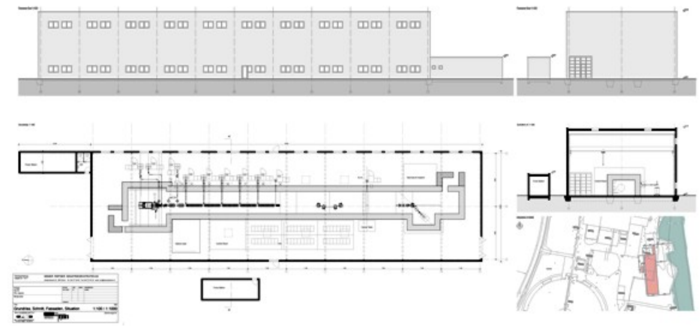
PAUL SCHERRER INSTITUT



The First

Simulation Results on Backup Injector for PSI XFEL Project

Yujong Kim

PSI, CH-5232 Villigen PSI, Switzerland

yujong.kim@PSI.ch, http://www.PSI.ch/~kim_y, http://FEL.WEB.PSI.ch

PSI XFEL-2008-01

Contents

PAUL SCHERRER INSTITUT

- Why we need a Backup Injector for PSI XFEL Project ?
  - Required Beam Parameters for PSI XFEL Project & Current Situation
  - A Backup Approach for PSI XFEL Project
  - Selection of an S-band RF Photoinjector for a Backup Injector
- How we can reduce beam emittance with an RF photoinjector
  - Relation between Thermal Emittance and Beam Size on the Cathode
  - Relation between Max. Gradient at the Cathode and Beamsize on the Cathode
- Simulations Results with the LCLS type S-band RF Photoinjector
  - Simulation Results for 0.1 nC Case
  - Simulation Results for 0.2 nC Case
  - Simulation Results for 0.4 nC case
- Summary and Acknowledgement

Required Beam Parameters for PSI XFEL

PAUL SCHERRER INSTITUT

Required Beam Parameters for 0.1 nm PSI XFEL Project

- beam energy = 5.8 GeV
- single bunch charge = 0.2 nC
- normalized slice emittance ≤ 0.2 μm
- rms slice energy spread = 0.6 MeV
- peak current = 1.5 kA
- saturation length ~ 32 m
- undulator period = 15 mm
- undulator strength *K* = 0.84 (rms)
- beta-function in undulator = 15 m

For PSI XFEL Project, we assumed :

- gap voltage of pulser = 1 MV (now 330 kV, we are still fighting ...)
- gap size = 4 mm, gradient = 250 MV/m (now < 30 MV/m, we are still fighting ...)
- normalized slice emittance at gun exit ≤ 0.1 μm (now ~ 0.5 μm, we are still fighting ...)
- peak current at gun exit = 5.5 A (now 0.3 A, it will be OK with new lasers)
- single bunch charge = 12 pC (it will be OK with new lasers)

Required Beam Parameters for PSI XFEL

PAUL SCHERRER INSTITUT

☐ Required Beam Parameters for 0.1 nm PSI XFEL Project

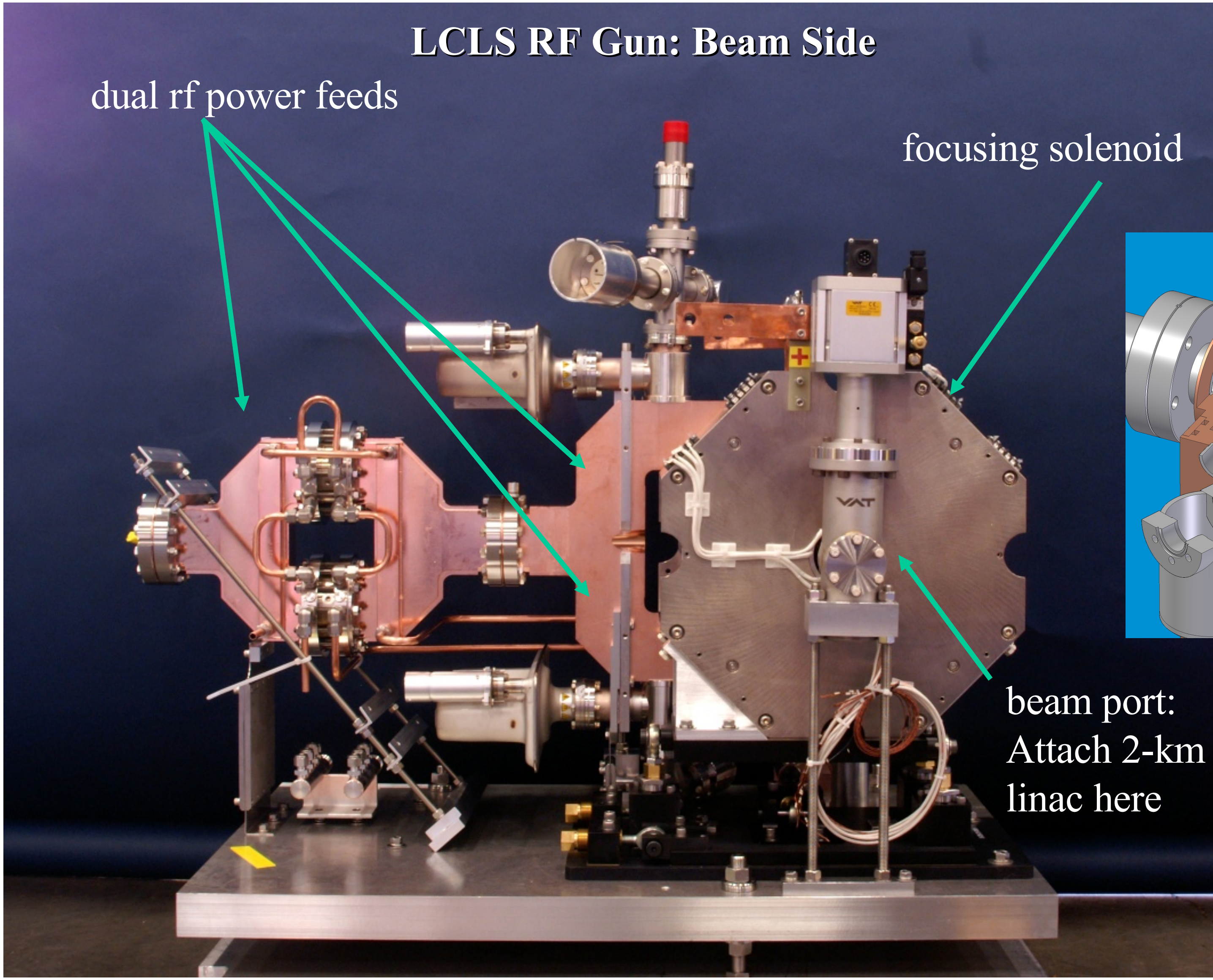
- beam energy = 5.8 GeV
- single bunch charge = 0.2 nC
- normalized slice emittance ≤ 0.2 μm
- rms slice energy spread = 0.6 MeV
- peak current = 1.5 kA

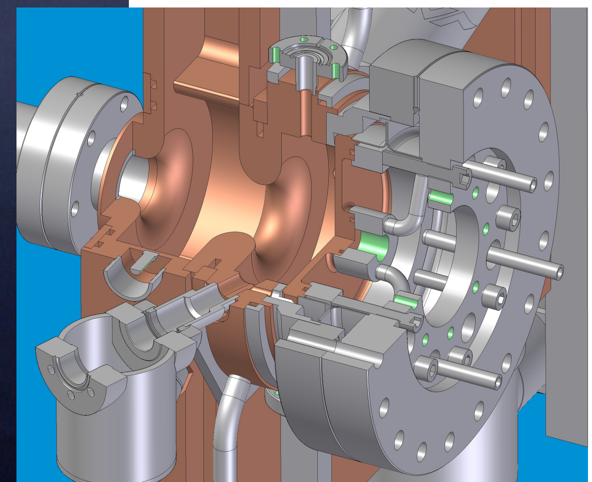
After consideration current situation, we need a backup solution to keep our project ! Alternatively, we can choose low-emittance & high peak current instead of ultra-low emittance & low peak current !

☐ For PSI XFEL Project, we assumed :

- gap voltage of pulser = 1 MV (now 330 kV, we are still fighting ...)
- gap size = 4 mm, gradient = 250 MV/m (now < 30 MV/m, we are still fighting ...)
- normalized slice emittance at gun exit ≤ 0.1 μm (now 0.5 μm, we are still fighting ...)
- peak current at gun exit = 5.5 A (now 0.3 A, it will be OK with new lasers)
- single bunch charge = 12 pC (it will be OK with new lasers)

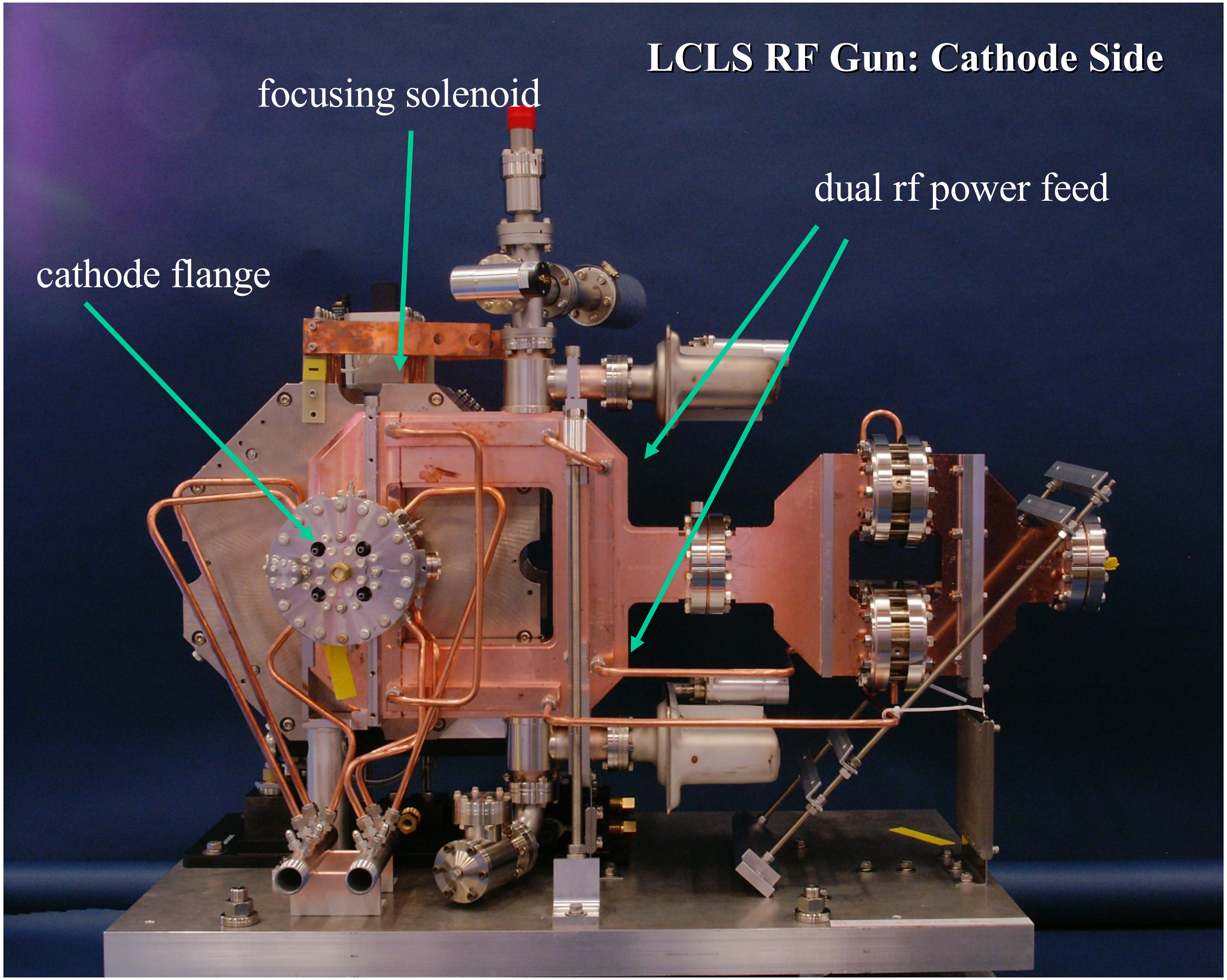
Demonstrated LCLS RF Photoinjector





Courtesy of Dr. Dowell

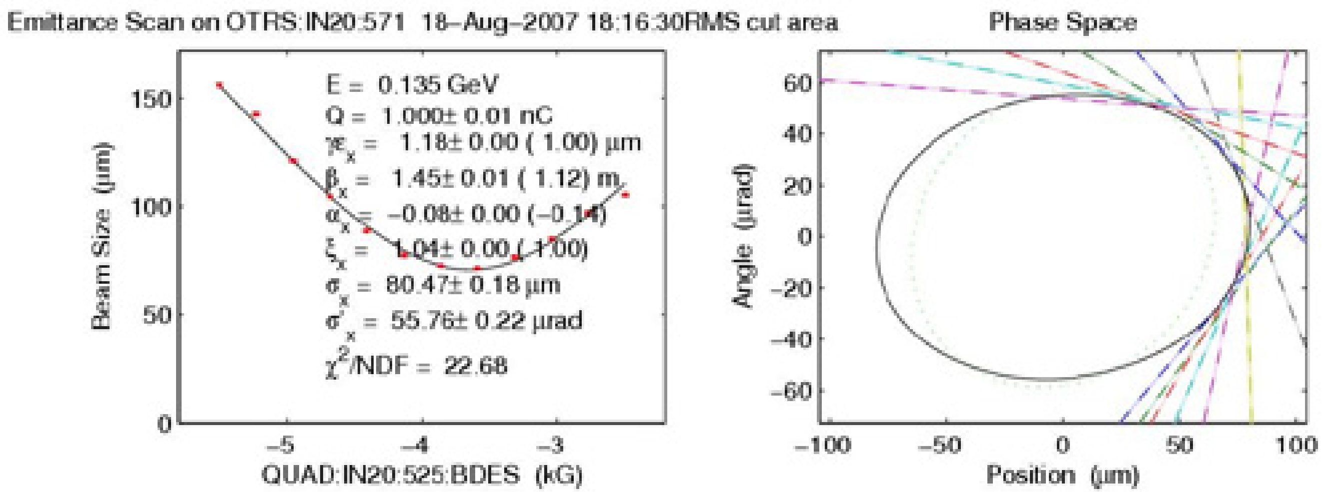
Demonstrated LCLS RF Photoinjector

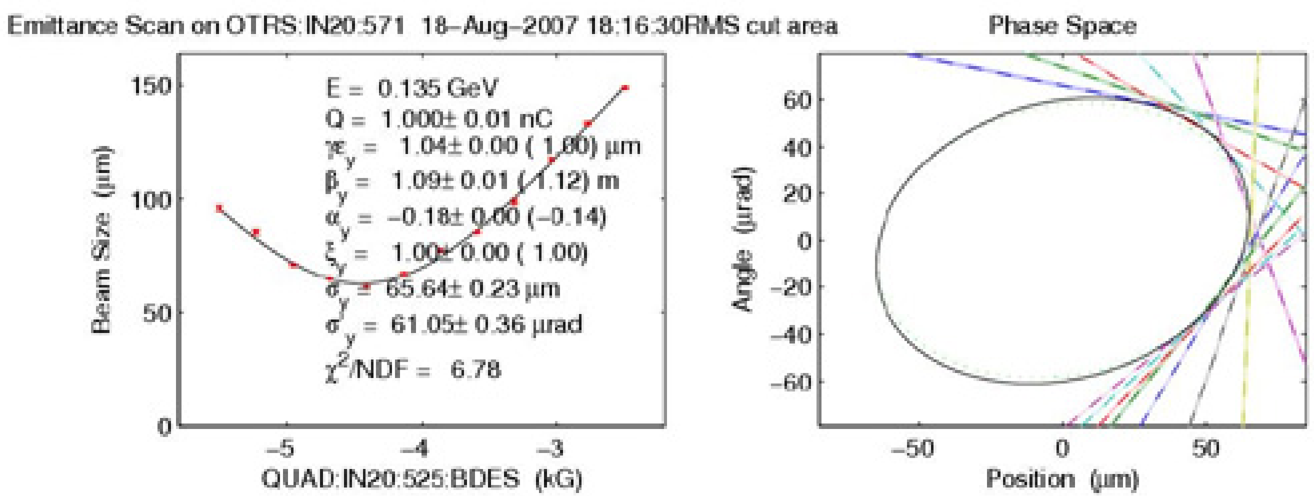


Courtesy of Dr. Dowell

Demonstrated LCLS RF Photoinjector

Measured in August, 2007, Courtesy of LCLS Commissioning Team

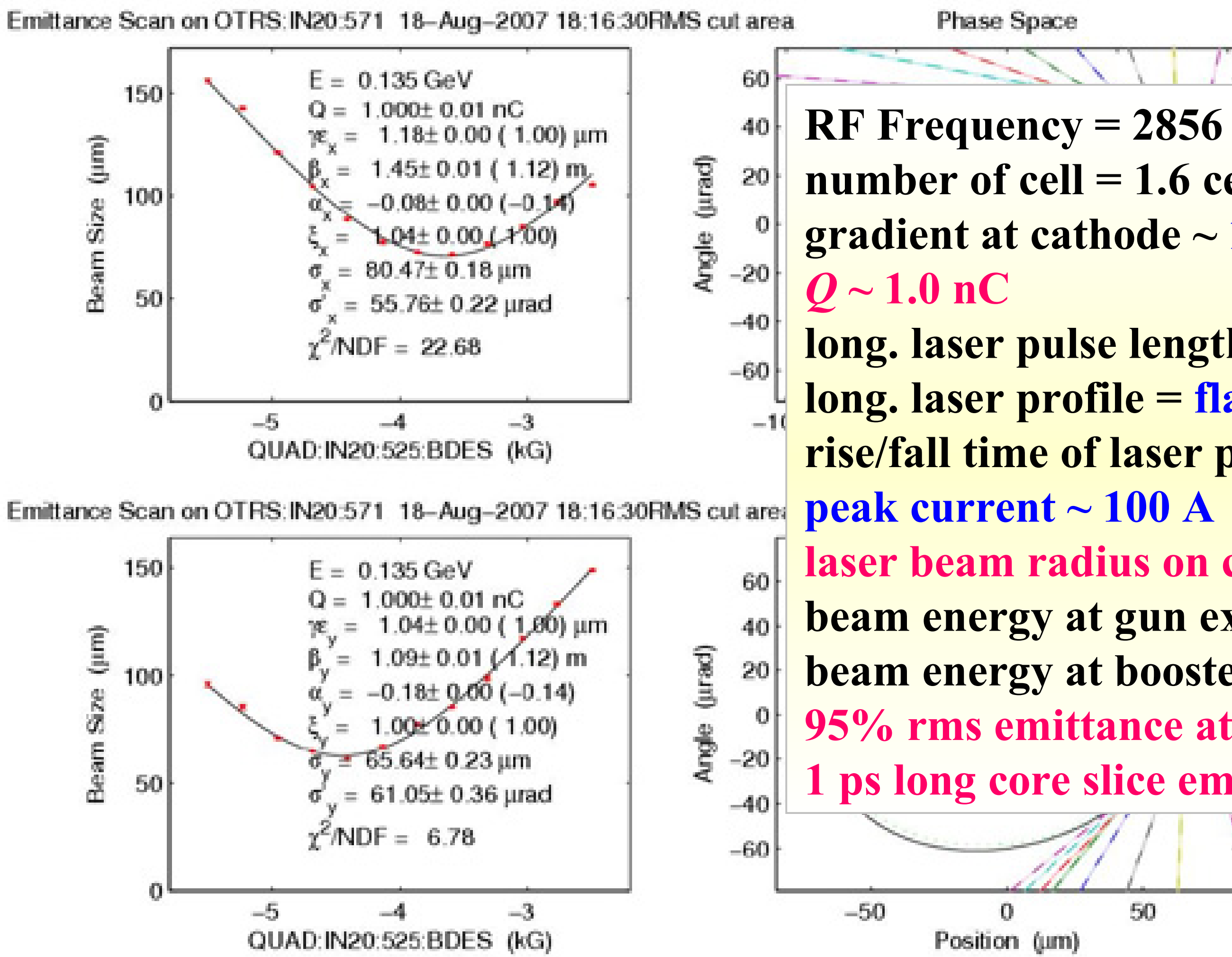




Demonstrated LCLS RF Photoinjector

PAUL SCHERRER INSTITUT

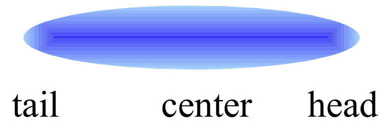
Measured in August, 2007, Courtesy of LCLS Commissioning Team

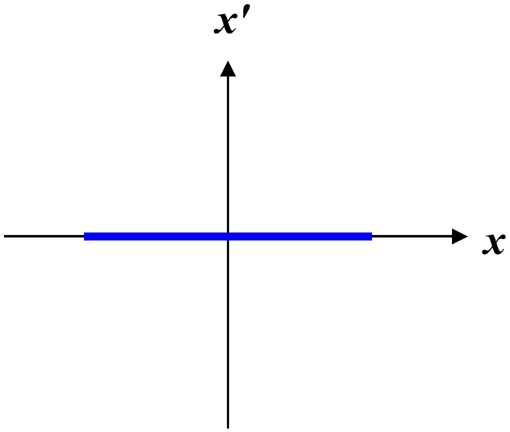


RF Frequency = 2856 MHz (S-band)
number of cell = 1.6 cells
gradient at cathode ~ 115 MV/m (Max 140 MV/m)
***Q* ~ 1.0 nC**
long. laser pulse length ~ 7.05 ps (FWHM)
long. laser profile = flat-top
rise/fall time of laser pulse ~ 2.0 ps
peak current ~ 100 A
laser beam radius on cathode ~ 0.33 mm (rms)
beam energy at gun exit ~ 7 MeV
beam energy at booster exit ~ 135 MeV
95% rms emittance at booster exit ~ 1.1 µm
1 ps long core slice emittance ~ 0.9 µm

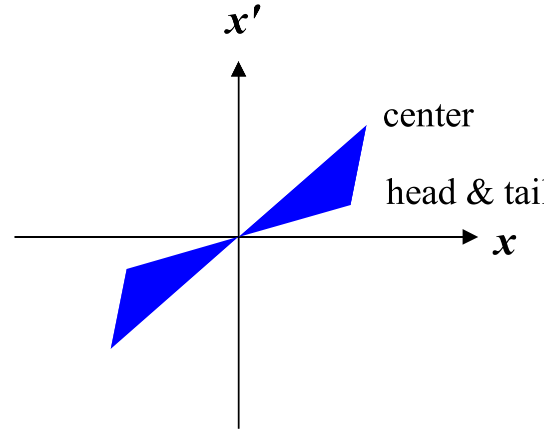
Projected Emittance Compensation

emitted electron bunch

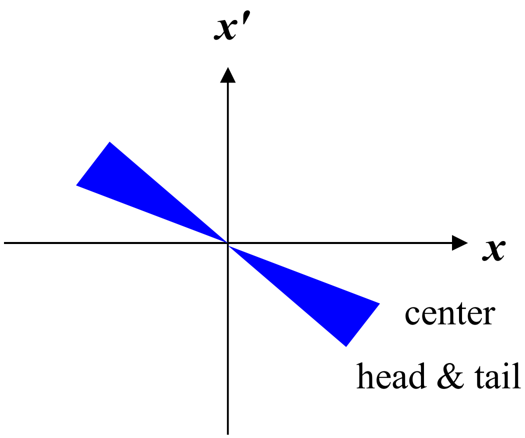




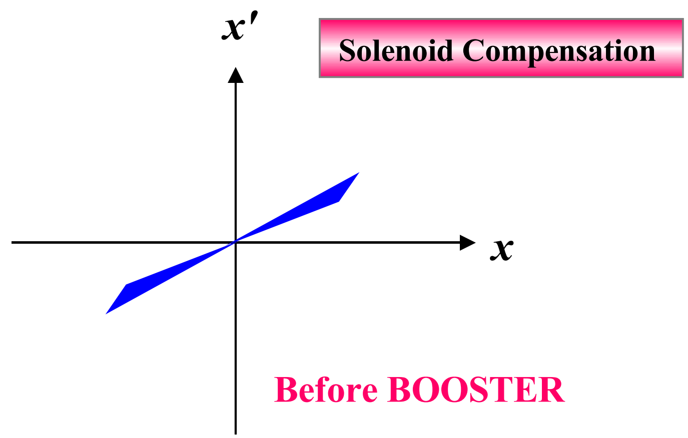
initial zero emittance just after emission from cathode



increased emittance due to space chare force



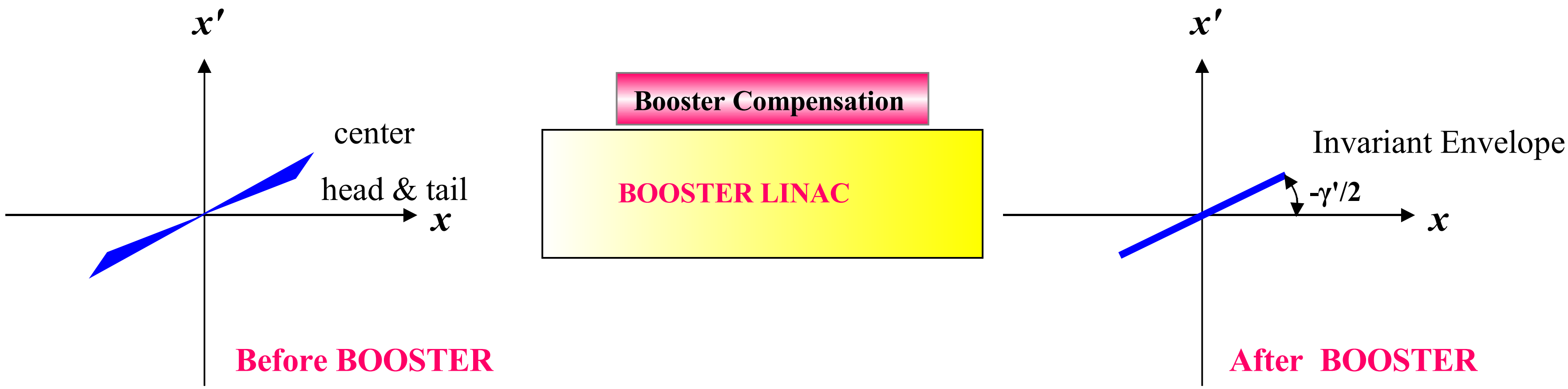
rotated phase space by an external focusing solenoid



compensation by reaction of space charge force after some drift

Invariant Envelope & Emittance Damping

PAUL SCHERRER INSTITUT



Space charge force induces oscillations in envelope and emittance.
The emittace and envelope oscillation around an ideal envelope can be damped by acceleration in booster. **(L. Serafini and J. Rosenzweig PRE Vol 55, Page 7565)**

$$\varepsilon_n \approx \frac{(\sigma_r - \sigma_{r,INV})}{\gamma'}\sqrt{\frac{I}{3I_0\gamma}}\left|\cos\psi - \sqrt{2}\sin\psi\right|, \quad \psi = \frac{1}{\sqrt{2}}\ln\left(\frac{\gamma}{\gamma_0}\right)$$

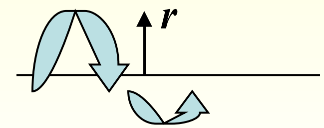
Invariant envelope is an ideal case which makes a constant slope (-γ'/2) for all different slices in the phase space by the acceleration of booster. In this case, beam spot size as well as transverse momentum are reduced together due to reduced space charge force in booster. Projected (and even slice) emittance damping in booster !!!

Booster Matching for Invariant Envelope

Pondermotive RF Focusing (PRE Vol. 47, page 2031, 1993)

Periodic longitudinal accelerating electric field E_z induces periodic transverse Lorentz force and electron's periodical transverse motion. Due to nonzero spatial gradient of the force, the net momentum transfer (or total effective focusing strength) for one periodic cycle is not zero, which is the ponderomotive RF focusing force.

$$\overline{F_r} \approx -r\frac{(eE_o)^2}{8\gamma mc^2} \quad \text{for fundamental mode in SW linac}$$



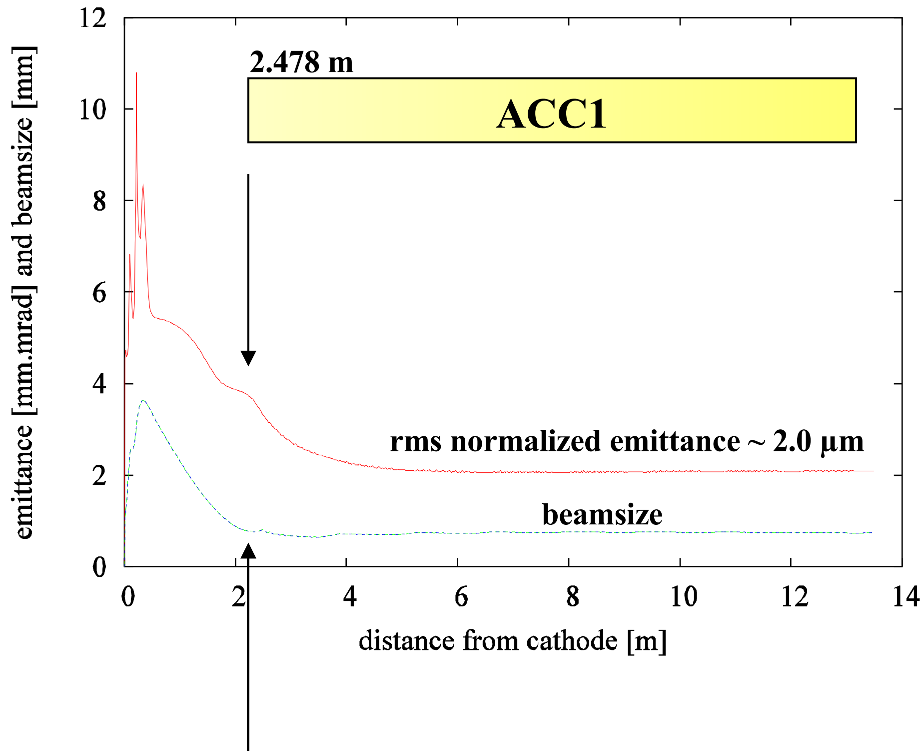
To avoid space charge effects in the drift space and to avoid too strong pondermotive RF focusing in the booster linac, at the entrance of booster, (PRE Vol 55, Page 7565 , SLAC-PUB-8400)

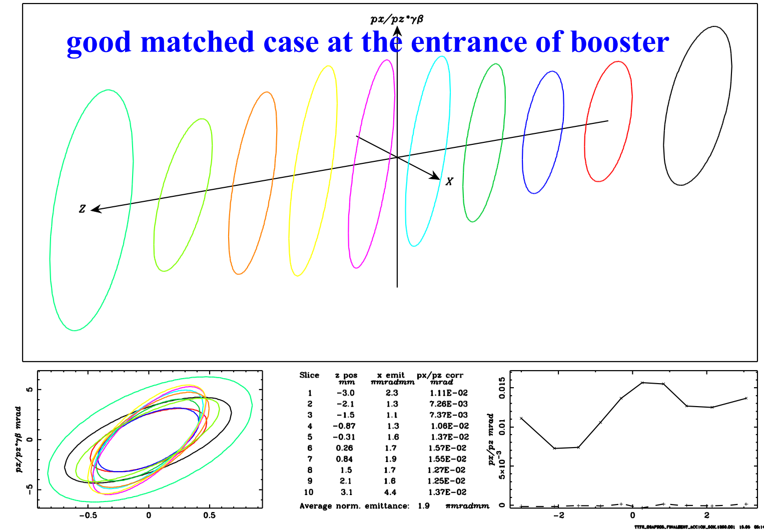
$$\sigma' = 0 \quad \text{(laminar waist)}$$

$$\gamma' = \frac{2}{\sigma_w}\sqrt{\frac{\hat{I}}{3I_o\gamma}} \quad \text{for SW linac (invariant envelope), } I_o = 17 \text{ kA.}$$

These means that at the entrance of booster linac, emittance should be its 2nd maximum, and beamsize should be its minimum. If these two conditions are satisfied, envelope is oscillated around the invariant envelope and we can get continuous emittance damping in booster linac.

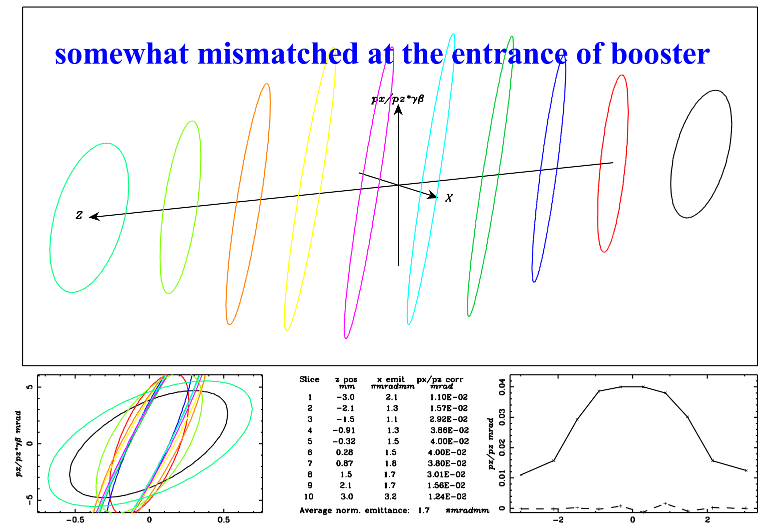
Matching Conditions at Booster





Slice	z pos mm	x emit πmradmm	px/pz corr mrad
1	−3.0	2.3	1.11E−02
2	−2.1	1.3	7.26E−03
3	−1.5	1.1	7.37E−03
4	−0.87	1.3	1.06E−02
5	−0.31	1.6	1.37E−02
6	0.26	1.7	1.57E−02
7	0.84	1.9	1.55E−02
8	1.5	1.7	1.27E−02
9	2.1	1.6	1.25E−02
10	3.1	4.4	1.37E−02

Average norm. emittance: 1.9 πmradmm



Slice	z pos mm	x emit πmradmm	px/pz corr mrad
1	−3.0	2.1	1.10E−02
2	−2.1	1.3	1.57E−02
3	−1.5	1.1	2.92E−02
4	−0.91	1.3	3.86E−02
5	−0.32	1.5	4.00E−02
6	0.28	1.5	4.00E−02
7	0.87	1.8	3.80E−02
8	1.5	1.7	3.01E−02
9	2.1	1.7	1.56E−02
10	3.0	3.2	1.24E−02

Average norm. emittance: 1.7 πmradmm

At the entrance of booster, invariant envelope concept based matching conditions should be satisfied to get emittance damping in booster !

- **local maximum emittance**
- **local minimum beamsize**

RF Photoinjector Based Compact XFELs

PAUL SCHERRER INSTITUT

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

higher peak current and lower slice emittance

→ higher ρ, shorter L_G, shorter saturation length L_{sat}

→ shorter undulator and possible compact XFELs (cXFELs)

$$N_{photon@sat,e^-} = \rho E_{beam} / E_{ph}, \qquad \text{Total } N_{photon@sat} = \rho E_{beam} Q_{lasing} / E_{ph}$$

here Q_{lasing} (<< Q) is charge which contributes lasing !

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

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

SCSS XFEL Vs. Q = 0.1 nC based cXFELs

PAUL SCHERRER INSTITUT

Parameter	SCSS XFEL	cXFELs
beam energy [GeV]	6	6
single bunch charge [nC]	0.8	0.1
slice emittance [μm]	0.85	0.4
slice energy spread	1×10^{-4}	1×10^{-4}
peak current [kA] /bunch length [μm]	3 / 33	4 / 3.3
undulator period [mm]	15	15
undulator gap [mm]	3.5	3.5
K-parameter	1.3	1.3
β-function [m]	30	30 (not optimized)
ρ FEL parameter	2.8×10^{-4}	4.0×10^{-4}
power gain length 3D [m]	4.0	2.0
saturation length [m]	75	38.7
total undulator length [m]	80	45 (~ 45% reduction)
wavelength [Å]	1.0	1.0
peak power [GW]	2.9	11
spectral bandwidth [%]	0.061	0.087
photon per pulse [#]	4.1×10^{11}	1.4×10^{11}
peak brilliance [B]	8.9×10^{32}	2.4×10^{33}

SCSS XFEL Vs. Q = 0.1 nC based cXFELs

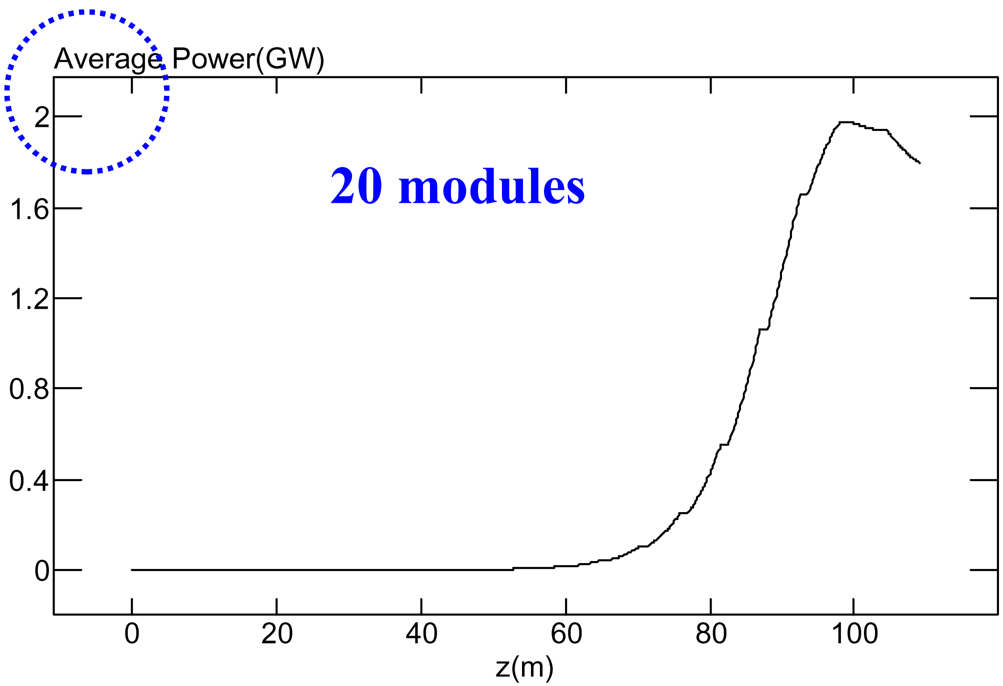
Parameter	SCSS XFEL	cXFELs
beam energy [GeV]	6	6
single bunch charge [nC]	0.8	0.1
slice emittance [µm]	0.85	0.4
slice energy spread	1×10^{-4}	1×10^{-4}
peak current [kA] /bunch length [µm]	3 / 33	4 / 3.3
undulator period [mm]	15	15
undulator gap [mm]	3.5	3.5
K-parameter	1.3	1.3
β-function [m]	30	30 (not optimized)
ρ FEL parameter	2.8×10^{-4}	4.0×10^{-4}
power gain length 3D [m]	4.0	2.0
saturation length [m]	75	38.7
total undulator length [m]	80	45 (~ 45% reduction)
wavelength [Å]	1.0	1.0
		11
		0.087
		1.4×10^{11}
		2.4×10^{33}

By improving slice emittance and peak current,
we can reduce saturation length !!!
We can realize XFEL with a much shorter undulator !

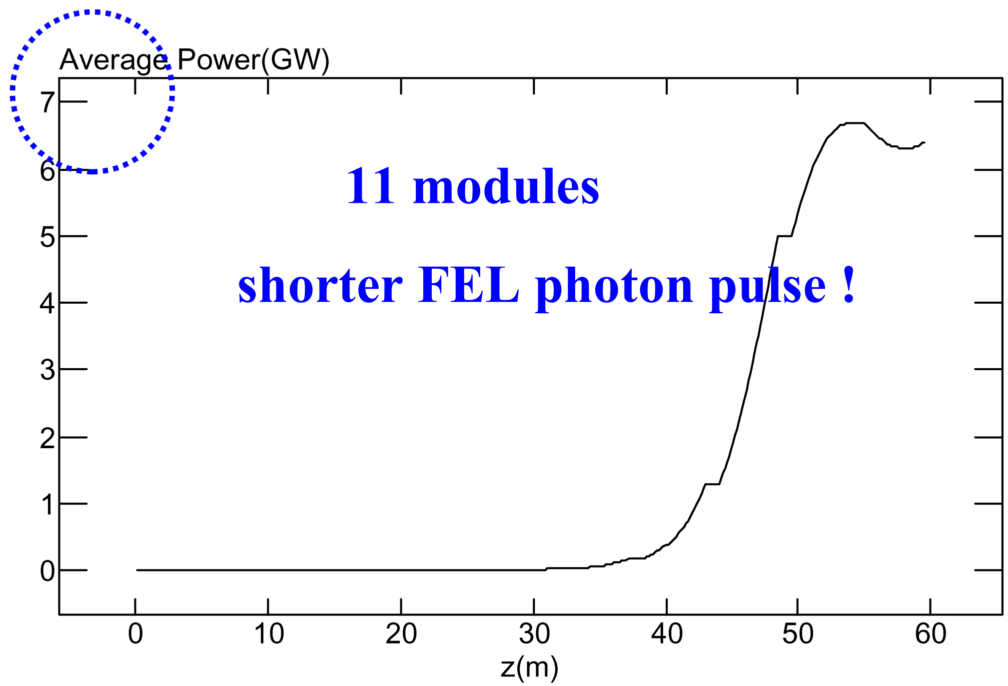
Average FEL Power along Undulator

PAUL SCHERRER INSTITUT

Length of Pure Undulator Module = 4.5 m
Length of Undulator + Drift Between Undulators = 5.5 m



[SCSS CDR2005]



[cXFELs]

~ 45% reduction in the needed undulator !!!

One Example - S2E simulation with 0.1 nC

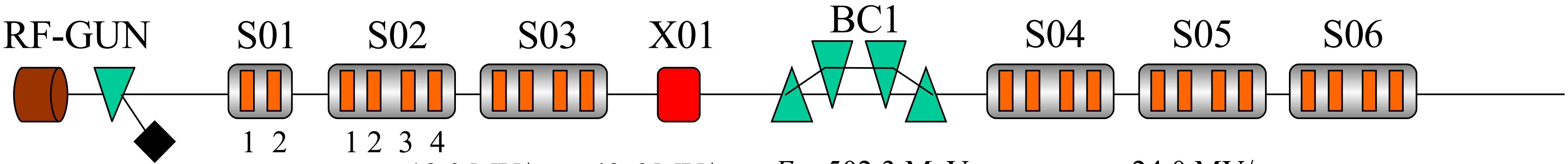
PAUL SCHERRER INSTITUT

S2E Simulation Results from Cathode to Entrance of Undulator

Q = 0.1 nC e-beams

σ_z = 400 μm → 25 μm →

Here assumed thermal emittance is 0.33 μm (upper limit) for Cu cathode !



120.1 MV/m
34 deg

17.8 MV/m
25.0 MV/m
0 deg

19.0 MV/m
-26.0 deg

43.6 MV/m
180 deg

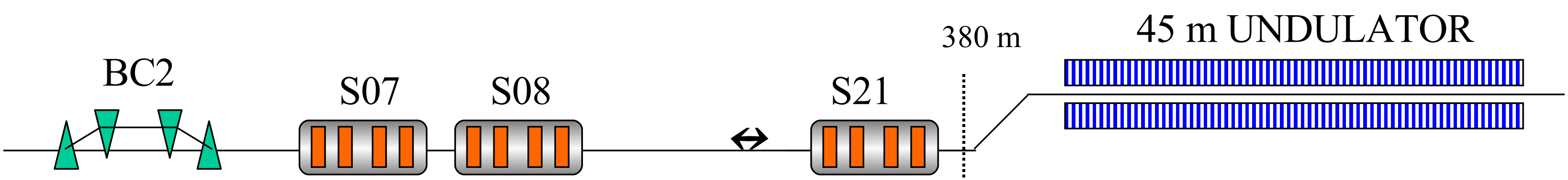
E = 502.3 MeV
$\sigma_\delta \sim$ 0.910%
R_{56} = 41.2 mm
θ = 3.6 deg

24.0 MV/m
-23 deg

ASTRA with Space Charge

To the end of LINAC : ELEGANT with consideration of CSR and geometric wakefields

σ_z = 25 μm → 3.3 μm



E = 1301.1 MeV
$\sigma_\delta \sim$ 0.367%
R_{56} = 5.78 mm
θ = 1.35 deg

26.7 MV/m
0 deg

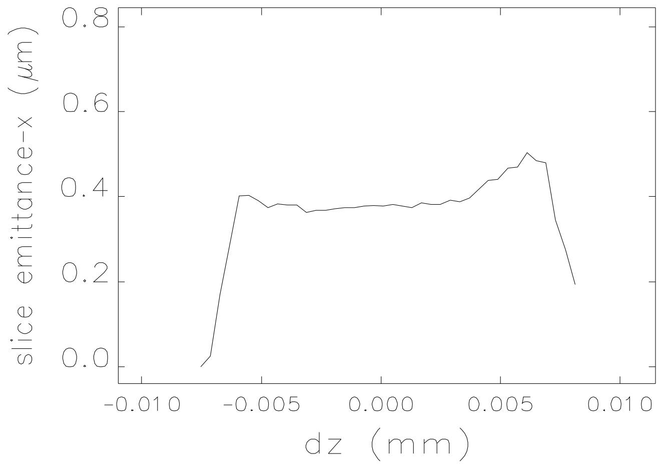
E = 6.0 GeV
σ_δ = 0.06%
σ_x = 21 μm, σ_y = 15 μm, σ_z = 3.3 μm
ε_{nx} = 0.578 μm, ε_{ny} = 0.409 μm

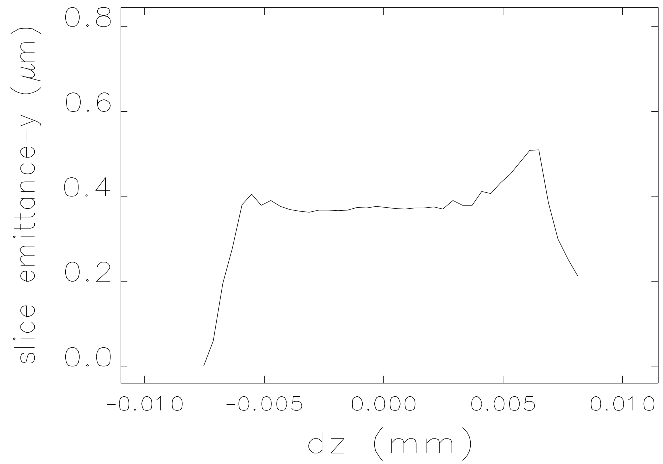
All parameters are projected values !

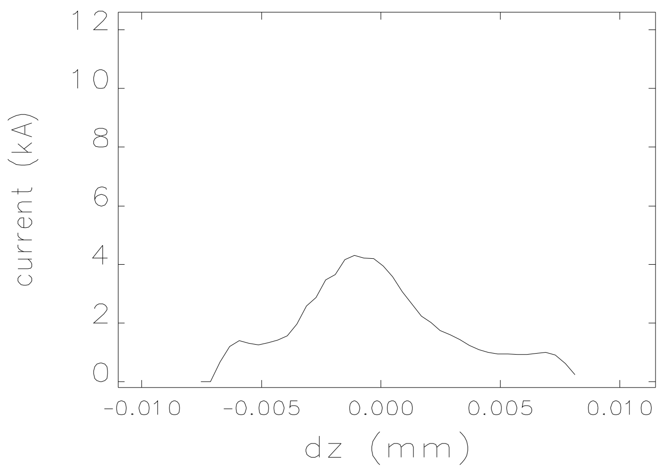
One Example - S2E simulations with 0.1 nC

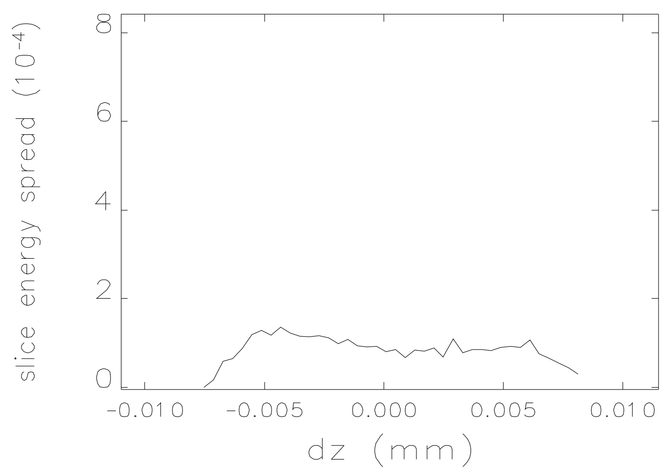
PAUL SCHERRER INSTITUT

S2E Simulation Results on Slice Parameters at the entrance of Undulator









Projected Parameters at the end of Linac

Q = 0.1 nC
E = 6.0 GeV
σ_δ = 0.06%
σ_x = 21 μm
σ_y = 15 μm
σ_z = 3.3 μm
ε_{nx} = 0.578 μm
ε_{ny} = 0.409 μm

Here all CSR, space charge, wakefields are considered !

Due to no high spike at head and tail, a much shorter undulator length, and a lower charge, effects of AC wakefields in undulator become weaker.

RF Photoinjector Based cXFELs

- Note that thermal emittance is the most biggest contribution in slice emittance
- We can reduce slice emittance by reducing thermal emittance on the cathode !

$$\varepsilon_{th} \approx \sigma_{x,y}\sqrt{\frac{2K}{3m_e c^2}}, \quad \sigma_x = \sigma_y \text{ for a round beam}$$

Assumed $K = 0.14 \sim 1.10376$ eV for Cu cathode

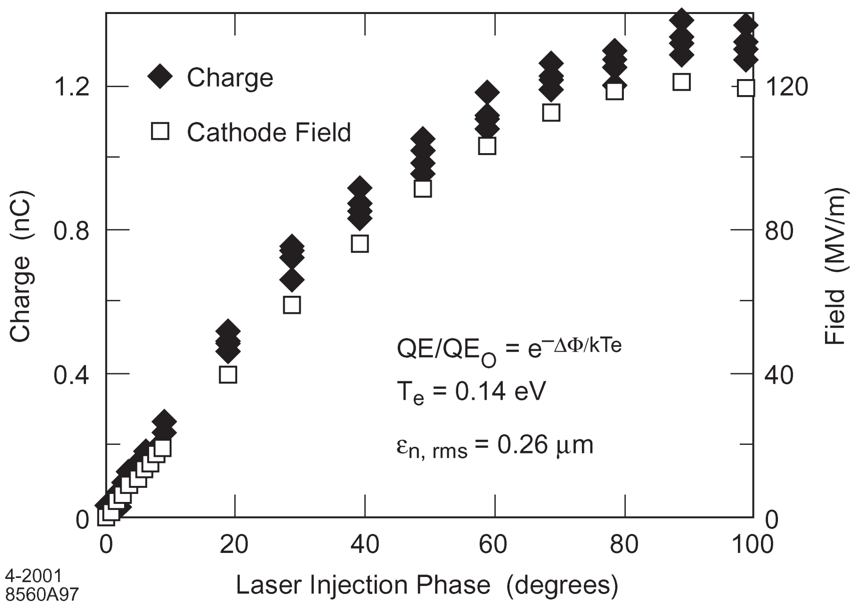
If we choose a smaller laser spotsize on the cathode, we can reduce the thermal emittance. But the space charge force becomes stronger if the laser spotsize is too small and the total emittance is increased again.

To reduce the emittance growth due to the space charge force on cathode, we need a higher gradient on the cathode surface. That is the reason why I choose 1.6 Cell S-band RF photoinjector (reliable operation ~ 125 MV/m & peak gradient ~ 140 MV/m).

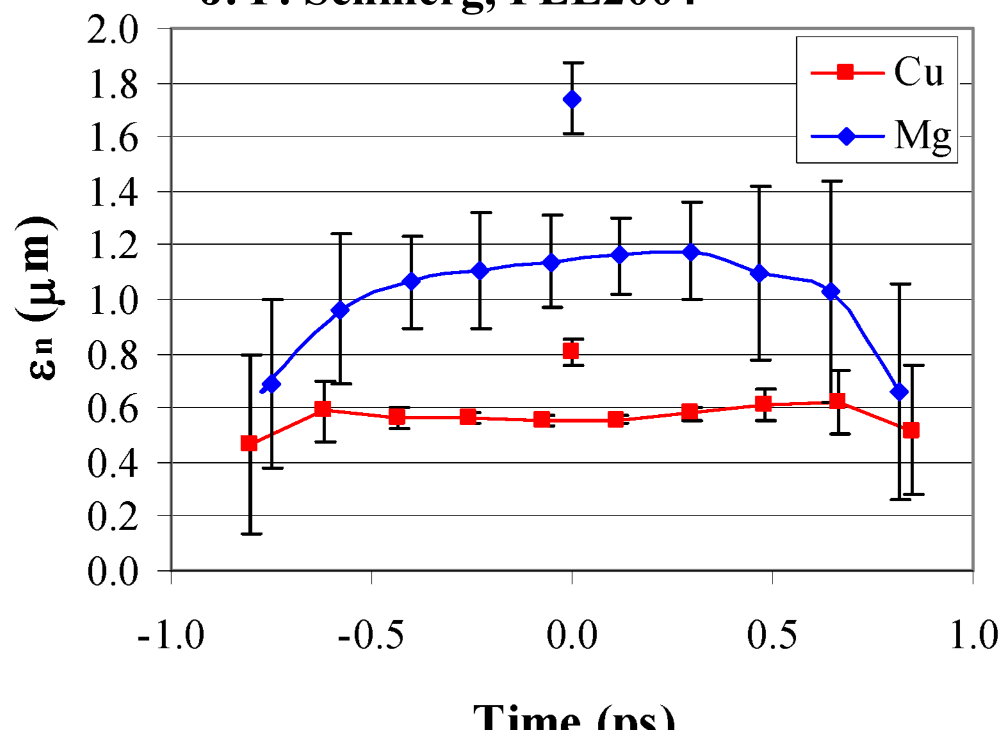
Recent Measured *K* with Cu Cathodes

- Note that it seems that recent measured *K* is smaller than 1.1 eV (upper limit).
- We can reduce slice emittance by reducing thermal emittance on the cathode !

SLAC-PUB-8284



J. F. Schmerg, FEL2004



Measured *K* with Cu cathode ~ 0.14 eV

At PAC2001, W. Graves reported that measured *K* is about 0.4 eV for Cu.
I used this *K* value of 0.4 eV for my new injector optimization.

RF Photoinjector Based cXFELs

PAUL SCHERRER INSTITUT

- Note that thermal emittance is the most biggest contribution in slice emittance
- We can reduce slice emittance by reducing thermal emittance on the cathode !

$$\varepsilon_{th} \approx \sigma_{x,y}\sqrt{\frac{2K}{3m_e c^2}}, \quad \sigma_x = \sigma_y \text{ for a round beam}$$

Here we assumed $K = 0.4$ eV for Cu cathode

Newly Optimized S-band RF Photoinjector for various Charges

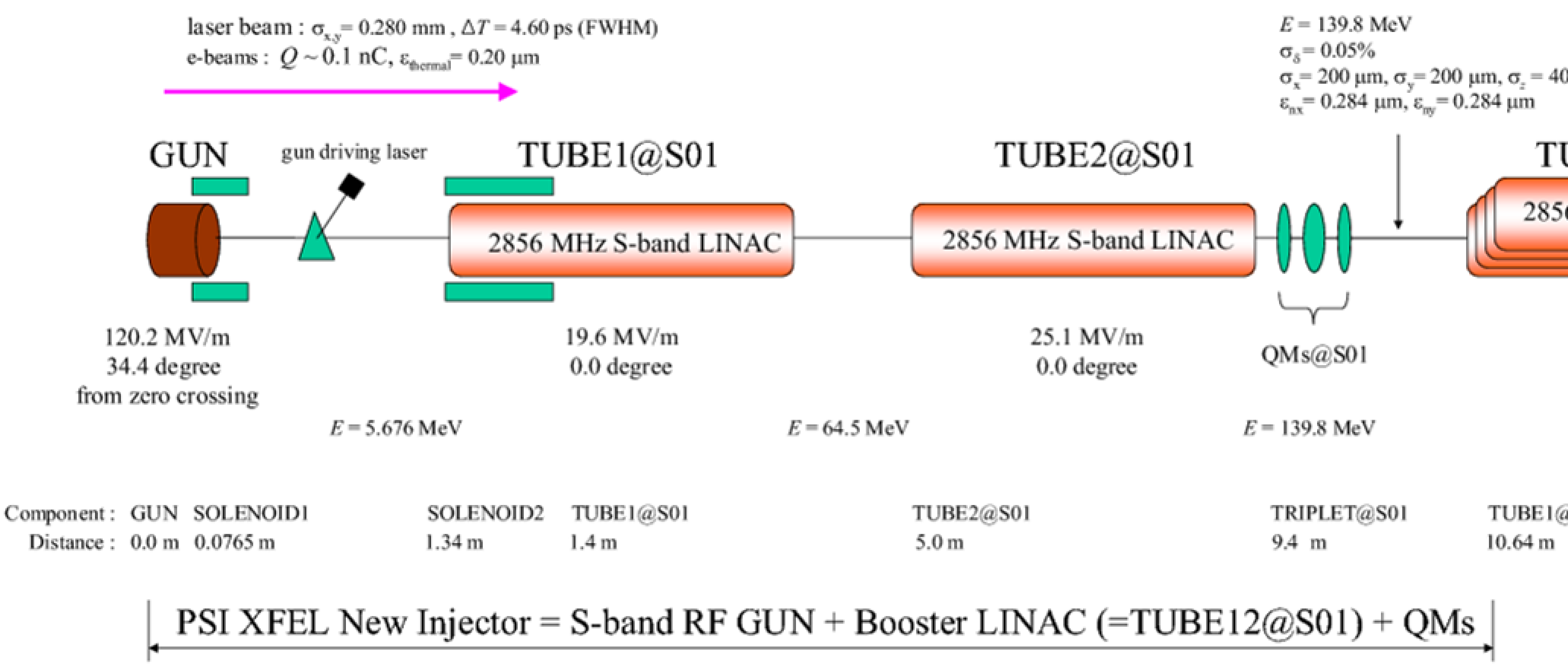
Q	laser length (FWHM)	$I_{\text{peak, cathode}}$	laser $\sigma_{\text{x,or y}}$	$\varepsilon_{\text{thermal}}$	$\varepsilon_{\text{projected, exit}}$
0.4 nC	7.4 ps	54 A	0.44 mm	0.32 μm	~ 0.47 μm
0.2 nC	5.8 ps	34 A	0.35 mm	0.25 μm	~ 0.37 μm
0.1 nC	4.6 ps	22 A	0.28 mm	0.20 μm	~ 0.28 μm

Note that peak current is much higher than 5.5 A !

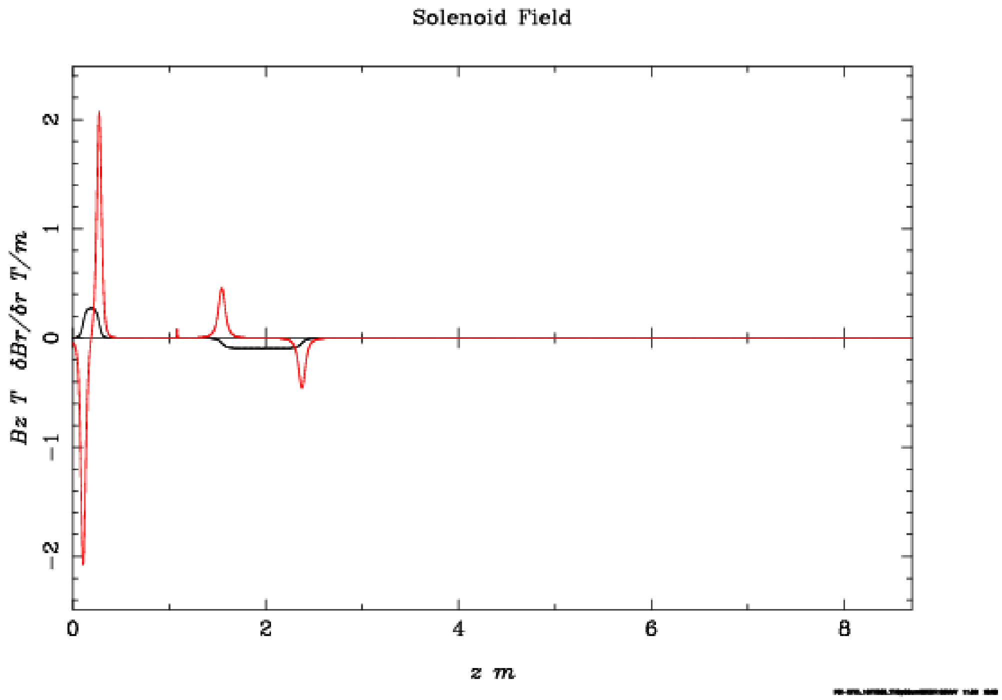
0.1 nC - Newly Optimized RF Photoinjector

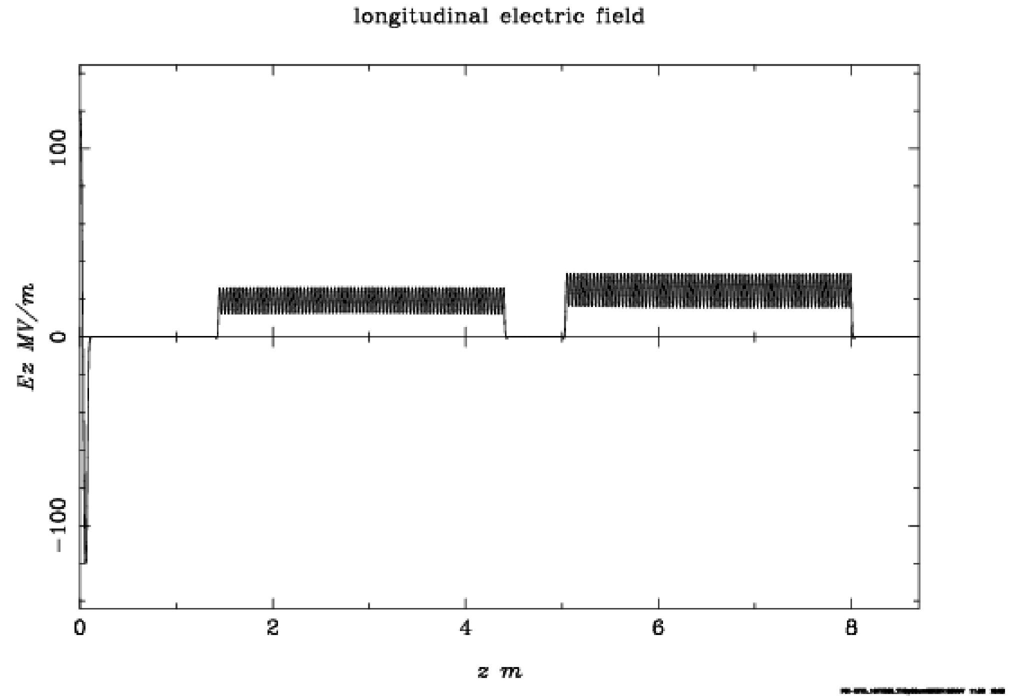
PAUL SCHERRER INSTITUT

Note that all parameters are projected ones



0.1 nC - Newly Optimized RF Photoinjector





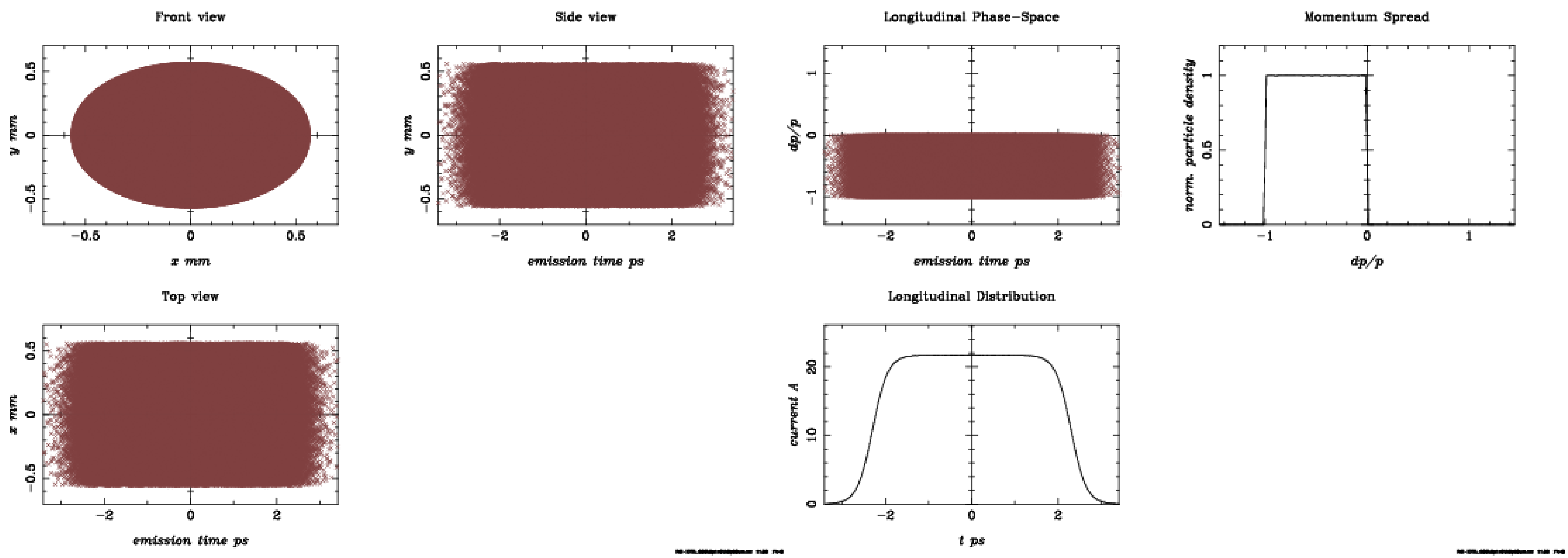
peak magnetic field of the 1st solenoid = 0.2731 T
length of the 1st solenoid = 0.225 m
peak magnetific field of 2nd solenoid = -0.0947 T
length of the 2nd solenoid = 0.8 m

peak gradient on cathode = 120.2 MV/m
gradient of the 1st accelerating tube = 19.6 MV/m
gradient of the 2nd accelerating tube = 25.1 MV/m

0.1 nC - Newly Optimized RF Photoinjector

PAUL SCHERRER INSTITUT

Laser Beam Profile : Uniform for Transverse and Flat-Top for Longitudinal



laser beam : $\sigma_{x,y}$= 0.280 mm , ΔT = 4.60 ps (FWHM)

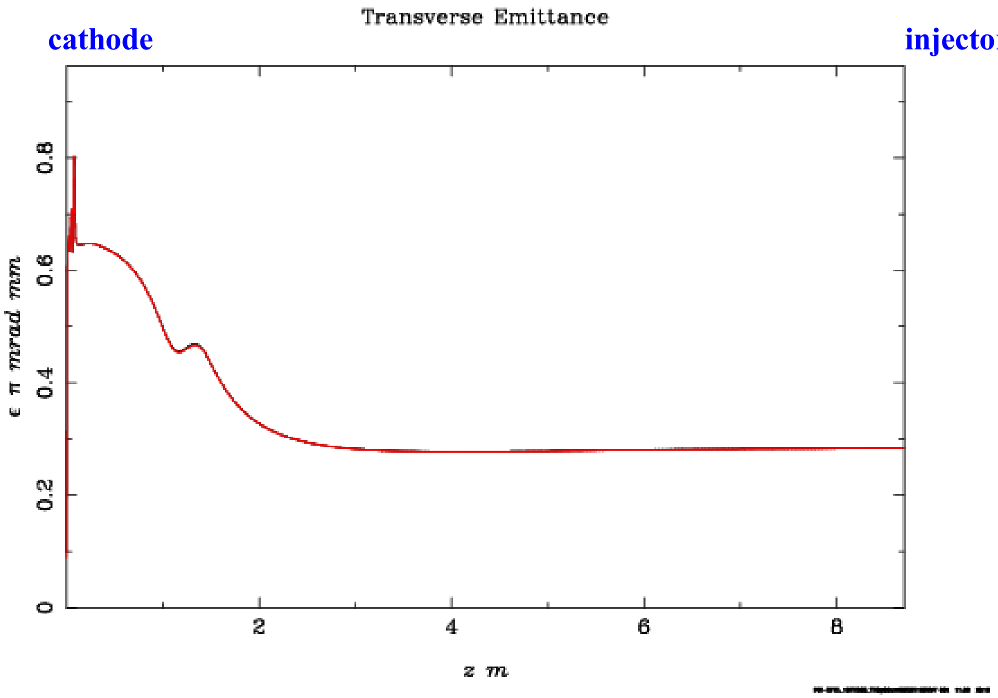
e-beams : Q ~ 0.1 nC, I_{peak} ~ 22 A, $\varepsilon_{thermal}$= 0.20 μm

0.1 nC - Newly Optimized RF Photoinjector

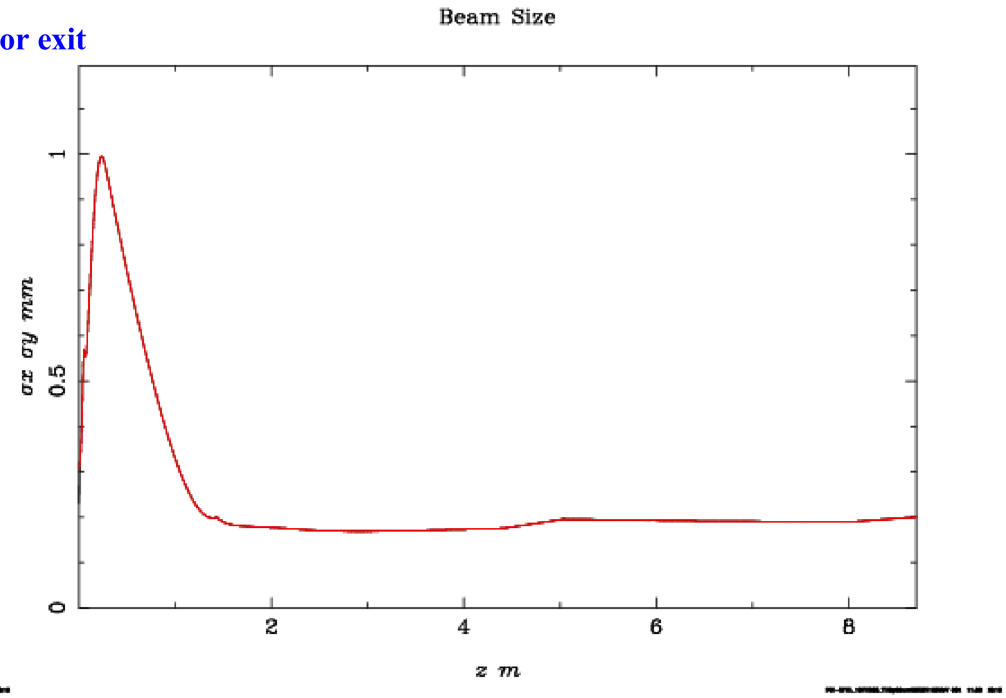
PAUL SCHERRER INSTITUT

ASTRA results along injector

cathode



injector exit



E = 139.8 MeV, σ_δ = 0.05%

σ_x = 200 μm, σ_y = 200 μm, σ_z = 401 μm

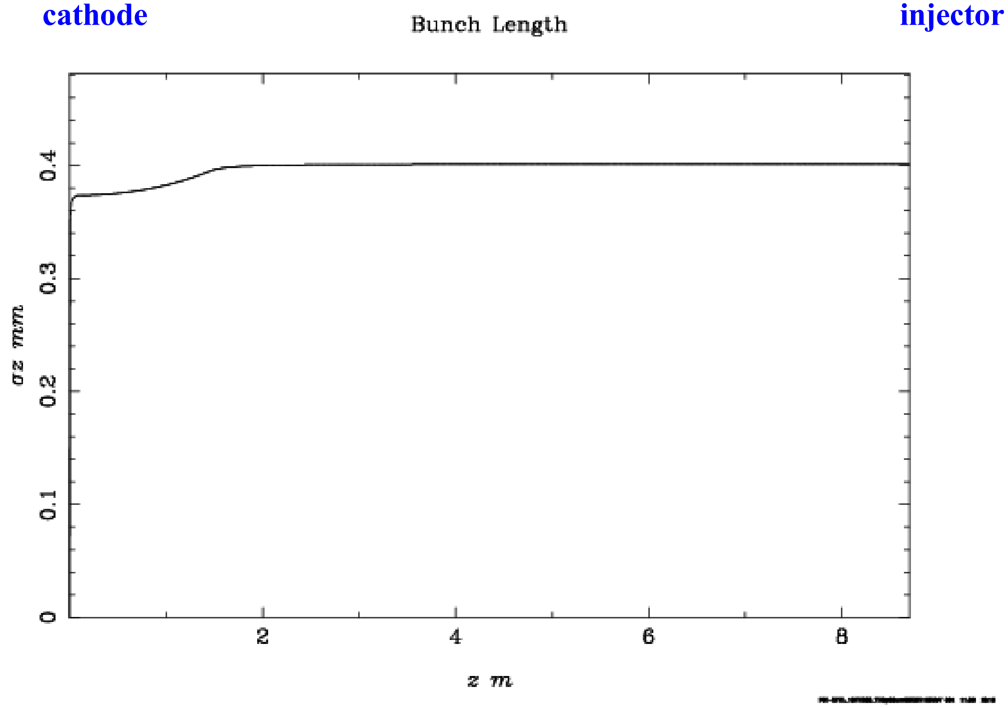
ε_{nx} = 0.284 μm, ε_{ny} = 0.284 μm

0.1 nC - Newly Optimized RF Photoinjector

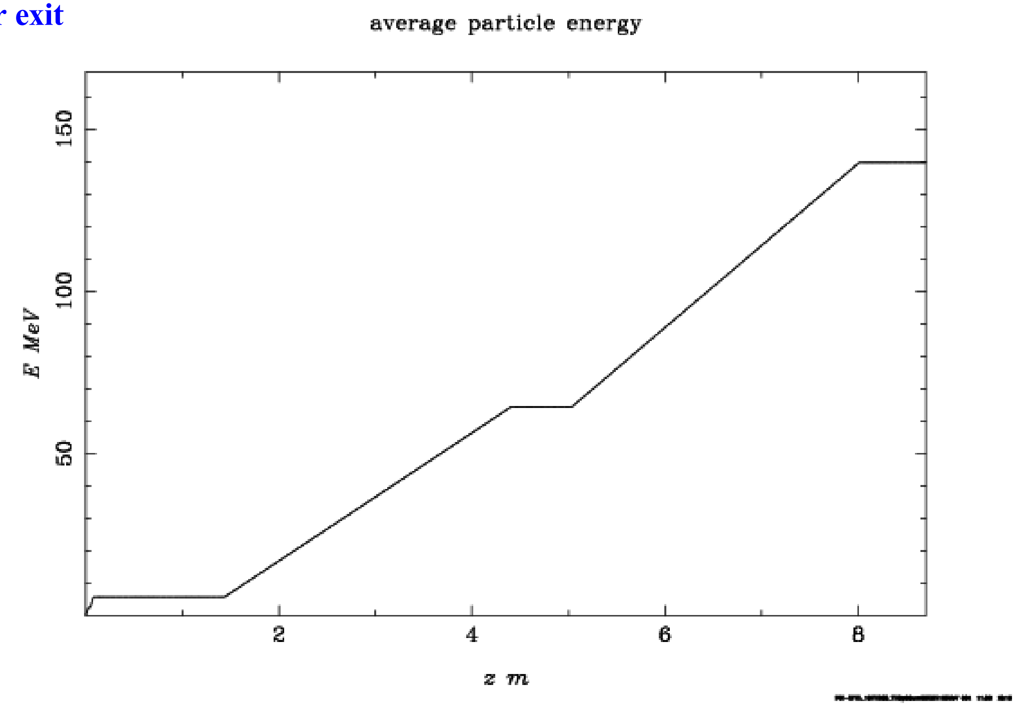
PAUL SCHERRER INSTITUT

ASTRA results along injector

cathode



injector exit



E = 139.8 MeV

σ_δ = 0.05%

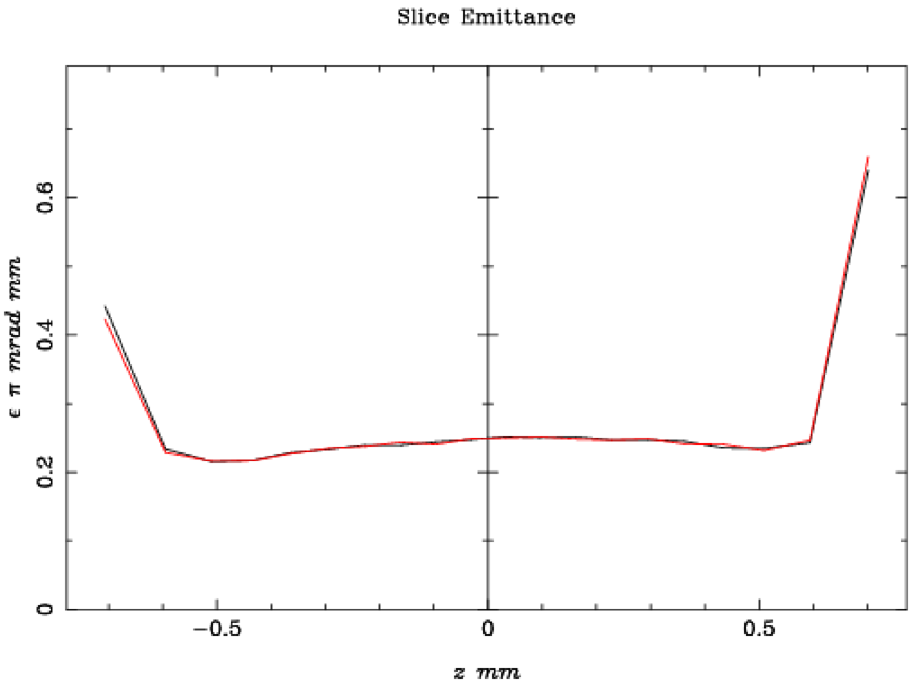
σ_x= 200 µm, σ_y= 200 µm, σ_z = 401 µm

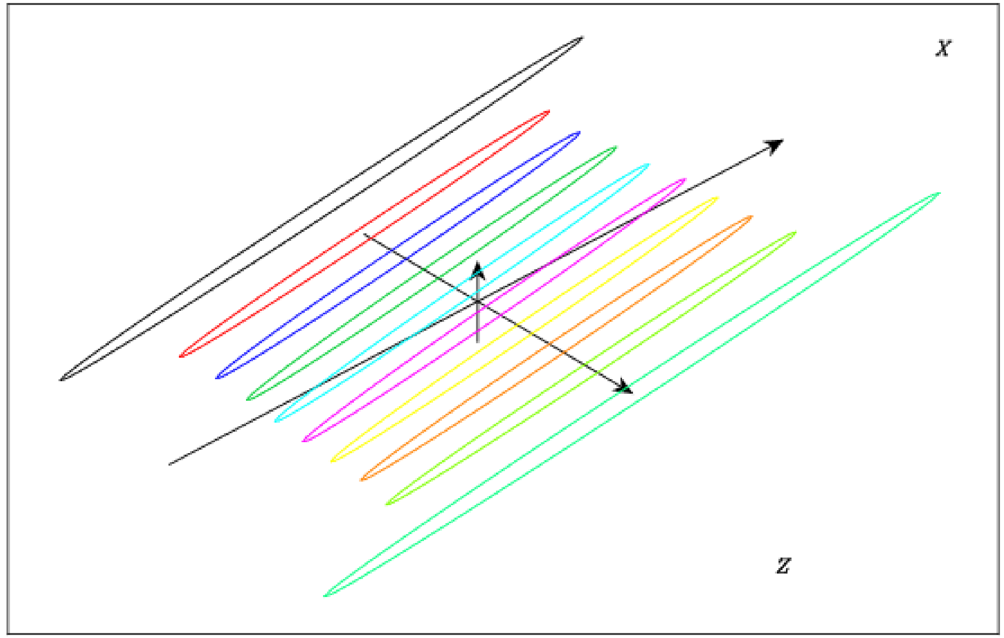
ε_{nx}= 0.284 µm, ε_{ny}= 0.284 µm

0.1 nC - Newly Optimized RF Photoinjector

PAUL SCHERRER INSTITUT

ASTRA results at the exit of RF photoinjector, 8.7 m



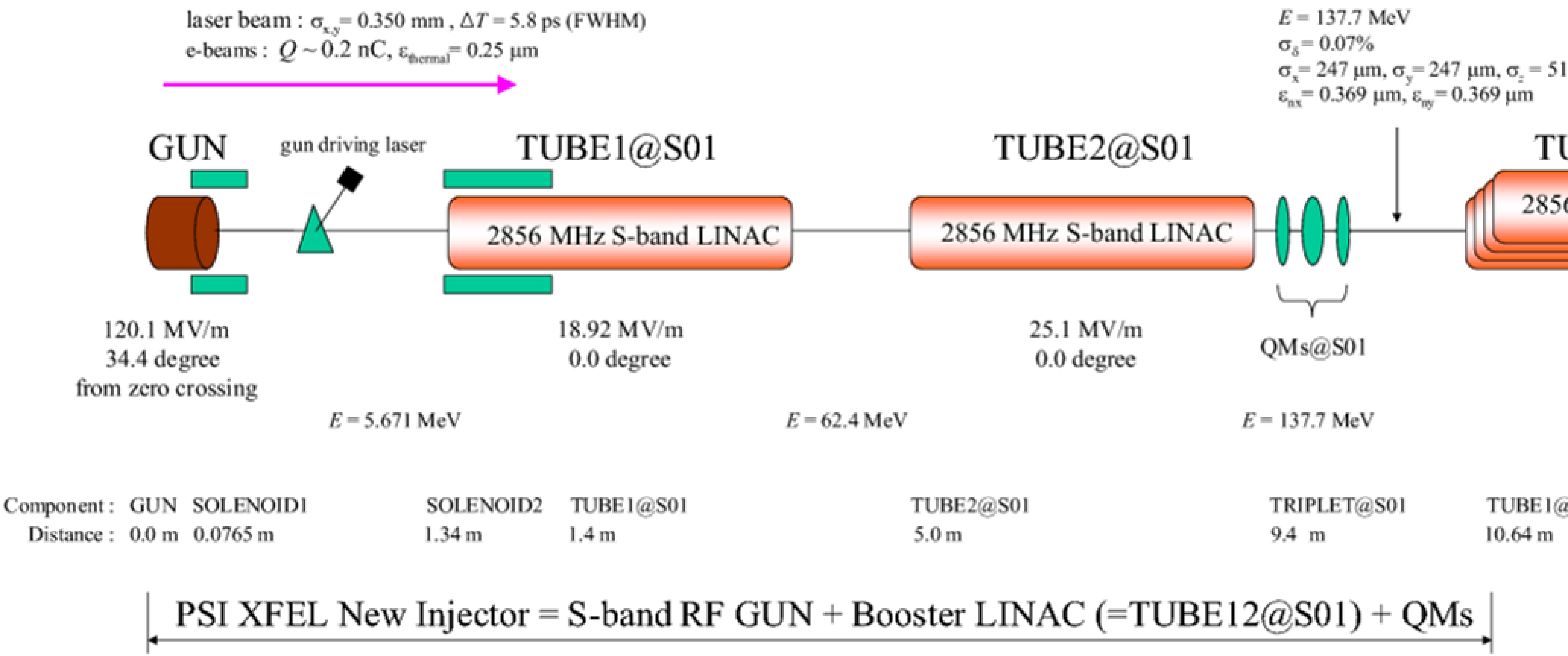


core slice $\varepsilon_n \sim 0.25\ \mu m$

0.2 nC - Newly Optimized RF Photoinjector

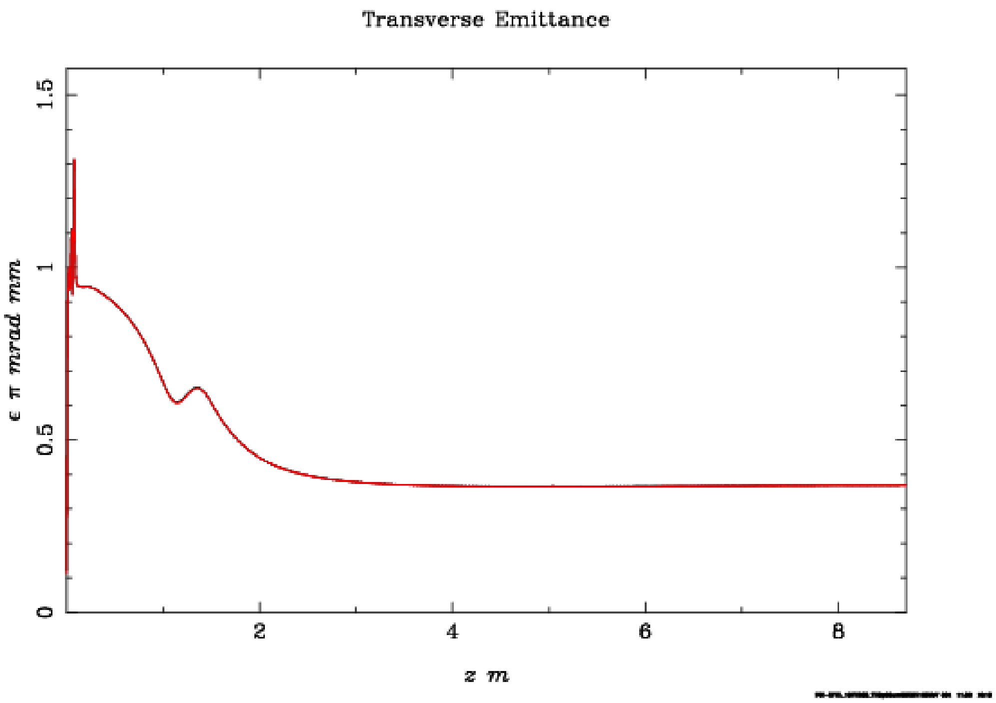
PAUL SCHERRER INSTITUT

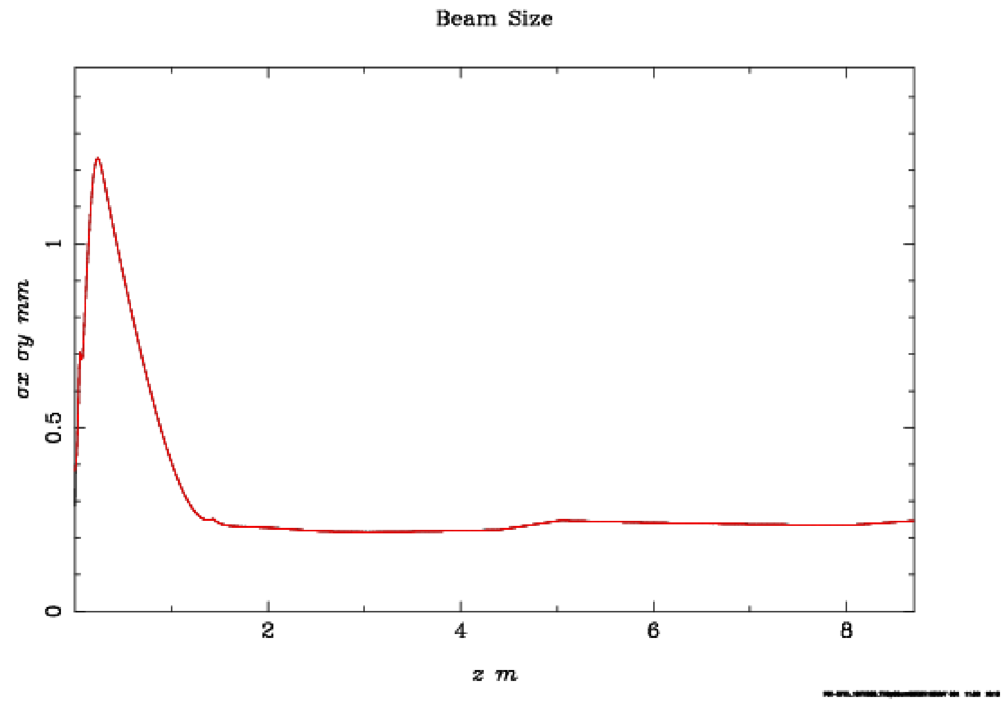
Note that all parameters are projected ones



0.2 nC - Newly Optimized RF Photoinjector

ASTRA results along injector





E = 137.7 MeV

σ_δ = 0.07%

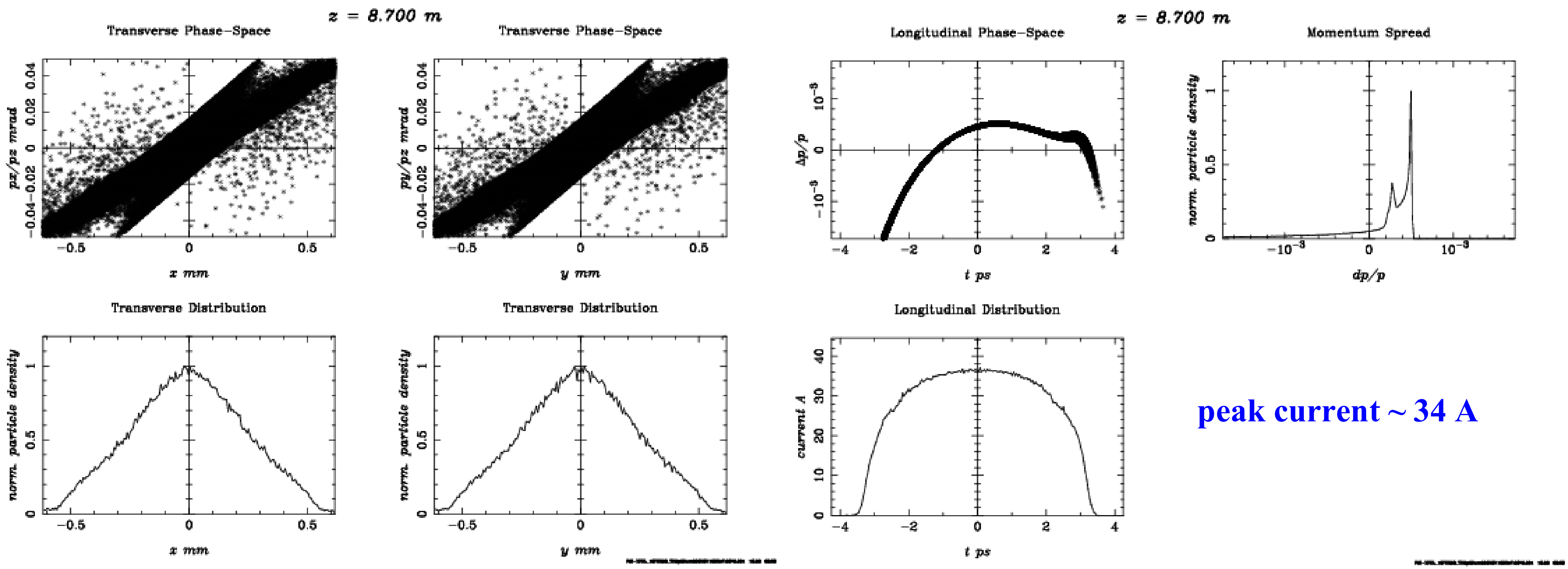
σ_x= 247 μm, σ_y= 247 μm, σ_z = 510 μm

ε_{nx}= 0.369 μm, ε_{ny}= 0.369 μm

0.2 nC - Newly Optimized RF Photoinjector

PAUL SCHERRER INSTITUT

ASTRA results at the exit of RF photoinjector, 8.7 m



peak current ~ 34 A

E = 137.7 MeV

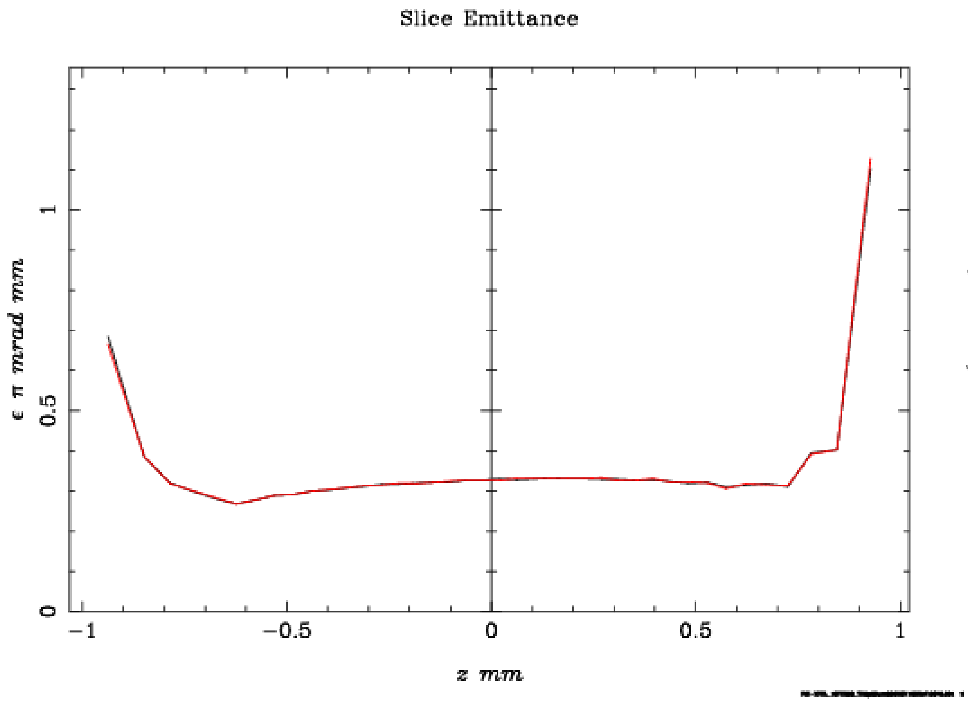
σ_δ = 0.07%

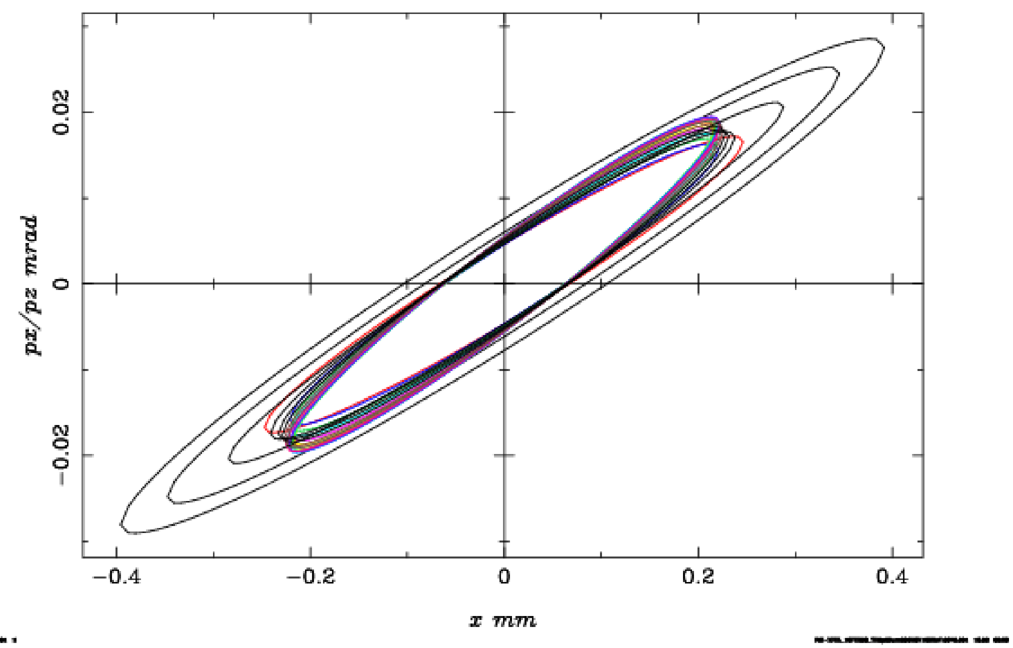
σ_x = 247 μm, σ_y = 247 μm, σ_z = 510 μm

ε_{nx} = 0.369 μm, ε_{ny} = 0.369 μm

0.2 nC - Newly Optimized RF Photoinjector

ASTRA results at the exit of RF photoinjector, 8.7 m



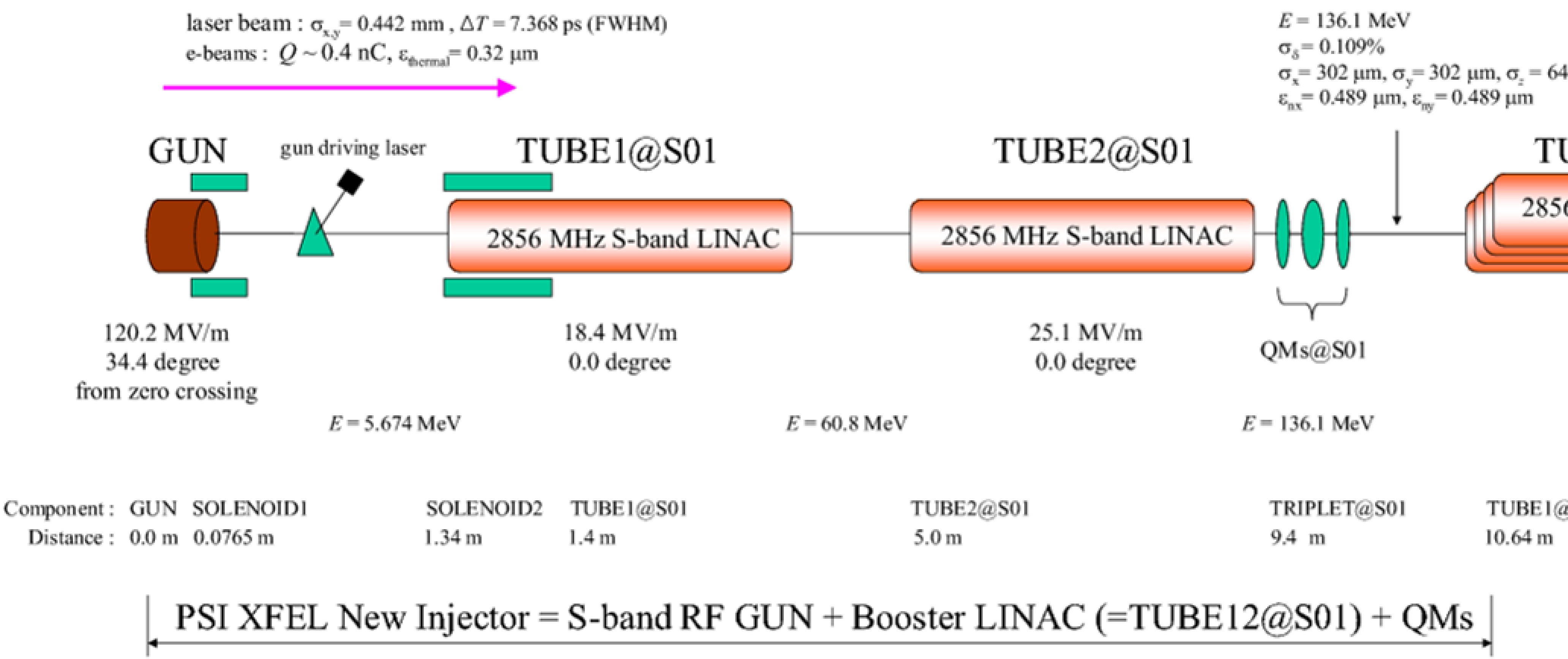


core slice $\varepsilon_n \sim 0.32\ \mu m$

0.4 nC - Newly Optimized RF Photoinjector

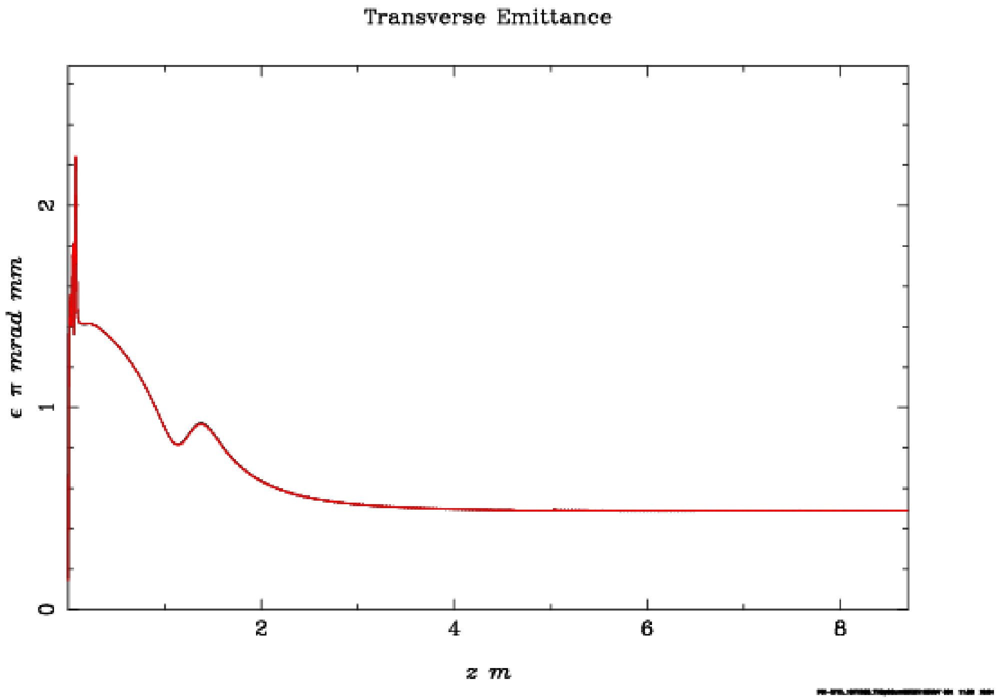
PAUL SCHERRER INSTITUT

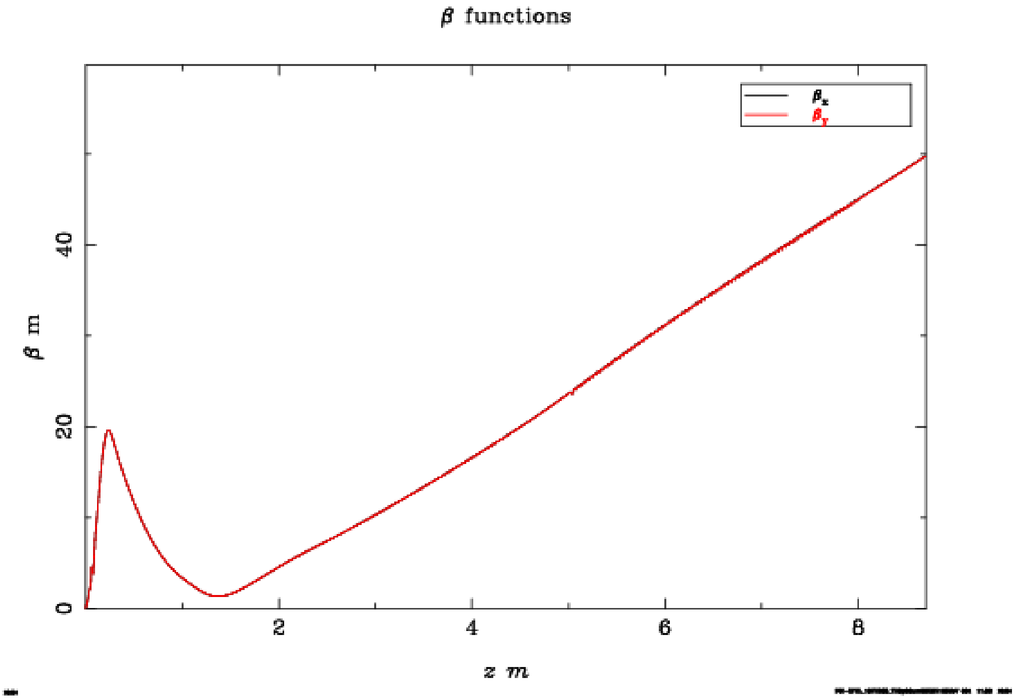
Note that all parameters are projected ones



0.4 nC - Newly Optimized RF Photoinjector

ASTRA results along injector





E = 136.1 MeV

σ_δ = 0.109%

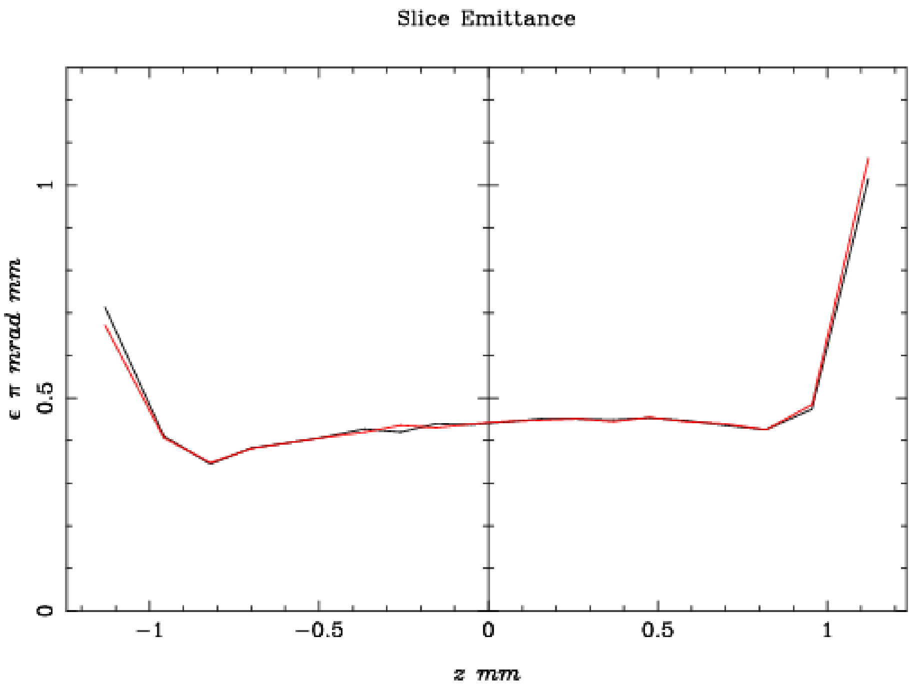
σ_x = 302 μm, σ_y = 302 μm, σ_z = 645 μm

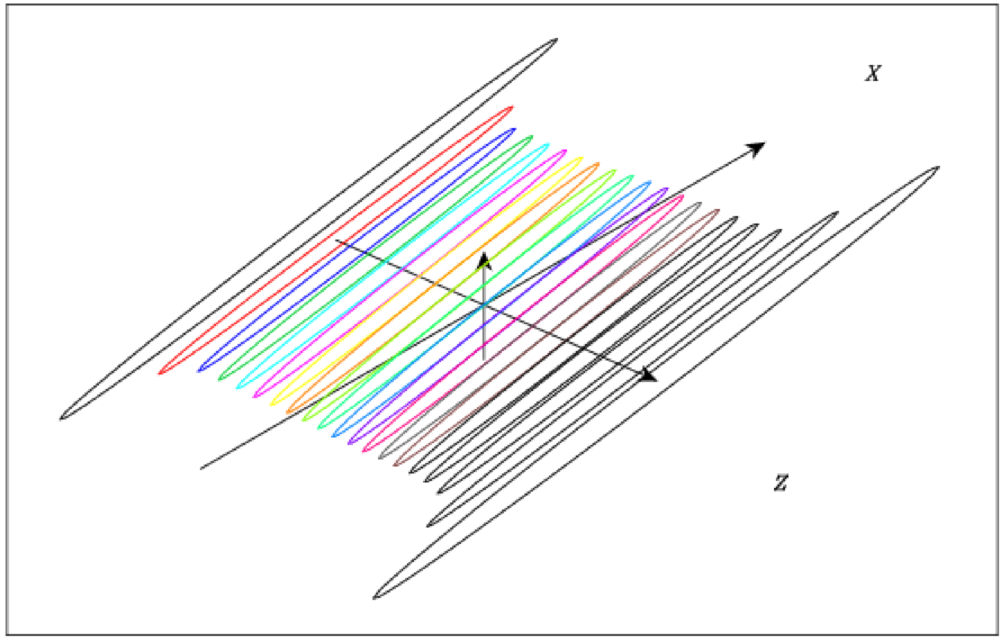
ε_{nx} = 0.489 μm, ε_{ny} = 0.489 μm

0.4 nC - Newly Optimized RF Photoinjector

PAUL SCHERRER INSTITUT PSI

ASTRA results at the exit of RF photoinjector, 8.7 m

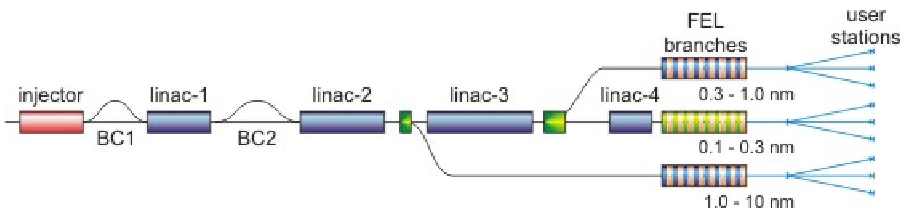




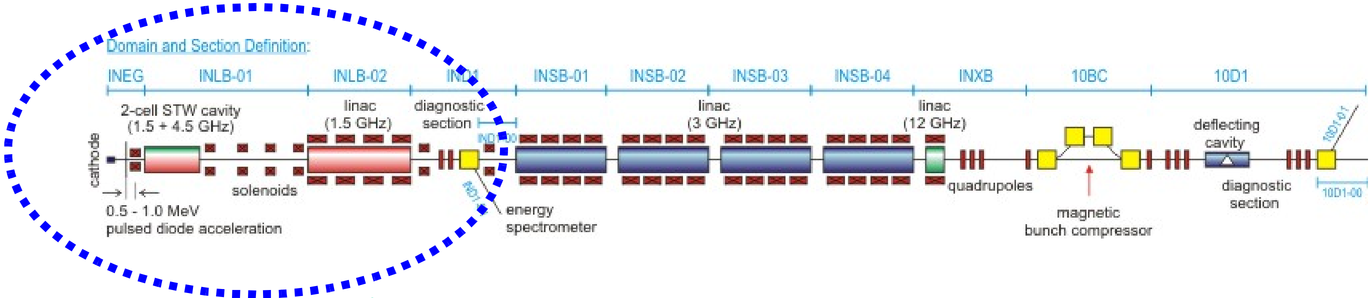
core slice $\varepsilon_n \sim 0.43$ µm

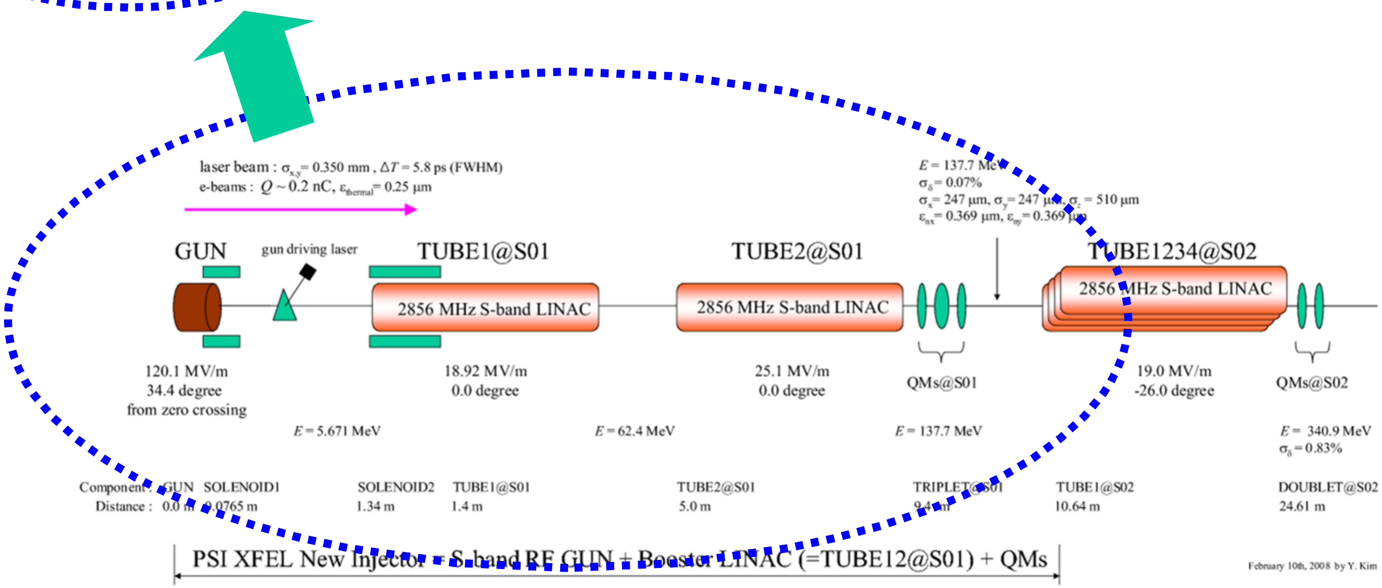
Modified Injector Layout

PAUL SCHERRER INSTITUT



With a new layout, overall compression factor of 272 will be dramatically reduced !





Summary

By changing our mind from ultra-low emittance & low peak current to low-emittance & high peak current, we can keep our compact PSI XFEL project continuously.

By the help of well optimized RF photoinjector which is based on invariant envelope matching concept, we can get continuous emittance damping at booster.

After consideration of the experimentally demonstrated high gradient of about 120 MV/m, we chose LCLS type 1.6 cell S-band RF photoinjector for the first simulation works. Later we will choose 2.5 cell CTF3 type S-band RF photoinjector.

For 0.1 nC, 0.2 nC, and 0.4 nC, estimated normalized projected emittances at 135 MeV are about 0.28 µm, 0.37 µm, and 0.47 µm, respectively. And their core slice emittances are about 0.25 µm, 0.32 µm, and 0.43 µm.
It seems that 0.1 nC and 0.2 nC operations are promising.

Summary & Acknowledgments

PAUL SCHERRER INSTITUT

To optimize a backup injector further, we need more detail information on *K* for the Cu cathode. We will try to measure *K* at OBLA.

By re-optimizing S-band RF photoinjector with 0.1 nC and 0.2 nC and by optimizing bunch compressors, we can get a backup solution for Compact PSI XFEL project.

For the backup injector layout, we do not need the velocity bunching and overall bunch compression factor of 272 will be dramatically reduced (< 100). And RF jitter sensitivity will be also dropped and machine will be simplified.

Y. Kim sincerely thank Dr. Andreas Adelmann, Dr. Rene Bakker, Dr. Andreas Streun, and Dr. Marco Pedrozzi for their encouragement for this work.