XFEL
X-Ray Free-Electron Laser

Summary from Beam Dynamics Meetings

T. Limberg for the (XFEL) Beam Dynamics Group

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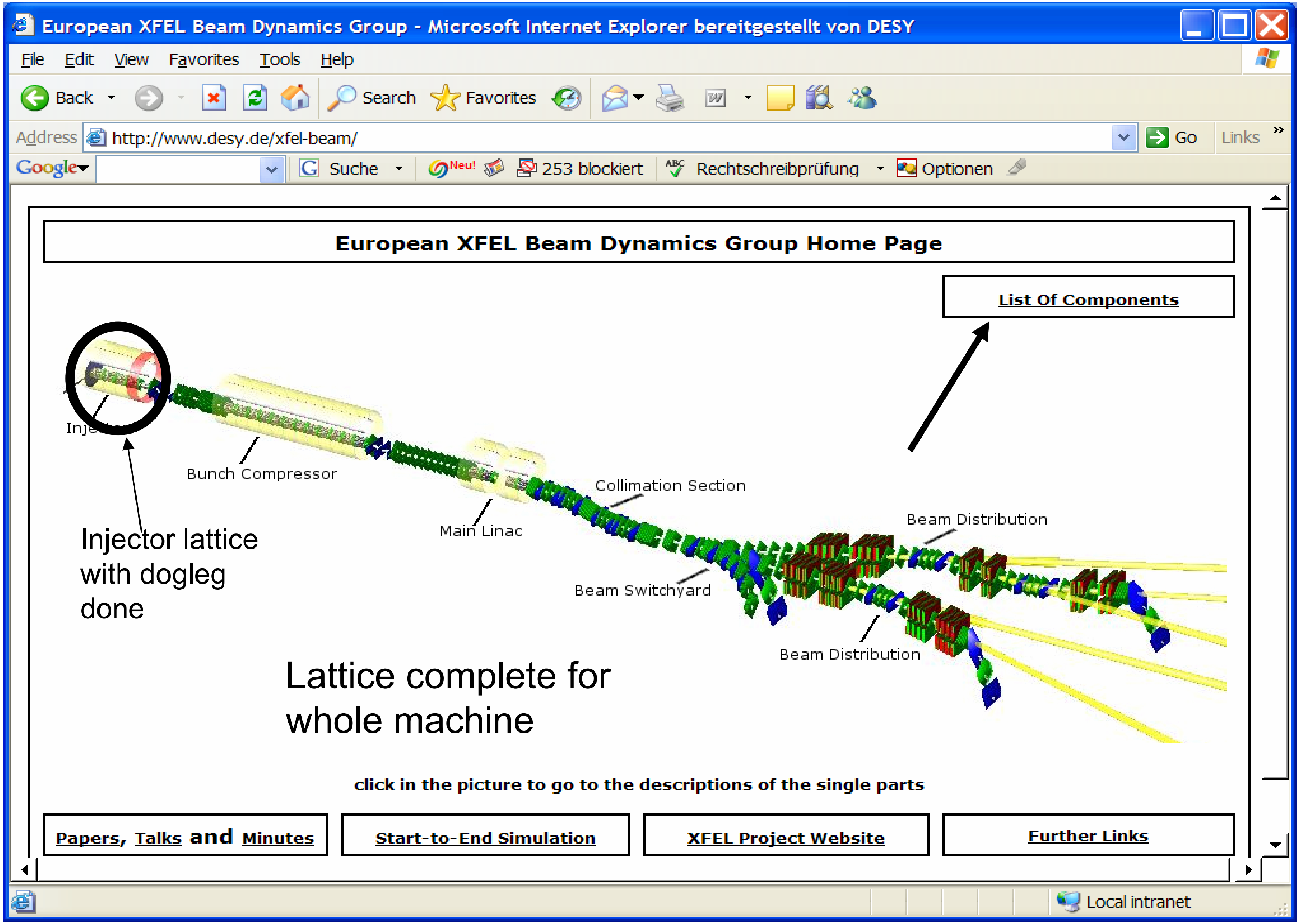
Lay Out

- Lattice Work and List of Components (W. Decking)
- Bunch compression stability dependence on rf parameters (Dohlus, Limberg), amplitude and phase stability for I/Q detection (H. Schlarb)
- Wake fields and their impact on SASE (Igor Zagarodnov, Martin Dohlus)
- VUV-FEL or TTF-II activities (Vladimir Balandin, M. Dohlus)

Lattice Work (W. Decking)

web page by Bartosz Poljancewicz



Injector Lattice

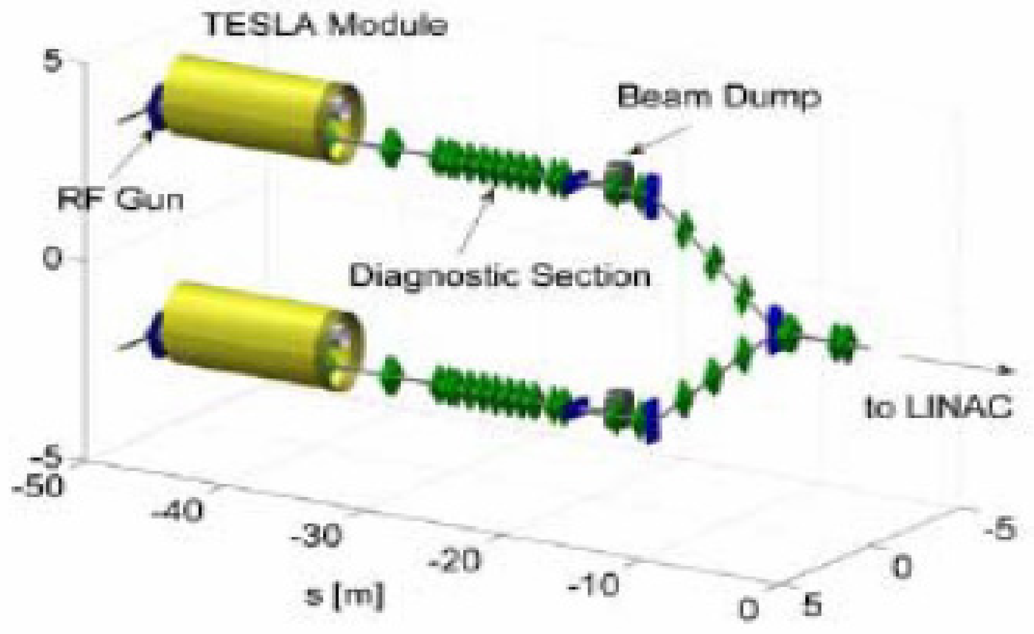


Figure 3: Injector layout of the XFEL

Graphics showing whole machine (directly derived from a MAD deck)

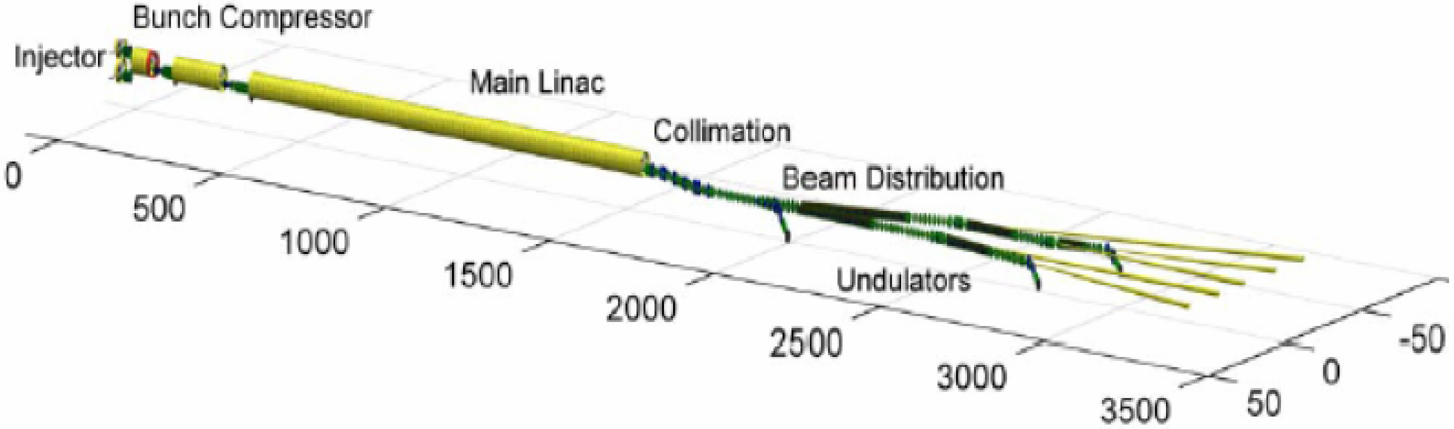
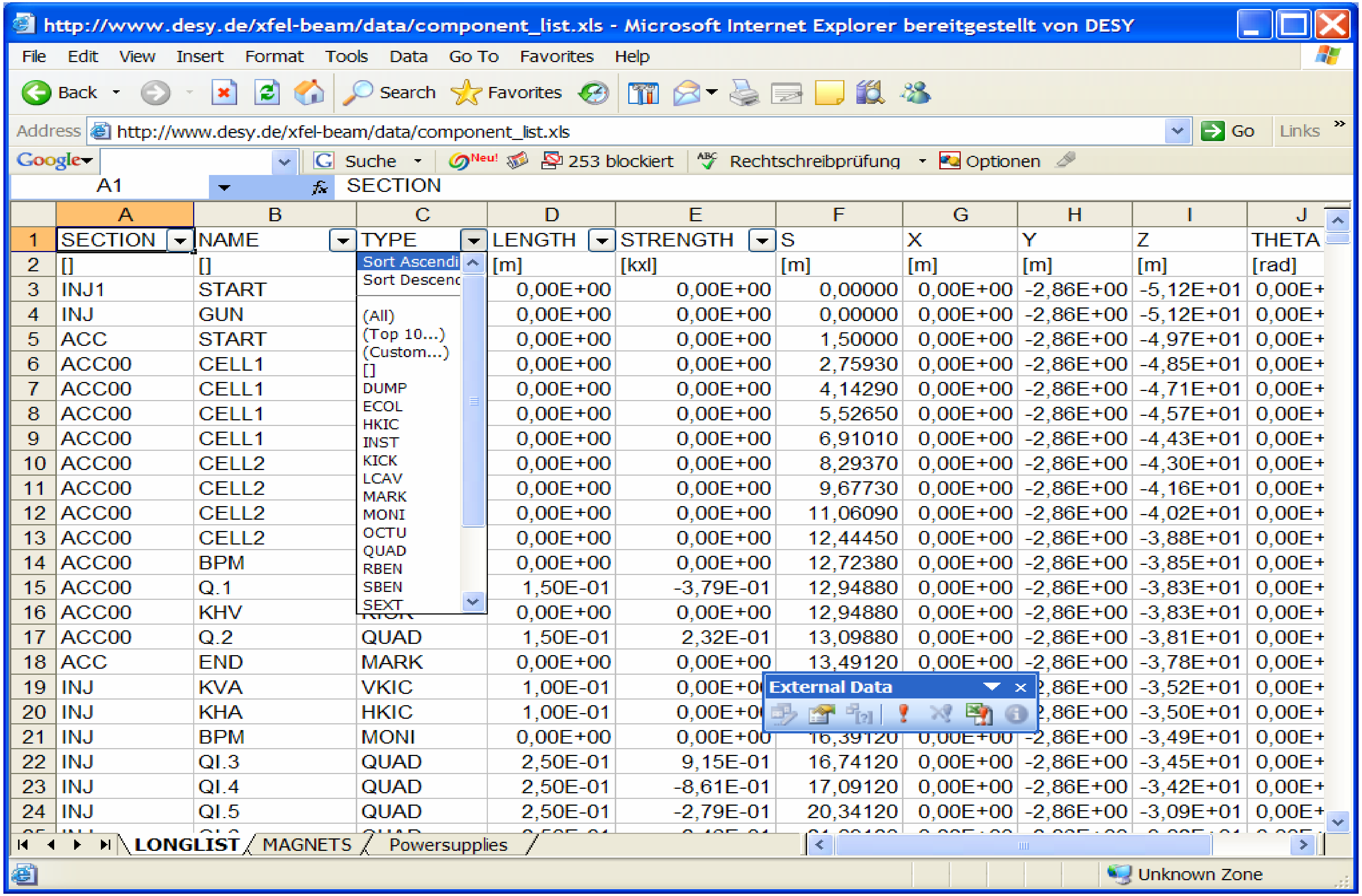


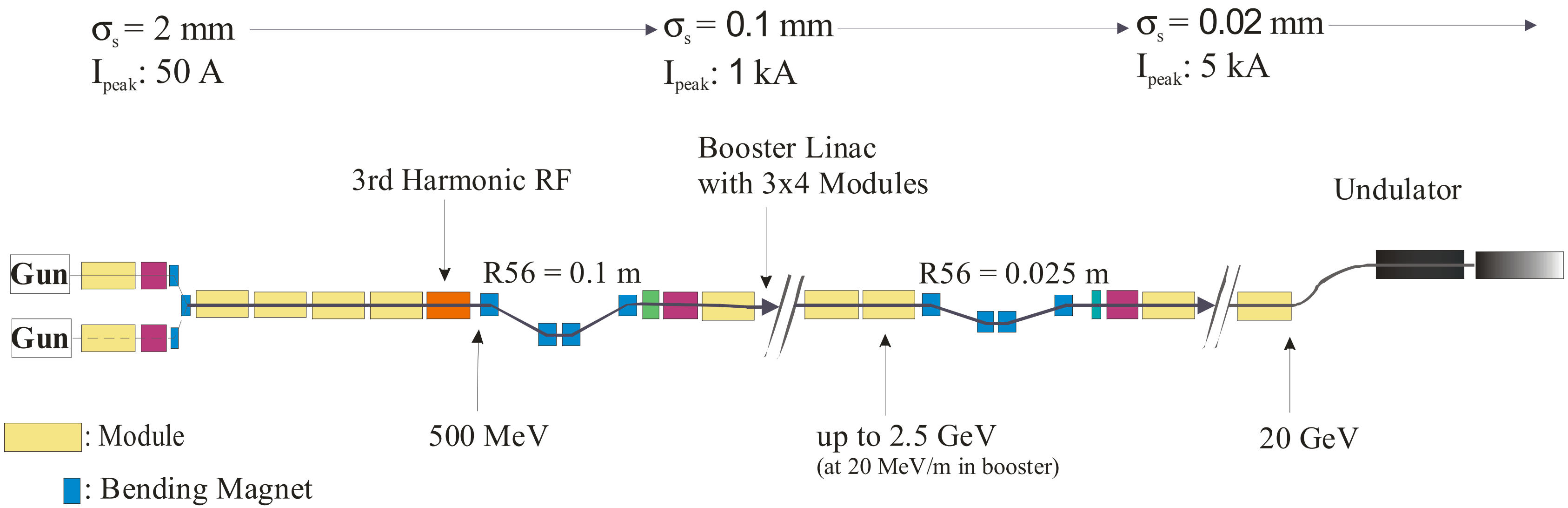
Figure 2: Layout of the XFEL

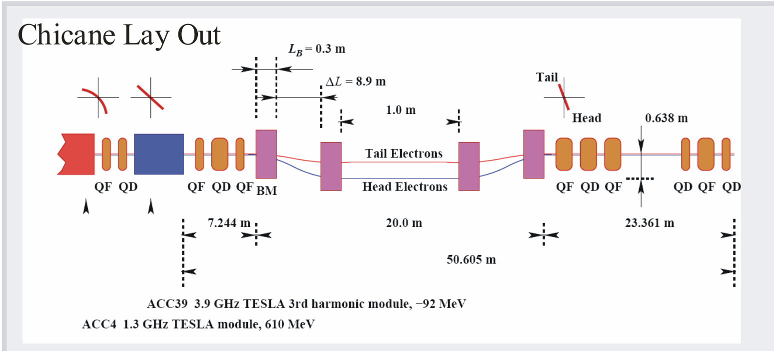
List of Components



	A	B	C	D	E	F	G	H	I	J
1	SECTION	NAME	TYPE	LENGTH	STRENGTH	S	X	Y	Z	THETA
2	[]	[]		[m]	[kxl]	[m]	[m]	[m]	[m]	[rad]
3	INJ1	START		0,00E+00	0,00E+00	0,00000	0,00E+00	-2,86E+00	-5,12E+01	0,00E+
4	INJ	GUN		0,00E+00	0,00E+00	0,00000	0,00E+00	-2,86E+00	-5,12E+01	0,00E+
5	ACC	START		0,00E+00	0,00E+00	1,50000	0,00E+00	-2,86E+00	-4,97E+01	0,00E+
6	ACC00	CELL1		0,00E+00	0,00E+00	2,75930	0,00E+00	-2,86E+00	-4,85E+01	0,00E+
7	ACC00	CELL1		0,00E+00	0,00E+00	4,14290	0,00E+00	-2,86E+00	-4,71E+01	0,00E+
8	ACC00	CELL1		0,00E+00	0,00E+00	5,52650	0,00E+00	-2,86E+00	-4,57E+01	0,00E+
9	ACC00	CELL1		0,00E+00	0,00E+00	6,91010	0,00E+00	-2,86E+00	-4,43E+01	0,00E+
10	ACC00	CELL2		0,00E+00	0,00E+00	8,29370	0,00E+00	-2,86E+00	-4,30E+01	0,00E+
11	ACC00	CELL2		0,00E+00	0,00E+00	9,67730	0,00E+00	-2,86E+00	-4,16E+01	0,00E+
12	ACC00	CELL2		0,00E+00	0,00E+00	11,06090	0,00E+00	-2,86E+00	-4,02E+01	0,00E+
13	ACC00	CELL2		0,00E+00	0,00E+00	12,44450	0,00E+00	-2,86E+00	-3,88E+01	0,00E+
14	ACC00	BPM		0,00E+00	0,00E+00	12,72380	0,00E+00	-2,86E+00	-3,85E+01	0,00E+
15	ACC00	Q.1		1,50E-01	-3,79E-01	12,94880	0,00E+00	-2,86E+00	-3,83E+01	0,00E+
16	ACC00	KHV		0,00E+00	0,00E+00	12,94880	0,00E+00	-2,86E+00	-3,83E+01	0,00E+
17	ACC00	Q.2	QUAD	1,50E-01	2,32E-01	13,09880	0,00E+00	-2,86E+00	-3,81E+01	0,00E+
18	ACC	END	MARK	0,00E+00	0,00E+00	13,49120	0,00E+00	-2,86E+00	-3,78E+01	0,00E+
19	INJ	KVA	VKIC	1,00E-01	0,00E+0			2,86E+00	-3,52E+01	0,00E+
20	INJ	KHA	HKIC	1,00E-01	0,00E+0			2,86E+00	-3,50E+01	0,00E+
21	INJ	BPM	MONI	0,00E+00	0,00E+00	16,39120	0,00E+00	-2,86E+00	-3,49E+01	0,00E+
22	INJ	QI.3	QUAD	2,50E-01	9,15E-01	16,74120	0,00E+00	-2,86E+00	-3,45E+01	0,00E+
23	INJ	QI.4	QUAD	2,50E-01	-8,61E-01	17,09120	0,00E+00	-2,86E+00	-3,42E+01	0,00E+
24	INJ	QI.5	QUAD	2,50E-01	-2,79E-01	20,34120	0,00E+00	-2,86E+00	-3,09E+01	0,00E+

BUNCH COMPRESSION STABILITY DEPENDENCE ON RF PARAMETERS:
Layout of the European XFEL Bunch Compression System





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Sensitivity Table for European XFEL

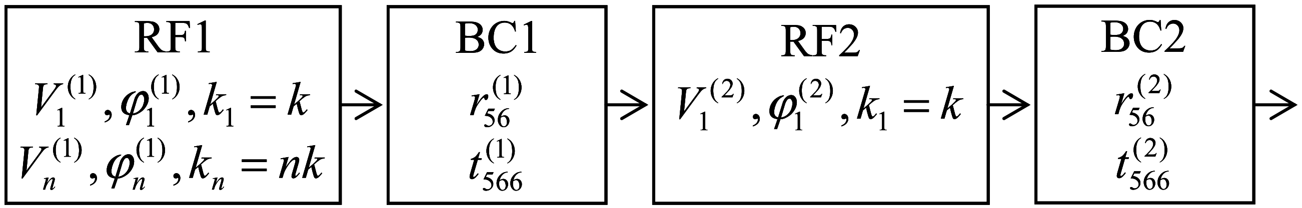
DESY

- Criterion: I_{peak} changes from 5 kA to 5.5 kA (SASE statistical fluctuation: 5-10%)

Can we relax this tolerance?

Linac Phase	0.013	degrees
3rd harmonic Phase	-0.04	degrees
3rd harmonic Amplitude	0.06 (~0.05%)	MV
Magnet Strength 1st Chicane	-0.0005	relative change
Magnet Strength 2nd Chicane	-0.01	"
Beam Parameters		
Charge (I_{peak} = constant)	0.05	relative change
I_{peak} (Charge = constant)	-0.02	"
Charge (Length = constant)	-0.05	"

Schematic of a Two-Stage Compression Scheme



$V_1, V_n, \varphi_1, \varphi_n$ are the voltages and phases for the fundamental mode rf and the nth harmonic of the first compression stage (n=3 for European XFEL, n=4 for LCLS)

V_1 and V_n are later on replaced by normalized amplitudes a_1 and a_n.

Error sensitivity of compression factor *C* with respect to phase (or amplitude) offset *x:*

$$\frac{1}{C_0}\frac{\partial C}{\partial x} = A\frac{\partial p}{\partial x} + B\frac{\partial p'}{\partial x}$$

$$p = p(s_a, x)$$

$$\partial p'/\partial x = \partial^2 p/\partial x \partial s_a$$

$$A = -2(C_0 - 1)t_{566}/r_{56}$$

$$B = -C_0 r_{56}$$

Example: For phase jitter of the fundamental mode rf (first stage) $(\varphi_1 = \varphi_{1\,\mathrm{design}} + x)$

$$p(s_a, x) = a_1 \cos(k\ s_a + \varphi_1 + x) + a_n \cos(nk\ s_a + \varphi_n)$$

And the bunch compression factor sensitivity is

$$\frac{1}{C_0}\frac{\partial C}{\partial x} = -a_1\left(A\sin\varphi_i + Bk_i\cos\varphi_i\right)$$

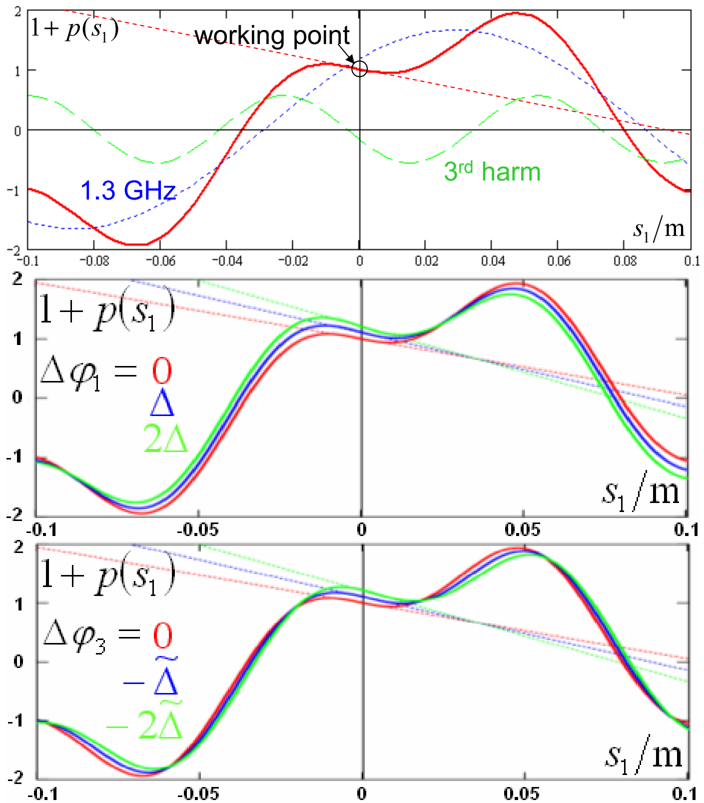
Cancellation possible?

Footnote: 2-stage system in the case of E-XFEL very similar to 1st stage:

$$\frac{\partial C^{(1+2)}}{C_0^{(1+2)}\partial x} = \frac{C_0^{(1+2)}}{C_0^{(1)}\widetilde{C}_0^{(2)}}\left\{\frac{\partial C^{(1)}}{C_0^{(1)}\partial x}\right\} - C_0^{(1+2)} r_{56}^{(2)} u \frac{\partial p'^{(1)}}{\partial x}$$

small for the E-XFEL

Impossible with a single frequency system, but for the combination of fundamental mode and higher harmonic rf systems a working point can be found…



…where for increased beam energy due to phase jitter, chirp increases in strength:

→ effectively reduced R56 of magnet chicane is compensated by the stronger chirp

RF Multi-Knobs

Amplitude (normalized) and phase of the fundamental mode rf (a_1,φ_1) and of the higher harmonic rf (a_n,φ_n) are combined to set up four 'knobs':

$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & -k & 0 & -(nk) \\ -k^2 & 0 & -(nk)^2 & 0 \\ 0 & k^3 & 0 & (nk)^3 \end{bmatrix} \cdot \begin{bmatrix} a_1 \cos\varphi_1 \\ a_1 \sin\varphi_1 \\ a_n \cos\varphi_n \\ a_n \sin\varphi_n \end{bmatrix} = \begin{bmatrix} 1 \\ p_0'^{(1)} \\ p_0''^{(1)} \\ p_0'''^{(1)} \end{bmatrix}$$

Beam energy (normalized)

Chirp

2nd and 3rd derivatives of particle momentum deviations

Impact on final longitudinal bunch shape weaker, can be used as a relatively free parameter to reduce rf phase tolerances

Let‘s pick this one ↓

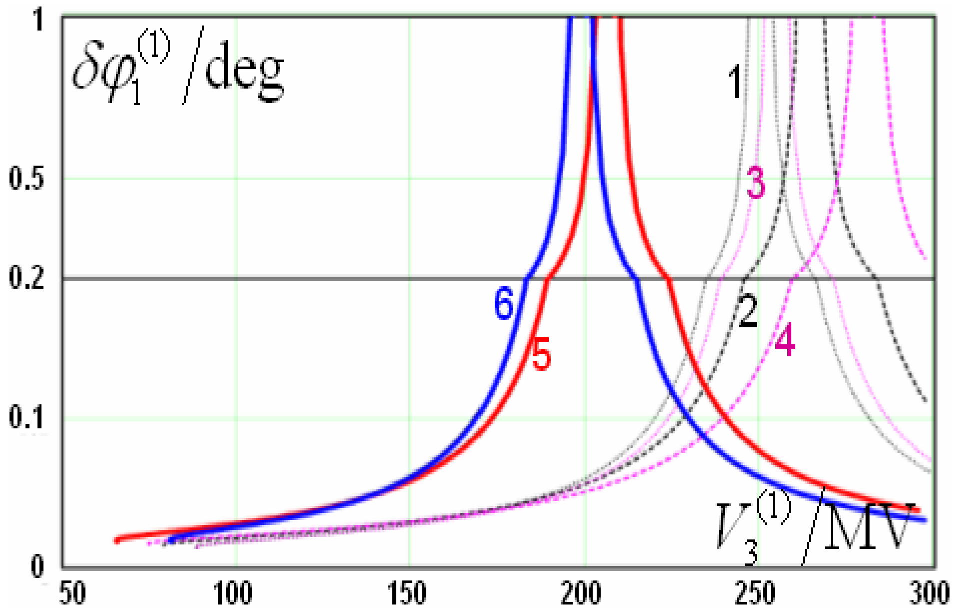
Scanned p''' for different scenarios:

	1	2	3	4	5	6
$E_0^{(1)}/\mathrm{MeV}$	500	500	500	500	**400**	**400**
$C^{(1)}$	20	14	20	14	**14**	**14**
$r_{56}^{(1)}/\mathrm{mm}$	84.4	101.4	82.3	109.3	**89.1**	**68.4**
$\varphi_1^{(2)}/\mathrm{deg}$	0	0	20	20	**20**	**20**
$r_{56}^{(2)}/\mathrm{mm}$	19.2	19.0	29	29.3	**29.3**	**23.5**

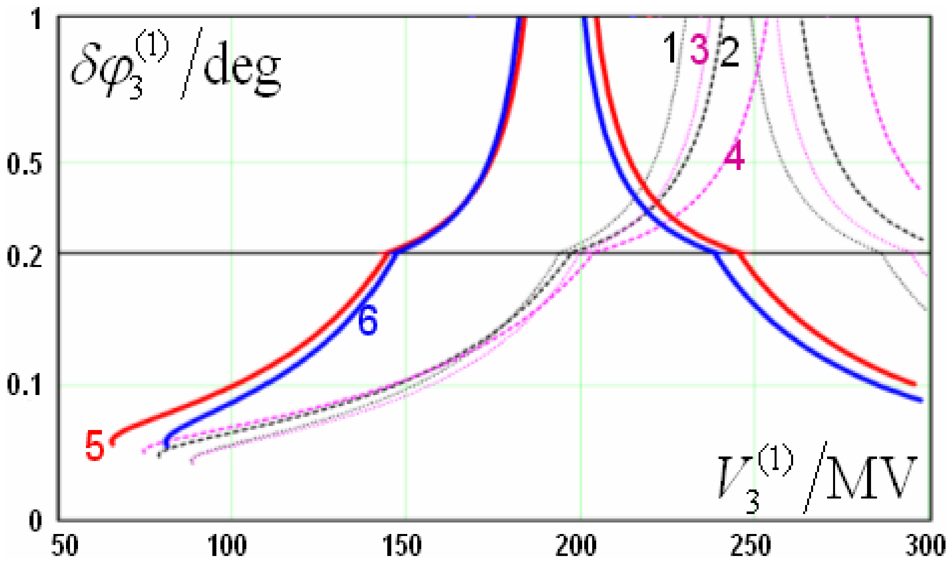
Used 1D tracking code which includes:

- wakefields
- non-linearities of rf and magnet chicanes
- longitudinal space charge

RF Phase Jitter Sensitivity Optimization Numerical Results: RF Phase Sensitivities

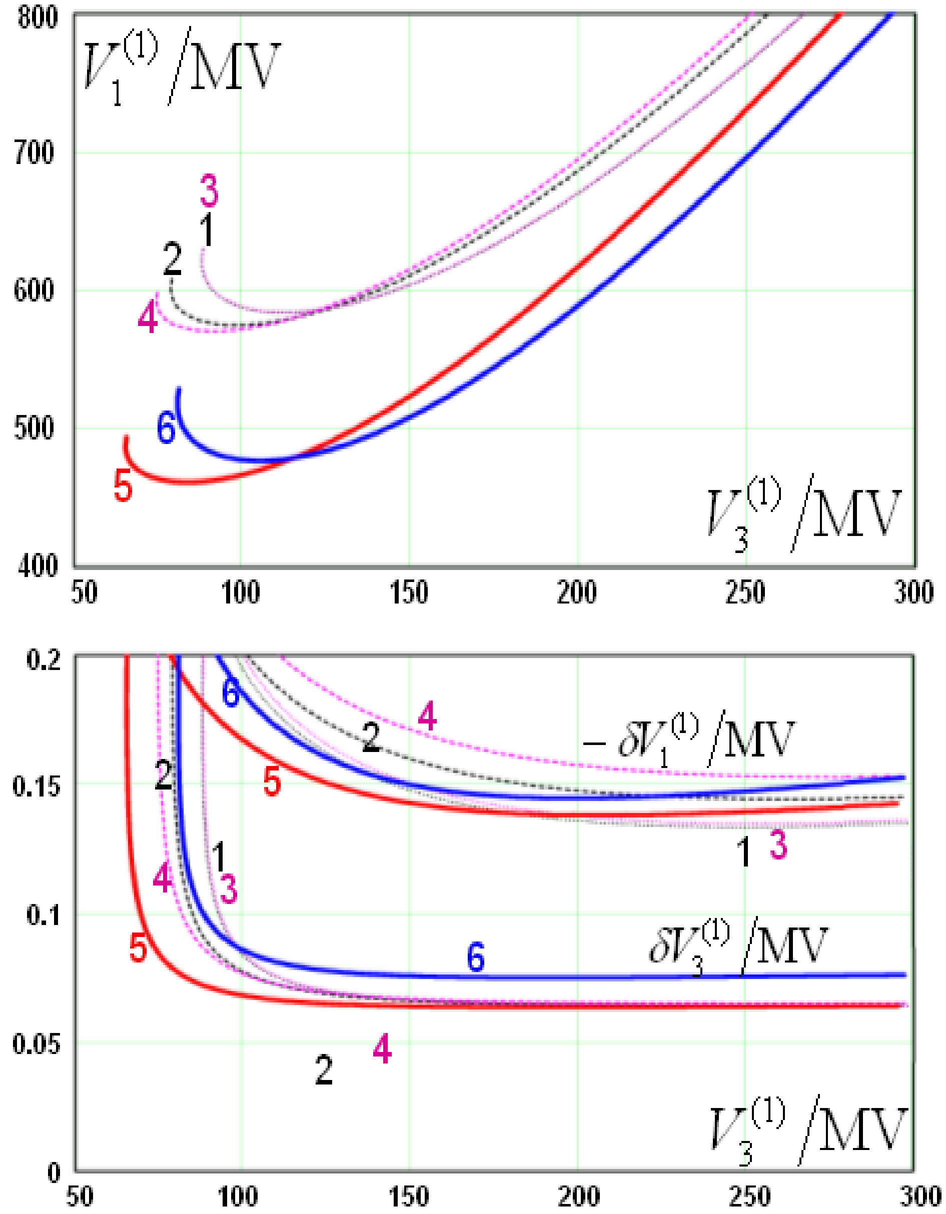


The phase and amplitude offsets which are plotted on the vertical scale cause a change of the final peak current of 10%.



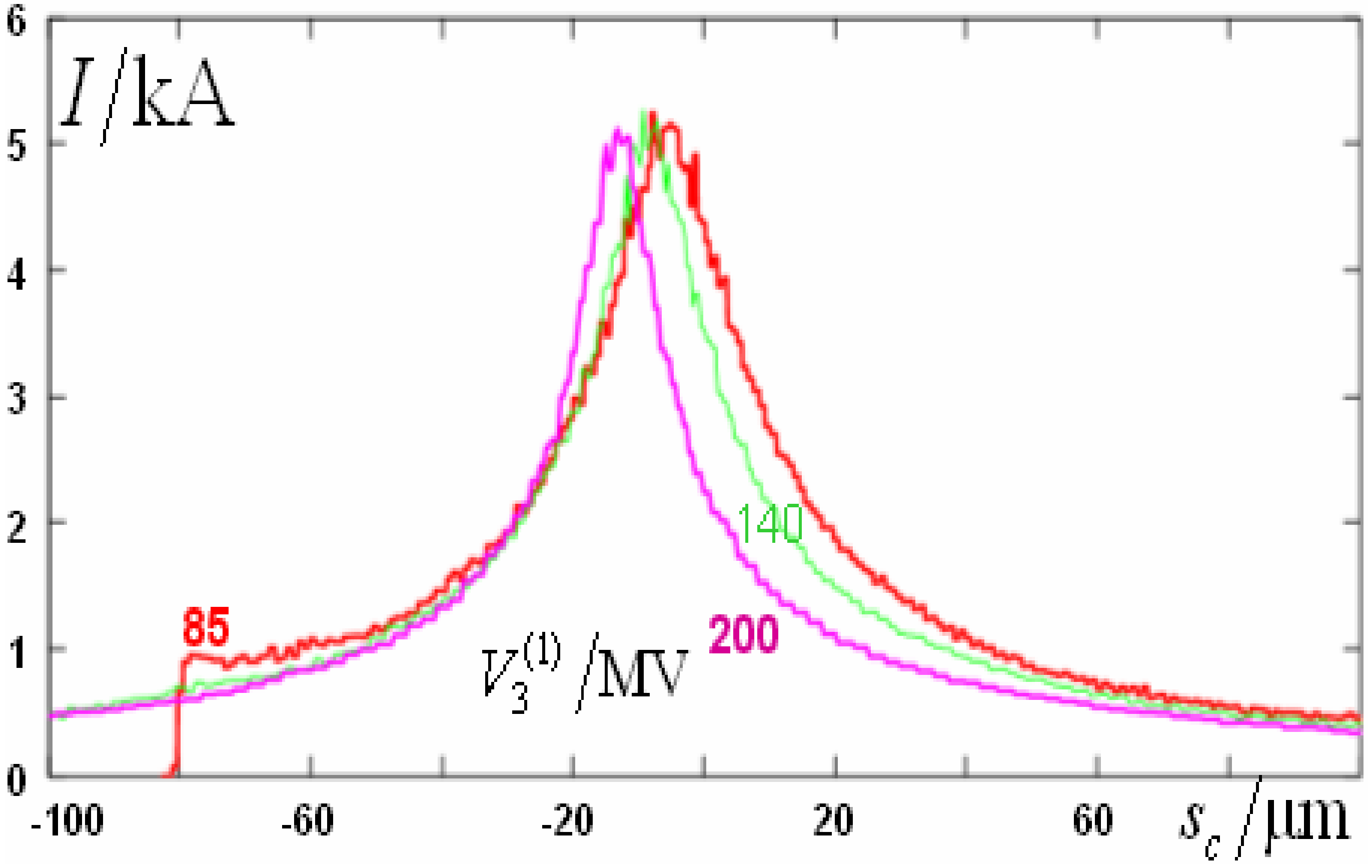
3rd harmonic rf voltage plotted on the horizontal axis; it scales with p'''

RF Phase Jitter Sensitivity Optimization Numerical Results: Fundamental Mode RF Voltage and Amplitude Sensitivities for both Systems



Final Longitudinal Beam Profiles for Different rf Settings (case 5)

Peak Current



Longitudinal bunch position

Conclusion

- The phase jitter sensitivity of the European XFEL bunch compression system can be reduced by more than an order of magnitude if the amplitudes and phases of the fundamental mode rf and the higher harmonic rf system are correctly chosen to provide phase jitter compensation.

- The 3rd harmonic system has to be operated with an amplitude of 200-250 MV, more than twice the minimum value necessary to compensate the non-linearities of the fundamental mode rf and the magnet chicanes.

  At that working point, phase jitter tolerances are of the order of a degree for both rf systems, compared to a few hundredth of a degree in the previous design. Amplitude jitter tolerances are $1.5 \cdot 10^{-4}$ for the 3rd harmonic rf and $3 \cdot 10^{-4}$ for the fundamental mode rf.

Phase and Amplitude error:

$$d\phi = \phi - \phi$$

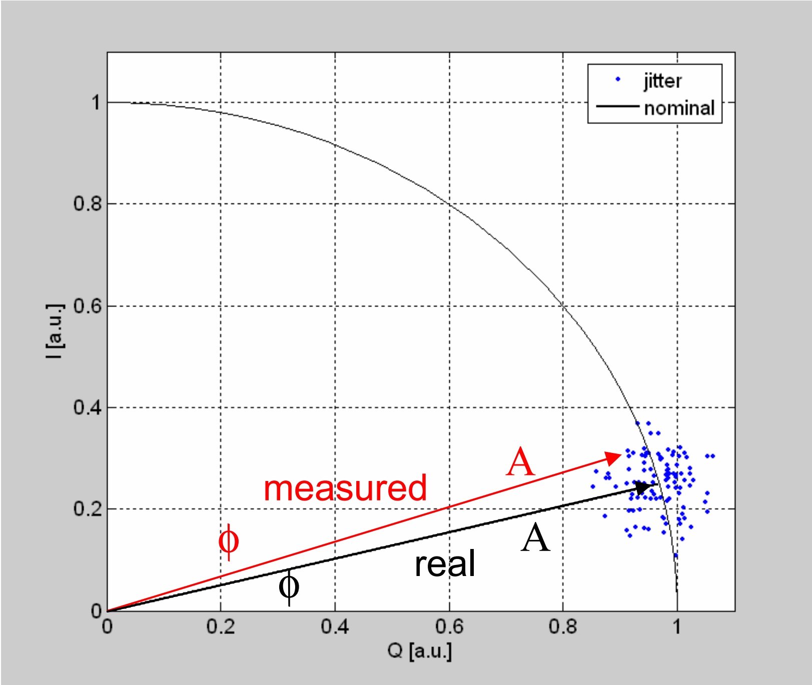
$$dA = A - A$$

Is determined by the resolution for I and Q measurements.

But resolution equals $\sigma_I = \sigma_Q$

$\Rightarrow$ $d\phi = dA/A$ or

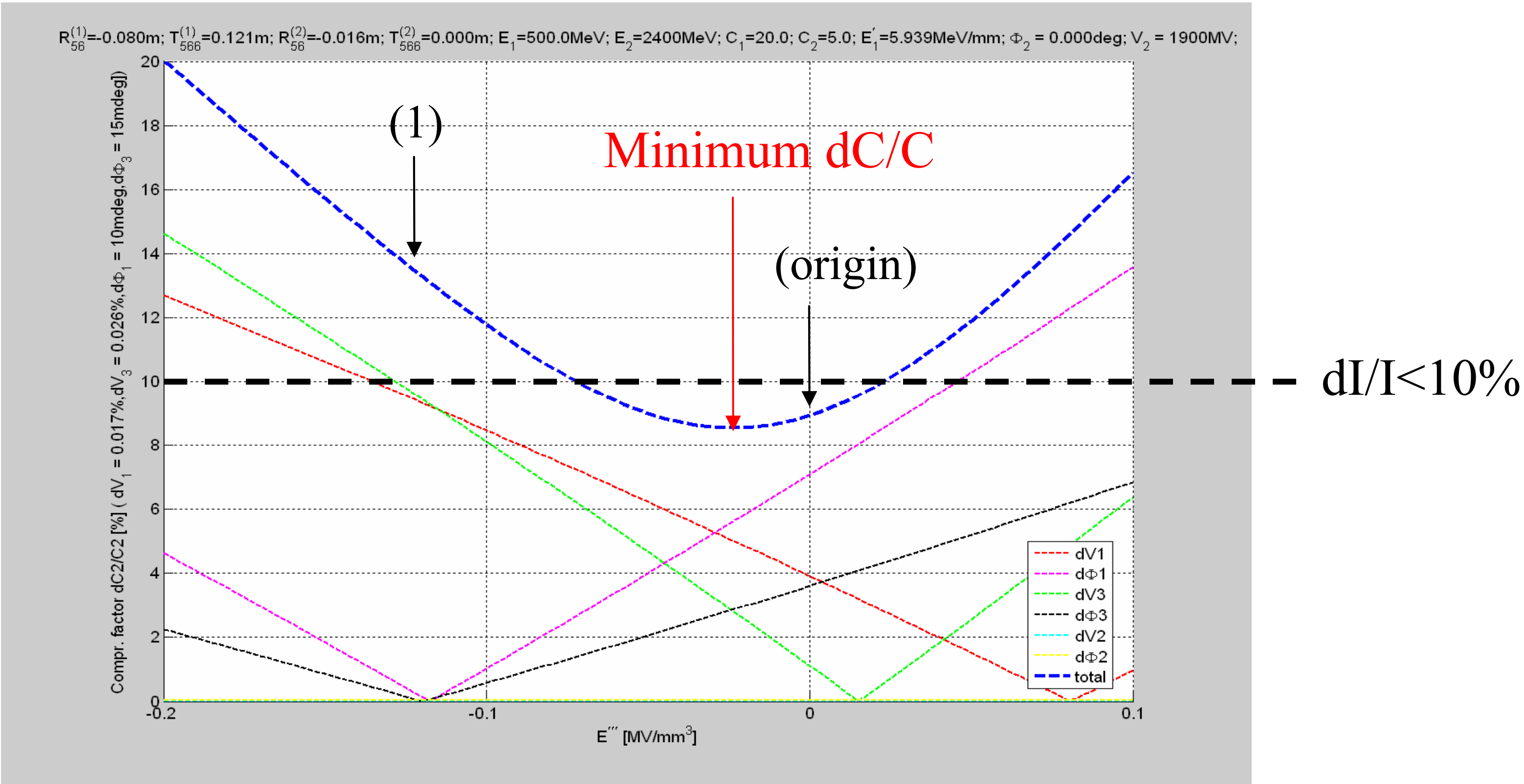
$\Rightarrow$ $1° \propto 1.75\%$



- To improve the amplitude stability additional detectors are required
- Slow phase drifts in cables and electronics reduce the accuracy
- Good phases reference (LO), e.g. new synchronization eliminates reference drifts

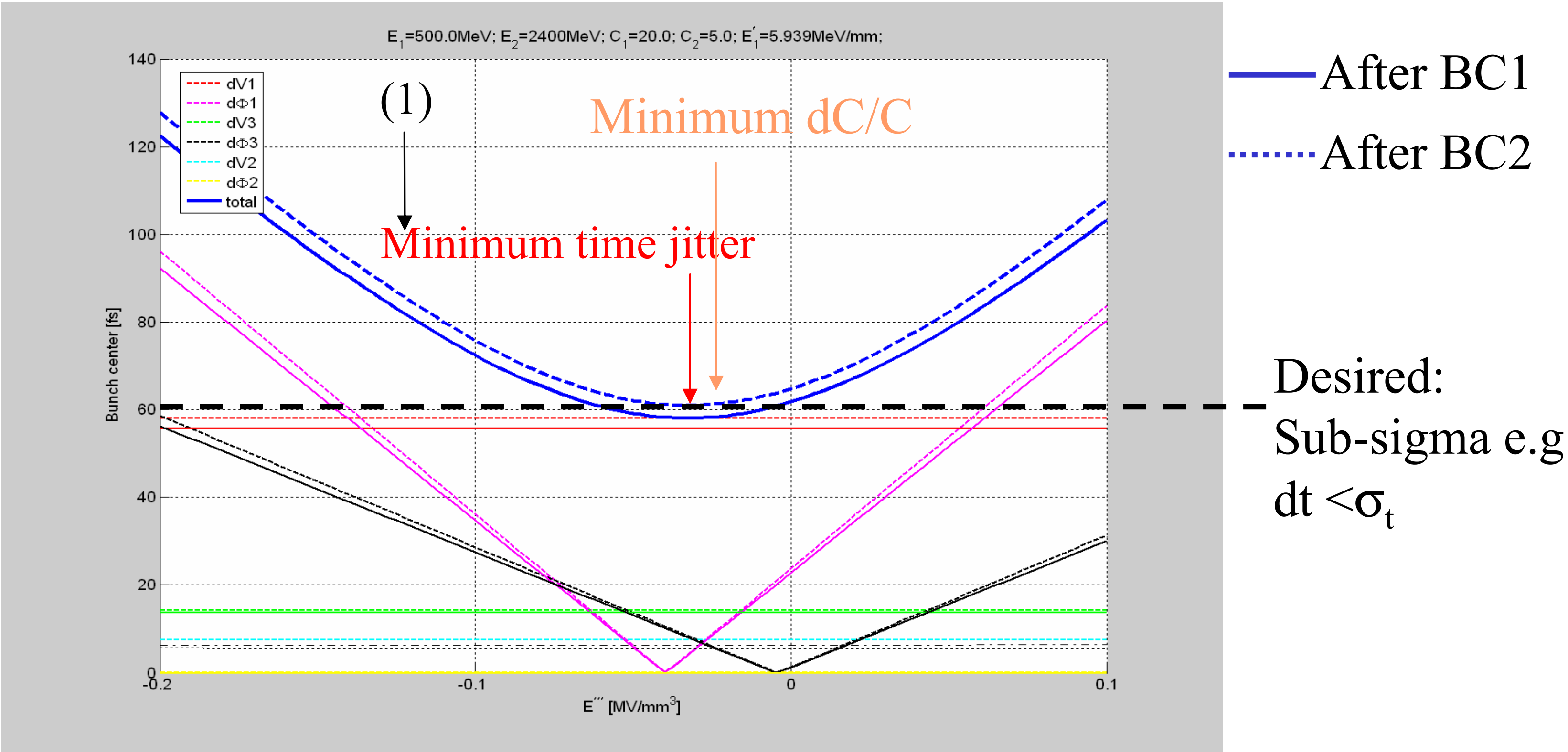
RF tolerance for XFEL variation of compression after BC2

- jitter assumptions: $dV_1/V_1 = dV_2/V_2 = 1.7e\text{-}4$ (0.01° L-Band)
  $dV_3/V_3 = 2.2e\text{-}4$ (0.015° at 3.9GHz [not full benefit or higher f])
- variation of E''' allows to operated with distributed tolerance (minimum)
- but relaxed phase sensitivity cause critical amplitude tolerance (1)



RF tolerance for XFEL - arrival time jitter -

- most critical is amplitude jitter of 1.3GHz V_1
- phase jitter dominates for larger |E'''| (correlated jitter with $\phi_1 = +3\phi_3$)
- operation point (1): arrival time jitter increased by 40%, ϕ_1 critical

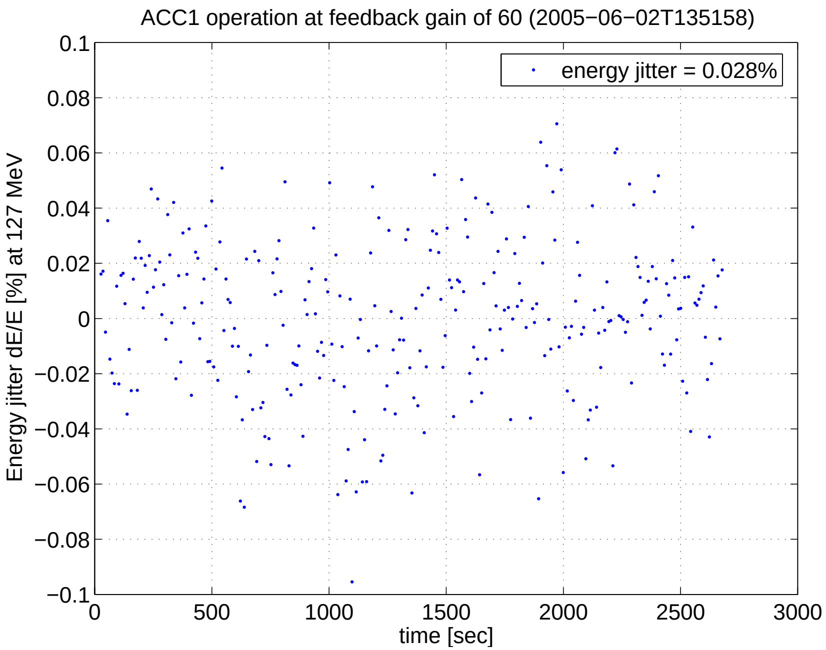


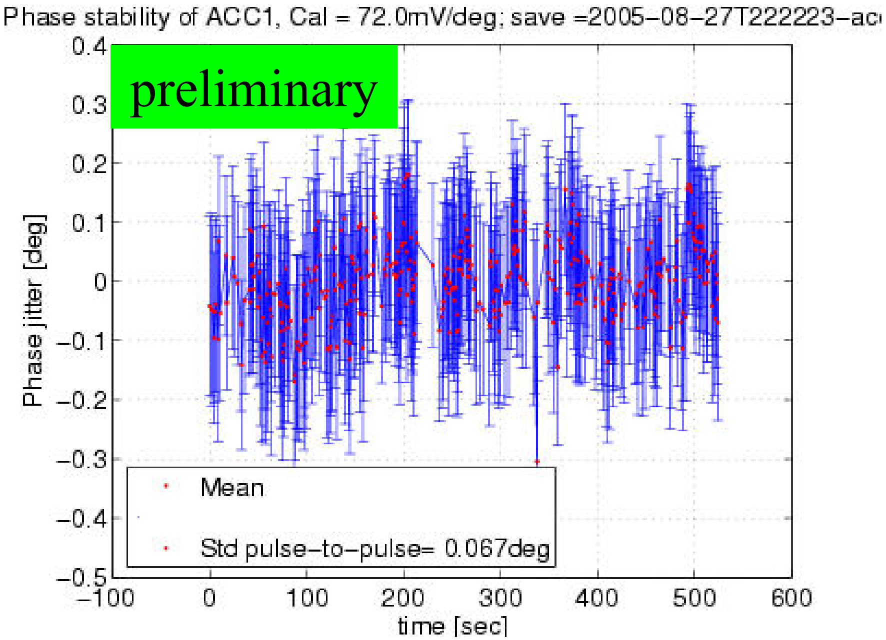
Example XFEL - conclusion -

- variation of E''' allows to select minimum
  - of compression jitter and
  - of arrival time jitter
- for I/Q detection 1° = 1.7% => both minima close to one another
- currently operation point (1) does not provide advantages
- preferable to develop additional RF amplitude detectors to reduce arrival time jitter and to achieve higher flexibility in the operation point of E'''.
- beam based monitors of the energy, the compression and the arrival timing for FBs are most critical and will dominantly influence the final choice of the machine operation settings.

RF tolerance for XFEL
- achievements at VUV-FEL -

- only measurements shot-to-shot (no detectors available for intra-pulse trains)
- amplitude stability ACC1 (8 cav.) best result $\sigma_A/A = 0.028\%$, typical =0.05%
- phase stability with pyro-detector $\sigma_\phi = 0.067°$ (but laser and gun phase included)





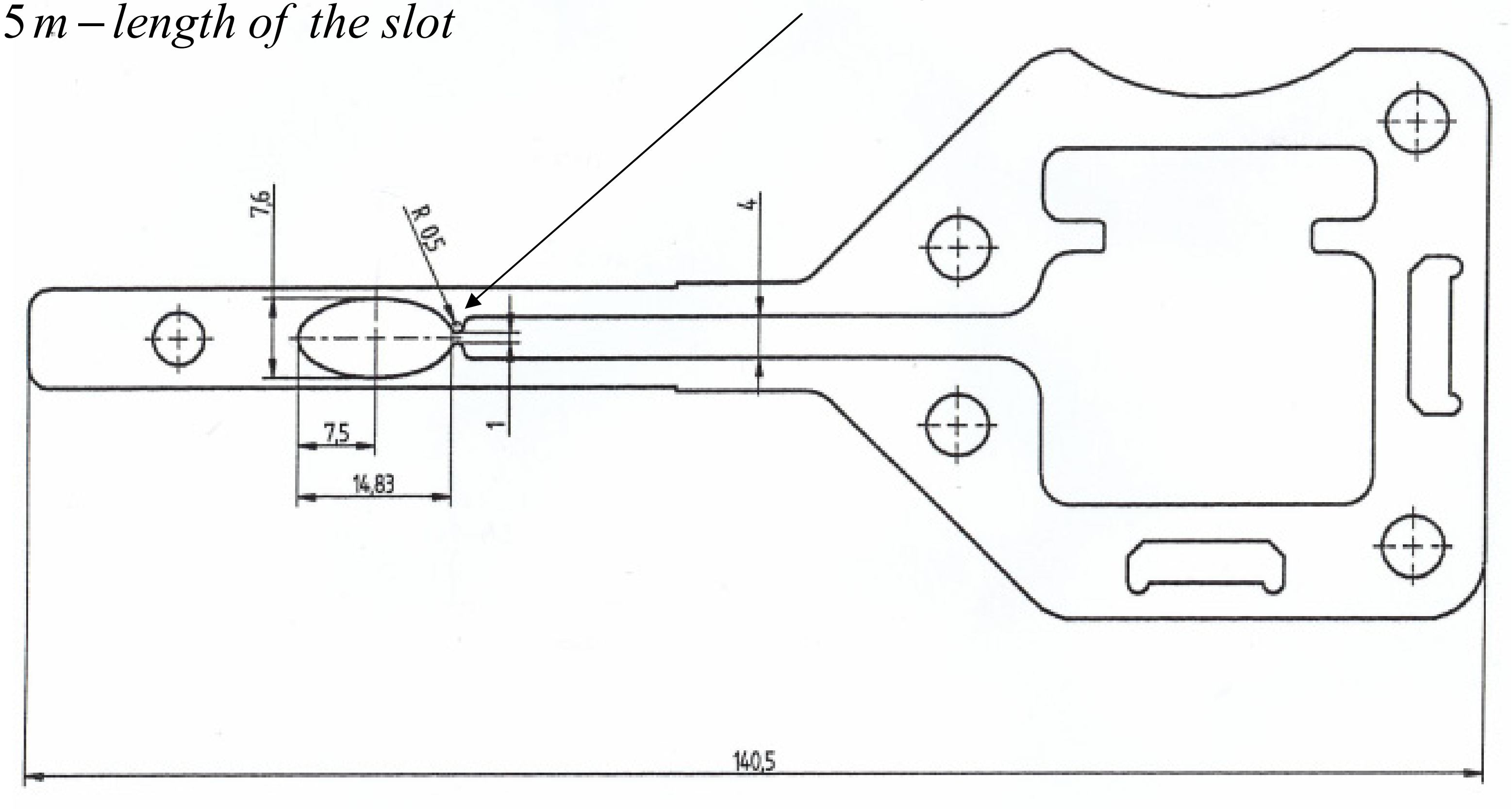
- TTF1: 5 times better within the macro-pulse compared to shot-to-shot
- upgrade of LLRF: DSP -> FPGA, down-converters from 250kHz -> 81MHz
  => high resolution, lower latency and no ripple -> high gain 100-200 possible

σ_A/A = 5e-5 within pulse possible => intrinsic 3 mdeg phase

Wake Fields: Undulator Chamber with Pump

$w = 1\,mm - width\ of\ the\ slot$

$L = 5\,m - length\ of\ the\ slot$



Other wakes are small (<25%) compared to Undulator Chamber (~250 m)

Effect of Pumping Slot

Effect of the slot is small.

↓

- Accuracy estimation of the numerical results.
- Wake scaling for geometry parameters.

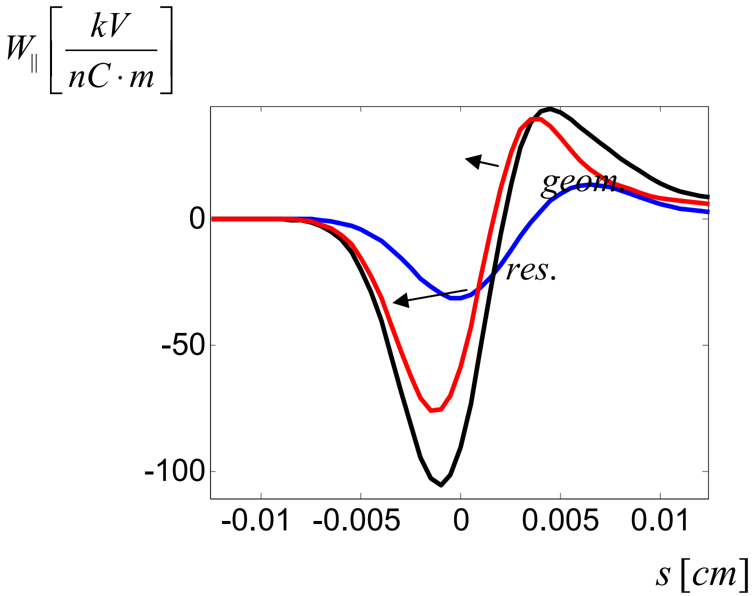
Used tools:

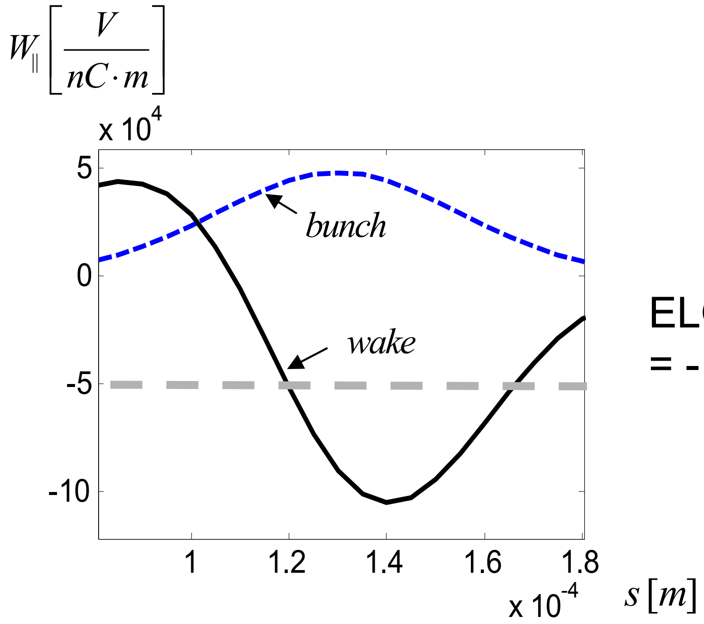
ECHO (time-domain),
CST Microwave Studio (modeling, meshing),
Matlab (pre- and postprocessing).

Longitudinal wake for the case of the elliptical pipe (3.8mm)

	pro section (6.1 m)	Loss, V/pC	Spread, V/pC	Peak, V/pC
absorber	1	42	16	-58
pumping slot	1	<0.2	<0.1	>-0.3
pump	1	9	4	-13
BPM	1			
bellow	1	13	5	-18
flange gap	1	6	2.4	-8.5
Total geom.		**70**	**<28**	**-98**
resistive (Cu)	6.1m	220	279	-542
resistive (Al)	6.1m	**303**	**325**	**-660**

Effect of wake fields (round pipe) on SASE



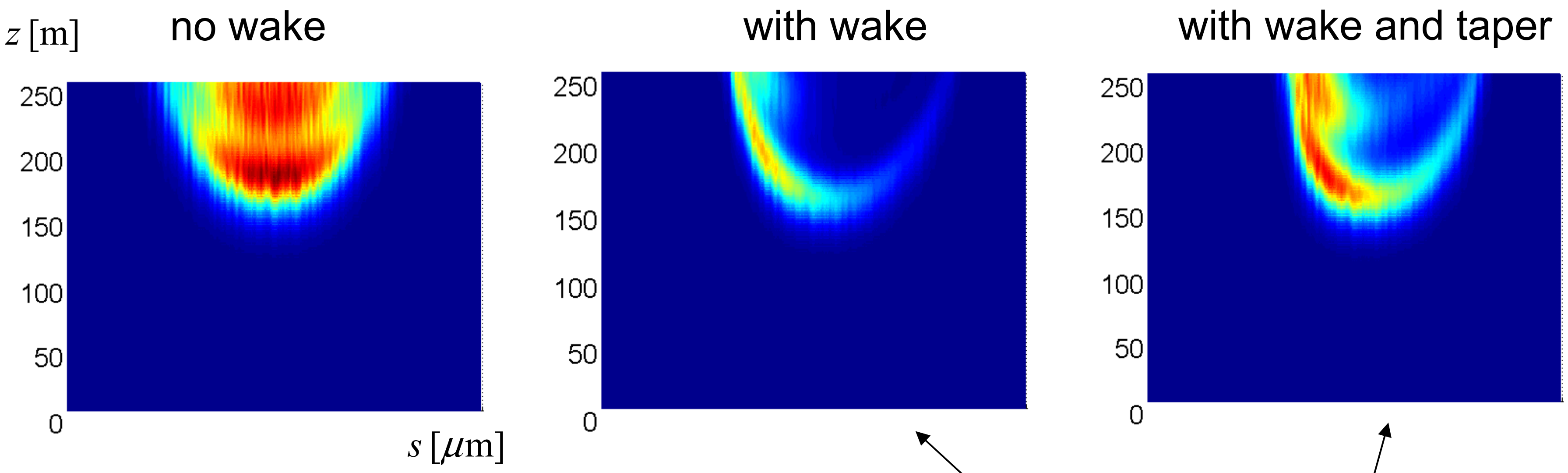


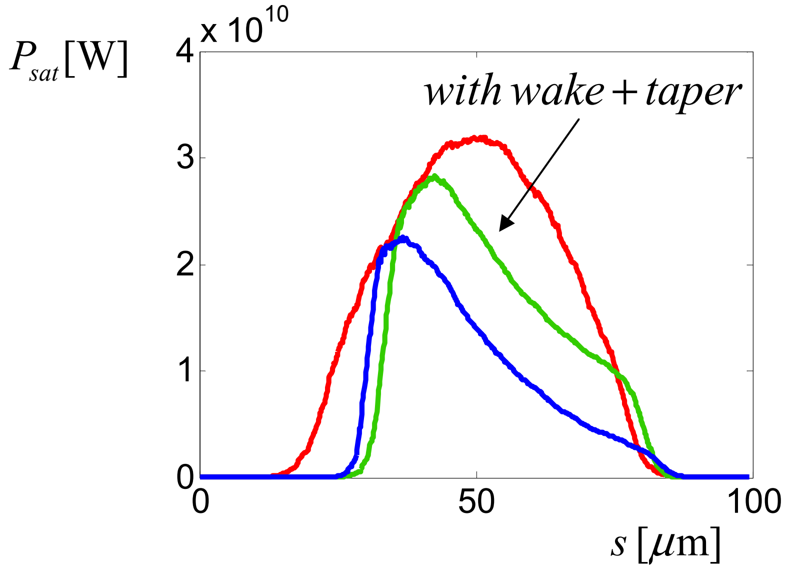
ELOSS=
= - 51keV/m

head tail tail head

	Loss, kV/nC/m	Spread, kV/nC/m	Peak, kV/nC/m
geometrical	20	12	-32
resistive	31	39	-75
total	**51**	49	-105

GENESIS Calculation of SASE Power with and without Undulator Tapering



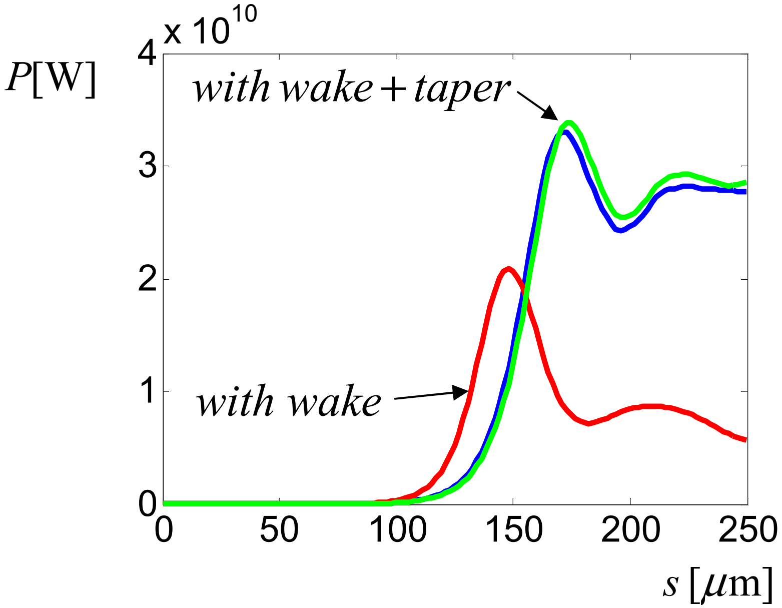


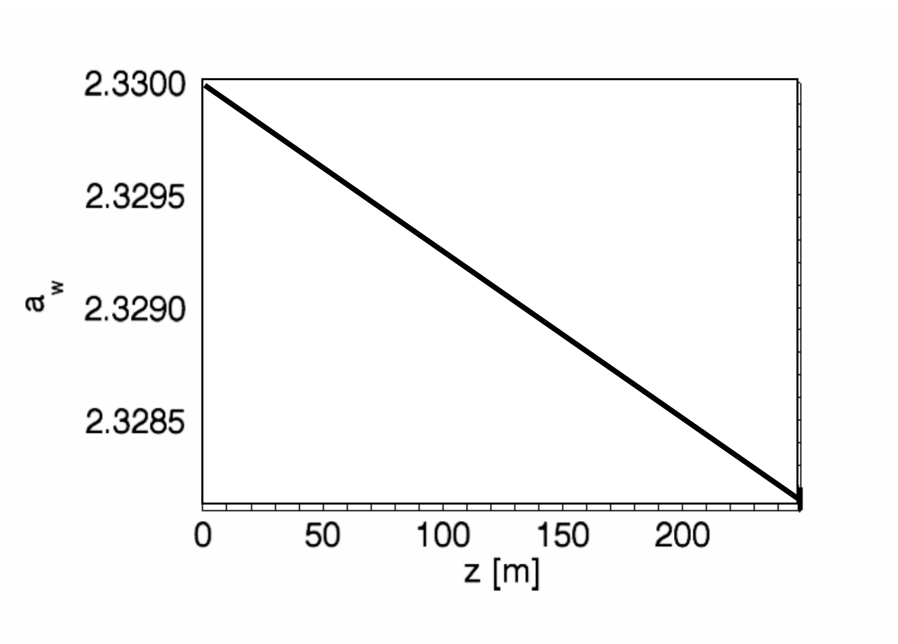
$$\frac{\langle P_{sat} \rangle}{\langle P_{sat}^{wake} \rangle} = 2.1$$

$$\frac{\langle P_{sat} \rangle}{\langle P_{sat}^{wake+taper} \rangle} = 1.5$$

Tapering (steady state)

with ELOSS = - 51keV/m





$$\frac{\Delta a_w}{a_w} \approx \frac{\Delta\gamma}{\gamma} = \frac{\Delta E}{E} = \frac{51[keV/m]\cdot 250[m]}{20[GeV]} = 6.375e-4$$

$$\frac{\Delta a_w}{a_w} = 8.0e-4 = 1.5\rho_1$$ ➡ Taper ~ 64 keV/m

Conclusions on Impact of Wakes on SASE (I. Zagarodnov)

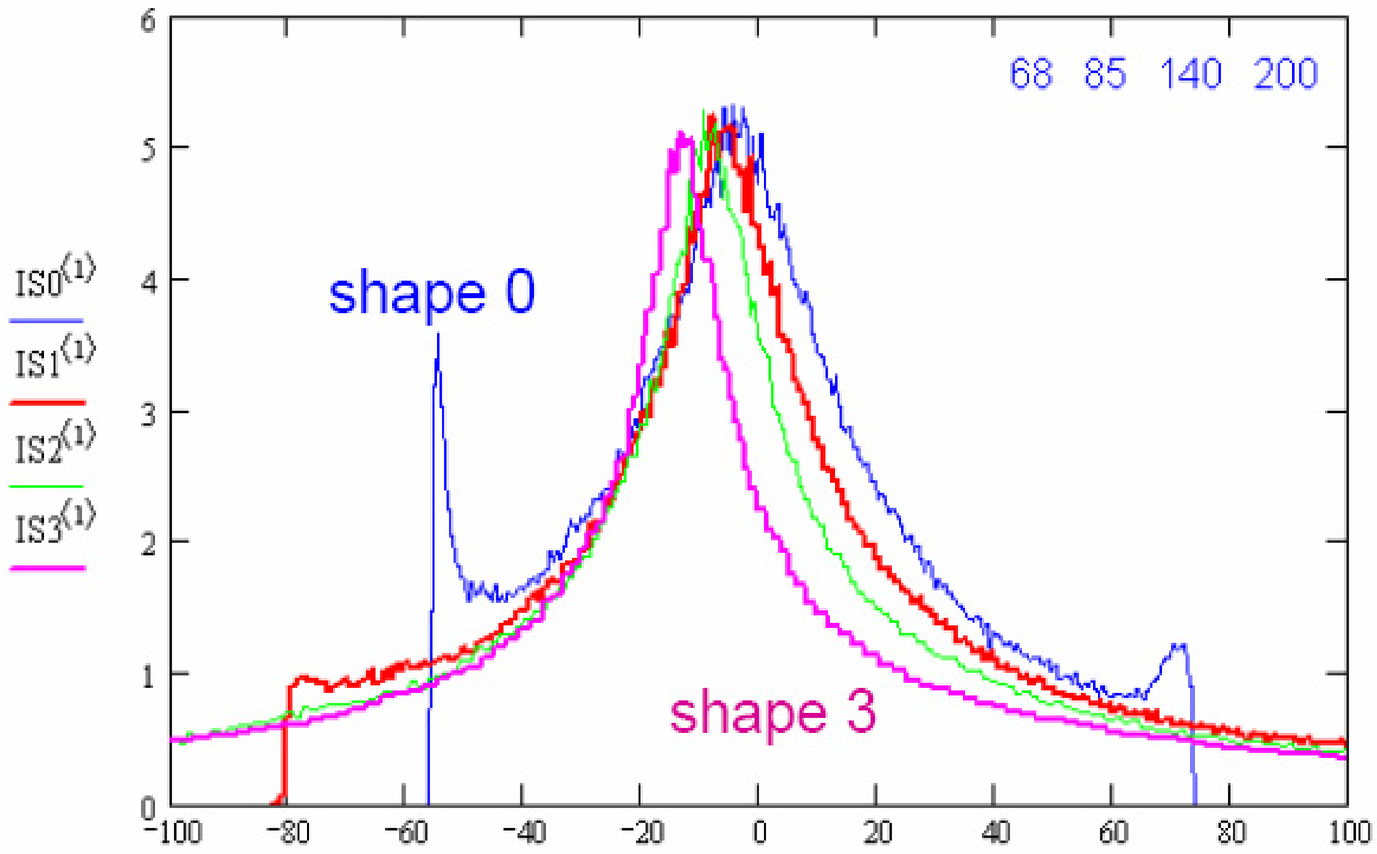
1. For smooth Gaussian bunch the wake field reduces the power by factor 2.1

2. The tapering allows to reduce the degradation to a factor of 1.5

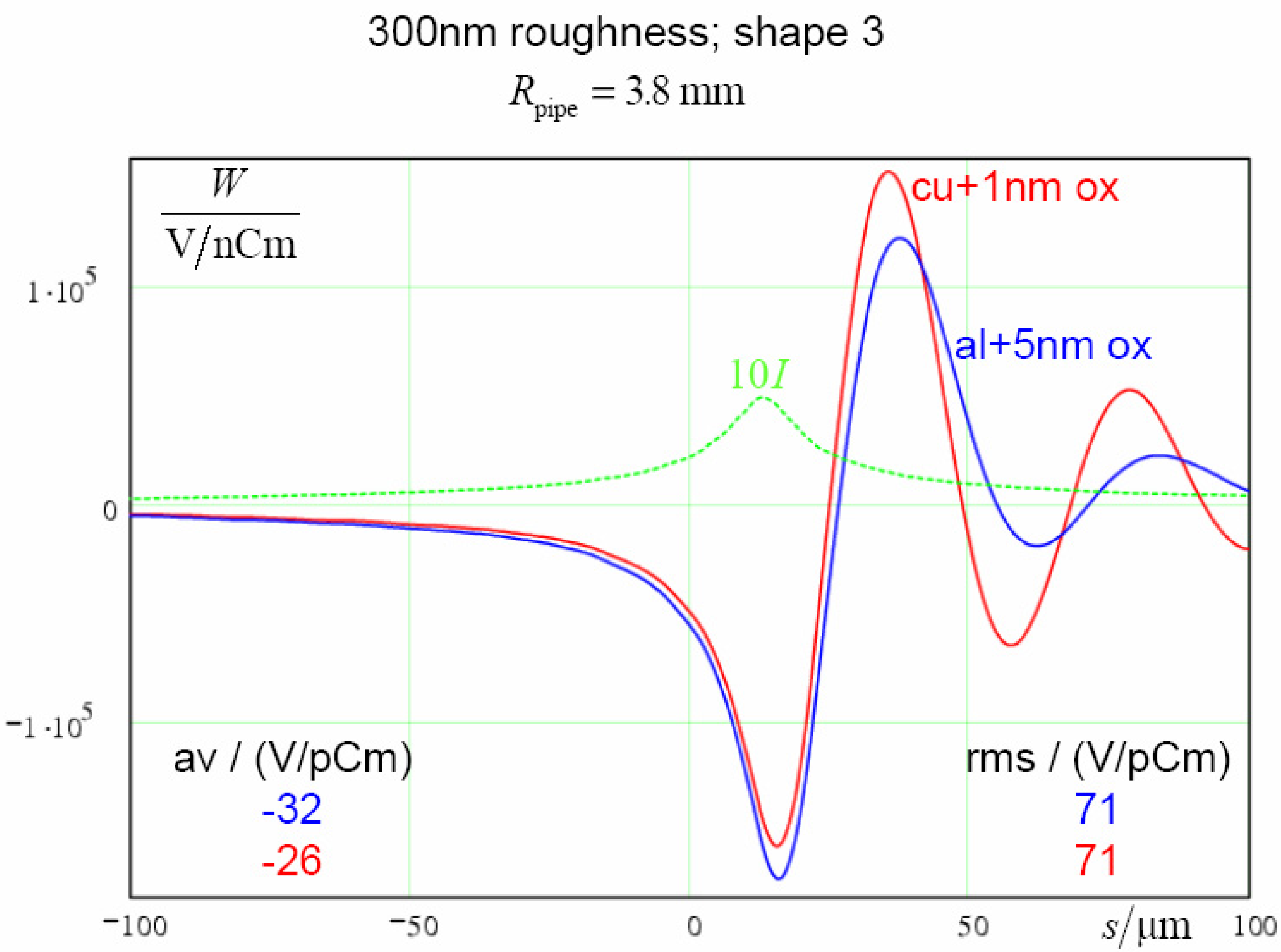
3. The numerical simulations are required to find an optimal tapering.

4. The wake effect for the expected bunch shape should be analyzed .

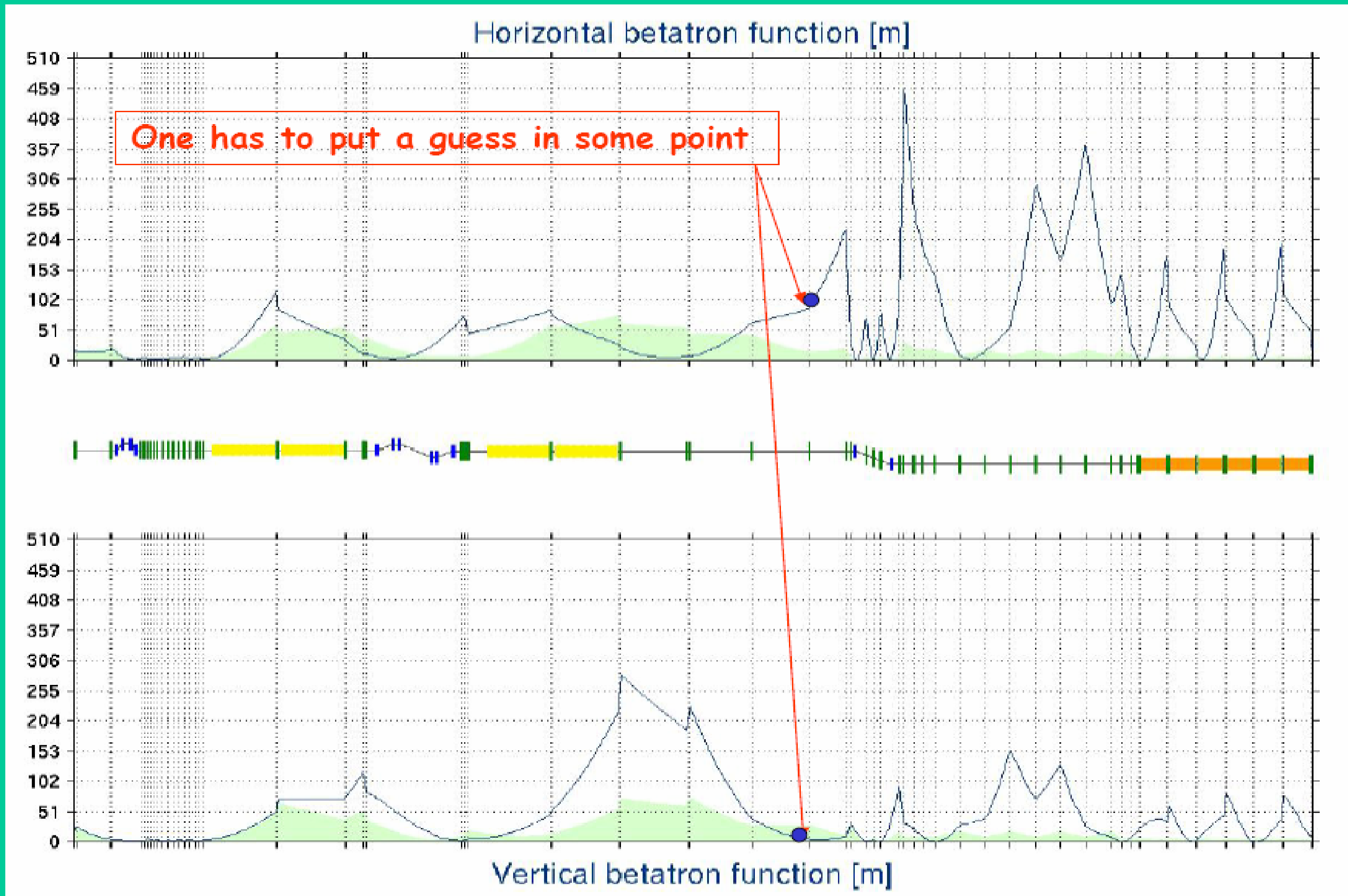
Wake Field Calculations for Different Bunch Shapes and Undulator Pipe Materials (M.D.)



No big difference between Al and Cu



On-Line Modelling of Linear Optics in TTF-II (V. Balandin)



CSR Calculation for TTF2