Preliminary design study of JUICE

Joint Universities International Circular Electronsynchrotron

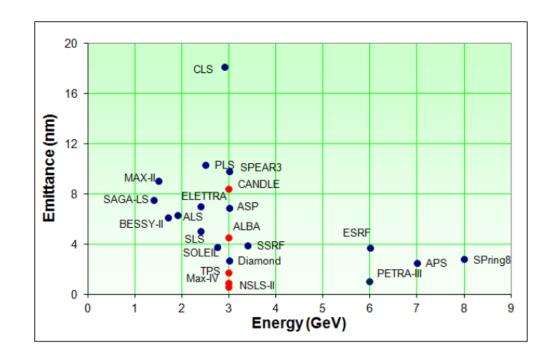




esi European Scientific Institute

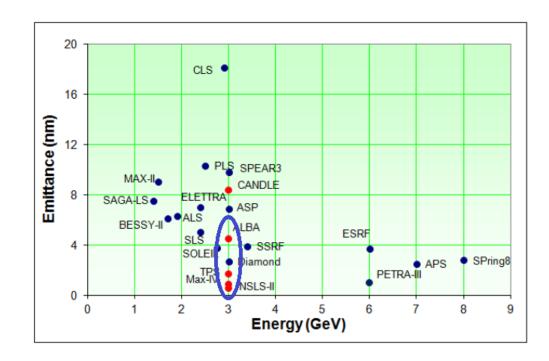
Goal
brilliance =
$$\frac{\text{flux}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \qquad \begin{aligned} \Sigma_x &= \sqrt{\sigma_{x,e}^2 + \sigma_{ph,e}^2} \\ \Sigma_{x'} &= \sqrt{\sigma_{x',e}^2 + \sigma_{ph,e}^{'2}} \end{aligned} \qquad \begin{aligned} \sigma_x &= \sqrt{\varepsilon_x \beta_x + (D_x \sigma_\varepsilon)^2} \\ \sigma_{x'} &= \sqrt{\varepsilon_x / \beta_x + (D'_x \sigma_\varepsilon)^2} \end{aligned}$$

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



Goal
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• Make a 3th generation Synchrotron Radiation Lightsource at 3 GeV



Specifications and requirements

Storage ring

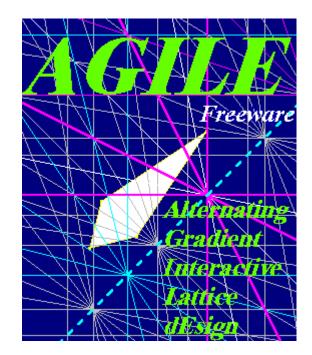
- 2 GeV → 3 GeV
- C < 700 m
- 24 cells
- Must provide
 - low horizontal emittance (<10 [π nm · rad])
 - long drift spaces for Insertion Devices
 - zero dispersion in drift sections
 - precision optics and orbit control
 - high stability
 - cost efficient
 - etc...

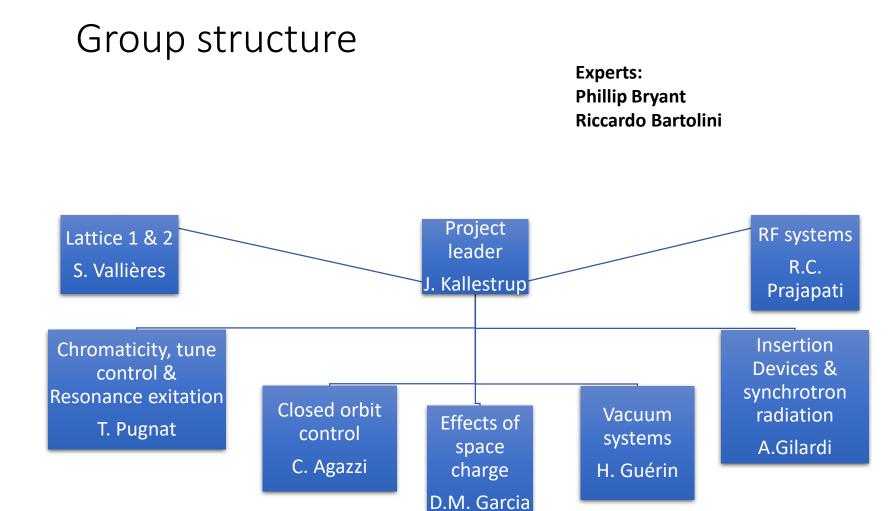
Booster ring

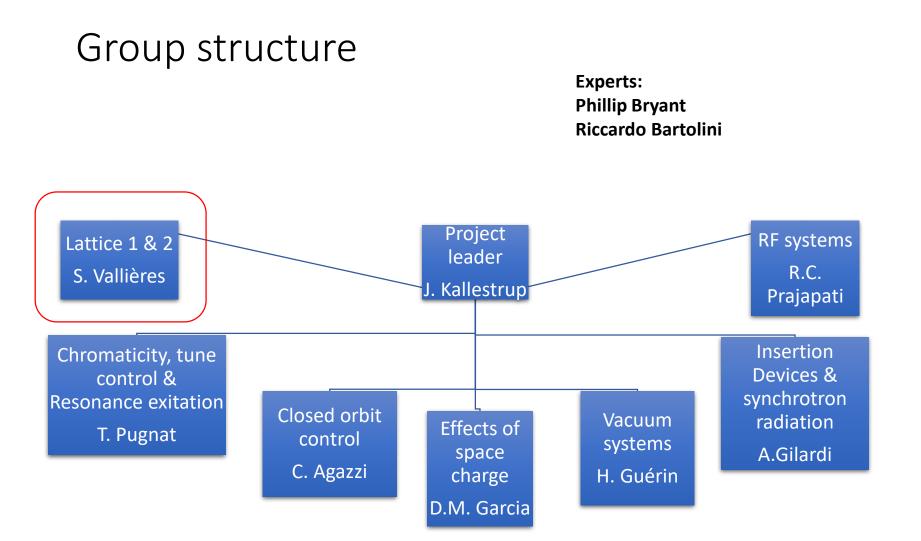
- 2 GeV
- $f_{RF} = 500 [MHz]$
- $\varepsilon_{x,y} = 0.15 [\pi mm \cdot mrad]$
- $\ell_{\text{bunch}} = 40 \ [ps] = 12 \ [mm]$ • $\frac{\Delta p}{\Delta m} = 10^{-3}$

Primary tool

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







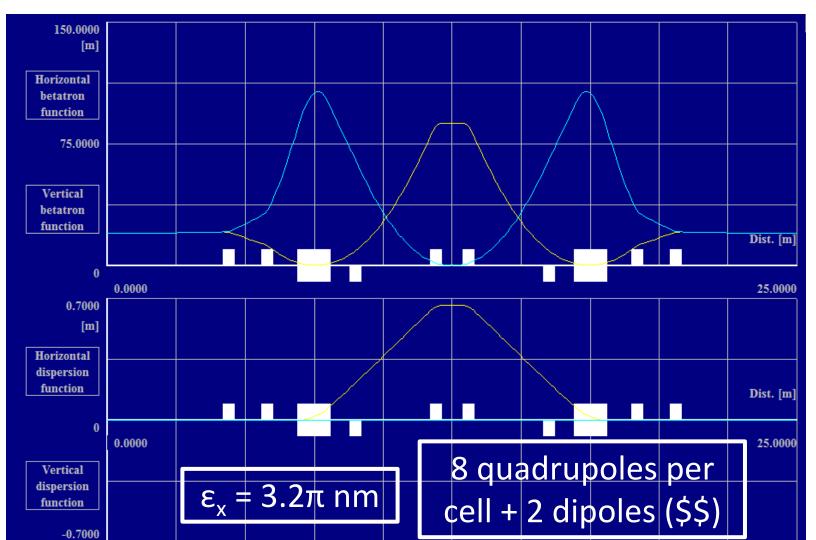
Lattice Group

Mandates to Fulfill

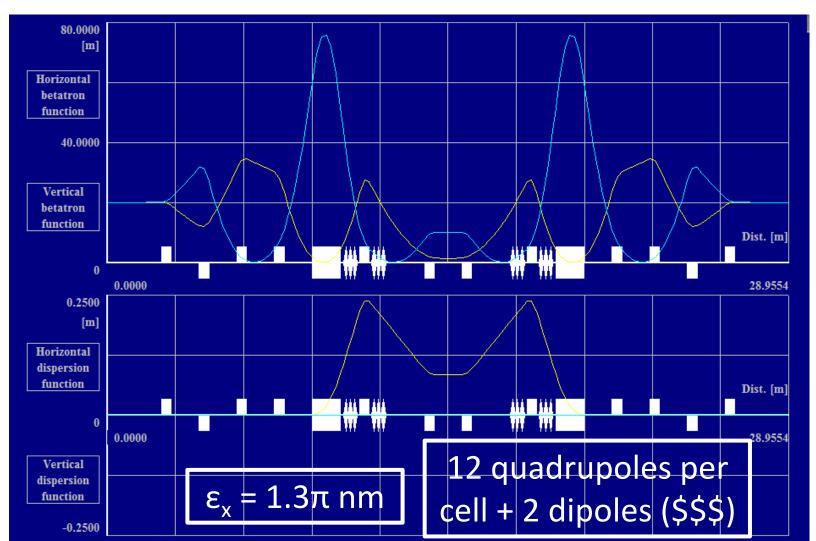
- Lattice 1 :
 - ✓ Try to improve the basic cell design.
 - ✓ Define apertures.
 - ✓ Get radiation parameters.

- 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.

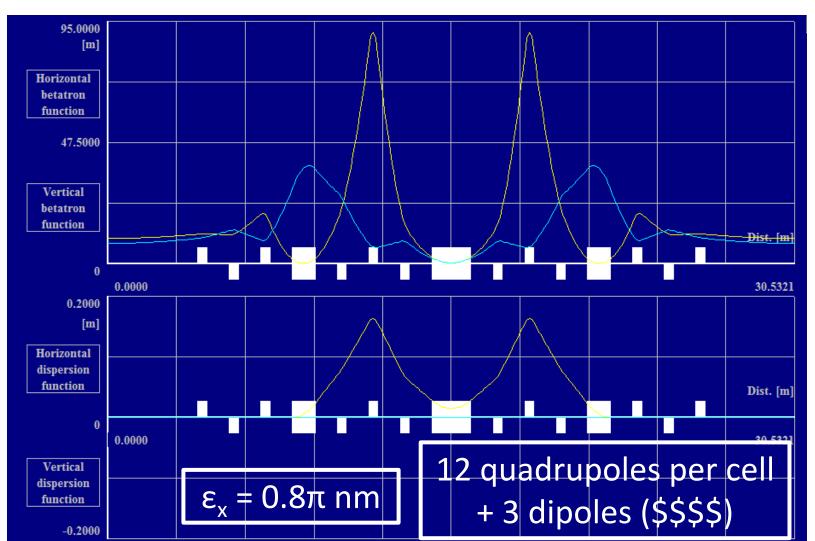
Basic Ring



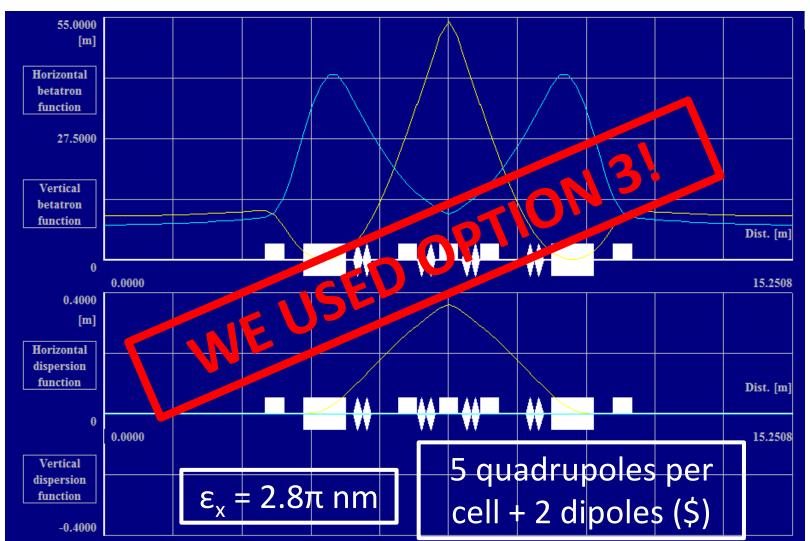
Option 1: DBA with many FODOs



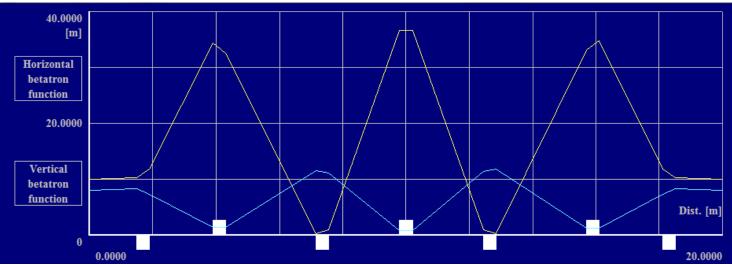
Option 2: TBA



Option 3: low cost DBA



MODULE 1:1

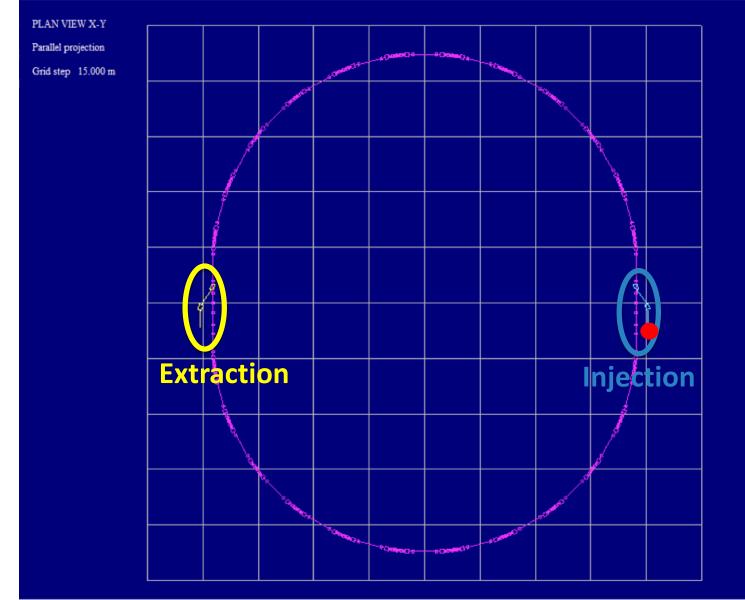


CENTRAL ORBIT Transfer line			
Length of beam line Horizontal phase advance Vertical phase advance Horizontal chromaticity Vertical chromaticity	[rad] =		

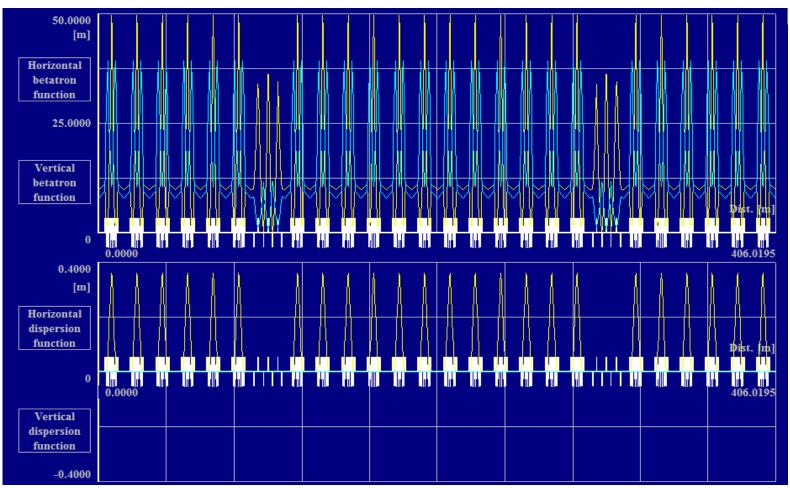
- $\beta_x^{\text{in}} = \beta_x^{\text{out}}$
- $\beta_y^{\text{in}} = \beta_y^{\text{out}}$
- $\alpha_x^{\text{in}} = \alpha_x^{\text{out}}$
- $\alpha_x^{\text{in}} = \alpha_x^{\text{out}}$
- $\mu_x^{out} = \mu_y^{out} = 2\pi$

As expected

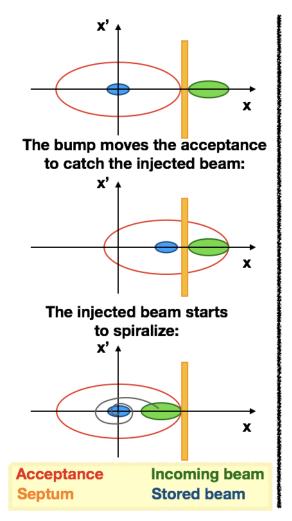
Туре	Beta-x	Alpha-x	Mu-x
3	[m] 5	6	[rad] 🛛
MARK	10.000	0.0000	0.0000
DRIFT	10.000	0.0000	0.0000
QUADR	10.225	-0.1500	0.1489
DRIFT	11.854	-4.1091	0.1861
QUADR	34.325	-7.1265	0.2854
DRIFT	32.507	11.3365	0.2969
QUADR	0.251	-0.0186	1.7983
DRIFT	1.027	-2.0795	2.7603
QUADR	36.620	-13.7394	3.1359
DRIFT	36.608	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. 99 87
QUADR	11.882	4.1852	6.0971
DRIFT	10.225	0.1500	6.1343
MARK	10.000	0.0000	6.2832



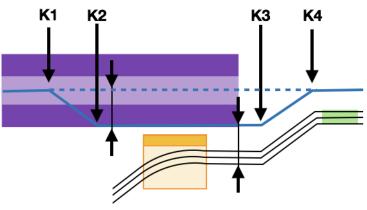
Twiss functions of the full ring with a low cost DBA



Injection/Extraction Scheme



Fast kickers: K1, K2, K3, K4



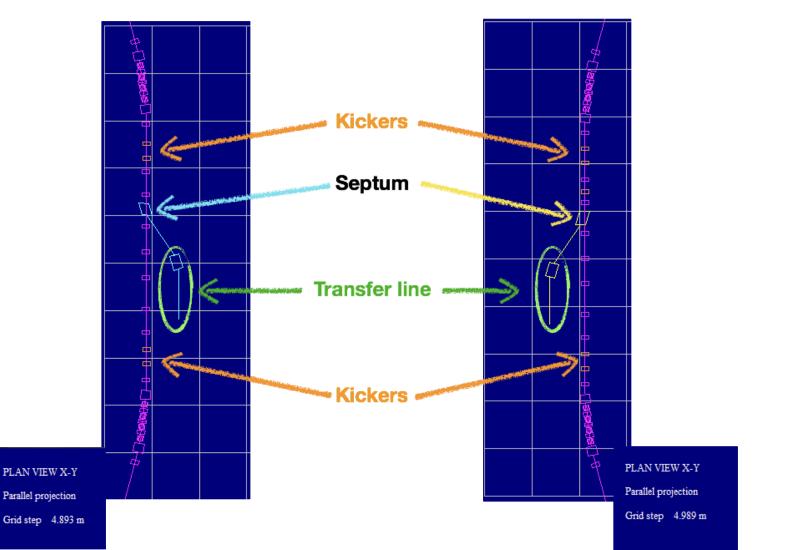
Place occupied by the injected beam, making betatron oscillation

Freshly injected beam Ring axis

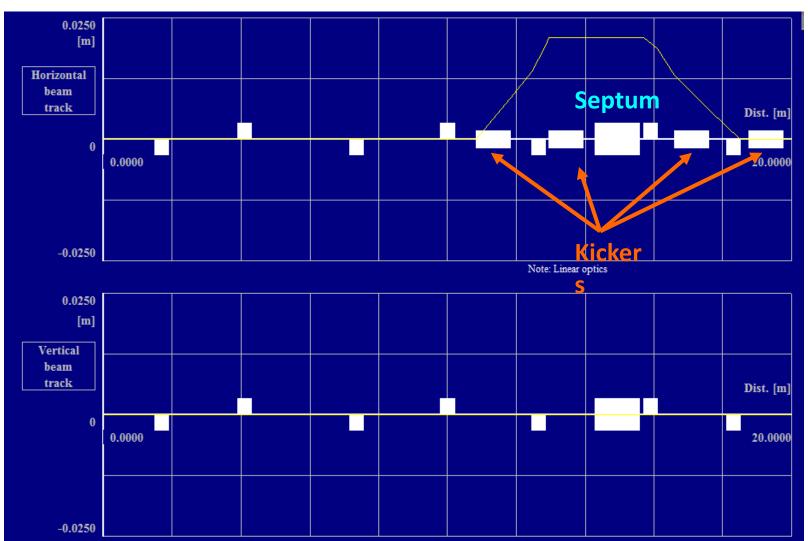
Septum



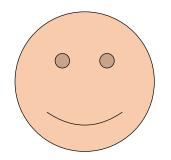
EXTRACTION



Injection with Orbit Bump



Many Thanks from Lattice Group!



Tune and Chromaticity control

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

D. VENTURA

Tune control

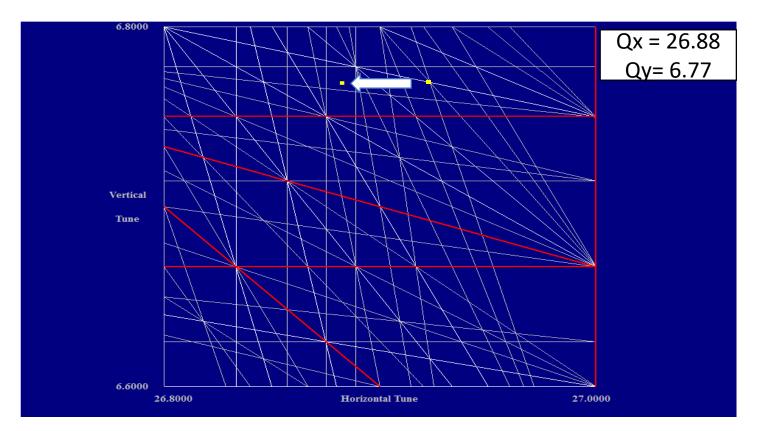
Why?

Prevent the machine to reach unstable region!

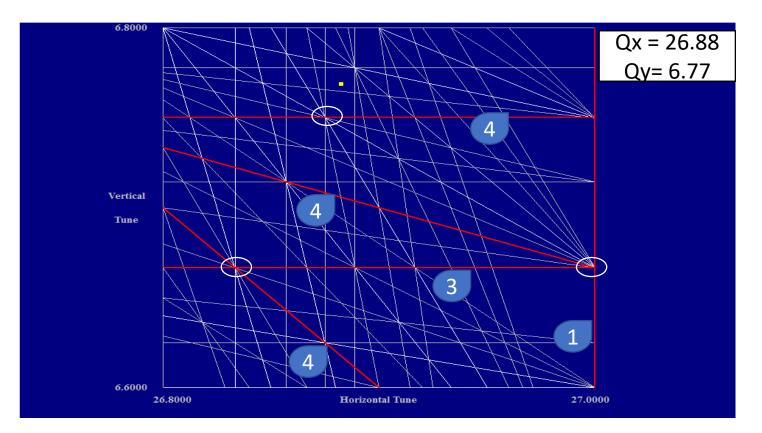
3 methods to correct the tune:

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

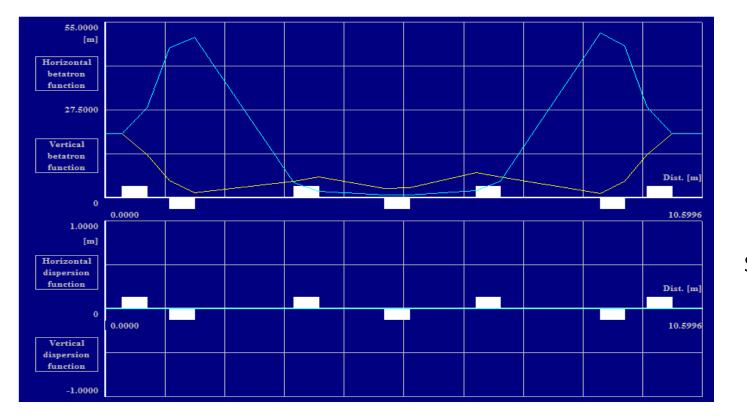
Tune control: using Quadrupole



Tune control: using Quadrupole



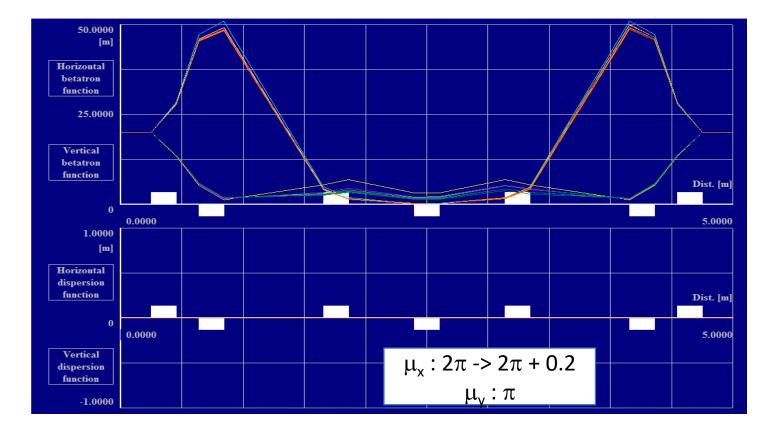
Tune control: Phase shifter



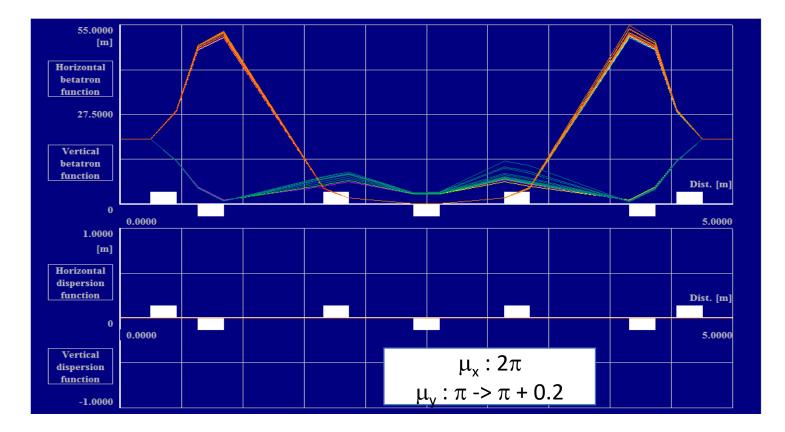
Length*Scale

Strength/Scale²

Tune control: Phase shifter



Tune control: Phase shifter



Achromaticity

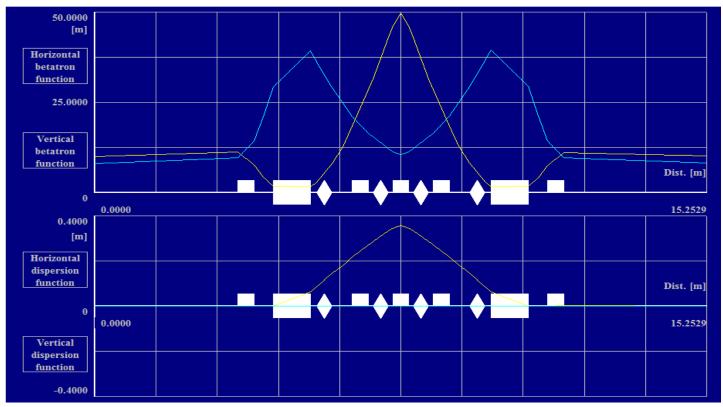


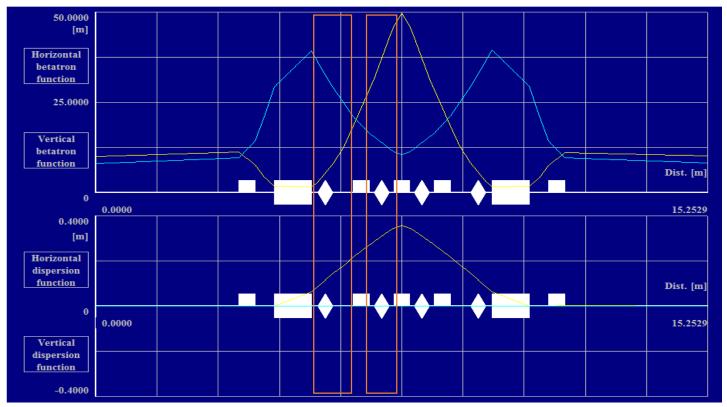
$$\Delta Q_x = \Delta Q_y = 0$$

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

$$\begin{aligned} \Delta Q_x &= \Delta k_q \ \beta_x \ L_q + \Delta K_s \ \beta_x \ D_x \ L_s \\ \Delta Q_y &= \Delta k_q \ \beta_y \ L_q + \Delta K_s \ \beta_y \ D_x \ L_s \end{aligned}$$

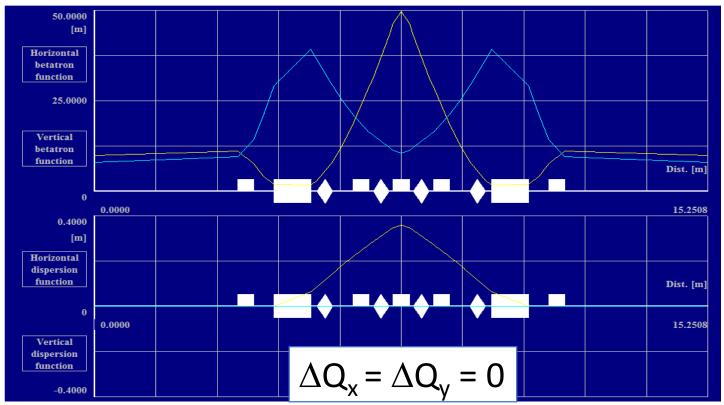
$$\begin{aligned} \beta_x \ / \ \beta_y >> 1 \ \text{or} \ \beta_x \ / \ \beta_y >> 1 \\ \beta_x \ D_x >> 0 \end{aligned}$$





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

Sextupole OFF



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

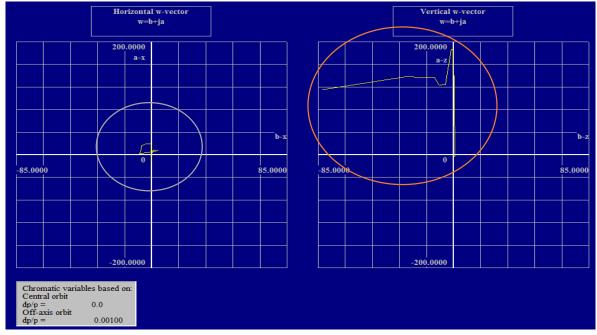
Sextupole ON

Chromaticity control: W-vector

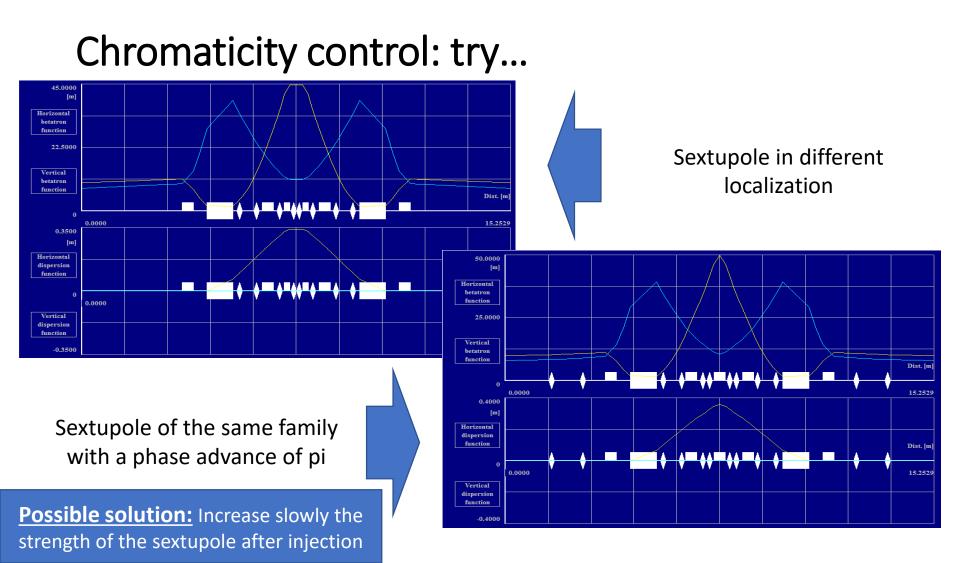
Global chromaticity provide beam stability and control of the working line



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



<u>Chromaticity control: W-vector</u> Vertical w-vector Horizontal w-vector w=b+ja w=b+ja 250.0000 250.0000 Horizontal w-vector Vertical w-vector w=b+ja w=b+ja b-x 500.0000 500.0000 a-x 0 200.0000 200.0000 -200.0000 b-x b-z -400.0000 400.0000 400.0000 400.0000 -250.0000 -250,0000 Horizontal w-vector Vertical w-vector w=b+ja Chromatic varial w=b+ja Central orbit dp/p = Off-axis orbit 2000.0000 2000.0000 dp/p = a-x a-z Scale Clip 0000 -500.0000 Graph 1 Gr All Graph + Save Print Help F1 0 Back F9 -95.0000 95.0000 -95.0000 95.0000 Graph - Erase Write Colours Graph 8 raph 3 Graph 4 Graph 5 Graph 6 Graph 7 Above Graphs: Saved = 0, Temp.=1, Showing= 1 2000.0000 -2000.0000 Chromatic variables based on: Central orbit dp/p = 0.0 Off-axis orbit dp/p = 0.00100 Print Help F1 Back Fi Horiz. All Graph + Save Scale Graph - Erase Clip Write Colours



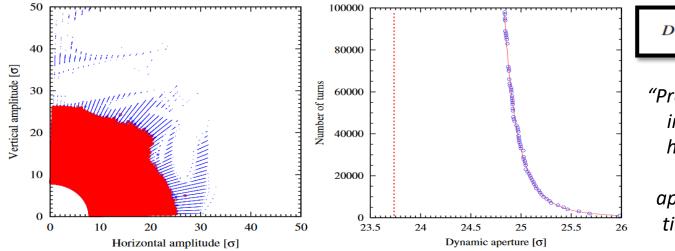
Dynamic aperture

Lyapunov exponant

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

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

<u>Closed Orbit Prognosis &</u> <u>Correction</u>

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.

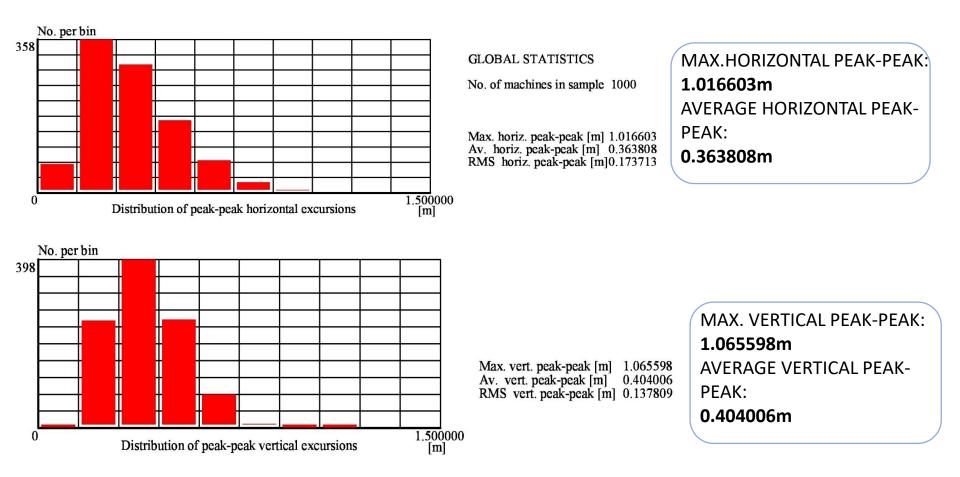
For example, a longitudinal position error of 1 mm for a dipole is represented as a missing-field kick at one end of the dipole and an additionalfield kick at the other end.

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.

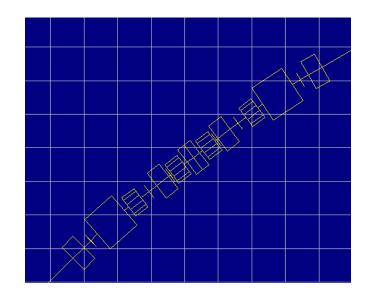
STATISTICS FOR RANDOMLY GENERATED CLOSED ORBITS



The closed orbit was measured and corrected by:

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

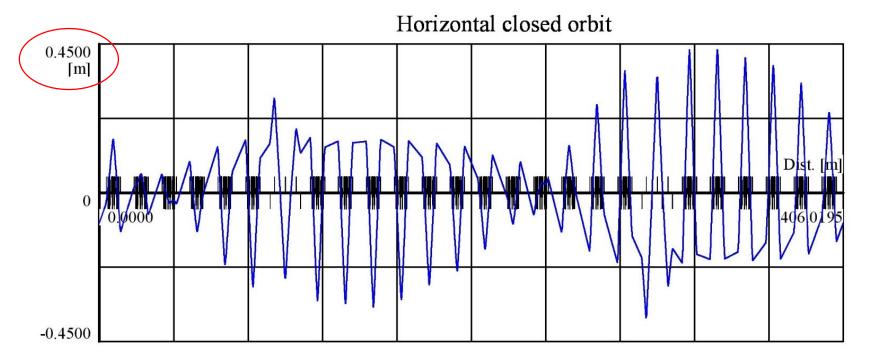
We placed BPMs and Correctors next to the Dipoles and close to Quadrupoles and Sextupoles, which represent the main sources of misalignment.

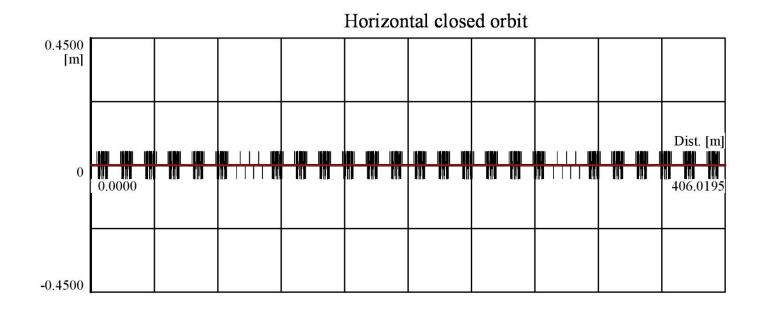


	Unit	Name	Туре	Length
	no. 1	2	3	[m] 4
	1	S0	DRIFT	3.5609
	2	QD1	QUADR	0.4000
ĺ	3	S2	DRIFT	0.2446
	4	BpmV	VPU	0.0000
ĺ	5	CorrV	VCORR	0.0000
	6	BpmH	HPU	0.0000
	7	CorrH	HCORR	0.0000
ĺ	8	S2	DRIFT	0.2446
ĺ	9	Dipole1	RBEND	0.9200
ĺ	10	S3a	DRIFT	0.1500
	11	XD	SEXTU	0.4000
	12	S3b1	DRIFT	0.2527
	13	BpmH	HPU	0.0000
	14	CorrH	HCORR	0.0000
	15	BpmV	VPU	0.0000
	16	CorrV	VCORR	0.0000
ĺ	17	S3b2	DRIFT	0.2527
ĺ	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

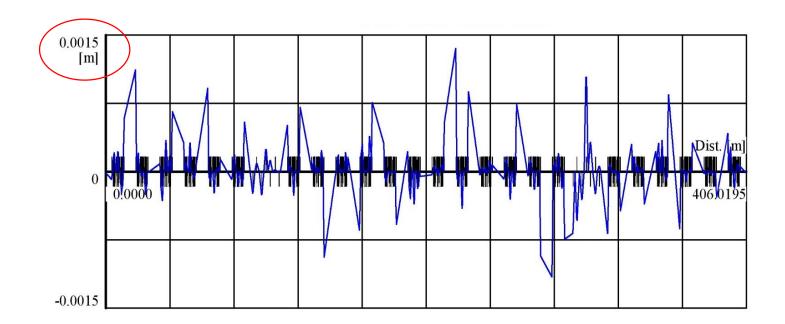
Before studying the 'Statistic for Corrected Closed Orbit', we investigated the behaviour of a single closed orbit and its correction.



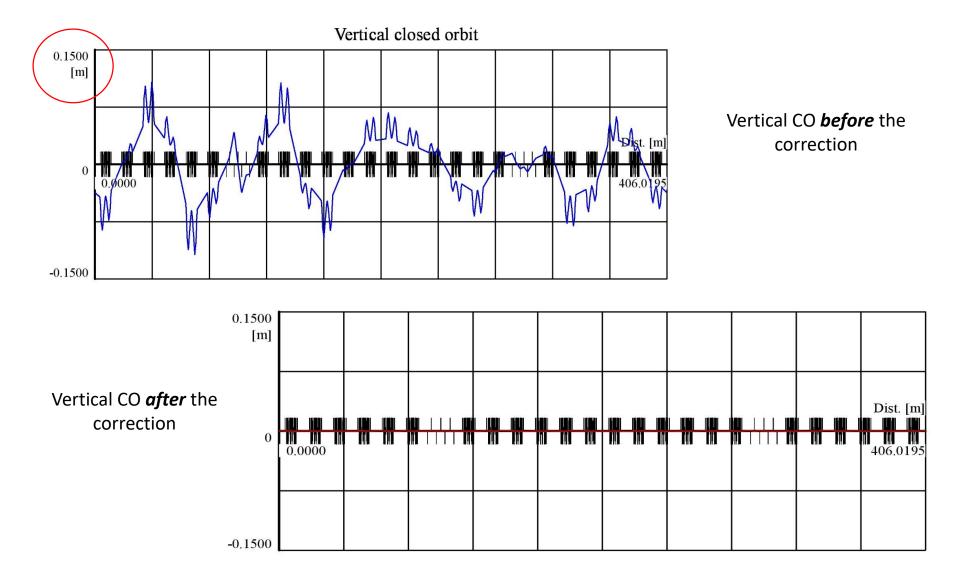


- We corrected the previous closed orbit using *all* the available correctors (158 in the horizontal plane).
- Once fixed the number of correctors and the plane to be corrected, the routine computes a selection of the '**best**' correctors out of those available.
- The Computation Method used to select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

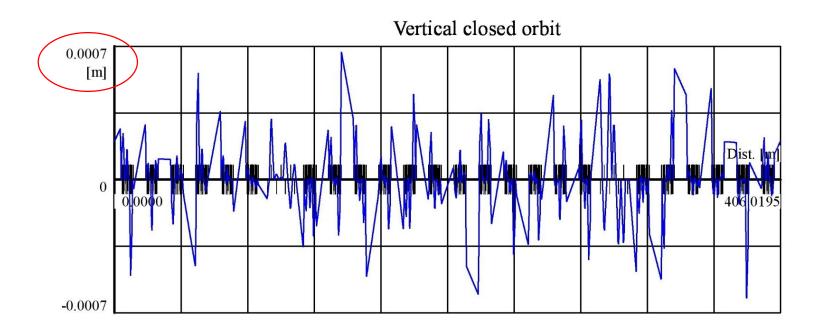
ZOOM of the corrected Closed Orbit:



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!



ZOOM of the corrected Closed Orbit:

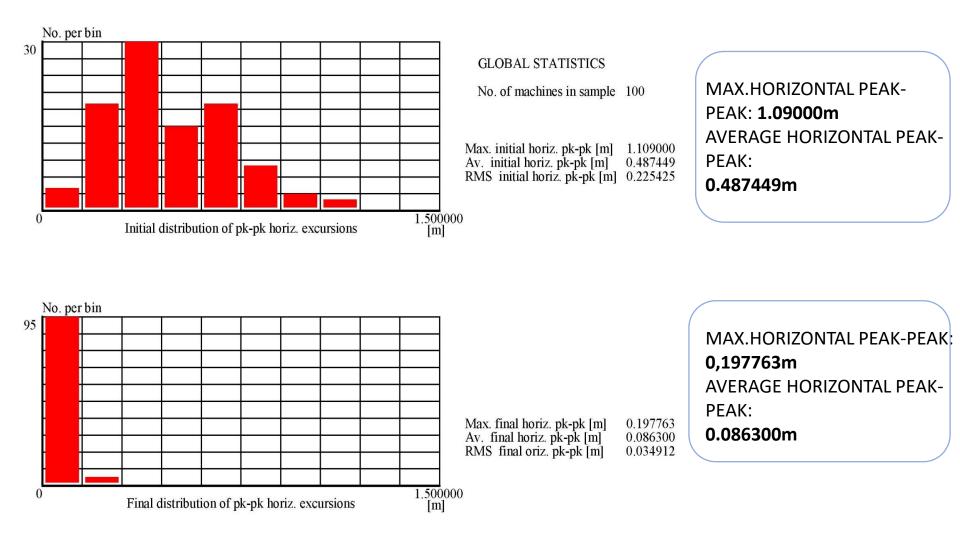


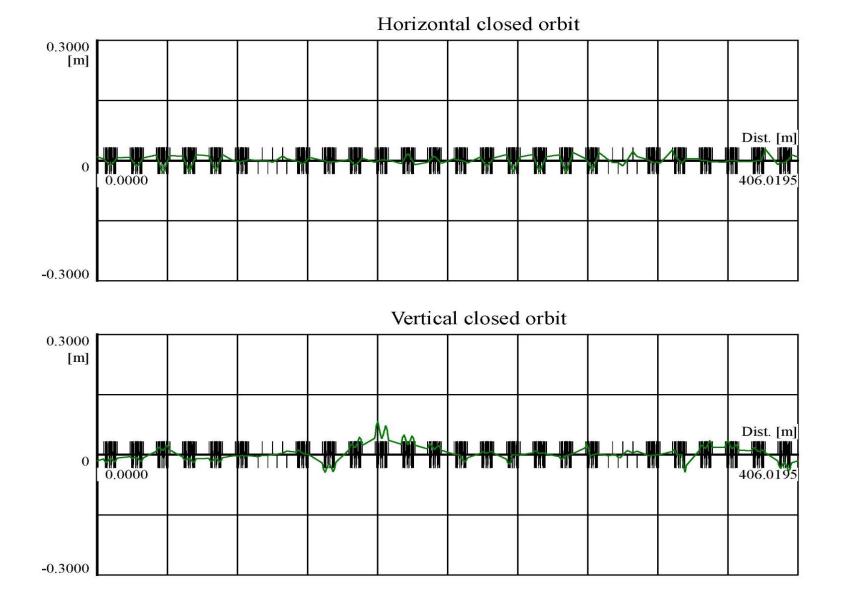
Starting from a closed orbit with maximum amplitude of around **0.15 m** we reached a final amplitude of **0.7 mm** in the vertical plane!

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 timesaving 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



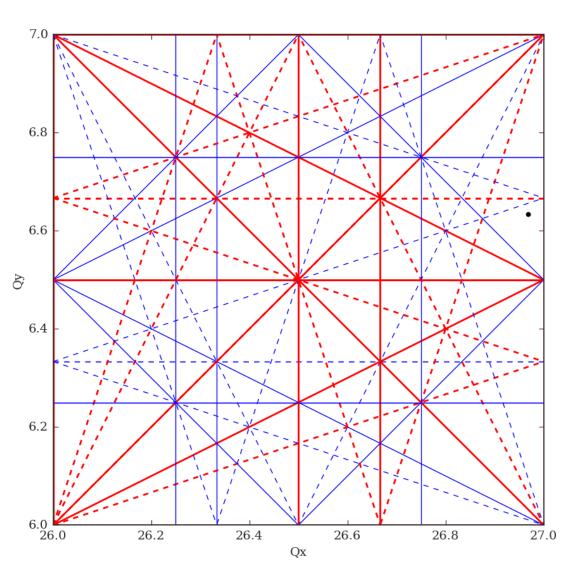


Space charge study for JUICE

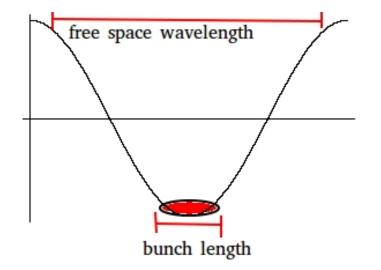


Tune diagram

	Value
Tune H	26.96856
Tune V	6.633655
r _e	$2.82 * 10^{-15} \text{ m}$
Ν	$2.22 * 10^8$ electrons
l_o	0.01 m
ρ	7.029 m
ϵ_x	$0.15 \ \pi \ \mathrm{mm} \ \mathrm{mrad}$
ϵ_y	$0.15 \ \pi \ \mathrm{mm} \ \mathrm{mrad}$
Е	$3 { m GeV}$
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

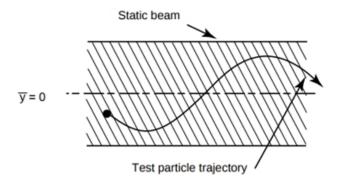
WinAgile

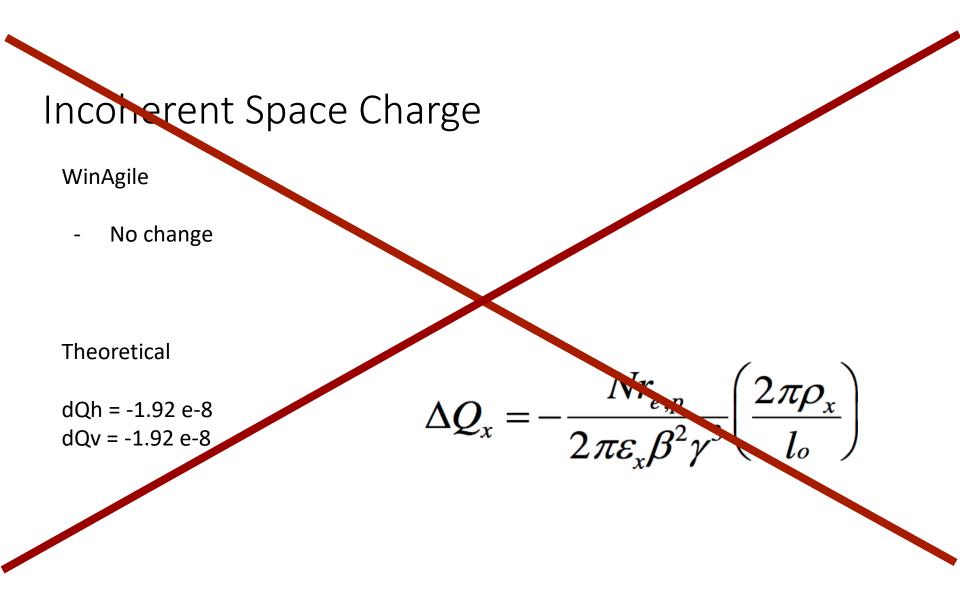
- No change

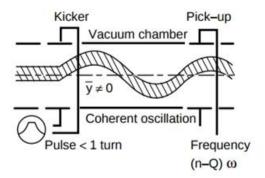


dQh = -1.92 e-8 dQv = -1.92 e-8

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







Coherent Space charge

WinAgile

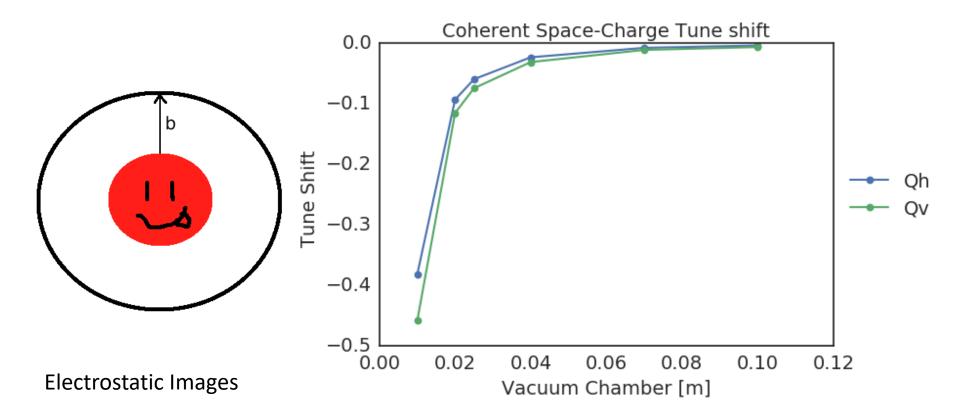
Tune H = 26.967827 \rightarrow dQh = - 0.000739 *5 = - 3.695 e-3 Tune V = 6.632407 \rightarrow dQv = - 0.001248 *5 = - 6.240 e-2

Theoretical

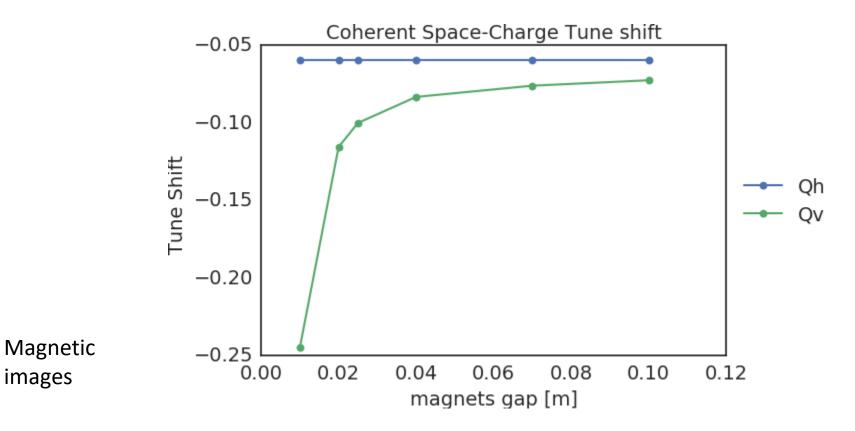
dQh = -0.000132 = -1.320 e-4 dQv = -0.000529 = -5.294 e-4

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

Change of Vacuum chamber aperture



Change of magnets' gap



Lower Energy

Energy equal to 2 GeV

• Incoherent:

No change

• Coherent:

Tune H = 26.967457 \rightarrow dQh = -0.001109 * 5 = -5.55 e-3 Tune V = 6.631783 \rightarrow 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 :

$$\sigma_{x} = \sqrt{\frac{\epsilon_{x}}{\pi}\beta_{x}^{max} + \left(D_{x}\frac{\Delta P}{P}\right)} = 2.74 mm$$

Injection parameters :

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

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

Chamber apertures :

$$5 \times 4 \ cm$$

WinAGILE Simulations

Equilibrium pressure calculation for an infinite array of uniformly spaced vacuum purps commerciant to a vacuum pipe of circular or elliptical cross-section (No beam) OUTPUT: Pump separation [m] = 7.5 Pump separation [m] = 7.5 Major half width of pipe [m] = 0.025 Minor half width of pipe [m] = 0.025 Specific surface area efpipe: COMPUTE The specific surface area efpipe: [M] = 2.98 Machine temperature [K] = 298 Matecular weight of pipe [m/s] = 1E-12 Absolute temperature [K] = 298 Matecular weight of area 'seen' by vacuum sheald be increased to account for shields, screens, bellows etc. It is of course an average value and cannot tudy represent the effect of localised sources. Sene typical outgassing rates are: Stainless steel unbuile date 100 hour pump-down = 2.3 Sene typical outgassing rates are: Stainless steel by ourpum, down = 2.5 Sene typical outgassing rates are: Stainless steel by ourpum, down = 2.4 Copper after 10 hour pump-down = 2.4 Stainless steel worpum, down Sene typical outgassing rates are: Stainless steel blow of a fafter 10 hour pump-down = 2.5 - 3 Stainless steel (unbulk after 100 hour pump-dow	INTRODUCTION:				
Image: connected to a vacuum pipe of circular or elliptical cross-section (No beam) Image: connected to a vacuum pipe of circular or elliptical cross-section (No beam) INPUT: Pump speed [1/b] = 100 Misor half width of pipe [m] = 0.025 Misor half width of pipe [m] = 0.025 Specific surface area slippic : COMPUTE The sreat that depressing rate [m/s] = 7.75 Specific surface area slippic : Specific confactors of pipe The sreat that depressing rate [m/s] = 58.83 Specific surface area (pipe) [m/s] = 58.83 Specific surface area (pipe) [m/s] = 58.13 QUIT Copy data to clipboard Copy data to clipboard Copy data to clipboard NoTES: The specific surface area (seer) by vacuum should be increased to account for shields, screens, bellows etc. It is of course an average value and carnot thuy represent the effect of localised sources. Stanlass steel, unbaked after 100 hour pump-down = 25.3 Series typical outgaming rates are: Stanlass steel, unbaked after 100 hour pump-down = 25.4 = 25.4 Stanlass steel, unbaked after 100 hour pump-down = 25.4 = 25.4 = 25.4 Stanlass steel, unbaked after 100 hour pump-down = 25.4 =	Familibrium annuar an	Inclusion for an is	- finite arrest of	mile mile and an one	
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Note: sum there is an intervent of pipe [Mail = 00000 Specific surface area stepipe: The save that degasses in can ² 2 for 1 m length of pipe [cm ²] = 39.83 Specific surface area stepipe: [m/s] = 68.13 Specific surface area stepipe: [m/s] = 68.13 Specific surface area stepipe: [m/s] = 68.13 Mailecular weight of residual gas = 2 QUIT NOTES: The specific surface area 'seen' by varuum should be intereased to account for shields, screens, bellows etc. It is of course an average value and cannot muly represent the effect of localised sources. Sense typical congassing mates are: Stainless steel, unbaked after 100 hour pump-down -25.8 Bases after 10 hour pump-down -25.8 Tefor and abasimium after 10 hour pump-down -25.8 Not addition B, D and F after 10 hour pump-down -45.8.6 -45.8.6	Major half-width of pipe [m] =	0.025	<u> </u>	Minimum pressure	[Terr] = 2.99E-0012
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- Some typical outgassing rates are: Stabiless steel, unbulked after 10 hour pump-down Copper after 10 hour pump-down Brass after 10 hour pump-down Teflon and akarinium after 10 hour pump-down Arabites B,D and F after 10 hour pump-down Arabites B,D and F after 10 hour pump-down Arabites D,D and F after 10 hour pump-down Star 25 E-3					ens, bellows etc.
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Copper after 10 hour pump-down = 5 E -0 Brass after 10 hour pump-down = 2.5 E -3 Taflon and akaminian after 10 hour pump-down = 1 E -7 Araldizes B, D and F after 10 hour pump-down = 8 E -7, 5 E -7, and 4 E -7 Nyton after 10 hour pump-down = 4 5 E -6	- Some typical outgassing rates a				
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Arabites B, D and F after 10 hour pump-down = 3 E -7, 5 E -7, and 4 E -7 Nyton after 10 hour pump-down = 4.5 E -6					
					= 8 E -7, 5 E -7, and 4 E -7
- Molecular weights: 2 (H2), 28 (N2), 32 (O2).	Nylon after 10 hour pump-d			down	=4.5E-6
	- Molecular weights: 2 (H2), 28 (N2), 32 (O2).			

Figure 1: WinAGILE vacuum simulation tool

- Stainless steel baked chambers
- Area that degasses :

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

Outputs : static Pressures

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

WinAGILE Simulations

NTRODUCTION:				
Equilibrium pressure c	alculation for an i	infinite array of	uniformly spaced vacuum	pumps
			cross-section (No beam)	
NPUT:			OUTPUT:	
ump separation [m] =	7.5	[]	Maximum pressure	[Terr] = 7.80E-0012
runp speed [1/8] =		COMPUTE	Average pressure	[Terr] = 6.20E-0012
		COMPUTE		
	0.025	L	Minimum pressure	[Terr] = 2.99E-0012
dinor half-width of pipe [m] =	0.025		Conductance of pipe (over separation lgth)	[Vs] = 7.75
specific surface area of pipe :			(ever reparation (gen)	feed - stres
The area that degasses in cm^2			Specific conductance	
for 1 m length of pipe [cm^2] =	39.83		of pipe	[l m/s] = 58.13
Specific out-gassing rate	17.14			Copy data to clipboard
enter #.#E##) [Torr l/s/cm^2] =				Copy data to captorate
Absolute temperature [K] = 298 QUIT				Copy data to notebook
falecular weight of residual gas =	2		Paste tirse stamp	Load from notebook
NOTES:				and balleness sta
 The specific surface area 'seen It is of course an average valu 				ens, bellows etc.
- Some typical outgassing rates	are: Stairdeau r	steel baked for 24	hour at 300 dag. C	= 1 E -12
Stainless steel, unbaked after 100 hour pump-down			= 2 E -9	
Copper after 10 hour pump-down Brass after 10 hour pump-down			= 5 E - 9	
			10 hour pump-down	= 2.5 E -8 = 1 E -7
			0 hour gung-down	= 8E-7, 5E-7, and 4E-7
Nyton after 10 hour pump-d				=4.5E-6

Figure 2: WinAGILE vacuum simulation tool

- Stainless steel baked chambers
- Area that degasses :

$$2\pi\sqrt{rac{5^2+4^2}{2}} imes 1.40$$

Outputs : static Pressures

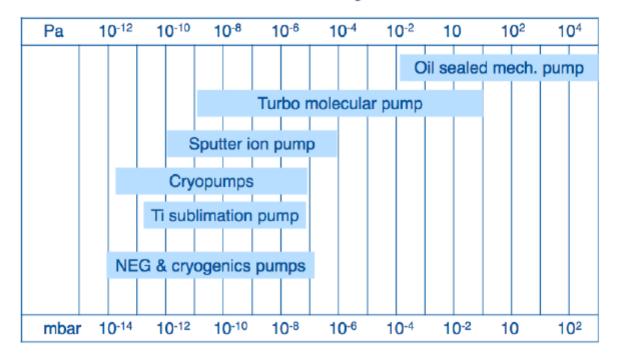
$$P_{max} \sim 10^{-11}$$
 Torr



Pumping System

Vacuum pumps pressure range

16 orders of magnitude !



Pumping System



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

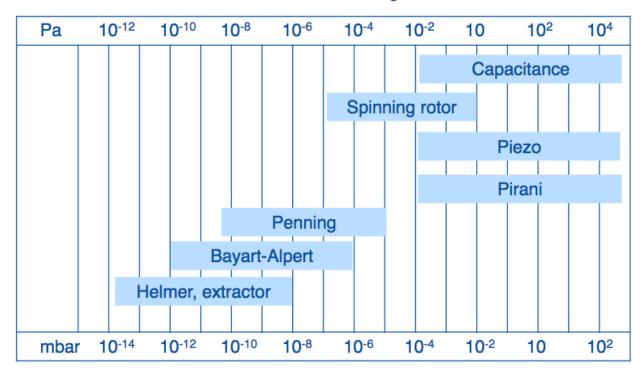


Figure 4: NEG pump: speed 100L/s datasheet



Figure 5: Sputter Ion Pump (SIP) datasheet

Vacuum gauges pressure range



16 orders of magnitude !

Practical Considerations

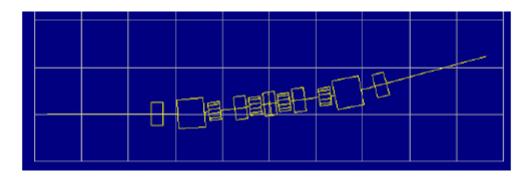


Figure 6: JUICE example cell

- 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 2nd 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

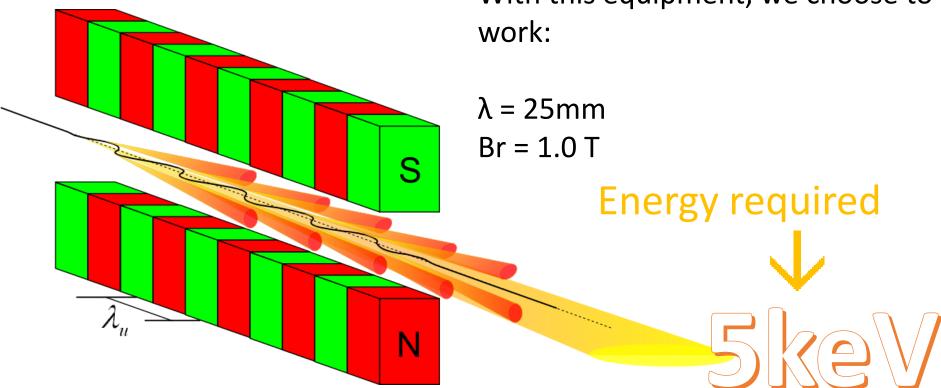
Bending field 1.4 T - bending radius 7.1 m energy loss per turn: Bending magnets $U_{\{0,bend\}} = 88.46 \frac{E[GeV]^4}{\rho[m]} \approx 1.0 \text{ MeV}$

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

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

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: πgap

$$K = 0.168 B_r \lambda_u e^{-\lambda_u}$$

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) :

$eB_{\circ}\lambda$	n	B_0	Gap	B_r
$K = \frac{c \Sigma_0 r_u}{2}$	3	0.45 T	11.2 mm	1
$2\pi mc$	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 + <u>all</u>wigglers
 - K = 1.03 $U_{\{0,wigglers\}} = N_{wig} \cdot U_{\{0,1 wiggler\}} = 22 \cdot 83 \text{ [keV]} = 1.83 \text{ [MeV]}$ $U_{\{0,total\}} = 1.0 \text{ [MeV]} + 1.83 \text{ [MeV]} = 2.83 \text{ [MeV]}$ • K = 1.56 $U_{\{0,wigglers\}} = N_{wig} \cdot U_{\{0,1 wiggler\}} = 22 \cdot 190 \text{ [keV]} = 4.18 \text{ [MeV]}$ $U_{\{0,total\}} = 1.0 \text{ [MeV]} + 4.18 \text{ [MeV]} = 5.018 \text{ [MeV]}$
 - Power emitted as Synchrotron Radiation:

 $\begin{array}{l} \textbf{P} \ [\textbf{kW}] = U_0 [keV] \cdot I_{beam} = 2.83 \cdot 10^3 [keV] \cdot 0.3 \ [A] = \textbf{849} \ [\textbf{kW}] \\ \textbf{P} \ [\textbf{kW}] = U_0 [keV] \cdot I_{beam} = 5.18 \cdot 10^3 [keV] \cdot 0.3 \ [A] = \textbf{1550} \ [\textbf{kW}] \end{array}$

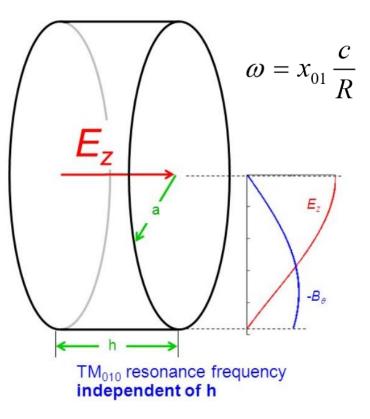
Compared to 300 kW for dipoles only we obtained a factor between 3 and 5

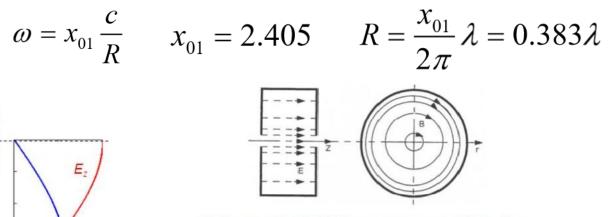
RF Design workshop

- 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





- 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} = 3x10⁸/406.195 = 738.561 kHz Harmonic Number (h) = f_{rf}/f_{rev} ≈ 677

Pill-Box RF Cavity: **Radius of Cavity = 0.383 \lambda = 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 GeVBending 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)

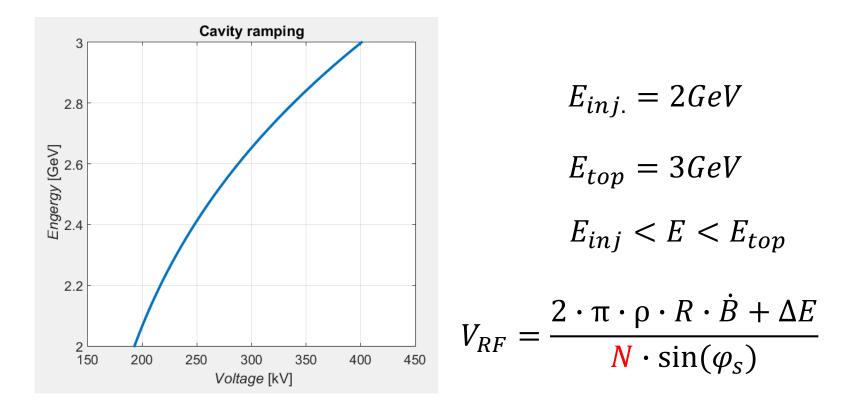
RF Power requirement

- 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}) = V²/ R_{sh} = (625 kV)²/3.5 M Ω = 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

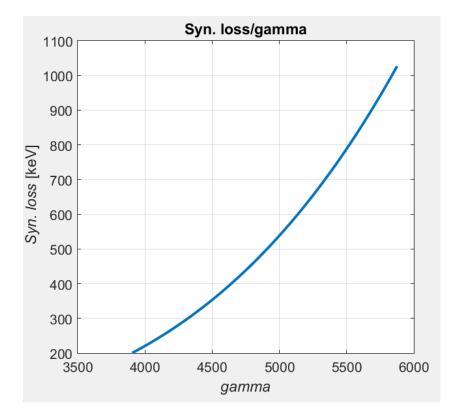
= 300 mA X 1MV = 300 kW

- 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



Gamma vs. synchtron loss



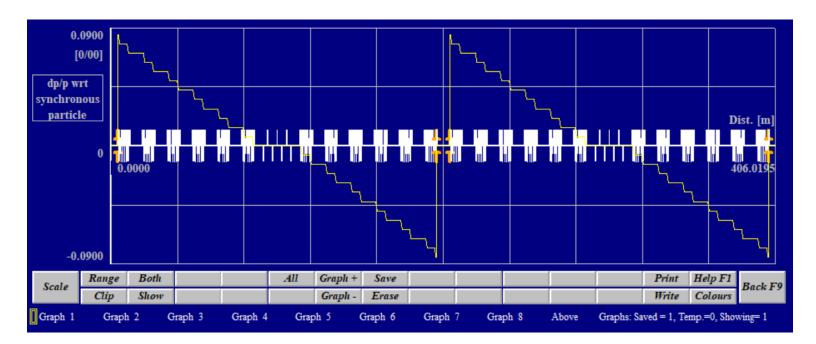
$$\gamma = \frac{E}{E_0} \qquad 2 \text{GeV} < \text{E} < 3 \text{GeV}$$

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

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.

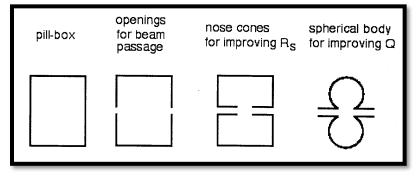


RF-Cavity design (from pill-box to Elliptical/spherical)

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

 $Q = \frac{\omega U}{P_{diss}} = \frac{RL}{\delta_{skin}(R+L)} \approx \frac{2V}{\delta_{skin}A} \xrightarrow{\text{volume}} \frac{\sqrt{2}}{\sqrt{2}}$ • Shunt Impedance R_s = (voltage gain per particle)² / ohmic loss

$$R_{s} = \frac{\left(E_{0}LT\right)^{2}}{P_{diss}} \propto \delta_{skin} \propto \frac{1}{\sqrt{\omega}} \propto \sqrt{cavitysize}$$



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:

$$P_{diss} \propto \frac{\rho_c}{\delta_{skin}} \qquad \qquad \delta_{skin} = \sqrt{\frac{2\rho_c}{\mu\omega}}$$

Block-diagram of accelerator rf system

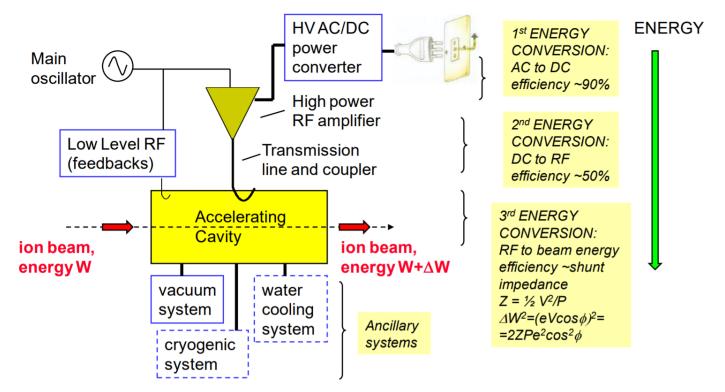


Fig. 13: Block-diagram scheme of an accelerator RF system

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

Thank you!

