Challenging Beam Diagnostic Systems for the SwissFEL Project

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Outline

□ Introduction to the SwissFEL (=old PSI-XFEL) Project

- Site Limitation, Beam Parameters for 200 pC and 10 pC
- Optimized Layouts for 200 pC and 10 pC
- Required Tolerances for the Single Spike Mode and Nominal Mode with 10 pC
- 250 MeV Injector Test Facility for the SwissFEL Project

□ Highlights of Beam Diagnostic Systems for 250 MeV Injector Test Facility

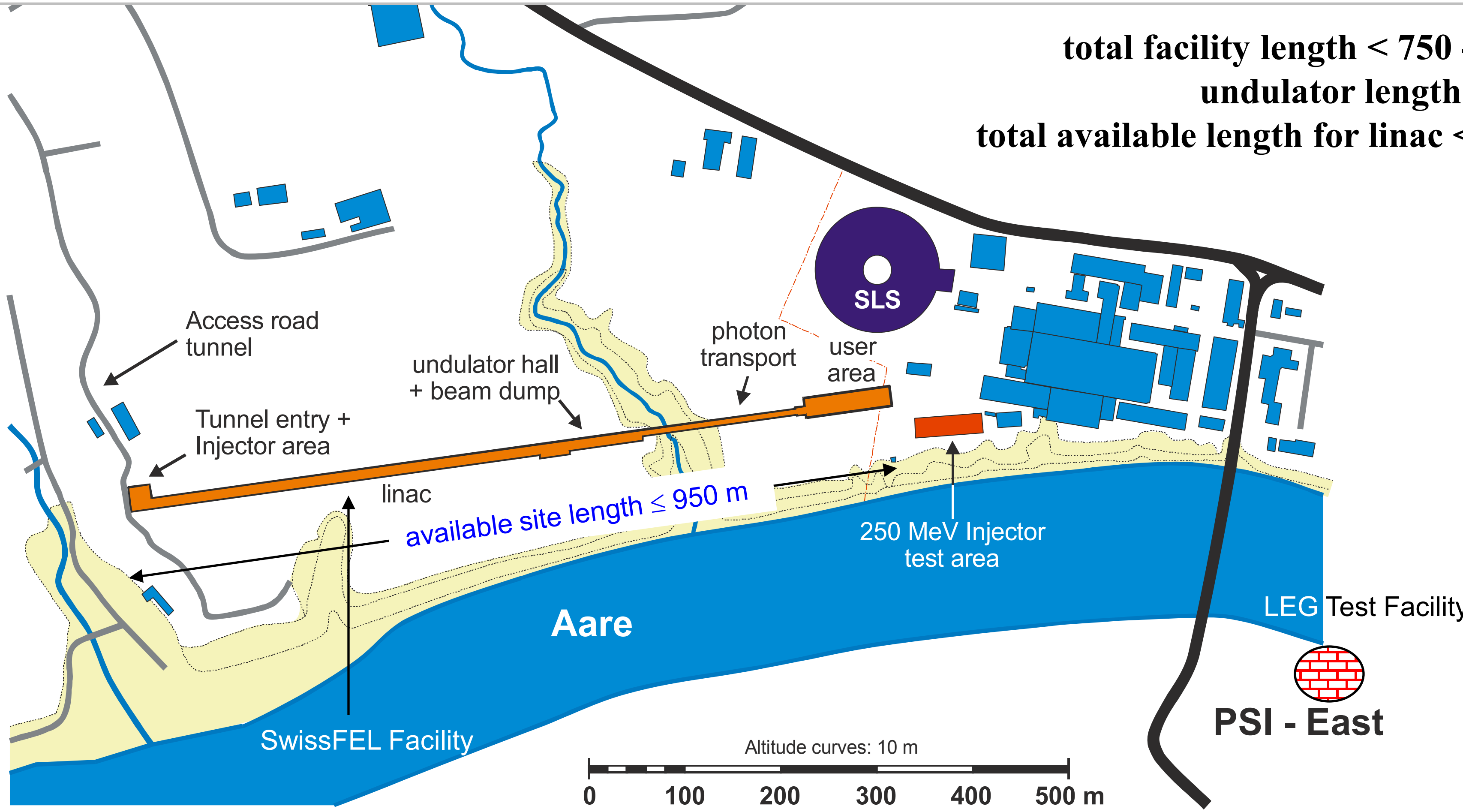
- Reference Timing Distribution
- Screen Monitor
- Beam Position Monitors
- X-band Linac Structure Alignment Monitor
- Compact Electro-Optical Bunch Length Monitor
- Transverse Deflecting Structures (TDS1, TDS2) + Advanced Diagnostic Section

□ Summary & Acknowledgements

SwissFEL - Limited Site

2008-2014 : 250 MeV Injector Test Facility - Commissioning will be started in October, 2009
2012-2016 : RF Gun + Short Linac + Cryo In-Vacuum Undulator based 5.8 GeV SwissFEL Facility
initial (2016-2020) operation modes : 100 Hz with two micro-bunches (0.1 nm to 25 nm)
upgrade (after 2020) : 400 Hz with three bunches + longitudinal single spike mode (0.7 nm to 1 nm)

total facility length < 750 - 890 m
undulator length < 70 m
total available length for linac < 540 m



SwissFEL - Required Beam Parameters

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To get power saturation at 1 Å with 5.8 GeV (or 7 Å with 3.4 GeV) with about 50 m undulator.

required or expected parameters	nominal operation mode		upgrade operation mode
	long pulse	short pulse	attosecond pulse
single bunch charge (pC)	200	10	10
required max core slice emittance (μm)	0.43 / 0.38	0.18	0.25
required max rms slice energy spread (keV)	350 / 250	250	1000
required min peak current at undulator (kA)	2.7 / 1.6	0.7	7
required min beam energy for 1 Å / 7 Å (GeV)	5.8	5.8	5.8 / 3.4
required max saturation length† (m)	48 / 55	50	30 / 25
expected max bunch compression factor	125 / 75	240	2400
expected max projected emittance (μm)	0.65	0.25	0.45
expected rms photon pulse length (fs)	12 / 19	2.3	0.25
expected number of photon ($\times 10^9$)	31 / 32	1.7	3.2 / 31
expected bandwidth (%)	0.031 / 0.029	0.035	0.05 / 0.35

†assumed in-vacuum (NdFeB with diffused dy) undulator parameters: $K = 1.2$, $\lambda_u = 15$ mm, $<\beta> = 15$ m, total length ~ 70 m for 1 Å

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right),\quad K \approx 0.934 B_o[\mathrm{T}]\lambda_u[\mathrm{cm}]$$

$$P = P_o \exp(z / L_G)$$

higher ρ → shorter L_G

$$\Delta\lambda / \lambda \sim 2\rho$$

$$L_{sat} \approx L_G \ln\left(\frac{P_{sat}}{\rho E e \Delta\omega}\right) \approx 20 L_G$$

$$L_G \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

$$\rho \approx \frac{1}{4}\left[\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_n}\left(\frac{K}{\gamma}\right)^2\right]^{1/3}$$

SwissFEL - Required Beam Parameters

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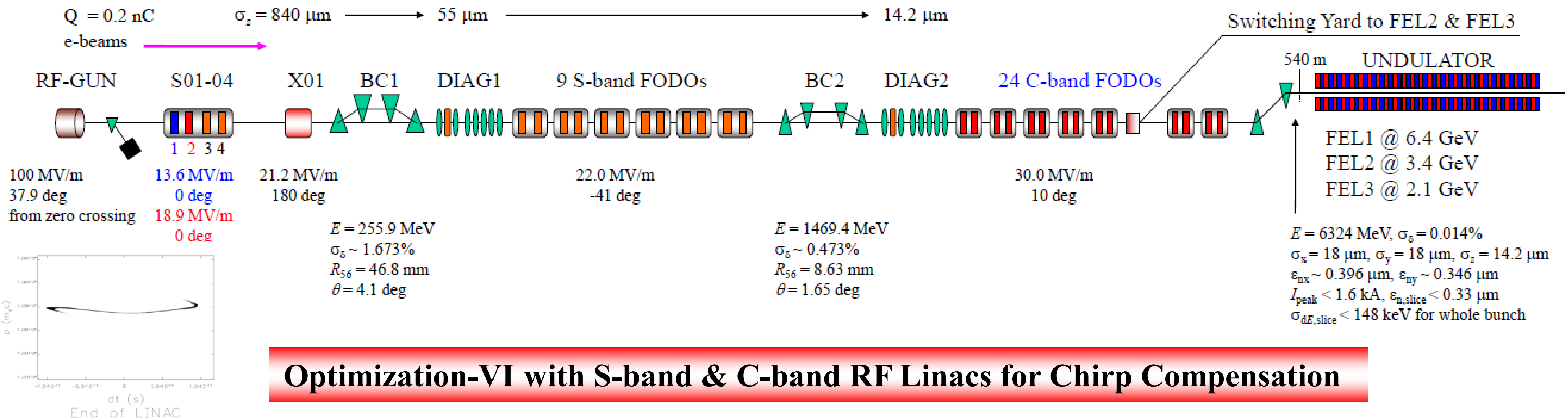
13 layouts with S-band and C-band linac were optimized to supply required beams for SwissFEL!

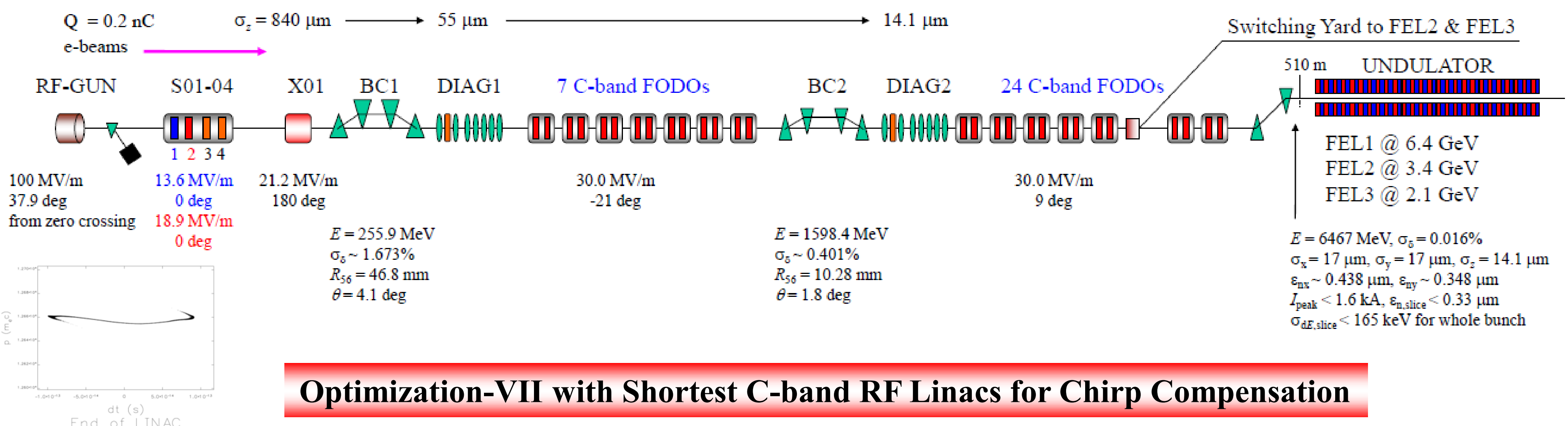
$$\Delta\lambda/\lambda \sim 2\rho \qquad L_{sat} \approx L_G \ln\left(\frac{P_{sat}}{\rho E e \Delta\omega}\right) \approx 20 L_G \qquad L_G \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho} \qquad \rho \approx \frac{1}{4}\left[\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_n}\left(\frac{K}{\gamma}\right)^2\right]^{1/3}$$

SwissFEL - Two Layouts for 200 pC

ASTRA up to exit of SB02 & ELEGANT from exit of SB02 to consider space chare, CSR, ISR, and wakefields !



Optimization-VI with S-band & C-band RF Linacs for Chirp Compensation



Optimization-VII with Shortest C-band RF Linacs for Chirp Compensation

SwissFEL - Two Layouts for 10 pC

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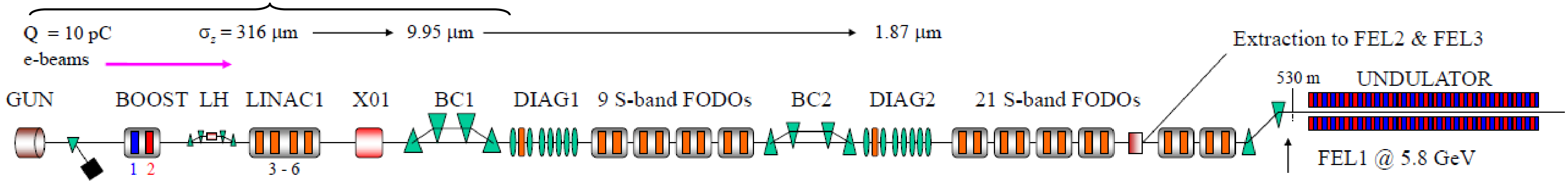
New Injector Layout with Laser Heater & BC1 @ ~ 450 MeV



100 MV/m
37.9 deg
from zero crossing

19.5 MV/m
0 deg
20.8 MV/m
0 deg

22.0 MV/m
-25.3 deg

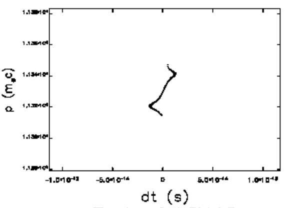
40.2 MV/m
180 deg

22.0 MV/m
-11.0 deg

E = 451.6 MeV
σ_δ ~ 0.666%
R_{56} = 45.98 mm
θ = 3.8 deg

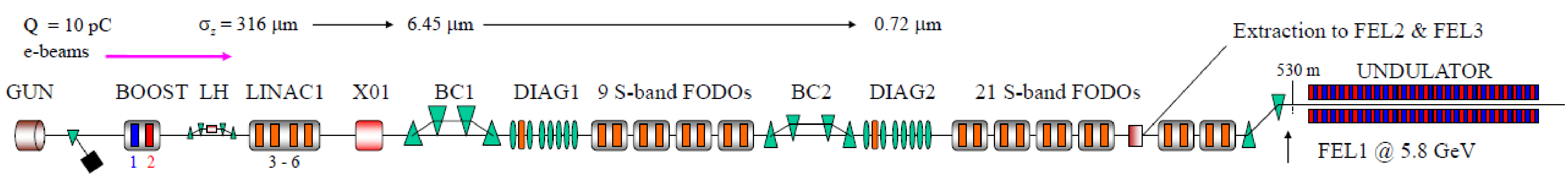
E = 2032.3MeV
σ_δ ~ 0.154%
R_{56} = 4.80 mm
θ = 1.23 deg

E = 5800 MeV, σ_δ = 0.052%
σ_x = 8.5 µm, σ_y = 8.5 µm, σ_z = 1.87 µm
ε_{nx} ~ 0.106 µm, ε_{ny} ~ 0.097 µm
I_{peak} < 728 A, $\varepsilon_{n,core,slice}$ < 0.079 µm
$\sigma_{dE,slice}$ < 220 keV for whole bunch



End of LINAC

Optimization-X with New Injector for 10 pC Nominal Mode



100 MV/m
37.9 deg
from zero crossing

19.5 MV/m
0 deg
20.8 MV/m
0 deg

22.0 MV/m
-25.55 deg

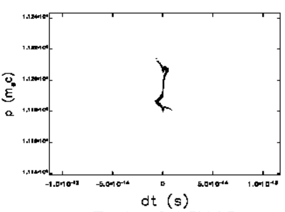
40.5 MV/m
180 deg

22.0 MV/m
- 20.0 deg

E = 450.7 MeV
σ_δ ~ 0.673%
R_{56} = 45.98 mm
θ = 3.8 deg

E = 1963.7 MeV
σ_δ ~ 0.161%
R_{56} = 3.17 mm
θ = 1.0 deg

E = 5800 MeV, σ_δ = 0.053%
σ_x = 13.0 µm, σ_y = 13.0 µm, σ_z = 0.72 µm
ε_{nx} ~ 0.240 µm, ε_{ny} ~ 0.097 µm
I_{peak} < 7 kA, $\varepsilon_{n,core,slice}$ < 0.150 µm
$\sigma_{dE,slice}$ < 800 keV for whole bunch



End of LINAC

Optimization-XI with New Injector for 10 pC Single Spike Mode

SwissFEL - Operation Modes with 10 pC

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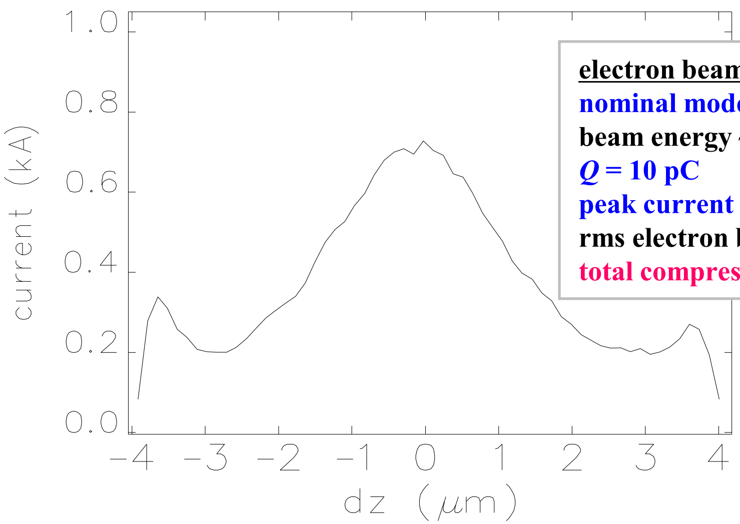
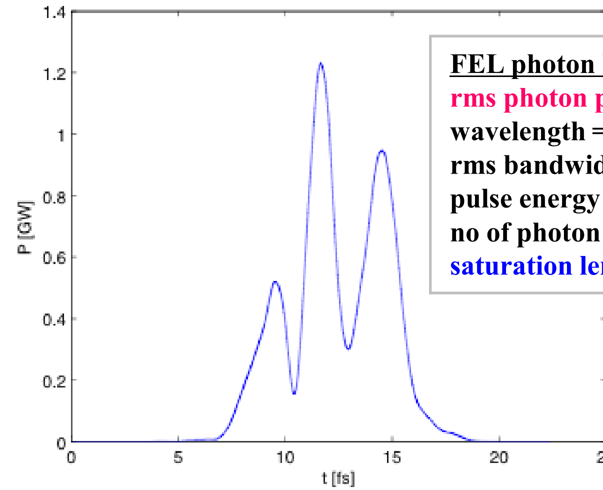
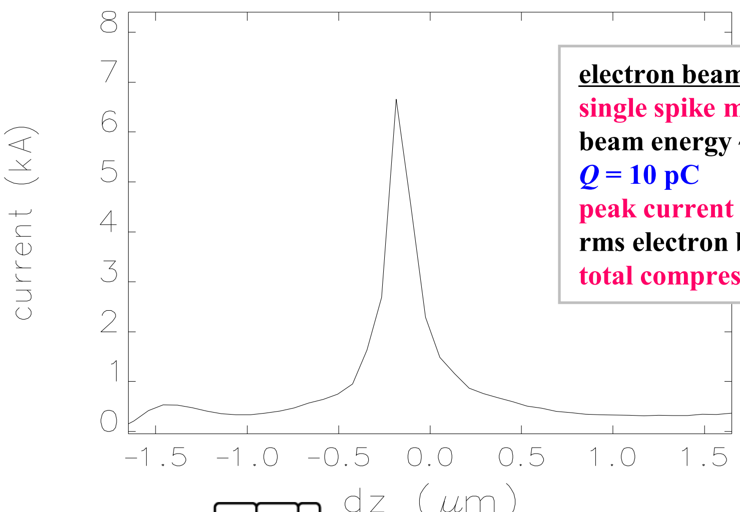
Even Q and I_{pk} are different, saturation length is shorter than 50 m for (0.7 nm to 7 nm)!



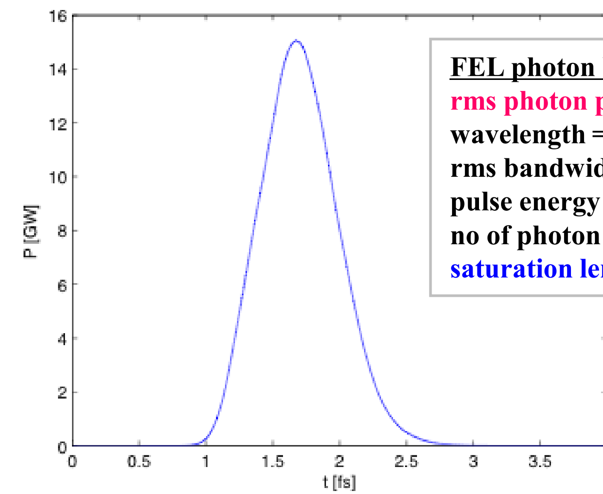
electron beam for Optimization-X
nominal mode
beam energy ~ 3.4 GeV
Q = 10 pC
peak current ~ 0.7 kA
rms electron bunch length ~ 6.2 fs
total compression factor = 240



FEL photon beam for Optimization-X
rms photon pulse length ~ 2.27 fs
wavelength = 0.7 nm with K = 1.05
rms bandwidth ~ 0.08% for 0.7 kA
pulse energy ~ 6 μJ
no of photon per pulse ~ 2.0×10^{10}
saturation length ~ 49.7 m for 0.7 kA



electron beam for Optimization-XI
single spike mode (1 nm ~ 7 nm)
beam energy ~ 3.4 GeV
Q = 10 pC
peak current ~ 7 kA
rms electron bunch length ~ 2.4 fs
total compression factor = 2400



FEL photon beam for Optimization-XI
rms photon pulse length ~ 250 as
wavelength = 0.7 nm with K = 1.05
rms bandwidth ~ 0.35% for 7 kA
pulse energy ~ 9 μJ
no of photon per pulse ~ 3.1×10^{10}
saturation length ~ 25 m for 7 kA

RF Tolerances for Single Spike with 10 pC

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For stable coherent single spike mode (0.7 nm to 7 nm) with 10 pC, 3.4 GeV beam.

parameters	tolerance (rms)	tolerance source
gun laser arrival timing error	≤ 1 fs (rms)	saturation length, arrival time
single bunch charge error	≤ 1% (rms)	saturation power
injector S-band RF phase error per klystron	≤ 0.005 deg (rms)	power, wavelength, arrival time
injector S-band RF voltage error per klystron	≤ 0.005% (rms)	arrival time
injector X-band RF phase error per klystron	≤ 0.005 deg (rms)	power, saturation length
injector X-band RF voltage error per klystron	≤ 0.025% (rms)	arrival time
BC1 dipole power supply error	≤ 7.5 ppm (rms)	arrival time
LINAC1 S-band RF phase error per klystron	≤ 0.015 deg (rms)	wavelength, power
LINAC1 S-band RF voltage error per klystron	≤ 0.010% (rms)	wavelength, arrival time
BC2 dipole power supply error	≤ 7.5 ppm (rms)	arrival time
LINAC2 S-band RF phase error per klystron	≤ 0.017 deg (rms)	wavelength
LINAC2 S-band RF voltage error per klystron	≤ 0.011% (rms)	wavelength

- beam arrival time error $\Delta T_{arrival} \leq$ 5 fs (zero-to-max) ~ electron bunch length order.
- saturation power error $\Delta P_{sat}/P_{sat} \leq$ 100% (zero-to-max) against any optics damage.
- wavelength error $\Delta\lambda/\lambda \leq$ 0.01% (zero-to-max) against intensity lowering due to collimator.
- saturation length error $\Delta L_{sat}/L_{sat} \leq$ 15% (zero-to-max) to get saturation with a given undulator length (undulator length margin ~ 30-40%).

Note that the total S-band and X-band klystrons in injector linac are six and six, respectively.

Requirements for Nominal Mode with 10 pC

parameters	requirements
gun laser arrival timing error	≤ 5 fs (rms)
single bunch charge error	≤ 1% (rms)
injector S-band phase error per klystron	≤ 0.01 deg (rms)
injector S-band voltage error per klystron	≤ 0.01% (rms)
injector X-band phase error per klystron	≤ 0.06 deg (rms)
injector X-band voltage error per klystron	≤ 0.06% (rms)
gun solenoid misalignment after BBA	≤ 20 μm (zero-to-max)
S-band structure misalignment after BBA	≤ 100 μm (zero-to-max)
S-band solenoid misalignment after BBA	≤ 50 μm (zero-to-max)
X-band structure misalignment after BBA	≤ 50 μm (zero-to-max)
BC dipole misalignments after BBA	≤ 50 μm (zero-to-max)
BC dipole role error after BBA	≤ 25 μrad (zero-to-max)
Linac BPM and QM offset (= BBA resolution)	≤ 2 μm (rms)
screen spatial resolution to detect 5% emittance growth	≤ 2 μm (zero-to-max)
gun solenoid power supply error dI/I	≤ 10 ppm (rms)
BC dipole power supply error dI/I	≤ 10 ppm (rms)
QM power supply error dI/I	≤ 10 ppm (rms)
steerer power supply error dI/I	≤ 10 ppm (rms)
girder vibration for 2 Hz to 100 Hz	≤ 50 nm (rms)
Undulator BPM resolution	≤ 0.85 μm (rms)

Tolerance Goal

$\Delta T_{arrival} \leq$ 30 fs (zero-to-max)
$\Delta P_{sat}/P_{sat} \leq$ 30% (zero-to-max)
$\Delta\lambda/\lambda \leq$ 0.001% (zero-to-max)
$\Delta L_{sat}/L_{sat} \leq$ 15% (zero-to-max)
from 80% core slices

Note that the total S-band and X-band klystrons in injector linac are six and two, respectively.

10 pC - Ultra-Sensitive Jitter Sources

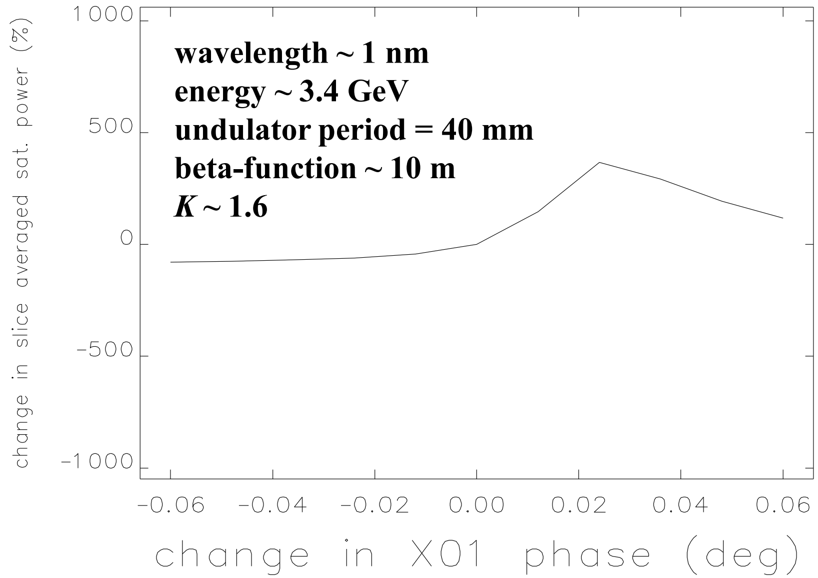
error source : X-band (X01) RF phase

error range : -0.06 deg to +0.06 deg with 10 steps

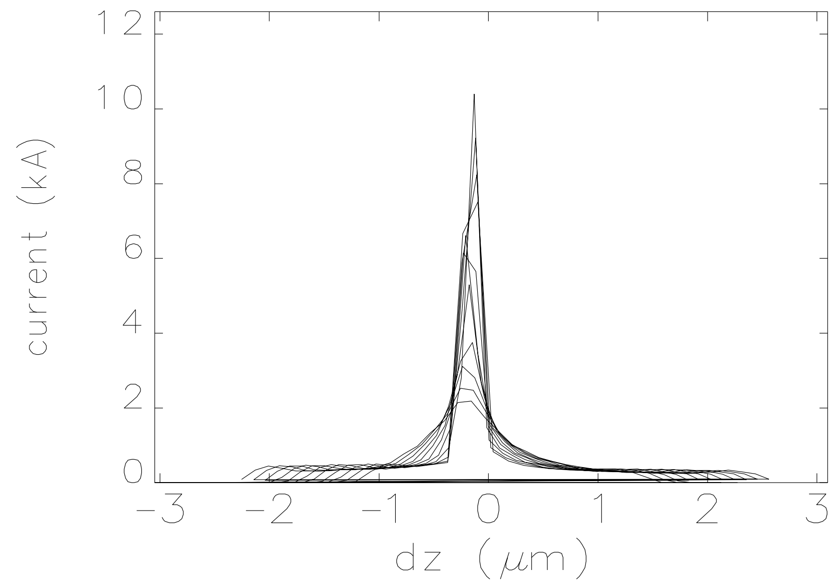
monitoring point : at the entrance of undulator @ 3.4 GeV

For $\Delta P_{sat}/P_{sat} \leq 100\%$ (zero-to-max), X-band RF phase error ≤ 0.002 deg (rms) for all six klystrons. This X-band RF phase tolerance is challenging !

FEL power change due to 10 X-band RF phase errors



peak current fluctuation due to 10 X-band RF phase errors

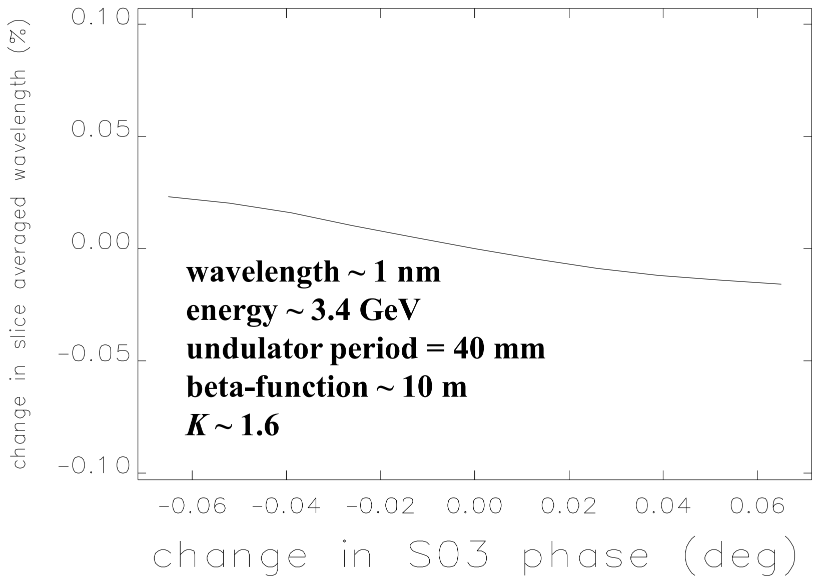


X-band RF phase error, single bunch charge error, and injector S-band RF phase errors are sensitive jitter sources to FEL saturation power.

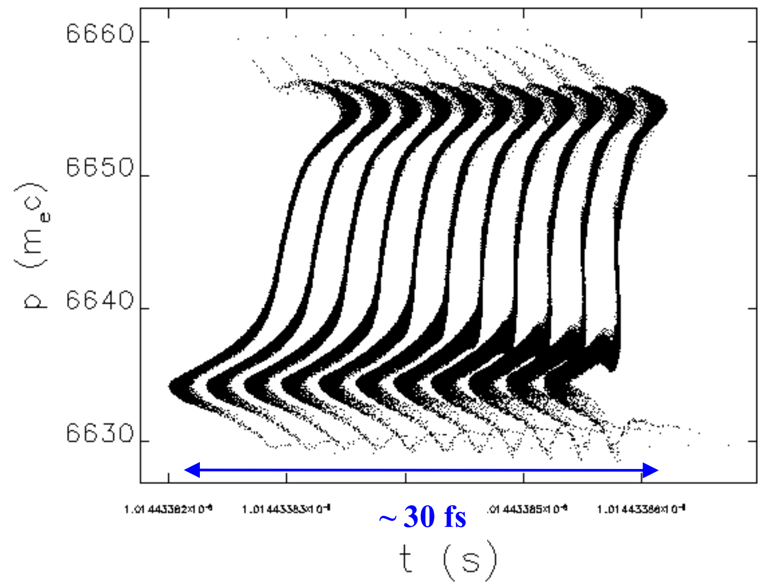
10 pC - Ultra-Sensitive Jitter Sources

error source : RF phase of S-band linac (S03) in injector
error range : -0.06 deg to +0.06 deg with 10 steps
monitoring point : at the entrance of undulator @ 3.4 GeV
For Δλ/λ ≤ 0.01% (zero-to-max), S-band RF phase error ≤ 0.005 deg (rms).
This S-band RF phase tolerance is challenging !

wavelength change due to 10 S-band phase errors



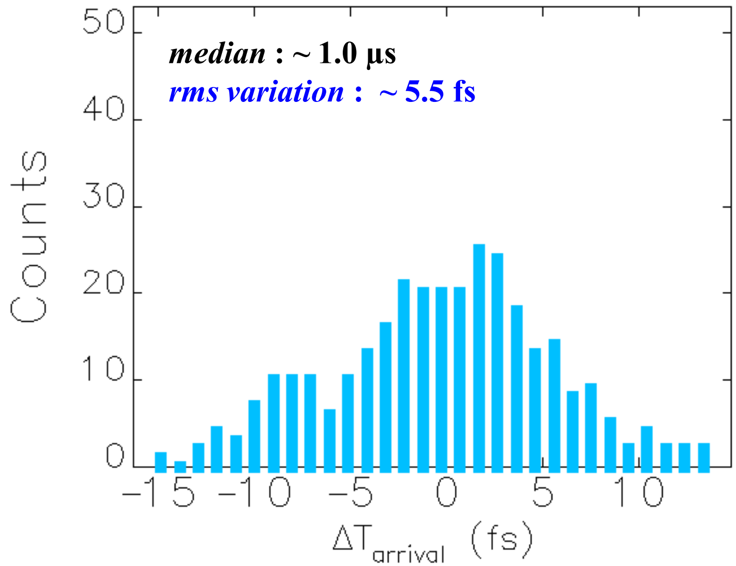
long. phase space & peak current fluctuation due to errors

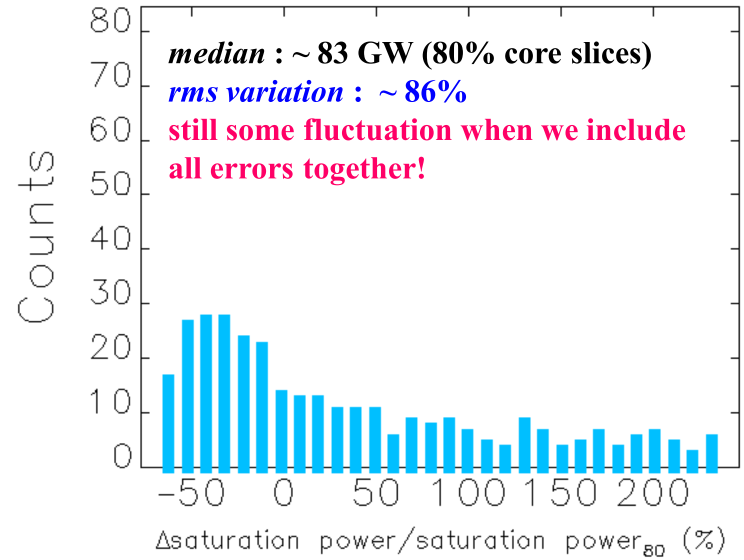


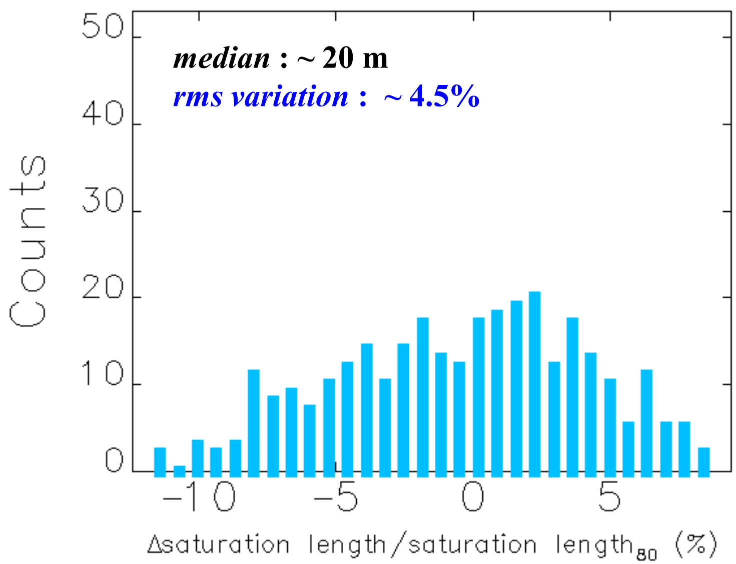
S03 phase change from -0.06 deg to +0.06 deg with 10 steps

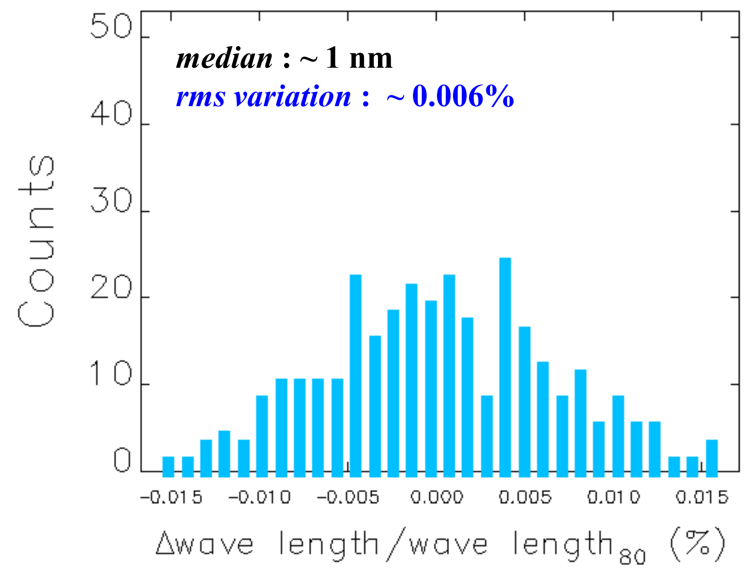
injector S-band RF phase errors and LINAC1 RF phase and voltage errors, and LINAC2 RF phase and voltage errors are sensitive jitter sources to photon beam wavelength.

10 pC - 300 Times S2E Simulation with Errors









SwissFEL - RF Development Milestone

year	requirements	compression factor	operation conditions
2010	$\phi_s \leq 0.1$ deg (rms) $\Delta V/V \leq 0.1\%$ (rms)	1	for injector gun with 22 A, 200 pC
2011	$\phi_s \leq 0.06$ deg (rms) $\Delta V/V \leq 0.06\%$ (rms)	16 34 for LCLS 1 nC case	for injector BC1 with 350 A, 200 pC
2012	$\phi_s \leq 0.04$ deg (rms) $\Delta V/V \leq 0.04\%$ (rms)	75 90 for LCLS 250 pC case	for XFEL BC1+BC2 with 1.6 kA, 200 pC
2014	$\phi_s \leq 0.02$ deg (rms) $\Delta V/V \leq 0.02\%$ (rms)	125	for XFEL BC1+BC2 with 2.7 kA, 200 pC
2016	$\phi_s \leq 0.01$ deg (rms) $\Delta V/V \leq 0.01\%$ (rms)	240	for XFEL BC1+BC2 with 0.7 kA, 10 pC
after 2020	$\phi_s \leq 0.005$ deg (rms) $\Delta V/V \leq 0.005\%$ (rms)	2400	for XFEL BC1+BC2 with 7 kA, 10 pC

Nominal Operation Modes

Upgrade Mode

These are requirements for S-band RF for about 1 minute. Requirements of X-band are four times of S-band.

SwissFEL - Required Linac BBA Resolution

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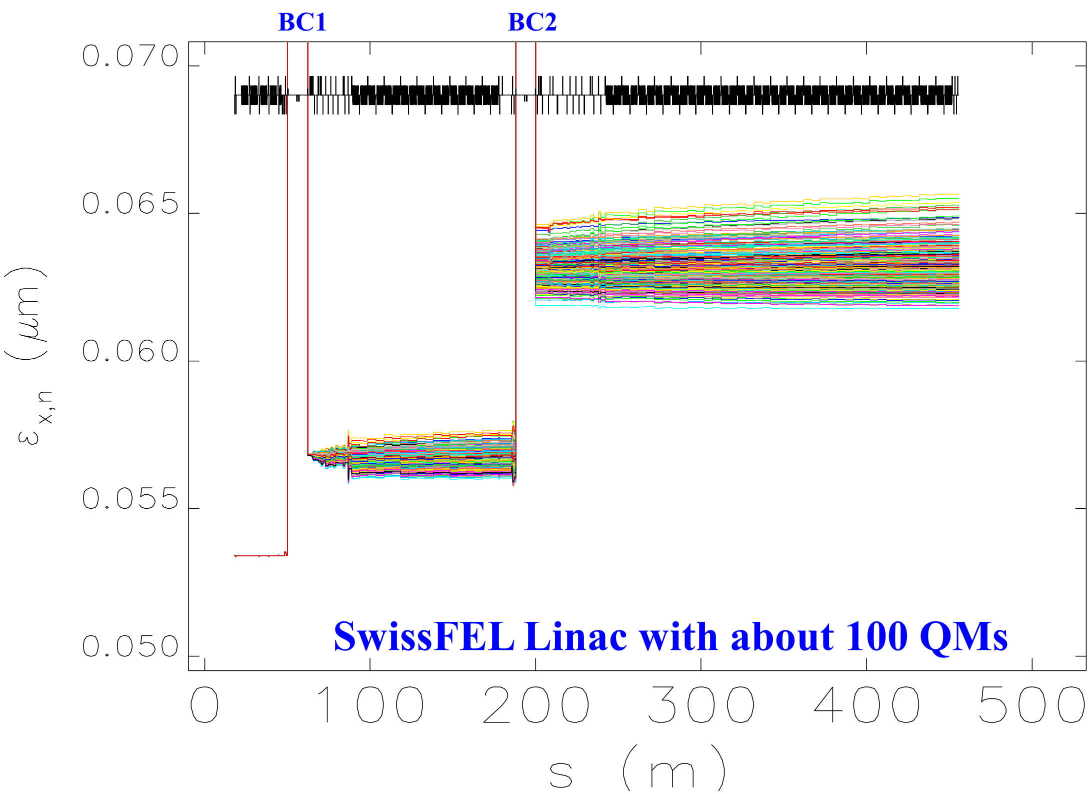
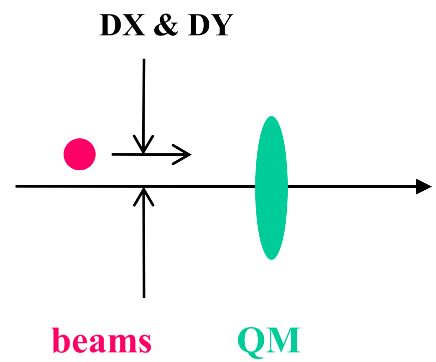
For 2 pC operation, after assuming without any QM misalignment, we applied 3 µm (zero-to max, rms = 1 µm) BBA position random errors (DX & DY) to all QMs for 300 steps. In this case, projected emittance growth ≤ about 6% (peak-to-peak) or 1% (rms). For SwissFEL project, to keep emittance growth within 2% (rms) in linac, required BPM resolution should be smaller than 2 µm (rms) for a low charge operation.



Emittance Growth due to BBA position random errors in all QMs.



DX & DY = BBA positioning error

SwissFEL - 250 MeV Injector Test Facility

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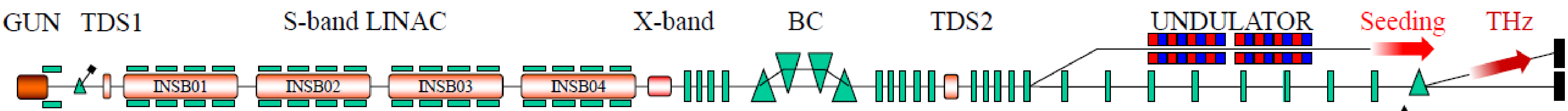
laser beam : $\sigma_{x,y}$= 270 μm, ΔT = 9.9 ps (FWHM), rise & falling time = 0.7 ps
e-beams : Q ~ 0.2 nC, $\varepsilon_{thermal}$= 0.195 μm, I_{peak} = 22 A

April 17th, 2009 by Y. Kim

σ_z = 840 μm ⟶ 58 μm

Future Possible Upgrades

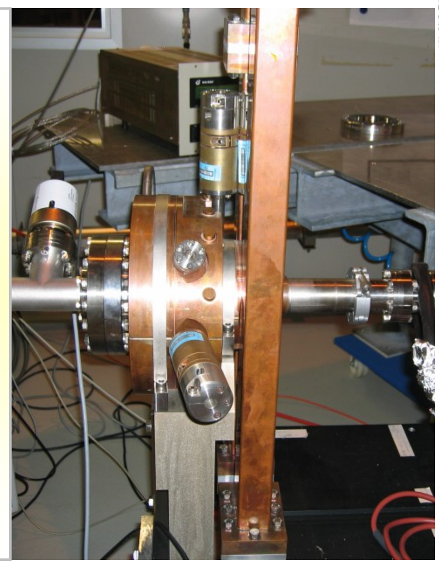


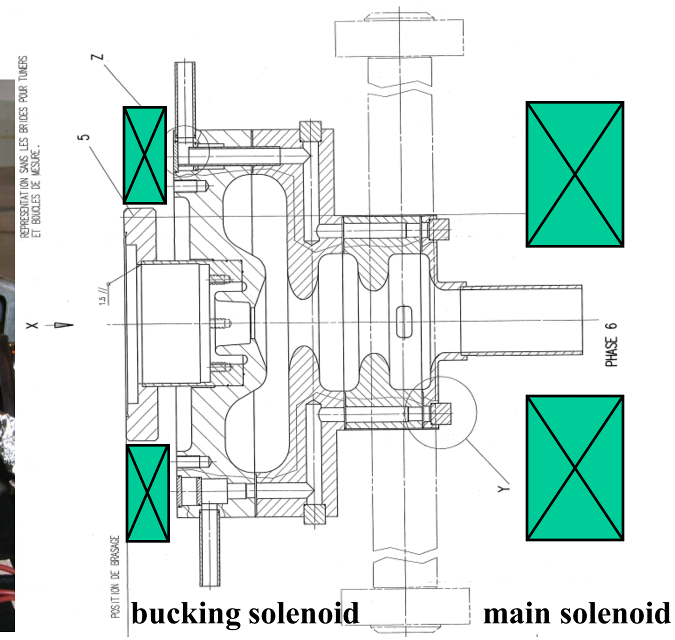
GUN	S-band LINAC		X-band	BC	End
100.0 MV/m 37.89 degree from zero crossing	13.59 & 18.86 MV/m 0.0 degree	17.5 MV/m -34.2 degree	21.2 MV/m 180 degree ΔE = -20 MeV	E = 255.6 MeV σ_δ ~ 1.674% R_{56} = 46.8 mm θ = 4.1 deg	E = 255.5 MeV, σ_δ = 1.665% σ_x~ 55 μm, σ_y~ 55 μm, σ_z ~ 58 μm ε_{nx}~ 0.379 μm, ε_{ny}~ 0.350 μm

s = 0.0 m 2.95 m 13.15 m 32.85 m 43.35 m 51.753 m 54.753 m 62.603 m 65 m

CTF3 RF GUN

RF tested @ 100 MV/m - two weeks operation at CERN
power for 100 MV/m = 22 MW with 4.5 μs RF pulse
power for 120 MV/m = 25 MW
RF frequency ~ 2998.5 MHz
cell = 2.5 cells (One TM02 + Two TM01)
Q_0 = 16300
number of bunch in a train = 48
cathode wall angle = 20 degree
total length ~ 0.25 m
full cell length ~ 50 mm
designed charge ~ 2.33 nC for CTF3



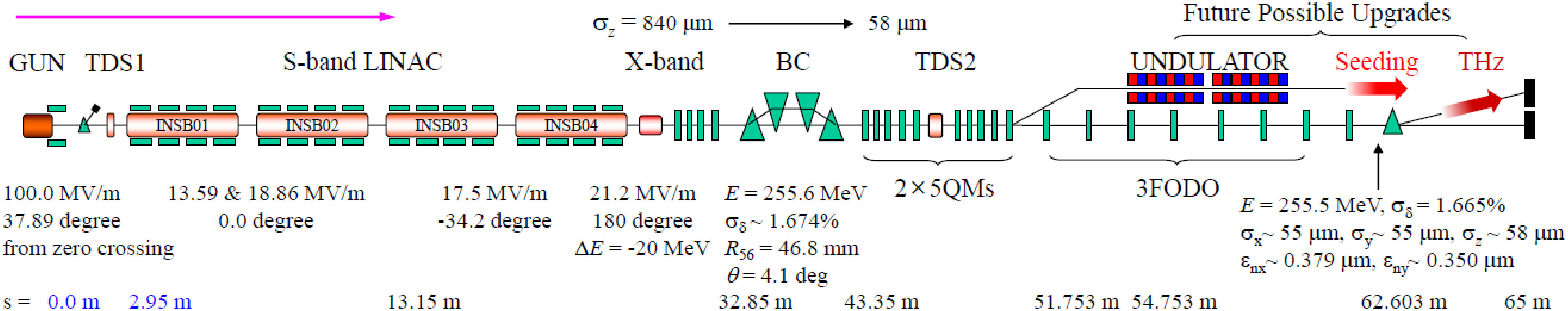


SwissFEL - 250 MeV Injector Test Facility

PAUL SCHERRER INSTITUT

April 17th, 2009 by Y. Kim

laser beam : $\sigma_{x,y}$= 270 μm, ΔT = 9.9 ps (FWHM), rise & falling time = 0.7 ps
e-beams : Q ~ 0.2 nC, $\varepsilon_{thermal}$= 0.195 μm, I_{peak} = 22 A



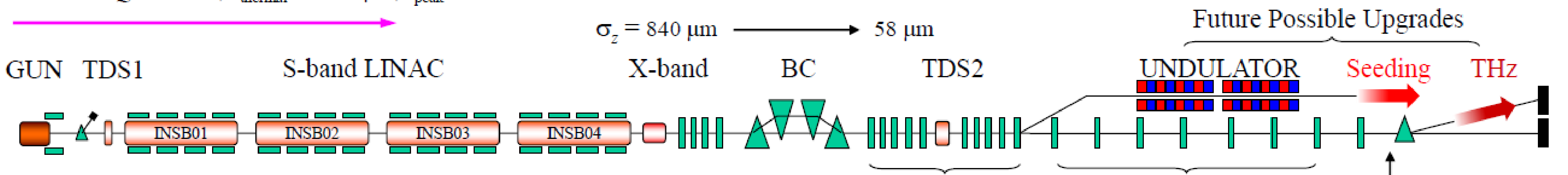
Parameters	10 pC	100 pC	200 pC
laser diameter on cathode	400 μm	857 μm	1080 μm
laser pulse length (FWHM)	3.7 ps	7.9 ps	9.9 ps
peak current on cathode	3 A	14 A	22 A
thermal emittance on cathode	0.072 μm	0.155 μm	0.195 μm
core slice emittance before / after BC	0.078 μm / 0.078 μm	0.213 μm / 0.213 μm	0.320 μm / 0.330 μm
projected emittance before BC	0.095 μm	0.233 μm	0.350 μm
bunch length before BC (rms)	1.05 ps	2.23 ps	2.80 ps
bunch length after BC (rms)	33.2 fs	117.6 fs	193.3 fs
peak current after BC	104 A	285 A	352 A
x / y projected emittance after BC	0.104 μm / 0.096 μm	0.268 μm / 0.233 μm	0.379 μm / 0.350 μm
arrival error for stable seeding at ~ 160 nm	~ 5.5 fs	~ 19.6 fs	~ 32.2 fs
min beam size on OTRs in 3FODO (rms)	~ 14 μm	~ 35 μm	~ 55 μm

SwissFEL - 250 MeV Injector Test Facility

PAUL SCHERRER INSTITUT

April 17th, 2009 by Y. Kim

laser beam : $\sigma_{x,y}$ = 270 µm, ΔT = 9.9 ps (FWHM), rise & falling time = 0.7 ps
e-beams : Q ~ 0.2 nC, $\varepsilon_{thermal}$ = 0.195 µm, I_{peak} = 22 A



100.0 MV/m
37.89 degree
from zero crossing

13.59 & 18.86 MV/m
0.0 degree

17.5 MV/m
-34.2 degree

21.2 MV/m
180 degree
ΔE = -20 MeV

E = 255.6 MeV
σ_δ ~ 1.674%
R_{56} = 46.8 mm
θ = 4.1 deg

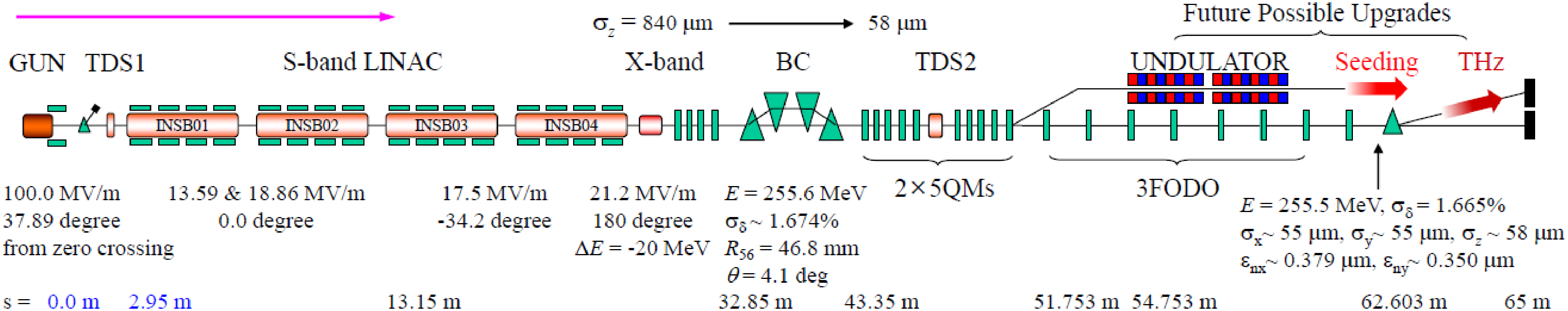
E = 255.5 MeV, σ_δ = 1.665%
σ_x ~ 55 µm, σ_y ~ 55 µm, σ_z ~ 58 µm
ε_{nx} ~ 0.379 µm, ε_{ny} ~ 0.350 µm

s = 0.0 m 2.95 m 13.15 m 32.85 m 43.35 m 51.753 m 54.753 m 62.603 m 65 m

SwissFEL - 250 MeV Injector Test Facility

April 17th, 2009 by Y. Kim

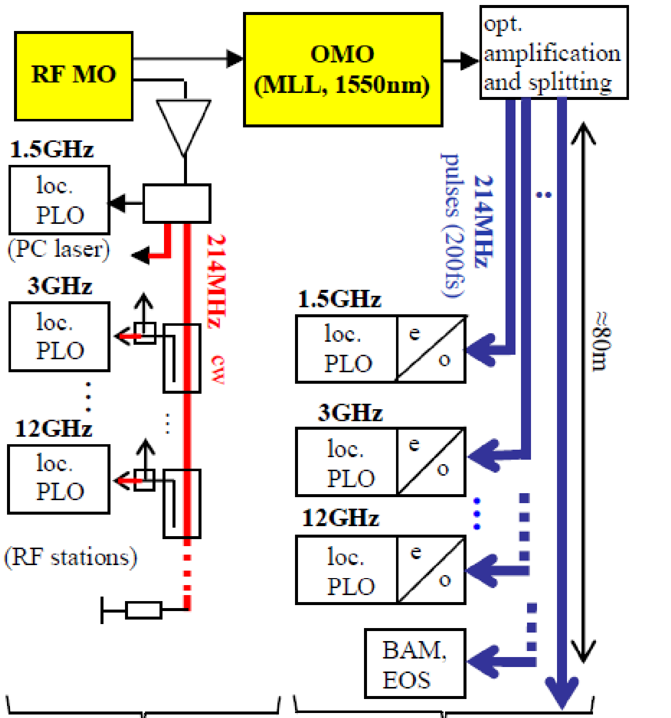
laser beam : $\sigma_{x,y}$= 270 µm, ΔT = 9.9 ps (FWHM), rise & falling time = 0.7 ps
e-beams : Q ~ 0.2 nC, $\varepsilon_{thermal}$= 0.195 µm, I_{peak} = 22 A



Challenging Beam Diagnostics at 250 MeV Injector

wide dynamic range (10 pC to 200 pC)
ultra-small beamsize (~ 14 µm) and ultra-small normalized emittance (~ 0.1 µm) for 10 pC
ultra-short bunch length (33 fs) for 10 pC

Highlights - Reference Timing Distribution



electrical: baseline

optical: has potential for XFEL sync syst. performance

temp. stabilized cables

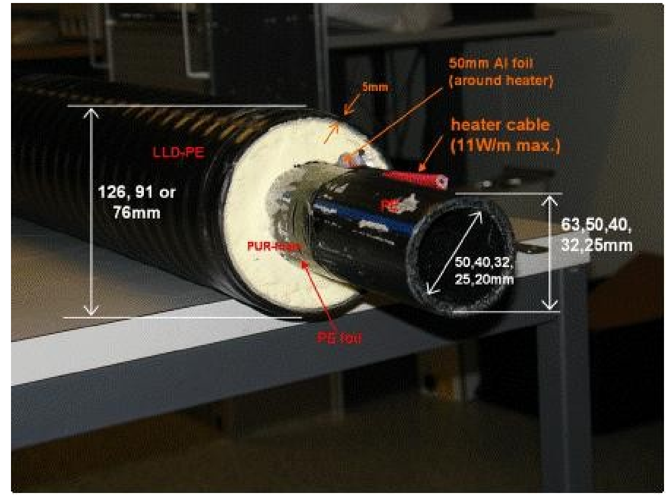
stabilized & disp. compens. FO links

S. Hunziker and V. Schlott - TUPB43

Electrical Reference Distribution

- **temperature controlled coaxial cable**
- **temperature stabilization : <0.2°C**

- **30 m Heliax 3/8" (<0.2°C stability) drift : < 15 fs**
- **some m of braided low drift cables (Sucoflex 404) for short distance at medium ins. loss (<0.2°C stability) < 10fs drift**
- **directional coupler timing drift : 3 fs/°C**
- **local PLO rms timing jitter: < 10 fs (1kHz..10MHz)**
- **total long term timing drift < 50 fs in injector**

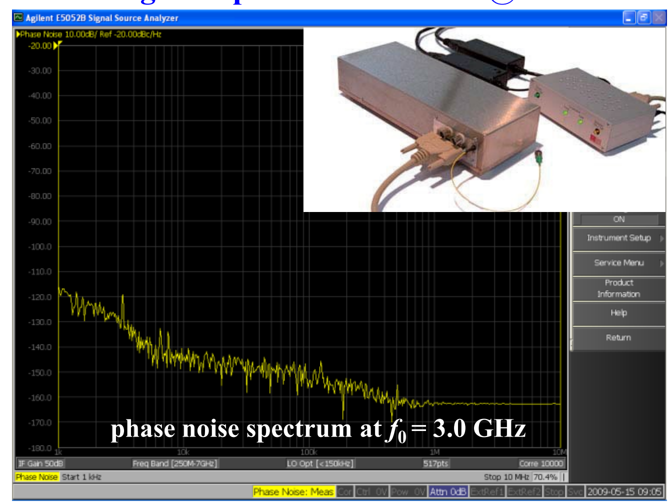


Optical Reference Distribution:

- **mode locked laser (MLL) based Optical MO**
- **OMO : Onefive Origani 15 Solition laser**
- **dispersion compensated FO links**
- **measured rms timing jitter : 3.3 fs (1kHz..10MHz)**
- **OMO wavelength: 1550 nm**
- **OMO max. opt. power: 120 mW (free space)**
  70 mW (fiber coupled)

- **fiber drift and mech. jitter will be stabilized using optical correlation technique**
- **expected total long term drift : < 10 fs**
- **optical-electrical phase detectors and direct harmonic extraction used in local PLLs, depending on drift/jitter requirements**

OMO signal + photodiode + BPF @ 3.0 GHz



with Agilent E5052B Signal Source Analyzer

Highlights - Screen Monitors

Specification

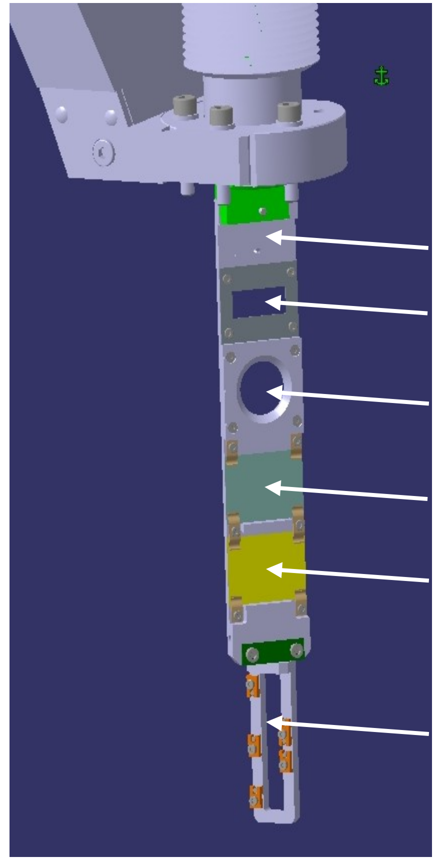
- charge range : 10 pC to 200 pC
- energy range : 7 MeV to 350 MeV
- beamsize range : 14 µm to 5 mm
- pixel size : 3.5 µm to 40 µm
- imaging angle : 45 degree w.r.t. optical axis
- methods : Ce:LuAG crystal, Ce:YAG crystal, OTR, DR and wire scanner on a ladder
- prototype was installed at the SLS linac for testing

On-Going Research

- higher optical resolution (~ 2 µm) for 10 pC operation
- extra large screen for BC operation (~ 10 cm)
- cooled CCD for improved S/N for 10 pC operation
- gated CCD or CMOS technology for 3 bunch operation
- study on COTR to use it for trans. and long. diagnostics

R. Ischebeck - TUPD45

Screen Ladder for High Energy Beam



Courtesy of AMI

Highlights - Beam Position Monitors

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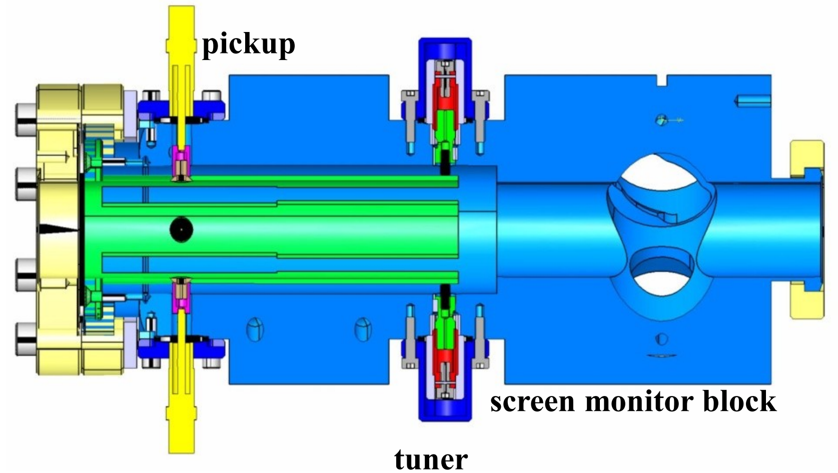
PSI Resonant Stripline BPM

- charge range : 10 pC to 200 pC
- resonant frequency : ~ 500 MHz
- energy range : 7 MeV to 350 MeV
- sensitivity : 1.53 dB/mm for 200 pC
- expected rms resolution : 5.5 µm for 200 pC
- 6 GSample/s DRS4 sampling chip, designed by S. Ritt
- improved resolution by 500 MHz bandpass filter

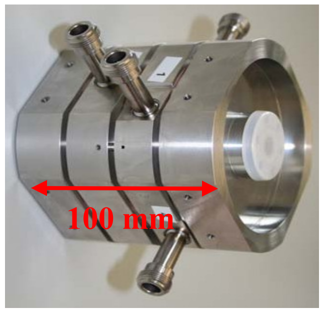
B. Keil - TUOC01 & A. Citterio - MOPD12



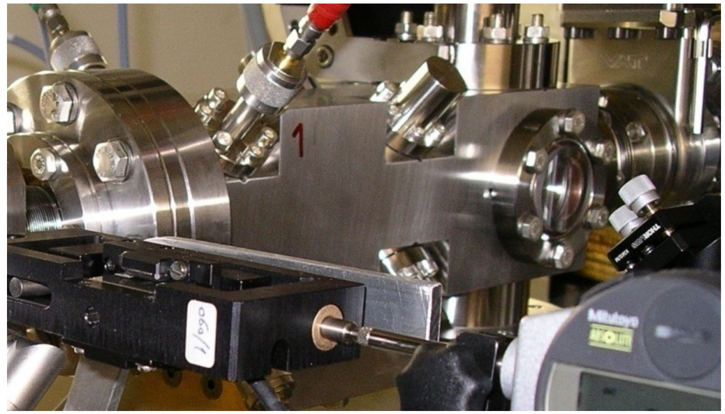
RF Cavity BPM

- collaboration with DESY, SPring-8, CERN, and PSI
- resonant frequency : ~ 3.3 GHz
- rms resolution ≤ 1 µm for single bunch
- three RF cavity BPMs will be installed

D. Lipka - MOPD02



RF Cavity BPM



New Prototype PSI Stripline BPM in SLS LINAC

On-Going Research

- higher resolution linac BPM (~ 1 µm) for 10 pC operation
- higher resolution undulator BPM (≤ 0.85 µm) for 10 pC operation
- BPM for BC operation (wide beam ~ 7 mm)

Highlights - X-band Alignment Monitor

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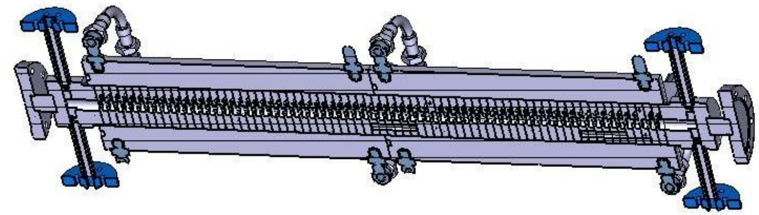
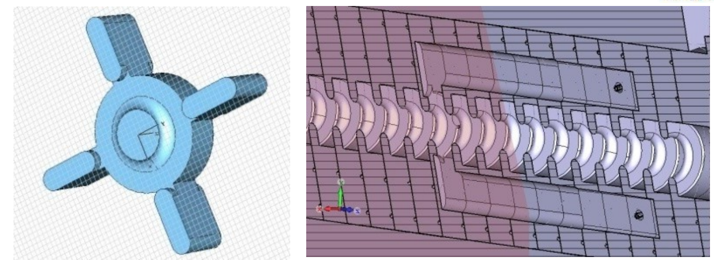
M. Dehler - MOPD04

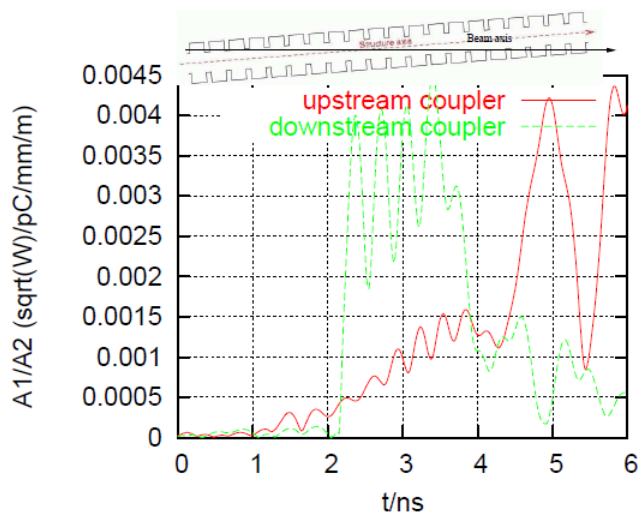
X-band Linac Structure with Alignemnt Monitor

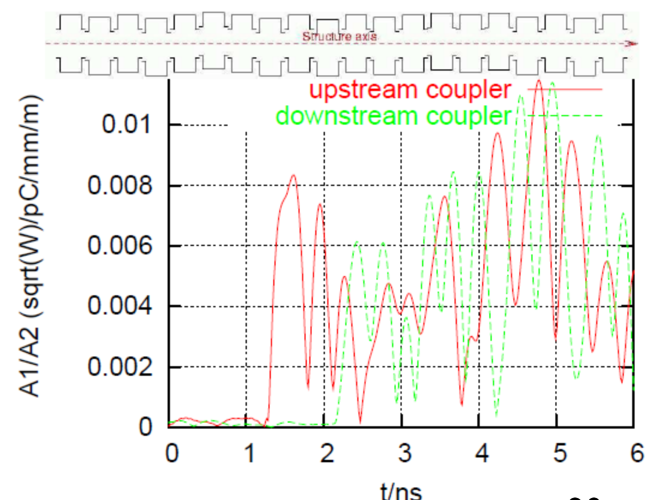
- developed with collaboration with CERN, ELETTRA & PSI
- resonance frequency : ~ 11991.648 MHz
- phase advance : $5\pi/6$
- cell number : 72
- active length / avaerga iris diameter : 750 mm / 9.1 mm
- max energy deceleration : 30 MeV
- average gradient : 40 MV/m with 29 MW
- sensitivity : 1.53 dB/mm for 200 pC
- cell 36 and 63 have radial coupling waveguides to extract dipole mode signals, which can be used to structure alignment
- expected alignment resolution ≤ 5 μm (rms)
- available signals : tilt, bend, offset, cell-to-cell misalignment





63th cell with radial coupling waveguides





Highlights - EO Bunch Length Monitor

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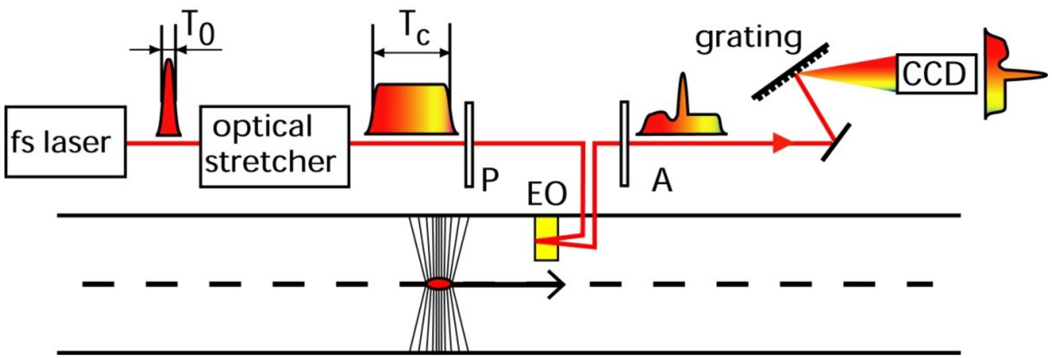
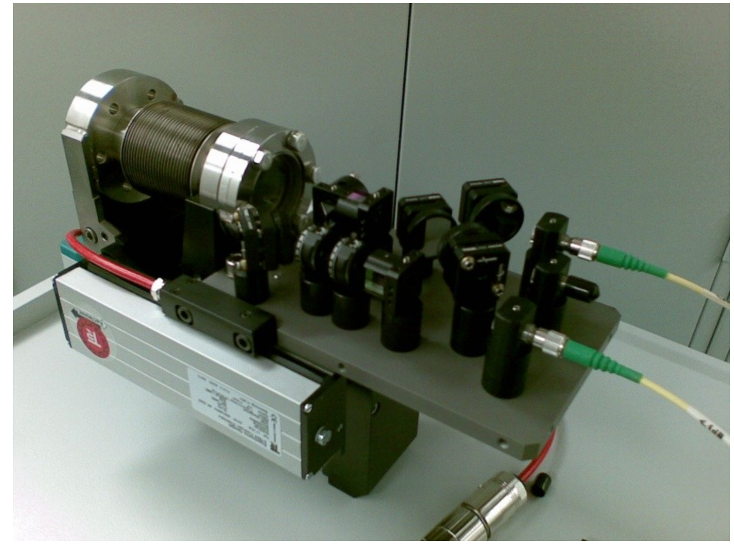
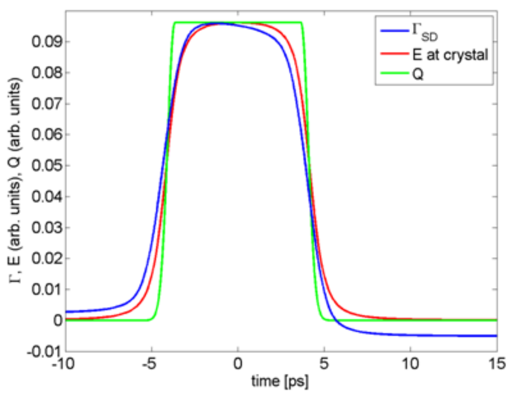




- linear relationship between wavelength and longitudinal position in laser pulse ("linear chirp")
- bunch profile is transferred to spectral profile of the laser pulse
- the first beam tests at the SLS linac planned for summer 2009
- rms resolution limit ~ $(T_0 \times T_c)^{1/2}$ ~ 100 fs

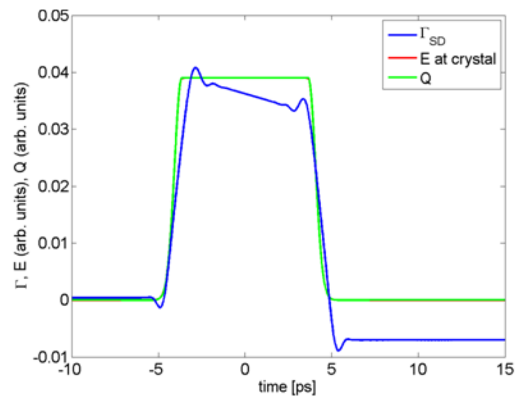
B. Steffen - TUPB42, F. Mueller - TUPD31

Gun (τ = 10 ps / τ_{rise} = 0.7 ps @ 7 MeV)



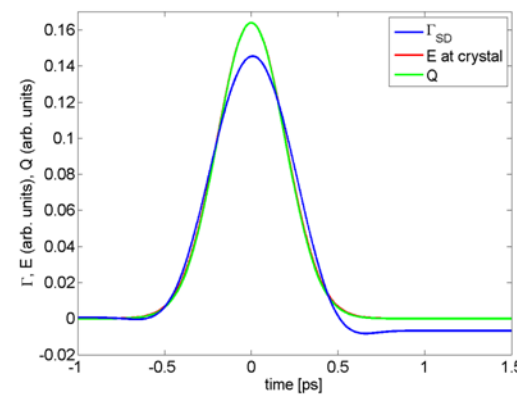
EO-crystal: 5 mm GaP,
Laser pulse: 20 fs (initial) chirped to 5 ps

Before BC1 (τ = 10 ps @ 250 MeV)



EO-crystal: 2 mm GaP,
Laser pulse: 20 fs (initial) chirped to 5 ps

After BC1 (τ = 195 fs rms @ 250 MeV)



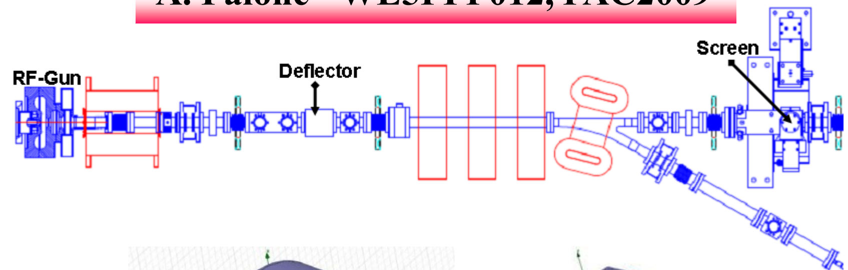
EO-crystal: 0.5 mm GaP,
Laser pulse: 20 fs (initial) chirped to 0.5 ps

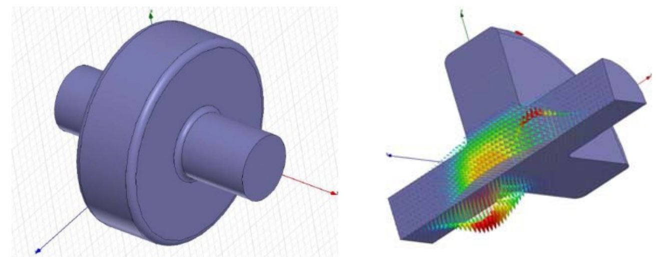
Highlights - Transverse Deflectors

Low Energy Transverse Deflecting Structure (TDS1)

- developed with collaboration with INFN and PSI
- resonance frequency : ~ 2997.912 MHz
- deflecting mode : TM_{110}
- type : single cell SW cavity
- physical length / average iris diameter : 100 mm / 38 mm
- max available klystron power : 25 kW
- max deflection voltage : 160 kV for 25 kW
- max slice number for 10 pC (200 pC) : 25 (30) slices
- operation energy : ~ 7 MeV (gun region)
- rms time resolution for 10 pC (200 pC) : 42 fs (93 fs) @ 160 kV

A. Falone - WE5PFP012, PAC2009

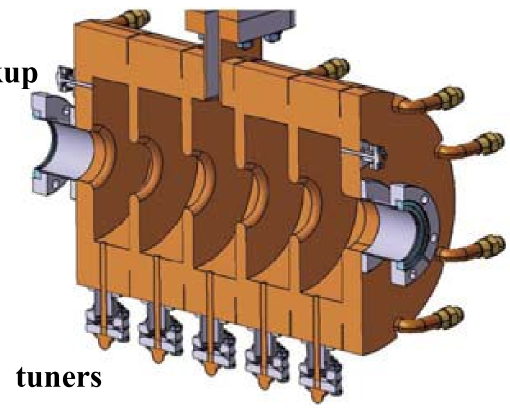




TDS1 with one cells

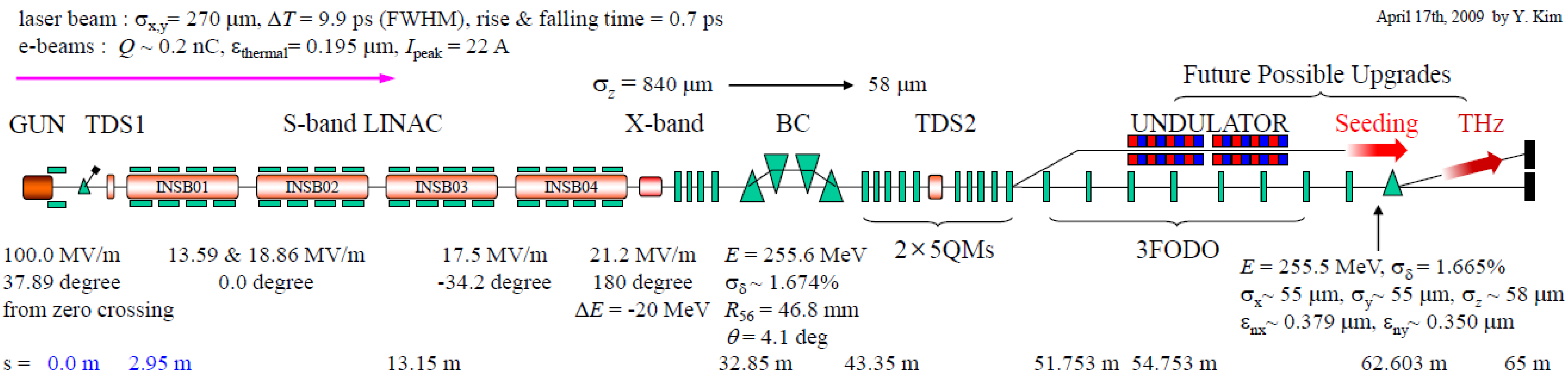
High Energy Transverse Deflecting Structure (TDS2)

- developed with collaboration with INFN and PSI
- resonance frequency : ~ 2997.912 MHz
- deflecting mode : TM_{110}
- type : five cell SW cavity
- physical length / average iris diameter : 441 mm / 36 mm
- max available klystron power : 7.5 MW
- max deflection voltage : 4.5 MV for about 4.1 MW
- max slice number for 10 pC (200 pC) : 3 (12) slices
- operation energy : ~ 250 MeV (gun region)
- rms time resolution for 10 pC (200 pC) : 11 fs (16 fs) @ 4.5 MV



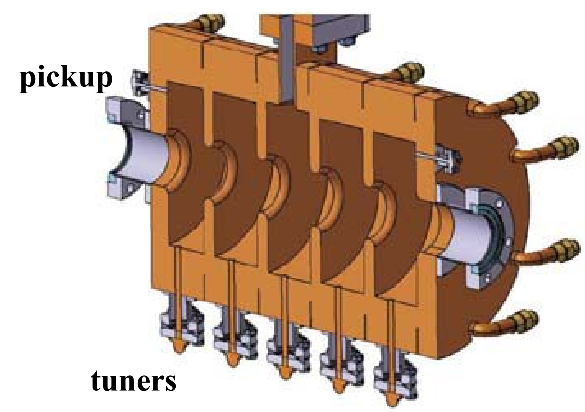
TDS2 with five cells

Highlights - Transverse Deflectors



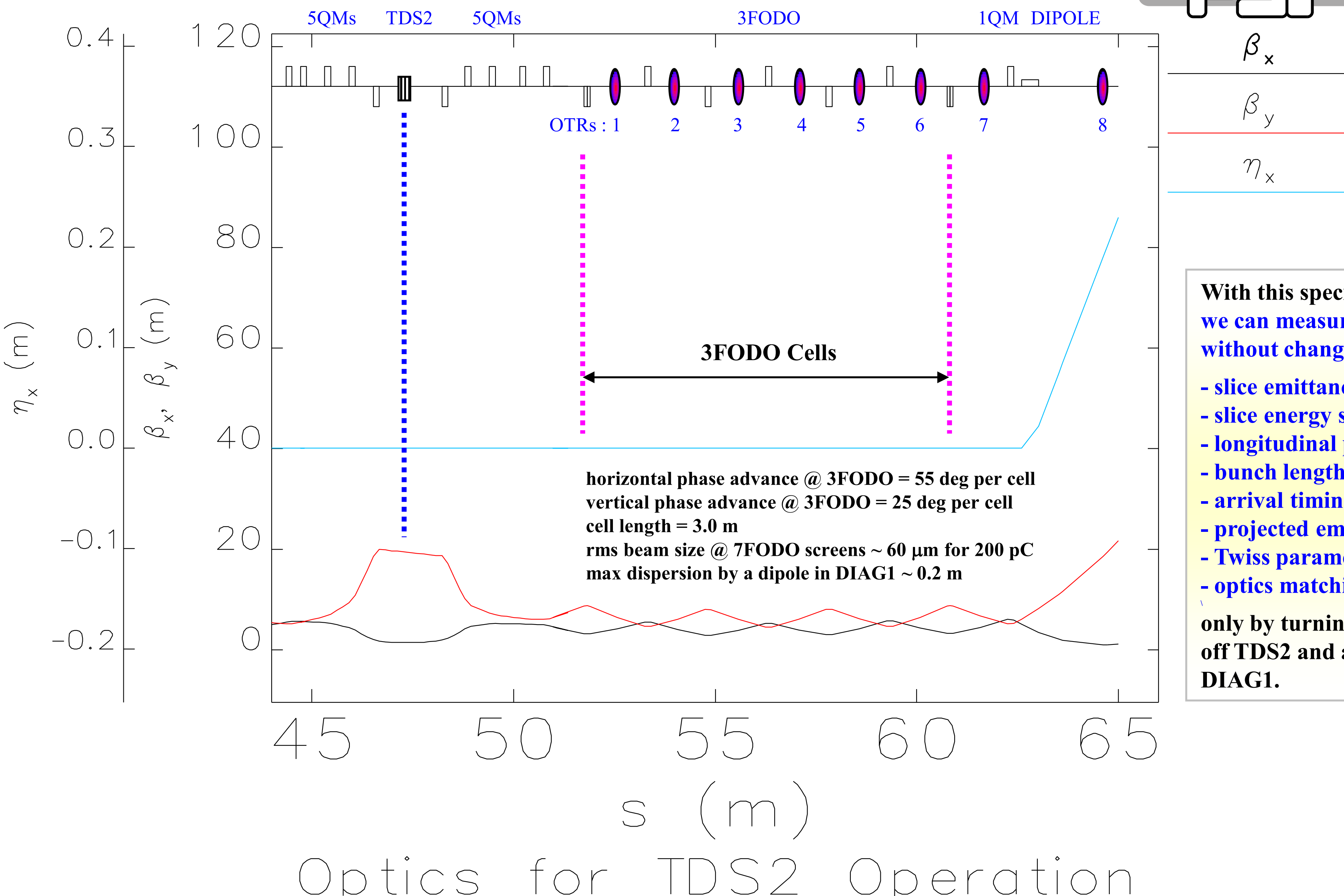
High Energy Transverse Deflecting Structure (TDS2)

- **developed with collaboration with INFN and PSI**
- **resonance frequency : ~ 2997.912 MHz**
- **deflecting mode : TM_{110}**
- **type : five cell SW cavity**
- **physical length / average iris diameter : 441 mm / 36 mm**
- **max available klystron power : 7.5 MW**
- **max deflection voltage : 4.5 MV for about 4.1 MW**
- **max slice number for 10 pC (200 pC) : 3 (12) slices**
- **operation energy : ~ 250 MeV (gun region)**
- **rms time resolution for 10 pC (200 pC) : 11 fs (16 fs) @ 4.5 MV**



TDS2 with five cells

Advanced Diagnostic Section - DIAG1

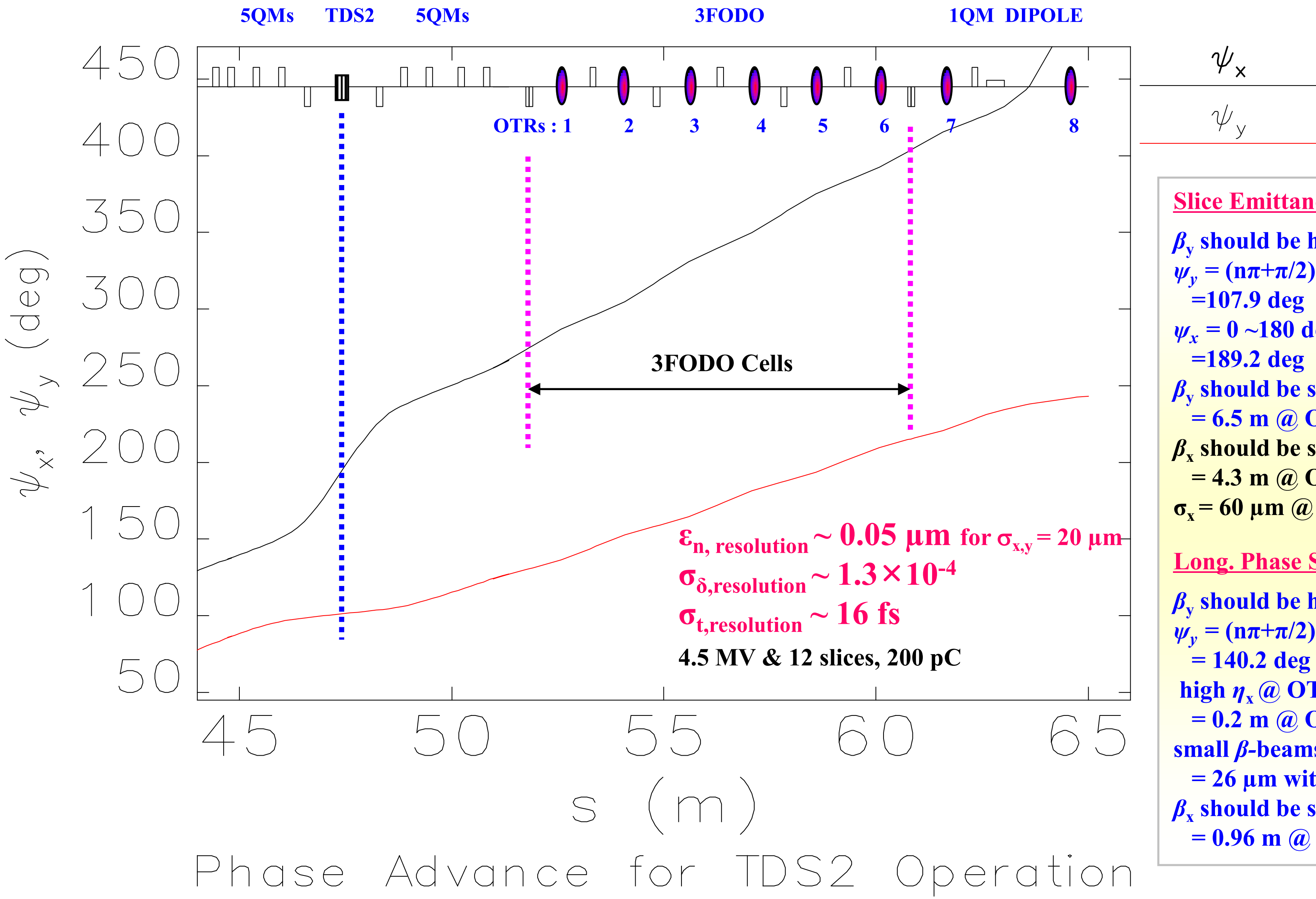


With this special DIAG1, we can measure followings without change any optics:

- **slice emittance**
- **slice energy spread**
- **longitudinal phase space**
- **bunch length**
- **arrival timing jitter**
- **projected emittance**
- **Twiss parameters**
- **optics matching**

only by turning on and/or off TDS2 and a dipole in DIAG1.

Phase Advance in DIAG1



Slice Emittance Measurement

β_y should be high at TDS2 = 20 m
$\psi_y = (n\pi+\pi/2)$ at OTRs
=107.9 deg @ OTR6
ψ_x = 0 ~180 deg at OTRs
=189.2 deg @ OTR6
β_y should be small at OTRs
= 6.5 m @ OTR6
β_x should be small at OTRs
= 4.3 m @ OTR6
σ_x = 60 μm @ OTRs for 200 pC

Long. Phase Space Reconstruction

β_y should be high at TDS2 = 20 m
$\psi_y = (n\pi+\pi/2)$ at OTR8
= 140.2 deg @ OTR8
high η_x @ OTR8
= 0.2 m @ OTR8
small β-beamsize σ_x at OTR8
= 26 μm without dipole
β_x should be small at OTR8
= 0.96 m @ OTR8

Emittance Measurements at DIAG1

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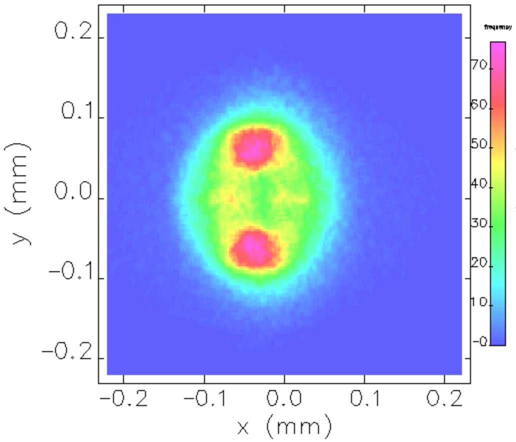
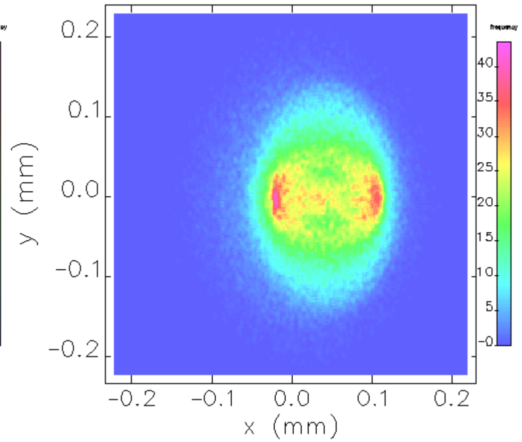
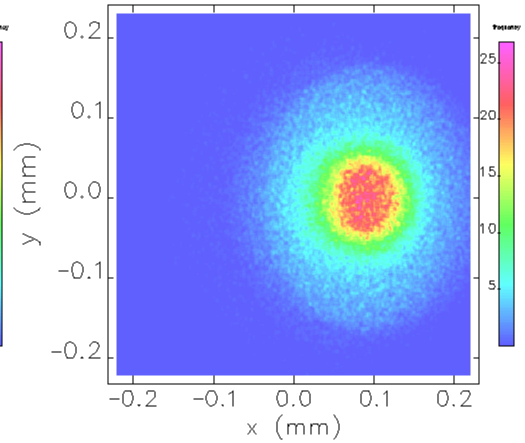


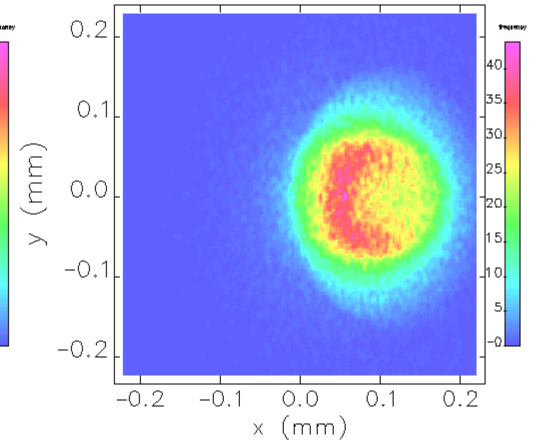
OTR1@3FODO



OTR3@3FODO



OTR5@3FODO



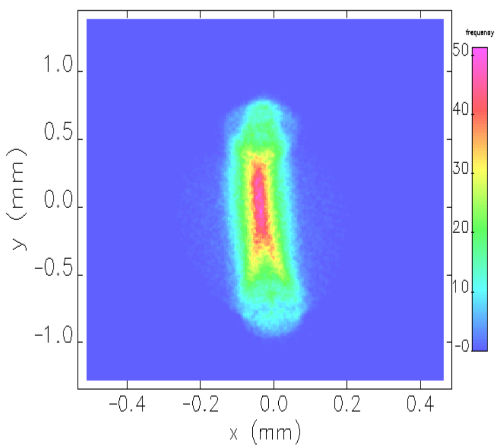
OTR7@3FODO

Q = 200 pC

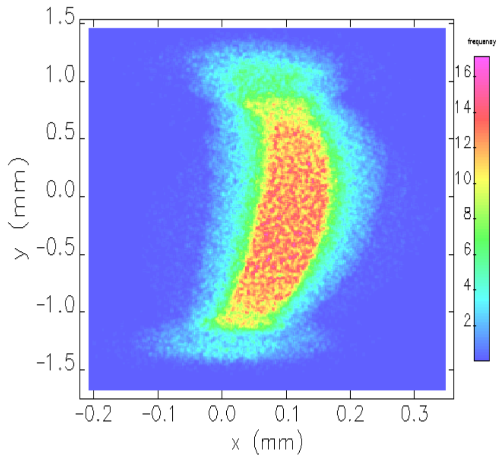
TDS2 Off for Projected Emittance Measurements

$\sigma_{\delta,\mathrm{resolution}} \sim 1.3\times10^{-4}$

$\sigma_{t,\mathrm{resolution}} \sim 16$ fs

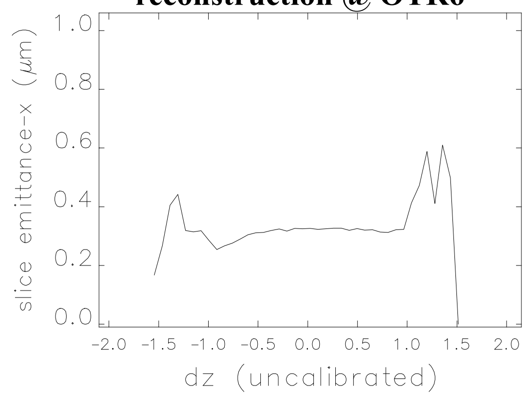


OTR1@3FODO

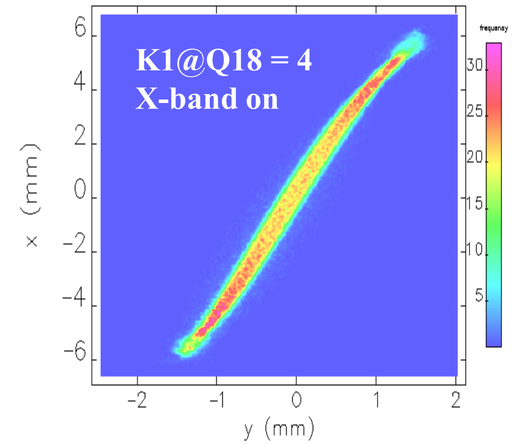


OTR6@3FODO

reconstruction @ OTR6



Slice X-Emittance Measurement at OTR6



OTR8@DBC1 y=dz x=dE

TDS2 = 4.5 MV, DM = 6 deg for Slice Emittance & Long. Phase Space Measurements

Summary

We designed 13 different linac layouts with S-band and C-band RF linacs for the SwissFEL project. Among them, C-band based ones satisfy our design goal more easily (linac length < about 530 m, saturation of FEL power within a 50 m long undulator).

By the help of the excellent emittance, the longitudinal coherent single spike pulse can be generated by operating linac with an ultra-low charge of 10 pC.

Due to a high compression factor of 2400, ultra-tight RF jitter tolerances are required to realize the stable single spike mode operation at 1 nm to 7 nm with 10 pC.

Due to a wide dynamic range (10 pC to 200 pC), an ultra-small beamsize (~ 8 μm), and an ultra-small normalized emittance (~ 0.1 μm), and an ultra-short bunch length (2.4 fs) for 10 pC, SwissFEL project requires challenging longitudinal and transverse beam diagnostic systems.

At the PSI 250 MeV injector test facility, various challenging beam diagnostic systems (an ultra-fine optical reference timing distribution system with a timing jitter of several fs, ladder type screen monitors with a resolution of a few μm range, sub-μm range BPMs for linac and undulator, an X-band linac structure alignment monitor with a resolution of several μm range, compact single shot EO bunch length monitor with a resolution of about 100 fs, and TDSs combined advanced beam diagnostic sections without changing any optics) will be developed for the SwissFEL project.

Acknowledgements

Y. Kim sincerely give thank to J.-Y. Raguin of PSI, Dr. Inagaki and Prof. Shintake of RIKEN/SPring-8, Dr. Miura of Mitsubishi Heavy Industries, Dr. Yushiro of Toshiba, K. Floettmann of DESY, M. Borland of ANL, D. Dowell, Y. Ding, J. Frisch, and P. Emma of SLAC for their encouragements, valuable comments, useful information, and discussions for these works.

Appendix - Used Thermal Emittance

LCLS Core Slice Emittance Measurements:

Q = 20 pC, E ~ 135 MeV
Method = QM scan with LOLA
E = 135 MeV
Q = 20 pC
$E_{cathode}$ ~ 115 MV/m
λ_{laser} = 253 nm (= 4.899 eV)
ΔT_{laser} ~ 3.8 ps (FWHM)
Laser profile = pseudo-Gaussian shape
σ_z ~ 1.3 ps
I_{peak} ~ 5 A

$$\varepsilon_{th} \approx \sigma_{x,y} \sqrt{\frac{2K_{ave}}{3m_e c^2}}$$

K_{ave} = 0.4 eV was used for our CTF3 RF gun based injector optimizations !

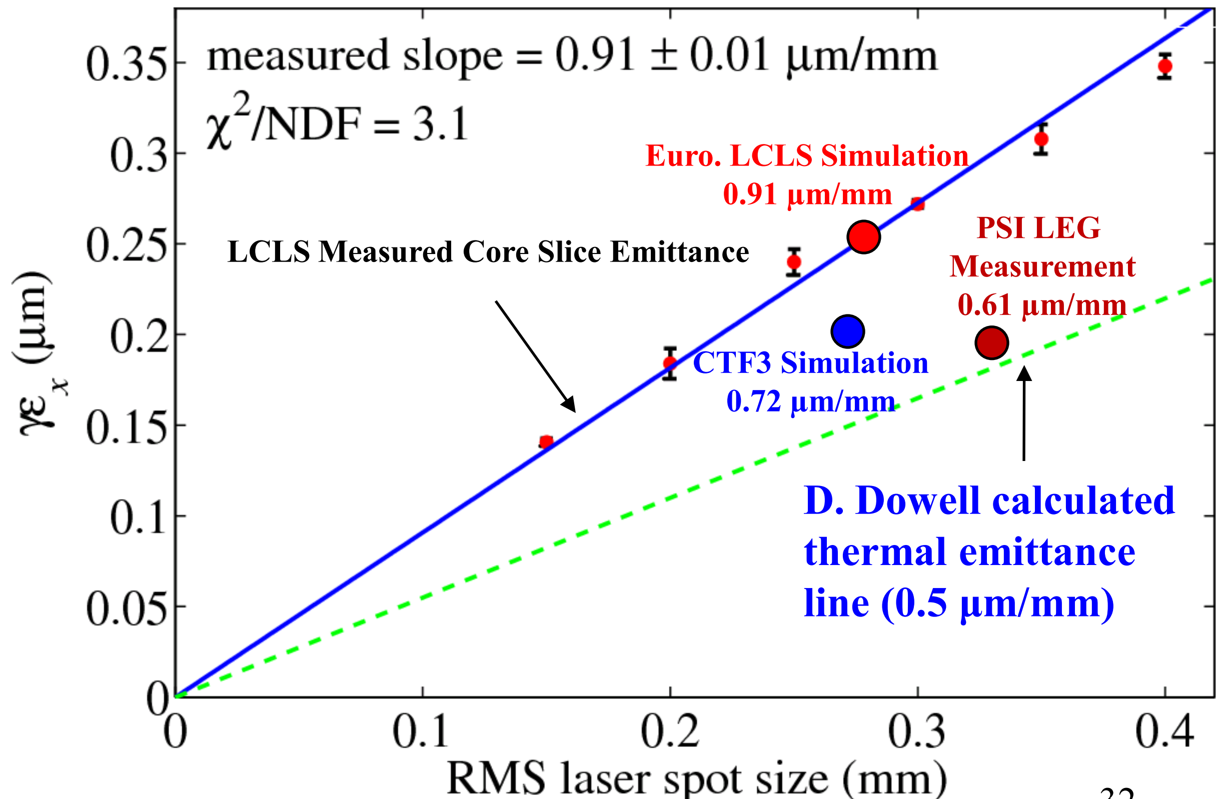
K_{ave} = 0.63 eV was used for our European LCLS RF gun based injector optimization !

$$\varepsilon_{th} \approx \sigma_{x,y} \sqrt{\frac{h\nu - \phi_0 + \phi_{schottky}}{3m_e c^2}}, \quad \sigma_x = \sigma_y \text{ for a round beam}$$

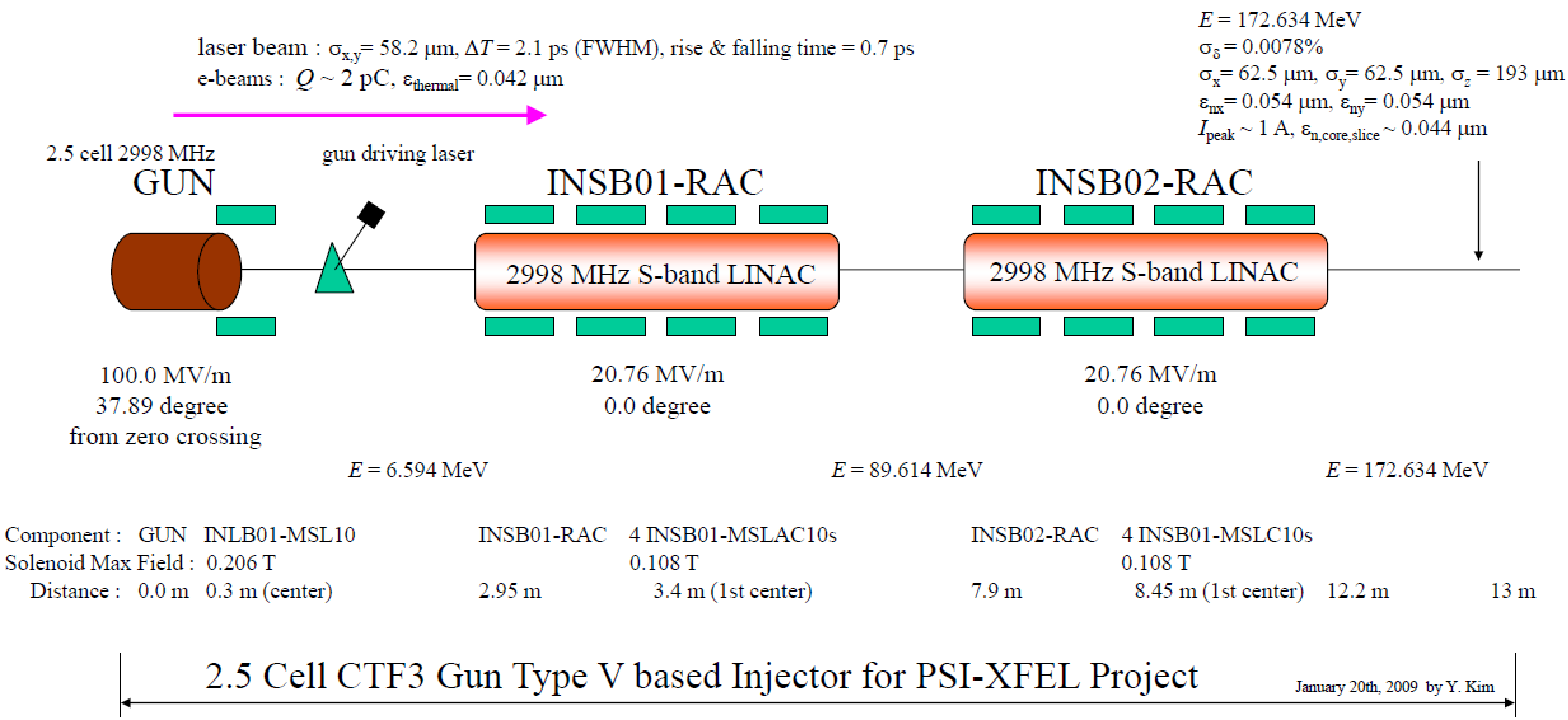
$$\phi_{schottky} \sim 3.7947 \times 10^{-5} \sqrt{E(\mathrm{V/m})}\ \mathrm{eV},$$

$$K_{ave} \approx 0.5 \times (h\nu - \phi_0 + \phi_{schottky})$$

P. Emma, XFEL2008 Workshop, Courtesy of D. Dowell



Appendix - Optimized Injector for 2 pC



CTF3 RF Gun may generate an ultra-low emittance < 0.06 μm for 2 pC !

Appendix - Optimized Injector for 2 pC

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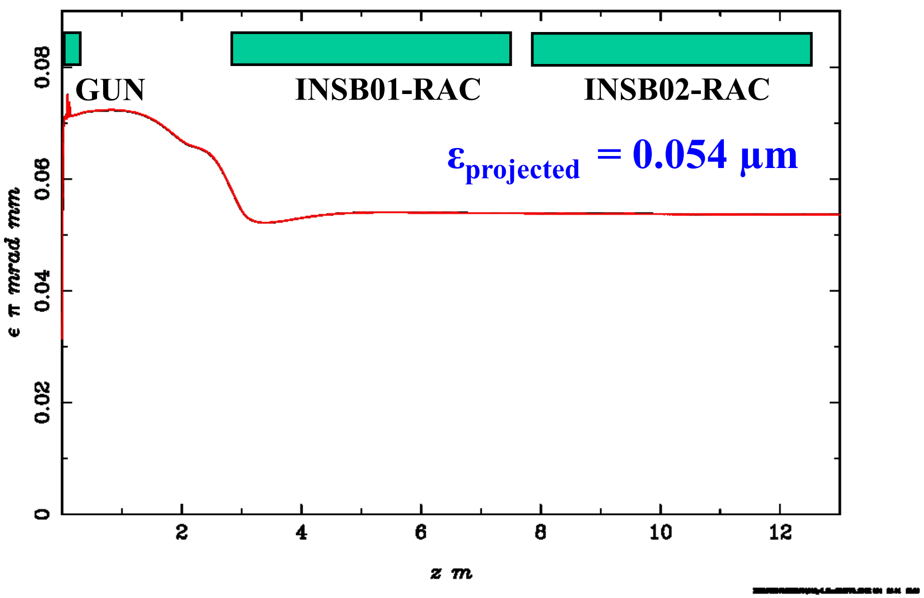
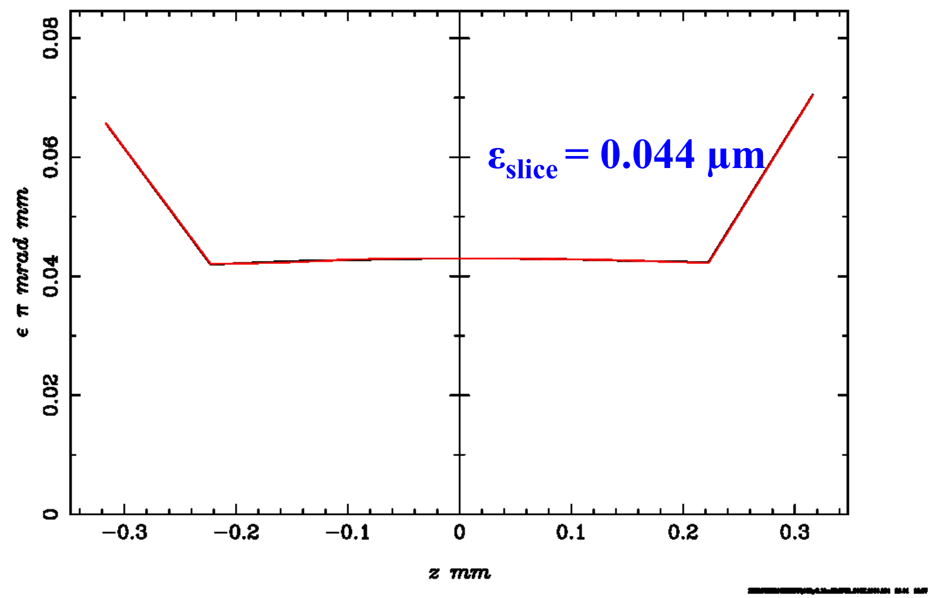
for 2 pC, slice & projected emittances ~ ε_{th} = 0.042 µm

ε_{nsc} contribution to ε_{slice} is ignorable !

Projected Emittance along Injector



Slice Emittance at 172 MeV



CTF3 RF Gun may generate an ultra-low emittance < 0.06 µm for 2 pC !

Appendix - SwissFEL Optimized Injectors

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ASTRA Simulation Results : CTF3 RF Gun based Injector for various Charges

Q	laser length (FWHM)	$I_{peak,\ cathode}$	laser $\sigma_{x,or\ y}$	$\varepsilon_{thermal}$	$\varepsilon_{slice}/\varepsilon_{projected}$
200 pC	9.9 ps	22 A	270 μm	0.195 μm	0.320/0.350 μm
150 pC	9.0 ps	18 A	245 μm	0.177 μm	0.272/0.283 μm
100 pC	7.9 ps	14 A	214 μm	0.155 μm	0.220/0.233 μm
50 pC	6.2 ps	8.7 A	170 μm	0.123 μm	0.160/0.174 μm
20 pC	4.6 ps	4.7 A	125 μm	0.091 μm	0.108/0.122 μm
10 pC	3.7 ps	3.0 A	100 μm	0.072 μm	0.080/0.096 μm
5 pC	2.9 ps	1.9 A	79 μm	0.057 μm	0.062/0.074 μm
2 pC	2.1 ps	1.0 A	58 μm	0.042 μm	0.044/0.054 μm

Final beam parameters are at the exit of the 2nd S-band structure (130 MeV - 172 MeV).

Gun max gradient = 100 MV/m, assumed K_{ave} = 0.4 eV.

For only $Q \leq 2$ pC, $\varepsilon_{projected} \approx \varepsilon_{slice} \approx \varepsilon_{thermal}$

For a much higher Q, $\varepsilon_{projected} > \varepsilon_{slice} >> \varepsilon_{thermal}$ due to the nonlinear space charge force.

We can get an excellent emittance with a lower charge for the single spike mode operation!

10 pC - Ultra-Sensitive Jitter Sources

error source : gun & laser synchronization timing

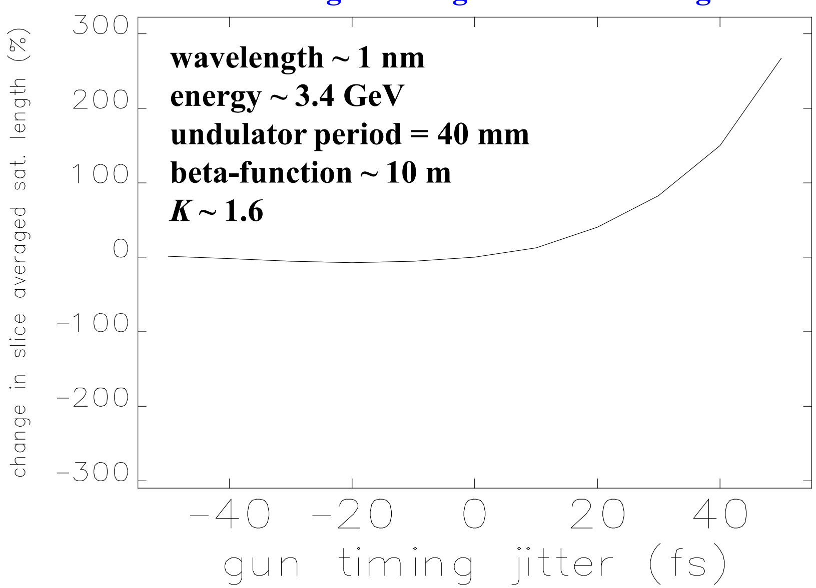
error range : -50 fs to +50 fs with 10 steps

monitoring point : at the entrance of undulator @ 3.4 GeV

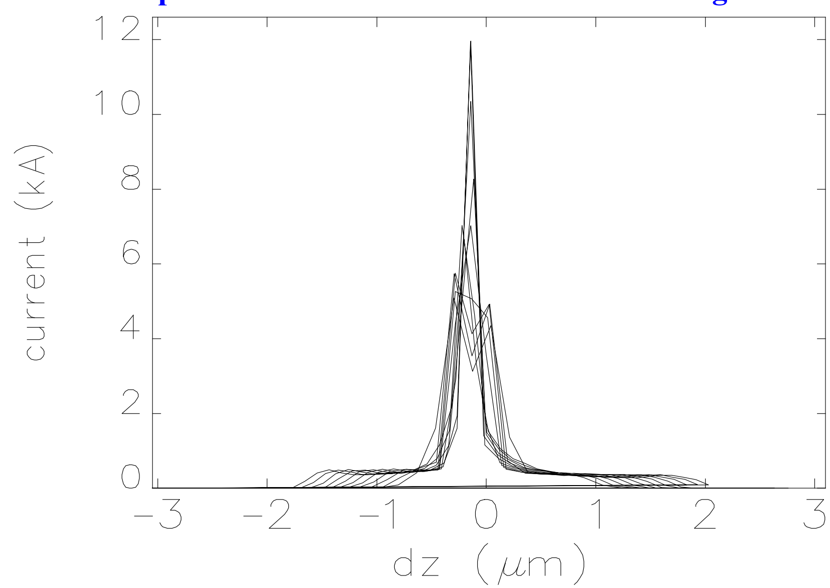
For $\Delta L_{sat}/L_{sat} \leq 15\%$ (zero-to-max), gun timing jitter $\leq$ 1 fs (rms).

This gun timing jitter tolerance is challenging !

saturation length change due to 10 timing errors



peak current fluctuation due to 10 timing errors

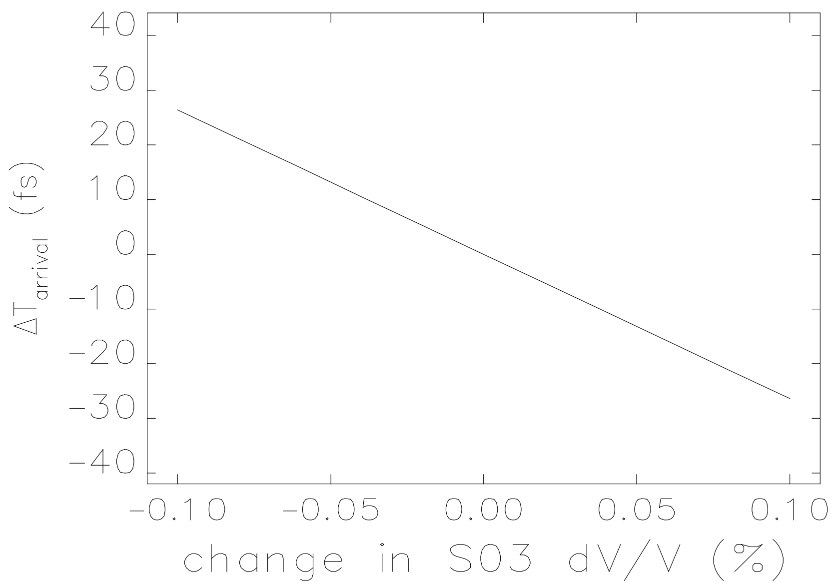


gun timing error, X-band RF phase error, and injector S-band RF phase errors are sensitive jitter sources to FEL saturation length.

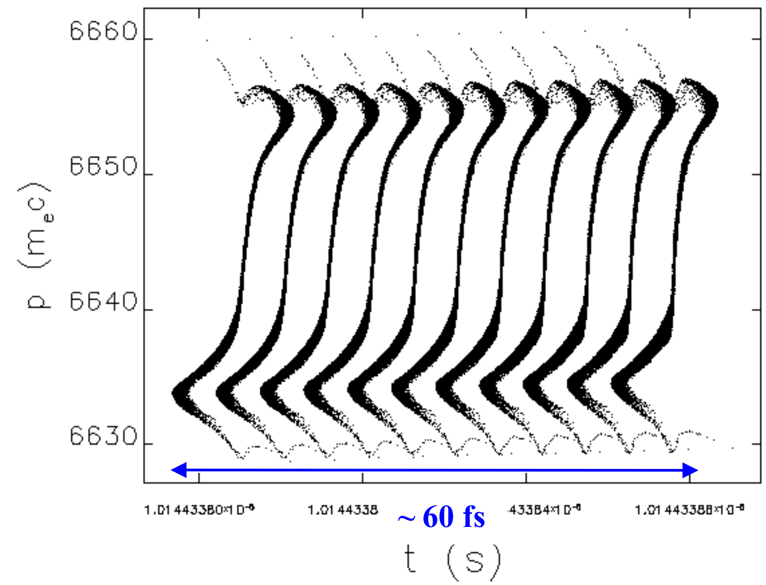
10 pC - Ultra-Sensitive Jitter Sources

error source : RF voltage of S-band linac (S03) in injector
error range : -0.10% to +0.10% with 10 steps
monitoring point : at the entrance of undulator @ 3.4 GeV
For $\Delta T_{arrival} \leq$ 5 fs (zero-to-max), S-band RF voltage error ≤ 0.005% (rms).
This S-band RF voltage tolerance is challenging !

arrival time change due to 10 S-band voltage errors



arrival time fluctuation due to 10 S-band voltage errors



S03 voltage change from -0.1% to +0.1% with 10 steps

BC1 chicane power supply error, gun timing error, injector S-band RF voltage and phase errors are sensitive jitter sources to photon beam arrival time.

10 pC - 300 Times S2E Simulation with Errors