Karlsruhe Institute of Technology

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CERN

Study of LWFA as Injectors for Synchrotron Light Sources

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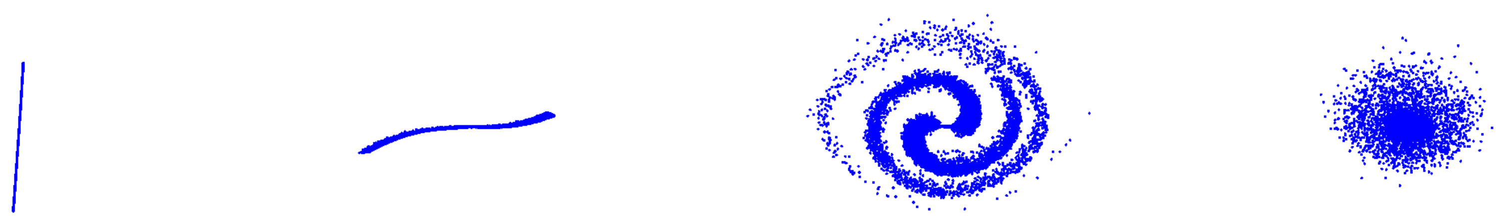

Outline

- Motivation
- Laser Wake Field Acceleration Simulations
- Transfer Line
- Behaviour in Synchrotron
- Summary

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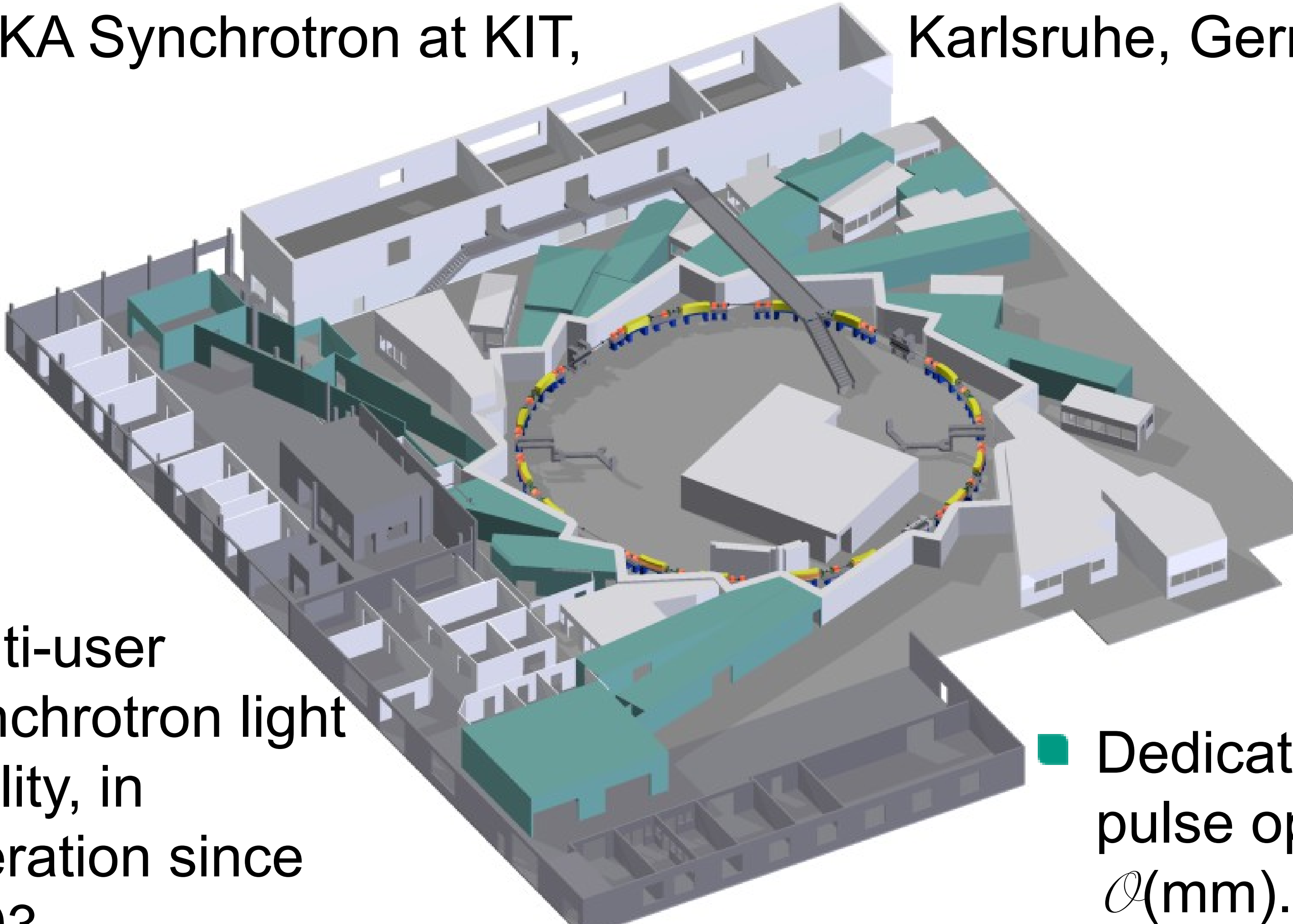
The ANKA Synchrotron

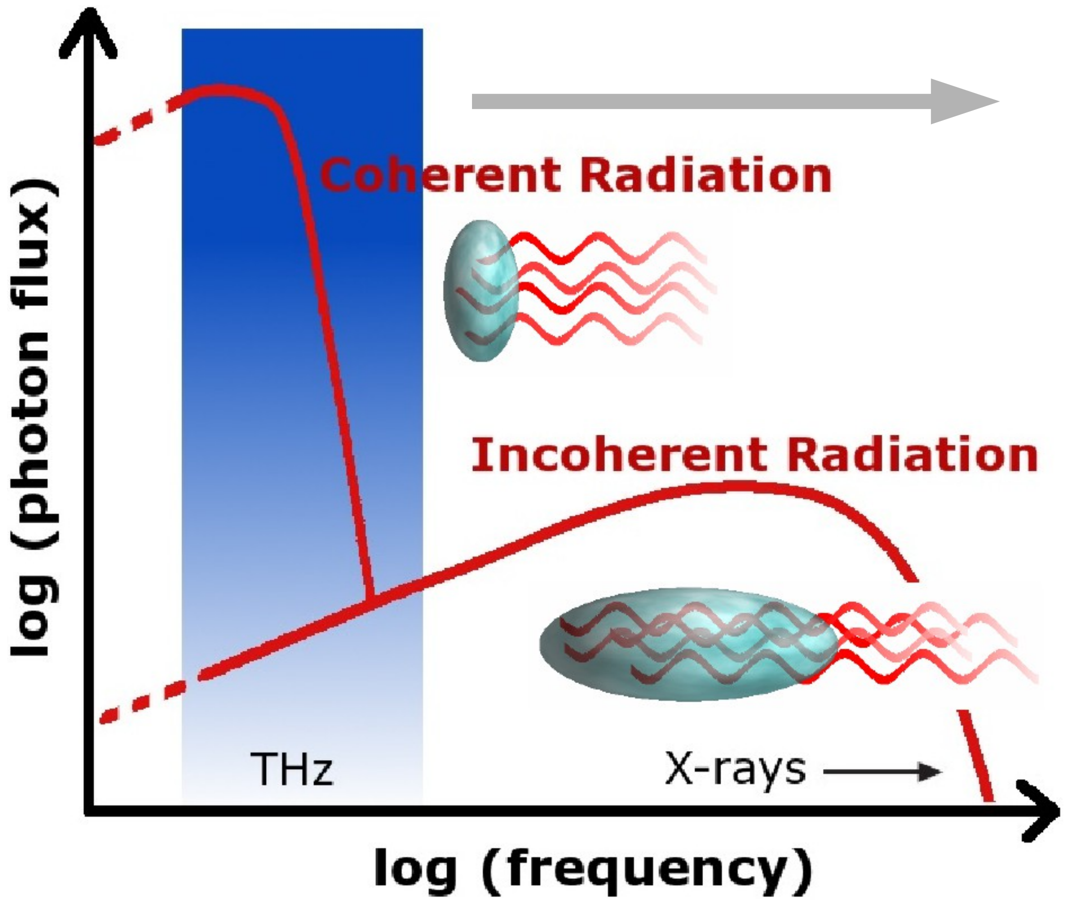
- Exemplary Simulations have been carried out using the ANKA Synchrotron at KIT, Karlsruhe, Germany.



- Multi-user Synchrotron light facility, in operation since 2003.
- Dedicated short pulse operation, $\mathcal{O}$(mm).

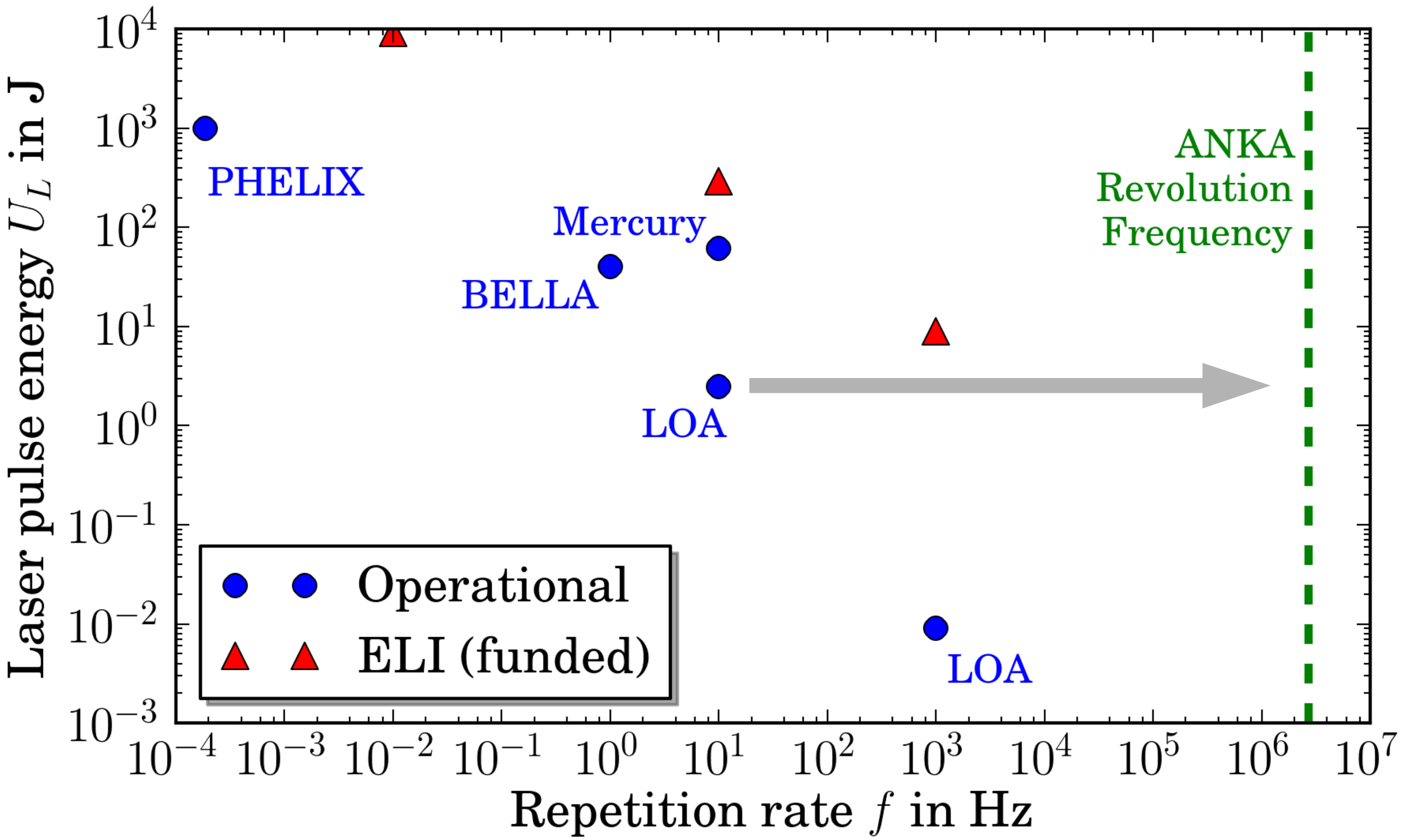
Radiation Spectrum

- For bunch lengths shorter than the emitted radiation wavelength, emission becomes coherent.
- THz region currently difficult to access with Synchrotrons.
- LWFA inherently deliver ultra short pulses.



Repetition Frequency

- Storing and “re-using” LWFA bunches in a Synchrotron would allow for much higher statistics for experiments.



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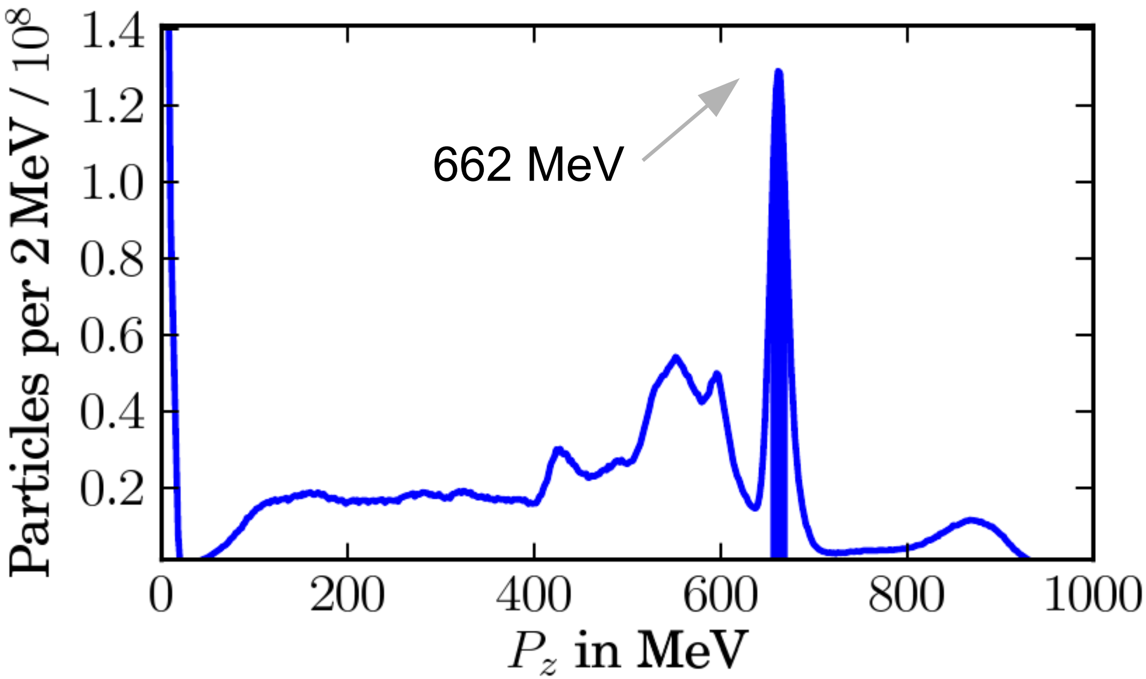
LWFA Simulation I / II

O. Jansen, A. Pukhov, HHUD Duesseldorf
Using the 3D-PIC code VLPL [1]

- Energy spectrum at time of laser depletion is shown to the right.
- Energy acceptance of the ANKA Synchrotron (p_0 ± 1%) is indicated by the solid area.

Table 1: VLPL Input Parameters

Plasma density n_0 in cm^{-3}	9×10^{18}
Laser wavelength λ_L in nm	800
RMS Laser pulse duration τ_L in fs	13
RMS Laser radius at focus r_L in nm	720
Laser pulse energy E_L in J	4.6



[1] Alexander Pukhov. Three-dimensional electromagnetic relativistic particle-in-cell code VLPL J. of Plasma Physics, 61(3):425, 1999.

LWFA Simulation II / II

O. Jansen, A. Pukhov, HHUD Duesseldorf
Using the 3D-PIC code VLPL

- All particles outside the ANKA energy acceptance have been discarded.
- Properties of the remaining bunch are given in Tab. 2

Table 2: LWFA e^--Beam Parameters

Central energy p_0 in MeV	662
Applied energy cut in MeV	655 - 669
RMS energy spread δ in %	0.5
Bunch charge q in pC	160
Number of particles N	1.0×10^9
Geometric emittance ϵ_{geo} in m $\times$ rad	$1.8 \cdot 10^{-8}$
Normalized emittance ϵ_{norm} in m $\times$ rad	$2.3 \cdot 10^{-5}$
RMS Bunch length σ_z in μm	1.1
RMS Bunch length σ_z in fs	3.7
RMS Bunch radius σ_r in μm	1.6
RMS Divergence in rad	0.01
Twiss $\alpha_x = \alpha_y$	0.0
Twiss $\beta_x = \beta_y$ in m	1.4×10^{-4}

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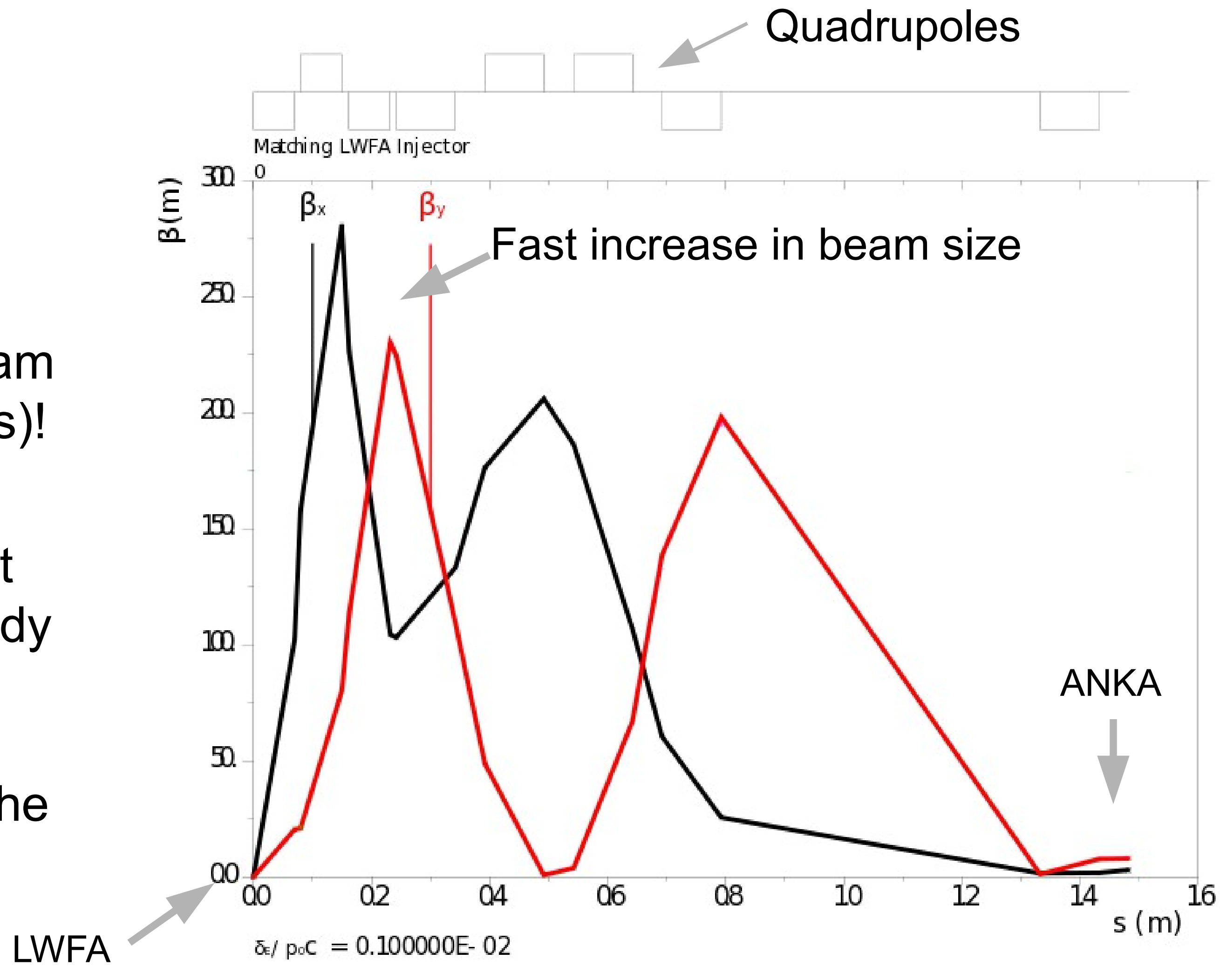
Transfer Line

- Exemplary transfer line.
- Note the initial explosion in beam size (β-functions)!
- Chromaticity not corrected, already resulting in a significant lengthening of the bunch.



Transfer Line - Comments

- Higher order multipoles could be used to (at least partially) compensate the chromaticity, mitigating the bunch lengthening (Cf. eg. [2]).

- If not achromatic, bunch already lengthens to a few mm in the transfer line (factor of ~5000)!

- LWFA simulations have been performed until laser depletion. Density drop at plasma exit should increase beam size and reduce divergence, mitigating the constraints on the transfer line.

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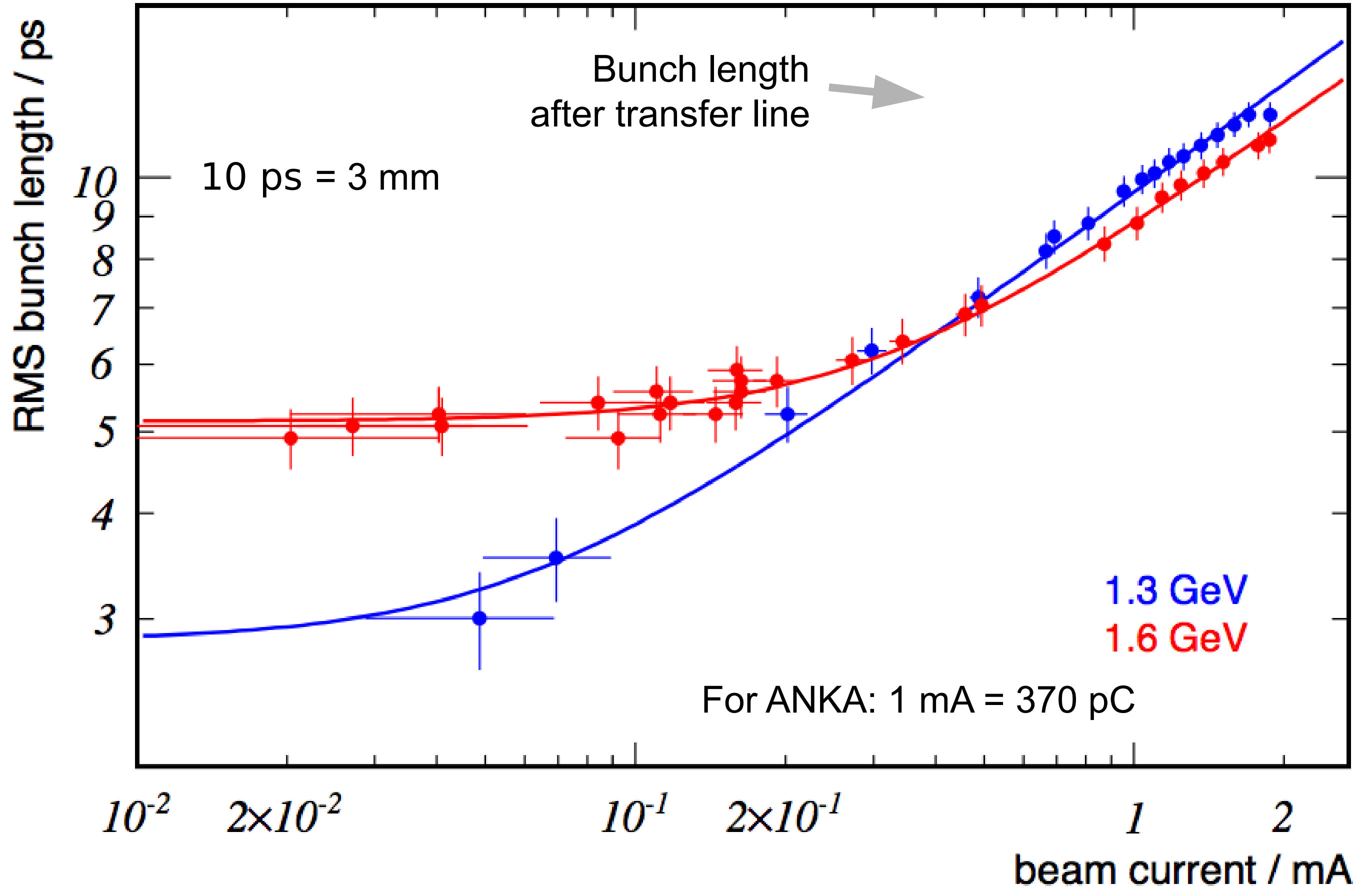
[2] C. Widmann, Design of a Dispersive Beam Transport Line for the JETI Laser Wakefield Accelerator, IPAC11

Comparison ANKA low-α

- Cf. *equilibrium* bunch length measurements at ANKA [3]



[3] N. Hiller et al., Status of Bunch Deformation and Lengthening Studies at the ANKA Storage Ring, IPAC11

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ANKA Lattice Parameter

- ANKA injection optic, scaled to 662 MeV central energy:

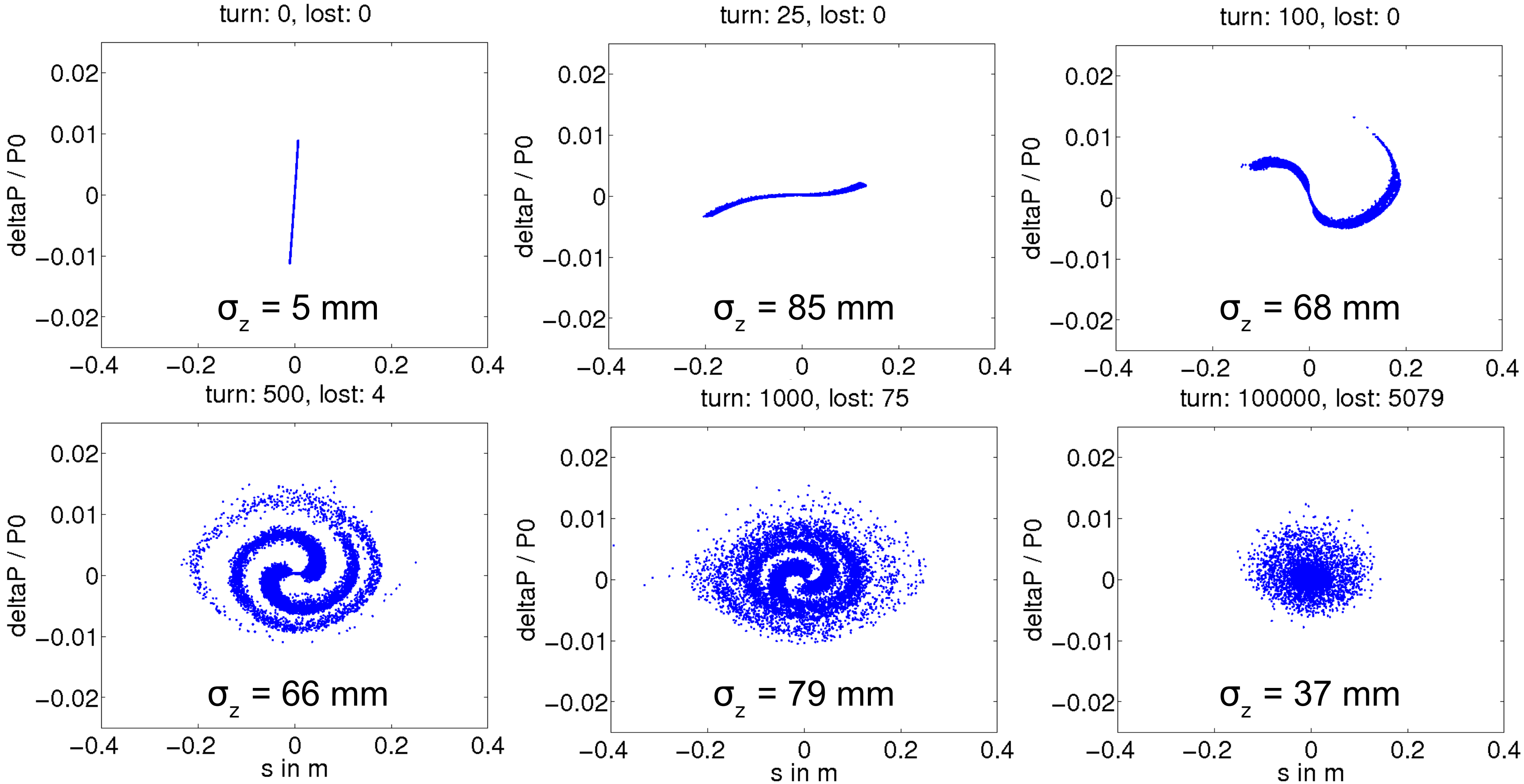
Central energy p_0 in MeV	662
Cavity voltage in kV	200
Cavity frequency in MHz	499
Circumference in m	110.4 ←
Revolution time in ns	368
Momentum compaction factor	0.008 ←
Natural RMS energy spread	2.4×10^{-4}
Natural geometric emittance in m×rad	$6.8 \cdot 10^{-9}$ ← Comparable to LWFA bunch
Radiation energy damping time in ms	79
Linear energy acceptance in %	1.1
Synchrotron tune in kHz	22.7
Synchrotron tune in turns	119.5
Bunch length in mm	4.0
Bunch length in ps	13.4

Reminder: Damping Time

- For electron storage rings, the emittance is given as the equilibrium between radiative damping and quantum excitation.
- Exact damping times depend on lattice structure and beam energy.
- For ANKA at 662 MeV, the (longitudinal) energy damping time is ~80 ms, corresponding to ~200.000 revolutions.
- Naively, one could expect that lengthening process happens on this time scale.

Longitudinal Results I / II

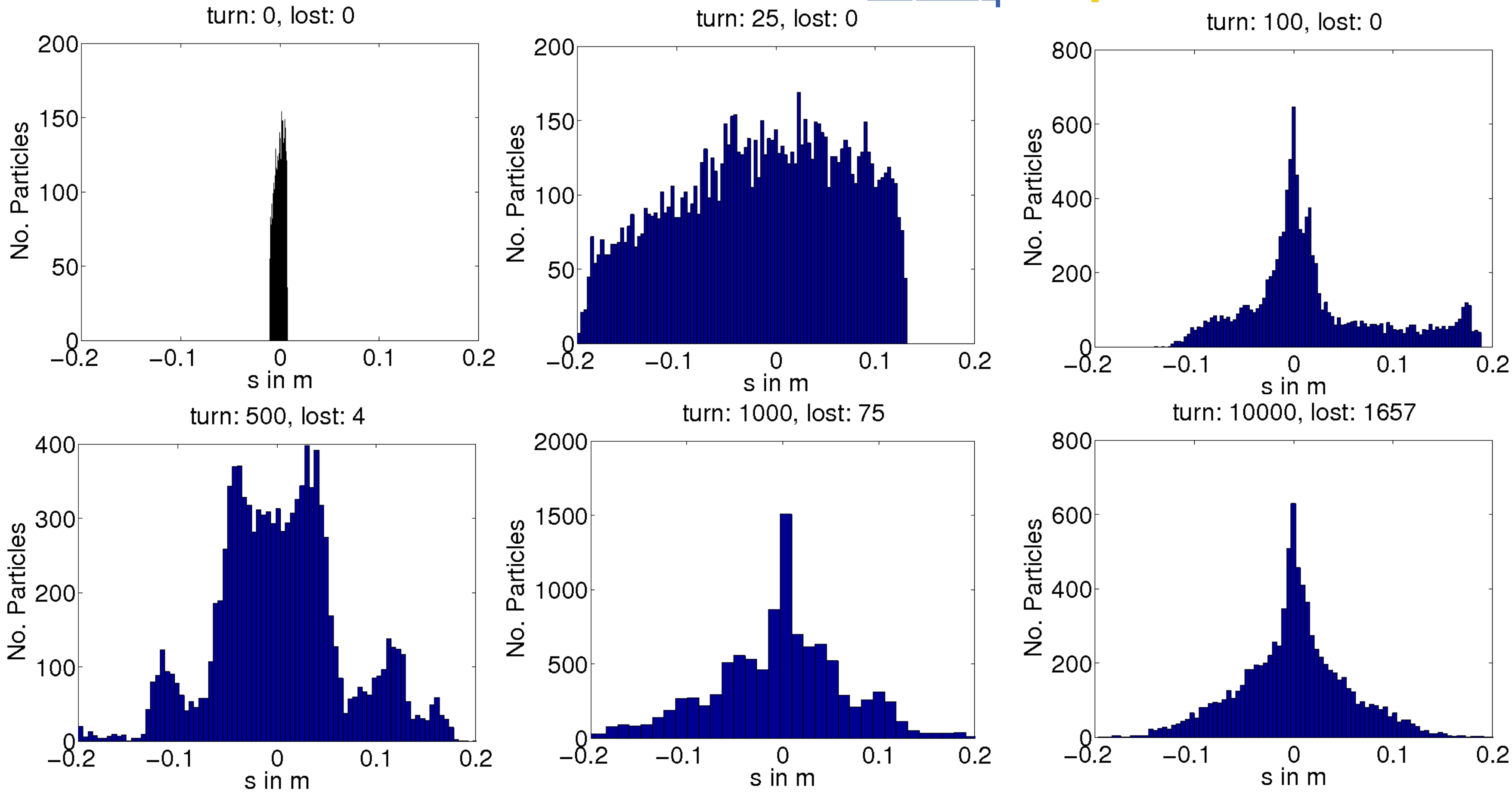
Using AT [4] with 10.000 simulated particles



- Bunch length increases rapidly (independent of initial length)!

[4] A.Terebilo, Accelerator Toolbox for MATLAB, SLAC-PUB-9732, 2001

Longitudinal Results II / II



- Density profiles could still lead to interesting radiation properties.
- Has to be investigated further.

Momentum Compaction

- The momentum compaction factor is defined as:

$$\alpha_c = 1/L \times \oint [D(s)/\rho(s)] ds$$

- It gives the path length difference ΔL per revolution for a particle with an energy deviation Δp via the relation

$$\alpha_c \frac{\Delta p}{p_0} = \frac{\Delta L}{L}$$

- For ANKA, $10^{-4} < \alpha_c < 10^{-2}$.

- The observed lengthening is consistent with analytical estimates.

Comments I / II

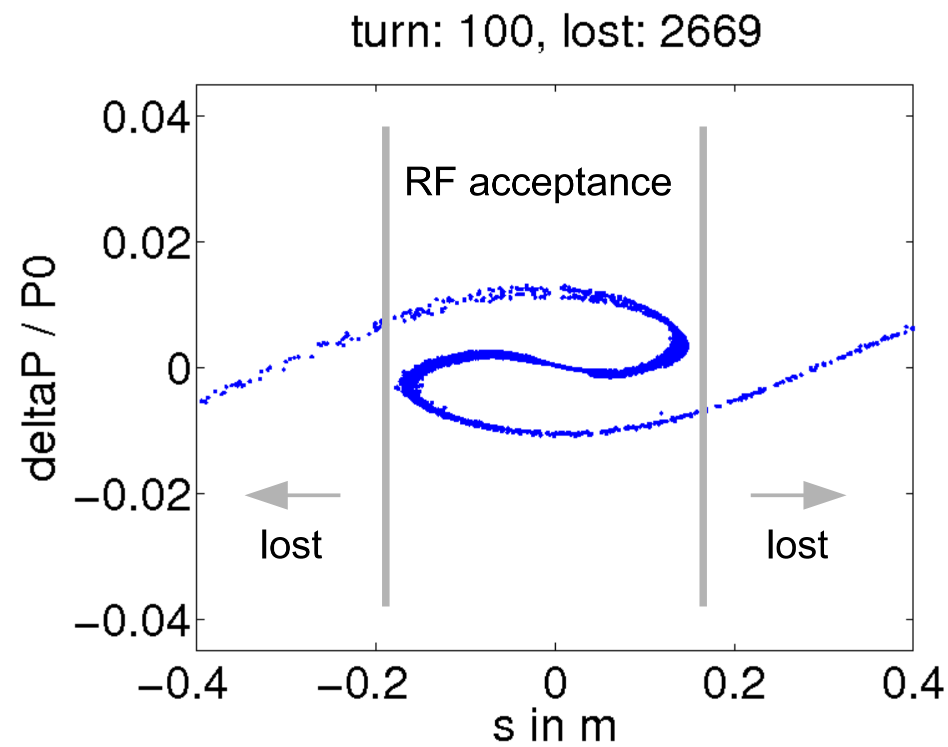
- Operating at a lower α_c and applying a stricter energy cut could slow the lengthening process by a factor ~1000.

- Assuming lengthening in the transfer line can be suppressed,
  the bunch length would still reach the length customary for Synchrotrons with dedicated low-α_c operation within a few 100 turns.

- Space charge and CSR (Coherent Synchrotron Radiation) effects should even accelerate this process.

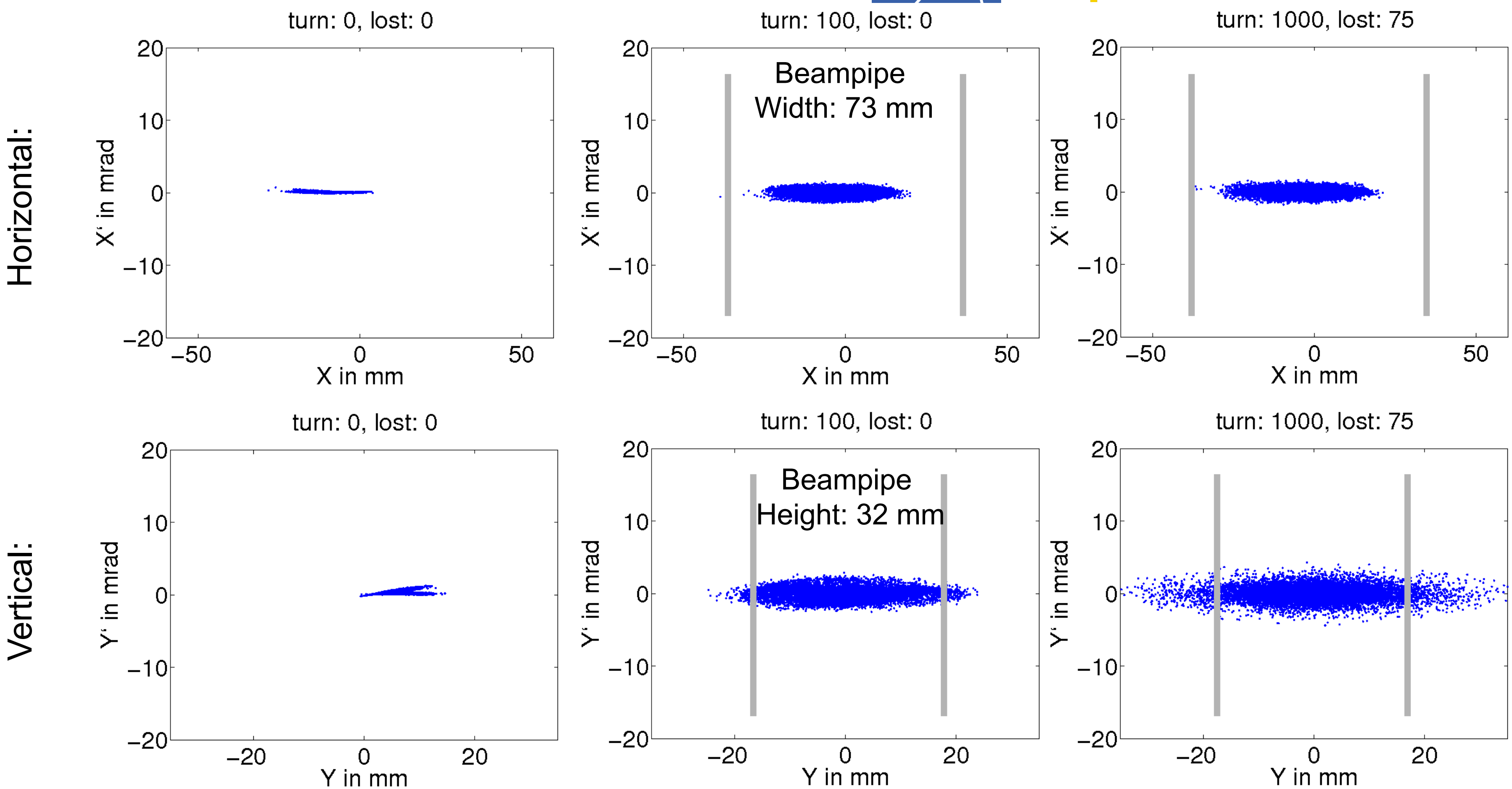
Comments II / II

- Only longitudinal losses considered so far, see example to the right for $p_0 \pm 3\%$.
- An increase of energy acceptance to a few percent seems feasible.



Max. energy deviation	100 %	10 %	5 %	3 %	0.25 %
Bunch charge q in pC	24000	370	270	240	61
Number of particles N	$1.5 \cdot 10^{11}$	$2.3 \cdot 10^{9}$	$1.7 \cdot 10^{9}$	$1.5 \cdot 10^{9}$	$3.8 \cdot 10^{8}$

Transverse Results



- Losses to the beam pipe have not yet been considered.
- They would soon become a major contribution.

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Summary

- The possibility to inject LWFA generated bunches into a Synchrotron has been studied.

- Preserving their ultra short length seems challenging.

- Evolution of bunch density profile could still lead to interesting radiation properties,
  but needs to be investigated further.

Fine

Thank you for your attention!

For more information, please see:
Steffen Hillenbrand *et al.*,
"Study of Laser Wakefield Accelerators as Injectors for Synchrotron Light Sources",
WEPEA012, Proceedings of IPAC'13

Backup slides

Transfer Line I / II

- Initially round beam has to be matched to flat ANKA lattice parameters (Tab. 3).
- Note the 5 orders of magnitude difference in the β-functions (beam size)!

Table 3: ANKA Twiss Parameters at Injection Point

Horizontal beta β_x in m	16.6
Vertical beta β_y in m	6.5
Horizontal alpha α_x	-0.03
Vertical alpha α_y	-0.07

- The matching has been performed using MAD-X [2].
- The large initial divergence made the use of pulses quadrupole magnets [3] necessary.

[2] W. Herr and F. Schmidt. A MAD-X primer. CERN-AB-2004-027-ABP, 2004.
[3] M. Winkler *et al.*, Development and test of iron-free quadrupole lenses with high magnetic flux densities, Nucl. Inst. B, 2003 DOI: 10.1016/S0168-583X(02)02120-1