Developing the Electron Source for the European X-ray Free Electron Laser Project

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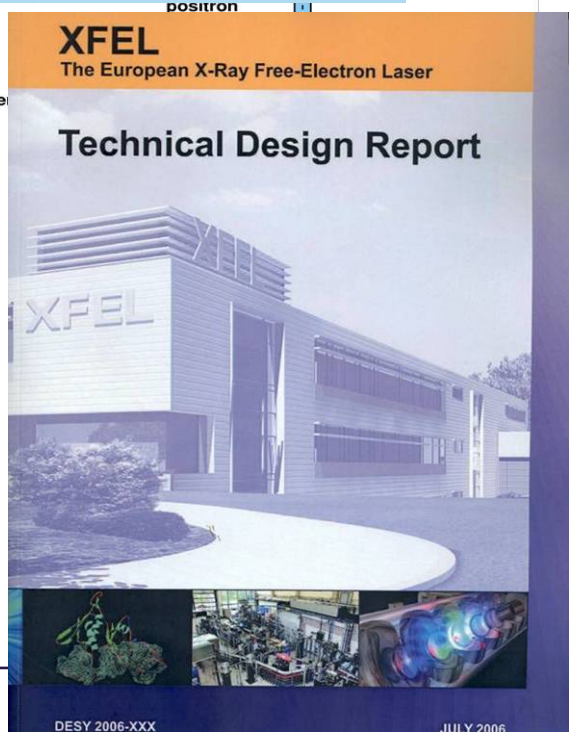
(**P**hoto **I**njector **T**est Facility at DESY, **Z**euthen site, **PITZ**)

Content:

- the European XFEL
- the PITZ facility and important results from the last years
- recent high brightness beam measurements at PITZ
- summary and outlook

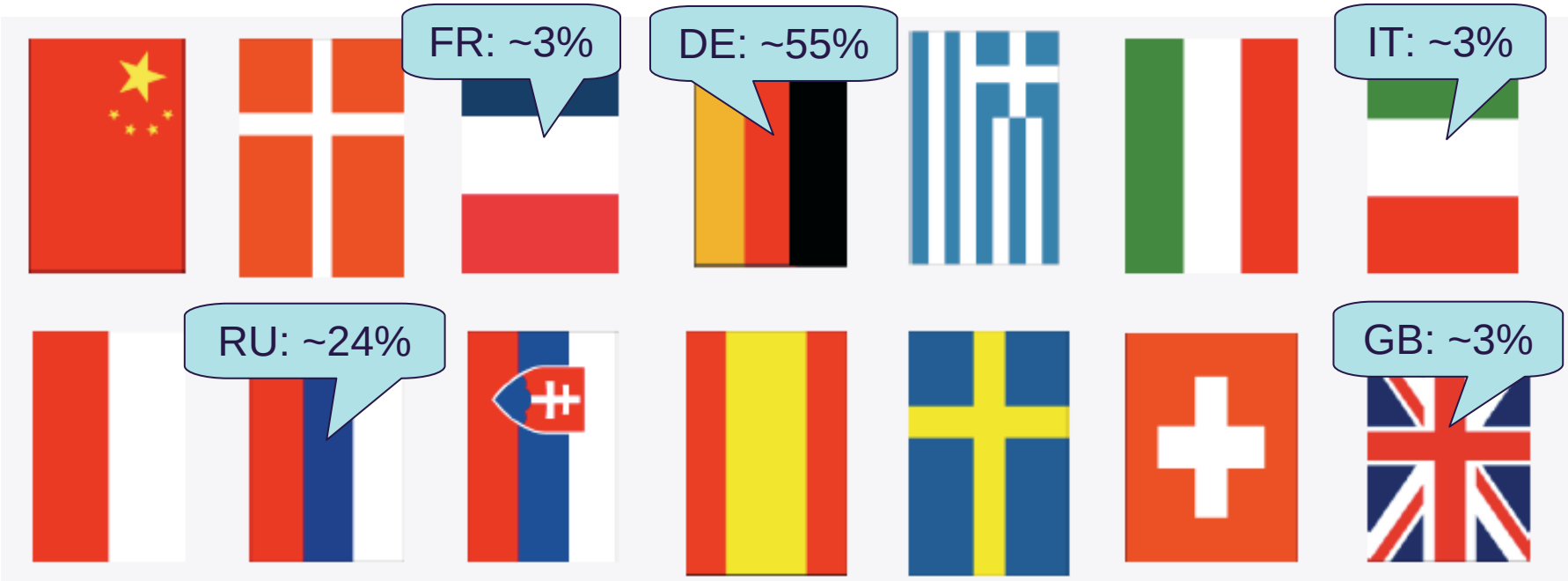
XFEL – how it began …

- 2001 – **TESLA Proposal** and Science Council Eval.
- Oct. 2002 – **X-ray FEL** with 20 GeV superconducting accelerator (TESLA-technology)
- Feb. 2003 - **Approval** by Federal Government as European project
- Nine countries signed **MoU for the Preparatory Phase** of the XFEL in January 2005
- July 2006 – **Technical Design Report**
- July 2006: **Plan Approval Process** completed
- 2009: groundbreaking started



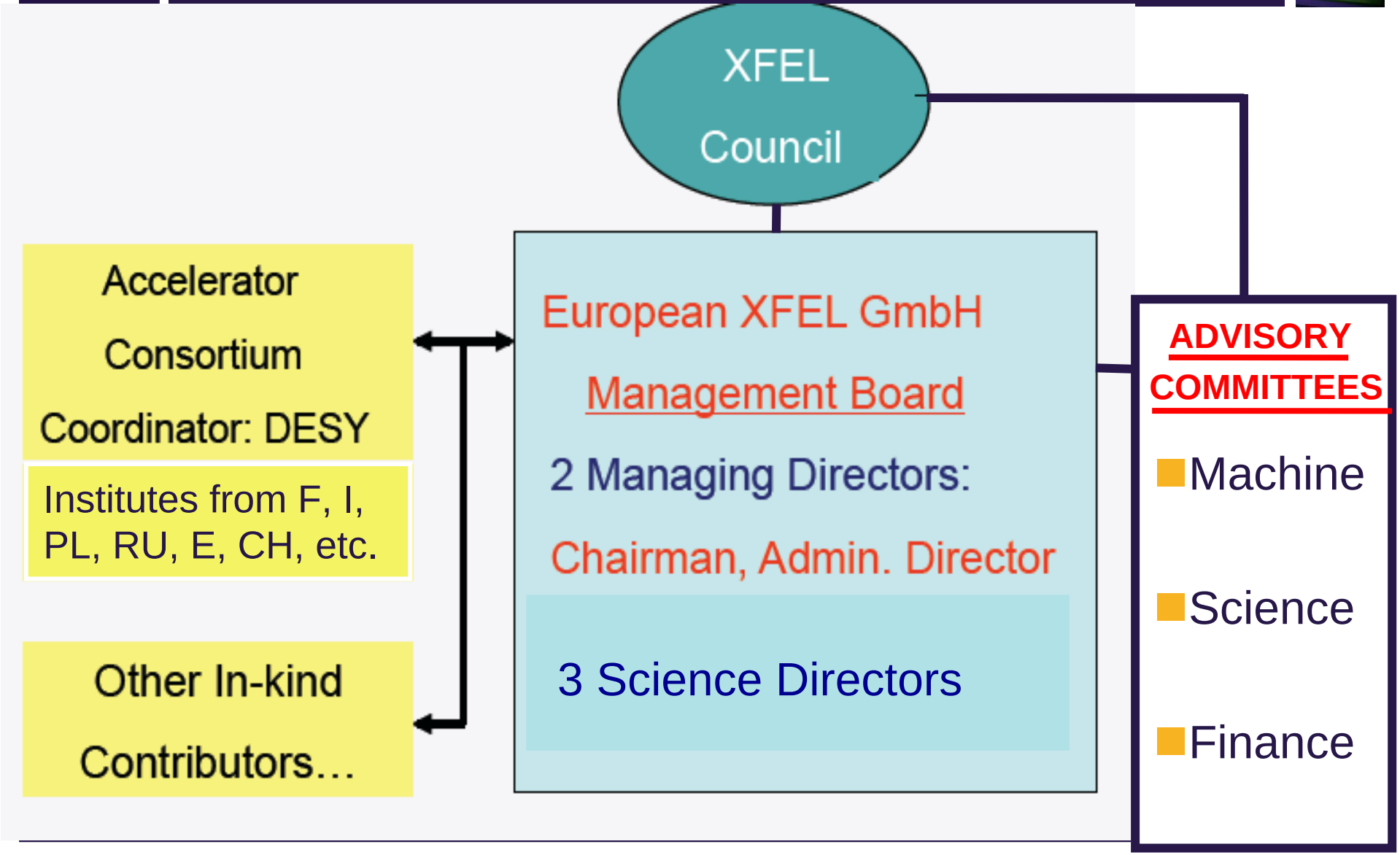
Partner countries contributing to European XFEL

The European XFEL GmbH is founded. Research institutes of the different countries will be shareholders. Construction and operation of the XFEL are entrusted to this company.



= contribution to start version of XFEL (total 1050 M€, preliminary)

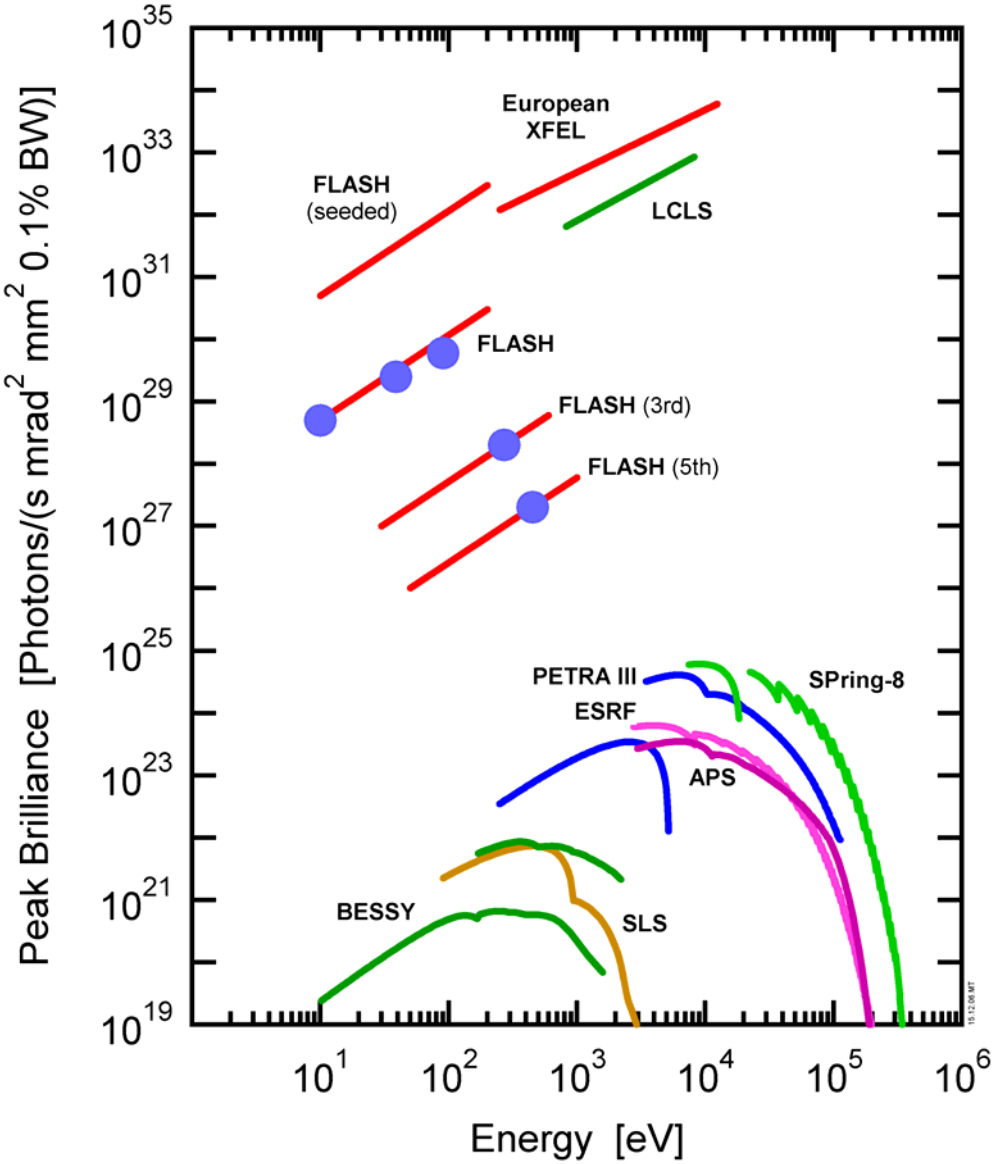
European XFEL project organisation



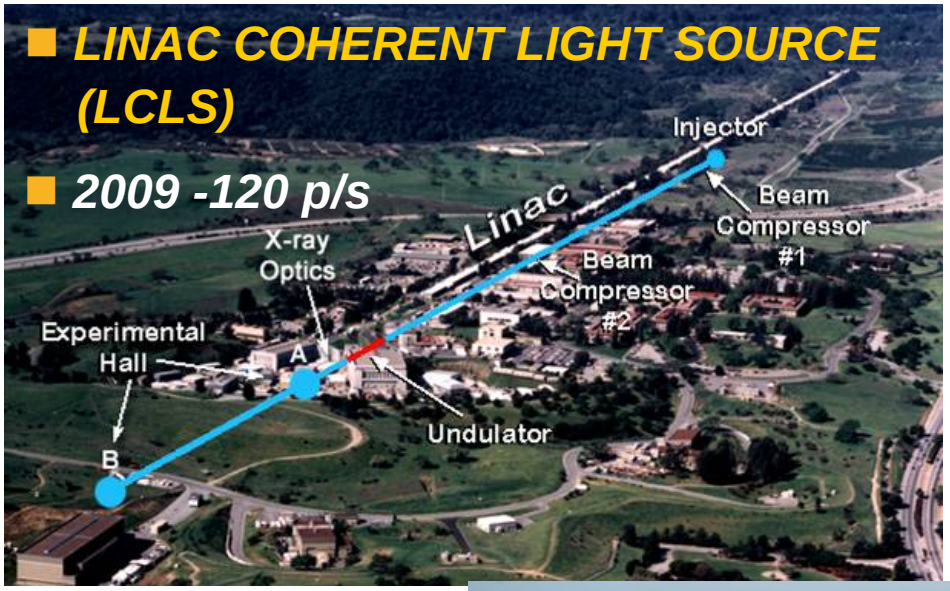
European XFEL - a next generation light source

The XFEL will deliver:

- wavelength down to 0.1 nm
  ➔ **atomic-scale resolution**
- ultra-short pulses (≤ 100 fs)
  ➔ **ultra-fast dynamics**, "molecular movies"
- ultra-high peak brilliance
  ➔ investigations of **matter under extreme conditions** (**Xe^{21+}**)
- transverse spatial coherence
  ➔ imaging of single nanoscale objects, possibly down to individual macromolecules (**no crystallisation needed !!**)



The European XFEL in the International Context



- *LINAC COHERENT LIGHT SOURCE (LCLS)*
- *2009 -120 p/s*

- *2011-60 p/s*
- *SPring-8 Compact SASE Source (SCSS)*

- *European XFEL Facility (XFEL)*
- *2014 - 30 000 p/s*

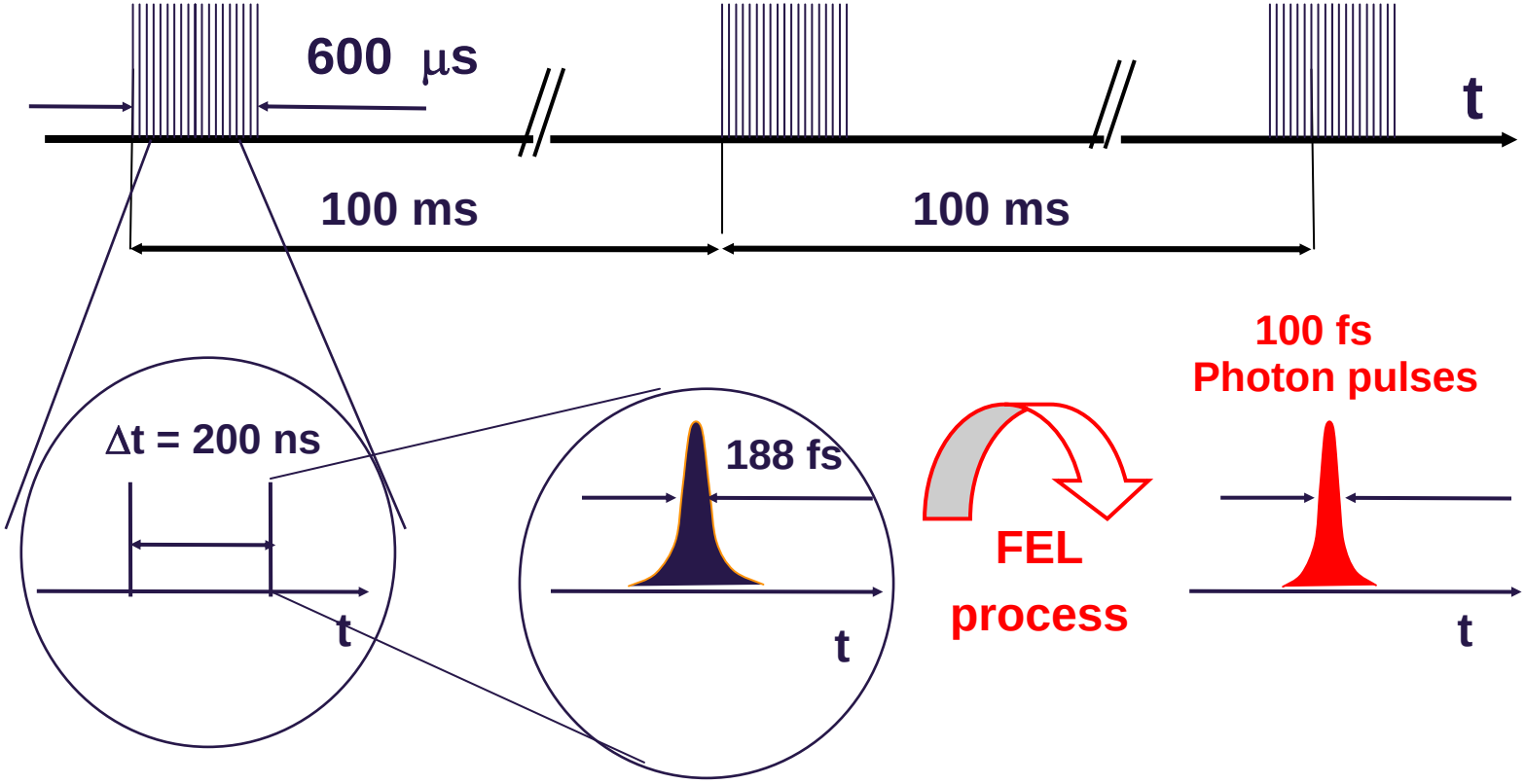
Comparison of X-ray FEL Projects

	LCLS (USA)	SCSS (JAPAN)	EUROPEAN XFEL (SASE1)
Minimum Wavelength (nm)	0.15	0.1	0.1
Peak Brilliance (phot/s/mm^2/mrad^2/0.1%BW)	8.5 10^{32}	5 10^{33}	5 10^{33}
Average Brilliance	2.4 10^{22}	1.5 10^{23}	1.6 10^{25}
Pulses/s	120	60	30 000
Pulse Duration (fs)	100 and below	500	100 and below
First Beam	2009	2011	2014

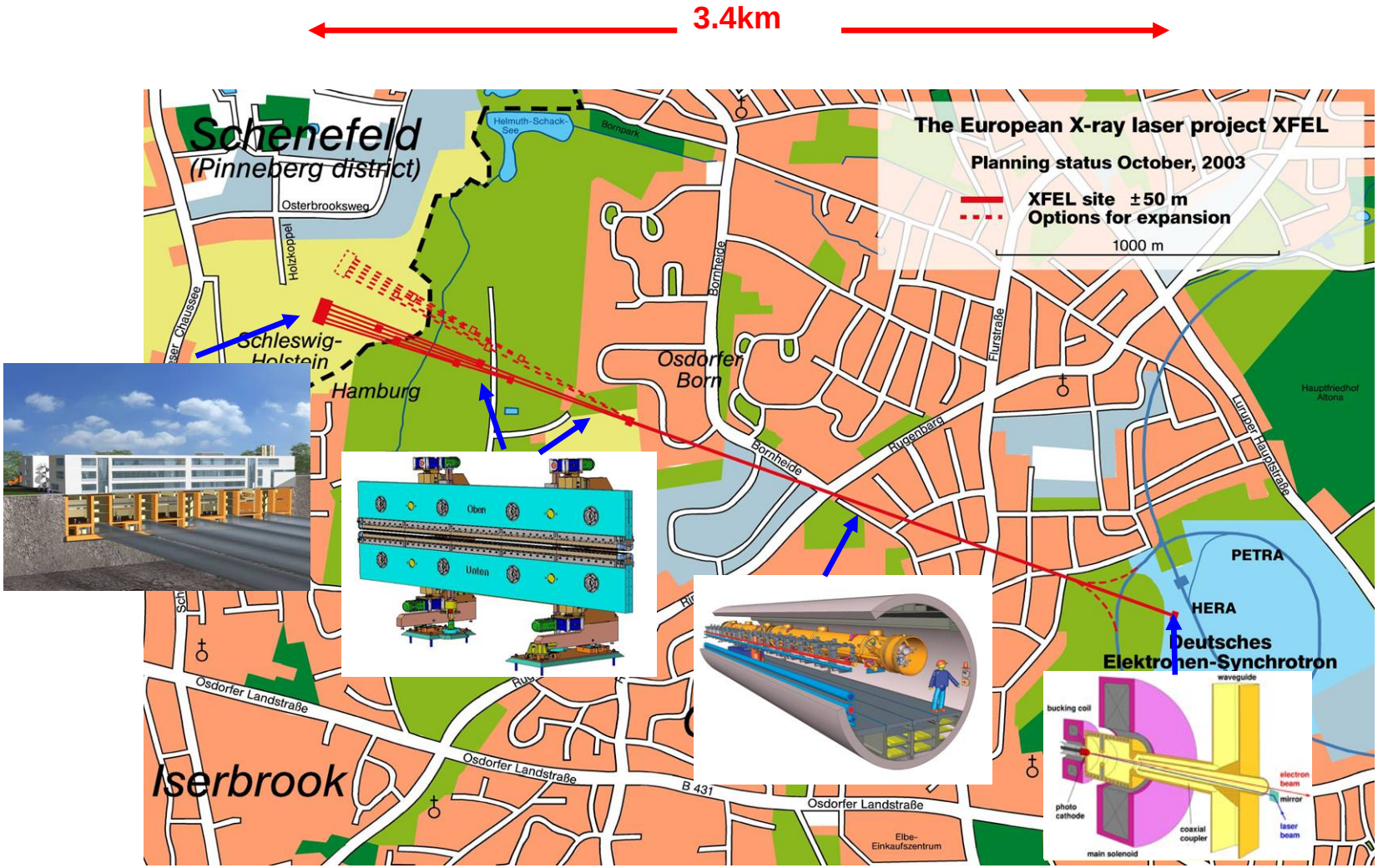
Advantages of Superconducting RF Technology for FEL's

- Possibility to inject thousands of bunches per RF pulse;
- Small wakefields: large iris even at high gradients (design value: 24 MV/m; tested up to 35 MV/m);
- High stability, intra bunch-train feedback for high quality beam;
- Operational flexibility of time structure and energy

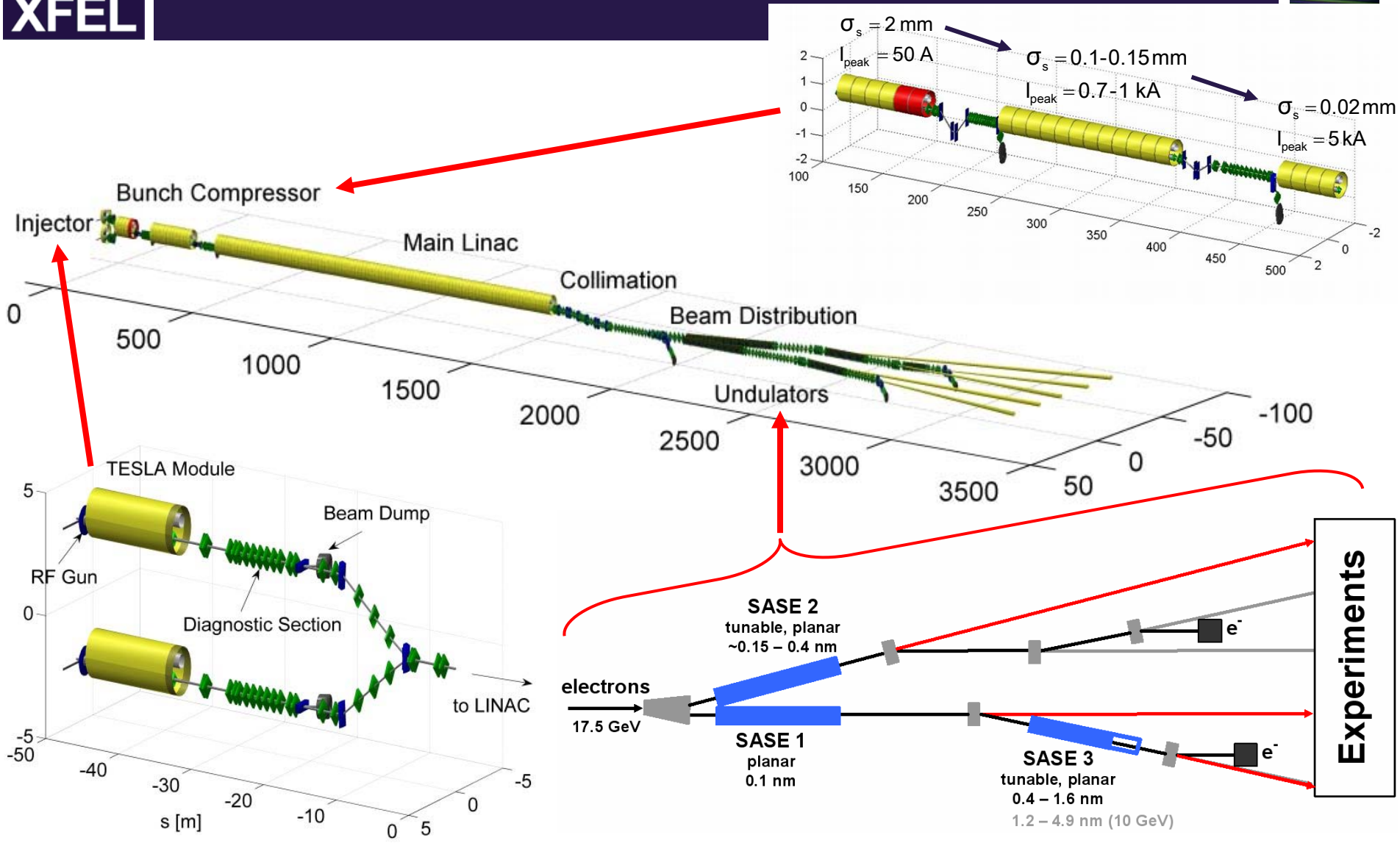
Electron bunch trains (with up to 3000 bunches of 1nC each)



Overall layout of the European XFEL

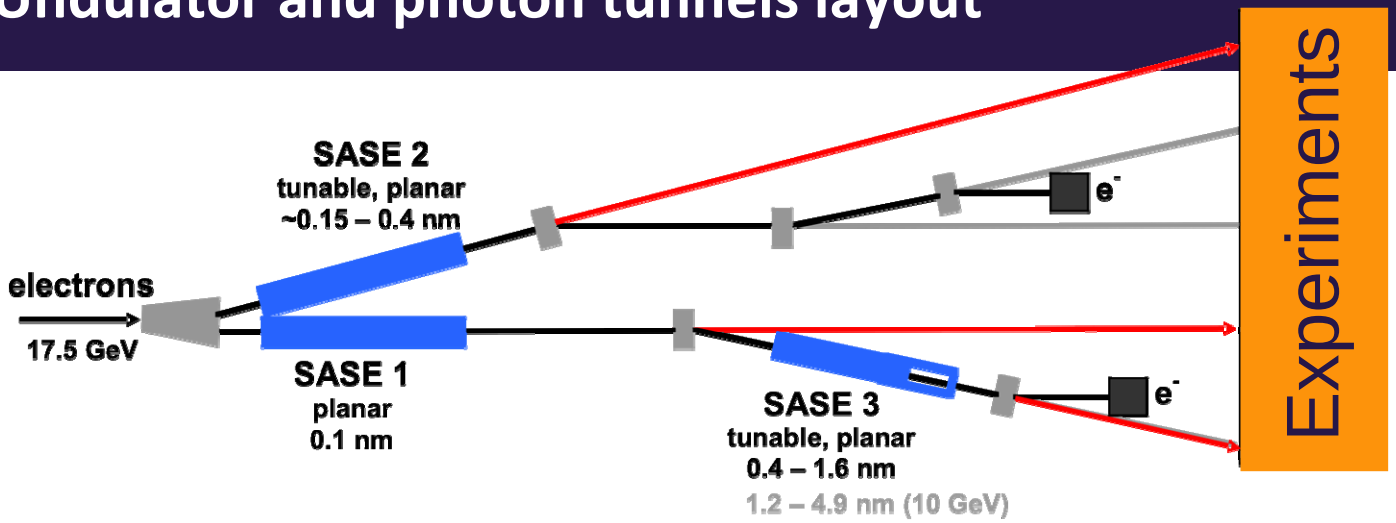


European XFEL – beam dynamic components



(„start-up“ version)

Undulator and photon tunnels layout



Parameter	Unit	SASE 1	SASE 2		SASE 3		
Electron energy	GeV	17.5	17.5	17.5	17.5	17.5	10.0**
Wavelength	nm	0.1	0.1	0.4	0.4	1.6	6.4
Photon energy	keV	12.4	12.4	3.1	3.1	0.8	0.2
Peak power	GW	20	20	80	80	130	135
Average power*	W	65	65	260	260	420	580
Photon beam size (FWHM)	µm	70	85	55	60	70	95
Photon beam divergence (FWHM)	µrad	1	0.84	3.4	3.4	11.4	27
Coherence time	fs	0.2	0.22	0.38	0.34	0.88	1.9
Spectral bandwidth	%	0.08	0.08	0.18	0.2	0.3	0.73
Pulse duration	fs	100	100	100	100	100	100
Photons per pulse	#	10^{12}	10^{12}	1.6×10^{13}	1.6×10^{13}	1.0×10^{14}	4.3×10^{14}
Average flux	#/s	3.3×10^{16}	3.3×10^{16}	5.2×10^{17}	5.2×10^{17}	3.4×10^{18}	1.4×10^{19}
Peak brilliance	B	5.0×10^{33}	5.0×10^{33}	2.2×10^{33}	2.0×10^{33}	5.0×10^{32}	0.6×10^{32}
Average brilliance*	B	1.6×10^{25}	1.6×10^{25}	7.1×10^{24}	6.4×10^{24}	1.6×10^{24}	2.0×10^{23}

Status of realization of the European XFEL

Construction of the underground buildings started!

- Contracts signed December 12, 200
- Construction started in early Januar
- http://www.xfel.eu/en/construction-w

One XFEL key component: → the high brightness electron source

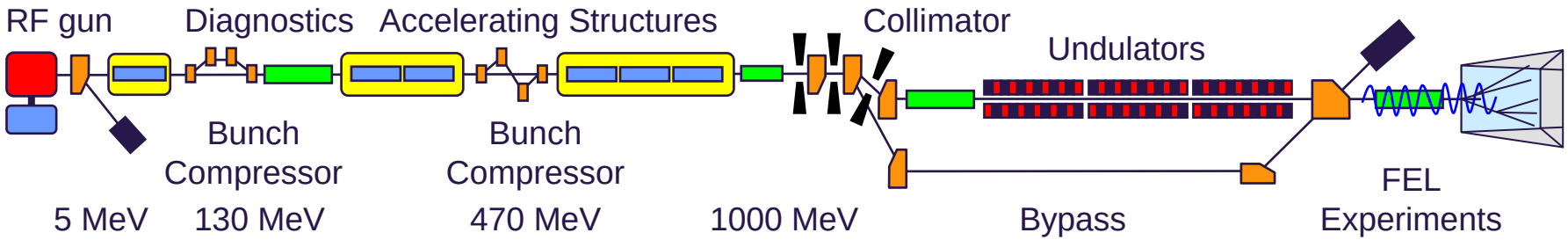
Why electron injector is so important …. ???

Any linac based short wavelength, high brilliance light source (e.g. SASE-FELs) contains the following main components:

- **electron source**
- **accelerating sections** → **e.g. wakefields, coupler kicks**
  - in between: **bunch compressor(s)** → **e.g. coherent synchrotron radiation (CSR)**

  } **increase normalized emittance**
- **undulator** to produce FEL radiation
- electron **beam dump**
- **photon beamline(s)** for the users

Example: FLASH



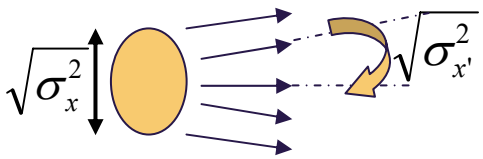
property of linacs: beam quality will DEGRATE during acceleration in linac

➔ electron source has to produce lowest possible emittance !!

What is Emittance ?

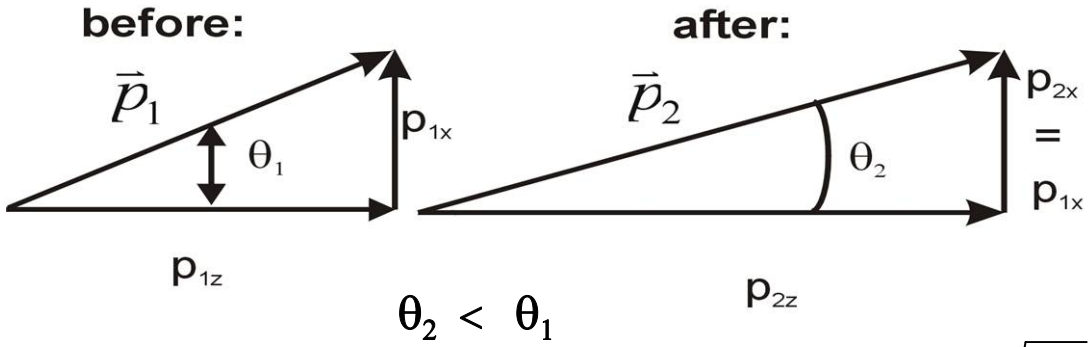
long.: ε_z ~ (e^- bunch length) • (energy spread of e^- bunch)

trans.: $\varepsilon_{x,y}$ ~ (e^- beam size) • (e^- beam angular divergence)



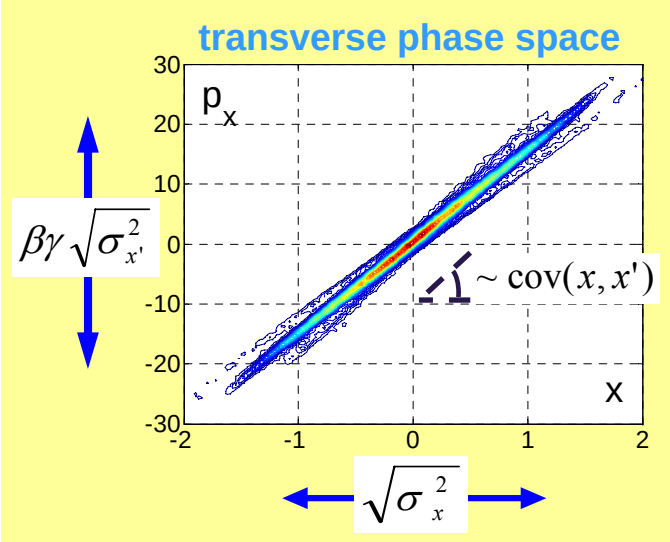
ε = 6 dimensional phase space volume occupied by given # of particles

effect of acceleration on transverse emittance (adiabatic damping):



$\theta_2 < \theta_1$

$\Rightarrow$ angular divergence is reduced $\Rightarrow \beta \bullet \gamma \bullet \sqrt{\sigma_{x'}^2}$



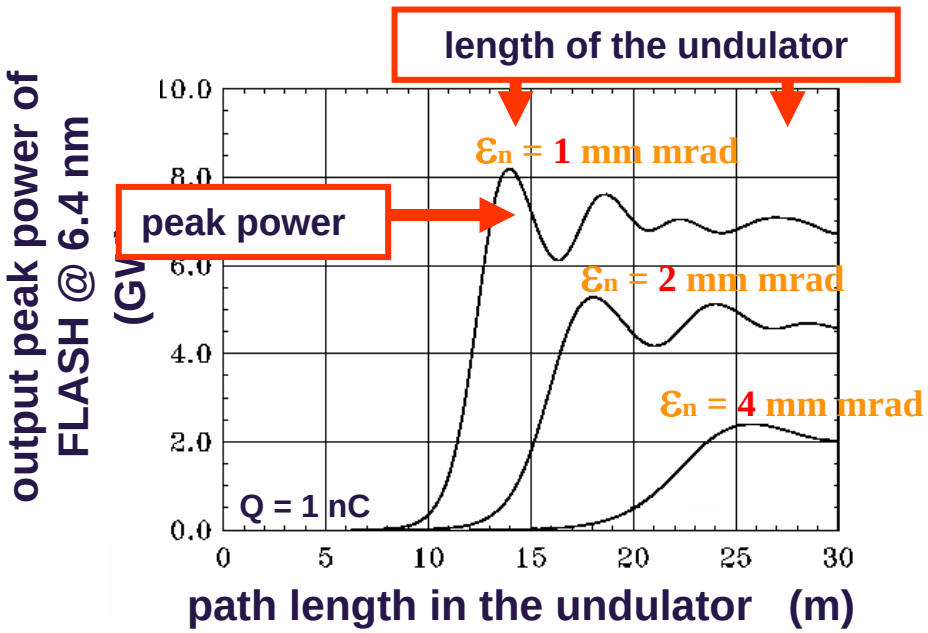
$\Rightarrow$ normalized RMS transverse emittance:

$$\varepsilon_x^n = \beta \bullet \gamma \bullet \sqrt{\sigma_x^2 \bullet \sigma_{x'}^2 - \mathrm{cov}^2(x, x')}\,; \quad \beta = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}, \quad x' = \frac{dx}{ds}$$

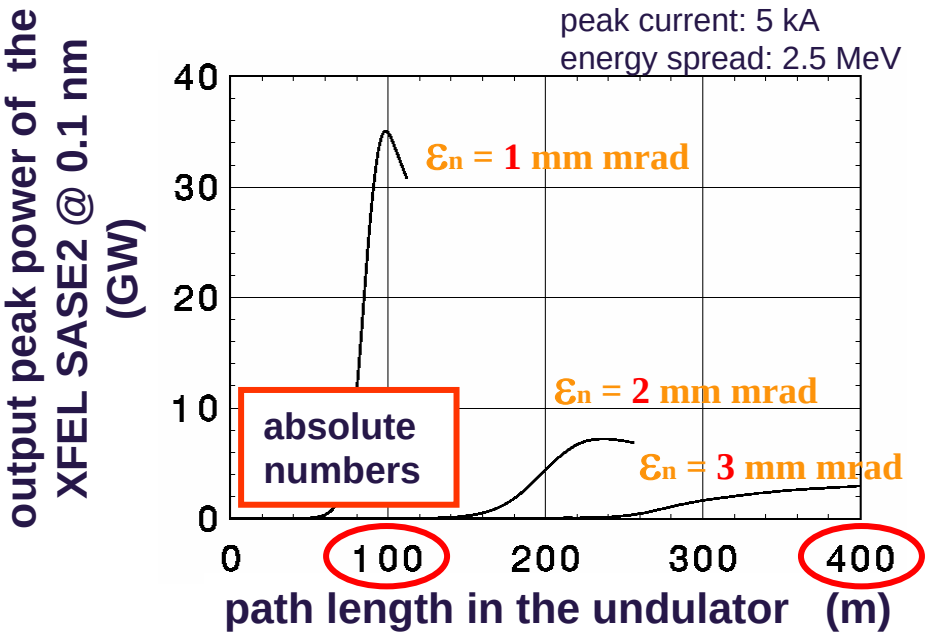
Why electron injector is so important … ???

- **Why emittance must be small …**

FLASH



XFEL

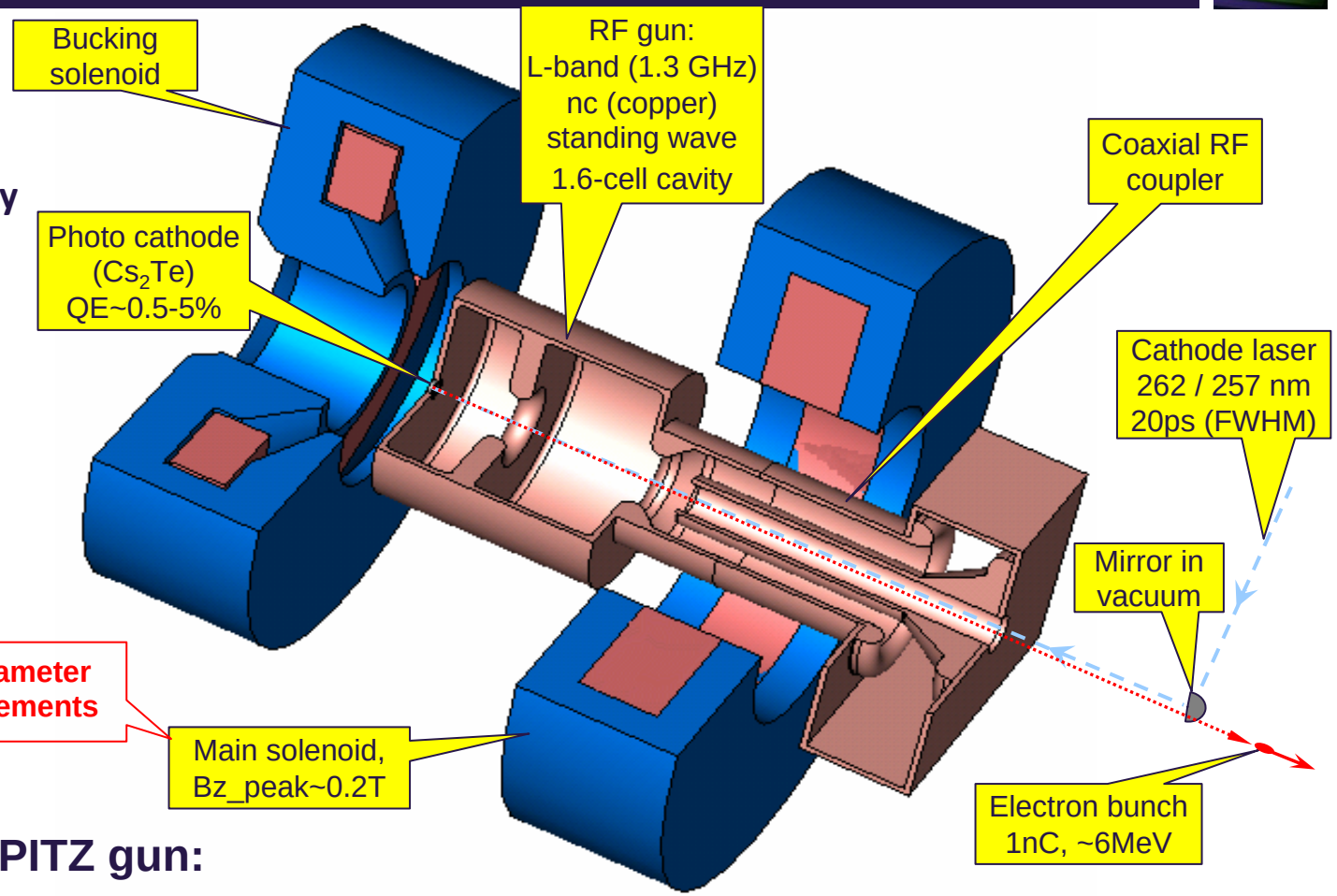


- **XFEL goal: 0.9 mm mrad@injector = 1.4 mm mrad@undulator**
- **if even smaller emittance ⇒ new horizons:**
  shorter wavelength, higher repetition rate

Most prominent solution: Photo Cathode RF Gun

Example: PITZ gun

(Photo Injector Test facility at DESY, Zeuthen site)



Main properties of PITZ gun:

- **1.3 GHz cavity, coaxial RF coupler (flexible solenoid position)**
- **Capable of high average power → long electron bunch trains (SC linac)**
- **Very low normalized transverse emittance**

The PITZ collaboration

Colleagues actively participating in measurements / new design:

- DESY, Zeuthen site:
  J. Bähr, A. Barnyakov*, H.J. Grabosch, Y. Ivanisenko, M. Hänel, M. Krasilnikov, M. Nozdrin**, M. Mahgoub, B. O'Shea***, M. Otevrel, B. Petrosyan, S. Riemann, S. Rimjaem, A. Shapovalov****, F. Stephan, G. Vashchenko
- DESY, Hamburg site:
  K. Flöttmann, S. Lederer, S. Schreiber
- BESSY Berlin:
  R. Ovsyannikov, D. Richter, A. Vollmer
- CCLRC Daresbury:
  B. Militsyn
- INRNE Sofia:
  G. Asova, K. Boyanov, L. Staykov, I. Tsakov
- INR Troitsk:
  A.N. Naboka, V. Paramonov, A.K. Skassyrskaia, A. Zavadtsev
- LAL Orsay:
  M. Jore, A. Variola
- LASA Milano:
  P. Michelato, L. Monaco, D. Sertore
- LNF Frascati:
  D. Alesini, L. Ficcadenti
- MBI Berlin:
  G. Klemz, I. Will
- TU Darmstadt:
  E. Arevalo, W. Müller
- Uni Hamburg:
  J. Rönsch
- YERPHI Yerevan:
  L. Hakobyan

* on leave from BINP, Novosibirsk, Russia
** on leave from INR, Dubna, Russia
*** on leave from UCLA, USA
**** on leave from MEPHI, Moscow, Russia

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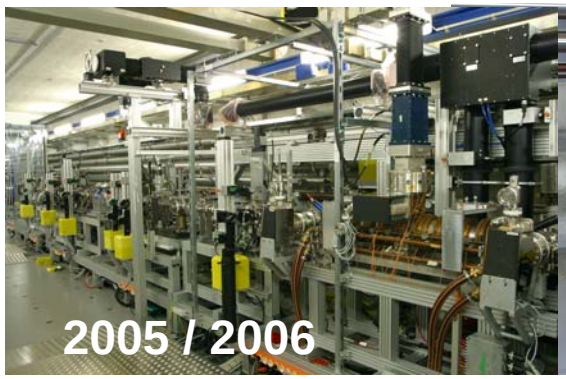
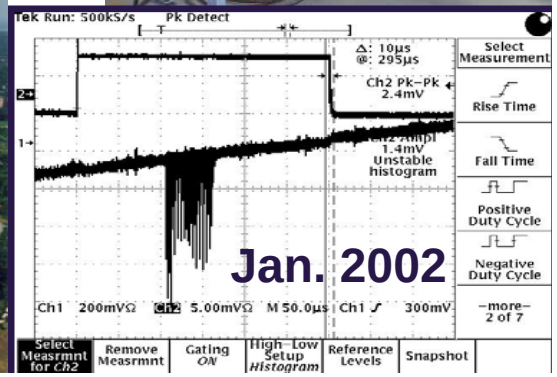
Short history of PITZ

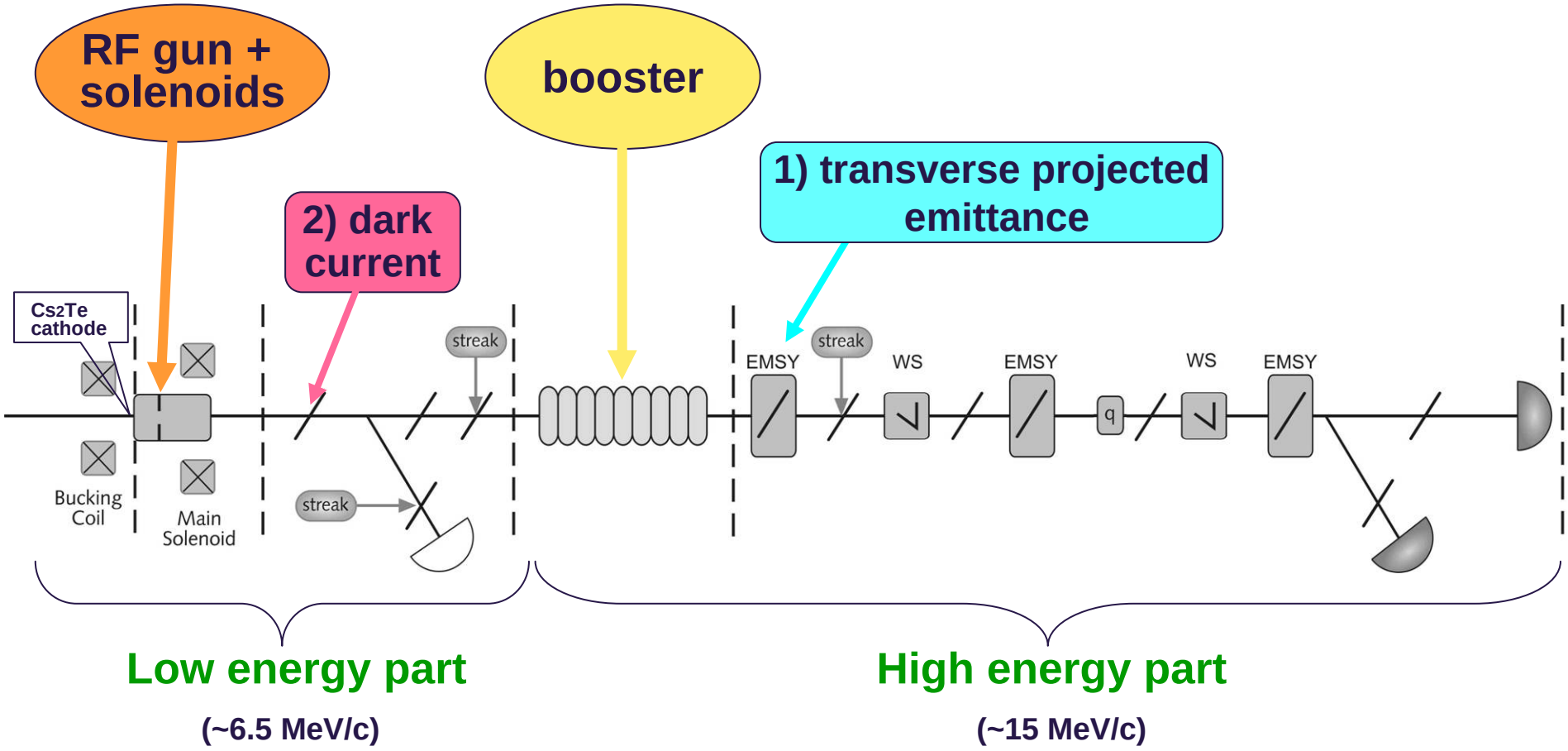
- September 1999: DESY directorate decision to build PITZ
- 2000: civil construction
- 2001: installation of infrastructure and first setup
- 13.1.2002: first photo electrons
- November 2003: fully characterized RF gun is sent to TTF2-FEL (FLASH)
- Upgrade of PITZ is continuously ongoing, periods for beam measurements in between
- 2005: first operation with booster cavity
- 2006: provide spare RF gun for FLASH
- 2007: first demonstration of XFEL requirements





PITZ experimental highlights in 2007/2008

Schematics of PITZ setup in 2007:



Projected Emittance Measurements: → Slit Scan Technique

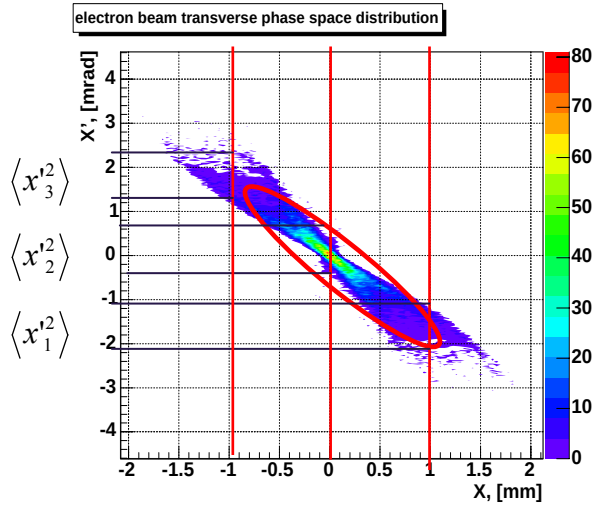
2007 analysis: $\varepsilon_{x,n} = \beta\gamma \cdot X_{rms} \cdot X'_{rms}$

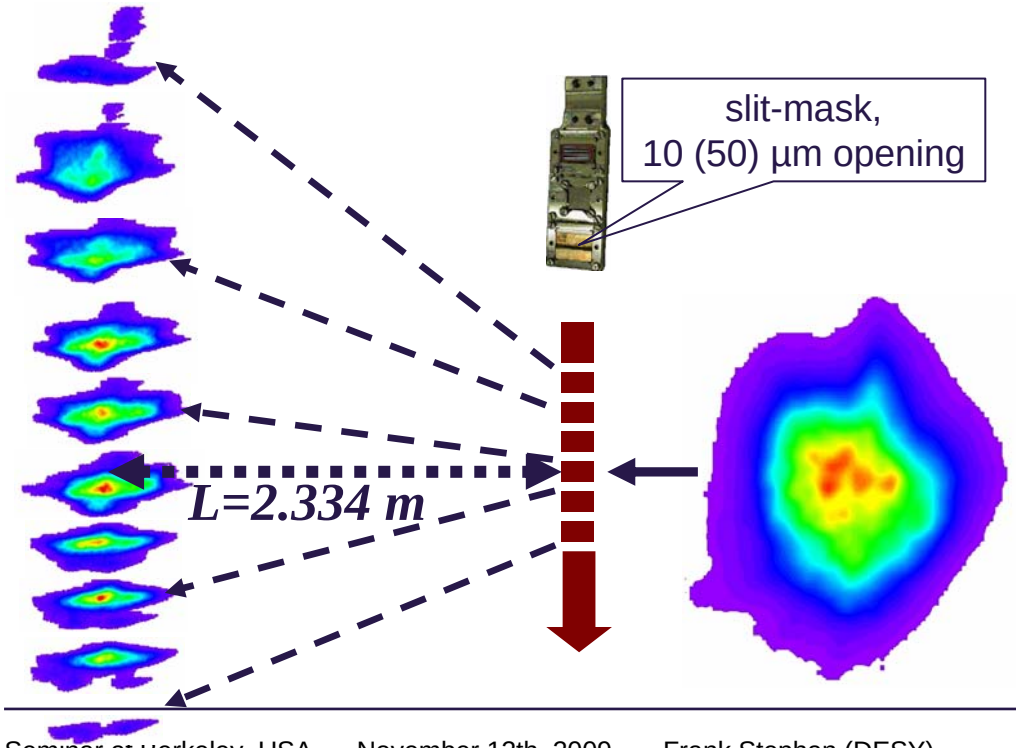
X_{rms} - RMS size of full beam at EMSY station (e.g. z = 4.3m)

$X'_{rms} = \frac{1}{L}\sqrt{\sum_{i=1}^{n} w_i \cdot \left(X_{rms}^{beamlet}\right)_i^2 \Big/ \sum_{i=1}^{n} w_i}$ - uncorrelated local divergence

$X_{rms}^{beamlet}$ - RMS size of the beamlet image

L - distance from slit location to screen for beamlets

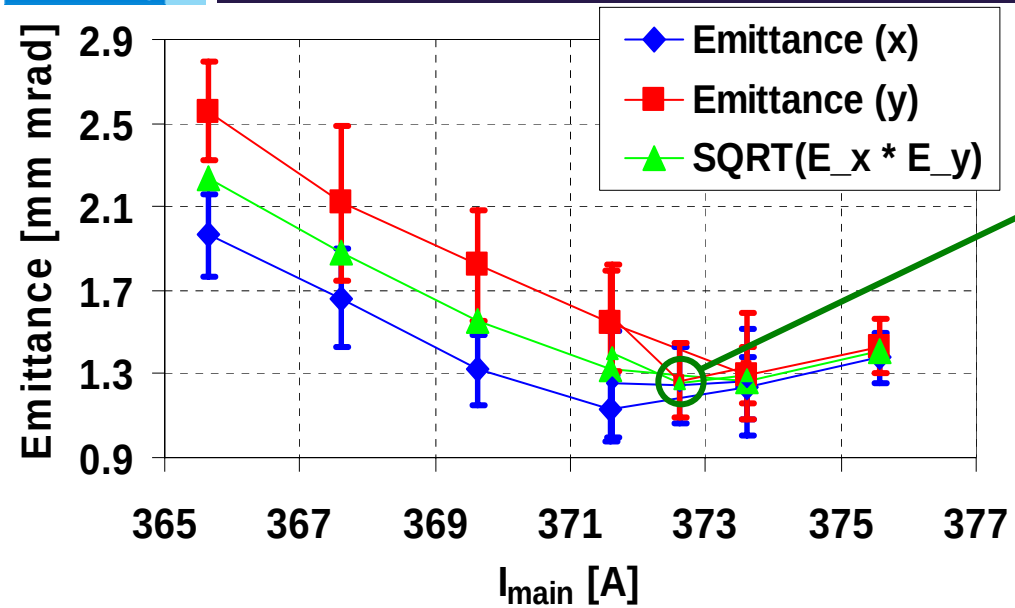




- **Standard procedure in 2007:**
  - take 11 equidistant beamlets over the full beam size (with statistics)
  - use 10 µm slit opening
- ultimate resolution:
  → 36µm x 15.4 µrad
- use camera with 12 bit signal depth for beamlet measurements

Transverse Projected Emittance Measurements

(summer 2007)



➔ for **~60 MV/m** we obtained

$\varepsilon_{x,n} = 1.25 \pm 0.19$ mm mrad

$\varepsilon_{y,n} = 1.27 \pm 0.18$ mm mrad

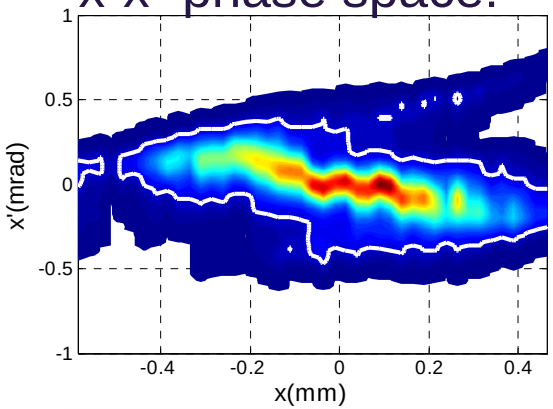
@1nC

for 100 % RMS emittance !

Cathode: # 90.1
Gun gradient: ~60 MV/m
Gun phase: $\Phi^{gun} = \Phi^{gun}_{ref}$
Momentum from gun: ~6.44 MeV/c

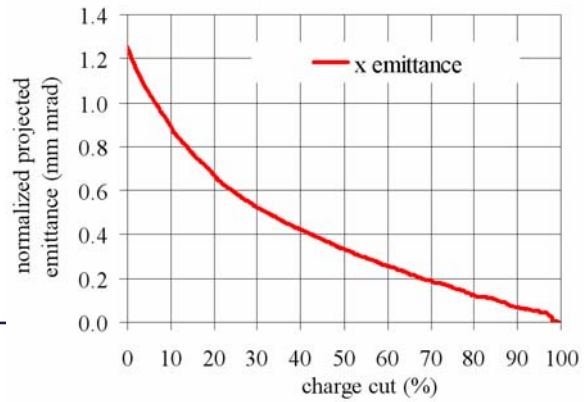
Booster phase: $\Phi^{booster} = \Phi^{booster}_{ref}$
Total beam momentum: 14.5 MeV/c

x-x´ phase space:



With a 10 % charge cut in the tails of the **phase space distribution** (~ remove non-lasing electrons)

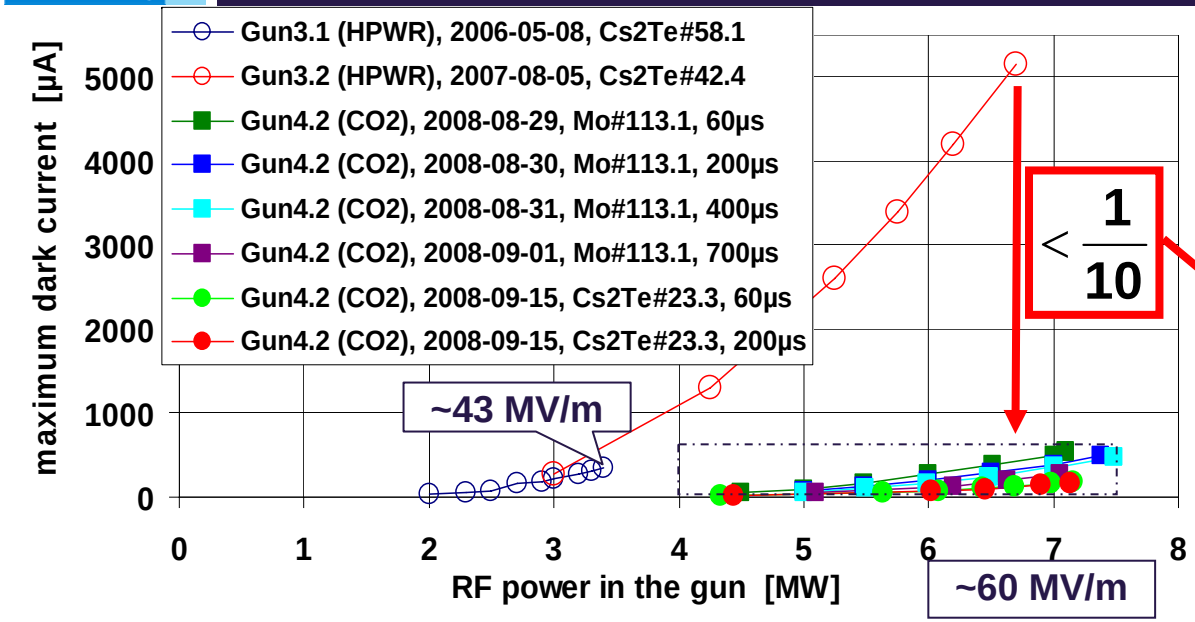
→ normalized projected emittance = **~0.9 mm mrad**



→ first demonstration of the beam quality required for the European XFEL !!!

Surface Cleaning ↔ Dark Current, High Average Power

(2008)

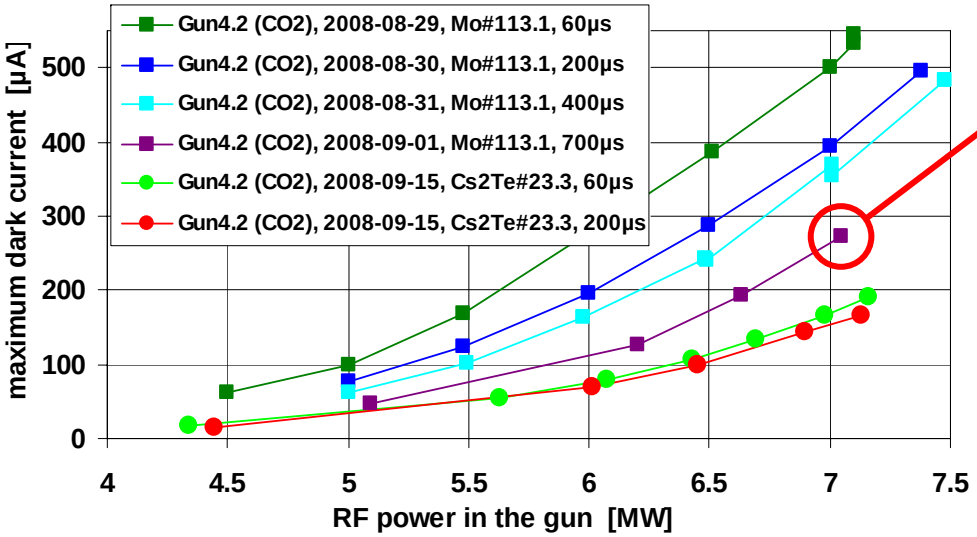


Surface cleaning techniques:

- HPWR: high-pressure water rinsing
- CO_2: dry-ice cleaning

Major reduction of dark current by CO_2 snow cleaning

zoom:

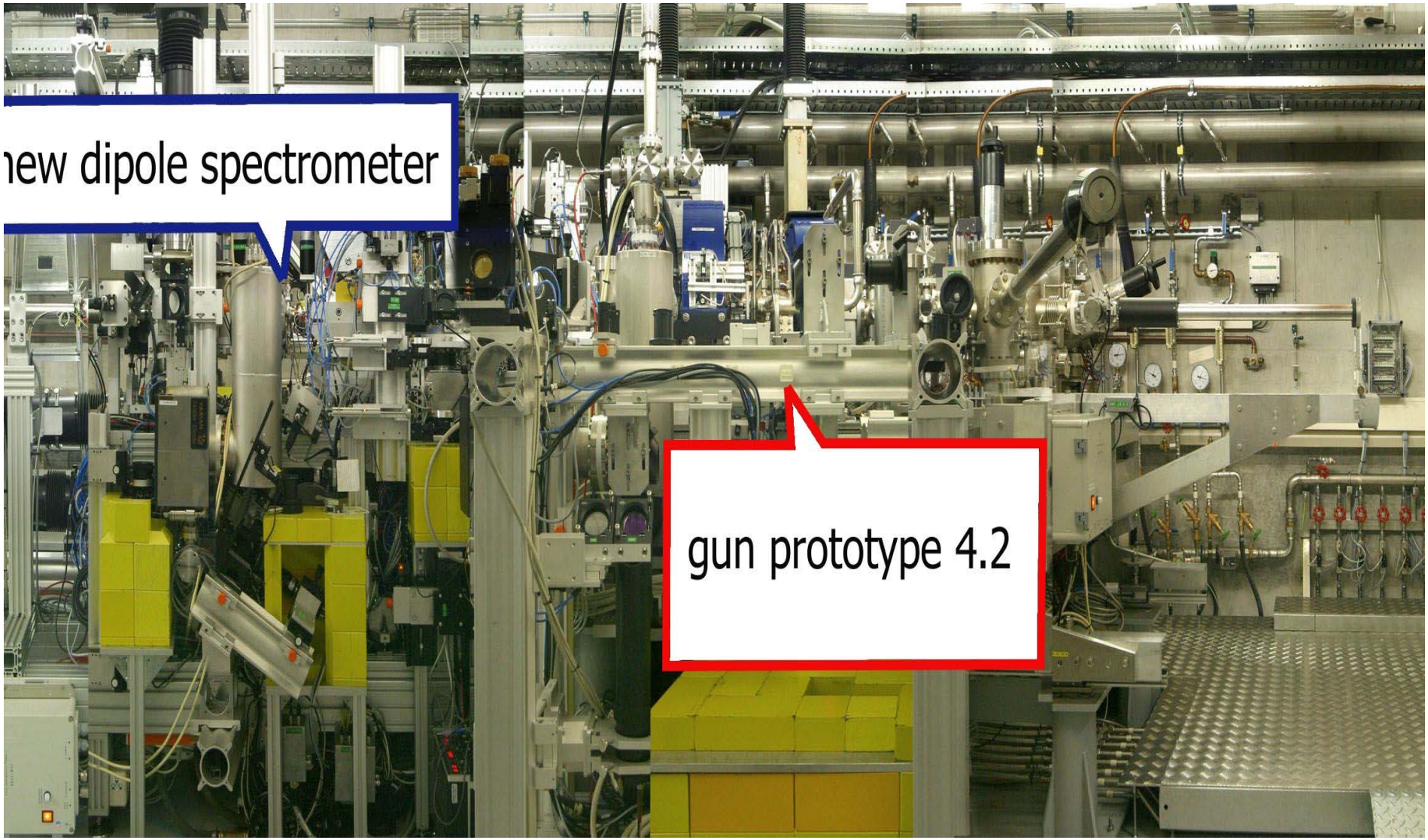


demonstrated operation with 50 kW average RF power

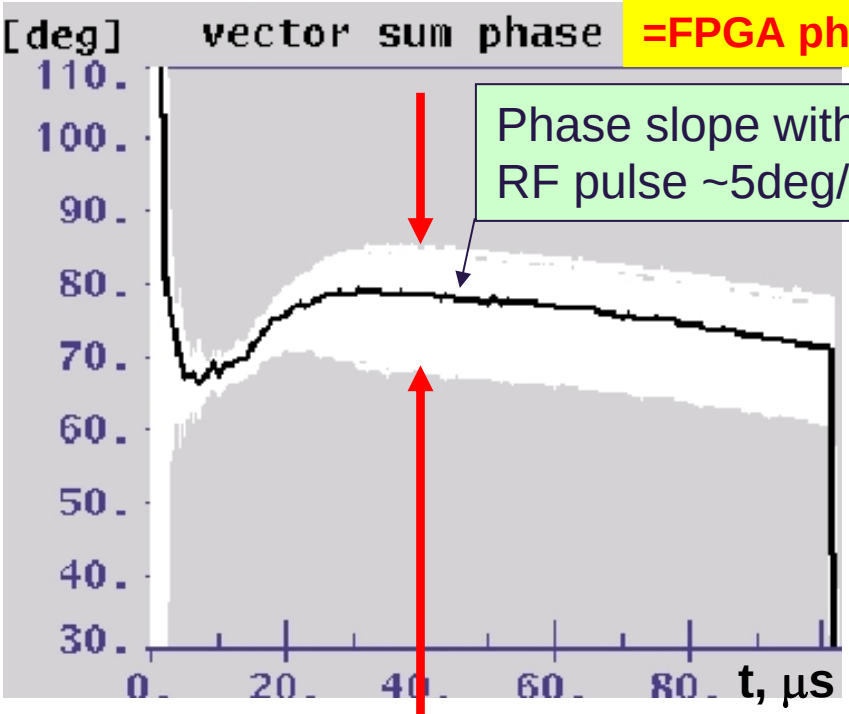
→ fulfills XFEL average RF power specs !

→ allows high brightness, high average current operation:
1–5 mA in 700 µs,
7–35 µA long term average

Panorama of the PITZ setup in 2009



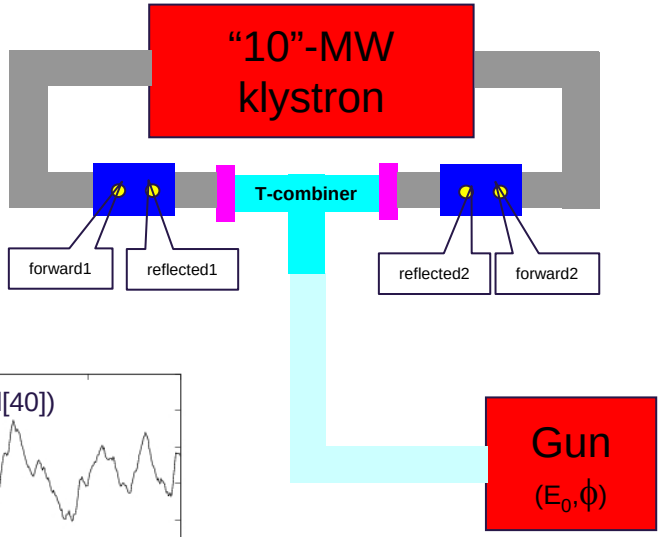
Machine stability problems – RF gun phase



=FPGA phase, reconstructed from virtual ADC probes

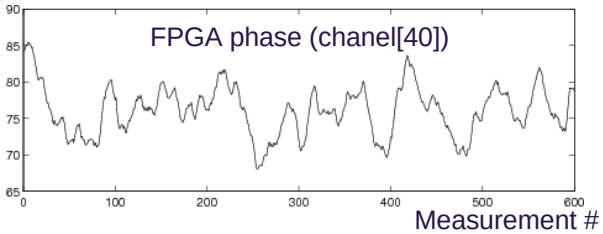
Phase slope within an RF pulse ~5deg/40us

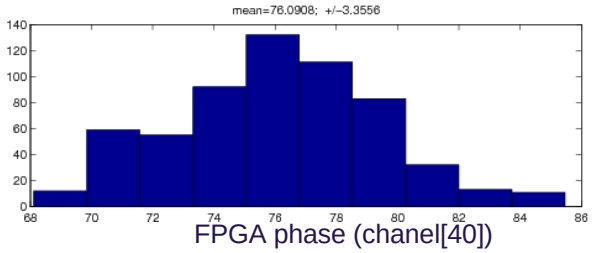
"10"-MW klystron is working close to the saturation, no LLRF regulation!



Fluctuations:

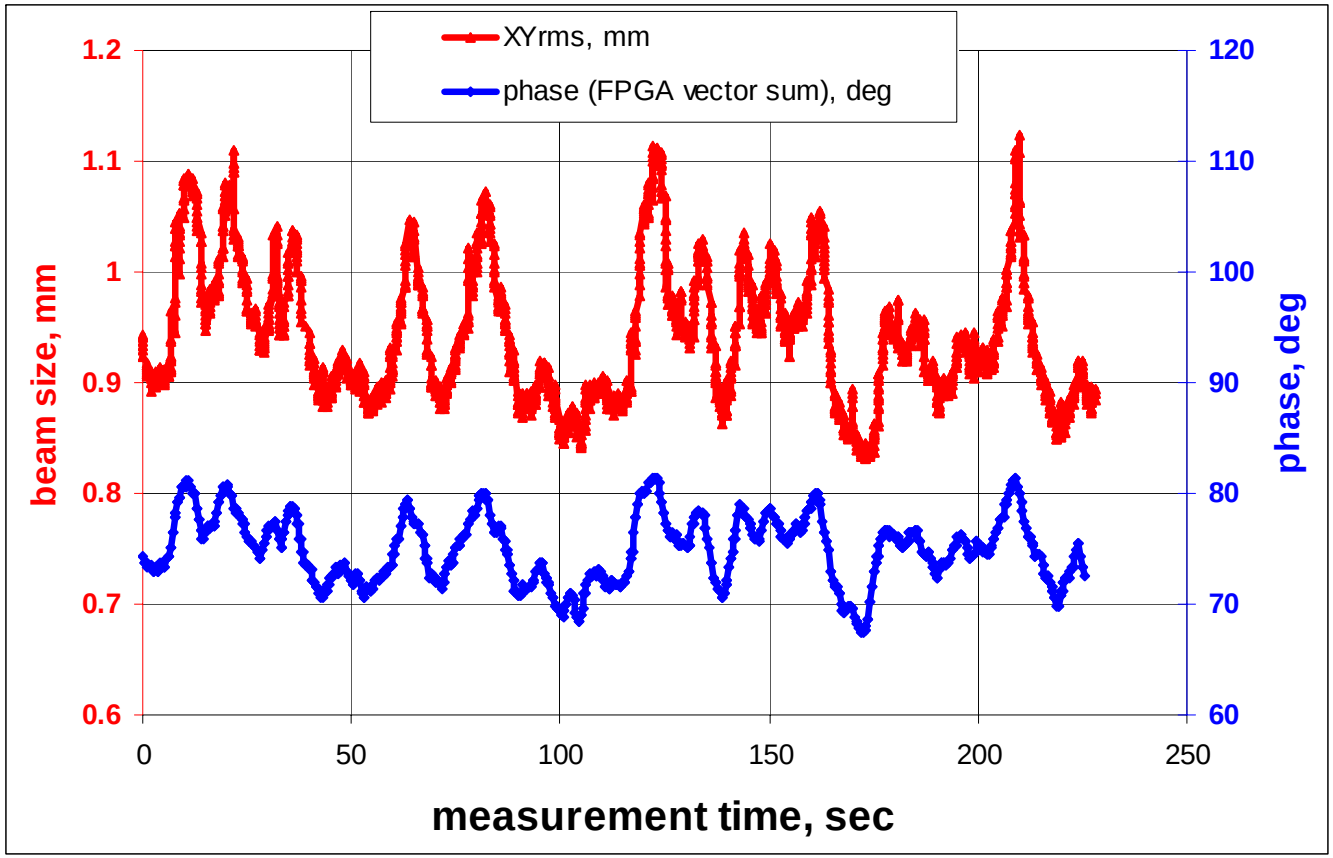
- **10..15deg (p-p)**
- 2..4 deg (rms)





Machine stability problems – RF gun phase

e-beam size fluctuations at EMSY1



FPGA phase:
14deg(p-p)

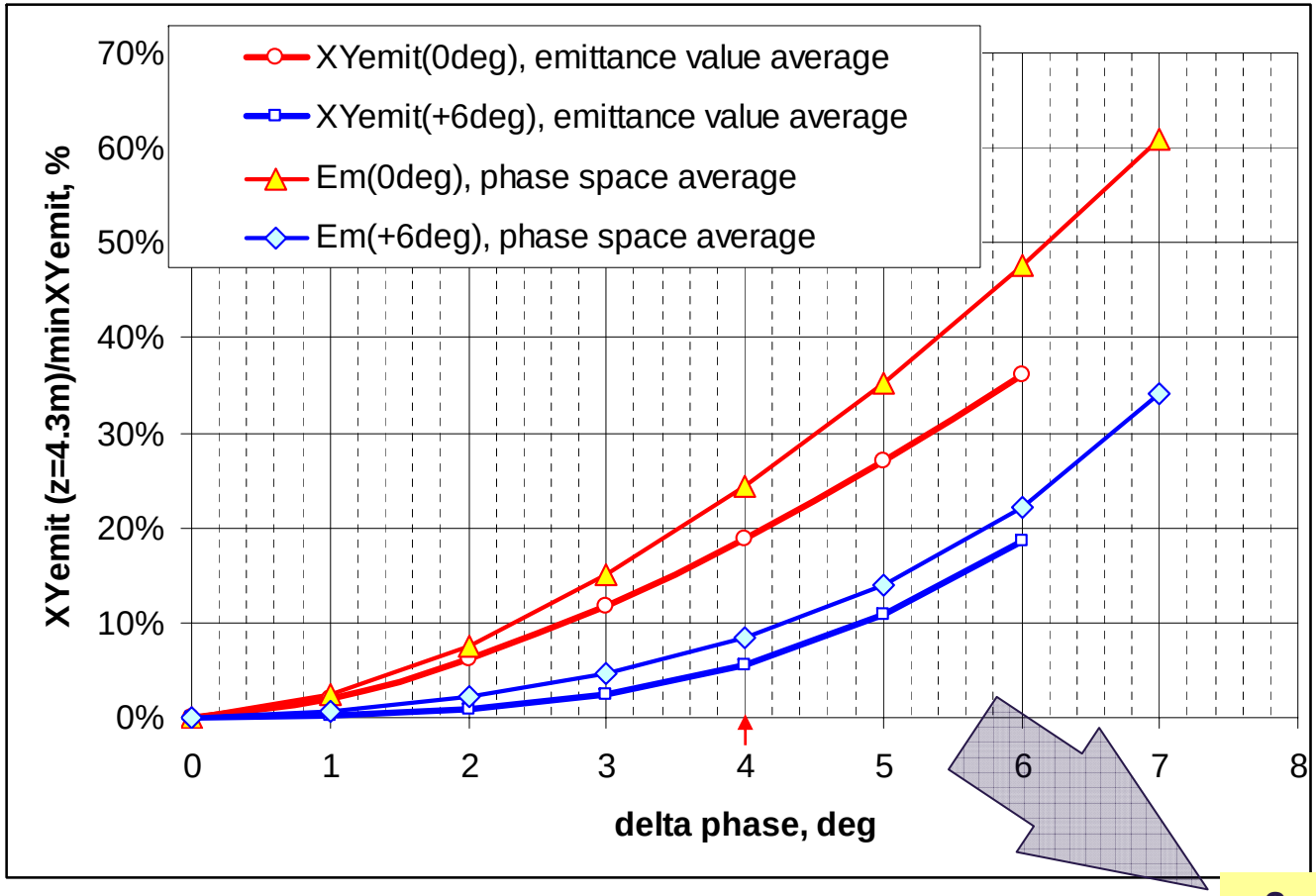
XYrms:
7% (rms), **38%(p-p)**

variation in rms beam size at EMSY1

impact on emittance measurements

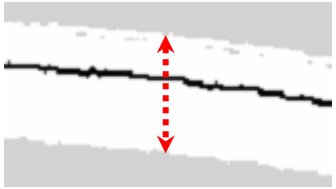
RF gun phase fluctuation -> simulations of the effect

emittance increase due to RF gun phase jitter



Fluctuations **10..15deg (p-p)**

Slope (pulse train) ~5deg/40us



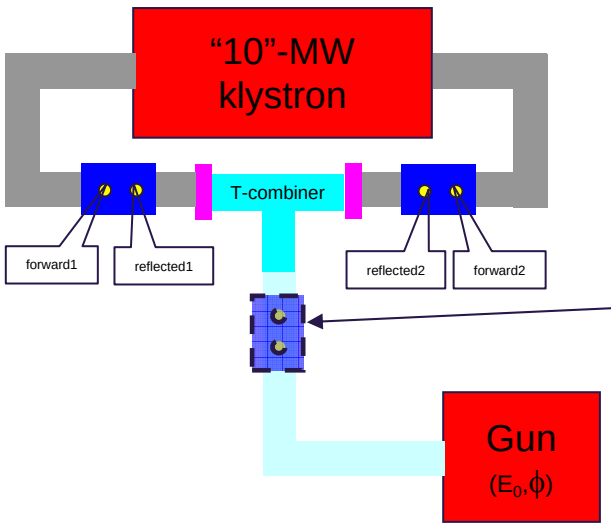
?possible explanation why measured emittance for gun at +6deg off-crest is better than on-crest?

RF gun phase fluctuations: summary

One of the most critical problem up to now!!!

- FPGA phase fluctuations (+slope) have been observed
- These fluctuations are correlated with beam momentum and beam size variations in time → results in measured emittance increase: shot-to-shot and within pulse train
- The stabilization tool does not improve the stability

Planned Upgrade for current shutdown



Hope that unique 10MW in-vacuum directional coupler will work ➔ then HH colleagues could install FLASH LLRF gun control at PITZ

Emittance measurements

- Measurement procedure improvements
- Nominal 1nC beam
- Various bunch charges
- Various laser temporal flat-top modulations
- Different rise/fall time

Emittance measurements: procedure improvement

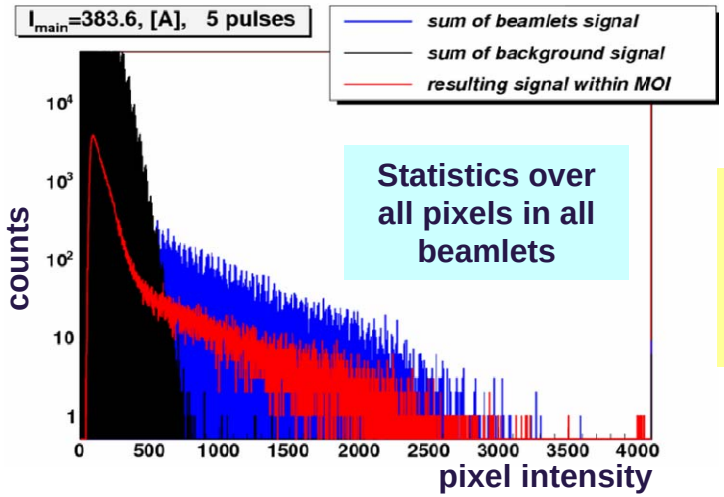
The main procedure – the single slit scan– has been accelerated:

Fast (slit) scan = beamlet image taking during continuous slit movement:

- Comparison to old standard method: * time: ~20 sec.(fast) vs. ~30 min (standard);
  * emittance value: the same trend (optimum), absolute values deviate (RF instability ?!!!);
  * transverse phase spaces are similar
- Usually quote 2D scaled emittance: $\varepsilon_n = \beta\gamma \frac{\sigma_x}{\sqrt{\langle x^2 \rangle}} \sqrt{\langle x^2 \rangle \cdot \langle x'^2 \rangle - \langle xx' \rangle^2}$; $\frac{\sigma_x}{\sqrt{\langle x^2 \rangle}} \; (>1)$

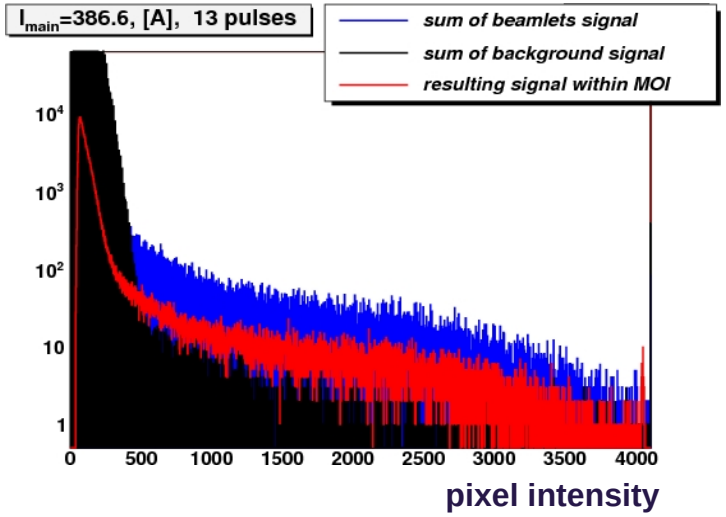
  beam

  beamlet
- More accurate criteria for the beamlet image quality



Statistics over all pixels in all beamlets

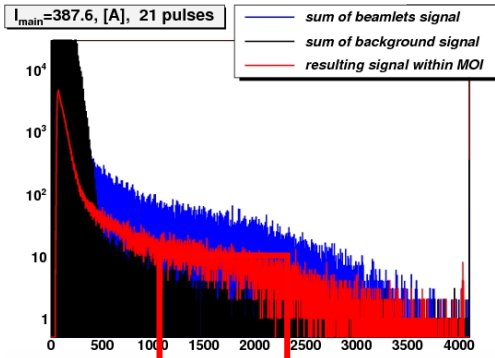
Check on saturation directly after fast scan data are taken!

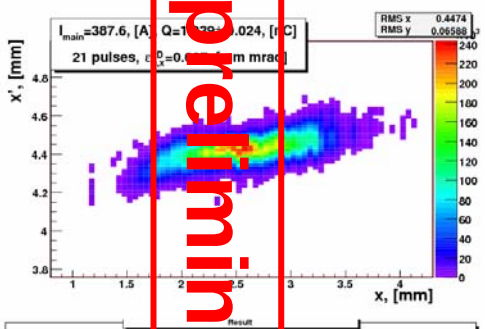


- Statistics of several fast scans

Nominal (1nC) measurements (21.08.2009M)

preliminary results

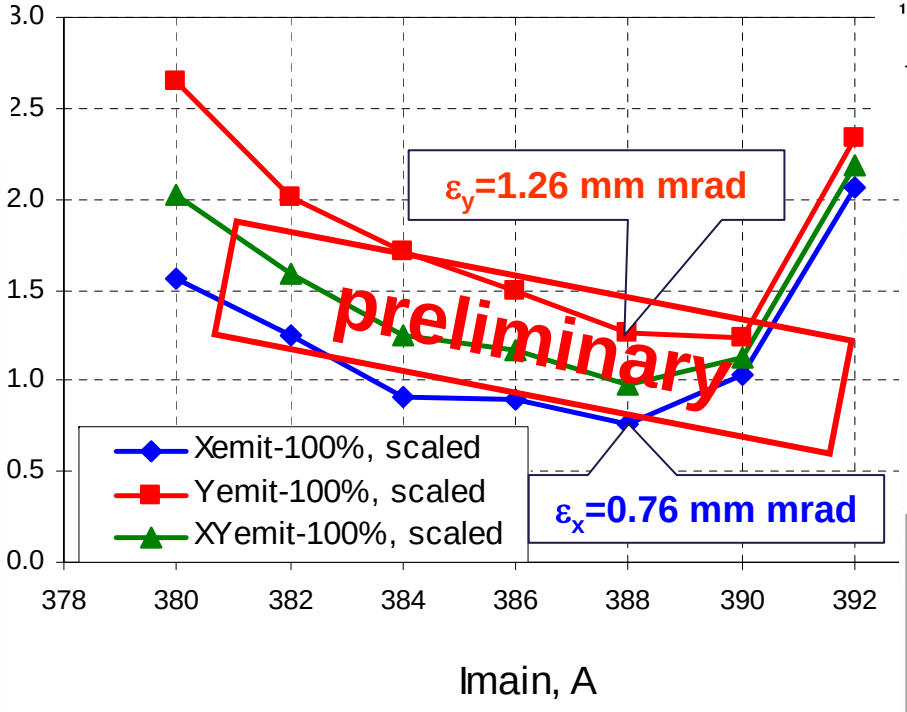




Laser: rms size	$\langle x^2\rangle_0$=0.44900, $\langle y^2\rangle_0$=0.36900,	[mm]
Electron beam: Momentum gun:	6.67000 ± 0.0381,	[MeV/c]
Momentum boo:	14.83800 ± 0.1600,	[MeV/c]
σ_{yag}	0.7[illegible]	[mm]
σ_{scan}	0.44738	[mm]
divergence	0.06588	[mrad]
covariance	0.01759	[mm mrad]
sheared div	0.02364	[mrad]
$\varepsilon^{scaled}_{sheared}$	0.743	[mm mrad]
$\varepsilon^{noscaled}_{2D}$	0.687	[mm mrad]
$\varepsilon^{scaled}_{2D}$	0.763	[mm mrad]

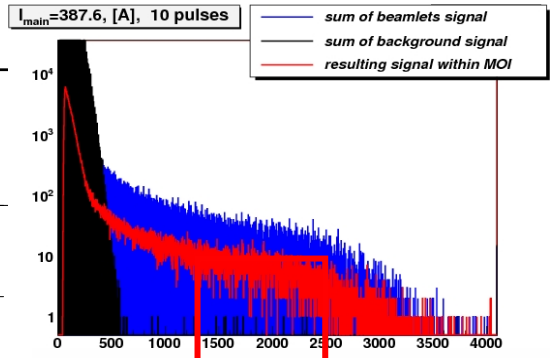
preliminary

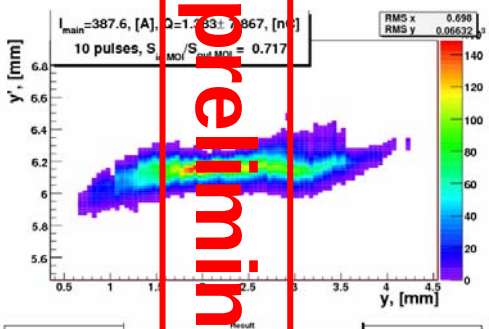
2D emittance for BSA=1.5mm, 1nC, gun: 6deg off-crest, booster: on-crest



preliminary

ε_{xy}(388A)=**0.98 mm mrad**





Laser: rms size	$\langle x^2\rangle_0$=0.44900, $\langle y^2\rangle_0$=0.36900,	[mm]
Electron beam: Momentum gun:	6.67000 ± 0.0381,	[MeV/c]
Momentum boo:	14.83800 ± 0.1600,	[MeV/c]
σ_{yag}	0.72[illegible]	[mm]
σ_{scan}	0.69798	[mm]
divergence	0.06632	[mrad]
covariance	0.02058	[mm mrad]
sheared div	0.04146	[mrad]
$\varepsilon^{scaled}_{sheared}$	1.154	[mm mrad]
$\varepsilon^{noscaled}_{2D}$	1.204	[mm mrad]
$\varepsilon^{scaled}_{2D}$	1.258	[mm mrad]

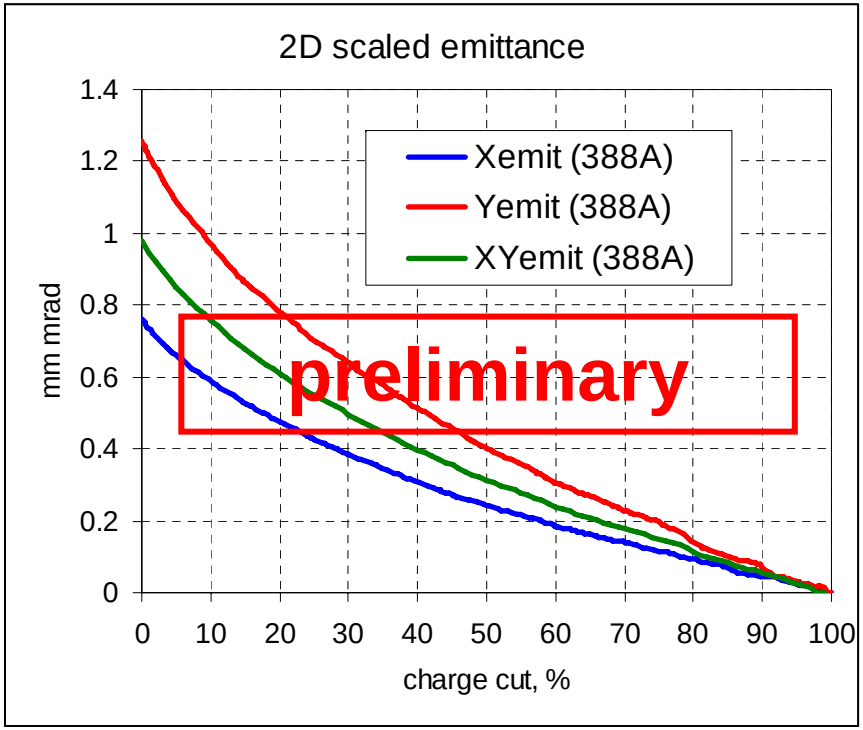
preliminary

(100% RMS emittance data !)

Nominal (1nC) measurements (21.08.2009M)

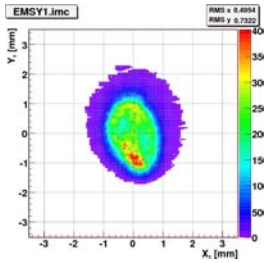
preliminary results

Now with charge cut:



Nominal (1nC) measurements (22.08.2009M)

preliminary results

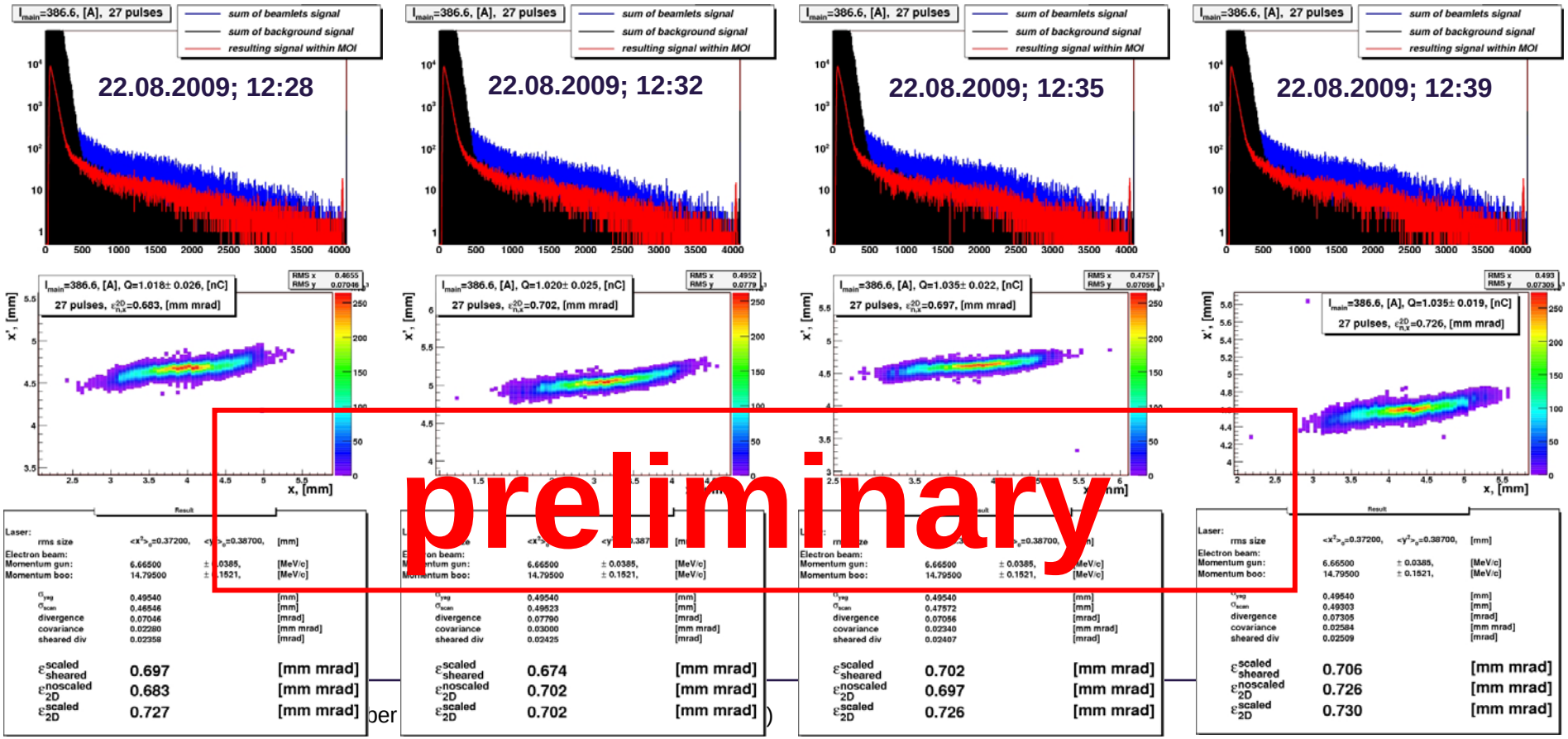


= beam @ EMSY1

X-X' phase space

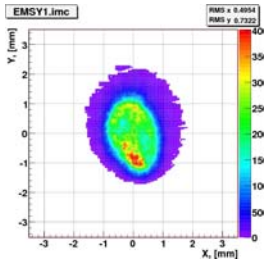
$$\varepsilon_x = (0.721 \pm 0.013)\,\text{mm mrad}$$

- Q=1nC
- Imain=387A
- Gun: +6deg off-crest
- Booster: on-crest
- Laser temp.:2.1/23.1/2.4ps
- Laser BSA=1.5mm



Nominal (1nC) measurements (22.08.2009M)

preliminary results

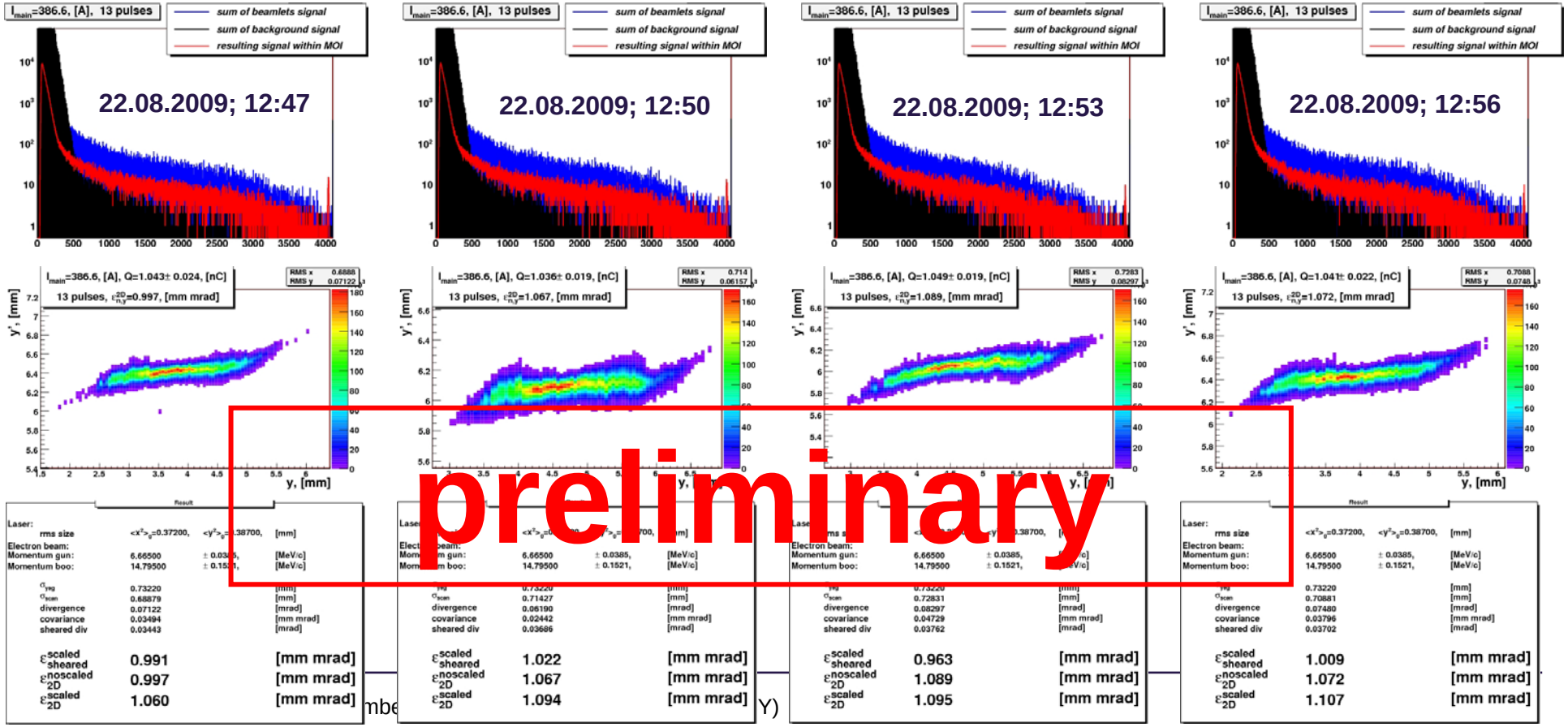


= beam @ EMSY1

Y-Y' phase space

$$\varepsilon_y = (1.089 \pm 0.020)\,\text{mm mrad}$$

- Q=1nC
- Imain=387A
- Gun: +6deg off-crest
- Booster: on-crest
- Laser temp.:2.1/23.1/2.4ps
- Laser BSA=1.5mm

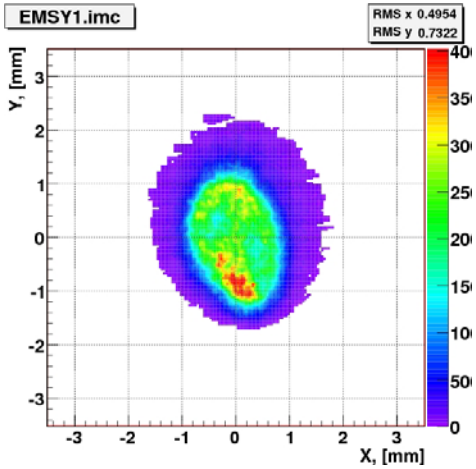


preliminary

Nominal (1nC) measurements (22.08.2009M)

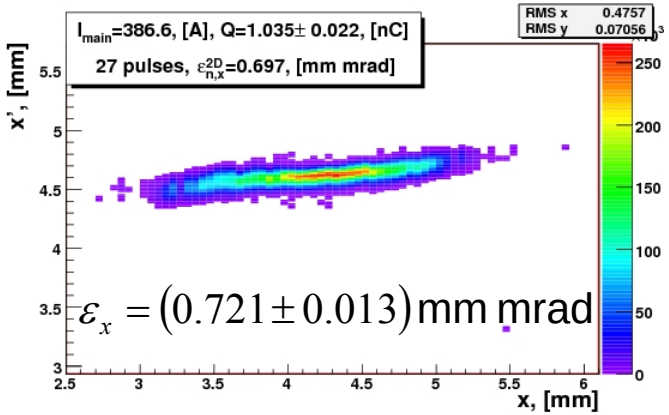
preliminary results

beam @ EMSY1

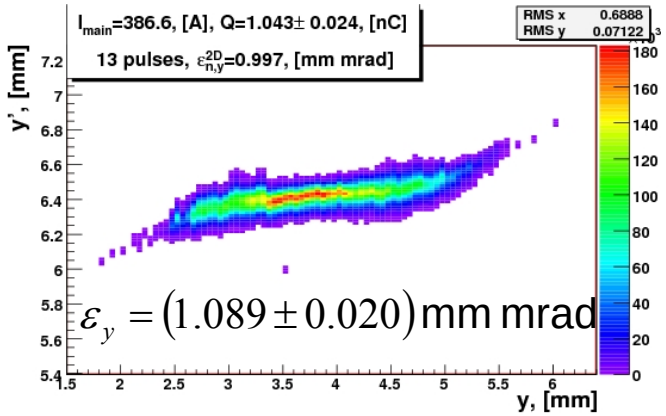


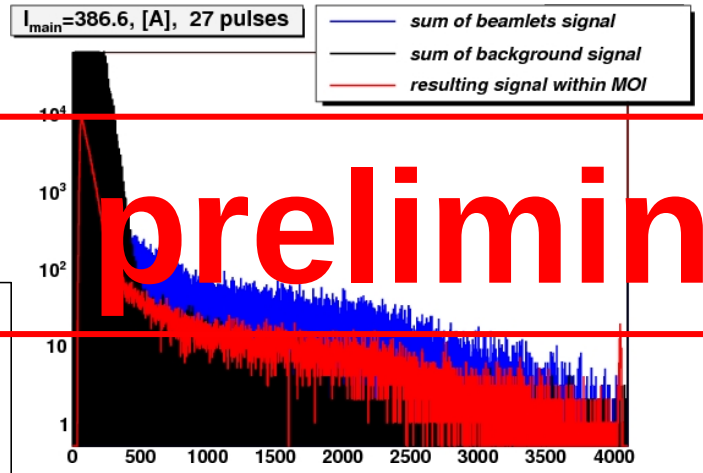
- Q=1nC
- Imain=387A
- Gun: +6deg off-crest
- Booster: on-crest
- Laser temp.:2.1/23.1/2.4ps
- Laser BSA=1.5mm

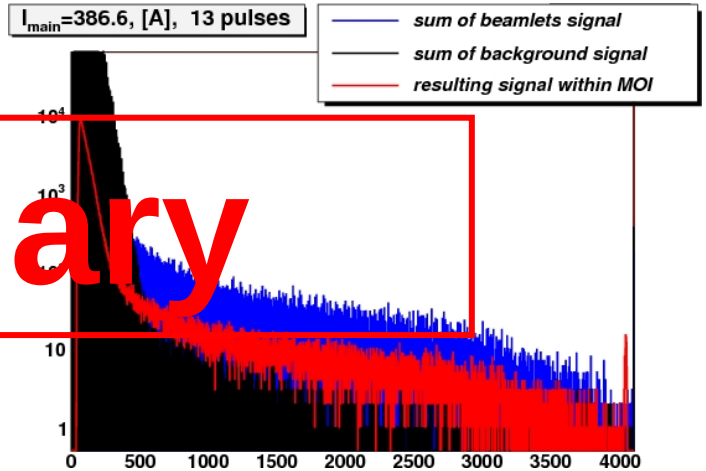
X-X' phase space



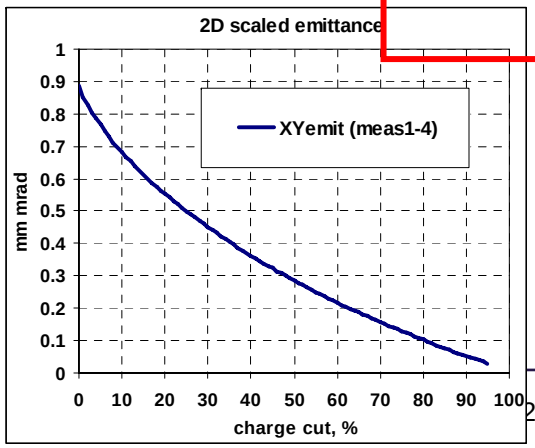
Y-Y' phase space







preliminary



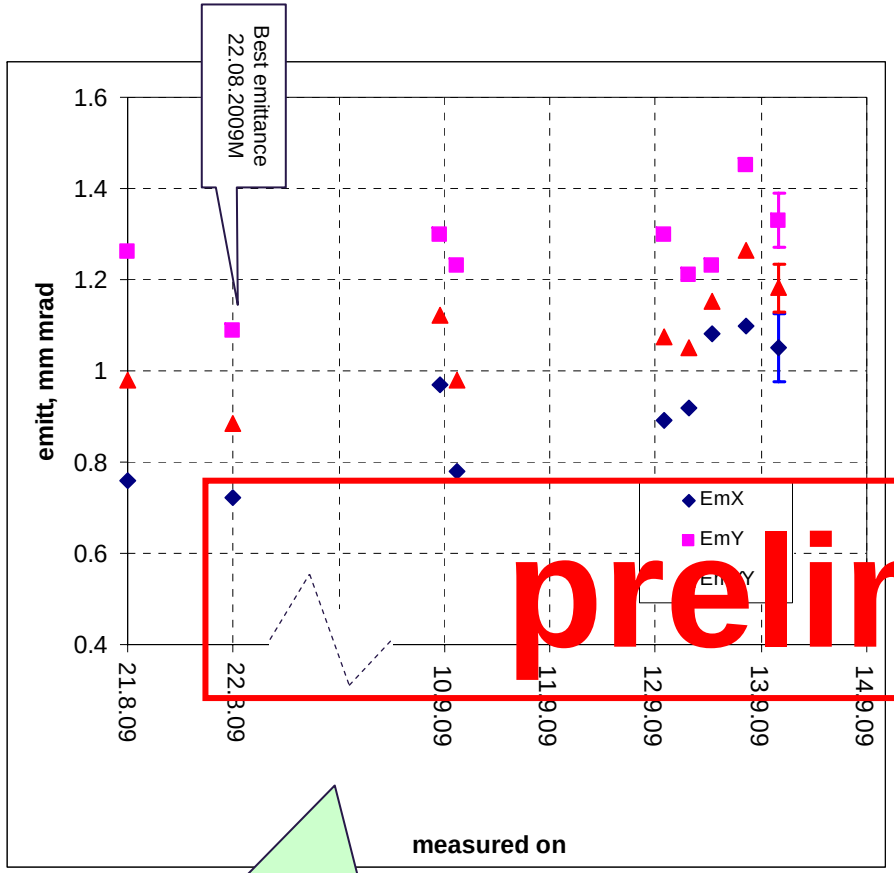
$$\varepsilon_{xy} = (0.886 \pm 0.011)\ \text{mm mrad}$$

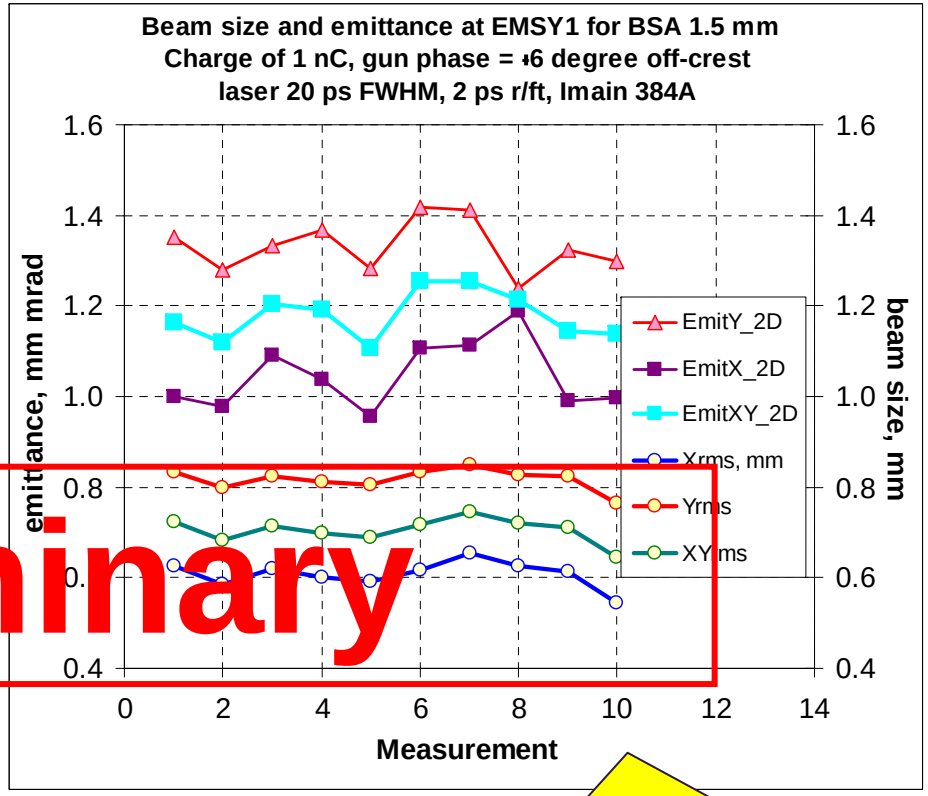
(100% RMS emittance)

But! It was not possible to reproduce it in next shifts!

Emittance statistics of several fast scans

preliminary results





preliminary

Long term(~4days): ~6..8.5% (stdev)
~16..21% (peak-to-peak)*

Short term (~3hours): ~4..7% (stdev)

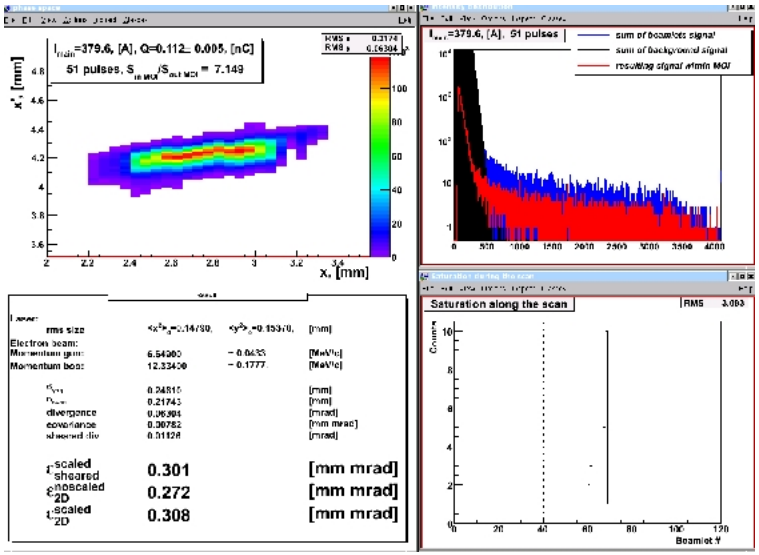
$$\varepsilon_x = (1.046 \pm 0.075)\,\text{mm mrad}$$

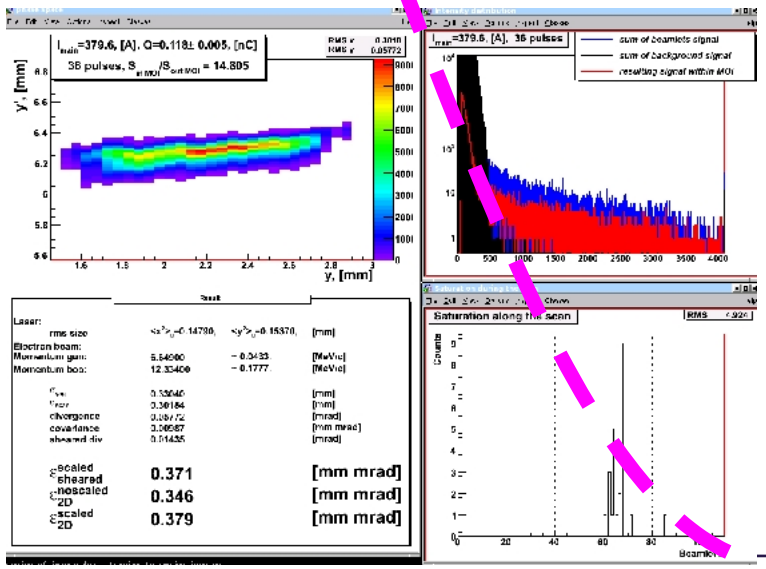
$$\varepsilon_y = (1.330 \pm 0.058)\,\text{mm mrad}$$

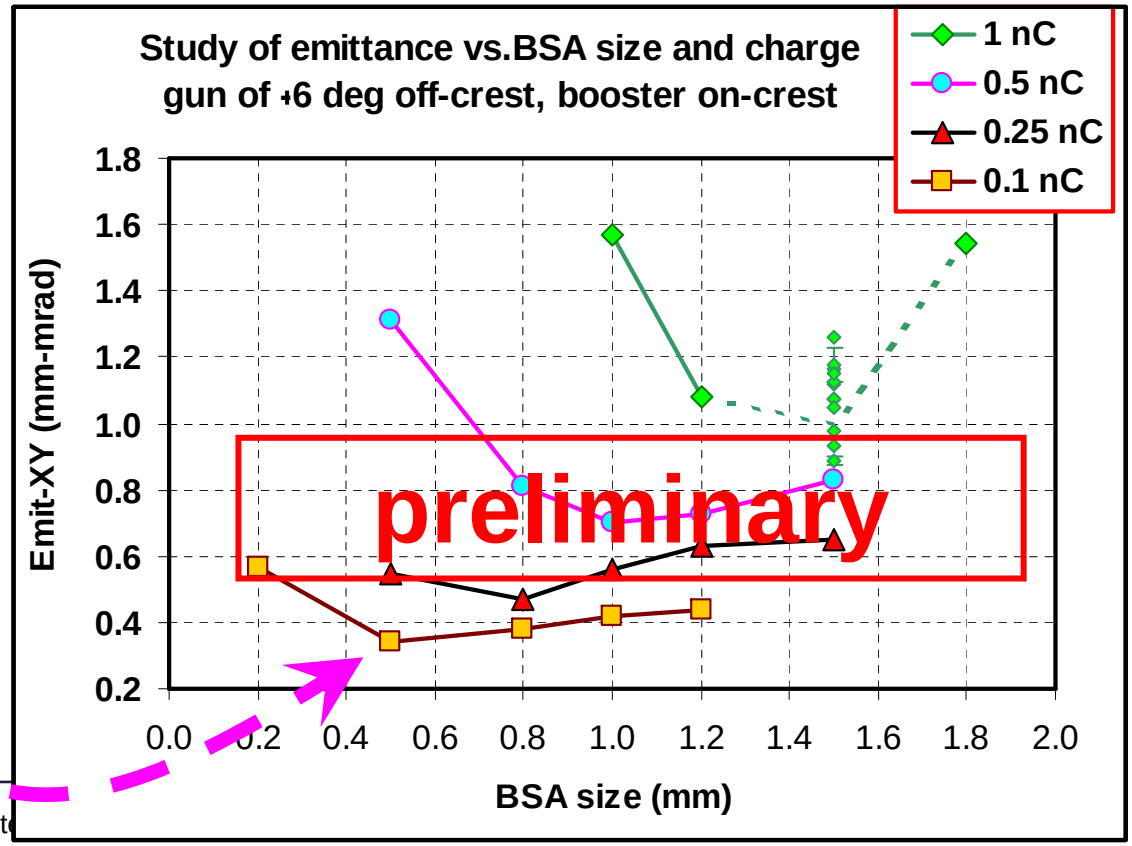
$$\varepsilon_{xy} = (1.179 \pm 0.052)\,\text{mm mrad}$$

Emittance vs. bunch charge

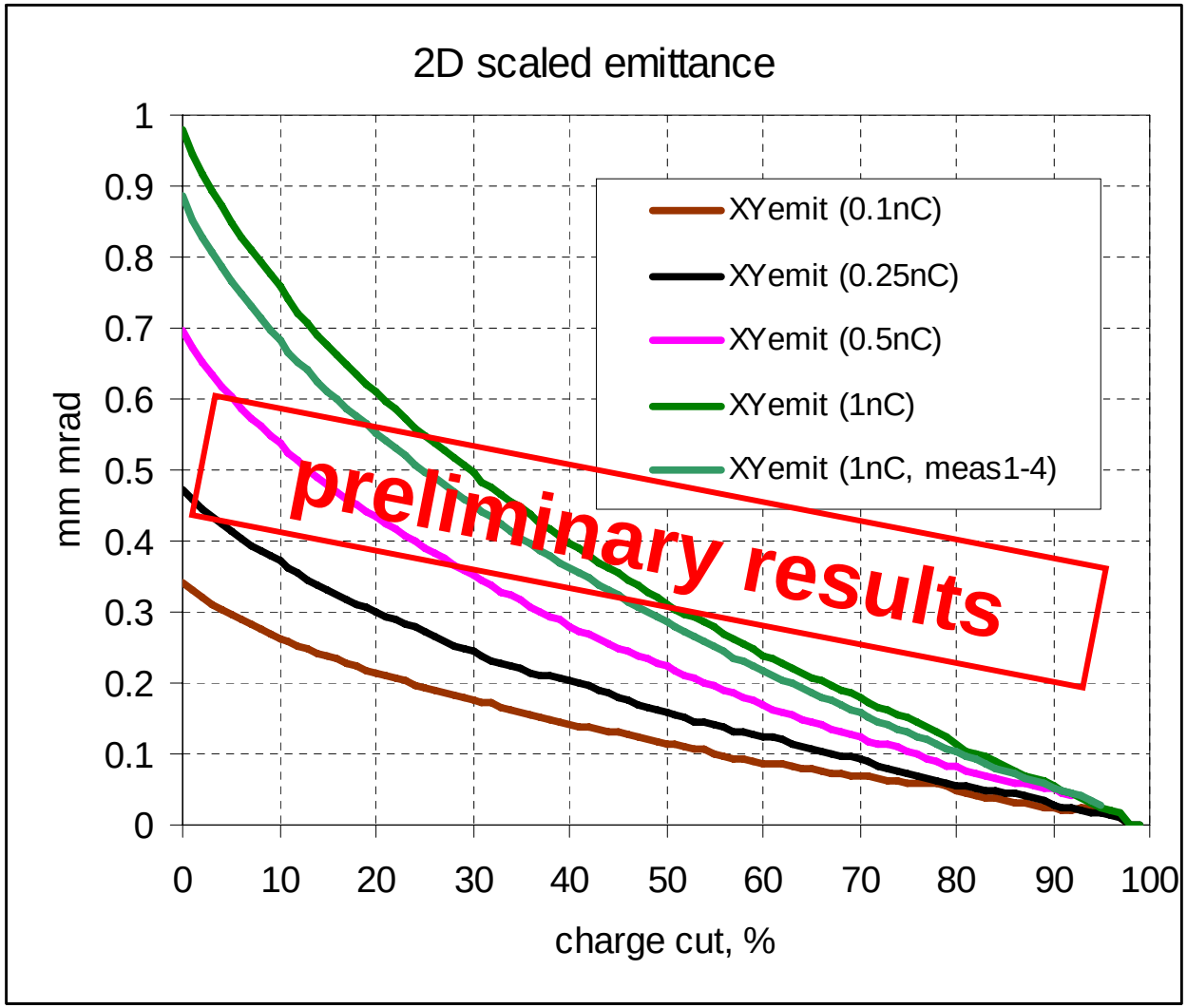
preliminary results







Emittance vs. bunch charge: → now with charge cut



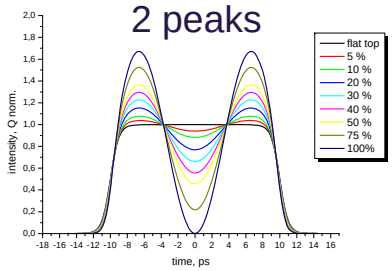
Various laser temporal flat-top modulations

Simulations

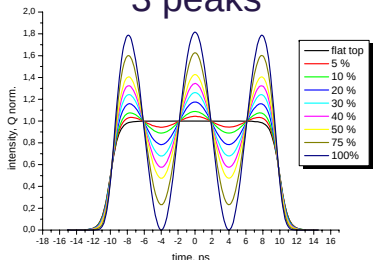
preliminary results

simulations with gun on-crest, other parameters optimized

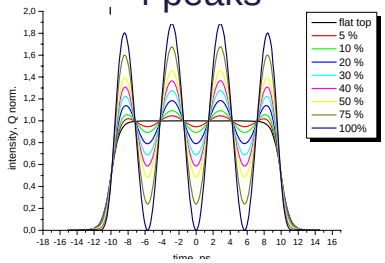
2 peaks



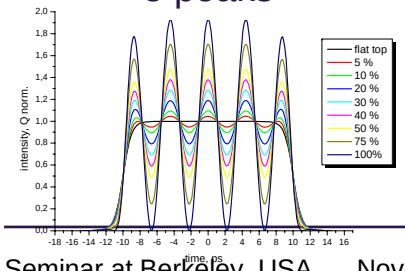
3 peaks



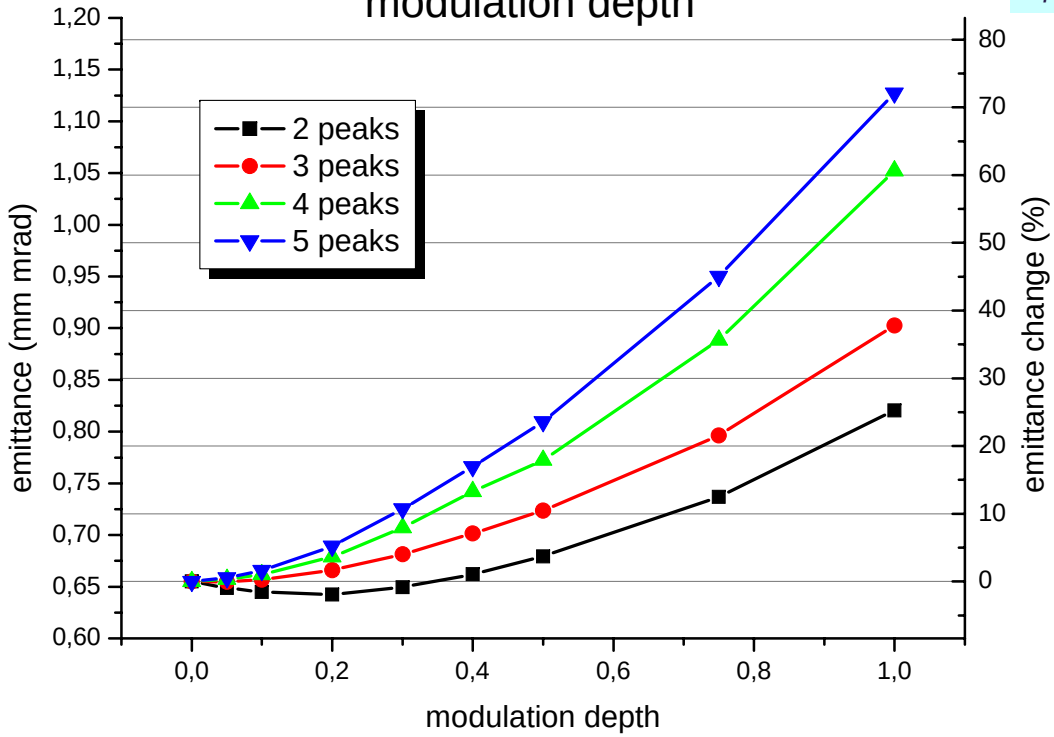
4 peaks



5 peaks



Simulated optimum emittance vs. modulation depth



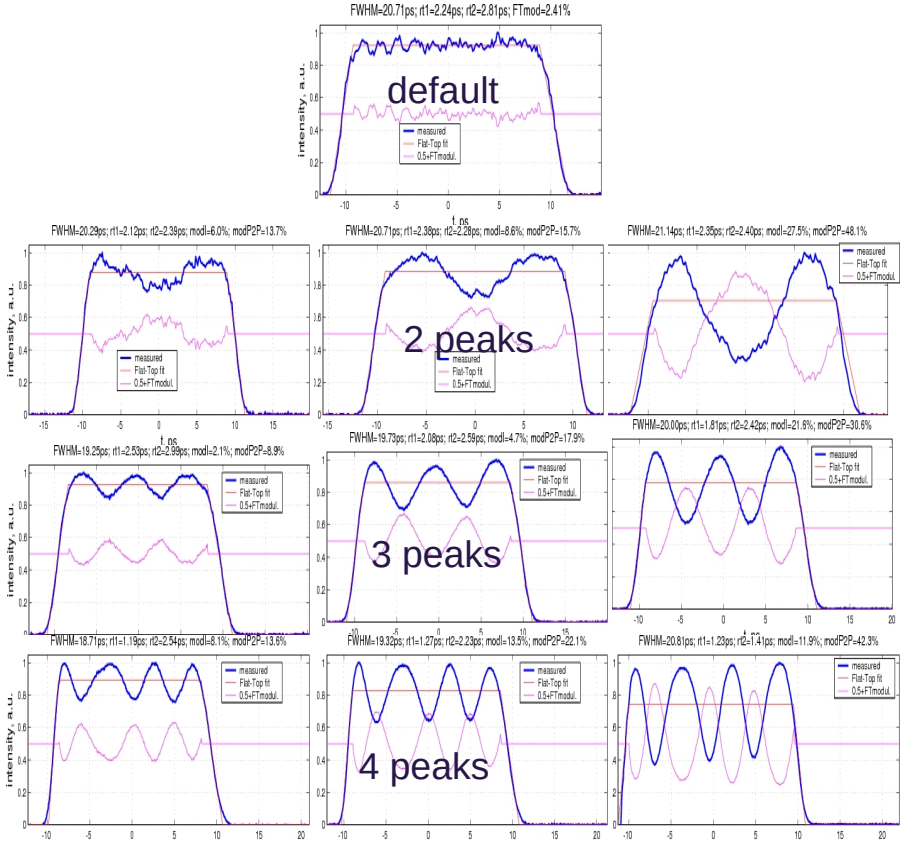
- higher modulation frequency ➔ larger emittance growth rate
- reliable simulations for modulations with >5 peaks are difficult

Laser temporal profile modulations

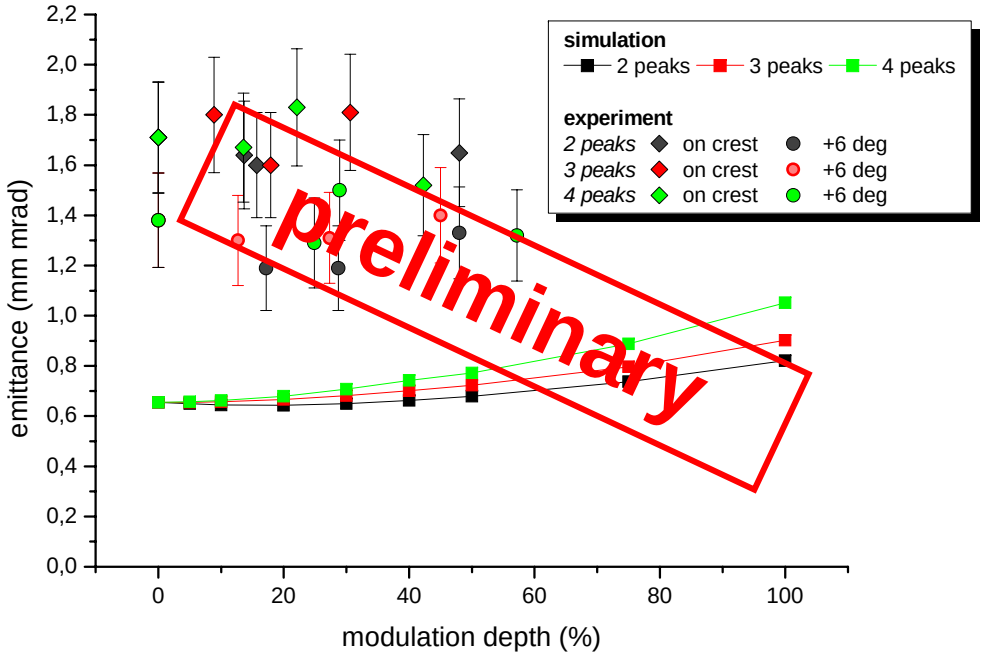
Measurements

preliminary results

Experimental temporal laser profiles



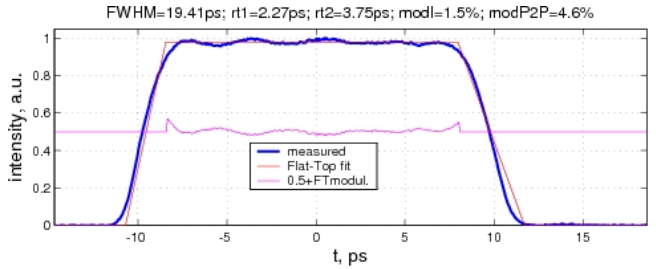
Experimental results compared to simulations

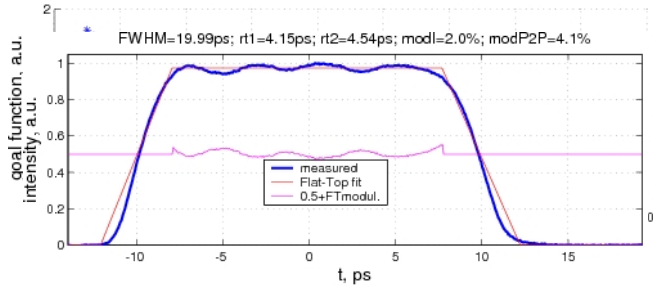


➔ **not possible to measure the effect with the current machine stability**

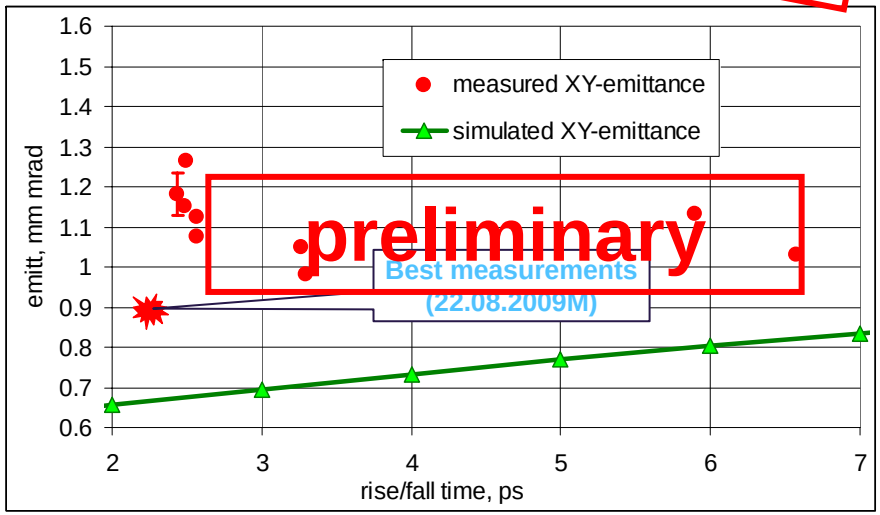
Check effect on rise/fall time

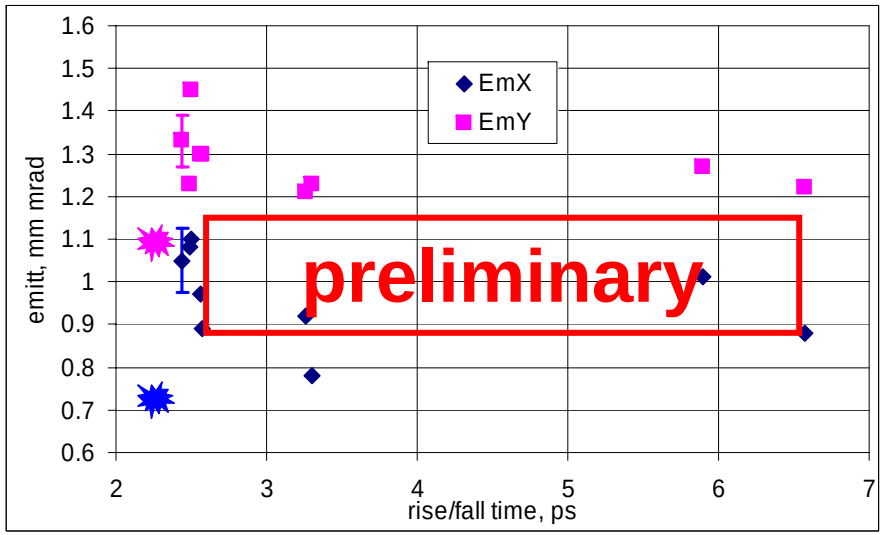
preliminary results





- Q=1nC
- Imain➔optimized
- Gun: +6deg off-crest
- Booster: on-crest
- Laser: temp FWHM~20ps, BSA=1.5mm





➔ **not possible to measure the effect with current machine stability**

Longitudinal momentum modulations and cathode laser temporal shaping

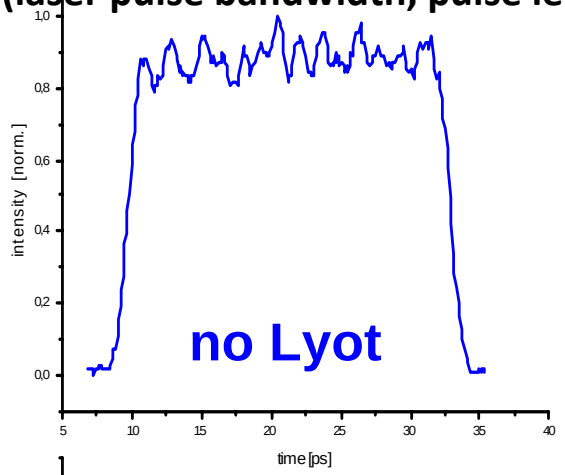
preliminary results

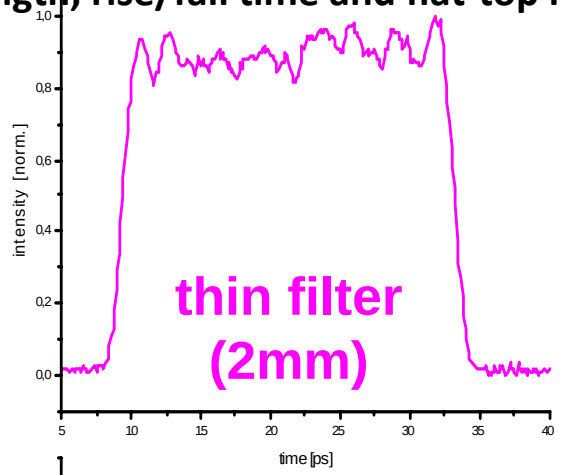
Pz-modulation for various:

- **bunch charges**
- **rf gun and booster phases**
- **Lyot filters (laser pulse bandwidth, pulse length, rise/fall time and flat-top ripple manipulation)**

FWHM: 23.3ps
rise: 1.86ps
fall: 1.86ps
FTmod: 3.88%

measured: 27.4.09
morning shift (8:52)



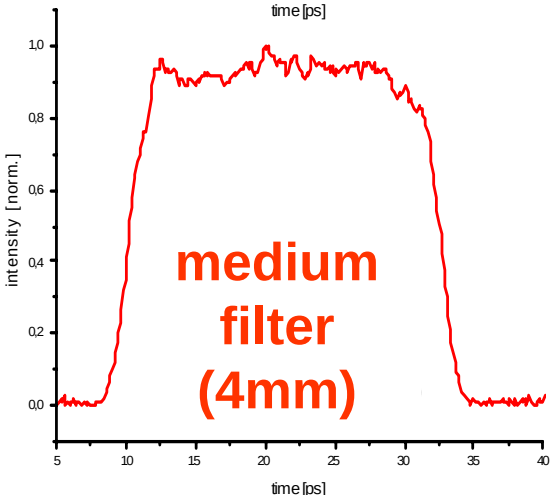


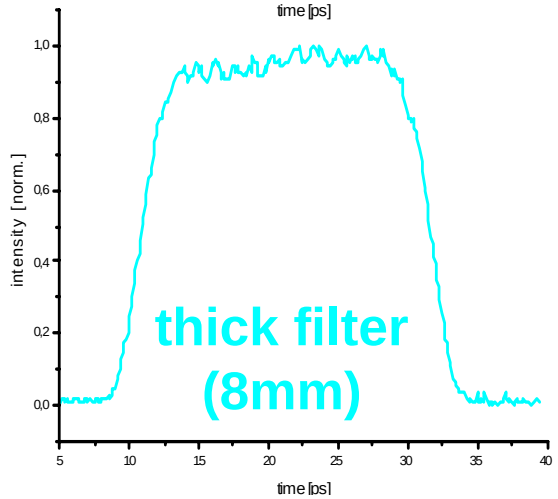
FWHM: 24.0ps
rise: 1.79ps
fall: 1.78ps
FTmod: 3.95%

measured: 28.4.09
late shift (16:56)

FWHM: 22.3ps
rise: 3.22ps
fall: 3.13ps
FTmod: 2.79%

measured: 27.4.09
morning shift (9:34)

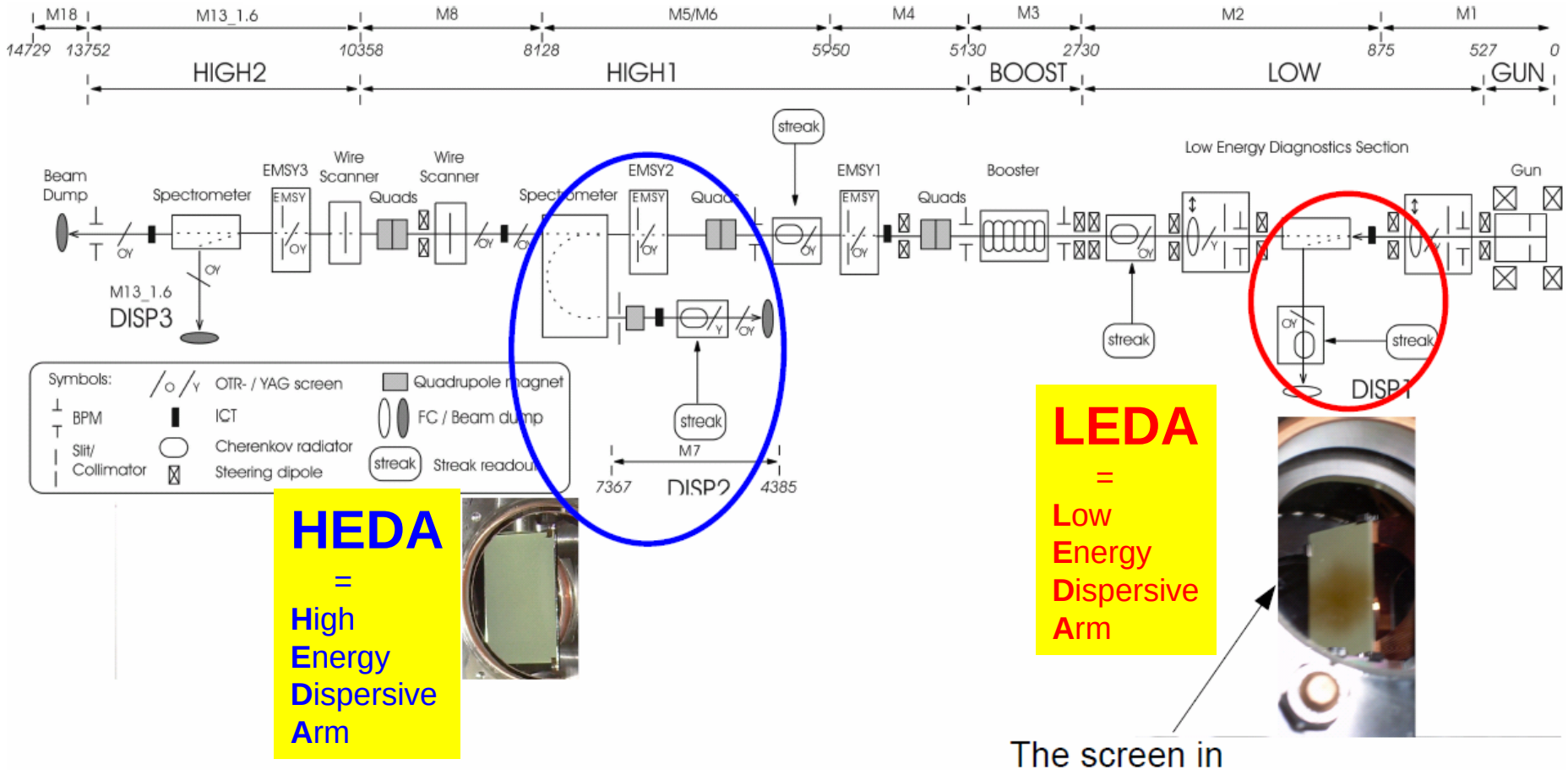




FWHM: 20.7ps
rise: 4.16ps
fall: 4.00ps
FTmod: 2.34%

measured: 29.4.09
late shift (11:46)

Longitudinal momentum modulations: meas. setup

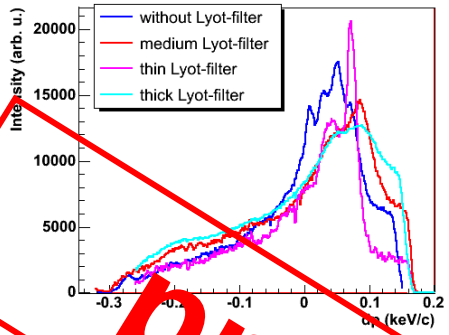
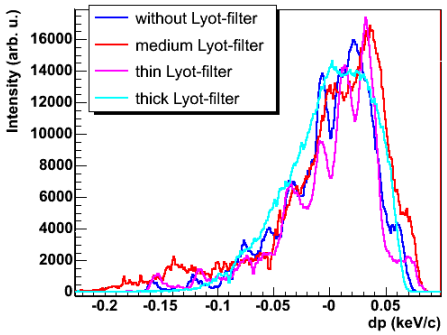
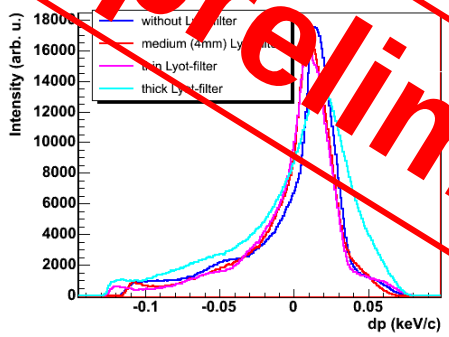
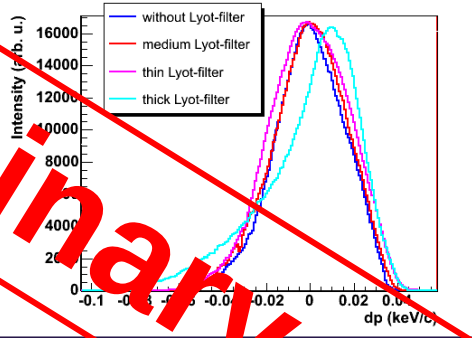
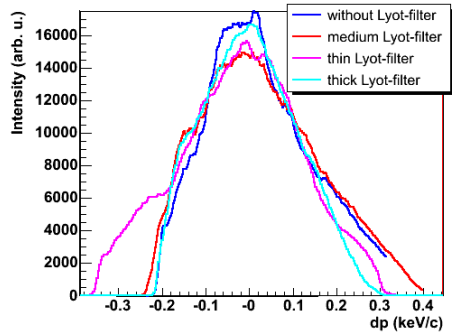
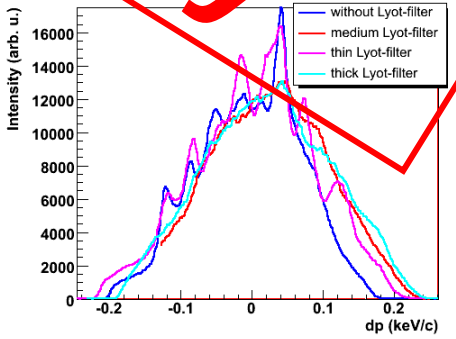


The screen in the low energy dispersive arm is strongly burned

- **BSA 1.5mm**
- **solenoid focusing for best momentum resolution in LEDA (appr. 460A)**
- **solenoid setting for HEDA measurements 390 A (good transport), focusing by quads**

Longitudinal momentum modulations and cathode laser temporal shaping

preliminary results

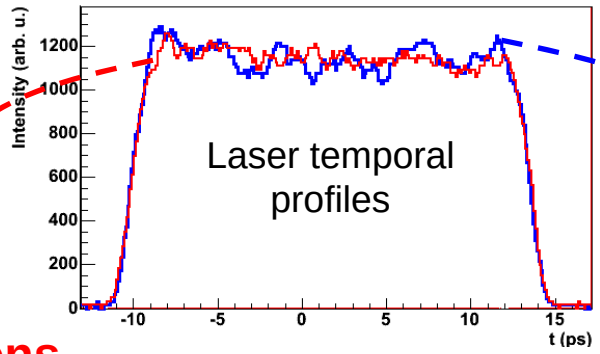
Gun phase	Booster phase	DA / # pulses	Q=1nC	Q=0.25nC	remarks
phase of maximum momentum gain -10deg (SPP)	no booster	LEDA / 30 pulses			■ Pz-modulations observed after RF-gun ■ higher bunch charge and thicker Lyot filter smear out the modulations
phase of maximum momentum gain					■ nominal rf-gun phase
	phase of maximum momentum gain -10deg (SPP)	HEDA / 10 pulses			■ although no modulations after RF-gun, off-crest booster phase reveals Pz-modulations

preliminary

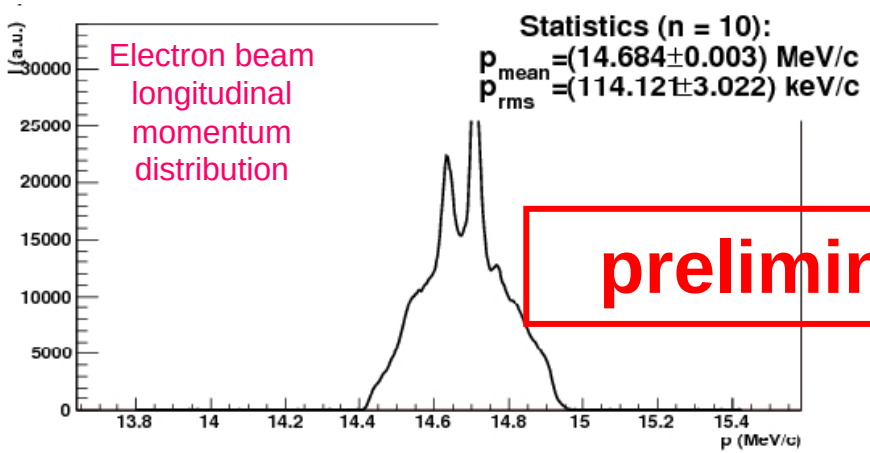
Measurements with / without modulations on the temporal laser distribution (medium Lyot filter)

Another approach → detuning of an aligned pulse shaper, i.e. by purpose introducing modulations on the flat-top of the temporal laser distribution and measuring momentum distribution in HEDA

Machine conditions:
- gun: on-crest
- booster: +10deg off-crest
- bunch charge: 500pC

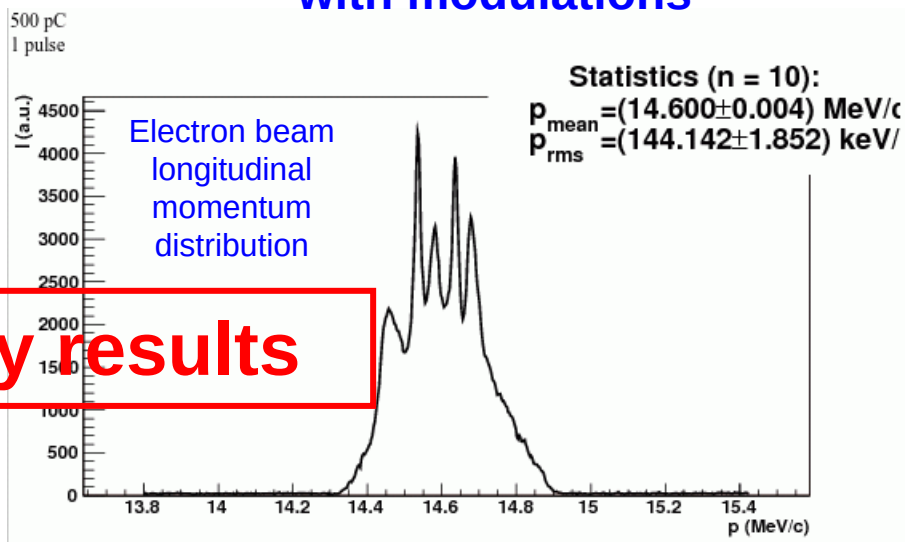


without modulations



(5 laser pulses used)

with modulations

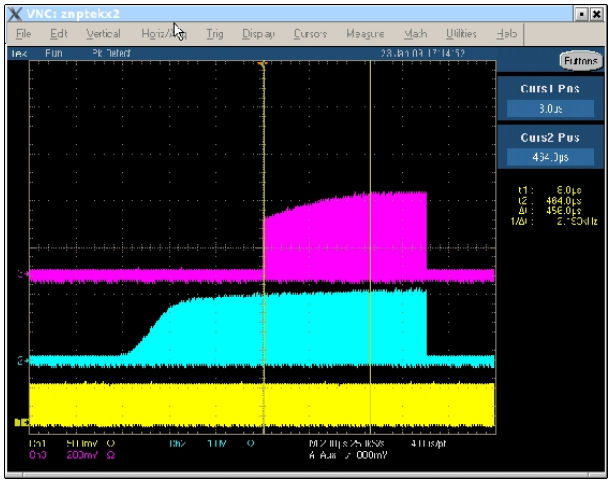


(1 laser pulse used)

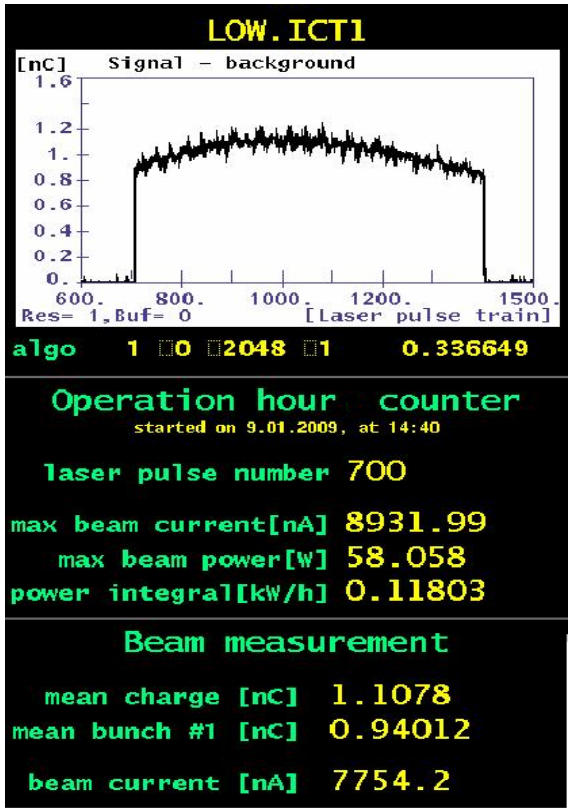
preliminary results

Long pulse train operation: 700 pulses x 1nC, 7 MW in gun (23.01.2009A)

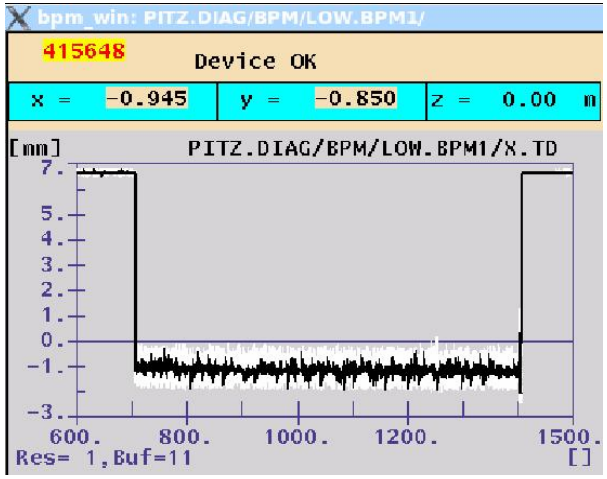
Laser scope



Bunch charge: LOW.ICT1



Beam position: LOW.BPM1



Long pulse operation (aver. current 7.8 μA) has been demonstrated, BUT laser pulse train envelope still to be improved

preliminary results

Summary and Outlook (1)

- **European X-ray Free Electron Laser (XFEL)**
  - will allow unprecedented experiments with **atomic** resolution on **femtosecond** time scales with ultra-high peak and average **brilliance** photon beams of transverse spatial **coherence** → construction has **started**

- **Photo Injector Test facility at DESY, Zeuthen site (PITZ):**
  - develops **electron source** for XFEL
  - very low **emittance** and high **average power** operation were demonstrated:
    - nominal 1nC, several consequent measurements (22.08.2009M) delivered:

$$\varepsilon_{xy}(100\%) = (0.886 \pm 0.011)\,\text{mm mrad}$$

$$\varepsilon_{xy}(90\%) = (0.681 \pm 0.010)\,\text{mm mrad}$$

but not reproduceable in next shifts → av. of 10 measurements (13.09.`09):

$$\varepsilon_{xy}(100\%) = (1.173 \pm 0.052)\,\text{mm mrad}$$

$$\varepsilon_{xy}(90\%) = (0.878 \pm 0.040)\,\text{mm mrad}$$

preliminary

    - for lower bunch charges, e.g.:

$$\varepsilon_{xy}(Q = 0.25nC, BSA = 0.8mm, 100\%) = 0.47\ \text{mm mrad}$$

$$\varepsilon_{xy}(Q = 0.1nC, BSA = 0.5mm, 100\%) = 0.34\ \text{mm mrad}$$

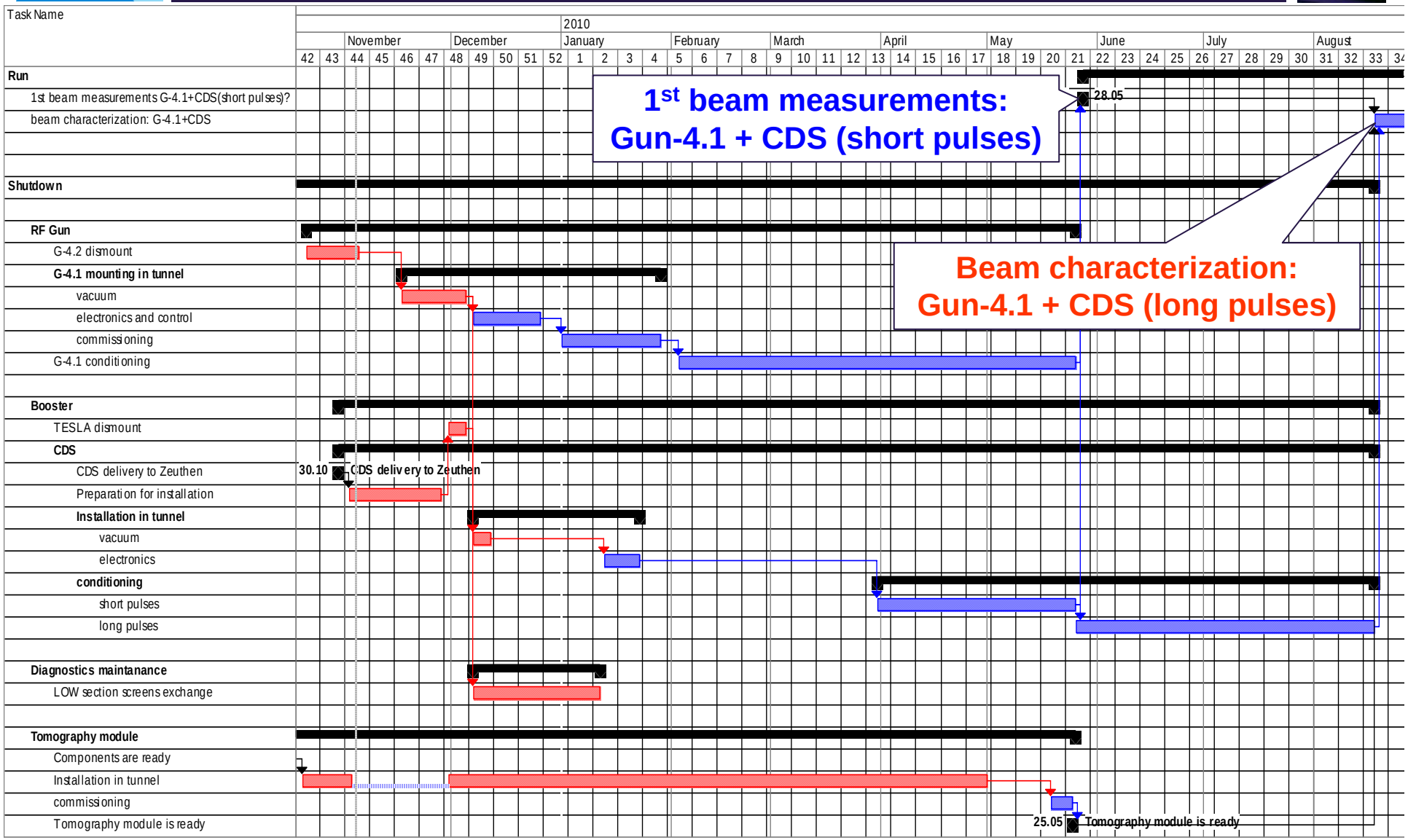
$$\varepsilon_{xy}(Q = 0.25nC, 90\%) = 0.37\ \text{mm mrad}$$

$$\varepsilon_{xy}(Q = 0.1nC, 90\%) = 0.26\ \text{mm mrad}$$

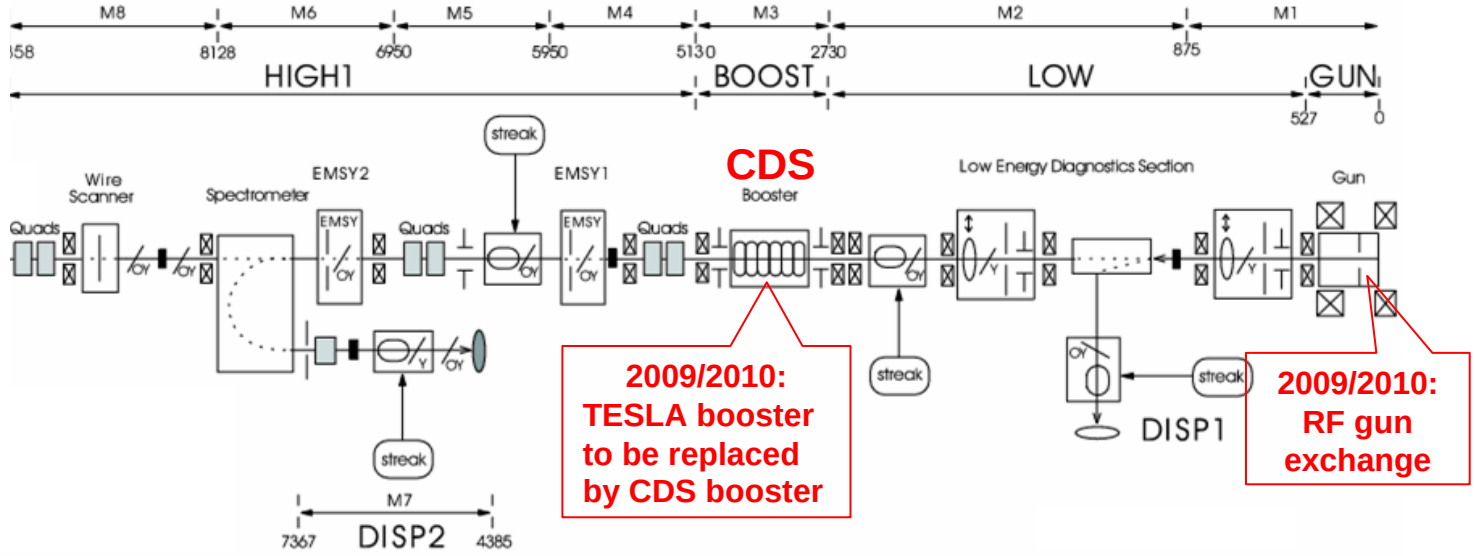
Summary and Outlook (2)

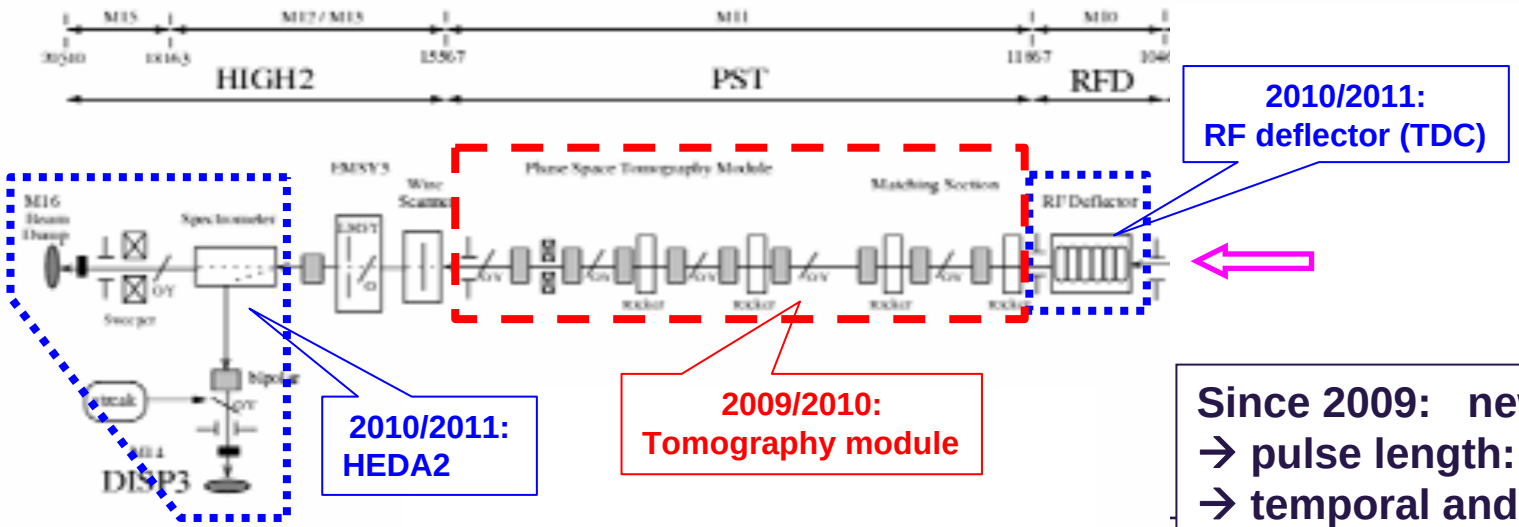
- **R&D at PITZ is ongoing → further improvements of facility,**
  → new operation modes,
  → new research fields
  - Major problem: rf gun phase instability → emittance fluctuations up to 10% (rms) and 20%(peak-to-peak).
    → hope that unique **10MW in-vacuum directional coupler** will solve problem (if it works→ FLASH LLRF to be installed at PITZ).
  - Laser transport to cathode is critical issue (e.g. vacuum mirror)
  - PITZ shutdown has started on 19.10.2009:
    - RF-Gun exchange (current one to FLASH, new one: CO_2 cleaned, LLRF)
    - new booster cavity (more stable and reliable, known field profile)
    - new tomography module (better characterization of trans. phase space)
    - diagnostics maintenance (burned screens, slit masks improvement)
  - More intensively study low charge operation modes, incl. single spike lasing
  - Interested in new research fields, e.g.:
    - CW electron source for XFEL with lowest possible emittance
    - acceleration of low emittance e-beams with laser plasmas → beam quality ?

Planning next steps



PITZ beamline: Status and Future





Since 2009: new laser system
→ pulse length: 2-24 ps (FWHM)
→ temporal and transverse laser shaping

Acknowledgments

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M. Altarelli, R. Brinkmann, S. Schreiber

the whole **PITZ collaboration**

and the whole European XFEL Project Team