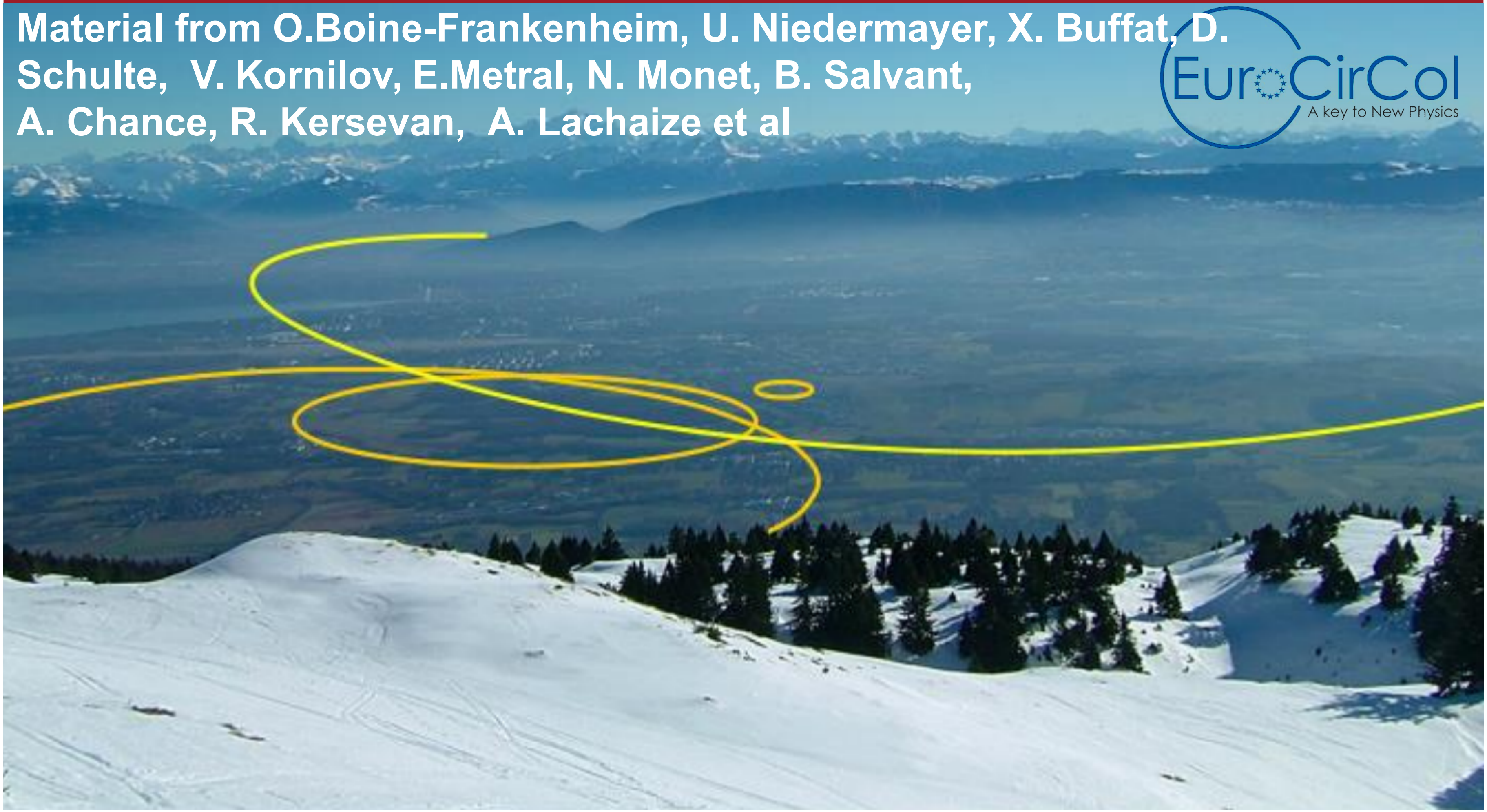
FCC-hh Impedances and Single-Beam Instabilities

F. Petrov (Task 2.4)

Material from O.Boine-Frankenheim, U. Niedermayer, X. Buffat, D. Schulte, V. Kornilov, E.Metral, N. Monet, B. Salvant, A. Chance, R. Kersevan, A. Lachaize et al



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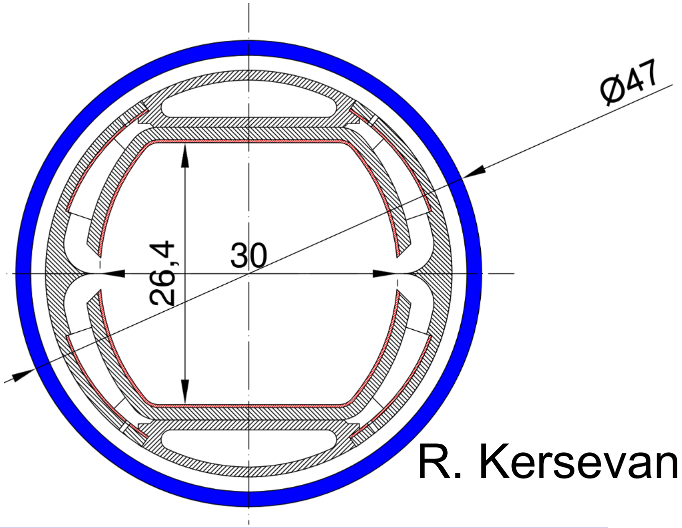
- Impedances
- Thresholds and growth rates
- Multi-bunch tracking
- Broad-band Impedance Sources. 3D simulations.
- Conclusions and outook

FCC reference parameters (used in this study)

Circumference [km]	100
Bunch spacing [ns]	25
Bunch length [cm]	8-12
Number of bunches	≈ 10000
Q_x / Q_y	108.28 / 107.31
Injection energies [TeV]	0.45; 1.5; 2.0; **3.3**; 5.0
Q_s	10^{-3}-$5\cdot10^{-3}$
Normalized emittance	2.2 µm

http://tlep.web.cern.ch/content/fcc-hh

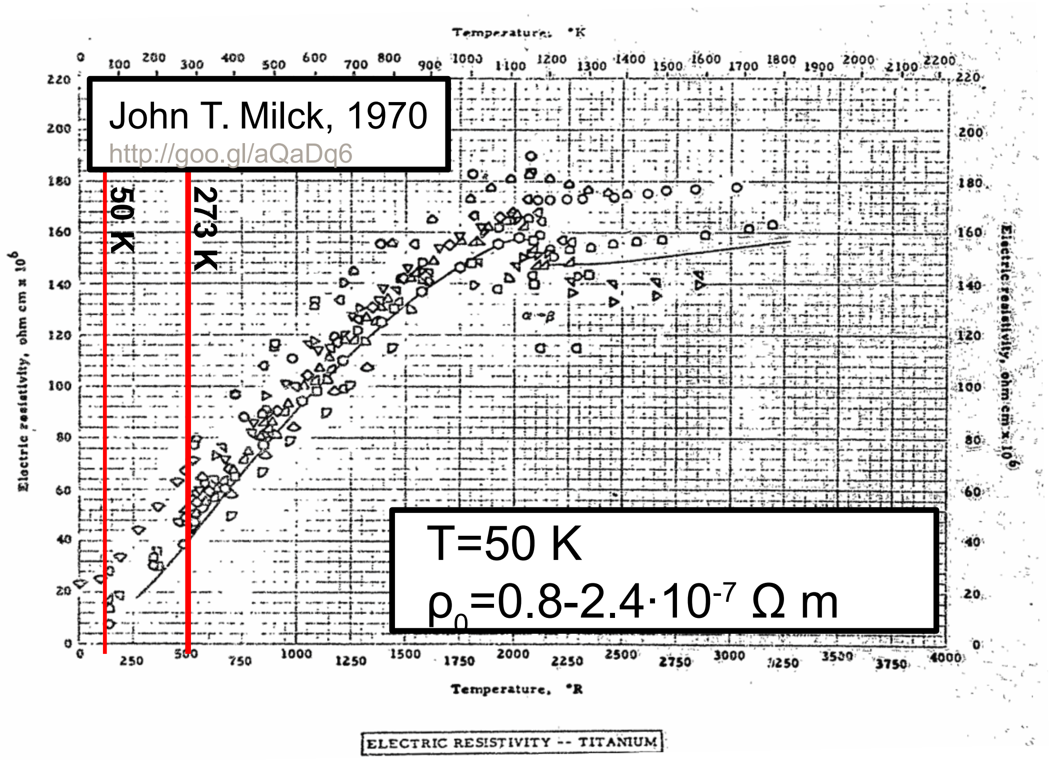
Beam pipe	
Material	Cu, Ti
Cu thickness [µm]	**300**



R. Kersevan

Betatron collimation (CFC)
3 primaries (7.6 σ) 11 secondaries (8.8 σ) 5 absorbers (12.6 σ)

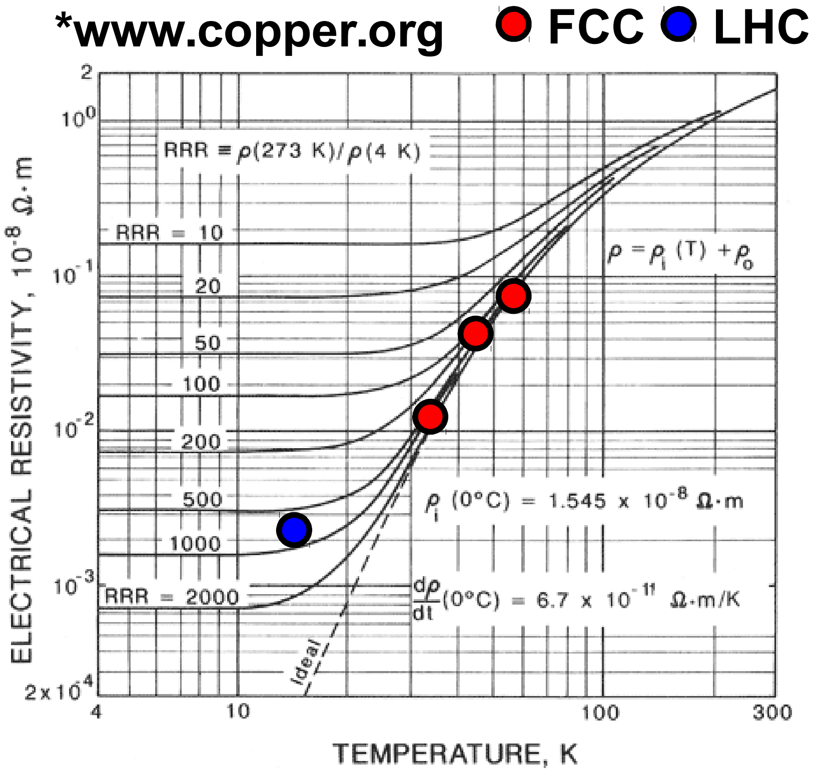
Resistivities



John T. Milck, 1970
http://goo.gl/aQaDq6

T=50 K
ρ_0=0.8-2.4·10^{-7} Ω m

*www.copper.org



T=50 K
ρ_0≈6·10^{-10} Ω m
k_0≈1.66 10^9 S/m

R(273 K)/R(50 K): resistivity reduces by factor **~3-10**.
Large uncertainty 0.8-2.4e-7 (50 K)

Magnetoresistivity

No Ti-magnetoresistivity data available.

Assuming the same dependence for titanium and for copper.

$$Z(\omega, B) = Z(\omega, 0)\sqrt{1.00 + 0.00204 \cdot (B \cdot RRR)^{1.055}}$$

Energies [GeV]	B [T]	Impedance increase factor	
		Purity RRR=70	Purity RRR=300
450	0.15	1.01	1.05
1500	0.5	1.04	1.18
2000	0.66	1.06	1.24
3300	1.1	1.10	1.38
5500	1.83	1.14	1.56

E. Metral http://arxiv.org/pdf/1108.1643.pdf

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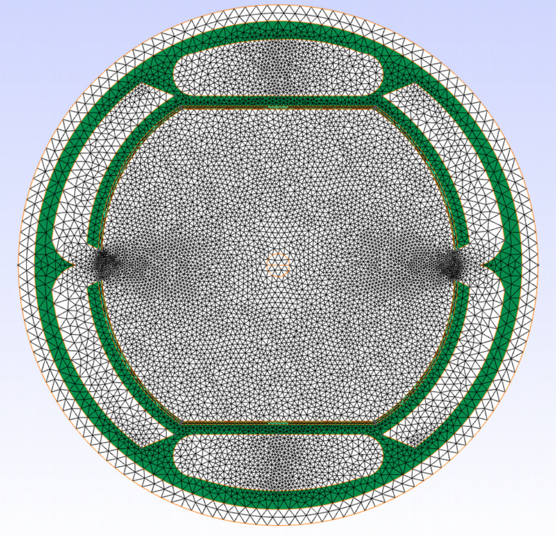
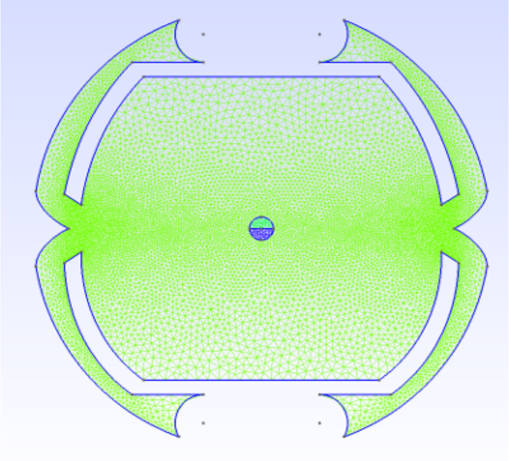
Impedance calculations in 2D. Discretization.

Full Geometry



Is necessary at low frequencies < 100 Hz.

Surface Impedance Boundary Conditions



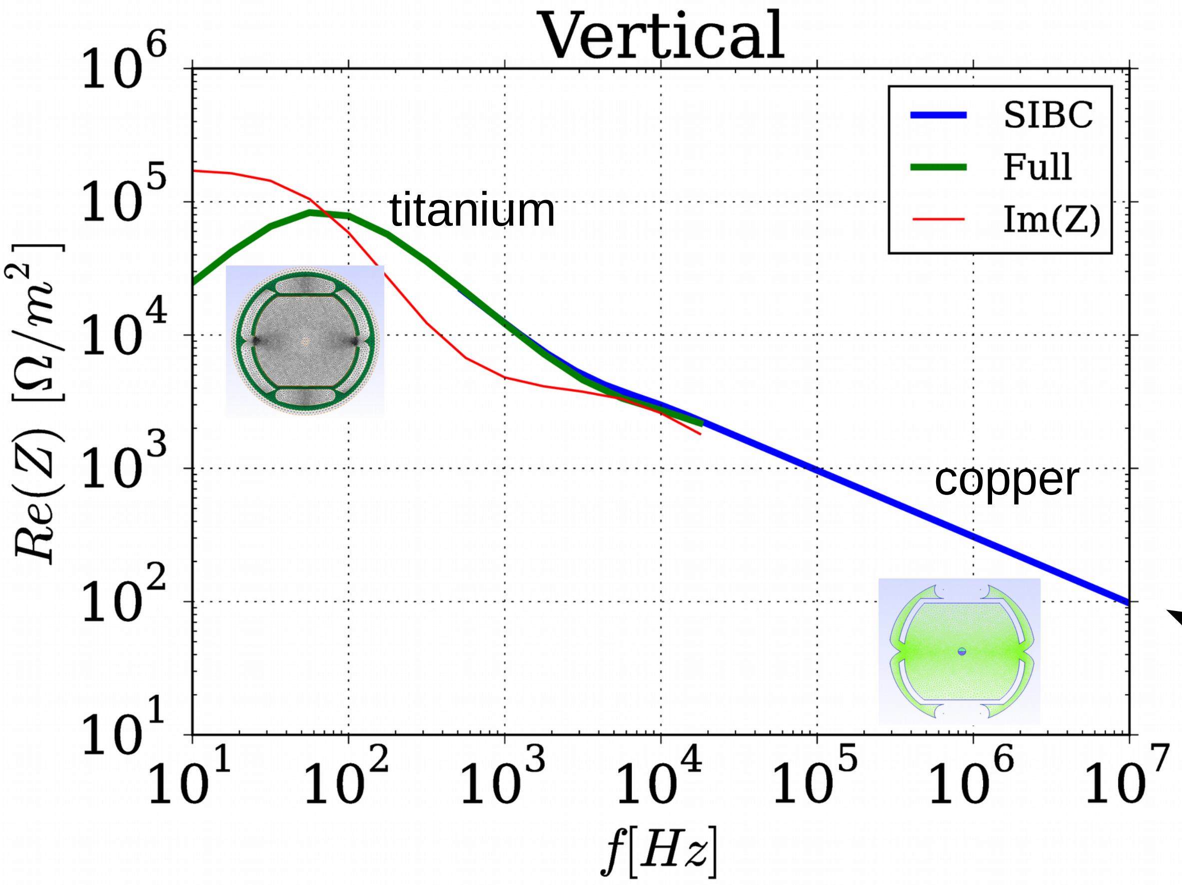
Acceleration of calculations at f> 100 Hz. Simplified geometry.

Meshing is done in gmsh.

Disadvantage: pumping holes, longitudinal discontinuities – broad-band impedance sources can not be simulated.

*code: U. Niedermayer https://bitbucket.org/uniederm/beamimpedance2d/

BeamImpedance2D results for Symmetric Beam Screen

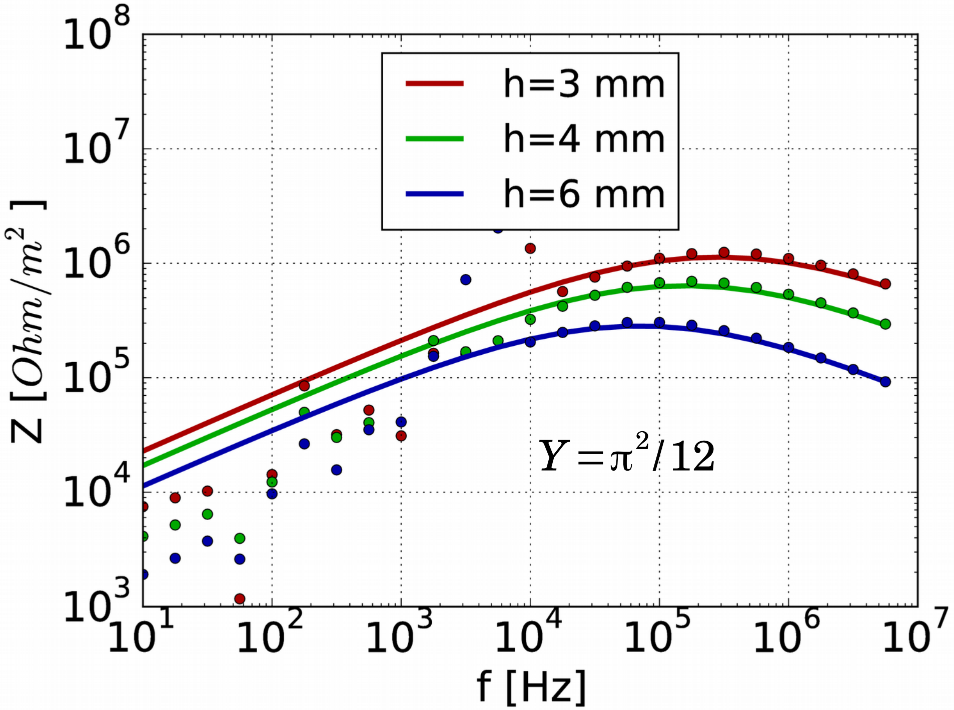


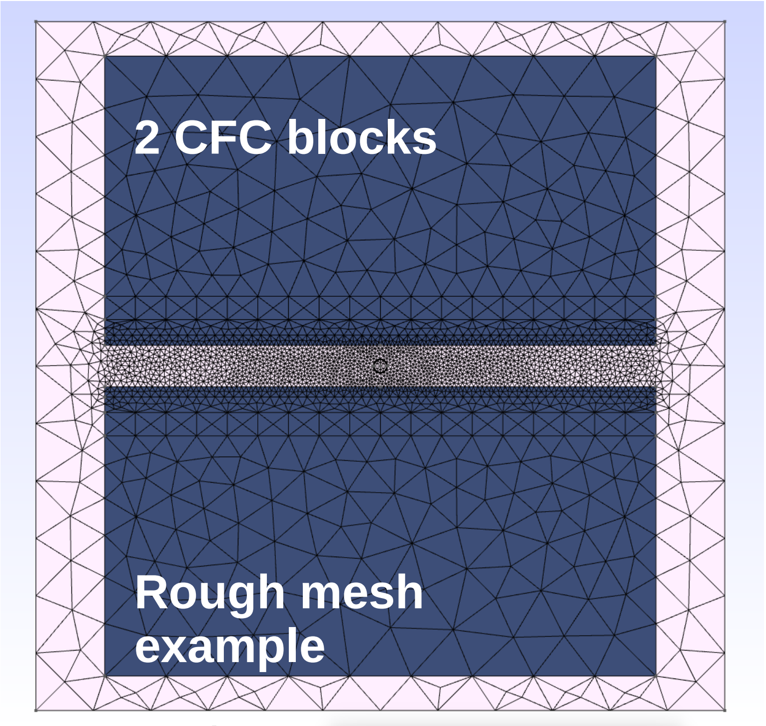
Betatron side-bands are at 1 kHz

SIBC impedance is valid down to 100 Hz and sufficient for further FCC estimations

High-frequency part should be obtained with other assumptions

BeamImpedance2D.py vs Inductive Bypass for Collimators





Good agreement at maximum and for large frequencies.
Lower numerical impedance at lower frequencies (and numerical problems).
Rather good approximation to perform stability analysis.

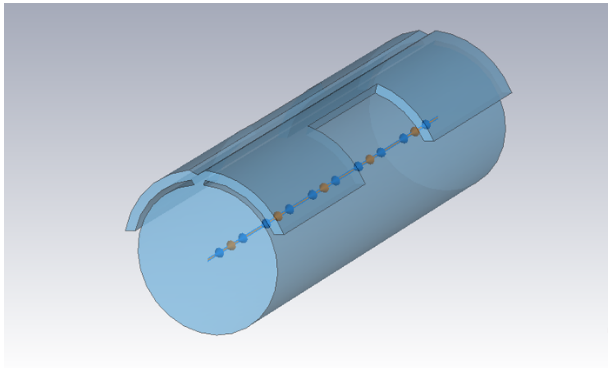
$$Z_{col}=Y\left(1+sign(\omega)i\right)\frac{c\mu_0 L_c}{2\pi b^2}\frac{1}{sign(\omega)\left(1+b\sqrt{\frac{\mu_0\omega\sigma_{DC}}{2}}\right)-i}$$

*Comparison also X. Buffat http://goo.gl/8f055x

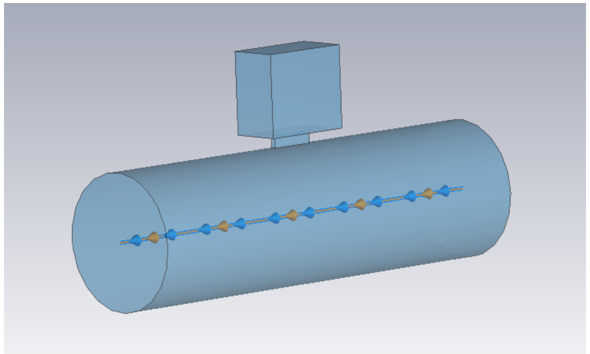
Contents

Broad-band impedances.
Holes, slits and rips

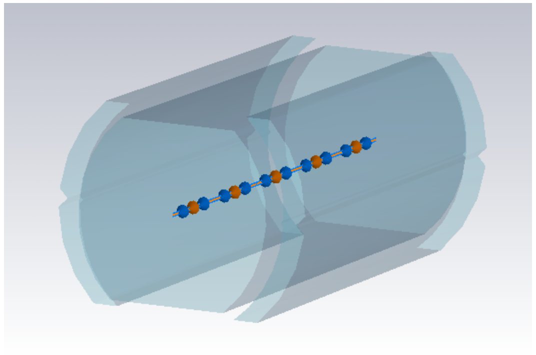
3D simulations in the time domain by CST Particle Studio®



Stabilization fins between beam pipe and reflector



Vacuum pumping holes



Long slits with connection at the end

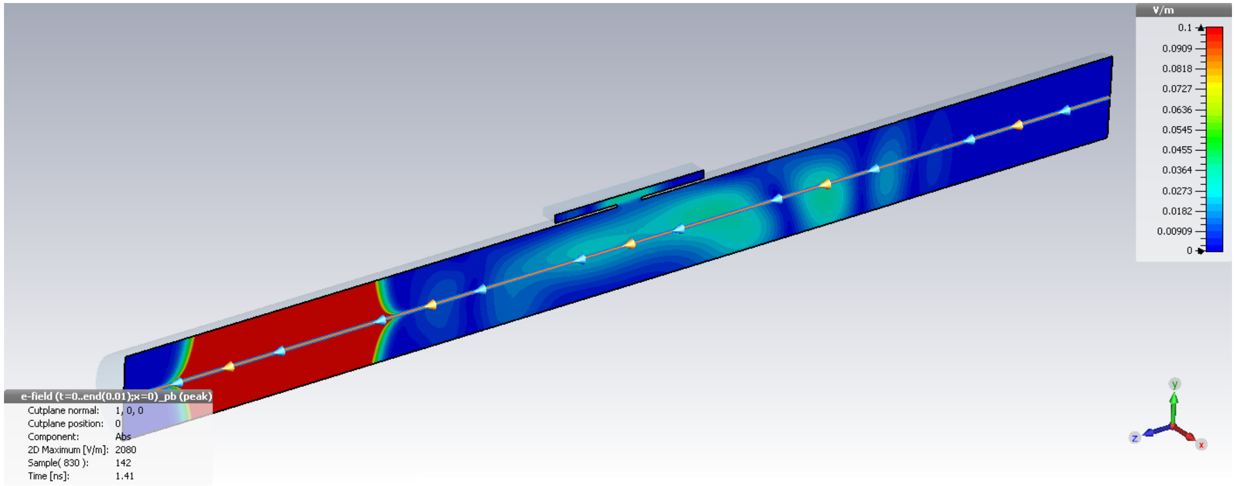
Simulations with reasonable computation time are inaccurate (not enough grid cells)

Necessary to study in frequency domain:

<u>- simulate two-wire measurements?</u>

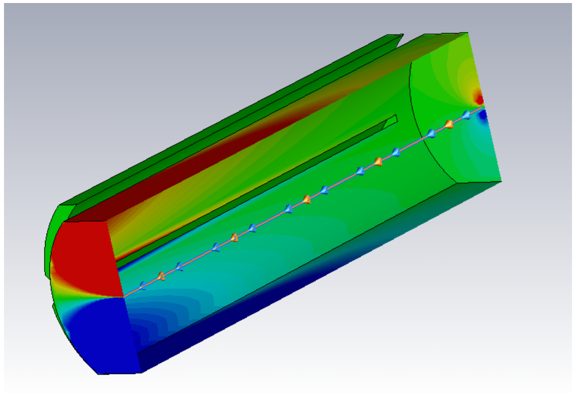
<u>- write a separate 3D tool similar to BeamImpedance2D?</u>

Wakefield simulation of hole/slits



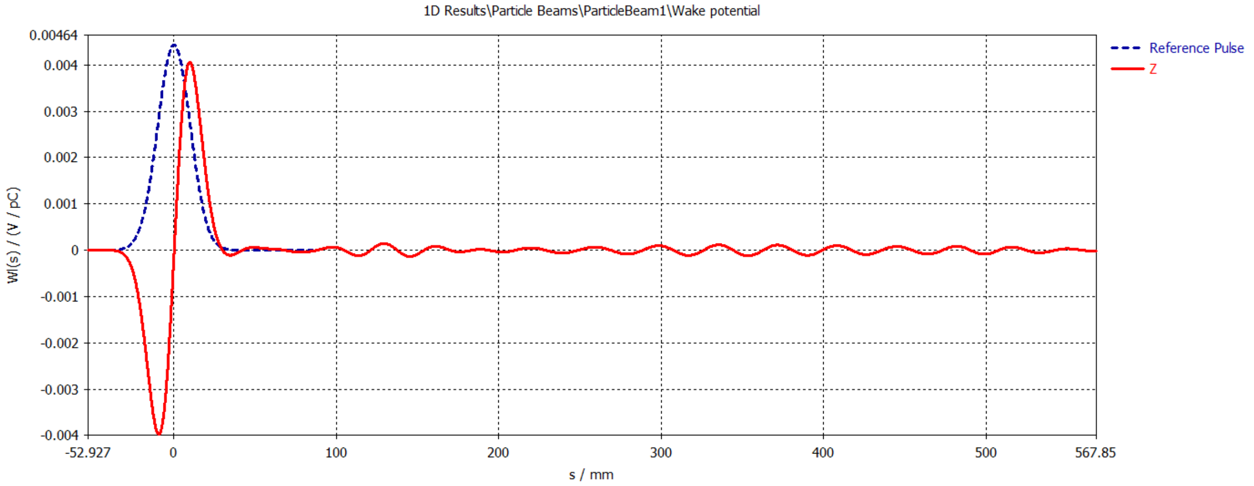
e-field (t=0..end(0.01);x=0)_pb (peak)

Cutplane normal: 1, 0, 0
Cutplane position: 0
Component: Abs
2D Maximum [V/m]: 2080
Sample(830): 142
Time [ns]: 1.41



Small effect, in the order of the numerical error!

The simulated wake is similar to the one without discontinuity



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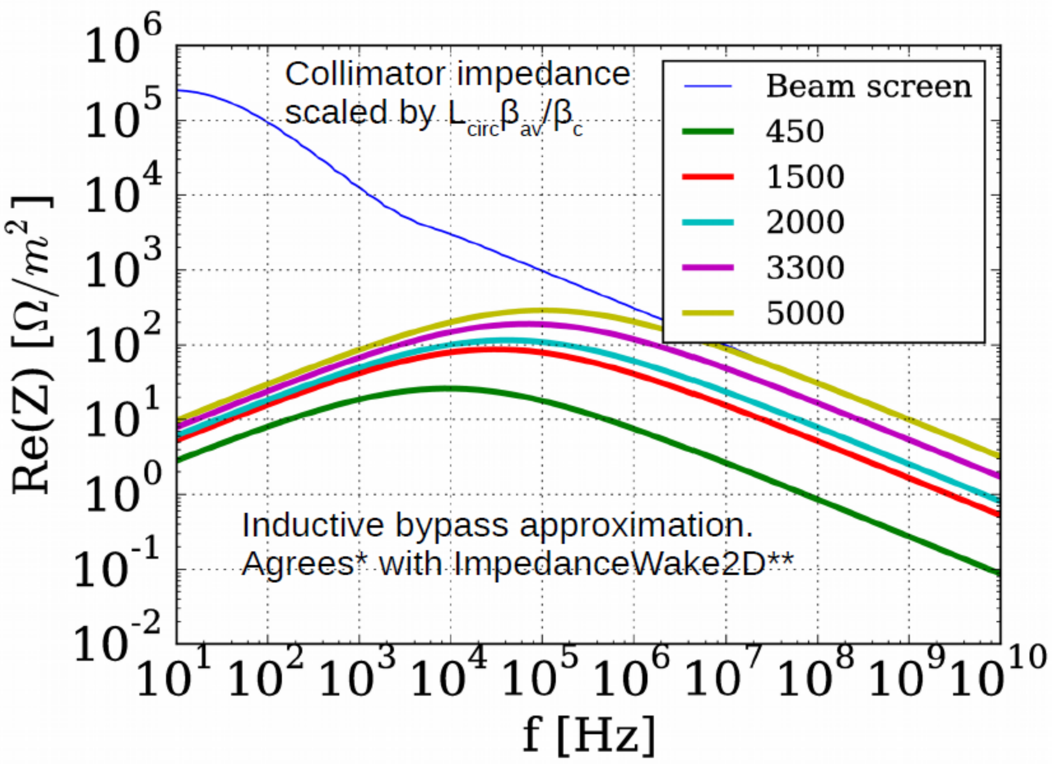
Collimator and Beam Screen Impedance

At collimator: β_c=745 m

ρ_{CFC}=5e-6 Ω/m

Gap sizes if scaled with energy

Energy [GeV]	Gap primary [mm]	Gap sec. [mm]
450	14.0	16.2
1500	7.7	8.9
2000	6.7	7.7
3300	5.2	6.0
5000	4.2	4.9



Collimator impedance scaled by $L_{circ}\beta_{av}/\beta_c$

Inductive bypass approximation. Agrees* with ImpedanceWake2D**

$$Z_{col} = Y\,(1+sign(\omega)\,i)\frac{c\mu_0 L_c}{2\pi b^2}\frac{1}{sign(\omega)(1+b\sqrt{\frac{\mu_0\omega\sigma_{DC}}{2}})-i}$$

**Code N. Mounet: http://goo.gl/5lgq6r

TMCI and coupled-bunch instability: beam screen

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TMCI threshold due to k=0 reaching -Q_s

$$N_{TMCI}=\frac{16\pi m_p \gamma Q_x \omega_0 \sigma_z Q_s}{\Im(Z_{Tr,0})e^2}$$

Coupled-bunch instability growth rate

$$\tau_0^{-1}=\frac{j}{2Q\omega_0}\frac{e\beta I_0}{\gamma m_0 L}\Re(Z_{tr,0})$$

Impedance averaged over the mode spectrum

$$Z_{Tr,k}=\frac{\sum Z(\omega_p)H(\omega_p,k)}{\sum H(\omega_p,k)}$$

E [GeV]	Q_s	N_{TMCI}	Growth rate [Turns]	
			Q_f=0.72 f_{sb}=837 kHz	Q_f=0.32 f_{sb}=2 kHz
450	$5.83\cdot10^{-3}$	$5.8\cdot10^{11}$	8	16
1500	$3.00\cdot10^{-3}$	$8.9\cdot10^{11}$	22	47
2000	$2.93\cdot10^{-3}$	$1.1\cdot10^{12}$	29	61
3300	$2.43\cdot10^{-3}$	$1.41\cdot10^{12}$	43	91
5000	$2.12\cdot10^{-3}$	$1.58\cdot10^{12}$	59	119

TMCI and coupled-bunch instabilities due to collimators.

TMCI threshold due to shift to Q_s

$$N_{TMCI}=\frac{16\pi m_p \gamma Q_x \omega_0 \sigma_z Q_s}{\Im(Z_{Tr,0})e^2}$$

Coupled-bunch instability growth rate

$$\tau_0^{-1}=\frac{j}{2Q\omega_0}\frac{e\beta I_0}{\gamma m_0 L}\Re(Z_{tr,0})$$

Impedance averaged over the mode spectrum

$$Z_{Tr,k}=\frac{\sum Z(\omega_p)H(\omega_p,k)}{\sum H(\omega_p,k)}$$

E [GeV]	Q_s	N_{TMCI}	**Growth rate [Turns]**
1500	$3.00\cdot10^{-3}$	$1.5\cdot10^{12}$	2145
3300	$2.43\cdot10^{-3}$	$2.5\cdot10^{12}$	3475

Beam screen + collimators

$$\frac{1}{N_{tot}}=\frac{1}{N_{col}}+\frac{1}{N_{screen}}$$

1.5 TeV	$5.6\cdot10^{11}$
3.3 TeV	$9\cdot10^{11}$

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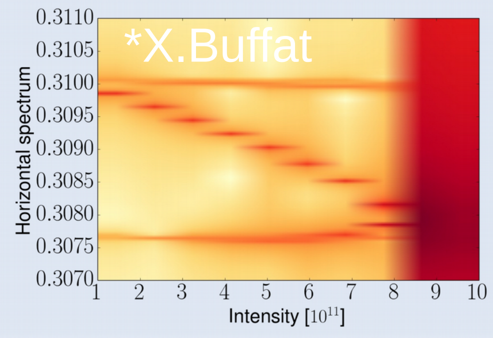
Towards the Multi-Bunch Tracking Simulations

Tracking simulations indicate lower ~20% TMCI thresholds than simple estimations



The 2D beam representation:

- **N_b - number of bunches; N – bunch population; only y,y',z,dp/p**

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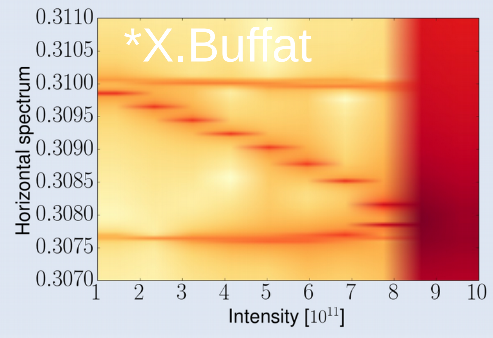

The 2D beam representation:

- **N_b - number of bunches; N – bunch population; only y,y',z,dp/p**
- **Each bunch consists of macroparticles N_{mac}**

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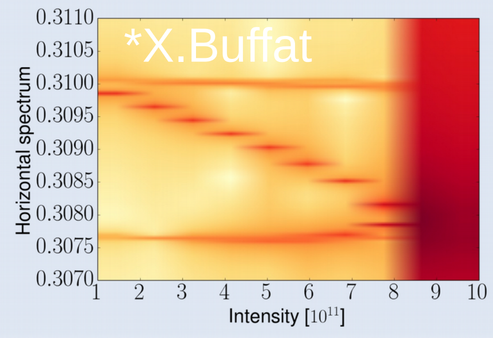


The 2D beam representation:

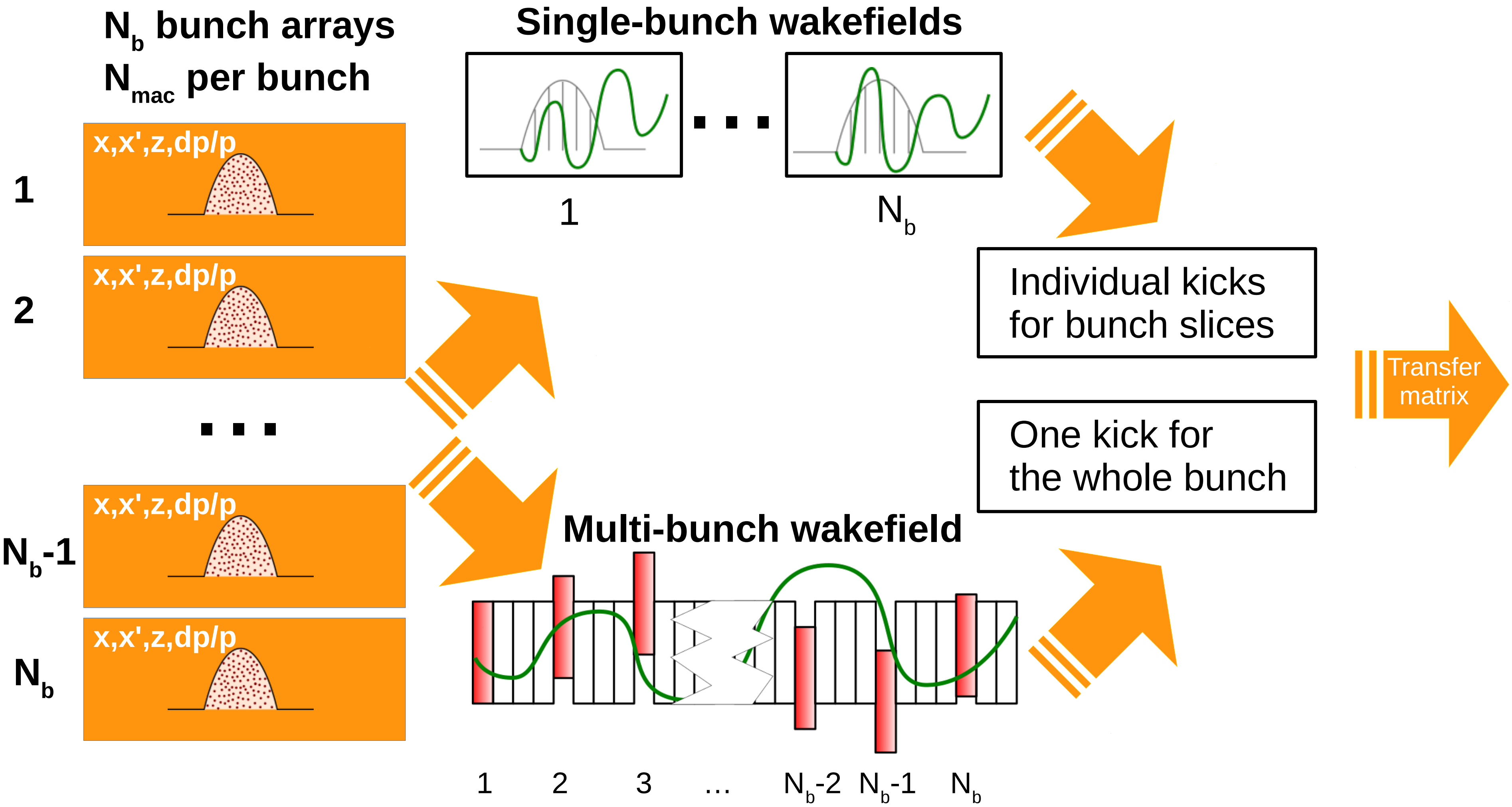
- **N_b - number of bunches; N – bunch population; only y,y',z,dp/p**
- **Each bunch consists of macroparticles N_{mac}**
- **2 grids longitudinally:**
  - fine grid to resolve bunch centroid (<1 cm);
  - coarse grid to resolve only coupled bunch motion (>7.5 m)
- **2 wakefield types are calculated:**
  - single-bunch wakefield for each bunch (applied to slices of a bunch)
  - multibunch wakefield (applied to each bunch as a kick)

Data storage

1. N_b-length array to store coupled-bunch centroid

2. 2D-[N_bxN_{mac}] array to store macroparticle positions and momenta inside each bunch

Schematic Steps Implemented in Python



N_b bunch arrays
N_{mac} per bunch

Single-bunch wakefields

Individual kicks for bunch slices

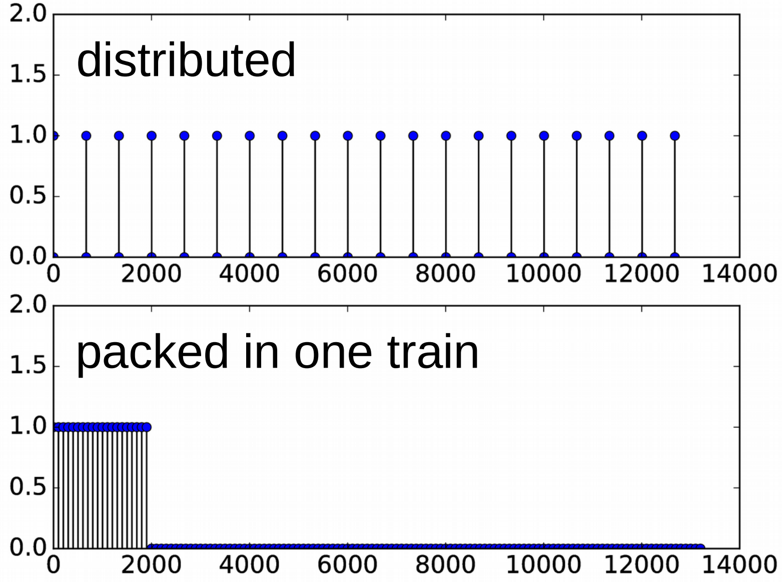
One kick for the whole bunch

Multi-bunch wakefield

Train of 200 bunches.

To estimate the coupled-bunch growth rate analytically a simple formula for coasting beam was utilized.
Disadvantage: synchrotron motion is absent.

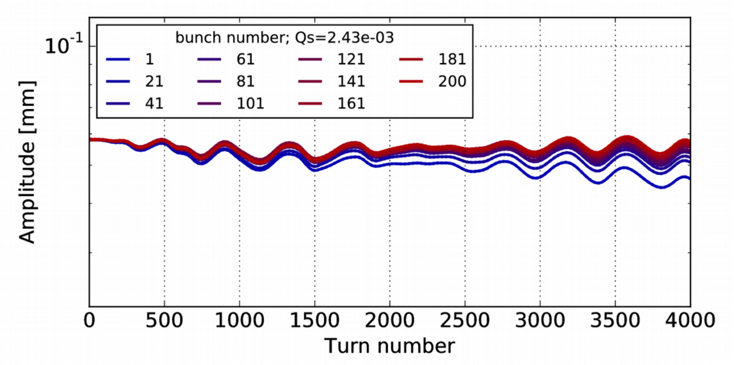
Comparison between the following cases:
- equidistant bunches (L_b=0.5 km) vs bunch train (L_b=7.5 m)
- finite synchrotron tune vs zero synchrotron tune



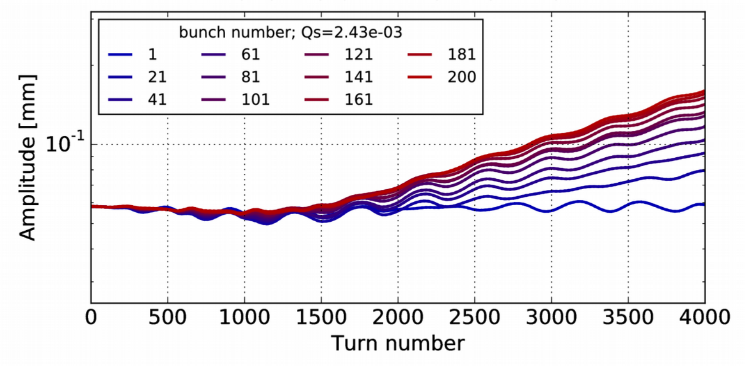
Examples: Bunch Amplitudes (Below Sacherer TMCI) 3300 GeV; 3.0·10^{11} p/b

Bunch average offset as a function of turn.

Distributed



Packed in one train



Examples: Bunch Amplitudes (Below Sacherer TMCI) 3300 GeV; $3.0 \cdot 10^{11}$ p/b

Bunch average offset as a function of turn.

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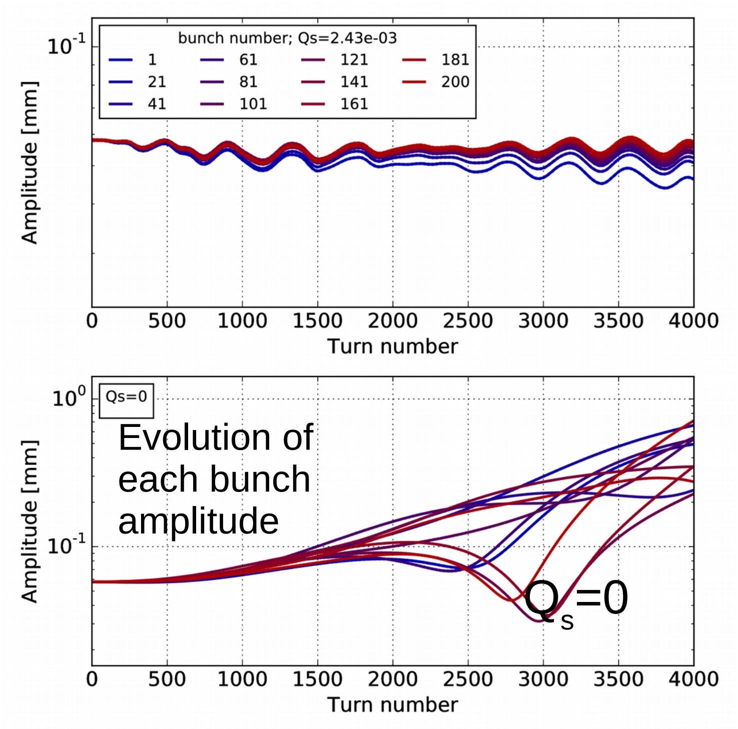
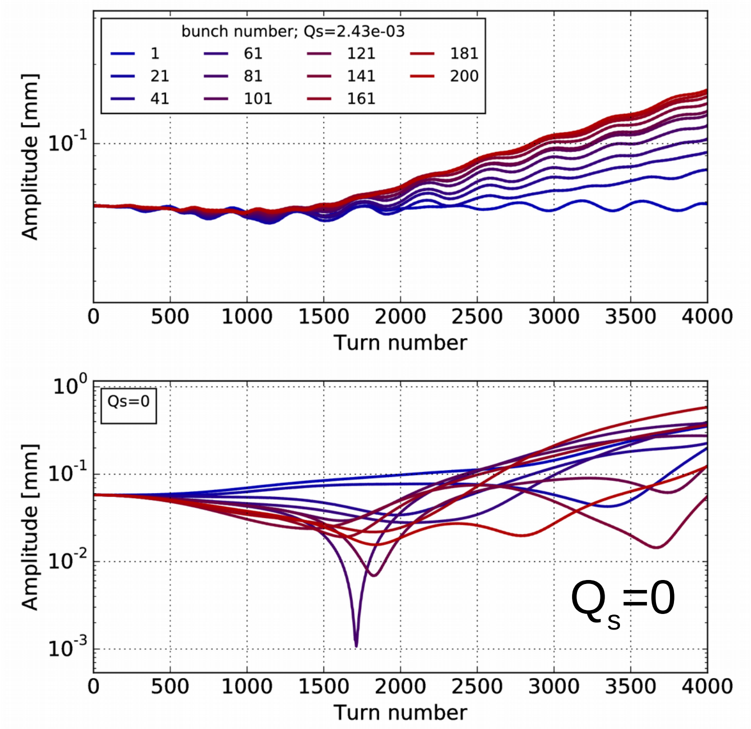


Evolution of each bunch amplitude

$Q_s=0$

Packed in one train



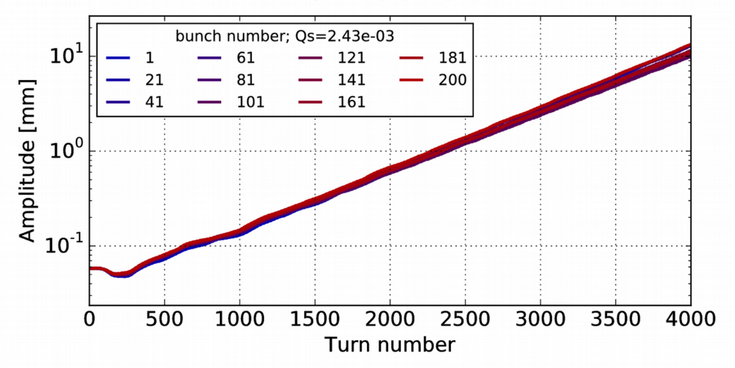
$Q_s=0$

Synchrotron tune itself leads to a stabilization of a coupled bunch motion. Frozen beams behave similarly

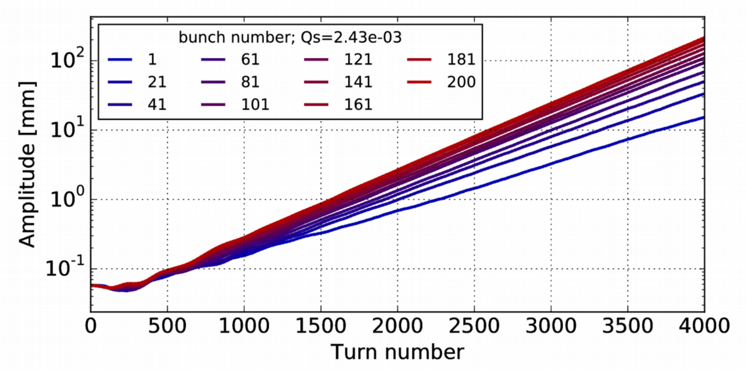
Examples: Bunch Amplitudes (Above Sacherer TMCI) 3300 GeV; 1.2·10^{12} p/b

Bunch average offset as a function of turn.

Distributed

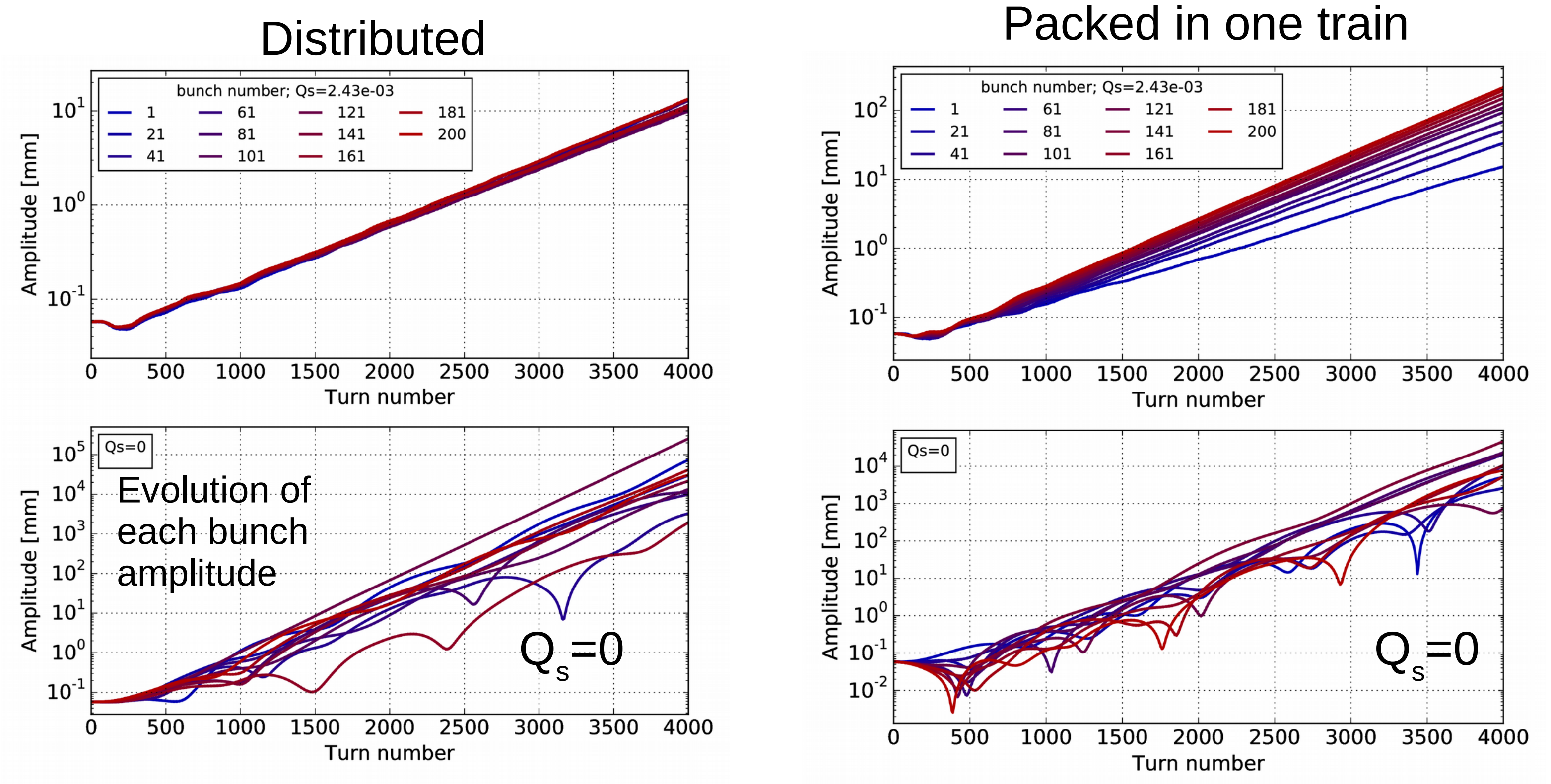


Packed in one train



Examples: Bunch Amplitudes (Above Sacherer TMCI) 3300 GeV; $1.2 \cdot 10^{12}$ p/b

Bunch average offset as a function of turn.



Distributed

Packed in one train

Evolution of each bunch amplitude

Q_s=0

Q_s=0

Above the TMCI threshold the growth rates are similar for both filling patterns.
Synchrotron tune reduces the growth rate as well.

Conclusions and Outlook

Conclusions

- ✓ Estimations of impedances of several components
- ✓ Beam screen + collimators lead to TMCI threshold of $5\text{-}9\cdot10^{11}$
- ✓ Multi-bunch simulations indicate that in presence of synchrotron motion coupled bunch instability growth rate in a bunch train reduces
- ✓ Dense train of bunches is more unstable than distributed bunches
- ✓ Simulations for long slits, holes, fins with CST Particle Studio lack precision; signal is of the order of noise.

Outlook

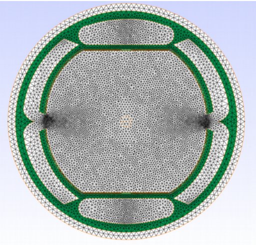
- Models for interconnects and other impedance sources (first guess Z-base)
- More precise collimator parameters (gap, material, beta-functions)
- Tools benchmarking (tracking vs DELFI)
- Search for a PhD student to work on 3D impedance code started

Thank you for your attention

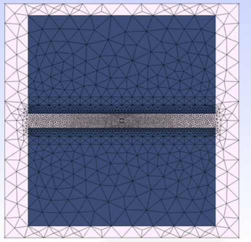
Short Summary

Impedances calculated so far with 2D code*

FCC two-slit beam screen



Collimator made of CFC

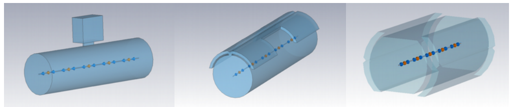


Collimator + beam screen

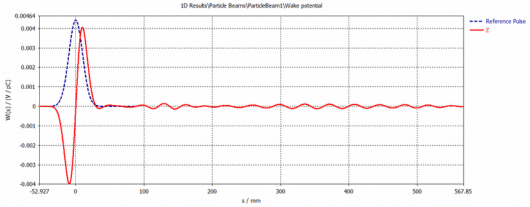
Energy	N_{TMCI}	Turns
1.5 GeV	$5.6 \cdot 10^{11}$	47
3.3 GeV	$9 \cdot 10^{11}$	91

Code by Niedermayer
https://goo.gl/Agb6nF

3D CST Particle Studio Simulations



Noise level is high!
Non-conclusive results.



Outlook

- either scale known LHC broad-band impedances to FCC conditions (Z-base)
- or develop a 3D code for frequency domain

Multi-bunch simulations

- Below TMCI threshold dense train is unstable at the end
- synchrotron motion reduces growth rates compared to cold coasting beam