

C = 549.1m
Energy = 4.0GeV
Total cells = 36

Ex = 83.8pm
Jx = 2.11
U0 = 0.698MeV
Sige = 0.94e-3
Sigs ~ 3.0mm
Cx = -121.6
Cy = -131.2

IDs L=3.0 parameters:
Betax = 2.10m
Dx = 1.0mm
Betay = 2.10m

H9BA

C = 576.5m
Energy = 4.0GeV
Total cells = 24

Ex = 81.7pm
Jx = 2.00
U0 = 0.610MeV
Sige = 0.81e-3
Sigs ~ 2.0mm
Cx = -95.3
Cy = -92.5

IDs L=4.0 parameters:
Betax = 2.20m
Dx = 0.0mm
Betay = 2.20m

H11BA

C = 569.7m
Energy = 4.0GeV
Total cells = 24

Ex = 46.2pm
Jx = 1.99
U0 = 0.625MeV
Sige = 0.82e-3
Sigs ~ 2.0mm
Cx = -150.8
Cy = -144.6

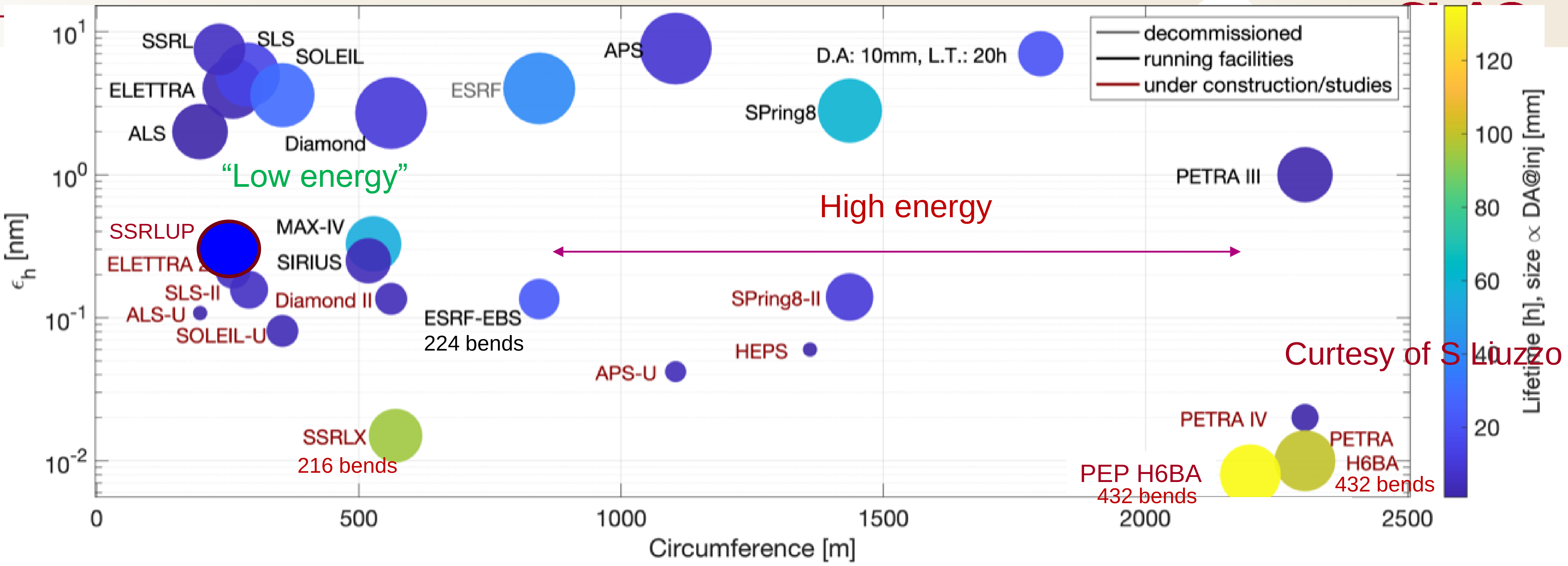
IDs L=3.8 parameters:
betax = betay=2.00m
dx = 0.0mm

IDs L=5.1 parameters:
betax = betay=2.60m
dx = 0.0mm

SIDs L~0.5m betax~betay~0.5m dx~3mm

SSRLX lattices options
H11BA has the smallest emittance
(preferred, just one wiggler is required for emittance stabilization)
H6BA has the largest number of IDs
H9BA had the smaller number of components

synchrotrons portfolio performances



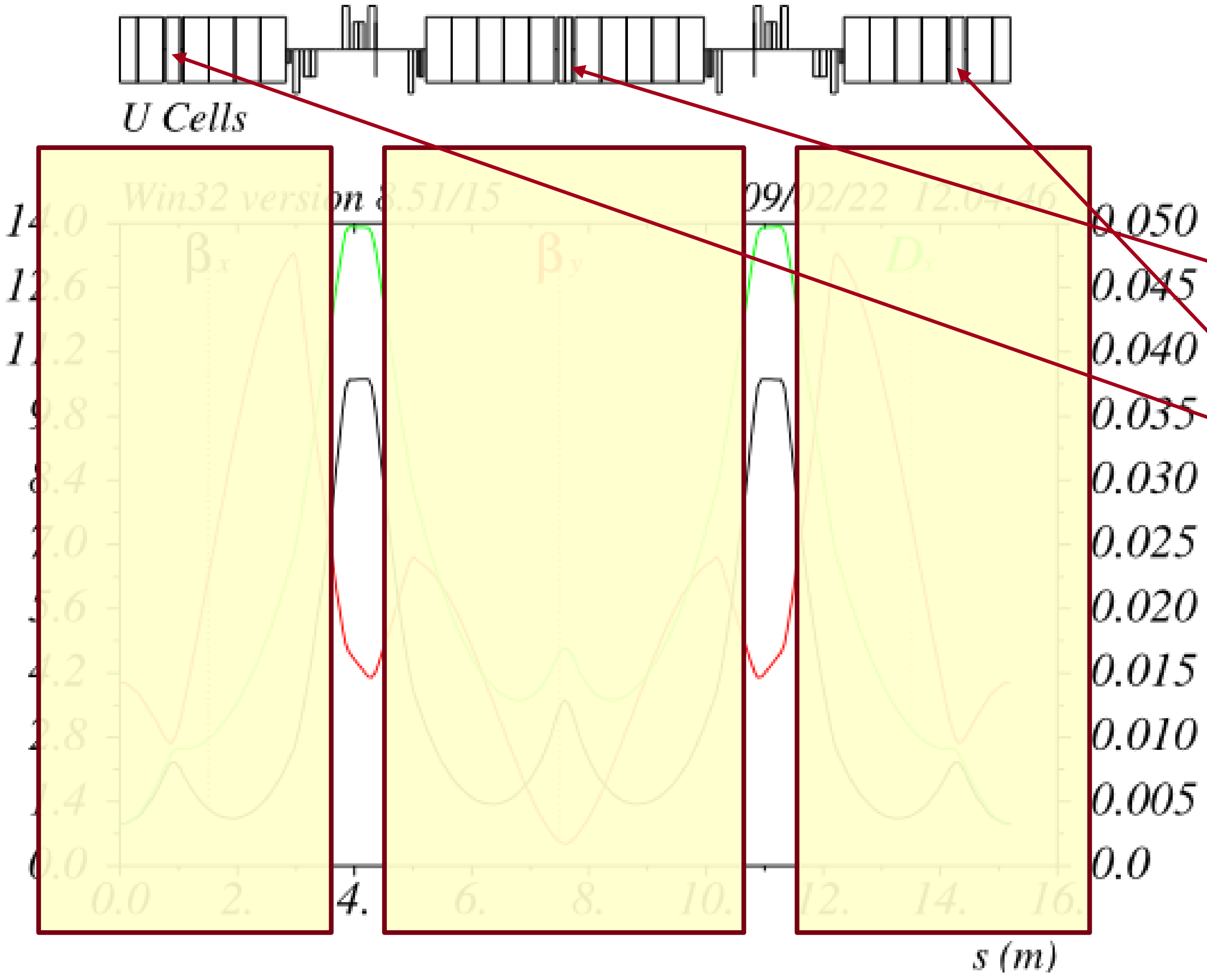
H9BA and H6BA could be a quantum leap in the synchrotron accelerator technology.
They can achieve the "long sought" diffraction limit, while keeping all the other DBA properties
They can provide a new window of discovery for Xray based science.

CONCLUSIONS

SLAC

- The accelerator scientific community is very active in order to produce a new generation of low emittance synchrotrons
- Based on the present know-how and technology it is conceivable to build synchrotrons that are at least 10 times more performing than the present state-of-the-art
- The long-sought Diffraction Limit is within our reach
- H7BA has pioneered the facilities upgrades
- H9BA, H6BA and H11BA have much higher performances wrt H7BA and very large flexibilities to cover all possible requirements for upgrades or green field projects
- It is possible to push forward the frontier of synchrotron based Xray science by at least another decade

Thanks for your attention



A TME that produces the same Ex has smaller DA/MA, stronger sextupoles and quadrupoles, less space for dipoles, stronger resonances etc…

Hybrid Minimum Emittance Cell

Starting from a 2*TME with Mux~0.33 between the SFs:

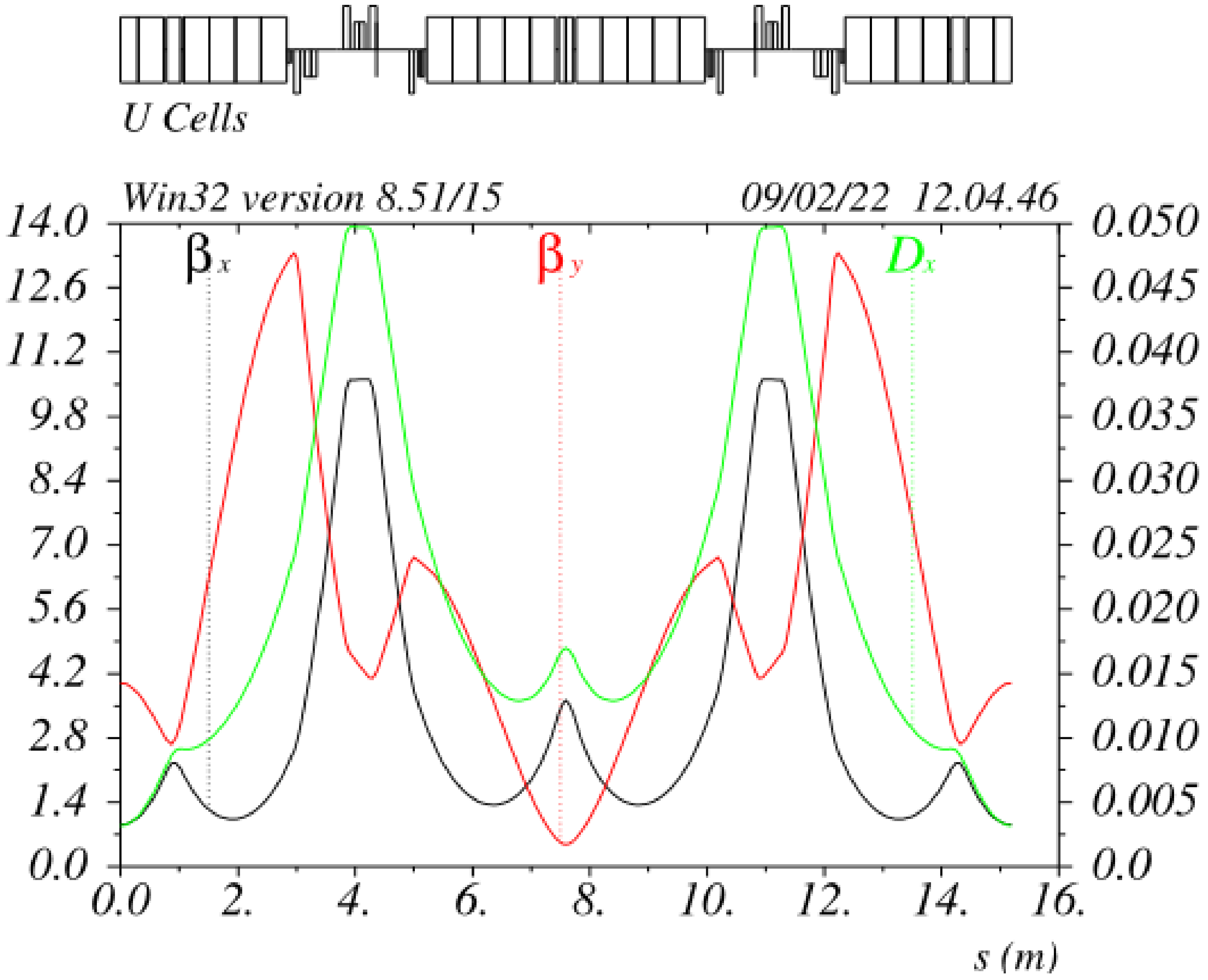
Central dipole is cut in two and a QF is inserted: Mux~Muy~0.5 between the SFs

The outer dipole is cut in three and two QFs are inserted: Mux~0.75, Muy~0.2, “outside” the SFs

⇒ Smaller Ex and larger DA/MA wrt TME

16 Cells/Arc => H81BA

Mux ~ 1.25 (0.66 for a 2*TME)
Muy ~ 0.70

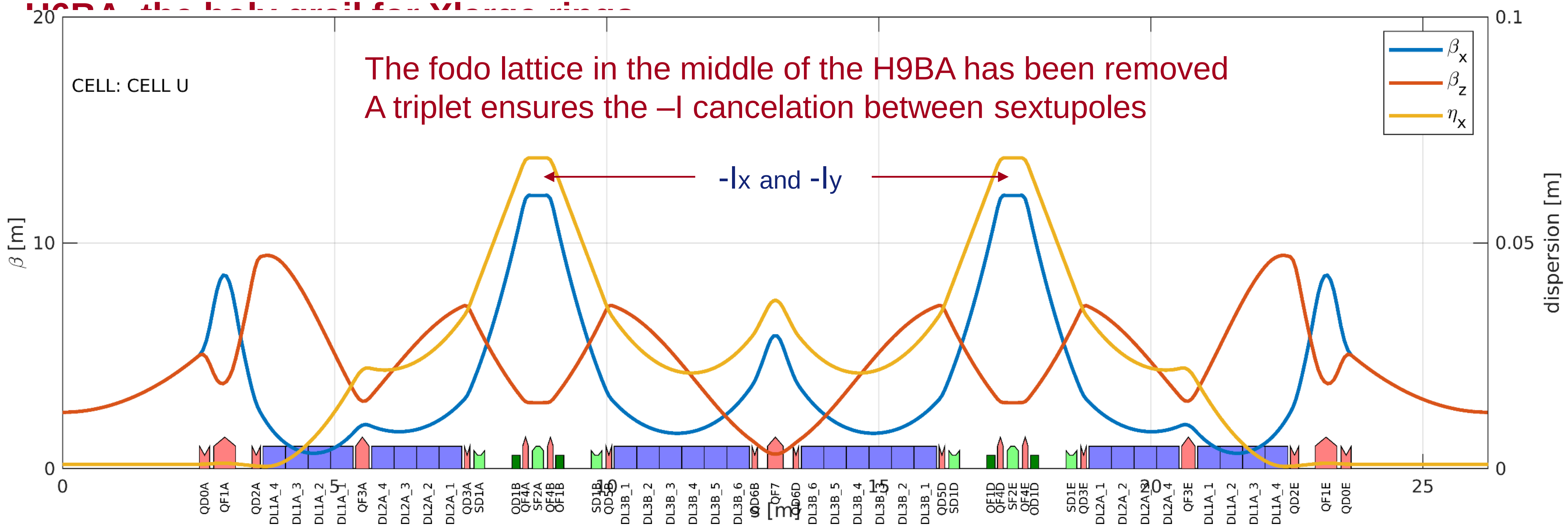


Ring made by HME cells only:

16 HME Cells/Arc
6 identical Arcs

Ex ~ 15.8pm
(Ex ~5pm with wgls&coupl)
Sige~0.47e-3
Jx~ 1.50
Eloss ~0.404MeV

Chromaticities about 30% lower in both planes wrt H6BA



- The first dipole has been cut and a QF has been inserted in the middle, this allows the freedom to chose the ideal phase advance in both planes for the cell. In addition it lowers the final Curl_H built by the dipole (DL1-DL2) and matches the natural Curl_H of the second (weaker) dipole (DL3).
- A triplet in the middle ensures the "-Ix/-Iy" cancelation between the sextupoles in both planes. (-3Ix/-Iy for EBS)
- The strong and very chromatic FODO present in EBS in beteewen the sextupoles is gone. H6BA quads are small and weak.
- About 60% of the cell is made by PM-DLs
- DA/EA properties are striking