Beam-Beam studies for TLEP (and update on TMCI)

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Thanks to E. Metral, R. Tomas and F. Zimmermann

Outline

Model and benchmarking

Parameters, layout,

simulation code, synchrotron radiation

Dynamic effects

Working point, phase advances

Simulated luminosity

Preliminary performance estimates

Lifetime

Preliminary estimates, number of IPs,

energy acceptance

Update on TMCI

Model, synchro-betatron effects, thresholds

Beam parameters

- Latest beam parameters provided by F. Zimmermann

	TELP Z	TLEP W	TLEP H	TLEP t	TLEP t B
E [GeV]	45	80	120	175	175
N [e/bunch]	4.0e11	1.0e11	3.7e11	0.88e11	7.0e11
$\varepsilon_{x/y}$ [nm]	29.2/0.06	3.3/0.017	7.5/0.015	2.0/0.002	16.0/0.016
$\beta_{x/y}$ [m]	0.5/1.0e-3	0.2/1.0e-3	0.5/1.0e-3	1.0/1.0e-3	1.0/1.0e-3
$\tau_{\|\|}$ [turns]	1319	242	72	23	23
$\xi_{x/y}$/IP	0.068	0.086	0.094	0.057	0.057
L/IP [$cm^2.s^{-1}$]	5.9e35	1.6e35	5.1e34	1.3e34	1.0e34

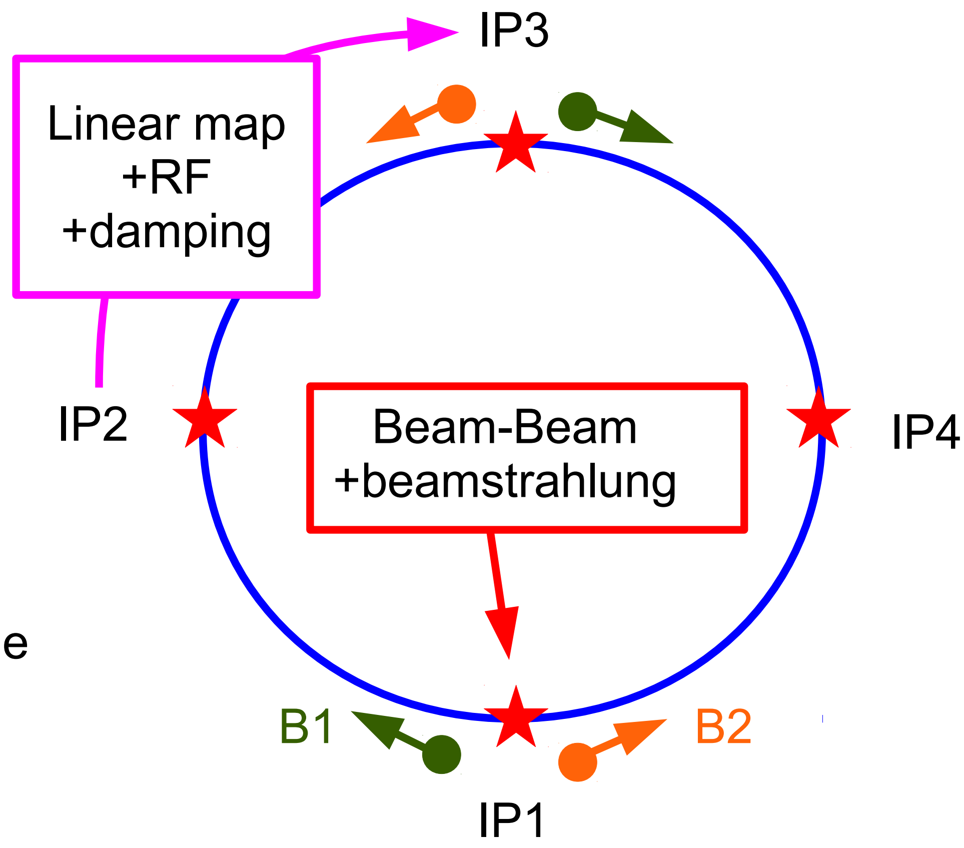
→ Beam parameters relevant for the beam-beam simulations

→ **Assume 100km circumference in all cases**

→ By design there are 4 IPs: the total beam-beam parameter scales accordingly

Model

- Strong-strong beam-beam model based on the code BeamBeam3D by J. Qiang
- Beam-beam module fully benchmarked against data and theory
- Allows to include impedance effects benchmarked with HEADTAIL and theory
- Track 2 bunches per beam: neglecting long-range interactions this covers the full picture
- Recently added synchrotron radiation (damping and beamstrahlung as relevant for TLEP)
- Benchmarking done against existing code and theory (will be presented in the following slides)
- Luminosity is computed in 3D taking into account the focusing effect of the beam-beam interaction



→ Only non linear elements are the beam-beam interactions

→ Arcs are modeled by linear transfer maps

→ Optics are the same in all IPs

Synchrotron radiation

- The average number of photons emitted for a given bending radius is:

$$n_\gamma = \frac{5\sqrt{3}}{6} \frac{\alpha \gamma}{\rho} \Delta s$$

- Photon emission follows a Poisson distribution:

$$P(n) = \frac{n_\gamma^n e^{-n_\gamma}}{n!}$$

- Cumulative distribution of energy probability law:

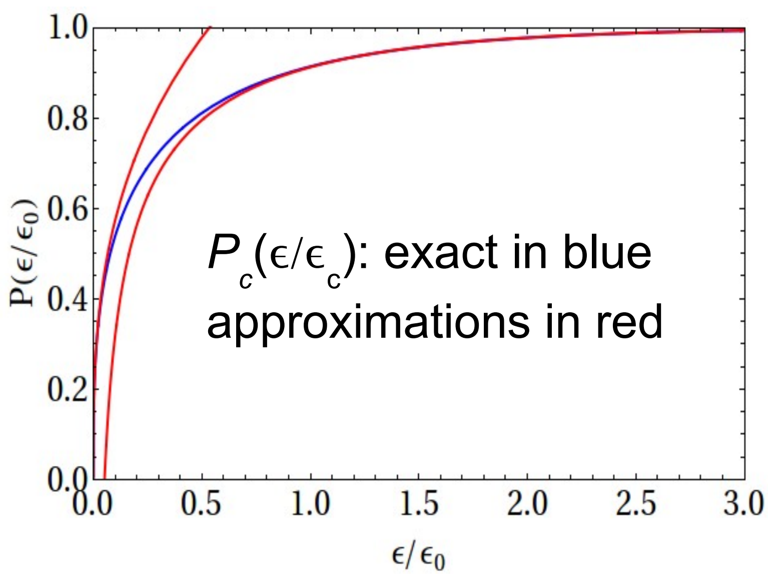
$$P_c(\epsilon/\epsilon_c) = \frac{3}{5\pi} \int_0^{\epsilon/\epsilon_c} \int_{\epsilon/\epsilon_c}^{\infty} K_{5/3}(x)\, dx$$

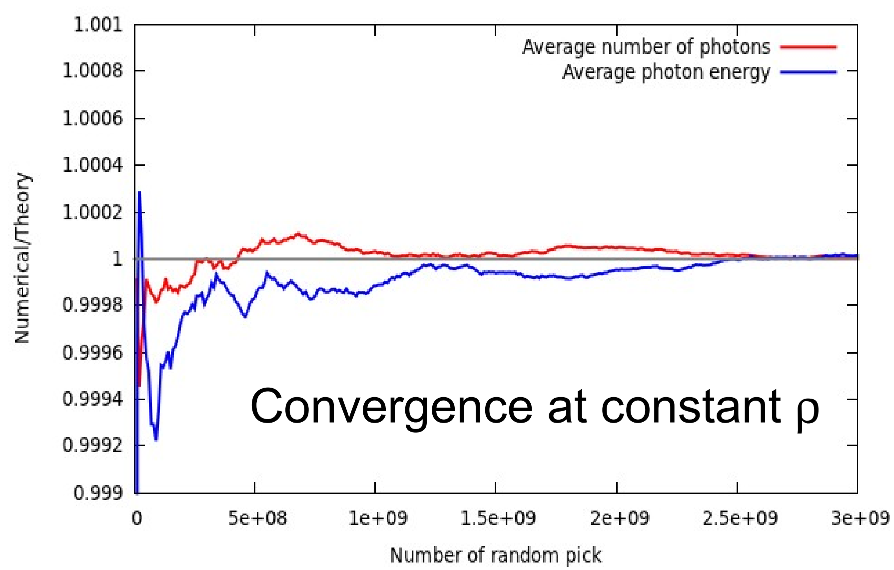
with $P_c(\epsilon/\epsilon_c \gg 1) \approx 1 - 0.24 \frac{e^{-\frac{\epsilon}{\epsilon_c}}}{\sqrt{\frac{\epsilon}{\epsilon_c}}}$ and $P_c(\epsilon/\epsilon_c \ll 1) \approx 1.23 \left(\frac{\epsilon}{\epsilon_c}\right)^{(1/3)}$

- Photon critical energy: $\epsilon_c = \frac{3\hbar \gamma^3 c}{2\rho}$

Photon emission

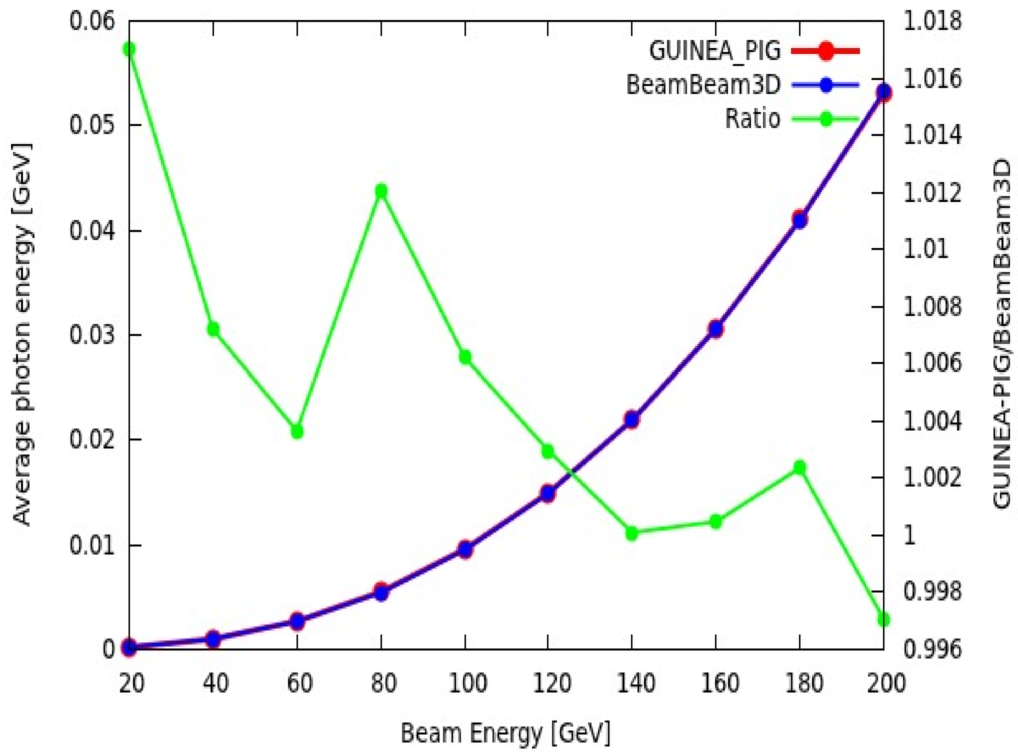
- Each time a kick is given to a particle ρ and ϵ_c are computed accordingly
- The number of photons emitted over the interaction length is selected at random following *P*(*n*)
- The energy of each photon is then computed by picking a random number between 0 and 1 and inverting $P_c(\epsilon/\epsilon_c)$
- For small and large energies analytical approximations are used. For intermediate energies a look-up table of the exact numerical integration is used: $0.02 < \epsilon/\epsilon_c < 5.0$

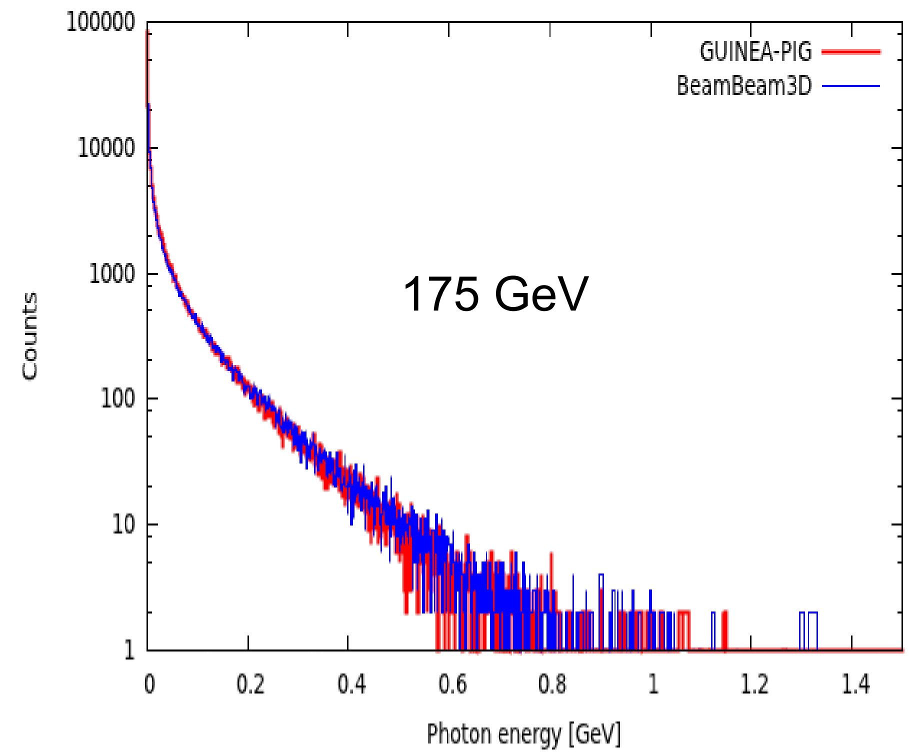




Comparison with GUINEA-PIG

- Test case with round beams at the IP. Photon energy distribution for 2M macro-particles, 13 slices and a grid of 128x128 after a single collision



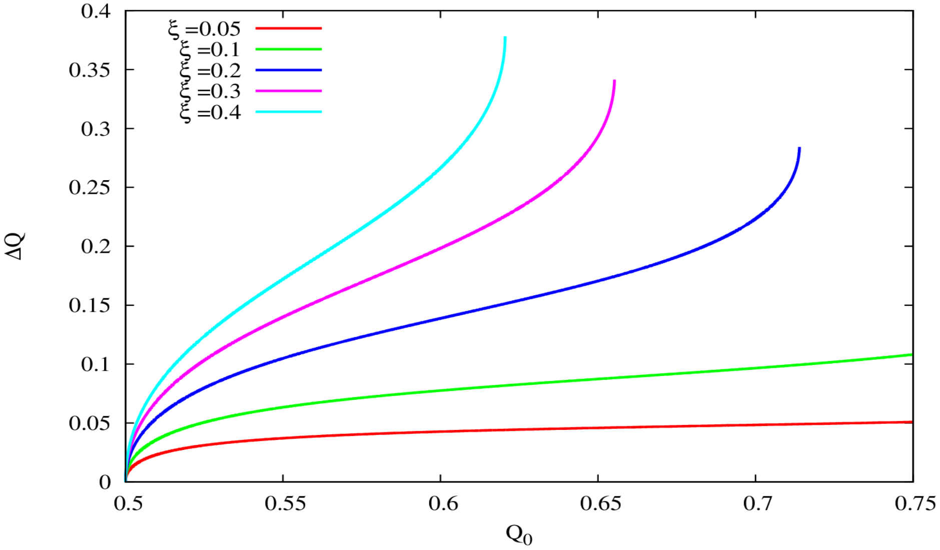


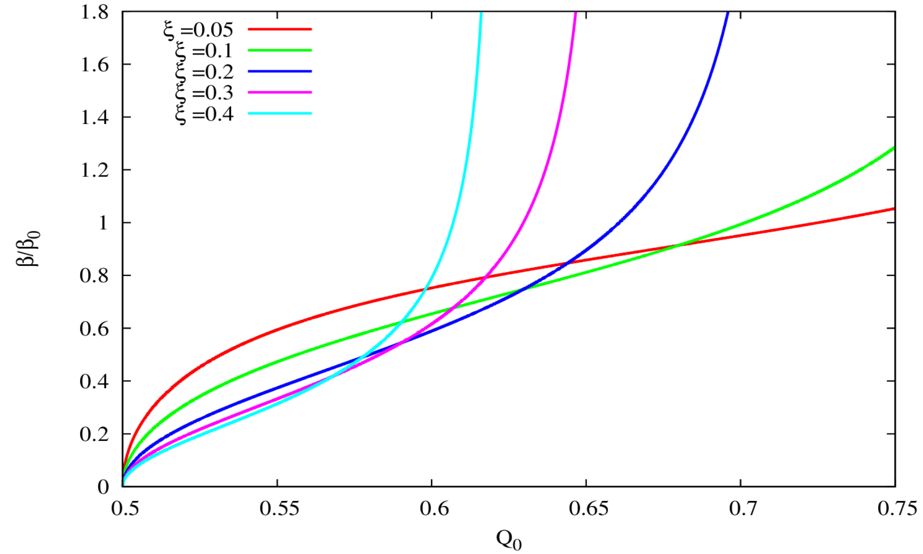
→ Photons energy distribution and average energy in good agreement

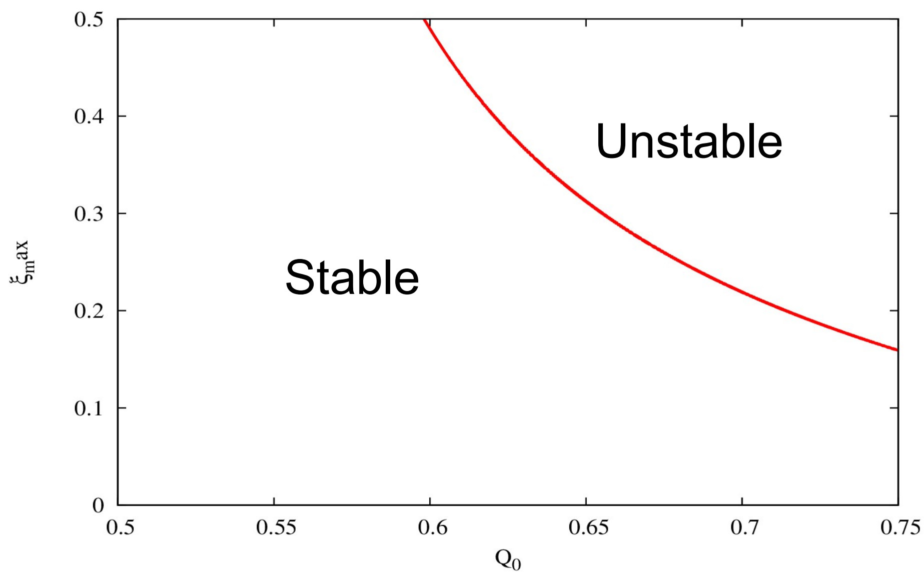
→ Some differences (~2%) at low energy – **agreement of 1% or better at higher energies**

Dynamic effects – single IP

- Depending on the working point strong beam-beam effects can distort the optics







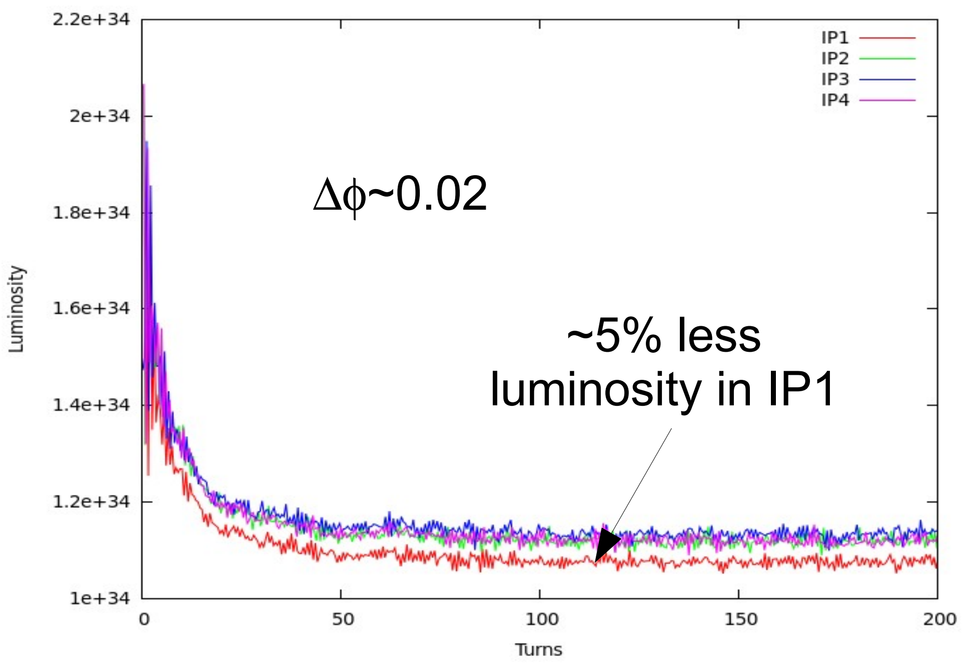
→ Linear dynamic effects: see Chao's Handbook, condition for stability (0→ 0.5):

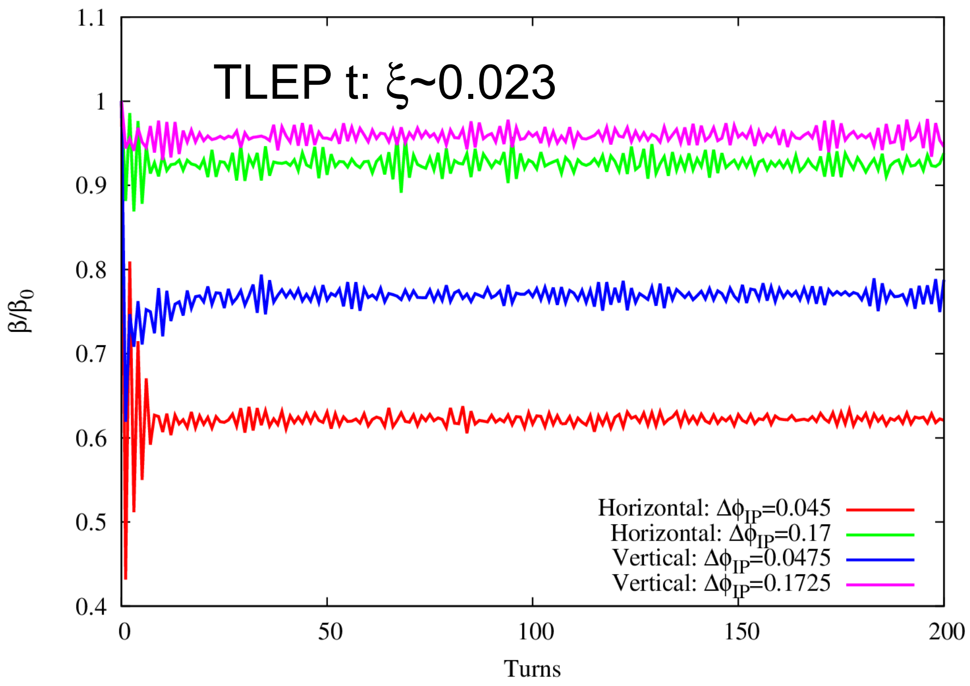
$$\xi_0 < \frac{1}{2\pi} \cot \frac{2\pi Q_0}{2}$$

→ Large beam-beam parameters requires to operate close to 0.5 or 1.0

→ **Very strong dynamic effects**

- Past studies have shown that breaking the collision symmetry can lead to excitation of additional resonances and different β-functions, i.e luminosities, at the different IPs
- For a symmetric case it is the phase advance between IPs that determines dynamic effects



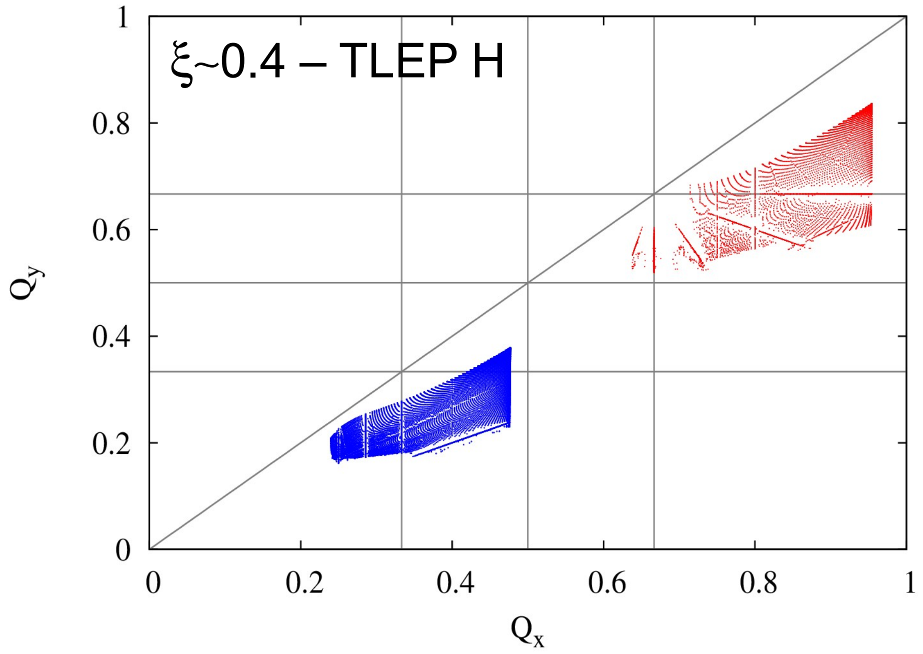


→ **Keeping collision symmetry is important: excellent optics control**
→ Dynamic effects can be violent: in case of problems can be mitigated by a **proper choice of the working point** – here β-functions after the collision in IP1

Choice of the working point

- Assumptions – **final values should be determined by detailed study**:
  → The footprint should not overlap half integer and integer resonances
  → Resonances of order 3 may be crossed (to be checked case by case)
  → Phase advance between IPs: 0.0 < Δϕ < 0.25: integer part multiple of 2
  → Dynamic effects should not be too strong: Δϕ not too small
  → Avoid the coupling resonance Qx – Qy = 0.0

- As a start take 4x LEP as integer part (for TLEPH) – two possibilities for fractional part:

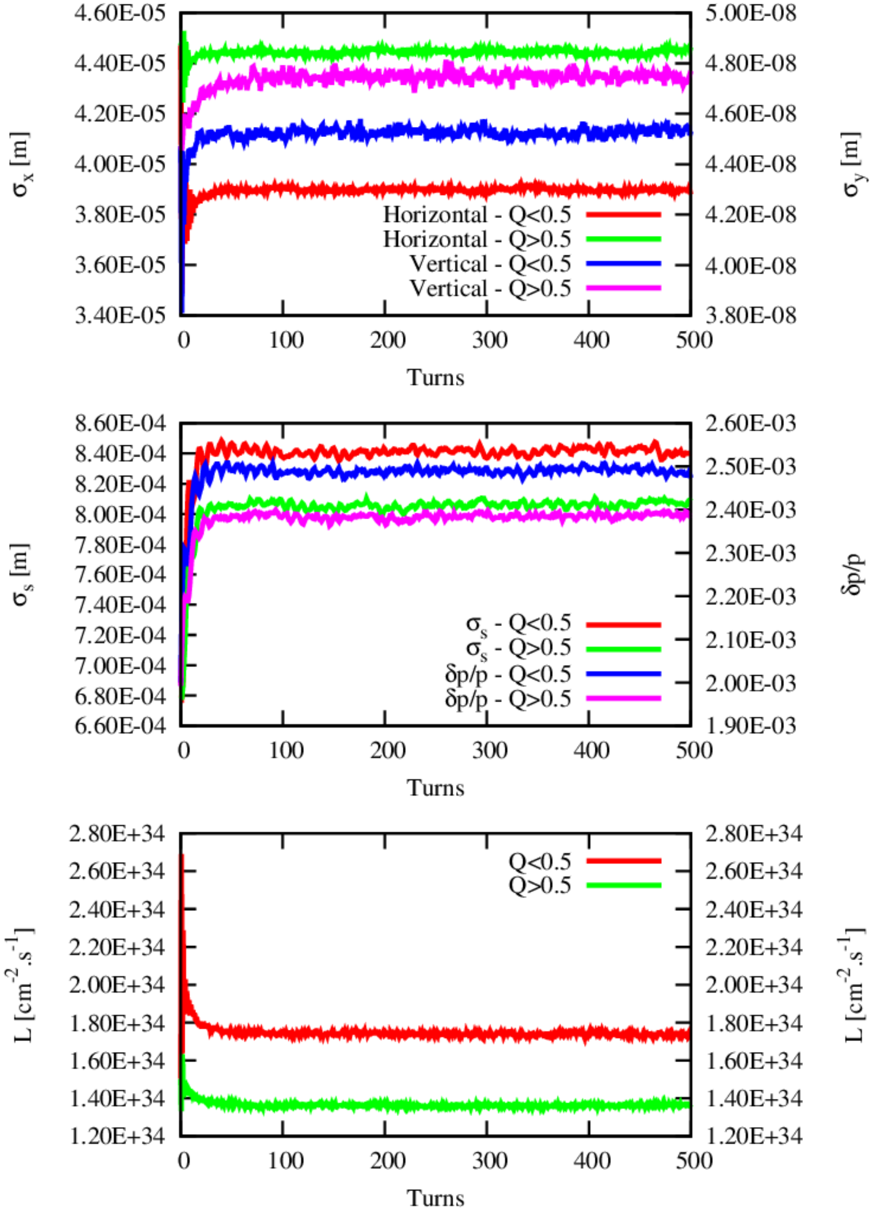


→ Below 0.5 smaller footprint but strong optics distortion

→ Above 0.5 larger footprint but very little optics distortion

TLEP t

	Design	Simulated Q>0.5	Simulated Q<0.5
E [GeV]	175	175	175
N [e/bunch]	0.88e11	0.88e11	0.88e11
$\varepsilon_{x/y}$ [nm]	2.0/0.002	2.1/0.0023	2.25/0.0025
$\beta_{x/y}$ [m]	1.0/1.0e-3	1.0/1.0e-3	1.0/1.0e-3
σ_s [mm] (BS)	0.77	0.8	0.84
$\sigma_{\delta p/p}$ [%] (BS)	0.23	0.24	0.25
$\tau_{\parallel}$ [turns]	23	23	23
$\xi_{x/y}$/IP	0.057/0.057	0.056/0.047	0.051/0.053
L/IP [$cm^2.s^{-1}$]	1.3e34	1.38e34	1.75e34



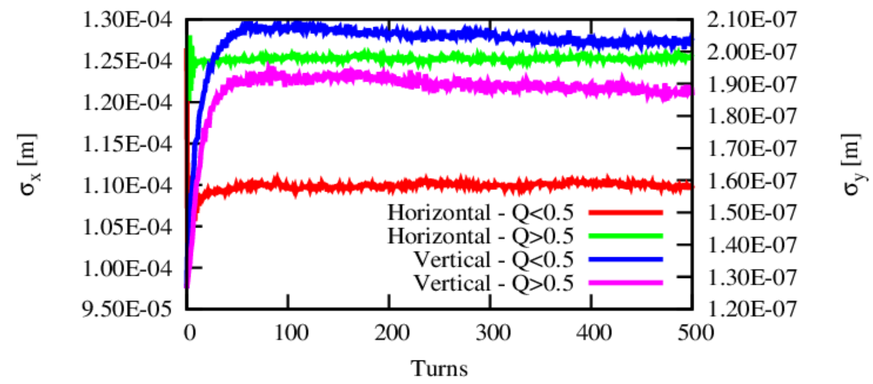
→ The simulated cases correspond to the footprints previously shown

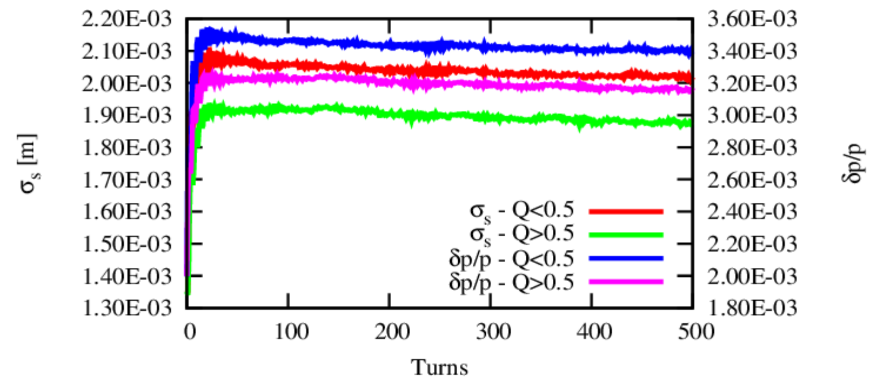
→ **Better than design luminosity achieved in both cases**

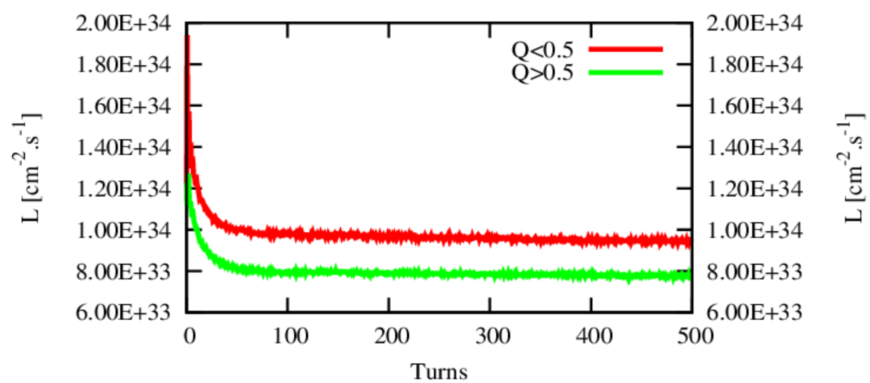
→ Dynamic effects boost the peak luminosity

TLEP t B

	Design	Simulated Q>0.5	Simulated Q<0.5
E [GeV]	175	175	175
N [e/bunch]	7.0e11	7.0e11	7.0e11
$\varepsilon_{x/y}$ [nm]	16.0/0.016	16.7/0.035	18.0/0.035
$\beta_{x/y}$ [m]	1.0/1.0e-3	0.96/1.03e-3	0.67/1.2e-3
σ_s [mm] (BS)	1.95	1.9	2.05
$\sigma_{\delta p/p}$ [%] (BS)	0.29	0.32	0.34
$\tau_{\parallel}$ [turns]	23	23	23
$\xi_{x/y}$/IP	0.057/0.057	0.055/0.04	0.051/0.050
L/IP [$cm^2.s^{-1}$]	1.04e34	0.8e34	1.0e34







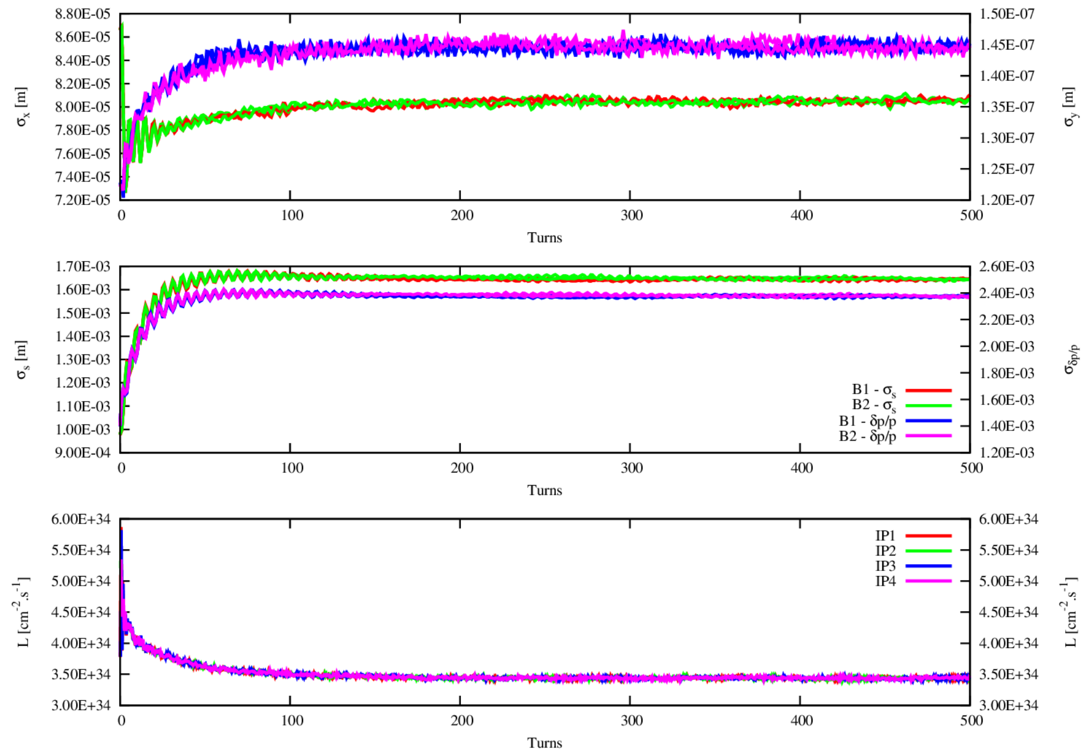
→ Same tunes as for TLEP t simulations

→ **Design luminosity barely reached for Q<0.5**

→ This scenario looks less promising than TLEP t: vertical blow-up much stronger

TLEP H

	Design	Simulated Q<0.5
E [GeV]	120	120
N [e/bunch]	3.7e11	3.0e11
$\varepsilon_{x/y}$ [nm]	7.5/0.015	8.8/0.019
$\beta_{x/y}$ [m]	0.5/1.0e-3	1.0/1.0e-3
σ_s [mm] (BS)	2.11	1.65
$\sigma_{\delta p/p}$ [%] (BS)	0.3	0.24
$\tau_{\parallel}$ [turns]	72	72
$\xi_{x/y}$/IP	0.094/0.094	0.065/0.054
L/IP [cm^2.s^{-1}]	5.08e34	3.5e34



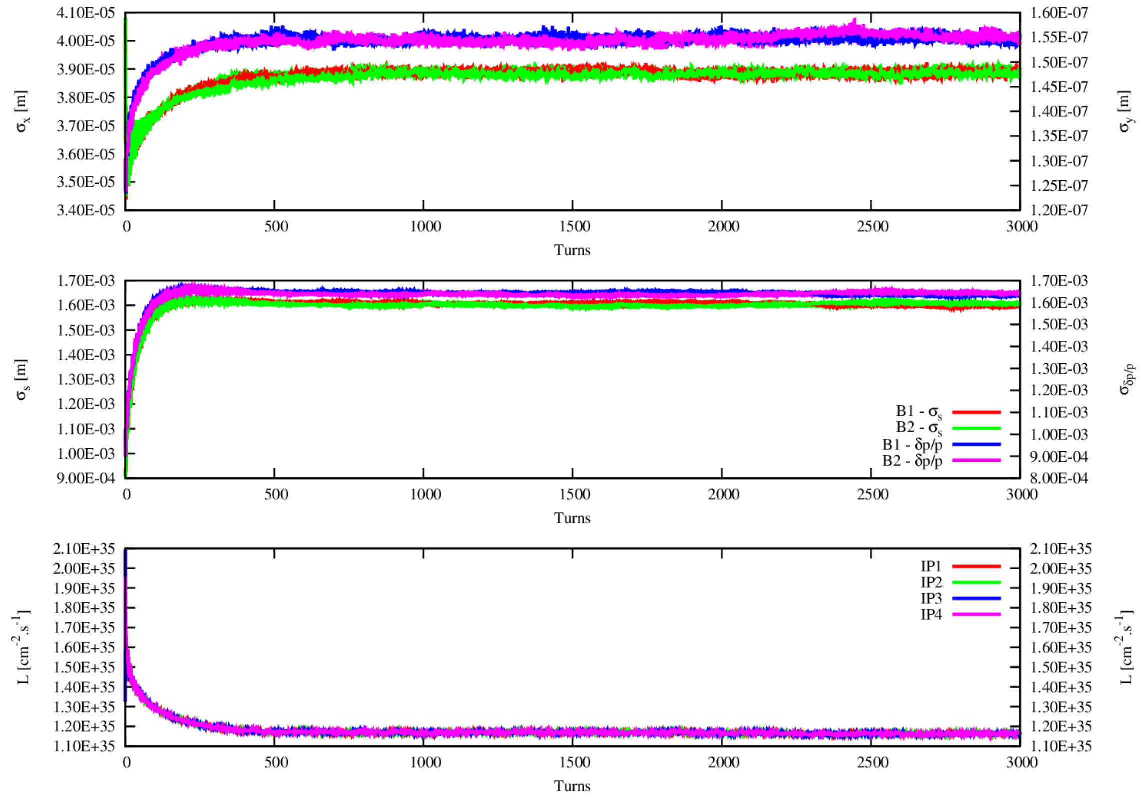
→ **TLEPH much more difficult**: try to achieve twice the beam-beam parameter with 3 times damping time: emittance blow-up of a factor 5 in few turns with nominal parameters

→ Reduced beam-beam parameter: relaxed β_x and bunch intensity, keep current constant

→ Making use of dynamic effects **~70% of design achieved**: could be pushed further but then lifetime becomes an issue

TLEP W

	Design	Simulated Q<0.5
E [GeV]	80	80
N [e/bunch]	1.0e11	1.0e11
$\varepsilon_{x/y}$ [nm]	3.3/0.017	4.1/0.022
$\beta_{x/y}$ [m]	0.2/1.0e-3	0.5/1.0e-3
σ_s [mm] (BS)	1.98	1.6
$\sigma_{\delta p/p}$ [%] (BS)	0.2	0.165
$\tau_{\parallel}$ [turns]	242	242
$\xi_{x/y}$/IP	0.086/0.086	0.068/0.051
L/IP [$cm^2.s^{-1}$]	1.64e35	1.15e35



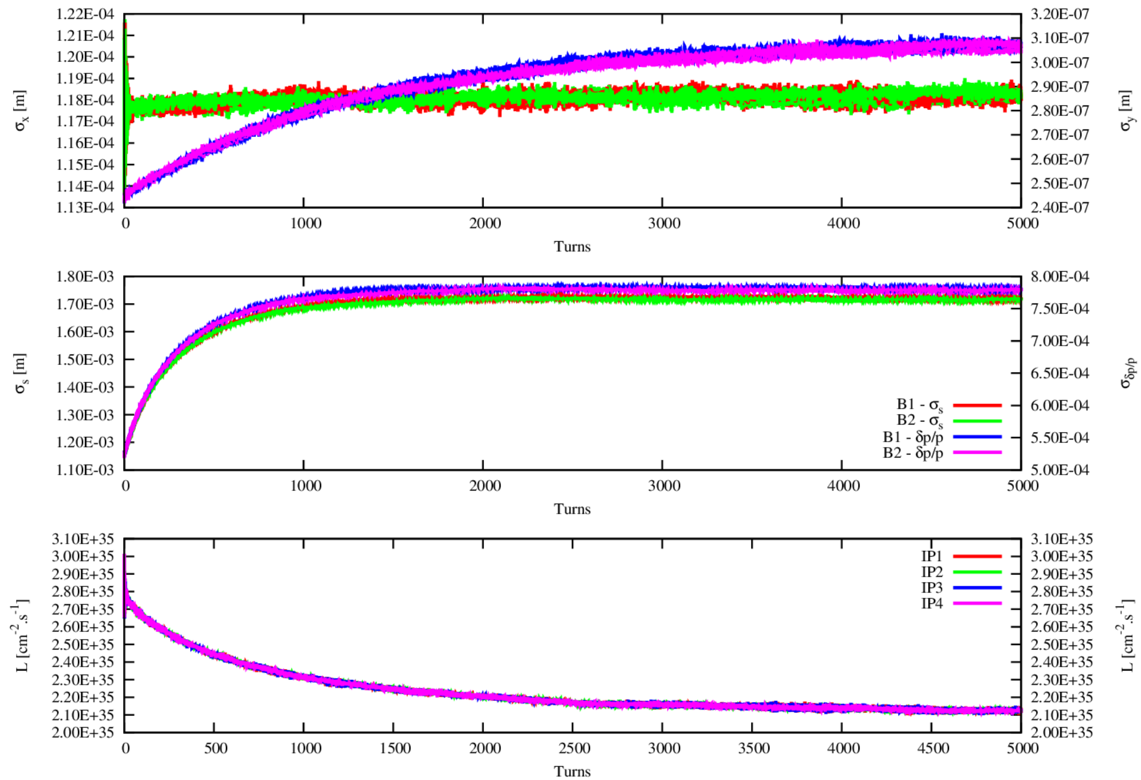
→ Again with design parameters strong emittance blow-up: reduced beam-beam parameter, relaxed β_x

→ Making use of dynamic effects **~70% of design achieved**

→ Q>0.5: luminosity well below design

TLEP Z

	Design	Simulated Q>0.5
E [GeV]	45	45
N [e/bunch]	4.0e11	1.5e11
$\varepsilon_{x/y}$ [nm]	29.2/0.06	29.7/0.09
$\beta_{x/y}$ [m]	0.5/1.0e-3	0.5/1.0e-3
σ_s [mm] (BS)	2.93	1.7
$\sigma_{\delta p/p}$ [%] (BS)	0.13	0.075
$\tau_{\|\|}$ [turns]	1319	1319
$\xi_{x/y}$/IP	0.068/0.068	0.029/0.024
L/IP [$cm^2.s^{-1}$]	5.86e35	2.1e35



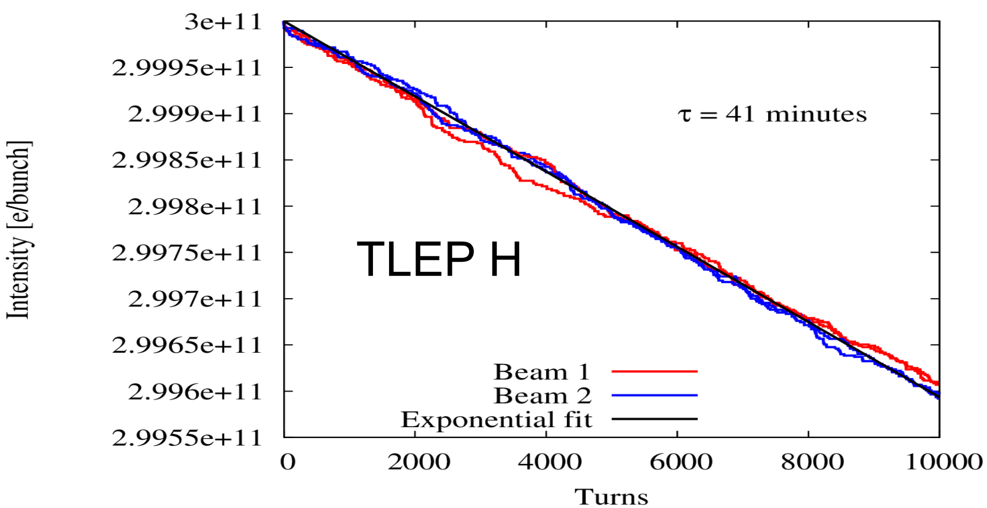
→ LEP at 45.6 GeV achieved $\xi_{x/y}$ ~ 0.03/0.044 per IP with a damping time of ~360 turns

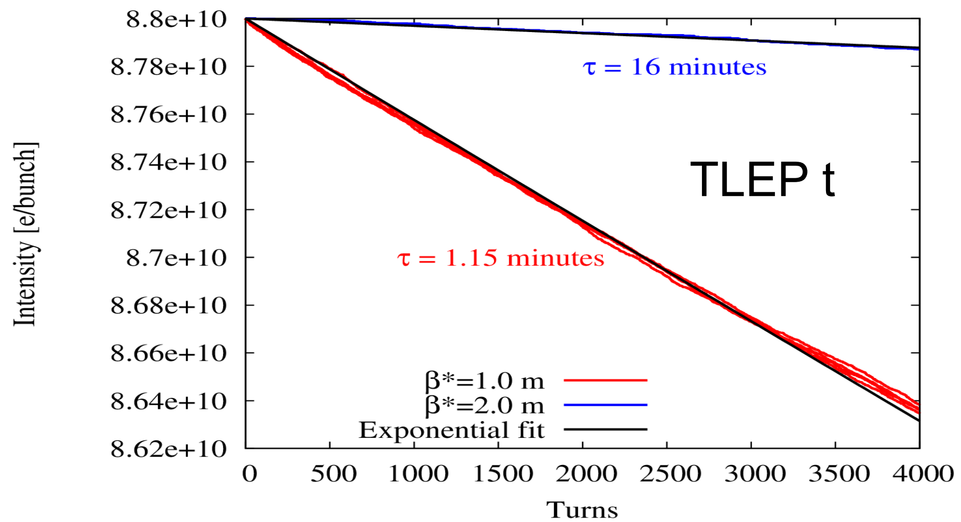
→ Can TLEP do better with ~4x longer damping time?

→ Had to significantly reduce the beam-beam parameter to achieve reasonable emittance blow-up

→ In this case **~36% of design reached but requires 20000 bunches (probably not realistic – electron cloud?)**

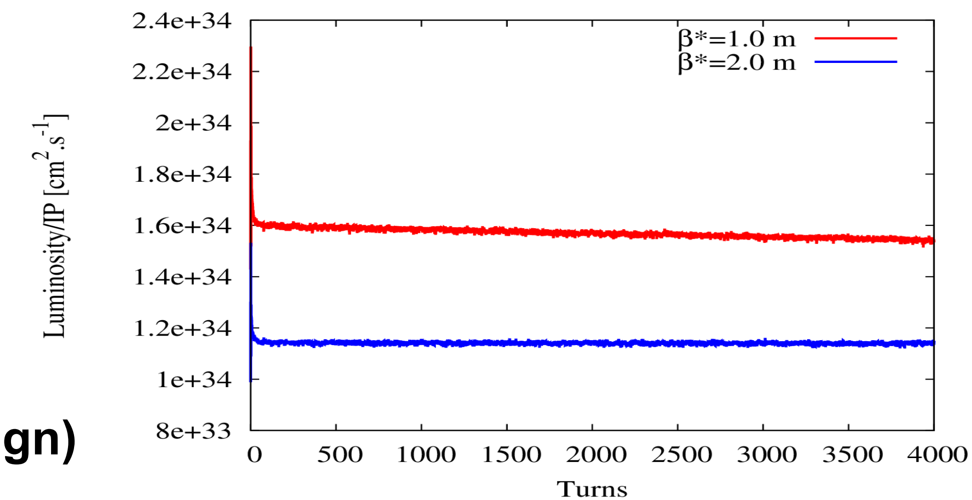
- Cases with strong beamstrahlung: TLEP t and TLEP H. Does not include burn off. Collimation performed at each IP with 14σ transverse and η=0.02





→ **TLEP H:** bunch intensity and β_x were already relaxed to reduce emittance blow-up. **simulated lifetime 41 minutes**

→ **TLEP t:** with nominal parameters lifetime barely above 1 minute. Relaxing β_x to 2.0m allows to increase it to **15 minutes with a luminosity reduce to 1.17e34 (~90% of design)**

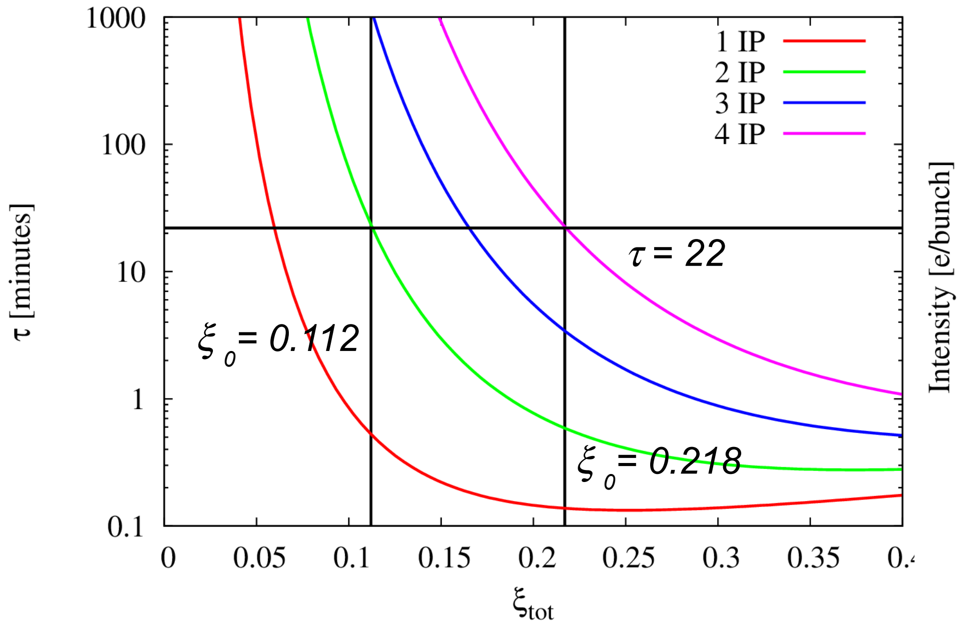


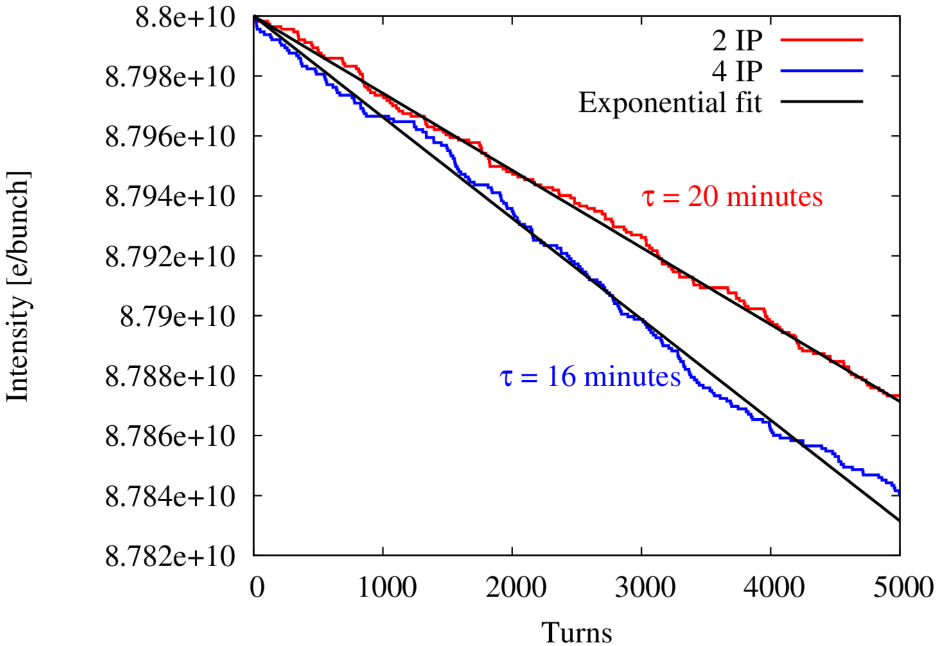
Performance with 2IPs

- Can we scale the beam-beam parameter, i.e luminosity per IP, with the number of IPs? Analytical lifetime estimate by Telnov:

$$\tau = \frac{20}{n_{IP}} \frac{\sqrt{6\pi} r_e \gamma}{\alpha^2 \eta \sigma_s} \frac{2\pi R}{c} u^{3/2} e^u \qquad \text{with} \qquad u = \eta \frac{\alpha \sigma_x \sigma_s}{3 \gamma r_e^2 N_p}$$

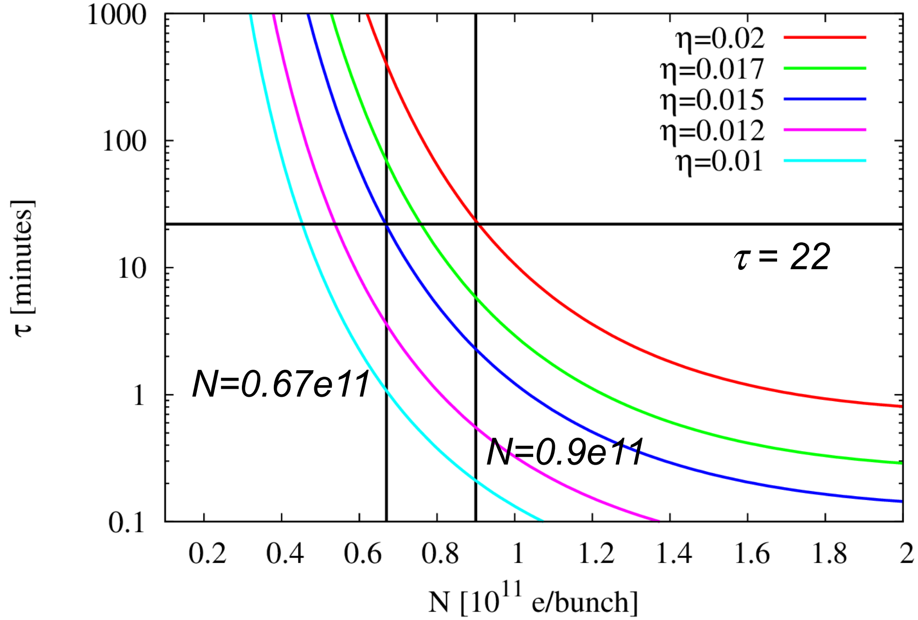
→ Much stronger dependency on the bunch intensity than number of IPs. The equilibrium bunch length and β also vary with ξ. Example of TLEP t ($\Delta\sigma_s$ included assume no dynamic β):

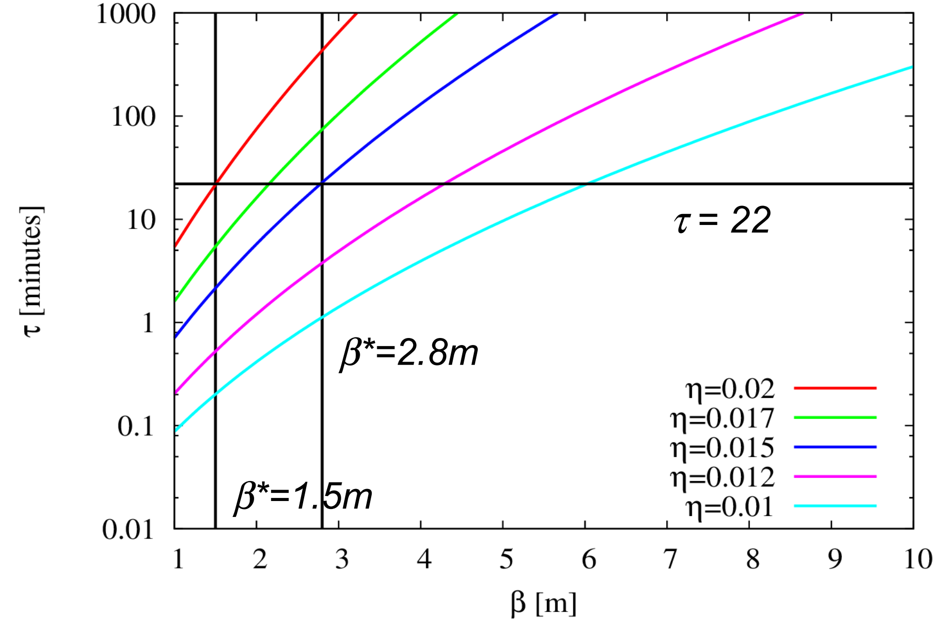




→ Reducing the number of IPs will degrade the total luminosity performance

Reduced energy acceptance

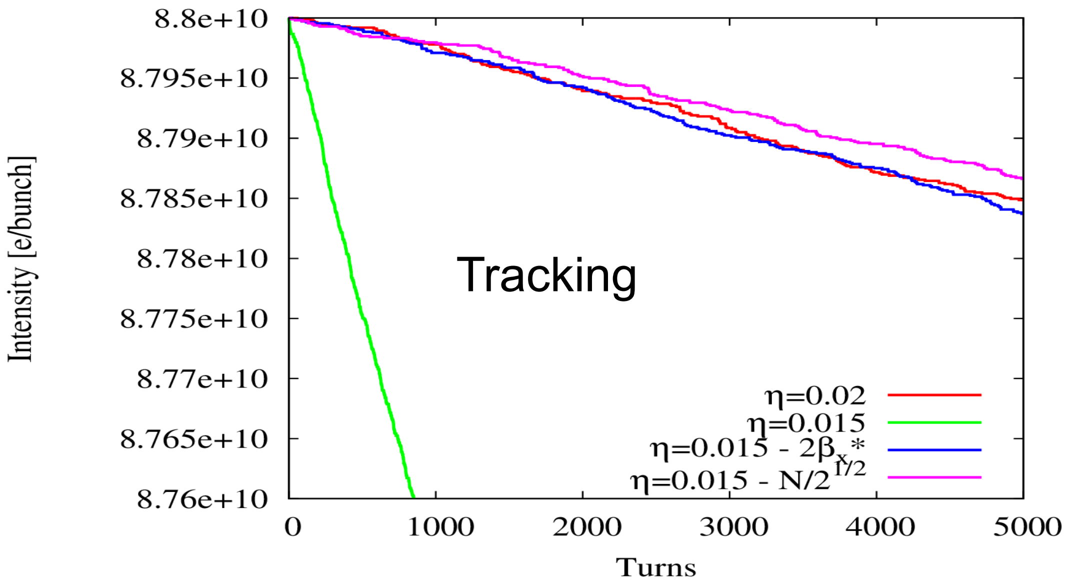




→ Reducing the energy acceptance will significantly degrade the beam lifetime

→ **Lifetime can be recovered by either increasing β_x or decreasing the bunch intensity**

→ For luminosity performance increasing **β_x is clearly better**



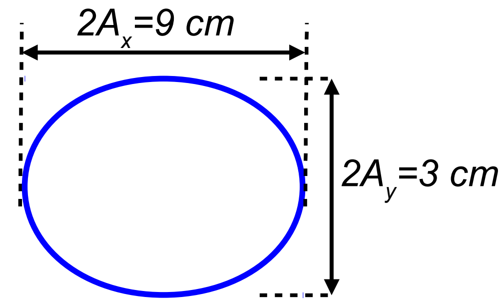
Summary

	TELP Z	TLEP W	TLEP H	TLEP t
E [GeV]	45	80	120	175
N [e/bunch]	1.5e11	1.0e11	3.0e11	0.88e11
# bunches	20000	3200	206	160
$\varepsilon_{x/y}$ [nm]	29.7/0.09	4.1/0.022	8.8/0.019	2.17/0.00217
$\beta_{x/y}$ [m] init.	0.5/1.0e-3	0.5/1.0e-3	1.0/1.0e-3	2.0/1.0e-3
$\beta_{x/y}$ [m] dist.	0.47/1.0e-3	0.36/1.1e-3	0.75/1.1e-3	1.6/0.85e-3
$\xi_{x/y}$/IP dist.	0.029/0.024	0.068/0.051	0.065/0.054	0.055/0.036
L/IP [$cm^2.s^{-1}$]	2.1e35	1.15e35	3.5e34	1.17e34
L/IP [% design]	36	70	69	89
τ_{BS} [min], η=0.02	-	-	~41	~15

→ **Good performance achieved in all cases except TLEP Z** (only 36% of design)
→ **Dynamic effects are essential** to reach these performance: choice of working point
→ **TLEP H and TLEP t are limited by lifetime not beam-beam**
→ Reducing the number of IPs would result in significant loss in total luminosity
→ **Reducing the energy acceptance is possible if β_x is increased**: lower luminosity
→ In case of strong hourglass (TLEP Z) we could try traveling focus to recover some luminosity

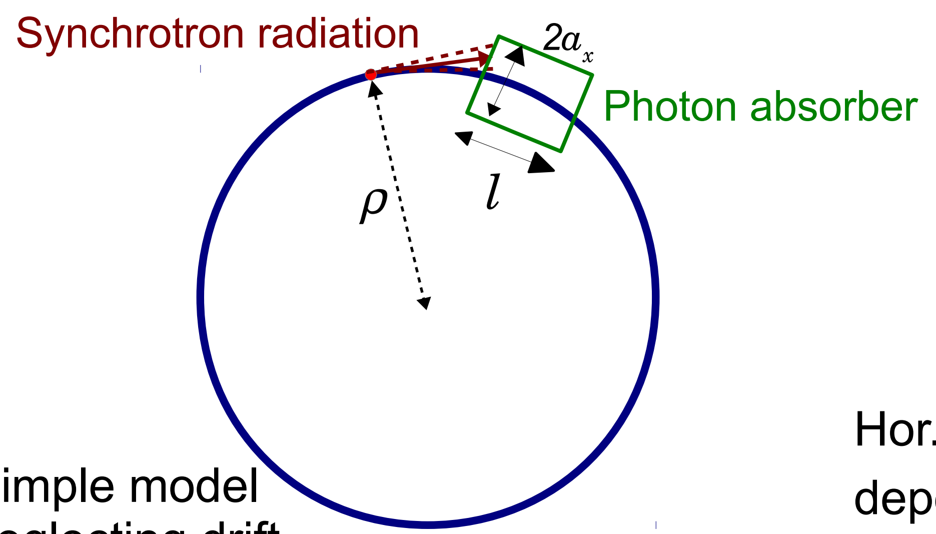
Impedance model: resistive wall

- Resistive-wall impedances considered:
  - Aluminum (σ = 3.7 10^7 S/m) main vacuum pipe



Elliptic shape

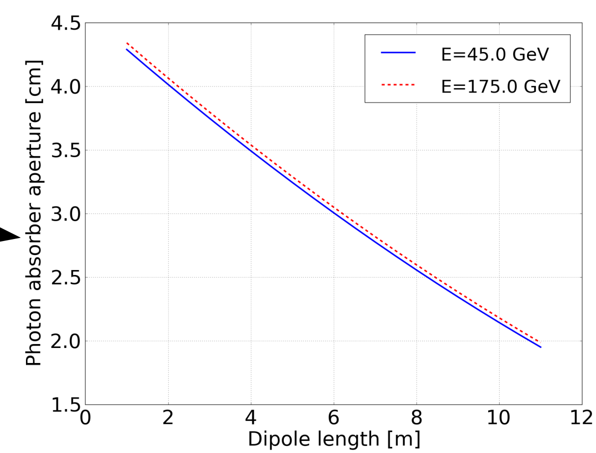
  - Tungsten (σ = 1.85 10^7 S/m) photon absorbers, intercepting synchrotron radiation from dipoles (elliptic with reduced aperture in horizontal). Transitions between vacuum pipe and photon absorbers cross-sections: imp. approximated using K. Yokoya's formula for round tapers [CERN SL/90-88]:



Simple model neglecting drift and straight sections

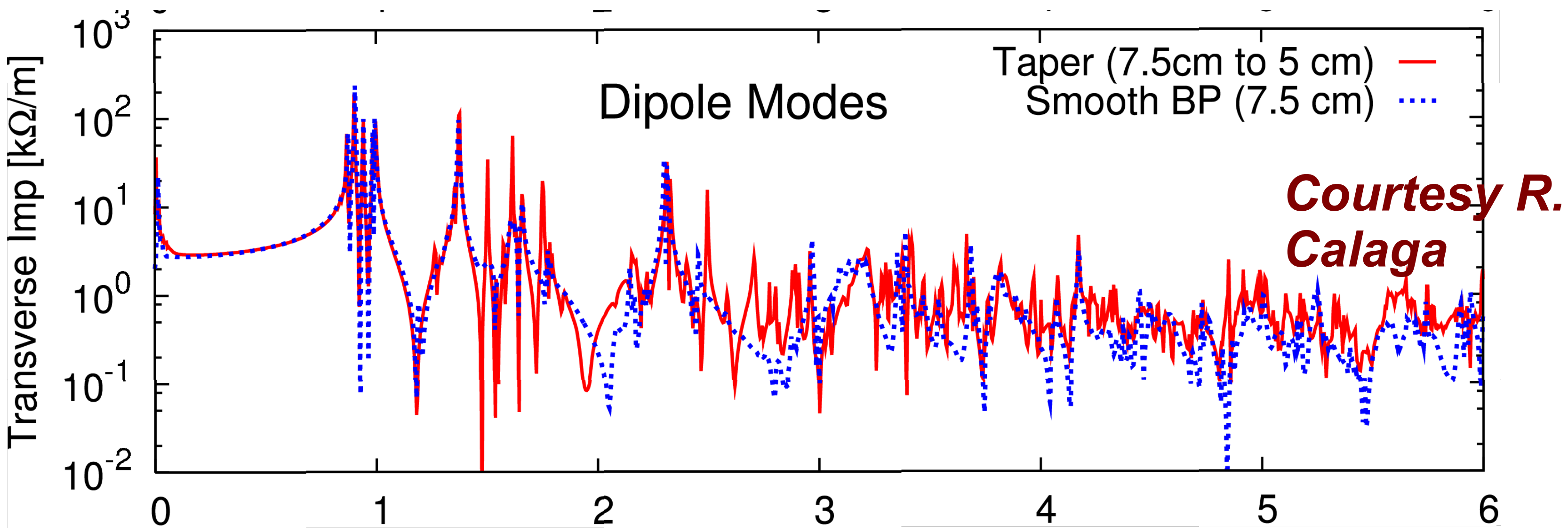
$$a_x = \rho \left(\frac{\cos\left(\frac{1}{\gamma}\right)}{\cos\left[\arccos\left(\frac{\rho\cos\left(\frac{1}{\gamma}\right)}{\rho + A_x}\right) + \frac{l - l_d}{\rho} - \frac{2}{\gamma}\right]} - 1 \right).$$

Hor. aperture a_x depends on dipole length l_d



Impedance model: RF cavities

- Broad-band resonator estimates (*Q=1*, f_r*=6* GHz):
  - RF cavities: from R. Calaga's PhD (BNL-SERL cavity, 700 MHz)



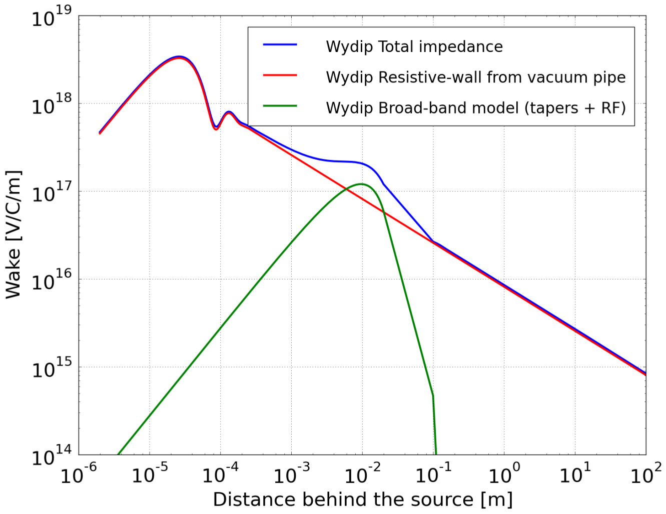
→ ”fit” low-frequency part by constant inductive impedance of 3 kΩ/m, multiplied by 600 (number of cavities).

- **All impedances weighted by approximative average beta function ~*2R/Q:***
  → Assume 4xLEP for TLEPH (312,392)
  → The tunes range from (104,130) for TLEPZ to (624,784) for TLEPt due to the different FODO cells length: **strong impact on the effect of impedance**

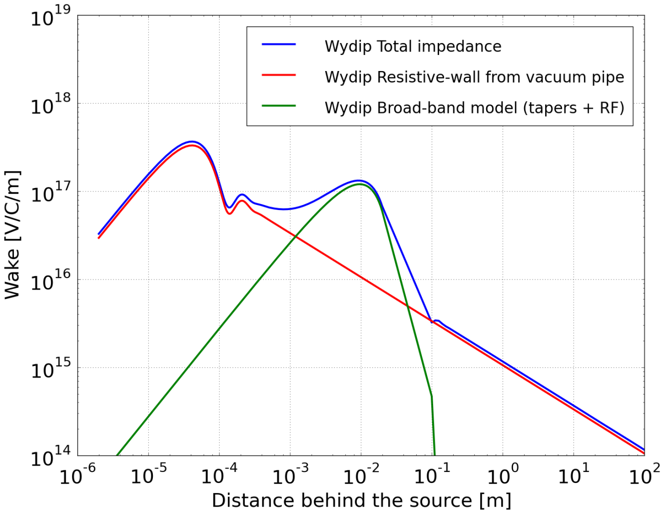
Dipolar wake function

- Transverse dipolar wake function in vertical: relative contributions for different vertical apertures of the vacuum pipe and different dipole lengths

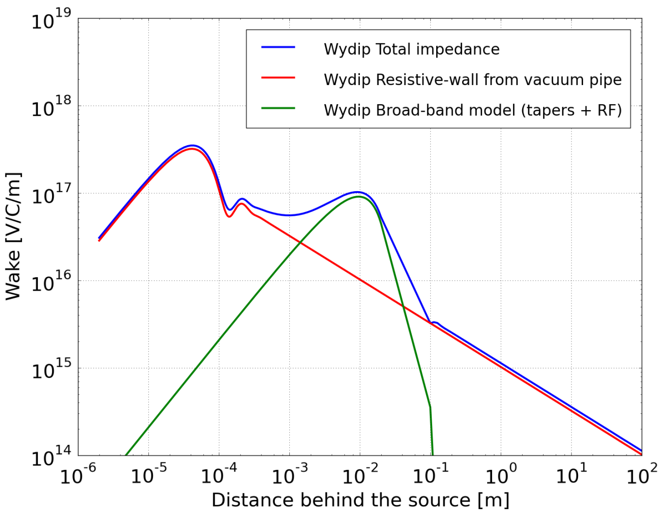
A_y=1.5 cm, l_d=11 m



A_y=3 cm, l_d=11 m



A_y=3 cm, l_d=5.5 m



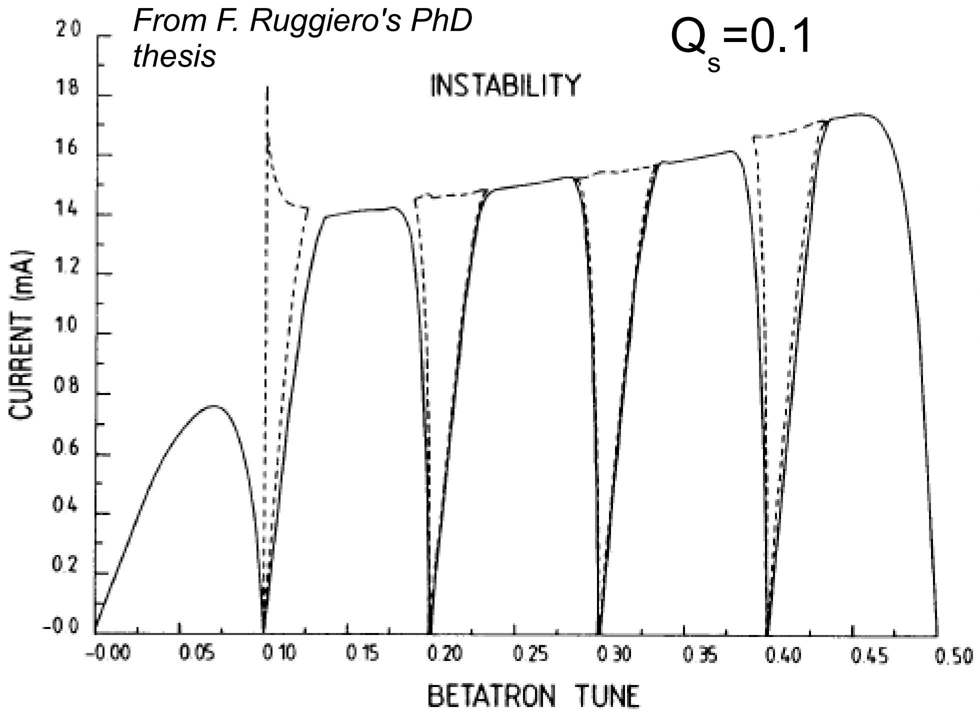
→ Increase of vertical aperture has a clear beneficial effect

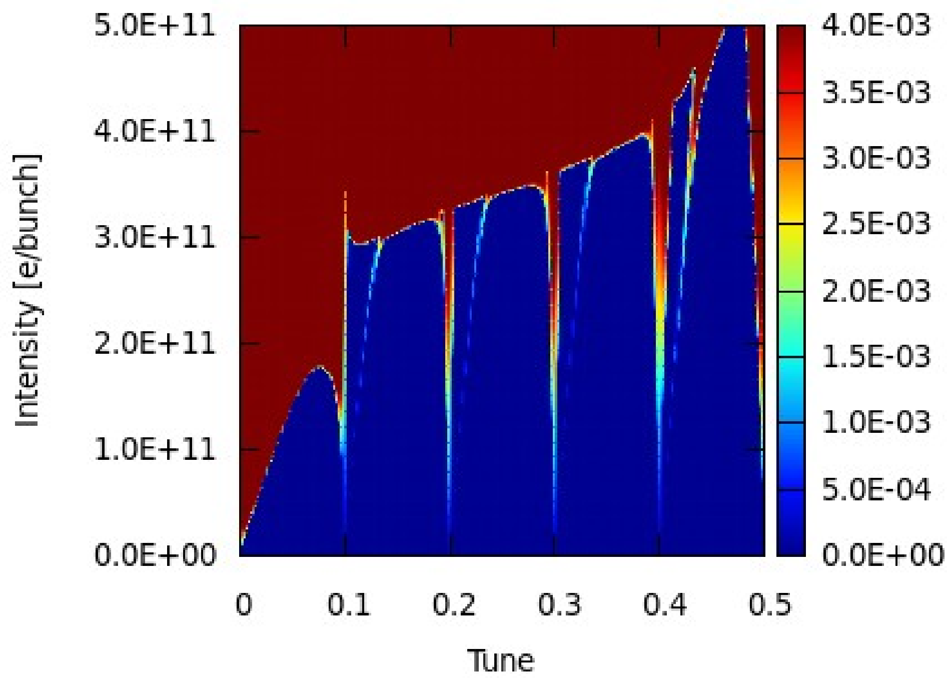
→ Length of dipoles has a smaller impact

→ TMCI will be estimated for these three cases

Synchro-betatron effects

- It was shown by F. Ruggiero that in case of large synchrotron tune one has to consider synchro-betatron resonances ($Q_\beta = Q_s$) and eventual coupling between modes 0 or -1 and reflexions of the synchrotron sidebands:

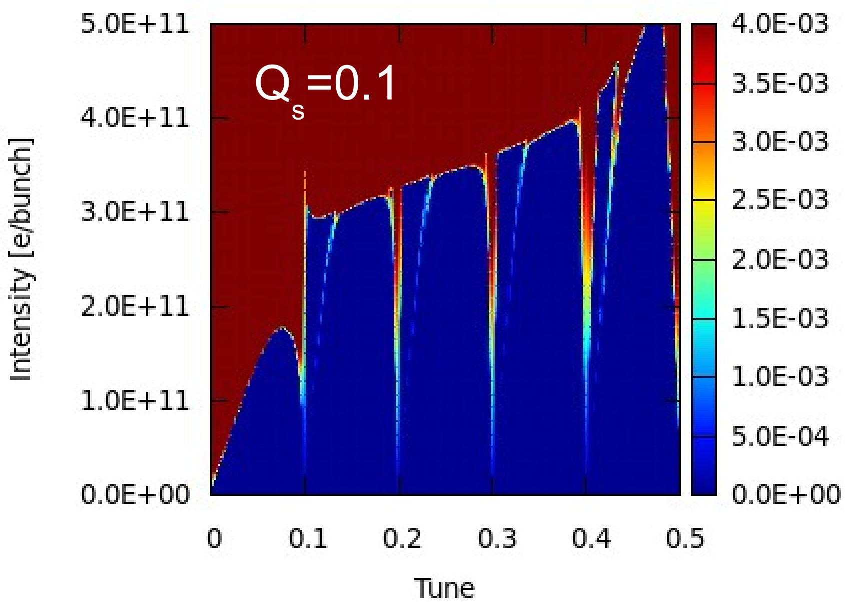


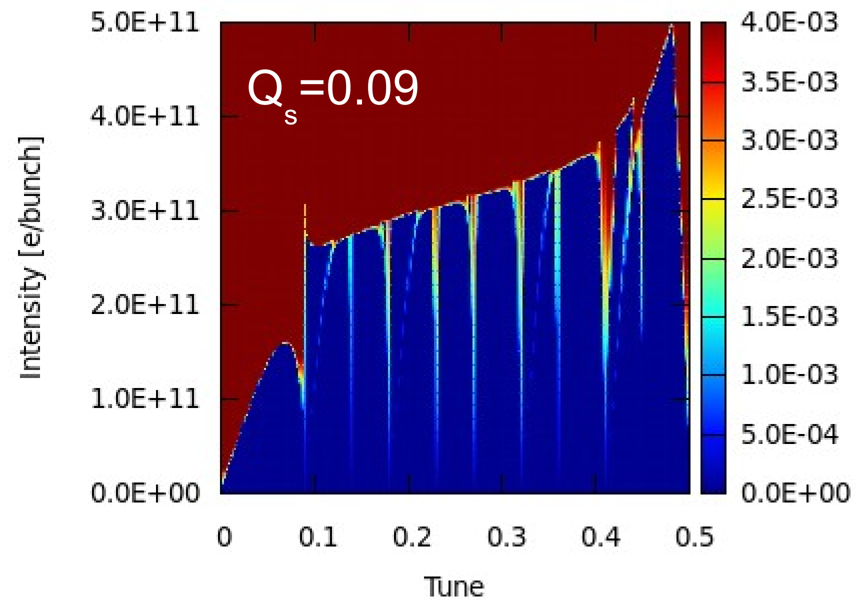


→ **Good qualitative agreement**, difference may be explained by impedance model
→ Consider enough sidebands to cover a full integer

Synchrotron tune

- When $0.5/Q_s$=integer all the reflexions line up and we get the clean picture shown in the previous slide. Example for Q_s~0.1:



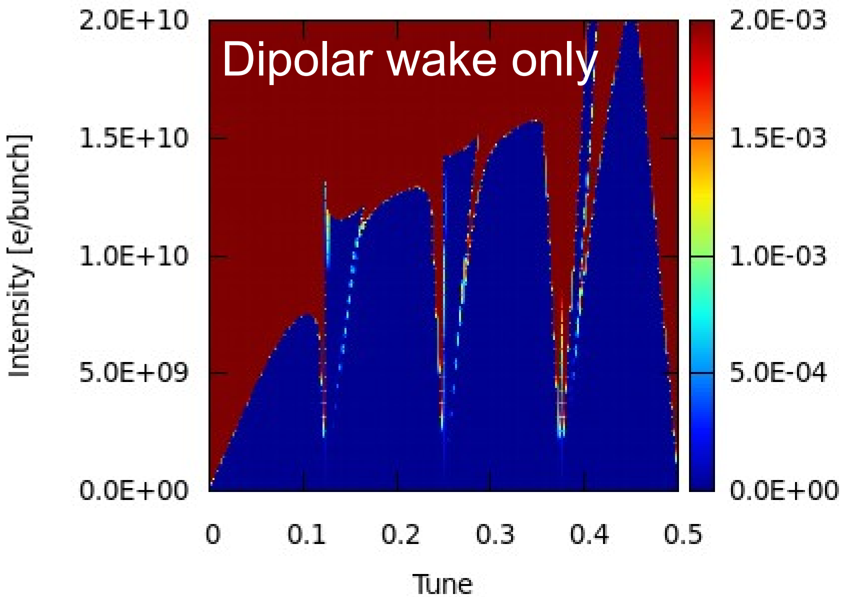


→ The TMCI threshold approximately scales with the synchrotron tune

→ When $0.5/Q_s$ is not an integer more synchro-betatron resonances are observed

→ It is not clear up to which order these resonances are harmful: would require dedicated study, for now stick with design values

Quadrupolar wake



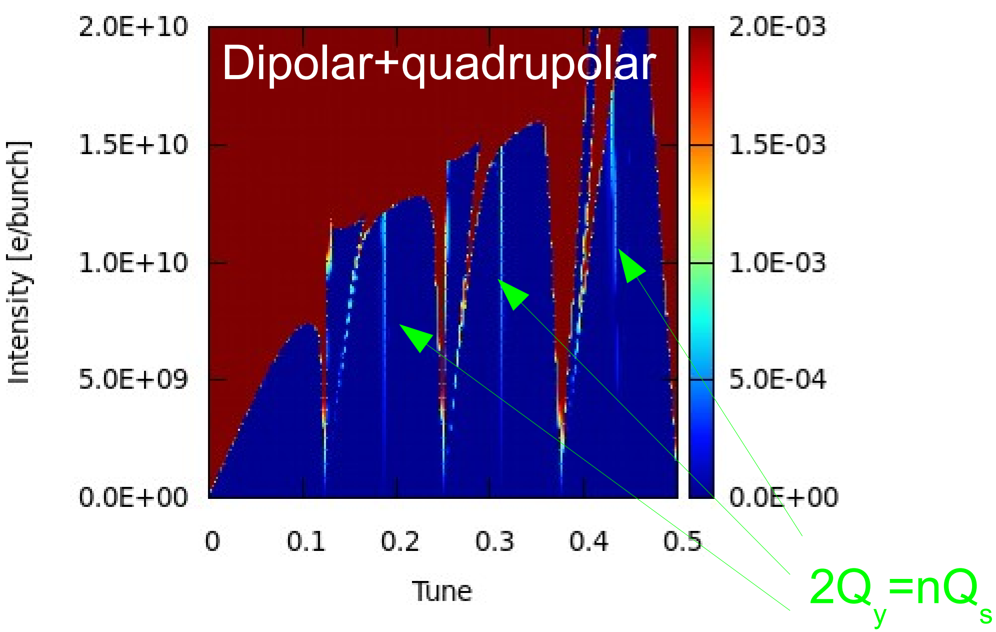
→ Use an exemple with Q_s=0.125

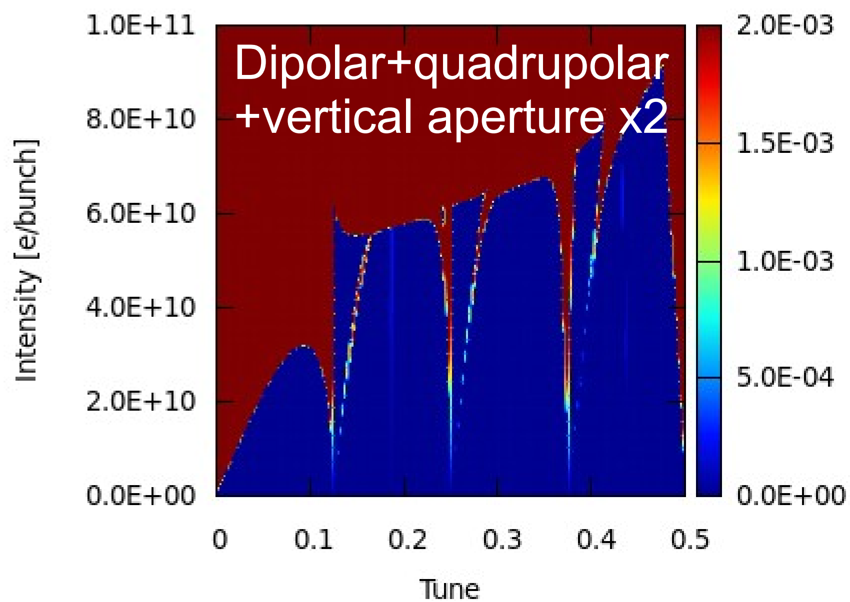
→ Dipolar wake only: resonance of type $Q_y=nQ_s$ observed

→ Dipolar and quadrupolar wake: additional resonances of type $2Q_y=nQ_s$

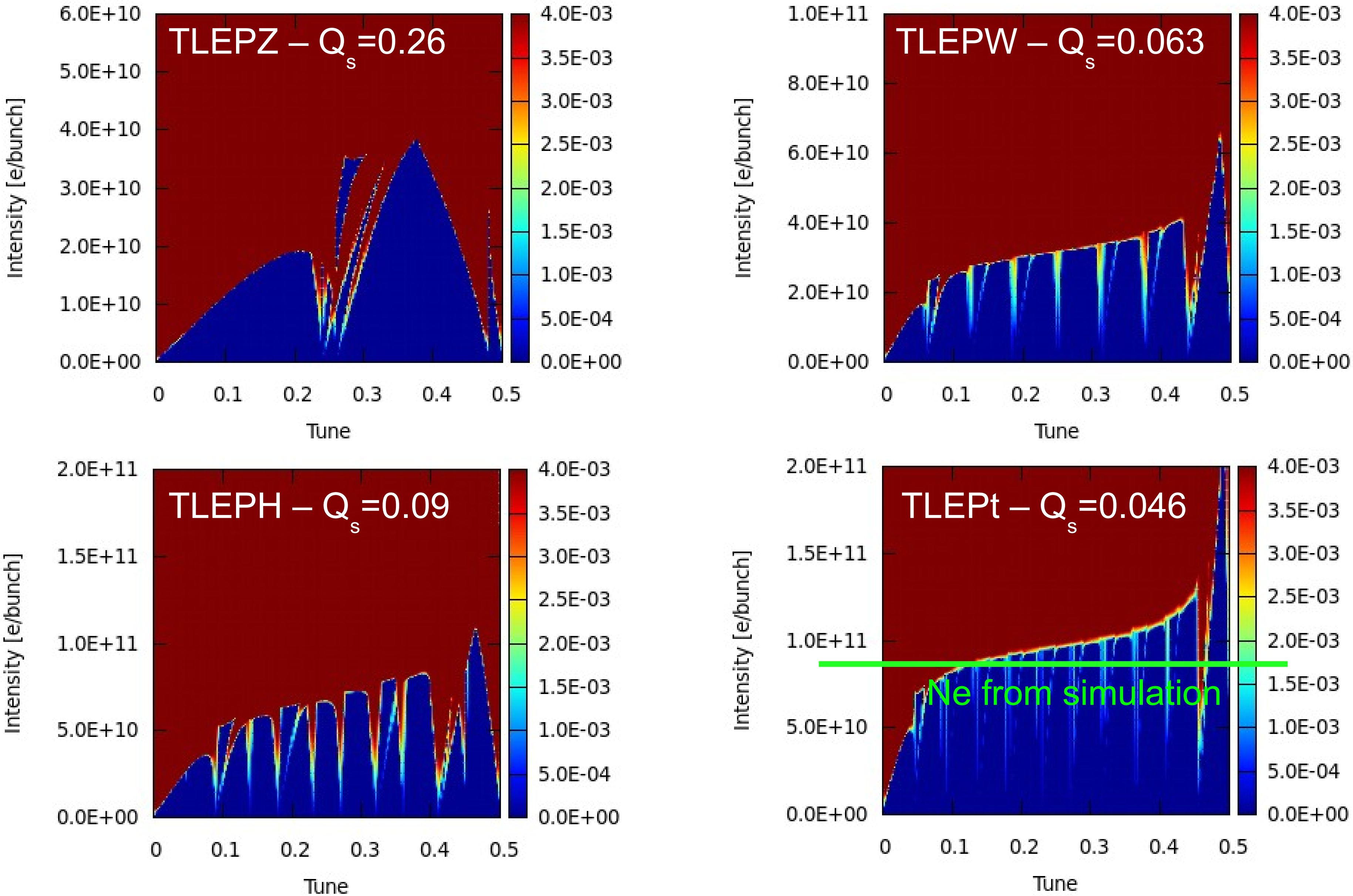
→ Increasing the vertical beam pipe by a factor 2 strongly mitigates the quadrupolar resonances

→ **No apparent effect from quadrupolar wake on TMCI threshold**

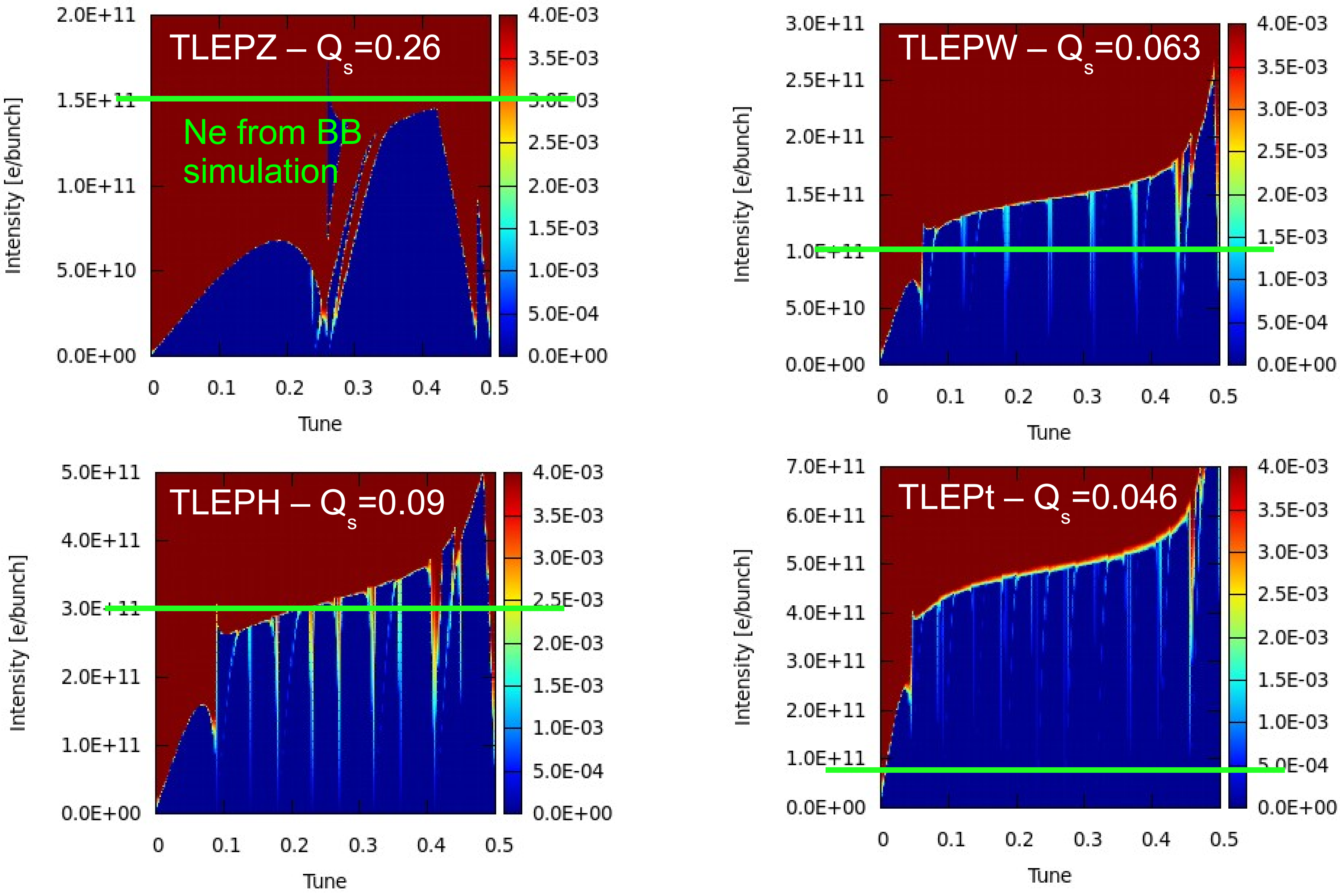




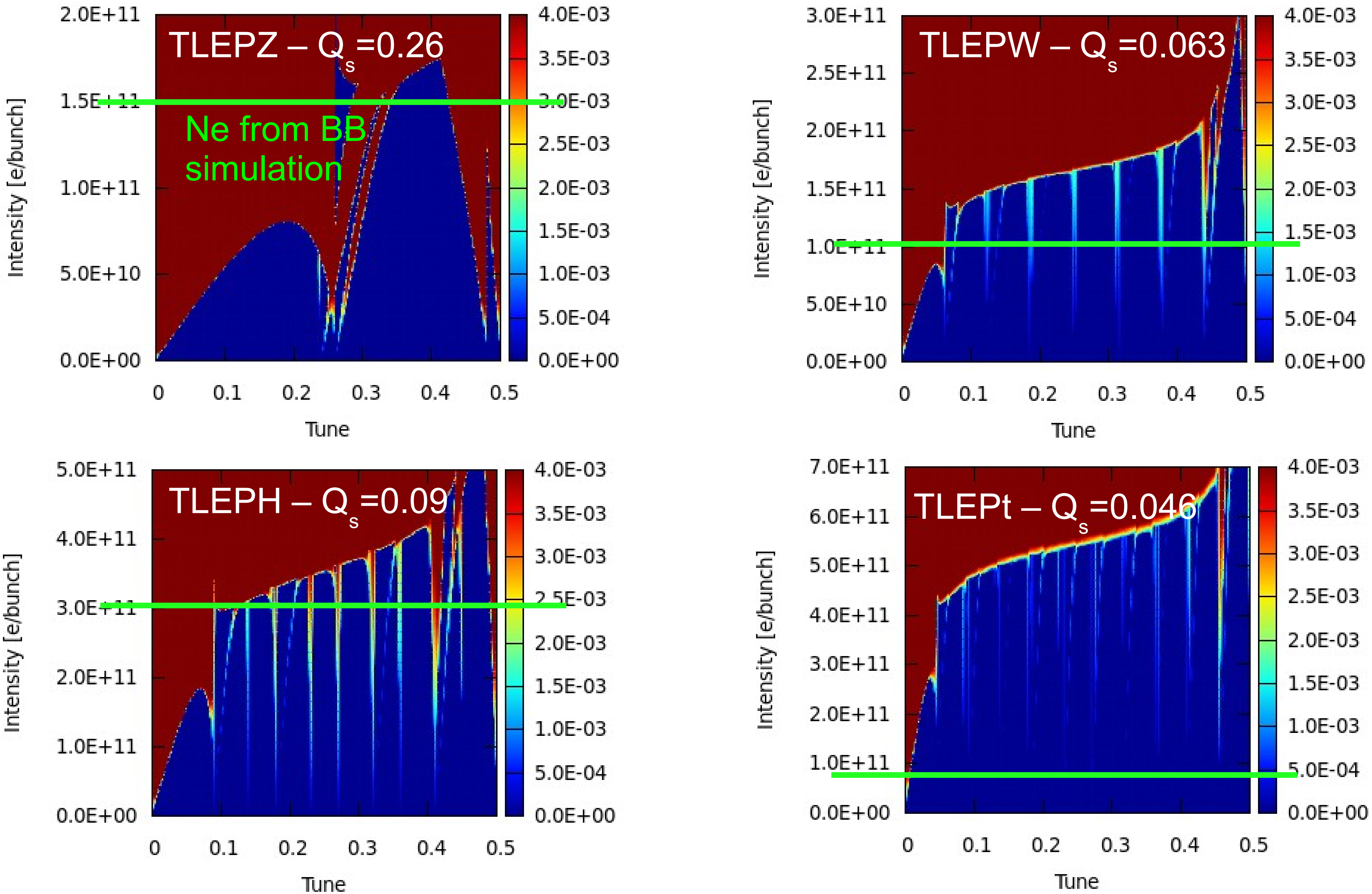
1.5cm half vertical aperture – 11m dipoles



3.0cm half vertical aperture – 11m dipoles



3.0cm half vertical aperture – 5.5m dipoles



Summary

- The impedance model was extended to include photo-absorber: impedance however dominated by the resistive wall from the beam pipe. **The results presented here are preliminary, more detailed studies (tracking) are required for validation.**

- Preliminary observations:
  - **Synchro-betatron resonances are important** and should be avoided: additional constraint on the choice of the working point
  - With a half vertical aperture of **1.5cm only TLEPt is below threshold**
  - Increasing the half vertical aperture to 3.0cm significantly improves the situation, reducing the dipole length and retracting the photo-absorbers further increases the threshold
  - With all this taken into account only **TELPZ remains as an issue** (already an issue for beam-beam, what about electron cloud? → review parameters?)
  - In the previous calculations the bunch lengthening from beamstrahlung was not taken into account: this will slightly increase the thresholds

- Next steps:
  - Validation of the results with tracking
  - Possible benefits of beam-beam tune spread, chromaticity, transverse damper, radiation damping
  - Multi-bunch resistive wall instability