Preliminary design study of JUICE

Joint Universities International Circular Electronsynchrotron

juas
Joint Universities Accelerator School

esi
European Scientific Institute

Goal

$$\text{brilliance} = \frac{\text{flux}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

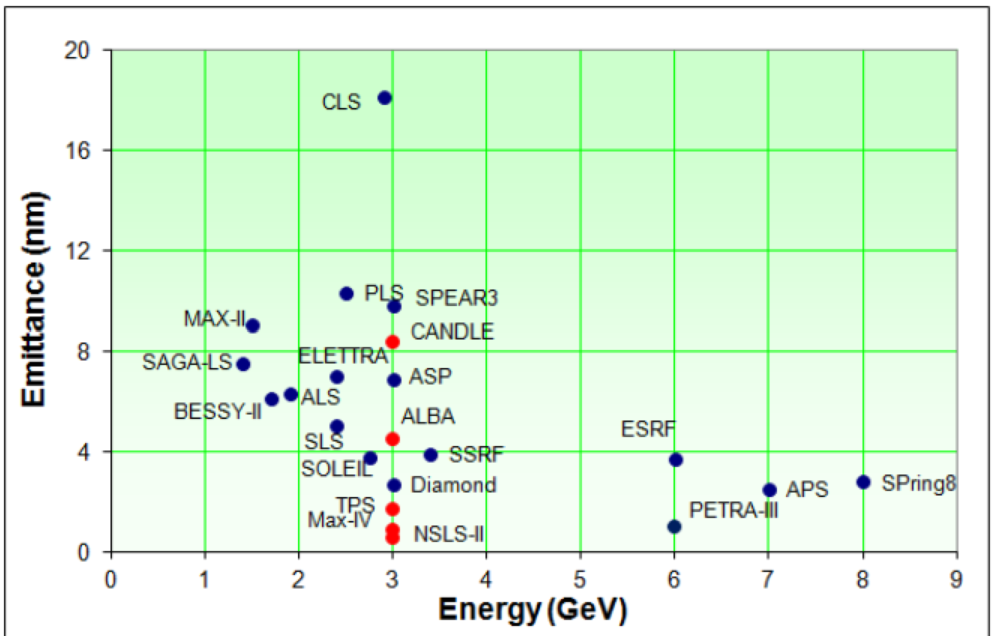
$$\Sigma_x = \sqrt{\sigma_{x,e}^2 + \sigma_{ph,e}^2}$$

$$\Sigma_{x'} = \sqrt{\sigma_{x',e}^2 + \sigma'^2_{ph,e}}$$

$$\sigma_x = \sqrt{\varepsilon_x \beta_x + (D_x \sigma_\varepsilon)^2}$$

$$\sigma_{x'} = \sqrt{\varepsilon_x / \beta_x + (D'_x \sigma_\varepsilon)^2}$$

- Make a 3th generation Synchrotron Radiation Lightsource at 3 GeV



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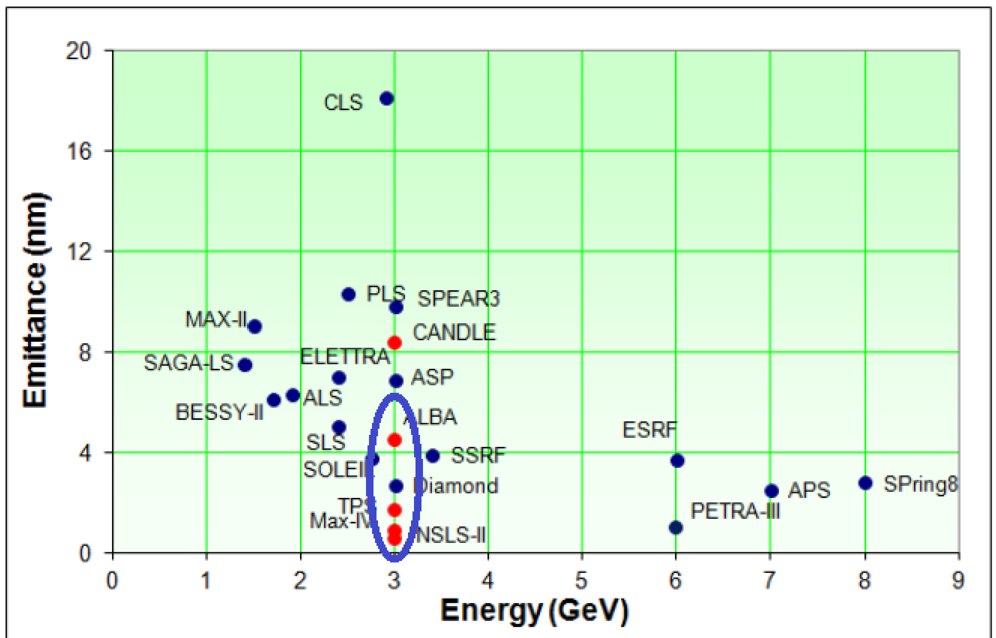


Specifications and requirements

Storage ring

- 2 GeV → 3 GeV
- C < 700 m
- 24 cells
- Must provide
  - low horizontal emittance (<10 $[\pi\ nm \cdot rad]$)
  - long drift spaces for Insertion Devices
  - zero dispersion in drift sections
  - precision optics and orbit control
  - high stability
  - cost efficient
  - etc…

Booster ring

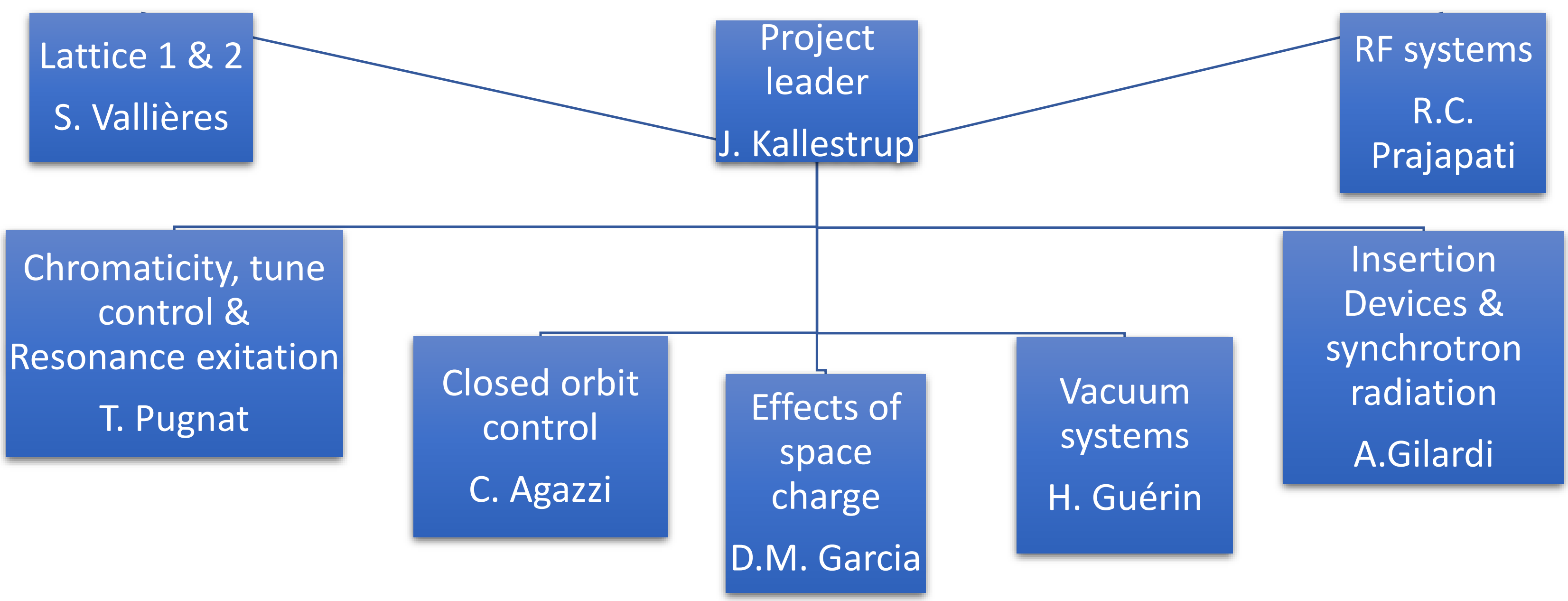
- 2 GeV
- $f_{RF} = 500\ [MHz]$
- $\varepsilon_{x,y} = 0.15\ [\pi\ mm \cdot mrad]$
- $\ell_{\text{bunch}} = 40\ [ps] = 12\ [mm]$
- $\frac{\Delta p}{p} = 10^{-3}$

Primary tool

- AGILE: Multi-purpose Freeware
  - Lattice construction
  - Linear Optics matching
  - Chromaticity correction
  - Radiation loss calculations
  - Vacuum calculations
  - Etc…….

Group structure

Experts:
Phillip Bryant
Riccardo Bartolini



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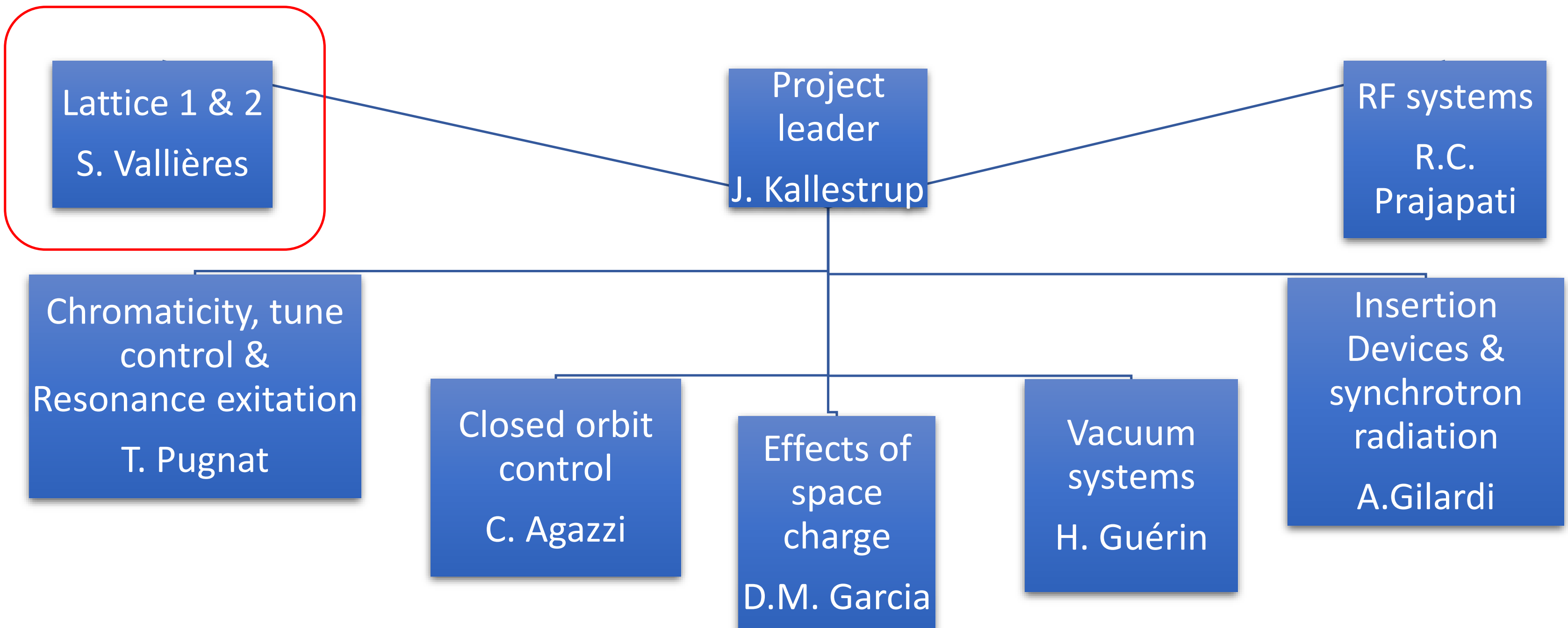


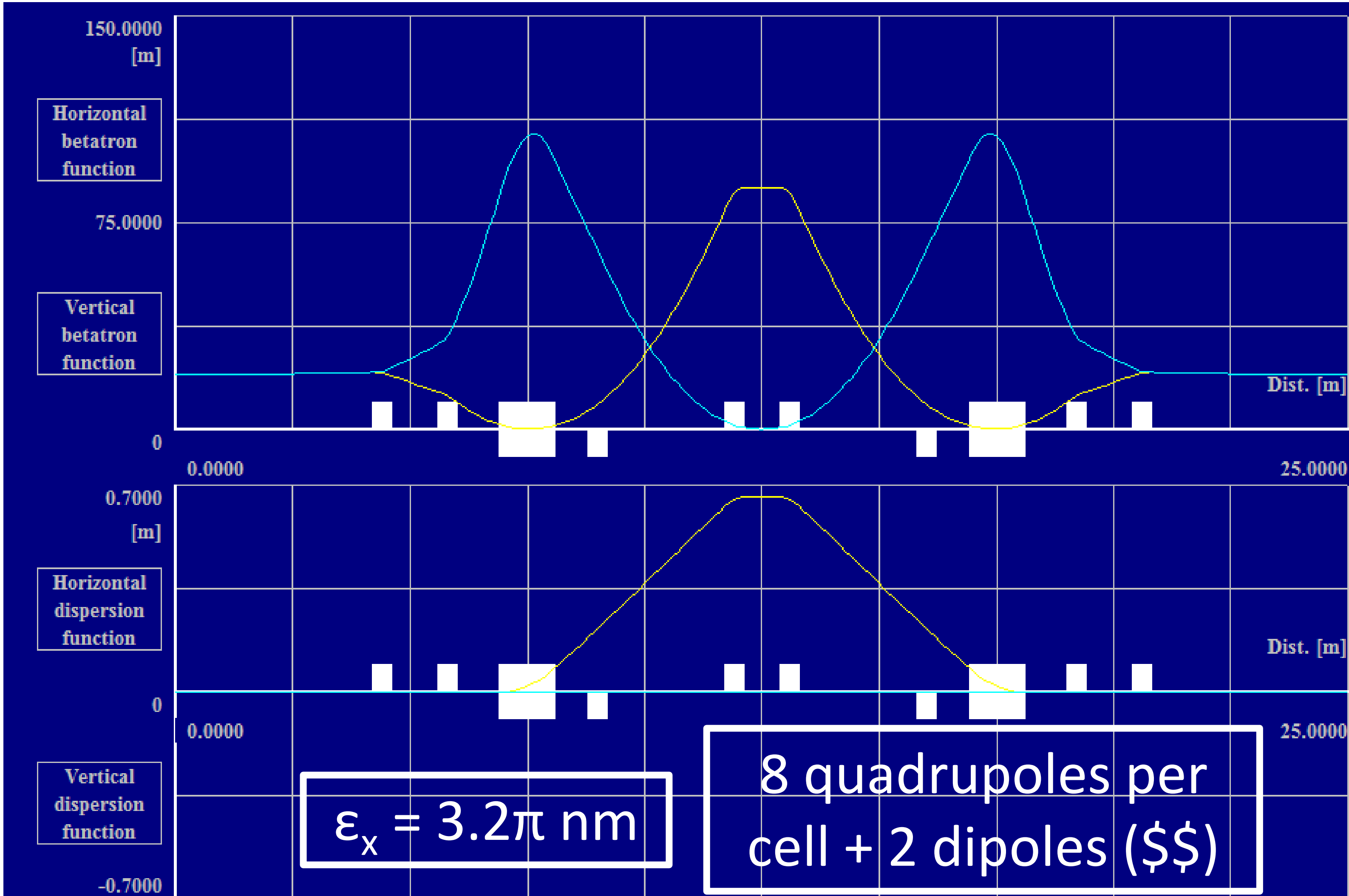
Lattice Group

Mandates to Fulfill

- **Lattice 1 :**
  - ✓ Try to improve the basic cell design.
  - ✓ Define apertures.
  - ✓ Get radiation parameters.

- **Lattice 2 :**
  - ✓ Create a dispersion-free 1:1 module to split the ring in 2 superperiods.
  - ✓ Integrate the injection and extraction into the previous module.

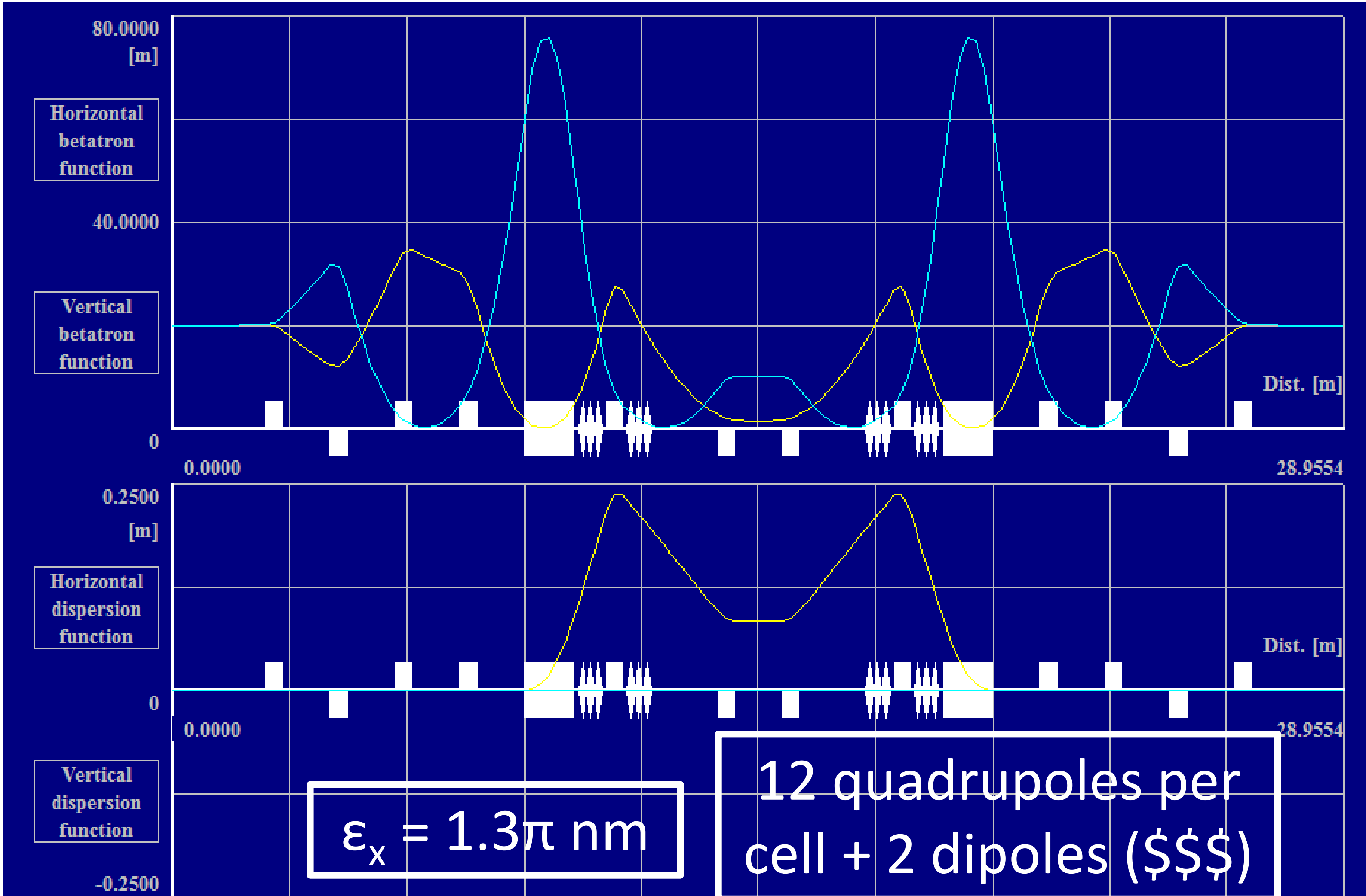
Basic Ring



$\varepsilon_x = 3.2\pi$ nm

8 quadrupoles per cell + 2 dipoles ($$)

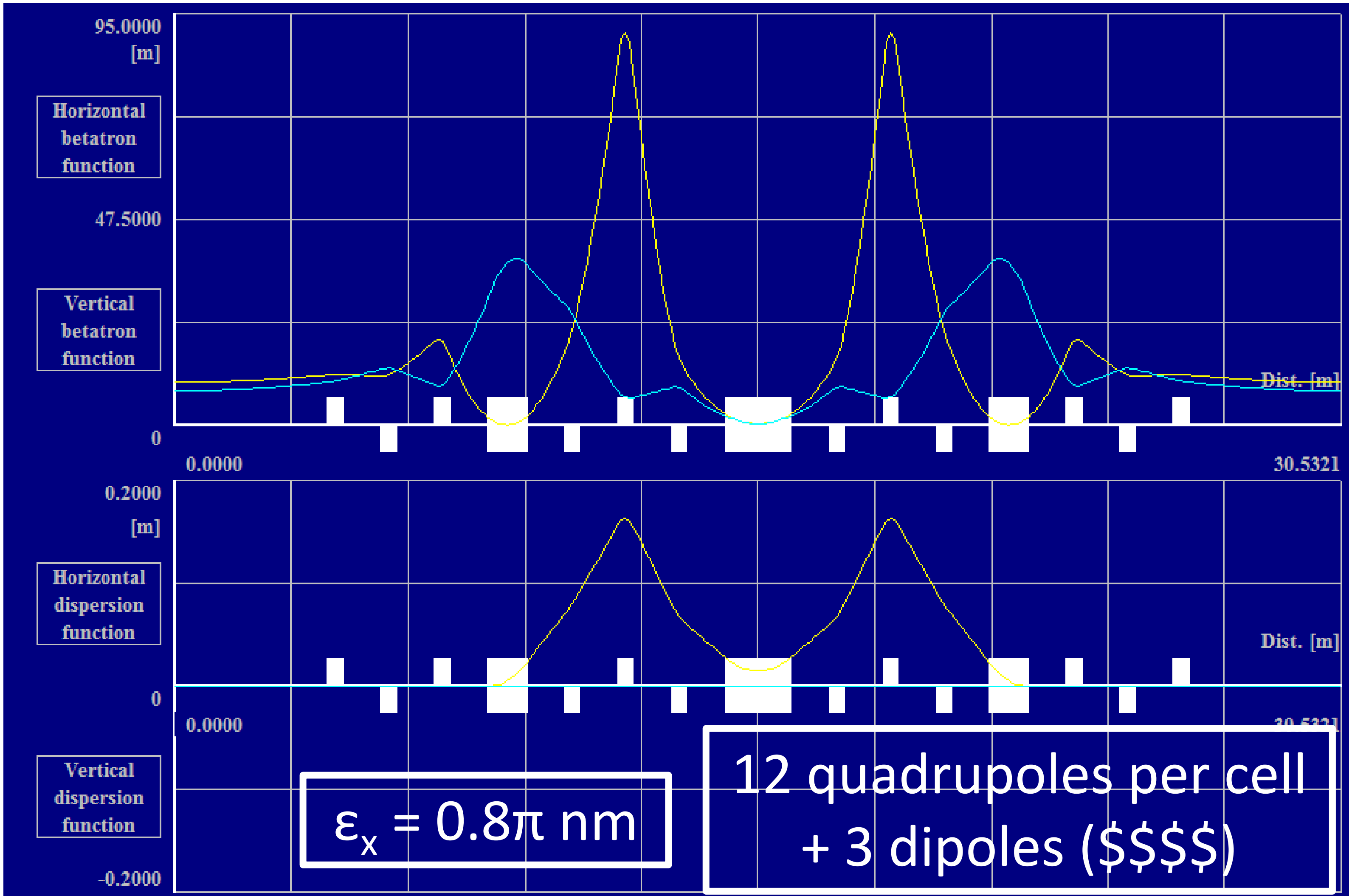
Option 1: DBA with many FODOs



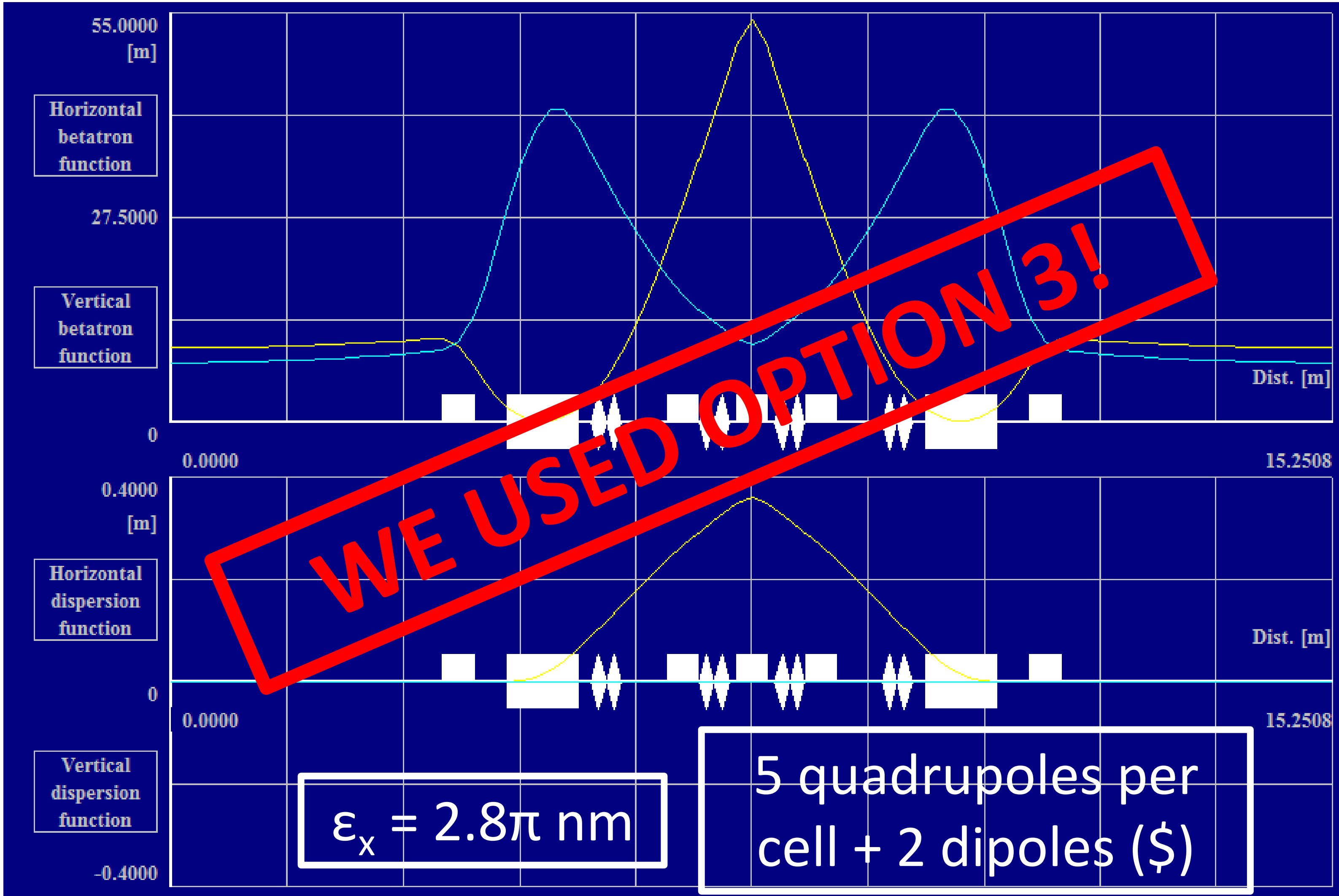
$\varepsilon_x = 1.3\pi$ nm

12 quadrupoles per cell + 2 dipoles ($$$)

Option 2: TBA


95.0000
[m]
Horizontal betatron function
47.5000
Vertical betatron function
0
Dist. [m]
0.0000
30.5321
0.2000
[m]
Horizontal dispersion function
0
Dist. [m]
0.0000
Vertical dispersion function
-0.2000
$\varepsilon_x = 0.8\pi$ nm
12 quadrupoles per cell
+ 3 dipoles ($$$$)

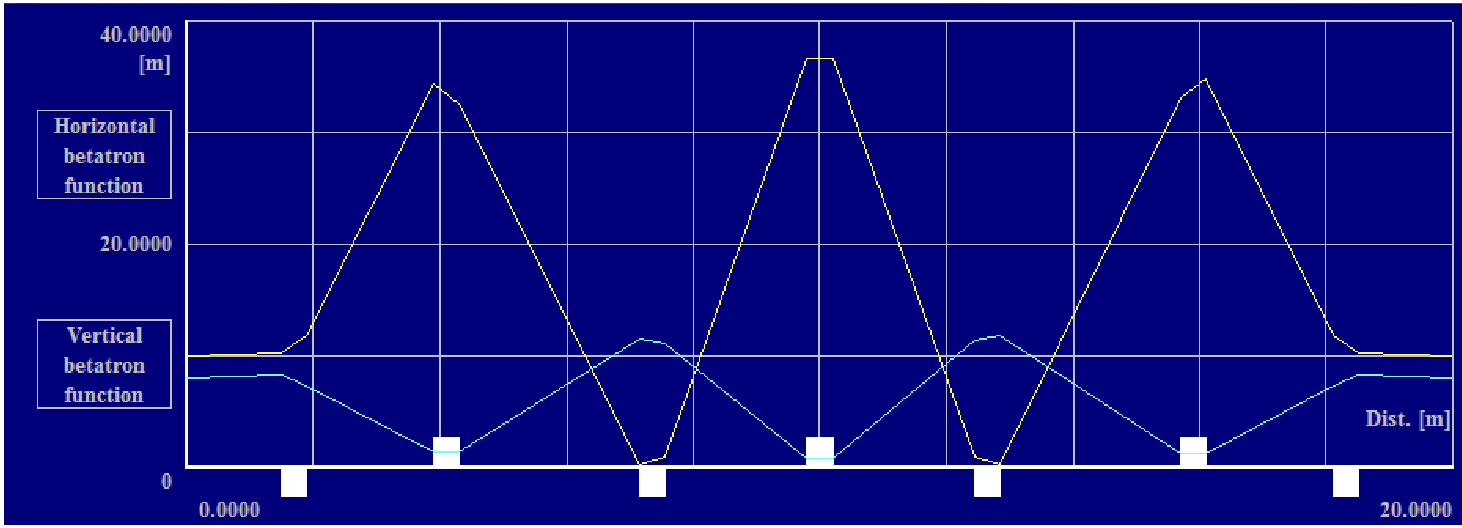
Option 3: low cost DBA



$\varepsilon_x = 2.8\pi$ nm

5 quadrupoles per cell + 2 dipoles ($)

MODULE 1:1



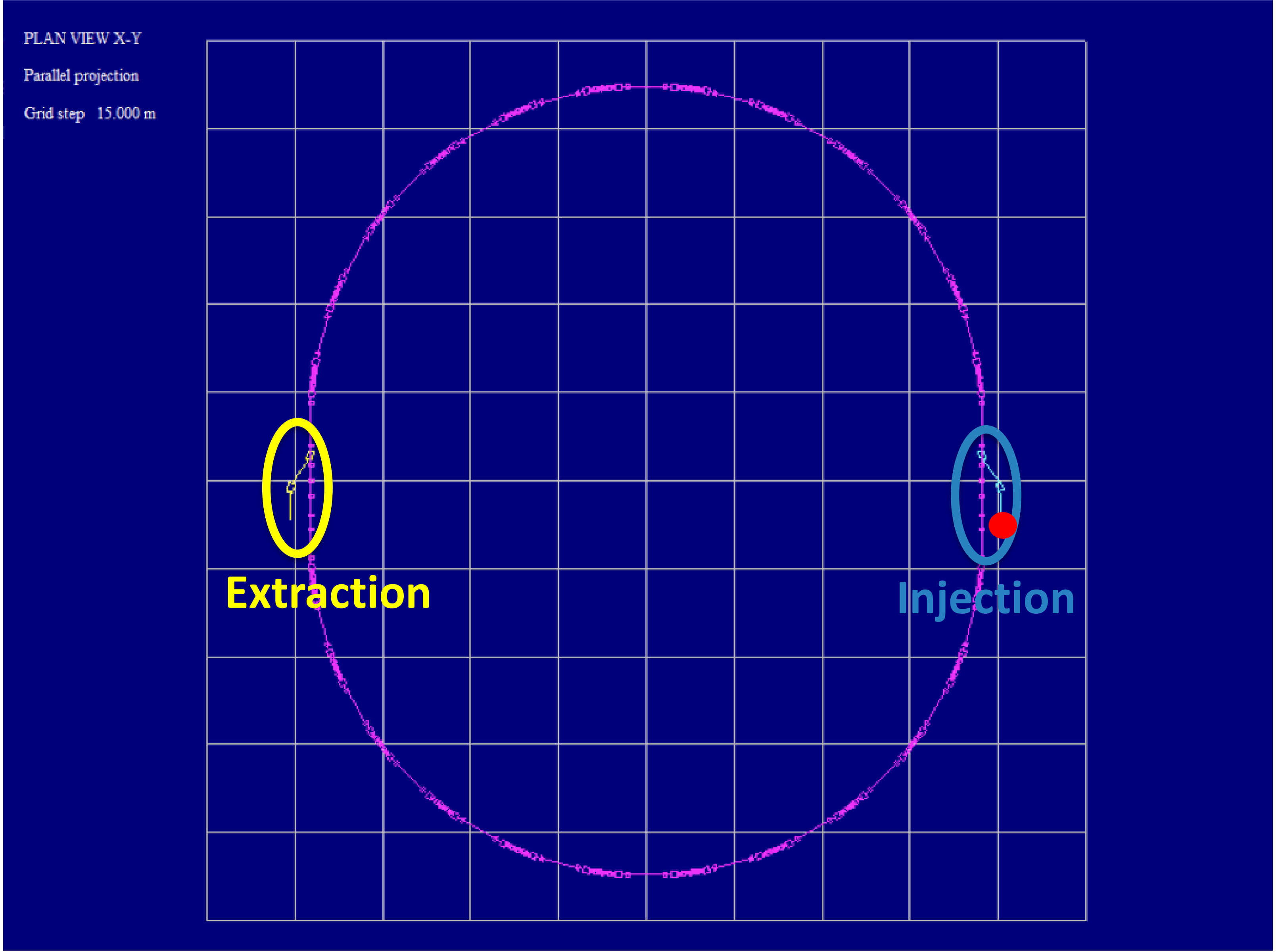
CENTRAL ORBIT
Transfer line

Length of beam line	[m] =	20.0000
Horizontal phase advance	[rad] =	6.283185
Vertical phase advance	[rad] =	6.283185
Horizontal chromaticity	dmux/dp/p =	-2.560
Vertical chromaticity	dmuz/dp/p =	-10.254

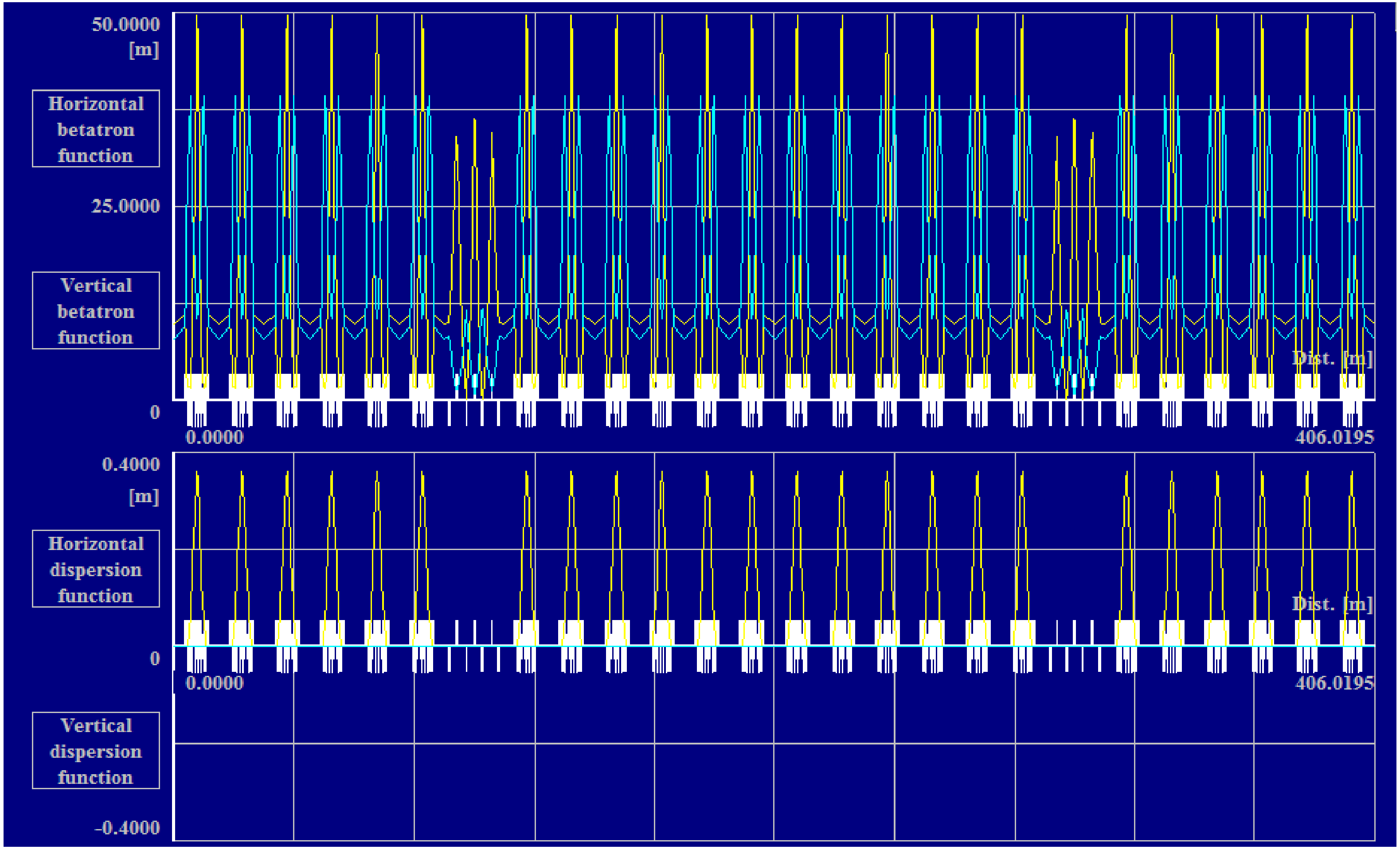
- $\beta_x^{in} = \beta_x^{out}$
- $\beta_y^{in} = \beta_y^{out}$
- $\alpha_x^{in} = \alpha_x^{out}$
- $\alpha_x^{in} = \alpha_x^{out}$
- $\mu_x^{out} = \mu_y^{out} = 2\pi$

As expected

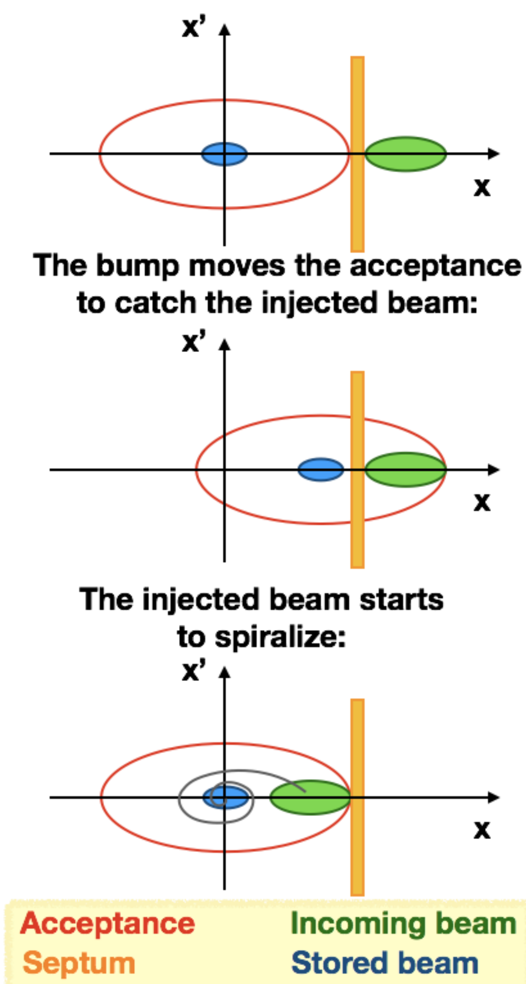
Type	Beta-x [m]	Alpha-x	Mu-x [rad]
MARK	10.000	0.0000	0.0000
DRIFT	10.000	0.0000	0.0000
QUADR	10.225	-0.1500	0.1489
DRIFT	11.854	-4.1091	0.1861
QUADR	34.325	-7.1265	0.2854
DRIFT	32.507	11.3365	0.2969
QUADR	0.251	-0.0186	1.7983
DRIFT	1.027	-2.0795	2.7603
QUADR	36.620	-13.7394	3.1359
DRIFT	36.608	13.7657	3.1463
QUADR	1.006	2.0576	3.5262
DRIFT	0.248	-0.0096	4.5129
QUADR	33.044	-11.4978	5.9873
DRIFT	34.856	7.3019	5.9987
QUADR	11.882	4.1852	6.0971
DRIFT	10.225	0.1500	6.1343
MARK	10.000	0.0000	6.2832

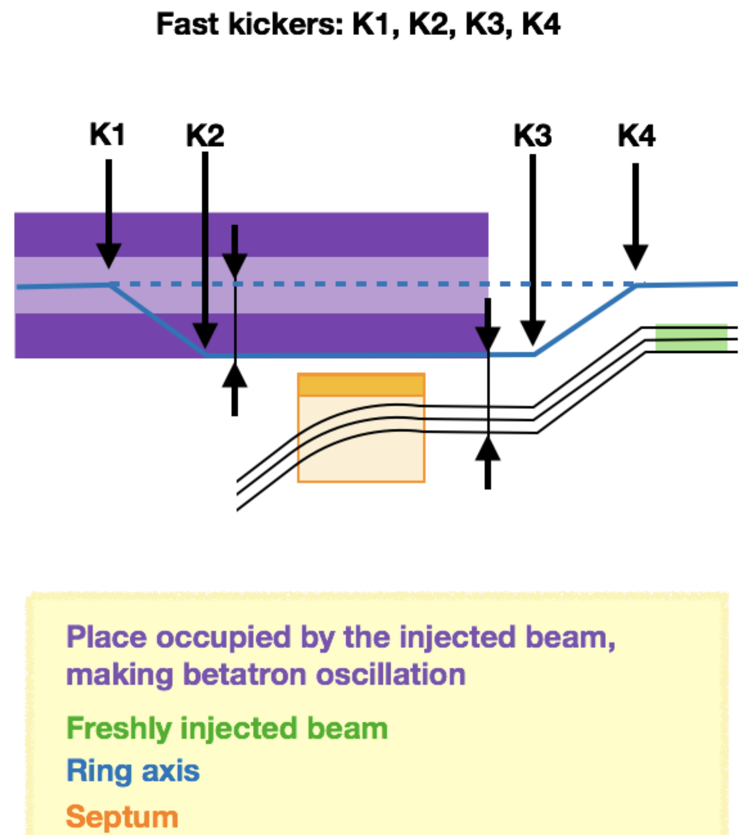

PLAN VIEW X-Y
Parallel projection
Grid step 15.000 m
Extraction
Injection

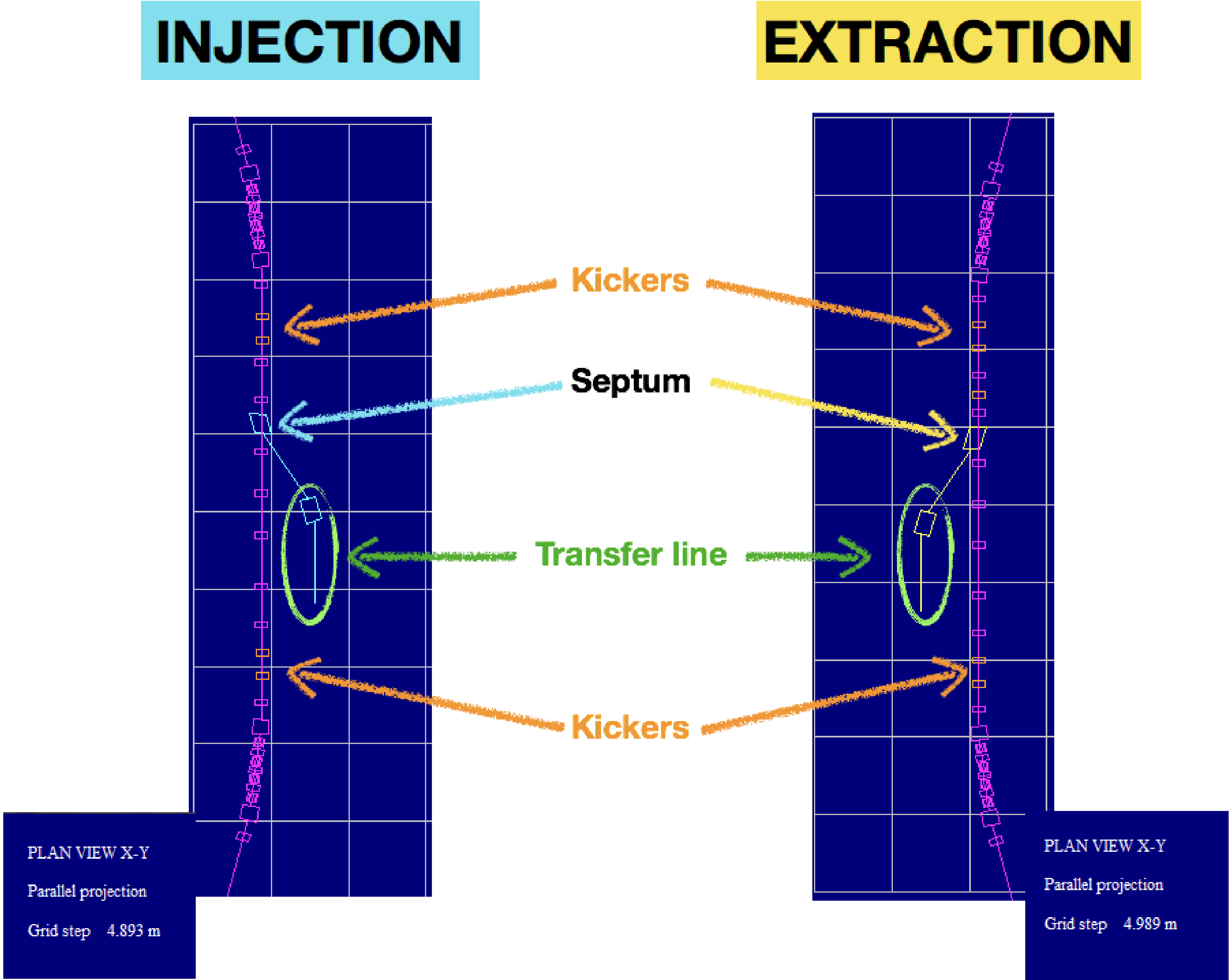
Twiss functions of the full ring with a low cost DBA



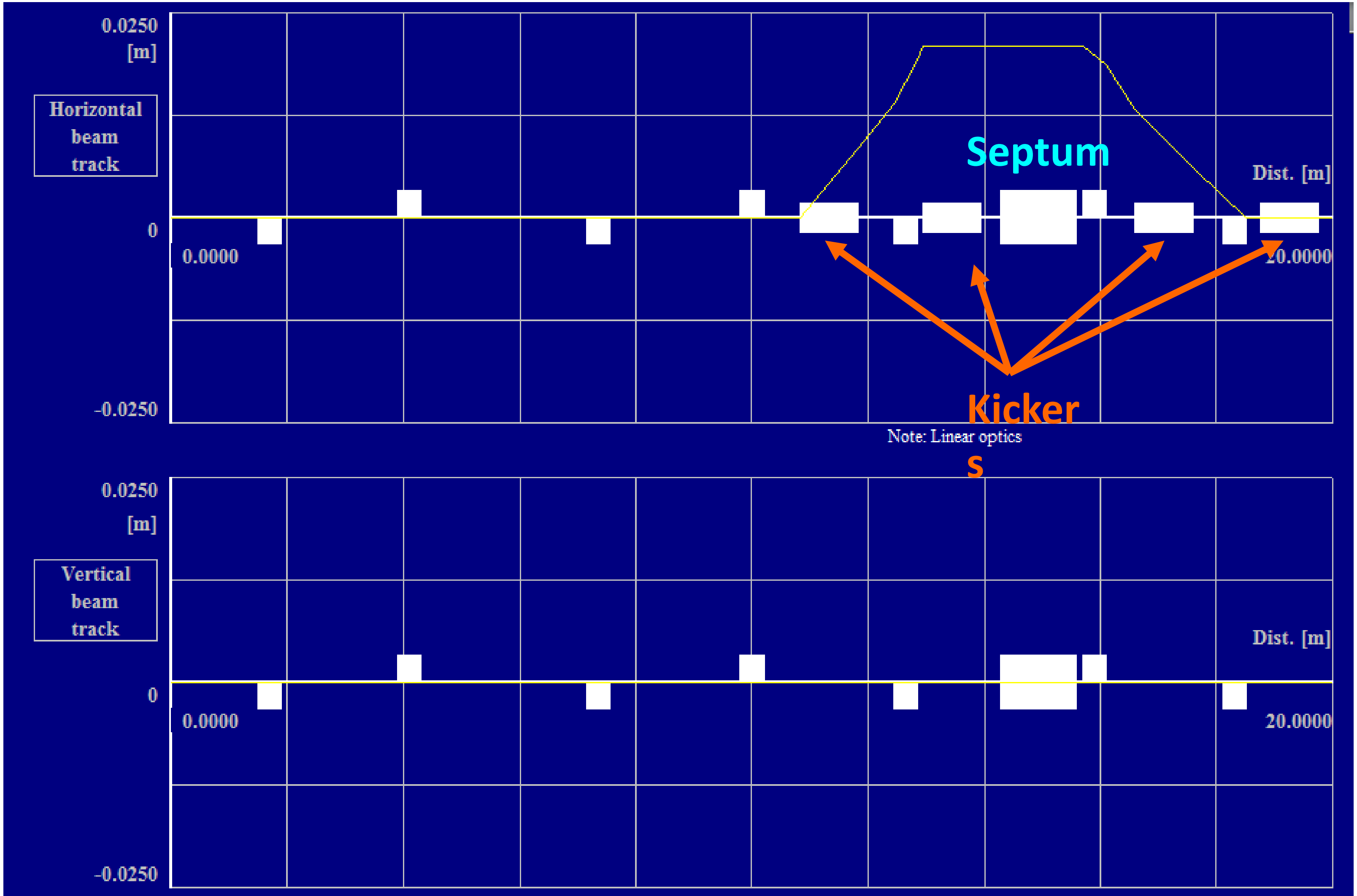
Injection/Extraction Scheme



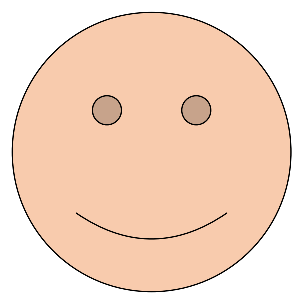



INJECTION
EXTRACTION
Kickers
Septum
Transfer line
Kickers
PLAN VIEW X-Y
Parallel projection
Grid step 4.893 m
PLAN VIEW X-Y
Parallel projection
Grid step 4.989 m

Injection with Orbit Bump



Many Thanks from Lattice Group!



Tune and Chromaticity control

By T. PUGNAT, V. CILENTO, E. FOL,

D. VENTURA

Tune control

Why?

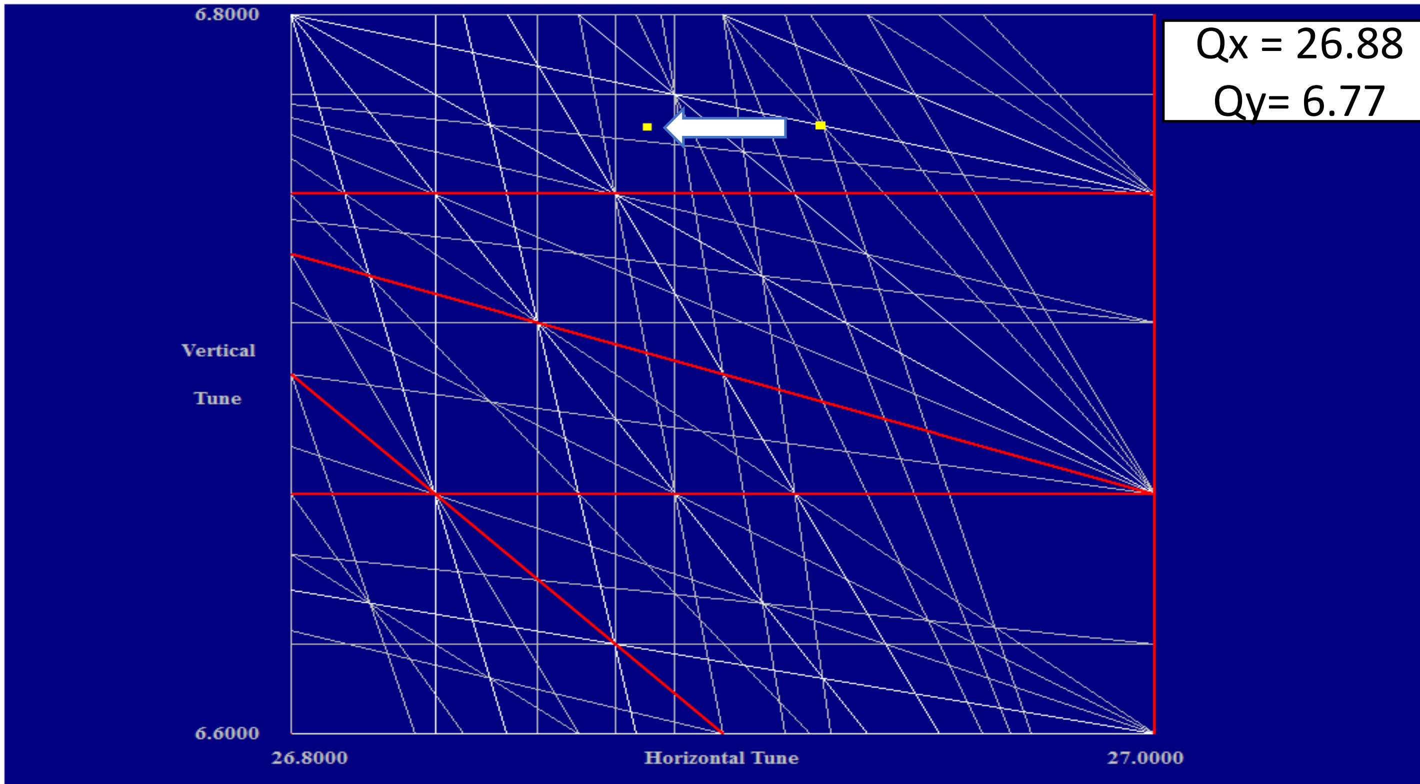
Prevent the machine to reach unstable region!

3 methods to correct the tune:

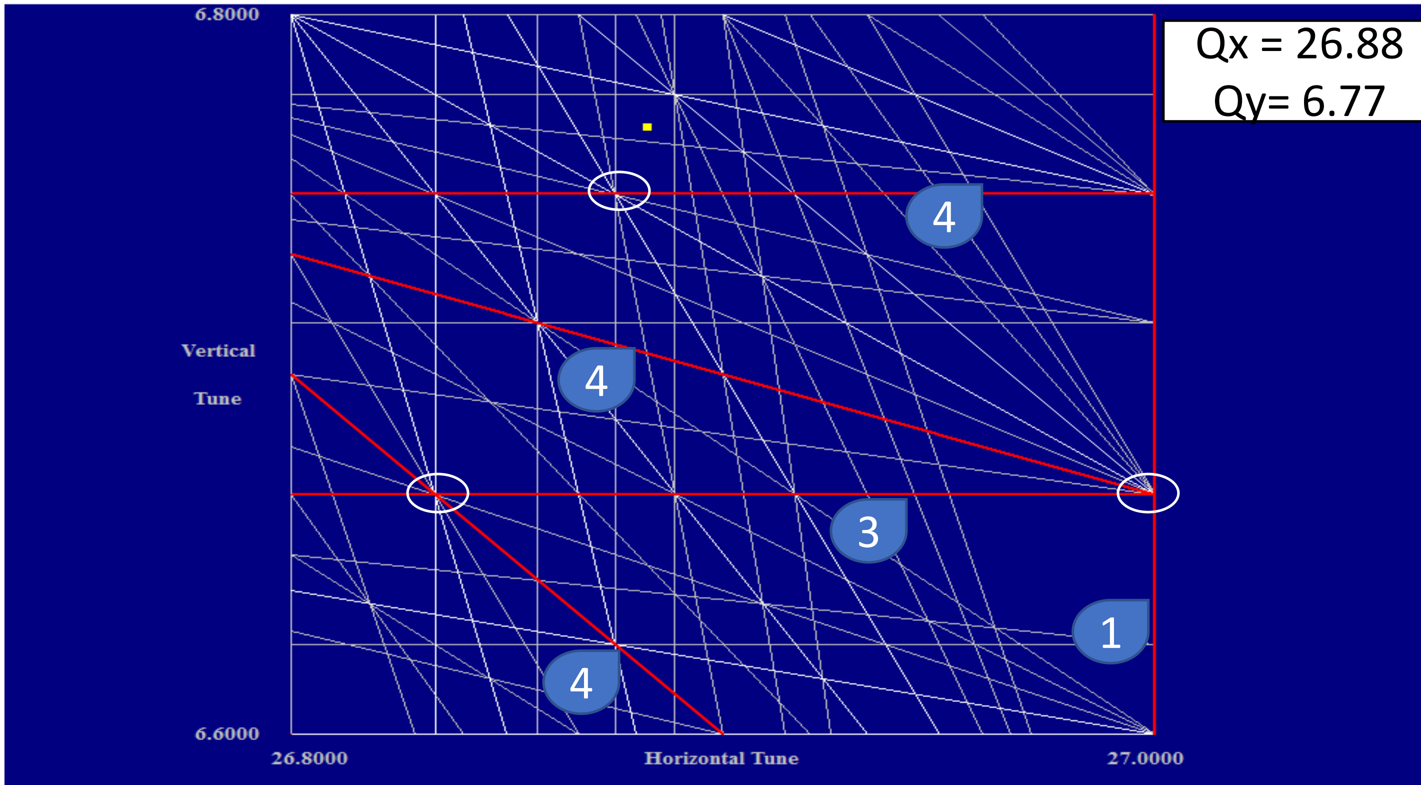
- *Using main quad*
- *Two serie families of smaller quads distributed around the ring*
- *Adding backleg windings to the main quadrupole*

p.51-52

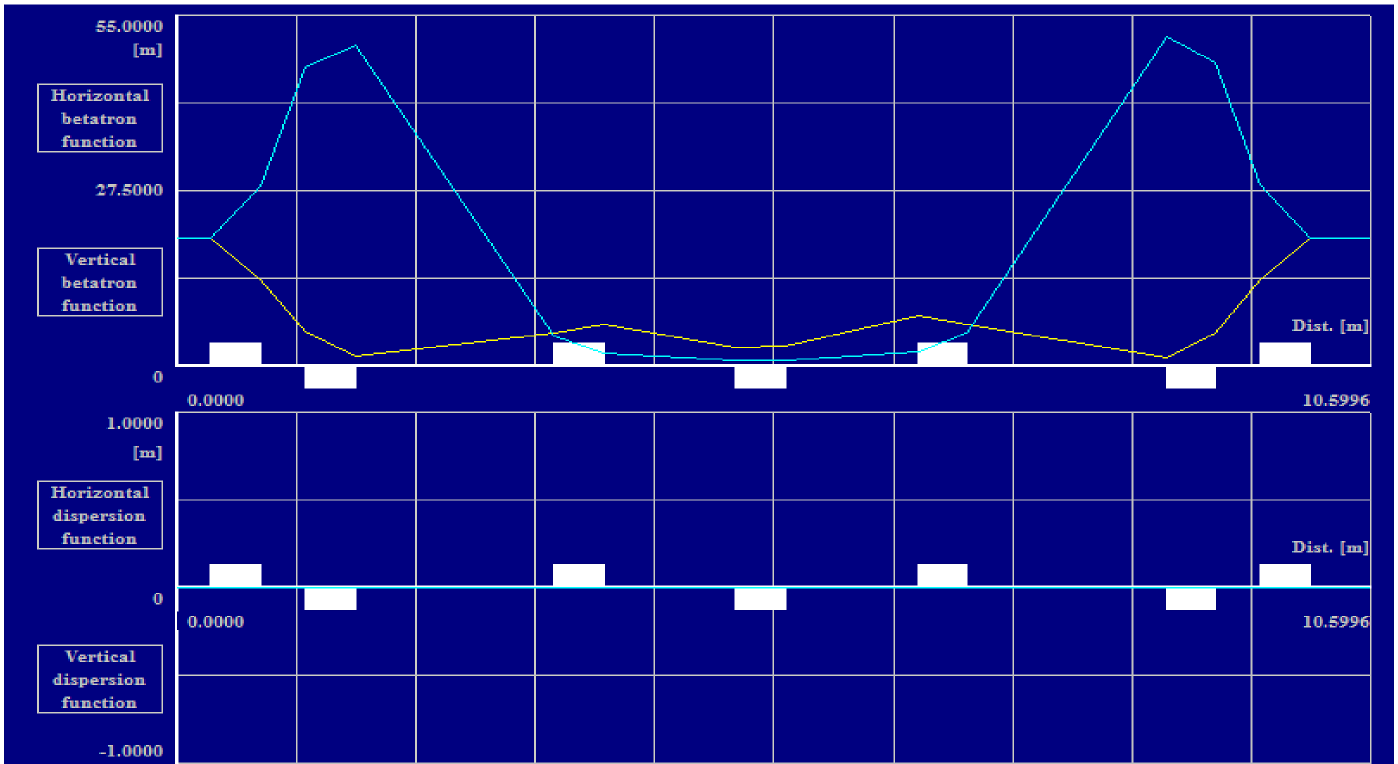
Tune control: using Quadrupole



Tune control: using Quadrupole



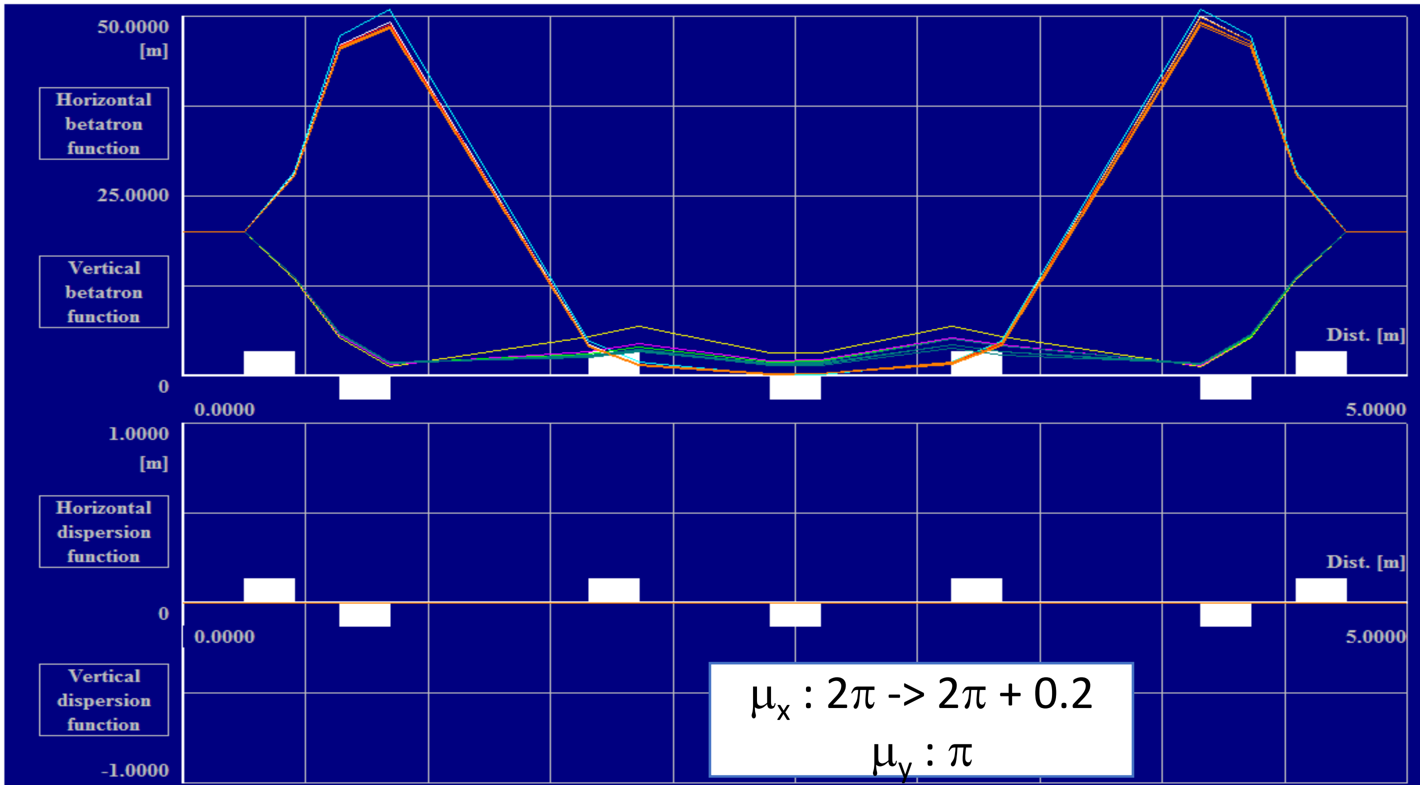
Tune control: Phase shifter



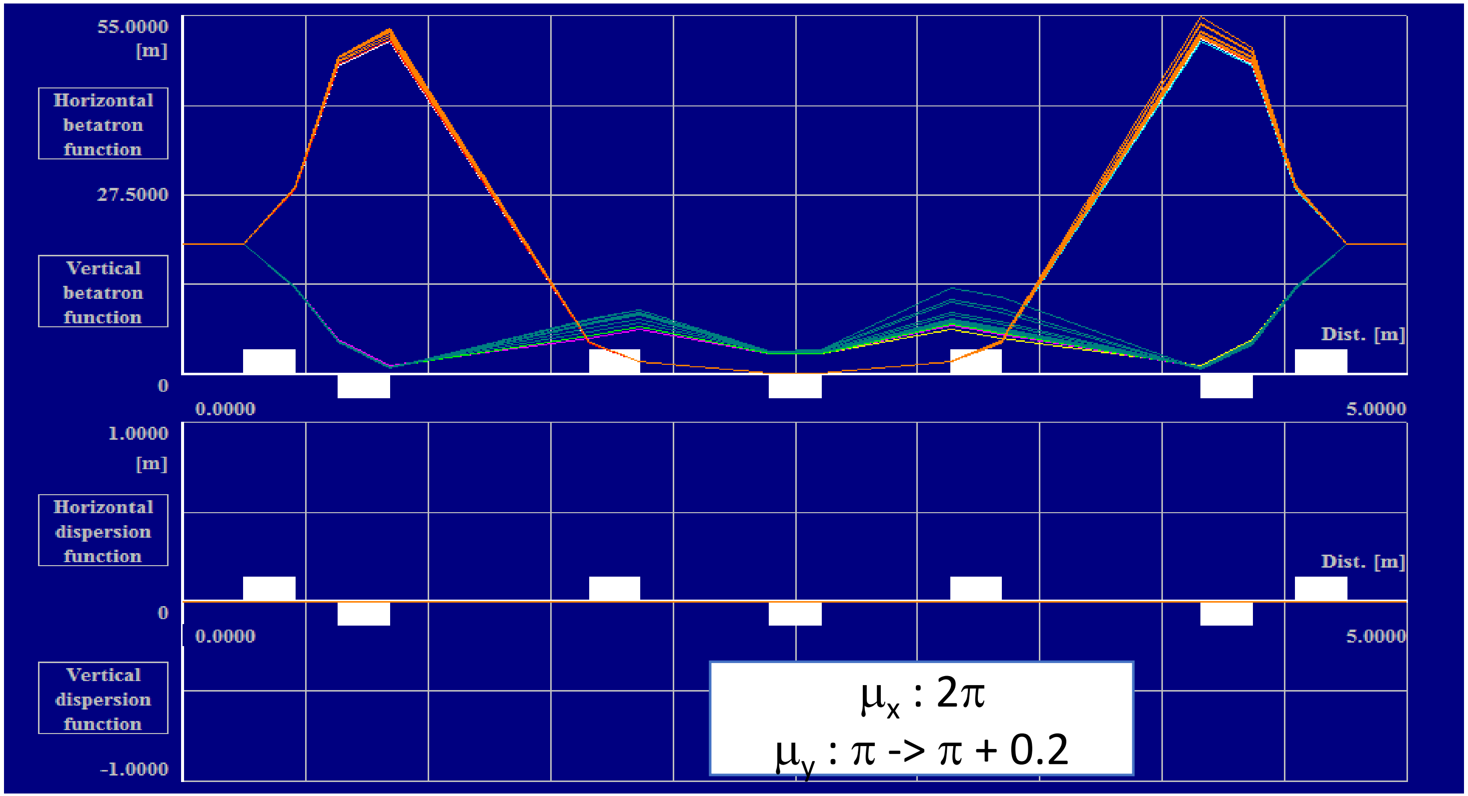
Length*Scale

Strength/Scale^2

Tune control: Phase shifter



Tune control: Phase shifter



Chromaticity control

Achromaticity → $\Delta Q_x = \Delta Q_y = 0$

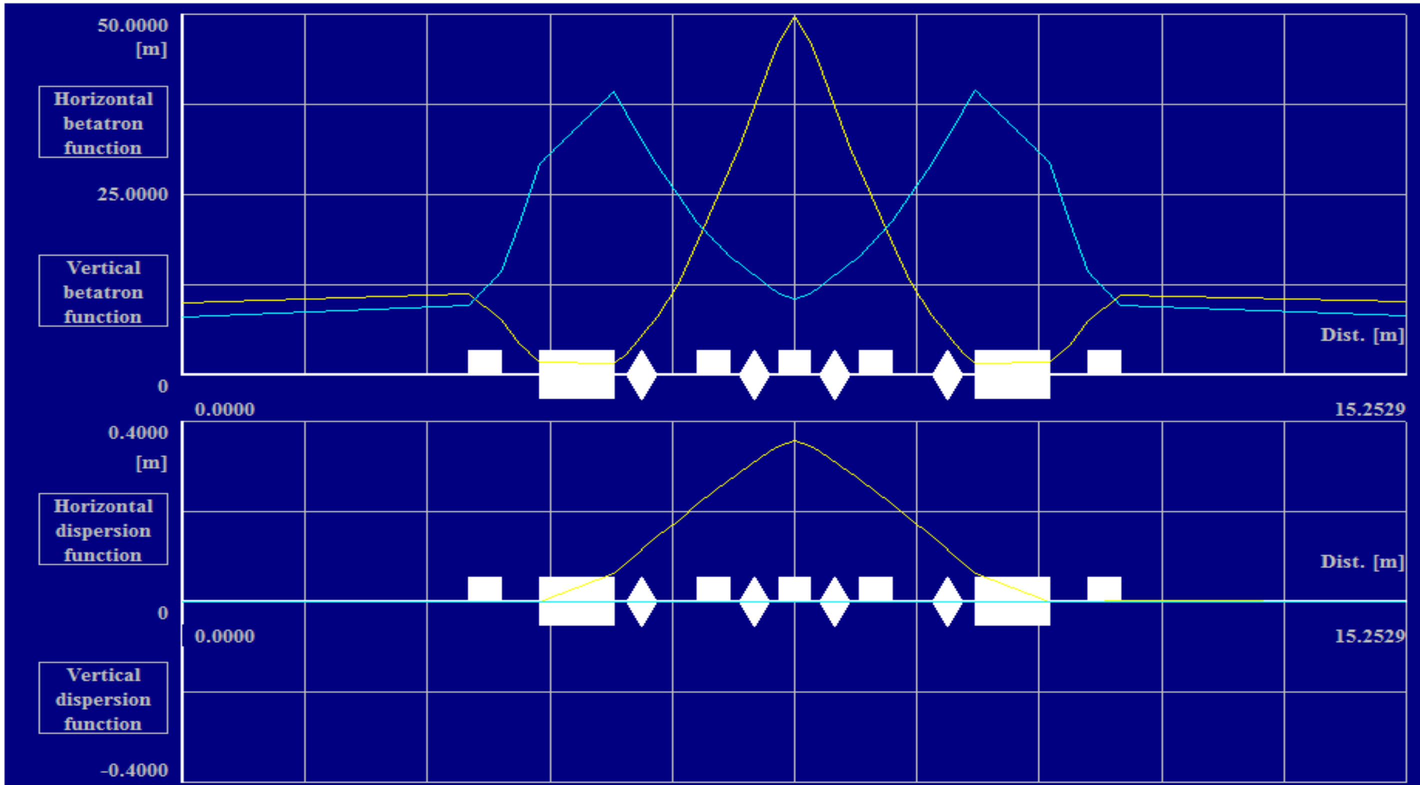
Relation between chromaticity, stength of the quadrupole and strength of the Sextupole:

$$\Delta Q_x = \Delta k_q \, \beta_x \, L_q + \Delta K_s \, \beta_x \, D_x \, L_s$$
$$\Delta Q_y = \Delta k_q \, \beta_y \, L_q + \Delta K_s \, \beta_y \, D_x \, L_s$$

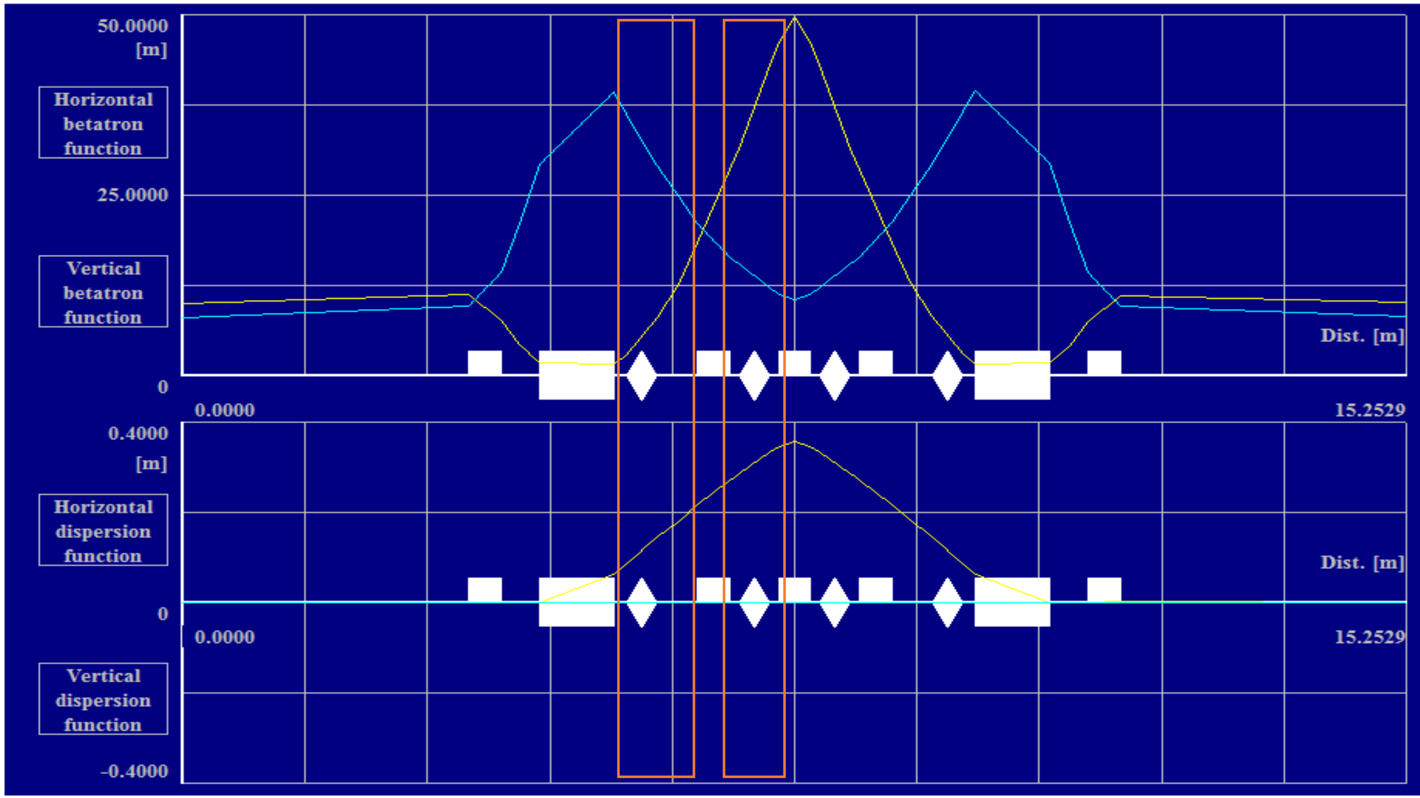
$$\beta_x / \beta_y >> 1 \text{ or } \beta_x / \beta_y >> 1$$
$$\beta_x \, D_x >> 0$$

p.51-52

Chromaticity control



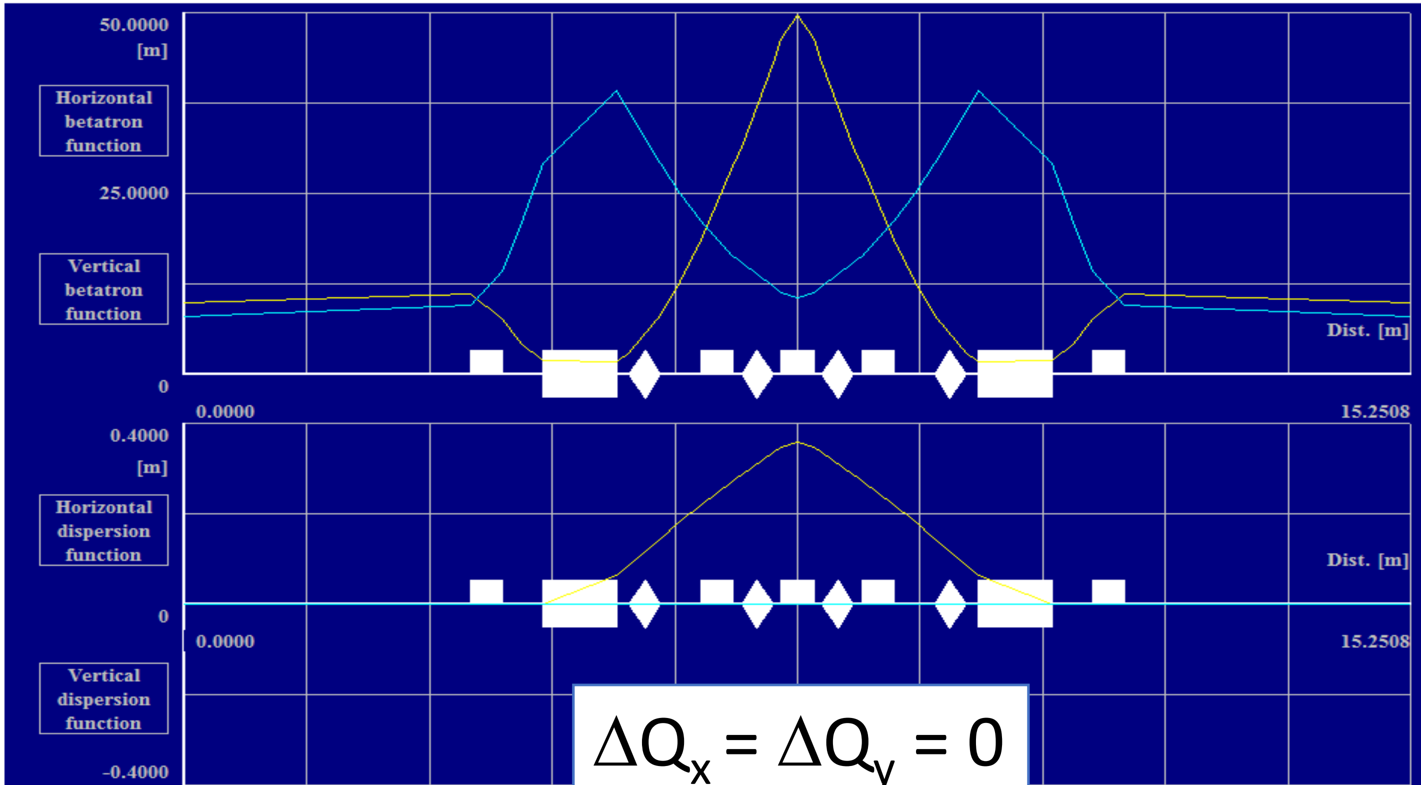
Chromaticity control



$\Delta Q_x = -1.318417$ & $\Delta Q_y = 0.299031$

Sextupole OFF

Chromaticity control



$$\Delta Q_x = \Delta Q_y = 0$$

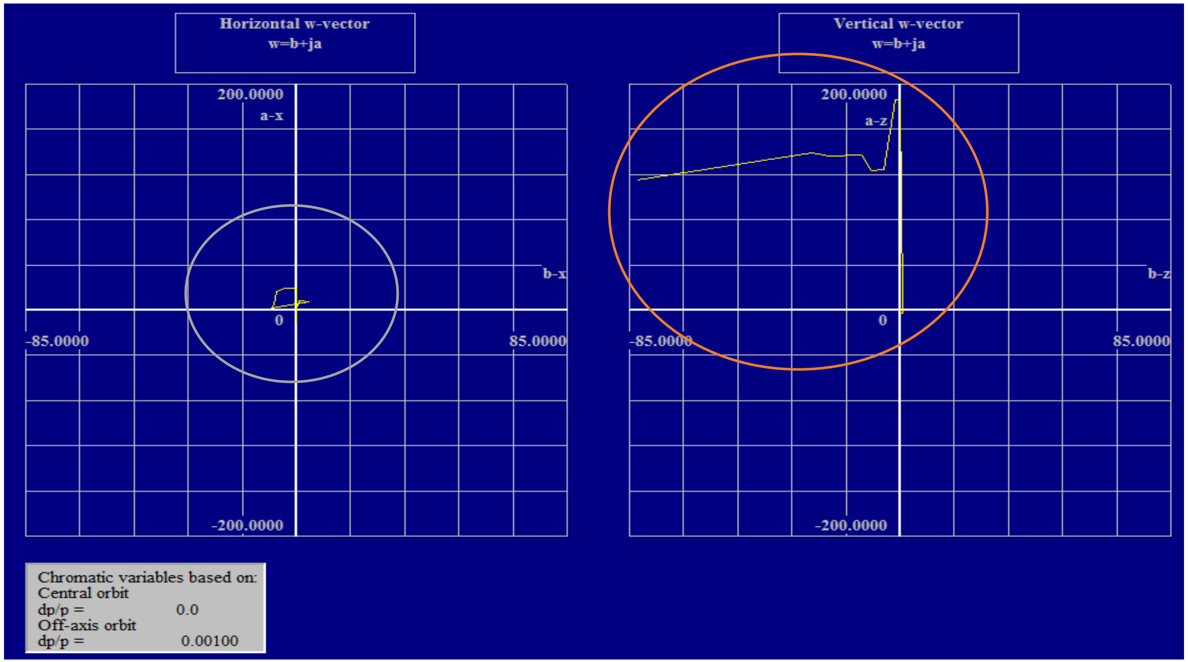
XD: k2 = 11.8527043000 m-3
XF: k2 = -13.3217690166 m-3

<u>Sextupole ON</u>

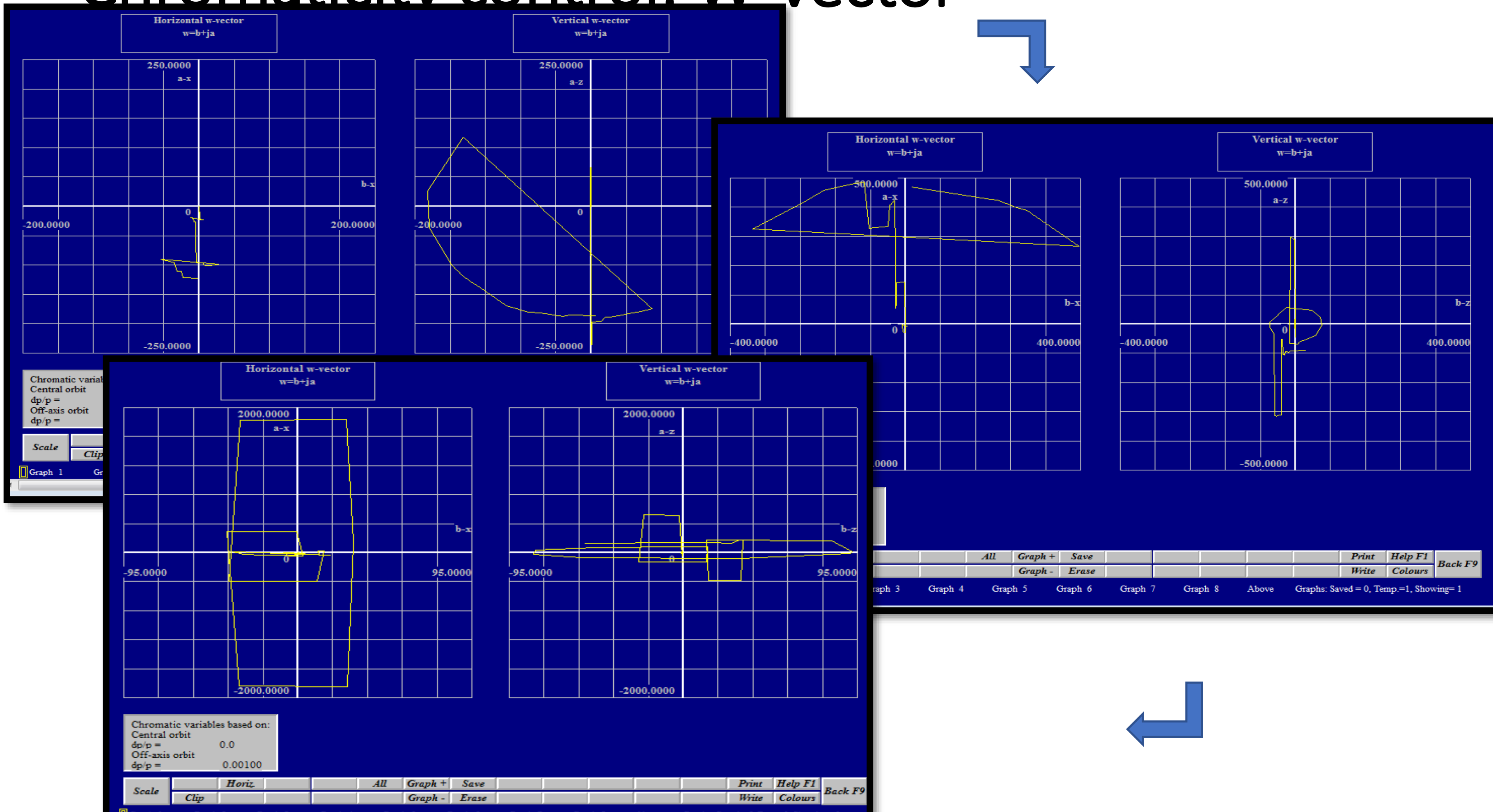
Chromaticity control: W-vector

Global chromaticity provide beam stability and control of the working line

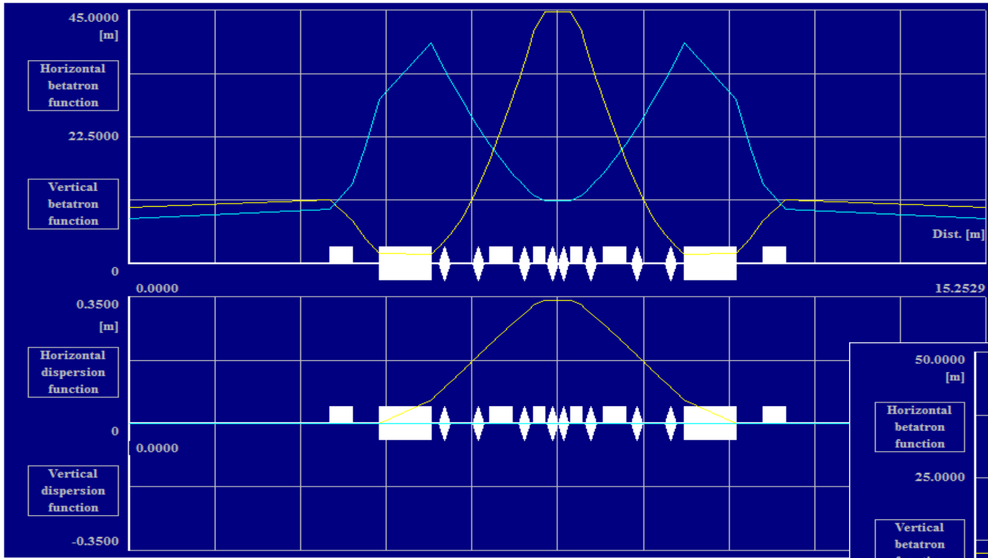
Local chromaticity prevent error from propagating from one cell to an other and necessary for undulator



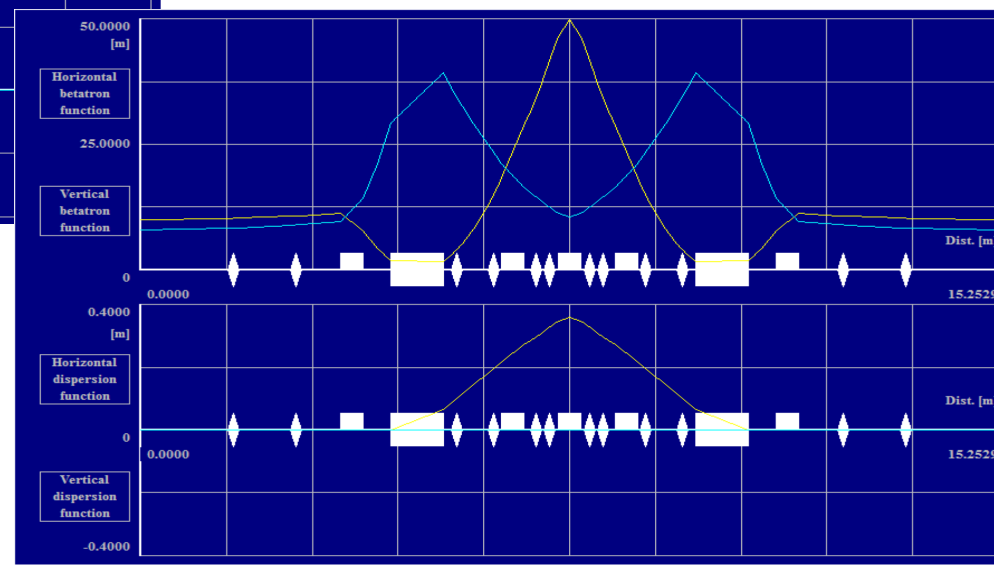
Chromaticity control: W-vector



Chromaticity control: try…



Sextupole in different localization



Sextupole of the same family with a phase advance of pi

Possible solution: Increase slowly the strength of the sextupole after injection

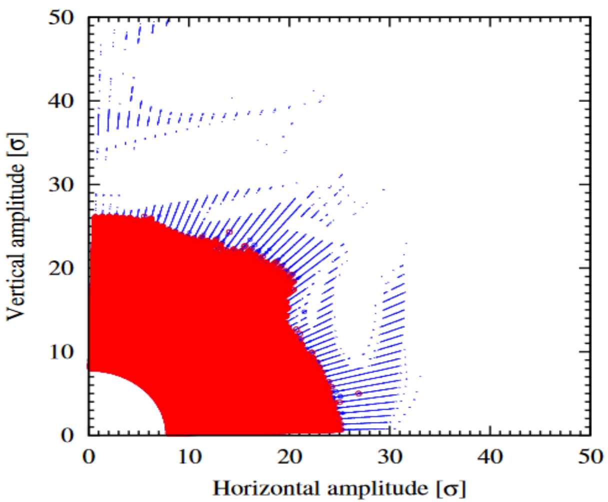
Dynamic aperture

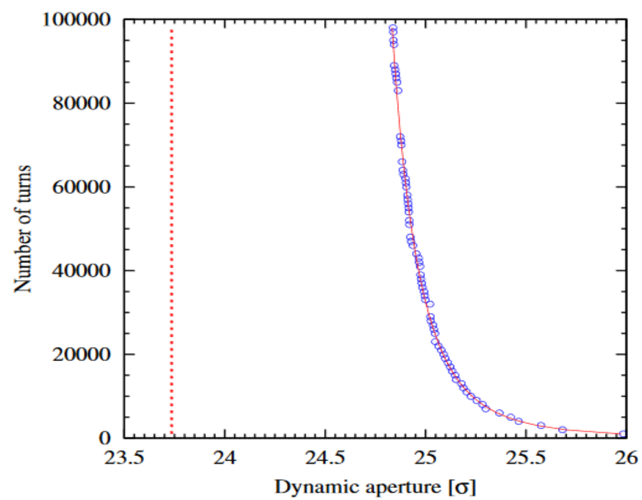
Lyapunov exponant

$$\lambda = \lim_{t\to\infty} \lim_{\delta \mathbf{Z}_0 \to 0} \frac{1}{t} \ln \frac{|\delta \mathbf{Z}(t)|}{|\delta \mathbf{Z}_0|}$$

Quantity that characterizes the rate of separation of infinitesimally close trajectories.

Multi-turn Tracking





$$D(N) = D_\infty\left(1 + \frac{b}{[\log N]^\kappa}\right),$$

"Proposed scaling law for intensity evolution in hadron storage rings based on dynamic aperture variation with time", M. Giovannozzi

Closed Orbit Prognosis & Correction

Costanza, Antonio, Alan

Prognosis: Statistic for Closed Orbit

HOW IT WORKS?

These prognosis are made by generating large numbers of **virtual machines** with estimated errors and calculating the statistics of the raw closed orbits and the corrected closed orbits.

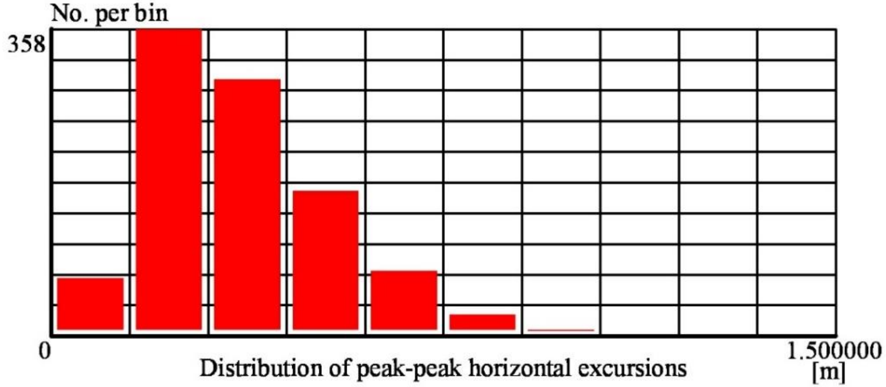
The error is interpreted as **dipole kicks.**

For example, a longitudinal position error of 1 mm for a dipole is represented as a missing-field kick at one end of the dipole and an additional-field kick at the other end.
This is done randomly with a uniform or Gaussian distribution.

WHAT WE HAVE DONE

- To perform our prognosis we set a **shift error** in the position of the quadrupoles of **0.001m,** first in the horizontal and then in the vertical plane.
- We used a **Gaussian distribution** of the kicks.
- We run a simulation of **1000 machines** and we studied separately the correction of a single closed orbit in the two planes.

STATISTICS FOR RANDOMLY GENERATED CLOSED ORBITS



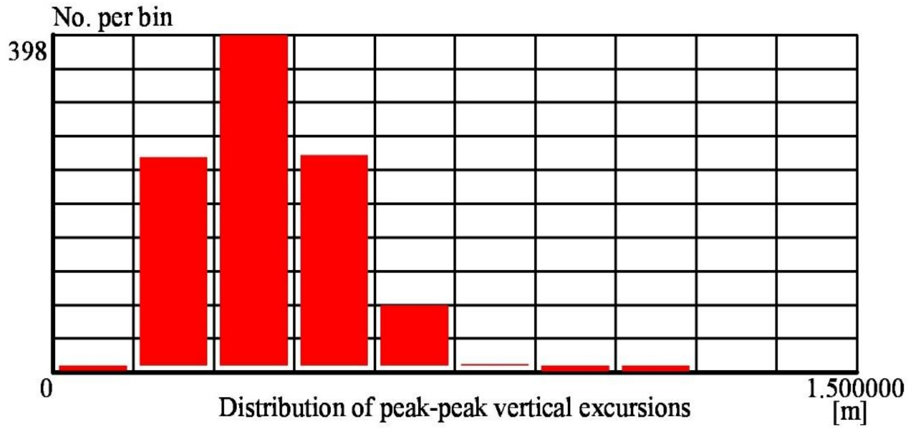
Distribution of peak-peak horizontal excursions

GLOBAL STATISTICS

No. of machines in sample 1000

Max. horiz. peak-peak [m] 1.016603
Av. horiz. peak-peak [m] 0.363808
RMS horiz. peak-peak [m]0.173713

MAX.HORIZONTAL PEAK-PEAK:
1.016603m
AVERAGE HORIZONTAL PEAK-PEAK:
0.363808m



Distribution of peak-peak vertical excursions

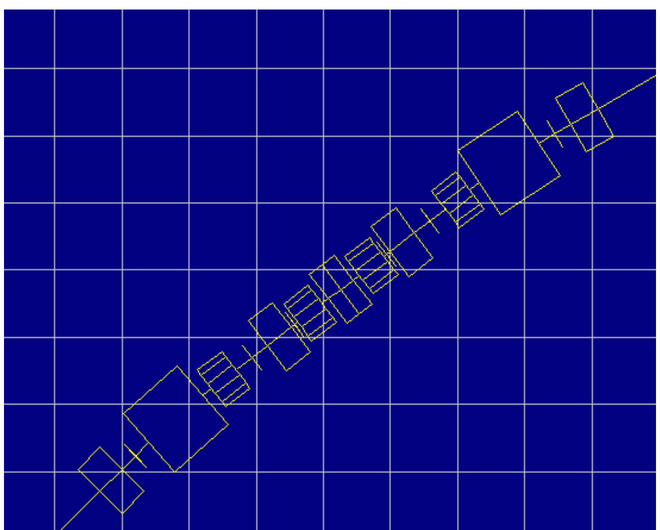
Max. vert. peak-peak [m] 1.065598
Av. vert. peak-peak [m] 0.404006
RMS vert. peak-peak [m] 0.137809

MAX. VERTICAL PEAK-PEAK:
1.065598m
AVERAGE VERTICAL PEAK-PEAK:
0.404006m

The closed orbit was measured and corrected by:

- **158**(x2) vertical (VPU) and horizontal (HPU) **BPMs**,
- **158**(x2) vertical (VCORR) and horizontal (HCORR) **correctors**

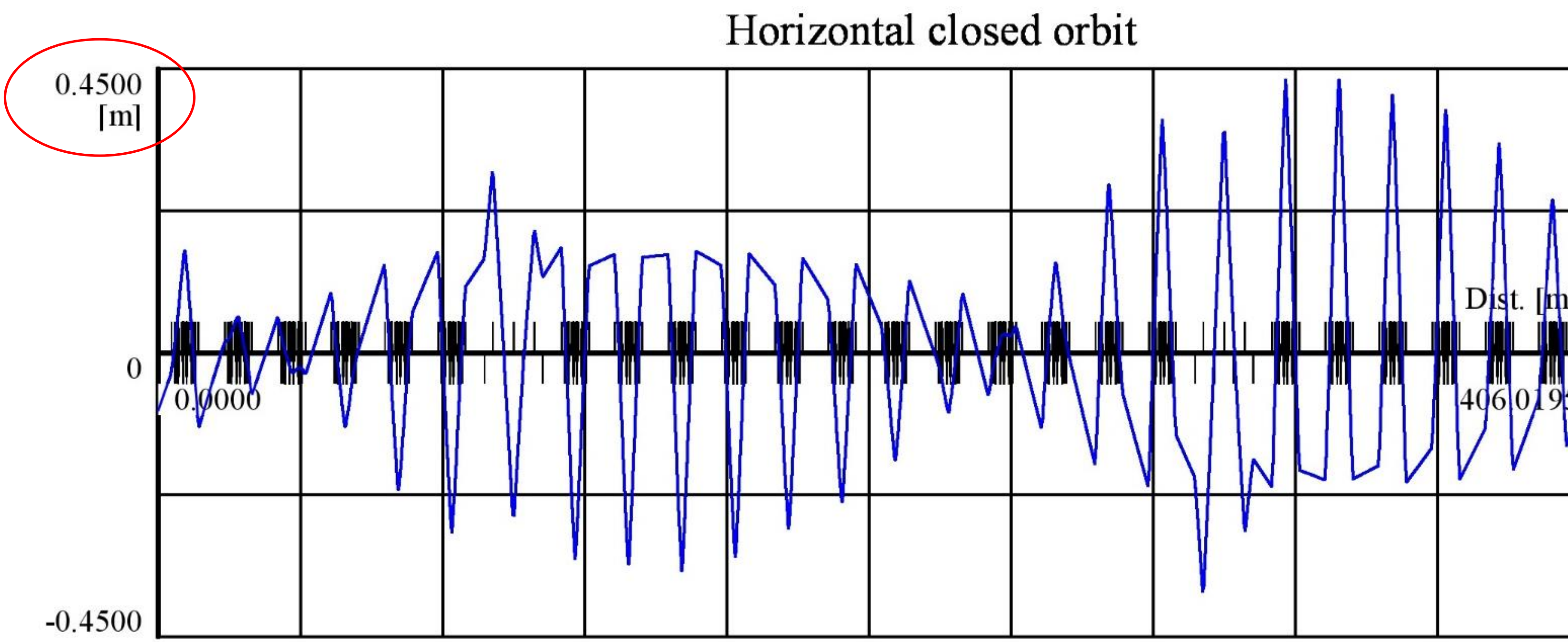
We placed BPMs and Correctors next to the Dipoles and close to Quadrupoles and Sextupoles, which represent the main sources of misalignment.

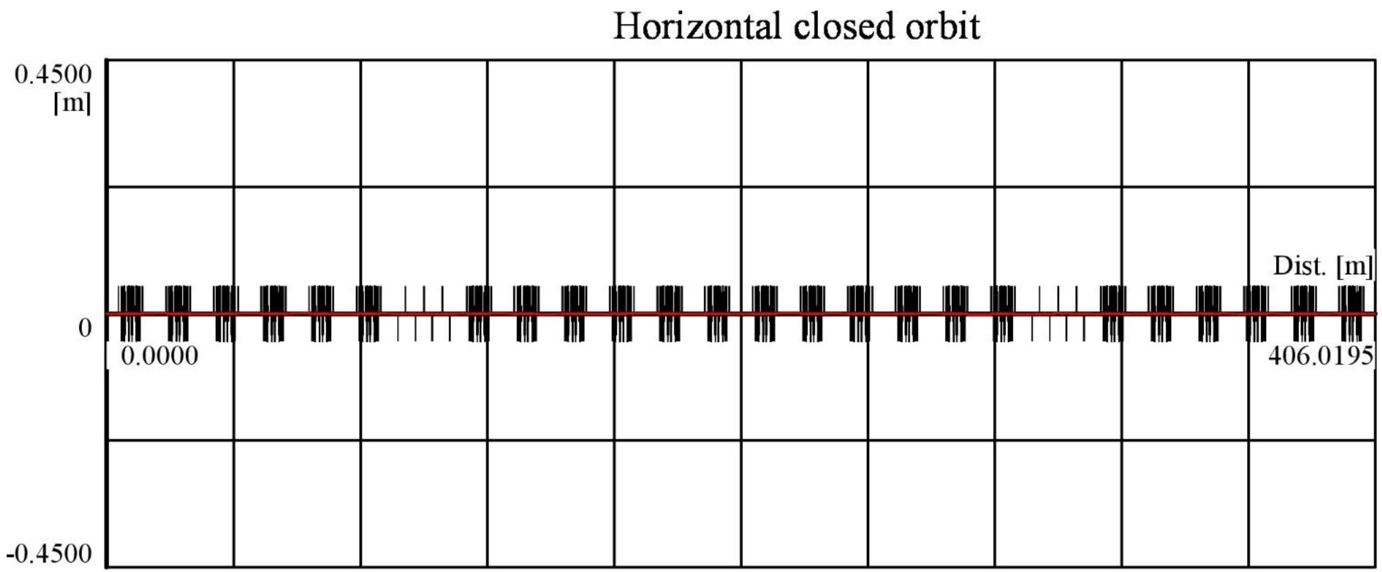


Unit no.	Name	Type	Length [m]
1	S0	DRIFT	3.5609
2	QD1	QUADR	0.4000
3	S2	DRIFT	0.2446
4	BpmV	VPU	0.0000
5	CorrV	VCORR	0.0000
6	BpmH	HPU	0.0000
7	CorrH	HCORR	0.0000
8	S2	DRIFT	0.2446
9	Dipole1	RBEND	0.9200
10	S3a	DRIFT	0.1500
11	XD	SEXTU	0.4000
12	S3b1	DRIFT	0.2527
13	BpmH	HPU	0.0000
14	CorrH	HCORR	0.0000
15	BpmV	VPU	0.0000
16	CorrV	VCORR	0.0000
17	S3b2	DRIFT	0.2527
18	QD2	QUADR	0.4000
19	S4a1	DRIFT	0.0499
20	BpmV	VPU	0.0000
21	CorrV	VCORR	0.0000
22	BpmH	HPU	0.0000
23	CorrH	HCORR	0.0000
24	S4a2	DRIFT	0.0499
25	XF	SEXTU	0.4000
26	S4b	DRIFT	0.1000
27	QF2	QUADR	0.2000

Correction

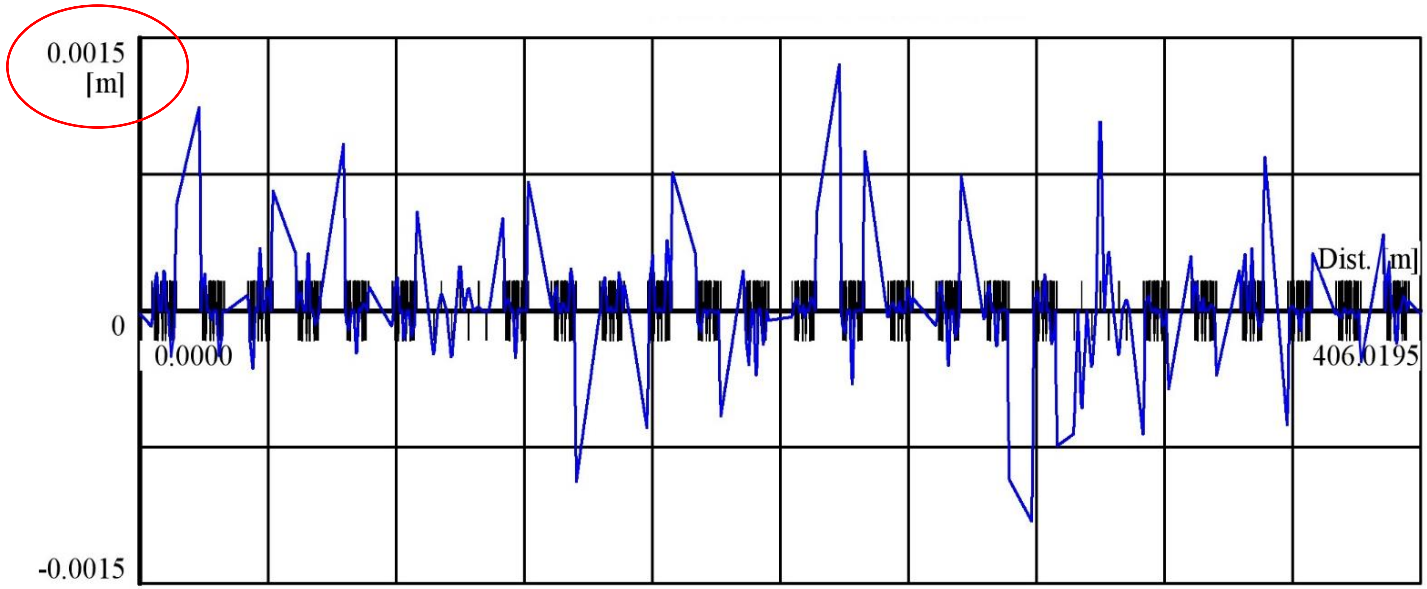
Before studying the '*Statistic for Corrected Closed Orbit*', we investigated the behaviour of a single closed orbit and its correction.



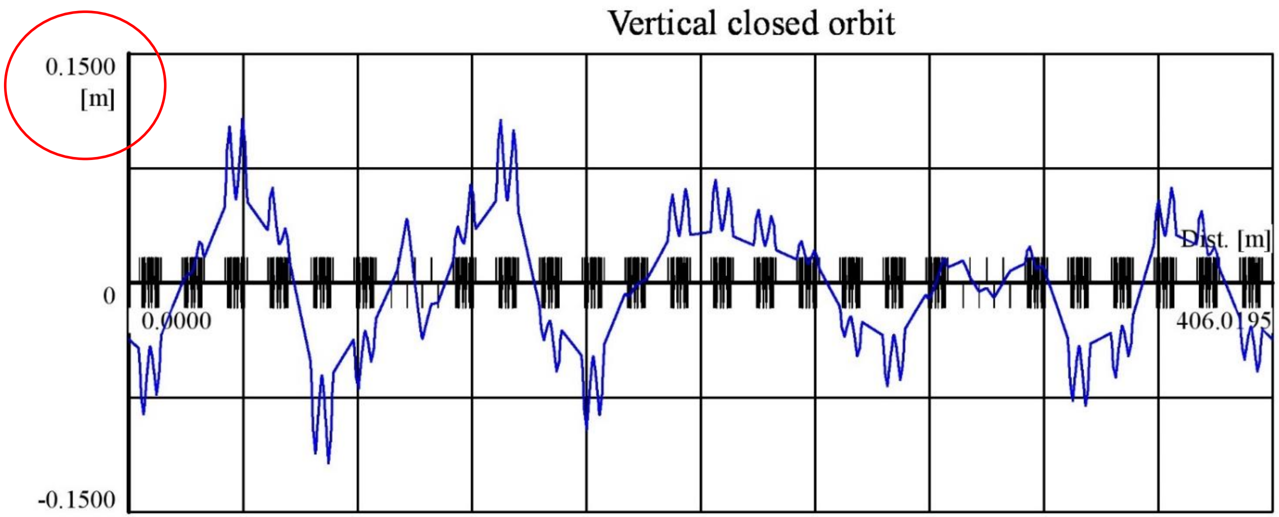


- We corrected the previous closed orbit using *all* the available correctors (158 in the horizontal plane).
- Once fixed the number of correctors and the plane to be corrected, the routine computes a selection of the '**best**' correctors out of those available.
- The Computation Method used to select the best correctors is a Least Square Fit (also an SVD method is available)

ZOOM of the corrected Closed Orbit:

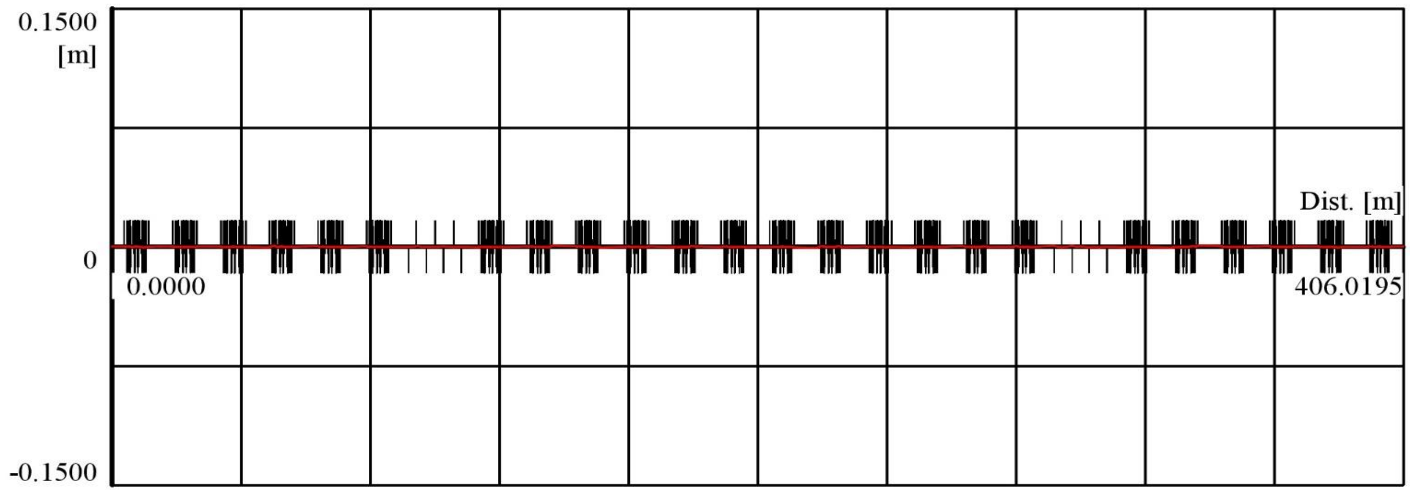


Starting from a closed orbit with maximum amplitude of around **0.45 m** we reached a final amplitude of **1.5 mm** in the horizontal plane!

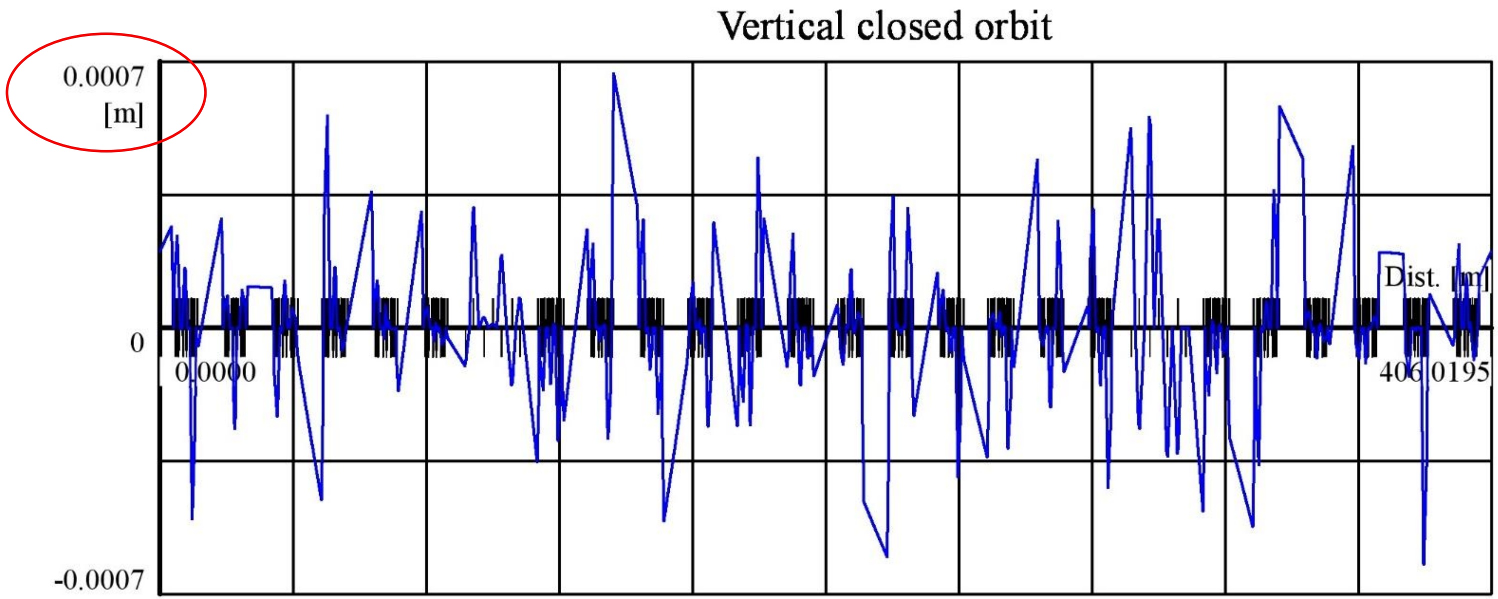


Vertical CO ***before*** the correction

Vertical CO ***after*** the correction



ZOOM of the corrected Closed Orbit:



Starting from a closed orbit with maximum amplitude of around **0.15 m** we reached a final amplitude of **0.7 mm** in the vertical plane!

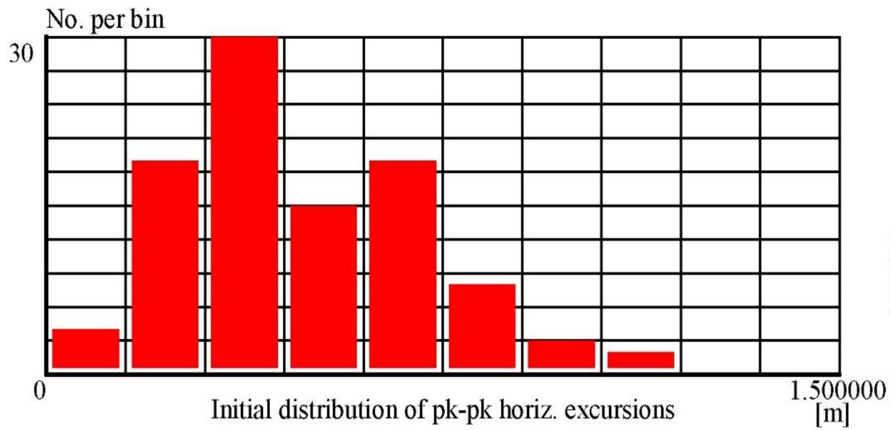
Statistic for Corrected Closed Orbit

- Although there may be a large number of correctors available, it is usually advantageous to check if a **small number** of correctors will correct the orbit. This increases reliability because :
  - there are fewer power converters working
  - it increases the currents delivered by those that are working, helping to prevent instabilities.

- The maximum number of calculations for a statistical analysis is 1000, but it is recommended that a test run is made with around 100 calculations .

- What we have done to compute the *Statistic for Corrected Closed Orbit* in a time-saving way was to run a test with **100** machines, limiting the number of the corrector to **20**.

STATISTICS FOR RANDOM CLOSED ORBITS BEFORE AND AFTER CORRECTION

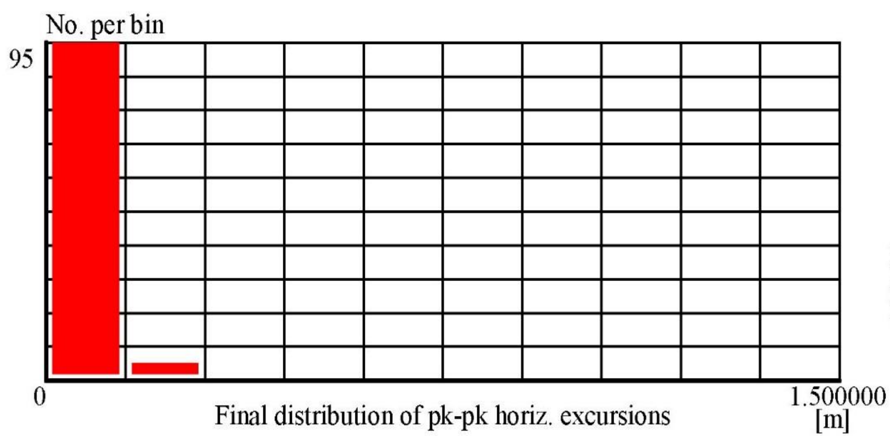


GLOBAL STATISTICS

No. of machines in sample 100

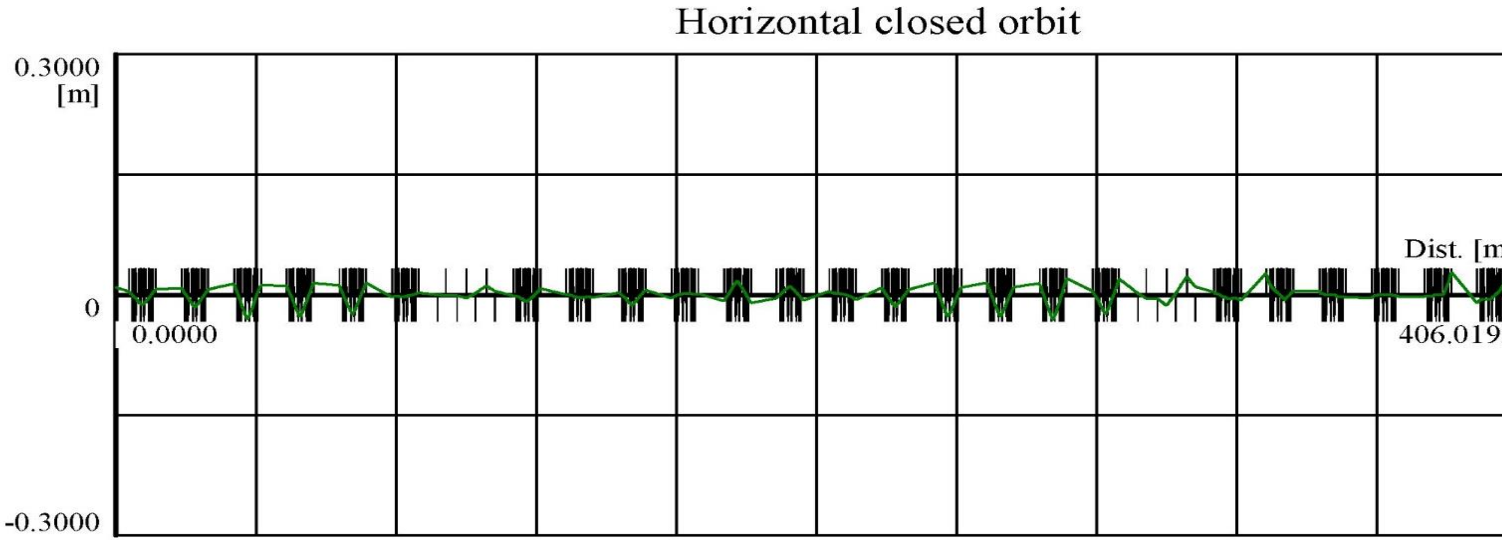
Max. initial horiz. pk-pk [m]	1.109000
Av. initial horiz. pk-pk [m]	0.487449
RMS initial horiz. pk-pk [m]	0.225425

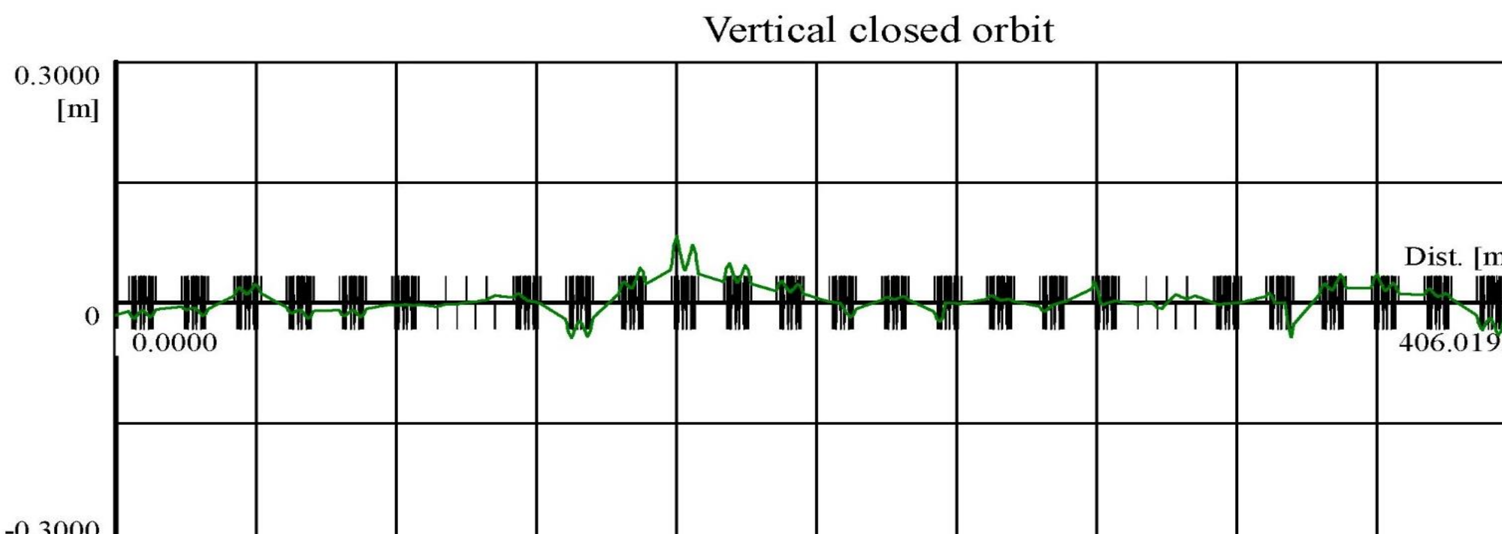
MAX.HORIZONTAL PEAK-PEAK: **1.09000m**
AVERAGE HORIZONTAL PEAK-PEAK: **0.487449m**



Max. final horiz. pk-pk [m]	0.197763
Av. final horiz. pk-pk [m]	0.086300
RMS final oriz. pk-pk [m]	0.034912

MAX.HORIZONTAL PEAK-PEAK: **0,197763m**
AVERAGE HORIZONTAL PEAK-PEAK: **0.086300m**

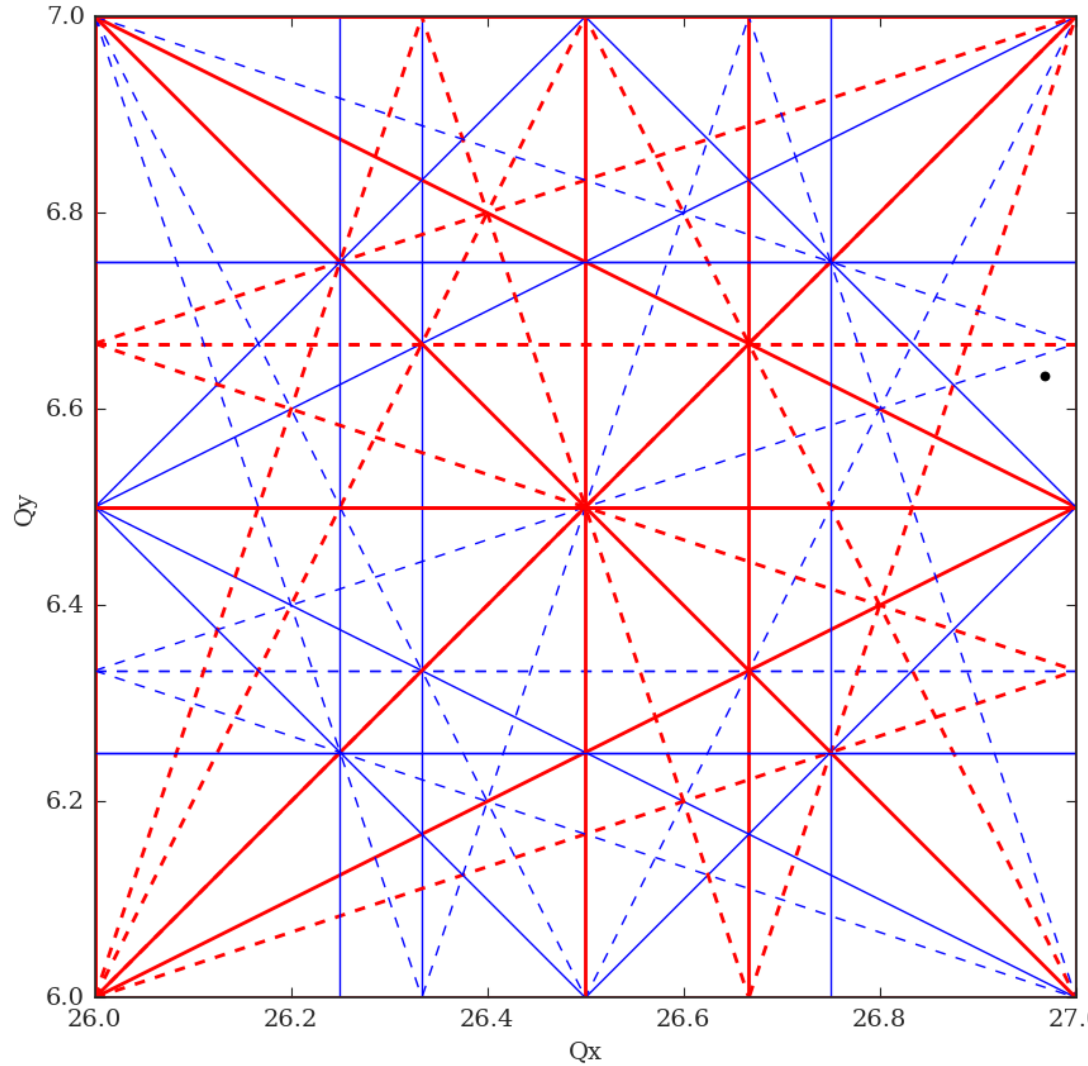

Horizontal closed orbit
0.3000
[m]
Dist. [m]
0
0.0000
406.0195
-0.3000


Vertical closed orbit
0.3000
[m]
Dist. [m]
0
0.0000
406.0195
-0.3000

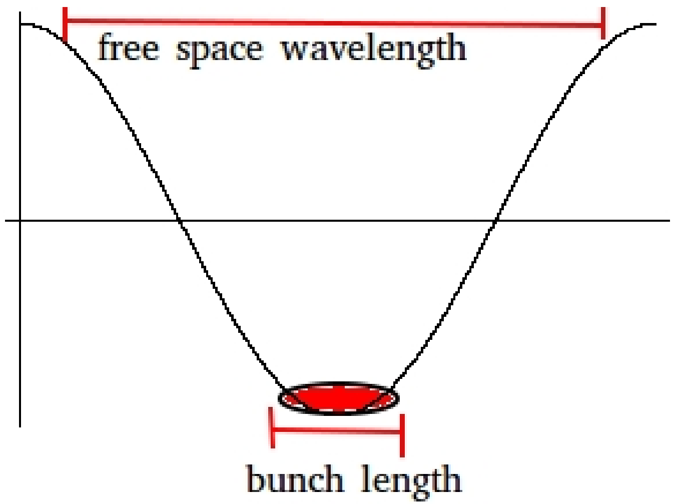
Space charge study for JUICE

Tune diagram

	Value
Tune H	26.96856
Tune V	6.633655
r_e	$2.82 * 10^{-15}$ m
N	$2.22 * 10^{8}$ electrons
l_o	0.01 m
ρ	7.029 m
ϵ_x	0.15 π mm mrad
ϵ_y	0.15 π mm mrad
E	3 GeV
Periodicity	2



Computation of Space Charge in WinAgile

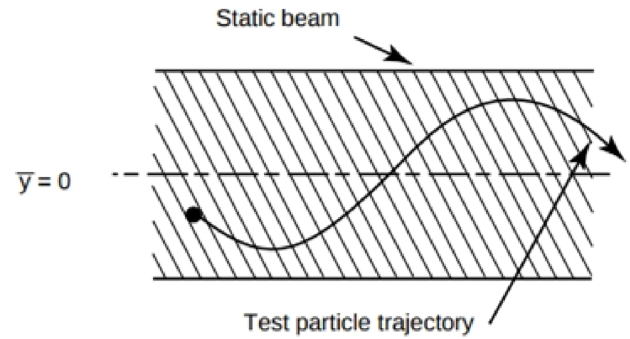


Free space wavelength = 0.6 m

Bunch length = 0.012 m

Bunching Factor = 0.6 / 0.012 = 5

Incoherent Space Charge



WinAgile

- No change

Theoretical

dQh = -1.92 e-8
dQv = -1.92 e-8

$$\Delta Q_x = -\frac{N r_{e,p}}{2\pi \varepsilon_x \beta^2 \gamma^3}\left(\frac{2\pi \rho_x}{l_o}\right)$$

Incoherent Space Charge

WinAgile

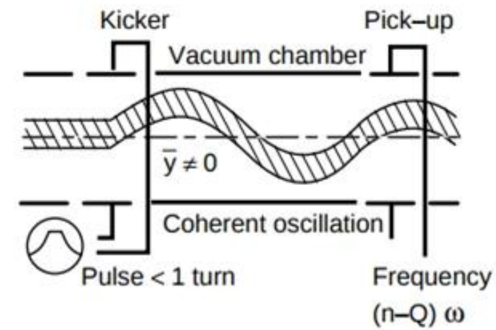
- No change

Theoretical

dQh = -1.92 e-8
dQv = -1.92 e-8

$$\Delta Q_x = -\frac{N r_{e,p}}{2\pi \varepsilon_x \beta^2 \gamma^3}\left(\frac{2\pi \rho_x}{l_o}\right)$$

Coherent Space charge



WinAgile

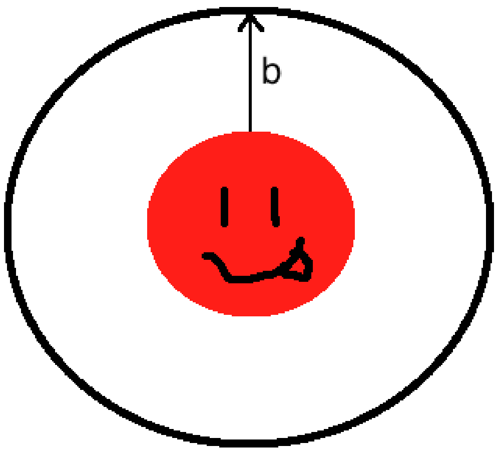
Tune H = 26.967827 → dQh = - 0.000739 *5 = - 3.695 e-3
Tune V = 6.632407 → dQv = - 0.001248 *5 = - 6.240 e-2

Theoretical

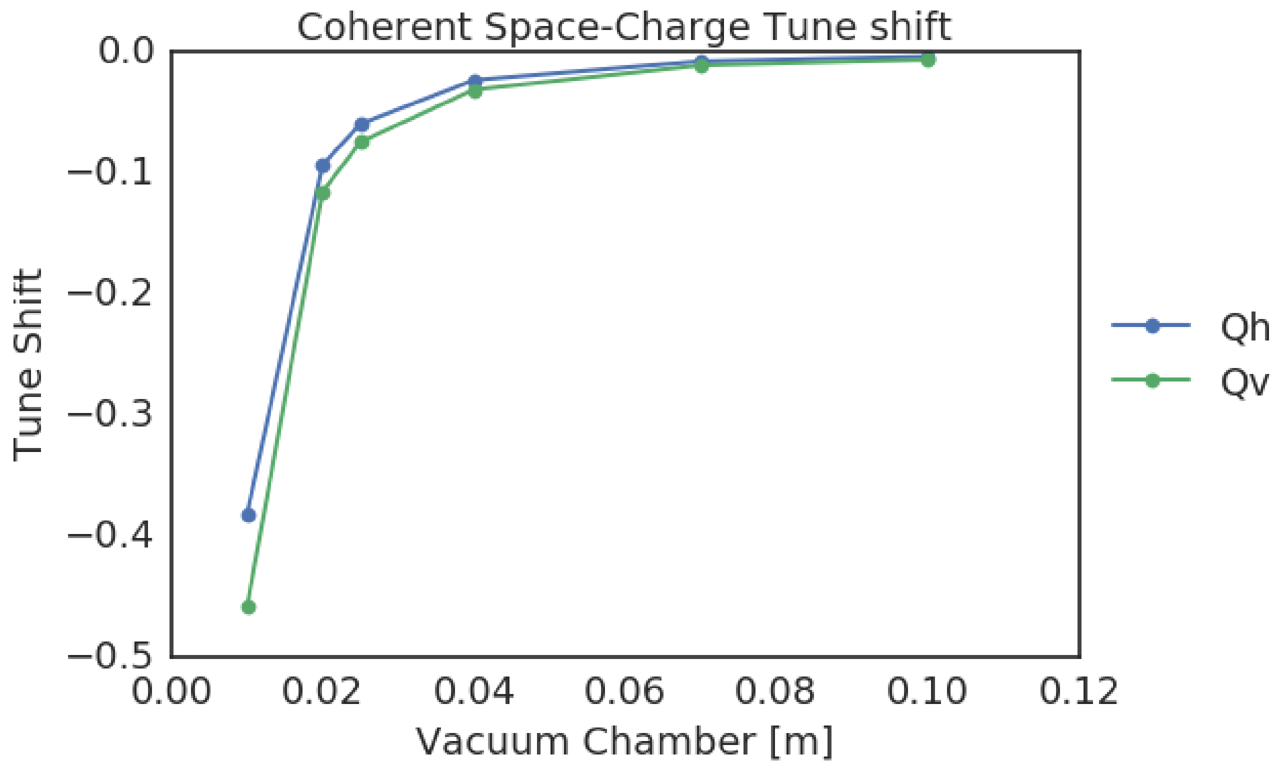
dQh = -0.000132 = -1.320 e-4
dQv = -0.000529 = -5.294 e-4

$$\Delta Q_{xc} = -\frac{r_e \rho_x^2}{\beta^2 \gamma Q_{x0}} \frac{N}{b^2 l_0}$$

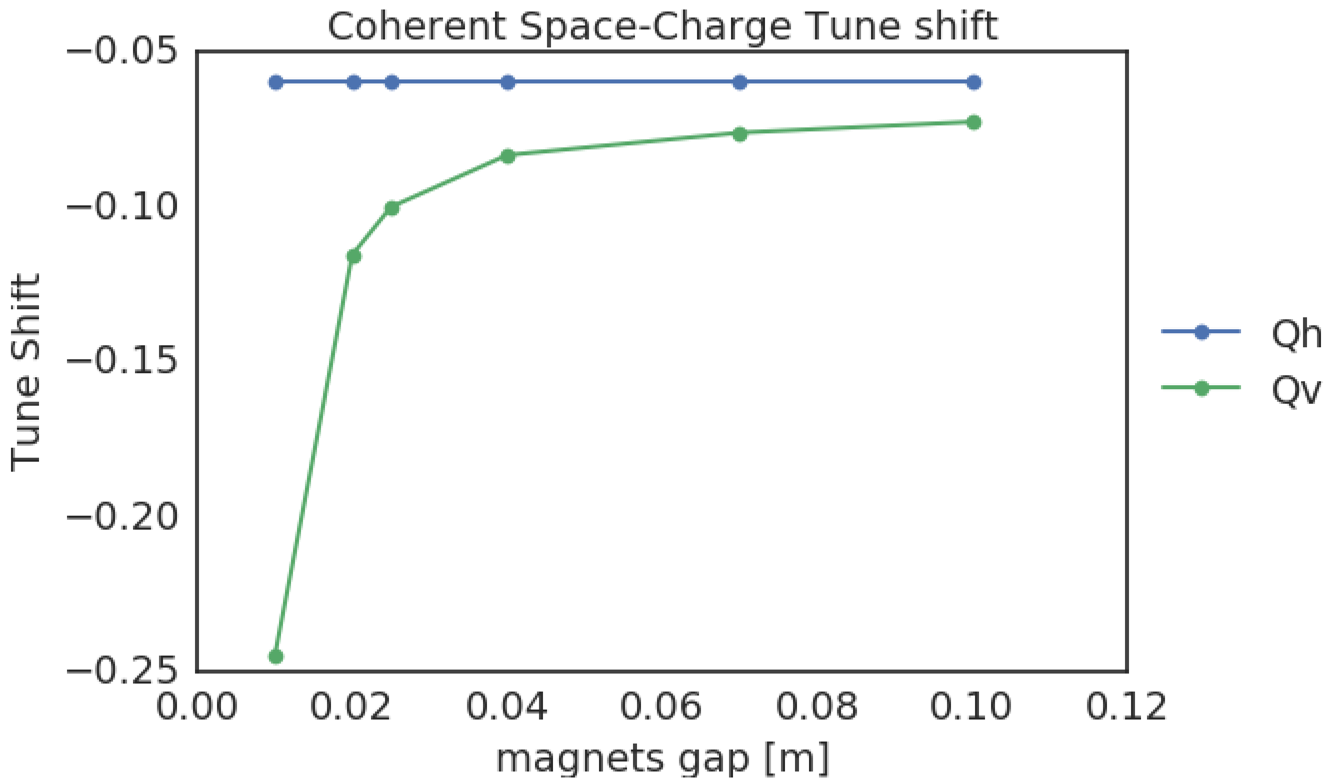
Change of Vacuum chamber aperture



Electrostatic Images



Change of magnets' gap



Magnetic images

Lower Energy

Energy equal to 2 GeV

- Incoherent:

  No change

- Coherent:

  Tune H = 26.967457 → dQh = - 0.001109 * 5 = - 5.55 e-3
  Tune V = 6.631783 → dQv = - 0.001872 * 5 = - 9.36 e-3

JUICE Vacuum System Design

Helene, Vacuum Team Leader

February 2, 2018

JUICE Vacuum chamber design

$$P_{dynamic} = 10^{-9} Torr$$

$\rightarrow$low enough not to constitute a limitation to the operation of the machine

Horizontal beam size :

$$\sigma_x = \sqrt{\frac{\epsilon_x}{\pi}\beta_x^{max} + (D_x\frac{\Delta P}{P})} = 2.74\ mm$$

Injection parameters :

$$\epsilon_x = \epsilon_y = 0.15\pi\ mrad.mm$$

Beam parameters : $\beta_x^{max} = 50m \quad \beta_y^{max} = 39m \quad D_x^{max} = 0.4\ m \quad \frac{\Delta P}{P} = 10^{-3}$

Chamber apertures :

$$\boxed{5 \times 4\ cm}$$

WinAGILE Simulations

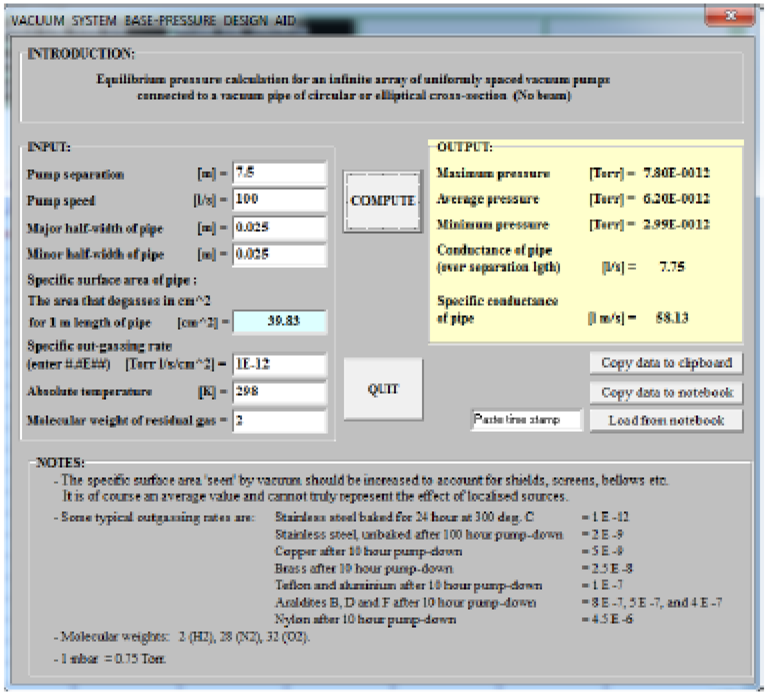


Figure 1: WinAGILE vacuum simulation tool

- Stainless steel baked chambers
- Area that degasses :

$$2\pi\sqrt{\frac{5^2+4^2}{2}} \times 1.40$$

- Outputs : static Pressures

$$\boxed{P_{max} \sim 10^{-11}\, Torr}$$

WinAGILE Simulations

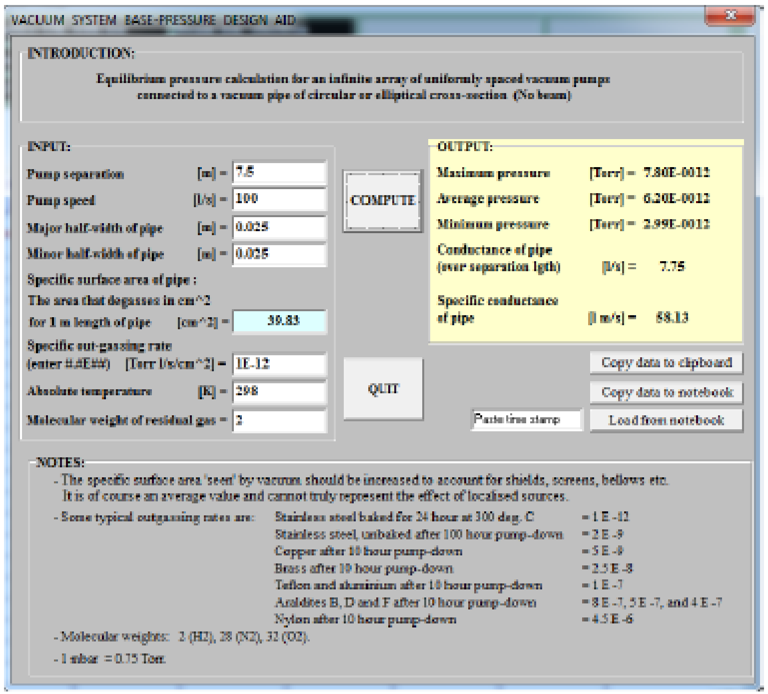


Figure 2: WinAGILE vacuum simulation tool

- Stainless steel baked chambers
- Area that degasses :

$$2\pi\sqrt{\frac{5^2+4^2}{2}} \times 1.40$$

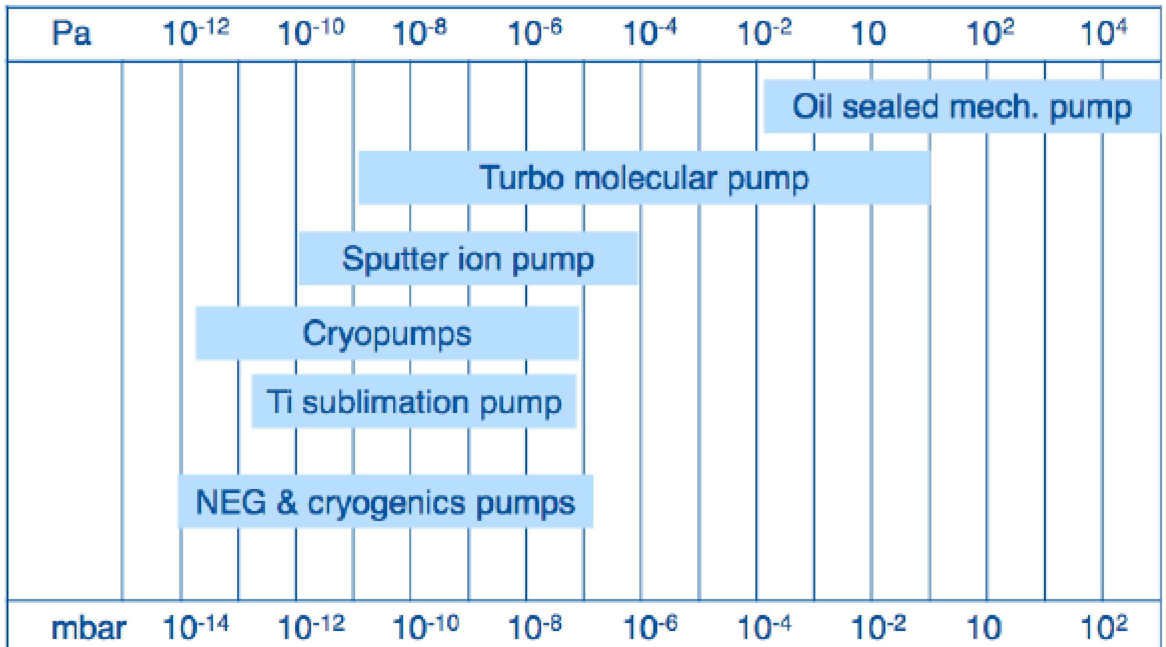
- Outputs : static Pressures

$$\boxed{P_{max} \sim 10^{-11}\,Torr}$$

Pumping System

Vacuum pumps pressure range

16 orders of magnitude !



Pumping System

Figure 3: Turbomolecular pump system
$\rightarrow 10^{-6} mbar$

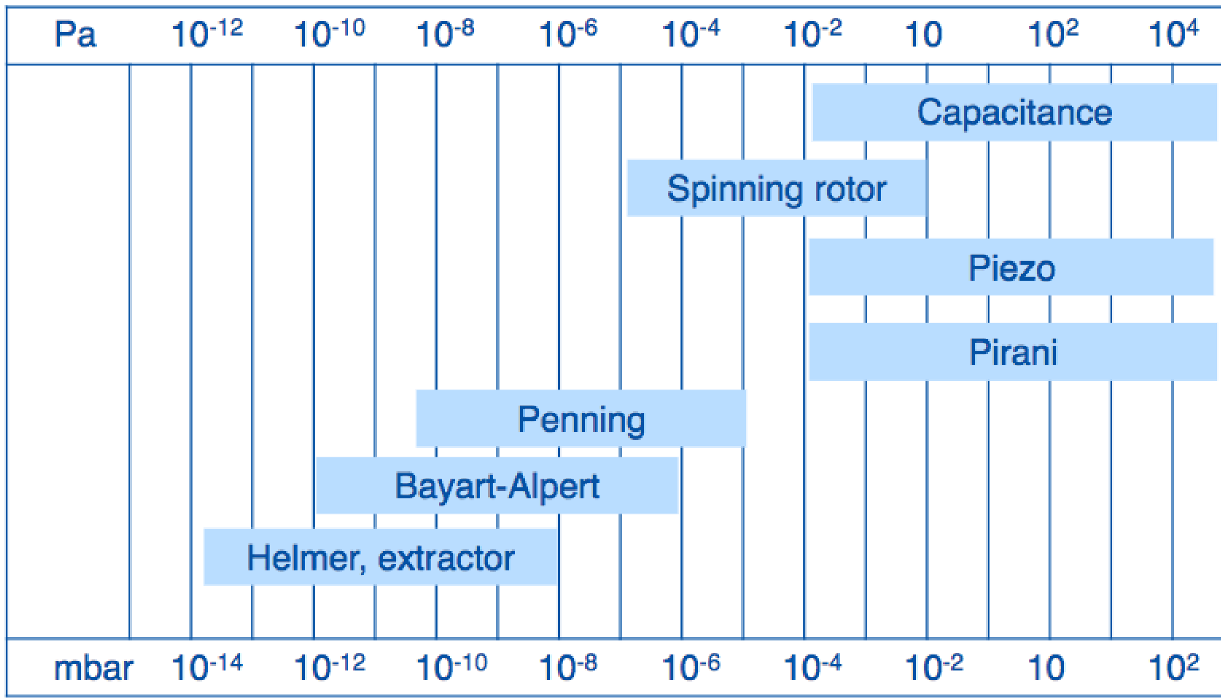
Figure 4: NEG pump: speed $100L/s$ datasheet

Figure 5: Sputter Ion Pump (SIP) datasheet

Gauges

Vacuum gauges pressure range

16 orders of magnitude !



Practical Considerations

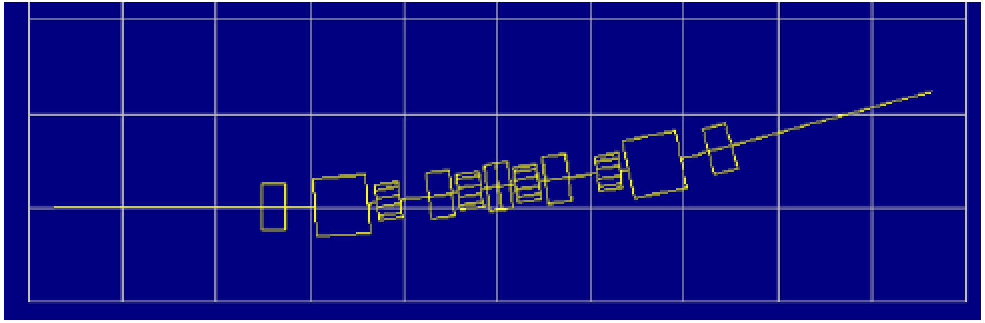


Figure 6: JUICE example cell

- Critical places : dipoles, kickers, septums, ID, crotches...
- NEG pumps (SAES), SIP (Agilent)
- Pirani and Penning gauges
- ID chambers Aluminium + NEG coating ($\rightarrow$ very low outgassing rate) (ESRF)

Thank you for your attention

Come to JUAS 2^{nd} Course : Accelerator Technologies

SR workshop (R. Bartolini)

The goal of the workshop is to design synchrotron light source based on a DBA lattice. The beam energy is 3 GeV.

From the initial DBA cell from P. J. Bryant

- **compute critical frequency of bending, energy loss, total power radiated**
- **Install IDs to reach 5 keV**
- **compute tuning range, bandwidth, energy loss per turn, total power emitted by the IDs, brilliance, tuning curves**
- **compute the RF power needed for 300 mA**
- **assume 8 DBA cells with 3.2 m straight sections**
- **complete matching (achieve betay = 2m in SS, check tunes)**
- **play with optics to reduce the emittance (break the achromatic condition)**
- **Investigate other cells (TBA)**

Radiation from bendings

Bending field 1.4 T - bending radius 7.1 m

energy loss per turn: Bending magnets

$$U_{\{0,bend\}} = 88.46\frac{E[GeV]^4}{\rho[m]} \approx 1.0\ MeV$$

Critical energy

$$\varepsilon_c = 2.218\frac{E[GeV]}{\rho[m]} = 8.4\ [keV]$$

Power emitted as Synchrotron Radiation:

$$P\ [kW] = U_0[keV] \cdot I_{beam} = 1.0 \cdot 10^3[keV] \cdot 0.3\ [A] = 300\ [kW]$$

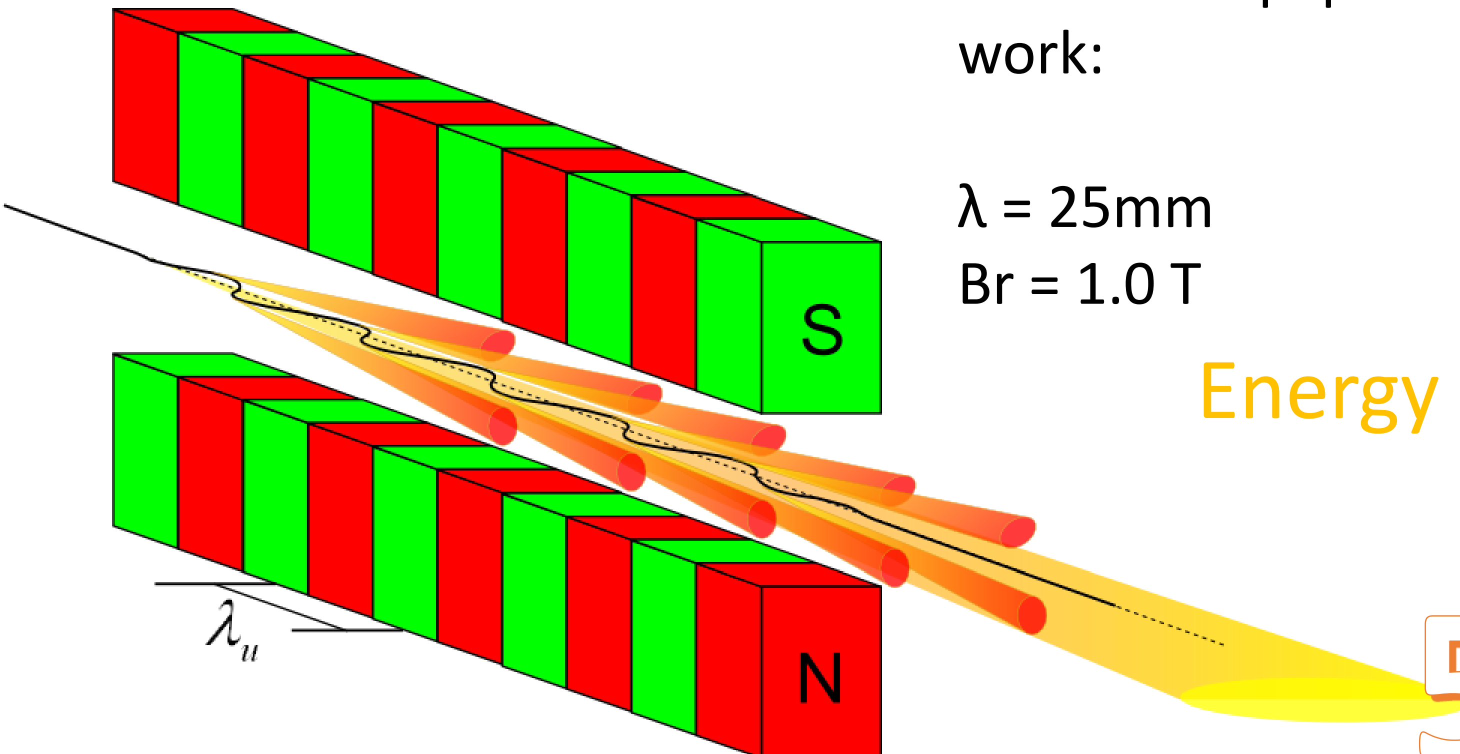
Assuming 50% efficiency the RF power must be:

$$P\ [kW] = 600\ [kW]$$

With this equipment, we choose to work:

λ = 25mm

Br = 1.0 T



Energy required

↓

5keV

From the following formula is possible to obtain K (the undulator parameter)

$$\varepsilon_n(eV) =: 9.496 \frac{nE[GeV]^2}{\lambda_u[m]\left(1+\frac{K^2}{2}\right)}$$

$$K = \sqrt{\frac{9.496 \cdot n \cdot E[GeV]^2}{\lambda_u[m] \cdot \varepsilon_n[eV]} - 1}$$

The value obtained is

K = 1.56 n = 5

K= 1.03 n = 3

Such photon energy can be radiated only in harmonics

After to check the feasibility of the project we go down to check the value of the remnant field B_r using the following formula:

$$K = 0.168\ B_r \lambda_u\, e^{-\frac{\pi\, gap}{\lambda_u}}$$

Mind that different parameterisations can be found

$$B_{y_0} = 1.72\, B_r e^{-\pi g/\lambda_u}$$

NOTE: First formula use lengths in mm

After we want to evaluate the B field at the centre of the structure (B_0):

$$K = \frac{e B_0 \lambda_u}{2\pi m c}$$

n	B_0	Gap	B_r
3	0.45 T	11.2 mm	1
5	0.67 T	7.9 mm	1

Tuning range:
K min ~ 0.5
K max (4 mm) = 2.54

Tuning range:
Third harmonics ~ 2.4 - 9.1 keV
Fifth harmonics ~ 4.0 – 15.2 keV

Energy loss per electron in one wiggler in 1 turn:

$$E_{loss} = 0{,}07257 \frac{E^2[GeV]\, K^2 l_w}{\lambda_w} =$$

Energy loss per turn (K=1.03) = 83 keV
Energy loss per turn (K=1.56) = 190 keV

Why not adding 22 WIGGLERS?

- Total energy loss: Bending magnets + all wigglers
  - K = 1.03

    $U_{\{0,wigglers\}} = N_{wig} \cdot U_{\{0,1\,wiggler\}}$ = 22 · 83 [keV] = 1.83 [MeV]

    $$\boldsymbol{U_{\{0,total\}}} = 1.0\,[MeV] + 1.83\,[MeV] = \mathbf{2.83\,[MeV]}$$
  - K = 1.56

    $U_{\{0,wigglers\}} = N_{wig} \cdot U_{\{0,1\,wiggler\}}$ = 22 · 190 [keV] = 4.18 [MeV]

    $$\boldsymbol{U_{\{0,total\}}} = 1.0\,[MeV] + 4.18\,[MeV] = \mathbf{5.018\,[MeV]}$$
  - Power emitted as Synchrotron Radiation:

    $$\boldsymbol{P\,[kW]} = U_0[keV] \cdot I_{beam} = 2.83 \cdot 10^3[keV] \cdot 0.3\,[A] = \mathbf{849\,[kW]}$$
    $$\boldsymbol{P\,[kW]} = U_0[keV] \cdot I_{beam} = 5.18 \cdot 10^3[keV] \cdot 0.3\,[A] = \mathbf{1550\,[kW]}$$

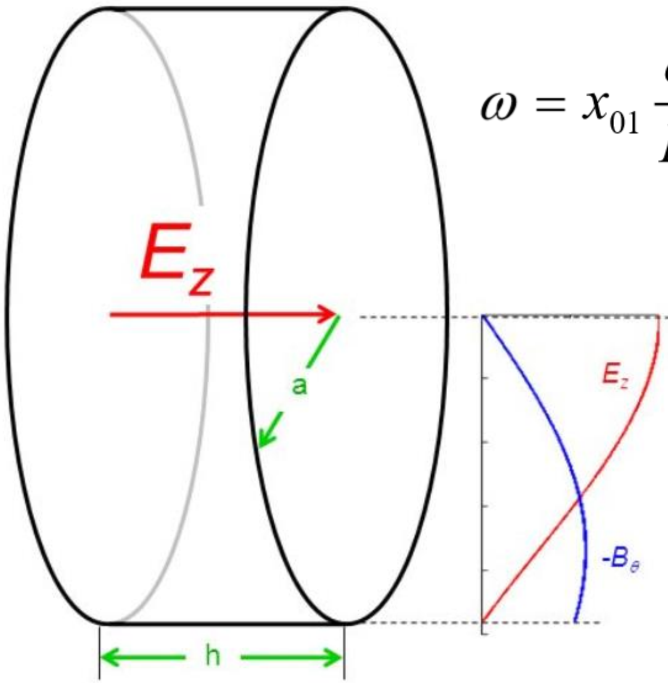
Compared to 300 kW for dipoles only we obtained a factor between 3 and 5

RF Design workshop

- **Goal: Design RF System**
- **Input Parameters:**
  - To operate at 500 MHz frequency (f_{rf})
  - To accelerate from 2 GeV to 3 GeV
- **Compensate Energy Losses** (Synchrotron Radiation, Wiggler)
- **Pill-Box RF Cavity**
- **Define RF System and RF Programme**
- **Calculate Voltage (V_{rf}), RF- Power**

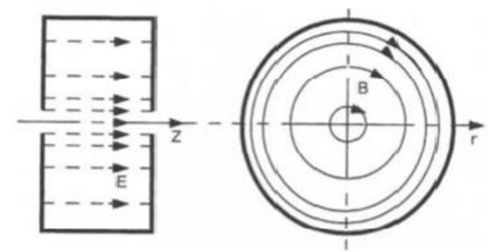
Presented by RF-Team
Francesco GIORDANO
Markus JAEGER
Mohamed KARIMELDIN
Rakesh Chandra PRAJAPATI

Pill-Box RF-Cavity for acceleration



TM010 resonance frequency **independent of h**

$$\omega = x_{01}\frac{c}{R} \qquad x_{01} = 2.405 \qquad R = \frac{x_{01}}{2\pi}\lambda = 0.383\lambda$$



- **Magnetic field is concentrated at the cylindrical wall, responsible for RF losses.**
- **Electric field is concentrated near axis, responsible for acceleration.**

RF Parameters (Frequency, Voltage, Power)

f_{rf} = 500 MHz

Circumference of Main Ring (C_{ring}) = 406.195 m

$f_{rev} = c/C_{ring} = 3x10^8/406.195$ = 738.561 kHz

Harmonic Number (h) = $f_{rf}/f_{rev} \approx 677$

Pill-Box RF Cavity:

Radius of Cavity = 0.383 λ = 0.383 x 60 = 23 cm

Length of Gap inside the Cavity = 10 cm

Accelerating Voltage (RF-Voltage)

$$\Delta E[keV] = 88.5 \frac{E^4[GeV]}{\rho[m]}$$

Partical Energy (E) = 3 GeV
Bending Radius (ρ) = 7 m

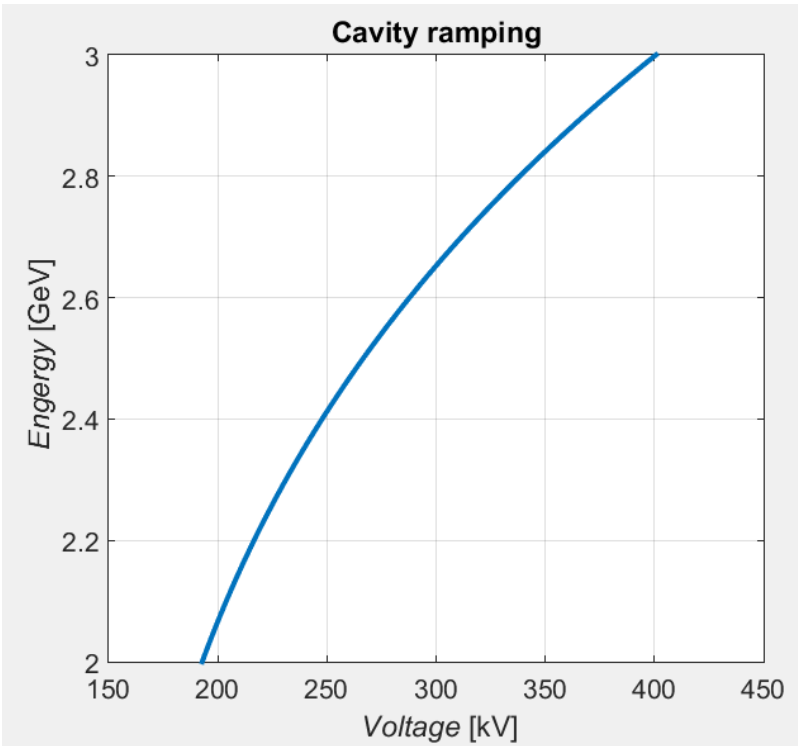
- Synchrotron Radiation (SR) Loss per Turn **(ΔE) = 1 MeV**
- Hence, to compensate SR Energy Loss, accelerating voltage of 1 MV is required.
- For sufficient beam life-time, **Over Voltage Factor** of at least 2 is required.
- Therefore, we provide **2.5 MV** accelerating voltage in the Main Ring through 4 RF-Cavities. (N_{cavity} = 4)

RF Power requirement

- 2.5 MV voltage in the Main Ring through 4 RF-Cavities. (N_{cavity} = 4)
- Therefore, each RF-cavity operates at 2.5 MV/4 = 625 kV
- **1. Power Required To Generate Accelerating Voltage**
- RF Cavity Power (P_{acc}) = V^2/R_{sh} = $(625\ kV)^2/3.5\ M\Omega$ = 112 kW (each RF cavitiy)
- **2. Power Required To Compensate for SR Loss**
- SR Loss Power (P_{SRL}) = Stored Current X Voltage for SR Loss Compensation

  = 300 mA X 1MV = 300 kW
- **3. Power Required To Compensate Wiggler Loss**
- Wiggler Loss Power (Pwiggler) = 1550 kW
- **Total Power Required (P_{total}) = (N x P_{acc}) + P_{SRL} + Pwiggler = 4x112 kW + 300 kW + 1550 kW = 748 kW + 1550 kW = 2.3 MW**

RF Voltage per Cavity vs. SynchtRon Loss



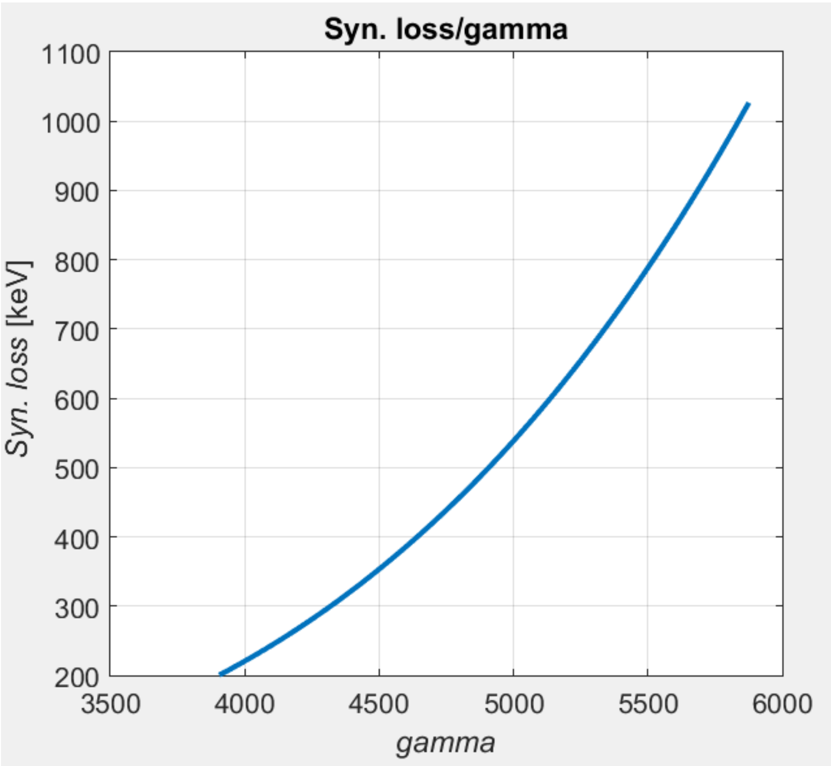
$$E_{inj.} = 2GeV$$

$$E_{top} = 3GeV$$

$$E_{inj} < E < E_{top}$$

$$V_{RF} = \frac{2 \cdot \pi \cdot \rho \cdot R \cdot \dot{B} + \Delta E}{N \cdot \sin(\varphi_s)}$$

Gamma vs. synchtron loss



$$\gamma = \frac{E}{E_0}$$

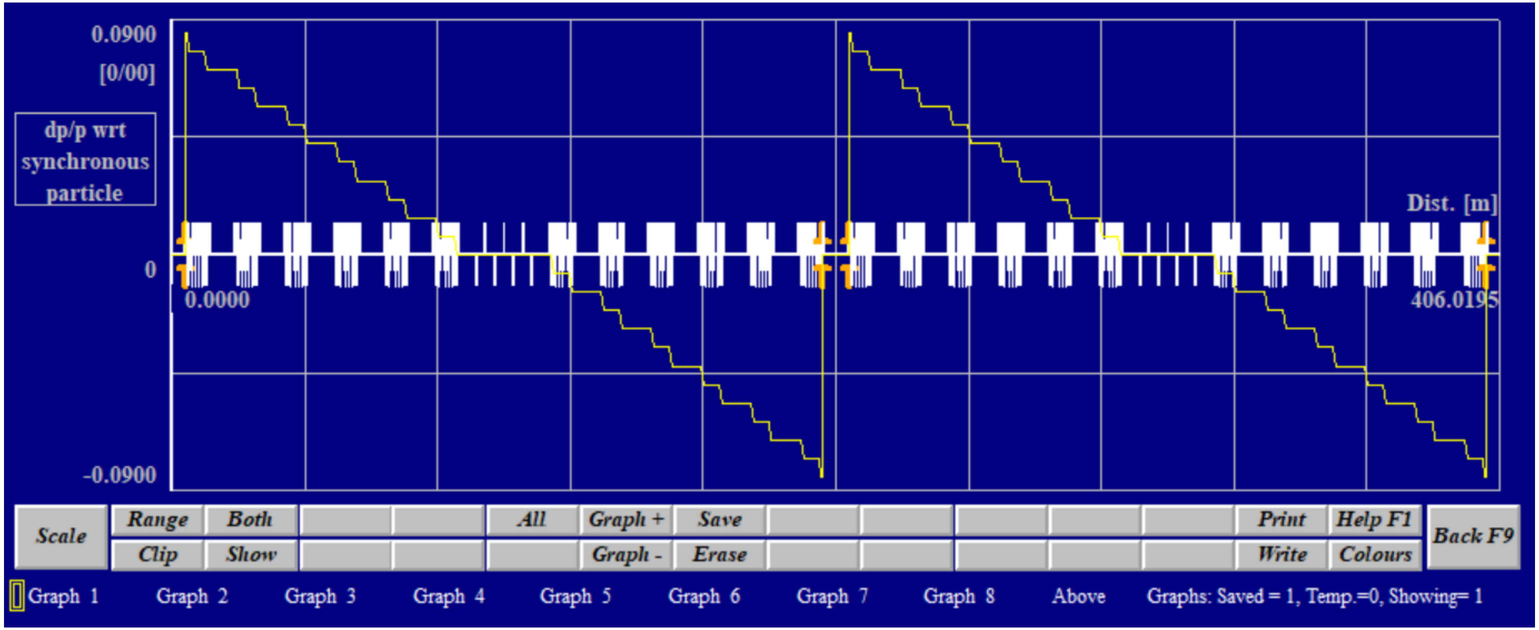
2GeV<E<3GeV

$$\Delta E[keV] = 88.5 \frac{E^4[GeV]}{\rho[m]}$$

Synchtron Radiation Loss Per Turn is 1 MeV.

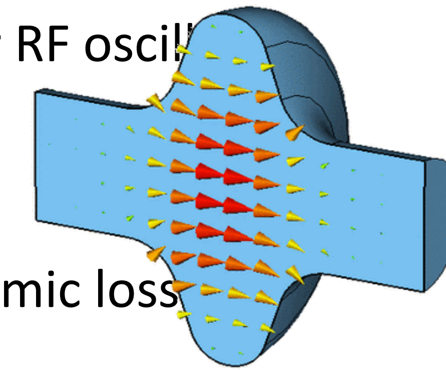
Synchtron radiation loss compensation

4 RF cavities are compensating the energy loss of the beam due to Synchtron Radiation.



RF-Cavity design (from pill-box to Elliptical/spherical)

- Improving the 3 Figures of Merit: ω_{rf}*(fixed), Q, R*$_s$
- Quality factor Q = stored field energy / ohmic loss per RF oscil



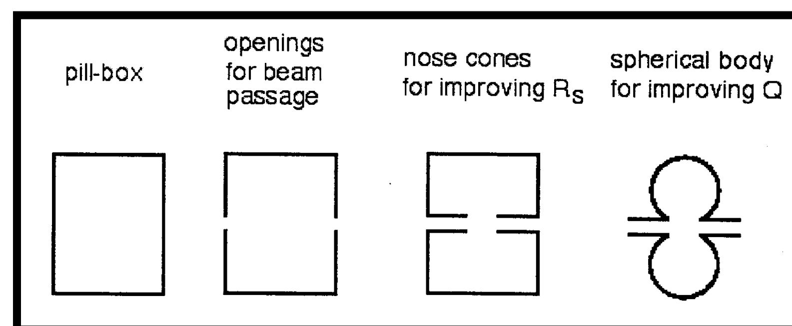
$$Q = \frac{\omega U}{P_{diss}} = \frac{RL}{\delta_{skin}(R+L)} \approx \frac{2V}{\delta_{skin} A}$$

volume (2V)

surface area (A)

- Shunt Impedance R_s = (voltage gain per particle)^2 / ohmic loss

$$R_s = \frac{(E_0 L T)^2}{P_{diss}} \propto \delta_{skin} \propto \frac{1}{\sqrt{\omega}} \propto \sqrt{cavitysize}$$



RF System from 'diamond' Light source

Table 2. Basic Storage Ring RF System Parameters.

		(Our Design Parameters)
Cavity Voltage	5.1 MV	2.5 MV
No. Cavities	6	4
Cavity Shunt Impedance	3.5 MΩ	0.625 MV
Voltage/cavity	0.85 MV	
Cavity Quality Factor (unloaded)	30000	
RF Frequency	499.654 MHz	500 MHz
Overvoltage	2.28	2.5
Synchrotron Frequency	9.6 kHz	
Quantum Lifetime	1E205 hrs	
Radiation Damping Time	0.76 ms	
Natural Bunch Length	13.7 ps	
Total Beam Power	670 kW	
Total Cavity Power	620 kW	
Required Cavity Coupling	2.1	
Window throughput Power	215 kW	
Total Source Power	1420 kW	

RF Engineering design consideration

- **Tuning Mechanism:**
- Frequency tuning of RF cavity should be non-contacting plunger, normal plunger movement can cause beam movement of the order 20 μm.
- **Cooling System:**
- Power Dissipate per Cavity = 748 kW / 4 = 187 kW. Thus, we need water-cooling mechanism. Specific heat capacity of water is C_P = 4185.5 J/(kg.K), thus, 400 liters/min cooling system will have 4°C difference in inlet and outlet. Proper cooling system should be used to keep uniform temperature gradient, otherwise, distortion in cavity geometry can result, and consequently change the frequency.
- Ohmic Heating/ Power dissipation: $P_{diss} \propto \frac{\rho_c}{\delta_{skin}}$ $\delta_{skin} = \sqrt{\frac{2\rho_c}{\mu\omega}}$

Block-diagram of accelerator rf system

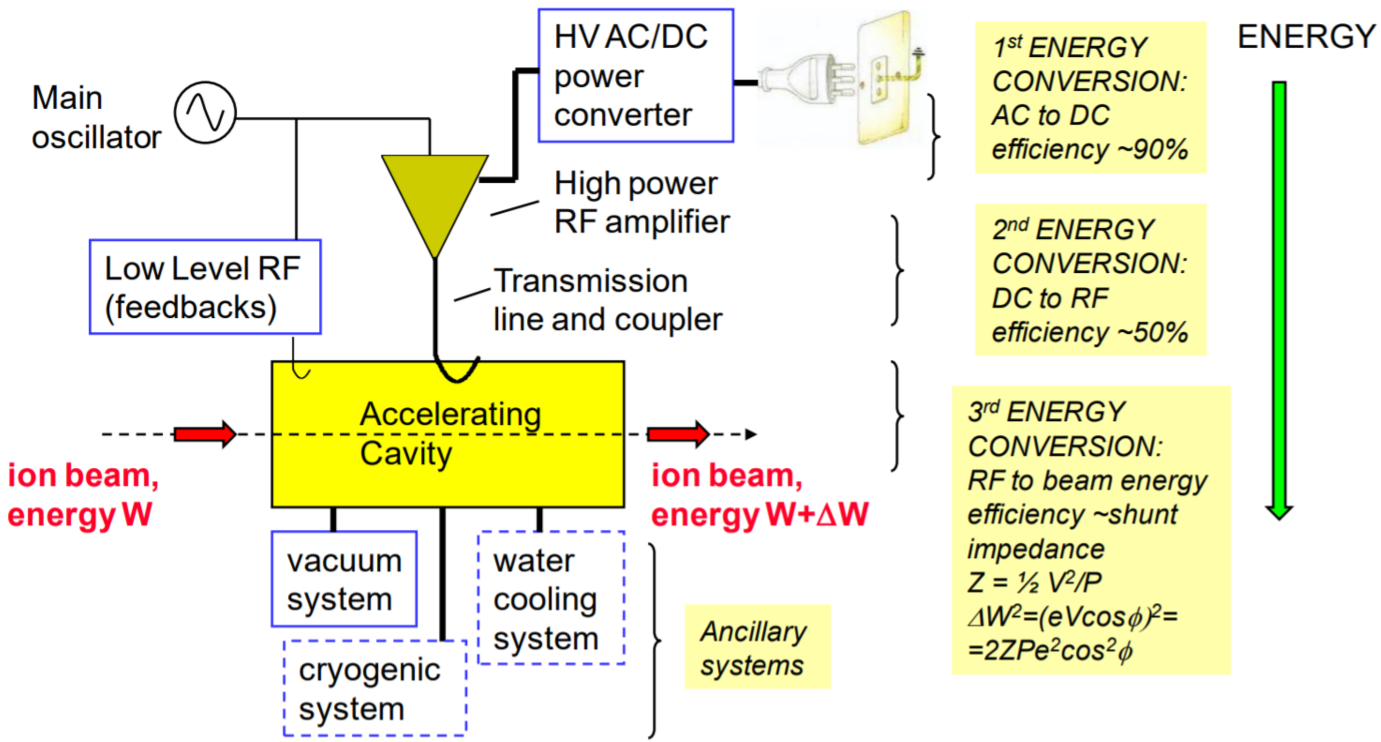


Fig. 13: Block-diagram scheme of an accelerator RF system

"Radio frequency for particle accelerators – evolution and anatomy of a technology"
By M. Vretenar, CERN, Geneva, Switzerland

Thank you!

JUICE

juas
Joint Universities Accelerator School

esi
European Scientific Institute