JUAS
Accelerator workshop
2016

Final presentation

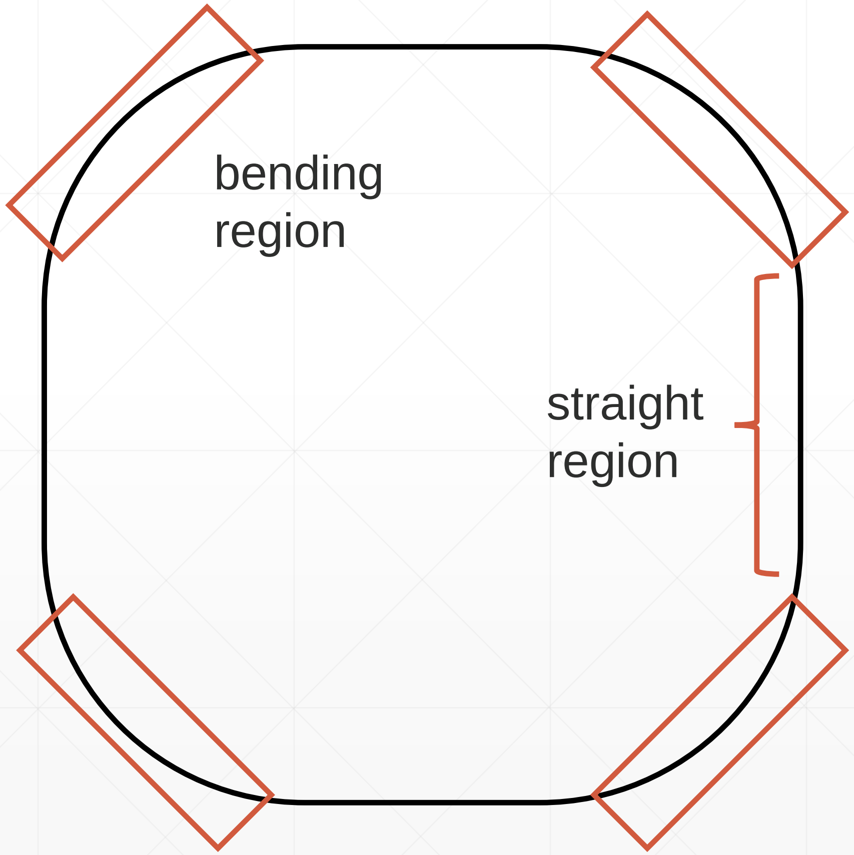
Outlook

- Presentation of the task & introduction of the team
- Lattice design
- RF design
- Collective effects and correction
- Vacuum considerations
- Magnet considerations
- Transition considerations

Presentation of the task & introduction of the team

Presentation of the task and the basic layout

- Replacement for the PS machine at CERN
- Acceleration of protons from a momentum of 3.5 GeV/c to a momentum of 20 GeV/c
- For the basic accelerator lay out a ‘rectangular’ ring design (with four superperiods) was chosen
  - Space for beam control, correction and instrumentation
  - Space for acceleration, injection and extractions
  - Space for future tasks the accelerator may have to handle



Presentation of the groups

- Design is a ‘rectangular’ ring (four super periods)

- The project was divided into three main groups
  - Lattice group
  - RF group
  - Collective effects group

- Special attention has been payed to the magnets, the vacuum and the crossing of the gamma transition

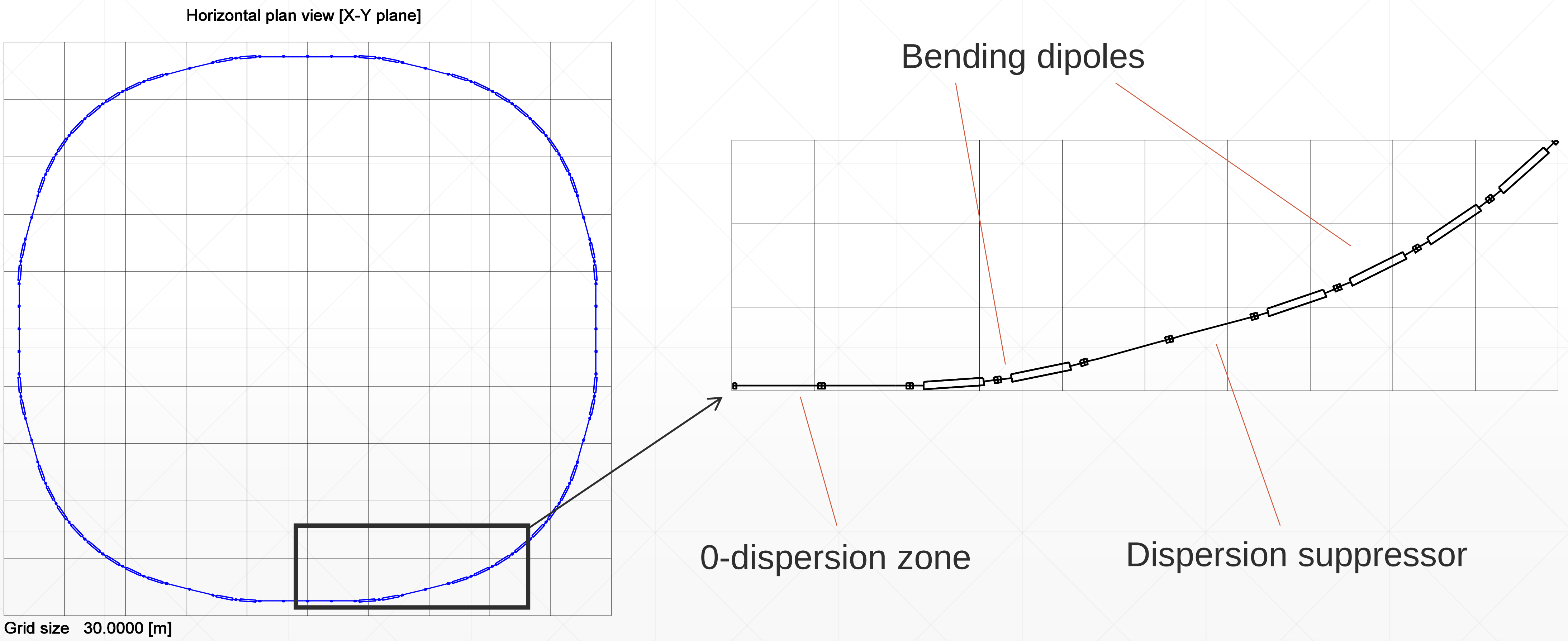
Lattice design

Lattice design – basic parameters

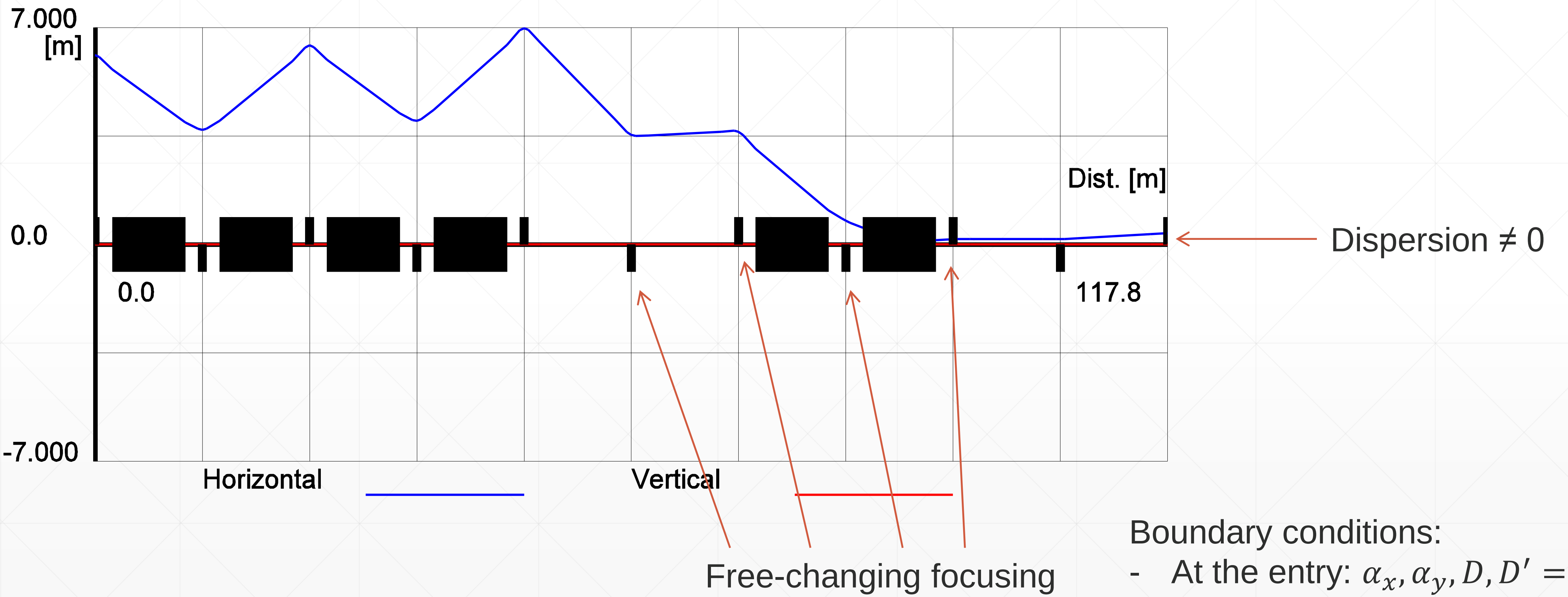
Element	Number	Length
Focusing quadrupoles	40	0,45m
Defocusing quadrupoles	40	0,45m
Bending dipoles	48	8m

$$\rho_d = \frac{L_d}{2\pi/N_d} = 61{,}12m \ \ (R = 150m)$$

Lattice design - geometry



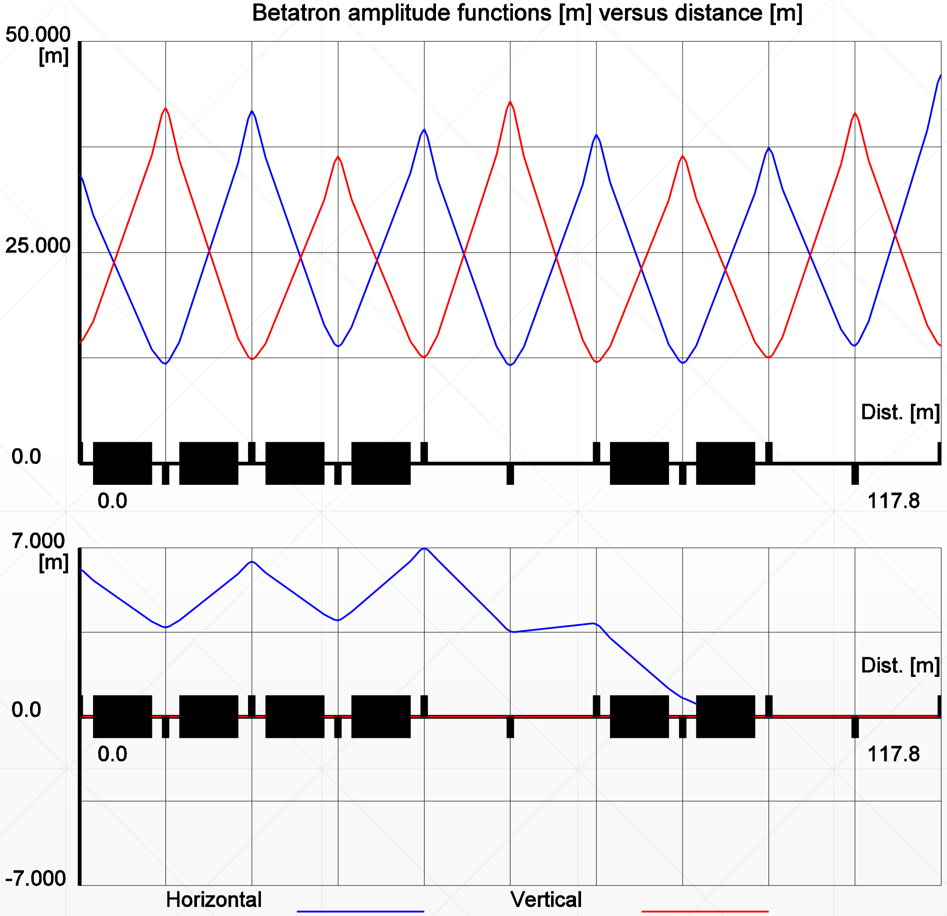
Lattice design – lattice optimization



Boundary conditions:

- At the entry: $\alpha_x, \alpha_y, D, D' = 0$
- At the exit: $\alpha_x, \alpha_y, D' = 0$

Lattice design – Twiss parameters



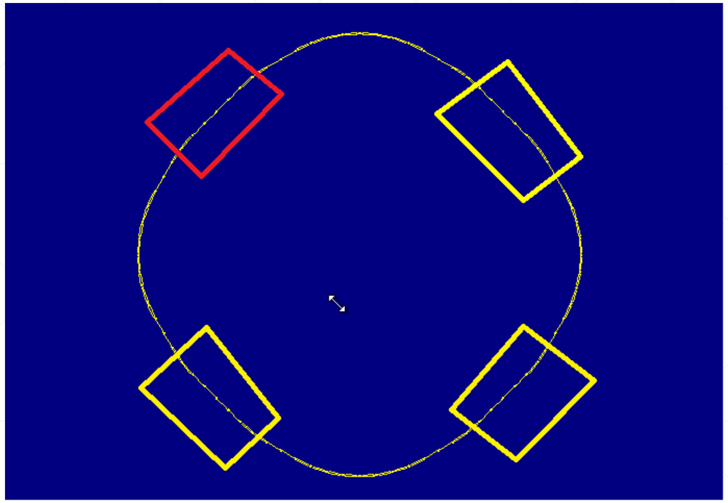
Average transversal dimension of the beam

$$\sigma_x = \sqrt{\varepsilon_x \cdot \beta_x} = 16.4mm$$

$$\sigma_y = \sqrt{\varepsilon_y \cdot \beta_y} = 11.6mm$$

RF design

What we need Vs What we have:



$\gamma_{transition} = 6.36$

$$Free\ Space = \frac{256}{4}$$

For R.F = 64 m

Objectives for the RF:

. Get to 20 GeV/c.

. Get the intensity of 3 x 10^{13} Protons/Beam.

. Preserve the beam from the booster.

. Try not to blow things up

$\Delta E = 16.4\ GeV$

$T_{REV\,(\mathrm{Inj})} = 3.25 \times 10^{-6}$ s

$T_{REV\,(\mathrm{Ext})} = 3.14 \times 10^{-6}$ s

$\rho = 61.115\ m\ (Bending\ Radius)$

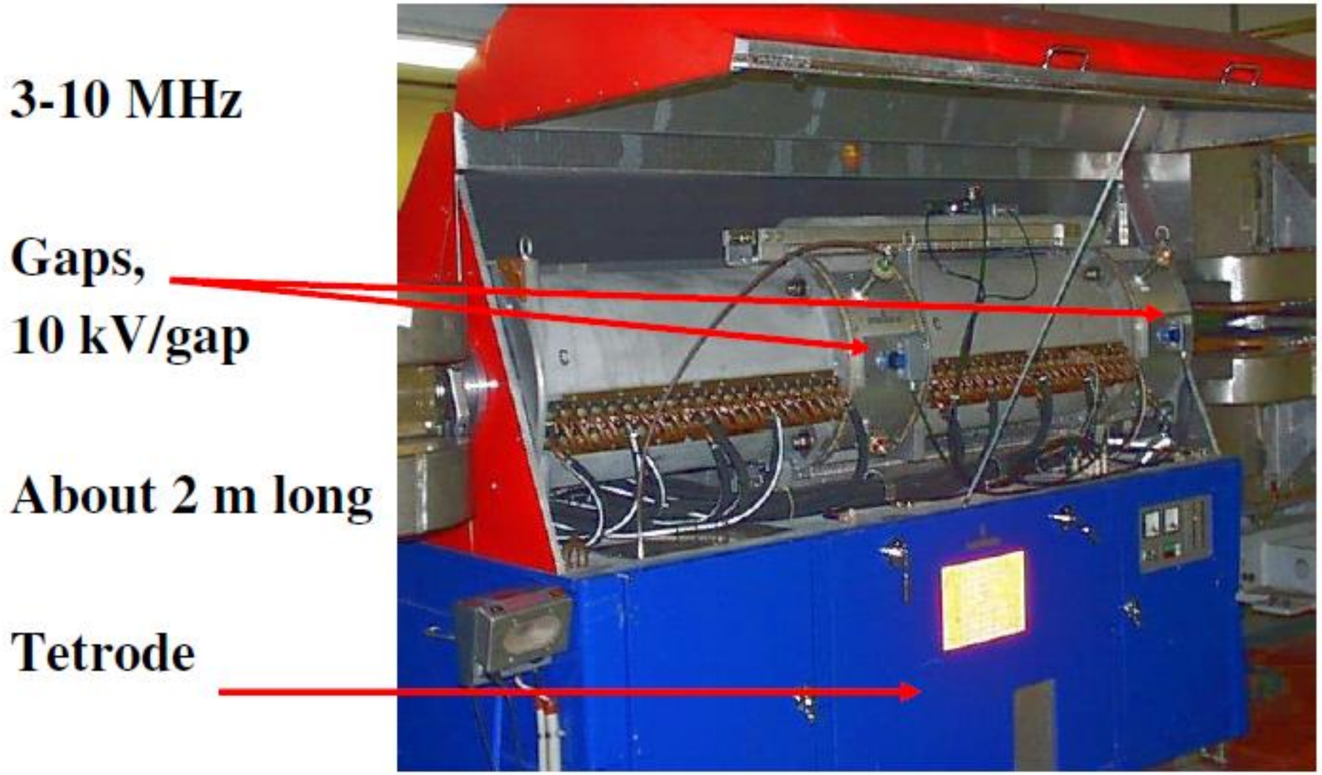
$$\frac{dB}{dt} = \frac{B_{ext} - Binj}{T} = 3.6\ [T/s]$$

Circumference (m)	982.48
Number of protons per pulse	3E13
Cycling frequency (Hz)	3.125
Momentum at injection (GeV/c)	3.5
Momentum at extraction (GeV/c)	20
Gamma at Injection	3.86
Gamma at Extraction	21.35

$$h = \frac{Number\ of\ proton\ /pulses\ wanted}{Number\ of\ proton\ /pulses\ from\ booster} = 20$$

$\in = 0.1\,\pi\, eV.s$
$\Delta t = 51.2\, ns$
$\Delta E = 3.9\, MeV$

Booster:	Number of rings	**4**		
(fast cycling)	Average radius	**37.5**	Circumference [m]	235.619449
	Dipole occupation [fraction]	**0.28**	Length [m]	65.97344573
	Extraction momentum [GeV/c]	**3.5**	Top field [T]	1.111866667
			Gamma at extraction	3.862040361
			Beta at extraction	0.965895958
			Extraction kinetic energy [GeV]	2.685323679
			Rigidity at extraction [Tm]	11.674600
			Extraction revolution period [s]	8.186139E-07
	Harmonic number	**4**	RF frequency [Hz]	4.886309E+06
	Bunching factor (peak/average)	**5.66**	Bunch lgth/RF period	0.249861053
			Extracted bunch lgth [s]	5.12E-08
			Gap for kicker [s]	1.54E-07
	Kicker rise or fall time [s]	**1.00E-07**		
	Assume multi-turn injection with 20 turns with 50% efficiency after bunching giving 6.E12 particles/ring			
	Particles per ring	**6.00E+12**	Particles/bunch	1.50E+12
	Norm. H emit. [π mm mrad]	**40**	Geom. H. emit.[π mm mrad]	10.72291429
	Norm. V emit. [π mm mrad]	**20**	Geom. V. emit.[π mm mrad]	5.361457143
	Longitudinal emittance [eV s]	**0.1**		



CERN PS cavity

$$f_{rev(inj)} = 307\text{KHz}$$

$$f_{rev(ext)} = 318\text{KHz}$$

$$f_{RF(inj)} = 6.14\text{MHz}$$

$$f_{RF(ext)} = 6.36\text{MHz}$$

$$\frac{\Delta f_{RF}}{f_{RF}} = 3.6\ \%$$

$\Delta EBucket_t = 7\, G(\emptyset_s)$ MeV → $G(\emptyset_s)$ >= 0.55

From the booster:

$\epsilon = 0.1\,\pi\, eV.s$

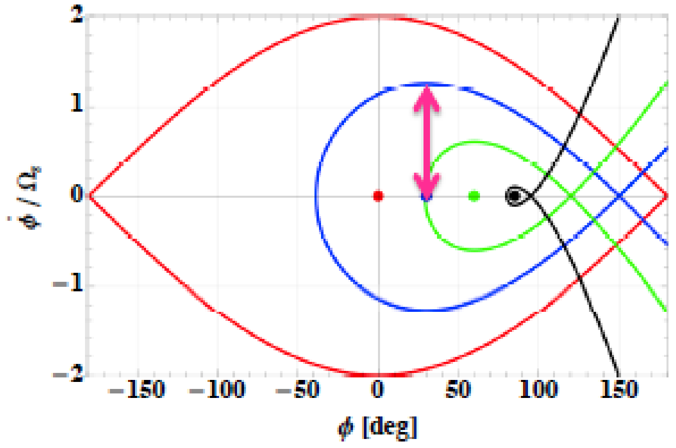
$\Delta t = 51.2\, ns$

$\Delta E_{Bunch} = 3.9\, MeV$

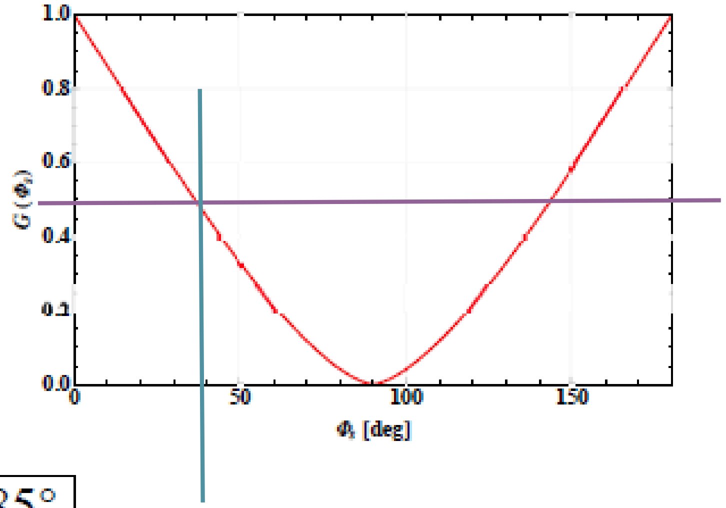
$$\Delta E_{max}^{sep}(\phi_s) = \sqrt{\frac{2\,\beta_s^2\, E_s\, e\, \hat{V}_{RF}}{\pi\, h\, \eta}}\; G(\phi_s)$$

with

$$G(\phi_s) = \frac{\sqrt{2\cos\phi_s - (\pi - 2\phi_s)\sin\phi_s}}{\sqrt{2}}$$



$\phi_s = 0°$ | $\phi_s = 30°$ | $\phi_s = 60°$ | $\phi_s = 85°$



$\emptyset_s$ < 40°

$\emptyset_s$ = 30°

$$\frac{dB}{dt} = \frac{V_{rf}\, N \sin(\emptyset_s)}{C\, \rho}$$

N(number of cavities) = 20

$20 * 2\, (Length\ of\ the\ cavity) = 40\, m$ → $Free\ space\ left = 24\, m$

Courtesy of Metral

Consideration for Transition:

$\gamma_{\ transition} = 6.36$ $\emptyset_s(\boldsymbol{After\ Transition})$ **= π-30º**

Some Numbers:

$Q_{Inj} = 8.29\ x\ 10 - 4$

$Q_{ext} = 2.265\ x\ 10 - 4$

$Ramp\ Time\ = 0.25\ second$

$(\Delta E)_{gain} = 200\ KeV$

$Number\ of\ Turns = 72500\ turn$

Group photo

Collective effects and corrections

Eleonora Belli, Rodrigo Varela, Jay Kalinani

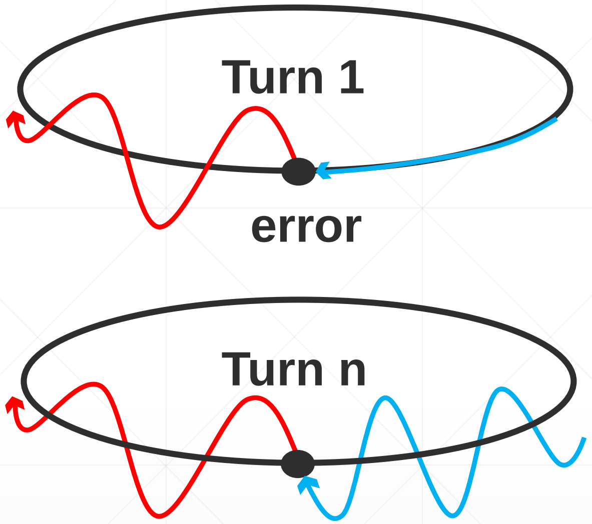
1. Tune control

Remind: the tune is the number of oscillations per turn

$$Q = \frac{1}{2\pi}\oint \frac{ds}{\beta(s)} = \frac{\mu}{2\pi}$$

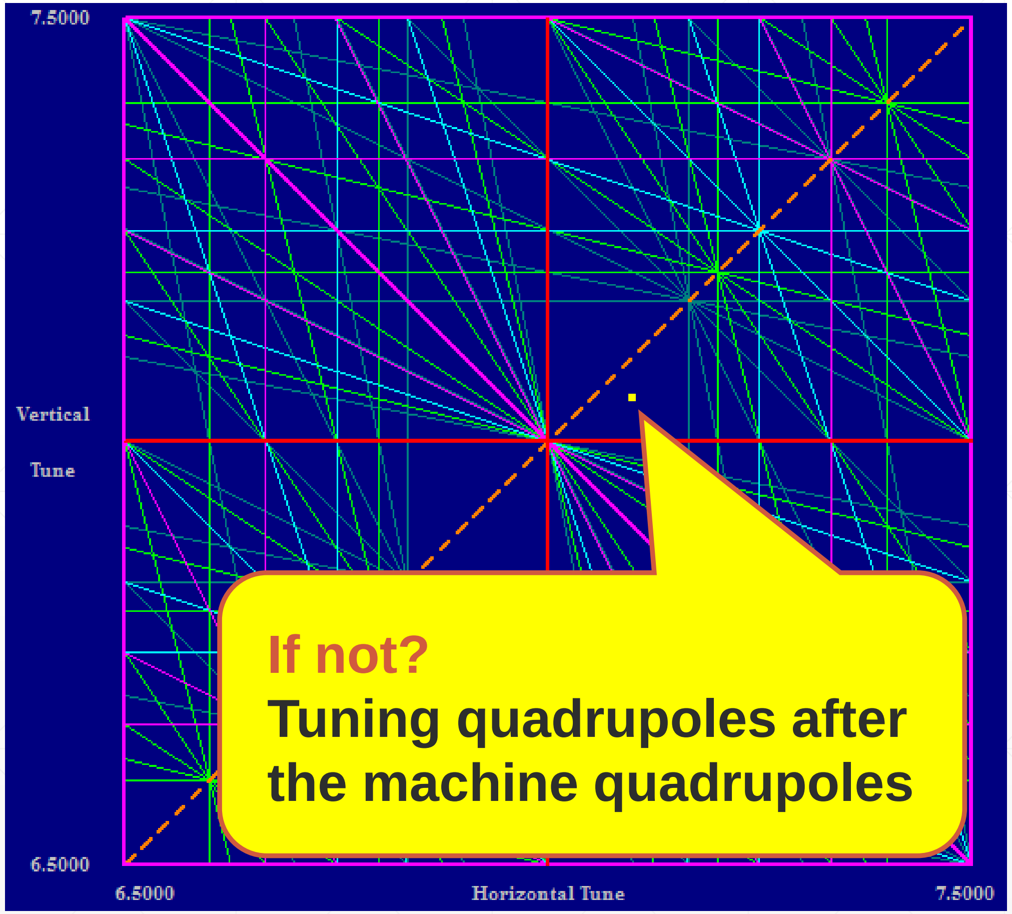
<u>Avoid resonance conditions (integer tune)</u>

Errors will sum-up in consecutive turns



- *Check your **working point**, i.e. the position of the tunes in the resonance diagram*

$$Q_x = 7.1 \qquad Q_y = 7.05$$

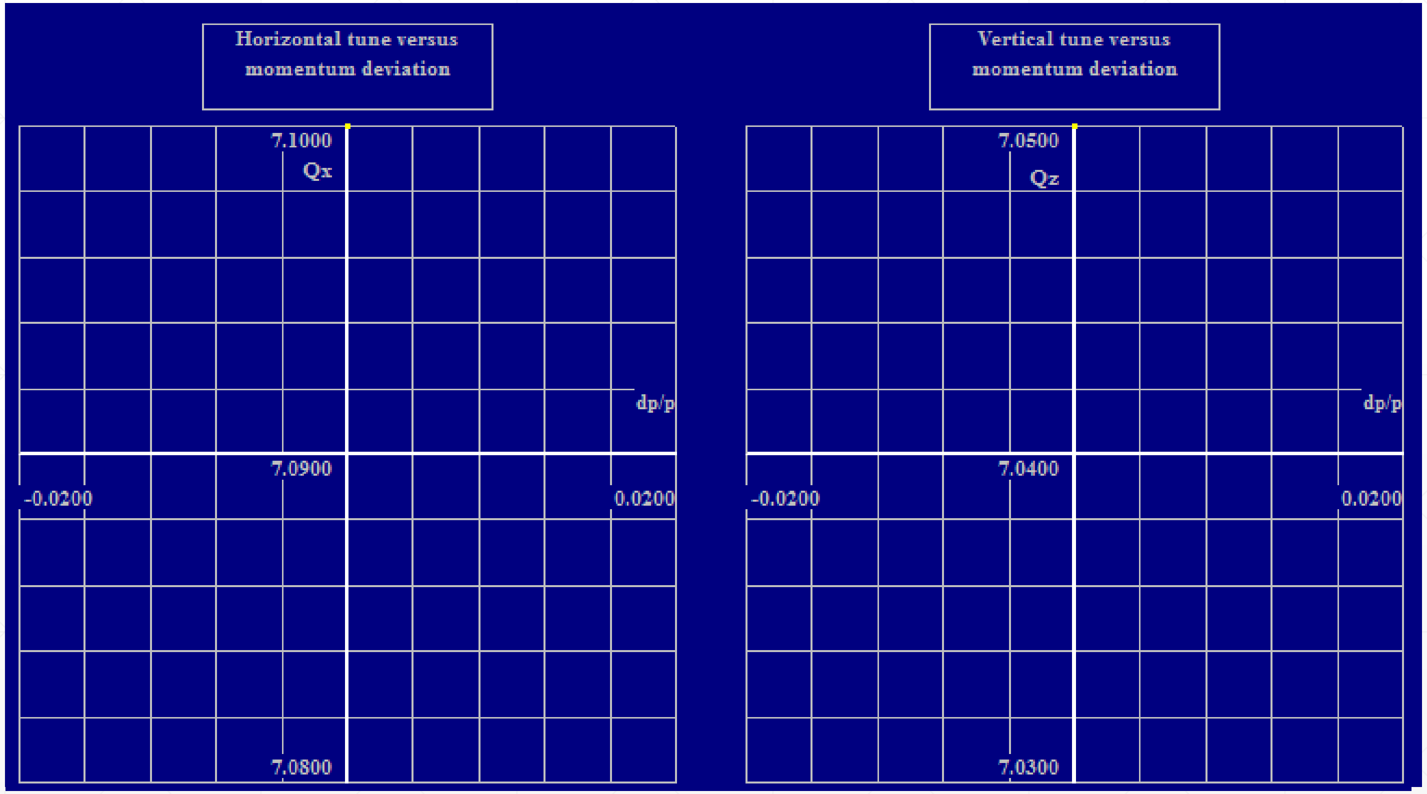


If not?
Tuning quadrupoles after the machine quadrupoles

1. Tune control (cont.)

The **tune shift** is induced by

- Errors in quadrupole strenght $\Delta Q = \frac{1}{4\pi}\oint_{quad} \Delta k(s)\beta(s)ds$
- Coherent and incoherent space charge effects



$$\Delta Q_{x,y} = -\frac{1}{2}\frac{N r_0}{\beta^2\gamma^3(2\epsilon_{x,y})}\frac{1}{1+\frac{b}{a}}$$

1.Coherent space charge

2. Incoherent space charge with $\frac{\Delta p}{p} = 10^{-3}$ @ 3.5GeV

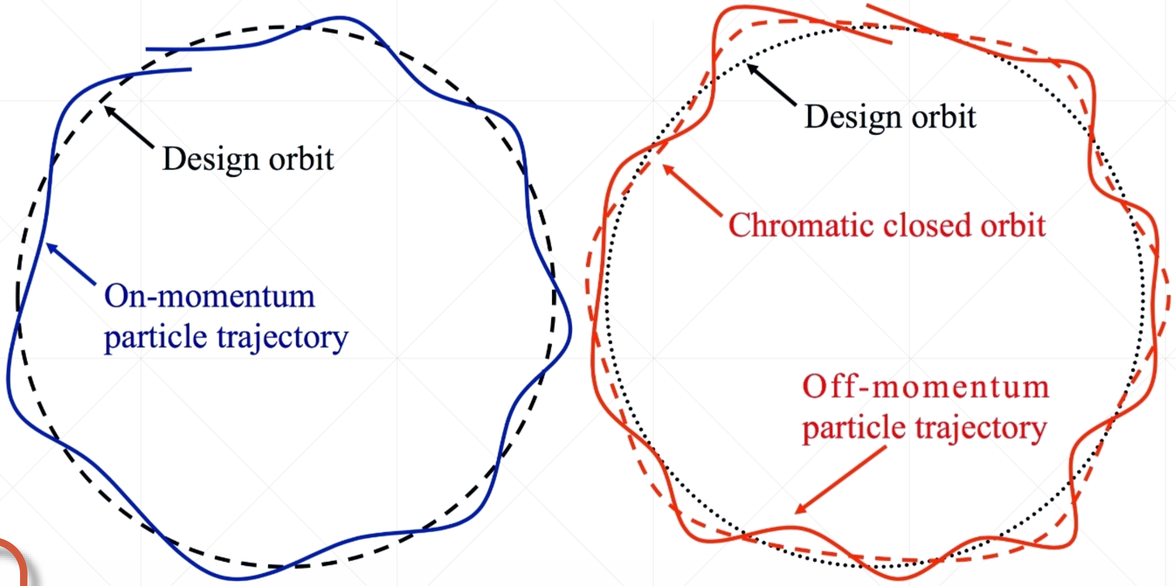
3. Incoherent space charge with $\frac{\Delta p}{p} = 10^{-1}$ @3.5GeV

4. Incoherent space charge with $\frac{\Delta p}{p} = 10^{-3}$ @ 20GeV

3. Closed orbit prognosis and correction

- On-momentum particle → design orbit
- Off-momentum particle → closed orbit

$$x = D\frac{\Delta p}{p}$$



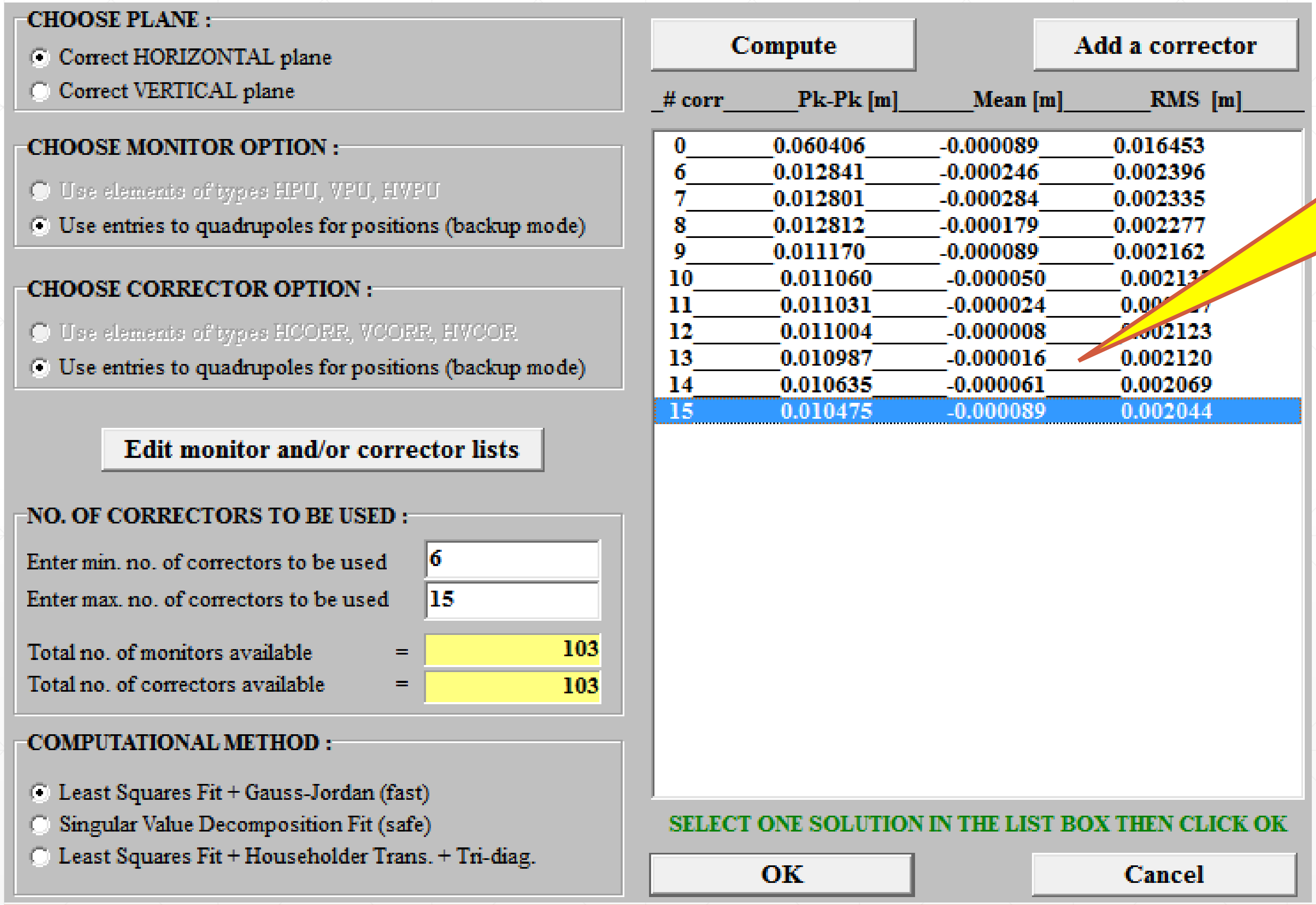
Distortion of the closed orbit

$$\langle \Delta z^2(s)\rangle^{1/2} = \frac{\overline{\beta_z}(s)}{2\sqrt{2}|\sin \pi Q|}\left[\sum_n \langle \delta_n^2\rangle\right]^{1/2}$$

- **Dipole misalignments (1mm)**
- Dipole rolls
- **Quadrupole misalignments (1mm)**

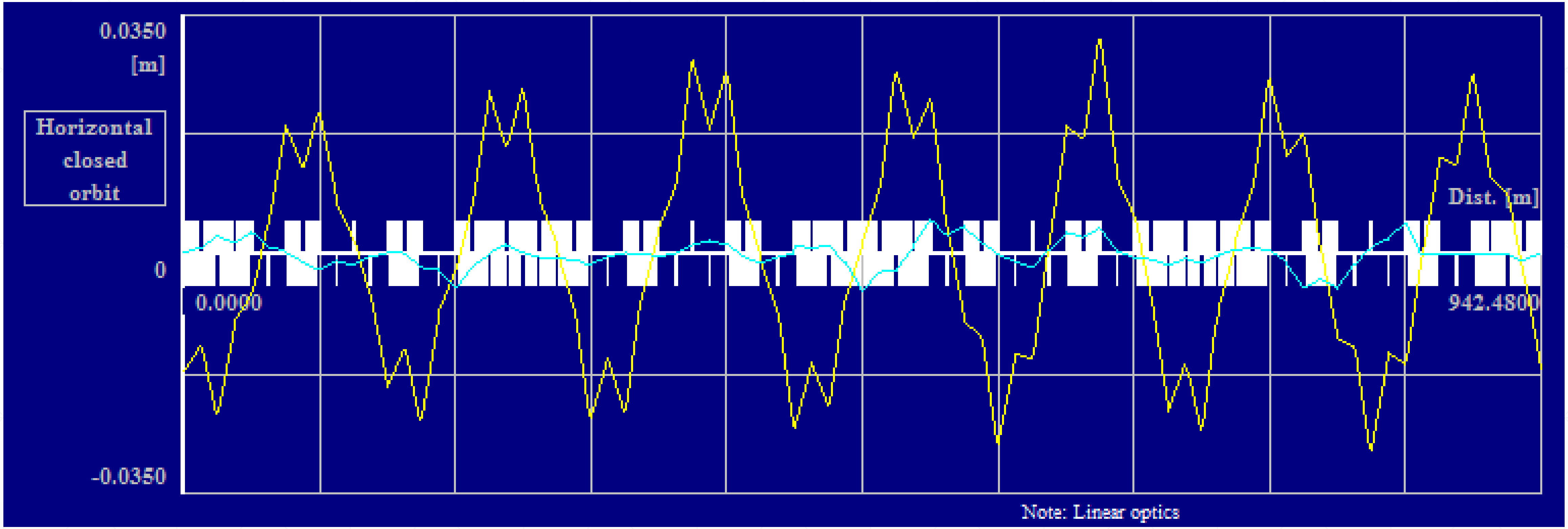
3. Closed orbit prognosis

3. Closed orbit correction



15 correctors
Expected closed orbit amplitude ≈ 1cm

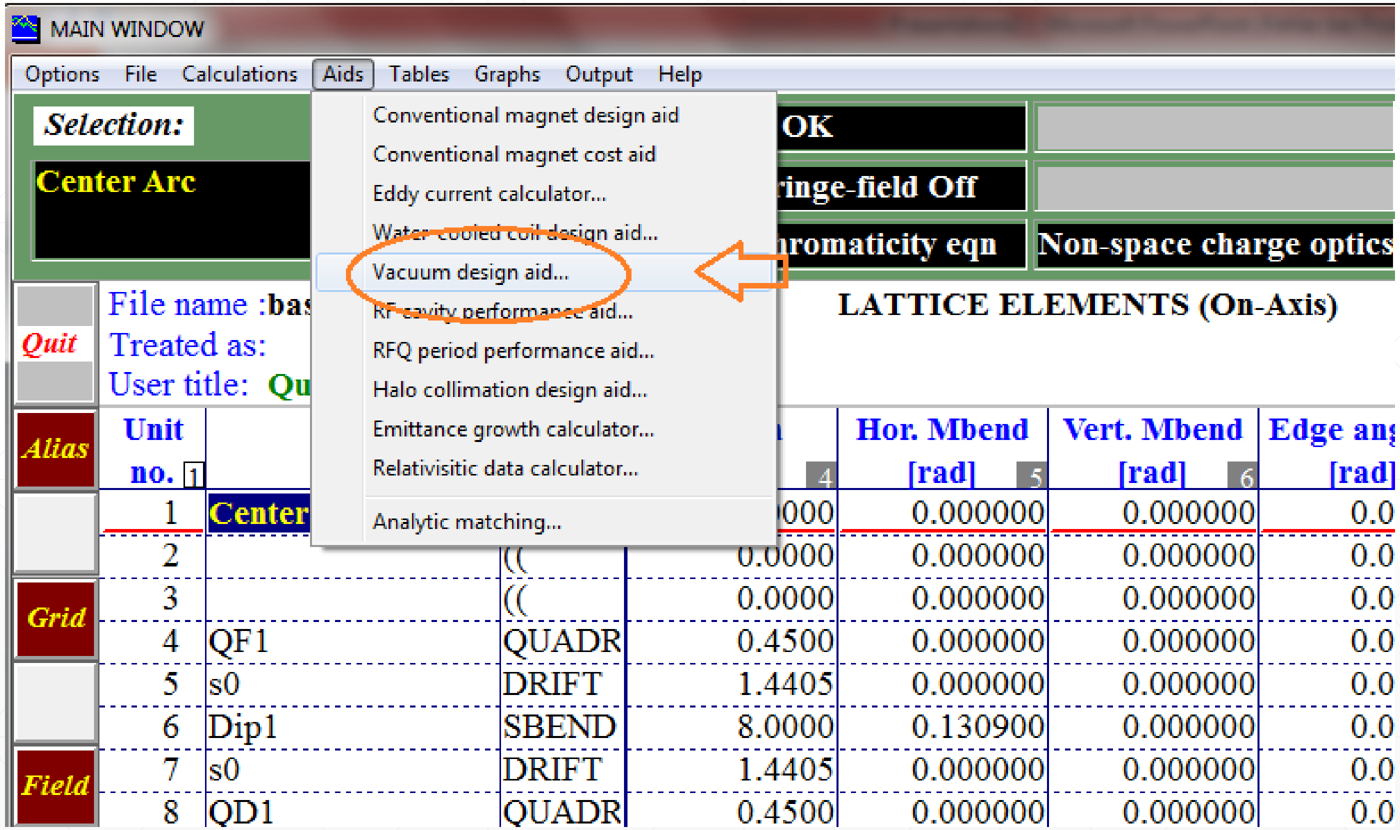
3. Closed orbit correction (cont.)

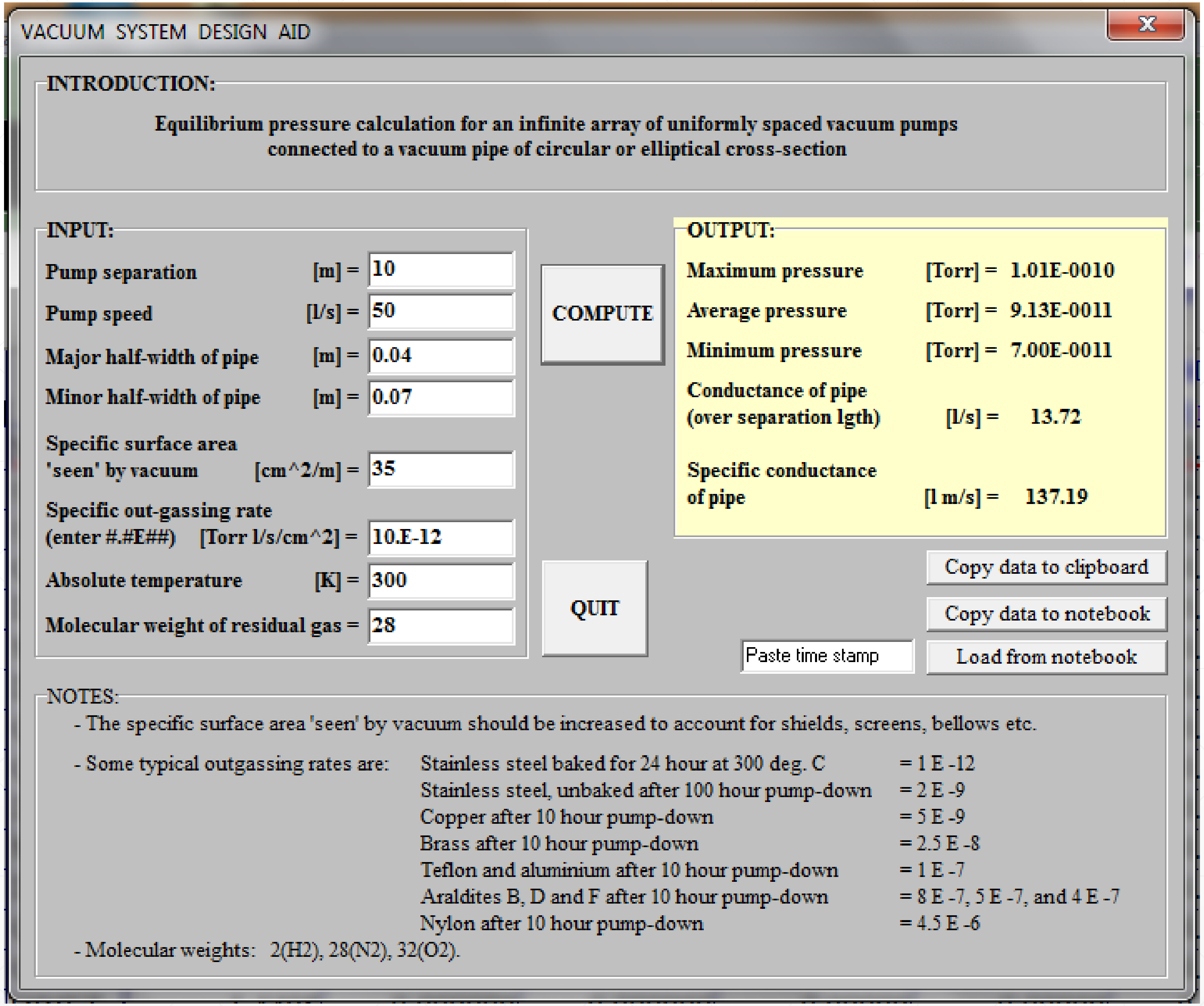


Pk-Pk amplitude $\approx 1cm$

Vacuum consideration

Vacuum considerations




VACUUM SYSTEM DESIGN AID
INTRODUCTION:
Equilibrium pressure calculation for an infinite array of uniformly spaced vacuum pumps connected to a vacuum pipe of circular or elliptical cross-section
INPUT:
Pump separation [m] = 10
Pump speed [l/s] = 50
Major half-width of pipe [m] = 0.04
Minor half-width of pipe [m] = 0.07
Specific surface area 'seen' by vacuum [cm^2/m] = 35
Specific out-gassing rate (enter #.#E##) [Torr l/s/cm^2] = 10.E-12
Absolute temperature [K] = 300
Molecular weight of residual gas = 28
COMPUTE
QUIT
OUTPUT:
Maximum pressure [Torr] = 1.01E-0010
Average pressure [Torr] = 9.13E-0011
Minimum pressure [Torr] = 7.00E-0011
Conductance of pipe (over separation lgth) [l/s] = 13.72
Specific conductance of pipe [l m/s] = 137.19
Copy data to clipboard
Copy data to notebook
Paste time stamp
Load from notebook
NOTES:
- The specific surface area 'seen' by vacuum should be increased to account for shields, screens, bellows etc.
- Some typical outgassing rates are:
Stainless steel baked for 24 hour at 300 deg. C = 1 E -12
Stainless steel, unbaked after 100 hour pump-down = 2 E -9
Copper after 10 hour pump-down = 5 E -9
Brass after 10 hour pump-down = 2.5 E -8
Teflon and aluminium after 10 hour pump-down = 1 E -7
Araldites B, D and F after 10 hour pump-down = 8 E -7, 5 E -7, and 4 E -7
Nylon after 10 hour pump-down = 4.5 E -6
- Molecular weights: 2(H2), 28(N2), 32(O2).

INPUT:

Pump separation [m] =	10
Pump speed [l/s] =	50
Major half-width of pipe [m] =	0.04
Minor half-width of pipe [m] =	0.07
Specific surface area 'seen' by vacuum [cm^2/m] =	35
Specific out-gassing rate (enter #.#E##) [Torr l/s/cm^2] =	10.E-12
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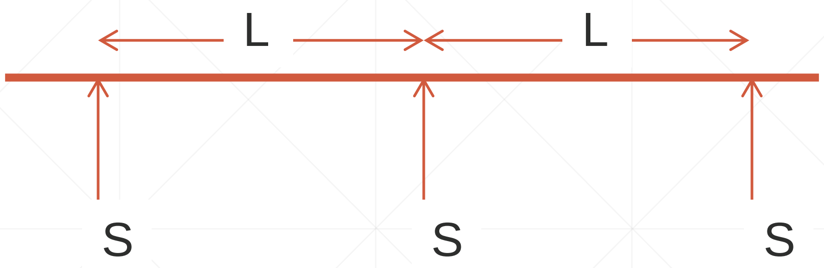
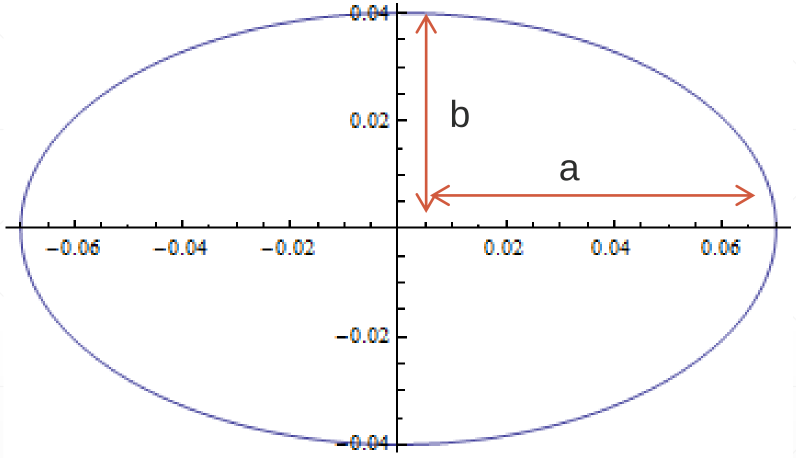
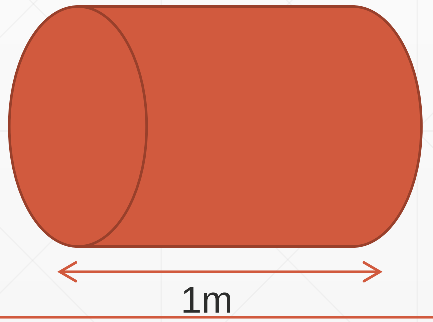






OUTPUT:

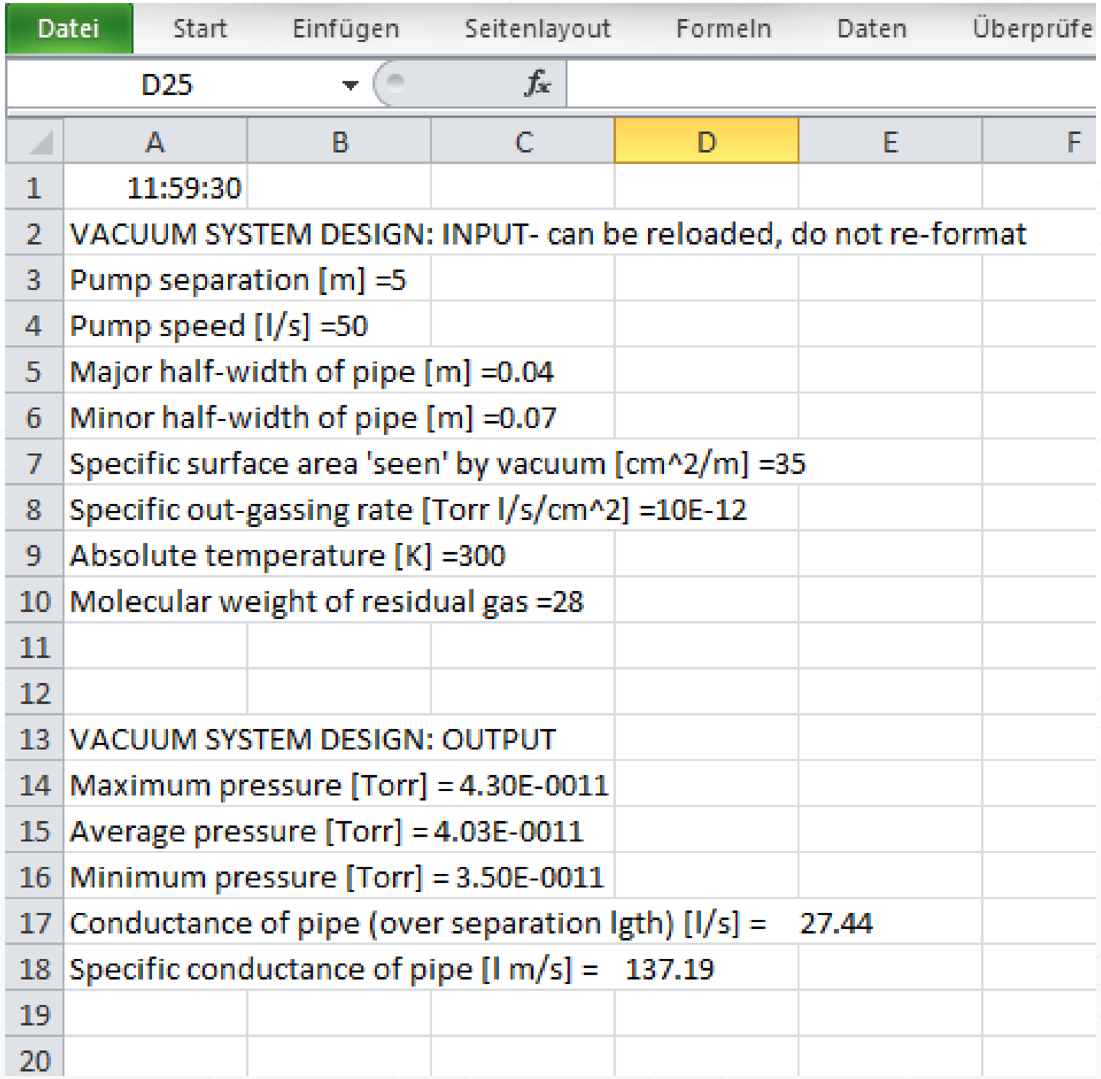
Maximum pressure	[Torr] =	1.01E-0010
Average pressure	[Torr] =	9.13E-0011
Minimum pressure	[Torr] =	7.00E-0011
Conductance of pipe (over separation lgth)	[l/s] =	13.72
Specific conductance of pipe	[l m/s] =	137.19

Pressure can be transformed to particle density:

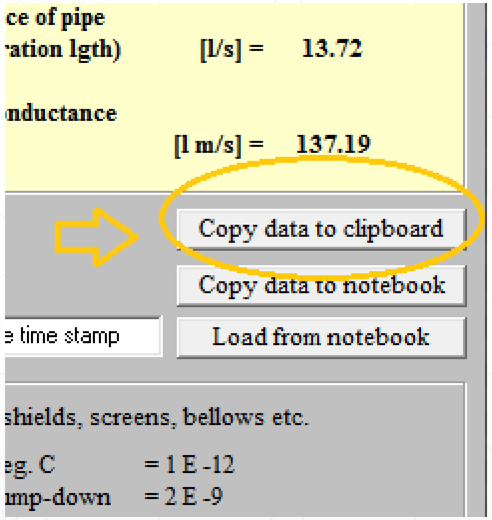
P.V = N.k.T

10^{-10} Torr ~ 3 million particles/cm^3

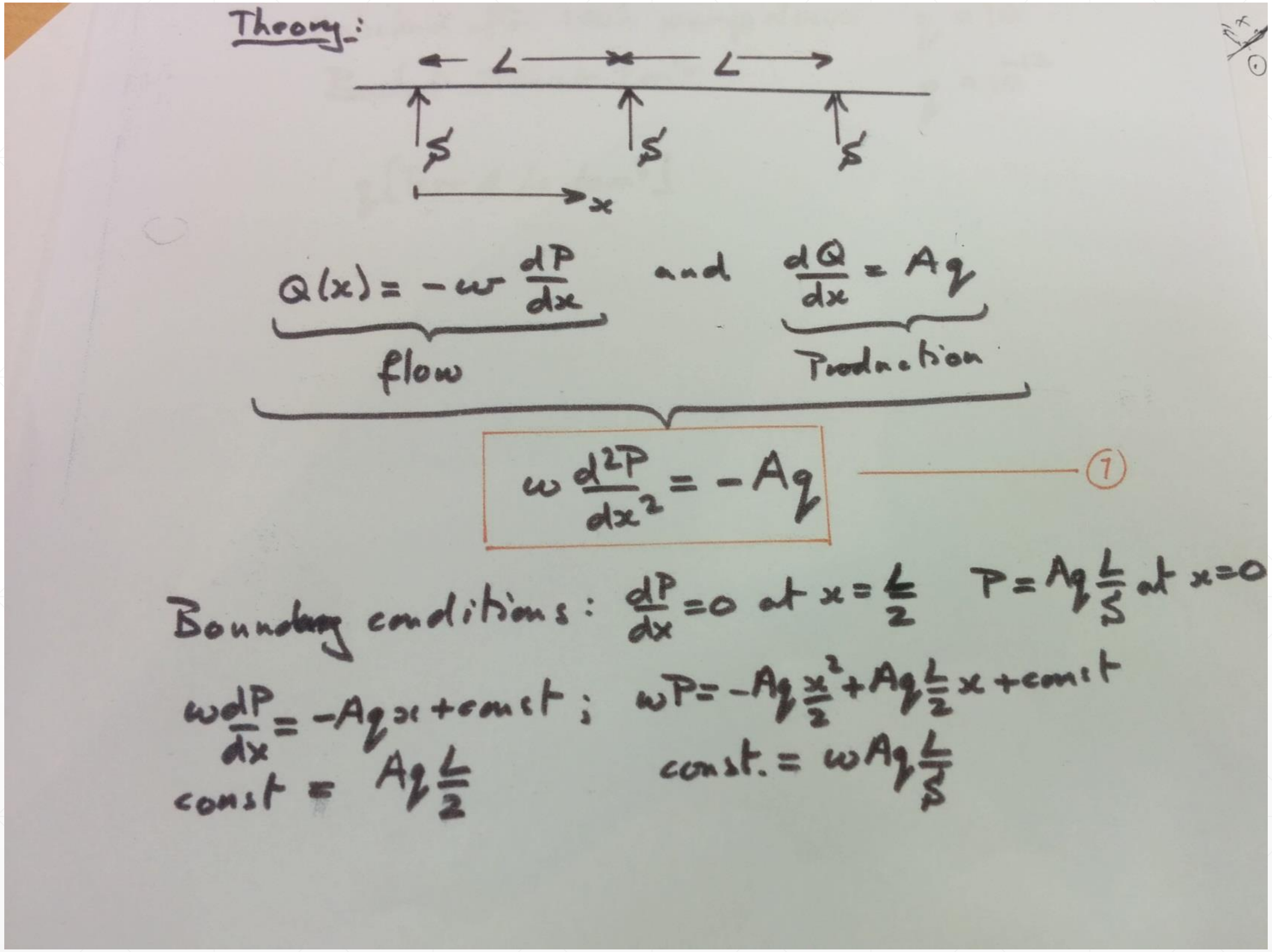
(1mbar ~0.75 Torr)



Output can be saved in an EXEL-file



Theory


Theory:
L
L
S
S
S
x
$Q(x) = -w \frac{dP}{dx}$ and $\frac{dQ}{dx} = Aq$
flow
Production
$w \frac{d^2P}{dx^2} = -Aq$
1
Boundary conditions: $\frac{dP}{dx} = 0$ at $x = \frac{L}{2}$ $P = Aq\frac{L}{S}$ at $x = 0$
$w\frac{dP}{dx} = -Aq\,x + const$; $wP = -Aq\frac{x^2}{2} + Aq\frac{L}{2}x + const$
$const = Aq\frac{L}{2}$
$const. = wAq\frac{L}{S}$

$$P(x) = Aq\left\{\frac{Lx - x^2}{2w} + \frac{L}{S}\right\}$$

$$P_{max} = Aq\left\{\frac{L^2}{8w} + \frac{L}{S}\right\}$$

$$P_{av} = Aq\left\{\frac{L^2}{12w} + \frac{L}{S}\right\}$$

(2)

$$P_{av} = Aq / S_{eff} \quad \text{where } S_{eff} = \left(\frac{L^2}{12w} + \frac{L}{S}\right)^{-1}$$

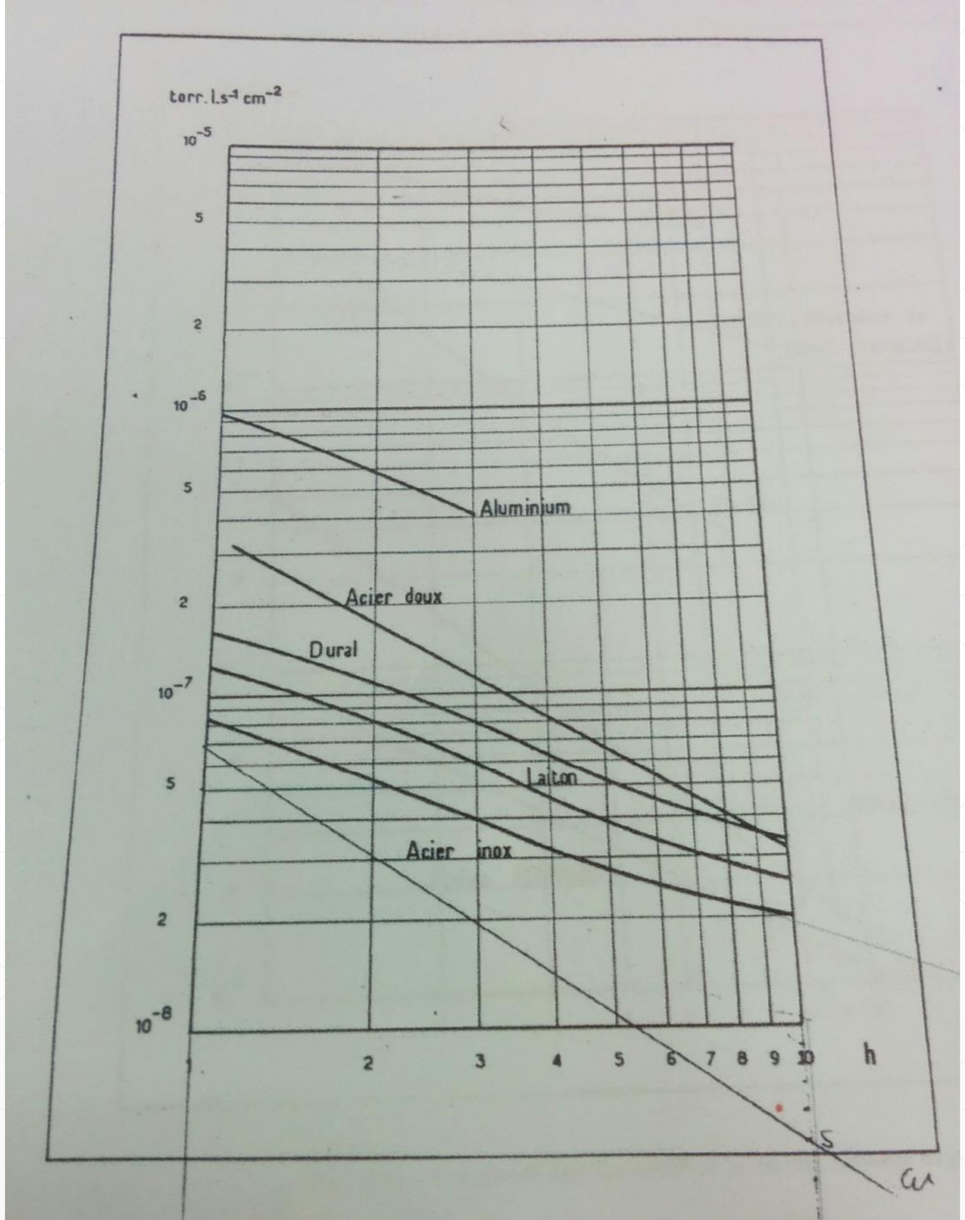


Fig. 5-14. — Courbes de dégazage spécifique en fonction du temps de pompage

Magnet consideration

Dipoles

MAIN SPECIFICATIONS

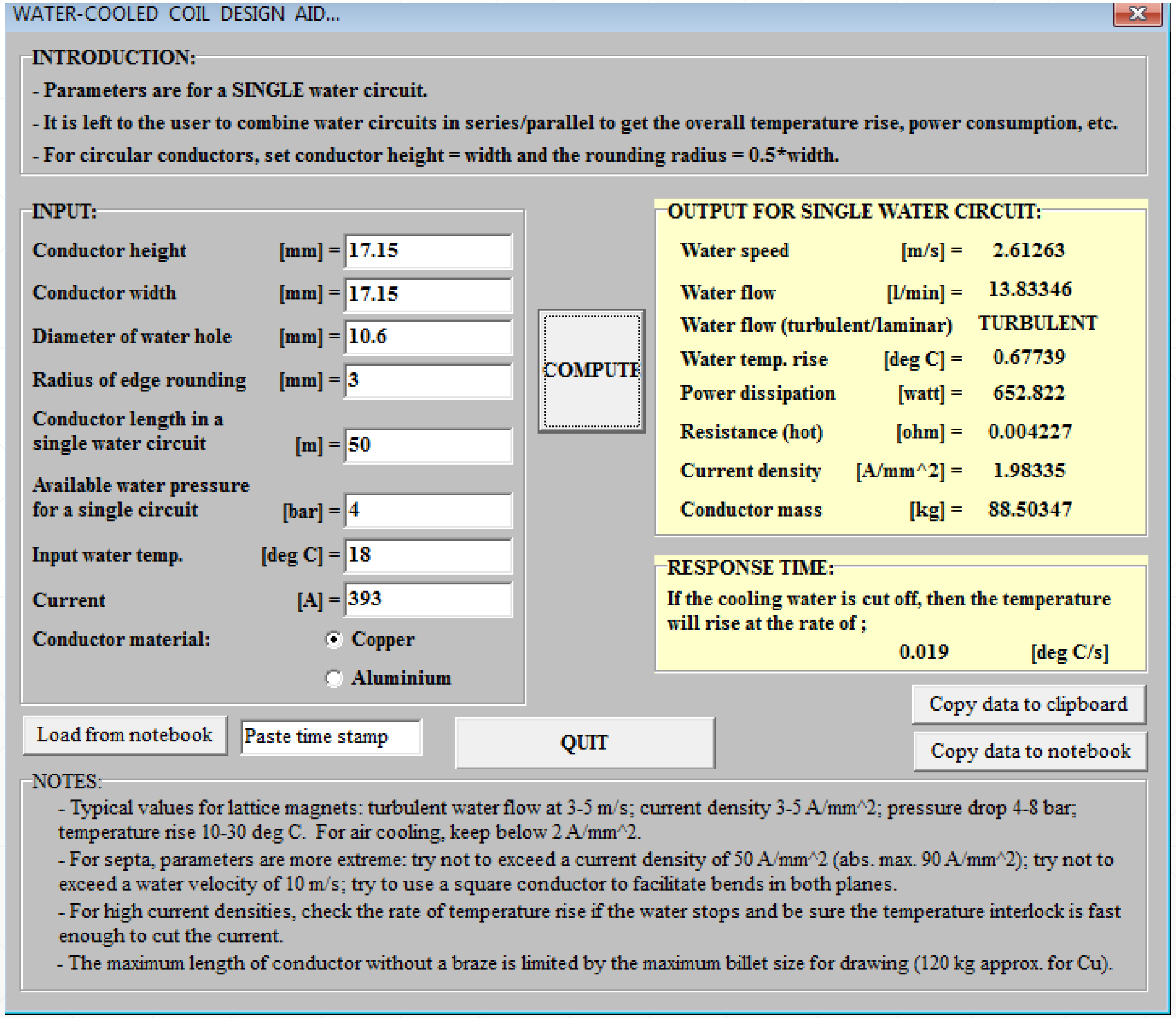
Bmax [T]	1.09
Bending Radius [mm]	61500
Bending Angle [°]	7,44
Magnet lenght [mm]	8000

IRON YOKE SPECIFICATIONS

Pole iron gap [mm]	100
L overall [mm]	8270
L iron [mm]	7870
Pole width [mm]	500
Overall width [mm]	1400
Overall height [mm]	1100

COIL SPECIFICATIONS

Number of turns	220
Nominal current [A]	393
Conductor type	Hollow
Conductor dimensions [mm]	14 x 14
Hole diamater [mm]	8,5



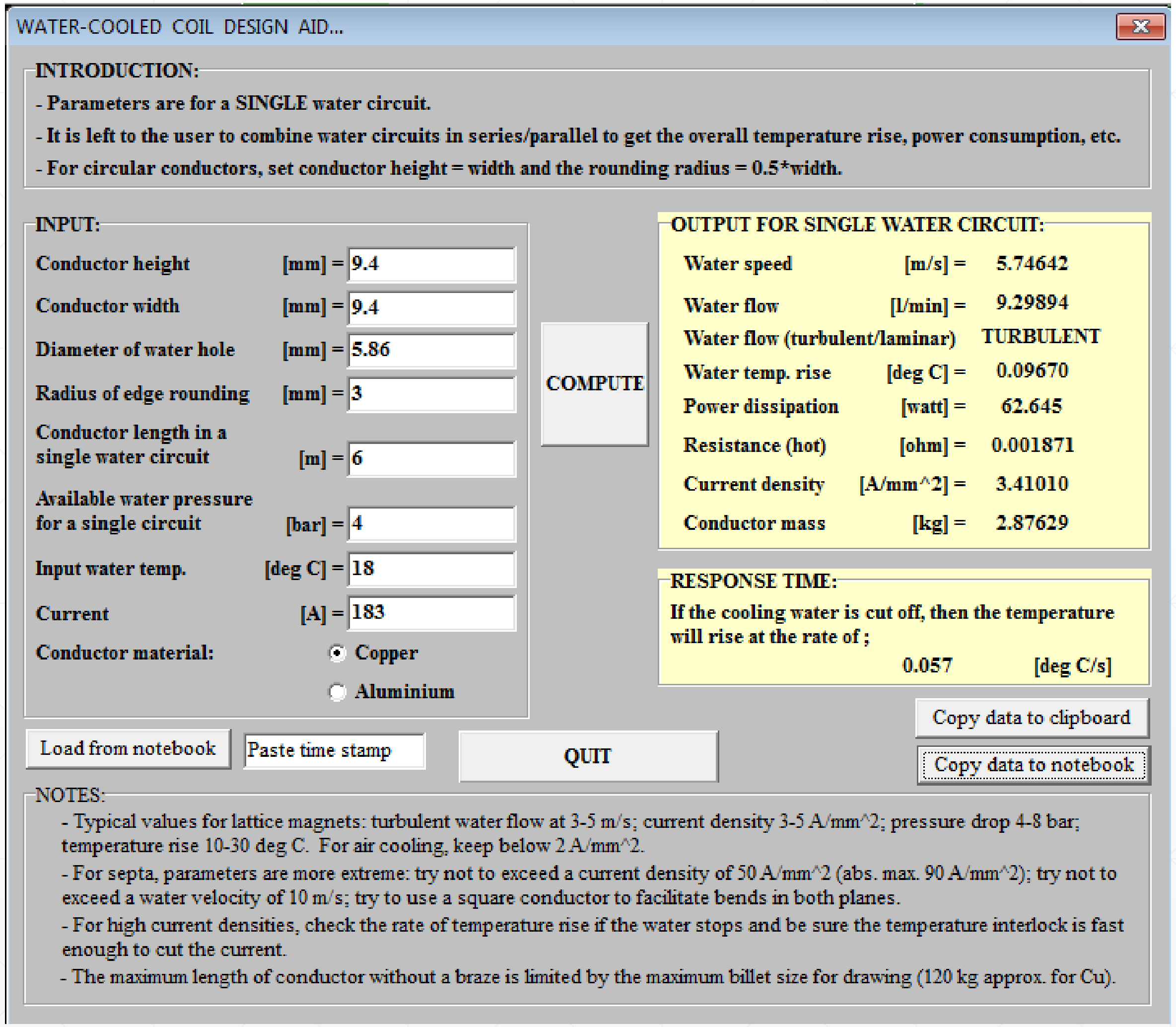
Qadrupoles

MAIN SPECIFICATIONS

Maximum gradient [T/m]	6,6
Magnet lenght [mm]	450
IRON YOKE SPECIFICATIONS	
Aperture diameter[mm]	100
L overall [mm]	500
Liron [mm]	450
Overall Width [mm]	400

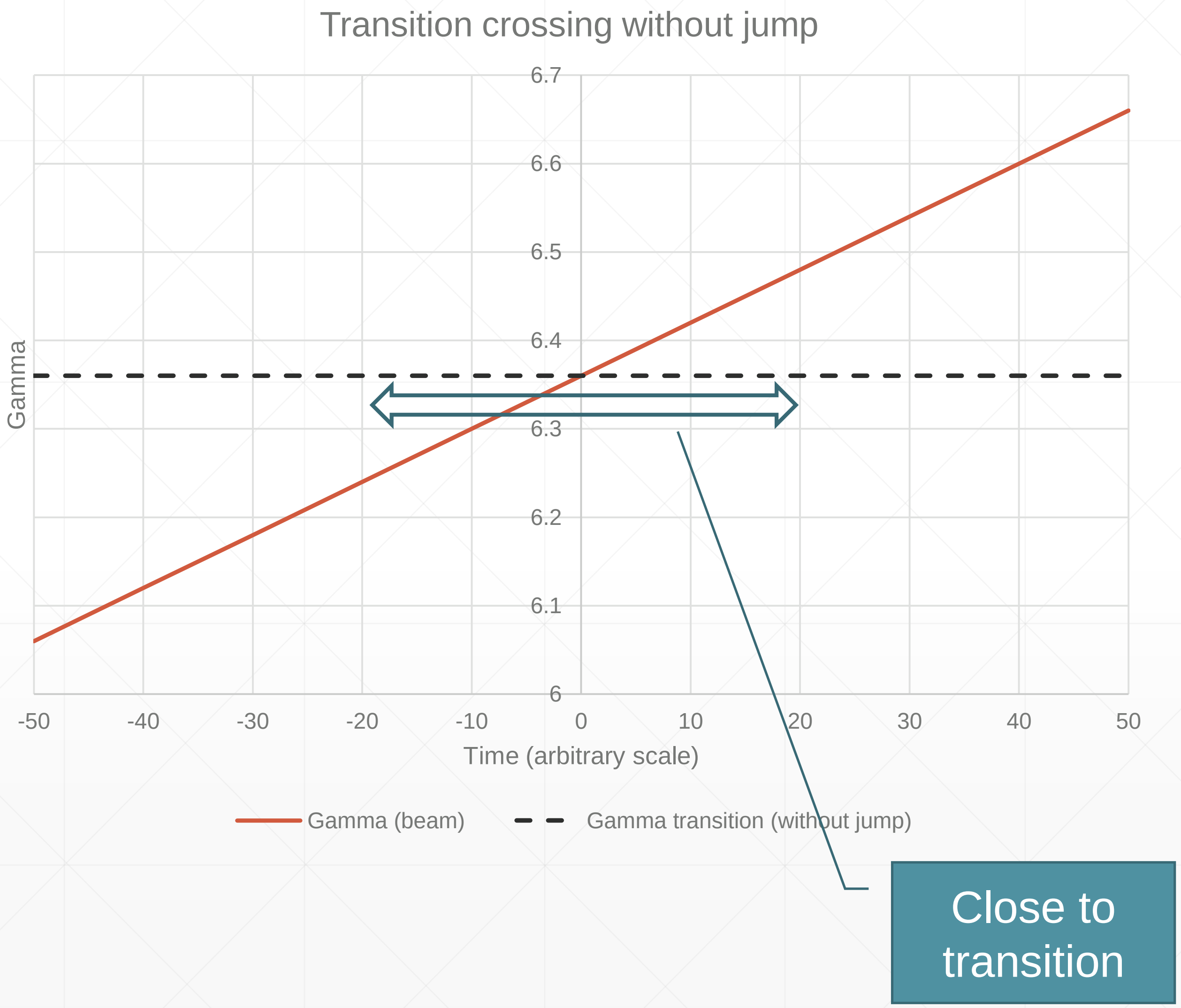
COIL FEATURES

Number of turns per pole	36
Nominal current [A]	183
Conductor type	Hollow
Conductor dimensions [mm]	9,4 x 9,4
Hole diamater [mm]	5,83



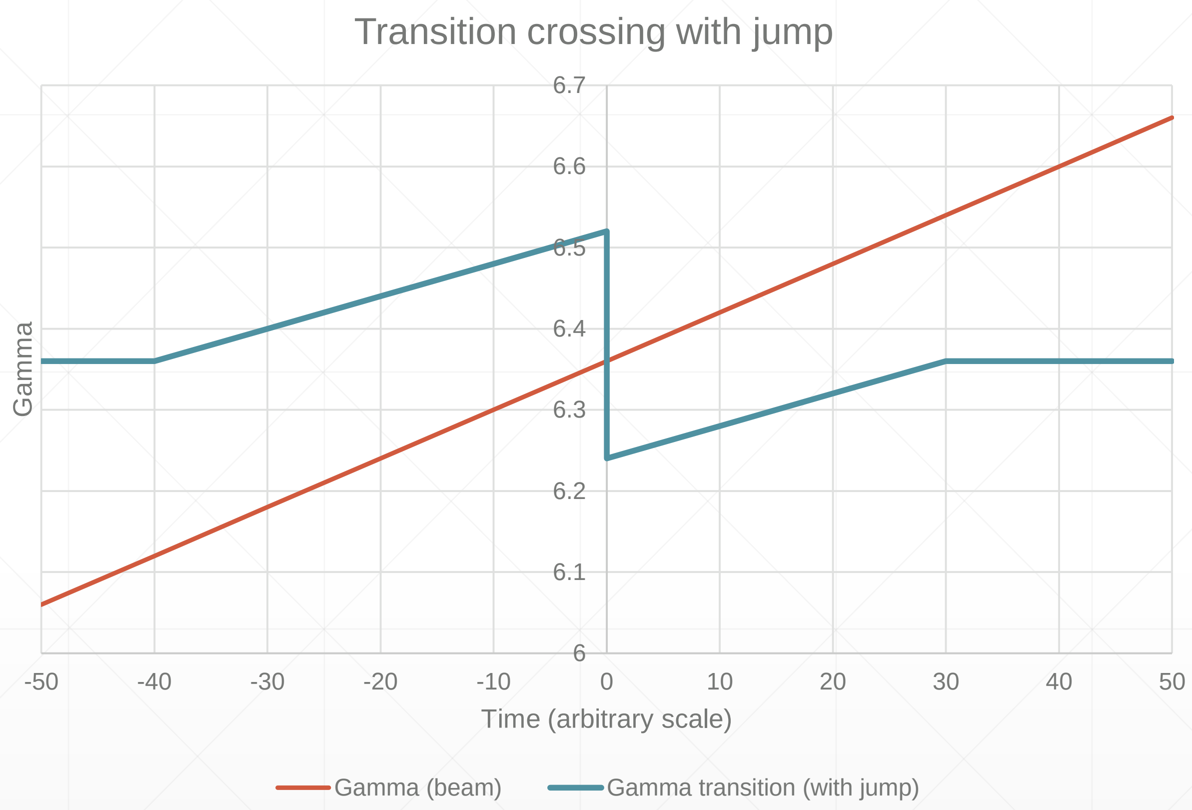
Transition considerations

Gamma transition crossing I



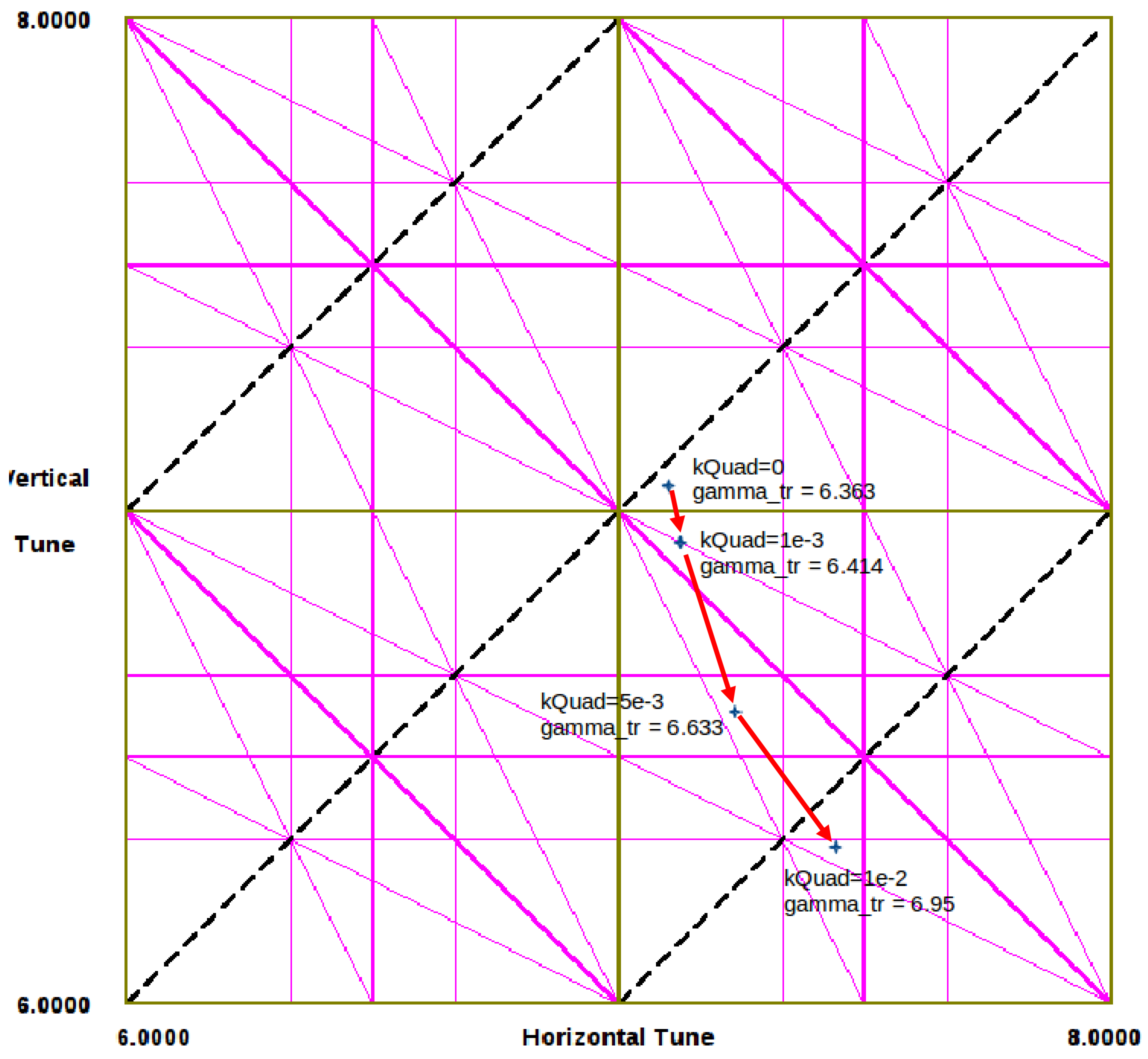
- Non adiabatic theory needed
- At transition, bunch length ↘ and momentum spread ↗
- Main risk: losses in the beam

Gamma transition crossing II



- Solution: create a jump in γ_{tr}
- How to: add quadrupoles to change the momentum compaction factor
- Problem: adding quadrupole changes the tune

Gamma transition crossing III



- Switch on the quadrupoles:
  - γ_{tr} increases
- Switch off or invert the polarity of the quadrupoles at the right time
  - γ_{tr} decreases suddenly
  - You have crossed transition
- The tune changes
  - You may cross resonances
  - To avoid it, one may want to change the tune before the gamma jump and reestablished it afterward

Gamma transition crossing

- Do we have time to do this gamma jump?
- Assume a 30kV RF cavity, a $\dot{B} = 3{,}6\ T/s$ and a $\gamma_{tr} = 6{,}36$
- Therefore $\Delta E = 10 MeV/turn$
- A $\Delta\gamma = 0{,}27$ means an increase in energy of $\Delta E = 250\ MeV$ so we would need approximately 10 turns to operate the quadrupoles (about 300µs)

Thanks for your attention

Spare slides

Chromaticity correction

Gerardo Guillermo, Shuang Ruan, Geng Wang, Kedong Wang, Liping Yao

Chromaticity correction I

- In order to correct the chromaticity 2 sextupoles were added, one focusing and one defocussing
- The sextupoles where placed next to the defocussing quadropoles
- WinAGILE calculated the closed orbit parameters (without sextupoles):

CENTRAL ORBIT Circular machine		
Circumference	[m] =	943.0480
Horizontal tune	Qx =	7.104830
Vertical tune	Qz =	7.054848
Horizontal chromaticity	dQx/dp/p =	-8.513
Vertical chromaticity	dQz/dp/p =	-3.349
Gamma transition	gamma tr =	6.36840

Chromaticity correction II

- To steps to find the strength of the sextupoles are:
  - Go into calculations menu
  - Select correct chromaticity
  - In the menu select the desired chromaticity, e.g. 0.
  - Click on recompute, and it will display the strength needed
- After getting the values, it is recommended that you check it is feasible within technological restrictions.