Normal-conducting RF Photo Injectors for Free Electron Lasers

Frank Stephan (DESY, Zeuthen site) for the PITZ team

Content:

- Introduction: FELs and their electron sources
- Different NC photo injectors
  - at SLAC for LCLS (low average current)
  - at Berkeley for NGLS (high average current)
  - at PITZ for FLASH and European XFEL (medium average current)
- Outlook and Summary

HELMHOLTZ ASSOCIATION

PITZ Photo Injector Test Facility Zeuthen

DESY

European XFEL - a next generation light source

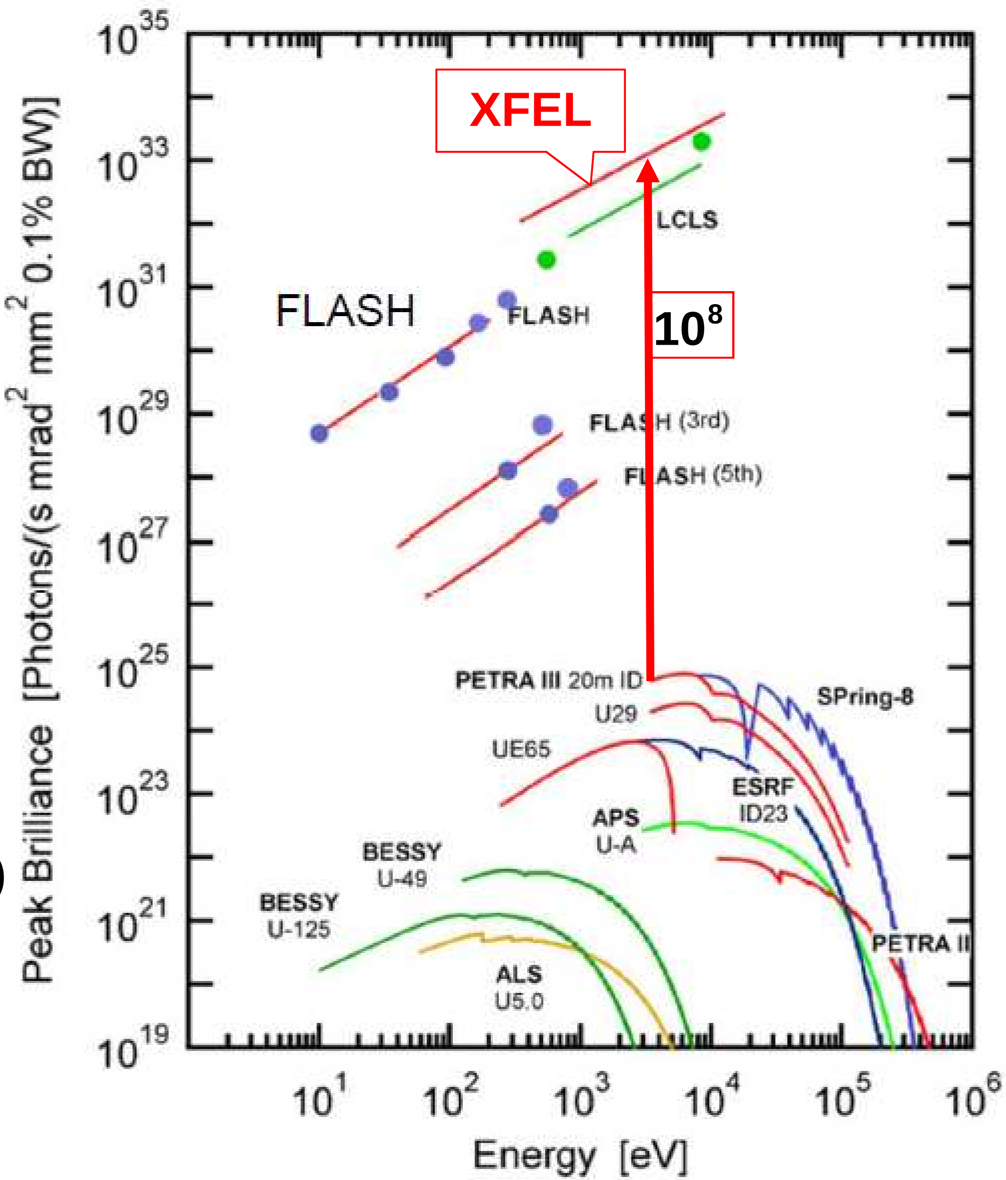
The XFEL will deliver:

- 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 !!**)

Why brilliance is ~10E+8 higher ?
Synchrotrons: $P \sim N \cdot e^2$
FELs (coherence):

$$P \sim (N \cdot e)^2 = N^2 \cdot e^2 ,$$

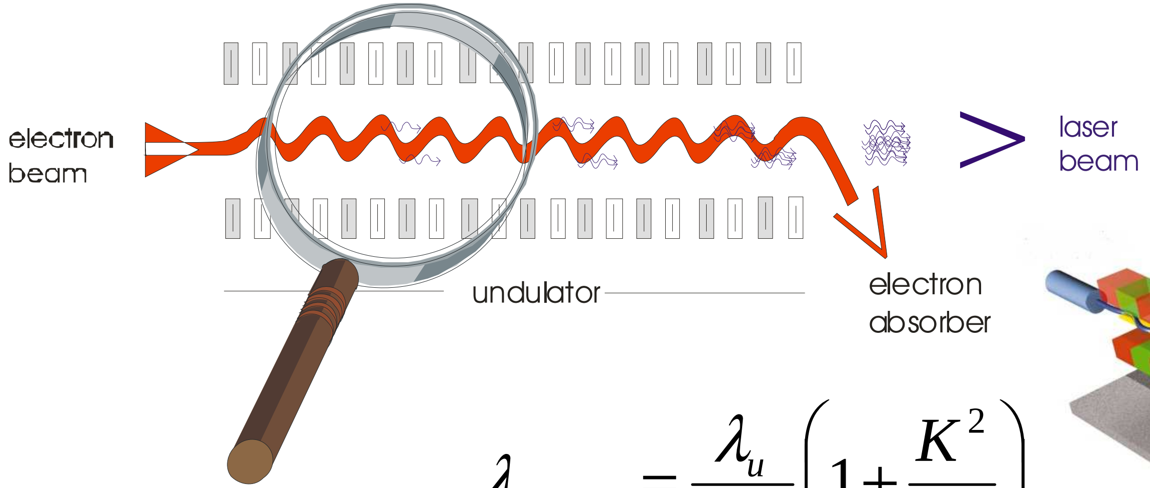
$$N \sim 10E+8$$



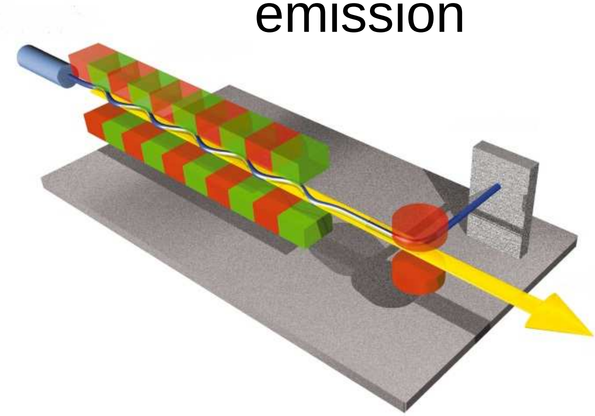
SASE FEL: How does it work?

Coherent motion is all we need !!

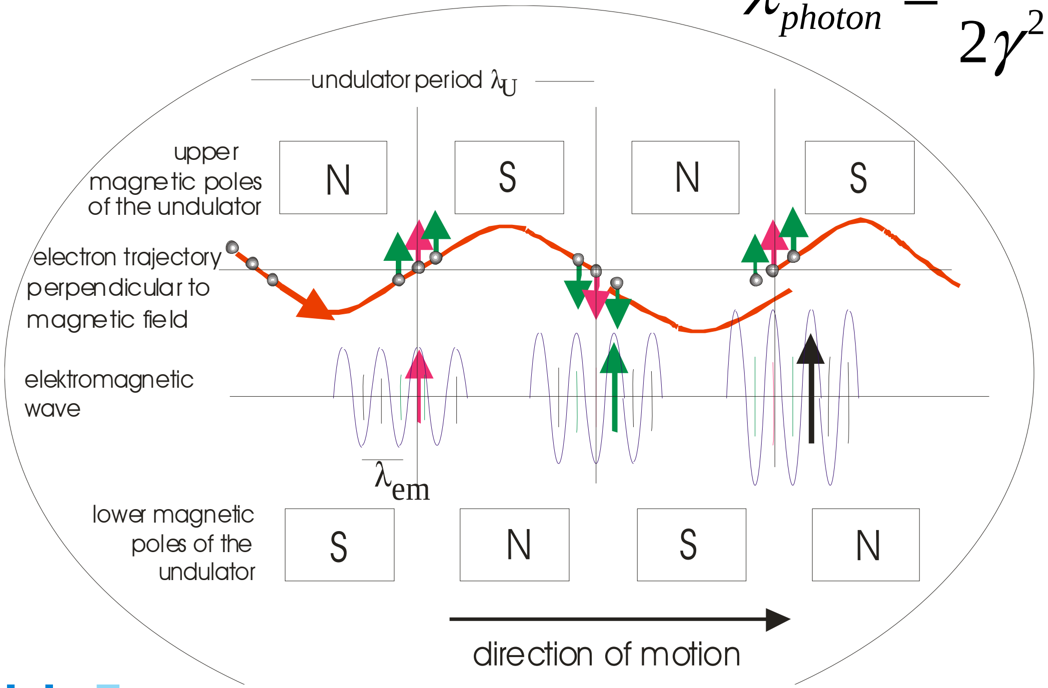
SASE FEL: How does it work?

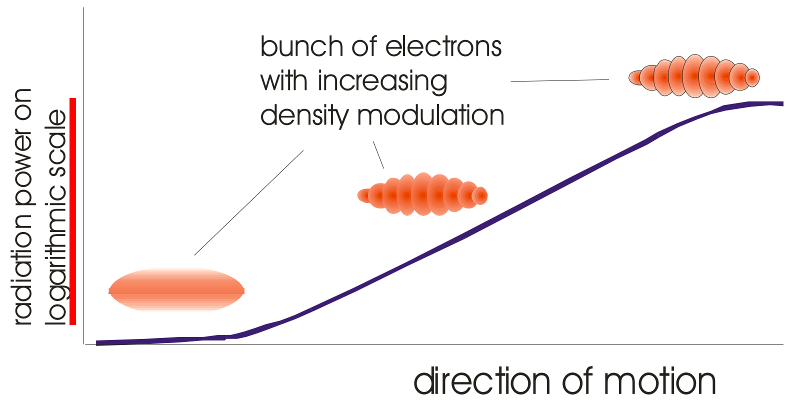


SASE =
self amplified
spontaneous
emission



$$\lambda_{photon} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$





$$\lambda_{min}[\mathrm{nm}] \approx \frac{4\pi}{10}\frac{\varepsilon_n[\mathrm{mm\ mrad}]}{\sqrt{I_p[\mathrm{kA}]\cdot L_u[\mathrm{m}]}}$$

One XFEL key component:
→ the high brightness electron source

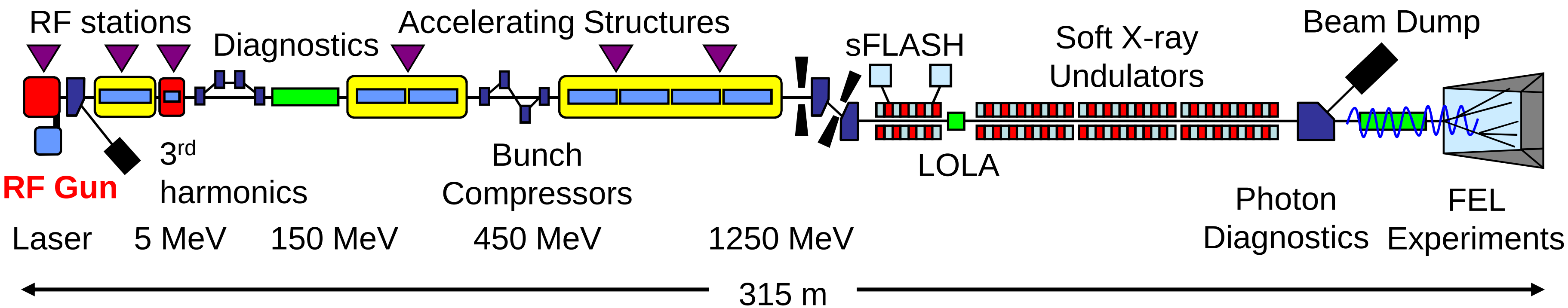
Why electron injector is so important …. ???

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

} **increase normalized emittance**

Example: **FLASH**



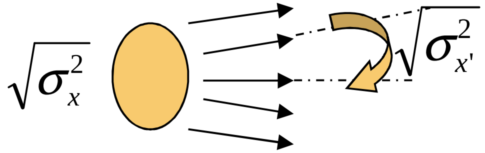
property of linacs: beam quality will DEGRADE during acceleration in linac

→ electron source has to produce lowest possible emittance !!

What is Emittance ?

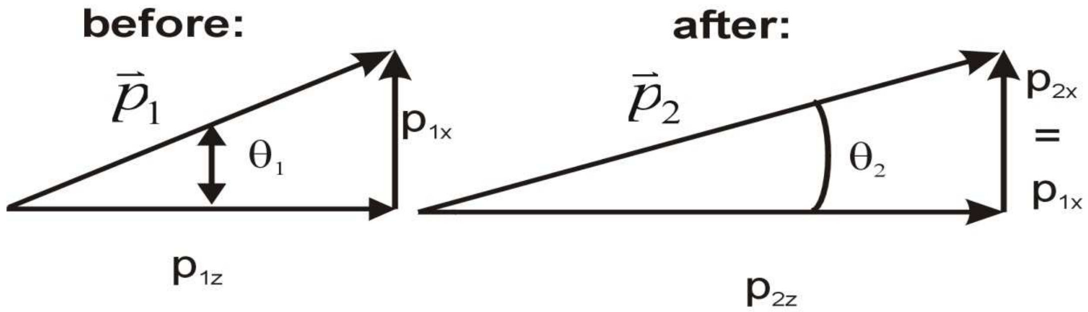
long.: ε_z ~ (e^- bunch length) • (energy spread of e^- bunch)

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



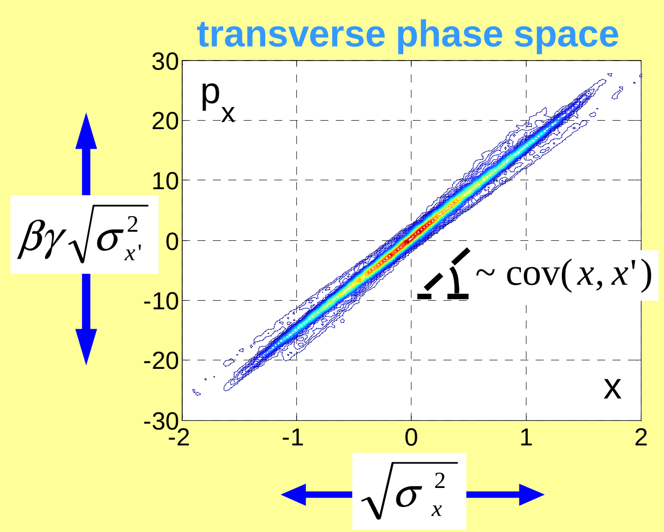
ε = 6 dimensional phase space volume occupied by given number of particles

effect of <u>acceleration</u> on transverse emittance (adiabatic damping):



$\theta_2 < \theta_1$

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



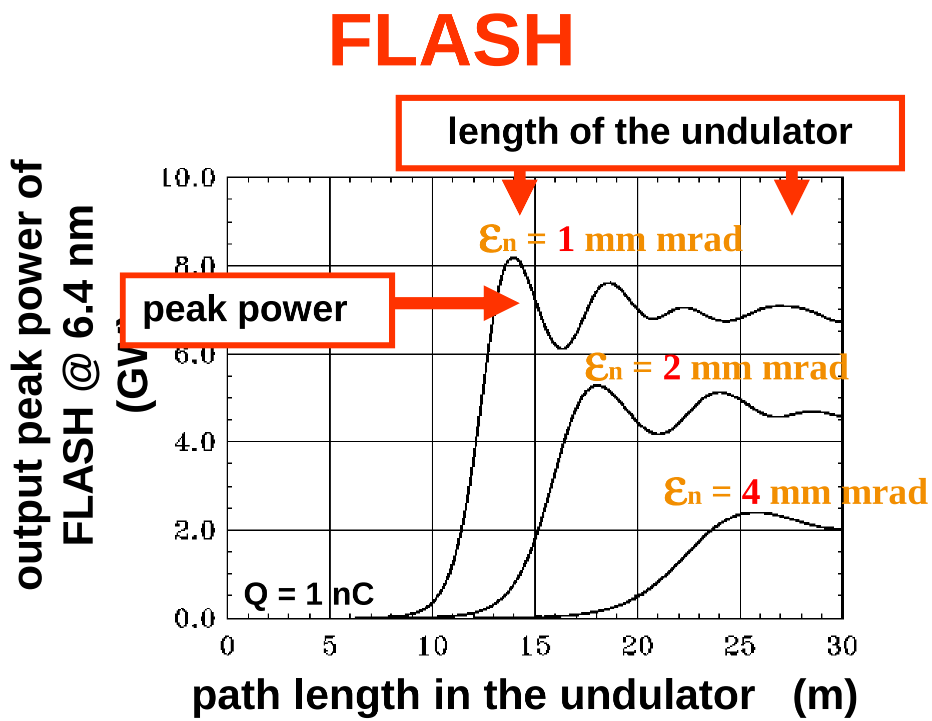
$\Rightarrow$ normalized RMS transverse emittance:

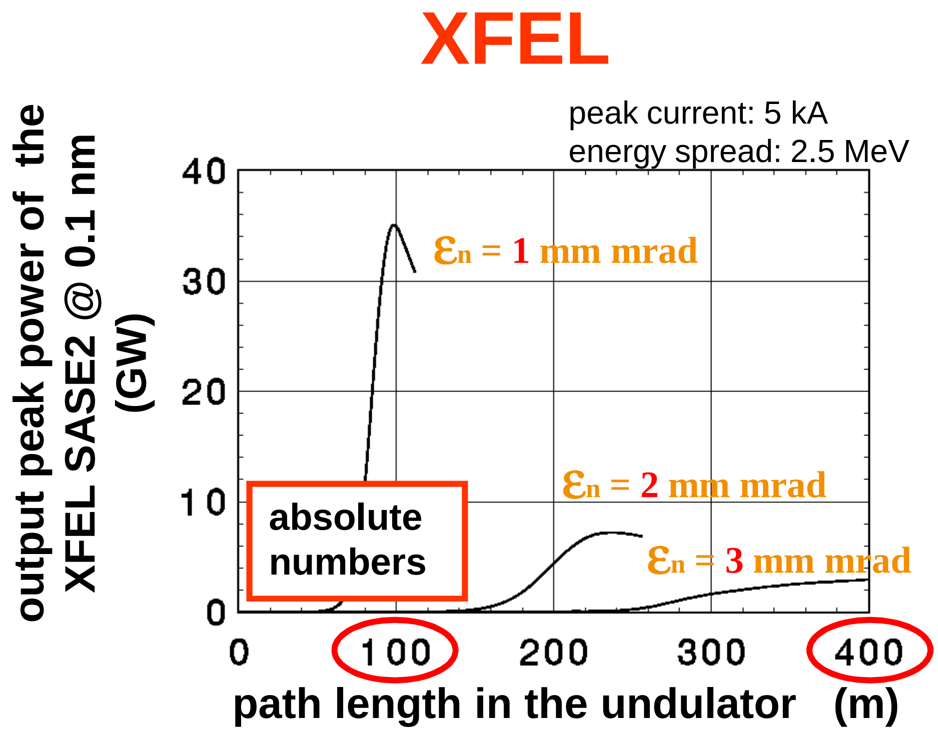
$$\varepsilon_x^n = \beta \bullet \gamma \bullet \sqrt{\sigma_x^2 \bullet \sigma_{x'}^2 - \mathrm{cov}^2(x, x')}\ ; \quad \beta = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}, \quad x' = \frac{dx}{ds}$$

(ε^n is conserved in general)

Why electron injector is so important …

• Why emittance must be small …





• **XFEL goal: 0.9 mm mrad@injector = 1.4 mm mrad@undulator**

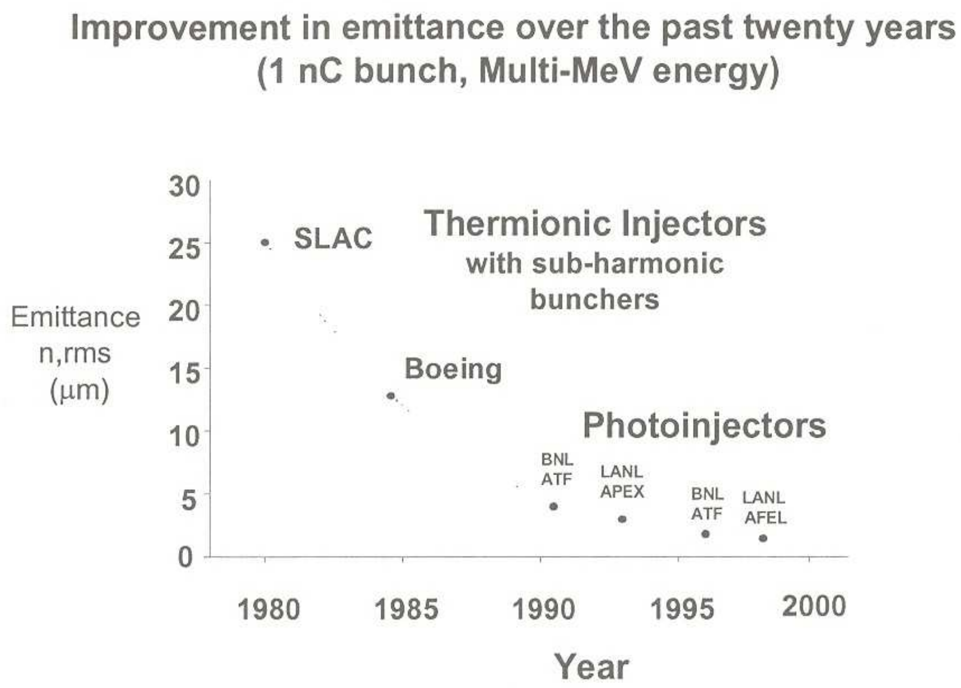
• **if even smaller emittance ⇒ new horizons:**

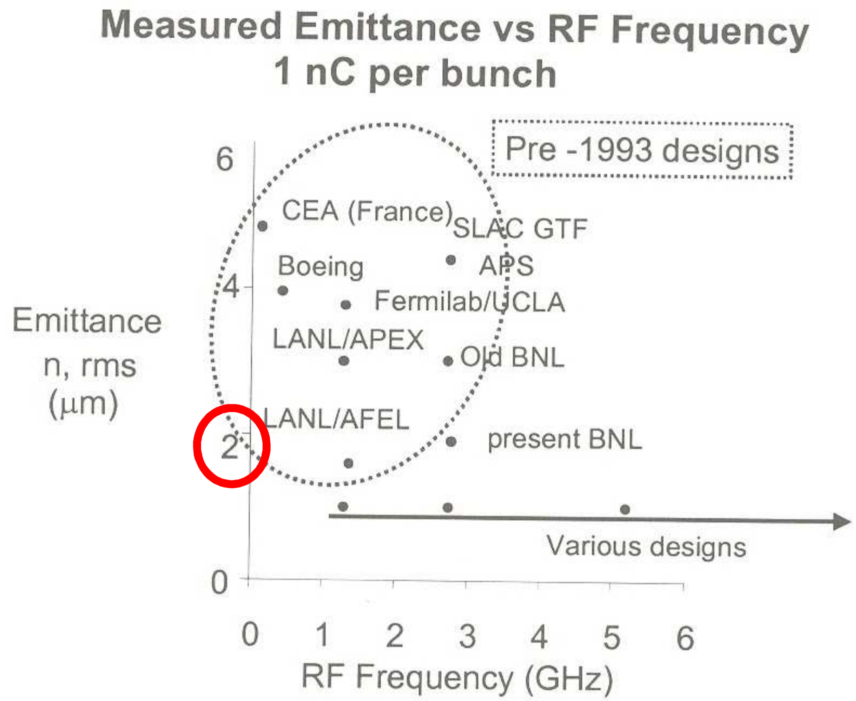
shorter wavelength, higher repetition rate

Situation in 1999

ICFA workshop on high brightness beams at UCLA in autumn 1999:

Summary talk of P. O'Shea (U Maryland, USA) on electron source developments:





"Goal for community in next years:

Get transverse normalized emittance of 1 mm mrad @ bunch charge of 1 nC !!!"

Different NC photo injectors

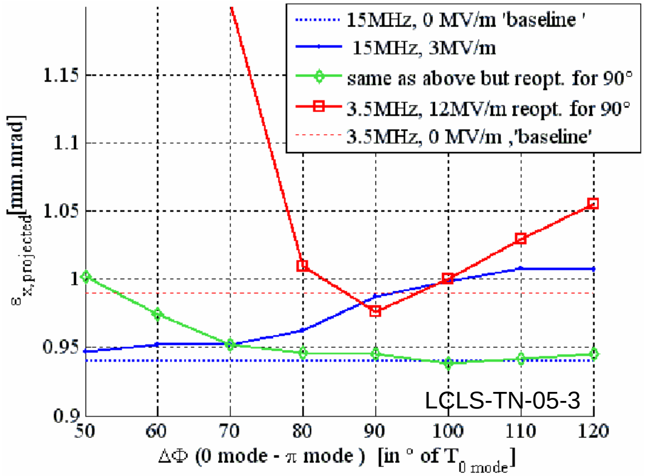
- at SLAC for LCLS (low average current)
- at Berkeley for NGLS (high average current)
- at PITZ for FLASH and European XFEL (medium average current)

NC RF Gun Design for LCLS

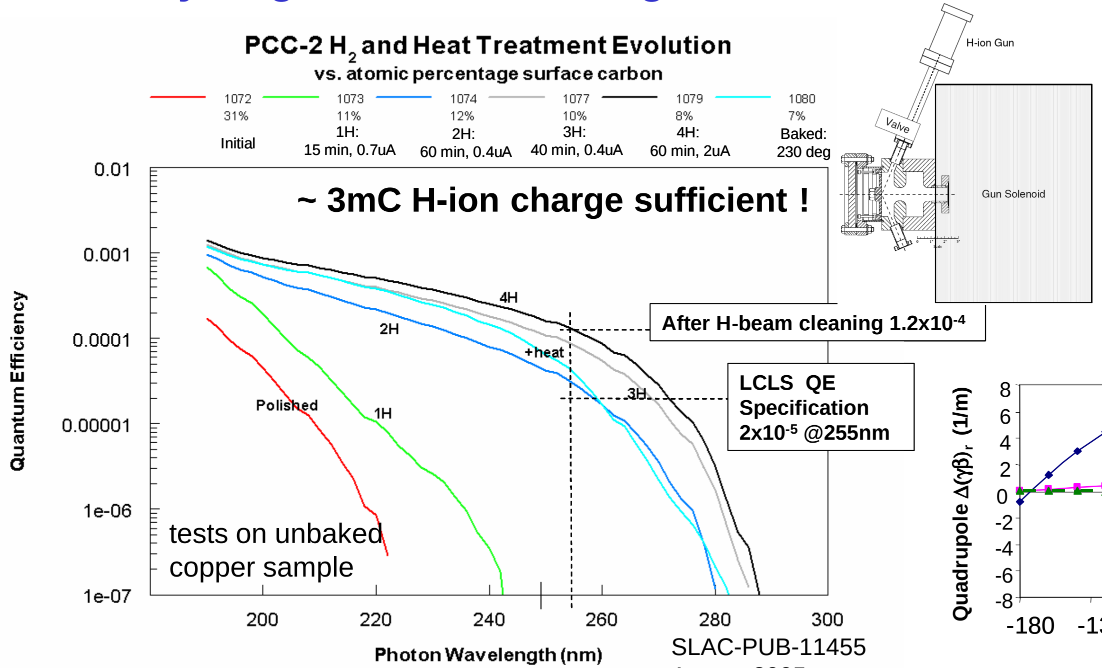
pulsed / CW	**pulsed**
single bunch charge	**1.0 / 0.2 nC**
single bunch rep rate	**120 Hz**
average current	**120 / 24 nA**
norm. trans. emittance (rms, slice)	**1.0 / 0.8 mm mrad @ 135 MeV**
rf frequency	**2856 MHz**

modified UCLA/BNL/SLAC 1.6 cell S-band gun:
- larger mode separation (3.5 → 15 MHz)
- larger iris radius, reduced iris surface field
- dual rf feed, z coupling, racetrack shape
- field probes in both cells
- increased cooling channels
- klystron pulse shaping → reduced dissipated power

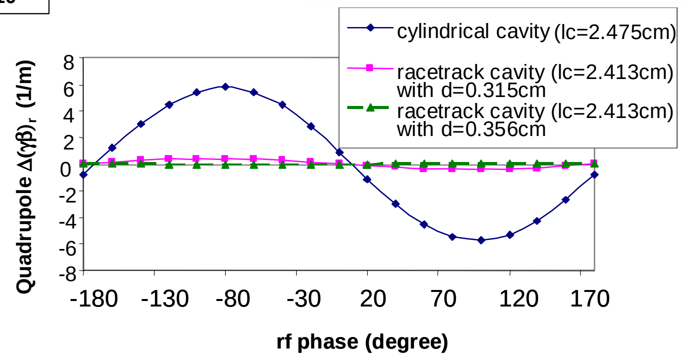
→improved emittance and stability

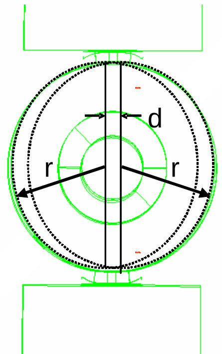


In-Situ Hydrogen Beam Cleaning of Cathode Surface



SLAC-PUB-11455
August 2005





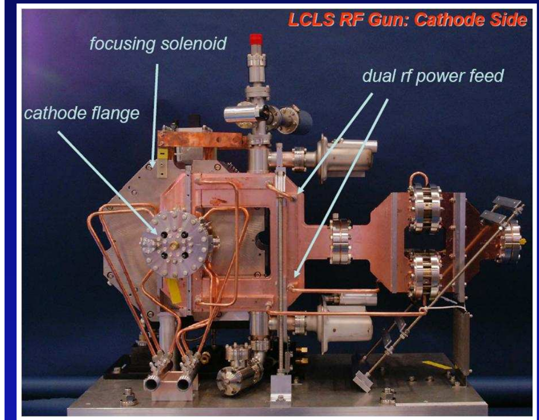
Courtesy of D. Dowell

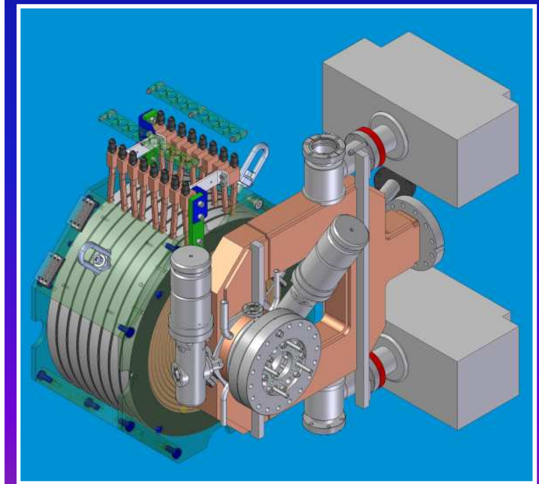
From Paul Emma, "First Lasing"-talk at FEL2009 in Liverpool:

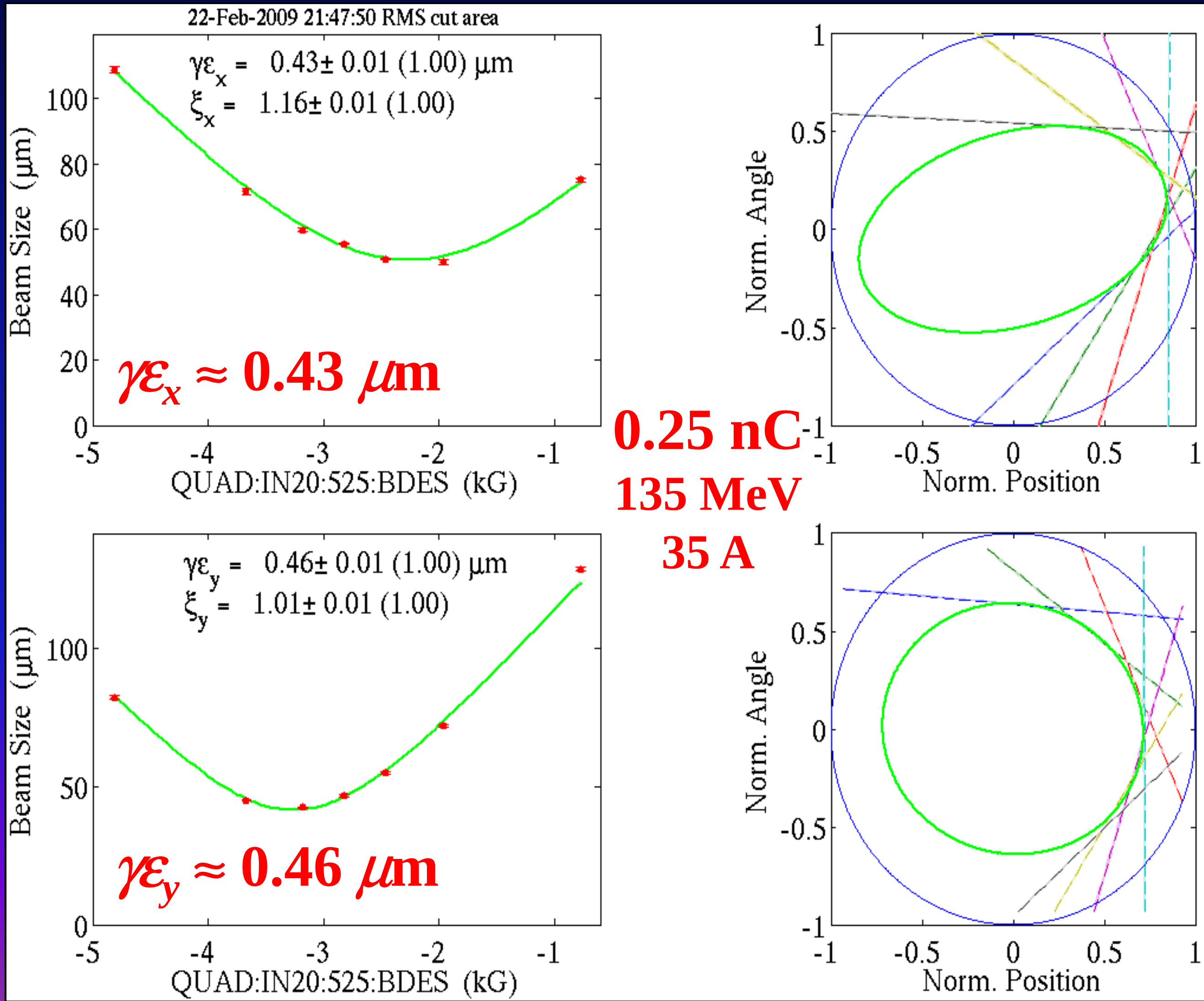
Injector Transverse Projected Emittance ~0.5 μm

Exceptional beam quality from S-band Cu-cath. RF gun…

Time-sliced x-emittance: 0.4 μm







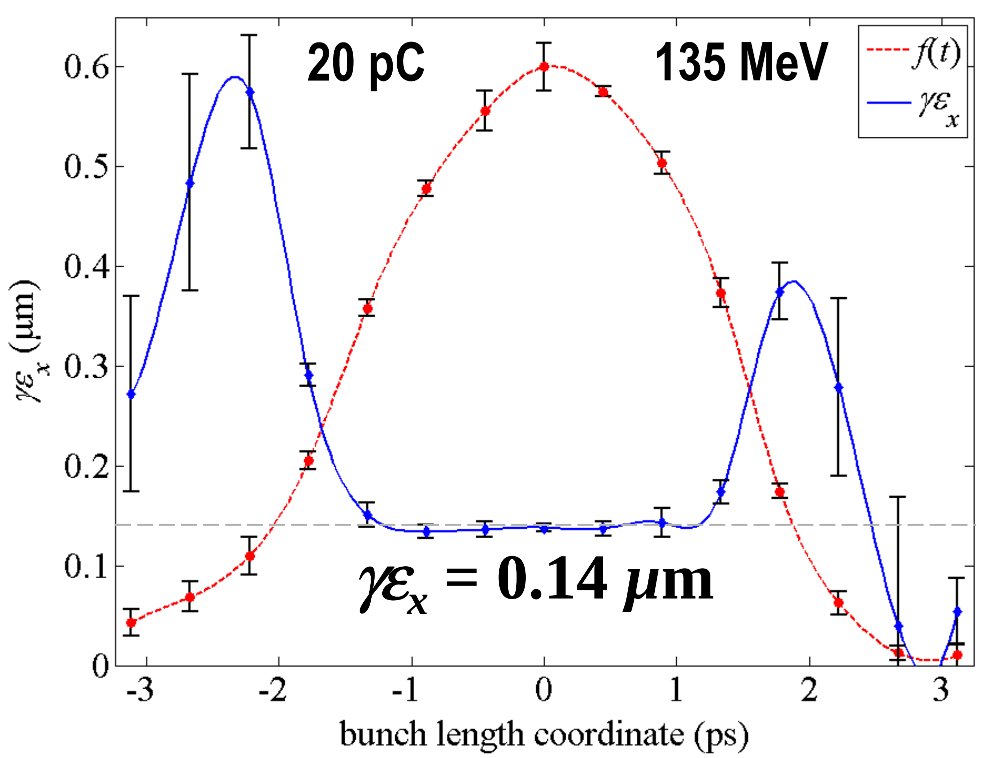
D. Dowell, *et al.*

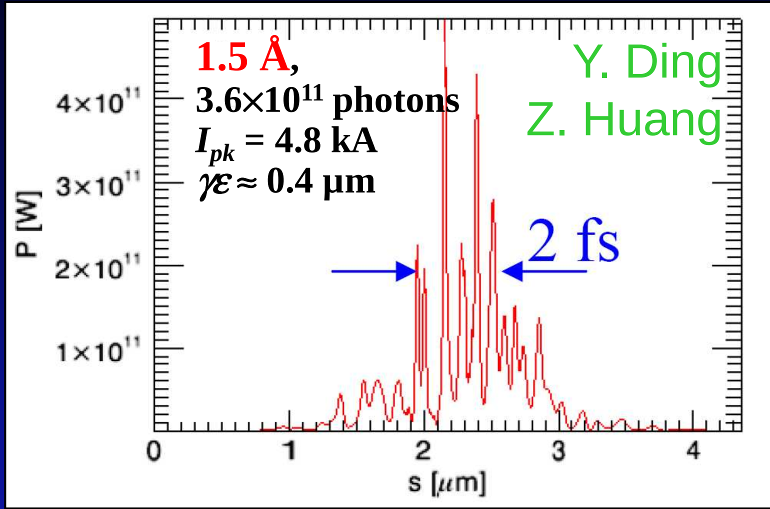
From Paul Emma, "First Lasing"-talk at FEL2009 in Liverpool:

Measurements and Simulations for 20-pC Bunch at 14 GeV

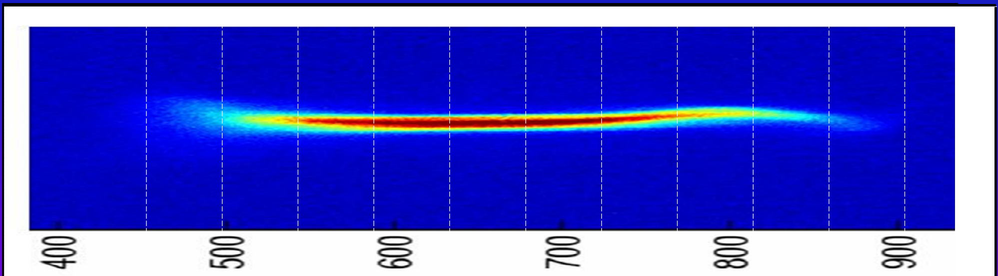
MEASURED SLICE EMITTANCE

SIMULATED FEL PULSES





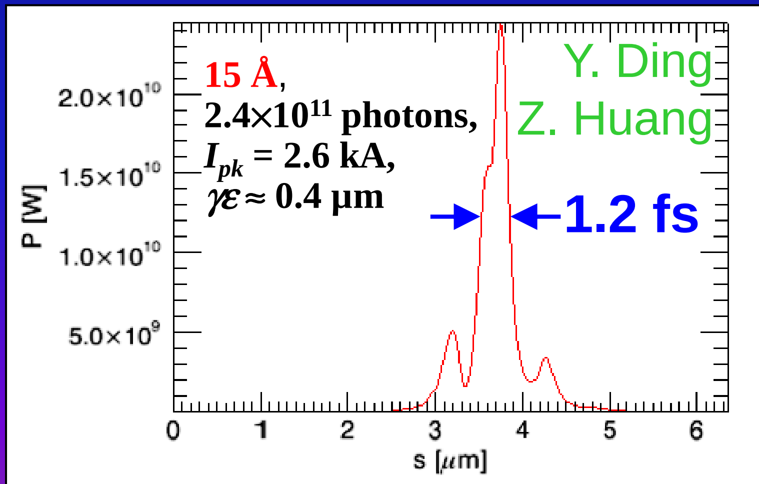
Simulation at 1.5 Å based on measured injector & linac beam & *Elegant* tracking, with CSR, at 20 pC.



← time-slicing at 20 pC →

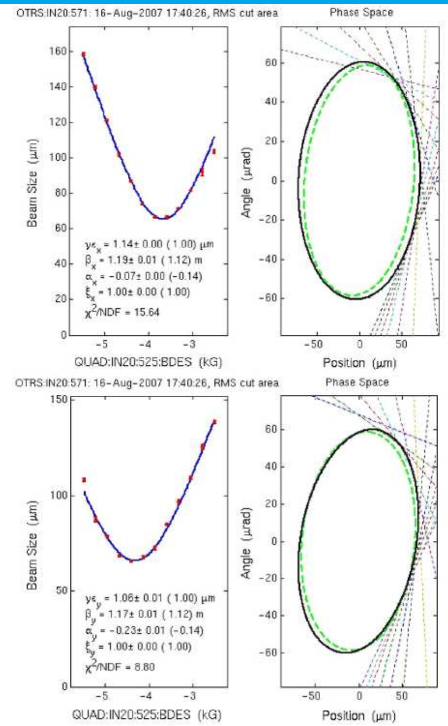
Y. Ding

PRL 102 854801



Simulation at 15 Å based on measured injector & linac beam & *Elegant* tracking, with CSR & 20 pC.

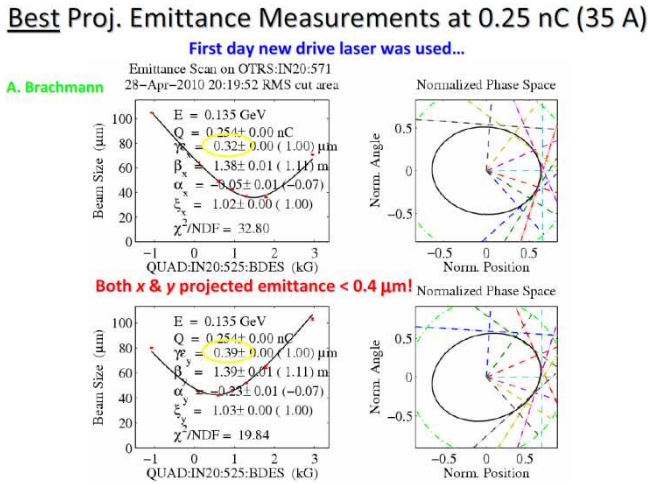
Some more experimental results from the LCLS gun:



- Phy.Rev. ST AB **11,** 030703 (2008):

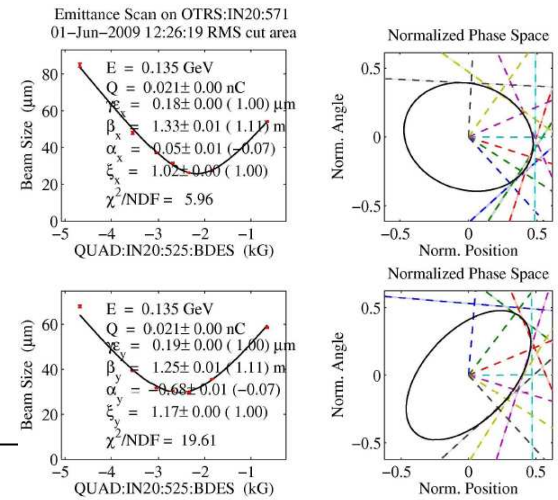
  1 nC, 100A bunch, 135 MeV: $\varepsilon_{n,\,x}$ (95%) = 1.14 mm mrad,
  $\varepsilon_{n,\,y}$ (95%) = 1.06 mm mrad

- P. Emma, "Beam Brightness Measurements in the LCLS Injector", Mini-WS on compact XFELs using HBB, LBNL, Berkeley, USA, 2010.



0.25 nC, 35A, 135 MeV

$\varepsilon_{n,\,x}$ (95%) = 0.32 mm mrad,
$\varepsilon_{n,\,y}$ (95%) = 0.39 mm mrad



- J. Frisch, "Operation and Upgrades of the LCLS", LINAC2010, Tsukuba, Japan: **0.02 nC**, 135 MeV:

  $\varepsilon_{n,\,x}$ (95%) = 0.18 mm mrad, $\varepsilon_{n,\,y}$ (95%) = 0.19 mm mrad

Different NC photo injectors

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- at PITZ for FLASH and European XFEL

  (medium average current)

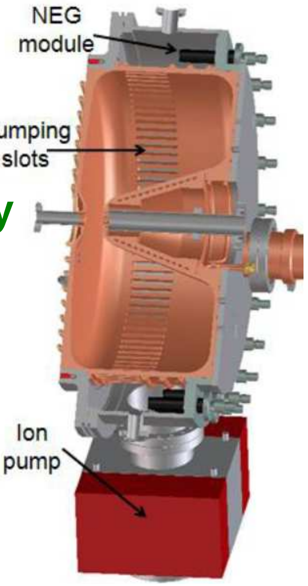
Berkeley approach: NC RF gun design for CW operation (1)

Design requirements

→ **high duty cycle, high average beam current, low emittance:**

- **repetition rate: up to ~1 MHz, CW**
- bunch charge: from ~1 pC to ~1 nC,
- normalized beam emittance: from sub 10^{-7} (low charge) to 10^{-6} m,
- beam energy at the gun exit: ≥ ~500 keV (space charge),
- electric field at the cathode: ≥ ~10 MV/m (space charge limit),
- bunch length control at cathode: from ~1ps to 10s of ps (to handle space charge effects, for allowing different modes of operation),
- compatibility with magnetic fields in the cathode and gun regions (mainly for emittance compensation)
- **operational vacuum pressure: 10^{-9} - 10^{-11} Torr** (high QE photo-cathodes),
- "easy" installation and conditioning of different kind of cathodes,
- high reliability compatible with the operation of a user facility.

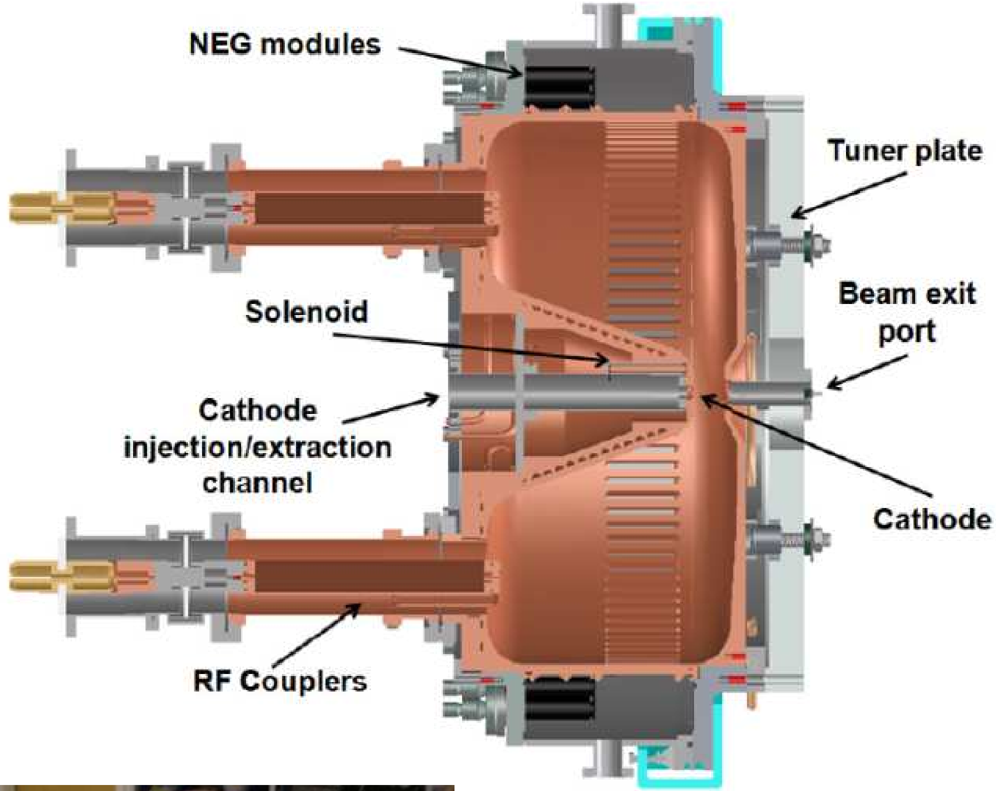
low RF frequency



(from Journal of Modern Optics, Vol. 58, No. 16, 1419-1437)

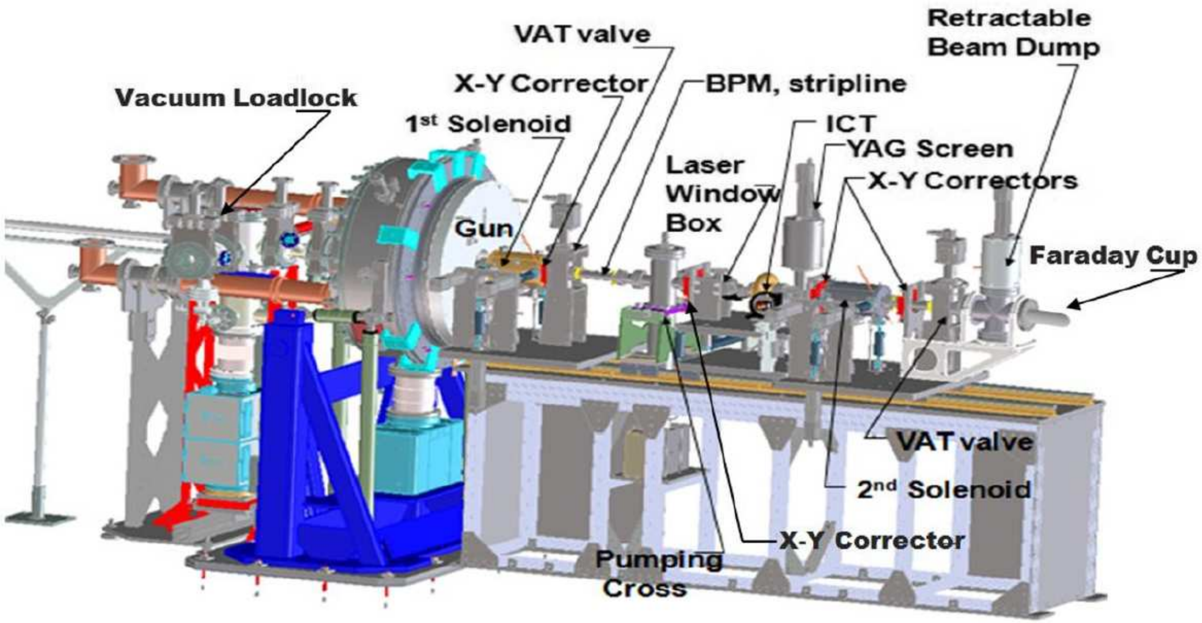
Berkeley approach: NC RF gun design for CW operation (2)

pulsed / CW	CW
single bunch charge	0.01 to 1 nC
single bunch rep rate	up to 1 MHz
average current	up to 1 mA
norm. trans. emittance (rms, slice)	< 1.0 mm mrad (design)
rf frequency	187 MHz



(pictures from F. Sannibale, Mini-WS on “Compact X-Ray FELs Using High Brightness Beams”, LBNL, August, 2010)

Berkeley approach: NC RF gun design for CW operation (3)



> **APEX phase 0 layout**

> Under preparation: further diagnostics for 6D phase space characterization and subsequently booster cavities for up to 30 MeV.

The following design parameters have already been demonstrated at Berkeley:

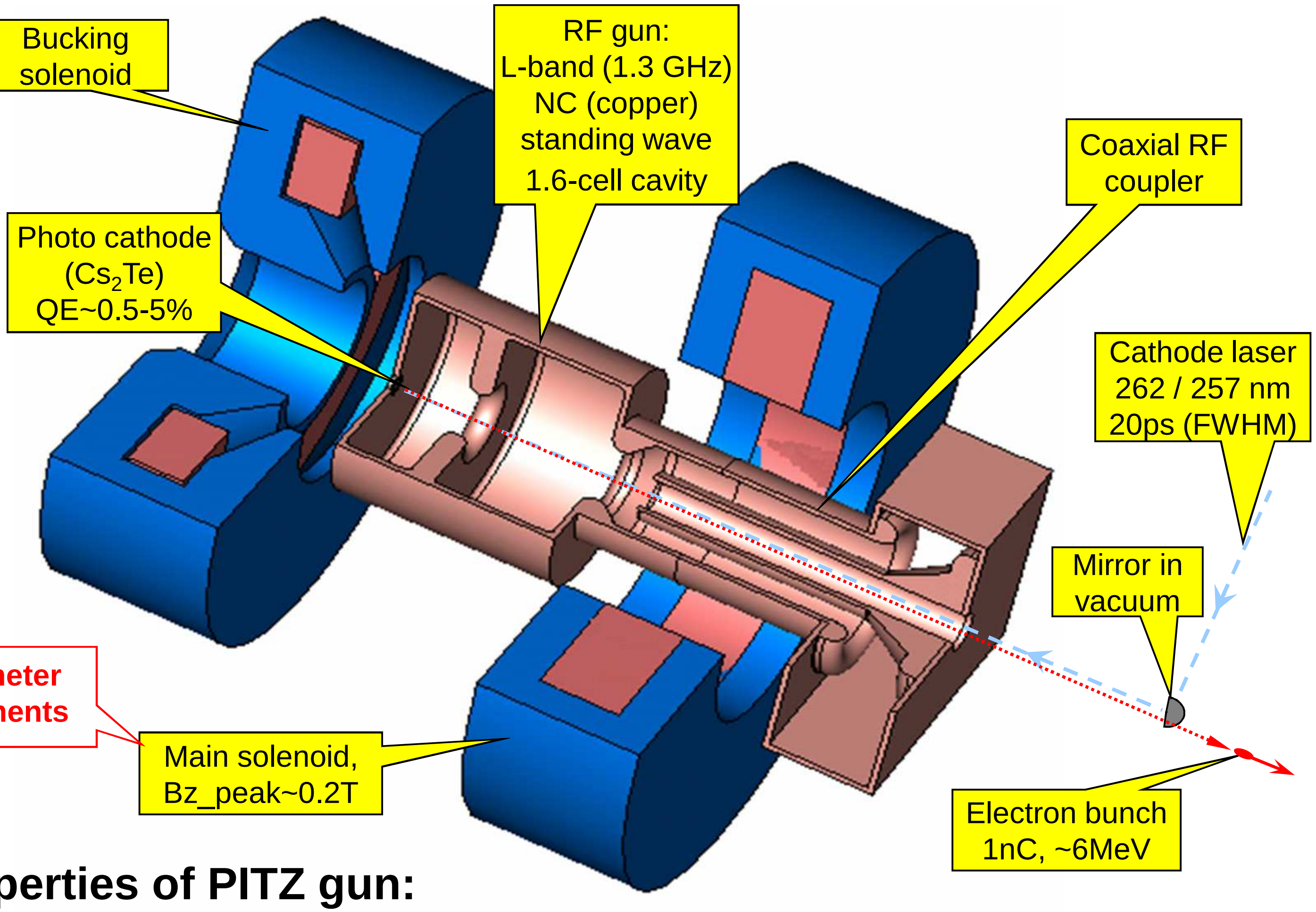
- **full conditioning** to max. RF power (**100kW** in CW mode, allow for 750keV beam energy) √
- max **dark current ~8µA @ 19.5MV/m** → should be OK for high rep rate FEL operation √
- first **photoelectrons at 1 MHz** from temporary molybdenum cathode √
- **beam energy: 745 ± 41 keV** √
- cathode field: >10 MV/m √
- **pressure: ~5x10^{-11} Torr** after baking (RF off, 1 of 20 NEG modules activated) (factor 3-4 higher with RF on) √

(from PRST-AB **15**, 103501 (2012))

Different NC photo injectors

- at SLAC for LCLS (low average current)
- at Berkeley for NGLS (high average current)
- at PITZ for FLASH and European XFEL
  (medium average current)

The PITZ gun (Photo Injector Test facility at DESY, Zeuthen site)



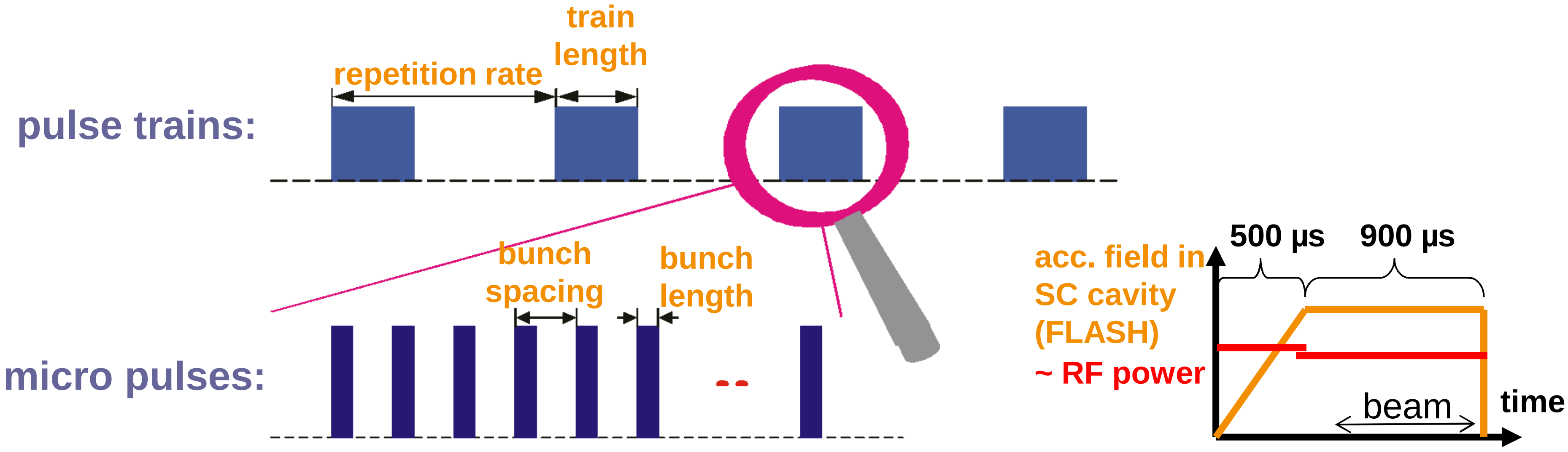
Main properties of PITZ gun:

1.3 GHz cavity, coaxial RF coupler (flexible solenoid position)

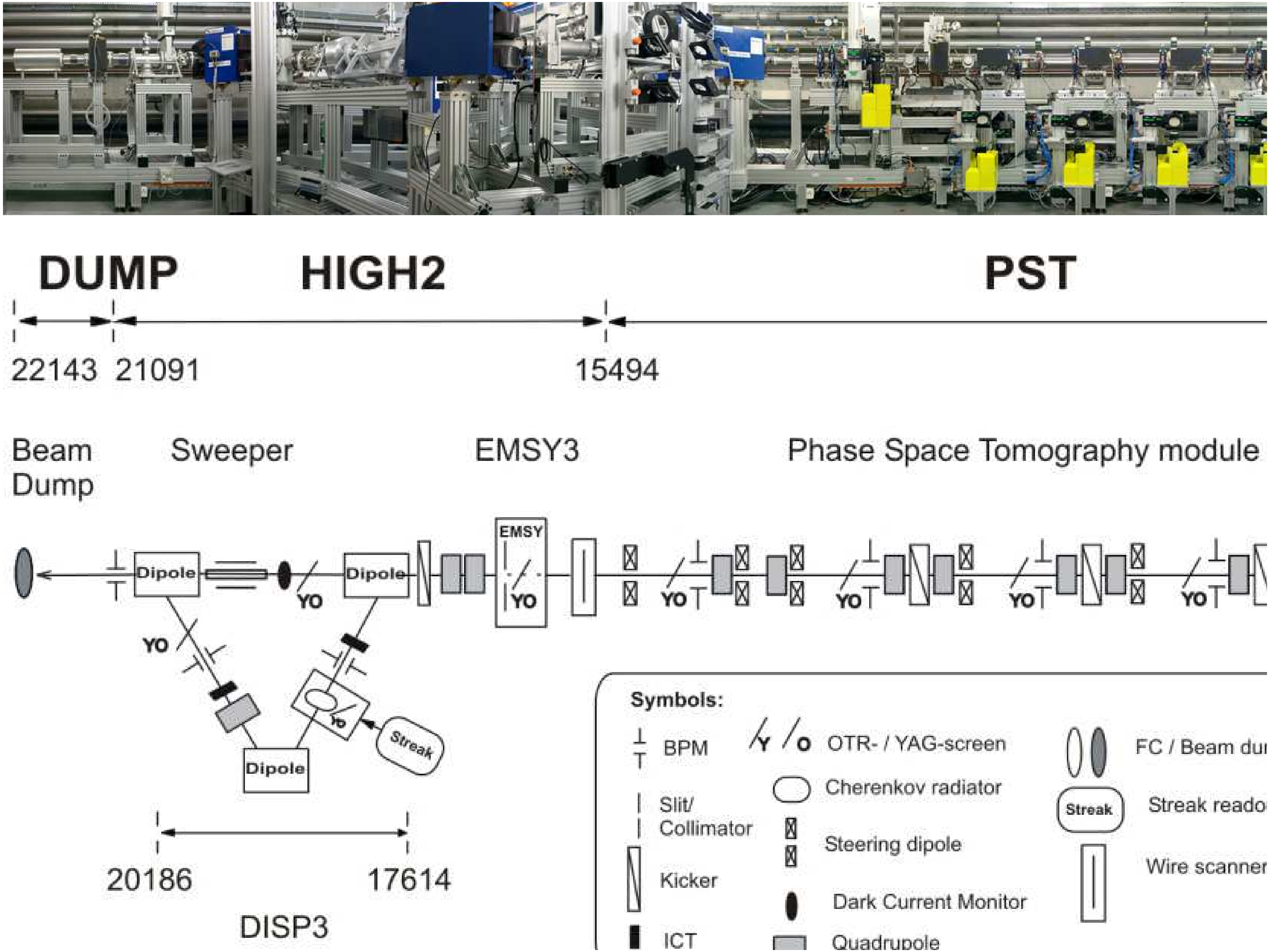
Capable of high average power → long electron bunch trains (SC linac) ⟶

Very low normalized transverse emittance

Some parameters of FLASH and European XFEL



	FLASH	European XFEL
final beam energy	1.2 GeV	17.5 GeV
max. repetition rate	10 Hz	10 Hz
max. train length	800 µs	650 µs
bunch spacing	1 – 20 µs	0.2 – 1 µs
required injector emittance (1 nC)	2 mm mrad	0.9 mm mrad
SASE output wavelength	4.1 – 45 nm	0.05 – 6.4 nm

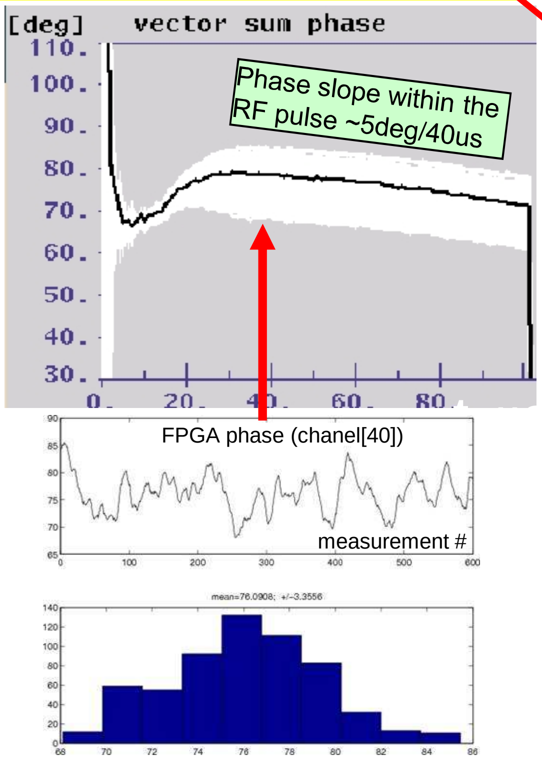


DUMP
HIGH2
PST
22143
21091
15494
Beam Dump
Sweeper
EMSY3
Phase Space Tomography module
Dipole
YO
EMSY
Streak
20186
17614
DISP3
Symbols:
BPM
OTR- / YAG-screen
FC / Beam du
Cherenkov radiator
Slit/ Collimator
Streak reado
Steering dipole
Wire scanner
Kicker
Dark Current Monitor
ICT
Quadrupole

Improvement of the RF gun phase stability (gun has no field probe)

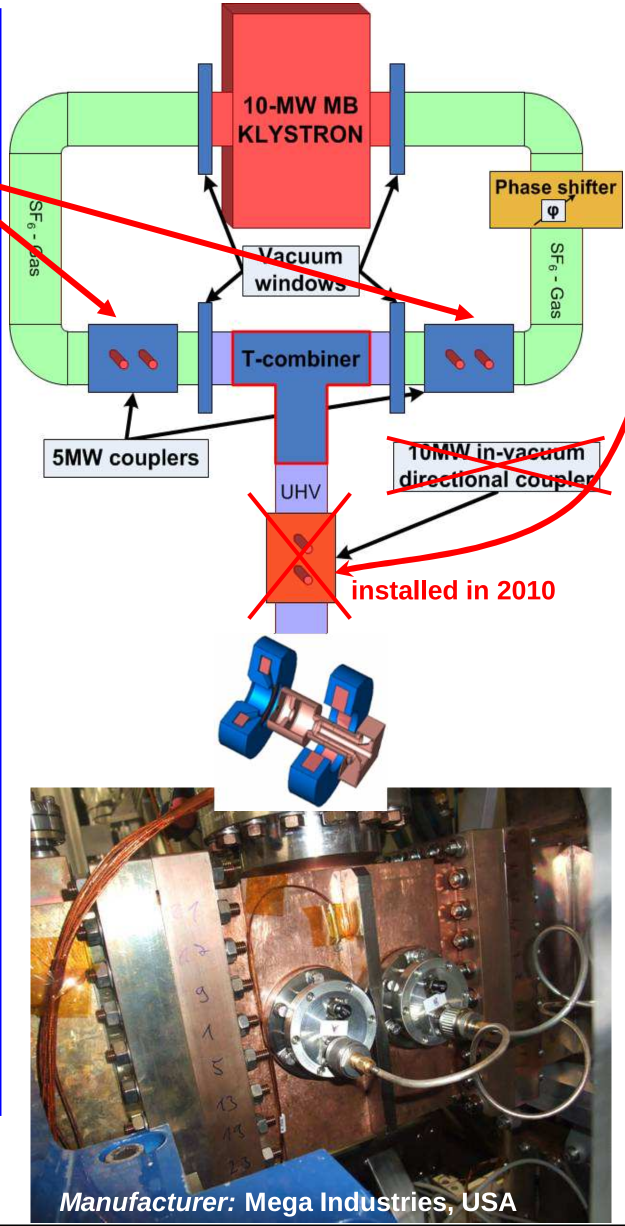
2009 (no FB)

FPGA phase, reconstructed from virtual ADC probes based on 2x5MW directional couplers



Phase fluctuations:

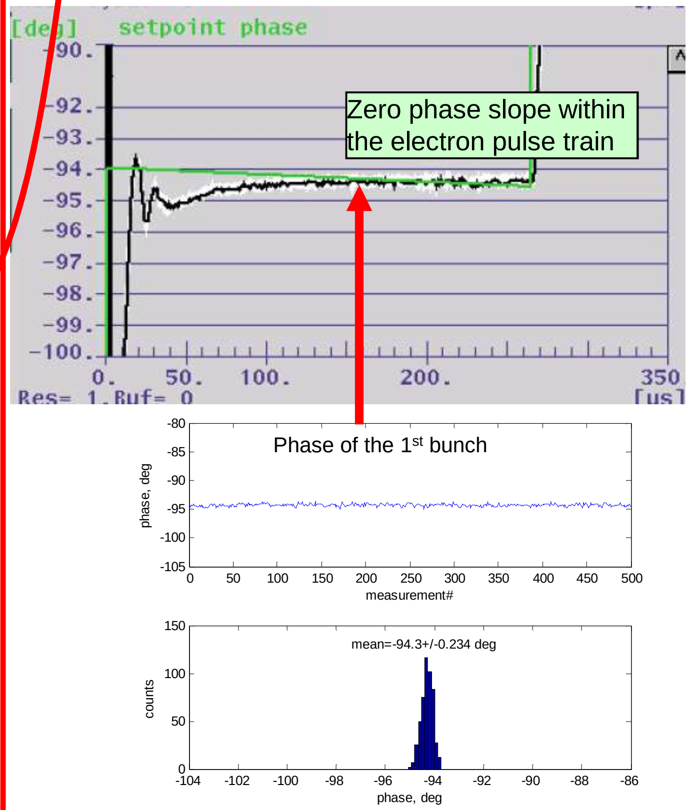
- **10..15 deg (p-p)**
- 2..4 deg (rms)



Manufacturer: Mega Industries, USA

2011 (FB is ON!)

FPGA phase, measured by 10MW in-vacuum directional coupler



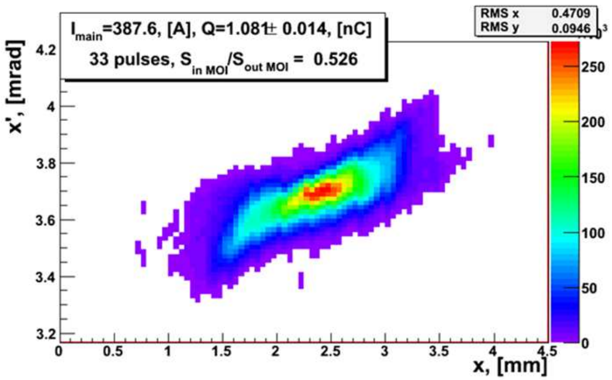
Phase fluctuations:

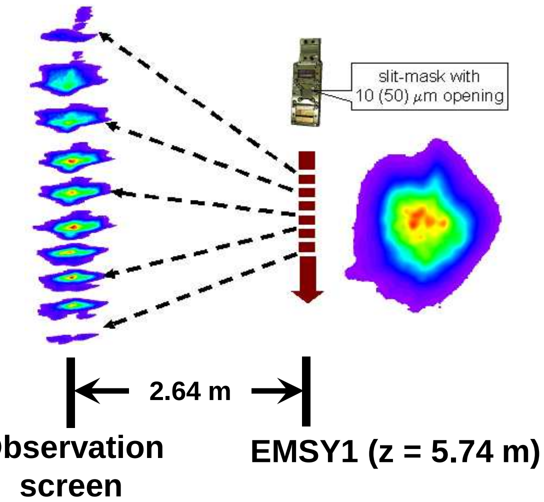
- **1..1.5 deg (p-p)**
- 0.2..0.3 deg (rms)

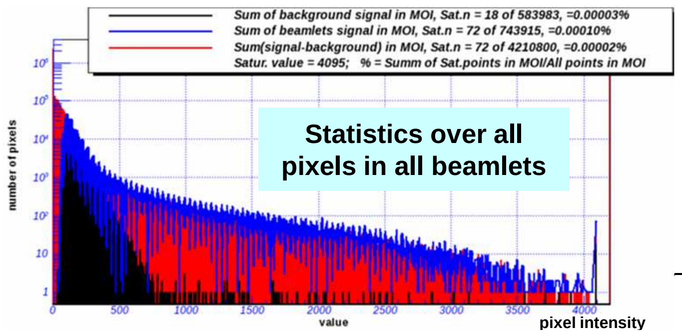
How we measure the transverse projected emittance

Single slit scan technique

- **>** **Emittance Measurement SYstem (EMSY)** consists of horizontal / vertical actuators with
  - **YAG** / OTR screens
  - **10** / 50 µm slits
- **>** Beam size is measured @ slit position using screen
- **>** Beam local divergence is estimated from beamlet sizes @ observation screen (12 bit camera)







2D corrected normalized RMS emittance

$$\varepsilon_n = \frac{\sigma_x}{\sqrt{\langle x^2 \rangle}} \beta\gamma \sqrt{\langle x^2 \rangle \cdot \langle x'^2 \rangle - \langle xx' \rangle^2}$$

correction factor (>1) introduced to correct for low intensity losses from beamlet measurements

σ_x - RMS beam size measured with YAG screen at slit location

SQRT(<x^2>) - RMS beam size at slit location estimated from slit positions and beamlet intensities

➔ "100% RMS emittance"

(conservative estimate)

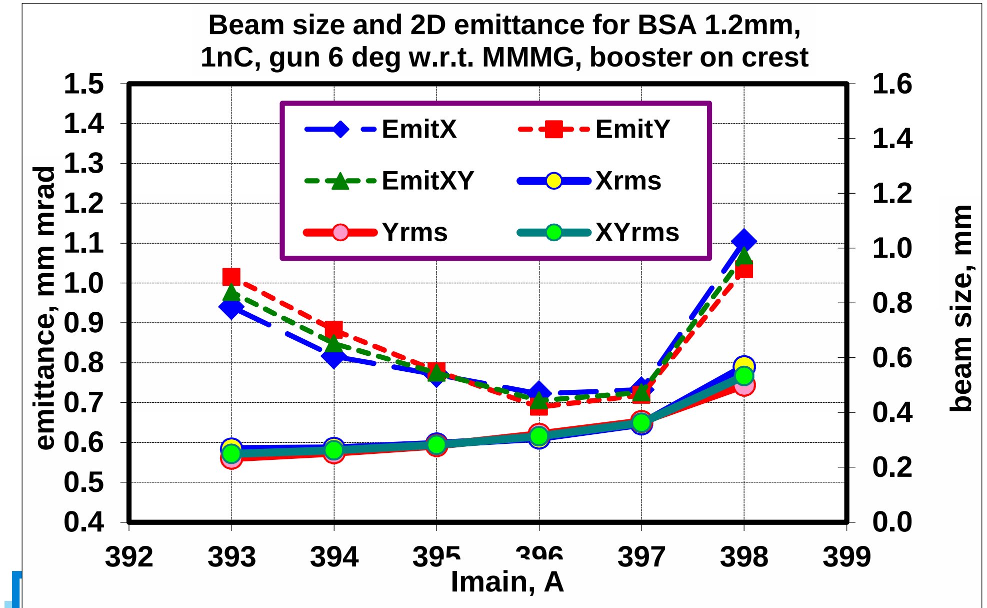
High stability of the measurement

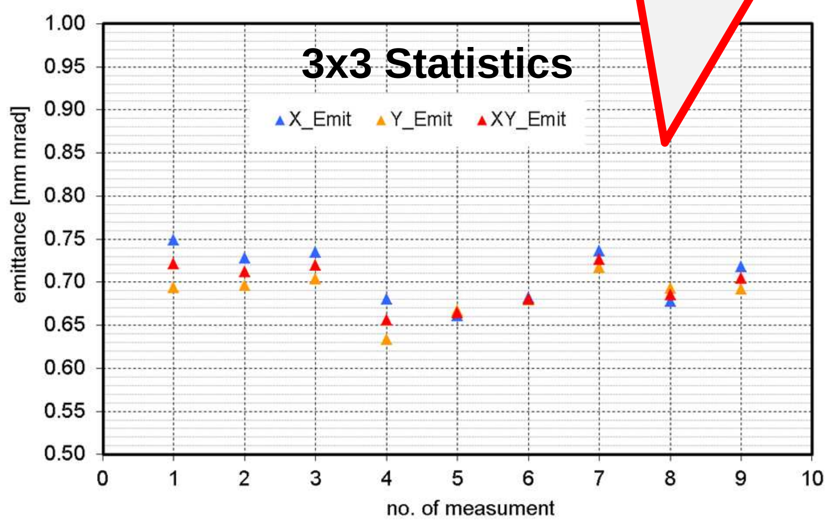
Example, measurement on 5.5.2011: 1nC, Emittance vs. Imain (gun SP phase=6deg)

For all measurements f250 lenses and 2x2 binning were used

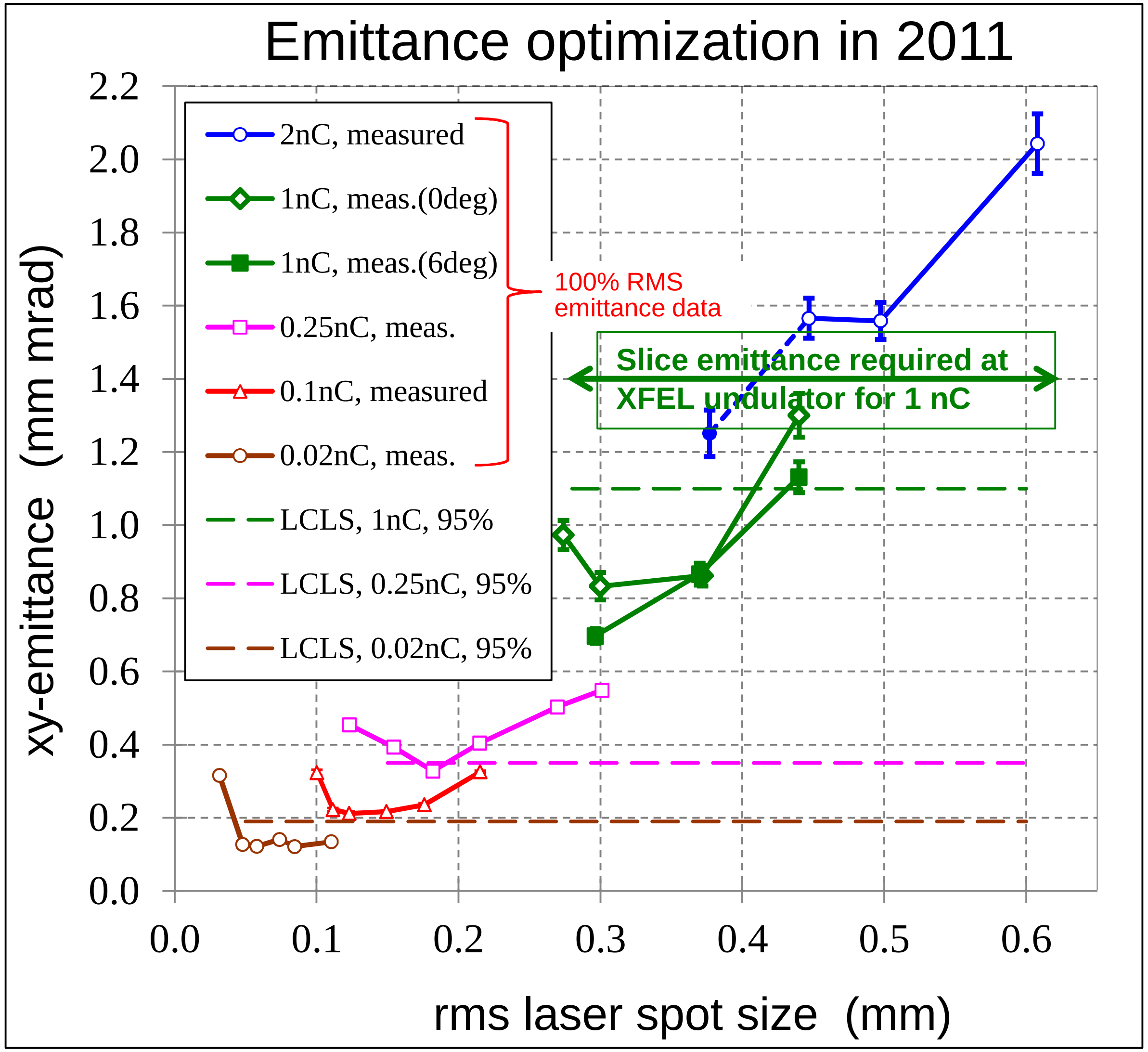
I_main (A)	Xrms, mm	Yrms, mm	EmitX_2D, mm mrad	EmitX_2D, nonscaled	XYrms, mm	EMSY1 NoP	EMSY1 Gain	MOI NoP	MOI, Gain	XBL NoP	XBL gain	EmitY_2D, mm mrad	EmitY_2D, nonscaled	YBL NoP	YBL gain	EmitXY_2D, mm.mrad	EmitXY_2D, nonscaled	X-scale factor	Y-scale factor
398	0.567	0.501	1.104	0.739	0.533	2	23	2	22	16	25	1.034	0.892	15	25	1.068	0.812	1.5	1.3
397	0.359	0.367	0.732	0.583	0.363	1	25	1	24	10	25	0.719	0.650	10	25	0.725	0.616	1.3	1.2
396	**0.307**	**0.320**	**0.722**	**0.479**	**0.313**	**1**	**21**	**1**	**21**	**5**	**25**	**0.689**	**0.584**	**7**	**24**	**0.705**	**0.529**	**1.5**	**1.3**
395	0.285	0.279	0.770	0.424	0.282	1	18	1	18	3	25	0.779	0.571	5	25	0.774	0.492	1.8	1.6
394	0.269	0.254	0.816	0.408	0.261	1	15	1	16	3	25	0.882	0.646	5	24	0.848	0.513	2.0	1.7
393	0.266	0.234	0.940	0.453	0.249	1	13	1	15	4	23	1.015	0.723	5	25	0.977	0.572	2.1	1.7

ε_x=(0.707±0.032) mm mrad
ε_y=(0.686±0.024) mm mrad
ε_{xy}=(0.697±0.026) mm mrad





Emittance vs. Laser Spot size for various charges in 2011



Minimum emittance

Charge, nC	PITZ, 100%, mm mrad	LCLS, 95% mm mrad
2	1.25	
1	0.70	1.10
0.7		0.80
0.25	0.33	0.35
0.1	0.21	
0.02	0.12	0.19

> **PITZ is setting a new benchmark for minimum emittance at a given charge**
> **+**
> **is capable of operation at fairly high duty cycle !!**

LCLS data:

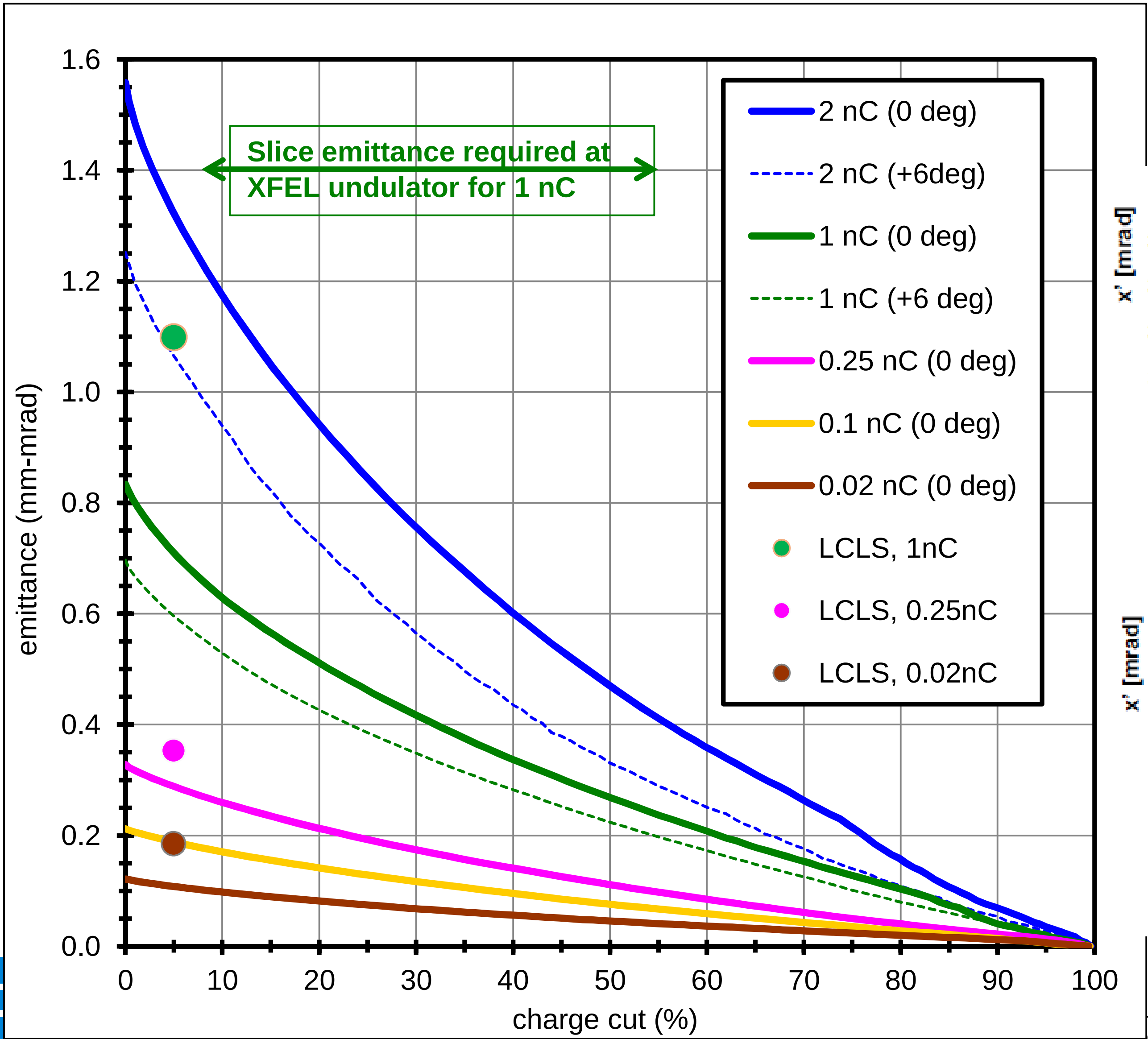
- P. Emma, "Beam Brightness Measurements in the LCLS Injector", Mini-WS on compact XFELs using HBB, LBNL, Berkeley, USA, 2010.
- J. Frisch, "Operation and Upgrades of the LCLS", LINAC2010, Tsukuba, Japan.

PITZ data:

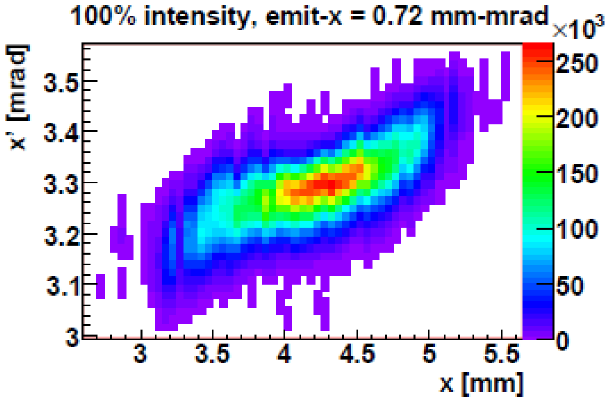
- M. Krasilnikov et. al., "Experimentally minimized beam emittance from an L-band photoinjector" , PRST-AB **15,** 100701 (2012).

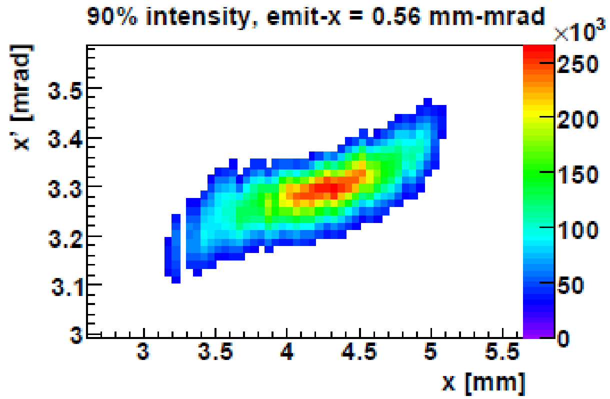
Core Emittance for various bunch charges

- **Idea: Cut low intensity region of MEASURED phase space (i.e. remove non-lasing part)**

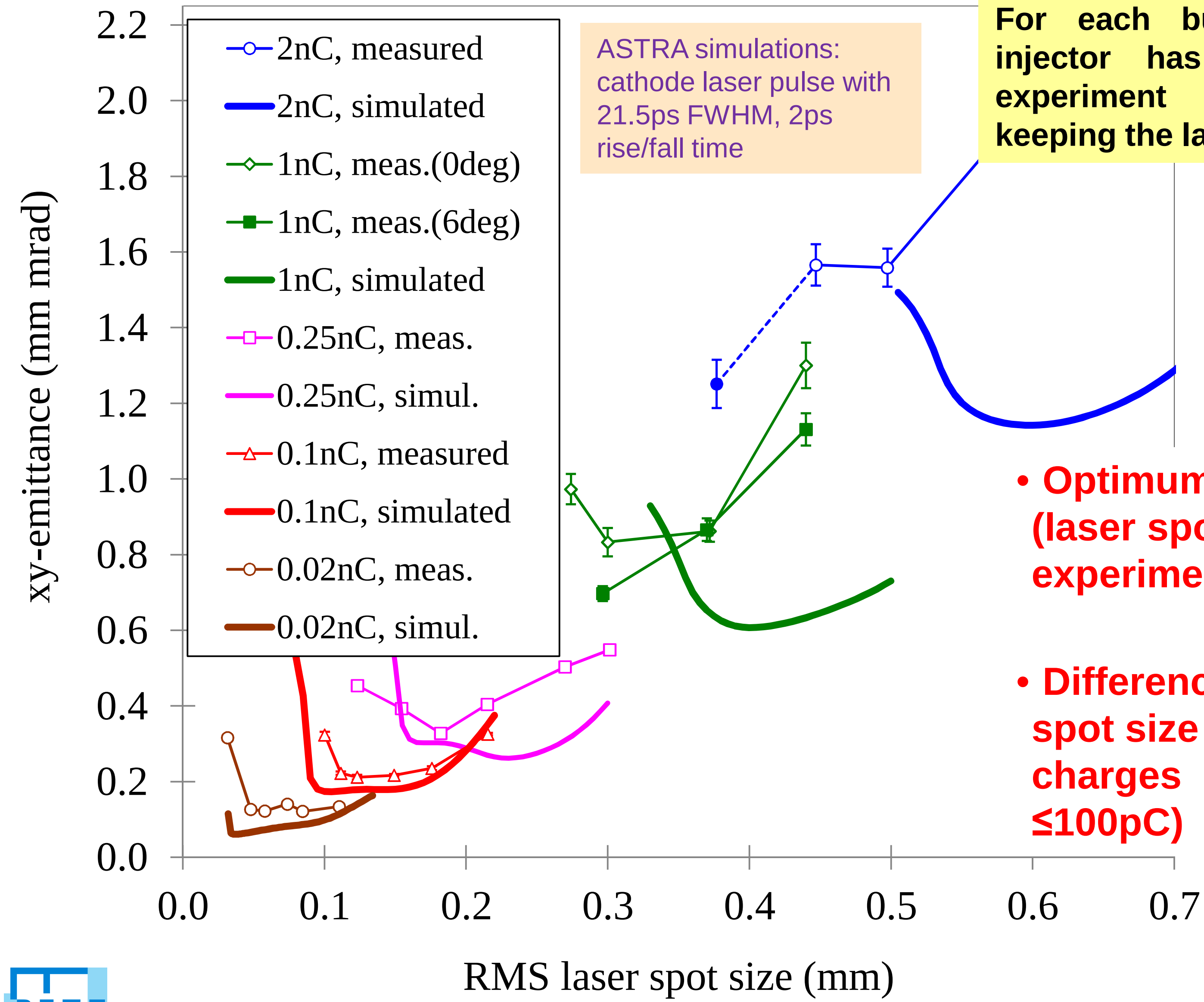


An example for 1 nC:





2011 PITZ 1.8: measurements vs. simulations

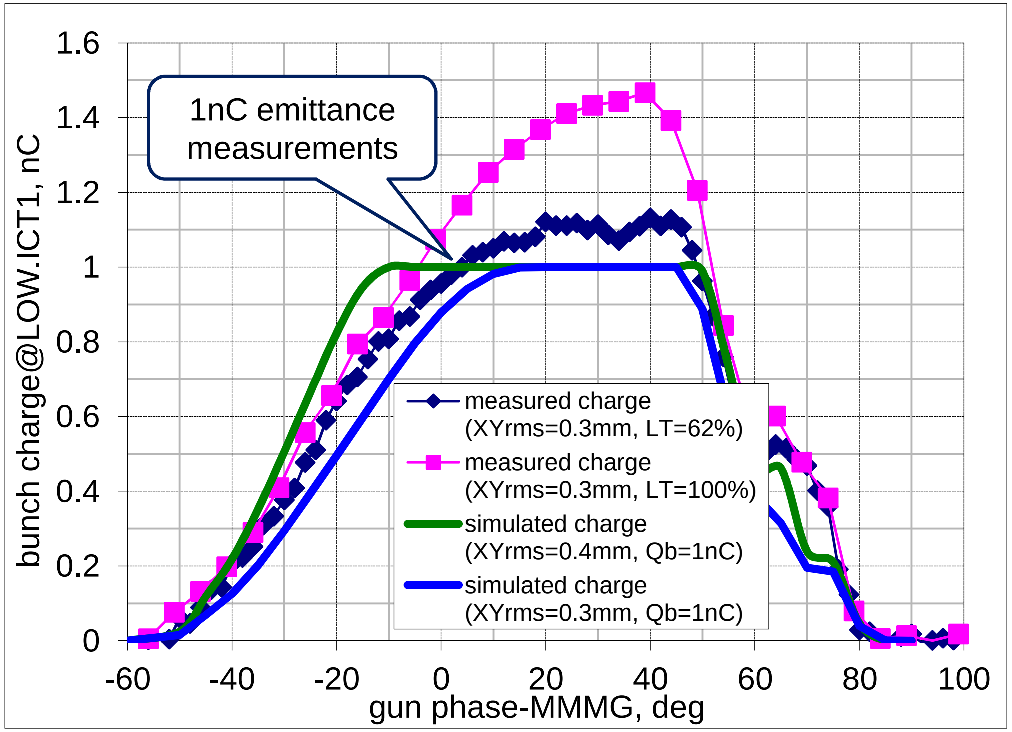


For each bunch charge the photo injector has been optimized (both experiment and simulations), but keeping the laser temporal profile fixed.

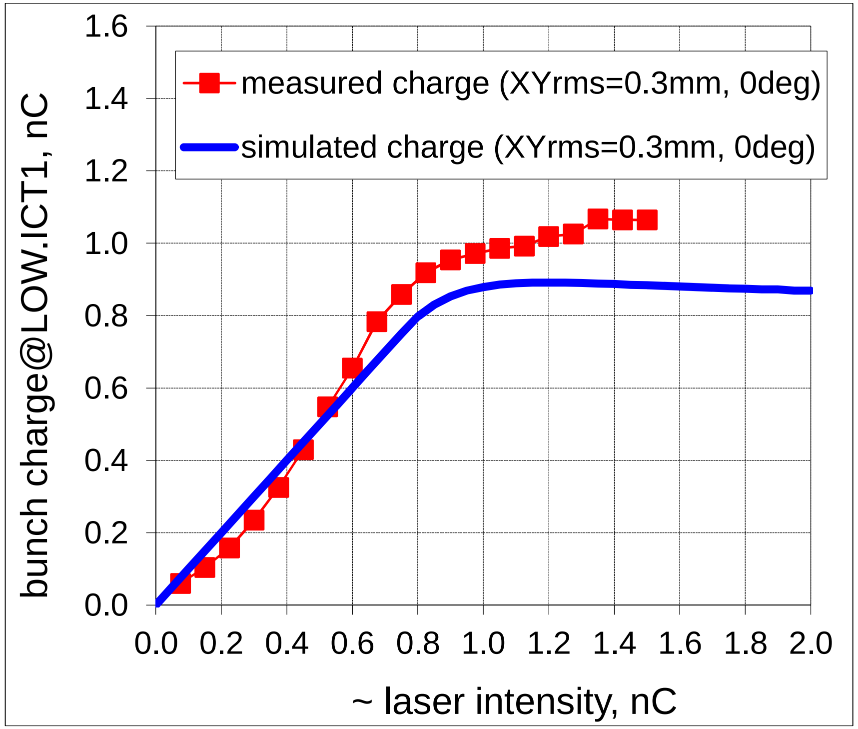
- **Optimum machine parameters (laser spot size, gun phase): experiment ≠ simulations (~on-crest)**
- **Difference in the optimum laser spot size is bigger for higher charges (good agreement for ≤100pC)**

Reasons of discrepancy for high Q? → Emission from the cathode?

Measured and simulated Schottky scans (1nC)



Measured and simulated laser energy scan (1nC)



- Direct plug-in machine settings into ASTRA does not produce 1nC at the gun operation phase (+6deg), whereas 1nC and even higher charge (~1.2nC) are experimentally detected
- Simulated (ASTRA) phase scans w/o Schottky effects (solid thick lines) have different shapes than the experimentally measured (thin lines with markers)

- Laser intensity (LT) scan for the MMMG phase (red curve with markers) shows higher saturation level, whereas the simulated charge even goes slightly down while the laser intensity (Qbunch) increases

Photo emission (bunch charge) needs more detailed modeling in simulations.

Key components for successful operation of NC RF photoinjectors

- good **RF stability**

- good cooling **water stability** (increasingly difficult for high average RF power)
  - e.g. better than ±0.05 degrees are needed at 50 kW average power for the PITZ case

- robust and **high** quantum efficiency (**QE**) **photo cathodes**
(especially important for high average current)
  - e.g. the PITZ photo cathode system was developed by INFN-LASA Milano
→ see talk of Daniele Sertore

- stable **photo cathode laser system** with high **flexibility**
  - e.g. the PITZ photo cathode laser system was developed by the Max-Born-Institute in Berlin
→ see talk of Ingo Will
  - High flexibility of photo cathode laser opens new research possibilities
→ excursion to **plasma acceleration**
  - **fancy shaping** of the photo cathode laser pulses can further improve the beam quality

Photo cathode laser system installed at PITZ

(for more see I. Will)

Yb:YAG laser with integrated optical sampling system

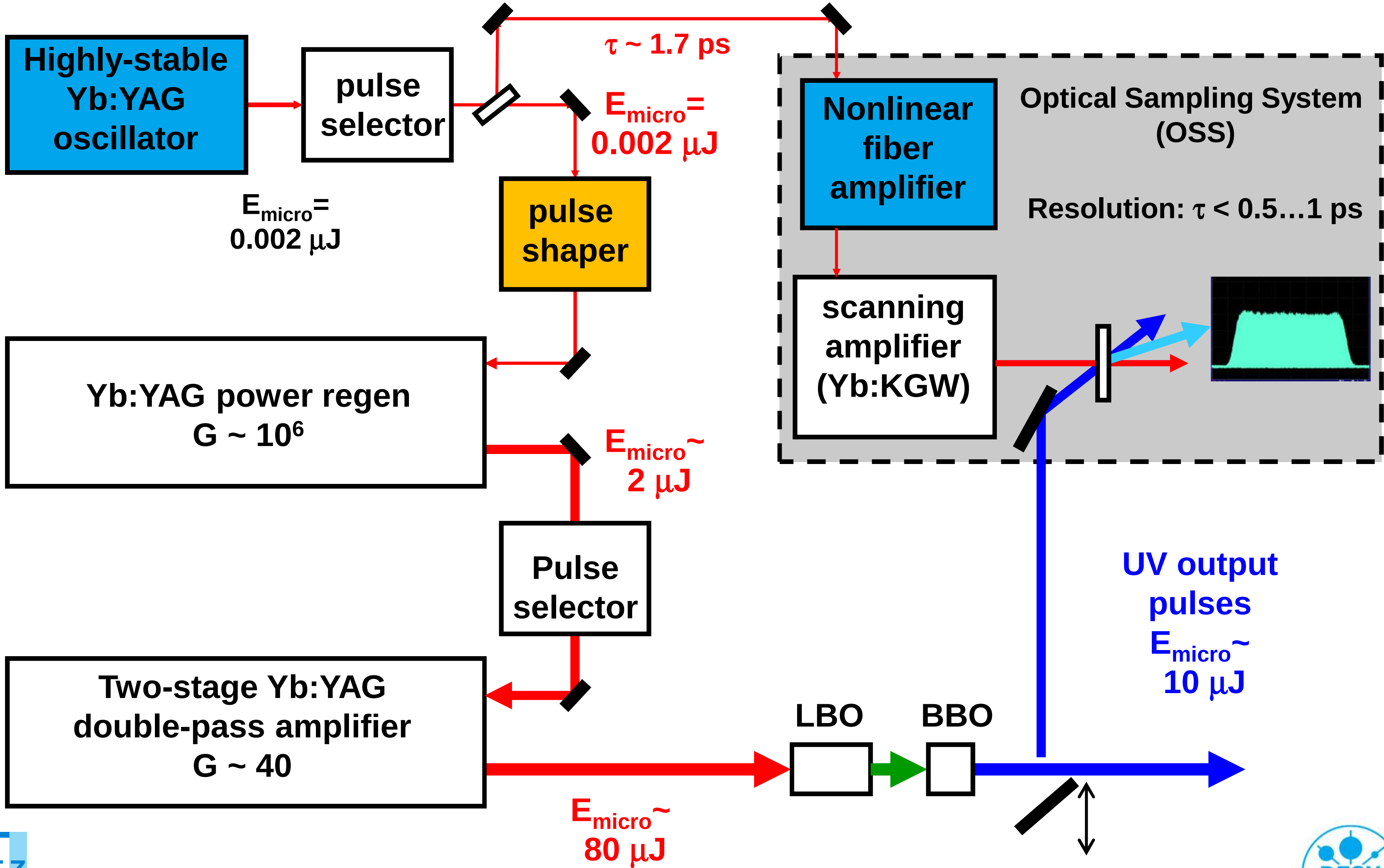
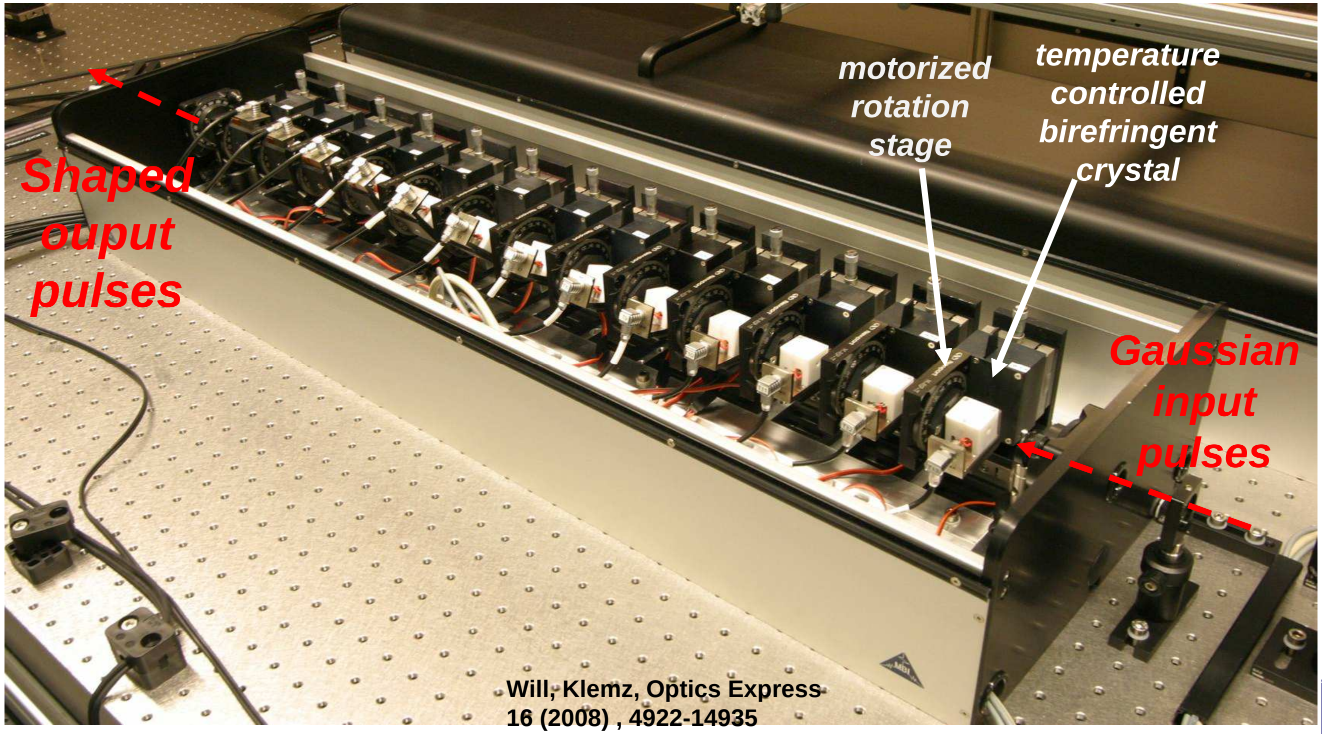


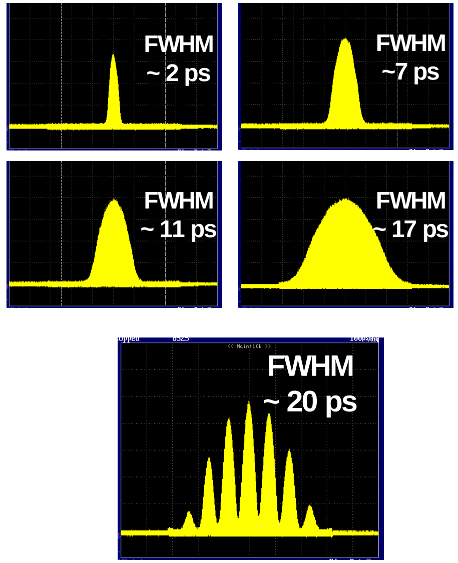
Photo cathode laser: temporal pulse shaping

(for more see I. Will)

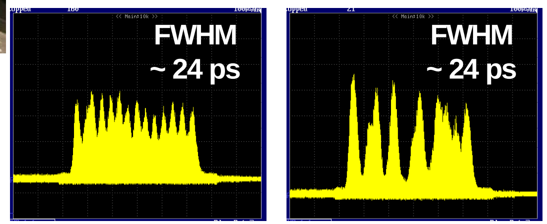
Multicrystal birefringent pulse shaper containing 13 crystals

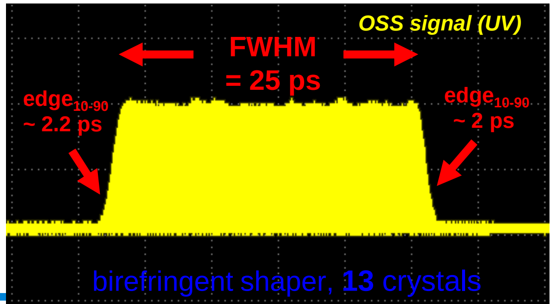


Gaussian:



Simulated pulse-stacker





→ important for good beam quality

→ high flexibility→ new options !

Particle driven plasma wakefield acceleration (PDPWA)

Proton-driven PWFA experiment proposed at CERN:

("AWAKE")

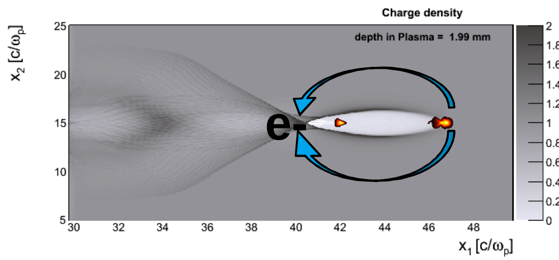
- Use high energy proton beams to drive wake (plasma wave)
- Convert proton beam energy into e^- or e^+ beam in a single stage

Caldwell *et al.*, Nature Physics (2009); Lotov, PRST-AB (2010)

$\Rightarrow$ high gradient requires high density: $E_z \propto n^{1/2}$

$\Rightarrow$ large wake requires resonance beam: $L_b \sim \lambda_p \propto n^{-1/2}$

$$E_{z,\max} \approx 3\ \mathrm{GV/m} \left(\frac{N_b}{10^{10}}\right)\left(\frac{100\mu\mathrm{m}}{\sigma_z}\right)^2 \ln(\sigma_z/\sigma_r)$$



$\Rightarrow$ high accelerating gradient requires **short** bunches $\sigma_z \lesssim 100\ \mu$m

$\Rightarrow$ existing proton machines produce **long** bunches $\sigma_z \sim 10$ cm

- Use beam-plasma instability to modulated the beam at λ_p, driving large plasma waves for acceleration Kumar *et al.*, PRL (2010); Lotov, Phys. Plasmas (2011)

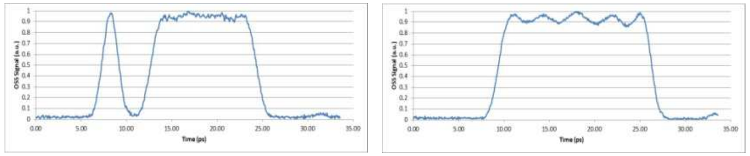
Does this work ?
→Dephasing ?
→Hose instability ?

Courtesy of Carl Schröder, LBNL

LAOLA @ PITZ: Studies for Particle Driven Plasma Acceleration

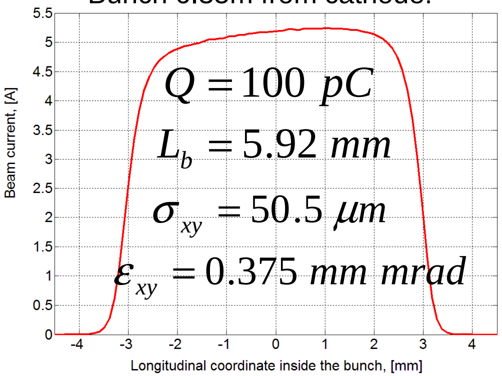
1) **Self-modulation of electron beam** (proof of principle for CERNs AWAKE exp.)

- use high flexibility of photo cathode laser system:

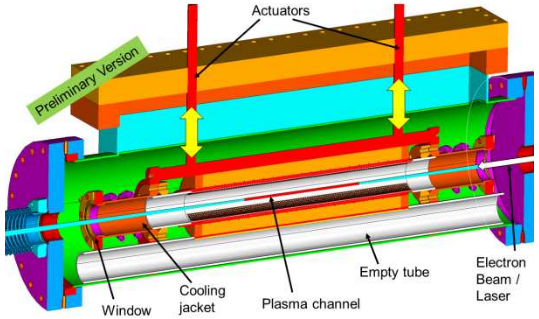


- **Example: flat-top e-beam through plasma cell:**

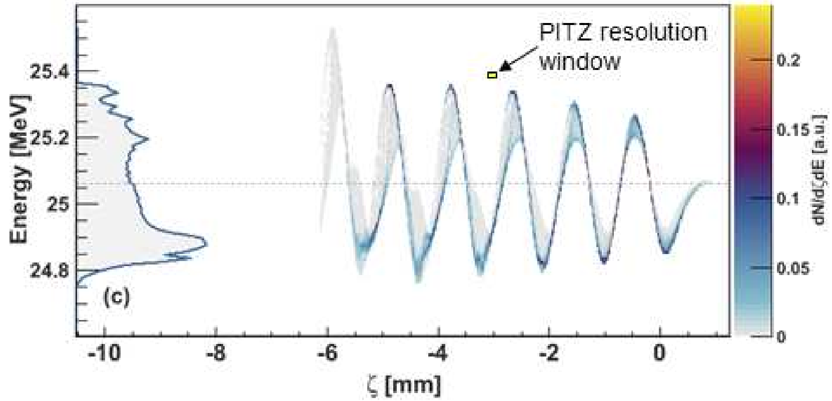
Bunch 6.35m from cathode:



Peak density ≈10^{13} e^-/cm^3



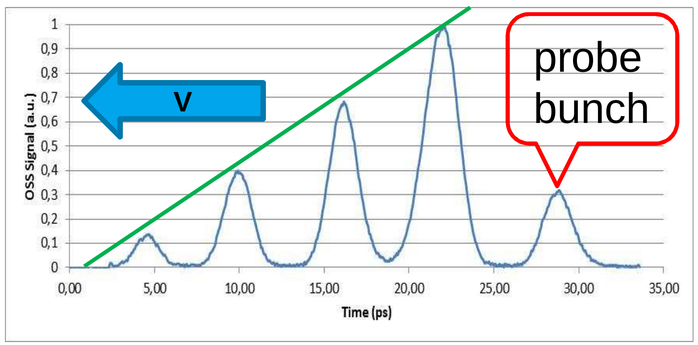
Plasma density ≈$10^{15}/cm^3$



2) **Study high transformer ratio**

- resonantly drive plasma wave with specially shaped electron bunch (5 bunchlets inside the bunch)

→ high transformation ratio:



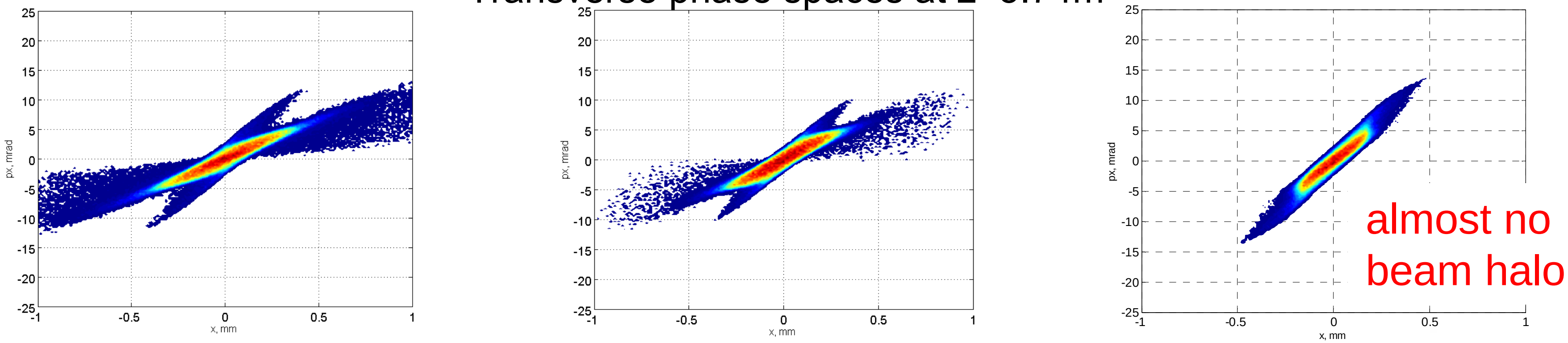
to be sent to bunch compres-sor

New option for the photo cathode laser → 3D ellipsoid

→ Collaboration IAP N.Novgorod / JINR Dubna / DESY
→ for more see Ekaterina Gacheva

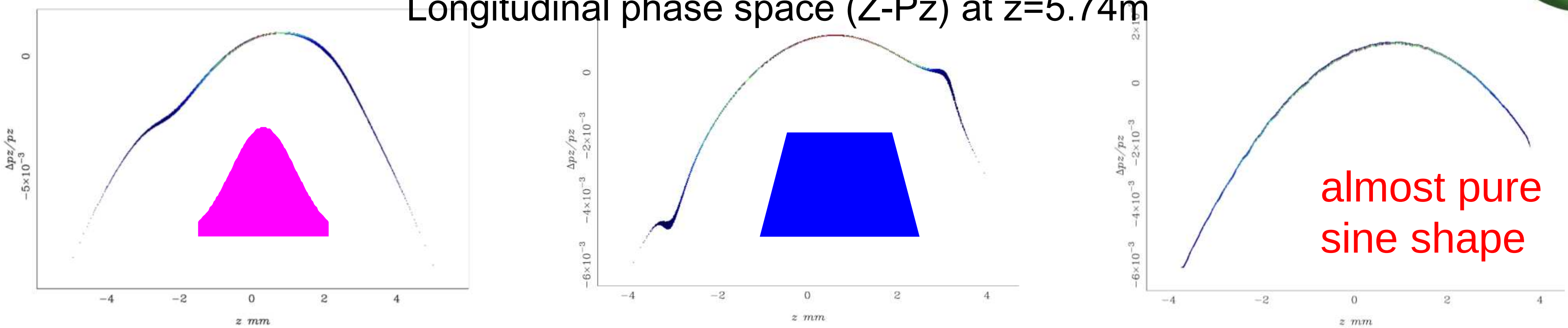
BD simulations for 100 pC bunch charge:

Transverse phase spaces at z=5.74m



Gaussian **Flat-top** **Ellipsoid**

Longitudinal phase space (Z-Pz) at z=5.74m



> **Benefits** **from 3D ellipsoidal laser pulses for ALL linac driven light sources:**
- **30-50% lower average slice emittance** → higher **brilliance**
- ~pure sinusoidal longitudinal phase space +3rd harm. →simplify/allow required **compression**
- ~no beam halo → better signal/noise, reduced **radiation damage**
- less sensitive to machine settings → higher **stability**

Summary

- Normal conducting RF photo injectors are a **mature and reliable technology** to produce **high brightness beams** for FEL applications
- From low to medium average currents (~30µA) a **new benchmark** in optimizing photo injector performance **was demonstrated**

TABLE IV. Core *xy* emittance (mm mrad) measured for various bunch charges and gun phases. Only statistical errors are shown (see text).

Bunch charge	Gun phase	0%	Charge cut 5%	10%	20%
2.0 nC	0 deg	1.558 ± 0.050	1.324 ± 0.045	1.173 ± 0.039	0.936 ± 0.031
2.0 nC	6 deg	1.251 ± 0.064	1.064 ± 0.054	0.939 ± 0.048	0.728 ± 0.037
1.0 nC	0 deg	0.833 ± 0.038	0.711 ± 0.033	0.629 ± 0.029	0.511 ± 0.024
1.0 nC	6 deg	0.696 ± 0.020	0.596 ± 0.017	0.529 ± 0.015	0.427 ± 0.013
0.25 nC	0 deg	0.328 ± 0.010	0.289 ± 0.009	0.260 ± 0.008	0.213 ± 0.006
0.10 nC	0 deg	0.212 ± 0.006	0.188 ± 0.006	0.170 ± 0.006	0.141 ± 0.006
0.02 nC	0 deg	0.121 ± 0.001	0.108 ± 0.001	0.098 ± 0.001	0.082 ± 0.002

from M. Krasilnikov et al., PRST-AB **15**, 100701 (2012).

- For high duty cycle / **CW** applications the main **challenges** (cooling, vacuum properties) **can be solved** → see Berkeley approach
- High brightness photo injectors are also interesting **beyond FEL applications**, e.g. plasma acceleration, electron diffraction (REGAE), …
- **Sincere Acknowledgements:** to all **international colleagues** for discussions over the years, colleagues at Hamburg and Zeuthen, the PITZ team, …