10 Years of Photo Electrons at PITZ

Frank Stephan (DESY) for the PITZ Collaboration

Content:

- Why now ?
- Motivation to build PITZ
- Historical overview
- Some highlights over the years and main results of the last year(s)
- Summary, Outlook and Future Plans

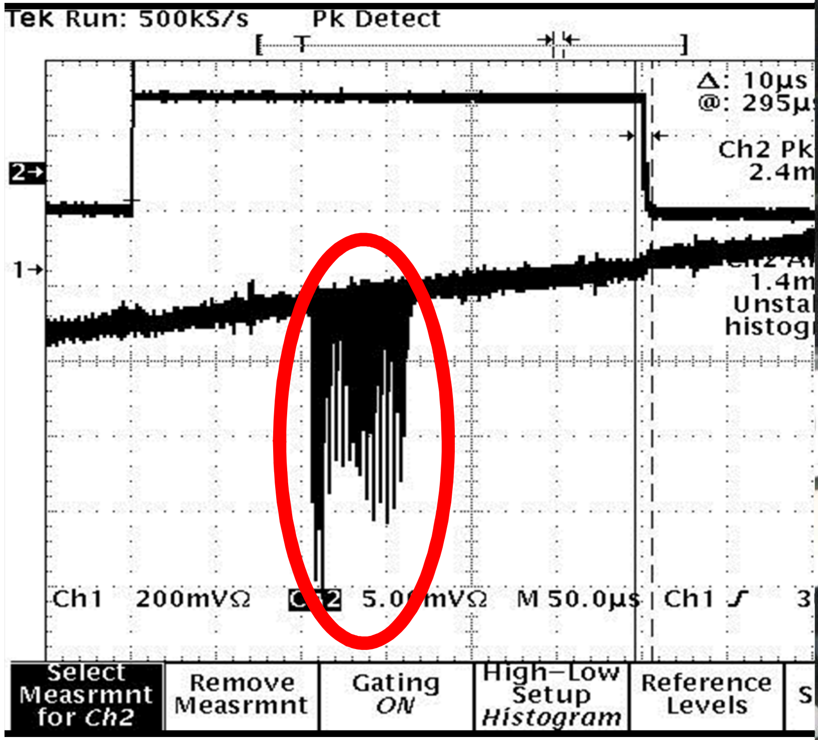
HELMHOLTZ ASSOCIATION

PITZ Photo Injector Test Facility Zeuthen

DESY

Why now ?

January 13th, 2002:
First photo electrons at PITZ

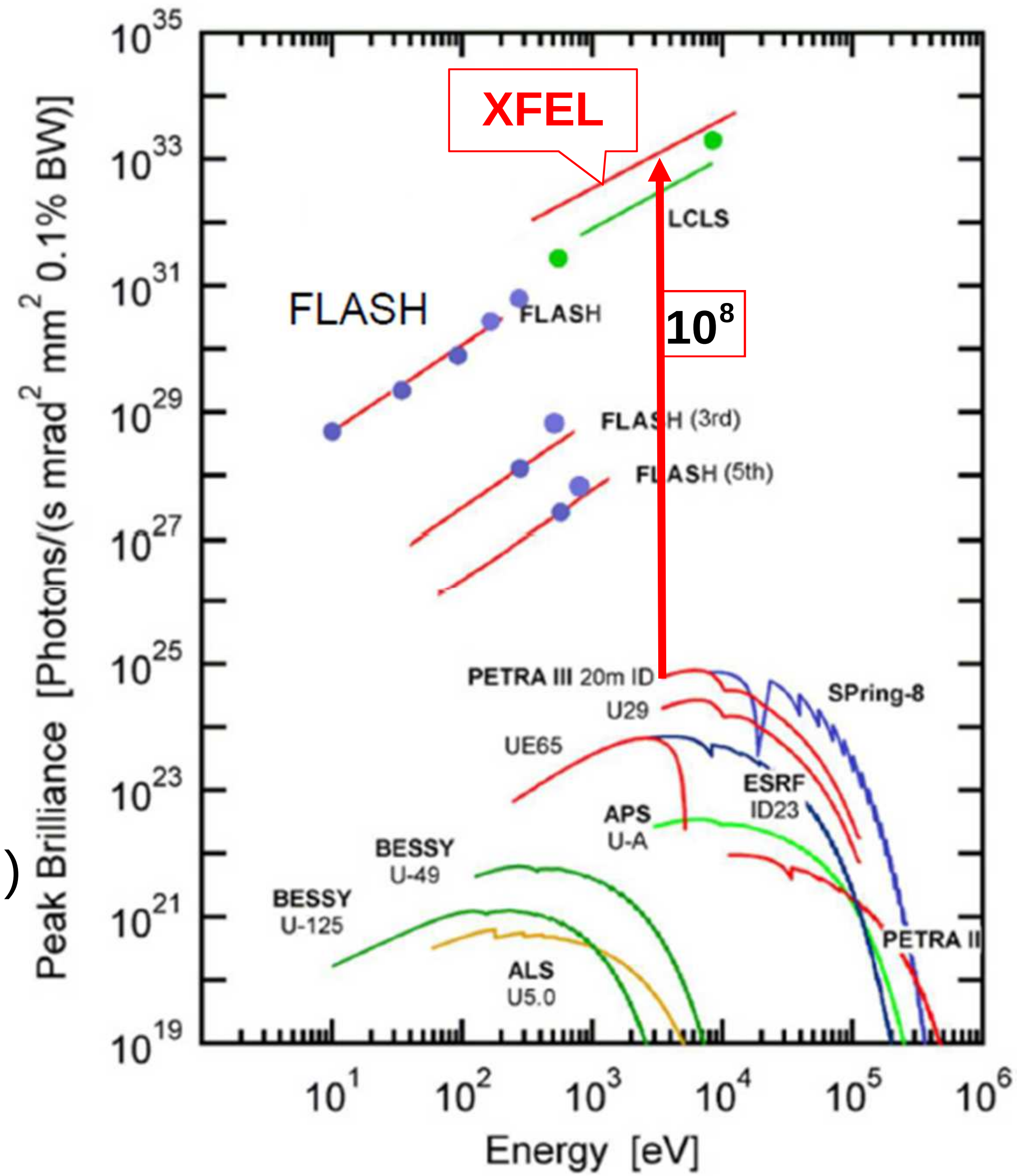


Official start of PITZ on 30.1.2002: Prof. Wagner and Prof. Wanka open the photo cathode laser shutter during the colloquium „10 years DESY in Zeuthen“

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 !!**)



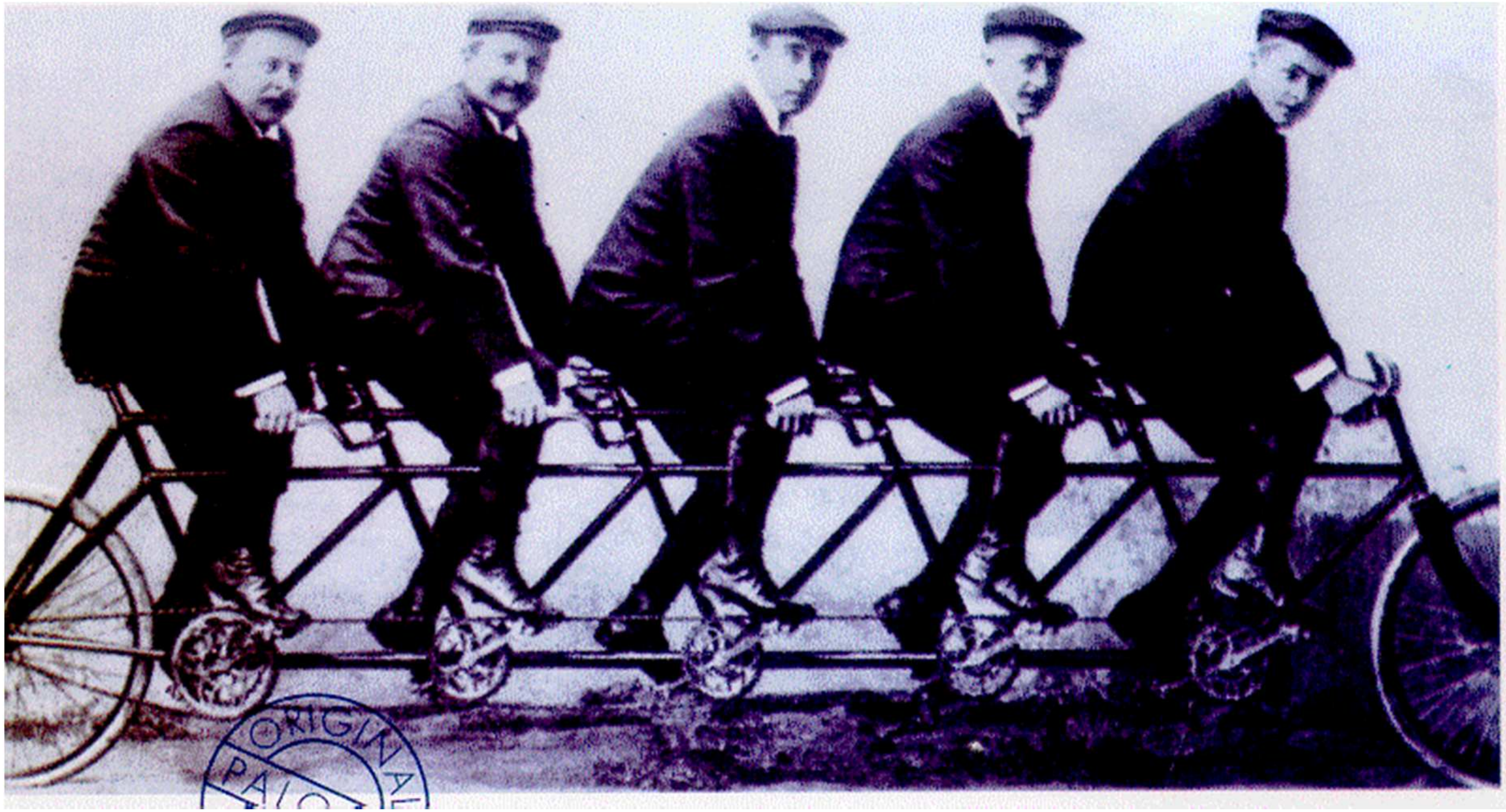
Why brilliance is ~10E+8 higher ?
Synchrotrons: $P \sim N \cdot e^2$
FELs (coherence):

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

$$N \sim 10E{+}8$$

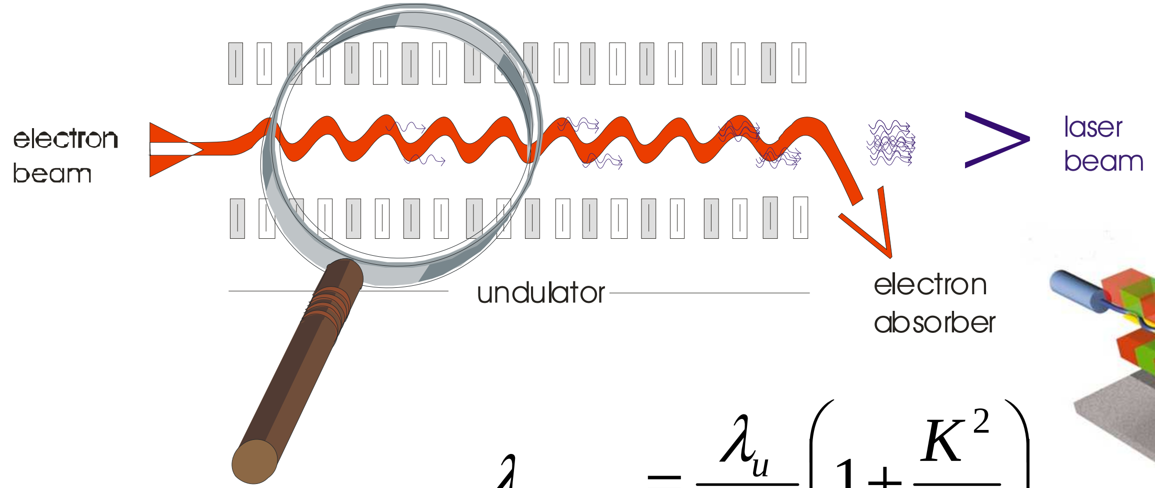
SASE FEL: How does it work?

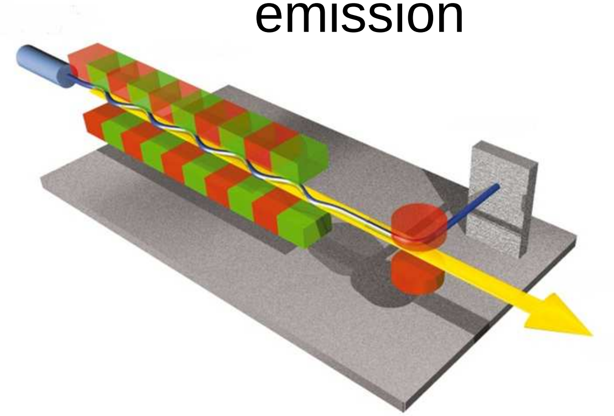
Coherent motion is all we need !!



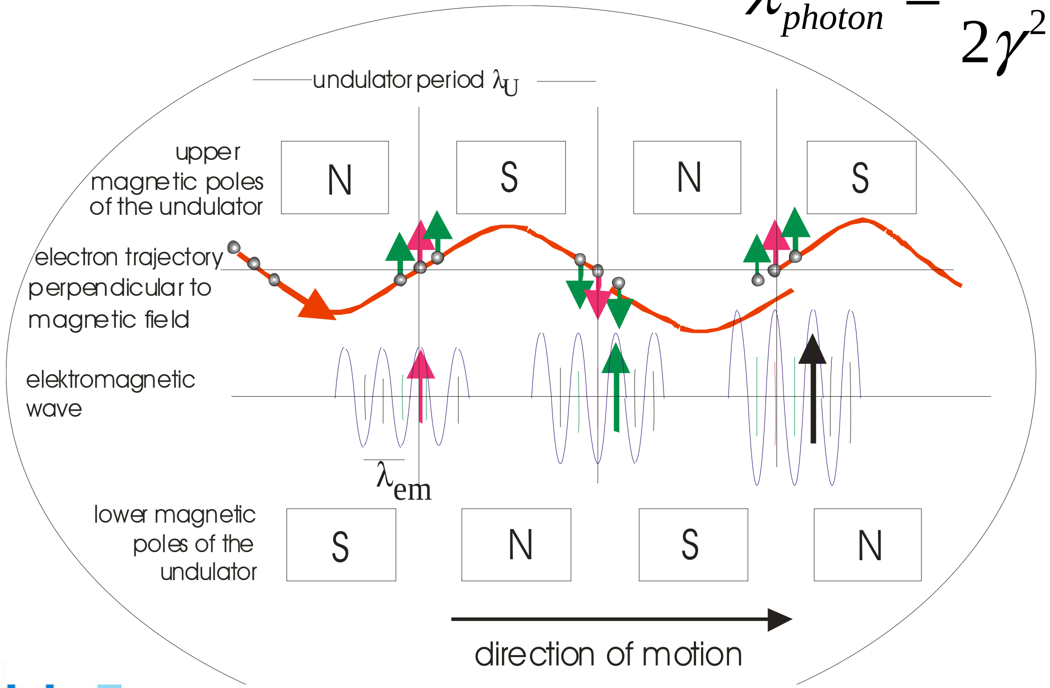
SASE FEL: How does it work?

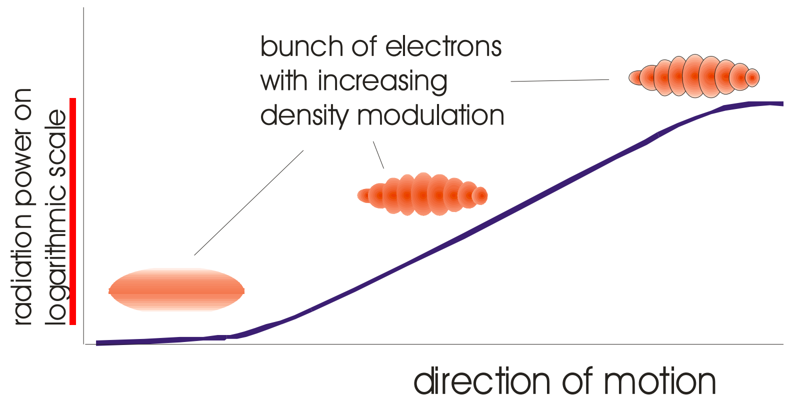
SASE =
self amplified
spontaneous
emission





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





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

One XFEL key component:
→ the high brightness electron source

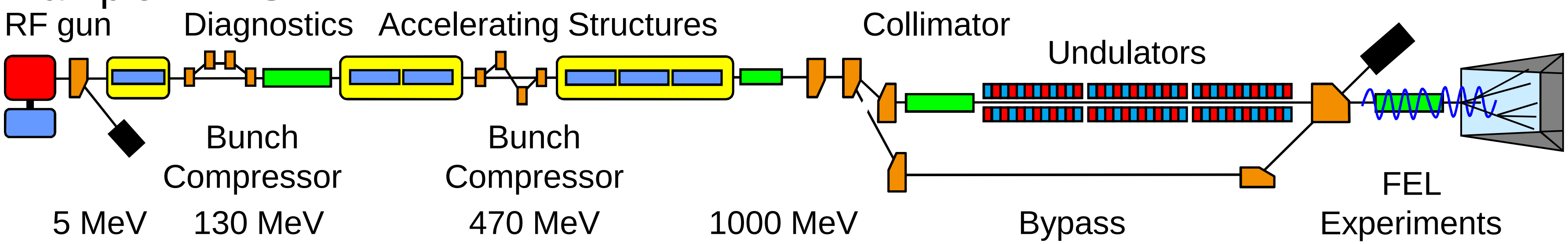
Why electron injector is so important …. ???

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



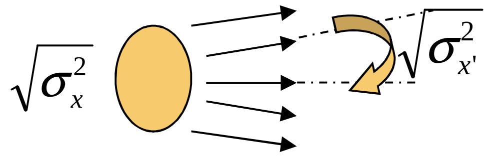
property of linacs: beam quality will DEGRATE during acceleration in linac

→ electron source has to produce lowest possible emittance !!

What is Emittance ?

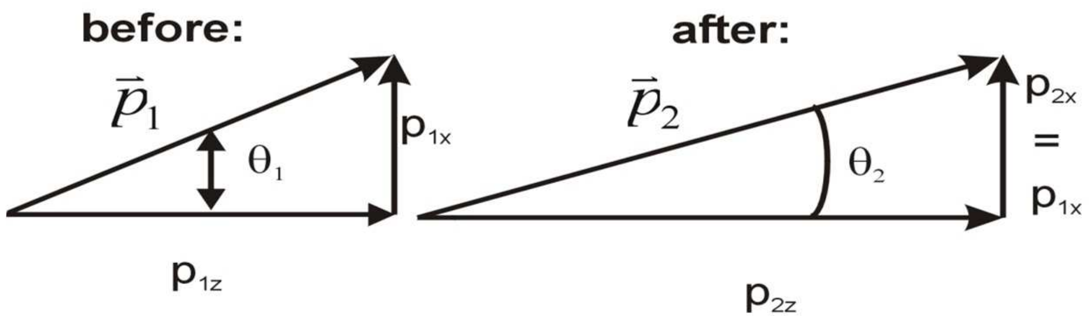
long.: ε_z ~ (e⁻ bunch length) • (energy spread of e⁻ bunch)

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



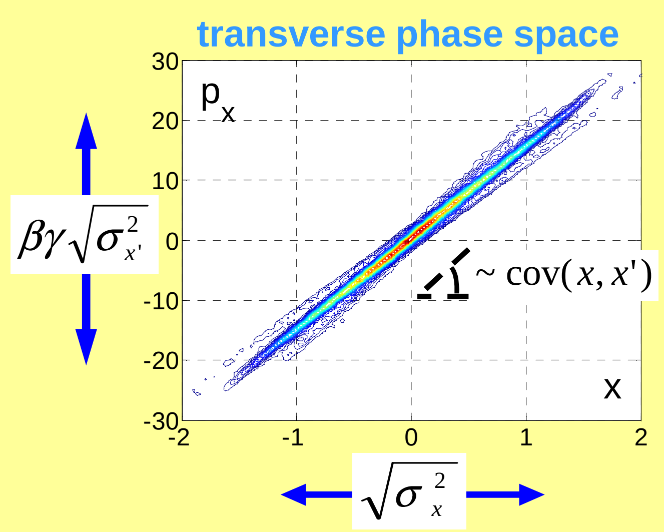
ε = 6 dimensional phase space volume occupied by given number of particles

effect of acceleration on transverse emittance (adiabatic damping):



$\theta_2 < \theta_1$

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



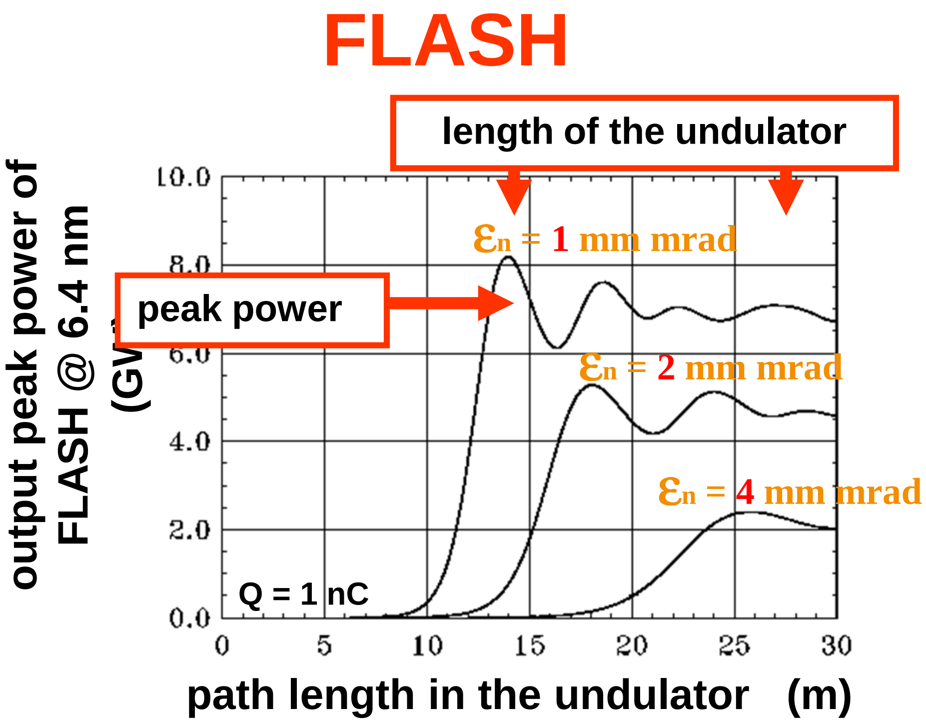
$\Rightarrow$ normalized RMS transverse emittance:

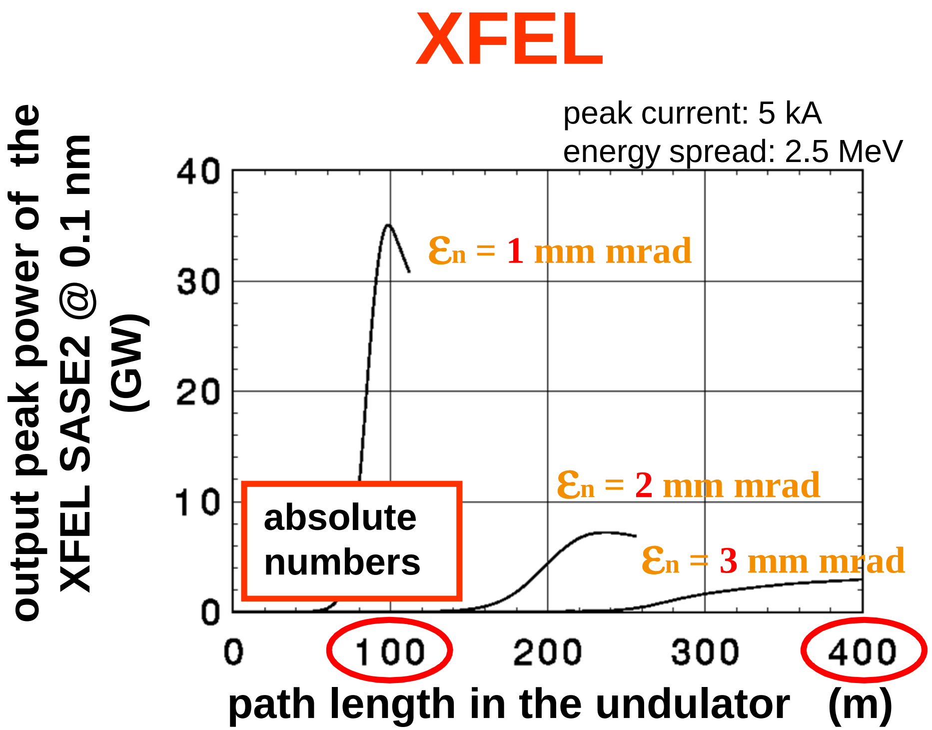
$$\varepsilon_x^n = ß \bullet \gamma \bullet \sqrt{\sigma_x^2 \bullet \sigma_{x'}^2 - \mathrm{cov}^2(x, x')}\,; \quad ß = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1 - ß^2}}, \quad x' = \frac{dx}{ds}$$

(ε^n is conserved in general)

Why electron injector is so important …

- **Why emittance must be small …**



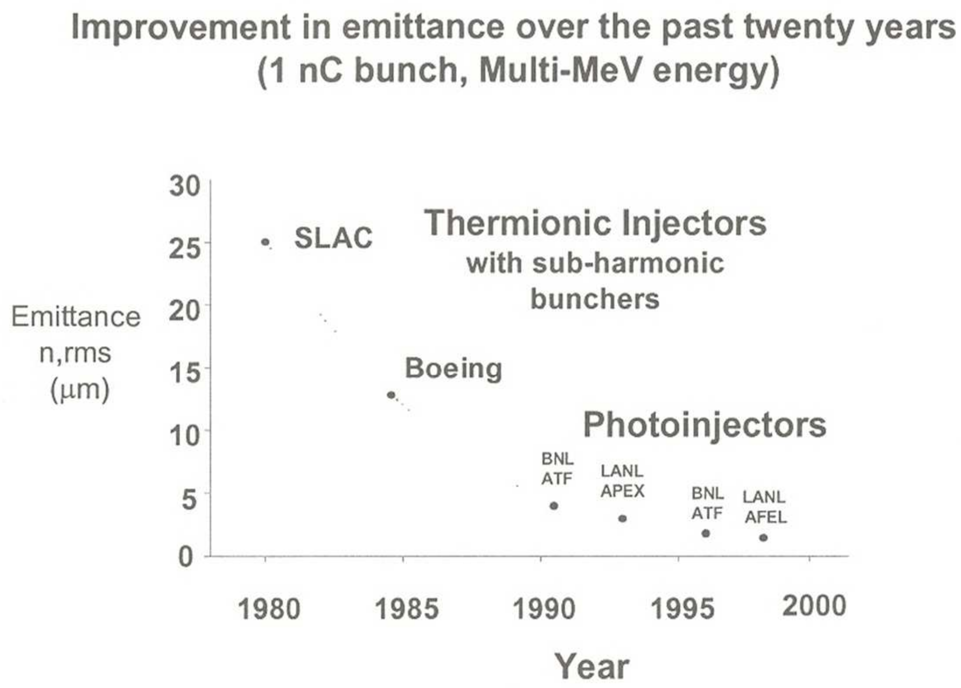


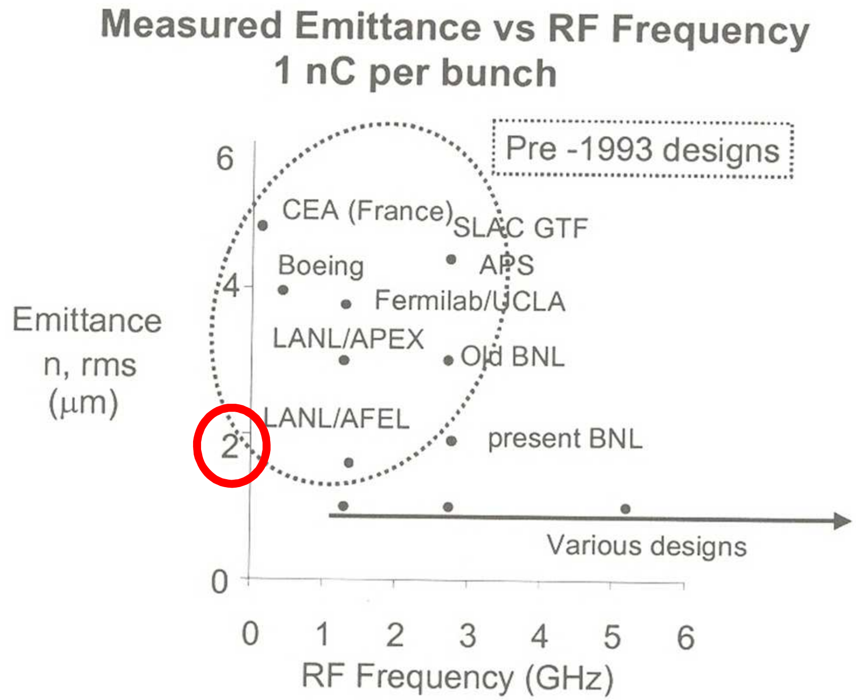
- **XFEL goal: 0.9 mm mrad@injector = 1.4 mm mrad@undulator**
- **if even smaller emittance ⇒ new horizons:**

  shorter wavelength, higher repetition rate

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

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





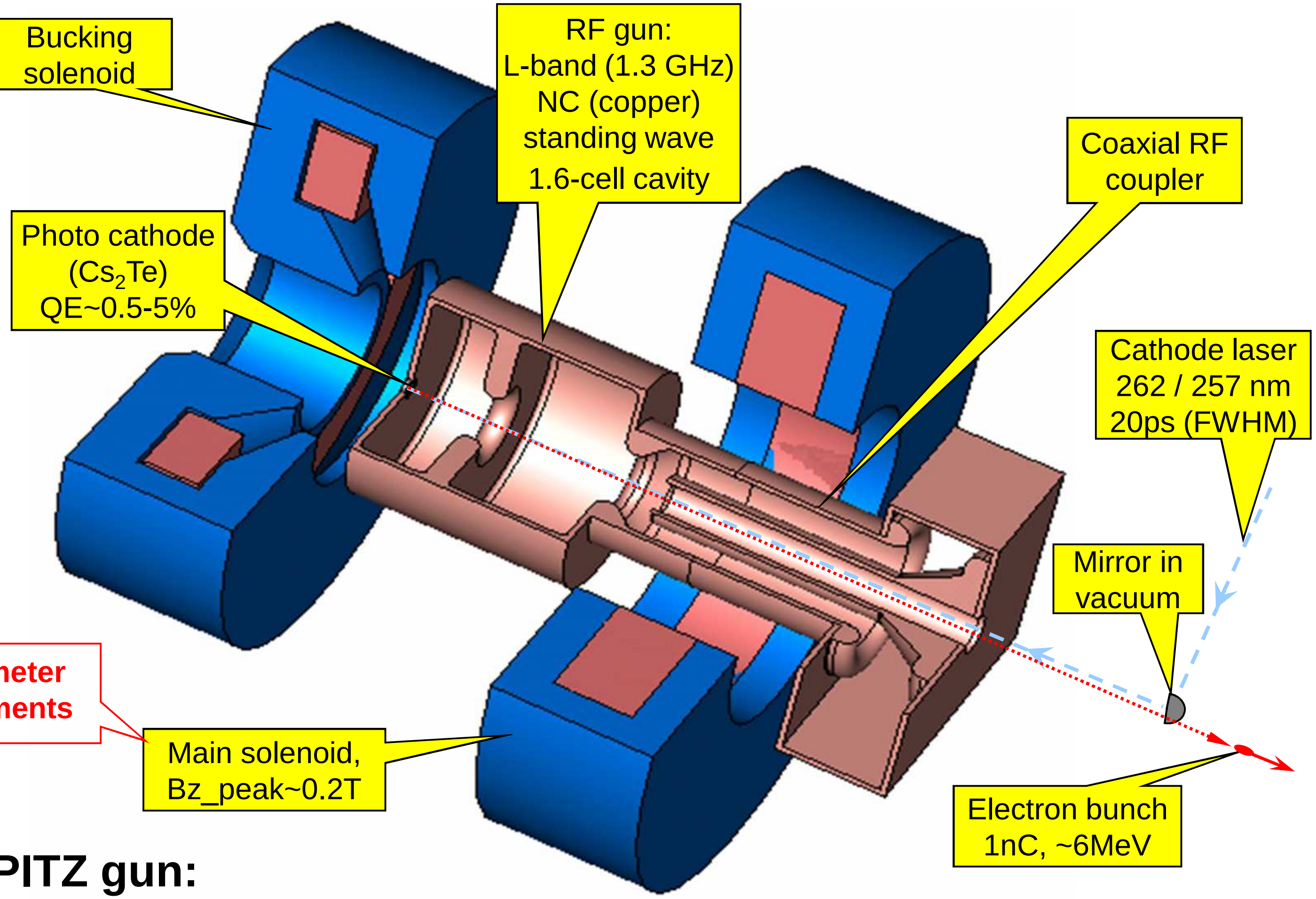
"Goal for community in next years:

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

Most prominent solution: Photo Cathode RF Gun

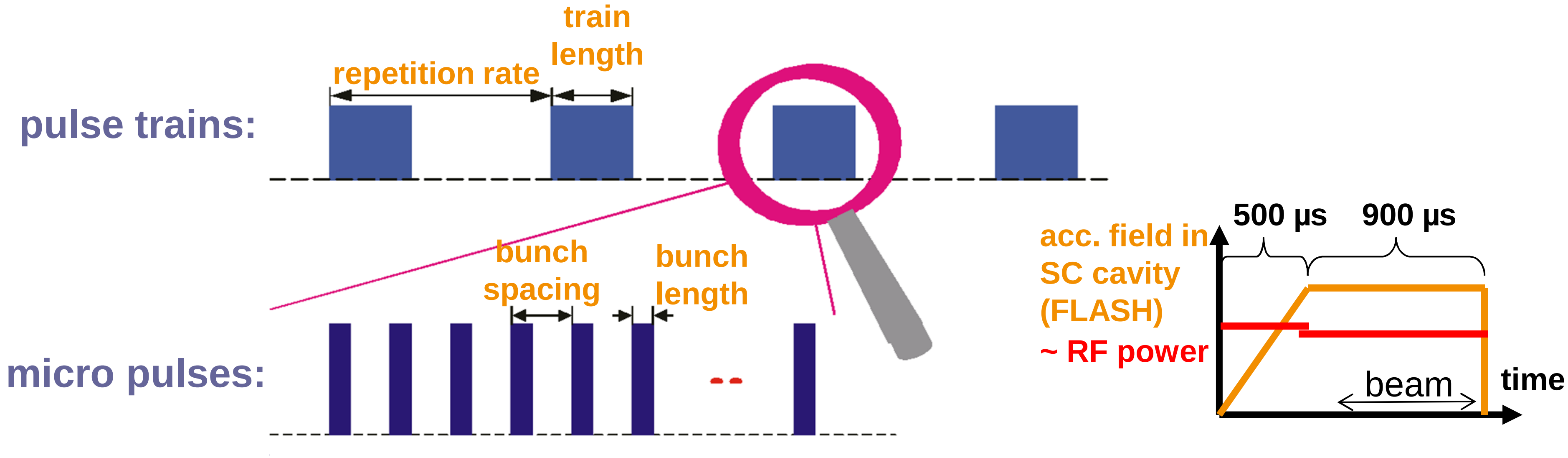
Example:
PITZ gun

(**P**hoto **I**njector **T**est facility at DESY, **Z**euthen 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

Collaborations

> Founding partners of PITZ:

- DESY, HH&Z (leading institute)
- HZB (BESSY): magnets, vacuum
- MBI (group W. Sandner): cathode laser
- TU Darmstadt (TEMF, T. Weiland): simulations

> Other national partners:

- Hamburg university:
  - most PhD students;
  - HGF-Vernetzungsfond;
  - generation of short pulses
  - plasma experiments
- FZD:
  - BMBF-PC-laser-project between MBI, DESY and FZD, unitl ~2009;
  - ~ regular exchange;
  - planned collaboration between HZB, FZD, MBI and DESY in SC-gun-cluster

> International partners in the **PITZ Collaboration**:

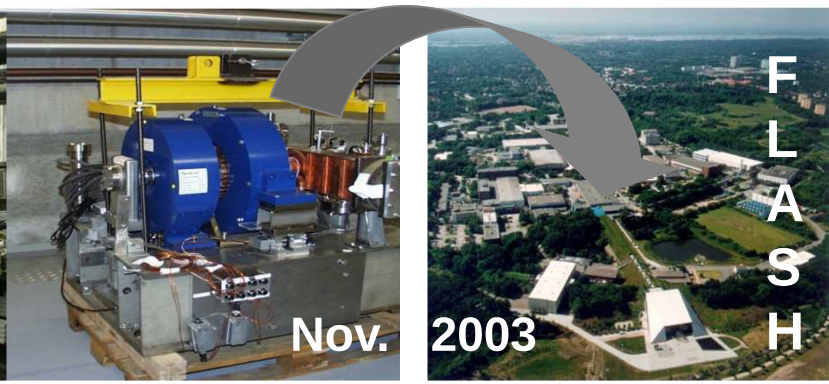
- CCLRC Daresbury (S. Smith, B.Militsyn): phase space tomography
- INR Troitsk (L. Kravchuk): CDS, TDS, Gun5
- INRNE Sofia (I. Tsakov): EMSY + personnel
- LAL Orsay (T. Garvey → A. Variola): HEDA1 + HEDA2
- Thailand Center of Excellence in Physics (T. Vilaithong, Ch. Thongbai): personnel

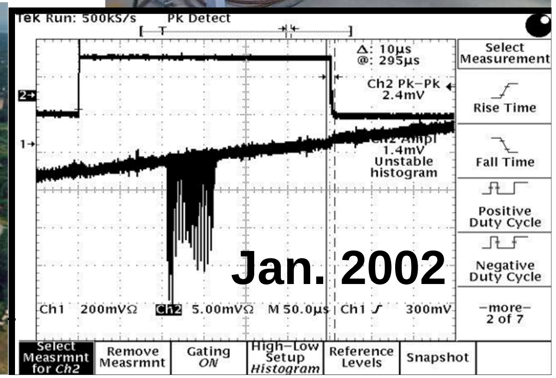
> Other international partners:

- INFN Milano (C.Pagani): photo cathodes
- INFN Frascati + Uni Roma (L. Palumbo, M. Ferrario): TDS and E-meter pre-studies
- YERPHI Yerevan (V. Nikoghosyan): personnel
- IAP Nizhny Novgorod + JINR Dubna in D-Ru-Collaboration: 3D elliptical laser pulses

Short history of PITZ

- Start 1999: request to BMBF: build gun test facilty independant from TTF
- September 1999: DESY directorate decision to build PITZ
- 2000: civil construction
- 2001: installation of infrastructure and first setup
- **13.1.2002: first photo electrons at PITZ**
- November 2003: 1. 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 (~13 MeV) at PITZ
- 2006: provide spare RF gun for FLASH
- 2007: first demonstration: XFEL requirements reachable !
- 2009: best measurements better than XFEL specs !





Original proposal to BMBF in 1999

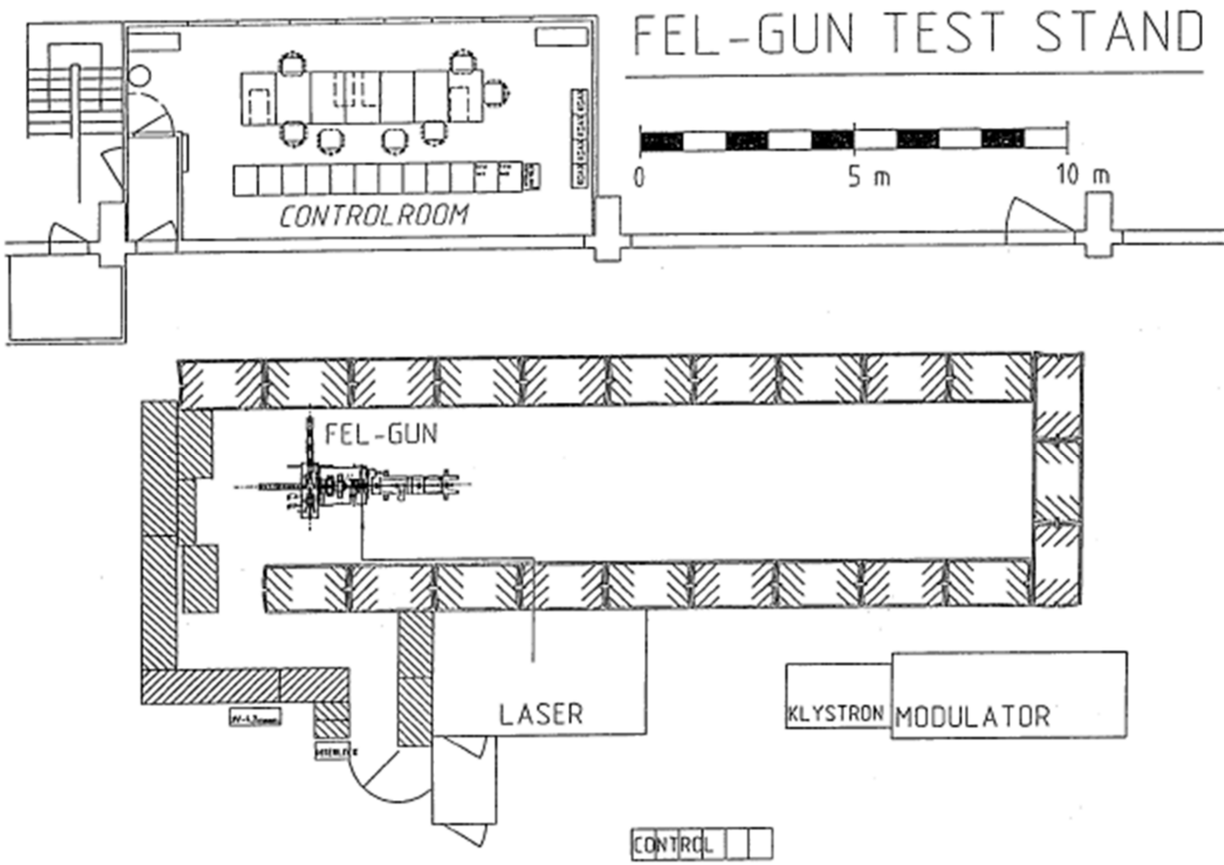
Proposal lead by Jörg Rossbach, with major contributions from Klaus Flöttmann and F. Stephan

RF Photoinjectors as Sources for Electron Bunches of Extremely Short Length and Small Emittance

Hochfrequenz-Photoinjektoren als Quellen für Elektronenpakete extrem kleiner Länge und Emittanz

Abstract

In collaboration with
DESY plans an int
Germany. This facil
elementary particle pl
diagnostics and mole
will lead to an integr
the VUV and the soft
For the FEL and linac
Therefore DESY run
the beam quality and
reach these goals it i
and theoretical appr
carried out. Experien
progress can be expe
An important challen
a pulse form, which i
time structure of the
the MBI, has a potent
femtosecond lasers w



ren und einer großen Zahl
für Angewandte- und
wird weltweit einmalige
tarteilchenphysik über die
bis hin zur medizinischen
fenden Forschungs- und
ierten Systemtest für einen
d weichen Röntgenbereich

onenstrahlen mit höchster
Entwicklungsprogramm im
iel einer Optimierung der
iebssicherheit, verfolgt. Zur
vicklung im Bereich der
insbesondere qualitativ
ingbar. Nach bisherigen
also nur aufgrund von

lung ist der Bedarf nach
er sub-pikosekunden-Skala
ronisiert sein müssen. Die
asis ist ausbaufähig und im
von breitem Interesse.

Fig. 9: Planned construction of the test stand in the area of the former S-band test linac.

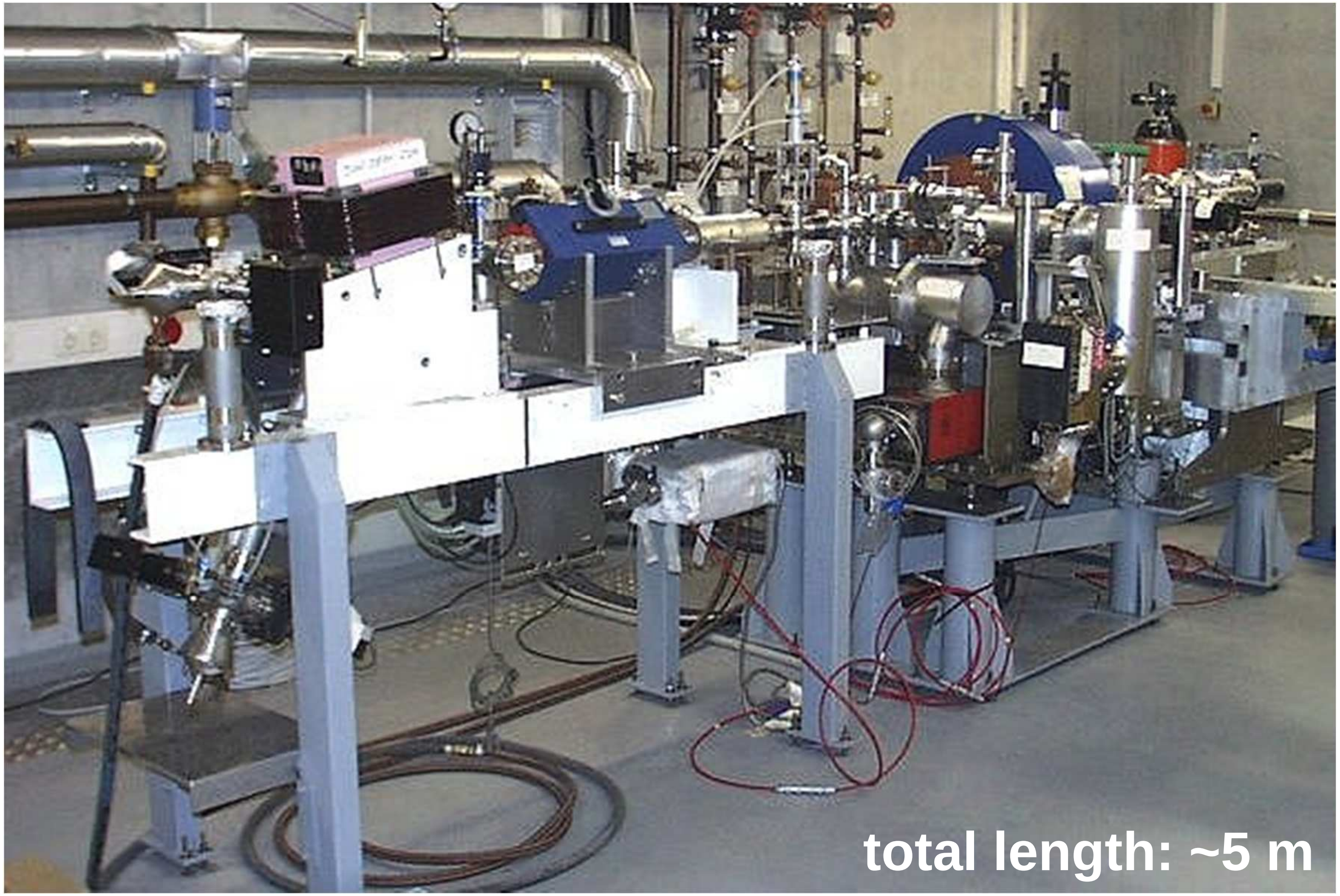
Spring 1999: foreseen to be realized in hall 2 in HH

Summer 2000 – Building the infrastructure

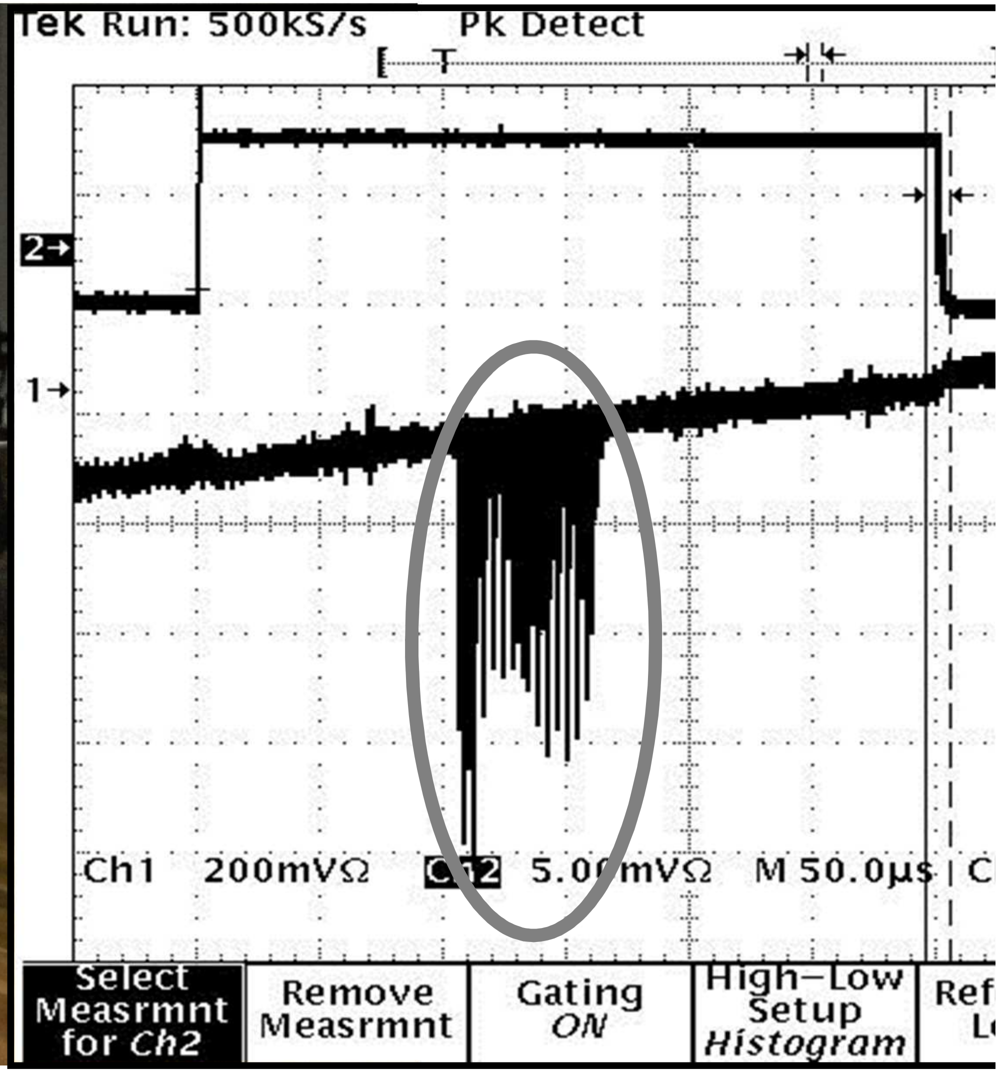
- **tunnel and klystron hall**
- **control room, laser hutch, rack room**
- **power station and cooling system**

December 2001

First installation and injector commissioning

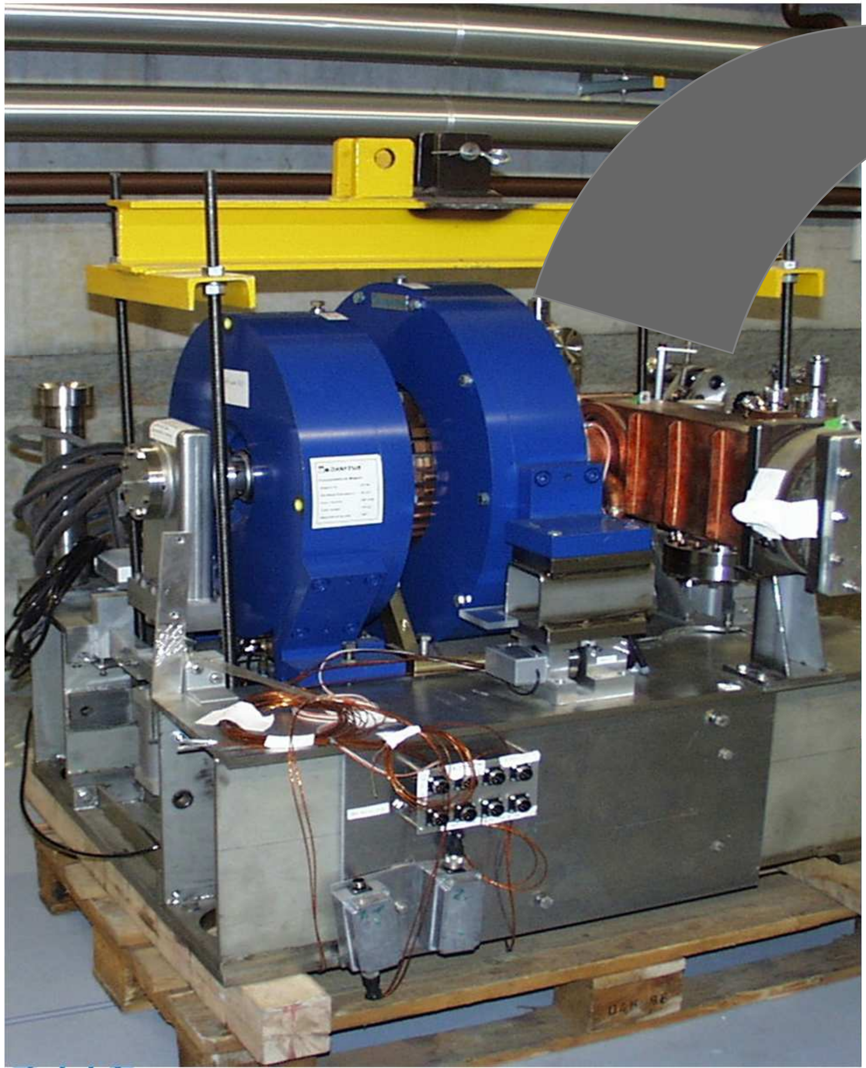


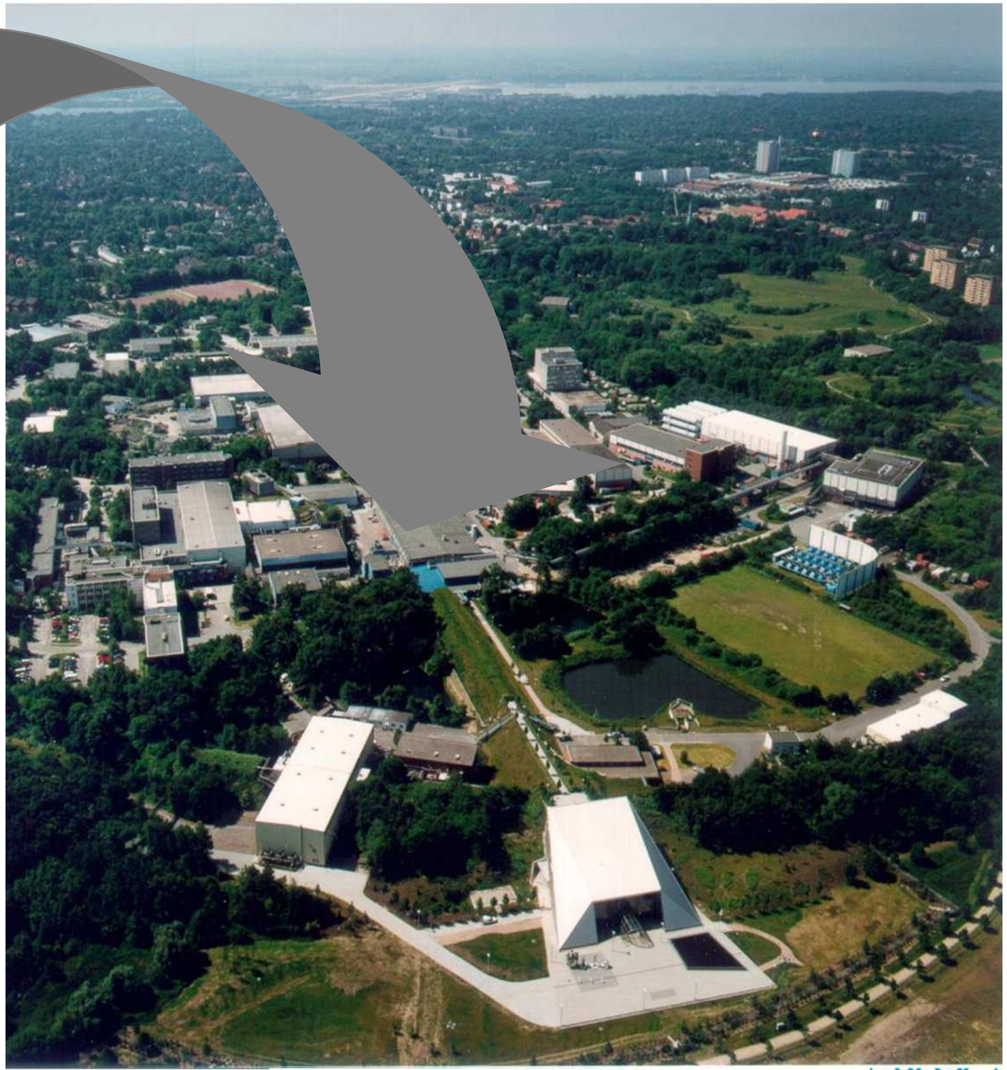
January 2002: First photo electrons produced



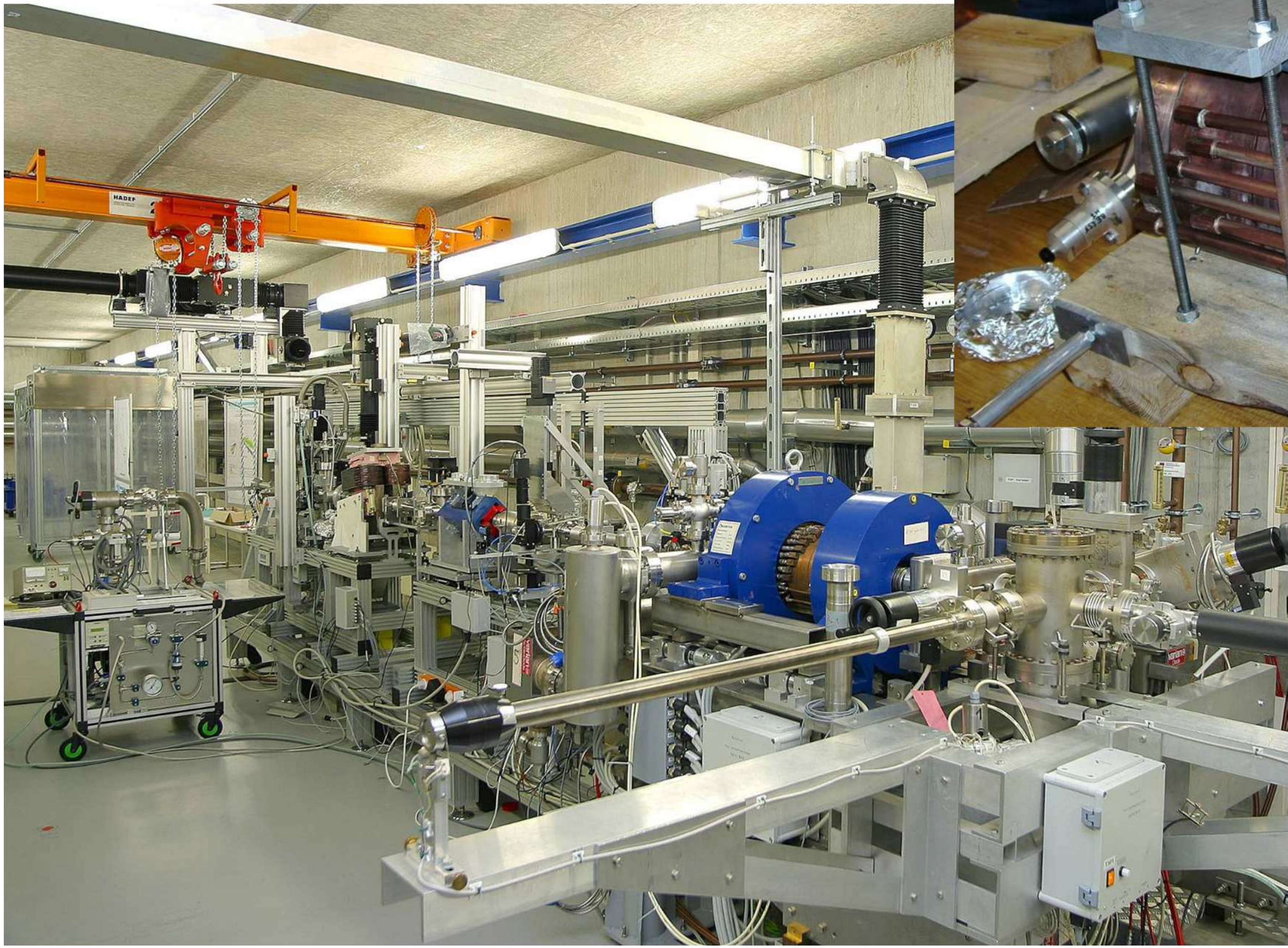
November 2003

First Gun (prototype #2) is characterized and sent to the FLASH facility



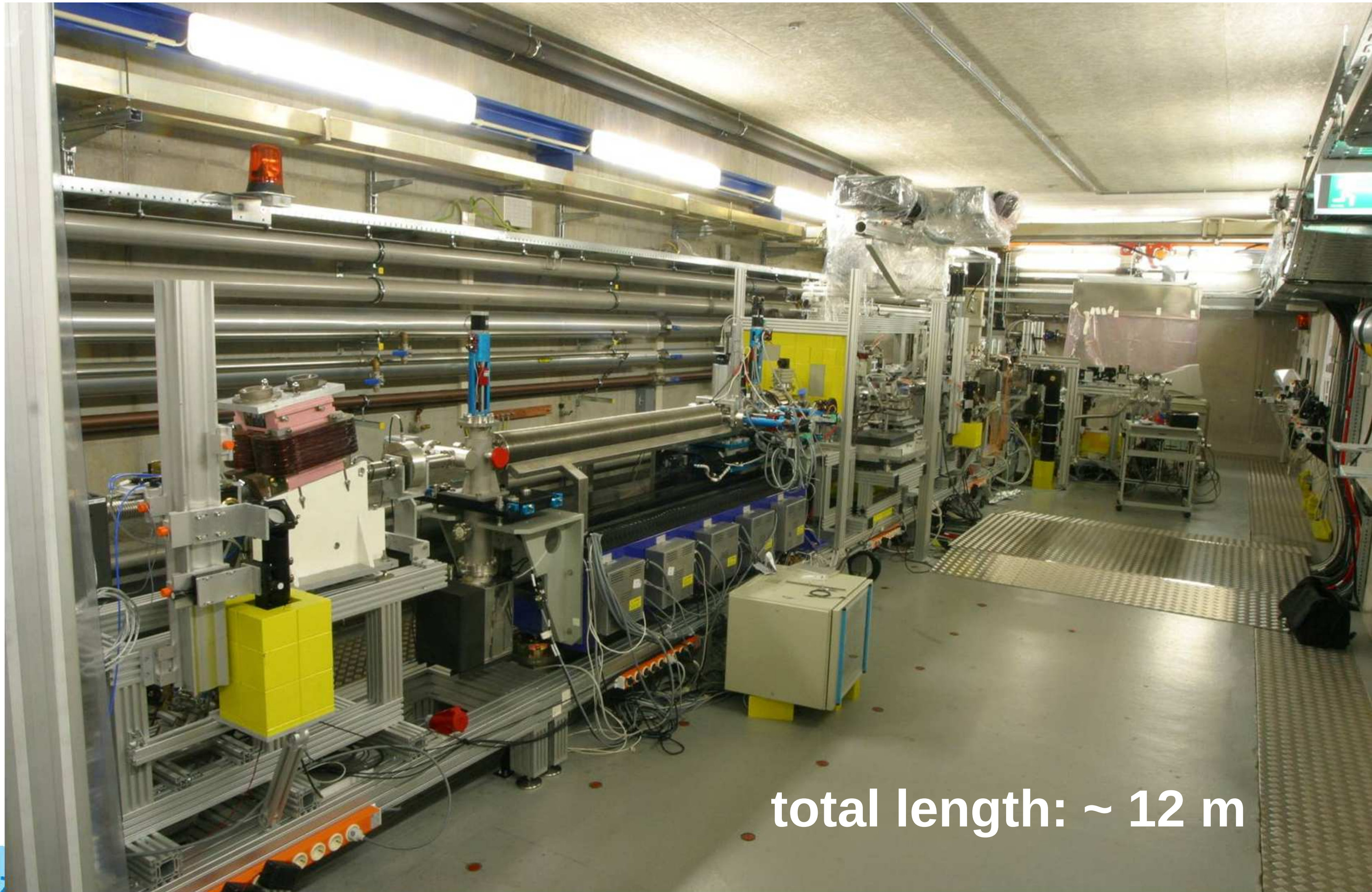


2004: PITZ continues with another gun



Spring 2005: Installation of PITZ1.5 …

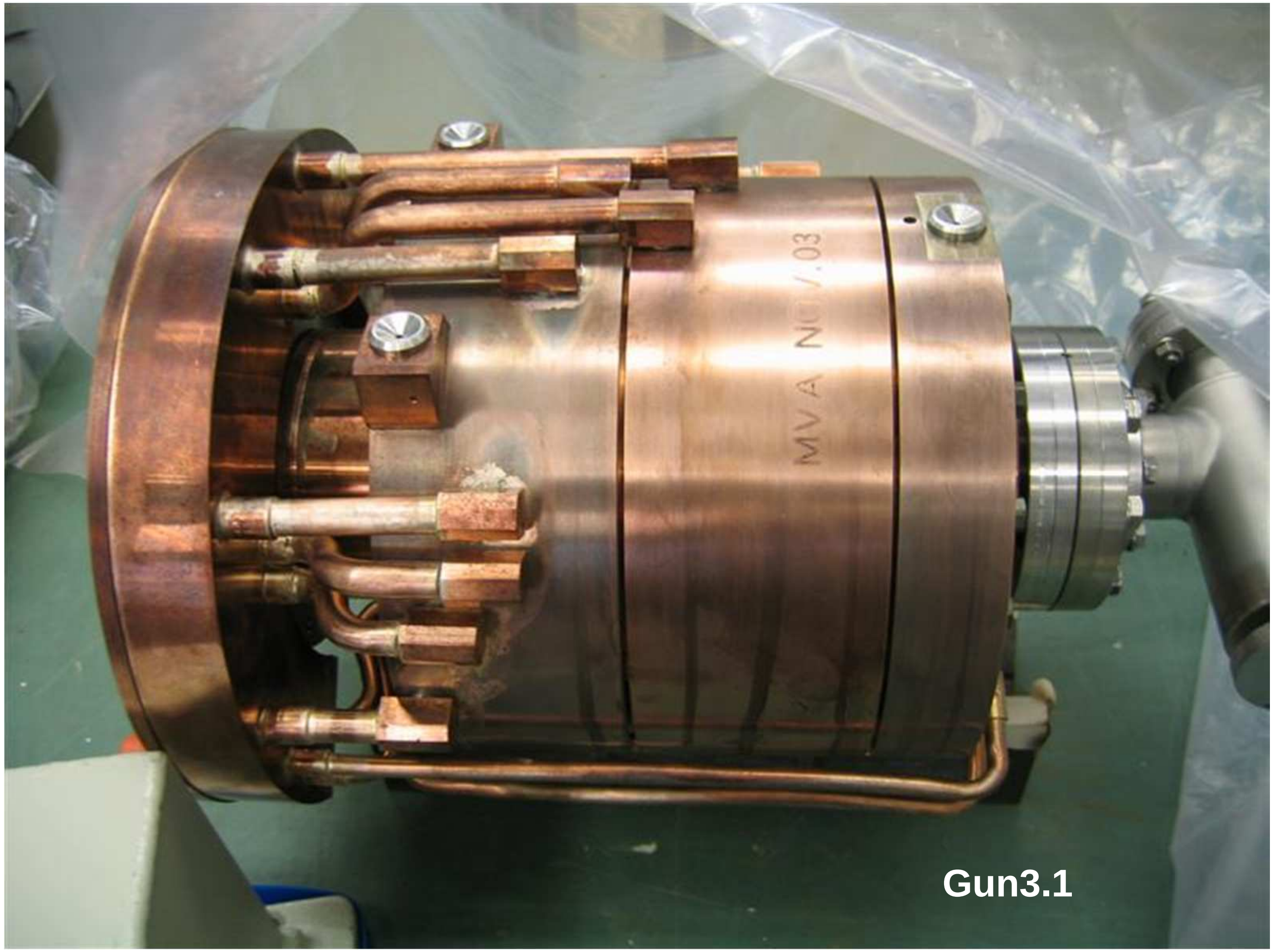
… with the booster cavity and the SPARC emittance meter



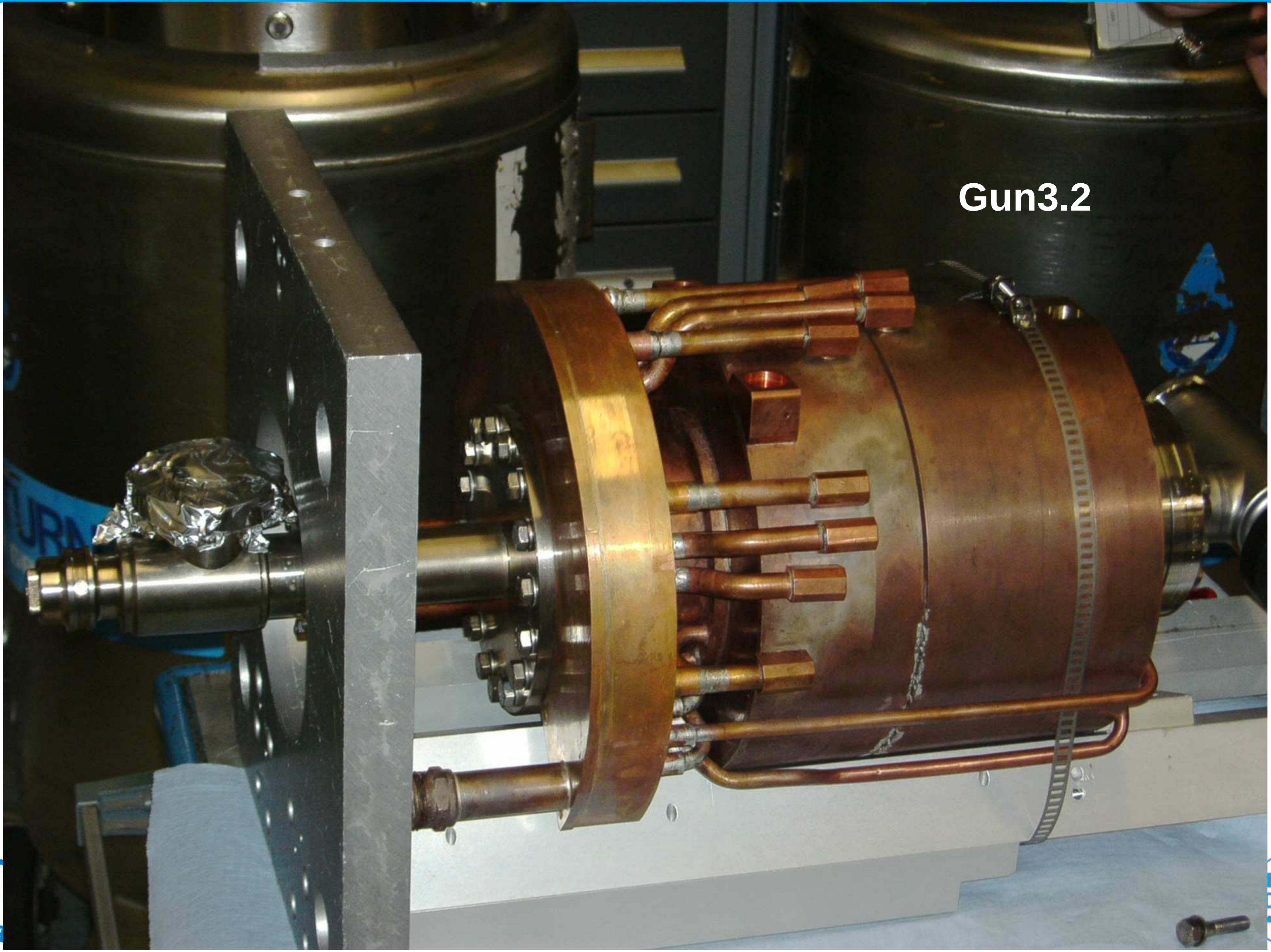
Summer 2005

- first measurements at increased beam energy (5 MeV → 13 MeV) using the TESLA booster cavity
- first high power tests of Gun1 with 10 MW klystron

2006: PITZ prepares a spare gun for FLASH



February 2007: The new PITZ gun is installed

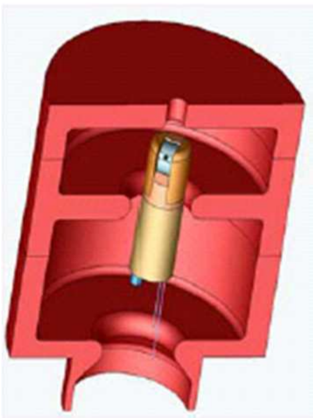


Operation at high duty cycle, reduction of dark current, 2008

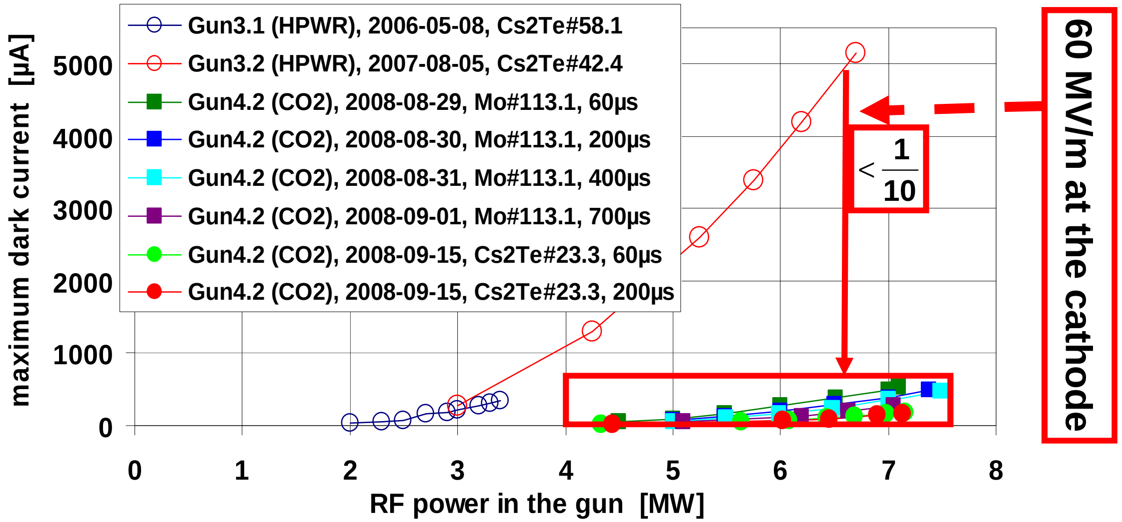
High Average Power Operation, Surface Cleaning ↔ Dark Current

Dry-ice sublimation-impulse cleaning
→ **dark current reduction**

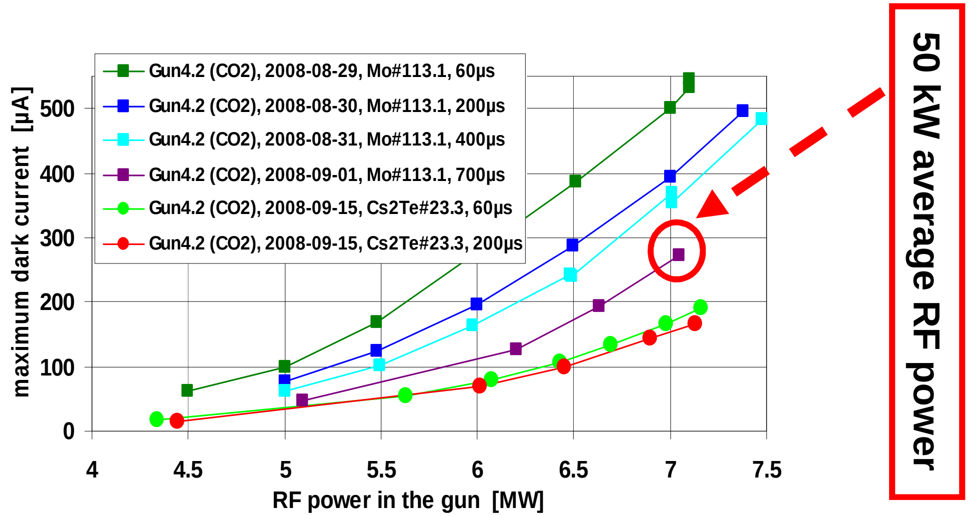
Vertical cleaning setup with 110° rotating nozzle.



Dark current measurements



zoom:

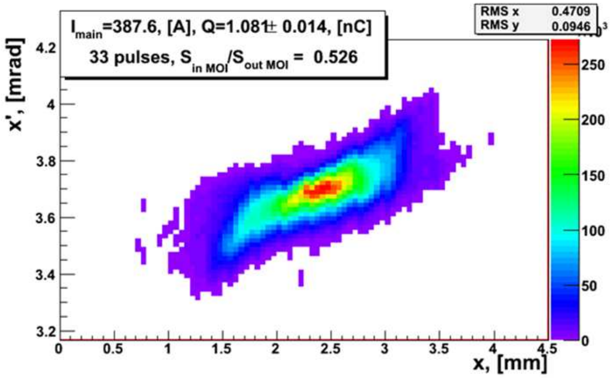


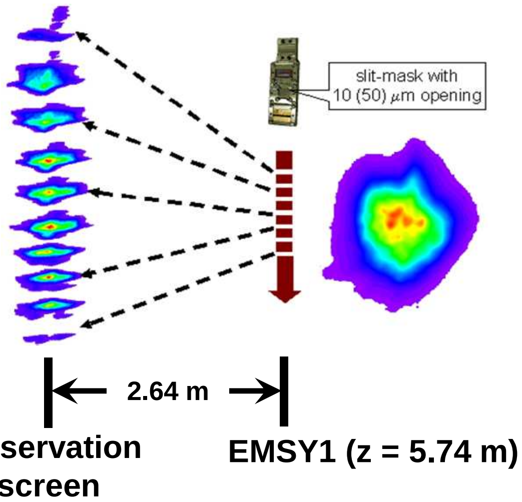
allows high brightness, high average current operation: 1–5 mA in 700 µs, 7–35 µA long term average

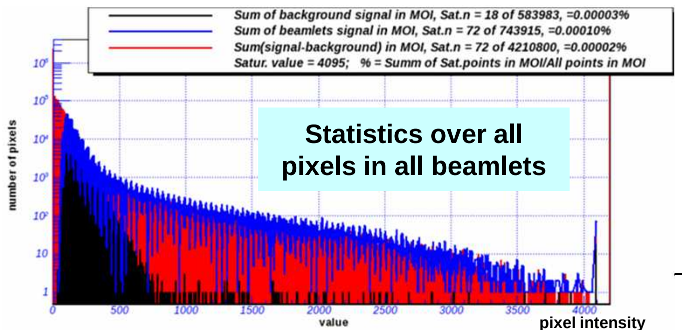
How we measure the transverse projected emittance

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

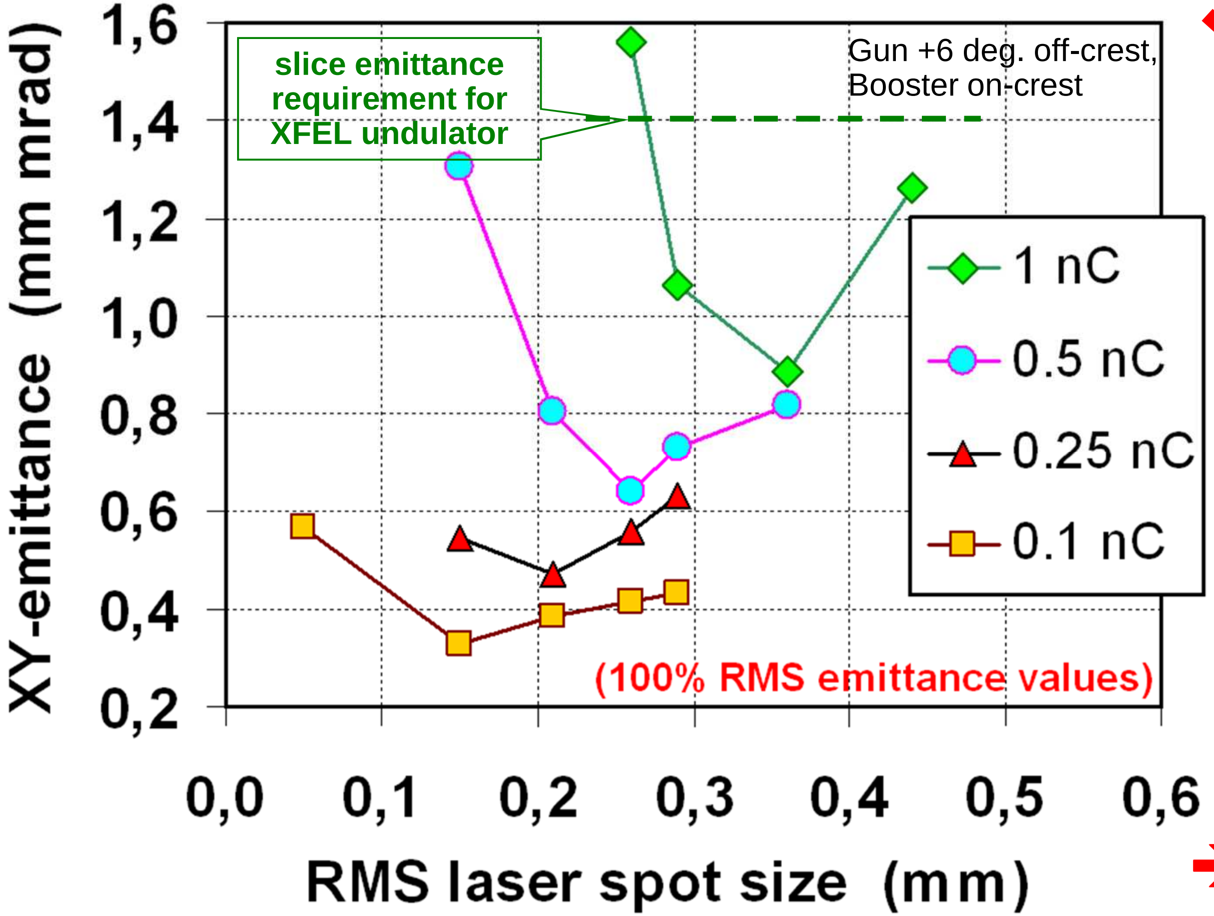
σ_x - RMS beam size measured with YAG screen at slit location

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

➔ **“100% RMS emittance”**

Emittanz results from 2009

Normalized projected Emittance vs. laser spot size@cathode for different bunch charges



these results + experience from LCLS (only small degradation of slice emitt. from gun to undulator)

➔XFEL can be operated with 14 GeV beam energy
(possibility to save ~33M€)

➔ Gun now in operation at FLASH

see e.g.:
S. Rimjaem et al., proceedings of FEL2010

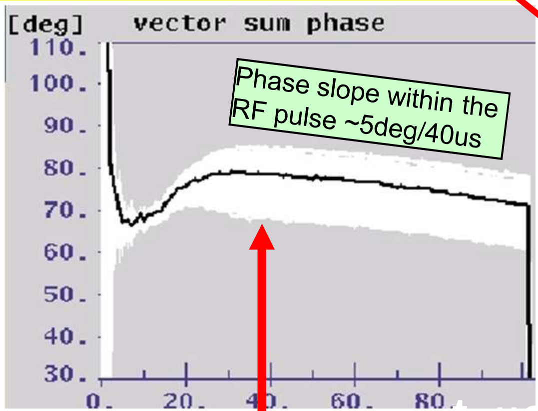
PITZ Photo Injector Test Facility Zeuthen

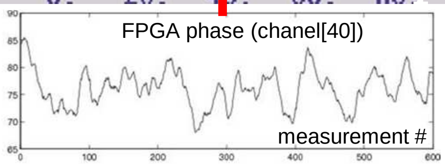
DESY

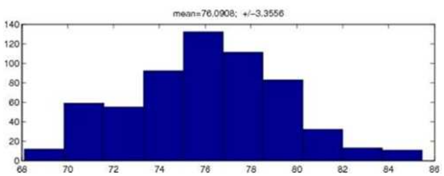
Improvement of the RF gun phase stability

2009 (no FB)

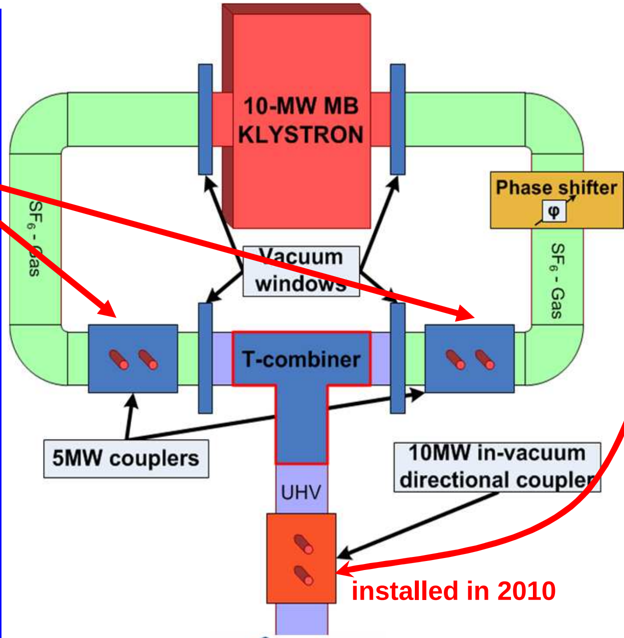
FPGA phase, reconstructed from virtual ADC probes based on 2x5MW directional couplers

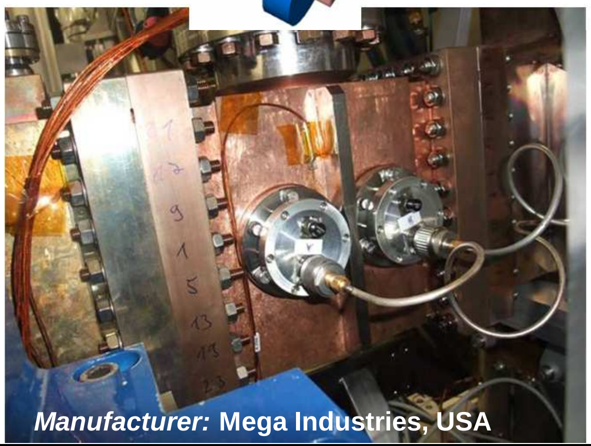






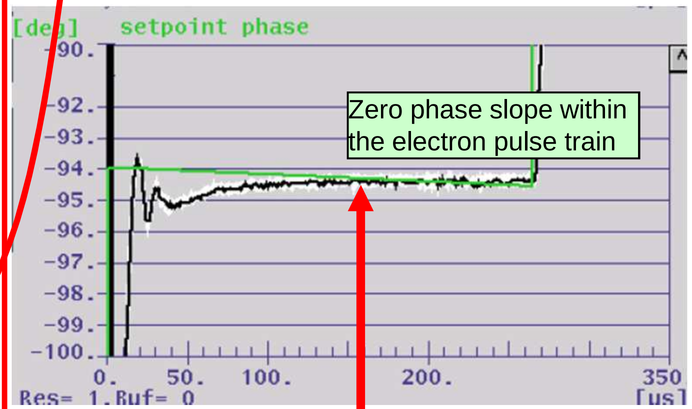
Phase fluctuations:
- **10..15 deg (p-p)**
- 2..4 deg (rms)

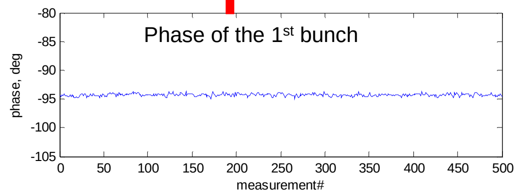


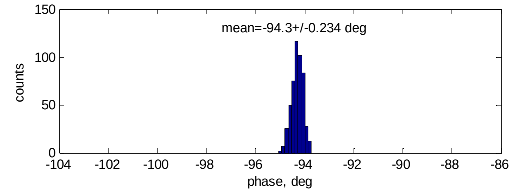


2011 (FB is ON!)

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

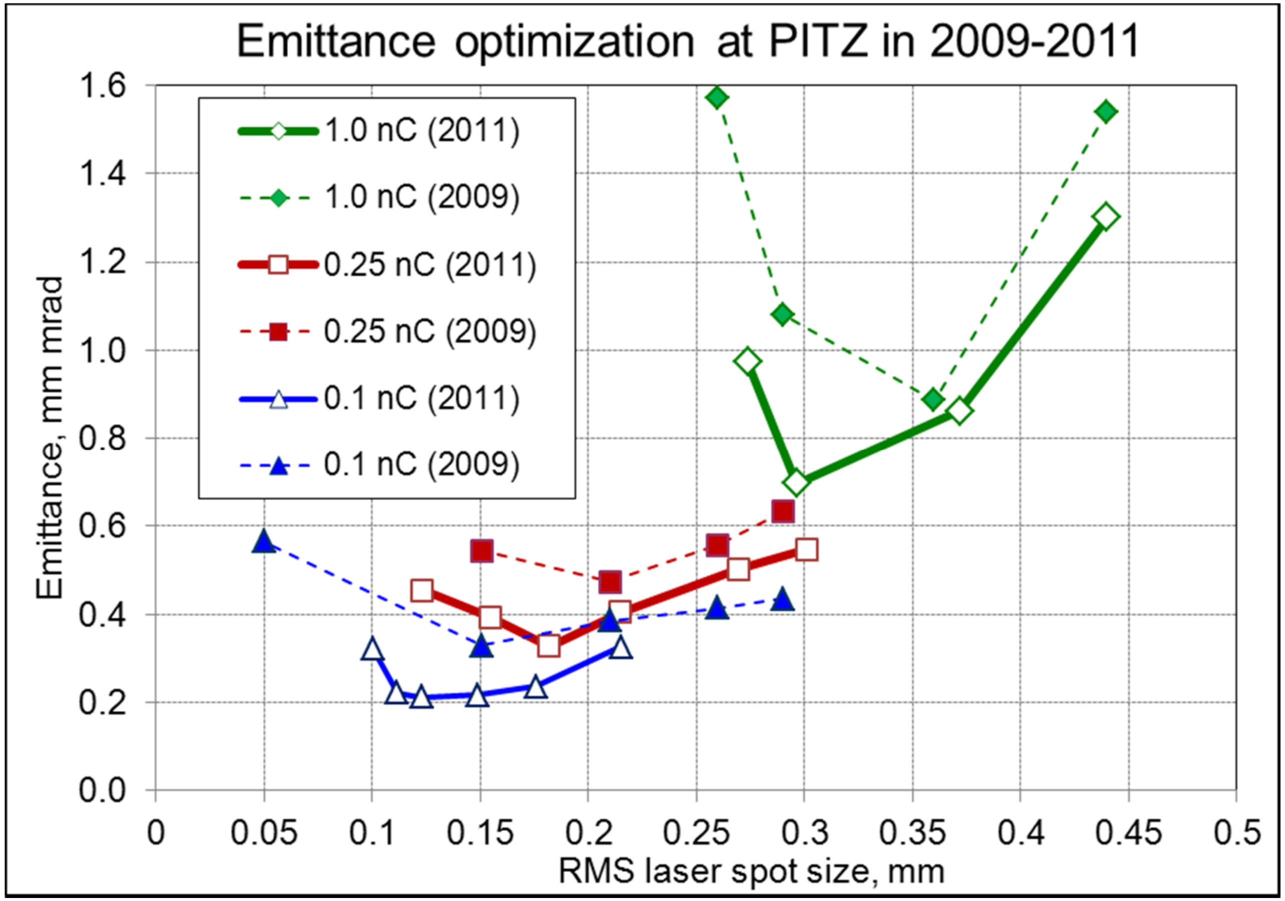






Phase fluctuations:
- **1..1.5 deg (p-p)**
- 0.2..0.3 deg (rms)

NEW Emittance Results: Improvement 2009 → 2011



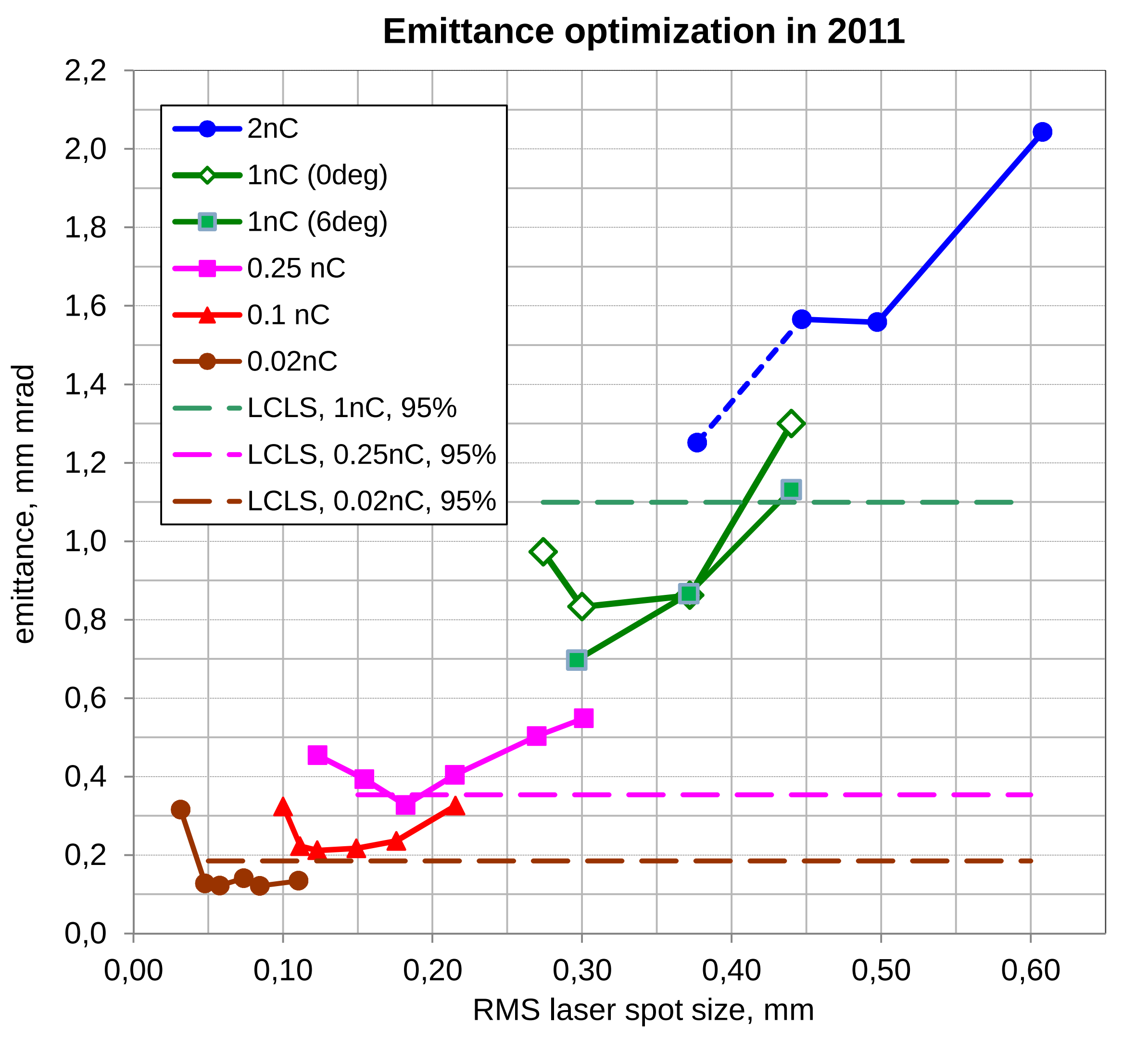
Improvements:

- **Gun phase stability** (10MW coupler+FB)
- Increased beam energy to ~25MeV (2009: <15MeV)
- Laser beam transport
- Removing magnetizable components

Q nC	ε(2011) mm mrad	δε(2011→2009) %
1.0	0.70	-20%
0.25	0.33	-30%
0.1	0.21	-35%

Higher emittance improvement for lower bunch charges → due to the long pulse train operation (→ “3000-creteria” = f[gain,NoP])

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

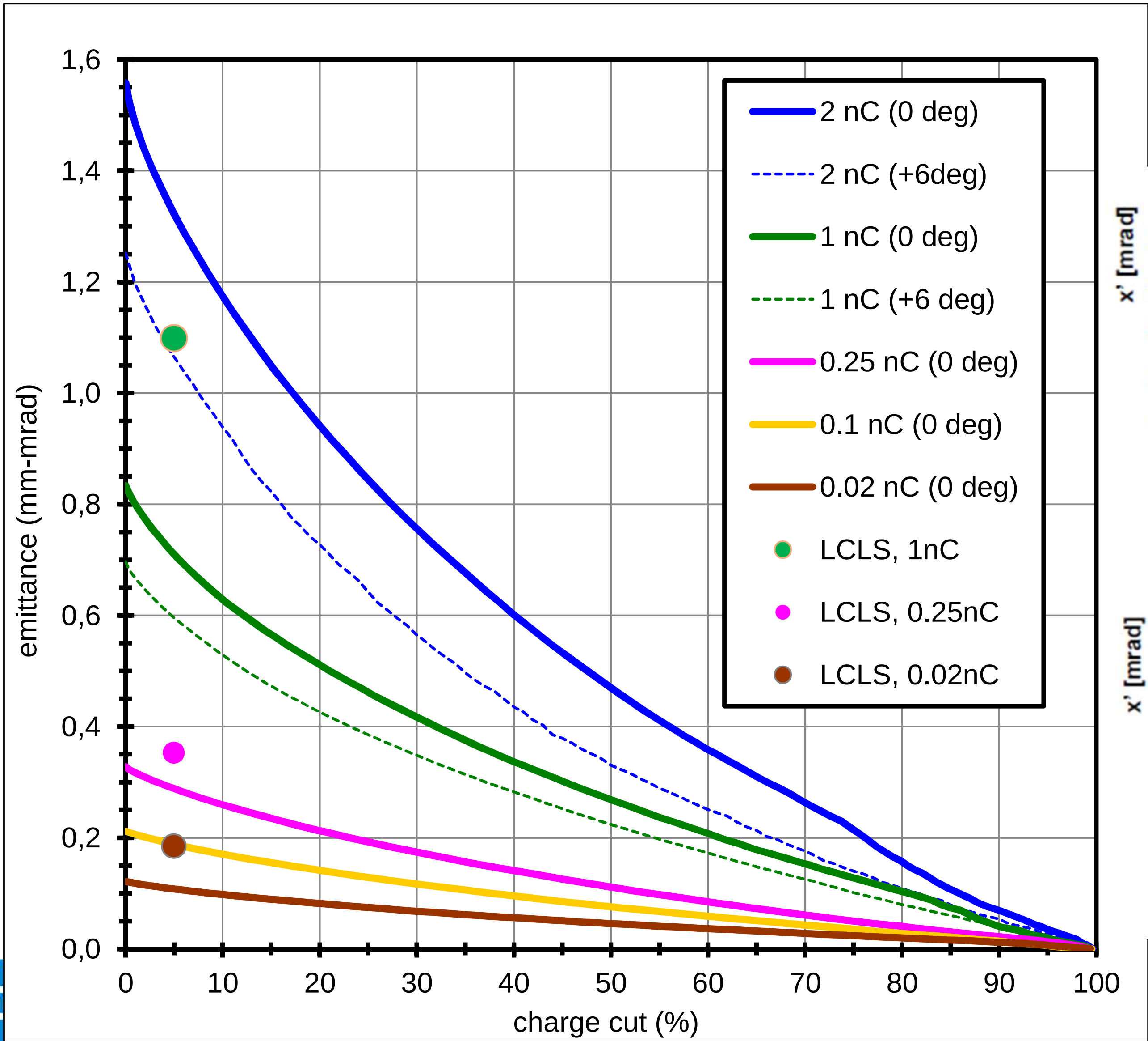
> **PITZ is setting a new benchmark for minimum emittance at a given charge**
> **+**
> **is capable of operation at high duty cycle !!**

LCLS data:

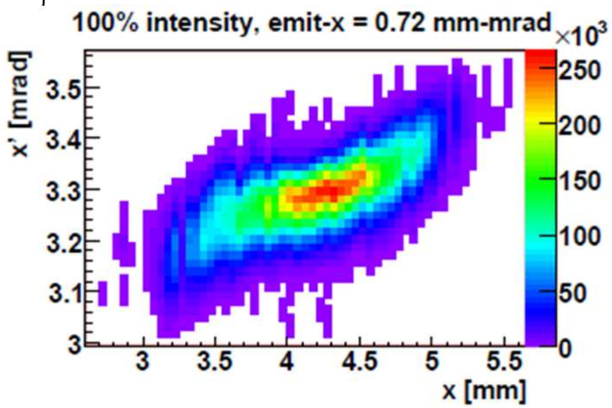
- P. Emma, "Beam Brightness Measurements in the LCLS Injector", Mini-WS on compact XFELs using HBB, LBNL, Berkeley, USA, 2010.
- J. Frisch, "Operation and Upgrades of the LCLS", LINAC2010, Tsukuba, Japan.

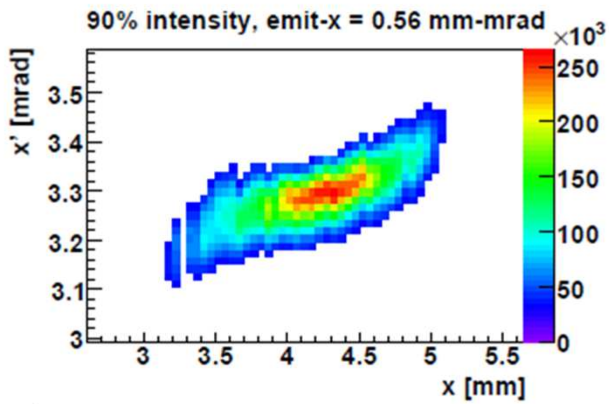
Core Emittance for various bunch charges

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



An example for 1 nC:



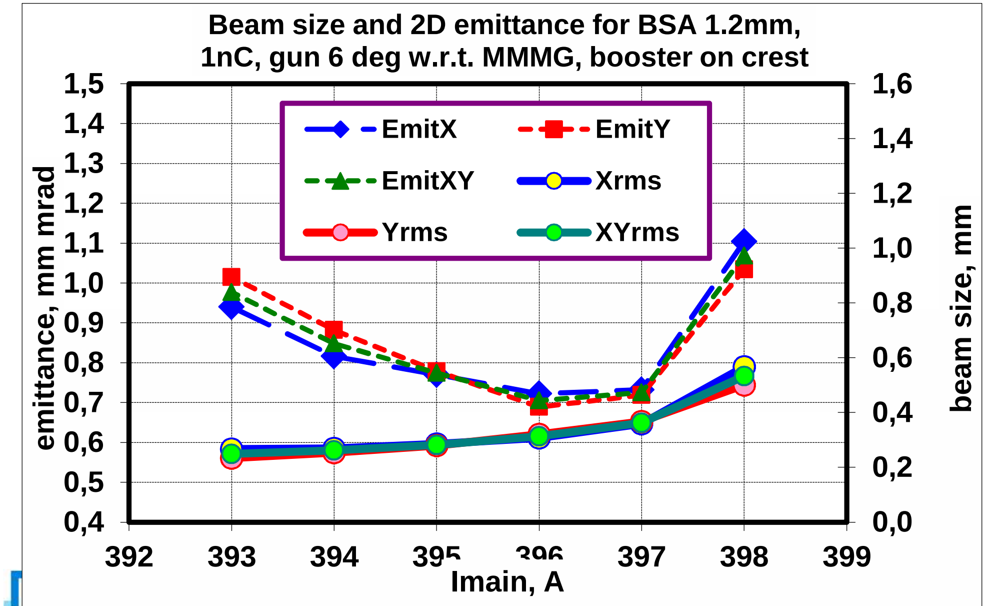


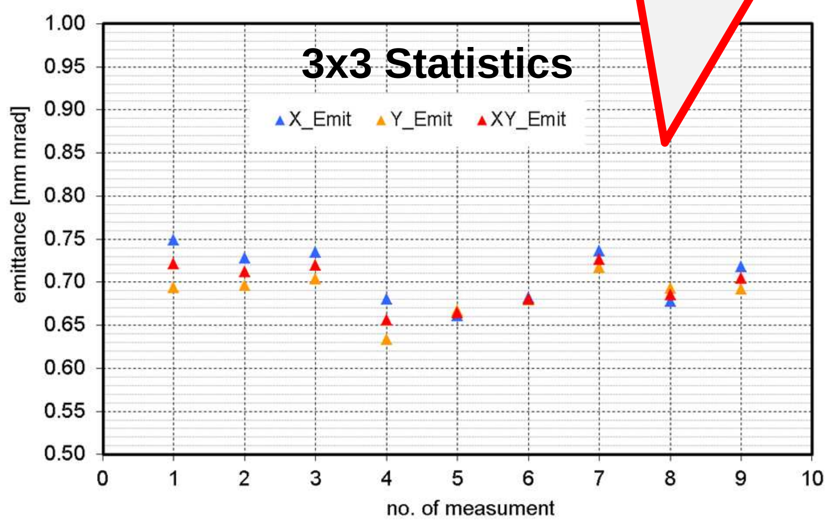
High stability of the measurement

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
For all measurements f250 lenses and 2x2 binning were used																			
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

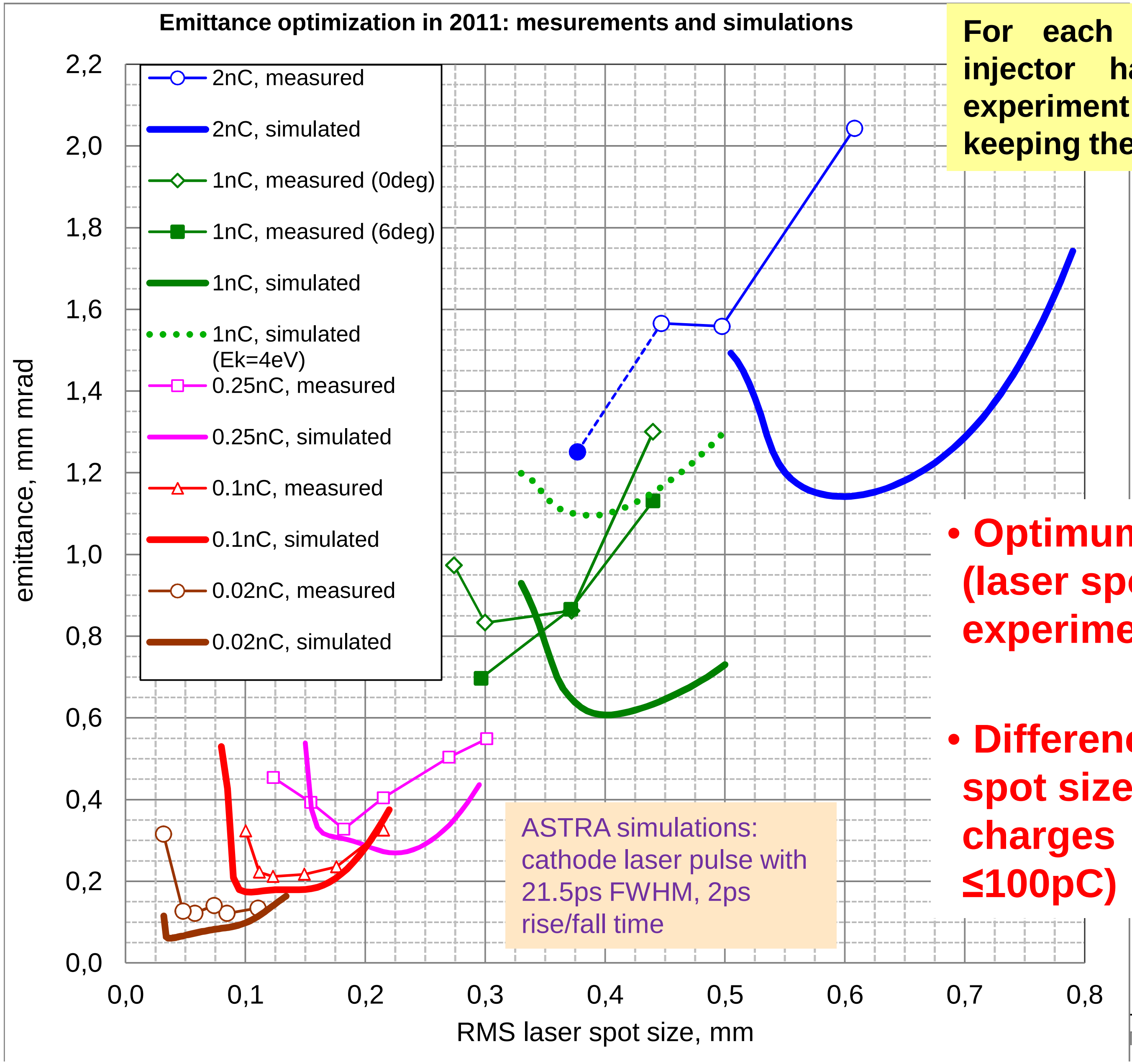
Example, measurement on 5.5.2011:
1nC Emittance vs. Iman
(gun SP phase=6deg)

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





2011 PITZ 1.8: measurements vs. simulations

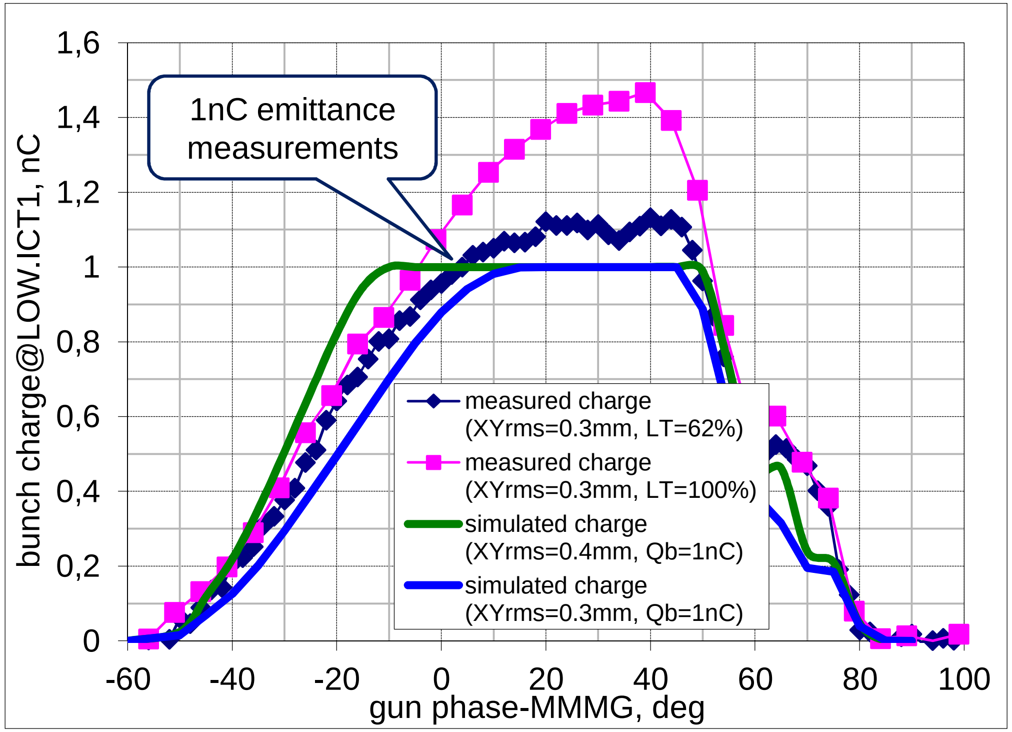


For each bunch charge the photo injector has been optimized (both experiment and simulations), but keeping the laser temporal profile fixed.

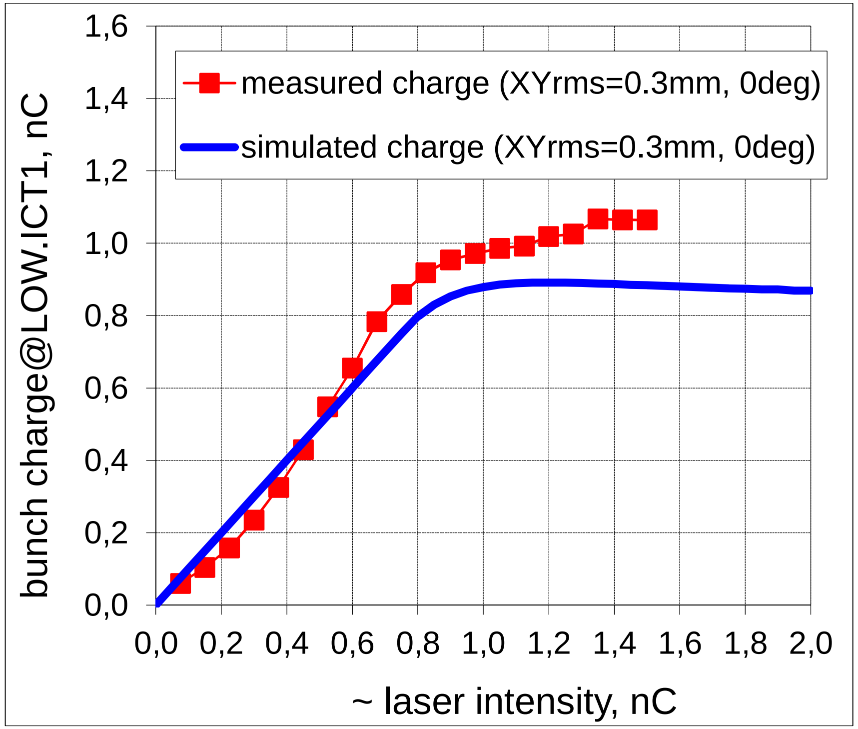
- **Optimum machine parameters (laser spot size, gun phase): experiment ≠ simulations (~on-crest)**
- **Difference in the optimum laser spot size is bigger for higher charges (good agreement for ≤100pC)**

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.

One important contribution to the success of PITZ …

… is the photo cathode laser system developed by the Max Born Institute in Berlin (MBI)

- development started 1998/99
- many intermediate steps have been realized and tested at PITZ
- spin-off of development is used at FLASH (and elsewhere)
- over the years direkt support for the photo cathode laser development has been acquired form the BMBF, major parts of the development costs were also covered by DESY and MBI
- Photo cathode laser systems developed by the MBI are running at
  - Hamburg: FLASH, in future of course also at European XFEL
  - Zeuthen: PITZ
  - Dresden/Rossendorf: ELBE
  - Berlin (HZB): SC gun test stand

Latest photo cathode laser system installed at PITZ

Yb:YAG laser with integrated optical sampling system

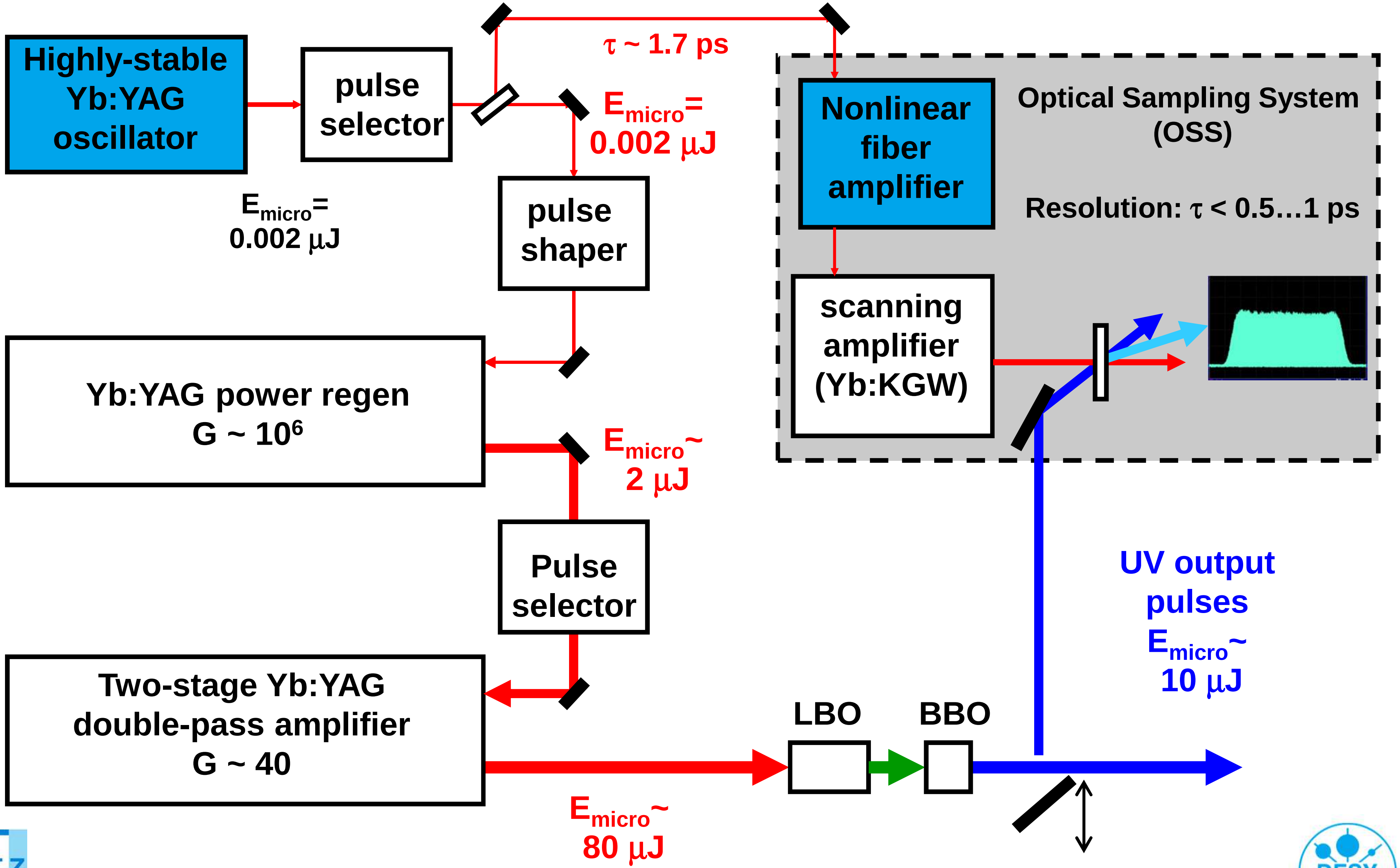
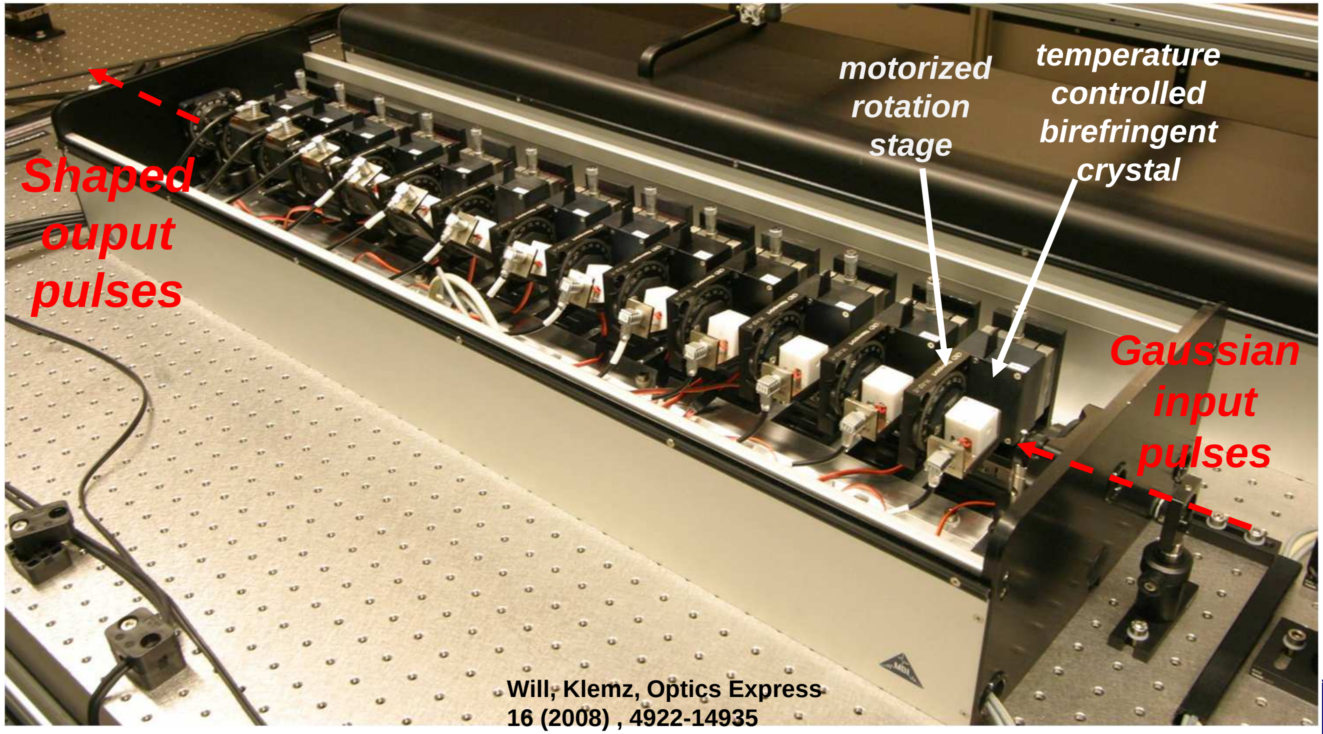
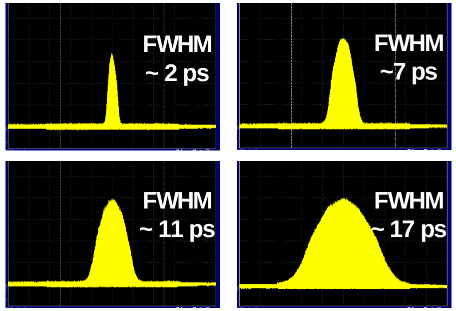


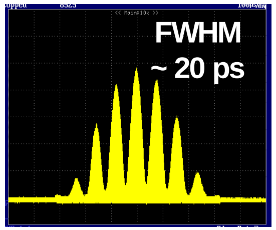
Photo cathode laser: temporal pulse shaping

Multicrystal birefringent pulse shaper containing 13 crystals

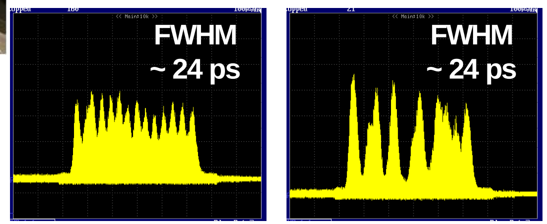


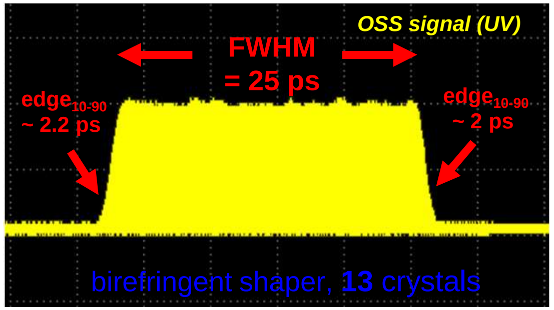
Gaussian:





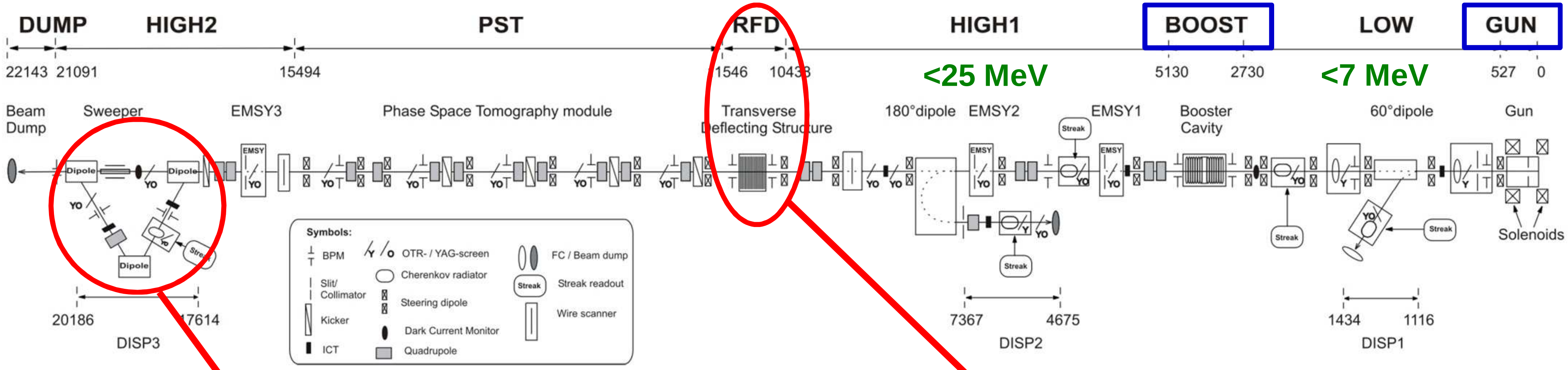
Simulated pulse-stacker

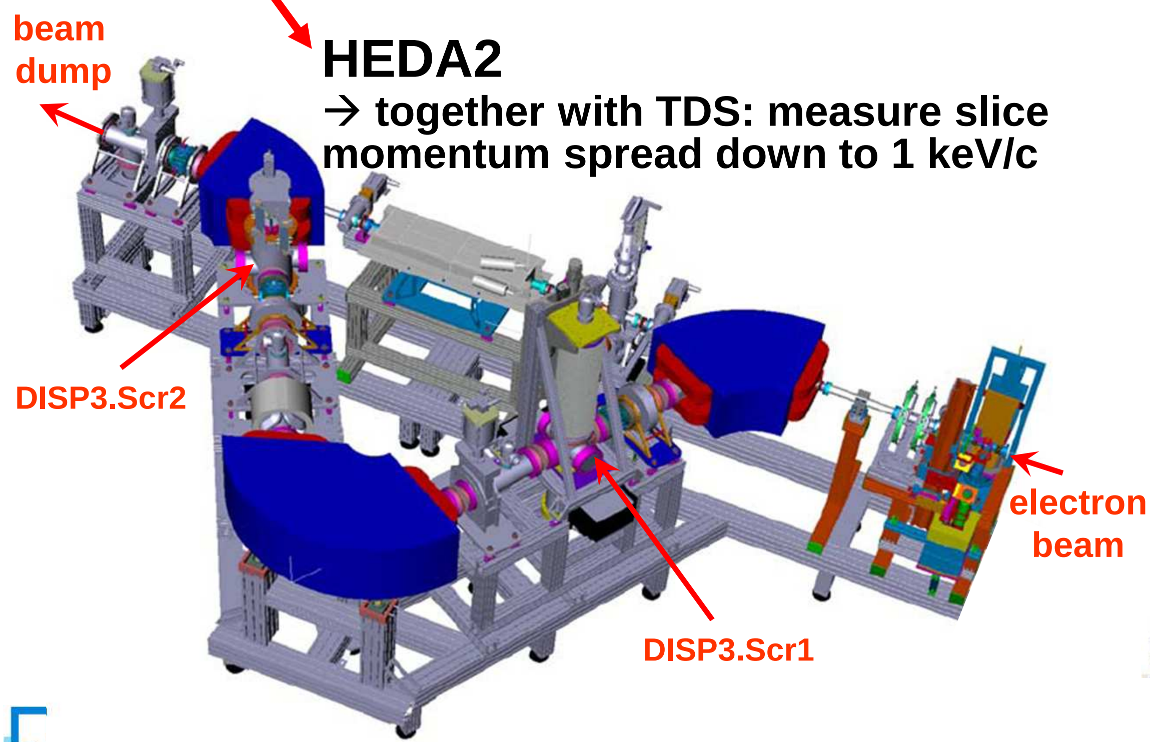




→ high flexibility
→ new options !

Current setup (with latest installations): PITZ 2 (~22 m total length)



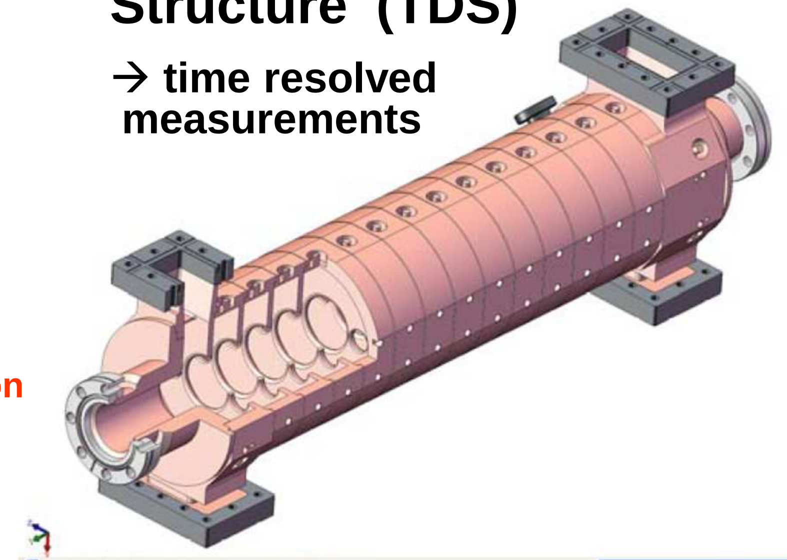


HEDA2

→ together with TDS: measure slice momentum spread down to 1 keV/c

Transverse Deflecting Structure (TDS)

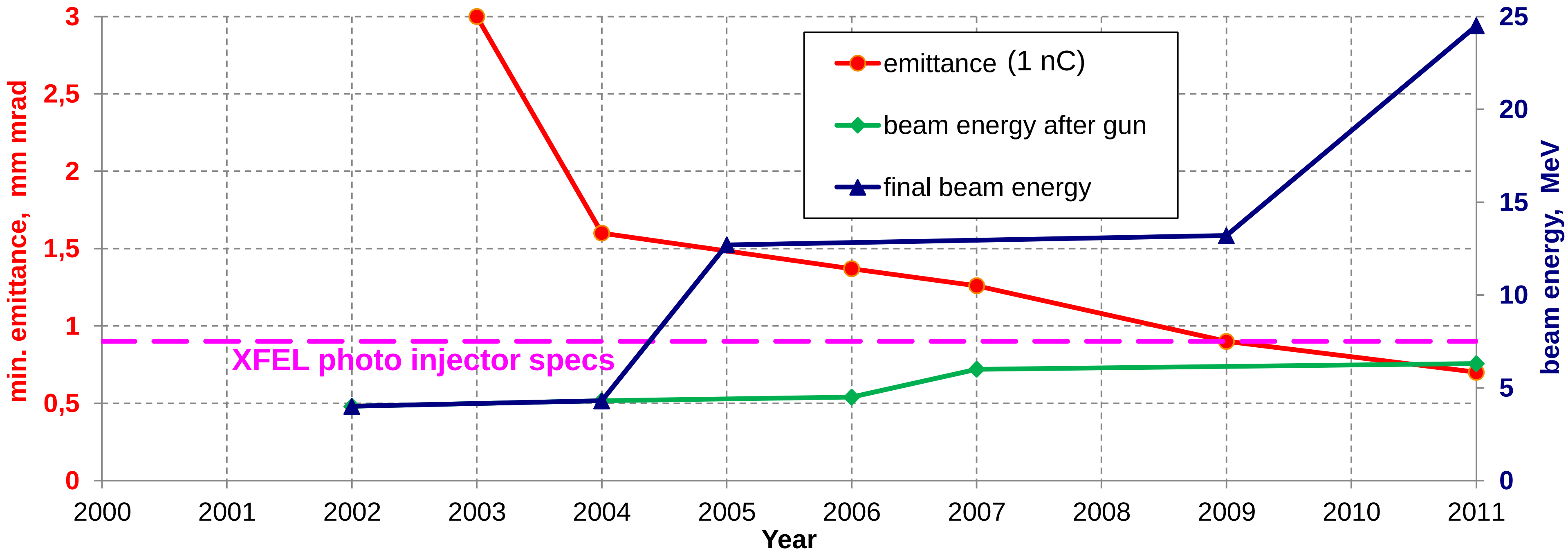
→ time resolved measurements



PITZ evolution 2000-2011

	Year-->	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
gun	cavity	gun-2		gun-1		gun-3.1	gun-3.2	gun-4.2		gun-4.1	
	Ez	35MV/m	37MV/m	42MV/m-->60MV/m		43MV/m	60MV/m				
	beam energy	~4MeV		4.3MeV-->6MeV		4.5MeV	~6MeV				
booster	cavity	no			TESLA at 2.5m		TESLA at 3.1m			CDS at 3m	
	beam energy				~13MeV					~25MeV	
laser	temporal	10ps	6/24\6ps				6/24\6ps	2/22\2ps			
emittance	EMSY1 at	z=1.618m			z=4.3m		z=5.74m				
	Ldrift	1.01m			2.334m		2.64m				
	methodics	center BL	3xBLs		e-meter	11xBLs			detailed scan		
	min ε_{xy} (1nC) mm mrad		**3**	**1.5-1.7**		**1.37**	**1.26**		**0.9**		**0.7**

FLASH



Summary

- Good decision to build PITZ in Zeuthen:
  - Close integration into DESYs **core program**, inclusion of Zeuthen **manpower**, spin-offs: e.g. competence on vacuum design and successful work of modulator test facility
  - Important contribution to European XFEL, **international visibility**
  - Right **size** to be done in Zeuthen
- In 2011 with Gun4.1, CDS booster and significantly improved RF regulation a **new benchmark** in optimizing photo injector performance **was set worldwide** (e.g. emittance values at different bunch charges: 1.25 mm mrad@2nC, 0.7 mm mrad@1nC, 0.12 mm mrad@0.02nC).
- Problem: **Simulations** do not reproduce the data (w.r.t. optimum laser spot size, gun phase, emitted charge). More studies (exp./sim.) needed.
- Available photo cathode laser gives **high flexibility**
- Sophisticated **diagnostics setup** almost complete

} → new options !

Outook, Scientific plans for the future

PITZ delievered decisive contributions to FLASH and XFEL and can also be a **goldmine** in future:

Bread & Butter (ongoing, partially done) **:**

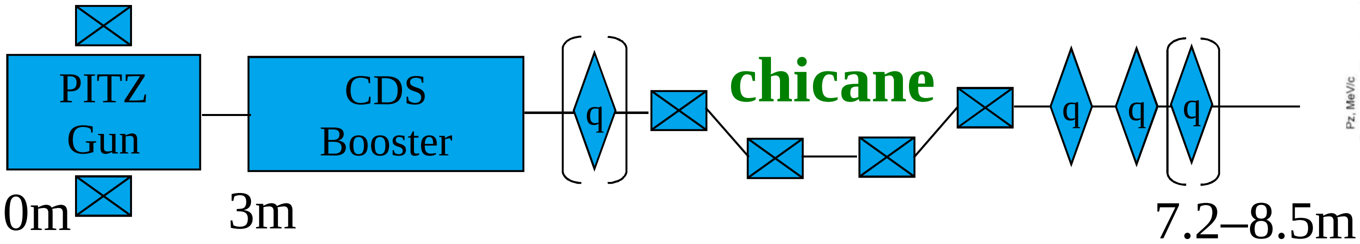
- Gun characterization
  - for XFEL: re-check different bunch charges (0.02 to 3 nC), **effect of different rise/fall times of the laser**, longitudinal phase space studies, slice emittance cross check, long term reliability
  - later: higher repetition rate
- XFEL **testbed**, e.g. laser system (4.5MHz + therm. lense), beam diagnostics
- Laser beam **imaging** onto photo cathode at FLASH & XFEL (→ low **ε**, Q & halo)
- Gun5 (RF amplitude & phase stability, higher average power)

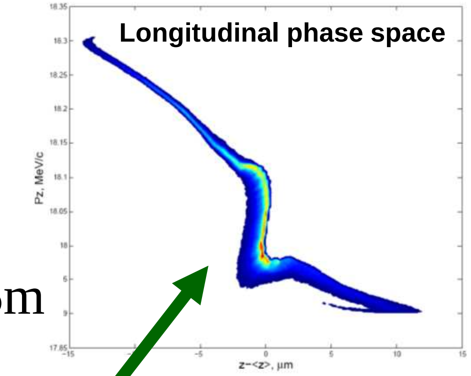
New tasks/options (sucking honey from low emittance and flexibility @PITZ) **:**

- Optimizing new operation modes: **ultra short bunches** (single spike lasing)
  → together with HH: S2E simulations, exp. tests, diagnostics
  → **3D elliptical laser pulses** on cathode: lower **ε,** halo, bunch length
- E.g. participation in **particle driven plasma wakefield acceleration**

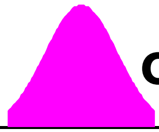
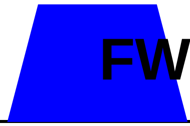
Generation of ultra short pulses, for LPA with external injection or other applications (e.g. THz)

Setup:





Vary parameters and try different laser shapes

Q = 1pC	 σ_t = 1.2ps	 FWHM = 9.4ps	 σ_t = 4ps
σ_t	9.1 fs	9.6…8 fs	10.3 fs
I_{peak}	~60A	65...90A	**~200A**
σ_x	8.5 µm	5.4…13.4 µm	7.7 µm
σ_y	8.8 µm	9.9…4.7 µm	10.4 µm

~10fs

<10µm²

All not yet fully optimized

Particle driven plasma wakefield acceleration (PDPWA)

Proton-driven PWFA experiment proposed at CERN:

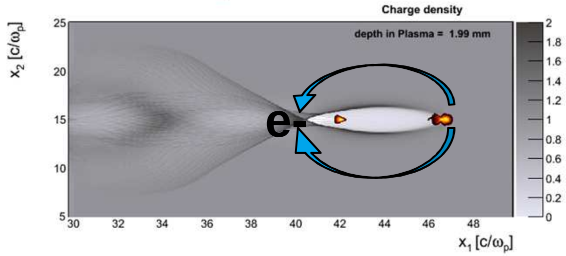
- Use high energy proton beams to drive wake (plasma wave)
- Convert proton beam energy into e^- or e^+ beam in a **single** stage

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

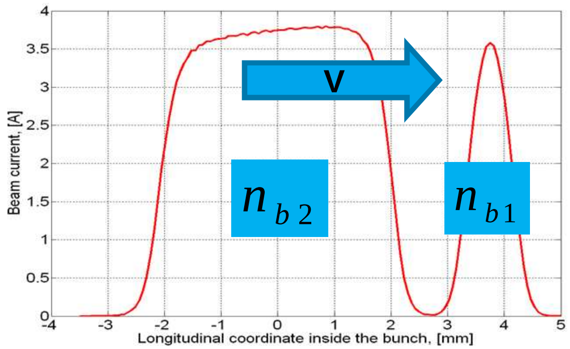
- Use beam-plasma instability to modulated the beam at λ_p, driving large plasma waves for acceleration Kumar *et al.*, PRL (2010); Lotov, Phys. Plasmas (2011)

Does this work ?
→Dephasing ?
→Hose instability ?

Courtesy of Carl Schröder, LBNL

Studies for Particle Driven Plasma Acceleration @PITZ

- **Self-modulation with seed pulse:**



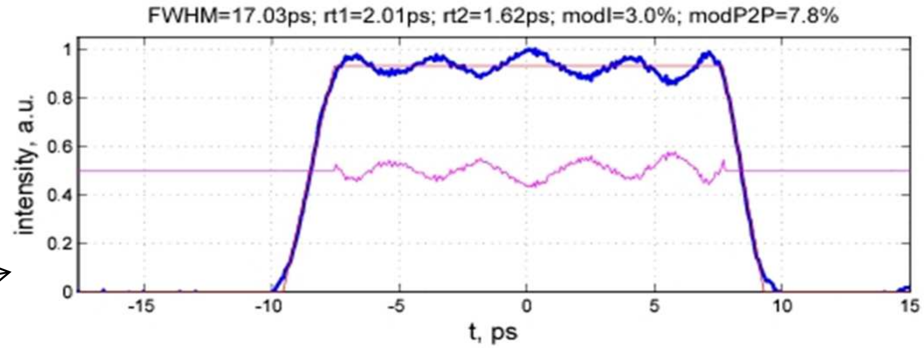
Output parameters for 2 sub-bunches @6.28m from cathode:

Gauss: $Q = 10pC,\ \sigma_z = 0.311mm$, $\sigma_{xy} = 83.25\,\mu m,\ \varepsilon_{xy} = 0.471\,mm\,mrad$ } $n_{b1}[cm^{-3}] = 3.69 \cdot 10^{12}$

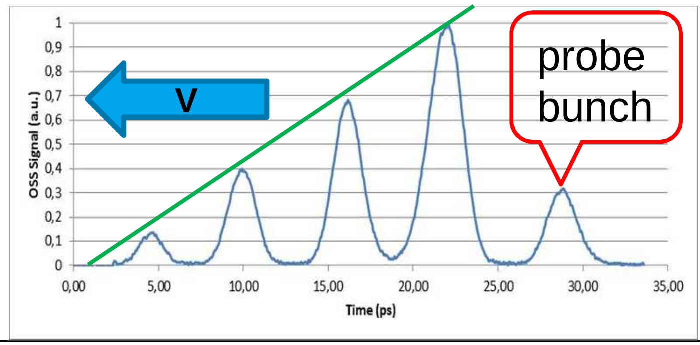
Flat-top: $Q = 50pC,\ L_b = 4.05mm$, $\sigma_{xy} = 48.45\,\mu m,\ \varepsilon_{xy} = 0.448\,mm\,mrad$ } $n_{b2}[cm^{-3}] = 1.05 \cdot 10^{13}$

- **Self-modulation without seed but with flat-top modulation:**

Photo cathode laser distributions



- **Resonantly driven plasma wave → high tranformation ratio → 5 Bunchlets inside the bunch:**



to be sent to bunch compres-sor

Thank you very much to everybody …..

who was/is participating in the success of PITZ:

> to the national and international partners [CCLRC Daresbury, FZDR, Hamburg-University, HZB(BESSY), IAP Nizhny Novgorod, INFN Frascati & Uni Roma, INFN Milano, INRNE Sofia, INR Troitsk, JINR Dubna, LAL Orsay, MBI, ThEP Chiang Mai, TU Darmstadt, YERPHI Yerevan]

> to the many colleagues from different groups at DESY, Hamburg site

> to the many colleagues at DESY, Zeuthen site, only some of them shown here →

The End