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Large Scale 3D Wakefield Simulations with PBCI

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"Wake Fest 07 - ILC wakefield workshop at SLAC”

11-13 December 2007

Technische Universität Darmstadt, Fachbereich Elektrotechnik und Informationstechnik
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Outline

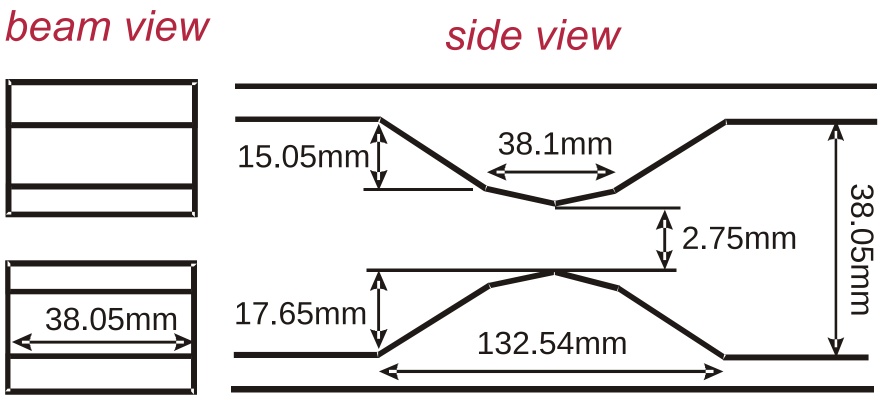
- Introduction
- Numerical Method
- Parallelization Strategy
- Modal Termination of Beam Pipes
- PBCI Simulation Examples

Introduction

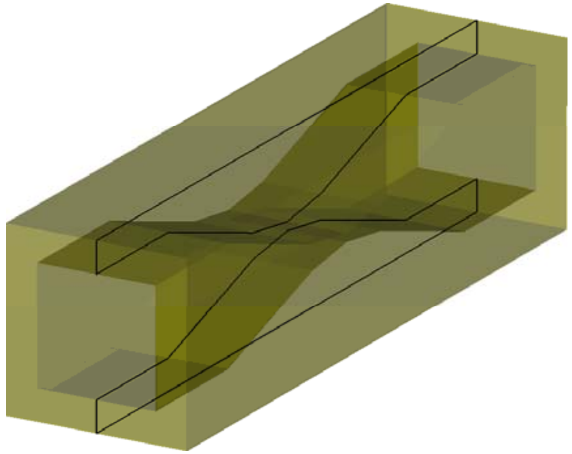
Motivation for PBCI:

1. A new generation of LINACs with ultra-short electron bunches
   a. *bunch size for ILC: 300 μm*
   b. *bunch size for LCLS: 20 μm*
2. Geometry of tapers, collimators… far from rotational
   a. *8 rectangular collimators at ILC-ESA in the design process*
   b. *30 rectangular-to-round transitions in the undulator of LCLS*
3. Many (semi-) analytical approximations become invalid
   a. *based on rotationally symmetric geometry*
   b. *low frequency assumptions (Yokoya, Stupakov)*
   c. *detailed physics needed for high frequency wakes (Bane)*

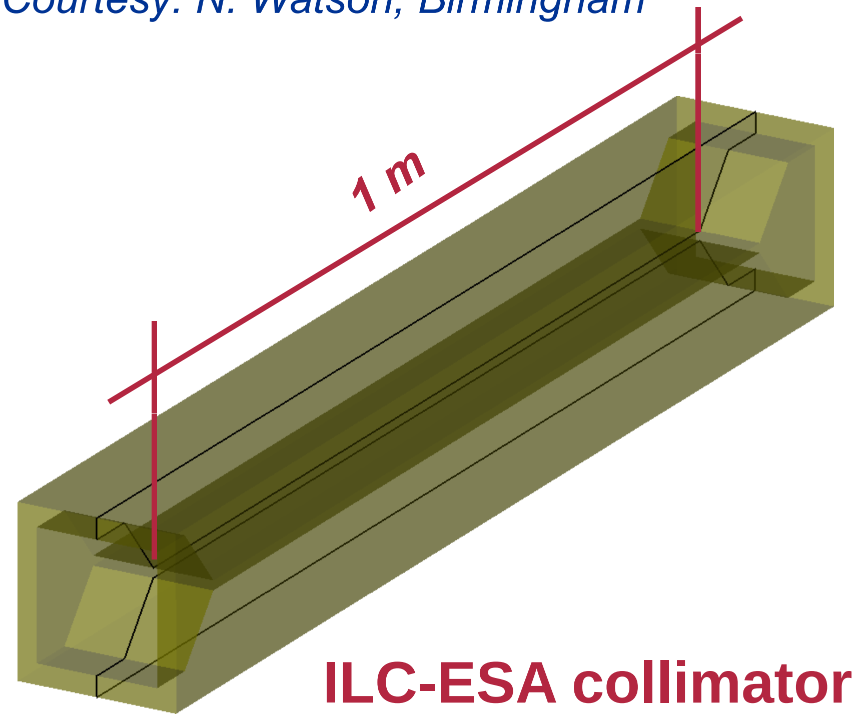
Introduction



Courtesy: N. Watson, Birmingham



ILC-ESA collimator #8



ILC-ESA collimator #3

bunch length	*300µm*
collimator length	*~1.2m*
catch-up distance	*~2.4m*

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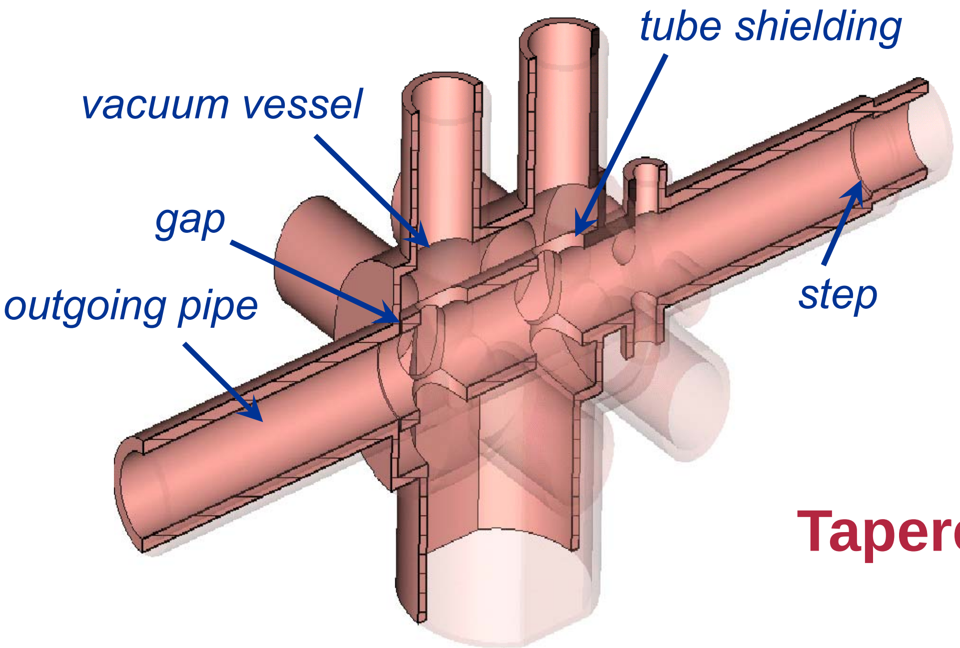
Introduction

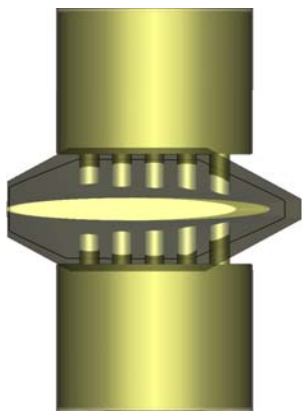


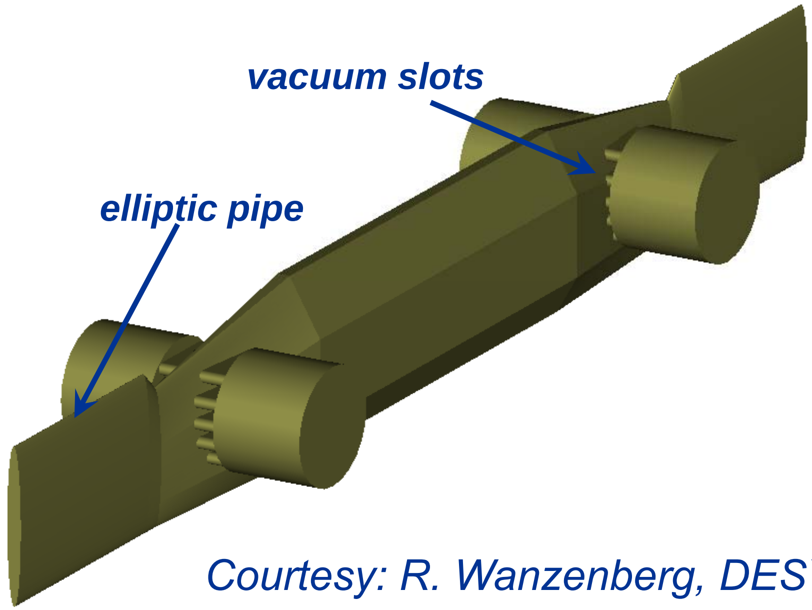
PITZ diagnostics double cross

bunch length	*2.5mm*
bunch width	*2.5mm*
structure length	*325mm*

Tapered transition @PETRA III

bunch length	*1cm*
taper length	*50cm*





Courtesy: R. Wanzenberg, DESY

There is an actual demand for:

1. Wake field simulations in arbitrary 3D-geometry

   3D-codes

2. Accurate numerical solutions for high frequency fields

   (quasi-) dispersionless codes

3. Utilizing large computational resources for ultra-short bunches

   parallelized codes

4. Specialized algorithms for long accelerator structures

   moving window codes

An (incomplete) survey of available codes

Time: 1980 — 20 years — 2002 — 5 years — 2007

	Dimensions	*Nondispersive*	*Parallelized*	*Moving window*
BCI / TBCI	**2.5D**	**No**	**No**	**Yes**
NOVO	**2.5D**	**Yes**	**No**	**No**
ABCI	**2.5D**	**No**	**No**	**Yes**
MAFIA	**2.5/3D**	**No**	**No**	**Yes**
GdfidL	**3D**	**No**	**Yes**	**Yes**
Tau3P	**3D**	**No**	**Yes**	**No**
ECHO	**2.5/3D**	**Yes**	**No**	**Yes**
CST Particle Studio	**3D**	**No**	**No**	**No**
PBCI	**3D**	**Yes**	**Yes**	**Yes**
NEKCEM	**3D**	**Quasi**	**Yes**	**No**

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Numerical Method

The FIT discretization

$$\oint_{\partial A} \vec{E} \cdot d\vec{s} = -\frac{\partial}{\partial t} \iint_A \mu \vec{H} \cdot d\vec{A}$$

$$\oint_{\partial A} \vec{H} \cdot d\vec{s} = \iint_A \left(\frac{\partial}{\partial t} \varepsilon \vec{E} + \vec{J} \right) \cdot d\vec{A}$$

$$\oiint_{\partial V} \mu \vec{H} \cdot d\vec{A} = 0$$

$$\oiint_{\partial V} \varepsilon \vec{E} \cdot d\vec{A} = \iiint_V \rho \, dV$$

FIT ⇒

$$\mathbf{C} \widehat{\mathbf{e}} = -\frac{d}{dt} \mathbf{M}_\mu \widehat{\widehat{\mathbf{h}}}$$

$$\tilde{\mathbf{C}} \widehat{\mathbf{h}} = \frac{d}{dt} \mathbf{M}_\varepsilon \widehat{\widehat{\mathbf{e}}} + \widehat{\widehat{\mathbf{j}}}$$

$$\tilde{\mathbf{S}} \mathbf{M}_\varepsilon \widehat{\mathbf{e}} = \mathbf{q}$$

$$\mathbf{S} \mathbf{M}_\mu \widehat{\mathbf{h}} = 0$$

Topology of FIT:

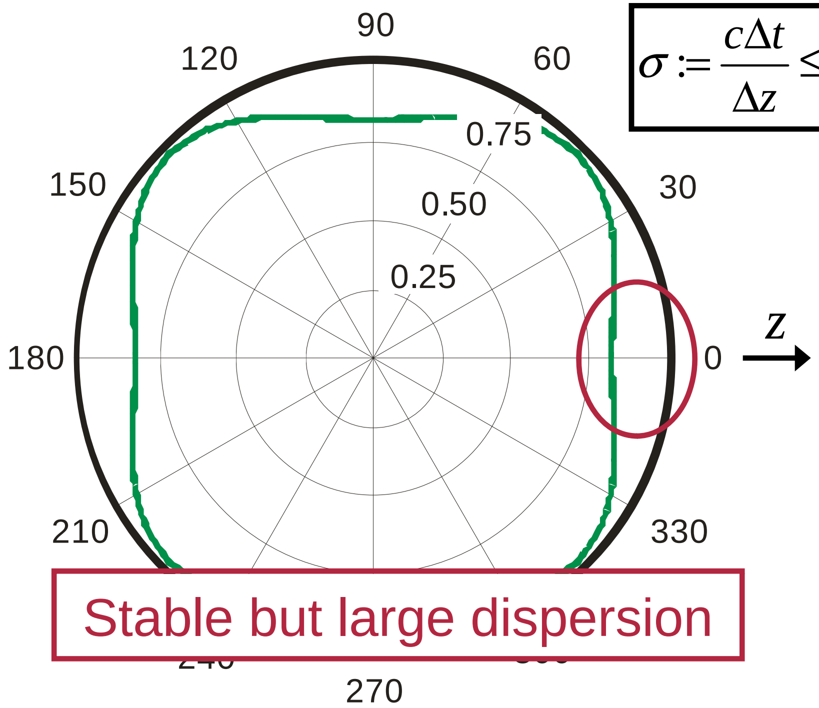
$\mathbf{C}^T = \tilde{\mathbf{C}}$ ⇒ *semidiscrete energy conservation*

$\tilde{\mathbf{S}}\mathbf{C} = \mathbf{S}\tilde{\mathbf{C}} = 0$ ⇒ *semidiscrete charge conservation*

Using the conventional leapfrog time integration

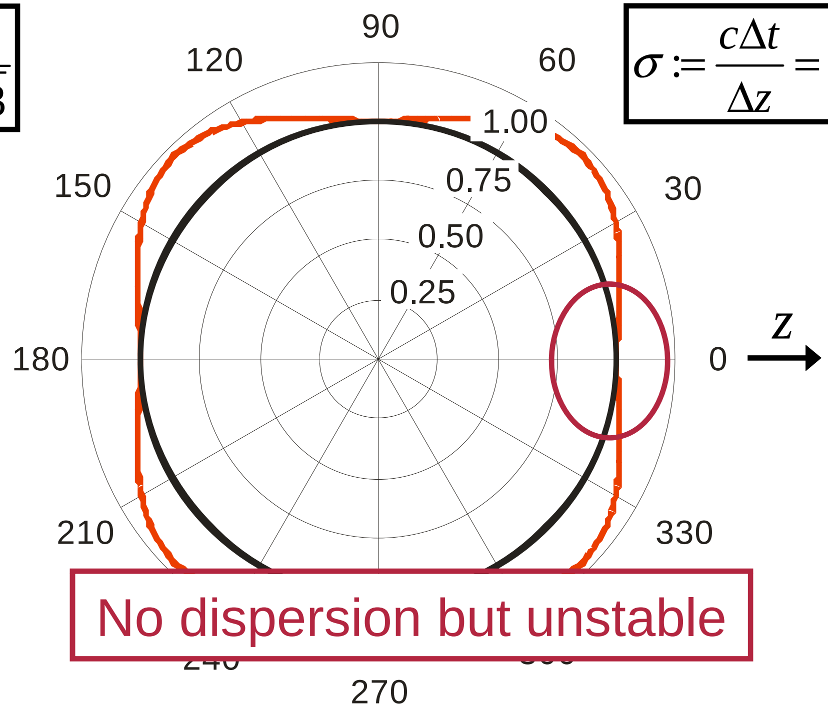
$$\begin{pmatrix}\widehat{\mathbf{e}}^{n+1/2}\\ \widehat{\mathbf{h}}^{n+1}\end{pmatrix} = \begin{pmatrix} \mathbf{1} & \Delta t \mathbf{M}_\varepsilon^{-1}\mathbf{C}^T \\ -\Delta t \mathbf{M}_\mu^{-1}\mathbf{C} & \mathbf{1} - \Delta t^2 \mathbf{M}_\mu^{-1}\mathbf{C}\,\mathbf{M}_\varepsilon^{-1}\mathbf{C}^T\end{pmatrix}\begin{pmatrix}\widehat{\mathbf{e}}^{n-1/2}\\ \widehat{\mathbf{h}}^{n}\end{pmatrix} - \begin{pmatrix}\Delta t \mathbf{M}_\varepsilon^{-1}\widehat{\mathbf{j}}^{n}\\ \mathbf{0}\end{pmatrix}$$

Behavior of numerical phase velocity vs. propagation angle



$$\sigma := \frac{c\Delta t}{\Delta z} \leq \frac{1}{\sqrt{3}}$$

Stable but large dispersion



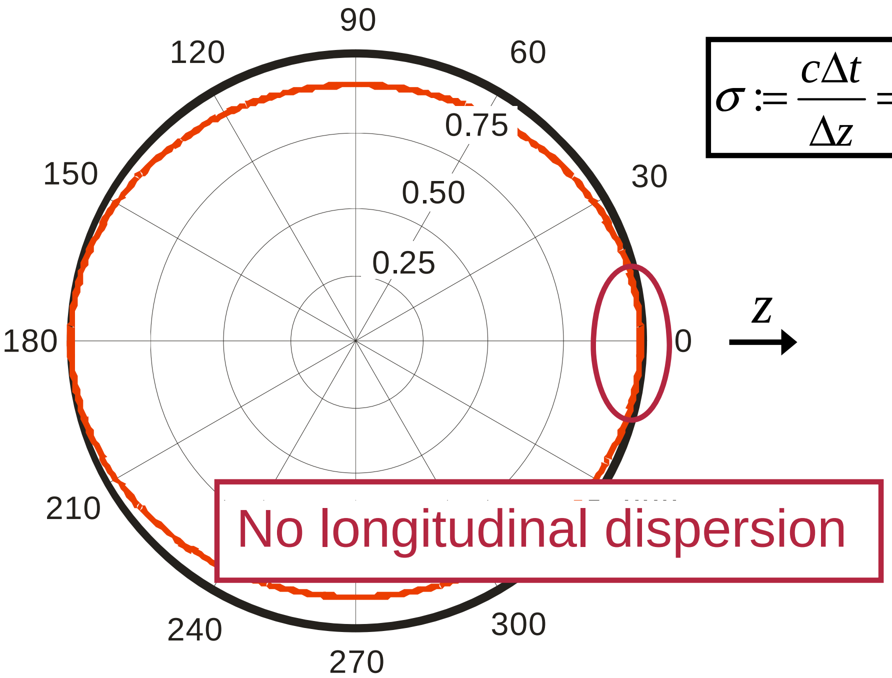
$$\sigma := \frac{c\Delta t}{\Delta z} = 1$$

No dispersion but unstable

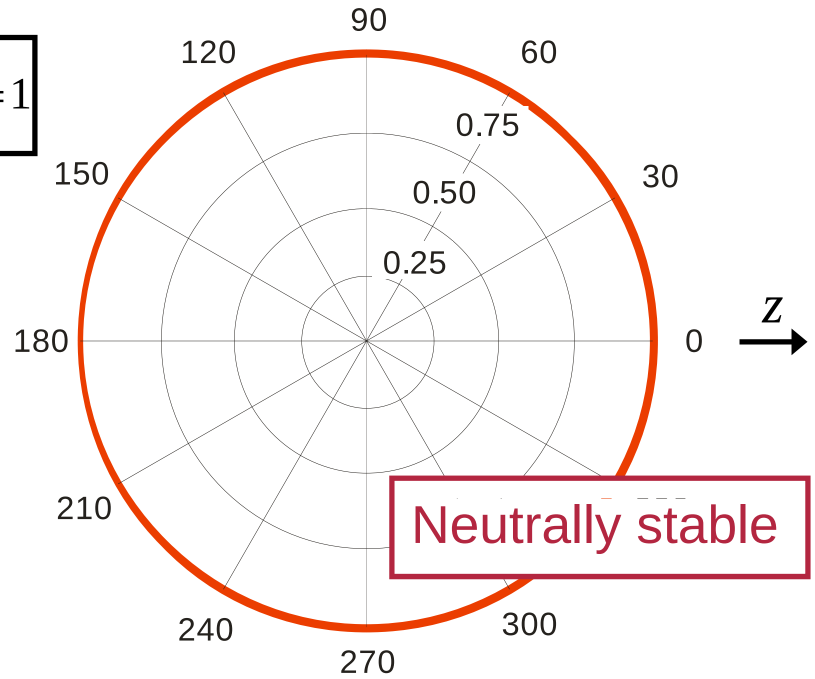
Numerical Method

Implementing a dispersion-free scheme leads to this:

Numerical phase velocity and amplification vs. propagation angle



$$\sigma := \frac{c\Delta t}{\Delta z} = 1$$



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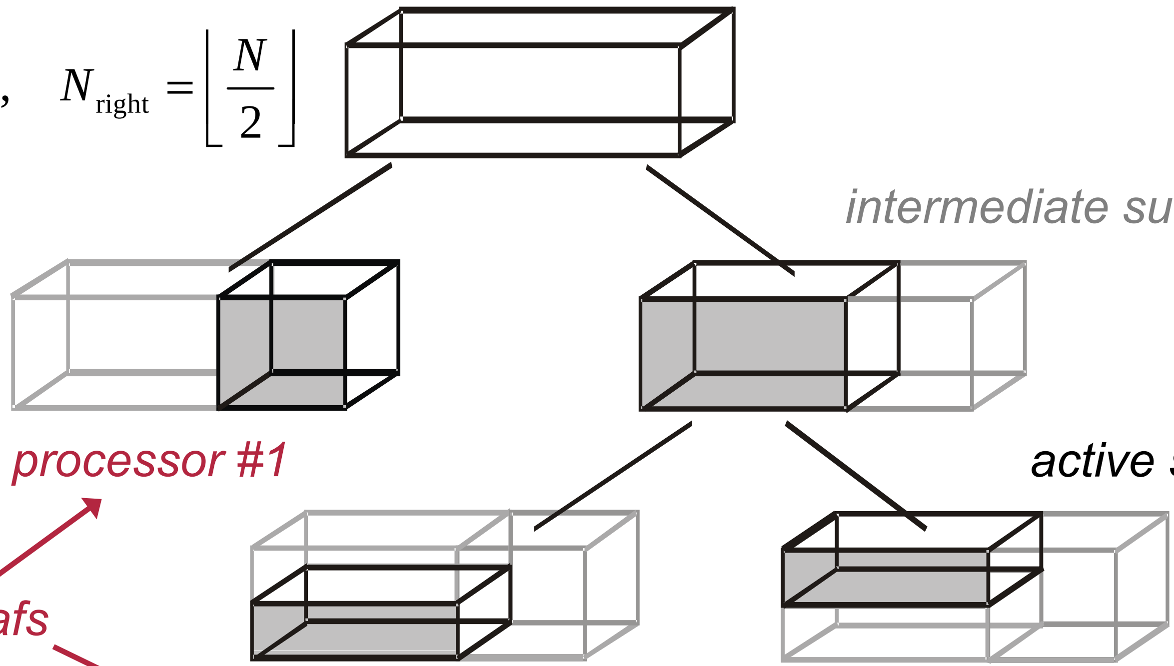
Parallelization Strategy

A balanced domain partitioning approach

$$N_{\text{left}} = \left\lceil \frac{N}{2} \right\rceil, \quad N_{\text{right}} = \left\lfloor \frac{N}{2} \right\rfloor$$

$$\frac{W_{\text{left}}}{W_{\text{right}}} = \frac{N_{\text{left}}}{N_{\text{right}}}$$



Equal loads assigned to each node: $W_{\text{Node}} = \alpha_{\text{Node}} \cdot \sum_{\text{Grid Points}} w_i$

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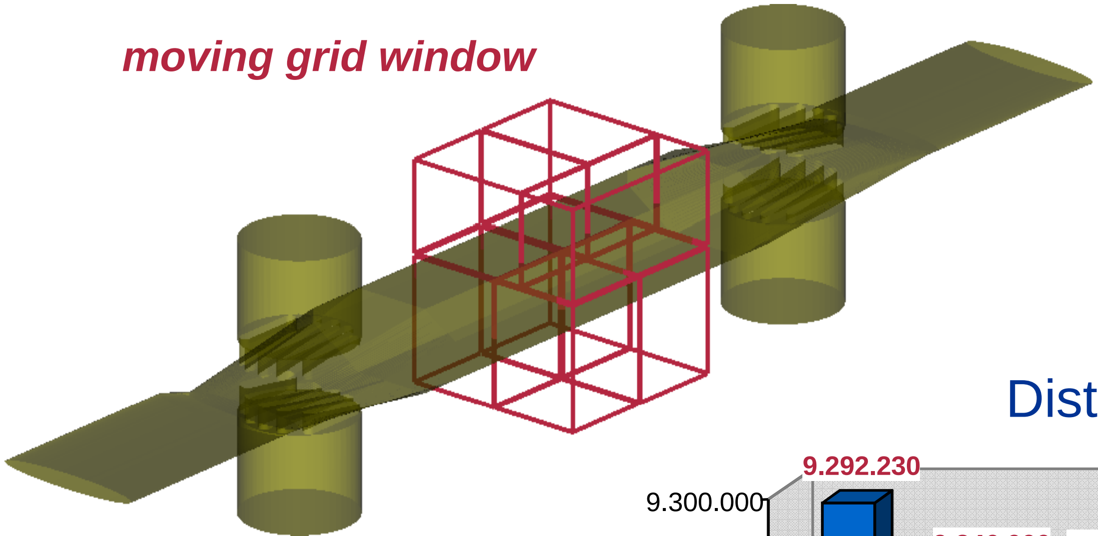
Parallelization Strategy

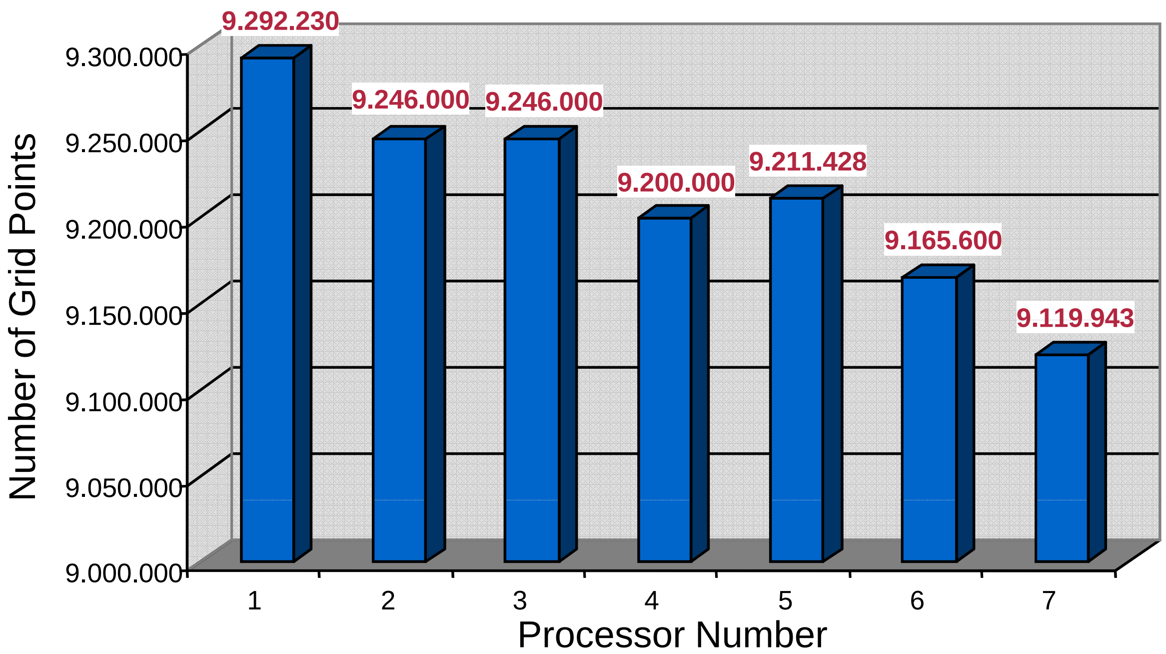
Example: Tapered transition for PETRA III

moving grid window



Domain partitioning pattern for 7 processors

Distribution of grid points



	Grid points
Total	64.481.201
Min	9.119.943
Max	9.292.230
Dev.	**< 1.0%**

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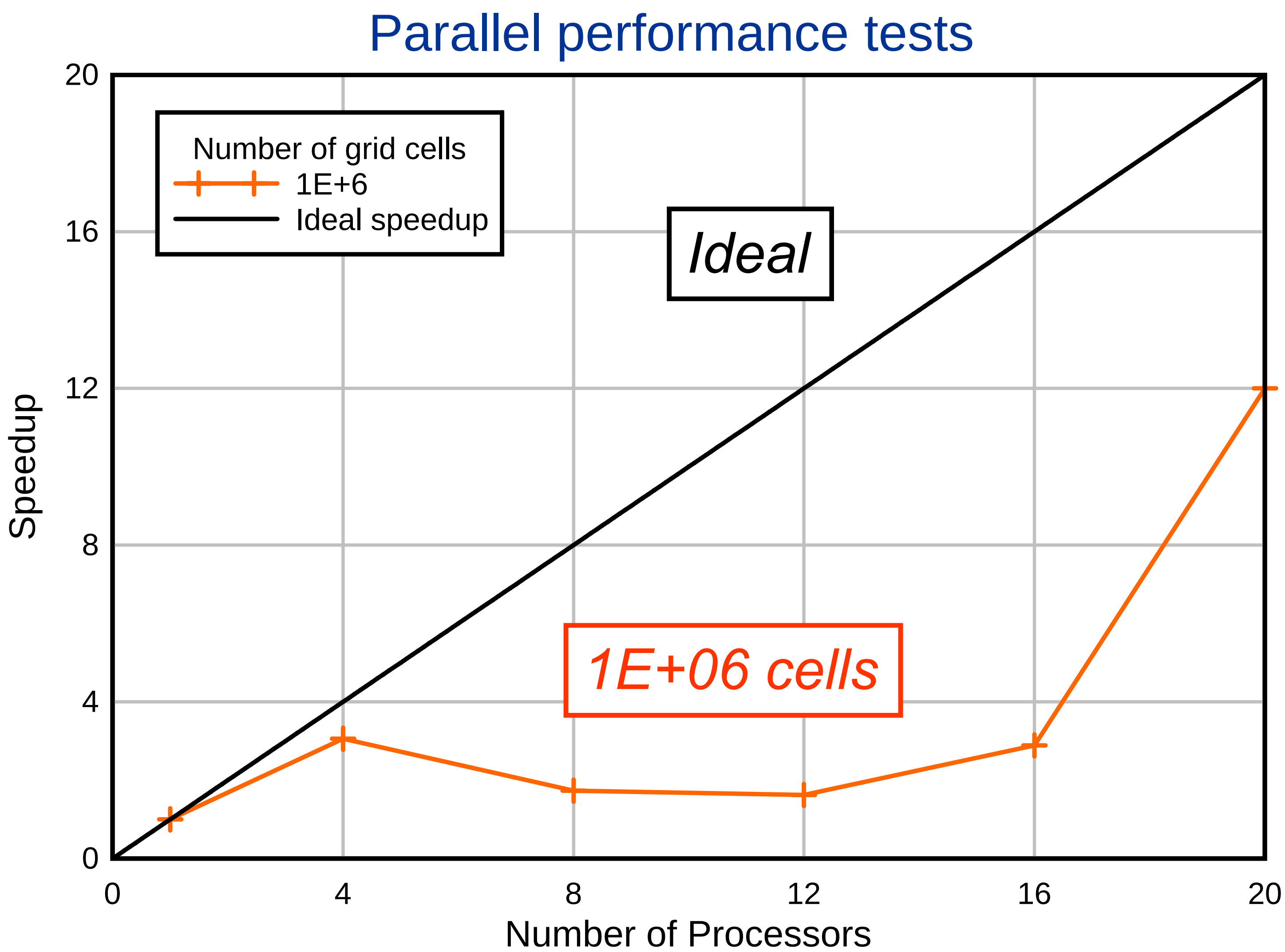
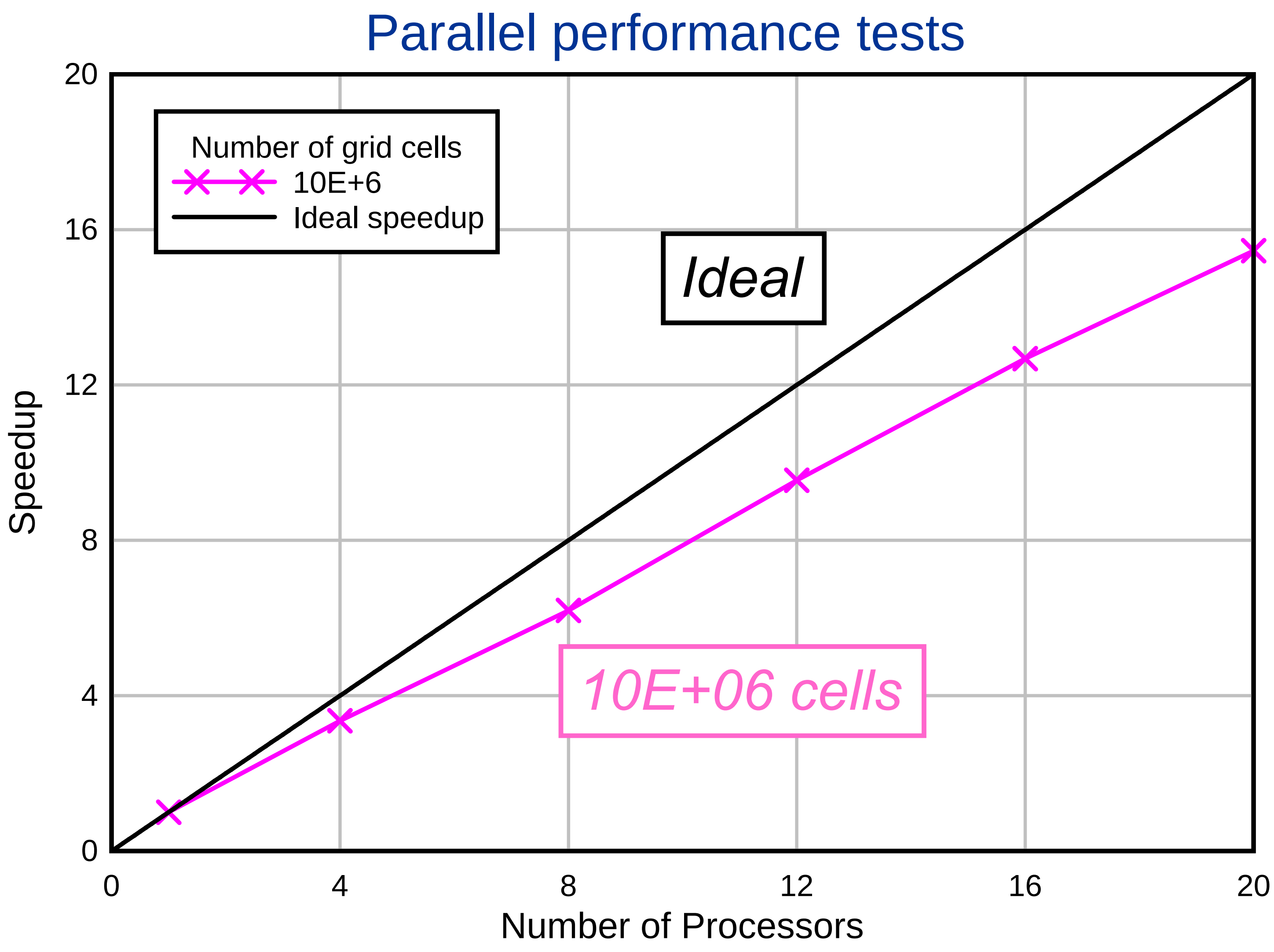
Parallelization

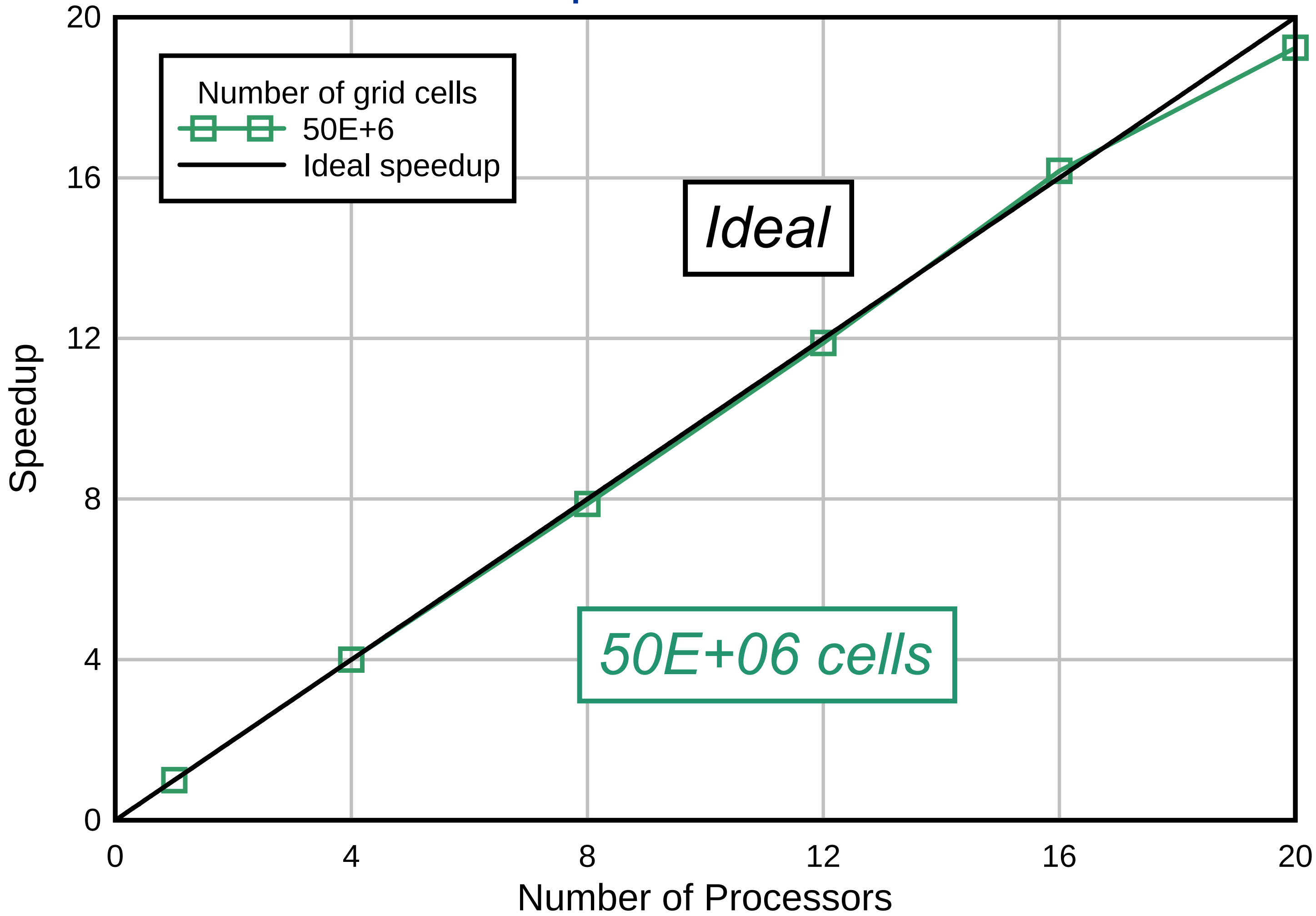


Parallelization



Parallelization

Parallel performance tests



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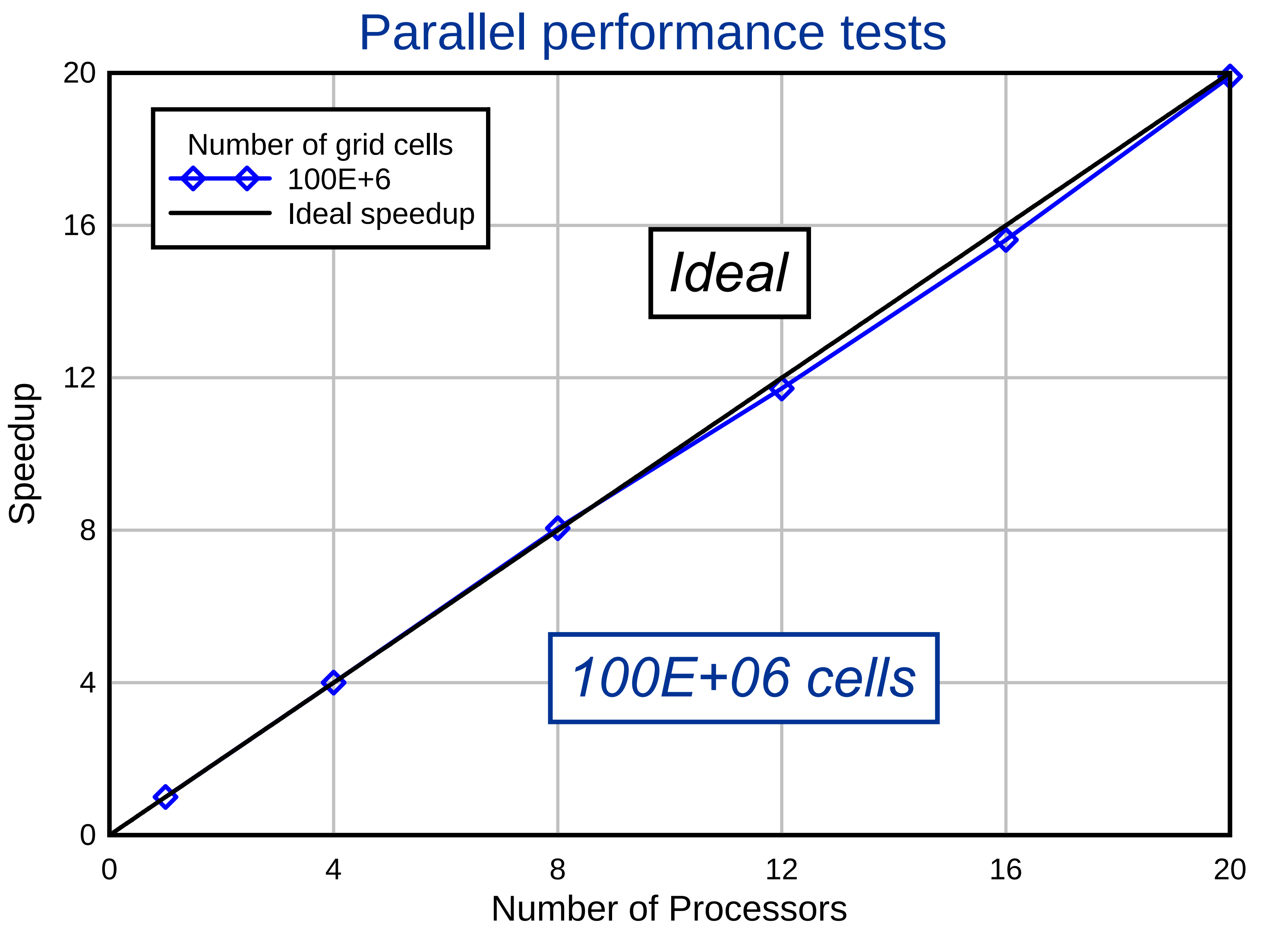
Parallelization



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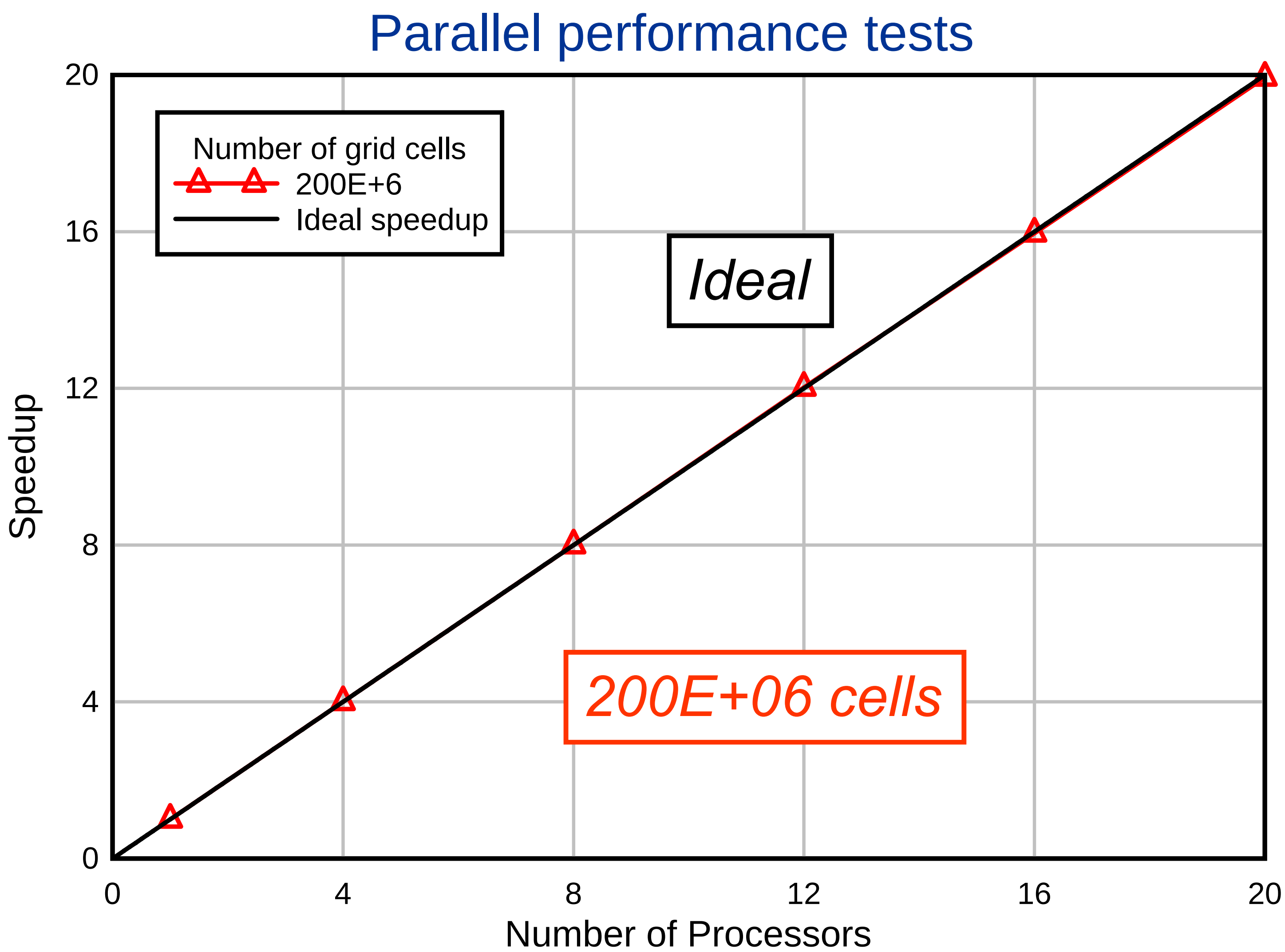
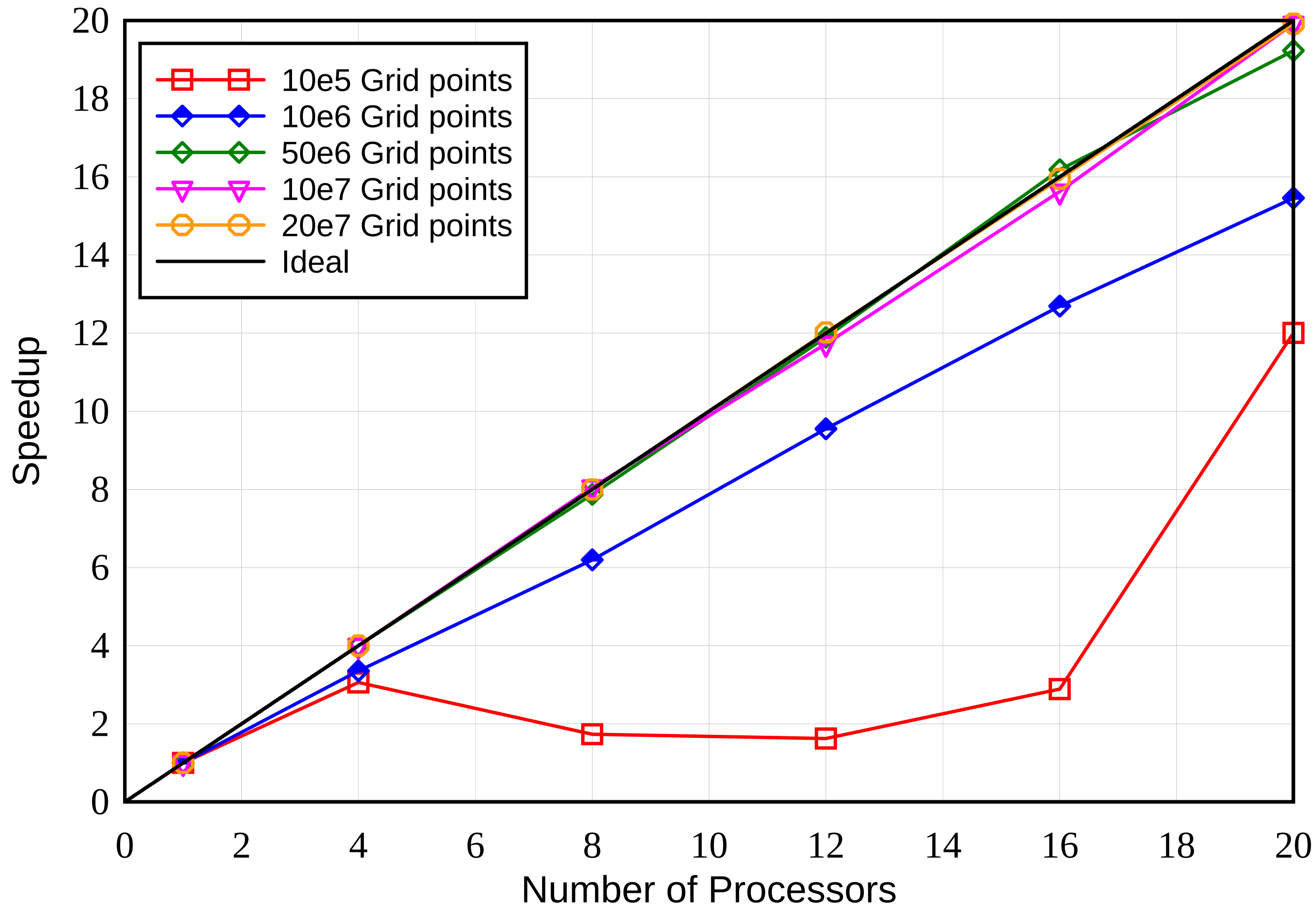
Parallelization



Parallelization Strategy

Parallel performance tests



*TEMF Cluster: **20** INTEL CPUs @ **3.4**GHz, **8**GB RAM, **1**Gbit/s Ethernet Network*

Parallelization Strategy

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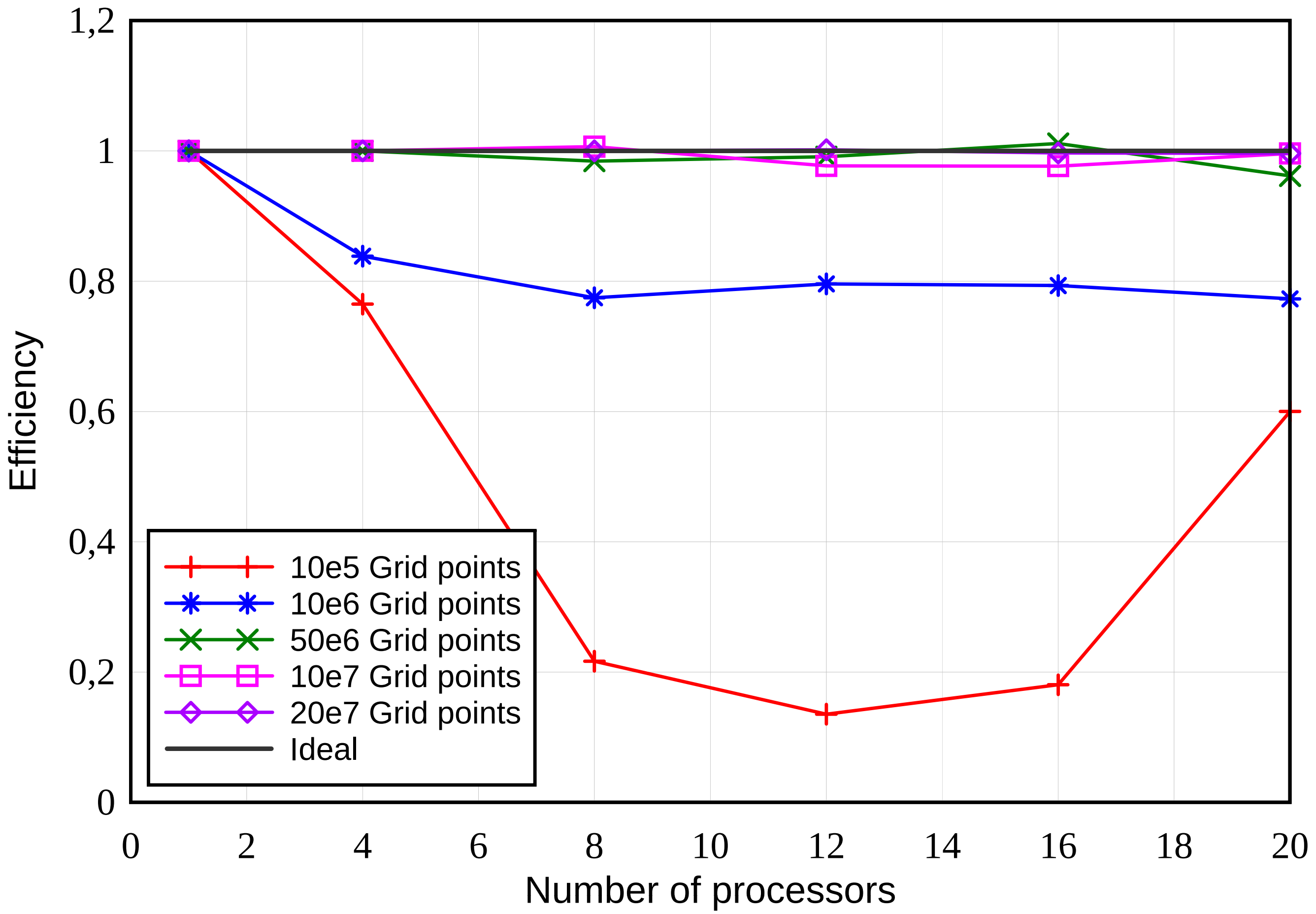
Parallel performance tests



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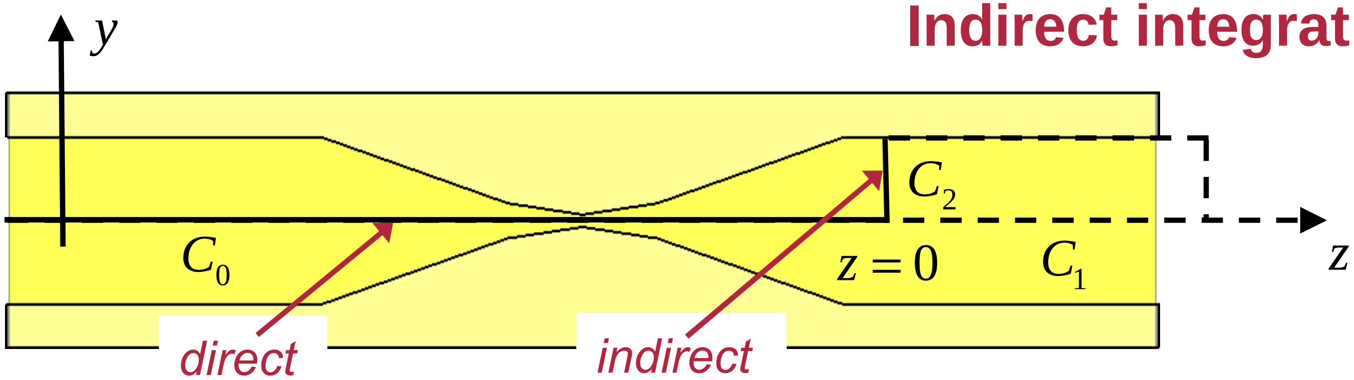
Modal Termination of Pipes

Indirect integration schemes



$$W_z(s) = -\frac{1}{Q}\int_{-\infty}^{\infty} dz\, E_z(z, t=\frac{z+s}{c}) = -\frac{1}{Q}\int_{C_0} dz\, E_z(z, t=\frac{z+s}{c}) - \frac{1}{Q}\int_{C_2} dy\, G_y^{TM}(0, t=\frac{s}{c})$$

1. Indirect integration of potential for 2D-structures *(Weiland 1983, Napoly 1993)*

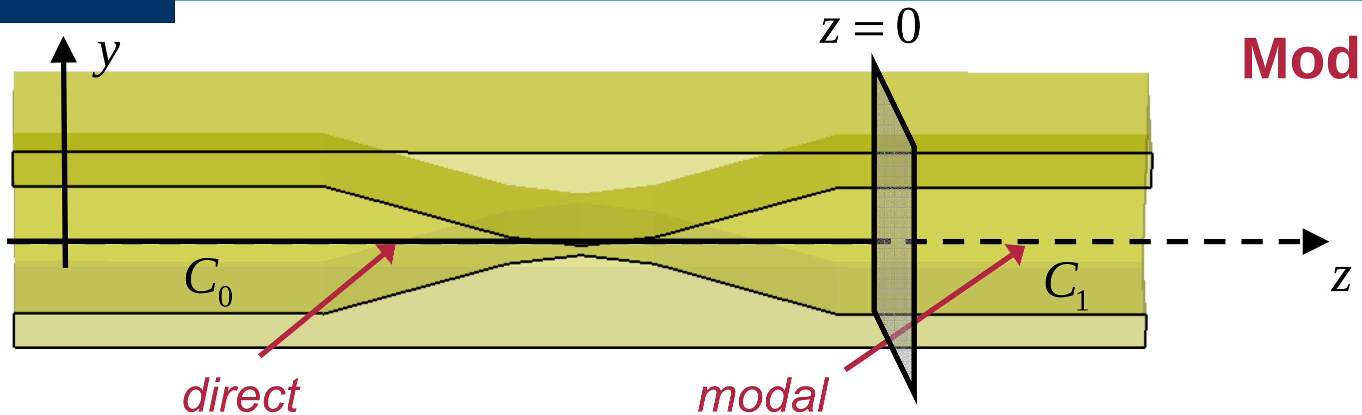
2. Generalization for 3D-structures *(A. Henke and W. Bruns, EPAC'06, July 2006, Edinburgh, UK)*

$$\vec{G}^{TM} = \vec{e}_x\left(E_x^{TM} + cB_y^{TM}\right) + \vec{e}_y\left(E_y^{TM} - cB_x^{TM}\right) + \vec{e}_z E_z$$

irrotational

Modal Termination of Pipes

Modal approach



$$W_z(s) = -\frac{1}{Q}\int_{-\infty}^{\infty} dz\, E_z\left(z, t=\frac{z+s}{c}\right) = -\frac{1}{Q}\int_{C_0} dz\, E_z\left(z, t=\frac{z+s}{c}\right) - \frac{1}{Q}\sum_n e_z^n(x,y) W_n(s)$$

$$\int_0^{\infty} dz\, E_z(x,y,z,t=(z+s)/c) = \int_0^{\infty} dz \left[\int_{-\infty}^{\infty} d\omega \sum_n C_n(\omega) e_z^n(x,y) e^{ik_n(\omega)z} e^{-i\omega\frac{z+s}{c}}\right] =$$

spectral coefficient of n-th (TM) mode

$$= \sum_n e_z^n(x,y) \int_{-\infty}^{\infty} d\omega\, C_n(\omega) \frac{1}{i\left(\omega/c - k_{z,n}(\omega)\right)} e^{-i(\omega/c)s}$$

n-th (TM) mode contribution

- ~ 1982 Robert Siemann
- *"Indirect methods for wake potential integration", I.* Zagorodnov, PRSTAB 9 '06
- *"Eigenmode expansion method in the indirect calculation of wake potential in 3D structures",* *X.* Dong, E. Gjonaj, ICAP'06

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Modal Termination of Pipes

1. Time domain integration in the inhomogeneous sections:

$$-\frac{1}{Q}\int_{-\infty}^{0} dz\, E_z(z, t = \frac{z+s}{c})$$

2. Modal analysis at z = 0: $E_z(x, y, 0, t) \quad \Rightarrow \quad E_z^n(0,t),\ e_z^n(x,y)$

3. Compute spectral coefficients (FFT): $E_z^n(0,t) \quad \Rightarrow \quad C_n(\omega)$

4. Compute wake potential contribution per mode (IFFT):

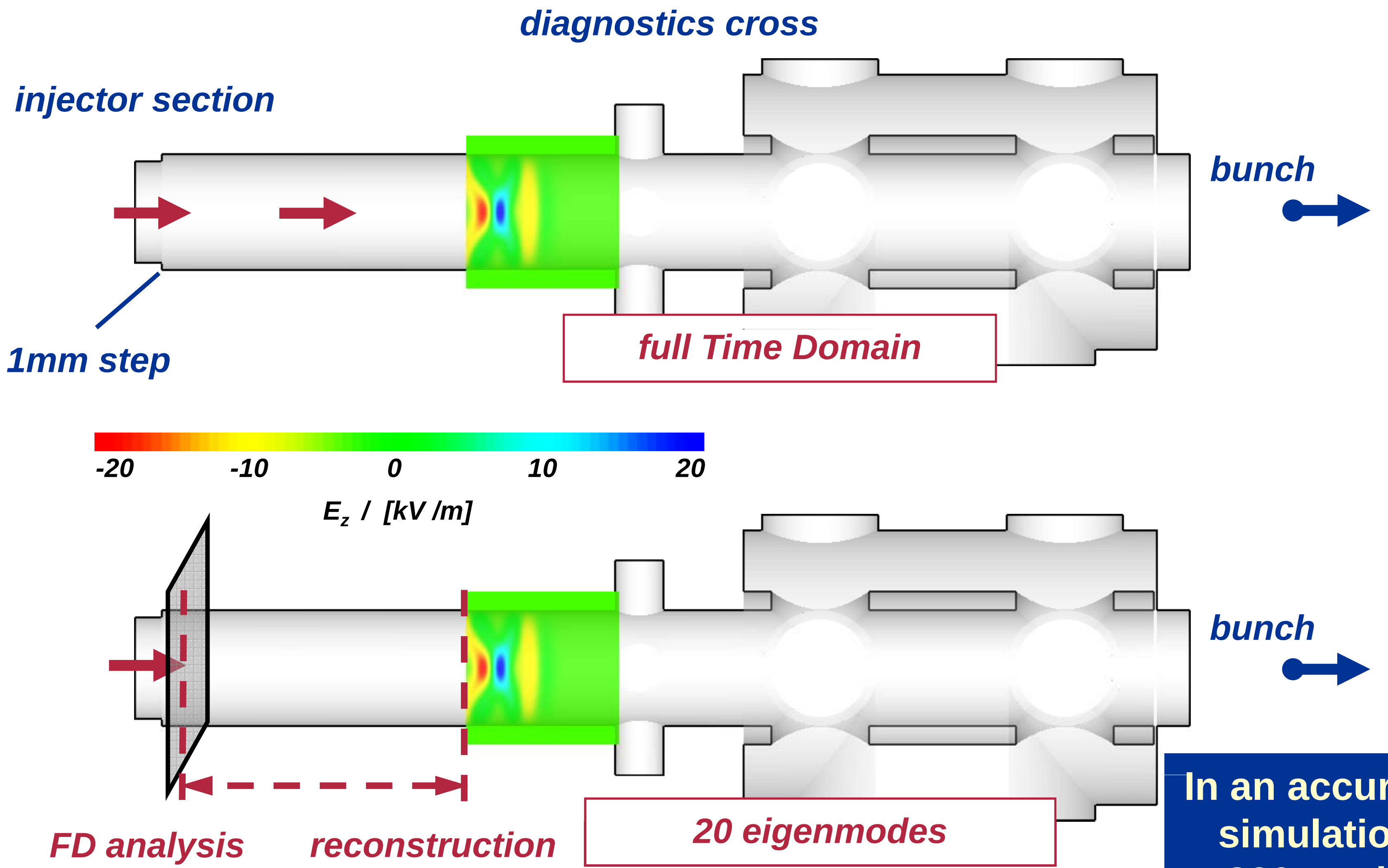
$$\frac{C_n(\omega)}{i\left(\omega/c - k_{z,n}(\omega)\right)} \quad \Rightarrow \quad W_n(s)$$

5. Compute wake potential transition in the outgoing pipe:

$$-\frac{1}{Q}\int_{0}^{\infty} dz\, E_z(z, t = \frac{z+s}{c}) = -\frac{1}{Q}\sum_n e_z^n(x,y) W_n(s)$$

Modal Termination of Pipes

Using FD reconstruction in long intermediate pipes



In an accurate simulation ~300 modes

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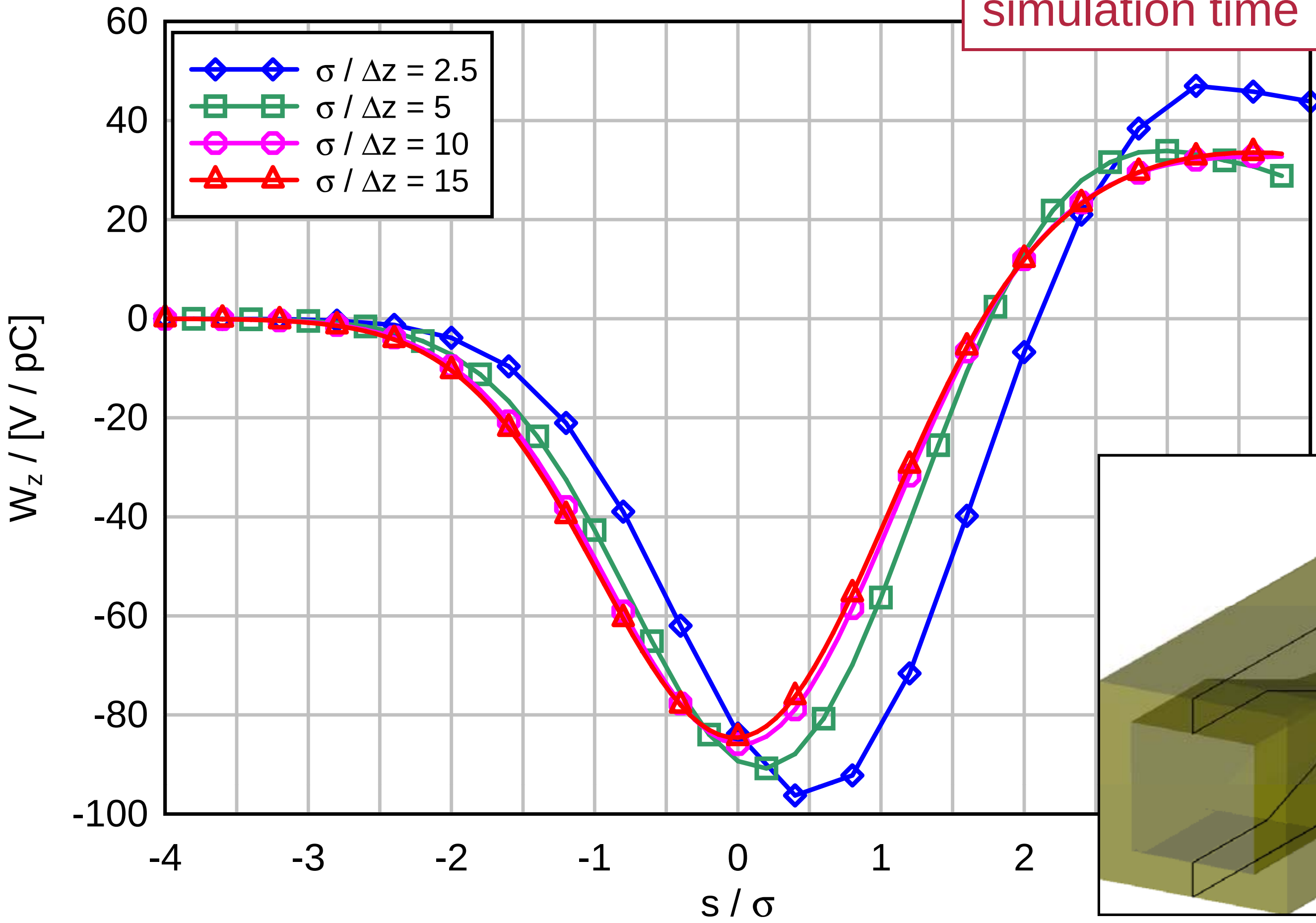
ILC-ESA collimator

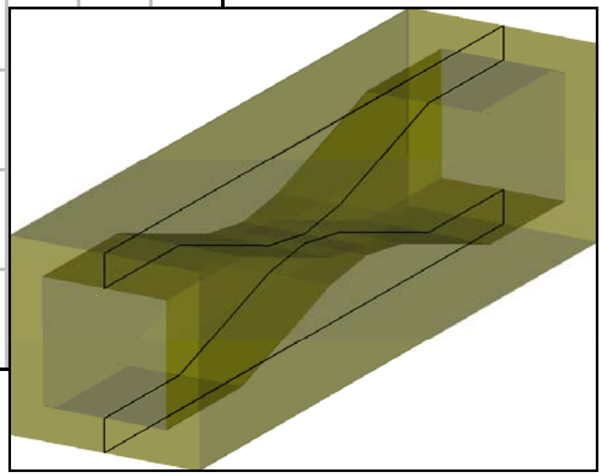
ILC-ESA collimator #8

bunch size	*300µm*
no. of grid points	~450M
no. of processors	24
simulation time	85hrs

Convergence vs. grid step



Moving window: 3 mm length



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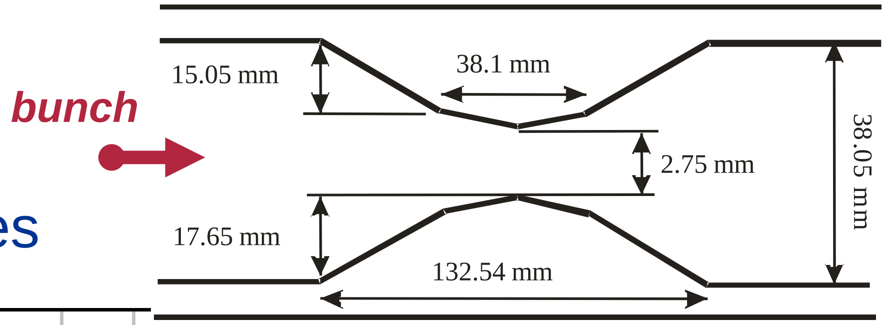
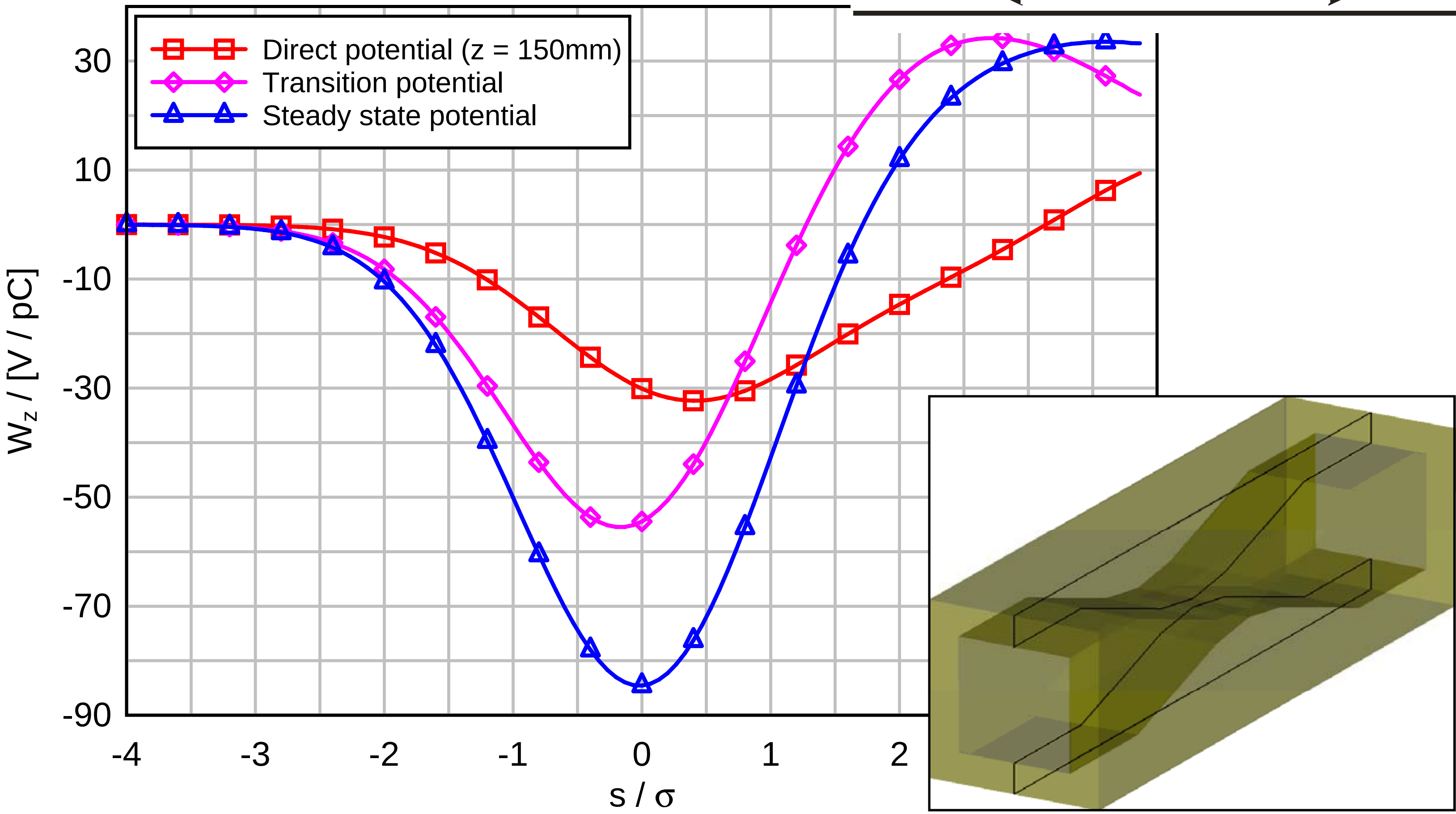
ILC-ESA collimator

ILC-ESA collimator #8



Direct and transition wakes



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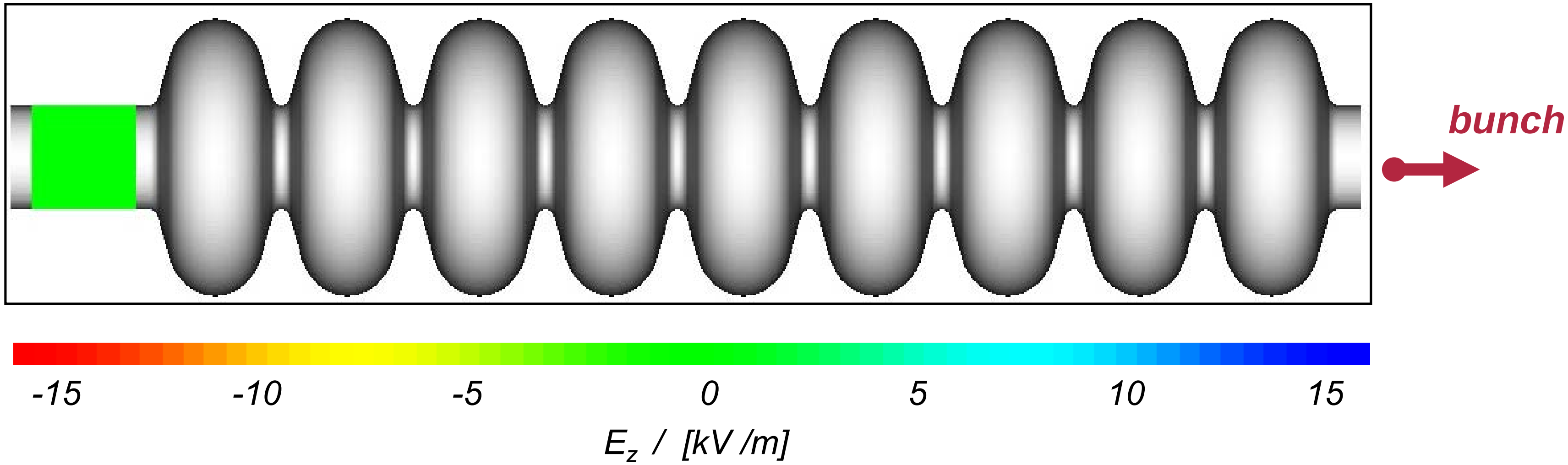
TESLA / HOM coupler

TESLA 9-cell cavity

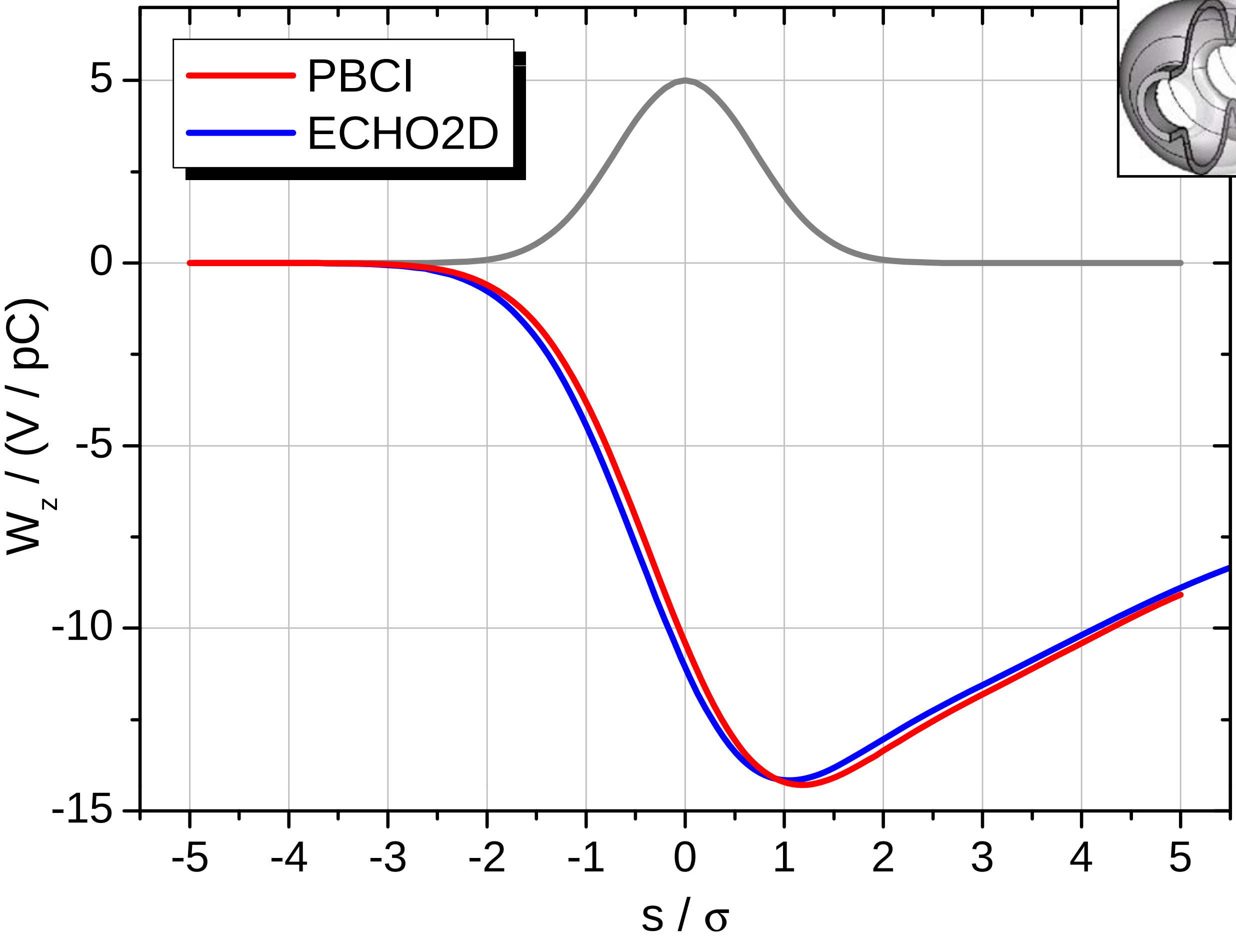


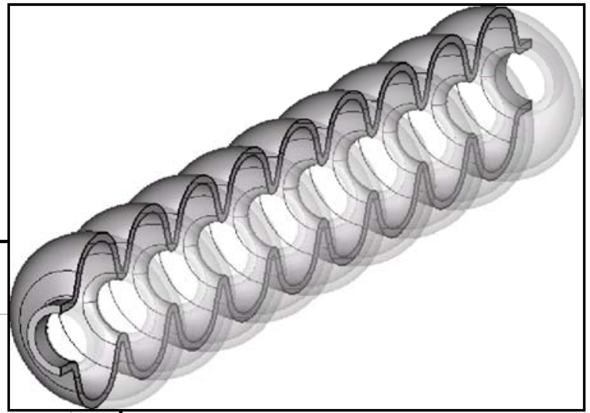
bunch length	1mm
bunch charge	1nC
cavity length	1.5m
no. of grid points	~760M
no. of processor cores	408
simulation time	~40hrs

TESLA / HOM coupler

TESLA 9-cell cavity

Longitudinal wake potential





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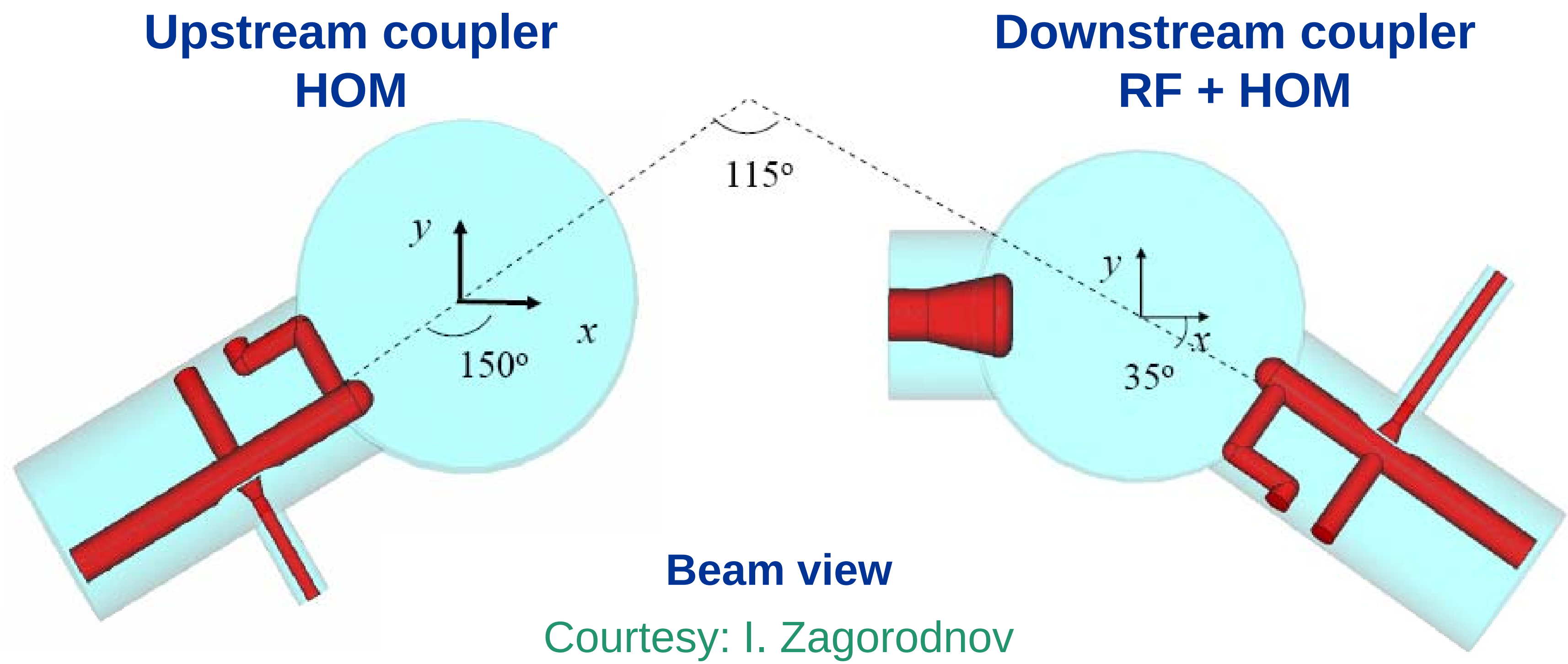
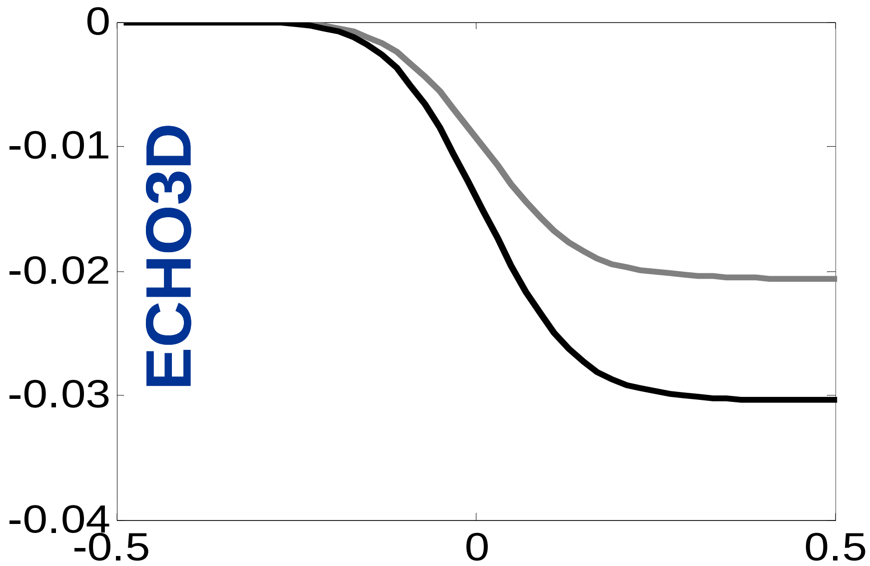
HOM / HOM-RF coupler (present DESY design)



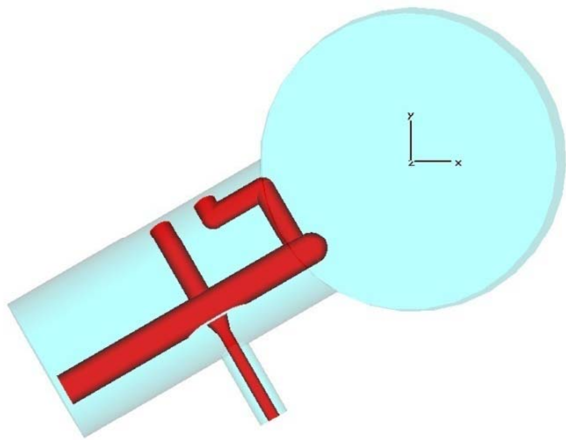
Beam view

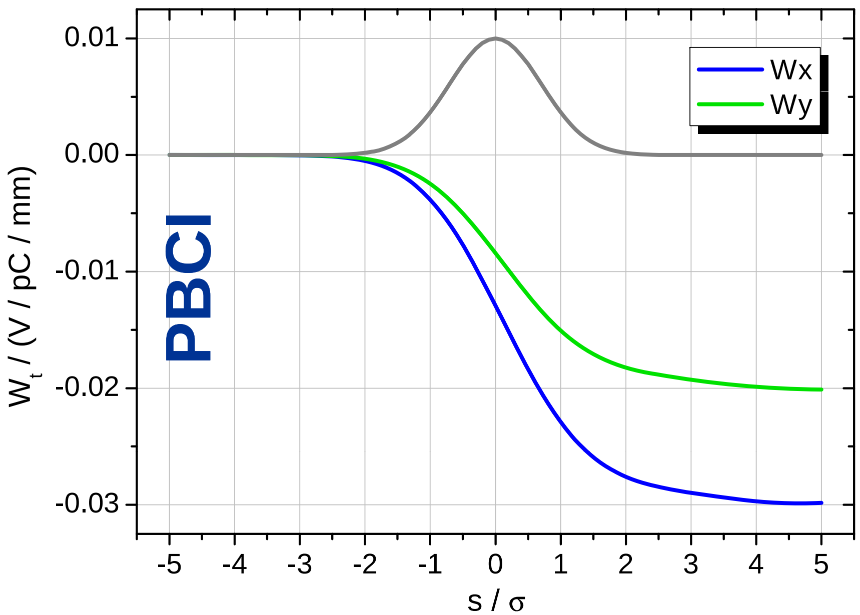
Courtesy: I. Zagorodnov

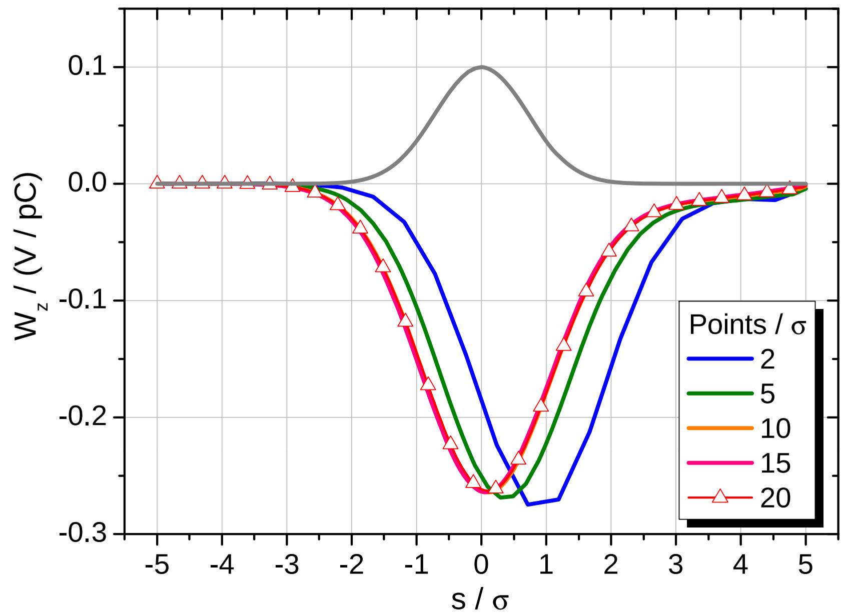
TESLA / HOM coupler



Upstream coupler







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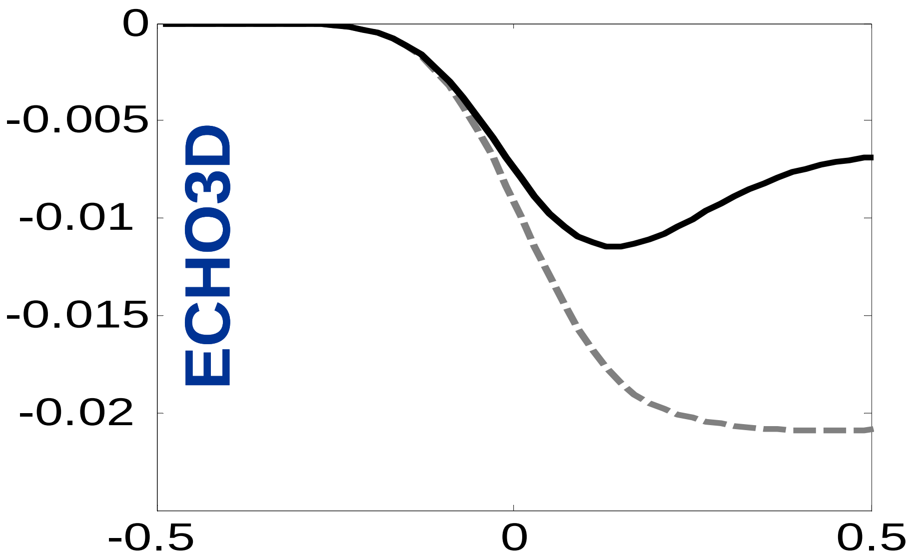
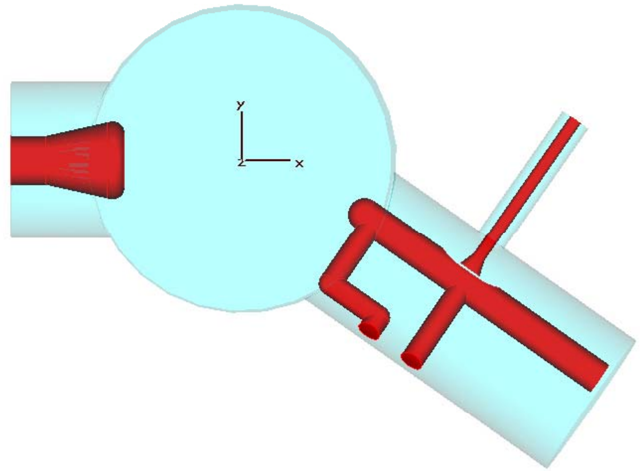
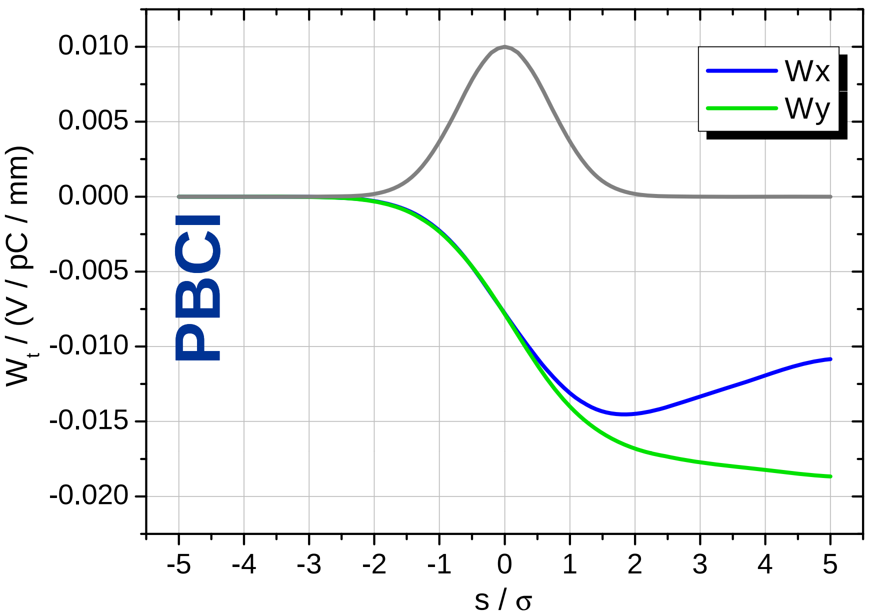
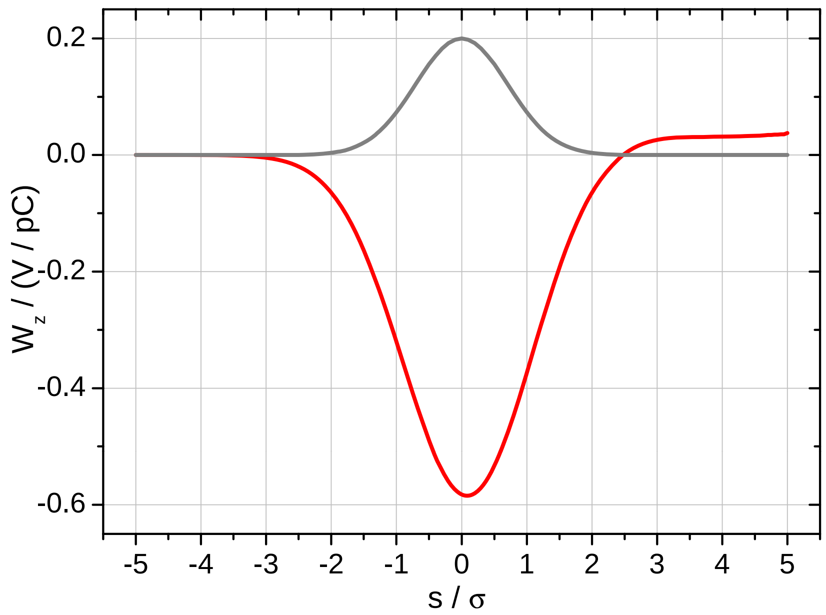


Downstream coupler







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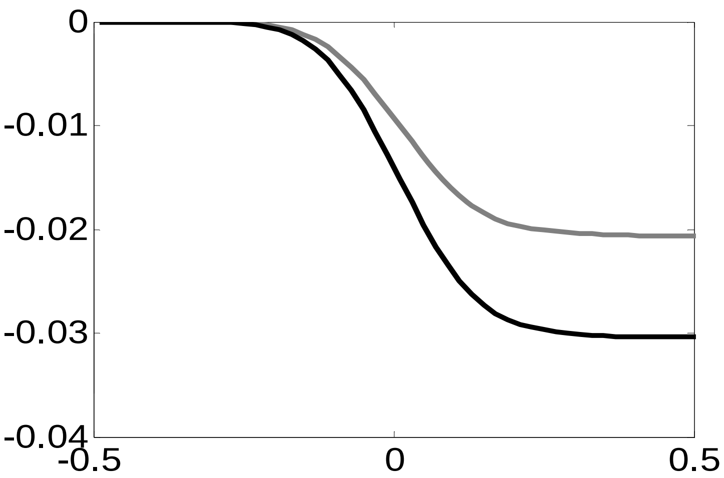
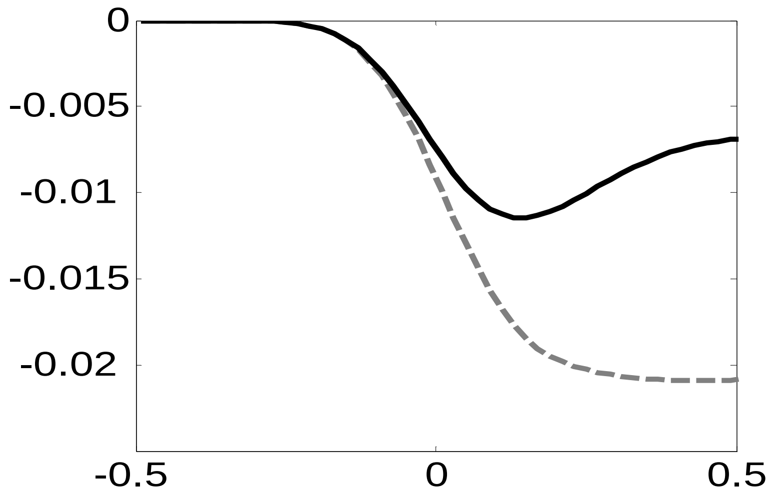
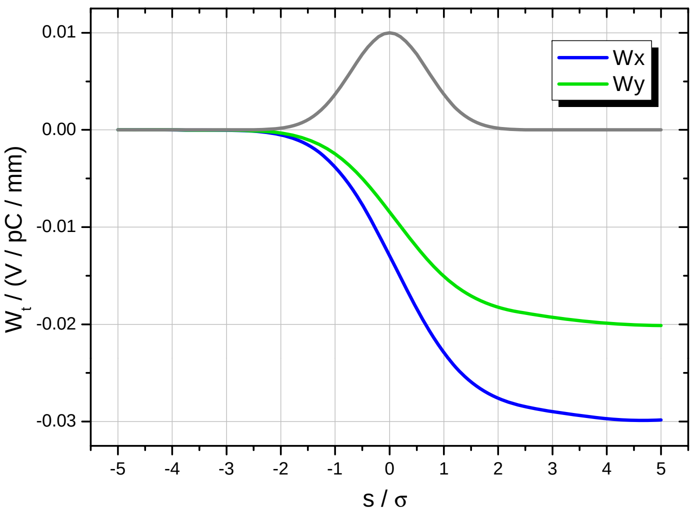
TESLA / HOM coupler

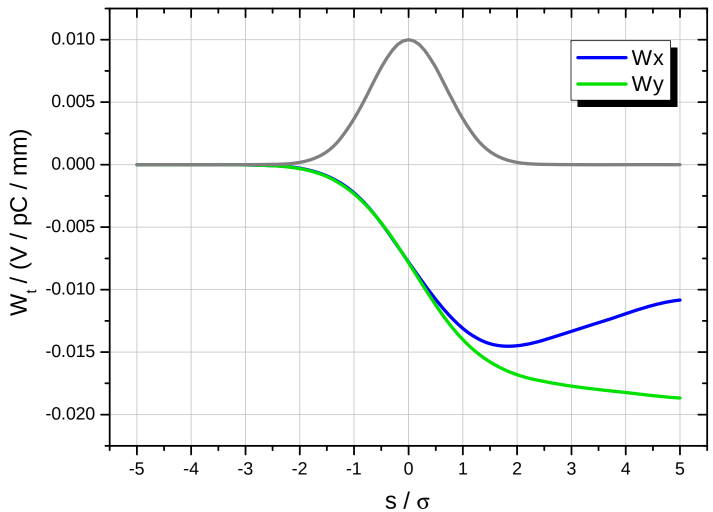
ECHO3D





PBCI

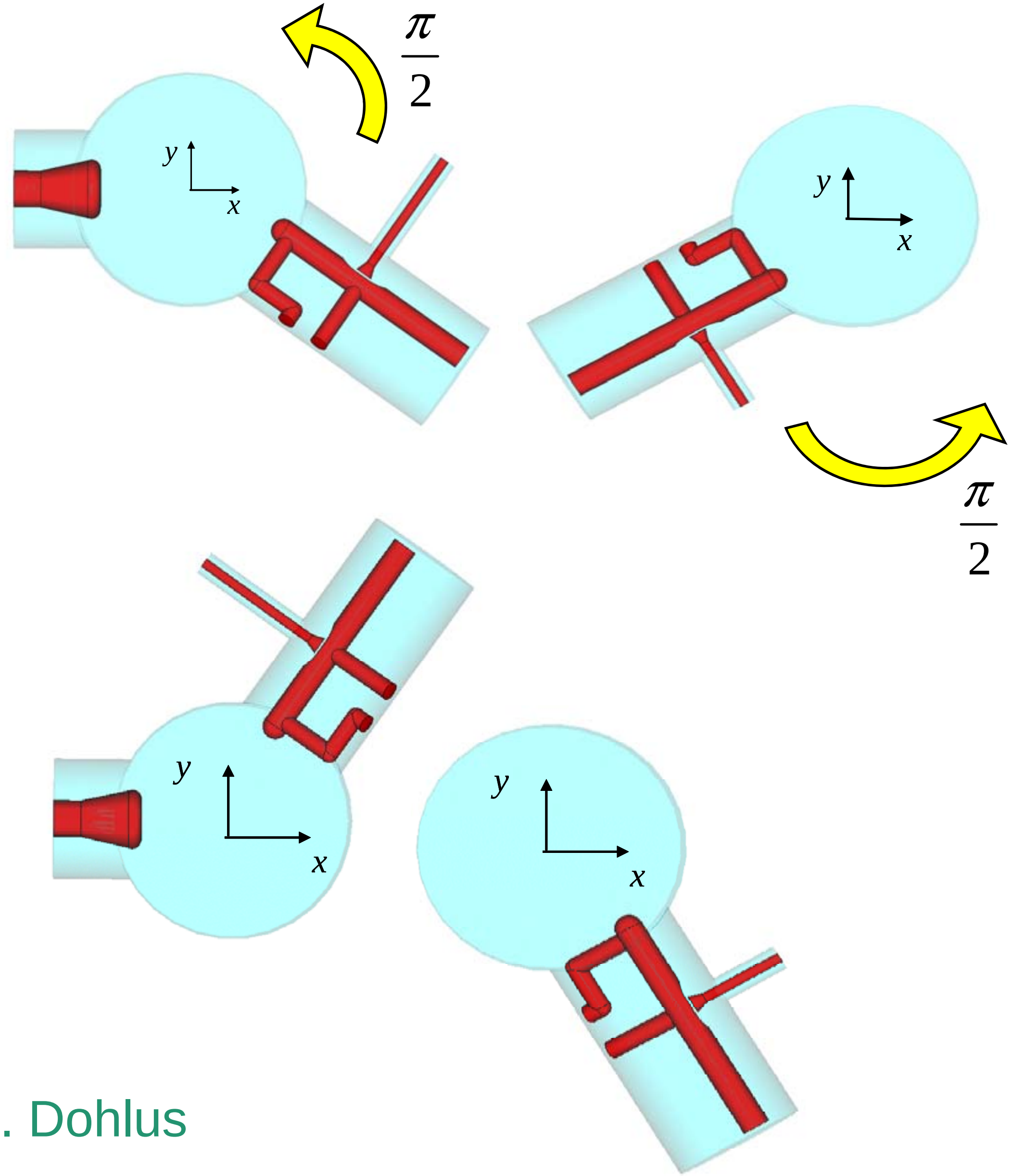




TESLA / HOM coupler

old

new



I. Zagorodnov, M. Dohlus

TESLA / HOM coupler

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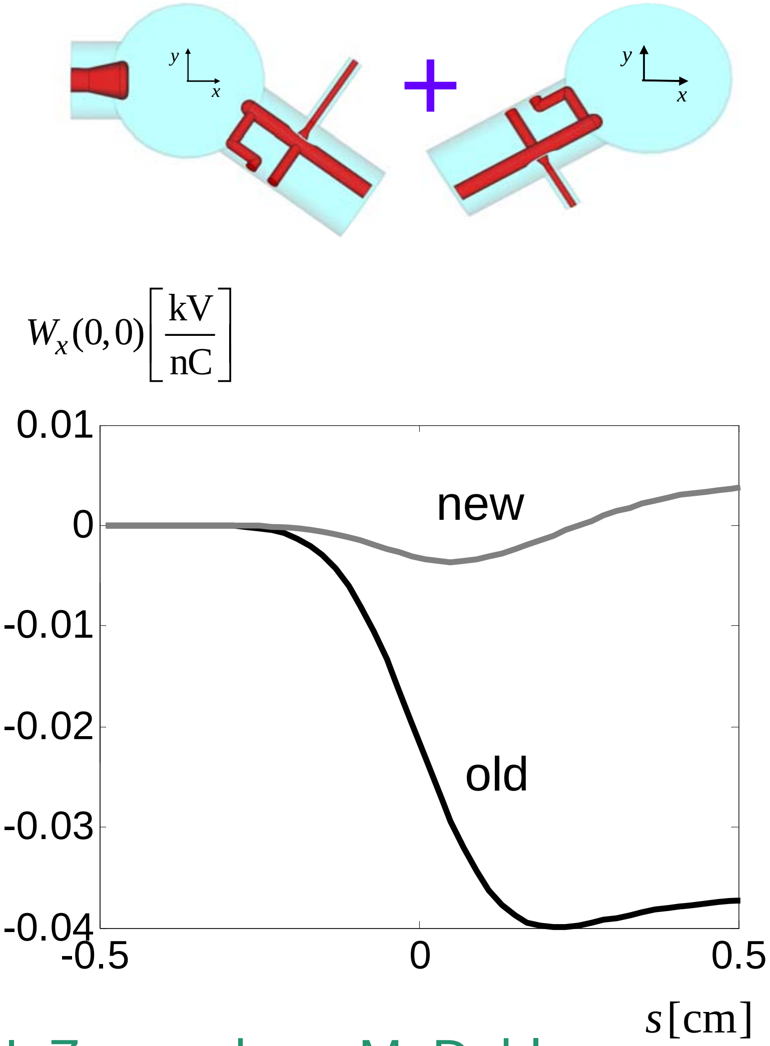
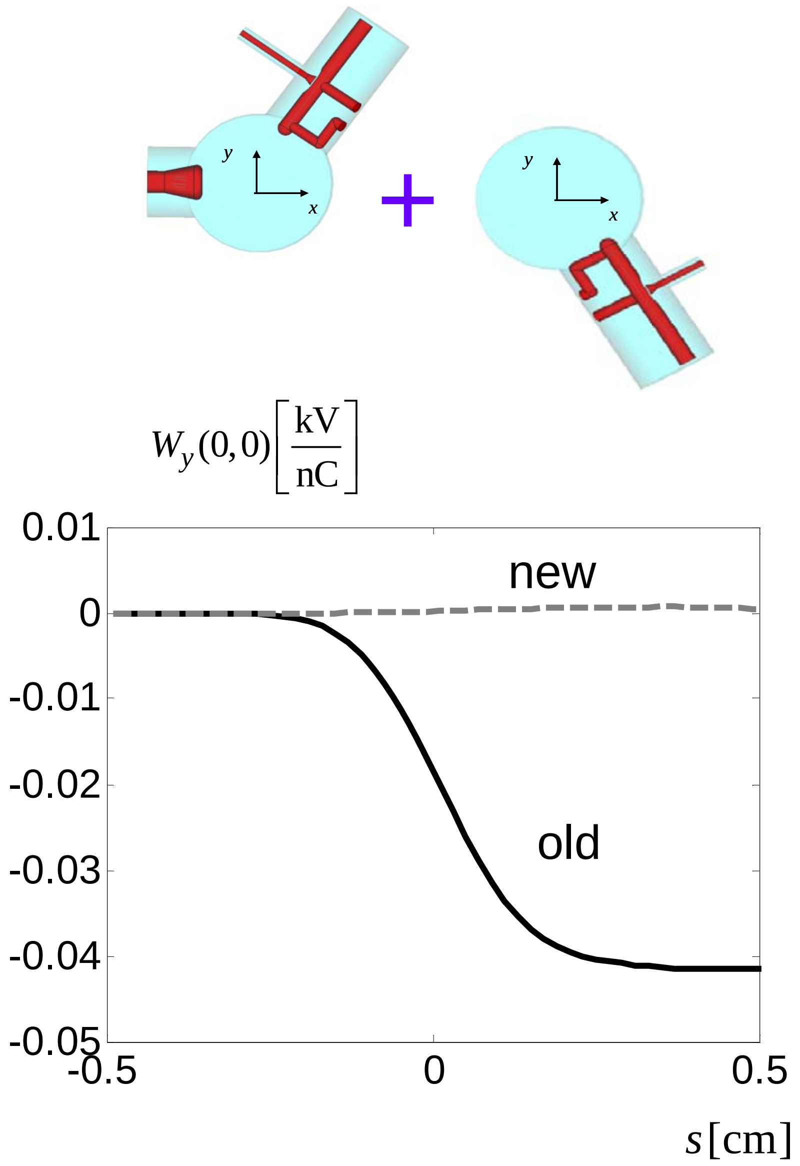
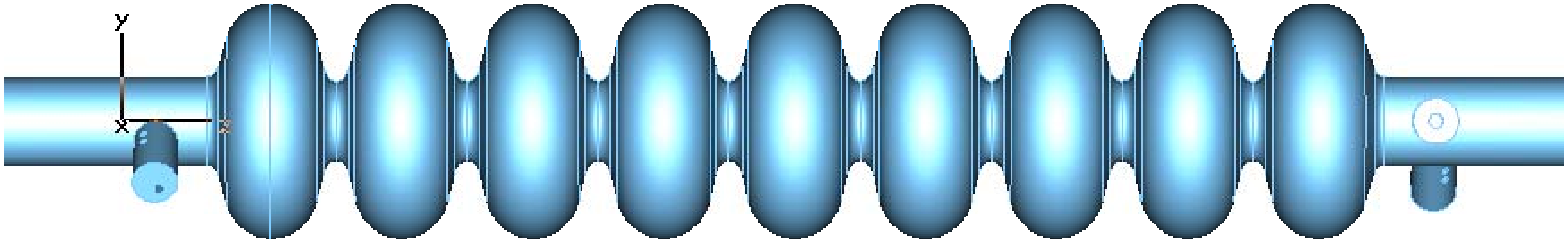




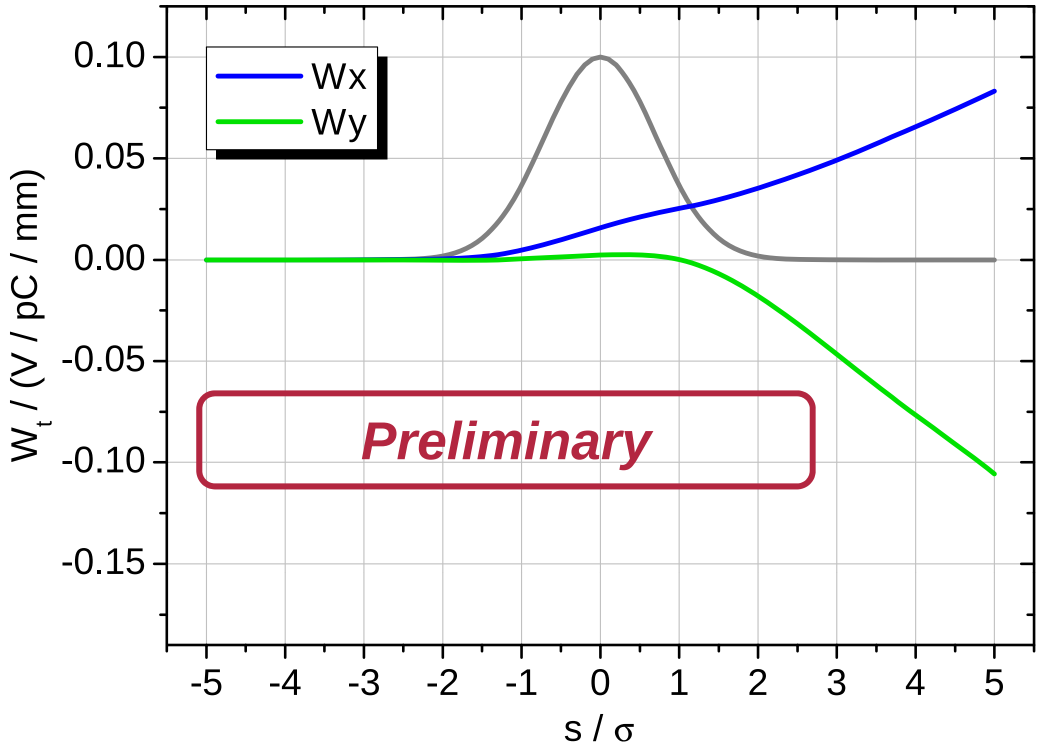
I. Zagorodnov, M. Dohlus

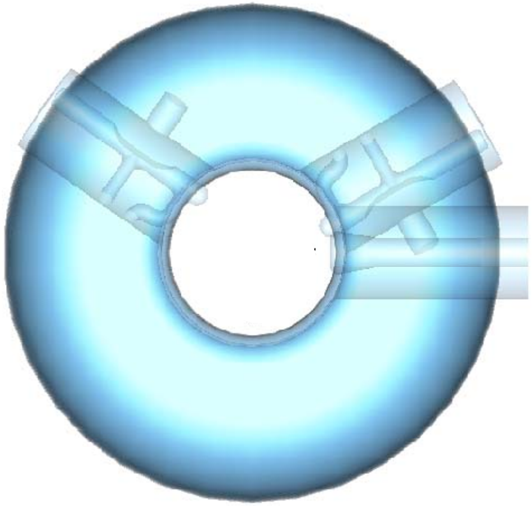
TESLA / HOM coupler

Present DESY Design



Transverse wake potential





Beam view

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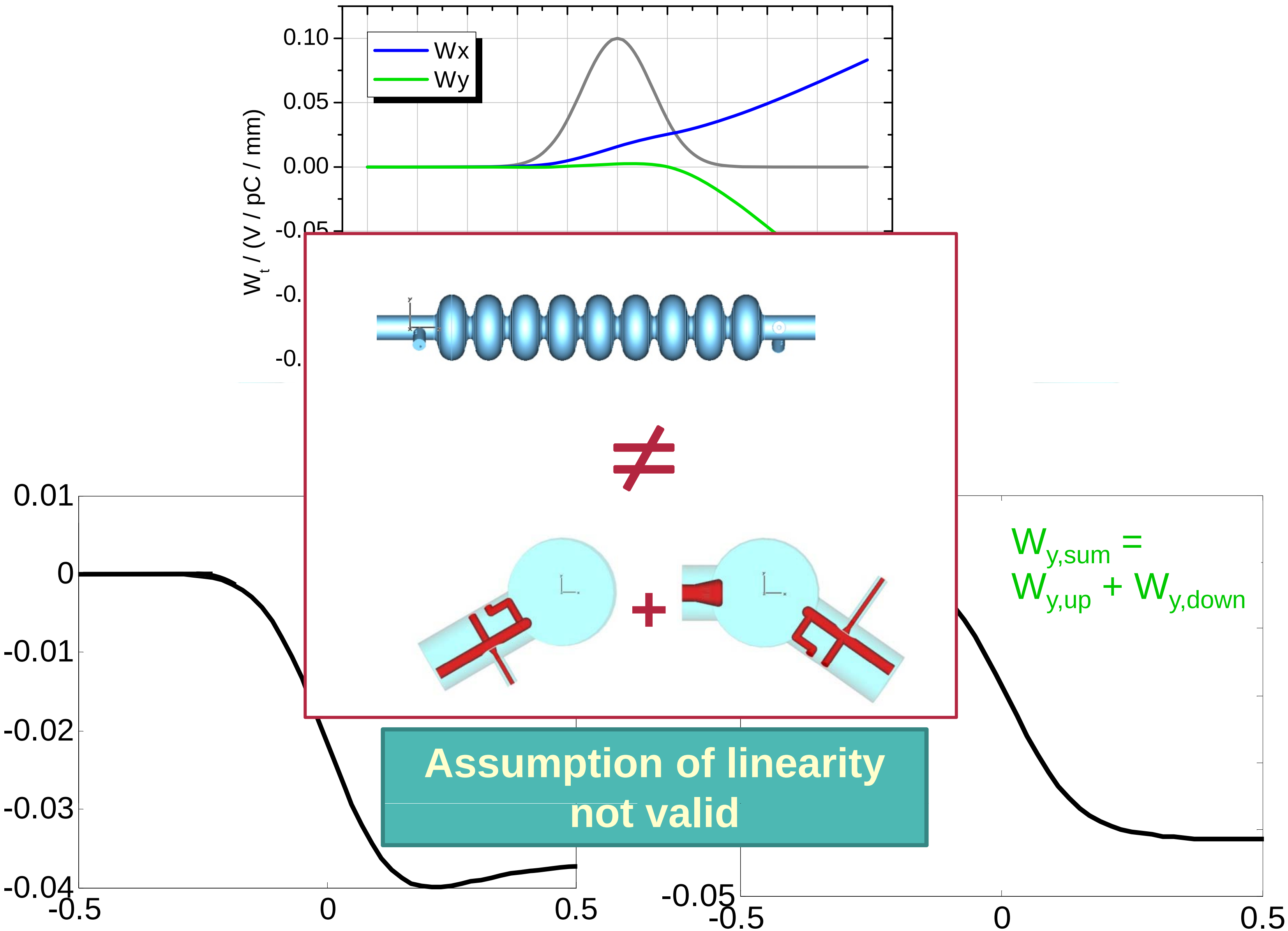
TESLA / HOM coupler



Assumption of linearity not valid

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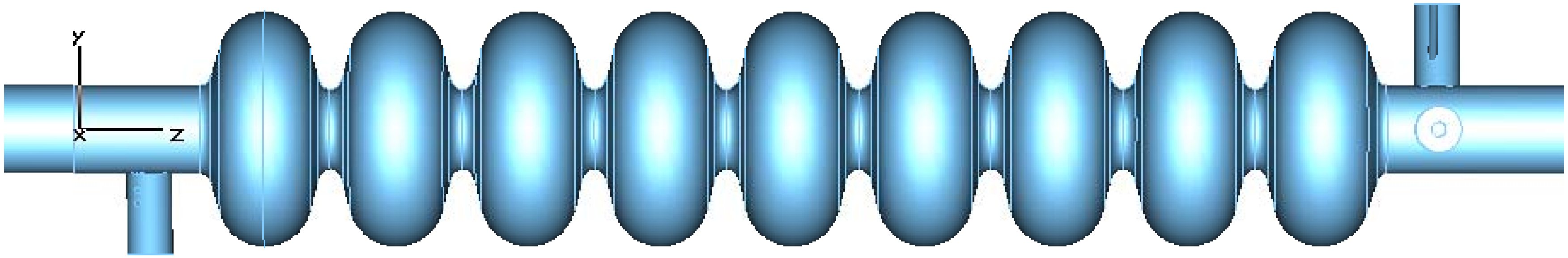
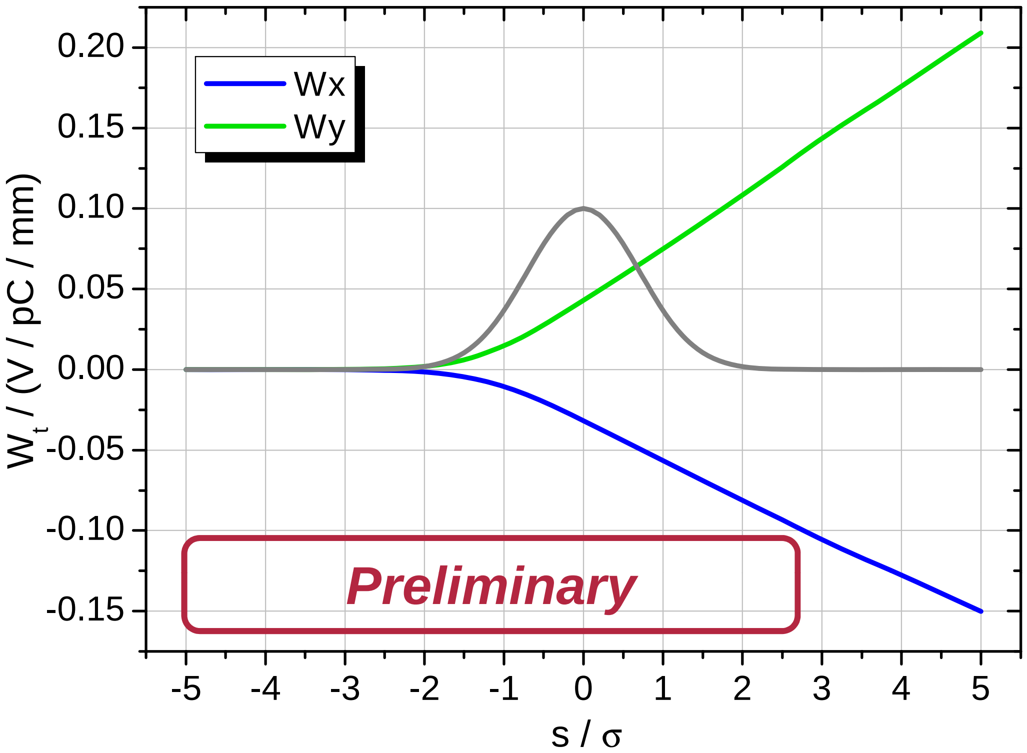
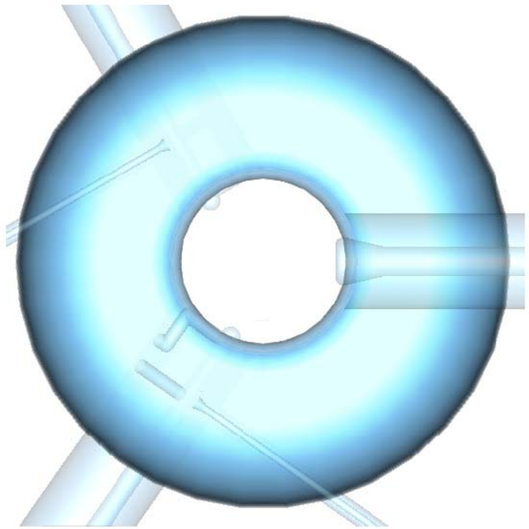
Proposed DESY Design (Dohlus, Zagorodnov)



Transverse wake potential





Beam view (symmetrical coupler positioning)

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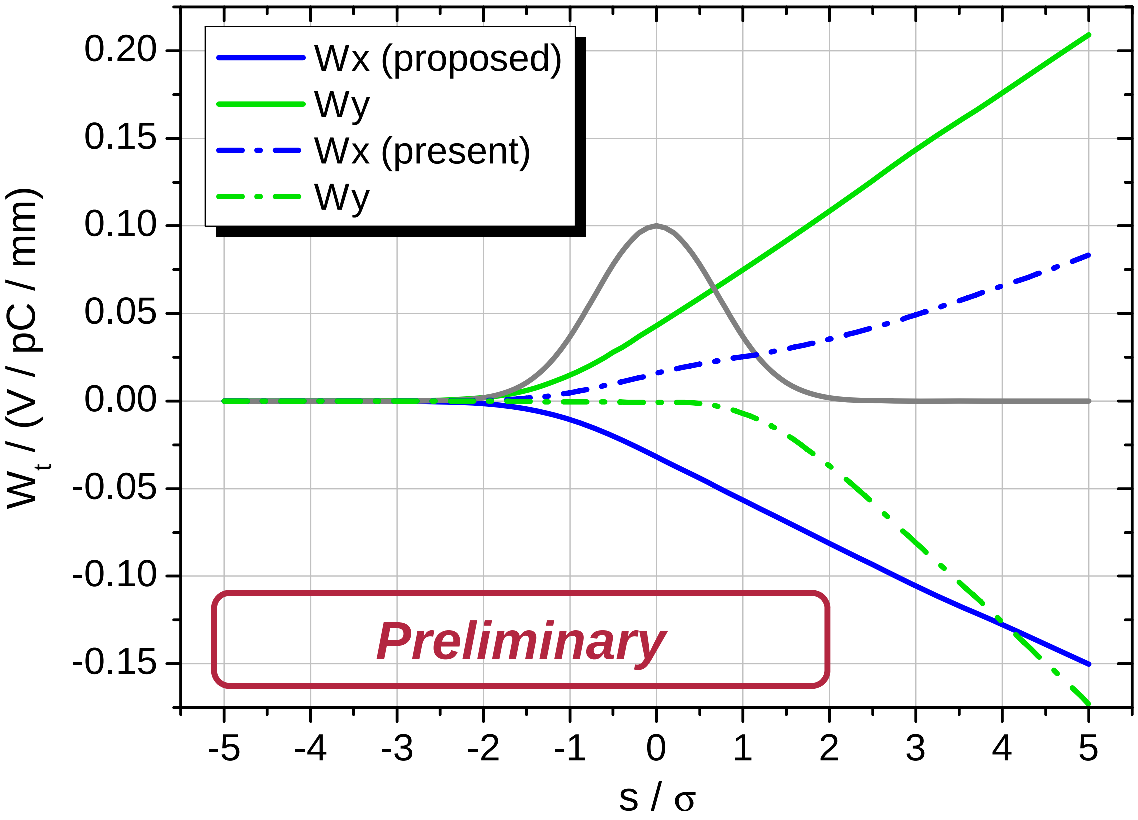
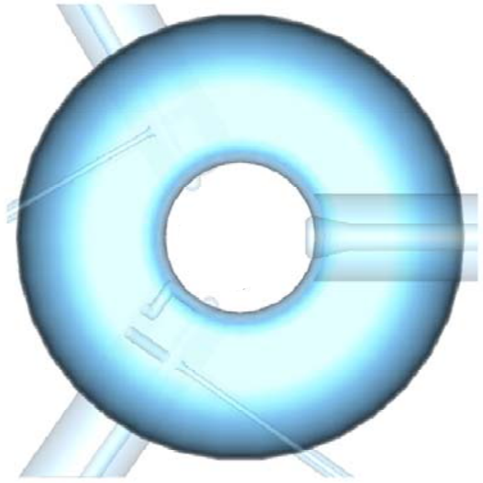
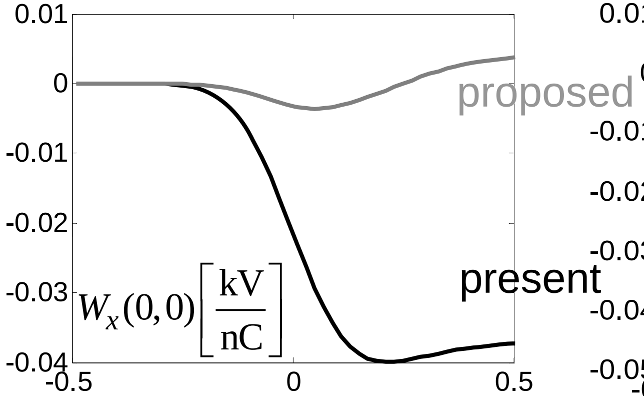
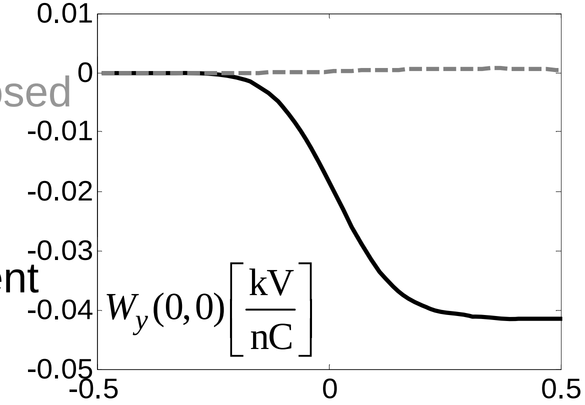
TESLA / HOM coupler

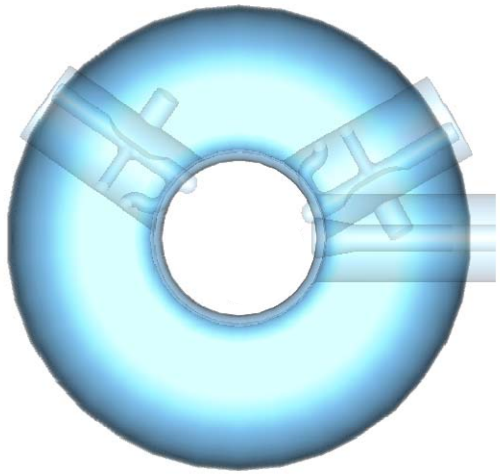




proposed







present

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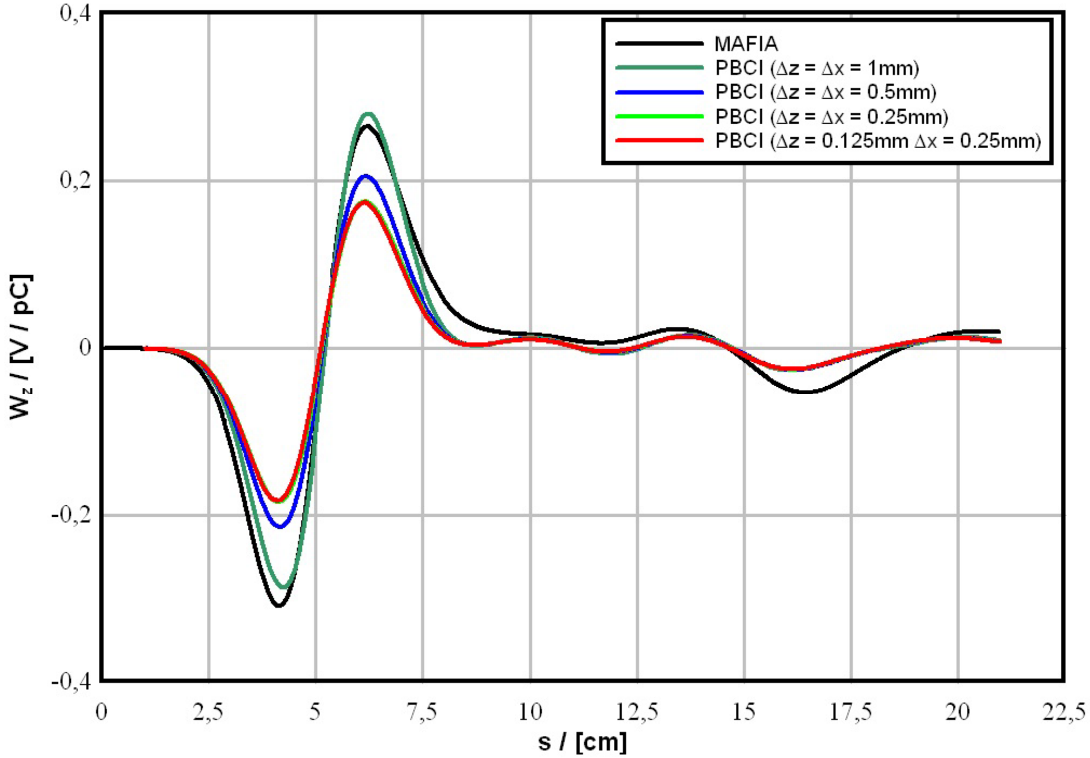
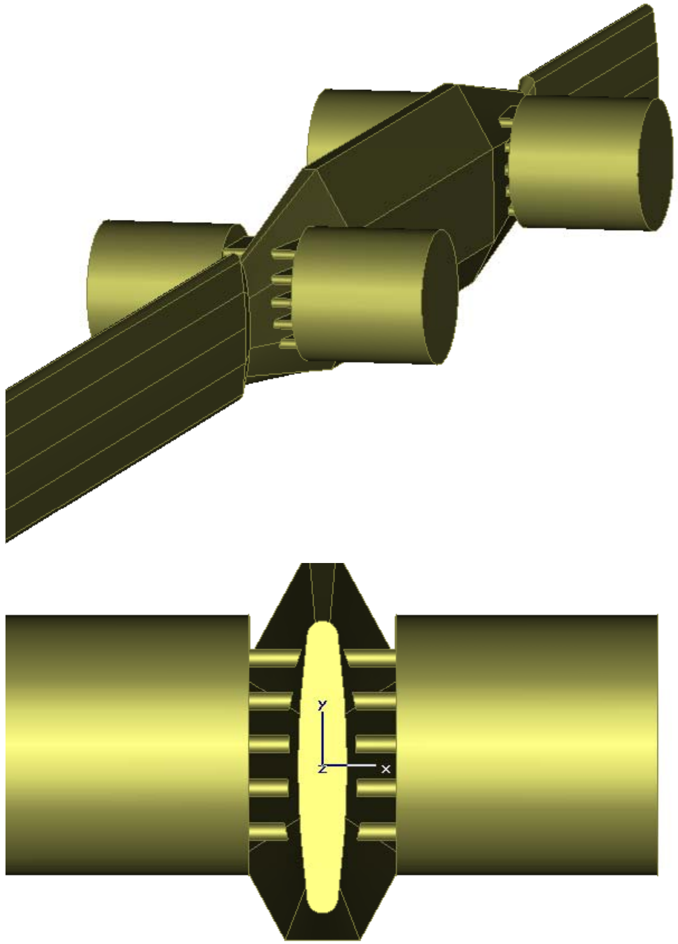
Tapered Transition PETRA III



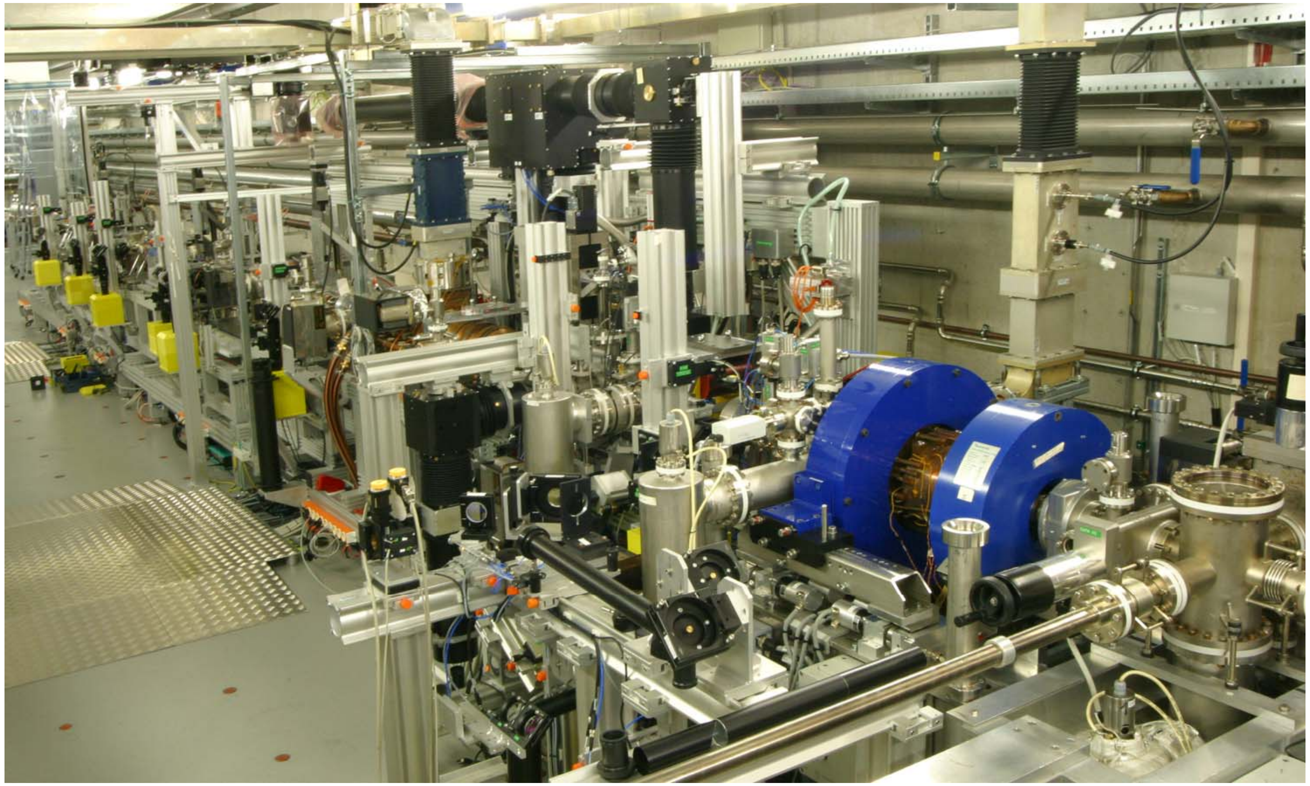


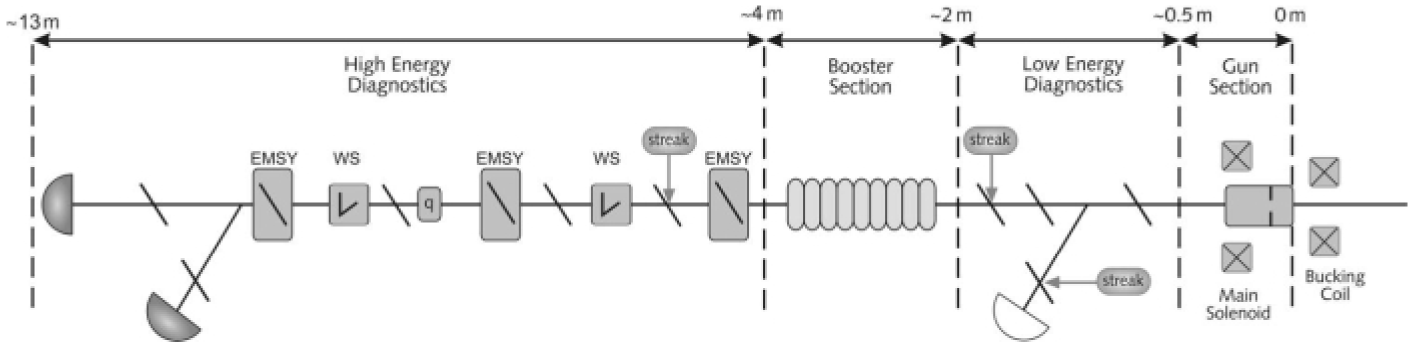
No convergence with MAFIA
due to memory limitations and dispersion

Complex geometry

"Wake Computations for Undulator Vacuum Chambers of PETRA III", R. Wanzenberg, PAC'07

Low-Emittance Injector Development DESY/Zeuthen





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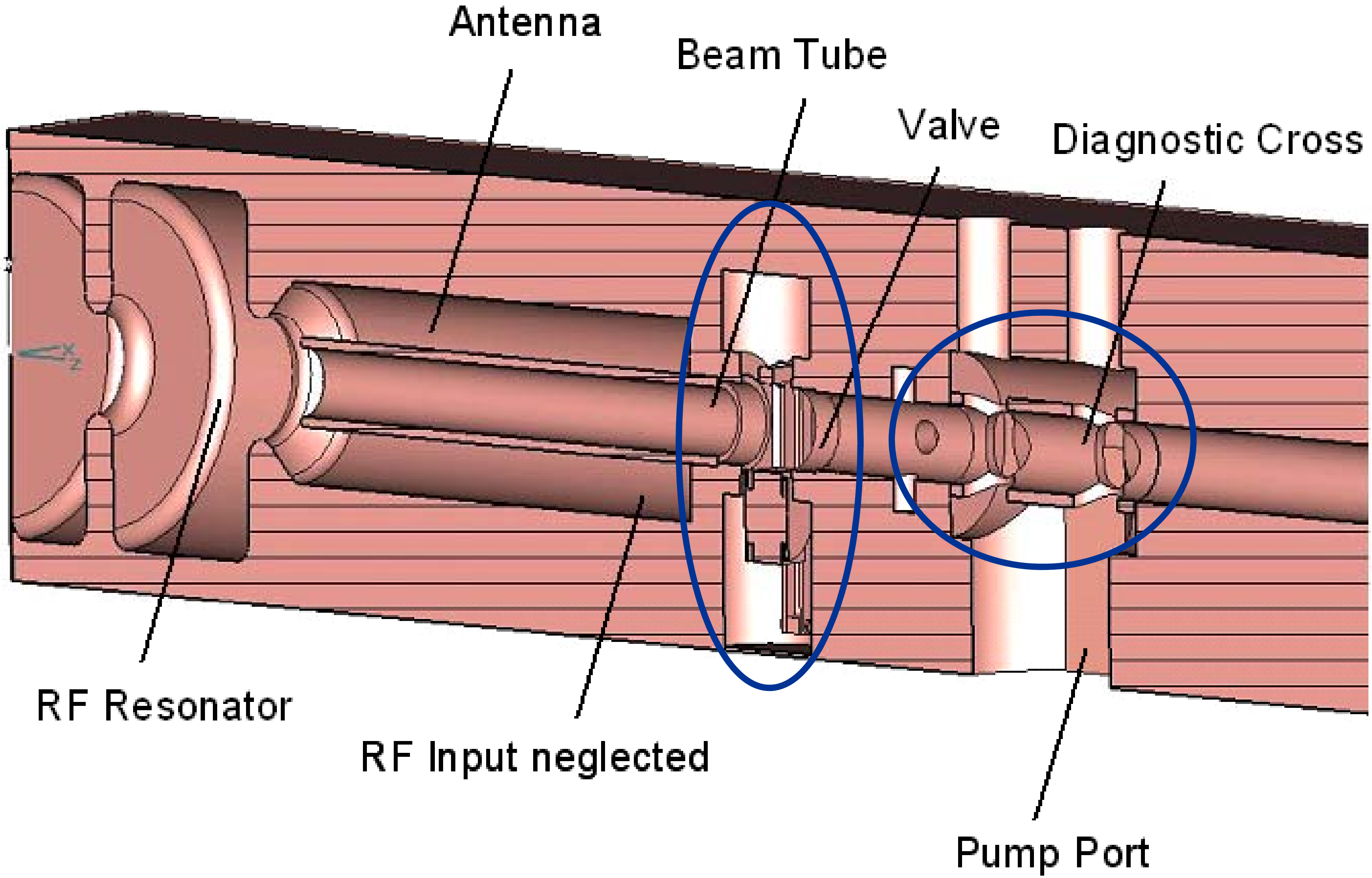
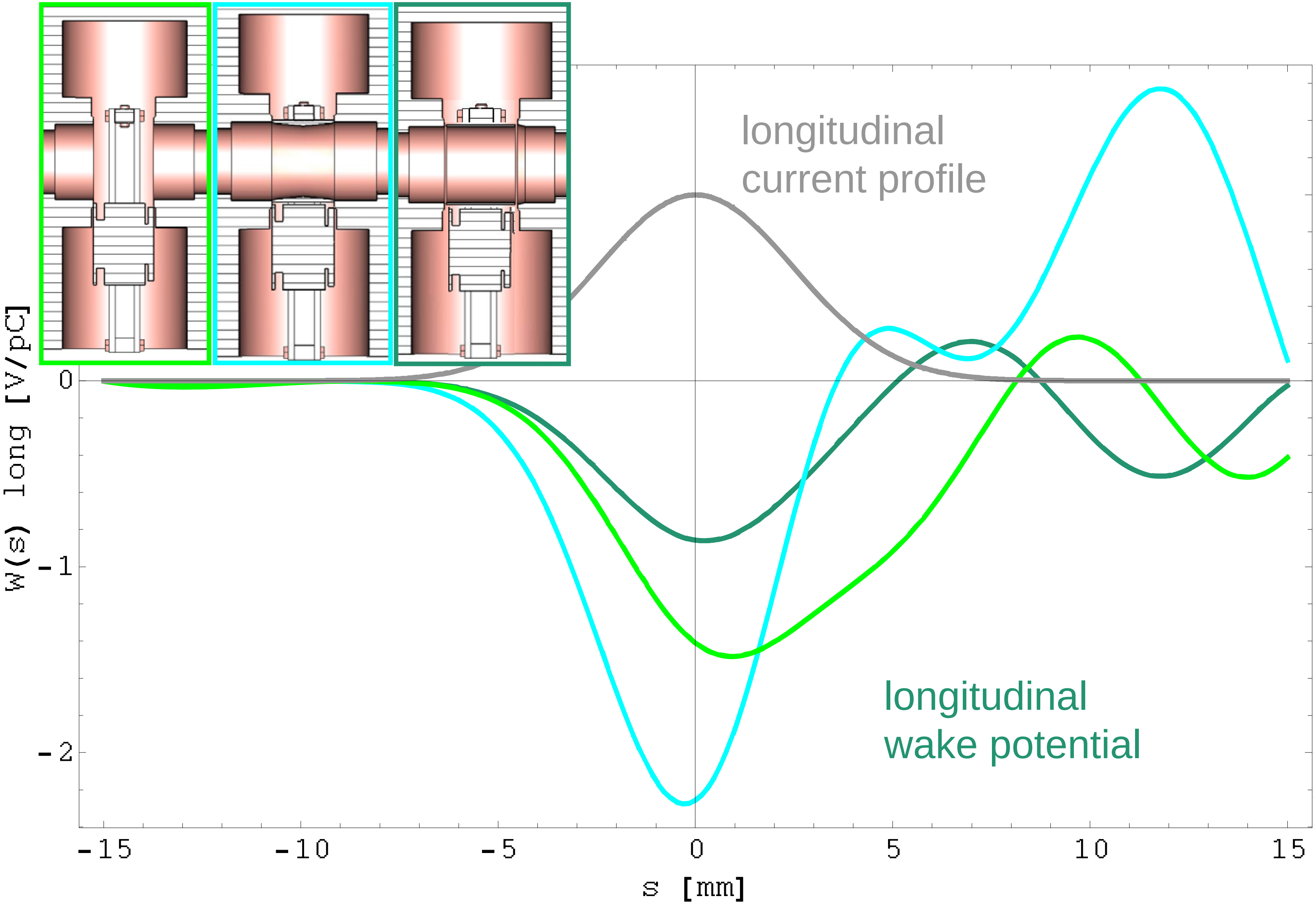
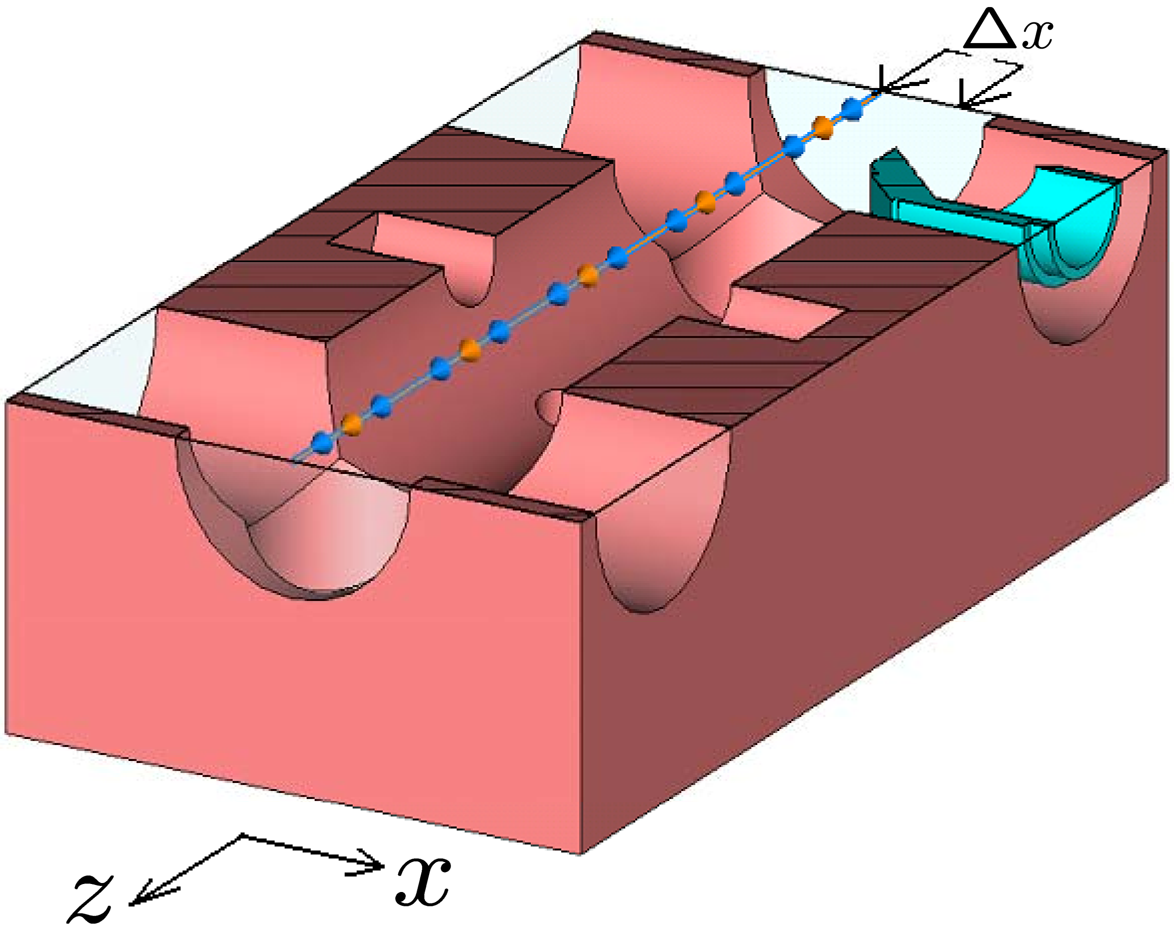
Optimization studies performed



PITZ Photoinjector

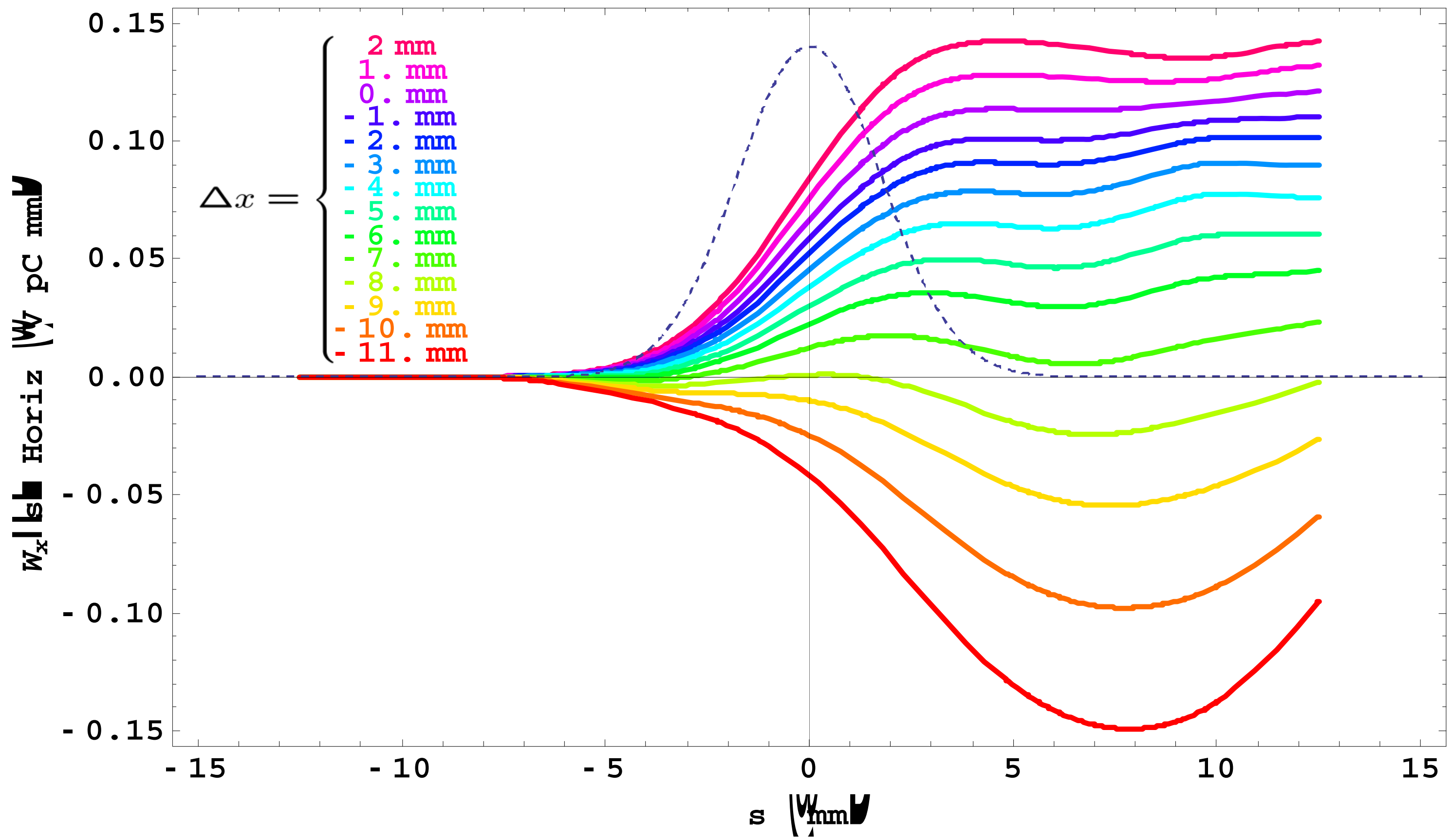


PITZ Photoinjector



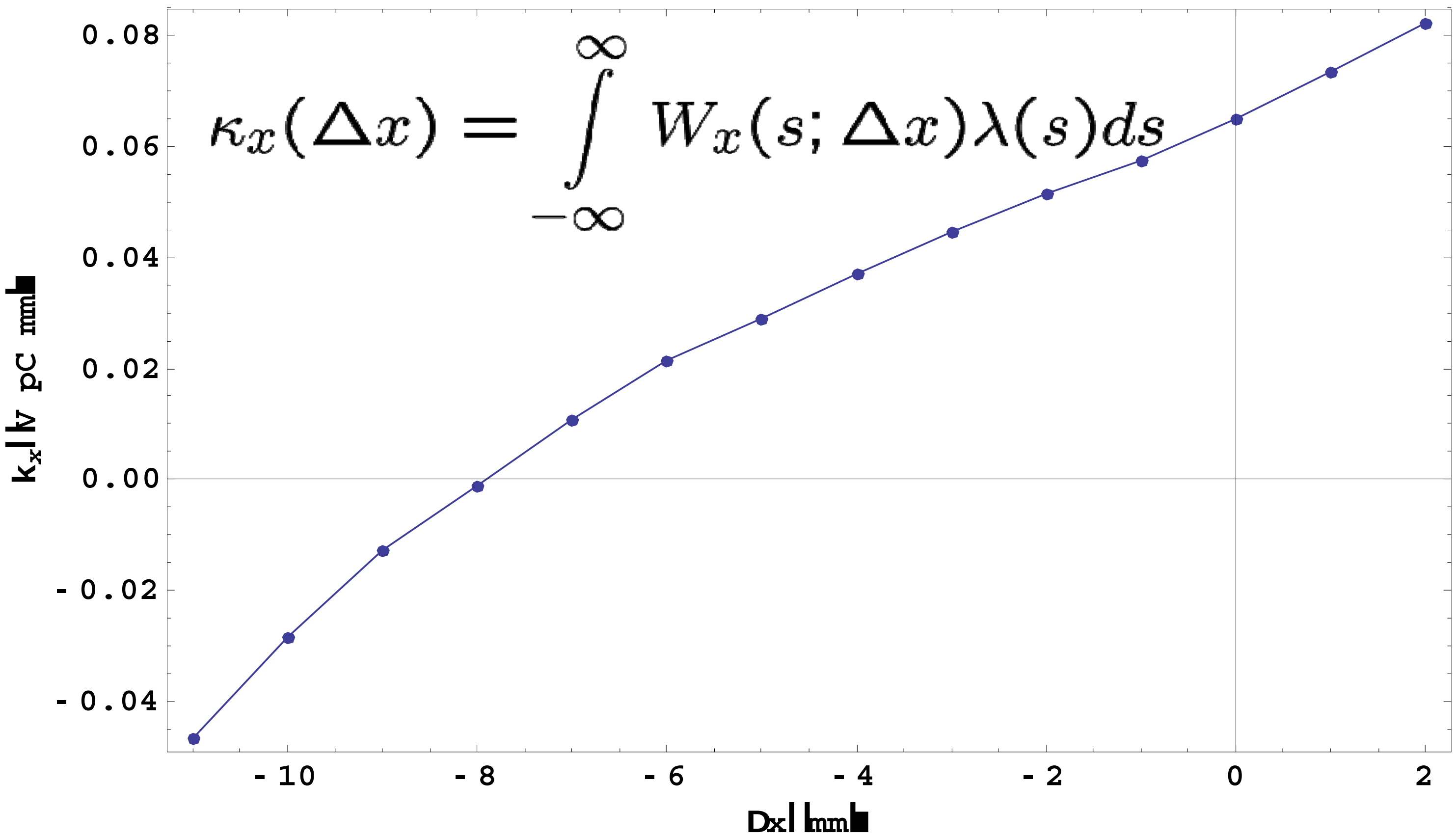
xz **plane**

PITZ Photoinjector



Plot of the horizontal wake potential for different shifts Δx of the particle path with respect to the longitudinal axis.

PITZ Photoinjector



A minimum of the transverse kick was found at 8mm distance.

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Large Scale 3D Wakefield Simulations with PBCI

S. Schnepp, W. Ackermann, E. Arevalo,
E. Gjonaj, and T. Weiland

"Wake Fest 07 - ILC wakefield workshop at SLAC"
11-13 December 2007

Technische Universität Darmstadt, Fachbereich Elektrotechnik und Informationstechnik
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